# Study of the decay $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ and its intermediate states

# DISSERTATION

zur Erlangung des akademischen Grades Doctor rerum naturalium (Dr. rer. nat.)

vorgelegt der Mathematisch-Naturwisenschaftlichen Fakultät der Universität Rostock

von Diplom-Physiker Thomas Hartmann geboren am 3. Dezember 1979 in Stadthagen

urn:nbn:de:gbv:28-diss2011-0084-8

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Eingereicht am 2. März 2011

Verteidigt am 15. April 2011

#### Abstract

In this thesis the analysis of the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  including the resonant decays  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  is presented. The measurement is based on about 467 million  $B\overline{B}$ -meson pairs, which were recorded with the *BABAR* detector at the PEP-II  $e^+e^-$ -storage rings at the SLAC National Accelerator Laboratory. In events of  $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ ,  $B^0$  and  $\overline{B}^0$  mesons were reconstructed in the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  with the subsequent decay  $\Lambda_c^+ \to pK^-\pi^+$ . Intermediate states with  $\Sigma_c^{++}(2455,2520)$  and  $\Sigma_c^0(2455,2520)$  baryons were searched for in the fully reconstructed signal decay. The numbers of events from resonant decay modes were determined in fits to the distributions of the two-dimensional planes of the invariant *B*-meson mass and the invariant mass of the *B*-meson daughters  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ , respectively. Decays without intermediate  $\Sigma_c$  baryons were determined in fits to the distribution of the invariant *B*-meson mass. Differences in the decay dynamics of the resonant decays were seen and an interpretation is given.

#### Kurzfassung

In dieser Dissertation wird die Analyse des Zerfalles  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  inklusive der resonanten Zerfälle  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  und  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  vorgestellt. Die Messung beruht auf 467 Millionen Paaren von  $B\overline{B}$ -Mesonen, die mit dem BABAR-Detektor an den PEP-II  $e^+e^-$ -Speicheringen des SLAC National Laboratory aufgezeichnet wurden. In Ereignissen  $e^+e^- \to \Upsilon(4S) \to B\overline{B}$  wurden  $B^0$ - und  $\overline{B}^0$ -Mesonen im Zerfall  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  mit dem nachfolgenden Zerfall  $\Lambda_c^+ \to pK^-\pi^+$  rekonstruiert. Zwischenzustände mit  $\Sigma_c^{++}(2455,2520)$ - und  $\Sigma_c^0(2455,2520)$ -Baryonen wurden im vollständig rekonstruierten Signalkanal gesucht. Die Anzahlen an Signalereignissen der resonanten Zerfallskanäle wurden mttels Fits an die zweidimensionalen Ebenen aus der invarianten *B*-masse und der invarianten Masse der *B*-Mesonentöchter  $m(\Lambda_c^+\pi^+)$  beziehungsweise  $m(\Lambda_c^+\pi^-)$  gemessen. Zerfälle ohne intermdiäre  $\Sigma_c$ -Baryonen wurden in Fits an die Verteilung der invarianten *B*-Mesonenmasse bestimmt. Unterschiede in den Zerfallsdynamiken der resonanten Kanäle wurden beobachtet und eine Interpretation dazu ist angegeben.

# Contents

1	Intr	roduction 1	
	1.1	Motivation and Outline 1	-
		1.1.1 Goals of this analysis	2
		1.1.2 General analysis outline	2
		1.1.3 Particle properties	3
	1.2	Theoretical and phenomenological considerations	j
		1.2.1 Introduction	j
		1.2.2 Direct decay diagrams	j
		1.2.3 Resonant decay diagrams	j
		1.2.3.1 $\Sigma_c$ production classification	j
		1.2.3.2 Further intermediate state combinations	7
		1.2.4 Effective three body diagrams	)
		1.2.5 Theoretical calculations	)
		1.2.5.1 SU(3) approach	)
		1.2.5.2 Diquark approach	)
	1.3	Related measurements	}
		1.3.1 Multiplicity dependent branching fractions	;
		1.3.2 Decay dynamics: baryon-antibaryon threshold enhancement	;
<b>2</b>	The	e BABAR experiment 17	,
	2.1	PEP-II linac and storage ring 17	7
	2.2	The BABAR detector	)
		2.2.1 Overview	)
		2.2.2 Silicon Vertex Tracker (SVT) $\ldots \ldots \ldots$	)
		2.2.3 Drift Chamber (DCH) $\ldots \ldots 20$	)
		2.2.4 Cherenkov Detector (DIRC)	)
		2.2.5 Electromagnetic Calorimeter (EMC)	_
		2.2.6 Instrumented Flux Return (IFR) 22	)
	2.3	Data processing and simulation	ŀ
		2.3.1 Level 1/ Level 3 Trigger system and data skimming 24	ŀ
		2.3.2 Track and particle ID reconstruction	ŀ
		2.3.3 Monte-Carlo event simulation	j
3	Dat	ca selection 27	,
	3.1	Software and datasets	,
		3.1.1 Reconstruction software	,
		3.1.2 Data set $\ldots$ 27	,
		3.1.3 Number of $BB$ events $\dots \dots \dots$	7
	3.2	Event selection	3

		3.2.1	<i>B</i> reconstruction variables	28
		3.2.2	$\Sigma_c$ reconstruction variables	29
		3.2.3	Track constraints	29
	3.3	$\Lambda_a^+$ sel	ection $\ldots$	29
	3.4	$\overline{B}^{c}_{0}$ sel	ection and $A^+$ mass constraint	30
	0.1	341	$\Lambda^+$ mass hypotheses in data and Monte-Carlo simulated events	30
		349	$\mathbf{R}_c$ mass hypotheses in data and monte carlo simulated events $\dots \dots \dots \dots$	33 33
	0 5	D.4.2	$\overline{D}_{1}^{++}$	).) 25
	3.5	Prepai	sations for $B^0 \to \Sigma_c^{-0} p\pi^+$ measurements	35
		3.5.1	$B^0$ signal and side band definitions	35
			3.5.1.1 Selection variables $m_{\rm ES}$ : $m_{inv}$	35
	3.6	$\Sigma_c$ fit	strategy $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\vdots$	38
		3.6.1	Fit variables $m_{inv}$ : $m(\Lambda_c^+\pi^\pm)$	39
	3.7	Signal	sources	41
		3.7.1	Signal contributions and fit parameters	41
		3.7.2	Events from $\overline{B}{}^0 \to \Sigma^{++}(2455)\overline{m}\pi^-$ decays	41
		373	Events from $\overline{B}^0 \to \Sigma^{++}(2520)\overline{p}\pi^-$ decays	12
		3.7.0	Events from $\overline{B}^0 \rightarrow \Sigma_c^{0}(2455)\overline{p}\pi^+$ decays	15
		3.7.4	Events from $\overline{D}^0 \to \Sigma_c^0(2405)p\pi^+$ decays	45 45
		3.7.5	Events from $B^{\circ} \to \mathcal{Z}_{c}^{\circ}(2520)p\pi^{+}$ decays	15
	3.8	Backg	round sources	15
		3.8.1	Combinatorial background	46
		3.8.2	Combinatorial background events with true $\Sigma_c$ resonances	51
		3.8.3	Non- $\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ events as background $\ldots \ldots \ldots$	53
		3.8.4	Background from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ with $\Sigma_c^+ \to \Lambda_c^+\pi^0$	55
		3.8.5	Background from $\overline{B}^0 \to D^0/D^+p\overline{p} + n \cdot \pi$ events	57
			0 , 11	
<b>4</b>	Mo	nte-Ca	rlo studies 6	33
	4.1	MC da	utasets	33
	$4.1 \\ 4.2$	MC da MC/D	ntasets	53 33
	$4.1 \\ 4.2$	MC da MC/D	ata misalignment	53 53 34
	4.1 4.2	MC da MC/D 4.2.1	ata misalignment $\dots$ <th>63 53 54 34</th>	63 53 54 34
	4.1 4.2	MC da MC/D 4.2.1	ata misalignment $\dots$ <th>53 53 54 54</th>	53 53 54 54
	4.1 4.2	MC da MC/D 4.2.1	ata misalignment $\dots$ <th>63 63 64 64 65</th>	63 63 64 64 65
	4.1 4.2	MC da MC/D 4.2.1	ata misalignment       6         Monte-Carlo/Data differences in $m_{inv}$ 6         4.2.1.1       Detector simulation misalignment       6         4.2.1.2 $p$ momentum correction       6         Resonance masses and widths in data and Monte-Carlo events       6	63 63 64 64 65 65 68
	4.1 4.2	MC da MC/D 4.2.1 4.2.2	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths6	53 53 54 54 55 58 58 58
	4.1 4.2	MC da MC/D 4.2.1 4.2.2	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)6	53 53 54 54 55 58 58 58 58
	<ul><li>4.1</li><li>4.2</li><li>4.3</li></ul>	MC da MC/D 4.2.1 4.2.2 Fit ver	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)64.2.2.3Monte-Carlo/Data difference for $\Sigma_c$ (2455)6	53 53 54 54 55 58 58 58 58 58 71
	4.1 4.2 4.3	MC da MC/D 4.2.1 4.2.2 Fit ver	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)6	53 53 54 54 55 58 58 58 58 71
5	<ul><li>4.1</li><li>4.2</li><li>4.3</li><li>Res</li></ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)6 $\Sigma_c$ (2455)7	53 53 54 54 55 58 58 58 58 58 71 <b>'3</b>
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res</li> <li>5.1</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on	ata misalignment6Monte-Carlo/Data differences in $m_{inv}$ 64.2.1.1Detector simulation misalignment64.2.1.2 $p$ momentum correction6Resonance masses and widths in data and Monte-Carlo events64.2.2.1 $\Sigma_c$ (2455,2520) masses and widths64.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)64.2.2.3Monte-Carlo/Data difference for $\Sigma_c$ (2455)6data7	53 53 54 54 55 58 58 58 58 58 71 73 73
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res</li> <li>5.1</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver <b>ults</b> Fit on 5.1.1	tasets	53 54 54 55 58 58 58 58 71 73 73 73
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res</li> <li>5.1</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2	$\begin{array}{c} \text{tasets} & \dots & $	53 54 54 55 58 58 58 58 71 73 73 73 78
5	<ul><li>4.1</li><li>4.2</li><li>4.3</li><li>Res</li><li>5.1</li></ul>	MC da MC/D 4.2.1 4.2.2 Fit ver <b>ults</b> Fit on 5.1.1 5.1.2 5.1.3	tasets	53 53 54 54 55 58 58 58 58 71 73 73 73 73 78 31
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3	tasets	53 53 54 55 58 58 58 71 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3	ata sets	53 53 54 55 58 58 58 58 58 71 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3	ata sets	53 53 54 55 58 58 58 58 71 73 73 73 73 73 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3	ata sets(ata misalignment(ata misalignmentMonte-Carlo/Data differences in $m_{inv}$ (ata differences in $m_{inv}$ 4.2.1.1Detector simulation misalignment(ata differences in $m_{inv}$ 4.2.1.2 $p$ momentum correction(ata and Monte-Carlo eventsA.2.2.1 $\Sigma_c$ (2455,2520) masses and widths(ata and Monte-Carlo events4.2.2.2Monte-Carlo/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)data(ata and Monte-Carlo)/Data difference for $\Sigma_c$ (2455)/Difference	53 53 54 55 58 58 58 58 58 58 58 71 73 73 73 73 73 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3	$\begin{array}{c} \text{ata misalignment} & \dots & $	53 53 54 54 55 58 58 58 58 71 73 73 73 73 73 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver <b>ults</b> Fit on 5.1.1 5.1.2 5.1.3	$\begin{array}{c} \text{tasets} & \dots & $	53 53 54 54 55 58 58 58 58 58 58 71 73 73 73 73 73 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver <b>ults</b> Fit on 5.1.1 5.1.2 5.1.3	$\begin{array}{llllllllllllllllllllllllllllllllllll$	53 53 54 54 55 58 58 58 58 58 57 73 73 73 73 73 73 73 73 73 73 73 73 73
5	4.1 4.2 4.3 <b>Res</b> 5.1	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3 5.1.4 Signal	tasets	53       53         53       54         54       55         58       58         71       73         73       73         73       73         31       31         32       37         33       31         34       32         37       38         32       37
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res 5.1</li> <li>5.2</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3 5.1.4 Signal 5.2.1	tasets	53       53         53       54         54       55         58       58         73       73
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res</li> <li>5.1</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3 5.1.4 Signal 5.2.1	tasets	63       64       65       64       65       66 <td< th=""></td<>
5	<ul> <li>4.1</li> <li>4.2</li> <li>4.3</li> <li>Res</li> <li>5.1</li> </ul>	MC da MC/D 4.2.1 4.2.2 Fit ver ults Fit on 5.1.1 5.1.2 5.1.3 5.1.4 Signal 5.2.1	tasets	53       54       55         54       55       58         55       58       57         73       73       73         73       78       31         32       37       83         32       37       83         32       37       83

		5.2.2	5.2.1.3 5.2.1.4 5.2.1.5 5.2.1.6 Interpret	Events from $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ Events from $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ Events from non- $\Sigma_c$ (2455,2520) $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ in region $I_c$ Events from non- $\Sigma_c$ (2455,2520) $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ in region $I_c$ tation	$I_{\Sigma_c}$ . $\Sigma_c$ .	· •	· · · ·	93 93 97 97 97
6	Bra	nching	ratio de	etermination				103
	6.1	Strate	gy for the	e reconstruction efficiency determination		••		103
	6.2	Efficie	ncy deter	mination from Monte-Carlo simulated events $\dots \dots \dots$		•		105
		6.2.1	Reconsti	ruction efficiency for resonant $B^0 \to \Sigma_c^0 \overline{p}\pi^+$ decays		••		105
			6.2.1.1	Reconstruction efficiency of $B^0 \to \Sigma_c^0(2455)p\pi^+$ decays Reconstruction efficiencies of $\overline{B}^0 \to \Sigma_c^0(2520)/\Sigma^{++}(2455)2520$		± .а	••••	105
		622	0.2.1.2 Reconsti	ruction efficiency for non-resonant $\overline{B}^0 \to A^+ \overline{n} \pi^+ \pi^-$ decays	<i>)</i> ) <i>p</i> <sub><i>k</i></sub>	u	ecay	107
		0.2.2	6.2.2.1	Non-resonant $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ decays in region $II_{-}(4^+ +)$ .			· · ·	107
			6222	Non-resonant $\overline{R}^0 \to \Lambda^+ \overline{n} \pi^+ \pi^-$ decays in region $I$				107
	63	Branch	bing fract	ions		•		107
	6.4	Systen	natic unce	ertainties				110
	6.5	Final 1	results					113
7	Con	clusio	n					117
•	COII	ciusioi	u					111
Α	App	endix	1					119
	A.1	Relate	a measur trocking	ements		••		119
	A.2	Becons	struction	and TD lists		•		125
	A 4	Monte	-Carlo da	tasets		•		126
	A.5	$\Lambda^+_{a}$ ma	ass related	1 measurements				129
		A.5.1	Run-dep	endent $\Lambda_c^+$ mass fits $\ldots \ldots \ldots$				129
		A.5.2	Influence	e of $\Lambda_c^+$ mass constraints and cut regions on the number of $\overline{B}{}^0$				130
	A.6	$m\left(\Lambda_{c}^{+}\right)$	$\pi^{\pm}$ ) distr	ibutions in signal and side band regions				134
	A.7	Plots f	from $\overline{B}{}^0$ -	$\rightarrow \Sigma_c^0 \overline{p} \pi^+$ Monte-Carlo simulated events $\ldots \ldots \ldots \ldots$				138
	A.8	Combi	natorial h	packground		•		140
		A.8.1	Combina	atorial background with $\Sigma_c$ resonances		•		140
	1.0	A.8.2	Fitting of	combinatorial background in $m(\Lambda_c^+\pi^+)$	•••	•		144
	A.9	$\Delta 0.1$	Backgro	$D \to \Lambda_c p \pi^- \pi^-$ multiplicate $\dots \dots \dots$		•		145
		A.9.2	$B^- \rightarrow \Sigma$	$L^+(2455, 2520)\overline{n}\pi^-$ in $m_{inv}$				145
	A.10	Backg	round from	m events with similar or the same final state particles				148
		A.10.1	Backgro	und from $B \to D^{(*)+/0} p \overline{p} X$ events				148
		A.10.2	Backgro	und from $\overline{B}{}^0 \to (c\overline{c})_{\text{charmonium}} + X$ events with $(c\overline{c}) \to p\overline{p} [\pi^+\pi^-$	].,			148
	A.11	Fit ver	rification	on Monte-Carlo and side-band data				154
		A.11.1	Non- $\Sigma_c$	$(2455,2520) B^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \text{ events } \dots \dots \dots \dots \dots \dots \dots$		• •		154
		A.11.2	Combina	atorial events with $\Sigma_c$ resonances $\ldots \ldots \ldots \ldots \ldots$	• • •	•		157
		A.11.3	$\Sigma_c (2453)$	$5,2520$ ) masses and widths $\ldots$		••		160
		A.11.4	Fit vorif	atorial background fit verifications		•		$101 \\ 177$
	A 19	Reson	ant signal	decay measurements in $m_{\perp}$ , $m(\Lambda^+\pi^{\pm})$	• • •	•		170
	11.L <i>L</i>	A.12.1	Fit to $m$	$m_{inv} m (\Lambda^+ \pi^-)$ for $\overline{B}^0 \to \Sigma^0 (2455, 2520) \overline{n} \pi^+$	• • •		•••	179
		A.12.2	Fit to m	$\sum_{inv} m(A_c^+ \pi^+) \text{ for } \overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^- \dots \dots \dots \dots$				181
	A 13	$\mathcal{Plots}$			-		-	184

$ \begin{array}{l} \text{A.13.1 Formalism} \dots \dots$	184 184 184 187 187 190
B List of Figures	194
C List of Tables	<b>204</b>
Bibliography	213

# Chapter 1

# Introduction

### 1.1 Motivation and Outline

*B* mesons are one of the lightest mesons with decays into final states with baryons, that contribute substantially to the total branching fraction. For  $B^+B^-/B^0\overline{B}^0$  mesons about  $(6.8 \pm 0.6)\%$  of all decays have a final state containing baryons [1]<sup>1</sup>. For comparison, baryonic branching fractions of lighter mesons are in the order  $\mathcal{B}(J/\psi \to \text{baryons}) \sim 3\%$  or  $\mathcal{B}(D_s^{\pm}, \eta_c \to \text{baryons}) \sim (0.1-0.3)\%$  [4].

However, o all exclusively measured branching fractions add up to only  $\sim 1/7$  of the total  $\mathcal{B}(B \to \text{baryons})$ [4].

In this analysis the baryonic *B*-meson decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  was studied. This decay mode<sup>2</sup> is of interest for studying baryonic *B* decays since it showed in previous measurements to have a substantial branching fraction of about  $\mathcal{B}\left(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-\right) = (1.1 \pm 1.2 \pm 1.9 \pm 2.9_{\mathcal{B}(\Lambda_c \to pK^- \pi^+)}) \cdot 10^{-3}$  [5] containing also several intermediate states with baryonic resonances [6]. For all decays containing a  $\Lambda_c^+$  baryon a large systematic uncertainty arises due to the uncertainty on the  $\Lambda_c$  branching ratios. While  $\Lambda_c$  decays are normalized to the dominating decay  $\Lambda_c^+ \to pK^-\pi^+$ , this mode itself is afflicted with an uncertainty of about 26% [4]<sup>3</sup>.

Similar modes with lower pion-multiplicity were studied at the BABAR B-factory [11] by S. Majewski  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$  and  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  [12, 13] and M. Ebert  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  [14, 15].

The four-body final state can be reached via several resonant intermediate states. The focus of this analysis was on the search for intermediate states with  $\Sigma_c$  baryons:

- $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$
- $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$
- $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$
- $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$

The main challenge in this analysis arose from peaking background, i.e. non-signal contribution with a similar distribution as signal events, and cross-feed, i.e. contribution from one signal class as background

<sup>3</sup>The branching ratio was calculated by [4] by averaging  $\mathcal{B}\left(\Lambda_c^+ \to pK^-\pi^+\right) = (4.41 \pm 0.91)$  % measured in *B*-decays [7,8] and  $\mathcal{B}\left(\Lambda_c^+ \to pK^-\pi^+\right) = (7.3 \pm 1.4)$  %  $\cdot f$  from semileptonic  $\Lambda_c^+$  decays [9,10]. See also footnote 1.

<sup>&</sup>lt;sup>1</sup>Note that the estimation of the ratio of B decays into baryonic final states is based on the assumption that baryonic B decays mainly proceed via charmed baryons as  $\Lambda_c$  or  $\Xi_c$ . Recently, baryonic decays with a large branching fraction were observed, which do not contain charmed baryons in an intermediate state; for example T. M. Hong reported for BABAR decays  $B \to D^{(*)}pn \cdot \pi$  (see [2,3]).

<sup>&</sup>lt;sup>2</sup>charge conjugation is implied throughout this document if not mentioned otherwise

to another signal class. For example, decays via  $\Sigma_c^0$  resonances  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  contribute as background to the isospin-related decays via  $\Sigma_c^{++}$  resonances  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ ; in the  $m(\Lambda_c^+\pi^+)$  invariant mass distribution  $\Sigma_c^0$  events distribute like background events while in the *B* invariant mass  $m_{inv}$  they naturally appear as signal. The same holds true vice versa. Additional further peaking background contributions to  $\Sigma_c^{++}$  modes were considered. Decays  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ ,  $\Sigma_c^+ \to \Lambda_c^+\pi^0$  could contribute as background when in the final state a  $\pi^0$  is exchanged with a  $\pi^-$  from the other *B*. In MC studies these modes appeared as peaking background shape in the *B* reconstruction variables  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$ .

Further resonances have not been measured in this analysis. Therefore, any additional resonant decay is considered part of the total non- $\Sigma_c$  (2455,2520) decay into the four-body final state.

Within this document the different  $\Sigma_c$  resonances are named by their masses of  $2.455 \text{ GeV}/c^2$  and  $2.520 \text{ GeV}/c^2$ .

#### 1.1.1 Goals of this analysis

The goals of this analysis were

- measurement of branching fractions for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$
- measurement of branching fractions for  $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$
- measurements of all remaining contributions to the four body final state  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (denoted as "non- $\Sigma_c$  (2455,2520)" or "non-resonant"
- a first survey for additional structures (baryon-anti-baryon threshold enhancement, nucleon resonances, mesonic resonances, decay cascades of resonances)

#### 1.1.2 General analysis outline

This analysis is separated into two parts

- 1. measurement of resonant intermediate states  $\overline{B}^0 \to \Sigma_c^{\phantom{a} 0} \overline{p} \pi^{\mp}, \ \Sigma_c^{\phantom{a} 0} \to \Lambda_c^+ \pi^{\pm}$
- 2. measurement of the remaining fraction of  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without  $\Sigma_c^{++} (2455,2520)$  resonances

The events used in this analysis were recorded at the BABAR detector. The data were analyzed with the **Beta** and with the **ROOT** software frameworks. The general event reconstruction and selection steps were

- $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal event reconstruction from BABAR data
  - 1. reconstructing a  $\Lambda_c^+$  candidate
  - 2. reconstructing a  $\overline{B}^0$  candidate
  - 3. applying cuts for background reduction
- reconstructed candidates for  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  decays were separated into resonant decays with intermediate  $\Sigma_c$  (2455,2520) baryons and decays without non- $\Sigma_c$  (2455,2520) resonances
  - reconstruction of events of the type  $\overline{B}{}^0 \to \Sigma_c^{+,+} \overline{p} \pi^{\mp}$ 
    - 1. reconstructing  $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  modes in the  $m_{inv}: m(\Lambda_c^+\pi^{\pm})$  planes, i.e the planes spanned by the invariant  $\overline{B}{}^0$ -mass  $m_{inv}$  and the invariant mass of the  $\Lambda_c^+$ -pion pair  $m(\Lambda_c^+\pi^{\pm})$
    - 2. discriminating signals from peaking backgrounds as  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  in the  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  planes

- 3. using the  ${}_{s}\mathcal{P}lot$ -technique [16], separate distributions of signal events in other variables, e.g.  $m(\overline{p}\pi^{+})$  for  $\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}$  events or  $m(\overline{p}\pi^{-})$  for  $\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$  events.
- 4. reweight Monte-Carlo simulated events for each  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  mode with *sPlots* signal event distributions from data to gain corrected reconstruction efficiencies
- 5. determine the reconstruction efficiencies from the corrected Monte-Carlo events
- determination of non- $\Sigma_c$  (2455,2520)  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  contributions
  - 1. reconstructing of non- $\Sigma_c$  (2455,2520) signal decays in  $m_{inv}$
  - 2. separate signal events with  $\Sigma_c^{++}(2455,2520)$  baryons with vetoes
  - 3. determine the yields and remove background contributions in fits to  $m_{inv}$  distributions
  - 4. determine the reconstruction efficiency from Monte-Carlo simulated events using  ${}_{s}\mathcal{P}lots$  signal event distributions from data for correction weights

#### 1.1.3 Particle properties

Table 1.1 and table 1.2 give the properties of mesons and baryons, which were relevant in this analysis [4].

Particle	Quark Content	Mass $\left[  \text{GeV} / c^2 \right]$	$\operatorname{Width}\Gamma\left[\operatorname{MeV}\!/c^2 ight]$ Lifetime $ au\left[s ight]$	$I\left(J^P\right)$
$\pi^+$ $\pi^0$	$\frac{(u\overline{d})}{\left(u\overline{u}-d\overline{d}\right)/\sqrt{2}}$	$\substack{0.13957018 \pm 0.00000035\\0.1349766 \pm 0.0000006}$	$\tau \begin{cases} (2.6033 \pm 0.0005) \cdot 10^{-8} \\ (8.4 \pm 0.5) \cdot 10^{-17} \end{cases}$	$1^{-}(0^{-})$
$K^-$ $K^0_s$	$rac{\overline{u}s}{\overline{d}s}$	$0.493677 \pm 0.000016$	$\tau = (1.2380 \pm 0.0021) \cdot 10^{-8}$ $\tau = (0.8953 \pm 0.0005) \cdot 10^{-10}$	$\tfrac{1}{2}\left(0^{-}\right)$
$\rho^0(770)$	$\left(u\overline{u}-d\overline{d}\right)/\sqrt{2}$	$0.7749 \pm 0.00034$	$\Gamma = 0.1491 \pm 0.0008$	$1^+(1^{})$
$f_0(980)$	$c_1\left(u\overline{u}+d\overline{d}\right)+c_2s\overline{s}$	$0.980\pm0.0010$	$\Gamma \approx 40 - 100$	$0^{+}(0^{++})$
$f_2(1270)$	$c_1\left(u\overline{u}+d\overline{d}\right)+c_2s\overline{s}$	$1.2751 \pm 0.00012$	$\Gamma = 0.1851^{+2.9}_{-2.4}$	$0^+(2^{++})$
$B^-$	$\overline{u}b$	$5.27917 \pm 0.00029$	$\tau = (1.638 \pm 0.011) \cdot 10^{-12}$	$\frac{1}{2}(0^{-})$
$\overline{B}{}^{0}$	$\overline{d}b$	$5.27950 \pm 0.00030$	$\tau = (1.525 \pm 0.009) \cdot 10^{-12}$	$\frac{1}{2}(0^{-})$
$\Upsilon(4S)$	$\overline{b}$	$10.5794 \pm 0.0012$	$\Gamma = (20.5 \pm 2.5) \cdot 10^{-12}$	$0^{-}(1^{})$

Table 1.1: Meson properties [4].

Particle	Quark Content	Mass $\left[\mathrm{GeV}\!/c^2\right]$	$\operatorname{Width}\Gamma\left[\operatorname{MeV}\!/c^2 ight]$ Lifetime $ au\left[s ight]$	$I\left(J^P\right)$
p	(uud)	$0.938272013 \pm 0.000000023$	$\tau > 3 \cdot 10^{38}$	$\frac{1}{2}\left(\frac{1}{2}^+\right)$
$N^0(1440)$	(udd)	$\approx 1.440$	200 - 450	$\frac{1}{2}\left(\frac{1}{2}^+\right)$
$N^0(1520)$	(udd)	$\approx 1.520$	100 - 125	$\frac{1}{2}\left(\frac{3}{2}^{-}\right)$
$N^0(1535)$	(udd)	$\approx 1.535$	125 - 175	$\frac{1}{2}\left(\frac{1}{2}^{-}\right)$
$N^0(1650)$	(udd)	$\approx 1.655$	145 - 185	$\frac{1}{2}\left(\frac{1}{2}\right)$
$N^0(1675)$	(udd)	$\approx 1.675$	130 - 165	$\frac{1}{2}\left(\frac{5}{2}\right)$
$N^0(1680)$	(udd)	$\approx 1.685$	120 - 140	$\frac{1}{2}\left(\frac{5}{2}^+\right)$
$\begin{array}{c} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{array} (1232)$	$(uuu)\ (uud)\ (udd)$	$\approx 1.232  {\rm GeV}/c^2$	$\Gamma \approx (1.209 - 1.211) \cdot 10^3$	$\frac{3}{2}\left(\frac{3}{2}^+\right)$
Л	(uds)	$1.115683 \pm 0.000006$	$\tau = (2.631 \pm 0.020) \cdot 10^{-10}$	$0\left(\frac{1}{2}^+\right)$
	$(uus)\ (uds)\ (dds)$	$\begin{array}{c} 1.18937 {\pm} 0.00007 \\ 1.192642 {\pm} 0.000024 \\ 1.197449 {\pm} 0.000030 \end{array}$	$\tau = \frac{(0.8018 \pm 0.0026) \cdot 10^{-10}}{(7.4 \pm 0.7) \cdot 10^{-10}}$ $(1.479 \pm 0.011) \cdot 10^{-10}$	$1\left(\frac{1}{2}^+\right)$
$\Lambda_c^+$	(udc)	$2.28646 \pm 0.00014$	$\tau = (200\pm) \cdot 10^{-15}$	$0\left(\frac{1}{2}^+\right)$
$\Lambda_{c}^{+}(2595)$	(udc)	$2.5954 \pm 0.0006$	$\Gamma = 3.6^{-1.3}_{+2.0}$	$0\left(\frac{1}{2}\right)$
$\Lambda_{c}^{+}(2625)$	(udc)	$2.6281 \pm 0.0006$	$\Gamma < 1.9 @90\% C.L.$	$0\left(\frac{3}{2}^{-1}\right)$
$\Lambda_{c}^{+}(2765)$		$2.7666 \pm 0.002.4$	$\Gamma \approx 50$	? (??)
$\Lambda_{c}^{+}(2880)$	(udc)	$2.88153 \pm 0.00035$	$\Gamma = 5.8 \pm 1.1$	$0\left(\frac{5}{2}^{+}\right)$
$\Lambda_{c}^{+}(2940)$	(udc)	$2.9393^{+1.4}_{-1.5}$	$\Gamma = 17^{+8}_{-6}$	$0\left(?^{?}\right)$
$\begin{array}{c} \Sigma_c^{++} \\ \Sigma_c^{+} \\ \Sigma_c^{0} \end{array} (2455) \\ \Sigma_c^{0} \end{array}$	$(uuc)\ (udc)\ (ddc)$	$\substack{2.45402\pm0.00018\\2.4529\pm0.0004\\2.45376\pm0.00018}$	$\Gamma \left\{ \begin{array}{c} 2.23 \pm 0.30 \\ < 4.6 @ 90\% \ CL \\ 2.2 \pm 0.4 \end{array} \right.$	$1\left(\frac{1}{2}^+\right)$
$ \begin{bmatrix} \Sigma_c^{++} \\ \Sigma_c^{+} \\ \Sigma_c^{0} \end{bmatrix} $ (2520)	$(uuc)\ (udc)\ (ddc)$	$\begin{array}{c} 2.5184 {\pm} 0.0006 \\ 2.5175 {\pm} 0.0023 \\ 2.5280 {\pm} 0.0005 \end{array}$	$\Gamma \left\{ \begin{array}{c} 14.9 \pm 1.9 \\ < 17 @ 90\% CL \\ 16.1 \pm 2.1 \end{array} \right.$	$1\left(\frac{3}{2}^+\right)$
$ \begin{bmatrix} \Sigma_c^{++} \\ \Sigma_c^{+} \\ \Sigma_c^{0} \end{bmatrix} $ (2800)	$(uuc)\ (udc)\ (ddc)$	$2.801^{+0.004}_{-0.006}$ $2.792^{+0.014}_{-0.005}$ $2.802^{+0.004}_{-0.007}$	$\Gamma \begin{cases} 75^{+22}_{-17} \\ 62^{+60}_{-40} \\ 61^{+28}_{-18} \end{cases}$	$1\left(?^{?}\right)$

Table 1.2: Baryon properties [4].

# 1.2 Theoretical and phenomenological considerations

#### 1.2.1 Introduction

The basis for understanding and describing the nature of fundamental particles and interactions is the *Standard Model of Particle Physics* (SM). Over the last 40 years it proved to be very successful in describing the processes of particle physics. It describes the fermions with spins 1/2 as fundamental constituent of matter and the gauge bosons with integer spins, which mediate the fundamental interactions in-between. A detailed introduction into the Standard Model can be found in [17] for example.

While the Standard Model in very successful in describing a wide range of observations, some detailed mechanisms are not fully understood yet.

For example, the baryon production is still missing a detailed description. To study mechanisms in the baryon production,  $B_{u,b}$ -mesons provide a system, where it can be measured in detail. Thanks to the *B*-factories *BABAR* and Belle, large recorded data sets of *B*-mesons are available.

The measured *B*-decays with baryons in the final states have a wide range of branching fractions. Furthermore, baryonic decays show some characteristics, that are distinct from pure mesonic or semileptonic *B*-decays. However, a comprehensive theoretical description is still missing, which could describe baryonic decays or make reliable, predictions. In the following, the classification scheme by R. Waldi [18] *er al.* is used for ordering Feynman diagrams of baryonic *B*-decays.

Low order Feynman diagrams are used as illustrations of baryonic B-decays . They can be ordered in three general classes:

- A: annihilation class diagrams, i.e. a W exchange between the B constituent quarks for a  $\overline{B}^0$ -meson or a constituent quark annihilation in case of a  $B^-$ -meson.
- 1: external W emission, i.e. assuming no direct interaction between the virtual W products and the rest- $\overline{B}^0$  fragments.
- 2: internal W emission, i.e. diagrams with W decay products and the rest- $\overline{B}^0$  fragments forming combined bound states.

#### 1.2.2 Direct decay diagrams

The direct decay into the four body final state  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  can proceed in the most simple diagrams in two ways: either by an *internal* W boson or via an *external* W boson interaction.

An *internal* interaction can proceed either via a suppressed W boson exchange between both constituent quarks (figure 1.1), classified as *type* A diagram, or via a  $\overline{u} d$  quark pair production (figure 1.2), classified as *type* 2 diagram, where the products can enter the final state baryons. In both cases colour suppression factors are expected, whereas the suppression is expected to be smaller than in mesonic decays. Because of the three quark alignment in baryons a naive assumption would be a suppression factor of about  $\sim \frac{2}{3}$  compared to  $\frac{1}{3}$  for mesonic decays.

An external W radiation (figure 1.3), classified as type 1 diagram, does not have such suppression factor for the resulting meson if one neglects all further gluon interactions. (For the time being further possible diagrams are neglected, e.g. when a virtual high momentum W is radiated and creates a baryonantibaryon pair as in  $\overline{B}^0 \to D^+ n\overline{p}$ ).



Figure 1.1: Type A diagram: Internal W boson exchange.



Figure 1.2: Type 2 diagram: Internal W boson radiation producing a  $\overline{u} d$  quark pair



Figure 1.3: Type 1 diagram: External W boson radiation producing a pion.

#### 1.2.3 Resonant decay diagrams

A feature of the decay  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  is that it can proceed via numerous resonant intermediate states. For example intermediate states with  $\Sigma_c^{++}(2455,2520,2800)$  or  $\Sigma_c^0(2455,2520,2800)$  baryon resonances<sup>4</sup> can be described with three body states diagrams. The four body final state is reached by cascading the  $\Sigma_c$  baryon resonance to  $\Lambda_c^+ \pi$ .

Examples for decay cascades are given for  $\Sigma_c^{++}$  resonances in figure 1.4 and for  $\Sigma_c^0$  resonances in figure 1.5.





Figure 1.4: Feynman diagram: *External* W boson radiation with an intermediate  $\Sigma_c^{++}$  resonance.  $\Sigma_c^{++}$  resonances can also be formed by *internal* W interaction similar as in figure 1.5.

Figure 1.5: Feynman diagram: Internal W boson exchange proceeding via a charmed  $\Sigma_c^0$  resonance. The  $\Sigma_c^0$  resonances can only be formed by internal W interaction.

#### **1.2.3.1** $\Sigma_c$ production classification

While intermediate states containing  $\Sigma_c$  baryons are three body decays, the production diagrams differ for decays with  $\Sigma_c^{++}$  and with  $\Sigma_c^0$  baryons.

 $\Sigma_c^0$  states can be produced by type 2a diagrams (figure 1.7) and 2b (figure 1.9) diagrams, i.e. internal W radiation where the W daughter quarks either end up in both baryons or in one of the baryons and the

<sup>&</sup>lt;sup>4</sup>Note that the  $\Sigma_c$  (2800) isospin triplet masses and widths have not been measured with high accuracy [19]. For example S. Majewski in  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  [13] and M. Ebert in  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  [15] found hints for intermediate  $\Sigma_c$  (2800) states, whereas the masses differ for the proposed intermediate states. This could be interpreted as hints for different higher excited  $\Sigma_c$  states with different angular momenta but with similar masses; however the statistics are far to low for a concrete conclusion. In the following such speculations are not considered and any possible higher  $\Sigma_c$  resonances with masses of about 2.8 GeV/ $c^2$  are subsumed as  $\Sigma_c$  (2800)

meson. Or the decay proceeds via a W exchange diagram of the annihilation type A (figure 1.11). Decays with intermediate  $\Sigma_c^{++}$  resonances can proceed via additional diagrams. In addition to an *internal* W radiation (figure 1.6) or a W exchange (figure 1.10)  $\Sigma_c^{++}$  states can also be formed in an external W radiation of type 1 (figure 1.8).

If one does not consider destructive interferences, one could draw a naive conclusion expecting a larger contribution from  $\Sigma_c^{++}$  intermediate states to the final four-body state as from the  $\Sigma_c^0$  due to the additional diagrams and the missing colour-matching constraint in the type 1 diagram as in figure 1.8.





Figure 1.6:  $\Sigma_c^{++}$  production diagram: internal W radiation of type 2g



Figure 1.7:  $\Sigma_c^0$  production diagram: internal W radiation of type 2a







Figure 1.9:  $\Sigma_c^0$  production diagram: internal W radiation of type 2b

Figure 1.10:  $\Sigma_c^{++}$  production diagram: W exchange of type А

Figure 1.11:  $\Sigma_c^0$  production diagram: W exchange of type A

#### Further intermediate state combinations 1.2.3.2

As for charmed baryon resonances corresponding diagrams can be drawn for nucleon or  $\Delta$  resonances. Since in this analysis only charmed  $\Sigma_c$  resonances are studied, these possibilities are only mentioned for completeness.

If proposing charmed and non-charmed baryonic resonances the four body final state could be reached via several decay cascades. One general decay chain type starts with two excited baryons both cascading 

1.13).

In addition, diagrams for three body states with mesonic resonances can be formed, e.g. as in figure 1.14 a resonant meson with vacuum quantum numbers could be a  $f_0$  decaying into the final state  $\pi^+\pi^$ pair.

Also more cascades with charmed or non-charmed baryonic resonances are plausible, which could be described accordingly. For example  $\Sigma_c$  intermediate states can also be reached via a  $\Lambda_c$  resonance as  $A_c(2593)$ . In figures 1.15-1.17 possible charmed decay cascades are shown schematically.

While *internal* W reactions have a minimum number of two initial state particles, i.e. a baryon-antibaryon pair, an *external* W radiation has necessarily a minimum number of three initial state particles.



Figure 1.12: Feynman diagram: Internal W boson exchange proceeding via a charmed  $\Sigma_c^0$  resonance and a nucleonic  $N^*$  resonance, i.e. an initial two baryon state.



Figure 1.13: Feynman diagram: Internal W boson exchange proceeding via a charmed  $\Lambda_c^{+*}$ resonance. Note that for some excited  $\Lambda_c^{+*}$  baryons cascades via intermediate  $\Sigma_c$  baryons are also possible, i.e.  $\Lambda_c^+(2593) \rightarrow \Sigma_c^{++}(2455)\pi^{\mp}$ 

 $\bar{B}^0$ 



Figure 1.14: Feynman diagram: Internal W boson exchange proceeding via a baryonantibaryon pair and a meson resonance which can decay into a  $\pi^+\pi^-$  pair in the fin al state.



Figure 1.15: Decay cascade: decays via  $\varSigma_c$  resonances



Figure 1.16: Decay cascade: decay chains as in figure 1.15 possible for different excitations of  $\Sigma_c^{++}$ (same for  $\Sigma_c^0$ )



Figure 1.17: Decay cascade: baryon-antibaryon initial state cascading into the four body final state (same for  $\Sigma_c^0$  and for direct decay  $\Lambda_c^{+*} \to \Lambda_c^+ \pi^- \pi^+$ )

#### 1.2.4 Effective three body diagrams

Using the decay type classification, one can further abstract the baryon production in *B*-decays and draw first conclusions. In the following, only final states with two or three particles are discussed. The following considerations can easily be extended to decays with additional daughters in the final state.

For final states with only two baryons the contributing diagrams are quite simple (either type 2 or type A diagrams as in figures 1.2 an 1.1 without an additional meson-meson-like pair).

However, for final states with three particles, i.e. a baryon-antibaryon pair and a meson, more diagram arrangements can contribute. Contributing diagrams can be sorted into two general classes.

In the first class, the initial step could be a meson-meson-like arrangement, where one of the mesons baryonizes, i.e. it decays into a baryon-antibaryon pair. The mesons have not to be necessarily real but can be virtual, denoted as *class* M.

In the second class, a baryon-antibaryon pair could be the first step and one of the baryons *radiates* a meson, denoted as *class* B.

#### • initial meson-meson-like arrangement(*class M*)

The most simple diagram of the class M for a B decay is shown in figure 1.18(a) ( $q_{sp}$  denotes the B's spectator quark in this process). The similar color-suppressed diagram is shown in figure 1.18(b). Since the virtual W is far from its mass shell, a W interaction diagram can be contracted to an effective four point interaction. Both diagrams can be summarized in an effective diagram as in figure 1.18(c). The arrangement of the decay quarks corresponds to two quark-antiquark pairs, i.e. a meson pair.

Similarly, a exchange type diagram (type A) as in figure 1.19(a) can be contracted to an effective diagram as in figure 1.19(b). Here the meson-meson-like pair is produced by a quark-antiquark-pair generated in the gluon field.

The baryon-production can take place involving the meson configuration with the spectator quark as in figure 1.20(a) or in the other (pseudo-)meson as in figure 1.20(b). For the exchange type the baryonization can take place correspondingly in one of the meson configurations (figure 1.20(c)).

#### • initial diquark-antidiquark/baryon-antibaryon arrangement (class B)

A rearrangement of the quarks after the *b*-decay would correspond to a diquark-antidiquark pair instead of a meson-meson-like pair. Such a *class B* diagram can be contracted to an effective diagram as in figure 1.21(a). Due to the color-confinement an additional quark-antiquark-pair is necessary and results in a baryon-antibaryon pair. Following, the three-body final state's missing meson can be produced in the fragmentation of one of the two baryons.

In an initial meson-meson-like arrangement of *class M*, the initial process is a two-body decay. The (real) meson, that does not produce the baryon-pair, *carries away* its fraction of the momentum and energy. Thus, the remaining quark-antiquark combination is driven oppositely and the available phase space for a baryon-antibaryon production is essentially "cooled down". So, the sub-sequentially produced baryon-pair would be concentrated into a subregion of the originally available phase space.

In an initial baryon-antibaryon arrangement both baryons would be produced back-to-back and a resonant baryon can cascade down producing the remaining final state particles. Here the complete phase space is available for the original baryon-pair.

With these assumptions one can draw some conclusions:

- Initial baryon-antibaryon arrangements would lead to decays that are convolutions of two two-bodydecays.
- Initial meson-meson-like arrangements of class M would lead to baryon-antibaryon-pairs<sup>5</sup> where the combined baryon-antibaryon invariant masses is smaller than in initial baryon-antibaryon

<sup>&</sup>lt;sup>5</sup>or, of course, meson-antimeson pairs if the hadronization proceeds only via mesons.

arrangements. In the two-body decay both mesons are driven back-to-back. Thus, the phase space available for the following baryonization of one of the mesons is naturally smaller than in the originally available phase space, i.e. the baryonization in the remaining quark-antiquark-arrangement is condensed to a smaller phase space compared to a *class B* baryonization.

- Thus, for *class M* initial meson-meson-like arrangements the baryon-antibaryon invariant mass can be expected to be enhanced at lower values compared to a simple phase space model.
- Obviously, no such enhancement at lower baryon-antibaryon invariant masses would be expected for decays that can only be produced by initial baryon-antibaryon-arrangements of class B, i.e. without contributions from class M diagrams. For example, the decay  $\overline{B}^0 \to \Sigma_c^0 \overline{p} \pi^+$  cannot be produced via an initial meson-meson-like pair but only via initial baryon-antibaryon-configurations. Possible initial baryon-antibaryon states could be  $\overline{B}^0 \to \Sigma_c^0 N$  with  $N \to \overline{p} \pi^+$  or  $\overline{B}^0 \to \Lambda_c^{+*} \overline{p}$  with  $\Lambda_c^{+*} \to \Sigma_c^0 \pi^+$ .
- for decays with two baryons and one meson in the final state no exclusive class M decay is possible without additions from class B diagrams.
- Most baryonic decays can proceed via diagrams of both *classes* of initial arrangements, i.e. decay amplitude contributions from both types. Nevertheless, both initial arrangements could lead to different behaviours in the final states.
- In this model a semi-leptonic decay would be related to the meson-meson-like initial state class M (without color-suppressed contributions). In a variation of the effective diagram 1.20(a) leptons could carry away four-momenta from the baryonizing rest. Examples would be decays of the type  $B \rightarrow \Lambda_c^+ \overline{p} \, l_{e,\mu}^- \overline{\nu}_{e,\mu} + n \cdot \pi \, (n=0,1,2,...)$  including resonant sub-modes.

A remotely related model is proposed by M. Suzuki [20] differentiating between two processes. He classifies both processes either by a hard virtual gluon, necessary for a baryon-antibaryon initial state, or a more on-shell soft gluon, i.e. more probable gluon, for a *baryon-antibaryon* plus meson initial state.



Figure 1.18: class M: Initial meson-meson-like states with W-radiation. Due to the large off-shell Wmass color-favored 1.18(a) and color-suppressed 1.18(b) contributions can be merged into an effective four point term 1.18(c). This gives an effective meson-meson-like initial decay state before baryonization.



Figure 1.19: class M: Initial meson-meson-like states with W-exchange. Due to the large off-shell W-mass the (type A) diagram 1.19(a) can be contracted into an effective four point term 1.19(b). This gives an effective meson-meson-like initial decay state before baryonization.



Figure 1.20: class M: Baryonization from initial meson-meson-like states: the baryonization takes place in one of the initial mesons, resulting in three particles in the initial decay state: either a baryonization involving the *B*-spectator quark  $\bar{q}_{sp}$  in *W*-radiation diagrams 1.20(a), or a baryonization without involvement of the *B*-spectator quark  $\bar{q}_{sp}$  in *W*-radiation diagrams 1.20(b), or a baryonization in one of the initial mesons in *W*-exchange diagrams 1.20(c).



Figure 1.21: class B: Arrangement of the initial quarks and W-daughters (type 2 diagram) to a diquark and antidiquark pair in figure 1.21(a) with the subsequent baryonization in figure 1.21(b) to comply with color-confinement. Figure 1.21(c) shows the arrangement for the exchange type (type A diagram). In both cases the initial decay state is a baryon-antibaryon pair. A three-body final state can be reached, if one of the baryons further fragments into a baryon-meson pair.

#### 1.2.5 Theoretical calculations

For baryonic B-decays no detailed theoretical predictions of branching fractions are known. Only rough estimates of B-decays have been calculated so far based on models similar to the presented as well as other models. Most of these theoretical calculations are up to 20 years old.

#### 1.2.5.1 SU(3) approach

One of the earliest theoretical approaches is to derive relations between decay rates from flavor SU(3) considerations  $[21]^6$ , which can only briefly be touched here. They derived from the approximate SU(3) flavour symmetry predictions on *B*-meson decays to baryon-antibaryon pairs, e.g.

$$\frac{\overline{B}^0 \to \Lambda_c^+ \overline{p}}{\overline{B}^0 \to \Sigma_c^{++} \overline{\Delta}^{--}} = \frac{|\alpha|^2}{|\eta_1|^2} \tag{1.1}$$

$$\frac{\overline{B}^0 \to \Lambda_c^+ \overline{p}}{\overline{B}^0 \to \Sigma_c^0 \overline{\Delta}^0} = \frac{|\alpha|^2}{\frac{1}{3} |\eta_1 + \eta_2|^2}$$
(1.2)

Here,  $\alpha, \eta_1, \eta_2$  are reduced matrix elements for the currents between baryon states, that describe the relationships between the corresponding baryon multiplets. These parameters have to be extracted from measurements. Unfortunately, no concrete branching fraction predictions can currently be made, since several necessary measurements are still missing and the system of branching fractions is not fully determined. For example, while  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$  has been measured [12], no measurement exists for  $B^- \to \Sigma_c^0 \overline{n}$  which is needed to derive a prediction for  $\overline{B}^0 \to \Sigma_c^+ \overline{p}$ . Such a prediction could be compared to a measured upper limit on  $\overline{B}^0 \to \Sigma_c^+ (2455) \overline{p}$  by M. Ebert [14].

Together with the measurement of  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$  [14] this analysis of the  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  could give predictions for equations 1.1 and 1.2, if the intermediate decays  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{\Delta}^{--}$  or  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{\Delta}^0$  could be measured.

#### 1.2.5.2 Diquark approach

Another theoretical approach is to use a diquark ansatz comparable to a mesonic decay. Instead of a constituent quark-antiquark pair and an additional quark-antiquark pair, which form two mesons during the initial fragmentation, an alignment of a diquark and antidiquark pair is assumed. Due to the color confinement, an additional quark-antiquark pair is followingly created from the color field to form an initial baryon-antibaryon pair. Naturally, these theoretical predictions cannot make predictions on *class* M diagrams.

In [24] two models are compared describing the quark-antiquark pair creation as an effective local or non-local pair production, in which an initial diquark-antidiquark pair is produced in an effective weak decay. The remaining quark-antiquark pair could be described by in an effective interactions or in a non-local, more elaborate gluon-string breaking model. Some estimates from [24] on ratios are:

$$\frac{\overline{B}^{0} \to u(cd)\overline{u}(\overline{u}\overline{d}): \Lambda_{c}^{+} \overline{p}}{\overline{B}^{0} \to u(cd)\overline{u}(\overline{u}\overline{d}): \Sigma_{c}^{+} \overline{p}} = 1.018_{\text{nonlocal pair}} \mid = 1.210_{\text{local pair}}$$
(1.3)

$$\frac{\overline{B}^{0} \to u(cd)\overline{u}(\overline{ud}) : \Lambda_{c}^{+}\overline{p}}{\overline{B}^{0} \to u(cd)\overline{u}(\overline{ud}) : \Lambda_{c}^{+}\overline{\Delta^{+}}} = 2.741_{\text{nonlocal pair}} \mid = 5.475_{\text{local pair}} \quad (1.4)$$

$$\frac{B^0 \to u(cd)\overline{u}(\overline{ud}) : \Lambda_c^+ \overline{p}}{\overline{B}^0 \to d(cd)\overline{d}(\overline{ud}) : \Sigma_c^0 \overline{\Delta^0}} = 0.632_{\text{nonlocal pair}} | = 1.301_{\text{local pair}}$$
(1.5)

<sup>&</sup>lt;sup>6</sup>Related works are [22] on decays of charmed baryons and [23] on *B*-meson decays to mesons. Note the archaic  $B^-$ ,  $B^0$  and  $B_s$  definitions in [21] eq. 17

Quarks in parenthesis are the initial diquark anti-diquark pairs, here the first ratio is based on a nonlocal and the second one on a local quark-antiquark creation model.

In this model resonant modes decaying into the same final state can contribute with quite different ratios. For the  $\overline{B}^0$  three body final state  $\Lambda_c^+ \overline{p} \pi^0$  contributions from  $\overline{B}^0 \to \Sigma_c^+ \overline{p}$  (eq. 1.3) and  $\overline{B}^0 \to \Lambda_c^+ \overline{\Delta^+}$  (eq. 1.4), respectively, would differ by a factor of  $(\sim 3 - 4) \times \frac{2}{3} \Delta^+ \to p \pi^0$ , depending on the model.

If the resonant decay  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{\Delta}{}^0$  could been measured clearly, one could use it together with the measurement of  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$  [14] to compare the ratio with the prediction in eq. 1.5.

### **1.3** Related measurements

Several baryonic *B*-decays have been measured from both *B*-factories *BABAR* and Belle as well as from CLEO-c. In this section an overview is given over the existing measurements of decays related to  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  and interesting properties of decays with baryons. Additional information can be found in the appendix in section A.1.

#### 1.3.1 Multiplicity dependent branching fractions

One feature of  $B \to \Lambda_c^+ \overline{p} (n \cdot \pi)$  decays is the increase of the branching fraction with each additional pion in the final state. The largest increase takes place from the two-body to the three-body final state (within larger uncertainties with respect to the CLEO results). However, the increase of branching fractions with additional final state particles is not as steep when resonant modes are compared with each other:

$$\begin{split} \mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right) & \mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\right) & \mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right) & (1.7) \\ \left(13.6\pm1.7\pm0.9\right) & \left(3.37\pm0.60\pm0.54\right) & \left(10.26\pm1.45\pm0.81\right) \\ \mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\right)_{\text{non-resonant}} & \mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}\right) & \mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\pi^{0}\right) \\ \left(2.49\pm0.21\pm0.38\right) & \left(3.14\pm0.97\pm0.57\right) & \left(9.32\pm1.70\pm1.31\right) \\ \mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\pi^{+}\pi^{-}\right)_{\text{non-resonant}} & \mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}\pi^{-}\right) & \mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\pi^{0}\right) \\ \left(3.52\pm0.45\pm0.62\right) & \mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\pi^{+}\pi^{-}\right) & \mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi$$

Figure 1.22:  $B \to \Lambda_c^+ \overline{p} + (\mathbf{n} \cdot \pi)$ : Relative change of the branching fractions with additional particles in the final state. "non-resonant" denotes the fraction of the branching ratio without intermediate  $\Sigma_c$  resonances.

A similar behaviour is visible in decays of the type  $B \to D^{(*)}p\overline{p}$   $(\mathbf{n} \cdot \pi)$  [2]. Here the *c*-quark enters the meson and the process is necessarily of *class* M. The branching fractions are ordered in table 1.3 with increasing number of final state particles and show also a behaviour as the decays were the *c*-quark enters the baryon and forms a  $\Lambda_c^+$  or  $\Sigma_c$ . In the measurements of decays  $B \to \Lambda_c^+ \overline{p} (\mathbf{n} \cdot \pi)$  with increasing pion numbers in the final states no decrease in the branching fraction were seen yet up to five particles in the final state. But for decays  $B \to D^{(*)}p\overline{p} (\mathbf{n} \cdot \pi)$  the peak in the branching fraction values seem to be at four particles in the final state.

For comparison table 1.4 sums up the most recent measurements of branching fractions for decays of the type  $B \to \Lambda_c^+ \overline{p} (\mathbf{n} \cdot \pi)$  and similar.

#### 1.3.2 Decay dynamics: baryon-antibaryon threshold enhancement

While an increase in the branching fractions up to a certain multiplicity was also observed in mesonic decays, e.g.  $D^+ \to K^-(n \cdot \pi)$ , the *threshold enhancement* in the baryon-antibaryon mass seems to

$B \rightarrow \dots$	$\mathcal{B} \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}} (10^{-4})$
$\overline{B}{}^0 \to D^0 p \overline{p}$	$1.02 \pm 0.04 \pm 0.05$
$\overline{B}{}^0 \to D^{*0} p \overline{p}$	$0.97 \pm 0.07 \pm 0.09$
$\overline{B}{}^0 \to D^+ p \overline{p} \pi^-$	$3.32 \pm 0.10 \pm 0.27$
$\overline{B}{}^0 \to D^{*+} p \overline{p} \pi^-$	$4.55 \pm 0.16 \pm 0.37$
$B^- \to D^0 p \overline{p} \pi^-$	$3.72 \pm 0.11 \pm 0.23$
$B^- \to D^{*0} p \overline{p} \pi^-$	$3.73 \pm 0.17 \pm 0.39$
$\overline{B}{}^0 \to D^0 p \overline{p} \pi^- \pi^+$	$2.99 \pm 0.21 \pm 0.44$
$\overline{B}{}^0 \to D^{*0} p \overline{p} \pi^- \pi^+$	$1.91 \pm 0.36 \pm 0.29$
$B^- \to D^+ p \overline{p} \pi^- \pi^-$	$1.66 \pm 0.13 \pm 0.27$
$B^- \rightarrow D^{*+} p \overline{p} \pi^- \pi^-$	$1.86 \pm 0.16 \pm 0.18$

Table 1.3: Branching fractions from decays  $B \to D^{(*)} p \overline{p} \ (n \cdot \pi) \ [2,3,25-29])).$ 

Table 1.4: Summary of the recent measurements of branching ratios of decays  $B \to \Lambda_c^+ \overline{p} (n \cdot \pi)$  and similar decays with charmed/stranged baryons.

$B \rightarrow \dots$	$\mathcal{B} \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}} (\pm \sigma_{\Lambda_c}) (10^{-4})$	
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$	$0.189 \pm 0.021 \pm 0.06 \pm 0.049$	[12]
$\frac{B^- \to \Sigma_c^0 (2455) \overline{p}}{B^- \to \Lambda_c^+ \overline{p} \pi^-}$	$\sim 0.42 \pm 0.04 \pm 0.03 \pm 0.10$	[12]
$\frac{B^- \to \Sigma_c^0 (2800) \overline{p}}{B^- \to \Lambda^+ \overline{n} \pi^-}$	$\sim 0.40 \pm 0.08 \pm 0.08 \pm 0.10$	[12]
$\overline{B}^{0} \to \Sigma_{c}^{+}(2455)\overline{p}$	< 0.015	[14]
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^0$	$1.94 \pm 0.17 \pm 0.14 \pm 0.5$	[14]
$B^- \to \Lambda_c^+ \overline{p} \pi^-$	$3.38 \pm 0.12 \pm 0.12 \pm 0.85$	[12]
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	$2.1 \pm 0.2 \pm 0.3 \pm 0.5$	[6]
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	$1.4 \pm 0.1 \pm 0.2 \pm 0.3$	[6]
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	$1.2 \pm 0.1 \pm 0.3 \pm 0.3$	[6]
$\overline{B}{}^0 \to \Sigma_c^{\bar{0}}(2520)\overline{p}\pi^+$	< 0.38	[6]
$\overline{B}{}^0 \to \Sigma_c^{++} \overline{p} K^-$	$0.111 \pm 0.030 \pm 0.009 \pm 0.029$	[30]
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \overline{\overline{K}}{}^{*0}$	$0.160 \pm 0.061 \pm 0.012 \pm 0.042$	[30]
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ nonresonant	$6.4 \pm 0.4 \pm 0.9 \pm 1.7$	[6]
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ total	$11.2 \pm 0.5 \pm 1.4 \pm 2.9$	[6]
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ K^{\text{total}}$	$0.433 \pm 0.082 \pm 0.033 \pm 0.113$	[30]
$B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^+ \pi^-$	$22.5 \pm 2.5^{+2.4}_{-1.9} \pm 5.8$	[31]
$B^- \to \Sigma_c^0 \overline{p} \pi^- \pi^+$	$4.4 \pm 1.2 \pm 0.5 \pm 1.1$	[31]
$B^- \to \Sigma_c^{++} \overline{p} \pi^- \pi^-$	$2.8 \pm 0.9 \pm 0.5 \pm 0.7$	[31]
$B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$	$18.1 \pm 2.9^{+2.2}_{-1.6} \pm 4.7$	[31]
$B^- \to \Sigma_c^0 \overline{p} \pi^0$	$4.2 \pm 1.3 \pm 0.4 \pm 1.1$	[31]
$B^0 \to \overline{\Lambda} p \pi^-$	$0.0307 \pm 0.0031 \pm 0.023$	[32]

be specific to numerous baryonic decays. An enhancement near the baryon-antibaryon invariant mass threshold was observed in various decays and production mechanisms with baryons in the final state. Such enhancements at the threshold in data compared to the distributions in MC following a phase space model were seen in *B* decays with charmed baryons as  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  (fig. 1.23(a)) or  $B^- \to \Lambda_c^+ \overline{p} \pi^-$ (fig. 1.23(b)) as well as in *B* decays with non-charmed baryons as in  $\overline{B}^0 \to D^0 p \overline{p}$  (fig. 1.23(c)). Also enhancements were observed in more *exotic B* decays as in the suppressed mode  $B^- \to \overline{\Lambda} p \pi^-$  (fig.

1.23(d)) as well as outside the *B*-physics in  $e^+e^- \rightarrow \gamma A \overline{A}$  (fig. 1.23(e)).

To explain this widespread behaviour several suggestions were made, ranging from final state interactions to *bound states* below the threshold, which are summed up by M. Suzuki in [20]. If the interpretation presented in section 1.2.4 holds true, then the mass enhancement can be interpreted by the suppression of hard gluons (i.e. high  $q^2$ ) necessary for *class B* processes to soft gluons (i.e. lower  $q^2$ ) as in *class M* processes. Following, one would not expect a enhancement in  $m\left(\Sigma_c^0(2455)\overline{p}\right)$  from  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ .



Figure 1.23: Enhancement at the baryon-antibaryon invariant mass threshold

# Chapter 2 The BABAR experiment

The data used in this analysis was collected with the BABAR detector located at the PEP-II B factory at the SLAC National Accelerator Laboratory (SLAC). A schematic plot is shown in figure 2.1 Using experiences from previous experiments, as ARGUS, the BABAR experiment and PEP-II storage ring were designed as high luminosity B-meson factory. A high luminosity, a clean  $e^+e^-$  initial environment and an improved vertex resolution were the primary goals to make detailed measurements of time dependent CP asymmetries in neutral B-meson systems feasible. Build as a general purpose detector, the BABAR experiment could also measure a wide range of physics as, for example, CKM unitary triangle parameters, rare and semi-leptonic B-decays,  $\tau$  and charm physics or, as in this analysis, B-meson decays into baryonic final states.



Figure 2.1: Schematic view of the LINAC linear accelerator and PEP-II  $e^+e^-$  storage rings. The BABAR detector is located at the interaction region (IR).

# 2.1 PEP-II linac and storage ring

The PEP-II asymmetric *B* Factory [34] consisted of an  $e^+e^-$  linear accelerator (LINAC) feeding two storage rings. The *BABAR* detector itself was located at the interaction region of the  $e^+$  and  $e^-$  rings. The LINAC accelerated and injected the  $e^-$  beam with an energy of  $E_{e^-} = 9.0$  GeV into the high energy electron ring (HER) and the  $e^+$  beam with an energy of  $E_{e^+} = 3.1$  GeV into the low energy positron ring (LER). Colliding both beams head-on in the interaction region resulted in an energy of  $\sqrt{s} = 10.58$  GeV in the center-of-mass system (cms). The particle production cross sections at this so-called *on-peak* energy are given in table 2.1. In addition to runs of the machine *on-peak*, periods of data taking with energies below the on-peak energy were done for background studies (denoted as *off-peak*).

The on-peak energy corresponds to the mass of the  $\Upsilon(4S)$  resonance  $m_{\Upsilon(4S)} = (10.5794 \pm 0.0012) \text{ GeV}/c^2$ [4] boosted with  $\beta\gamma = 0.55$ . The  $\Upsilon(4S)$  resonance, i.e. the 4S excitation of the  $b\overline{b}$  bound system, is the first  $b\overline{b}$  state that lies above the  $B\overline{B}$  production threshold (~ 10.56 GeV). Consequently, the  $\Upsilon(4S)$  resonance decays nearly solely into a  $B\overline{B}$  meson pair, i.e.  $\Upsilon(4S) \stackrel{(51.6\pm0.6)\%}{\longrightarrow} B^+B^-$  or  $\Upsilon(4S) \stackrel{(48.4\pm0.6)\%}{\longrightarrow} B^0\overline{B}^0$  [4]. The produced *B*-mesons are nearly at rest in the  $\Upsilon(4S)$  rest frame; but due to the boost of the  $\Upsilon(4S)$  system they are boosted in the laboratory frame as well. Despite the relatively short life times of the *B*-mesons  $\tau = \begin{pmatrix} 1.638_{B^-}\pm0.011\\ 1.530_{B^0}\pm0.009 \end{pmatrix} \cdot 10^{-12}s$  [4] the boost makes a destinction between *B*-vertices and the primary interaction point possible. This is in particular necessary for life-time and  $B^0\overline{B}^0$  oscillation measurements and in consequence for CP-measurements.

In the data acquisition period of *BABAR* between 1999 and 2008 *BABAR* recorded ~ 433 fb<sup>-1</sup> on-peak data as well as ~ 53 fb<sup>-1</sup> of off-peak data, which were taken about 40 MeV below the  $\Upsilon(4S)$  threshold (see figure 2.2). In an additional data taking period *BABAR* collected ~ 30 fb<sup>-1</sup> at the  $\Upsilon(3S)$  ( $m_{\Upsilon(3S)} = (10.3552 \pm 0.0005) \text{ GeV}/c^2$ ) resonance and ~ 30 fb<sup>-1</sup> at the  $\Upsilon(2S)$  ( $m_{\Upsilon(2S)} = (10.02326 \pm 0.00031) \text{ GeV}/c^2$ ) resonance [4].

This analysis used data from the 1-6 run periods taken between 2000 and 2008. Data taken during the run 7 period were not used since the energies were below the  $B\overline{B}$  threshold.

Table 2.1: PEP-II: pair production cross sections at the on-peak cms energy  $\sqrt{s} = 10.58 \text{ GeV} [35] [36]$ .

$e^+e^- \rightarrow$	$e^+e^-$	$\mu^+\mu^-$	$\tau^+\tau^-$	$u\overline{u}$	$d\overline{d}$	$s\overline{s}$	$c\overline{c}$	$b\overline{b}$
$\sigma \left[ nb  ight]$	$\approx 40$	1.16	0.94	1.39	0.35	0.35	1.30	1.10



Figure 2.2: PEP-II/BABAR: Delivered and recorded luminosities at  $\Upsilon(4S), \Upsilon(3S), \Upsilon(2S)$  and off-peak energies over the run time

### 2.2 The BABAR detector

#### 2.2.1 Overview

Located at the PEP-II interaction region the BABAR detector had to deliver a good track reconstruction as well as a good particle type identification for charged particles; correspondingly for neutral particles a good energy resolution was required. To achieve these goals BABAR consisted of several specialized sub-detectors. A detailed description of the detector can be found in [11], [37], [38].

From the innermost to the outermost the sub-detectors were the Silicon Vertex Tracker (SVT), the Drift Chamber (DCH), the Detector of Internally Reflected Cherenkov Light (DIRC), the Electromagnetic Calorimeter (EMC) and the superconducting solenoid, and the Instrumented Flux Return (IFR) with the iron yoke for the magnetic field. Muon detectors were integrated in the IFR; for the first three runs of data taking the muon detectors were Resistive Plate Chambers (RPC), which were replaced successively for the following runs by Limited Streamer Tubes (LST).

As preselection and to remove dominant background events, the raw data from the sub-detectors were processed by the *BABAR* trigger system. The trigger system was divided into a hardware based level 1 trigger (L1) and a software based level 3 trigger (L3).

After suppressing noise and main background events, the raw data were processed to reconstruct particle trajectories (tracks) and to assign particle identification hypotheses (PID) to the found tracks. Only particles were reconstructed in this process, which interacted with the detector and had life times long enough to be *stable* within the *BABAR* detector. Thus, the primary particles usable in a *BABAR* analysis are  $p, \bar{p}, e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}$  and  $K^{\pm}$ . Neutral particles as photons could only be reconstructed with information from the calorimeter. For the reconstruction of charged particles also information from the other subdetectors were used (however, muons take a special role because of their low interaction rate with detector material).

Since the studied final state contains only charged particles, this analysis relied mainly on the particle track finding and particle identification. The tracking algorithm used information from the SVT and DCH to reconstruct the trajectories of particles. It used a Kalman fit which tried to reconstruct the flight path of a particle by connecting measured transition points (hits). The Kalman fit added the various points one by one together and calculated the probability for the combined points belonging to a common track. This was done for hits in the SVT and for hits in the DCH, if a particle's momentum was large enough to reach the sub-detector. Tracks found in both sub-detectors were connected if possible. If a particle's velocity was also large enough to reach and deposit its energy in the EMC, this information was included as track end point. For some secondary particles only the DCH provided tracking information.

To identify the particle type for a given track, the deflection in the magnetic field was used. Since a particle's deflection depends also on the mass and velocity, also a measurement of the velocity was necessary to calculate the particle's mass. Such a velocity measurement was done by the DIRC, which exploited that a particle passing through matter radiates Cherenkov radiation depending on its velocity. Furthermore, the SVT and DCH added energy loss measurements and the EMC energy measurements to the PID hypothesis calculation. Combining the various sub-detector information, particle ID hypotheses were calculated for each track.

#### Coordinate system

The origin of the BABAR coordinate system was the nominal point of interaction. The z-axis was aligned parallel to the magnetic field in the direction of the  $e^-$ -beam. The y-axis pointed upwards and the x-axis was aligned horizontally from the center of the PEP-II storage ring.

#### 2.2.2 Silicon Vertex Tracker (SVT)

The purpose of the SVT was the precise measurement of trajectories of charged particles near the interaction region. The SVT was in particular important to reconstruct the B decay vertex from its daughter particles with a high resolution. Also the SVT was the only BABAR component able to measure low momentum particles with transverse momenta  $p_t$  smaller than 100 MeV/c, since these particles did not reach the outer sub-detectors. Figure 2.3(a) shows a section drawing of the SVT.

The SVT was composed of five double-sided layers of silicon microstrip sensors with diameters from 3.3 cm to 14.6 cm cylindrical arranged around the beam pipe. The inner to outer layers consisted of 6, 6, 16 and 18 semiconductor modules. The outer two SVT layer endings were tilted towards the beam pipe for a good coverage of the interaction region. The spatial resolution was about  $15\mu m$  for the three inner layers and about  $40\mu m$  for the two outer layers. This spatial resolution was achieved by tilting the individual layers of double-sided semiconductor strips against each other. The efficiency distribution for the five SVT layers is shown in figure 2.3(b). The SVT's coverage in the polar angle was between 350mrad and 520mrad.

In addition to the spatial resolution the semiconductor layers were used to measure the energy loss dE/dx of particles passing the material, which was used as input for the particle identification (figure 2.3(c)).

#### 2.2.3 Drift Chamber (DCH)

The drift chamber was surrounding the SVT and the beam pipe. In addition to the SVT data, it measured further track and energy loss information of particles with higher momenta. Charged particles passing the drift chamber ionized the gas mixture of 80% helium and 20% isobutane. The electrons and ions were accelerated towards gold-coated tungsten-rhenium signal and gold-coated aluminum field wires, which had diamaters of  $20\mu m$  and  $120\mu m$ , respectively. The wires were organized in cell structures with a central signal wire and six field wires forming a surrounding hexagonal cell with a height and width of about  $12\text{mm} \times 18\text{mm}$ . Between a signal wire and the field wires a high voltage of 1960V was applied. In total the DCH consisted of 7104 of these drift cells in 40 layers. Similar to the SVT strip detectors, the drift cells were organized in an alternating alignment to achieve a spatial resolution. A section drawing of the drift chamber is shown in figure 2.4(a). The spatial information of a passing particle was measured with the drift time and the time of the signal to travel to the signal wire ends. The achieved mean spatial resolution was between  $125\mu m$  and  $150\mu m$  (figure 2.4(b)).

The DCH contributed to the particle identification by measuring the charge deposit of a particle passing a drift cell. The charge deposit is proportional to the energy loss and particle type. Figure 2.4(c) shows the resulting energy loss per momentum and particle type.

#### 2.2.4 Cherenkov Detector (DIRC)

The purpose of the 'Detection of Internally Reflected Cherenkov light' detector was to provide particle identification for charged particles with higher momenta. While SVT and DCH could only discriminate particles with momenta p up to 0.7 GeV/c (compare figures 2.3(c) and 2.4(c)), the DIRC measured pions and kaons with momenta  $p_{\pi^{\pm},K^{\pm}}$  between 0.7 GeV/c and 4 GeV/c and protons with momenta  $p_p$  between 1.3 GeV/c.

The DIRC consisted of 144 silica bars and a water filled standoff box with photomultipliers. The bars, each with dimensions of  $17mm \times 35mm \times 490mm$ , were orientated in a 12 sided polygonal around the drift chamber. The DIRC covered in the azimuthal angle about 87% and in the polar angle about 93% of the detector. As illustrated in figure 2.5(a) charged particles with relativistic velocities produced Cherenkov light when traversing the bars. The opening angle  $\theta_C$  of the Cherenkov light cone depends on the particle's velocity and the refraction index of the silica bars n = 1.473

$$\theta_C(E) = \cos^{-1}\left(\frac{1}{\left[\frac{v}{c}\right]_\beta n}\right) \tag{2.1}$$



(a) SVT: Schematic section drawing of the Silicon Vertex Tracker



(b) SVT: Spatial dependent efficiency distri- (c) SVT: Distribution of momentum dependent energy loss per distance  $\frac{dE}{dx}$  bution for each SVT layer for different particle types

Figure 2.3: SVT: Design and parameters

The Cherenkov light was guided by internal total reflection through the bars into the standoff box outside the main detector, where the Cherenkov light cones were measured by about 110000 photomultipliers. Figure 2.5(b) shows a schematic drawing of the DIRC design. The angular resolution for a single photon is about 9mrad and about 2.8mrad in total. Figure 2.5(c) shows the opening angles for different particles at different momenta.

#### 2.2.5 Electromagnetic Calorimeter (EMC)

While the inner detectors can only measure the tracks, momenta or velocities of charged particles, the electromagnetic calorimeter was designed to measure the energy deposit of charged as well as neutral particles as  $\pi^0$  and  $\gamma$ . The EMC was composed of 5760 thallium-doped caesium iodide crystals, which were orientated in 48 rings with 120 crystals around the drift chamber and additional 820 crystals in the forward direction for a good coverage in the center-of-mass system. The achieved coverage in the cms



Figure 2.4: DCH: Design and parameters

frame was in the azimuth angle  $-0.916 < \cos(\theta_{cms}) < 0.895$ . The measurable energy range was between 20 MeV and 9 GeV.

Electromagnetically interacting particles were decelerated or stopped in the crystals producing bremsstrahlung. The caesium iodide crystals were chosen, since they have a short radiation length of about  $X_0 = 1.85cm$ . Therefore, most of the particles deposited all their energy in the crystals making a precise energy measurement possible. The emitted photon showers were measured by photo diodes. For an improved particle identification charged particle tracks and momentum/velocity information from the SVT, DCH and DIRC were connected to energy deposits and lateral energy spreads in the crystals were taken into account, if possible. For neutral particles the energy distributions in the crystals were measured, which were not assigned to charged particle tracks.

Figure 2.6 shows a schematic drawing of the electromagnetic calorimeter.

#### 2.2.6 Instrumented Flux Return (IFR)

To deflect charged particles and make a velocity/momentum measurement possible, the inner detectors were surrounded by a superconducting solenoid. With a current of 4.6A a magnetic field of 1.5T was



(b) DIRC: Schematic drawing of the DIRC

(c) DIRC: Opening angles of Cherenkov light cones for different particles and momenta

Figure 2.5: DIRC: Design, location and principle of operation

produced deflecting the produced charged particles. To return the magnetic flux of the solenoid massive steel plates with thicknesses between 2cm and 10cm were used. The gaps between the steel plates were equipped for the first three runs with resistive plate chambers (RPC) and were replaced successively with limited streamer tubes (LST). The purpose of the RPCs and LSTs was the measurement of muons and hadrons as  $K_L^0$ , which were able to pass the other sub-detectors without major interactions. Here the steel plates provided further dense interaction material.

The initially installed 774 RPC modules were filled with an argon(57%)-freon(29%)-isobutane(5%) gas mixture and measured streamers of traversing ionizing particles. It achieved a muon identification efficiency of 65%-80% depending of the muon momenta. The RPC system was replaced by LSTs because of aging problems. LSTs are gas detectors similar to ionization chambers but working at higher voltage near the point of breakdown.



Figure 2.6: EMC: Schematic section drawing

# 2.3 Data processing and simulation

#### 2.3.1 Level 1/ Level 3 Trigger system and data skimming

The purpose of the trigger system was the recognition of  $B\overline{B}$  (and  $\tau^+\tau^-$ ) events and to suppress background events, e.g. Bhabha scattering processes  $e^+e^- \rightarrow e^+e^-$  with cross sections about 40 times larger than signal events (compare table 2.1).

The level 1 trigger (L1) was realized in hardware and contained sub-triggers at the various sub-detectors. The following level 3 trigger (L3) was a software based trigger system running on a computer farm.

The level 1 trigger, as the first trigger entity, preselected the events with information on charged tracks. It consisted of three hardware triggers, which processed the data from the drift chamber (DCH Trigger, DCT), from the electromagnetic calorimeter (EMC Trigger, EMT) and from the flux return (IF Trigger, IFT). A fourth L1 component was the global trigger Global Level Trigger (GLT), which used the output data from the three sub-trigger for a first processing of the information of the whole event. The level 1 event trigger rate was at 700Hz.

The L3 trigger was realized in software running on a Linux computer farm. It further processed the preselected events from the L1 trigger and worked at a trigger rate of 85Hz. A decision criterion of the L3 to distinguish between signal and background events was for example the event shape. For signal  $B\overline{B}$  events the events shape is more spherical, while events from  $e^+e^- \rightarrow u\overline{u}$ ,  $d\overline{d}$ ,  $s\overline{s}$  processes have a more jet-like shape. The L3 trigger further made an online luminosity calculation based on  $e^+e^- \rightarrow \mu^+\mu^-$  events.

After passing the trigger system, the processed data were saved in data sets. These data sets are still available to BABAR users for their specific analyses. To reconstruct a specific decay or similar analyses a user can process the data within the Beta software framework. The AllEvents data set has to be reprocessed several times to take into account updated measurements of the BABAR detector response and to include further improvements in the event reconstruction.

Furthermore the data were reprocessed to speed up data processing by users. To condense the data into relevant sub-sets for specific analyses topics, e.g. candidates for unstable particles were searched for in the *so-called* skimming. For example, data sub-sets were created, which are very probable to contain candidates for  $D^+$ ,  $D^0$  or  $\Lambda_c^+$  particles. These *skims* were distributed to several computing centers to distribute the work load of the analyses.

#### 2.3.2 Track and particle ID reconstruction

Tracks of particles were reconstructed with a Kalman filter using hits in the SVT or DCH ([39], [40]). A description of the track finding and particle identification as well as their momentum dependend

efficiencies can be found in [37]. Found tracks are sorted by quality criteria based on:

- $\theta_{lab}$ : polar angle of the track in the laboratory frame
- $p_{lab}$ : momentum of the track in the laboratory frame
- $DCH_{hits}$ : number of hits in the DCH
- $z_{Doca}$ : the closest approach along the z-axis to the  $\sqrt{x^2 + y^2}$  plane
- $xy_{Doca}$ : the closest approach in the x-y-plane to the z-axis
- $P(\chi^2)$ : Successful track finding by the Kalman algorithm
- $p_t$ : transverse momentum of the track

Generally used tracking lists with their quality criteria are given in appendix section A.2 in table A.1. For neutral particle identification the information from the EMC of energy deposits is used. These information include the number of crystals affected by the energy deposit, the total energy deposit, the lateral moment in the affected crystals and the angle of the energy deposit distribution in the affected clusters.

Similarly, a track's particle identification *(PID)* is sorted by quality criteria. Also, a track can have more than one different PID hypothesis, if the PID was not unambiguously. At *BABAR* several PID algorithms are in use; in this analysis likelihood based PID lists were used. Here, for each particle type combined likelihood is calculated from individual the likelihoods from the sub-detectors:

$$\mathcal{L}_{i_x} = \mathcal{L}_{i_x}^{DIRC} \cdot \mathcal{L}_{i_x}^{DCH} \cdot \mathcal{L}_{i_x}^{SVT}$$
(2.2)

The likelihoods from the SVT and DCH are calculated from the comparison of the measured to the hypothetic energy loss for a given particle ID hypothesis following the Bethe-Bloch parameterization [41] [42] (see figure 2.3(c) and 2.4(c)). For the SVT calculations a modified Bethe-Bloch parameterization is used with calibration dependent parameters  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$ 

$$-\frac{dE}{dx}(p,m_i) = \alpha_1 \cdot (\beta_i)^{-\alpha_2} \cdot (\beta_i \gamma_i)^{\alpha_3}$$
(2.3)

The DCH is described with the calibration parameters  $\alpha_1...\alpha_5$ 

$$-\frac{dE}{dx}(p,m_i) = \frac{\alpha_1}{\left(\beta_i\right)^{-\alpha_5}} \left(\alpha_2 - \left(\beta_i\right)^{-\alpha_5} - \ln\left(\alpha_3 + \left(\beta_i\gamma_i\right)^{\alpha_4}\right)\right)$$
(2.4)

The likelihoods for the SVT and DCH are calculated with

$$\mathcal{L}_{i,SVT} = \frac{1}{\sqrt{2\pi}} \frac{2}{\sigma_m + \sigma_p} e^{-\chi_{i,SVT}^2/2}, \ \mathcal{L}_{i,DCH} = \frac{1}{\sqrt{2\pi}\sigma} e^{-\chi_i^2/2}$$
(2.5)

For the likelihoods Gaussian-distributed probability distributions are assumed. The  $\chi^2$  probabilities are calculated from the measured values and the expected values for a particle hypothesis *i*. For the SVT an asymmetric Gaussian is used with different width  $\sigma_p$  and  $\sigma_m$  for the two tails and a modifier  $\alpha$  depending on the number of SVT hits:

$$\chi_{i,DCH}^{2} = \frac{|(dE/dx)_{measured} - (dE/dx)_{i}|^{2}}{(0.08 (dE/dx)_{measured})^{2}}$$
(2.6)

$$\chi_{i,SVT}^{2} = \frac{\ln \frac{(dE/dx)_{measured}}{(dE/dx)_{i}}}{\sigma_{l}^{2}\alpha^{2}}, \ \alpha = \sqrt{\frac{5}{N_{measured}}}, \sigma_{l} = \begin{cases} \sigma_{p}, & \ln \frac{(dE/dx)_{measured}}{(dE/dx)_{i}} \ge 0\\ \sigma_{m}, & \ln \frac{(dE/dx)_{measured}}{(dE/dx)_{i}} < 0 \end{cases}$$
(2.7)

The particle ID likelihood of the DIRC is calculated from the opening angle of the Cherenkov light cone  $\theta_C(E)$ . The opening angle is fitted  $\Theta_C^{fit}$  with an uncertainty  $\sigma_{\Theta}^{fit}$  and is compared to the expected opening angle for particle hypothesis *i*. The likelihood is calculated with

$$\mathcal{L}_{i,DIRC} = \frac{1}{\sqrt{2\pi}\sigma_{\Theta}^{fit}} e^{-\chi_{i,DIRC}^2/2}$$
(2.8)

with a  $\chi^2$  calculated with

$$\chi^2_{i,DIRC} = \frac{\left(\Theta^i_C - \Theta^{fit}_C\right)^2}{\left(\sigma^{fit}_C\right)^2} \tag{2.9}$$

Table A.2 in appendix section A.2 lists the likelihood based PID lists for the particles relevant in this analysis.

#### 2.3.3 Monte-Carlo event simulation

Computer generated events were used to understand the detector response, i.e. the efficiency of BABAR to detect and reconstruct an event or a specific particle correctly. Furthermore, these *Monte-Carlo* (MC) simulations [43] were used to search for background sources. The event simulations were done at the various computing centers. Specialized generators as EvtGen for the generation of  $B\overline{B}$  events [44] are used to simulate specific event classes. Further fragmentations are simulated by programs as Jetset [45] and PYTHIA [46,47] or for final state gamma radiation the program Photos [48]. The interaction of the generated particles with the detector were simulated with the GEANT4 package [49]. After passing the detector simulation of GEANT4 the Monte-Carlo simulated events look ideally like real data including detector noise and other background effects.

Following the generation, the Monte-Carlo data are reprocessed like real data. For an analysis the Monte-Carlo simulated data are reconstructed parallel to the real data, whereas one can access the information of the true initial states and their decay products, which is of course not possible for the real data.

MC data sets are divided into two classes:

Generic Monte-Carlo sets contain events from a specific event class, e.g. only  $B^+B^-$  events, only  $B^0\overline{B}{}^0$  or only  $c\overline{c}$  events, but are not limited to specific modes. Generic Monte-Carlo can be studied for general background or signal sources and detector behaviour.

SP signal Monte-Carlo is generated for a specific decay mode, where one B-meson has to decay in the desired decay channel in a specific decay model, while the remaining B-meson can decay freely. SP signal Monte-Carlo can be studied for the reconstruction efficiencies of the individual modes as well as their specific traits, e.g. to study suspected background decays if they contribute significantly in one or the other variable.

For the Monte-Carlo generation of well understood modes specific decay models can be applied, e.g. the generation and oscillation of  $B^0$ - $\overline{B}^0$  or angular momentum relations.

However, for decays missing a detailed description, as baryonic decays, only phenomenological models can be used. In a **phase space model** the momenta of the decaying particle's daughters are distributed according to the available phase space. Since a simple **phase space model** does only a basic physical description of a decay, one has to take differences between the real data and Monte-Carlo simulated data into account and cannot rely solely on the Monte-Carlo simulation.

# Chapter 3

# Data selection

Event reconstruction was done using the BABARBeta framework on a data set based on the  $\Lambda_c$  skim. The  $\Lambda_c$  skim is a subset of the complete BABAR data set (see subsection 2.3.1) that was enriched with events, which passed general requirements necessary for a  $\Lambda_c$ -candidate (see table 3.1).

### **3.1** Software and datasets

The BABAR software framework has gradually been updated and expanded. To avoid inconsistencies, an analysis is performed in a certain software release version on the data set version and detector conditions corresponding to the software release.

#### 3.1.1 Reconstruction software

This analysis was performed using the software release analysis-50 on run 1-6 data from the R22 data reprocessing. To use R22 reprocessed data within analysis-50(R24) the release condition "anal50boot" was used. The specific software packages and versions are given in the appendix in sectionA.3.

#### 3.1.2 Data set

Data were processed at the CNAF computing site of the Italian National Institute for Nuclear Physic at Bologna. As data input the LambdaC-skim LambdaC-Run{1-6}-OnPeak-R22d-v10 was processed, which is a subset of the total dataset and is enriched with  $\Lambda_c$ -candidates. The conditions on an event to be added to the  $\Lambda_c$  skim are given in tabel 3.1.

### **3.1.3** Number of $B\overline{B}$ events

The Luminosity and number of  $B\overline{B}$  pairs were calculated with the BABARBbkLumi script [50], [51]. The script calculates the number of events from the number of hadronic events  $N_{MH}$  and muonic events  $N_{\mu\mu}$  at on-peak and off-peak energies (see definitions in subsection 2.1). Basically, to subtract the non- $b\overline{b}$  hadronic contribution, it is measured below the  $b\overline{b}$ -threshold and scaled onto on-peak energy using the measured cross-sections for muon-production at both energies:  $N_{B\overline{B}} = N_{MH}^{on-peak} - N_{MH}^{off-peak} \cdot \frac{N_{\mu+\mu^-}^{on-peak}}{N_{\mu+\mu^+}^{off-peak}} \cdot \kappa$ . The parameter  $\kappa$  subsumes the reconstruction efficiencies  $\varepsilon$  and cross-sections  $\sigma$  for the muon-events  $\mu\mu$  and non- $B\overline{B}$  hadron events MH<sub>1B</sub> at both beams energies:  $\kappa = \frac{\sigma_{\mu\mu}^{off-peak}}{\sigma_{\mu\mu}^{on-peak}} \cdot \frac{\varepsilon_{\mu\mu^-}^{off-peak}}{\sigma_{MH_{1B}}^{on-peak}} \cdot \frac{\varepsilon_{MH_{1B}}^{off-peak}}{\varepsilon_{MH_{1B}}^{on-peak}} \cdot \frac{\varepsilon_{MH_{1B}}^{off-peak}}{\varepsilon_{MH_{1B}}^{on-peak}}$ . The analyzed dataset had an integrated luminosity and number of  $B\overline{B}$  pairs of:

$$L_{\rm Onpeak} = 425676.760 \, \rm{pb}^{-1} \tag{3.1}$$

$$N_{B\overline{B}} = 467358936.0 \pm 114852.8_{stat} \pm 5140948.3_{sys} \tag{3.2}$$

Table 3.1:  $\Lambda_c$  skim: Conditions for an event to be included in the  $\Lambda_c$  skim for the decay  $\Lambda_c^+ \to p K^- \pi^+$ .  $\Lambda_c$ -candidates were reconstructed with a vertex fit in the invariant mass  $m(pK^-\pi^+)$ , for which the potential  $\Lambda_c$ -daughters had to pass soft particle ientification criteria.

Parameter	Constraint
proton PID	pLHVeryLoose
kaon PID	KLHVeryLoose
pion PID	piLHVeryLoose
$m\left(pK^{-}\pi^{+}\right)$	$\in (2.185, 2.385) \text{ GeV}/c^2$
$\Lambda_c$ fit	$P_{A}^{fit}(\chi^2) > 0.001$

### 3.2 Event selection

First a  $\Lambda_c^+$  candidate was formed by combining p,  $K^-$  and  $\pi^+$  and first cuts for background suppression were applied. To form a  $\overline{B}{}^0$  candidate a  $\Lambda_c^+$  candidate was combined with  $\overline{p}$ ,  $\pi^+$  and  $\pi^-$ . After applying additional cuts for background suppression, the candidates were stored into a ROOT n-tuple data format. The in-detail study was performed on the n-tuple data using the ROOT data analysis program and libraries [52], [53]. The invariant mass  $m_{inv}$  of the reconstructed  $\overline{B}{}^0$ -candidate was used as primary reconstruction variable. For studying the resonant substructures, four-vector momentum sums of  $\overline{B}{}^0$ daughters were used.

#### 3.2.1 *B* reconstruction variables

In general, particles can be reconstructed by calculating the invariant mass  $m_{inv}$  from a candidate's four-momentum. For *B*-candidates created at the *B*-factories *BABAR* and Belle two kinematic variables  $m_{\rm ES}$  and  $\Delta E$  can be used.

In this analysis  $\overline{B}^0$  candidates were selected using the variables  $m_{inv}$  and  $m_{\rm ES}$ .

The B-invariant mass is defined as

$$m_{inv} = \sqrt{E_B^2 - \vec{p}_B^2} \tag{3.3}$$

for a *B*-candidate with the momentum  $\vec{p}$  and energy *E*. The energy-substituted mass  $m_{\rm ES}$  is used at *BABAR* in a Lorentz invariant form [54]:

$$m_{\rm ES} = \sqrt{\frac{\left(s/2 + p_i \cdot p_B\right)^2}{E_i^2} - p_B^2} \tag{3.4}$$

Here index *i* denotes the initial state of the  $e^+e^-$  beam and index *B* denotes the the reconstructed B-meson;  $\sqrt{s}$  is the total energy in the center-of mass (cms) system. Both B-daughters of the  $\Upsilon(4S)$ conserve the four-momentum of the  $e^+e^-$ -beam and have in the center-of-mass frame a momentum of  $p_B^* \approx 0.325 \text{ GeV}/c$ . Since the initial state of the  $e^+e^-$  is known within the beam uncertainties, one can use the four-momentum of the initial  $e^+e^-$  system as constraints on the  $B\overline{B}$  system. For a true *B* the  $m_{\rm ES}$  value has to peak around the nominal *B* mass [4]. The  $m_{\rm ES}$  parameter was used in this analysis as veto against background and not for reconstruction of *B*-candidates.

If the momentum of  $e^+e^-$  is used as constraint, then the energy difference between the initial  $e^+e^$ and  $B\overline{B}$  has to be close to zero, i.e. measuring the energy conservation for true *B*-mesons. The energy
difference  $\Delta E$  can be written in a Lorentz-invariant form and in a more common form in the center-ofmass system(denoted with \*) as

$$\Delta E = (2q_i \cdot q_B - 2) / 2\sqrt{s} = E_B^* - E_{Beam}^*$$
(3.5)

with the four-momenta  $q_i$  of the initial  $e^+e^-$  system and  $q_B$  of the reconstructed  $B^{1}$ .

#### 3.2.2 $\Sigma_c$ reconstruction variables

To reconstruct intermediate  $\Sigma_c^{++}$  resonances their invariant mass was used, combining  $\Lambda_c^+$  and  $\pi^{\pm}$  fourmomenta. In the *B*-reconstruction the mass of the  $\Lambda_c^+$ -candidate was constraint to its nominal mass (see following section 3.4.1).

$$m\left(\Lambda_{c}^{+}\pi^{\pm}\right) = \sqrt{\left(E_{\Lambda_{c}^{+}} + E_{\pi^{\pm}}\right)^{2} - \left(\vec{p}_{\Lambda_{c}^{+}} + \vec{p}_{\pi^{\pm}}\right)^{2}}$$
(3.6)

#### 3.2.3 Track constraints

The following requirements on each event were applied before any candidate reconstruction:

- minimum number of tracks in GoodTracksVeryLoose > 4
- at least one proton and one antiproton candidate fulfilling pLHVeryLoose and GoodTracksVery-Loose

The used tracks and particle ID lists are given in table 3.2.

Table 3.2: Event preselection: Tracking and PID requirements for  $\overline{B}^0$  and  $\Lambda_c^+$  daughters.

Particle	Tracking	PID
$\overline{p}_{B^0}$	GoodTracksVeryLoose	pLHVeryLoose
$\pi_{B^0}^{\pm}$	GoodTracksVeryLoose	-
$p_{A_c^+}^-$	GoodTracksVeryLoose	pLHVeryLoose
$\pi^+_{\Lambda^+_c}$	GoodTracksVeryLoose	piLHVeryLoose
$K_{\Lambda^+}^{-}$	GoodTracksVeryLoose	KLHVeryLoose

## **3.3** $\Lambda_c^+$ selection

For  $\Lambda_c$  reconstruction only its dominant decay mode  $\Lambda_c^+ \to pK^-\pi^+$  was used. Its branching fraction and uncertainty are  $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3)\%$  [4]. Potential  $\Lambda_c^+$  daughters  $p \ K^- \ \pi^+$  were combined using the TreeFitter algorithm to form a  $\Lambda_c^+$ -candidate. Candidates had to have a mass within (2.235,2.335) GeV/ $c^2$  and a vertex fit probability larger than  $P_{\Lambda_c^+}(\chi) > 0.001$ .  $\Lambda_c$ -candidates passing these cuts, summarized in table 3.3, were further used to form  $\overline{B}^0$  candidates. Figure 3.1 shows the distribution of events in  $m(pK^-\pi^+)$ , which passed the selection cuts.

 $<sup>^{1}\</sup>Delta E$  was initially used as reconstruction variable for *B*-candidates but replaced by  $m_{inv}$ . In some kinematic regions  $m_{\rm ES}$  and  $\Delta E$  are nearly uncorrelated, however for *B*-decays with heavy daughters particles, as baryons, the correlation becomes significant. Instead,  $m_{inv}$  and  $m_{\rm ES}$  were used because their insignificant correlation, accepting the broader signal spread in  $m_{inv}$  compared to the constraint  $\Delta E$  signal (see section 3.4.2)

## **3.4** $\overline{B}{}^0$ selection and $\Lambda_c^+$ mass constraint

 $\Lambda_c^+$ -candidates passing the event selection cuts given in table 3.3 were used to form a  $\overline{B}^0$ -candidate. A  $\Lambda_c^+$ -candidate was combined with a  $\overline{p}$  and two oppositely charged pions.

Both  $\overline{B}^0$ -daughters,  $\Lambda_c^+$  and  $\overline{p}$ , were required to be oppositely charged. For the  $\overline{B}^0$ -candidate the whole decay tree including  $\Lambda_c^+$ -daughters was fitted.

In the decay tree fit a mass constraint was applied to the  $\Lambda_c^+$ -candidate. Since in data and in events from Monte-Carlo simulations (MC) the  $\Lambda_c$  mass is not consistent two different mass constraints were applied.

#### 3.4.1 $\Lambda_c^+$ mass hypotheses in data and Monte-Carlo simulated events

By default a  $\Lambda_c$  mass of 2.2849 GeV/ $c^2$  is used at BABAR, the nominal mass found in PDG Volume 2004 [55]. It is used for event generation in the Monte-Carlo simulation and is also the default for mass constraints applied during reconstruction.

For reconstructing Monte-Carlo simulated events the  $\Lambda_c$  mass was constraint to the default mass, i.e. 2.2849 GeV/ $c^2$ . On data,  $\Lambda_c$ -candidates were constraint to a value of 2.2856 GeV/ $c^2$ , which was extracted from data itself.

One reason to use different  $\Lambda_c^+$  masses in reconstructing events from data and from Monte-Carlo was the result of a more precise BABAR measurement [56]. The study, based on runs 1-4, measured a  $\Lambda_c$ mass of (2.28646  $\pm$  0.00014) GeV/ $c^2$ . However, the modes studied in analysis [56] were  $\Lambda_c^+ \rightarrow \Lambda K_s^0 K^+$ and  $\Lambda_c^+ \rightarrow \Sigma^0 K_s^0 K^+$ , which have a lower Q-value compared to the mode  $\Lambda_c^+ \rightarrow p K^- \pi^+$  used in this analysis. The Q-value has an impact on the track reconstruction, since uncertainties on tracking-related parameters as the energy-loss or magnetic field strength tend to scale with the Q-value. Also in [56] several corrections were applied, that were not applied in this analysis. The result from [56] is the only measurement of the  $\Lambda_c^+$  mass that is used as accepted value since PDG Volume 2006 [57] onward.

Thus, neither the  $\Lambda_c^+$  mass used in the Monte-Carlo simulation nor the result from [56] could be used for the reconstruction of  $\Lambda_c^+$  candidates in data. Therefore, it was assumed that for constraining the  $\Lambda_c$ mass in data the constraint value had to be extracted from  $m (pK^-\pi^+)$  in data itself.

To measure the  $\Lambda_c^+$  mass in data,  $\Lambda_c^+$ -candidates were reconstructed in  $m(pK^-\pi^+)$ . The TreeFitter algorithm was used to combine p,  $K^-$  and  $\pi^+$  to form  $\Lambda_c^+$ -candidates in  $m(pK^-\pi^+)$ , requiring a vertex fit probability of  $P(\chi^2) > 0.001$ . The mass distribution of  $m(pK^-\pi^+)$  from all runs is shown in figure 3.1.  $m(pK^-\pi^+)$  was fitted run-wise with a Gaussian for the signal and a second order polynomial for background, to search for run dependent effects. Since no significant run-dependence was found, the mean  $\Lambda_c$  mass for all runs 1-6 was about 2.2856 GeV/ $c^2$  for the decay mode  $\Lambda_c^+ \to pK^-\pi^+$ . A further study of the influence of the mass constraints hypothesis on the *B*-reconstruction can be found in the appendix section A.5.2.

Thus, for reconstructing  $\overline{B}^0$ -candidates in data this mass, i.e.  $2.2856 \text{ GeV}/c^2$ , was used for constraining  $\Lambda_c^+$ -candidates. Additional information on the study of the  $\Lambda_c$  mass in the different data taking runs and the influence of the  $\Lambda_c^+$  selection on the  $\overline{B}^0$ -candidates can be found in the appendix section A.5.

To reduce combinatorial background a mass cut was applied to the  $\Lambda_c^+$ -daughter in the *B*-fit. The mass cut windows were adjusted to the mass constraint values. In Monte-Carlo and data the mass cut borders were shifted accordingly to the mass constraints. For Monte-Carlo the mass cut window was chosen to be  $m (pK^-\pi^+)_{MC} \in (2.272, 2.297) \text{ GeV}/c^2$ . In data the mass window was shifted accordingly and covered the range  $m (pK^-\pi^+)_{data} \in (2.2727, 2.2977) \text{ GeV}/c^2$ . Background was further reduced by selecting a wide window in  $m_{\text{ES}}$  and  $\Delta E$  around the nominal  $\overline{B}^0$ -

Background was further reduced by selecting a wide window in  $m_{\rm ES}$  and  $\Delta E$  around the nominal  $B^0$ signal values. For each *B*-candidate the Lorentz-invariant values of  $m_{\rm ES}$  and  $\Delta E$  were provided by the BtaCandidate and BtaBVariables routines of the Beta framework.  $\overline{B}^0$ -candidates had to be within a window of  $m_{\rm ES} \geq 5.2 \,\text{GeV}/c^2$  and  $\Delta E \in (-0.3, 0.3) \,\text{GeV}$ . In addition, the  $\overline{B}^0$  tree fit had to have a probability  $P_{\overline{B}^0}^{\text{fit}}(\chi^2)$  larger than 0.001. Vetoes on  $D^0$  and  $D^+$  invariant masses were applied to several combinations of final state particles. Decays of the type  $\overline{B}{}^0 \to D^0/D^+ p\overline{p} (\mathbf{n} \cdot \pi)$  with  $D^0 \to K^- \pi^+ \pi^- \pi^+$ ,  $D^+ \to K^- \pi^+ \pi^-$  or  $D^0 \to K^- \pi^+$  have the same final state particles as signal decays  $\overline{B}{}^0 \to \overline{p}_{\overline{B}{}^0} \pi^+_{\overline{B}{}^0} \pi^-_{\overline{B}{}^0} \left[ K^-_{A_c^+} \pi^+_{A_c^+} p_{A_c^+} \right]_{A_c^+}$ . The final state particles can be rearranged and fake a signal decay. These events are removed by applying vetoes to the corresponding invariant masses of  $D^0/D^+$  daughter combinations. In section 3.8.5 these modes are described in more detail.

The reconstruction cuts and constraints for  $\overline{B}^0$ -candidates are summarized in table 3.4. Events passing these cuts were used to reconstruct signal events and study background events. The background and signal event suppression efficiencies of the cuts are given in table 3.5. Vetoes on  $\overline{B}^0 \to D^0/D^+p\overline{p}(\mathbf{n}\cdot\pi)$  modes were generally applied except while studying these specific modes (see section 3.8.5).



Figure 3.1:  $\Lambda_c$  mass:  $m(pK^-\pi^+)$  from runs 1-6 in data.

Table 3.3: Event reconstruction: Cuts on  $\Lambda_c^+$  candidates during event reconstruction and event selection on ROOT ntuple level.

Event reconstruction	parameter	$\operatorname{Cut}$
Event reconstruction	fit algorithm	TreeFitter
	$m\left(pK^{-}\pi^{+}\right)$	$(2.235, 2.335) \mathrm{GeV}/c^2$
	fit result	successful & $P_{\Lambda_c}^{fit}(\chi^2) > 0.001$

Table 3.4: Event reconstruction: Cuts on  $\overline{B}^0$ -candidates. Shifts between masses from  $\Lambda_c$  generated in Monte-Carlo simulations and  $\Lambda_c$  in data were taken into account.

parameter	MC/Data	Cut
$\Lambda_c^+$ -candidates	general	table 3.3
	MC	mass constraint $2.2849 \text{GeV}/c_{MC}^2$
	Data	mass constraint $2.2856 \text{ GeV}/c^2_{data}$
$\Lambda_c^+$ mass in ntuple	MC	$(2.272, 2.297)  \text{GeV}/c^2_{MC}$
	Data	$(2.2727, 2.2977)  \text{GeV}/c^2_{\ data}$
algorithm	general	TreeFitter
fit		successful & $P_{\overline{R}^0}^{fit}(\chi^2) > 0.01$
$m_{\rm ES}$ preselection		$> 5.2 \mathrm{GeV}$
$\Delta E$ preselection		$(-0.3, 0.3){ m GeV}$
$m\left(K_{A_c^+}^-\pi_{A_c^+}^+\pi_{\overline{B}^0}^+\right)$	general	$i i \in (1.869 \pm 0.020)  \text{GeV}/c^2$
$m\left(K_{\Lambda_c^+}^-\pi_{\Lambda_c^+}^+\pi_{\overline{B}{}^0}^+\pi_{\overline{B}{}^0}^-\right)$		$i i \in (1.865 \pm 0.020)  \text{GeV}/c^2$
$m\left(K^{-}_{\Lambda^{+}_{c}}\pi^{+}_{\overline{B}^{0}} ight)$		$\ni (1.865\pm0.020)\mathrm{GeV}\!/c^2$

Table 3.5: Constraint acceptances for background and signal decay simulated Monte-Carlo events for consecutively applied cuts. For signal Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  events with with positively mapped signal events (*truthmatched*) was used, i.e. including the efficiency of the truthmatching algorithm. Efficiencies of  $\overline{B}^0$  signal event selections in  $m_{\rm ES}$  and  $m_{inv}$  are given in table 3.7. Efficiencies of vetoes on  $\overline{B}^0 \to D^0/D^+ p\overline{p} (n \cdot \pi)$  are discussed in detail in table 3.11 in section 3.8.5.

Constraint	uds	$c\overline{c}$	$B\overline{B}$	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{\rm truthmatched}^-$
Geometric & PID/Tracking	$2.38 \cdot 10^{-5}$	$8.92 \cdot 10^{-4}$	$3.49 \cdot 10^{-3}$	17.49%
Charge Orientation	$1.40 \cdot 10^{-5}$	$5.20 \cdot 10^{-4}$	$1.99 \cdot 10^{-3}$	
Fit $P(\chi^2) > 0.01$	$1.17 \cdot 10^{-5}$	$4.21 \cdot 10^{-4}$	$1.63 \cdot 10^{-3}$	16.23%
$m(pK^{-}\pi^{+}) \in (2.272, 2.297) \text{ GeV}/c^{2}$	$6.78 \cdot 10^{-6}$	$2.57\cdot 10^{-4}$	$1.108 \cdot 10^{-3}$	14.78%

#### 3.4.2 Reconstruction variables: Correlation considerations

Typically, *B*-candidates are reconstructed in  $m_{\rm ES}$  or  $\Delta E$  to exploit the constraints from the beam fourmomentum conservation. Either, one variable is used for background suppression and one for signal reconstruction or the signal is reconstructed in both variables in a simultaneous fit. However, in general these approaches assume no correlation between both variables (The *BABAR* measurement described in [12] takes a correlation into account by redefining the kinematic variables).

For  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  a correlation can be seen by eye between  $m_{\rm ES}$  and  $\Delta E$ . In figure 3.2 the binned distributions in the two-dimensional signal regions in  $m_{\rm ES}:m_{inv}$  and  $m_{\rm ES}:\Delta E$  are shown for events from the non-resonant signal Monte-Carlo simulation. While the correlation is obvious in  $m_{\rm ES}:\Delta E$ , no significant correlation appears in  $m_{\rm ES}:m_{inv}$ .

As pointed out in [58],  $m_{\rm ES}$  and  $\Delta E$  were initially assumed to have only a marginal correlation. In a naive comparison of  $\Delta E$  and of the non-Lorentz-invariant definition of  $m_{\rm ES}$ 

$$\Delta E = E_B - E_{Beam}$$
$$m_{\rm ES} = \sqrt{E_{Beam}^2 - \vec{p}_B^2}$$

it was assumed that the *B* energy  $E_{Beam}$  and the *B* momentum  $\vec{p}_B$  are not correlated (except for a marginal correlation due to the influence of the momentum measurement on the energy measurement). However, a correlation between both variables becomes visible if the detector resolution is good enough to resolve the beam-energy spread. In this case an anti-correlation between  $m_{\rm ES}$  and  $\Delta E$  is apparent, i.e for larger beam energies  $\Delta E$  decreases while  $m_{\rm ES}$  increases and vice versa.

$$E_{Beam}^{I} < E_{Beam}^{II}$$

$$\Rightarrow \left[\Delta E^{I} = E_{B} - E_{Beam}^{I}\right] > \left[\Delta E^{II} = E_{B} - E_{Beam}^{II}\right]$$

$$\Rightarrow \left[m_{\rm ES}{}^{I} = \sqrt{E_{Beam}^{I}}^{2} - \vec{p}_{B}^{2}\right] < \left[m_{\rm ES}{}^{II} = \sqrt{E_{Beam}^{II}}^{2} - \vec{p}_{B}^{2}\right]$$

Since  $m_{inv}$  does not use the beam energy no such correlation appears. (See in note [58] the section *B.1* on the correlation between  $m_{ES}$  and  $\Delta E$  as well as on the correlation between  $m_{inv}$  and  $\Delta E$ . Obviously, the pairing of the variables  $m_{inv}$  and  $\Delta E$  for reconstruction was ruled out as well, because of their naturally larger correlation)

Therefore,  $m_{\rm ES}$  and  $m_{inv}$  were used as general variables for selecting and reconstructing  $\overline{B}^0$  candidates.  $m_{\rm ES}$  was used for background separation, while  $m_{inv}$  was used for reconstructing the non-resonant  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  events. Events from resonant intermediate decays  $\overline{B}^0 \to \Sigma_c^{++}$  (2455, 2520) $\overline{p} \pi^\mp$  were reconstructed in the  $m_{inv}:m(\Lambda_c^+\pi^+)$  and the  $m_{inv}:m(\Lambda_c^+\pi^-)$  planes.

The events from resonant decays were reconstructed first to separate them from the remaining signal events.



Figure 3.2:  $m_{inv}$  : $m_{\rm ES}$  and  $\Delta E$ : $m_{\rm ES}$ : plots from  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal MC (SP-5076). In the upper plot, a correlation between  $m_{\rm ES}$  and  $\Delta E$  is visible by eye; a fit with 2D-Gaussian (eq. 3.9) found a correlation of  $\rho_{\Delta E:m_{\rm ES}} = -0.2879 \pm 0.0028$ . In the lower plot, for  $m_{inv}$  and  $m_{\rm ES}$  no immediate correlation is noticeable; correlation; a fit with 2D-Gaussian found a correlation of  $\rho_{m_{inv}:m_{\rm ES}} = -0.023 \pm 0.005$ . The nominal  $B^0$  mass,  $m_{\rm ES}$  and energy difference values are denoted as dashed lines.

# **3.5** Preparations for $\overline{B}{}^0 \to \Sigma_c^{++} \overline{p} \pi^{\mp}$ measurements

Before measuring the total  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  branching fraction, the contributions from resonant decay modes with  $\Sigma_c$  resonances were studied.  $\Sigma_c$  candidates in the  $\overline{B}{}^0$  signal region appear as signal in the  $m(\Lambda_c^+ \pi^{\pm})$  invariant masses.

Resonant intermediate states of the signal mode could contain  $\Sigma_c^{++}$  and  $\Sigma_c^0$  baryons, decaying further into the final state particles

$$\overline{B}{}^{0} \to \Sigma_{c}^{++} \overline{p} \pi^{-}; \qquad \Sigma_{c}^{++} \to \Lambda_{c}^{+} \pi^{+} \\
\overline{B}{}^{0} \to \Sigma_{c}^{0} \overline{p} \pi^{+}; \qquad \Sigma_{c}^{0} \to \Lambda_{c}^{+} \pi^{-}$$

Several excited states have been observed in inclusive measurements. In the following the states are distinguished by their nominal masses  $\Sigma_c^{++}(2455)$  and  $\Sigma_c^{++}(2520)$ . Inclusively measured resonances are  $\Sigma_c$  (2455),  $\Sigma_c$  (2520) and  $\Sigma_c$  (2800) [19,59–61]. In this analysis only modes with the first two resonances were searched for, i.e. decays via  $\Sigma_c^{++}(2800)$  were subsumed in the remaining non- $\Sigma_c$  (2455,2520)  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  rest.

The single charged decays  $\Sigma_c^+(2455, 2520) \to \Lambda_c^+ \pi^0$  are not possible in thr signal decay but could contribute via the decay  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  as background source.

### **3.5.1** $\overline{B}^0$ signal and side band definitions

Since resonant intermediate states with  $\Sigma_c$  baryons were reconstructed in  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  decays, a two stage selection was applied.

A cut in  $m_{\rm ES}$  was applied to separate signal candidates from background events.  $m_{inv}$  was used for reconstructing a  $\overline{B}^0$ -candidate and for separating signal and side bands. Following, the  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  invariant masses were used for reconstructing  $\Sigma_c^{++}$ -candidates.

Instead of using only  $m_{inv}$  or  $m(\Lambda_c^+\pi^{\pm})$  signal events were reconstructed in the planes  $m_{inv}: m(\Lambda_c^+\pi^+)$ and  $m_{inv}: m(\Lambda_c^+\pi^-)$  in a two-dimensional fit. The  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  plane showed to be successful in differentiating between signal events and peaking background, which was not distinguishable in  $m_{inv}$  or  $m(\Lambda_c^+\pi^{\pm})$  alone or in a simultaneous fit of both variables.

#### **3.5.1.1** Selection variables $m_{\rm ES}$ : $m_{inv}$

To separate signal and background in  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal and side band regions were defined in the  $m_{\rm ES}$ - $m_{inv}$ -plane. The regions are shown in figure 3.3 and are listed in table 3.6.

The  $m_{\rm ES}$ - $m_{inv}$ -plane is divided into four signal and side band regions.  $m_{\rm ES}$  and  $m_{inv}$  are both divided into two bands, a signal band containing the  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal events and a side band for background studies. The  $m_{\rm ES}$  signal and side bands consist of two continuous regions in  $m_{\rm ES}$  separated by a gap. In  $m_{inv}$  the side band consists of two sub-side bands which are symmetric around the signal band. Both  $m_{inv}$  sub-side bands are separated from the signal region by a gap. The  $m_{inv}$  sub-side bands (denoted as  $m_{inv} \stackrel{I}{_{SB}}$  and  $m_{inv} \stackrel{II}{_{SB}}$ ) were chosen to cover the same intervals. In the following the  $m_{inv}$  sub-side bands were combined into a single  $m_{inv}$  side band (if not stated otherwise).

Regions formed by intersecting  $m_{\text{ES}}$  and  $m_{inv}$  bands are denoted in the following as signal region or side band regions. These regions are denoted with I - IV.

The region that contains the expected signal events is denoted in the following as region I or as  $m_{\text{ES}}$ - $m_{inv}$  signal region. Side band regions are denoted as II ( $m_{\text{ES}}$  side band,  $m_{inv}$  signal band), III ( $m_{\text{ES}}$  signal band,  $m_{inv}$  side band)), IV ( $m_{\text{ES}}$  and  $m_{inv}$  side bands).

The  $m_{\rm ES}$ - $m_{inv}$ -plane from data is shown in figure 3.4<sup>2</sup>. The projection of the  $m_{\rm ES}$  signal band onto

 $<sup>^{2}</sup>$ All following plots and figures were made with the cuts applied given in tables 3.3 and 3.4, if not stated otherwise

 $m_{inv}$  is given in figure 3.5. The signal and side band borders for  $m_{inv}$  are denoted as red and blue lines. At smaller values  $m_{inv} < 5.15 \text{ GeV}/c^2$  a bump is visible in the combinatorial background. This bump results from higher multiplicity modes, i.e.  $B^- \to \overline{\Lambda}_c^- p \pi^- \pi^+ \pi^-$  or  $\overline{B}^0 \to \overline{\Lambda}_c^- p \pi^- \pi^+ \pi^0$ . To avoid contributions from these modes the side band definitions in  $m_{inv}$  were chosen with a safety margin. The corresponding projection of events in the  $m_{inv}$  signal band onto  $m_{\rm ES}$  is given in figure 3.6.

 $m_{inv}$  was fitted width a double Gaussian and the signal region was chosen to be about four times the narrow width  $\sigma_{m_{inv}}$ . The sub-side bands in  $m_{inv}$  were chosen to lay symmetrically around the signal band. The sub-regions width is  $60 \text{ GeV}/c^2$ , giving enough statistics for side band studies while keeping distance to the higher multiplicity bump. Both  $m_{inv}$  were chosen to be symmetrical in width for a convenient merging of both sub-side bands into a combined  $m_{inv}$  side band region.

Table 3.7 gives the acceptances of the signal region cuts for truthmatched<sup>3</sup>, non-resonant signal Monte-Carlo events and background modes in generic Monte-Carlo event simulations (see also table 3.11 for acceptances of  $D^0/D^+$  vetoes on background Monte-Carlo modes and non-resonant signal events).



Figure 3.3: Signal and side band regions in the  $m_{\rm ES}$ - $m_{inv}$ -plane. The plane is divided into four bands, for  $m_{\rm ES}$  and  $m_{inv}$  a signal and a side band each. The intersections define the signal and side regions. The borders are given in table 3.6.

 $\begin{array}{c} 5.5 \\ 5.4 \\ 5.2 \\ 5.1 \\ 5.2 \\$ 

Figure 3.4:  $m_{\text{ES}}$ - $m_{inv}$ -plane from data after passing  $\overline{B}^0$  selection cuts (see tables 3.3 and 3.4).

<sup>&</sup>lt;sup>3</sup> "*Truthmatched Monte-Carlo events*" means the mapping of a particle after reconstruction to the generated true particle's track and type, i.e. selecting in MC only the reconstructed particles that were reconstructed truly.



Figure 3.5:  $m_{inv}$ : distribution for events in the  $m_{\rm ES}$  signal region. Borders of the signal region in  $m_{inv}$  are given in red; side band borders in dashed blue.



Figure 3.6:  $m_{\rm ES}$ : distribution for events in the  $m_{inv}$  signal region. Borders of the signal region in  $m_{\rm ES}$  are given in red; side band borders in dashed blue.

Table 3.6: Definitions for signal and side bands in the  $m_{\rm ES}$ - $m_{inv}$ -plane. The bands and regions are shown in figure 3.3.

variable	band	$\operatorname{start}$	end
$m_{\rm ES}$	signal	$5.272 \mathrm{GeV}/c^2$	$5.285 \mathrm{GeV}/c^2$
$m_{\rm ES}$	side	$5.2 \mathrm{GeV}/c^2$	$5.26 \mathrm{GeV}/c^2$
$m_{inv}$	signal	$5.252 \mathrm{GeV}/c^2$	$5.3 \mathrm{GeV}/c^2$
$m_{inv}$	$side_1$	$5.17  \text{GeV}/c^2$	$5.23 \mathrm{GeV}/c^2$
$m_{inv}$	$side_2$	$5.322 \mathrm{GeV}/c^2$	$5.382 \mathrm{GeV}/c^2$

Table 3.7: Constraint acceptances for generic background and signal Monte-Carlo for consecutively applied selection windows in  $m_{\rm ES}$  and  $m_{inv}$  after passing the constraints given in table 3.5. Truthmatched non-resonant  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal Monte-Carlo events were used, i.e. including the efficiency of the truthmatching algorithm (see footnote 3).

Constraint	uds	$c\overline{c}$	$B\overline{B}$	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{\text{truthmatched}}^-$
$m_{\rm ES} \in (5.272, 5.28) \; {\rm GeV}/c^2$	$4.83 \cdot 10^{-7}$	$1.92 \cdot 10^{-5}$	$1.114 \cdot 10^{-4}$	13.89%
$m_{inv} \in (5.252, 5.3) \text{ GeV}/c^2$	$3.52 \cdot 10^{-8}$	$1.45 \cdot 10^{-6}$	$7.49 \cdot 10^{-6}$	12.41%

### **3.6** $\Sigma_c$ fit strategy

The following resonant decays were measured in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  planes

- $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-; \ \Sigma_c^{++}(2455) \to \Lambda_c^+\pi^+ \text{ in } m_{inv}:m\left(\Lambda_c^+\pi^+\right)$
- $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-; \ \Sigma_c^{++}(2520) \to \Lambda_c^+\pi^+ \text{ in } m_{inv}:m(\Lambda_c^+\pi^+)$
- $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+; \ \Sigma_c^0(2455) \to \Lambda_c^+\pi^- \text{ in } m_{inv}:m(\Lambda_c^+\pi^-)$
- $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+; \ \Sigma_c^0(2520) \to \Lambda_c^+\pi^- \text{ in } m_{inv}:m(\Lambda_c^+\pi^-)$

Besides signal contributions from the resonant states  $\Sigma_c$  (2455,2520) for both charge combination, several peaking background sources were found that could contribute to the signal. Background contributions can be divided according to their behaviour:

- combinatorial background, that does not appear as a signal-like shape in  $m_{inv}$  or in  $m(\Lambda_c^+\pi^\pm)$
- background, that appears as signal in  $m_{inv}$  but not in  $m(\Lambda_c^+\pi^{\pm})$
- background, that appears as signal in  $m(\Lambda_c^+\pi^{\pm})$  but not in  $m_{inv}$
- background, that appears in projections to  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  similar to signal but has a significant correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$

For each relevant background and signal source a two dimensional probability density function (PDF) was searched for by using Monte-Carlo events and events from side band regions in data. For a contribution with a significant correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  or  $m(\Lambda_c^+\pi^-)$  a binned histogram from MC was used as PDF, if no continuous function could be found including the correlation.

Extracting the signal yields was done by combining all fit components for signal and background contributions into a binned maximum likelihood fit which was applied to the data in the  $m_{inv}:m(\Lambda_c^+\pi^+)$  and  $m_{inv}:m(\Lambda_c^+\pi^-)$  planes:

$$\mathcal{L}(p_1...p_M|n_1...n_N) = \sum_{i=1}^{N_{\text{bin}}} n_i \cdot (\ln \mu_i - \ln n_i)$$
(3.7)

where  $\mathcal{L}$  is the logarithmized likelihood, which estimates the parameters  $p_j$  from the observed values in the  $N_{\text{bin}}$  bins of the histogram.  $n_i$  is the actual bin content and  $\mu_i$  is the estimated value of bin i, which all add up to the total number of events in the histogram  $\sum_{i=1}^{N_{\text{bin}}} \mu_i = n_{\text{total}}$ . The expected value  $\mu_i$  is estimated in the two-dimensional bin range with  $\mu_i = n_{\text{total}} \int_{\Delta x_i, \Delta y_i} f(x|p_j)$  from the total PDF  $f(x|p_j)$ , which consists of the respective signal and background PDFs  $f = \sum_{fcn=1}^{n_{fcn}} f_{fcn}$ . For several signal and background contributions scaled binned histograms were used as PDFs, here the bin content could easily be read. For an analytic PDF its bin contents was estimated by numerically integrating the function in the bins (for a faster processing a forerun fit was performed, in which the bin content was estimated from the PDF function value in the bin center. The fitted parameters were then used as start values for the actual fit using an integral estimate for the bin contents).

For the most probable parameterization the maximum of the log-likelihood is searched for

$$\mathcal{L}\left(\hat{\vec{p}}\right) = \max \mathcal{L}\left(\vec{p}\right) \tag{3.8}$$

### **3.6.1** Fit variables $m_{inv}$ : $m(\Lambda_c^+\pi^\pm)$

In the following, only events from the  $m_{\rm ES}$  signal band were selected if not stated otherwise.

Since non- $\Sigma_c$  (2455,2520)  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  decays peak in  $m_{inv}$  as well as resonant signal modes with  $\Sigma_c$  baryons,  $m(\Lambda_c^+ \pi^{\pm})$  was used for discriminating both signal classes. Figure 3.7 shows the  $m_{inv}:m(\Lambda_c^+ \pi^+)$  and  $m_{inv}:m(\Lambda_c^+ \pi^-)$  planes. The resonant and non- $\Sigma_c$  (2455,2520) signal events are visible at the nominal *B*-mass at  $m_{inv} \approx 5.279 \text{ GeV}/c^2$  and along the  $m(\Lambda_c^+ \pi^-)$  invariant mass. Resonances stand out as peaks along  $m(\Lambda_c^+ \pi^{\pm})$ . Also background events from five-body final states as  $B \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \pi^{0/-}$  are visible below  $m_{inv} < 5.15 \text{ GeV}/c^2$ .

In figure 3.8 the distributions of  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  are shown. The upper two plots show the side band subtracted  $m(\Lambda_c^+\pi^+)$  distribution and the original distributions from the  $m_{\rm ES}$ - $m_{inv}$  signal region I overlayed with scaled events from region III. The side band distributions from region III were scaled onto signal region I using the ratio of event numbers in regions II/IV. To do so, it was assumed that combinatorial background events distribute linearly over regions I and III as well as in regions II and IV; so assuming that the combined sub-sidebands  $III_{a,b}$  and  $IV_{a,b}$  estimate an averaged combinatorial background in regions I and II, respectively. For the scaling also linearity was assumed; so that the ratio of numbers of combinatorial background events in the regions II and IV is the same as for the numbers of combinatorial background events in regions I and III (see also figure 3.3 and table 3.6).

. Since a side band subtraction can only remove background continuous over the signal and side bands, the subtracted plots still contain background that peaks only in the signal region<sup>4</sup>. A related but more elaborated method is the  $_{s}\mathcal{P}lot$ -technique, which is able to separate the known signal and background contributions [16], which is discussed in more detail later on in section 5.2.

In the  $m(\Lambda_c^+\pi^+)$  distributions signals are visible for states with  $\Sigma_c^{++}(2455)$ ,  $\Sigma_c^{++}(2520)$  and  $\Sigma_c^{++}(2800)$  baryons in intermediate states. Whereas for  $m(\Lambda_c^+\pi^-)$  only a clear signal is visible for intermediate states with a  $\Sigma_c^0(2455)$  baryon.

Signal regions in  $m(\Lambda_c^+\pi^{\pm})$  were defined for separating the resonances in  $m(\Lambda_c^+\pi^{\pm})$  (see table 3.8).

In appendix section A.6 additional information can be found as supplementary plots of  $m(\Lambda_c^+\pi^{\pm})$  distributions in the signal and side band regions.

resonance	start	end
$\Sigma_{c}^{++}(2455)$	$2.447 \mathrm{GeV}/c^2$	$2.461{\rm GeV}/c^2$
$\Sigma_{c}^{++}(2520)$	$2.498  \text{GeV}/c^2$	$2.538 \mathrm{GeV}/c^2$

Table 3.8:  $\Sigma_c$ : Borders for the  $\Sigma_c$  (2455, 2520) signal regions in  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ .

<sup>&</sup>lt;sup>4</sup>The side band subtraction just removes combinatorial background. Side band subtraction along  $m_{inv}$  cannot distinguish events that appear as signal in  $m_{inv}$ . For example, background that also peaks in  $m_{inv}$  survives a side band subtraction. Especially in the  $m\left(\Lambda_c^+\pi^\pm\right)$  distribution all events peaking in  $m_{inv}$  remain after a side band subtraction, i.e. after side band subtracting in  $m_{inv}$  the  $m\left(\Lambda_c^+\pi^+\right)$  distribution still contains events from non- $\Sigma_c$  (2455,2520)  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^$ events or from  $\overline{B}^0 \to \Sigma_c^0 \overline{p} \pi^+$  events.



Figure 3.7:  $m_{inv}: m(\Lambda_c^+\pi^\pm)$ : 2D distribution of events in the  $m_{\rm ES}$  signal band in  $m_{inv}: m(\Lambda_c^+\pi^+)$  (upper plot) and  $m_{inv}: m(\Lambda_c^+\pi^-)$  (lower plot).



Figure 3.8:  $m(\Lambda_c^+\pi^\pm)$ : distributions of invariant masses  $m(\Lambda_c^+\pi^+)$  in the two upper plots and  $m(\Lambda_c^+\pi^-)$  in the two lower plots. The upper  $m(\Lambda_c^+\pi^\pm)$  distributions are events from the signal region I with sideband region *III* subtracted. The lower  $m(\Lambda_c^+\pi^\pm)$  distributions show the original distribution from the  $m_{\text{ES}}-m_{inv}$  signal region I overlayed with scaled side band *III*.

#### 3.7 Signal sources

#### 3.7.1 Signal contributions and fit parameters

Each resonant signal mode was studied in data and Monte-Carlo simulated events. In the following, characteristics of the resonant decays

- $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$
- $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$
- $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$
- $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$

are presented. Since the distributions from phase space generated Monte-Carlo events are similar for  $\overline{B}^0 \to \Sigma_c^0 \overline{p} \pi^+$  and for  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^-$  under *pion-conjugation*  $\pi^+ \leftrightarrow \pi^-$ , the distributions from Monte-Carlo simulations are shown for  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^-$  modes only (the corresponding Monte-Carlo plots for  $\overline{B}^0 \to \Sigma_c^{0} \overline{p} \pi^+$  can be found in the appendix section A.7).

Background sources are studied in section 3.8 . When possible, a background source was vetoed. If no veto was applicable, a source-specific PDF was added to the fit.

## 3.7.2 Events from $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ decays

The distribution of the  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane in signal Monte-Carlo simulation for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^$ is shown in figure 3.9 in the upper two plots. The top plot covers the whole  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane over the allowed  $m(\Lambda_c^+\pi^+)$  phase space and in  $m_{inv}$  including side band regions. The middle plot is a zoom to the immediate environment around the  $\Sigma_c^{++}(2455)$  signal in  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  with the signal peak at the *B*-mass in  $m_{inv}$  and at the  $\Sigma_c$ -mass in  $m(\Lambda_c^+\pi^+)$ . A small correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$ is apparent for the actual signal. Partly reconstructed signal events are spread diagonal over the plane, i.e. having a large correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$ . Here, for example one pion-daughter from the  $\overline{B}^0$  could been interchanged with a pion from the other  $B^0$ .

The signal Monte-Carlo distribution in the conjugated  $m_{inv}:m(\Lambda_c^+\pi^-)$  is in the lower plot. No correlations were found between  $m_{inv}:m(\Lambda_c^+\pi^-)$ . As visible in the projections 3.10 and 3.11,  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^$ appears as signal in  $m_{inv}$  while it is distributed as combinatorial background in  $m(\Lambda_c^+\pi^-)$  in the phase space generated Monte-Carlo.

Since the two-dimensional planes  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  were fitted, an analytical function would have been the first choice as PDF. However, a correlation between both dimensions was seen. To measure the correlation a two-dimensional Gaussian was fitted to truthmatched signal events from Monte-Carlo:

$$\mathcal{G}_{2D}(x,y;N,\mu_1,\sigma_1,\mu_2,\sigma_2,\rho) =$$

$$N\frac{1}{2\pi \cdot \sigma_1 \sigma_2 \sqrt{1-\rho^2}} \exp\left(-\frac{1}{2}\frac{1}{\sqrt{1-\rho^2}} \left(\frac{(x-\mu_1)^2}{\sigma_1^2} + \frac{(y-\mu_2)^2}{\sigma_2^2} - 2\rho \cdot \frac{(x-\mu_1)}{\sigma_2} \cdot \frac{(y-\mu_2)}{\sigma_2}\right)\right)$$
(3.9)

with  $\mu_{1,2}$  and  $\sigma_{1,2}$  the masses and widths in the two dimensions and  $\rho$  the correlation between both dimensions. The correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  was fitted to  $0.189 \pm 0.005$ , which was not negligible. Therefore, a analytical signal PDF-function would have to take the correlation into account. The use of a 2D-Gaussian, as most simple 2D-function with a correlation parameter and a signal-like shape, was dismissed for the signal extraction. The fit with a two-dimensional Gaussian converged on the distributions of signal Monte-Carlo events and the correlation cold be extracted. However, the fitted PDF showed deviances to the distribution along  $m(\Lambda_c^+\pi^{\pm})$  and the fit resulted in a small  $P(\chi^2)$  fit probability value, indicating a bad fit quality. While the projection onto  $m_{inv}$  could be described with a one-dimensional Gaussian plus a polynomial for background, a fit to the projection of signal Monte-Carlo events onto  $m(\Lambda_c^+\pi^+)$  had a better  $\chi^2/$ fit probability using a non-relativistic Breit-Wigner function than using a single Gaussian. Both functions were only approximations to the ideal signal shape consisting of the resonance's natural width folded with the (multi-)Gaussian like smearing of the signal by detector. For the two-dimensional fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  a factorized two-dimensional PDF, consisting of a Gaussian in  $m_{inv}$  multiplicated with a non-relativistic Breit-Wigner in  $m(\Lambda_c^+\pi^+)$ , had to be rejected. Obviously, such a separation ansatz would not take into account the correlation between  $m_{inv}:m(\Lambda_c^+\pi^+)$ .

A further search for a correlated 2D-function describing the two-dimensional signal distribution was dismissed. Instead a binned histogram was chosen as fit PDF for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  events. Assuming that the Monte-Carlo simulation reproduces the behaviour of data signal events in  $m_{inv}:m(\Lambda_c^+\pi^+)$ , a two-dimensional histogram hist<sup>input</sup> in  $m_{inv}:m(\Lambda_c^+\pi^+)$  from signal Monte-Carlo events contains naturally any correlations. As fit component the binned  $m_{inv}:m(\Lambda_c^+\pi^+)$  histogram has one free parameter for scaling. This scaling parameter was allowed to float in fits to adapt the Monte-Carlo histogram to the signal. As example a total PDF of three event classes could look like

$$\begin{aligned} \mathsf{FitPDF} &(m_{inv}, m\left(\Lambda_{c}^{+}\pi^{+}\right); a, b, ...; p, q, ...; S_{1}, S_{2}, S_{hist}) = \\ &S_{1} \cdot \mathsf{fcn}_{1} \left(m_{inv}, m\left(\Lambda_{c}^{+}\pi^{+}\right); a, b, ...\right) + \\ &S_{2} \cdot \mathsf{fcn}_{2} \left(m_{inv}, m\left(\Lambda_{c}^{+}\pi^{+}\right); p, q, ...\right) + \\ &S_{hist} \cdot \mathsf{hist}^{input} \left[m_{inv}, m\left(\Lambda_{c}^{+}\pi^{+}\right)\right] \end{aligned}$$

Here  $fcn_1$  and  $fcn_2$  are analytical 2D-functions in  $m_{inv}:m(\Lambda_c^+\pi^+)$  with their shape parameters  $a, \ldots; p, \ldots$ and scaling parameters  $S_{1,2}$ , that could describe for example two classes of background. hist<sup>input</sup> is a binned histogram added to FitPDF with a scaling factor  $S_{hist}$  as free parameter. For a point in  $m_{inv}:m(\Lambda_c^+\pi^+)$  the corresponding bin content value is taken.

The floating scaling parameters are proportional to the number of events in each event class. For hist<sup>input</sup> the number of signal events can easily be calculated from the events in the histogram and the fitted scaling parameter. For an analytical function the number of events can be calculated from the scaling parameter compared with the PDF integral normalized to one.

## 3.7.3 Events from $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ decays

Similar to their lighter counterparts events from  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  could be fitted in the onedimensional projections with a Gaussian in  $m_{inv}$ . The distribution in  $m(\Lambda_c^+\pi^+)$  follows a Gaussian convoluted with a Breit-Wigner function; in fits also a broader Breit-Wigner distribution as estimate on an appropriate PDF worked. And as for the  $\Sigma_c^{++}(2455)$  mode a correlation between  $m_{inv}:m(\Lambda_c^+\pi^+)$  was seen, which would have to be included in a two-dimensional PDF. So, a truthmatched signal histogram in  $m_{inv}:m(\Lambda_c^+\pi^+)$  from signal Monte-Carlo events was used as signal PDF for  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^$ events.

The two-dimensional distributions in  $m_{inv}$  : $m(\Lambda_c^+\pi^\pm)$  from signal Monte-Carlo for  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^$ are shown in figure 3.12 and the projections onto  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  are given in figures 3.13 and 3.14). In the conjugated  $m(\Lambda_c^+\pi^-)$  distribution these events appear as background (lower plot in figure 3.12, projection onto  $m(\Lambda_c^+\pi^-)$  in figure 3.14).



Figure 3.9:  $m_{inv}: m(\Lambda_c^+\pi^\pm)$  from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  signal Monte-Carlo events: The upper plot shows the signal event distribution in  $m_{inv}: m(\Lambda_c^+\pi^+)$ , the middle plot  $m_{inv}: m(\Lambda_c^+\pi^+)$  more in detail, the lower plot shows the  $m_{inv}: m(\Lambda_c^+\pi^-)$  distribution.



Figure 3.10:  $\overline{B}^0 \rightarrow \Sigma_c^{++}(2455)\overline{p}\pi^-$  signal Monte-Carlo:  $m_{inv}$  from  $m_{\rm ES}$  signal band,  $m_{\rm ES}$  from  $m_{inv}$  signal band and the  $m_{inv}$ : $m_{\rm ES}$ plane

Figure 3.11:  $\overline{B}^0 \rightarrow \Sigma_c^{++}(2455)\overline{p}\pi^-$  signal Monte-Carlo:  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions from  $m_{inv}$  and  $m_{\rm ES}$  signal region



Figure 3.12:  $m_{inv}: m\left(\Lambda_c^+\pi^\pm\right)$  from  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  signal Monte-Carlo: The upper plot shows the signal event distribution in  $m_{inv}: m\left(\Lambda_c^+\pi^+\right)$ , the middle plot  $m_{inv}: m\left(\Lambda_c^+\pi^+\right)$  more in detail, the lower plot shows the  $m_{inv}: m\left(\Lambda_c^+\pi^-\right)$  distribution.



Figure 3.13:  $\overline{B}^0 \rightarrow \Sigma_c^{++}(2520)\overline{p}\pi^-$  signal Monte-Carlo:  $\overline{B}^0 \rightarrow \Sigma_c^{++}(2520)\overline{p}\pi^-$ :  $m_{inv}$  from  $m_{\rm ES}$  signal band,  $m_{\rm ES}$  from  $m_{inv}$  signal band and the  $m_{inv}$ : $m_{\rm ES}$  plane

Figure 3.14:  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  signal Monte-Carlo:  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ :  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions from  $m_{inv}$  and  $m_{\rm ES}$  signal region

## 3.7.4 Events from $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ decays

The distributions from the signal Monte-Carlo similation for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  in  $m_{inv}, m_{\rm ES}, m(\Lambda_c^+\pi^+)$ and  $m(\Lambda_c^+\pi^-)$  are similar to the corresponding distributions for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  as in section 3.7.2. For the distributions from signal Monte-Carlo see figures A.21, A.22, A.23 in the appendix. Because of the also appearing correlation in  $m_{inv}:m(\Lambda_c^+\pi^-)$ , the truthmatched signal histogram from SP-6981 was used as signal PDF for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ .

## 3.7.5 Events from $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ decays

The distributions for signal MC  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  in  $m_{inv}, m_{\rm ES}, m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  are similar to the 'pion conjugated' distributions for  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  in the previous section 3.7.3. The plots from the signal Monte-Carlo simulation  $(\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+)$  are given in the appendix in figures A.24, A.25, A.26. As signal PDF for  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  a signal histogram in  $m_{inv}:m(\Lambda_c^+\pi^-)$  from  $(\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+)$  Monte-Carlo was used.

### 3.8 Background sources

Four possible sources of background contributing to the resonant decays  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^{\mp}$  were studied:

- 1. Combinatorial background
- 2. Non-resonant  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ 
  - including other resonant sub-modes without a signal in the  $m(\Lambda_c^+\pi^{\pm})$  signal region
  - including  $\overline{B}{}^0 \to \Sigma_c^{++} \overline{p} \pi^-$  events in  $m(\Lambda_c^+ \pi^-)$  as background for  $\overline{B}{}^0 \to \Sigma_c^0 \overline{p} \pi^+$  and vice versa
- 3.  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  and  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$
- 4. Combinatorial background events with true  $\Sigma_c$  resonances
- 5.  $\overline{B}{}^0 \to D^0/D^+p\overline{p} \ (+\mathbf{n}\cdot\pi)$

Background contributions were searched for in side bands in data, in generic Monte-Carlo and in Monte-Carlo for specific decays.

Scaled generic Monte-Carlo for uds,  $c\bar{c}$ ,  $B^+$   $B^-$  and  $B^0\bar{B}^0$  is shown in the left plot figure 3.15 for  $m_{\rm ES}$ . In the signal region the agreement between data and Monte-Carlo is pretty good and reproduces the data quantitatively. In the  $m_{\rm ES}$  side band region a divergence is visible between data and Monte-Carlo towards smaller  $m_{\rm ES}$  values. Similar for  $m_{inv}$  in the right plot figure 3.15 the agreement is pretty fair in the signal region with deviations to the borders. Here, the generic Monte-Carlo simulations were produced without an input from a previously measured  $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$  branching fraction or of another measured baryonic *B*-decay.

Since baryonic decays are barely understood and since all generic baryonic decays were therefore simulated following a phase space model by JETSET, the agreement between data and MC surprisingly good compared to the small knowledge. Nevertheless, Monte-Carlo of baryonic decays has to be taken with caution. For example no resonant intermediate states with  $\Sigma_c$  (2800) baryons or higher resonances appear in generic Monte-Carlo events. Also, as seen later in the efficiency correction in section 6.2.1, the MC does not reproduce the substructures in  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  or in the resonant decays  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^{\mp}$ .



Figure 3.15: Comparisons in  $m_{\rm ES}$  (left plot) and  $m_{inv}$  (right plot) between the distributions from data and generic Monte-Carlo sets. The distributions from Monte-Carlo for generic *uds*-events,  $c\bar{c}$ -events,  $B^+B^-$ -events and  $B^0\bar{B}^0$ -events where scaled on the On-peak luminosity [38] and stacked onto each other. Signal decays were not removed from  $B^0\bar{B}^0$  Monte-Carlo.

#### 3.8.1 Combinatorial background

Generic Monte-Carlo eimulations of the events classes  $e^+e^- \rightarrow u\overline{u}, d\overline{d}, s\overline{s}, c\overline{c}, b\overline{b} \rightarrow B^+B^-, b\overline{b} \rightarrow B^0\overline{B}^0$  were studied on the search for background contributions.

After applying all constraints in the reconstruction (table 3.4), no significant background contribution were expected from *uds* events, i.e.  $e^+e^- \rightarrow u\overline{u}, e^+e^- \rightarrow d\overline{d}$  or  $e^+e^- \rightarrow s\overline{s}$ . Also from events of the type  $e^+e^- \rightarrow c\overline{c}$  only about 100 events were be expected in the signal range. These events distribute in  $m_{\rm ES}$  following an Argus function<sup>5</sup>.  $m_{inv}$  can be described with a polynomial in the  $m_{inv}$  signal region. The  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions show no significant peaks originating from  $\Sigma_c^{0}$  baryons from  $c\overline{c}$  events. The distributions in  $m(\Lambda_c^+\pi^\pm)$  could be described with a phenomenological function. Suplementary information can be found in appendix section A.8.

Main contributions to combinatorial background arose from  $B\overline{B}$  events. Figure 3.16 shows distributions from the generic  $B^+B^-$  Monte-Carlo simulation. In  $m_{\rm ES}$  no peaking structure is visible on-top of the Argus shaped background. Also in  $m_{inv}$  no peaking structure appears on-top of the linear background in the signal region. Contributions from the five body modes as  $B^- \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \pi^-$  appear at lower  $m_{inv}$  values about one pion mass away from the *B* mass. With the chosen  $m_{inv}$  signal and side bands these contributions did not influence the signal mode. In  $m(\Lambda_c^+ \pi^{\pm})$  events distribute mainly as combinatorial background following the phenomenological function (eq. 3.20). On-top the combinatorial events  $m(\Lambda_c^+ \pi^{\pm})$  peaks are apparent, which come from *B*-events with true  $\Sigma_c^{+}$  resonances.

Figure 3.17 shows the distributions for generic  $B^0\overline{B}^0$  Monte-Carlo. Signal and resonant signal decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  were removed. Remaining signal peaks in  $m_{\rm ES}$  and  $m_{inv}$  are remnant of  $\overline{B}^0 \to D^0/D^+ p\overline{p}$  (+n  $\cdot \pi$ ) decays. These decays can end in the same final state particles as signal decays and can be rearranged and fake a signal. In section 3.8.5 these background components are described in more detail. In data these background modes were removed by vetoing the mass ranges of the potential  $D^+$  and  $D^0$  candidates.

Figures 3.18 and 3.19 show the  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions in data in the  $m_{inv}$  side-bands. While peaks on-top the combinatorial background are visible for  $\Sigma_c^{++}$  (2455) resonances, no distinct

$$\mathcal{F}_{Argus}(x;\mathcal{E};P_{Argus},c) = P_{Argus} \cdot x \cdot \sqrt{1 - \left(\frac{x}{\mathcal{E}}\right)^2} e^{-c \cdot \left(1 - \left(\frac{x}{\mathcal{E}}\right)^2\right)}$$
(3.10)

<sup>&</sup>lt;sup>5</sup>Phenomenological function with the end point f the function  $\mathcal{E}$ , a scaling factor  $P_{Argus}$  and the shape variable c [62]

signals appear for the  $\Sigma_c^{0}(2520)$  resonances. Which is somewhat different to events in distributions from the generic  $B^+B^-$  Monte-Carlo simulation where also a clear  $\Sigma_c^0(2520)$  signal is visible in the  $m(\Lambda_c^+\pi^-)$  distribution, thus the Monte-Carlo simulation does not fully reproduces the combinatorial background as in data:

 $\Sigma_c^{++}(2455)$  contributions only appear in generic  $B^+B^-$  Monte-Carlo and not in generic  $B^0\overline{B}^0$  Monte-Carlo; this holds also for  $\Sigma_c^0(2455)$  contributions. The heavier  $\Sigma_c^{++}(2520)$  and  $\Sigma_c^0(2520)$  contributions are visible in both generic  $B\overline{B}$  Monte-Carlo samples and more prominent compared to the  $\Sigma_c^{-0}(2455)$ . In data the  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions from the  $m_{inv}$  side-bands show contributions only from the lighter  $\Sigma_c^{++}(2455)$  and  $\Sigma_c^0(2455)$  resonances. For the heavier  $\Sigma_c$  (2520) resonances no significant peak structure is visible, neither in  $m(\Lambda_c^+\pi^+)$  nor in  $m(\Lambda_c^+\pi^-)$ .

In  $m_{inv}$  the three backgrounds, combinatorial background, combinatorial background with true  $\Sigma_c$  (2455) resonances and combinatorial background with true  $\Sigma_c$  (2520) resonances, could be fitted with a linear polynomial. However, the slopes and offsets were found to be different. Thus, combinatorial background and combinatorial background with true  $\Sigma_c$  resonances were different in both dimensions of the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  plane and for each contribution separate PDFs had to be implemented for the fit.

The fit components for true  $\Sigma_c$  from non-signal modes are described in detail in the following section 3.8.2.

Combinatorial background was described by a factorized two-dimensional function as PDF. To describe  $m_{inv}$  a first order polynomial was used

$$\mathcal{POLY}_{1st}\left(x;b\right) = \left(b \cdot x + 1\right) \tag{3.11}$$

To describe  $m(\Lambda_c^+\pi^\pm)$  an analytical function was used, where the upper and lower phase space borders in  $m(\Lambda_c^+\pi^\pm)$  were included with  $e_{psb}^{low} = 2.4249 \,\text{GeV}/c^2$  and  $e_{psb}^{up} = 4.215 \,\text{GeV}/c^2$  as scaling constant:

$$\mathcal{F}_{\mathsf{Combi}\,\mathsf{Bkg}}(y;p,q;e_{psb}^{up},e_{psb}^{low}) = (4.108 - y)^p \cdot \left(y - e_{psb}^{low}\right)^q \cdot e_{psb}^{up} \tag{3.12}$$

Up to  $m(\Lambda_c^+\pi^\pm) \leq 3.2 \text{ GeV}/c^2$  the function fitted successfully to various studied  $m(\Lambda_c^+\pi^+)$  or  $m(\Lambda_c^+\pi^-)$  distributions from  $m_{inv}$  side-bands in data or from non-resonant Monte-Carlo samples.

For fits to the whole allowed range in  $m(\Lambda_c^+\pi^{\pm})$  up to the phase space border, a modified polynomial was used:

$$\mathcal{F}_{\mathsf{Combi}\,\mathsf{Bkg\,total}}(y;n,p,q,r;e^{up}_{psb}) = n \cdot (y-r) \cdot y^p \cdot \left(e^{up}_{psb} - y\right)^q \tag{3.13}$$

To reduce the number of parameter by one, fits in the range of  $m(\Lambda_c^+\pi^{\pm})$  relevant for  $\Sigma_c^{0}$  resonances  $(m(\Lambda_c^+\pi^{\pm}) \leq 3.0 \text{ GeV}/c^2)$  were using equation 3.12. For fits covering the whole  $m(\Lambda_c^+\pi^{\pm})$  range equation 3.13 was used. (See also examples in appendix section A.8.2).

Both functions were combined into a two-dimensional PDF:

$$\mathcal{BG}_{\mathsf{Combi}\,\mathsf{Bkg}}\left(x, y, S; b, p, q; e_{psb}^{up}, e_{psb}^{low}\right) = S \tag{3.14}$$

$$\times \mathcal{POLY}_{1st}\left(x; b\right)$$

$$\times \mathcal{F}_{\mathsf{Combi}\,\mathsf{Bkg}}(y; p, q; e_{psb}^{up}, e_{psb}^{low})$$



Figure 3.16: Generic  $B^+B^-$  Monte-Carlo event distributions (not scaled onto luminosity): upper row:  $m_{\rm ES}, m_{inv}$ ; second row  $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}-m_{inv}$  signal region); third row detailed  $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}-m_{inv}$  signal region); lower row  $m_{inv}:m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$ signal band)



Figure 3.17: Generic  $B^0\overline{B}^0$  Monte-Carlo event distributions (not scaled onto luminosity): upper row:  $m_{\rm ES}$ ,  $m_{inv}$ ; second row  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$ - $m_{inv}$  signal region); third row detailed  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$ - $m_{inv}$  signal region); lower row  $m_{inv}$ : $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$  signal band). Signal mode components  $(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-; \to \Sigma_c^{++} \overline{p} \pi^-; \to \Sigma_c^0 \overline{p} \pi^+; \to \Lambda_c^+ \overline{p} \rho/f_2; \to \Lambda_c^+ \Delta \pi^-)$  are removed. No vetoes on  $D^0$  or  $D^+$  background are applied here; the signal peak remains from modes  $\overline{B}^0 \to D^0/D^+ p\overline{p} + n \cdot \pi$ .



Figure 3.18: Data:  $m(\Lambda_c^+\pi^+)$  distributions from  $m_{inv}$  side band. plots top-down:  $m(\Lambda_c^+\pi^+)$  from left  $m_{inv}$  side-band  $[m_{inv} \in (5.17, 5.23) \text{ GeV}/c^2]$ ,  $m(\Lambda_c^+\pi^+)$  from right  $m_{inv}$  side-band  $[m_{inv} \in (5.322, 5.382) \text{ GeV}/c^2]$ ,  $m(\Lambda_c^+\pi^+)$  from both  $m_{inv}$  side-bands combined



Figure 3.19: Data:  $m(\Lambda_c^+\pi^-)$  distributions from  $m_{inv}$  side band. plots top-down:  $m(\Lambda_c^+\pi^-)$  from left  $m_{inv}$  side-band  $[m_{inv} \in (5.17, 5.23) \text{ GeV}/c^2]$ ,  $m(\Lambda_c^+\pi^-)$  from right  $m_{inv}$  side-band  $[m_{inv} \in (5.322, 5.382) \text{ GeV}/c^2]$ ,  $m(\Lambda_c^+\pi^-)$  from both  $m_{inv}$  side-bands combined

## 3.8.2 Combinatorial background events with true $\Sigma_c$ resonances

As reported in the previous section 3.8.1, background contributions were seen from true  $\Sigma_c^{(0)}$  baryons from non-signal decays in side band data and generic Monte-Carlo. These events show up in  $m(\Lambda_c^+\pi^{\pm})$ with a signal-like shape but distribute as background in  $m_{inv}$ .

with a signal-like shape but distribute as background in  $m_{inv}$ . Examples for decays with such a signature are  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  or  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$  for  $\Sigma_c^0$ resonances in  $m(\Lambda_c^+\pi^-)$ . The upper left plot in figure 3.20 shows  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  in  $m_{inv}:m(\Lambda_c^+\pi^+)$  from Monte-Carlo for this specific mode. It is distributed over a broad range and would contribute to  $m(\Lambda_c^+\pi^+)$  and  $m_{inv}$  as combinatorial background. In the upper right plot the Monte-Carlo events distribute in  $m(\Lambda_c^+\pi^-)$  as a strip of reconstructed  $\Sigma_c^0$ ; in the  $m_{inv}$  signal region they distribute linearly like combinatorial background. In the lower row  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$  events from Monte-Carlo distribute analogous for the  $\Sigma_c^0(2520)$  resonance.

Other decays with true  $\Sigma_c^{++}$  or  $\Sigma_c^0$  resonances were expected to distribute similarly in  $m_{inv}:m(\Lambda_c^+\pi^+)$  or  $m_{inv}:m(\Lambda_c^+\pi^-)$ . Both distributions show  $\Sigma_c^{++}$  contributions to combinatorial background. Since also peaks in  $m(\Lambda_c^+\pi^+)$  appear, additional modes<sup>6</sup> were assumed to exist containing true  $\Sigma_c^{++}$ . It is reasonable to assume, that also more modes exist with true  $\Sigma_c^0$  addition to the example modes  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$ .

It was not feasible to add a  $\Sigma_c$  shape to the combinatorial background PDF. Both, combinatorial background without and with true  $\Sigma_c$ , scaled differently in the side band regions and the fitted polynomials had different slopes in  $m_{inv}$ . Therefore, two separated 2-dimensional PDFs had to be defined (see previous section 3.8.1 for the non- $\Sigma_c$  (2455,2520) combinatorial background PDF).

 $\Sigma_c^{++}(2455, 2520)$  baryons were fitted in  $m(\Lambda_c^+\pi^{\pm})$  with a non-relativistic Breit-Wigner as effective shape function

$$\mathcal{BW}_{\text{NonRel}}\left(x;\mu,\tilde{\gamma}\right) = \frac{1}{2\pi \left[\left(x-\mu\right)^2 + \left(\frac{\tilde{\gamma}}{2}\right)^2\right]}$$
(3.15)

with  $\mu$  the mean and  $\tilde{\gamma}$  an effective width of the signal. For the invariant mass a first order polynomial (eq. 3.11) as for the combinatorial background without resonances was used.

The 2D-function for  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  was defined as uncorrelated product with the scaling parameter S:

$$\mathcal{BG}_{\text{true}\Sigma_{c}}\left(x_{-}m_{inv}, y_{m\left(\Lambda_{c}^{+}\pi^{\pm}\right)}; S; \mu, \gamma; b\right) = S$$

$$\times \mathcal{BW}_{\text{NonRel}}\left(x; \mu, \gamma\right)$$

$$\times \mathcal{POLY}_{1st}\left(y; b\right)$$

$$(3.16)$$

For fits on data the Breit-Wigner shape parameters were fixed to values obtained from MC (see section 4.2.2.1 for more details on masses and widths of  $\Sigma_c$  (2455,2520)).

Further information on this type of background, as additional distributions of specific Monte-Carlo simulated events  $B^- \to \Sigma_c^0 \overline{p} \pi^-$  and distributions from side bands in data, can be found in the appendix section A.8.1.

<sup>&</sup>lt;sup>6</sup>Compared to  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$  a similarly simple *B* decay with true  $\Sigma_c^{++}$  baryons was not found, i.e.  $B^- \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^2$ , candidates for contributing decays could be modes with a higher final state multiplicity etc.



Figure 3.20: Monte-Carlo events for  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$  background: left column  $m_{inv}:m(\Lambda_c^+\pi^+)$ , right column  $m_{inv}:m(\Lambda_c^+\pi^-)$ ; upper row  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ , lower row  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$  (from the  $m_{\rm ES}$  signal band)

## 3.8.3 Non- $\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ events as background

Signal decays were labeled as non- $\Sigma_c$  (2455,2520) if they ended in the four-body final state  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without an intermediate  $\Sigma_c$  (2455,2520) resonance, i.e. these non- $\Sigma_c$  signal decays do not have signal structures in the signal regions in  $m(\Lambda_c^+ \pi^+)$  or  $m(\Lambda_c^+ \pi^-)$  and distribute like combinatorial background in  $m(\Lambda_c^+ \pi^\pm)$  ( $\Sigma_c$  signal region definitions given in table 3.8). Please note that signal decays via  $\Sigma_c^{++}$  resonances appear as  $non-\Sigma_c$ , i.e.  $non-\Sigma_c^0$ (2455,2520), in  $m(\Lambda_c^+ \pi^-)$ . Signal decays via  $\Sigma_c^0$  resonances appear as  $non-\Sigma_c$  events, i.e.  $non-\Sigma_c^{++}$ (2455,2520), in  $m(\Lambda_c^+ \pi^+)$ . Other possible resonant sub-modes, as  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\rho$ ;  $\rho \to \pi^+ \pi^-$  or  $\overline{B}^0 \to \Lambda_c^+ \overline{\Delta}^{--} \pi^+$ ;  $\overline{\Delta}^{--} \to \overline{p}\pi^-$ , would also appear as combinatorial background in  $m(\Lambda_c^+ \pi^+)$  and  $m(\Lambda_c^+ \pi^-)$  and are included in the  $non-\Sigma_c$  signal decays. In  $m_{inv}$  non-resonant, i.e.  $non-\Sigma_c$  (2455,2520),  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  events are signal, i.e. distributed with a Gaussian-like shape.

To study non-resonant signal contributions signal Monte-Carlo data sets and toy Monte-Carlo samples composed of specific signal Monte-Carlo modes were used. Since the individual contributions from possible *non-resonant* signal decays in  $m(\Lambda_c^+\pi^+)$  or  $m(\Lambda_c^+\pi^-)$  were not known, toy Monte-Carlo were produced with randomly scaled contributions from non- $\Sigma_c$  signal Monte-Carlo. A random number of events was selected from each signal Monte-Carlo set and added up into a toy Monte-Carlo mixture. (In appendix section A.8.2 an example is given.)

A dependency of the Gaussians width in  $m_{inv}$  from the  $m(\Lambda_c^+\pi^{\pm})$  invariant mass was found in the studied Monte-Carlos. Figure 3.21 shows the distribution of the Gaussians width depending on  $m(\Lambda_c^+\pi^{\pm})$ . The distribution was fitted with a second order polynomial. The fit result is given in table 3.9.

Thus, the  $m(\Lambda_c^+\pi^{\pm})$  dependency of the signal width in  $m_{inv}$  had to be taken into account. This was done by describing the width of the signal in  $m_{inv}$  as a 2nd order polynomial depending on  $m(\Lambda_c^+\pi^{\pm})$ 

$$\sigma\left(y = m\left(\Lambda_c^+ \pi^{\pm}\right); a_{\sigma}, b_{\sigma}, c_{\sigma}\right) = c_{\sigma} \cdot \left[a_{\sigma} \cdot y^2 + b_{\sigma} \cdot y + 1\right]$$
(3.17)

In  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  non-resonant events distributed as combinatorial background (for example see signal decay distribution in the "conjugated"  $m(\Lambda_c^+\pi^-)$  invariant masses in figures 3.9 and 3.12 for  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ , the equivalent figures for  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  can be found in the appendix section A.7). To describe in  $m(\Lambda_c^+\pi^\pm)$  the shape of *non-resonant* signal events also a PDF based on function 3.13 was used. The function was chosen since it proved to be flexible enough to describe a range of background mixtures Monte-Carlo samples:

$$\mathcal{F}_{!\Sigma_{c}}(y = m\left(\Lambda_{c}^{+}\pi^{\pm}\right); p, q, r; e_{psb}) = (y - r) \cdot y^{p} \cdot \left(e_{psb} - y\right)^{q}$$
(3.18)

here p, q, r are shape parameters and  $e_{psb}$  is a constant for the end point of the phase space. The PDF for combinatorial background in  $m(\Lambda_c^+\pi^{\pm})$  was combined with a Gaussian as signal PDF in  $m_{inv}$  into a two-dimensional PDF with a scaling factor S. Here, the Gaussian depended on  $m_{inv}$  and  $m(\Lambda_c^+\pi^{\pm})$  due to the modified width  $\sigma$ :

$$\mathcal{BG}_{\mathsf{non}-\Sigma_{\mathsf{c}}}\left(x = m_{inv}, y = m\left(\Lambda_{c}^{+}\pi^{\pm}\right), S, \mu, \sigma\left[y; a_{\sigma}, b_{\sigma}, c_{\sigma}\right], p, q, r; e_{psb}\right) = S$$

$$\times \frac{1}{\sigma(y)\sqrt{2\cdot\pi}} \exp\left(-\frac{1}{2}\frac{(m_{inv}-\mu)^{2}}{\sigma^{2}(y)}\right)$$

$$\times \mathcal{F}_{\mathsf{non}-\Sigma_{\mathsf{c}}}\left(m\left(\Lambda_{c}^{+}\pi^{\pm}\right); p, q, r; e_{psb}\right)$$
(3.19)

Because of the smaller statistics in data, the shape parameters  $a_{\sigma}$  and  $b_{\sigma}$  of the Gaussian's width in  $m_{inv}$  were extracted from Monte-Carlo events in a two-dimensional fit. For fits in data  $a_{\sigma}$  and  $b_{\sigma}$  were fixed and only the width scaling parameter  $c_{\sigma}$  was allowed to float.

Additional information on this backgound type can be found in appendix section A.8.2 on one-dimensional fits for combinatorial-like background from non- $\Sigma_c$  signal decays in  $m(\Lambda_c^+\pi^{\pm})$ .

Table 3.9: Width of  $m_{inv}$  for non-resonant signal Monte-Carlo: Results of fitting the Gaussian width in  $m_{inv}$  in subranges of  $m(\Lambda_c^+\pi^\pm)$  in a mixture of non-resonant signal Monte-Carlo composed of  $0.38 \times \text{SP} - 5076 + 0.25 \times \text{SP} - 6980 + 0.12 \times \text{SP} - 6983 + 0.04 \times \text{SP} - 6984 + 0.24 \times \text{SP} - 6989$ . The fit is shown in figure 3.9 with ( $\chi^2 = 5.744$ , ndf = 14) [ $P(\chi^2) = 0.9725$ ].

Parameter	$\mathbf{Fit}$
$a_{\sigma}$	$0.00236 \pm 0.00012$
$b_{\sigma}$	$-0.0156 \pm 0.0008$
$c_{\sigma}$	$0.0336 \pm 0.00119$



Figure 3.21: Width of  $m_{inv}$  for non-resonant signal Monte-Carlo: The Monte-Carlo sample was divided in subranges in  $m(\Lambda_c^+\pi^{\pm})$ . For each subrange  $m_{inv}$  was fitted with a Gaussian for signal and a 1st order polynomial for background. The fitted widths are shown here and were fitted with a 2nd order polynomial. The fit results are given in table 3.9

## 3.8.4 Background from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ with $\Sigma_c^+ \to \Lambda_c^+\pi^0$

In studies on Monte-Carlo events resonant decays with the same final state multiplicity as the signal mode showed to be dangerous as potential peaking background sources.

Due to the similarity to the signal mode Monte-Carlo was studied for the charged B decays  $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$ ,  $B^- \to \Sigma_c^+ (2455) \overline{p} \pi^-$  and  $B^- \to \Sigma_c^+ (2520) \overline{p} \pi^-$  with the resonant decay  $\Sigma_c^+ \to \Lambda_c^+ \pi^0$ . Branching fractions were measured for the four body final state  $\mathcal{B}\left(B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0\right) = (1.8 \pm 0.6) \cdot 10^{-3}$  and the first resonance mode  $\mathcal{B}\left(B^- \to \Sigma_c^+ (2455) \overline{p} \pi^0\right) = (4.4 \pm 1.8) \cdot 10^{-4}$  [31] only. Since the  $B^-$  decay is of the same magnitude as the signal mode and since further intermediate states can be assumed, unobserved modes could not be neglected.

In Monte-Carlo studies the non-resonant decay  $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$  and the resonant mode  $B^- \to \Sigma_c^+(2800)\overline{p}\pi^-$  did not pose a problem, since their signatures in  $m_{inv}$  or  $m(\Lambda_c^+\pi^{\pm})$  were found to be smeared broadly over the signal ranges (For more details on these modes in the Monte-Carlo simulation see appendix section A.9.1).

Since the  $\Sigma_c^+(2455,2520)$  baryons exist near the phase space border in  $m(\Lambda_c^+\pi^0)$ ,  $\pi^0$  daughters from  $\Sigma_c^+ \to \Lambda_c^+\pi^0$  have low momenta in the center-of-mass system of the  $\Sigma_c^+$ . In Monte-Carlo it was found, that these low momentum  $\pi^0$  in the  $B^-$  system could be replaced by a charged pion from the other  $B^+$ . The resulting fake events tend to peak in  $m(\Lambda_c^+\pi^+)$  as well as in  $m_{\rm ES}$  and also with a broader structure in  $m_{inv}$ . The upper left plot in figure 3.22 shows the  $m_{inv}:m(\Lambda_c^+\pi^+)$  distribution from  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  Monte-Carlo.  $\Sigma_c^+(2455)$  events distribute ellipse-like and peak in the  $m_{inv}:m(\Lambda_c^+\pi^+)$  signal region. The correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  is visible by eve. In the upper right plot for the conjugated plane  $m_{inv}:m(\Lambda_c^+\pi^-)$  no peaking structure is visible and the events distribute as combinatorial background. As shown in the lower row  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  events distribute similarly. Here the ellipse in  $m_{inv}:m(\Lambda_c^+\pi^+)$  is shifted to larger  $m(\Lambda_c^+\pi^+)$  by about the mass difference between the  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) resonances. In  $m_{inv}:m(\Lambda_c^+\pi^-) B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  events distribute also like combinatorial background.

Figure 3.23 shows projections onto  $m(\Lambda_c^+\pi^+)$  within the  $m_{inv}$  and  $m_{\rm ES}$  signal region. The distributions from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  Monte-Carlo are arbitrary scaled and overlayed with the distribution from data for comparison. In Monte-carlo both decays produce broader peaks in  $m(\Lambda_c^+\pi^+)$ . Both modes could contribute to  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  and especially to  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  signal decays in  $m(\Lambda_c^+\pi^+)$ . In  $m_{\rm ES}$  both  $\Sigma_c^+$ -modes produce a peaking structure that could not be described by an Argus function. In  $m_{inv}$  the distributions are broader but cannot be described by a simple polynomial but with two Gaussians with separate means and widths.

An one-dimensional extraction of signal events or peaking background events in  $m(\Lambda_c^+\pi^+)$ ,  $m_{inv}$  or  $m_{\rm ES}$  was discarded, since in each of the three variables one-dimensional fits showed to be unusable to discriminate between different background hypotheses (For details on the unseuccessful one-dimensional fits including background with  $\Sigma_c^+$  resonances see section A.9.2 in the appendix).

The  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  planes were chosen for the signal extraction to take advantage of the correlation between  $m_{inv}$  and  $m(\Lambda_c^+\pi^+)$  for  $B^- \to \Sigma_c^+\overline{p}\pi^-$  background. True  $\overline{B}^0 \to \Sigma_c^{++}\overline{p}\pi^-$  signal events do not have such a correlation (compare figures 3.9 and 3.12). If  $B^- \to \Sigma_c^+\overline{p}\pi^-$  background decays exist with a substantial branching fraction, it was assumed that their correlation in  $m_{inv}:m(\Lambda_c^+\pi^+)$  can be used as discriminator against true signal events.

For each  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  mode binned histograms from Monte-Carlo were used as PDFs in the fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  for the  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  signal decays. For  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  signal decays it was assumed that  $\Sigma_c^+$  events are absorbed in the combinatorial background (see section 3.8.3).



Figure 3.22:  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  background Monte-Carlo events: left column  $m_{inv}:m(\Lambda_c^+\pi^+)$ , right column  $m_{inv}:m(\Lambda_c^+\pi^-)$ ; upper row  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$ , lower row  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$ 



Figure 3.23:  $m(\Lambda_c^+\pi^+)$ : arbitrary scaled Monte-Carlo distribution for  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  in  $m(\Lambda_c^+\pi^+)$  overlayed by the distribution from data.



Figure 3.24:  $m_{\rm ES}$  distribution from  $B^- \rightarrow \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  Monte-Carlo



Figure 3.25:  $m_{inv}$  distribution from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  Monte-Carlo

## 3.8.5 Background from $\overline{B}{}^0 \to D^0/D^+p\overline{p} + n \cdot \pi$ events

T.M. Hong measured branching fractions of the order  $\sim 10^{-4}$  in his analysis of baryonic *B* decays without a charmed baryon [2]. Apparently, decays  $\overline{B}^0/B^- \to D_0^+(*)p\overline{p} + n \cdot \pi$  contribute noticeable to all baryonic *B* decays (see table 1.3). Depending on the  $D^0/D^+$  decay these modes can have the same final state particles as the signal decay  $\overline{B}^0 \to \overline{p}_{\overline{B}^0}\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\left[K_{A_c^+}^-\pi_{A_c^+}^+p_{A_c^+}\right]_{A^+}$ .

- Decays  $\overline{B}^0 \to D^0 p_{\overline{B}^0} \overline{p}_{\overline{B}^0}$  with  $D^0 \to K_{D^0}^- \pi_{D^0}^+ \pi_{D^0}^- \pi_{D^0}^+ \pi_{D^0}^- \pi_{D^0}^+ \pi_{D^0}^- \pi_{D^0}^+ \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} K_{D^0}^- \pi_{D^0}^+ \right]_{\sim \Lambda_c^+}$ . Figure could be rearranged according to the signal mode  $\sim \overline{B}_{fake}^0 \to \pi_{D^0}^- \pi_{D^0}^+ \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} K_{D^0}^- \pi_{D^0}^+ \right]_{\sim \Lambda_c^+}$ . Figure 3.26(a) shows the signal distributions in  $m_{\rm ES}$ ,  $m_{inv}$  and the  $m_{inv}$ :m\_{\rm ES} plane from the Monte-Carlo simulation of  $\overline{B}^0 \to D^0 p \overline{p}$ ;  $D^0 \to K^- \pi^+ \pi^- \pi^+$ . Since this background mode originates from true  $\overline{B}^0$  and is suppressed only by the  $\Lambda_c^+$  selection. Consequently, in both variables a distinct peak is visible. Figure 3.27(a) shows the distributions in the  $m(\Lambda_c^+ \pi^\pm)$  projections and the  $m_{inv}$ :m( $\Lambda_c^+ \pi^\pm)$  planes for events in the  $m_{\rm ES}$  and  $m_{inv}$  signal region. Here,  $D^0$  events appear as combinatorial
  - background to a  $\Sigma_c$  signal.
- In the charged  $D^+$  mode with  $\overline{B}^0 \to D^+ p_{\overline{B}^0} \overline{p}_{\overline{B}^0} \pi_{\overline{B}^0}^-$  and  $D^+ \to K_{D^+}^- \pi_{D^+}^+ \pi_{D^+}^+$  the final state particles can be rearranged to form a signal with  $\to \overline{B}^0_{fake} \to \pi_{\overline{B}^0}^- \pi_{D^+}^+ \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} K_{D^+}^- \pi_{D^+}^+ \right]_{\sim \Lambda_c^+}$ . Figure 3.26(b) shows the  $m_{\rm ES}$  and  $m_{inv}$  distributions from Monte-Carlo for  $\overline{B}^0 \to D^+ p \overline{p} \pi^-$ ;  $D^+ \to K^- \pi^+ \pi^+$ . Furthermore  $m(\Lambda_c^+ \pi^+)$  does not distribute like combinatorial background. Here, a fake structure near an expected  $\Sigma_c$  (2800) resonances could be composed of one of the  $\overline{B}^0$  proton daughters and the true  $D^+$  as  $\to \overline{B}^0_{fake} \to \pi_{\overline{B}^0}^- \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} \left[ K_{D^+}^- \pi_{D^+}^+ \pi_{D^+}^+ \right]_{D^+} \right]_{\sim \Sigma_c^{++}}$ . Such a fake  $\Sigma_c^{++}$  candidate would have a minimal mass of  $m(D^+p) \approx 2.804 \,{\rm GeV}/c^2$  comparable to the mass of a  $\Sigma_c^{++}(2800)$ resonance  $m(\Sigma_c^{++}(2800)) = 2.801^{+0.004}_{-0.006} \,{\rm GeV}/c^2$  [4].
- $\overline{B}^0 \to D^0 p_{\overline{B}^0} \overline{p}_{\overline{B}^0} \pi_{\overline{B}^0}^+ \pi_{\overline{B}^0}^-$  with  $D^0 \to K_{D^0}^- \pi_{D^0}^+$  can be rearranged in two combinations equivalent to the signal mode. A signal is produced with  $\to \overline{B}_{fake}^0 \to \pi_{\overline{B}^0}^- \pi_{D^0}^+ \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} K_{D^0}^- \pi_{\overline{B}^0}^+ \right]_{\sim A_c^+}$  as shown in figure 3.26(c). It also deviates in  $m(A_c^+\pi^+)$  from combinatorial background. Here, a  $\overline{B}^0$  proton and pion can be added to the  $D^0$  and fake a structure, that could be interpreted as a heavier  $\Sigma_c$ -like resonance  $\to \overline{B}_{fake}^0 \to \pi_{\overline{B}^0}^- \overline{p}_{\overline{B}^0} \left[ p_{\overline{B}^0} \pi_{\overline{B}^0}^+ \left[ \pi_{D^0}^+ K_{D^0}^- \right]_{D^0} \right]_{\sim \Sigma_c^{++}}$  with a minimal invariant mass of  $\sim 3.2 \text{ GeV}/c^2$  as visible in figure 3.27(c).

Interchanging  $\pi_{\overline{B}0}^+ \leftrightarrow \pi_{D^0}^+$  to form a combination  $\sim \overline{B}_{fake}^0 \to \pi_{\overline{B}0}^- \pi_{\overline{B}0}^+ \overline{p}_{\overline{B}0} \left[ p_{\overline{B}0} K_{D^0}^- \pi_{D^0}^+ \right]_{\sim A_c^+}$  would contribute only as peaking background. Because of the mass cut on  $m (pK^-\pi^+)_{A_c^+}$  the allowed momentum region of  $m \left( K_{D^0}^- \pi_{D^0}^+ \right)$  lies outside of the  $D^0$  mass region.

The decay  $\overline{B^0} \to D^{*+} p \overline{p} \pi^-$  with  $D^{*+} \to D^0 \pi^+$ ;  $D^0 \to K^- \pi^+$  is a resonant decay to  $\overline{B^0} \to D^0 p_{\overline{B^0}} \overline{p}_{\overline{B^0}} \pi^+_{\overline{B^0}} \pi^-_{\overline{B^0}}$  and has equivalent features and both were therefore subsumed.

(For additional information on the resonant and non-resonant decays to  $\overline{B}{}^0 \to D^0 p_{\overline{B}{}^0} \overline{p}_{\overline{B}{}^0} \pi^+_{\overline{B}{}^0} \pi^-_{\overline{B}{}^0}$ see appendix section A.10.1)

Reconstruction efficiencies and expected peaking events in the signal region are given in table 3.10. The number of  $D^0/D^+$  background events in data corresponds to the expectations.

The distributions of the final state particle combinations prone to  $D_0^+$  infestation is shown in figure 3.28. For each  $D_0^+$  mode a peak is visible. In total about 4% of the  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal would come from events with a  $D_0^+$  origin. Vetoes on the affected invariant masses  $m(K^-\pi^+)$ ,  $m(K^-\pi^+\pi^+)$  and  $m(K^-\pi^+\pi^+\pi^-)$  were applied to remove these backgrounds. The veto regions were set to  $m_{D^0/D^+} \notin (m_{D^0/D^+} \pm 0.020)$  GeV/ $c^2$  around the nominal  $D^0$  and  $D^+$  masses [4]. The vetoes were applied as general cuts on all data and Monte-Carlo (see cut table 3.4). Table 3.11 gives the averaged signal reduction rates of the  $D^0/D^+$  vetoes applied to signal and peaking background modes. About 1.7 background events were expected to pass the vetoes, which were taken into account by an systemtic uncertainty. To assure that the vetoes on  $D^+_0$ masses do not distort  $\Sigma_c^{\ 0}$  signal shapes, the differences in  $m(\Lambda_c^+\pi^\pm)$  from signal mode Monte-Carlos  $\overline{B}^0 \to \Sigma_c^{\ 0}$  (2455, 2520) $\overline{p}\pi^{\mp}$  with and without vetoes were studied. Figures 3.29(a)-3.29(d) show the binwise relative signal reduction by  $D^0/D^+$  vetoes for  $\overline{B}^0 \to \Sigma_c^{\ 0} \overline{p}\pi^{\mp}$ . No significant distortions in the resonance shapes were apparent.

Further peaking background was searched for in similar decays of the form  $B \to Dp\overline{p} X$ . Except for the presented modes all studied decays would only contribute as combinatorial background (see appendix section A.10.1 for details)

Since also B decays via charmonia as  $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} [\pi^+\pi^-]$ ;  $(c\overline{c}) \to p\overline{p} [\pi^+\pi^-]$ ;  $\overline{K}^{*0} \to K^-\pi^+$  could end up in the same final state particles as the signal decay, signal Monte-Carlo of these decays was studied as well. Decays of this slightly exotic origin were found to be not significant contributing at most about 4.5 signal events; a systematic uncertainty on these modes was included (see for details appendix section A.10.2).

Table 3.10:  $\overline{B}^0 \to D^0/D^+ p\overline{p} + n \cdot \pi$ : reconstruction efficiencies in the signal decay reconstruction, measured branching fractions [2], [25],  $D^0/D^+$  branching ratios [57] and expected contributions to  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without vetoes.

mode	$\epsilon_{\overline{\mathrm{B}}{}^{0}\to\Lambda_{\mathrm{c}}^{+}\overline{\mathrm{p}}\pi^{+}\pi^{-}}$	$\mathcal{B}\left(\overline{\mathbf{B}^{0}} ightarrow\mathbf{D}^{+}_{0}\ldots ight)$	$\mathcal{B}\left(\mathbf{D}^{o}_{o}^{+} ightarrow\ldots ight)$	$\mathbf{n}_{\mathrm{expected}}$
$ \begin{array}{c} \overline{B}{}^{0} \rightarrow D^{0} p \overline{p}; \\ D^{0} \rightarrow K^{-} \pi^{+} \pi^{-} \pi^{+} \end{array} $	$(6.79 \pm 0.19) \cdot 10^{-3}$	$(1.02 \pm 0.06) \cdot 10^{-4}$	$(8.10 \pm 0.20) \cdot 10^{-2}$	$\sim 26$
$ \overline{B}{}^{0} \to D^{+}p\overline{p}\pi^{-};  D^{+} \to K^{-}\pi^{+}\pi^{+} $	$(7.28 \pm 0.17) \cdot 10^{-3}$	$(3.32 \pm 0.29) \cdot 10^{-4}$	$(9.22\pm0.21)\cdot10^{-2}$	$\sim 103$
$ \begin{array}{c} \overline{B}{}^{0} \rightarrow D^{0} p \overline{p} \pi^{+} \pi^{-}; \\ D^{0} \rightarrow K^{-} \pi^{+} \end{array} $	$(4.19 \pm 0.15) \cdot 10^{-3}$	$(2.99 \pm 0.21) \cdot 10^{-4}$	$(3.89 \pm 0.05) \cdot 10^{-2}$	$\sim 22.5$
$ \begin{array}{c} \overline{B}{}^{0} \rightarrow D^{*+} p \overline{p} \pi^{+}; \\ D^{*+} \rightarrow D^{0} \pi^{+} \\ D^{0} \rightarrow K^{-} \pi^{+} \end{array} $	$(2.44 \pm 0.12) \cdot 10^{-3}$	$(4.55 \pm 0.40) \cdot 10^{-4}$	$(0.67 \pm 0.05)_{D^{*+}}.(3.89 \pm 0.05)_{D^0} \cdot 10^{-2}$	$\sim 13.4$

Table 3.11:  $D^0/\text{Dp}$  Veto signal reduction and remaining background events (expecting about 1.7 background events in total).

mode	reduction	remaining events
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$	6.18%	
$\overline{B}{}^0 \to D^0 p \overline{p}; \ D^0 \to K^- \pi^+ \pi^- \pi^+$	99.29%	0.26
$\overline{B}{}^0 \to D^+ p \overline{p} \pi^-; D^+ \to K^- \pi^+ \pi^+$	98.79%	1.04
$ \begin{array}{c} \overline{B}{}^0 \rightarrow D^0 p \overline{p} \pi^+ \pi^-; \ D^0 \rightarrow K^- \pi^+ \\ \overline{B}{}^0 \rightarrow D^{*+} p \overline{p} \pi^+; \ D^{*+} \rightarrow D^0 \pi^+; \ D^0 \rightarrow K^- \pi^+ \end{array} $	96.92%	$\begin{array}{c} 0.23 \\ 0.14 \end{array}$



Figure 3.26: Monte-Carlo for  $\overline{B}^0 \to D^0/D^+p\overline{p} + n \cdot \pi$  without  $D^{+}_0$  veto:  $m_{\rm ES}$ ,  $m_{inv}$  and  $m_{inv}:m_{\rm ES}$  distributions from  $\overline{B}^0 \to D^0p\overline{p}$ ;  $D^0 \to K^-\pi^+\pi^-\pi^+$  (a), from  $\overline{B}^0 \to D^+p\overline{p}\pi^-$ ;  $D^+ \to K^-\pi^+\pi^+$  (b) and from  $\overline{B}^0 \to D^0p\overline{p}\pi^+\pi^-$ ;  $D^0 \to K^-\pi^+$  (c).



Figure 3.27: Monte-Carlo for  $\overline{B}^0 \to D^0/D^+p\overline{p} + \mathbf{n} \cdot \pi$  without  $D_0^+$  veto: left row  $m(\Lambda_c^+\pi^+)$  and  $m_{inv}:m(\Lambda_c^+\pi^+)$  distributions, right row  $m(\Lambda_c^+\pi^-)$  and  $m_{inv}:m(\Lambda_c^+\pi^-)$  distributions from  $\overline{B}^0 \to D^0p\overline{p}; D^0 \to K^-\pi^+\pi^-\pi^+$  (a), from  $\overline{B}^0 \to D^+p\overline{p}\pi^-; D^+ \to K^-\pi^+\pi^+$  (b) and from  $\overline{B}^0 \to D^0p\overline{p}\pi^+\pi^-; D^0 \to K^-\pi^+$  (c).



Figure 3.28: Data distributions without  $D_{c}^{+}$  veto with background from  $\overline{B}^{0} \to D^{0}/D^{+}p\overline{p} + n \cdot \pi$ :  $m\left(K_{A_{c}^{+}}^{-}\pi_{A_{c}^{+}}^{+}\pi_{\overline{B}^{0}}^{+}\right)$ ,  $m\left(K_{A_{c}^{-}}^{-}\pi_{\overline{B}^{0}}^{+}\pi_{\overline{B}^{0}}^{-}\right)$ ,  $m\left(K_{A_{c}^{-}}^{-}\pi_{\overline{B}^{0}/A_{c}^{+}}^{+}\right)$ . In the lower plot the  $K^{*}$  peak from  $A_{c}^{+} \to K^{*}p$ ;  $K^{*} \to K^{-}\pi^{+}$  is visible in  $m\left(K_{A_{c}^{+}}^{-}\pi_{A_{c}^{+}}^{+}\right)$ , which contributes to the signal decay  $m\left(pK^{-}\pi^{+}\right)$ .



Figure 3.29: Distributions in  $m(\Lambda_c^+\pi^{\pm})$  before and after applying  $D^0/D^+$  vetoes. The upper row shows the events from signal Monte-Carlo for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  (a) and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  (b), the lower row for  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  (c) and  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  (d). Shown are the the original  $\bullet$  and post-veto  $\circ$  and binwise relative signal reduction  $\bullet$  distributions.

## Chapter 4

# Monte-Carlo studies

### 4.1 MC datasets

Signal Monte-Carlo simulations were requested from the BABAR Monte-Carlo group for events decaying as non-resonant  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  and for decays with  $\Sigma_c$  resonances. Also Monte-Carlo events were requested for decay modes that were suspected as possible background contributions. The signal Monte-Carlo modes can be identified by their SP names (i.e. SP-####), within this document the Monte-Carlo data sets are named by their decay mode. Used signal Monte-Carlo data sets are listed in table 4.1. (Details on which background Monte-Carlo simulated modes were studied can be found in the appendix section A.4)

Furthermore, generic Monte-Carlo simulations were studied for additional background sources from  $B^0\overline{B}^0$  or  $B^+B^-$  events and from contributions from non- $b\overline{b}$  events (table 4.2).

Table 4.1: Data sets of Monte-Carlo simulated events. For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data and including the branching fraction of the reconstructed  $\Lambda_c^+$  decay  $(N_{B\overline{B}} \sim 462 \cdot 10^6, \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.05 \text{ from [4]}).$ 

mode	decay	produced events	$\times$ on-peak
SP-5076	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \text{ (non-resonant)}$	778000	52.6
SP-6980	$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-, \ \Sigma_c^{++}(2455) \to \Lambda_c^+\pi^+$	387000	76.2
SP-6981	$\overline{B}{}^0 \to \Sigma^0_c(2455)\overline{p}\pi^+, \ \Sigma^0_c(2455) \to \Lambda^+_c\pi^-$	387000	111.7
SP-6982	$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-, \ \Sigma_c^{++}(2520) \to \Lambda_c^+\pi^+$	387000	139.6
SP-6983	$\overline{B}{}^0 \to \Sigma^0_c(2520)\overline{p}\pi^+, \ \Sigma^0_c(2520) \to \Lambda^+_c\pi^-$	387000	> 306.4
SP-6984	$\overline{B}{}^0 \to \Sigma_c^{++}(2800)\overline{p}\pi^-, \ \Sigma_c^{++}(2800) \to \Lambda_c^+\pi^+$	387000	-
SP-6985	$\overline{B}{}^0 \to \Sigma_c^0(2800)\overline{p}\pi^+, \ \Sigma_c^0(2800) \to \Lambda_c^+\pi^-$	387000	-
SP-7185	$\overline{B}{}^0 \to \Lambda_c^+(2593)\overline{p}, \ \Lambda_c^+(2593) \to \Lambda_c^+\pi^-\pi^+ \& \ \Sigma_c^{++}\pi^- \& \ \Sigma_c^0\pi^+$	175000	> 68.9
SP-8843	$\overline{B}{}^0 \to \Lambda_c^+(2625)\overline{p}, \ \Lambda_c^+(2625) \to \Lambda_c^+\pi^-\pi^+$	387000	> 112.9

## 4.2 MC/Data misalignment

The analysis showed to be sensible to divergences between data and Monte-Carlo events. While one reason was the large statistics of the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ , the main reason was the decision to use binned histograms from Monte-Carlo events as PDFs in fits to data. While analytical PDFs could adapt

mode	decay	produced events
SP-998	$e^+e^- \rightarrow uds \rightarrow anything$	938312000
SP-1005	$e^+e^- \rightarrow c\overline{c} \rightarrow anything$	1132468000
SP-1235	$e^+e^- \rightarrow B^+B^- \rightarrow anything$	731146000
SP-1237	$e^+e^- \rightarrow B^0 \overline{B}{}^0 \rightarrow anything$	735850000

Table 4.2: Monte-Carlo simulated event: generic background Monte-Carlo data sets.

to small differences between Monte-Carlo and data, binned PDFs were not as obedient<sup>1</sup>. A divergence between data and Monte-Carlo was found in  $m_{inv}$  and  $\Delta E$ , that would have affected the signal yield measurements. Presumably, the misalignment is due to a too light SVT material assumptions in the Monte-Carlo detector simulation. The misalignment was corrected by applying adjustments on the protons' momenta.

Furthermore, also differences between data and Monte-Carlo in  $m(\Sigma_c(2455))$  had to be corrected.

#### 4.2.1 Monte-Carlo/Data differences in $m_{inv}$

Fitting the  $\overline{B}^0$  signal in the *B* invariant mass  $m_{inv}$  with a Gaussian as signal PDF showed a difference of  $(2-3) \text{ MeV}/c^2$  between the Gaussian means in data  $\mu_{data}^{\text{Gauss}}$  and in Monte-Carlo  $\mu_{MC}^{\text{Gauss}}$  (in the related variable  $\Delta E$  correspondingly). Table 4.3 shows the measured signal Gaussian means and widths from fits to data and Monte-Carlo. To check if the the difference in  $m_{inv}$  depends on the  $\Lambda_c^+$ -mass constraint or  $\Lambda_c^+$ -mass cut, fits were done for data on  $\overline{B}^0$  reconstructions with the different  $\Lambda_c$  mass constraints and cuts. Fits on  $m_{inv}$  in the different  $\overline{B}^0 \to \Sigma_c^{++}$  (2455, 2520, 2800) signal Monte-Carlo had the benefit of checking different phase space regions in  $m(\Lambda_c^+\pi^{\pm})$  on their potential influence on the shift in  $m_{inv}$ .

The  $\overline{B}^0$  invariant mass  $m_{inv}$  mass does not depend on a certain  $\Lambda_c^+$ -mass constraint and corresponding  $\Lambda_c^+$ -mass cuts. Also the  $m_{inv}$  shift does not depend on  $m(\Lambda_c^+\pi^\pm)$  since in the studied resonant signal Monte-Carlo  $m_{inv}$  is stable.

The  $\overline{B}^0$  mass used by the Monte-Carlo generator is  $m_{inv} = 5.279 \,\text{GeV}/c^2$ . Fits in the invariant mass on different signal Monte-Carlo samples, representing different phase space regions in  $m(\Lambda_c^+\pi^\pm)$ , reproduce the Monte-Carlo generator mass  $m_{inv} = \sim 5.279 \,\text{GeV}/c^2$  (see table 4.3). In data  $m_{inv} = (5.27669 \pm 0.00025) \,\text{GeV}/c^2$  was found using the standard constraints and cuts for data (table 3.4.1). Thus, a mass shift between data and Monte-Carlo exists with  $(2.30 \pm 0.25) \,\text{MeV}/c^2$ .

Figure 4.1(a) shows the difference between data and Monte-Carlo. Here, the  $m_{inv}:m(\Lambda_c^+\pi^-)$  plane from data was fitted with signal PDFs for  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  from binned histograms from signal Monte-Carlos, i.e.  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  signal Monte-Carlos which were generated with  $m_{inv}\overline{B}^0 = 5.279 \,\text{GeV}/c^2$ . The fit result was subtracted from data. The difference in the  $\Sigma_c$  (2455) signal region in  $m(\Lambda_c^+\pi^-)$  was projected onto  $m_{inv}$ . An over-/undershot due to the  $m_{inv}$  difference is clearly visible.

#### 4.2.1.1 Detector simulation misalignment

The difference between data and Monte-Carlo is presumably caused by a misalignment in the detector material description in Monte-Carlo. For example, Brian Peterson found 2006 in his measurement of the  $\Lambda_c$  mass that assuming a 20% more dense SVT gives the best description of events in Monte-Carlo compared to events from data [63], [64]. Protons as heavier particles suffer more from a lighter material simulation compared to mesons or leptons, which is why measurements without baryons are not affected

<sup>&</sup>lt;sup>1</sup>See also section 3.4.1, where the differences between data and Monte-Carlo with respect to the mass of the  $\Lambda_c^+$  are described. Since the  $\Lambda_c^+$  mass hypothesis determines the  $\Lambda_c^+$ -mass cuts and  $\Lambda_c^+$ -mass constraint, the whole *B*-reconstruction chain was affected.
notably. Naturally, because of baryon number conservation baryonic (B-)decays have two baryons and suffer twice from this penalty.

#### 4.2.1.2 p momentum correction

Thus, Monte-Carlo generated events had to be adapted to data to use them as basis for binned histogram PDFs. Since mainly baryon momenta were affected,  $p_{A_c^+}$  and  $\overline{p}_{\overline{B}^0}$  momenta were corrected on N-tuple level. Per Monte-Carlo event each proton absolute three-vector momentum was increased by  $S_p^{MC} = 2.30 \text{ MeV}/c^2$  to compensate the too light material assumption; the proton's energy is corrected accordingly to keep the proton mass properly constrained:

$$\left| \mathbf{p}^{\vec{p}'} \right| = \left| \mathbf{p}^{\vec{p}} \right| + S^{p}_{MC}$$

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Accordingly, the mass constrained  $\Lambda_c^+$ , as mother of one of the protons, had to be corrected as well

$$\mathbf{p}_{x,y,z}^{A_c^+\prime} = \mathbf{p}_{x,y,z}^{A_c^+} + \left(\mathbf{p}_{x,y,z}^{p\prime} - \mathbf{p}_{x,y,z}^p\right) \quad ; \quad \mathbf{E}^{A_c^+\prime^2} = \mathbf{m}^{A_c^{+2}} + \mathbf{p}^{\vec{A_c^+\prime}^2}^2 \tag{4.2}$$

The  $\overline{B}{}^0$  and  $\Sigma_c$  invariant masses were calculated with the scaled baryon four-momenta and the unaffected meson four-momenta.

After applying the momentum corrections, the fit to the invariant  $\overline{B}^0$  mass in corrected non-resonant Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  found

$$\mu_{Gauss}^{m_{inv}} = (5.27688 \pm 0.000026) \text{ GeV}/c^2 \quad ; \quad \sigma_{Gauss}^{m_{inv}} = (0.00826 \pm 0.000026) \text{ GeV}/c^2$$

giving a better Monte-Carlo to data alignment. Figure 4.2 shows comparisons for corrected and uncorrected Monte-Carlo samples. The momentum correction only affected  $m_{inv}$  and other distributions showed no significant deviations between the distributions from corrected and un corrected Monte-Carlo events.

Fits to  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  from data with corrected Monte-Carlo histograms as signal PDF show a good agreement as visible in the difference between the input from data and the fit result in figure 4.1(b). Using the the corrected Monte-Carlo sets, binned histograms were created as fit PDFs for the  $\overline{B}^0 \rightarrow \Sigma_c^{++}$  (2455, 2520) $\overline{p}\pi^{\mp}$  signal and the  $B^- \rightarrow \Sigma_c^+$  (2455, 2520) $\overline{p}\pi^-$  background contributions. In addition, the signal Monte-Carlo for  $\overline{B}^0 \rightarrow \Sigma_c^{++}$  (2455) $\overline{p}\pi^{\mp}$  had to be corrected also in  $m(\Lambda_c^+\pi^{\pm})$ .

Table 4.3: Invariant mass distributions in data and resonant Monte-Carlo for  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^{\mp}$ ; the distributions were fitted with a single Gaussian for signal and a polynomial for background. In data the  $\Lambda_c^+$  mass was constrained to the Monte-Carlo generator mass 2.2849 GeV/ $c^2$ , to the fitted mass in data 2.2856 GeV/ $c^2$  and without a constraint, the  $\Lambda_c^+$  mass cuts were chosen correspondingly. In Monte-Carlo the  $\Lambda_c^+$  mass was constrained to the Monte-Carlo the  $\Lambda_c^+$  mass.

$\mathrm{Data}/\mathrm{MC}$	$\Lambda_c^+$ Mass Constraint	$\Lambda_c^+$ Mass Cuts	$\mu^{m_{inv}}_{Gauss}$	$\sigma^{m_{inv}}_{Gauss}$
Data	$2.2856  { m GeV}/c^2$	$(2.2727, 2.2977)$ GeV/ $c^2$	$(5.27669 \pm 0.00025) \text{ GeV}/c^2$	$(0.00857 \pm 0.00025) \text{ GeV}/c^2$
Data	—	$(2.2727, 2.2977)$ GeV/ $c^2$	$(5.27644 \pm 0.00038) \text{ GeV}/c^2$	$(0.01057 \pm 0.00041) \text{ GeV}/c^2$
Data	—	$(2.272, 2.297) \mathrm{GeV}/c^2$	$(5.27625 \pm 0.00038) \text{ GeV}/c^2$	$(0.01052 \pm 0.00042) \text{ GeV}/c^2$
Data	$2.2849\mathrm{GeV}/c^2$	$(2.272, 2.297) \mathrm{GeV}/c^2$	$(5.27592 \pm 0.00033) \text{ GeV}/c^2$	$(0.00837 \pm 0.00038) \text{ GeV}/c^2$
MC $\Sigma_{c}^{++}(2455)$	$2.2849{\rm GeV}/c^2$	$(2.272, 2.297)$ GeV/ $c^2$	$(5.27919 \pm 0.00006) \text{ GeV}/c^2$	$(0.01006 \pm 0.000057) \text{ GeV}/c^2$
MC $\Sigma_c^0(2455)$	$2.2849\mathrm{GeV}/c^2$	$(2.272, 2.297) \mathrm{GeV}/c^2$	$(5.27931 \pm 0.00005) \text{ GeV}/c^2$	$(0.00971 \pm 0.000048) \text{ GeV}/c^2$
MC $\Sigma_{c}^{++}(2520)$	$2.2849\mathrm{GeV}/c^2$	$(2.272, 2.297) \mathrm{GeV}/c^2$	$(5.27903 \pm 0.00005) \text{ GeV}/c^2$	$(0.00948 \pm 0.000046) \text{ GeV}/c^2$
MC $\Sigma_c^{++}(2800)$	$2.2849\mathrm{GeV}/c^2$	$(2.272, 2.297) \mathrm{GeV}/c^2$	$(5.27892 \pm 0.00004) \text{ GeV}/c^2$	$(0.00841 \pm 0.000036) \text{ GeV}/c^2$



Figure 4.1:  $m_{inv}$ : the  $m_{inv}:m(\Lambda_c^+\pi^-)$  distribution in data was fitted with binned signal Monte-Carlo for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  as signal PDF. The difference between the distribution and the fit result the  $\Sigma_c^0(2455)$  signal region in  $m(\Lambda_c^+\pi^-)$  was projected onto  $m_{inv}$ . In the left figure (a) the signal PDF from Monte-Carlo simulated events was uncorrected, i.e.  $m_{inv}(\overline{B}^0) = 5.279 \,\text{GeV}/c^2$ . In the right plot (b) the Monte-Carlo events were corrected before the histogram PDF was created from them, i.e.  $m_{inv}(\overline{B}^0) = 5.2766 \,\text{GeV}/c^2$ .



Figure 4.2: Monte-Carlo to data mass shift: Comparison between the  $m_{inv}$  distributions from uncorrected and corrected Monte-Carlo events plus the difference between both. Left: non-resonant SP-5076  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ , right: resonant signal Monte-Carlo  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ .)

## 4.2.2 Resonance masses and widths in data and Monte-Carlo events

In addition to the  $\overline{B}{}^0$  mass in data and Monte-Carlo events, the consistency of  $\Sigma_c^{++}$  masses and width in data and Monte-Carlo were studied.

#### 4.2.2.1 $\Sigma_c$ (2455,2520) masses and widths

The  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions from signal Monte-Carlo for  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^$ and  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  were used to study the masses and widths. After mapping reconstructed events from Monte-Carlo to the truly generated events, the distributions in  $m(\Lambda_c^+\pi^\pm)$  were fitted with a non-relativistic Breit-Wigner (eq. 3.15). Here, for the primarily mass measurement the Breit-Wigner was used as approximation on an effective signal shape, ignoring further impacts on the signal, e.g. the detector resolution. For comparison data was fitted in  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  as well.  $m(\Lambda_c^+\pi^\pm)$ from data was side-band subtracted to remove combinatorial background<sup>2</sup>. Tables 4.4-4.7 give the fitted masses and widths for signal Monte-Carlo and data for  $\Sigma_c^{++}$  (2455,2520).<sup>3</sup>

Since a difference between data and Monte-Carlo was found in the  $\Sigma_c^{++}(2455)$  masses, the  $\Sigma_c^{++}(2455)$  baryons in Monte-Carlo simulated events had to be corrected. Without a corrected  $\Sigma_c^{++}(2455)$  mass the signal Monte-Carlo distributions from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$  Monte-Carlo could not have been used to as source for binned histograms, which were designated as PDFs for fits on data distributions.

#### 4.2.2.2 Monte-Carlo/Data difference for $\Sigma_c$ (2455)

For  $\Sigma_c^{++}(2455)$  resonances a small deviation of Monte-Carlo from data was measured in  $m(\Lambda_c^+\pi^{\pm})$ . The deviation is clearly visible in the difference between data and Monte-Carlo. Data was fitted in a 2-dimensional fit with the binned signal distribution from Monte-Carlo as PDF for  $\overline{B}^0 \to \Sigma_c^{++} \overline{p} \pi^{\mp}$ . The difference between data and the fit result was projected onto  $m(\Lambda_c^+\pi^{\pm})$ .

Figures 4.3(a) and 4.3(b) show the differences in  $m(\Lambda_c^+\pi^{\pm})$  from the  $m_{inv}$  signal band. Because of its small width the  $\Sigma_c^{0}$  (2455) states are very sensible to deviations between data and the Monte-Carlo input, which appear as distinct *two-bin oscillations*. For the broader  $\Sigma_c^{++}$  (2520) resonances no significant deviations between data and Monte-Carlo were visible (see tables 4.6 and 4.7 for mass and widths from 1D fits to  $m(\Lambda_c^+\pi^{\pm})$  in data and Monte-Carlo).

Since the overall effect is small, the difference between data and Monte-Carlo was used as correction. A mean correction summand of

$$m_{corr}^{\Sigma_c^{0}}(2455) = (0.000441 \pm 0.000096) \text{ GeV}/c^2$$
(4.3)

was calculated from the difference between data and Monte-Carlo of the fitted  $\Sigma_c^{++}$  masses (see table 4.4).

For resonant  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$  signal events the correction summand was added in their signal Monte-Carlo samples  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$  to  $m(\Lambda_c^+\pi^{\pm})$  for each event. The corrected histograms were used as PDFs for fits to data.

Figures 4.4(a) and 4.4(b) show the difference between data and fitted Monte-Carlo after applying the correction to  $\Sigma_c^{++}$  (2455) signal Monte-Carlo. Table 4.8 sums up the (corrected) masses and width from

<sup>2</sup> 

<sup>&</sup>lt;sup>3</sup>Note that the side-band subtraction in data does not removes non-resonant signal events in  $m\left(\Lambda_c^+\pi^\pm\right)$  below the resonances. For simplification, it was assumed here, that such background has no significant influence near the phase space border of  $m\left(\Lambda_c^+\pi^\pm\right)$ . The plots of the fits to the  $m\left(\Lambda_c^+\pi^\pm\right)$  distributions can be found in the appendix section A.11.3.Note that for  $\Sigma_c^0(2520)$  no significant signal was be found.

#### Monte-Carlo.

For fitting combinatorial backgrounds with  $true \Sigma_c^{\dagger 0}$  (2455,2520) baryons in data (see previous section 4.2.2.1), masses and widths were fixed to the values fitted in Monte-Carlo. For combinatorial background events with true  $\Sigma_c^{\dagger 0}$  (2455) the mass obtained from Monte-Carlo was corrected by  $m_{corr}^{\Sigma_c^{0}}$  (2455) as well, assuming the same deviation between data and Monte-Carlo as for signal  $\Sigma_c^{\dagger 0}$  (2455) resonances. See table 4.8 for the  $\Sigma_c$  parameters.



Figure 4.3: Monte-Carlo misalignment: difference in the  $m_{inv}$  signal region between data and fit with  $\Sigma_c^{0}$  (2455,2520) histograms from signal Monte-Carlo. The two-dimensional difference between data and fit result was projected onto  $m(\Lambda_c^+\pi^{\pm})$ . No correction was applied onto the  $\Sigma_c$  (2455) mass in Monte-Carlo.



Figure 4.4: Monte-Carlo misalignment: difference in the  $m_{inv}$  signal region between data and fit with  $\Sigma_c^{++}$  (2455,2520) histograms from signal Monte-Carlo. The 2D difference between data and fit result was projected onto  $m(\Lambda_c^+\pi^{\pm})$ . The  $\Sigma_c^{++}$  (2455) mass was corrected in  $m(\Lambda_c^+\pi^{\pm})$  corrected for signal Monte-Carlo.

 $\begin{array}{|c|c|c|c|c|} \hline \mathbf{Data/MC} & \mu \, (\Lambda_c^+ \pi^\pm)_{\Sigma_c(2455)} \\ \hline \mathrm{MC} \ \Sigma_c^{++}(2455) & (2.452726 \pm 0.000012) \ \mathrm{GeV}/c^2 \\ \hline \mathrm{Data} \ \Sigma_c^{++}(2455) & (2.45322 \pm 0.000098) \ \mathrm{GeV}/c^2 \\ \hline \mathrm{MC} \ \Sigma_c^0(2455) & (2.4522834 \pm 0.000098) \ \mathrm{GeV}/c^2 \\ \hline \mathrm{Data} \ \Sigma_c^0(2455) & (2.45267 \pm 0.00016) \ \mathrm{GeV}/c^2 \\ \end{array}$ 

Table 4.4:  $\Sigma_c^{++}(2455)$ : Fitted Breit-Wigner masses in  $m(\Lambda_c^+\pi^{\pm})$  from data and Monte-Carlo events.

Table 4.5:  $\Sigma_c^{++}(2455)$ : Fitted Breit-Wigner widths in  $m(\Lambda_c^+\pi^{\pm})$  from data and Monte-Carlo events.

$\mathrm{Data}/\mathrm{MC}$	$\gamma \left( \Lambda_c^+ \pi^\pm \right)_{\Sigma_c(2455)}$
MC $\Sigma_c^{++}(2455)$	$(0.003225 \pm 0.000025) \text{ GeV}/c^2$
Data $\Sigma_{c}^{++}(2455)$	$(0.00386 \pm 0.00023) \text{ GeV}/c^2$
MC $\Sigma_{c}^{0}(2455)$	$(0.002754 \pm 0.000018) \text{ GeV}/c^2$
Data $\Sigma_c^0(2455)$	$(0.00496 \pm 0.00039) \text{ GeV}/c^2$

Table 4.6:  $\Sigma_c^{++}(2520)$ : Fitted Breit-Wigner masses in  $m(\Lambda_c^+\pi^{\pm})$  from data and Monte-Carlo events.

$\mathrm{Data}/\mathrm{MC}$	$\mu \left( \Lambda_c^+ \pi^\pm \right)_{\Sigma_c(2520)}$
MC $\Sigma_c^{++}(2520)$	$(2.52021 \pm 0.000059) \text{ GeV}/c^2$
Data $\Sigma_{c}^{++}(2520)$	$(2.51810 \pm 0.00078) \text{ GeV}/c^2$
MC $\Sigma_{c}^{0}(2520)$	$(2.51805 \pm 0.000047) \text{ GeV}/c^2$
Data $\Sigma_c^0(2520)$	$(2.5108 \pm 0.0019) \text{ GeV}/c^2$

Table 4.7:  $\Sigma_c^{++}(2520)$ : Fitted Breit-Wigner widths in  $m(\Lambda_c^+\pi^{\pm})$  from data and Monte-Carlo events.

$\mathrm{Data}/\mathrm{MC}$	$\gamma \left( \Lambda_c^+ \pi^\pm \right)_{\Sigma_c(2520)}$
MC $\Sigma_{c}^{++}(2520)$	$(0.02010 \pm 0.00016) \text{ GeV}/c^2$
Data $\Sigma_{c}^{++}(2520)$	$(0.0255 \pm 0.0022) \text{ GeV}/c^2$
MC $\Sigma_{c}^{0}(2520)$	$(0.01591 \pm 0.00012) \text{ GeV}/c^2$
Data $\Sigma_c^0(2520)$	$(0.0378 \pm 0.0061) \text{ GeV}/c^2$

Table 4.8:  $\Sigma_c^{++}(2455,2520)$ : Widths and (corrected) masses from Monte-Carlo used as shape parameters in fits to data and Monte-Carlo. The uncorrected values from  $\Sigma_c^{++}(2455)$  in Monte-Carlo are given for comparison.

$\Sigma_c^{++}$	$\mu \left( \Lambda_c^+ \pi^\pm \right)$	$\gamma \left( \Lambda_{c}^{+} \pi^{\pm} \right)$
MC $\Sigma_{c}^{++}(2455)_{MC}$	$2.453167  \text{GeV}/c^2$	$0.003225  \text{GeV}/c^2$
MC $\Sigma_{c}^{0}(2455)_{MC}$	$2.4522834\mathrm{GeV}/c^2$	$0.002754\mathrm{GeV}/c^2$
MC $\Sigma_{c}^{++}(2455)_{Corr}$	$2.452726  \text{GeV}/c^2$	$0.003225  \text{GeV}/c^2$
MC $\Sigma_c^0(2455)_{Corr}$	$2.4527244  \text{GeV}/c^2$	$0.002754\mathrm{GeV}/c^2$
MC $\Sigma_c^{++}(2520)$	$2.52021  \text{GeV}/c^2$	$0.02010  \text{GeV}/c^2$
MC $\Sigma_{c}^{0}(2520)$	$2.51805\mathrm{GeV}/c^2$	$0.01591\mathrm{GeV}/c^2$

## 4.3 Fit verification on MC

The applicability of the analytical PDFs was verified in fits on  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  from Monte-Carlo simulated events or side band distributions from data.

Studies were done for:

- the two-dimensional PDF eq. 3.20 for non- $\Sigma_c$  (2455,2520) signal events in  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ , which was tested on toy Monte-Carlo samples. Here, different non-resonant Monte-Carlo samples with random numbers of events were merged and the resulting distributions in  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  were fitted. (Details in appendix section A.11.1)
- combinatorial events with  $\Sigma_c$  (2455,2520) resonances were studied in Monte-Carlo events of the decays  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$ . As high-luminosity samples, the  $m_{inv}:m(\Lambda_c^+\pi^-)$  distributions of these samples were successfully fitted with PDF eq. 3.17. (Details in appendix section A.11.2)
- combinatorial events including  $\Sigma_c$  resonances. The combined PDF was studied on distributions of  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  from generic Monte-Carlo simulations of  $B^0\overline{B}{}^0$  or  $B^+B^-$  events. Furthermore, it was studied in events from the  $m_{inv}$  side bands. The PDF was able to fit to the several distributions with their varying contributions from  $\Sigma_c$  (2455,2520) resonances. (Details in appendix section A.11.4)
- resonant and non-resonant signal events. For signal events with  $\Sigma_c$  (2455,2520) resonances plus background from non- $\Sigma_c$  signal decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  toy Monte-Carlo samples were fitted. Here, again Monte-Carlo simulated events from resonant as well as non-resonant modes were merged with random weighting into mixed distributions in  $m_{inv}:m(\Lambda_c^+\pi^\pm)$ . The resulting distributions were fitted with the binned signal histograms from signal Monte-Carlo as PDFs for  $\overline{B}^0 \to \Sigma_c^{\phantom{0}0}(2455, 2520)\overline{p}\pi^+\pi^-$  signal events and PDF eq. 3.20 for the non-resonant- $\Sigma_c$ contributions. Furthermore, a potential bias from events of the type  $\overline{B}^0 \to \Sigma_c(2800)\overline{p}\pi^+\pi^-$  was studied. (Details in appendix section A.11.5)

All PDFs listed in the previous chapter showed to be able to fit to their specific background or signal event type. From the positive results it was assumed that fits to data distributions in  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  are feasible for the signal yield determination of the decays  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$ . Full details on the verification studies can be found in the appendix section A.11.

# Chapter 5

# Results

The measurement of the signal decays consisted of several steps. The yields of signal decays with  $\Sigma_c^{++}$  (2455,2520) resonances and the remaining non- $\Sigma_c$  (2455,2520) signal decays were measured in fits. While the substructures in  $\overline{B}^0 \to \Sigma_c^{++}$  (2455) $\overline{p}\pi^{\mp}$  could be studied in Dalitz plots [65], this was not feasible for events with  $\Sigma_c$  (2520) resonances and non- $\Sigma_c$  (2455,2520) signal events, due to the higher background contributions. To separate background from signal events the  $_s\mathcal{P}lot$ -technique was used [16].

## 5.1 Fit on data

While the resonant modes  $\overline{B}^0 \to \Sigma_c^{+, +}(2455, 2520)\overline{p}\pi^{\mp}$  were measured in two-dimensional fits to the  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  planes, the yield of the remaining non- $\Sigma_c$  (2455,2520) signal events was fitted in  $m_{inv}$ . The number of signal events for resonant sub-modes were extracted by fits in the two planes:

•  $m_{inv}:m\left(\Lambda_c^+\pi^-\right)$ 

for  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ and  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ 

•  $m_{inv}:m\left(\Lambda_c^+\pi^+\right)$ 

for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^$ and  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ 

in the ranges  $m_{inv} \in (5.17, 5.38) \text{ GeV}/c^2$  and  $m(\Lambda_c^+\pi^{\pm}) \in (2.425, 2.625) \text{ GeV}/c^2$ . The non- $\Sigma_c$  (24552,2520) decays to  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  were fitted in the  $m_{inv}$  signal range. To take background from  $B^- \to \Sigma_c^+ \overline{p} \pi^-$  events into account, the fit was divided into two sub-measurements.

## 5.1.1 Fit for $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$

The  $m_{inv}:m(\Lambda_c^+\pi^-)$  plane was fitted with PDFs for contributions from:

- signal events from  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$
- signal events from  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$
- non- $\Sigma_c^0(2455,2520) \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$
- combinatorial background

- combinatorial background with  $\Sigma_c^0(2455)$
- combinatorial background with  $\Sigma_c^0(2520)$

Using the fit region including the  $m_{inv}$  side band regions (table 3.6) gave a better estimate of background the PDFs. Although no clear signal from  $\overline{B}^0 \to \Sigma_c^0(2800)\overline{p}\pi^+$  was visible in  $m(\Lambda_c^+\pi^-)$ , the fit was not extended beyond the  $\Sigma_c^0(2520)$  signal region to avoid any influences from potential  $\Sigma_c$  (2800) resonances in addition to the non- $\Sigma_c^0(2455,2520)$  signal.

The contributions of combinatorial background events with  $\Sigma_c^0(2520)$  resonances were ambiguous. While in generic Monte-Carlo combinatorial background events with  $\Sigma_c^0(2520)$  resonances appeared (see figures 3.16 and 3.17), this background source was not significant in data in the  $m_{inv}$  side-bands as in figure 3.19 (Supplementary information on this background types can be found in the appendix section A.11.4). Tus, simulated events and data seemed to contradict each other over the the existence of this background.

To study the significance of combinatorial background with  $\Sigma_c^0(2520)$  events, the  $m_{inv}:m(\Lambda_c^+\pi^-)$  sideband region was fitted with and without including the PDF. The fit including the PDF for combinatorial background with  $\Sigma_c^0(2520)$  did not improve the fit result<sup>1</sup>. Because of the ambiguity between data and Monte-Carlo the PDF for combinatorial background with  $\Sigma_c^0(2520)$  was included nevertheless in the fit for the signal extraction. However, the allowed floating range of the slope in  $m_{inv}$  was limited to a reasonable range, i.e.  $A_{\Sigma_c^0(2520)} \in (-100, 0.)$ , which included the slopes from fits to generic and signal Monte-Carlo events. To ensure that no systematic error was introduced due to the combinatorial background with  $\Sigma_c^0(2520)$ , the fit on data was compared including and excluding the PDF. It was found, that the statistical uncertainty on the  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  yield properly includes the uncertainty combinatorial background with  $\Sigma_c^0(2520)$  resonances.

The following fits to data included the PDF for events from combinatorial background with  $\Sigma_c$  (2520) resonances.

The fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  from data is shown in figure 5.1. The projection onto the  $m_{inv}$  and  $m(\Lambda_c^+\pi^-)$  axes of the difference between data and fit and the bin-wise  $\chi^2$  distribution are given in figure 5.2. The correlation matrix and fit results are given in tables 5.1, 5.2 and 5.3. The scaling variables  $S_{\Sigma_c(2455)}$  and  $S_{\Sigma_c(2520)}$  are equal to the number of events for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  and  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ . The slope parameters  $A_{\Sigma_c(2455,2520)Bkg}$  for combinatorial backgrounds with  $\Sigma_c$  (2455,2520) resonances were allowed to float within (-10, 0).

While the significance of the  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  signal is larger than  $10\sigma$ , the significance for  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  is just about  $3\sigma$ . Supplementary information as the covariance matrix and the fitted PDFs for the signal and background contributions can be found in the appendix section A.12.1. All measured signal mode yields are summarized in table 5.12.

<sup>&</sup>lt;sup>1</sup>The fit was done in  $m_{inv} \in (5.324, 5.38) \text{ GeV}/c^2, m(\Lambda_c^+ \pi^\pm) \in (2.425, 2.625)$  and  $m_{inv} \in (5.172, 5.228) \text{ GeV}/c^2, m(\Lambda_c^+ \pi^-) \in (2.425, 3.025)$ . The fit excluding the  $\Sigma_c^0(2520)$  combinatorial background PDF converged with:  $\chi^2 = 1384.47, \ nDOF = 1344, \ P(\chi^2) = 0.2160189$ ; The fit including the  $\Sigma_c^0(2520)$  combinatorial background PDF converged with:  $\chi^2 = 1383.53, \ nDOF = 1342, \ P(\chi^2) = 0.21002435$ 

Table 5.1:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : results from fitting data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).)

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$2682.18 / 2586 \rightarrow 0.0917024$
$S_{CombiBkg}$	$5819.47 \pm 2434.26$
$A^{m_{inv}}_{CombiBkq}$	$-0.1724 \pm 0.0020$
$A_{CombiBkq}^{\Lambda_c \pi}$	$2.55 \pm 1.15$
$B_{CombiBkq}^{\Lambda_c \pi}$	$0.44 \pm 0.05$
$S_{\Sigma_c(2455)Bkg}$	$141.5 \pm 24.5$
$A_{\Sigma_c(2455)Bkg}$	$-6.01\pm2.02$
$S_{\Sigma_c(2520)Bkg}$	$62.3 \pm 55.8$
$A_{\Sigma_c(2520)Bkg}$	$-9 \cdot 10^{-10} \pm 4.8$
$S_{\Sigma_{c}(2455)}$	$346.60 \pm 24.19$
$S_{\Sigma_c(2520)}$	$86.82 \pm 27.19$
$S_{NonResSignal}$	$295.72 \pm 660.27$
$\sigma_{NonResSignal}$	$0.0113 \pm 0.0015$
$B_{NonResSignal}$	$4.432 \pm 5.007$
$C_{NonResSignal}$	$0.01 \pm 0.17$

Table 5.2:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Correlation matrix from fitting data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). (Table I, continued in Table II 5.3)

	$S_{CombiBkg}$	$A^{m_{inv}}_{CombiBkq}$	$A^{\Lambda_c \pi}_{CombiBkq}$	$B^{\Lambda_c \pi}_{CombiBkq}$	$S_{\Sigma_c(2455)Bkg}$	$A_{\Sigma_c(2455)Bkg}$	$S_{\Sigma_c(2520)Bkg}$
$S_{CombiBkq}$	1	-0.299212	-0.952508	-0.789442	0.0787813	0.0813054	0.448922
A <sup>m</sup> inv CombiBka		1	0.0295579	0.0212816	0.0126353	-0.158238	-0.0988661
$A_{CombiBkg}^{\Lambda_C \pi}$			1	0.891743	-0.0531976	-0.0292271	-0.457047
$B_{CombiBka}^{\Lambda_c \pi}$				1	0.0922551	0.0210687	-0.363893
$S_{\Sigma_c(2455)Bkg}$					1	0.0825037	0.11471
$A_{\Sigma_c(2455)Bkq}$						1	0.0514818 3
$S_{\Sigma_c(2520)Bkg}$							1
$A_{\Sigma_c(2520)Bkg}$							
$S_{\Sigma_{c}(2455)}$							
$S_{\Sigma_{c}(2520)}$							
$S_{NonResSignal}$							
$\sigma_{NonResSignal}$							
$B_{NonResSignal}$							
$C_{NonResSignal}$							

Table 5.3:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Correlation matrix from fitting data. (Table II, continued from Table I 5.2)

	$A_{\Sigma_c(2520)Bkg}$	$S_{\Sigma_{c}(2455)}$	$S_{\Sigma_{c}(2520)}$	$S_{NonResSignal}$	$\sigma_{NonResSignal}$	$B_{NonResSignal}$	$C_{NonResSignal}$
$S_{CombiBkg}$	0.004901	-0.0323327	-0.112847	-0.298012	-0.0244325	0.299769	0.269711
$A_{CombiBkg}^{m_{inv}}$	0.0158565	-0.00354733	0.0312799	0.00665357	-0.00161225	-0.00693627	-0.00550813
$A_{CombiBkq}^{\Lambda_c \pi}$	-0.0113629	0.0320841	0.110624	0.291509	0.0159389	-0.298191	-0.29272
$B_{CombiBkq}^{\Lambda_c \pi}$	-0.0187896	0.0122339	0.0798533	0.192462	0.039943	-0.21027	-0.289155
$S_{\Sigma_c(2455)Bkq}$	-0.00938587	-0.269596	-0.0364099	-0.0604586	0.0271333	0.0565988	0.00324472
$A_{\Sigma_c(2455)Bkg}$	-0.00265459	-0.0245024	-0.0177128	-0.0184405	0.0057641	0.0178121	0.0046033
$S_{\Sigma_c(2520)Bkq}$	0.0149053	-0.0278193	-0.316765	-0.107552	-0.0115334	0.118453	0.12695
$A_{\Sigma_c(2520)Bkg}$	1	0.000119319	-0.00401027	0.0110385	0.00197339	-0.00975351	-0.00208483
$S_{\Sigma_{c}(2455)}$		1	0.0994213	0.160581	-0.0283553	-0.15499	-0.0620143
$S_{\Sigma_{2}(2520)}$			1	0.300601	0.061879	-0.32341	-0.306237
S <sub>Non</sub> ResSignal				1	0.011453	-0.994363	-0.807624
$\sigma_{NonResSignal}$					1	0.0109297	-0.0249891
$B_{NonResSignal}$						1	0.859492
$C_{NonResSignal}$							1



Figure 5.1: Fit for  $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  in data: plots from top - down: data distribution, difference between data and fit, bin-wise  $\chi^2$  distribution. The projection of the difference and bin-wise  $\chi^2$  distributions onto the axes is shown in figure 5.2



Figure 5.2: Fit for  $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  in data: upper row: projections onto  $m(\Lambda_c^+\pi^-)$  and  $m_{inv}$  of the difference between data and fit, lower row: projection of the bin-wise  $\chi^2$  residuals onto the axes in the signal ranges, i.e. the bin-wise sums along the projections of the  $\chi^2$  distribution in the signal region.

## 5.1.2 Fit for $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ in data

The  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane was fitted with PDFs for contributions from:

- signal events from  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$
- signal events from  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$
- non- $\Sigma_c^{++}(2455,2520) \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$
- combinatorial background
- combinatorial background with  $\Sigma_c^{++}(2455)$
- combinatorial background with  $\Sigma_c^{++}(2520)$
- background from  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$
- background from  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$

Both signal decays in the  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane were significant with more than  $10\sigma$  each. Both measured  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  signal yields were significantly larger than their  $\Sigma_c^0$  counterparts. The distribution in data, the differences between data and fit and the bin-wise  $\chi^2$  distribution are shown in figure 5.3. The projections onto the axes of the difference and of the  $\chi^2$ -distribution are given in figure 5.4. The fitted PDFs are shown in figures A.68 and A.69. The correlation and covariance matrices are given in tables 5.5 and A.29, the fit results are given in table 5.4. The scaling variables  $S_{\Sigma_c(2455)}$  and  $S_{\Sigma_c(2520)}$  are equal to the number of events for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  and  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ . The slope parameters  $A_{\Sigma_c(2455,2520)Bkg}$  for combinatorial backgrounds with  $\Sigma_c$  (2455,2520) resonances were allowed to float within (-10, 0). Supplementary information as the fitted PDFs can be found In appendix section A.12.2.

All measured signal mode yields are summarized in table 5.12.

Table 5.4:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : results from fitting data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$2592.14 / 2585 \rightarrow 0.45682$
$S_{CombiBkg}$	$10134.1 \pm 1864.6$
$A^{m_{inv}}_{CombiBkq}$	$-0.1751 \pm 0.0016$
$A_{CombiBkg}^{\Lambda_c \pi}$	$1.8\pm0.7$
$B_{CombiBkq}^{\Lambda_c \pi}$	$0.375 \pm 0.051$
$S_{\Sigma_c(2455)Bkg}$	$105.69 \pm 25.17$
$A_{\Sigma_c(2455)Bkg}$	$-3.99\pm3.16$
$S_{\Sigma_c(2520)Bkg}$	$181.5\pm52.5$
$A_{\Sigma_c(2520)Bkg}$	$-8.75313 \pm 7 \cdot 10{-7}$
$S_{\Sigma_c(2455)}$	$722.6\pm32.3$
$S_{\Sigma_c(2520)}$	$458.2 \pm 38.2$
$S_{NonResSignal}$	$402.03 \pm 129.42$
$\sigma_{NonResSignal}$	$0.0178 \pm 0.0035$
$C_{NonResSignal}$	$0.04 \pm 0.12$
$S_{\Sigma_c(2455)^+}$	$164.4\pm104.3$
$S_{\Sigma_{c}(2520)^{+}}$	$272.8 \pm 132.7$

Table 5.5:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Correlation matrix from fitting data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). (Table I, continued in Table II 5.6)

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A^{\Lambda_c \pi}_{CombiBkg}$	$B^{A_c\pi}_{CombiBkg}$	$S_{\Sigma_c(2455)Bkg}$	$A_{\Sigma_c(2455)Bkg}$	$S_{\Sigma_c(2520)Bkg}$	$A_{\Sigma_c(2520)Bkg}$
$S_{CombiBkg}$	1	0.140121	-0.793665	-0.487329	0.0352337	-0.243593	0.0924304	-0.240287
$A_{CombiBkq}^{m_{inv}}$		1	-0.667469	-0.652709	-0.0733101	-0.181161	0.408922	-0.0230757
$A^{A_c\pi}_{CombiBkq}$			1	0.852743	0.0559877	0.259124	-0.31871	0.174083
$B_{CombiBka}^{\Lambda_c \pi}$				1	0.200607	0.191507	-0.258283	0.0773143
$S_{\Sigma_c(2455)Bkq}$					1	0.140782	0.180813	0.0567679
$A_{\Sigma_c(2455)Bkg}$						1	-0.0532042	0.187362
$S_{\Sigma_c(2520)Bkg}$							1	-0.00123184
$A_{\Sigma_c(2520)Bkg}$								1
$S_{\Sigma_{c}(2455)}$								
$S_{\Sigma_{c}(2520)}$								
$S_{NonResSignal}$								
$\sigma_{NonResSignal}$								
$C_{NonResSignal}$								
$S_{\Sigma_{c}(2455)}+$								
$S_{\Sigma_{c}(2520)}+$								

Table 5.6:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Correlation matrix from fitting data. (Table II, continued from Table I 5.5)

	$S_{\Sigma_{c}(2455)}$	$S_{\Sigma_c(2520)}$	$S_{NonResSignal}$	$\sigma_{NonResSignal}$	$C_{NonResSignal}$	$s_{\Sigma_{c}(2455)}+$	$s_{\Sigma_{c}(2520)}+$
$S_{CombiBkg}$	0.166656	-0.00278244	0.275692	-0.0264021	0.177165	-0.0841411	-0.349194
$A_{CombiBka}^{m_{inv}}$	0.0658532	-0.0725321	0.131402	0.175195	0.0396243	-0.461579	-0.0166313
$A_{CombiBkg}^{\Lambda_c \pi}$	-0.167888	0.0502756	-0.355995	-0.0772002	-0.229326	0.340329	0.234271
$B_{CombiBka}^{\Lambda_C \pi}$	-0.137889	0.0141262	-0.318486	-0.0655927	-0.258109	0.460454	0.236561
$S_{\Sigma_c(2455)Bkq}$	-0.278635	-0.0574393	-0.00069141	-0.0906375	-0.0109643	0.150866	0.0104686
$A_{\Sigma_c(2455)Bkg}$	-0.108655	-0.0159975	-0.0300566	-0.0888157	0.0221075	0.00133686	0.305288
$S_{\Sigma_c(2520)Bkq}$	0.0450285	-0.333863	0.21321	-0.0267658	0.124965	-0.111403	-0.0694988
$A_{\Sigma_c(2520)Bkg}$	-0.166778	0.0346489	-0.0969793	-0.0440053	-0.0422329	-0.0635032	0.212998
$S_{\Sigma c}(2455)$	1	0.141084	0.050437	0.0457841	0.110402	-0.0944863	-0.0330312
$S_{\Sigma_{c}(2520)}$		1	-0.266998	0.208547	-0.130905	-0.0188504	-0.131481
S <sub>Non</sub> ResSignal			1	0.164263	0.848534	0.153489	-0.0641793
$\sigma_{NonResSignal}$				1	-0.166765	-0.209136	-0.155296
$C_{NonResSignal}$					1	0.256905	-0.0208581
$S_{\Sigma_{c}(2455)}+$						1	-0.16491
$S_{\Sigma_{c}(2520)}^{+}$							1



Figure 5.3: Fit for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  in data: plots from top - down: data distribution, difference between data and fit, bin-wise  $\chi^2$  distribution. The projection of the difference and bin-wise  $\chi^2$  distributions onto the axes is shown in figure 5.4



Figure 5.4: Fit for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  in data: upper row: projections of the difference between data and fit onto the axes, lower row: projection of the bin-wise  $\chi^2$  residuals onto the axes in the signal ranges, i.e. the bin-wise sums along the projections of the  $\chi^2$  distribution in the signal region.

## 5.1.3 Determination of non- $\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ events in data

The signal yield for decays into the four-body final state without intermediate  $\Sigma_c^{\uparrow \uparrow}$  (2455,2520) resonances was measured in an one-dimensional fit to the invariant mass  $m_{inv}$ . It was not feasible to extract the total signal yield of non- $\Sigma_c$  signal events from the fits in the  $m_{inv}$ :m  $(\Lambda_c^+\pi^+)$  and  $m_{inv}$ :m  $(\Lambda_c^+\pi^-)$  planes. While both fits in the  $m_{inv}$  :m  $(\Lambda_c^+\pi^+)$  and  $m_{inv}$ :m  $(\Lambda_c^+\pi^-)$  planes gave yields for the corresponding non- $\Sigma_c$  signal contribution, the two measured non- $\Sigma_c$  signal yields are correlated.

Both planes overlap and share partly the same non- $\Sigma_c$  signal events. Also both isospin modes contribute as mutual cross-feed as non- $\Sigma_c$  signal events. For illustration, see in figure 5.5(a) the sketch of the  $m(\Lambda_c^+\pi^+):m(\Lambda_c^+\pi^-)$  plane. The red hatched regions mark the fit ranges in  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ , both overlap for  $m(\Lambda_c^+\pi^+) < 2.625 \text{ GeV}/c^2$  and  $m(\Lambda_c^+\pi^-) < 2.625 \text{ GeV}/c^2$ .

Thus, the total non- $\Sigma_c$  signal yield was extracted in an one-dimensional fit to the  $m_{inv}$  distribution. The signal PDF in  $m_{inv}$  was a Double-Gaussian with one mean

$$\mathcal{G}_{2}(x; N, \mathcal{R}_{1,2}, \mu_{1}, \sigma_{1}, \sigma_{2}) = N \cdot \left(\frac{1 - \mathcal{R}_{1,2}}{\sigma_{1}\sqrt{2 \cdot \pi}} \exp\left(-\frac{1}{2} \frac{(x - \mu_{1})^{2}}{\sigma_{1}^{2}}\right) + \frac{\mathcal{R}_{1,2}}{\sigma_{2}\sqrt{2 \cdot \pi}} \exp\left(-\frac{1}{2} \frac{(x - \mu_{1})^{2}}{\sigma_{2}^{2}}\right)\right)$$
(5.1)

and the combinatorial background was described with a first order polynomial.

Since the resonant modes  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ ,  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  have the same signal shape in  $m_{inv}$  as non- $\Sigma_c$  decays, they had to be removed. In principle, the measured yields of  $\Sigma_c^{++}(2455,2520)$  signal decays could simply be subtracted from the total signal yield in  $m_{inv}$ .

However, peaking backgrounds from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  could not be taken into account by such a subtraction of their number of events, since in  $m_{inv}$  the shapes from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  differ from the signal event shape.

#### 5.1.3.1 $m_{inv}$ sub-division in regions $I_{\Sigma_c}$ and $II_{\Sigma_c}$

The resonant decays  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  were removed by excluding each  $\Sigma_c^{++}(2455, 2520)$  signal region (see table 3.8).

Furthermore, for the following efficiency correction it was necessary to extract the yield in two phase space regions:

- region  $I_{\Sigma_c}$ : containing the fitted two-dimensional ranges  $m(\Lambda_c^+\pi^-) < 2.625 \,\text{GeV}/c^2$  and  $m(\Lambda_c^+\pi^+) < 2.625 \,\text{GeV}/c^2$ . To vetoe resonant decays, the  $\Sigma_c^{++}$  (2455,2520) signal regions, given in table 3.8, were excluded. The separation in the to regions is outlined in figure 5.5(b) with the vetoes on the resonant decays marked as stripes.
- region  $II_{\Sigma_c}$  with  $m\left(\Lambda_c^+\pi^-\right) \geq 2.625 \,\text{GeV}/c^2$  and  $m\left(\Lambda_c^+\pi^+\right) \geq 2.625 \,\text{GeV}/c^2$

The sub-division was applied, since the  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  background contributions were measured with a large uncertainty and would contribute only in region  $I_{\Sigma_c}$ . Also the overall contribution of non- $\Sigma_c$  signal decays is small in region  $I_{\Sigma_c}$  lying near the phase space borders in  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ . Thus, the main amount of non- $\Sigma_c$  decays in region  $I_{\Sigma_c}$  could be measured and efficiency corrected without the need for an extensive correction.

#### 5.1.3.2 $m_{inv}$ fit in region $I_{\Sigma_c}$

While the signal yields for  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  were measured in  $m_{inv}:m(\Lambda_c^+\pi^+)$ , only a fraction of ~ 3% of these events contribute to  $m_{inv}$  in region  $I_{\Sigma_c}$  with vetoes on the  $\Sigma_c^{0}$  (2455,2520) signal regions. To take the contributions from these events to region  $I_{\Sigma_c}$  into account, it was necessary to include

their distributions in the description of  $m_{inv}$  in region  $I_{\Sigma_c}$ .

The shapes from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  were determined in Monte-Carlo and added as PDFs to the one-dimensional fit in  $m_{inv}$ . The contributions from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  were fixed to the measured yields from the previous fit to the  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane.

A double-Gaussian with two independent means was used to describe the shape of  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^$ in the  $m_{inv}$  distribution

$$\mathcal{G}_{2}(x; N, \mathcal{R}_{1,2}, \mu_{1}, \mu_{2}, \sigma_{1}, \sigma_{2}) = N \cdot \left(\frac{1 - \mathcal{R}_{1,2}}{\sigma_{1}\sqrt{2 \cdot \pi}} \exp\left(-\frac{1}{2}\frac{(x - \mu_{1})^{2}}{\sigma_{1}^{2}}\right) + \frac{\mathcal{R}_{1,2}}{\sigma_{2}\sqrt{2 \cdot \pi}} \exp\left(-\frac{1}{2}\frac{(x - \mu_{2})^{2}}{\sigma_{2}^{2}}\right)\right)$$
(5.2)

For  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  a single Gaussian was used as PDF. Fits to  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  events from the Monte-Carlo simulation are shown in figure 5.6; the fit results are given in table 5.7.

Since the measured numbers of events were not significant  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ , three fits were performed to estimate the maximal and minimal contributions from these) backgrounds. One fit was done excluding the  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  PDFs, i.e. assuming no contributions. The main fit was performed including the  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  PDFs. Here, the shape parameters were fixed to the values obtained from Monte-Carlo (table 5.7). The numbers of events were fixed to the yields obtained from fitting  $m_{inv}:m(\Lambda_c^+\pi^+)$  in data (table 5.12) with respect to the  $\Sigma_c^{++}$  (2455,2520) vetoes: in Monte-Carlo the constraint on region  $I_{\Sigma_c}$  including  $\Sigma_c^{+0}$  (2455,2520) vetoes reduced the number of events from  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  by 0.528 ± 0.011 and the number of events from  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^$ by 0.475 ± 0.004. Because of the large uncertainty on the  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  yields a third fit was performed including the PDFs for  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  with fixed shape parameters while the numbers of events were overestimated by a factor of two.

The fits are shown in figure 5.7; solid lines represent the fit with fixed  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  PDFs and dashed lines represent the fit without. The fit results are shown in table 5.8. The covariance matrix for fitting signal and combinatorial background including fixed  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  PDFs is given in table 5.9.

The signal yields  $N^{Signal}$  are consistent within their uncertainties. The  $N^{Signal}$  signal yields from the fits with under- and overestimated  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  constributions vary both as expected by sim40 events below and above the yield obtained from fitting with  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  PDFs scaled according to the fit results from  $m_{inv}:m(\Lambda_c^+\pi^+)$ . The larger deviance was assumed as systematic uncertainty on the  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  constributions.

$$N_{I_{\Sigma_c}}^{m_{inv}} = 809.79 \pm 88.03 \pm 38.11_{B^- \to \Sigma_c^+ \overline{p}\pi^-}$$
(5.3)

#### 5.1.3.3 $m_{inv}$ fit in region $II_{\Sigma_c}$

Since no peaking background was expected, the signal extraction in  $m_{inv}$  for events from region  $II_{\Sigma_c}$  was done using as PDFs a Double-Gaussian for signal and a first order polynomial for background. The fit is shown in figure 5.8 with fit results given in tables 5.10 and 5.11.

Table 5.13 sums up the two non- $\Sigma_c$  signal yields without efficiency correction.



Figure 5.5: non- $\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ : division of the  $m(\Lambda_c^+ \pi^+):m(\Lambda_c^+ \pi^-)$  plane for the signal yield measurement in  $m_{inv}$ . The left ploz (a) shows the general division in regions  $I_{\Sigma_c}$  and  $II_{\Sigma_c}$  as hatched areas; the right plot (b) marks the vetoes against  $\Sigma_c^{0}$  (2455, 2520) resonances as green bands.

Table 5.7: Fit results for fitting the  $m_{inv}$  distribution from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  signal Monte-Carlos in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $I_{\Sigma_c}$ .

Parameter	$B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$	$B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$255.228/294 \to 0.95025$	$351.25/297 \rightarrow 0.016579$
$N^{Signal}$	$40555.3 \pm 867.8$	$35499.9 \pm 262.6$
$\mu^{Signal}$	$5.2949 \pm 0.0023$	$5.2787 \pm 0.0008$
$\sigma_1^{Signal}$	$0.0461\pm0.003$	$0.0996 \pm 0.0010$
$\mu_2^{Signal}$	$5.3542 \pm 0.007$	
$\sigma_2^{Signal}$	$0.105 \pm 0.006$	
$\mathcal{R}_{1,2}$	$0.750 \pm 0.041$	



Figure 5.6: Fits to  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  signal Monte-Carlo in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $I_{\Sigma_c}$ . The left plot (a) shows  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  fitted with a ouble Gaussian; the right plot (b) shows  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  fitted with a single Gaussian



Figure 5.7: Fit to the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $I_{\Sigma_c}$  with excluded  $\Sigma_c^{+,+}$  (2455,2520) bands. Solid lines represent the fit including PDFs for  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$  background with fixed parameters; dashed lines represent the fit including only signal and combinatorial background.

Table 5.8: Fit results for fitting the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  fit region  $I_{\Sigma_c}$  without  $\Sigma_c^{++}(2455,2520)$  bands. Three fits were performed to estimate the systmatic uncertainty of the  $\Sigma_c^+$  contribution, due to their large uncertainty. The first fit was performed excluding  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$  PDFs. The second fit was performed including background from  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$  with fixed PDF parameters. The third fit was repeated with  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$  PDFs while the number of  $\Sigma_c^+$  events was overestimated by a factor of 2. The covariance matrix from fitting with  $\Sigma_c^+$ -PDFs is given in table 5.9. The fits are shown in figure 5.7.

Parameter	w/o $\Sigma_c^+$ PDFs	with $\Sigma_c^+ \mathbf{PDFs}$	with $\Sigma_c^+ \mathbf{PDF} \times 2$
$N_{\mathrm{fixed}}^{\Sigma_c^+(2455)}$	-	86.75	173.49
$N_{\mathrm{fixed}}^{\Sigma_c^+(2520)}$	-	129.63	259.27
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$213.08/201 \rightarrow 0.26634$	$213.799/201 \rightarrow 0.255152$	$214.624/201 \rightarrow 0.242653$
$Slope^{Bkg}$	$-2.19\pm0.22$	$-2.34\pm0.23$	$-2.50\pm0.23$
$N^{Bkg}$	$6085.4 \pm 117.0$	$5904.6 \pm 114.07$	$5721.2 \pm 111.5$
$N^{Signal}$	$847.9 \pm 91.5$	$809.79 \pm 88.03$	$773.5 \pm 84.7$
$\mu^{Signal}$	$5.2776 \pm 0.0012$	$5.2776 \pm 0.0012$	$5.2776 \pm 0.0012$
$\sigma_1^{Signal}$	$0.009 \pm 0.003$	$0.009 \pm 0.003$	$0.009\pm0.003$
$\sigma_2^{Signal}$	$0.021\pm0.006$	$0.020 \pm 0.006$	$0.019\pm0.006$
$\mathcal{R}_{1,2}$	$0.62\pm0.27$	$0.6 \pm 0.3$	$0.6 \pm 0.4$

Table 5.9: Covariance matrix for fitting the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  fit region  $I_{\Sigma_c}$  without  $\Sigma_c^{0}(2455,2520)$  bands and including background PDFs for  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$ . The  $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$  shape parameters were fixed to Monte-Carlo values (table 5.7), the number  $\Sigma_c^+$  of events were fixed to the scaled number from the two-dimensional fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  in data with respect to the  $\Sigma_c$  (2455,2520) vetoes (table 5.12). Fit results are given in the middle column in table 5.8. The fit is shown in figure 5.7.

	$Slope^{Bkg}$	$N^{Bkg}$	$N^{Signal}$	$\mu^{Signal}$	$\sigma_1^{Signal}$	$\sigma_2^{Signal}$	$N_{1}/N_{2}$
$SlopeBkg$ $N^{Bkg}$ $N^{Signal}$ $\sigma_{1}^{Signal}$ $\sigma_{2}^{Signal}$ $N_{1}/N_{2}$	0.0510119	2.5461 13010.7	-1.2041 -6907.31 7749	-4.0976e-05 0.012647 -0.0136597 1.4326e-06	-3.82456e-05 -0.0221261 0.0213197 7.94167e-07 9.68922e-06	-9.57196e-05 -0.282303 0.281921 -2.76057e-07 1.13442e-05 3.75032e-05	0.00343327 1.88046 -1.79815 -5.13865e-05 -0.000837812 -0.00140454 0.0919569

Table 5.10: Covariance matrix for fitting the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $II_{\Sigma_c}$ .

	$Slope^{Bkg}$	$Offset^{Bkg}$	$N^{Signal}$	$\mu^{Signal}$	$\sigma_1^{Signal}$	$\sigma_2^{Signal}$	$\mathcal{R}_{1,2}$
$SlopeBkg$ $OffsetBkg$ $NSignal$ $\mu$ Signal $\sigma_{1}$ Signal $\sigma_{2}$ Signal $\sigma_{2}$ R12	0.0177838	0.515973 20617.3	-0.0369647 -6520.14 8214.2	-1.61911e-06 0.000890667 -0.00137721 8.77946e-08	2.34267e-06 -0.0794298 0.0824991 -1.22188e-08 4.0664e-06	1.88142e-06 -0.00394282 0.00524447 -9.82768e-09 7.39495e-07 3.8117e-07	$\begin{array}{c} 0.000218041\\ 0.0631312\\ 0.265082\\ -5.33921e-07\\ 0.000179095\\ 6.46378e-05\\ 0.0147711 \end{array}$

Table 5.11: Fit results for fitting the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $II_{\Sigma_c}$ .

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$190.076 \ / \ 201 \rightarrow 0.699037$
$Slope^{Bkg}$	$-1.46\pm0.13$
$N^{Bkg}$	$14218.9 \pm 143.6$
$N^{Signal}$	$1918.3\pm90.6$
$\mu^{Signal}$	$5.2767 \pm 0.0003$
$\sigma_1^{Signal}$	$0.0123 \pm 0.0020$
$\sigma_2^{Signal}$	$0.0051 \pm 0.0006$
$\mathcal{R}_{1,2}$	$0.51\pm0.12$



Figure 5.8: Fit to the  $m_{inv}$  distribution from data in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  fit region  $II_{\Sigma_c}$ .

Table 5.12: Measured signal yields of resonant  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  modes without efficiency corrections applied.

Decay	Signal Yield
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	$346.6\pm24.2$
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	$86.8\pm27.2$
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	$722.6\pm32.3$
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	$458.2\pm38.2$
$B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$	$164.4\pm104.3$
$B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$	$272.8 \pm 132.7$

Table 5.13: Measured signal yields of non- $\Sigma_c$  contributions to  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without efficiency corrections applied for the sub-regions  $I_{\Sigma_c}$  and  $II_{\Sigma_c}$  as shown in figures 5.1.3.3.

Region	Signal Yield
$I_{\Sigma_c}$	$809.79 \pm 88.03 \pm 38.11_{B^- \to \Sigma_c^+ \overline{p} \pi^-}$
$II_{\Sigma_c}$	$1918.30 \pm 90.63$

## 5.1.4 Dalitz distribution from $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$

Since the background contribution is small near the  $m(\Lambda_c^+\pi^\pm)$  phase space borders (see for example distributions from signal and from side bands at small  $m(\Lambda_c^+\pi^+)$  in figure 3.8), the Dalitz distributions [65] of  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  could be studied for further resonances or correlations without being affected significantly by background.

Since the  $\Sigma_c^{++}(2520)$  resonance in  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  is more broad and since the background contribution in the  $\Sigma_c^{++}(2520)$  signal region is larger than for the  $\Sigma_c$  (2455) resonance, Dalitz distributions for  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  were not feasible. The same holds for the  $\Sigma_c^0(2520)$  resonance in  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  which in addition was not significant. As alternative, the  ${}_s\mathcal{P}lot$  projections of the Bdaughter invariant masses  $m\left(\Sigma_c^{++}(2520)\overline{p}\right), m\left(\Sigma_c^{+++}(2520)\pi^+\right)$  and  $m\left(\overline{p}\pi^{-}\right)$  were be studied and are given in section 6.2.1.2. However, correlations in the Dalitz plane are lost in the  ${}_s\mathcal{P}lot$  projection onto the invariant masses.

### 5.1.4.1 Dalitz distribution from $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$

To select  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  events, they had to be within the  $m(\Lambda_c^+\pi^+)$  signal region for  $\Sigma_c$  (2455) (table 3.8) and in the  $m_{\rm ES}:m_{inv}$  signal region (table 3.6).

Figure 5.9 shows the Dalitz plot for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  (including about ~  $109 \pm 6$  background events, i.e. ~ 15%, remaining in the signal regions).

In  $m(\Sigma_c^{++}(2455)\pi^-)$  two bands appear at  $\sim [2.6 \text{ GeV}/c^2]^2 \approx 6.8 \text{ GeV}^2/c^4$  and  $\sim [2.9 \text{ GeV}/c^2]^2 \approx 8.4 \text{ GeV}^2/c^4$ . This suggests two body cascades  $\overline{B}^0 \to \Lambda_c^{+*}\overline{p}$ ;  $\Lambda_c^{+*} \to \Sigma_c^{++}(2455)\pi^-$ . The lower band could consists of  $\Lambda_c^+$  resonances  $\Lambda_c^{+*}(2595)$  or  $\Lambda_c^{+*}(2625)$  (for  $\Lambda_c^{+*}(2625)$  no decay cascades via  $\Sigma_c$  resonances have been seen but only direct three body decays  $\Lambda_c^{+*}(2625) \to \Lambda_c^{+}\pi^+\pi^-$ ). The upper band of heavier  $\Lambda_c^+$  resonances could consist of  $\Lambda_c^{+*}(2880)$  or  $\Lambda_c^{+*}(2940)$  resonances. In the projections in figure 5.10 these intermediate states appear as structures at the phase space border and as structure around  $m(\Sigma_c^{++}(2455)\pi^-) \sim 2.9 \text{ GeV}/c^2$ . The remaining events with  $m(\Sigma_c^{++}(2455)\pi^-) > 3 \text{ GeV}/c^2$  populate mainly the right hemisphere in  $m(\overline{p}\pi^-)$  with  $m(\overline{p}\pi^-) > 2 \text{ GeV}/c^2$ .

No structures are visible indicating resonances as  $\overline{\Delta}^{--}(1232, 1600, ..., 1950)$ , which would have width of  $\Gamma_{\overline{\Delta}^{--}(1232,...,1950)} \sim 0.1 \text{ GeV}/c^2 \dots 0.4 \text{ GeV}/c^2$  [4]. The left hemisphere for  $m^2 (\overline{p}\pi^-) < 4 \text{ GeV}^2/c^4$ appears rather unpopulated except for the the  $\Lambda_c^*$  bands. By contrast the upper hemisphere  $m^2 (\overline{p}\pi^-) > 4 \text{ GeV}/c^2$  is more densely populated. In the projections in figure 5.11 a structure could be around  $m(\overline{p}\pi^-) \sim 1.4 \text{ GeV}/c^2$ , which could be interpreted as a projection onto  $m^2 (\overline{p}\pi^-)$  of the  $\Lambda_c^*$  events in  $m^2 (\Sigma_c^{++}(2455)\pi^-)$ , which are accumulated in the down left corner of the Dalitz plot 5.1.4.1. Also for the *narrow structure* of 3-4 bins around  $m(\overline{p}\pi^-) \sim 2.1 \text{ GeV}/c^2$  no fitting baryon  $\overline{X}^{--}$  is known and it is probably a fluctuation or threshold effect.

For  $m(\Sigma_c^{++}(2455)\overline{p})$  as in the side band subtracted  $m(\Sigma_c^{++}(2455)\overline{p})$  projection in figure 5.11 the two separated regions are visible with a gap at ~ 3.9 GeV/ $c^2$ . The first structure could point to a *threshold* enhancement as seen in other decays (see section 1.3.2). The broader second section seems to be separated and more phase space like.

The Dalitz structures could be interpreted in a way that  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  can be produced in two distinct mechanisms:

- 1. either a cascade from an initial two body state  $\overline{B}^0 \to \Lambda_c^* \overline{p}$  with the  $\pi^-$  produced in the  $\Lambda_c^* \to \Sigma_c^{++}(2455)\pi^-$  decay.
- 2. or an original initial three body state where the pion is emitted before the initial baryon-antibaryon state has further *baryonized*, i.e. hadronization into the final state baryons, or, i.e. the meson is not the product of an initial baryon.

The meson could be *radiated* from the initial quark-antiquark arrangement. Such a *meson-cooling* would result for the baryon-antibaryon initial state to be in a lower momentum region, which would

lead to the baryon-antibaryon-pair settling at smaller baryon-antibaryon-masses, i.e. a threshold enhancement



Figure 5.9:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : Dalitz plot in  $m^2(\overline{p}\pi^-)$ :  $m^2(\Sigma_c^{++}(2455)\pi^-)$ . Events are from the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^{++}(2455)$  signal region in  $m(\Lambda_c^+\pi^+)$ ; combinatorial background and other  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  signal events in the  $\Sigma_c^{++}(2455)$  signal region are not removed.

## **5.1.4.2** Dalitz distribution from $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$

Also for  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  the background contribution is reasonable low in the  $m_{inv}:m_{\rm ES}$  and  $\Sigma_c^0(2455)$  signal regions allowing to study the Dalitz plots. Compared to  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  in the previous section 5.1.4.1  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  behaves quite different.

In the Dalitz plot in figure 5.13 the deviation from a uniform distribution are obvious. Similar to  $\Sigma_c^{++}(2455)$  in  $m \left(\Sigma_c^0(2455)\pi^+\right)^2$  bands are visible around ~  $6.8 \,\mathrm{GeV}^2/c^4$  and probably around ~  $8.4 \,\mathrm{GeV}^2/c^4$  pointing to excited  $\Lambda_c^+$  baryons as  $m \left(\Lambda_c^{+*}(2595, 2625)\right)^2 \approx 6.8 \,\mathrm{GeV}^2/c^4$  or  $m\left(\Lambda_c^{+*}(2880,2940)\right)^2 \approx 8.4 \,\text{GeV}^2/c^4$ . Also in the side band subtracted projection on  $m\left(\Sigma_c^0(2455)\pi^+\right)$ 

in figure 5.1.4.2 these structures appear. In contrast to  $m (\bar{p}\pi^{-})^{2}_{\Sigma_{c}^{++}}$  events in the nucleon-pion invariant mass distribution  $m (\bar{p}\pi^{+})^{2}_{\Sigma_{c}^{0}(2455)}$  are almost limited to the lower hemisphere. Roughly one or two bands appear in mass regions where also excited nucleons or  $\overline{\Delta}$  baryons exist. In figure 5.14 the side band subtracted projection  $m(\overline{p}\pi^+)$  shows clearly that the nucleon-pion invariant masses are limited to masses  $m(\bar{p}\pi^+) \leq 1.8 \,\text{GeV}/c^2$  for decays via  $\Sigma_c^0(2455)$  resonances. However, no clear nucleon resonances or  $\overline{\Delta}$  baryons are obvious. Since the possible excited states have all widths between 0.1 and  $0.4 \,\text{GeV}/c^2$ , more than one baryonic resonance could also overlap or interfere. Note that also possible  $\Lambda_c^{+*}$  resonances would be limited to the lower  $m(\bar{p}\pi^+)$  region in the projection.

Consequently, in the baryon-antibaryon combination  $m\left(\Sigma_c^0(2455)\overline{p}\right)^2$  no obvious enhancement at the phase space border is apparent (see also the side band subtracted projection in figure 5.15). Compared to  $\Sigma_c^{++}(2455)$  in figure 5.11 only the region  $m\left(\Sigma_c^0(2455)\overline{p}\right) > 3.9 \,\text{GeV}/c^2$  is populated similar while the



Figure 5.10:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : projections on  $m(\Sigma_c^{++}(2455)\pi^-)$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^{++}(2455)$  signal region in  $m(\Lambda_c^{+}\pi^+)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.



Figure 5.11:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : projections on  $m(\overline{p}\pi^-)$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^{++}(2455)$  signal region in  $m(\Lambda_c^+\pi^+)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.



Figure 5.12:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : projections on  $m(\Sigma_c^{++}2455)\overline{p})$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^{++}(2455)$  signal region in  $m(\Lambda_c^+\pi^+)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.

bump near the phase space border is missing. This could suggest that the mechanism is missing in the  $\Sigma_c^0(2455)$  production, which is responsible for threshold enhancements in other baryonic *B*-decays as the  $\Sigma_c^{++}(2455)$  mode.

Since only regions with potential nucleon resonances in  $m(\overline{p}\pi^+)$  are populated and since an enhancement in the baryon-antibaryon mass is missing, it is reasonable that in  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^+$  the  $\Sigma_c^0(2455)$  is only produced in a baryon-antibaryon initial states. For example, such an initial state could be  $\overline{B}^0 \to \Lambda_c^* \overline{p}$ ,  $\Lambda_c^* \to \Sigma_c^0(2455)\pi^+$  or  $\overline{B}^0 \to \Sigma_c^0(2455)N^{0(*)}$ ,  $N^{0(*)} \to \overline{p}\pi^+$ . From a first order comparison of diagram contributions in section 1.2.4 one can see that  $\overline{B}^0 \to$ 

From a first order comparison of diagram contributions in section 1.2.4 one can see that  $\overline{B}^0 \rightarrow \Sigma_c^0(2455)\overline{p}\pi^+$  cannot be produced via an initial meson-meson-state. Without a real initial meson, that can carry away four-momentum, the baryon-antibaryon cannot be *cooled down* into lower phase space regions. This would leave only the production of a baryon-antibaryon pair back-to-back, ruling out an enhancement near the baryon-antibaryon threshold.



Figure 5.13:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : Dalitz plot in m<sup>2</sup> ( $\overline{p}\pi^+$ ) : m<sup>2</sup> ( $\Sigma_c^{++}(2455)\pi^+$ ). Events are from the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^0(2455)$  signal region in  $m(\Lambda_c^+\pi^+)$ ; combinatorial background and other  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  signal events in the  $\Sigma_c^0(2455)$  signal region are not removed.



Figure 5.14:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : projections on  $m\left(\Sigma_c^0(2455)\pi^+\right)$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^0(2455)$  signal region in  $m\left(\Lambda_c^+\pi^-\right)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.



Figure 5.15:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : projections on  $m(\overline{p}\pi^+)$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c^0(2455)$  signal region in  $m(\Lambda_c^+\pi^-)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.



Figure 5.16:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : projections on  $m\left(\Sigma_c^02455\right)\overline{p}\right)$  for events in the  $m_{inv}:m_{\rm ES}$  signal region and within the  $\Sigma_c \ 0(2455)$  signal region in  $m\left(\Lambda_c^+\pi^-\right)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band subtraction.

## 5.2 Signal event distributions from $_{s}\mathcal{P}lots$

While a simple background subtraction is able to remove continuous combinatorial background, it cannot remove peaking background, e.g. non- $\Sigma_c$  events  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  that appear as peaking background to the resonant modes. Consequently, the more elaborate  ${}_s\mathcal{P}lot$ -technique was used to extract the distribution of *pure* signal events from the fitted data [16].

Conceptually, it is similar to a side-band subtraction. The method generates weights, called  ${}_{s}Weights$ , for each event, under the assumption of knowing the shapes of all contributing signal and background types (*signal classes*). The weights are a measure of the probability for an event to belong to a specific signal class. For each signal class its distribution in a specific variable can be generated by weighting each event with the corresponding signal class weight. Obviously, the  ${}_{s}\mathcal{P}lot$ -technique can only provide histograms.

An introduction to the  $_{s}\mathcal{P}lot$ -technique can be found in the appendix in section A.13.1.

#### 5.2.1 $_{s}\mathcal{P}lotted$ distributions

For each resonant decay and the non- $\Sigma_c$  (2455,2520) signal events  ${}_s\mathcal{P}lot$  distributions were generated based on the previous fits to data. The fit results from each fit can be found in the appendix section A.13.2.

### 5.2.1.1 Events from $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$

The three body decays  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  can be studied in a two-dimensional Dalitz plot [65], which include background from non- $\Sigma_c^0(2455, 2520)$  signal events, as shown in the previous section 5.1.4.2. To remove also these backgrounds  ${}_s\mathcal{P}lots$  were drawn. Since the number of events from  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  were not sufficient for producing a meaningful two-dimensional Dalitz histogram, the projections (after extracting the roots) were used, i.e. the signal distributions in the three invariant masses  $m(\Lambda_c^+\overline{p}\pi^{\pm}), m(\overline{p}\pi^{\mp})$  and  $m(\Lambda_c^+\pi^-\pi^+)$ . This was done to retrieve some of the total information of the two-dimensional Dalit space:

For a three-body decay with particles  $p_1$ ,  $p_2$ ,  $p_3$  in the final state, the information about a correlation between  $p_2$ ,  $p_3$  etc. would be lost in the projections onto  $m^{(2)}(p_1, p_2)$  and  $m^{(2)}(p_1, p_3)$ . By adding  $m^{(2)}(p_2, p_3)$  this information is *retrieved*. However, information about further correlations would be still missing and the Dalitz plot would have to be approximated with further combinations of  $p_1$ ,  $p_2$  and  $p_3$ . Figure 5.17 shows the distributions of  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  signal events in the three invariant masses. The distributions are naturally similar to the related side-band subtracted distributions in figures 5.14-5.16 which still contain *peaking* background from  $non-\Sigma_c$  (2455,2520) signal events. In  $m\left([\Lambda_c^+\pi^+]_{\Sigma_c^0(2455)}\overline{p}\right)$ no structure near the phase space border is evident. The  $_s\mathcal{P}lotted m(\overline{p}\pi^+)$  distribution shows the same accumulation of events around ~ 1.5 GeV/ $c^2$  as in the side-band subtracted signal distribution (with respect to the limited statistics and the  $_s\mathcal{P}lot$  uncertainties). In  $m\left([\Lambda_c^+\pi^-]_{\Sigma_c^0(2455)}\pi^+\right)$  an enhancement near the phase space border is visible, which could probably be related to  $\Lambda_c$  (2625) intermediate states; no possible structure is visible for  $\Lambda_c$  (2880) states.

## 5.2.1.2 Events from $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$

Figure 5.18 gives the distributions of  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  signal events in the three invariant masses. Since the  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  signal is not significant, it applies for the  ${}_s\mathcal{P}lot$  distributions as well. In the invariant masses distributions no interpretable structures are evident for  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ .

## 5.2.1.3 Events from $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$

The  ${}_{s}\mathcal{P}lot$ ted distributions for  $\overline{B}{}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$  in figure 5.19 are also similar to the side-band sub-tracted distributions as in figures 5.10-5.12.

The behaviour of  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  differs somewhat from the related decay  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ . As visible in the comparisons of both modes in figure 5.21, especially  $m(\overline{p}\pi^+)_{\Sigma_c^0(2455)}$  differs from  $m(\overline{p}\pi^-)_{\Sigma_c^{++}(2455)}$ . While in  $m(\overline{p}\pi^+)_{\Sigma_c^0(2455)}$  events are limited to masses  $m(\overline{p}\pi^+) < 2 \text{ GeV}/c^2$ , events are more uniformly distributed over the whole allowed phase space for  $m(\overline{p}\pi^-)_{\Sigma_c^{++}(2455)}$ .

Vice versa, in  $m(\Lambda_c^+\overline{p}\pi^-)_{\Sigma_c^0(2455)}$  events do not contribute at the lower phase space border  $m(\Lambda_c^+\overline{p}\pi^-) \lesssim$ 3.8 GeV/ $c^2$ , while the equivalent region is quite populated in  $m(\Lambda_c^+\overline{p}\pi^+)_{\Sigma_c^{++}(2455)}$ . From the difference between  $m(\Lambda_c^+\overline{p}\pi^+)_{\Sigma_c^{++}(2455)}$  and  $m(\Lambda_c^+\overline{p}\pi^-)_{\Sigma_c^0(2455)}$  one could speculate, that the surplus of  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  events to  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  could come mainly from events in  $m(\Lambda_c^+\overline{p}\pi^+)_{\Sigma_c^{++}(2455)} \lesssim$ 3.8 GeV/ $c^2$ . Within the assumptions presented in section 1.2.4, events in  $m(\Lambda_c^+\overline{p}\pi^\pm) \gtrsim$  3.8 GeV/ $c^2$  would be produced by the same mechanism in both decays. This mechanism would be based on baryon-antibaryon initial state diagrams, since only these types can contribute to  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ . Thus, the surplus of events from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  would come from decay mechanisms with meson-meson-like diagrams, which are additionally available.

In  $m(\Lambda_c^+\pi^+\pi^-)_{\Sigma_c^{++}(2455)}$  the surplus of  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  events to  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  distributes without striking structures.

## 5.2.1.4 Events from $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$

The  ${}_{s}\mathcal{P}lot$ ted distributions for  $\overline{B}{}^{0} \to \Sigma_{c}^{++}(2520)\overline{p}\pi^{-}$  are similar to  $\overline{B}{}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$ . Here, only the  ${}_{s}\mathcal{P}lots$  can give insight into the signal event distributions, since a side-band subtraction would have left too much  $non \cdot \Sigma_{c}^{0}(2455, 2520)$  signal events peaking as background.  $m(\overline{p}\pi^{+})_{\Sigma_{c}^{0}(2520)}$  and  $m(\Lambda_{c}^{+}\pi^{+}\pi^{-})_{\Sigma_{c}^{++}(2520)}$  distribute similarly to the distributions from  $\overline{B}{}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$  without striking structures.



Figure 5.17:  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : sPlotted signal distributions in  $m(\Lambda_c^+\overline{p}\pi^-), m(\overline{p}\pi^+)$  and  $m(\Lambda_c^+\pi^-\pi^+)$ .



Figure 5.18:  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : sPlotted signal distributions in  $m(\Lambda_c^+\overline{p}\pi^-), m(\overline{p}\pi^+)$  and  $m(\Lambda_c^+\pi^-\pi^+)$ .



Figure 5.19:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : sPlotted signal distributions in  $m(\Lambda_c^+\overline{p}\pi^+)$ ,  $m(\overline{p}\pi^-)$  and  $m(\Lambda_c^+\pi^-\pi^+)$ .



Figure 5.20:  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : sPlotted signal distributions in  $m(\Lambda_c^+\overline{p}\pi^+)$ ,  $m(\overline{p}\pi^-)$  and  $m(\Lambda_c^+\pi^-\pi^+)$ .



Figure 5.21:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$ : comparison between  $m(\Lambda_c^+\overline{p}\pi^{\pm})$ ,  $m(\overline{p}\pi^{\pm})$  and  $m(\Lambda_c^+\pi^+\pi^-)$  from  ${}_s\mathcal{P}lot$ ted decays  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ .

## 5.2.1.5 Events from non- $\Sigma_c$ (2455,2520) $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ in region $II_{\Sigma_c}$

The measurement of non-resonant signal events, i.e. all decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without intermediate  $\Sigma_c^{++}(2455,2520)$  baryons, was divided into two regions  $I_{\Sigma_c}$  and  $II_{\Sigma_c}$  (see section 5.1.3).  ${}_s\mathcal{P}lots$  were produced for the signal event distributions in the three-body and the two-body invariant masses for the  $\overline{B}^0$ -daughters from  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ .

For events from region  $II_{\Sigma_c}$  the invariant three-body mass distributions in figure 5.2.1.5 show no prominent structures. Shifts from the nominal lower phase space border are due to the cut on region  $II_{\Sigma_c}$ . Negative values at upper phase space borders are remnants of the  ${}_s\mathcal{P}lot$ -technique: on the one hand the  ${}_s\mathcal{P}lot$ -technique is in principle only valid for projecting variables uncorrelated to the discriminating variables, which is not necessarily given for three-body invariant masses from the four-body final state; on the other hand no further physical constraints were taken into account, i.e. the signal *B*-mesons invariant masses are limited while combinatorial background events can have masses beyond  $\frac{\sqrt{s}}{2}$ . However, the  ${}_s\mathcal{P}lot$ -technique 'discriminates' signal and background beyond the *B*-mass constraint.

In figure 5.23(a) with two-body invariant masses the intermediate  $\Sigma_c^{++}(2800)$  resonance is obvious in the  $m(\Lambda_c^+\pi^+)$  distribution.

Contributions from  $\Sigma_c^{++}(2800)$  resonances are visible in the  $m(\Lambda_c^+\pi^+)$  distribution in the upper upper plot of figure 5.23(a). In the  ${}_s\mathcal{P}lotted \ m(\Lambda_c^+\overline{p})$  distribution no structure is visible.

In figure 5.23(b) the non-charmed invariant masses  $m(\overline{p}\pi^+)$  and  $m(\overline{p}\pi^-)$  differ somewhat. In  $m(\overline{p}\pi^-)$  at lower values around ~ 1.4 GeV/ $c^2$  an accumulation of events could be suspected which seems not to be present in  $m(\overline{p}\pi^+)$ . Further structures like hints for nucleon or  $\Delta$  resonances seem not to be present in  $m(\overline{p}\pi^{\pm})$ . In  $m(\pi^+\pi^-)$  statistics are not sufficient to verify the existence of a  $\rho(770)$  resonance.

## 5.2.1.6 Events from non- $\Sigma_c$ (2455,2520) $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ in region $I_{\Sigma_c}$

Since the background contributions from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  were fixed in the fit to the  $m_{inv}$  distribution of events from region *I*, these signal classes were *known* and the fixed yields were taken into account in the  $_sWeight$  calculations. This case is discussed in [16] in appendix *B*.

In figure 5.24 the  ${}_{s}\mathcal{P}lot$ ted distribution of  $m(\Lambda_{c}^{+}\overline{p}\pi^{\pm})$  shows the reflections of the mother  $\overline{B}^{0}$  with the remaining  $\pi^{\mp}$  missing. In both distributions  $m(\Lambda_{c}^{+}\pi^{+}\pi^{-})$  and  $m(\overline{p}\pi^{+}\pi^{-})$  no structures appear that could not be explained by the vetoed  $m(\Lambda_{c}^{+}\pi^{\pm})$  ranges.

Figure 5.25(a) shows the  ${}_{s}\mathcal{P}lots$  of the charmed two-body invariant masses. Due to the constraint on  $m(\Lambda_{c}^{+}\pi^{\pm}) < 2.625 \,\text{GeV}/c^{2}$ , events in  $m(\Lambda_{c}^{+}\pi^{+})$  and  $m(\Lambda_{c}^{+}\pi^{-})$  are mostly limited to this range. The range beyond  $m(\Lambda_{c}^{+}\pi^{\pm}) > 2.625 \,\text{GeV}/c^{2}$  is only populated by events that lie within the  $I_{\Sigma_{c}}$  band of the conjugated  $m(\Lambda_{c}^{+}\pi^{\pm})$  (compare figure 5.5(a)). In the  ${}_{s}\mathcal{P}lot$ ted two-baryon invariant mass no structure or enhancement at the phase space border is apparent.

In the non-charmed invariant masses in figure 5.25(b) enhancements at lower invariant masses are visible. These could prematurely be interpreted as intermediate states with nucleonic or  $\Delta^{--}$  resonances in  $m(\bar{p}\pi^{\pm})$  or  $\rho(770)$  in  $m(\pi^{+}\pi^{-})$ . However in region  $I_{\Sigma_c} m(\Lambda_c^{+}\pi^{+})$  and  $m(\Lambda_c^{+}\pi^{-})$  were constraint to lower masses, i.e. confining the pion momenta to lower values as well. When comparing Monte-Carlo simulated events and data  $_{s}\mathcal{P}lots$  distributions, no significant deviation from each other was visible, that could have indicated  $\rho(770)$  intermediate states. Thus, the *structures* were assumed to be remnants of the pion momenta constraints. Additional information on the comparison between data and Monte-Carlo events can also be found in appendix section A.14.2.

#### 5.2.2 Interpretation

In the baryon-antibaryon invariant mass  $m\left(\Sigma_c^0(2455)\overline{p}\right)$  in figure 5.17 no structure near the phase space border is evident. Here a baryon-antibaryon mass-enhancement can be ruled out, which was seen in other baryonic decays as mentioned in subsection 1.3.2. This is consistent with the assumptions made



Figure 5.22:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $II_{\Sigma_c}$ ):  ${}_s \mathcal{P}lot$ ted signal distributions of three-body *B*-daughter invariant masses.

in section 1.2.4. Following this assumptions the three body final state  $\Sigma_c^0(2455)\overline{p}\pi^+$  can only be reached via a two-baryon initial decay state, i.e. class *B* diagrams. Since no two-meson initial state (class *M*) is possible, both initial baryons are produced back to back. Thus also the final state baryons cannot be concentrated near the baryon-antibaryon phase space border. Possible initial two-baryon states could be  $\overline{B}^0 \to \Lambda_c (2625) \overline{p}$  or  $\overline{B}^0 \to \Sigma_c^0(2455) \overline{N}^*$  (1440, 1520, ...).

In contrast, in the conjugated baryon-antibaryon distribution  $m\left(\Sigma_c^{++}(2455)\overline{p}\right)$  in figure 5.19 a surplus near the phase space border is apparent. Especially in the comparison between the baryon-antibaryon distributions from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^{\mp}$  in figure 5.21 it is striking that the main difference between both modes is the surplus near the phase space border of  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  events. Thus, following the hypothesis in section 1.2.4 one would argue that this surplus of  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  is due to the additional possible class M contributions, i.e. initial three-body decays.

According to this  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  would have contributions from both classes, while  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  would only have contributions from class *B* type diagrams. Especially the accumulation in  $m(\overline{p}\pi^+)_{\Sigma_c^0(2455)}$  around ~ 1.5 GeV/ $c^2$  suggests resonant nucleons as intermediate states; however no conclusion on concrete modes can be drawn here, due to the overlaps of the possible nucleon resonances

in this region<sup>2</sup>. The conjugated distribution  $m(\overline{p}\pi^+)_{\Sigma_c^{++}(2455)}$  does not show such a preference and is more uniformly distributed over the whole available phase space, suggesting also 'non- $\overline{N}^*$ ' contributions. Also around  $m\left(\Sigma_c^0(2455)\pi^+\right) \sim (2.5-2.7) \,\text{GeV}/c^2$  a surplus of events compared to higher values is visible and the contribution is nearly of the same amount as the equivalent distribution  $m(\Sigma_c^{++}(2455)\pi^{-})$ . This could suggest lighter excited  $\Lambda_c^{*+}$  baryons, however the statistic do not allow to discriminate between the known lighter  $\Lambda_c^{*+}(2.595, 2.625)$  here. Here, one has to keep in mind that the number of  $\Sigma_c^0(2455)$ events is just about  $^2/_3$  of  $\Sigma_c^{++}(2455)$  events, which would be able to contribute to  $\Lambda_c^{*+} \to \Sigma_c^{++}(2455)\pi^{\mp}$ intermediate baryons. Interestingly, around  $m\left(\Sigma_{c}^{++}(2455)\pi^{\mp}\right) \sim (2.9-3.0) \,\text{GeV}/c^2$  one could speculate about a surplus for  $\Sigma_c^{++}(2455)$  events compared to  $\Sigma_c^0(2455)$ , which could possibly be linked to heavier excited baryons as  $\Lambda_c^{*+}(2.880, 2.940)$ . (Compare also the Dalitz plots in the previous sections 5.1.4 and 5.1.4.2). Unfortunately, the signal of  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  was not significant making no comparisons to  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  possible. From figure 5.20 from  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^$ intermediate states with resonant nucleons  $\overline{N}^*$  could be ruled out. In the baryon-antibaryon invariant mass distribution  $m\left(\Sigma_c^{++}(2520)\overline{p}\right)$  is similar to the distribution from  $\Sigma_c^{++}(2455)$  events, while the surplus near the allowed phase space border is smaller. Obviously,  $m\left(\Sigma_c^{++}(2520)\overline{p}\right)$  cannot be reached via  $A_c^{*+}(2.595, 2.625)$  baryons, thus one can only speculate about a slight contribution from  $A_c^{*+}(2.880, 2.940)$ in  $m(\Sigma_c^{++}(2520)\pi^{-})$ .

<sup>&</sup>lt;sup>2</sup>Figure A.70 in the appendix section A.13.3 sketches the nominal distributions of nucleon resonances in  $m(\bar{p}\pi^+)$  with an arbitrary scaling.



Figure 5.23:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $II_{\Sigma_c}$ ):  ${}_s \mathcal{P}lot$ ted signal distributions of two-body *B*-daughter invariant masses. The upper plot (a) shows the charmed two-body masses, the non-charmed two-body masses are shown in the lower plot (b).


Figure 5.24:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $I_{\Sigma_c}$ ):  ${}_s \mathcal{P}lot$ ted signal distributions of three-body *B*-daughter invariant masses.



Figure 5.25:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $I_{\Sigma_c}$ ):  ${}_s \mathcal{P}lotted$  signal distributions of two-body *B*-daughter invariant masses. The upper plot (a) shows the charmed two-body masses, the non-charmed two-body masses are shown in the lower plot (b).

## Chapter 6

# Branching ratio determination

#### 6.1 Strategy for the reconstruction efficiency determination

For each resonant signal modes and for the non- $\Sigma_c$  signal decays the efficiency of the reconstruction was determined separately.

Since the resonant signal Monte-Carlo events were generated with a simple phase space model, the natural decay dynamics were not reproduced completely. While the natural masses and widths of the  $\overline{B}^0$ -meson and the  $\Sigma_c^{0}$  (2455,2520) baryons as well as the detector response were reproduced fairly in the Monte-Carlo simulation (with the aforementioned necessary corrections applied), differences between data and Monte-Carlo events were seen in other invariant masses of  $\overline{B}^0$ -daughters as  $m(\overline{p}\pi^{\mp})$  or  $m([\Lambda_c \pi^{\pm}]_{\Sigma_c} \overline{p})$ . For example, compare in figure 6.2 the  $m(\overline{p}\pi^+)$  distribution from data with the corresponding distribution from signal Monte-Carlo  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ . Both distributions were selected from the  $\Sigma_c^0(2455)$  signal region and side-band subtracted; both distribution were scaled to the same integral. While in Monte-Carlo events are distributed uniformly over the available phase space projected onto  $m(\overline{p}\pi^+)$ , the events in data distribute quite differently and are confined mostly to the lower half of  $m(\overline{p}\pi^+)$  (see also section 5.1.4.2). Similarly, Monte-Carlo simulations do not reproduce completely the behaviour in the baryon-antibaryon masses for the decays via the  $\Sigma_c$  (2455) resonances as shown in figure 6.1.

Since events in real data deviate from the naive phase-space model assumption, corrections had to be applied to Monte-Carlo events for calculating the reconstruction efficiencies. Without corrections, effects would be neglected, which depend on the different reconstruction efficiencies in different sections of the phase space, e.g. because of the momentum dependence of the track/particle reconstruction [37]. Especially when events cluster near phase space borders, as in  $m(\bar{p}\pi^+)$  for  $\bar{B}^0 \to \Sigma_c^0(2455)\bar{p}\pi^+$ , the reconstruction efficiency should be influenced perceptibly.

Also, as visible in figure 6.3, the reconstruction efficiencies from signal Monte-Carlo for  $\overline{B}^0 \rightarrow \Sigma_c^{++}$  (2455) $\overline{p}\pi^{\mp}$  distribute not uniformly, which had to be taken into account as well.

Thus, either the efficiency correction had to be performed in bins of data or the Monte-Carlo had to be adapted to the distributions. The correction of the Monte-Carlo events was chosen because of the higher statistics.

Ideally, the Monte-Carlo correction would have to be applied in the whole Dalitz plane. But because of the limited statistics, the invariant masses were used instead of the whole Dalitz plane. To correct Monte-Carlo for a resonant decay, the data distributions of its signal events in the invariant masses of  $\overline{B}^0$ -daughters had to be known, e.g.  $m(\overline{p}\pi^+)$  from  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  signal events.

To remove in data all background contributions the so-called  ${}_{s}\mathcal{P}lot$ -technique was applied [16]. The signal Monte-Carlo events were re-weighted in the distributions and the reconstruction efficiency was measured on the weighted Monte-Carlo events.

For example, the generated signal Monte-Carlo events were weighted along the invariant mass  $m \left( pq \right)^{MC}$ 

with the ratio of  ${}_{s}\mathcal{P}lot$ ted data and the distribution  $\frac{m(pq)^{data}}{m(pq)^{MC}}$  from the Monte-Carlo simulation, thus imposing the distribution in data on Monte-Carlo. The weighting had to be applied to the reconstructed events from Monte-Carlo as well as to the generated Monte-Carlo events. The actual scaling of the weights from data is not an issue, since the efficiency is calculated from the ratio of reconstructed and generated Monte-Carlo; thus, canceling the weights out.



Figure 6.1:  $m(\Lambda_c^+\pi^\pm\overline{p})$ : comparison of signal distribution from Monte-Carlos ( $\circ$ )  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ (a) and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^-$  (b) and from side-band subtracted data ( $\times$ ) with  $m(\Lambda_c^+\pi^\pm)$  in the  $\Sigma_c^{++}(2455)$  signal region. The histograms were scaled to the same integral.



Figure 6.2:  $m(\overline{p}\pi^+)$ : comparison of the signal distribution from Monte-Carlo (•) and from side-band subtracted data (×) with  $m(\Lambda_c^+\pi^\pm)$  in the  $\Sigma_c^0(2455)$  signal region. Both histograms were scaled to the same integral.



Figure 6.3:  $m(\Lambda_c^+\pi^\pm\overline{p})$ : efficiency distributions from Monte-Carlo for  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^- \circ$ and for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+ \checkmark$ .

#### 6.2 Efficiency determination from Monte-Carlo simulated events

## 6.2.1 Reconstruction efficiency for resonant $\overline{B}{}^0 \to \Sigma_c^{+,+} \overline{p} \pi^{\mp}$ decays

The phase-space generated resonant signal Monte-Carlo events were weighted along the invariant masses  $m(\Lambda_c^+ \overline{p} \pi^{\pm})$ ,  $m(\overline{p} \pi^{\mp})$  and  $m(\Lambda_c^+ \pi^- \pi^+)$  to reflect the measured data better. For each invariant mass correction weights w(a b) were calculated from data  ${}_s\mathcal{P}lots$  and the original Monte-Carlo distributions. The weighting was done in 100 MeV/ $c^2$  steps. Each event in the Monte-Carlo sample was weighted and the resulting re-weighted distributions were created in variables other than the discriminating variables  $m_{inv}$  and  $m(\Lambda_c^+ \pi^{\pm})$ . Both, generated and reconstructed Monte-Carlo events were weighted. Thus, the ratio between the re-weighted reconstructed event numbers and the re-weighted generated event numbers gave the corrected reconstruction efficiency.

If a weight was negative, i.e. a negative  ${}_{s}\mathcal{P}lot$  value in data (due to the statistical fluctuation), it was fixed to zero to avoid an unphysical amplification.

To weight along more than one variable, the process was iterated. The *algorithm* proceeded as follows:

#### prerequisites:

- generate signal  ${}_{s}\mathcal{P}lots$  histograms  $\mathcal{N}[m(ab)]_{data}$  for the invariant masses<sup>1</sup> of *B*-daughters  $m(ab)_{data}, \ldots$  from all *N* events with  $\mathcal{N}^{x}[m(ab)] = \sum_{j=1}^{N} {}_{s}\mathcal{W}eight_{j} \cdot 1_{j}^{x}$  in the bin x[m(ab)].
- also necessary are the binned distributions from Monte-Carlo simulated events  $\mathcal{N}[m(ab)]_{MC}^{1}$ .

#### iteration:

- start iteration along m(a b) with initial weights:  $w^{i=1}[m(a b)] = \frac{\mathcal{N}[m(a b)]_{data}}{\mathcal{N}[m(a b)]_{MC}^1}$
- iteratively weight Monte-Carlo along each invariant mass  $m(pq)_{MC}^i$ : i = 1, ..., n, ..., v for the v mass combinations
  - 1. calculate weights for Monte-Carlo along m(pq):  $w_{p,q} = \frac{\mathcal{N}[m(pq)]_{data}}{\mathcal{N}[m(pq)]_{MC}^{n-1}}$
  - 2. weight each Monte-Carlo event with  $w^n = w^{n-1} \cdot w_{p,q}$
  - 3. from the re-weighted Monte-Carlo get histogram  $\mathcal{N}[m(st)]_{MC}^{n}$  for the next iteration step repeat 1-3 for  $m(st)_{MC}$
- after weighting along all invariant masses, calculate re-weighted reconstruction efficiency from the final weighted Monte-Carlo

## 6.2.1.1 Reconstruction efficiency of $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ decays

For example,  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  was weighted in the first step along  $m\left(\Sigma_c^0\overline{p}\right)$  with the weights gained from the  ${}_s\mathcal{P}lot$  data to Monte-Carlo ratio. After re-weighting, the resulting Monte-Carlo distribution in  $m(\overline{p}\pi^+)$  and the data  ${}_s\mathcal{P}lot$  distribution were used to calculate the weights along  $m(\overline{p}\pi^+)$ . The combined weight was calculated with the product of the weights along  $m\left(\Sigma_c^0\overline{p}\right)$  and along  $m(\overline{p}\pi^+)$ . In the next step the resulting  $m\left(\Sigma_c^0\pi^+\right)$  distribution was used to calculate weights along  $m\left(\Sigma_c^0\pi^+\right)$  with the corresponding  ${}_s\mathcal{P}lot$ . For the last iteration step the combined weight was calculated from the product of weights along  $m\left(\Sigma_c^0\pi^+\right)$  and the combined weight of the previous iteration step.

Finally, the reconstruction efficiency in  $m_{inv}$  was calculated from the ratio of the reconstructed and generated events. The number of reconstructed Monte-Carlo events was measured with a fit, while for the number of generated Monte-Carlo events the sum of the weighted values of the generated events was

<sup>&</sup>lt;sup>1</sup>Or other variables, that are convenient and applicable for the Monte-Carlo weighting.

calculated. Table 6.1 gives the reconstruction efficiencies for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  without any weighting, after one-dimensional weightings along just one variable and for correlated weightings. Compared to the unweighted efficiency, the most significant change in the efficiency comes from the weighting along  $m(\overline{p}\pi^+)$ , which is understandable since the accumulation in  $m(\overline{p}\pi^+)$  at lower momenta ~ 1.2 GeV/ $c^2$  is not present in phase-space Monte-Carlo simulation.

Figure 6.4(a) shows the resulting invariant masses after applying weightings along  $m(\Lambda_c^+ \overline{p}\pi^-)$  and following along  $m(\overline{p}\pi^+)$ . Since  $m(\Lambda_c^+ \overline{p}\pi^-)$  was corrected in the first step and re-weighted in the second step, the resulting distribution in  $m(\Lambda_c^+ \overline{p}\pi^-)$  differs slightly compared to the input  $_s\mathcal{P}lot$ . Naturally, the re-weighted  $m(\overline{p}\pi^+)$  Monte-Carlo distribution matches its  $_s\mathcal{P}lot$  input. The distribution in  $m(\Lambda_c^+ \pi^- \pi^+)$  is also weighted with the combined weight  $w(\Sigma_c^{++} \overline{p}) \cdot W(\overline{p}\pi^{\mp})$  and does not match the  $_s\mathcal{P}lot$  distribution from data yet.

The distributions after weighting along  $m(\Lambda_c^+\pi^-\pi^+)$  are shown in figure 6.4(b). The re-weighting of  $m(\Lambda_c^+\overline{p}\pi^-)$  and  $m(\overline{p}\pi^+)$  did not produce significant distortions and the resulting distributions lie within the uncertainties of the  ${}_s\mathcal{P}lots$  except for one bin in  $m(\Lambda_c^+\overline{p}\pi^-)_{4.99 \text{ GeV}/c^2, 5.09 \text{ GeV}/c^2}$ . To test the significance of this deviation, the weighting along all three invariant masses was repeated with the weight for  $m(\Lambda_c^+\overline{p}\pi^-)_{4.99 \text{ GeV}/c^2, 5.09 \text{ GeV}/c^2}$  set to the value of the uncorrelated iteration, so that the Monte-Carlo value complies with the  ${}_s\mathcal{P}lot$  value from data. The resulting distributions are shown in figure 6.4(c). The effects of the constraint weight are insignificant with small changes at lower values in  $m(\Lambda_c^+\pi^-\pi^+)$  and in  $m(\overline{p}\pi^+)$ . The resulting reconstruction efficiency uncertainty is within the statistical uncertainty of the unmodified reconstruction efficiency.

After re-weighting the mass distributions from signal Monte-Carlo match the distributions from data; the determined reconstruction efficiency is

$$\varepsilon_{\overline{B}^0 \to \Sigma^0(2455)\overline{p}\pi^+} = 0.16374 \pm 0.00301$$
(6.1)

Table 6.1:  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : reconstruction efficiencies without and with applying weights from data  ${}_s\mathcal{P}lots, '\times'$  denotes the weighting along the invariant-mass projection.

mode	$m\left(\Lambda_{c}^{+}\overline{p}\pi^{-}\right)$	$m\left(\overline{p}\pi^{+}\right)$	$m\left(\Lambda_c^+\pi^-\pi^+\right)$	ε	figure
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$				$0.1507 \pm 0.0012$	
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	×			$0.1525 \pm 0.0016$	
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$		×		$0.1623 \pm 0.0023$	
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$			×	$0.1548 \pm 0.0021$	
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	×	×		$0.1603 \pm 0.0024$	6.4(a)
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	×	×	×	$0.1637 \pm 0.0030$	6.4(b)
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	$\times_{mod}$	×	×	$0.1617 \pm 0.0026$	6.4(c)

## 6.2.1.2 Reconstruction efficiencies of $\overline{B}{}^0 \to \Sigma_c^0(2520)/\Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\pm}$ decays

The procedures for the other resonant decays were equivalent to the procedure for  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ Monte-Carlo events. Details as figures of the re-weighted Monte-Carlo sets and efficiencies after each weighting can be found in the appendix in section A.14.

The fit result for  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  was not significant and the  ${}_s\mathcal{P}lot$  distribution suffered followingly from random fluctations. To take these fluctations in the  ${}_s\mathcal{P}lots$  into account, a smoothing algorithm was applied to the invariant masses washing out fluctuations between the bins. Negative  ${}_s\mathcal{P}lot$  values were fixeded to zero. The reconstruction efficiency for  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  is

$$\varepsilon_{\overline{B}^0 \to \Sigma^0(2520)\overline{p}\pi^+} = 0.1684 \pm 0.0030$$
(6.2)

For  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  a final reconstruction efficiency was determined of

$$\varepsilon_{\overline{B}{}^0 \to \Sigma_{a}^{++}(2455)\overline{p}\pi^{-}} = 0.1451 \pm 0.0013$$
(6.3)

and for  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  a reconstruction efficiency of

$$\varepsilon_{\overline{B}^0 \to \Sigma_a^{++}(2520)\overline{\nu}\pi^-} = 0.1702 \pm 0.0020$$
 (6.4)

was found.

### 6.2.2 Reconstruction efficiency for non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ decays

The Monte-Carlo re-weighting for non- $\Sigma_c$  (2455,2520) signal events was done along the two-body and three-body invariant masses.

## 6.2.2.1 Non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ decays in region $II_{m(\Lambda_c^+ \pi^\pm)}$

Because of the prominent  $\Sigma_c^{++}(2800)$  baryon signal in the non- $\Sigma_c$  (24552520)  $m(\Lambda_c^+\pi^+)$  distribution, four-body signal Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  was combined with resonant signal Monte-Carlo  $\overline{B}^0 \to \Sigma_c^{++}(2800)\overline{p}\pi^-$  to avoid disproportionately high weights in  $m(\Lambda_c^+\pi^+)$ .

The weighting was done consecutively along the invariant masses  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$ ,  $m(\Lambda_c^+\overline{p}\pi^+)$ ,  $m(\overline{p}\pi^+\pi^-)$ ,  $m(\Lambda_c^+\pi^+\pi^-)$ ,  $m(\Lambda_c^+\overline{p}\pi^-)$ ,  $m(\Lambda_c^+\overline{p})$ ,  $m(\pi^-\pi^+)$ ,  $m(\overline{p}\pi^+)$ ,  $m(\overline{p}\pi^-)$ . After the weighting the distributions from Monte-Carlo matched the counterparts from data within the uncertainties. The reconstruction efficiency after the final weighting iteration is

$$\varepsilon_{\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-}^{II} = 0.16877 \pm 0.00075 \tag{6.5}$$

Further details as the comparison between data and Monte-Carlo after all weightings and the reconstruction efficiencies after each weighting iteration can be found in the appendix section A.14.2.

## 6.2.2.2 Non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ decays in region $I_{m\left(\Lambda_c^+ \pi^\pm\right)}$

Due to the vetoes on  $\Sigma_c^{+,+}(2455,2520)$  baryons for  $m(\Lambda_c^+\pi^{\pm})$  in region  $I_{m(\Lambda_c^+\pi^{\pm})}$  (see subsection 5.1.3), the reconstruction efficiency in region  $I_{m(\Lambda_c^+\pi^{\pm})}$  is expected to be necessarily smaller than in region  $II_{m(\Lambda_c^+\pi^{\pm})}$ .

As for the correction of events from region  $II_{\Sigma_c}$ , events in region  $I_{\Sigma_c}$  from non-resonant signal Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  and resonant Monte-Carlo  $\overline{B}^0 \to \Sigma_c^{++}(2800)\overline{p}\pi^-$  were weighted along the threeand two-body invariant masses.

The weighted reconstruction efficiency is

$$\varepsilon^{I}_{\overline{B}{}^{0} \to \Lambda^{+}_{c} \overline{p} \pi^{+} \pi^{-}} = 0.1163 \pm 0.0072 \tag{6.6}$$

Supplementary details can also be found in the appendix section A.14.2.

### 6.3 Branching fractions

A branching fraction was calculated from the signal yield  $N_i$  for each resonant decay  $\overline{B}^0 \rightarrow \Sigma_c^{+,+}(2455, 2520)\overline{p}\pi^{\mp}$  and the non- $\Sigma_c$  (2455, 2520) decays  $\overline{B}^0 \rightarrow \Lambda_c^+ \overline{p}\pi^+\pi^-$  in regions  $I_{\Sigma_c}$  and  $II_{\Sigma_c}$ . The signal yields were corrected for the measured reconstruction efficiency  $\varepsilon_i$  and divided by the total number of produced *B*-meson pairs  $N_{B\overline{B}}$  (see section 3.1.2).

For the number of B-meson pairs  $N_{B\overline{B}}$  it was assumed that  $B^{0}\overline{B}{}^{0}$  and  $B^{+}B^{-}$  are produced in the same ratio<sup>2</sup>, i.e.  $\frac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.$ 

Since only the dominant decay  $\Lambda_c^+ \to p K^- \pi^+$  was used in the reconstruction, the product branching ratio could be calculated as

$$\mathcal{B}\left(\overline{B}^{0} \to \left[\Lambda_{c}^{+}\pi^{\pm}\right]\overline{p}\pi^{\mp}\right)_{i} \cdot \mathcal{B}\left(\Lambda_{c}^{+} \to pK^{-}\pi^{+}\right) = \frac{N_{i}}{N_{B\overline{B}}} \cdot \frac{1}{\varepsilon_{i}}$$
(6.7)

Hence, the branching ratios were calculated with:

$$\mathcal{B}\left(\overline{B}^{0} \to \left[\Lambda_{c}^{+}\pi^{\pm}\right]\overline{p}\pi^{\mp}\right)_{i} = \frac{N_{i}}{N_{B\overline{B}}} \cdot \frac{1}{\varepsilon_{i}} \cdot \frac{1}{\mathcal{B}\left(\Lambda_{c}^{+} \to pK^{-}\pi^{+}\right)}$$
(6.8)

which adds a large systematic uncertainty due to the uncertainty of  $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3)\%$ .

The  $\Sigma_c$  resonances decay exclusively into a  $\Lambda_c^+ \pi$ -pair [4]

$$\mathcal{B}\left(\Sigma_{c}^{++}(2455, 2520) \to \Lambda_{c}^{+}\pi^{\pm}\right) \approx 100\%$$
 (6.9)

The efficiency corrected number of events from the two non- $\Sigma_c$  (2455,2520) decay measurements were added and their statistical uncertainties were added quadratically  $\left(N_{I+II}^{\text{eff corr}} = \frac{N_I}{\varepsilon_I} + \frac{N_{II}}{\varepsilon_{II}}\right)$ . The statistical uncertainty of  $N_{B\overline{B}}$  was incorporated in the branching fraction calculation of the efficiency

corrected numbers. The branching ratios are summarized in table 6.2.

Table 6.2: Branching fractions of resonant and non- $\Sigma_c$  (2455,2520) decays into  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  after efficiency corrections without systematic uncertainties. The subscript symbol  $_{\Lambda^+}$  denotes the uncertainty on  $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$  [4]. Events from resonant  $\Sigma_c$  (2455,2520) modes were vetoed in the fit to the  $m_{inv}$  distribution from events in region I. The uncertainty on the total branching fraction for all decays into the final state  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  includes the small correlations between the  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) signal event yields (see tables 5.2 and 5.5).

Mode/Region	$\mathcal{B}\left(\overline{B}^{0}\right) \cdot \mathcal{B}\left(\Lambda_{c}^{+} \to pK^{-}\pi^{+}\right) \left[10^{-6}\right]$	$\mathcal{B}\left(\overline{B}{}^{0} ight)$ $\left[10^{-5} ight]$
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	$(4.53\pm0.33_{\rm stat})$	$\left(9.06 \pm 0.65_{stat} \pm 2.36_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	$(10.66\pm0.49_{\rm stat})$	$\left(21.31 \pm 0.97_{\text{stat}} \pm 5.54_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	$(1.10\pm0.35_{\rm stat})$	$\left(2.21 \pm 0.69_{\text{stat}} \pm 0.57_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	$(5.76\pm0.48_{\rm stat})$	$\left(11.52 \pm 0.97_{\rm stat} \pm 2.99_{A_c^+}\right)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_I^-$	$(14.90\pm1.86_{\rm stat})$	$\left(29.79 \pm 3.72_{stat} \pm 7.75_{\Lambda_c^+} ight)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{II}^-$	$(24.32\pm1.15_{\rm stat})$	$\left(48.64 \pm 2.31_{\text{stat}} \pm 12.65_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{I+II}^-$	$(39.22\pm2.19_{\rm stat})$	$\left(78.44 \pm 4.38_{\text{stat}} \pm 20.39_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{\rm total}^-$	$(61.3\pm2.5_{\rm stat})$	$\left(122.5 \pm 4.7_{\rm stat} \pm 31.9_{\Lambda_c^+}\right)$

<sup>&</sup>lt;sup>2</sup>Currently, the branching ratios  $\mathcal{B}(\Upsilon(4S) \to B^+B^-) = (51.5 \pm 0.6)\%$  and  $\mathcal{B}(\Upsilon(4S) \to B^0\overline{B^0}) = (48.4 \pm 0.6)\%$  do not differ significantly (yet) [4]. Also comparisons with other decays can be drawn more easily under the assumption of equal branching ratios.



Figure 6.4:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : invariant masses from signal Monte-Carlo events ( $\blacksquare$ ) with weights from  ${}_s\mathcal{P}lots$  (•) applied. Corrections were applied along  $m(\Lambda_c^+\overline{p}\pi^-)$  and  $m(\overline{p}\pi^+)$  in the upper plot (a), along  $m(\Lambda_c^+\overline{p}\pi^-)$ ,  $m(\overline{p}\pi^+)$  and  $m(\Lambda_c^+\pi^-\pi^+)$  in the middle plot (b) and along  $m(\Lambda_c^+\overline{p}\pi^-)_{\mathsf{mod}}$ ,  $m(\overline{p}\pi^+)$  and  $m(\Lambda_c^+\pi^-\pi^+)$  with adjusted bin  $m(\Lambda_c^+\overline{p}\pi^-)_{4.99 \text{ GeV}/c^2, 5.09 \text{ GeV}/c^2}$  in the lower plot (c).

#### 6.4 Systematic uncertainties

Besides specific systematic uncertainties affecting only specific modes, systematic uncertainties, that were shared by all measured decays, were studied. Such general systematic uncertainties were studied on non-resonant signal Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ . For example the resonant and non- $\Sigma_c$  modes are all affected by the same uncertainties on the six final state tracks and particle identifications. The systematic uncertainties are given as relative uncertainties  $u_x = \frac{\delta N_c}{N}$ 

#### **B**-counting uncertainty

The total number of B-events (see section 3.1.2) was calculated with the BABAR BbkLumi script. A relative systematic uncertainty on the number of B-events was assumed with

$$u_{N\left(B\overline{B}\right)} = 0.011\tag{6.10}$$

#### Particle tracking uncertainty

For determining the uncertainty of the particle tracking the recipe from the BABAR tracking group was used [66]. The uncertainties per track were added linearly. For six charged tracks in the final state a systematic uncertainty was assumed with:

$$u_{Tracking} = 0.0117\tag{6.11}$$

#### Particle identification uncertainty

To determine the uncertainty of the particle identification the recipe from the BABAR PID group was used [67]. MC was reconstructed twice. One reconstruction was done without taking known differences between data and the Monte-Carlo simulation into account. The second reconstruction of Monte-Carlo data was done including correction tables, which were obtained by the BABAR PID group from control measurements.

The number of signal events was fitted in both reconstructed MC sets in  $m_{inv}$  and are given in table 6.3. The relative difference between the number of events from both PID methods were taken as systematic uncertainty:

$$u_{PID} = 0.043$$
 (6.12)

Table 6.3: PID systematic uncertainties: number of signal events from non-resonant signal Monte-Carlo  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  reconstructed (1) without PID tweaking and (2) with PID tweaking settings.

PID method	signal events
plain	$115140.38 \pm 640.19$
tweaking	$120340.67 \pm 650.18$

non- $\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  background shape in  $m_{inv}: m\left(\Lambda_c^+ \pi^\pm\right)$ 

For the shape of the PDF for  $non-\Sigma_c$  signal events in the  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$  planes an uncertainty was taken into account (see subsections A.11.1 and 3.8.3).

The linear and quadratic width parameters  $a_{sigma}$  and  $b_{sigma}$  were fixed in fits to data. To determine the systematic uncertainty each parameter was individually varied by a standard deviation and the fit was repeated. The maximal deviation from the originally found number of signal events was taken as systematic uncertainty:

$$u_{\text{non-res shape}} \left( \overline{B}^0 \to \Sigma_c^{++} (2455) \overline{p} \pi^{\pm} \right) = 0.001$$
(6.13)

$$u_{\text{non-res shape}} \left( \overline{B}^0 \to \Sigma_c^{++}(2520) \overline{p} \pi^{\pm} \right) = 0.004$$
(6.14)

#### Combinatorial background shape

The stability of the PDF for combinatorial background was tested using the PDF's phase space end point parameter  $e_{psb}^{up}$  in  $m(\Lambda_c^+\pi^{\pm})$  (see equation 3.12).

The constant was varied between the upper phase space limit and the end of the fit region. Table 6.4 shows the relative differences of the signal yields compared to the fit with  $e_{psb}^{up} = 4.215 \text{ GeV}/c^2$ . The all fits converged properly and returned signal yields with less than 1% variation. The maximal

deviation was assumed as systematic uncertainty

$$u_{\text{Comb Bkg shape}}\left(\overline{B}^0 \to \Sigma_c^{++}{}^0(2455)\overline{p}\pi^{\pm}\right) = 0.0000143 \tag{6.15}$$

$$u_{\text{Comb Bkg shape}}\left(\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^{\pm}\right) = 0.0066 \tag{6.16}$$

Table 6.4: Combinatorial background shape: Relative signal yield variation with respect to the variation of the phase space end point  $e_{psb}^{up}$  in eq. 3.12.

$e_{psb}^{up} \left[ \text{GeV}/c^2 \right]$	$\Sigma_{c}^{0}(2455)$	$\Sigma_{c}^{0}(2520)$
4.015	0.00084%	0.432%
3.815	0.00096%	0.249%
3.615	0.00023%	0.018%
3.415	0.00084%	0.476%
3.215	0.00060%	0.249%
3.015	0.00143%	0.660%

 $B^- \to \Sigma_c^+ \overline{p} \pi^0$  in  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  in region  $I_{\Sigma_c}$ 

The systematic uncertainty of the contribution from  $B^- \to \Sigma_c^+ \overline{p} \pi^0$  to  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  for events in region  $I_{\varSigma_c}$  was estimated in section 5.1.3.2 with

$$u_{B^-I} = 0.047 \tag{6.17}$$

which translates to a systematic uncertainty for the combined  $non-\Sigma_c$  signal yield from regions I + II of

$$u_{B^-(I+II)} = 0.018 \tag{6.18}$$

#### Efficiency correction weighting

A systematic uncertainty was included to take variations in the reconstruction efficiency into account between the iterative weighting steps on the Monte-Carlo datasets as described in chapter 6. The weighting iterations were assumed to had converged if the variation between the efficiencies of two successive iteration steps was small, i.e. within about the statistical uncertainty. This was the case for all modes after one round over the available mass combinations. For all modes except  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ 

the differences in the last iteration steps were within the statistical uncertainties (see tables 6.1, A.35-A.37), therefore no systematic uncertainties were included.

The efficiencies for  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  differed by 1.9% compared to a statistical uncertainty of 1.8%. The difference  $u_{\text{Eff. Corr.}} = 0.1\%$  was taken into account as additional systematic uncertainty.

## Contribution from $B \to D_0^+ p\overline{p} \ (n \cdot \pi)$ and B-decays with charmonia

As decribed in section 3.8.5 events from decays  $B \to D_{-p}^{\circ} p\overline{p} (n \cdot \pi)$  were vetoed. Furthermore, decays of the type  $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} [\pi^+\pi^-]$ ;  $(c\overline{c}) \to p\overline{p} [\pi^+\pi^-]$ ;  $\overline{K}^{*0} \to K^-\pi^+$  could contribute. At most six events were expected to contribute to all signal events decaying into the four-body final state  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ . From the number of events a conservative systematic uncertainty was estimated for the remaining background events from these modes:

$$u_{B\to Dp\overline{p}\,n\cdot\pi}\left(\overline{B}^0\to\Lambda_c^+\overline{p}\pi^+\pi^-\right)=0.0006\tag{6.19}$$

$$u_{B\to Dp\overline{p}\,n\cdot\pi}\left(\overline{B}^0\to\Sigma_c^{++}(2455,2520)\overline{p}\pi^{\pm}\right)=0.005\tag{6.20}$$

#### Consistency check for $\Sigma_c$ candidates from combinatorial events

The consistency of fitting the PDFs for combinatorial background events with  $\Sigma_c$  (2455) resonances was studied by varying and fixing the shape parameter in  $m_{inv}$  and the scale within their uncertainty. The statistical uncertainty of the signal yields while fitting with free floating parameter  $u_{stat.}^{free}$  was compared to the statistical uncertainty of the signal yields while fitting with fixed parameters  $u_{stat.}^{fixed}$  and the relative differences of the signal yields, i.e.

$$\begin{split} u_{\text{add}}^{\text{fixed}} &= \sqrt{u_{stat.}^{\text{fixed}}^2 + \left(\frac{S^{\text{free}} - S^{\text{fixed}}}{S^{\text{free}}}\right)^2} \\ \left|u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}}\right| &\stackrel{?}{=} 0 \end{split}$$

The differences in the signal yields uncertainties were:

$$\begin{split} & \left| u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}} \right| \left( \overline{B}^0 \to \Sigma_c^{++} (2455) \overline{p} \pi^{\pm} \right) = 0.00026 \\ & \left| u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}} \right| \left( \overline{B}^0 \to \Sigma_c^{++} (2520) \overline{p} \pi^{\pm} \right) = 0.00105 \\ & \left| u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}} \right| \left( \overline{B}^0 \to \left( \Lambda_c^+ \pi^{\pm} \right)_{! \Sigma_c^0} \overline{p} \pi^{\mp} \right) = 0.00162 \end{split}$$

Since the differences are all in good agreement with *zero*, it is assumed that the statistic uncertainty of the free floating fit includes the shape uncertainty making no systematic uncertainty necessary.

#### Consistency check of combinatorial background with $\Sigma_c$ resonances

The existence of combinatorial background events with  $\Sigma_c^0(2520)$  as contributions to  $\overline{B}^0 \rightarrow \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  was ambiguous. In side-band projection from data no signal was seen, while from generic  $B^0\overline{B}^0$  and  $B^+B^-$  MC such background could be expected (see section 3.8.1). The fit was repeated with and without the  $\Sigma_c^0(2520)$  combinatorial background PDF. Including the PDF gave a fit probability of  $P(\chi^2)_{w\Sigma_c(2520)} = 0.0913987$  with a large uncertainty on the  $\Sigma_c^0(2520)$  back-

ground scale. Without the PDF the fit had a probability of  $P(\chi^2)_{wo\Sigma_c(2520)} = 0.08499$ . The differences of the statistical uncertainties and differences were

$$\begin{aligned} \left| u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}} \right| \left( \overline{B}^0 \to \Sigma_c^0(2455) \overline{p} \pi^{\pm} \right) &= 0.00046\\ \left| u_{stat.}^{\text{free}} - u_{\text{add}}^{\text{fixed}} \right| \left( \overline{B}^0 \to \Sigma_c^0(2520) \overline{p} \pi^{\pm} \right) &= 0.00199 \end{aligned}$$

The differences of the uncertainties are in good agreement with zero. It is therefore assumed that the statistical uncertainty of the  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  signal yield describes also properly the uncertainty on combinatorial background with  $\Sigma_c$  (2520).

#### Summary of systematic uncertainties

The systematic uncertainties were added quadratically. Not included was the uncertainty of the  $\Lambda_c^+$  branching fraction, which was treated separately. Table 6.5 sums up the considered systematic uncertainties.

Table 6.5: Summary of systematic uncertainties for  $non-\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ , resonant  $\overline{B}{}^0 \to \Sigma_c(2455) \overline{p} \pi^{\pm}$  and resonant  $\overline{B}{}^0 \to \Sigma_c(2520) \overline{p} \pi^{\pm}$  decays.

Uncertainty	non- $\Sigma_c$	$\Sigma_{c}^{0}(2455)$	$\Sigma_{c}^{++}(2455)$	$\Sigma_{c}^{0}(2520)$	$\Sigma_{c}^{++}(2520)$
$u_N(B\overline{B})$	0.011	0.011	0.011	0.011	0.011
$u_{Tracking}$	0.0117	0.0117	0.0117	0.0117	0.0117
$u_{PID}$	0.043	0.043	0.043	0.043	0.043
$u_{non-resshape}$		0.001	0.001	0.004	0.004
uCombi Bkg shape		0.0000143	0.0000143	0.0066	0.0066
$u_{Eff. Corr.}$				0.001	
$u_{B\to Dp\overline{p}n\cdot\pi}$	0.0006	0.005	0.005	0.005	0.005
$u_{B^-(I+II)}$	0.018				
$\sqrt{\sum u_i^2}$	0.0493	0.0462	0.0462	0.0466	0.0466

## 6.5 Final results

The branching fractions for the resonant decays and the decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without an intermediate  $\Sigma_c^{++}$  (2455,2520) resonance are given in table 6.6. The measured resonant branching fractions are in good agreement the previous measurement from Belle [6] (table 1.4) within their uncertainties, whereas in this analysis the uncertainties could be reduced.

Since signal of the decay  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  was not significant, an upper limit of the branching

Table 6.6: Branching fractions of the resonant decays  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  and non- $\Sigma_c$  (2455, 2520) decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ 

Mode/Region	$\mathcal{B}\left(\overline{B}^{0}\right) \cdot \mathcal{B}\left(\Lambda_{c}^{+} \to pK^{-}\pi^{+}\right) \left[10^{-6}\right]$	$\mathcal{B}\left(\overline{B}^{0} ight)$ $\left[10^{-5} ight]$
$\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$	$(4.53 \pm 0.33_{\rm stat} \pm 0.21_{\rm sys})$	$\left(9.06 \pm 0.65_{\text{stat}} \pm 0.42_{\text{sys}} \pm 2.36_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	$(10.66\pm0.49_{\rm stat}\pm0.49_{\rm sys})$	$(21.31 \pm 0.97_{\text{stat}} \pm 0.98_{\text{sys}} \pm 5.54_{\Lambda_c^+})$
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	$(1.10\pm 0.35_{\rm stat}\pm 0.05_{\rm sys})$	$\left(2.21 \pm 0.69_{stat} \pm 0.10_{sys} \pm 0.57_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	$(5.76\pm0.48_{\rm stat}\pm0.27_{\rm sys})$	$\left(11.52 \pm 0.97_{stat} \pm 0.54_{sys} \pm 2.99_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{non-\Sigma_c}^-$	$(39.22 \pm 2.19_{\rm stat} \pm 1.93_{\rm sys})$	$\left(78.44 \pm 4.38_{stat} \pm 3.87_{sys} \pm 20.39_{\Lambda_c^+}\right)$
$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi_{\rm total}^-$	$(61.3\pm2.4_{\rm stat}\pm3.7_{\rm sys})$	$\left(122.5 \pm 4.7_{\text{stat}} \pm 7.3_{\text{sys}} \pm 31.9_{A_c^+}\right)$

fraction was calculated using a Bayesian approach. The statistical and systematic uncertainties were

added quadratically. With the Gaussian distributed uncertainty and the branching fraction the integral of the Gaussian was calculated, which contained 90% of the physical meaningful area > 0

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2520)\overline{p}\pi^{+}\right) \cdot \mathcal{B}\left(\Lambda_{c}^{+} \to pK^{-}\pi^{+}\right) \leq 1.55 \cdot 10^{-6} @ 90\% C.L.$$
(6.21)

As seen in this analysis, the resonant decays with  $\Sigma_c$  resonances have large contributions to  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ . The resonant decays via  $\Sigma_c$  (2455,2520) resonances are dominated by  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ . The branching fractions of the other significant resonant decays were found to be just about a half of the branching fraction from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ , i.e.

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\right)} = 0.425 \pm 0.036 \tag{6.23}$$

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2520)\overline{p}\pi^{-}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\right)} = 0.541 \pm 0.052$$
(6.24)

The domination of the decay  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  over  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  is presumably due to the different spins of the two  $\Sigma_c$  baryons. In  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  the  $^1/_2$  spins of the  $\Lambda_c^+$  and the  $\overline{p}$  together with the pseudoscalar  $\pi^-$  can be arranged to the mother  $\overline{B}^0$  without the need of an orbital angular momentum for conservation. In  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  the  $\Sigma_c^{++}(2520)$  carries a spin of  $^3/_2$ , so for angular momentum conservation an compensating orbital angular momentum is necessary, suggesting to act as a suppression factor.

Also,  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  itself is a dominating contribution to all decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ . The branching fraction from  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  is more than  $1/_5$  of all integrated branching fractions from the remaining *non-* $\Sigma_c$  (2455,2520) contributions in  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ 

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\pi^{+}\pi_{\mathsf{non}-\Sigma_{c}(2455,2520)}\right)} = 0.227 \pm 0.019$$
(6.25)

Both resonant decays via the lighter  $\Sigma_c^{++}(2455)$  resonances are preferred to decays via the same charged  $\Sigma_c^{++}(2520)$  resonances. Especially in decays via neutral  $\Sigma_c$  baryons only the decay via the lightest  $\Sigma_c^{0}(2455)$  resonance is significant, presumably due to the same spin-argument stated above.

Thus in *B*-meson decays the baryon production seems to be preferred if the available phase space is restricted. Also decays via double-charged  $\Sigma_c^{++}$  resonances are preferred compared to decays via the neutral  $\Sigma_c^0$  resonances, which could be explained by the additional available mechanisms in decays with  $\Sigma_c^{++}$ . Apparently these additional mechanisms do not add destructively. Indications of different decay mechanisms in decays  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  and  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  can be seen in the  $_s\mathcal{P}lot$  distributions of the  $m(\overline{p}\pi^{\pm})$ .

Unfortunately, no intermediate states with only a baryon-antibaryon pair could be measured, e.g.  $\overline{B}^0 \to \Sigma_c^0(2455) \sim \overline{\Delta}^0$  or  $\overline{B}^0 \to \Sigma_c^{++}(2455) \sim \overline{\Delta}^{--}$ , due to the limited statistics and due to the multitude of possible broad baryon states in  $m(p\pi)$ , making it difficult to separate them. Thus, no ratios can be calculated, which would be necessary for narrow some of the parameters down for the SU(3) predictions in eq. 1.1 and eq. 1.2. However, an estimate can be derived, when all events in the presumed mass range of the  $\Delta$  baryon with  $m_{\Delta} \approx 1.232 \,\text{GeV}/c^2$ ,  $\gamma_{\Delta}^{\text{FW}} \approx 0.118 \,\text{GeV}/c^2$  [4] in the  $_s\mathcal{P}lot$  distribution of  $m(\overline{p}\pi^{\pm})$  are subsumed (see for the  $_s\mathcal{P}lot$ ted  $m(\overline{p}\pi^{\pm})_{\Sigma_c^{-0}}$  (2455)

5.19). Here, all events were assumed to originate from a decay with a  $\Delta(1232)$  baryon, if they were within two times the nominal width around the nominal invariant mass in the  ${}_{s}\mathcal{P}lotted \ m(\overline{p}\pi^{\pm})$ , which would

contain in the physical allowed region about 92.2% of the nominal  $\Delta$  baryons:

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{\Delta}^{--}\right)} = \frac{|\alpha|^{2}}{|\eta_{1}|^{2}} \gtrsim \frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\left[\overline{p}\pi^{-}\right]_{\sim\bar{\Delta}^{--}}\right)} = 0.67 \pm 0.05_{\mathsf{stat}} \tag{6.26}$$

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{\Delta}^{0}\right)} = \frac{|\alpha|^{2}}{\frac{1}{3}\left|\eta_{1} + \eta_{2}\right|^{2}} \gtrsim \frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\left[\overline{p}\pi^{+}\right]_{\sim}\overline{\Delta}^{0}\right)} = 0.63 \pm 0.06_{stat} \qquad (6.27)$$

Under the same assumption one can compare the measured branching ratios with the predictions from the diquark approach in equation 1.5

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{\Delta}^{0}\right)} \gtrsim 0.63 \pm 0.06_{\mathsf{stat}} \begin{cases} 0.632_{\mathrm{nonlocal pair}}\\ 1.301_{\mathrm{local pair}} \end{cases}$$
(6.28)

in which the measured branching fraction ratio just sets the lower limit near to the prediction assuming a nonlocal pair production. Due to the limited explanatory power of the ratio under the necessary assumptions, one cannot draw a conclusion here between both predictions (assuming that one of both describes the decay process). For an explicit distinction between the two diquark-model prediction a further detailed analysis of the decay  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  would be necessary with higher statistics and a approach to discriminate between intermediate baryons decaying to  $\overline{p}\pi^+$ .

## Chapter 7

# Conclusion

In the presented analysis the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  was studied. A dataset of ~ 433 fb<sup>-1</sup> was used, which was recorded with the *BABAR* detector at the PEP-II  $e^+e^-$  storage ring at the SLAC National Accelerator Laboratory. The dataset corresponds to ~ 467 \cdot 10^6 B\overline{B} pairs, that were produced in the reaction  $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ .

 $\overline{B}^0$ -mesons were reconstructed in the signal decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  with the subsequent decay  $\Lambda_c^+ \to p K^- \pi^+$ . In the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  intermediate states with resonant  $\Sigma_c$  baryons were searched for. Significant contributions to the signal decay were found from the intermediate decays  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-, \overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  and  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  with the subsequent decays of the resonant baryons  $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$  or  $\Sigma_c^0 \to \Lambda_c^+ \pi^-$ . An only insignificant signal was found for the resonant decay  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ .

The resonant intermediate decays were determined in fits to the two two-dimensional distributions spanned by the invariant mass of the reconstructed *B*-meson  $m_{inv}$  and the invariant masses  $m(\Lambda_c^+\pi^+)$ and  $m(\Lambda_c^+\pi^-)$ , respectively. In the planes background from decays  $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  and  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  with subsequent decays  $\Sigma_c^+ \to \Lambda_c^+\pi^0$  could be discriminated from signal decay events, which was not possible in one-dimensional variables. Additional sources of background to signal decay events were combinatorial events from  $B\overline{B}$ -reactions, combinatorial events from  $B\overline{B}$ -reactions with  $\Sigma_c$ resonances, the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$  without intermediate  ${\Sigma_c^+}^0$  (2455,2520) resonances and decays of the type  $B \to Dp\overline{p} + n \cdot \pi$ .

The yield from the decay  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  without intermediate  $\Sigma_c^{++}(2455,2520)$  resonances was determined in one-dimensional fits to the invariant  $\overline{B}{}^0$ -mass.

In the analysis particular attention was paid to study differences between reconstructed events from data and events from Monte-Carlo simulations. Corrections on Monte-Carlo simulated events were applied in the invariant mass of the  $\Lambda_c^+$ -baryon, in the invariant mass of the  $\overline{B}^0$ -meson and in the invariant masses of the  $\Sigma_c^{++}$  (2455) resonances.

The reconstruction efficiencies from the signal decays were studied on Monte-Carlo simulated events. To take phase space dependencies of the reconstruction efficiency and decay dynamics into account, the Monte-Carlo simulated events were weighted according to the distributions of signal events in data. To separate distributions of events from signal decays from background events, the  $_{s}\mathcal{Plot}$ -technique was used.

The branching fractions were determined to be

$$\begin{split} \mathcal{B} \left( \overline{B}^{0} \to \Sigma_{c}^{0} (2455) \overline{p} \pi^{+} \right) &= \left( 9.06 \pm 0.65_{\mathsf{stat}} \pm 0.42_{\mathsf{sys}} \pm 2.36_{A_{c}^{+}} \right) \cdot 10^{-5} \\ \mathcal{B} \left( \overline{B}^{0} \to \Sigma_{c}^{++} (2455) \overline{p} \pi^{-} \right) &= \left( 21.31 \pm 0.97_{\mathsf{stat}} \pm 0.98_{\mathsf{sys}} \pm 5.54_{A_{c}^{+}} \right) \cdot 10^{-5} \\ \mathcal{B} \left( \overline{B}^{0} \to \Sigma_{c}^{0} (2520) \overline{p} \pi^{+} \right) \cdot \mathcal{B} \left( A_{c}^{+} \to p K^{-} \pi^{+} \right) &\leq 1.55 \cdot 10^{-6} \quad @ 90\% C.L. \\ \mathcal{B} \left( \overline{B}^{0} \to \Sigma_{c}^{++} (2520) \overline{p} \pi^{-} \right) &= \left( 11.52 \pm 0.97_{\mathsf{stat}} \pm 0.54_{\mathsf{sys}} \pm 2.99_{A_{c}^{+}} \right) \cdot 10^{-5} \\ \mathcal{B} \left( \overline{B}^{0} \to A_{c}^{+} \overline{p} \pi^{+} \pi_{\mathsf{non}-\Sigma_{c}(2455,2520)} \right) &= \left( 78.44 \pm 4.38_{\mathsf{stat}} \pm 3.87_{\mathsf{sys}} \pm 20.39_{A_{c}^{+}} \right) \cdot 10^{-5} \\ \mathcal{B} \left( \overline{B}^{0} \to A_{c}^{+} \overline{p} \pi^{+} \pi_{\mathsf{non}-\Sigma_{c}(2455,2520)} \right) &= \left( 122.5 \pm 4.7_{\mathsf{stat}} \pm 7.3_{\mathsf{sys}} \pm 31.9_{A_{c}^{+}} \right) \cdot 10^{-5} \end{split}$$

where the first error is due to the statistical uncertainty, the second error is due to systematic uncertainties and the third error is due to the uncertainty on the branching fraction of the decay  $\Lambda_c^+ \to p K^- \pi^+$ . For the insignificant decay  $\mathcal{B}\left(\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+\right)$  an upper limit on the branching fraction was determined. Differences in the decay dynamics were seen, especially between the distributions from the decays  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  and  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ . Events from these decays were found to favour different regions of the phase space. An interpretation is given by classifying the primal baryon production mechanisms of the initial states.

Since the mechanisms in decays with baryons in the final state are still not very well known, the presented measurements and interpretations are an important contribution for an understanding of the baryon production.

## Appendix A

# Appendix

### A.1 Related measurements

Measurements of decays  $\overline{B}{}^0/B^- \to \Lambda_c^+ \overline{p} \ n \cdot \pi$  are ordered by the number of pions in their final state. Intermediate states with resonances are arranged corresponding to their  $\Lambda_c^+ \overline{p}$  final states. For measurements with a small significance, the significance is denoted in square brackets.

## $\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$

The two body mode  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$  was measured by S.Majewski for BABAR [12] ([13]) with

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)_{BABAR} = \left(1.89 \pm 0.21 \pm 0.06 \pm 0.49_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-5} \tag{A.1}$$

A previous measurement by Belle [68] gives

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\right)_{\text{Belle}} = \left(2.19 \begin{array}{c} +0.56\\ -0.49 \end{array} \pm 0.32 \pm 0.57_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-5} \tag{A.2}$$

while CLEO only found an upper limit of

$$\mathcal{B}\left(\overline{B}^0 \to \Lambda_c^+ \overline{p}\right)_{\text{CLEO}} < 0.9 \cdot 10^{-4} \tag{A.3}$$

All three measurements are compatible within their uncertainties.

## $B \to \Lambda_c^+ \overline{p} \pi$

Three body final states were measured at *BABAR* by S. Majewski  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  [12], [13] and M. Ebert  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  [14], [15] with

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-}\right)_{BABAR} = \left(3.38 \pm 0.12 \pm 0.12 \pm 0.88_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.4}$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{0}\right)_{BABAR} = \left(1.94 \pm 0.17 \pm 0.14 \pm 0.5_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \tag{A.5}$$

Resonances were observed for the charged mode while for the neutral mode only an upper limit could been found

$$\frac{\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\right)_{BABAR}}{\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\right)} = (12.3 \pm 1.2 \pm 0.8) \cdot 10^{-2}$$
(A.6)

$$\frac{\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2520)\overline{p}\right)_{BABAR}}{\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\right)} < 0.9 \cdot 10^{-2}$$
(A.7)

$$\frac{\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2800)\overline{p}\right)_{BABAR}}{\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{-}\right)} = (11.7 \pm 2.3 \pm 2.4) \cdot 10^{-2}$$
(A.8)

$$\mathcal{B}\left(\overline{B}^0 \to \Sigma_c^+(2455)\overline{p}\right)_{BABAR} < 0.19 \cdot 10^{-4} \tag{A.9}$$

Belle measurements  $[69]^1$  found

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\right)_{\text{Belle}} = \left(3.7 \pm 0.7 \pm 0.4 \pm 1.0_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-5} \tag{A.10}$$

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2520)\overline{p}\right)_{\text{Belle}} < 2.7 \cdot 10^{-5} \tag{A.11}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\bar{\Delta}^{--}(1232)\right)_{\text{Belle}} < 1.9 \cdot 10^{-5}$$
 (A.12)

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\bar{\Delta}_{X}^{--}(1600)\right)_{\text{Belle}} = \left(5.9 \pm 1.0 \pm 0.6 \pm 1.5_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-5} \tag{A.13}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+}\bar{\Delta}_{X}^{--}(2420)\right)_{\text{Belle}} = \left(4.7 \pm 1.0 \pm 0.4 \pm 1.2_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-5} \tag{A.14}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-}\right)_{\text{Belle}} = \left(20.1 \pm 1.5 \pm 2.0 \pm 5.2_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-5} \tag{A.15}$$

In a previous Belle measurement [70] branching fractions were measured

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\right)_{\text{Belle}} = \left(0.45 \begin{array}{c} +0.26\\ -0.19 \end{array} \pm 0.08 \pm 0.12_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \left[3.0\sigma\right]$$
(A.16)

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2520)\overline{p}\right)_{\text{Belle}} = \left(0.14 \begin{array}{c} +0.15\\ -0.09 \end{array} \pm 0.02 \pm 0.04_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \left[1.8\sigma\right]$$
(A.17)

CLEO found [31]

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\right)_{\text{CLEO}} < 0.8 \cdot 10^{-4} \tag{A.18}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-}\right)_{\text{CLEO}} = \left(2.4 \pm 0.6 \ \frac{+2.9}{-1.7} \ \pm 0.6_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.19}$$

To some extent diquark predictions (see previous section 1.2.5.2) can be compared to the already measured ratios of decays into two or three body final states. Results found by S. Majewski [12], [13] gave ratios of about

$$\frac{\overline{B}^0 \to \overline{p} \Lambda_c^+}{B^- \to \overline{p} \Sigma_c^0(2455)} \approx 0.528 \tag{A.21}$$

$$\frac{\overline{B}^0 \to \overline{p} \Lambda_c^+}{B^- \to \overline{p} \Sigma_c^0(2800)} \approx 0.555 \tag{A.22}$$

<sup>1</sup>Note that  $B^- \to \Lambda_c^+ \bar{\Delta}_X^{--}(1600, 2420)$  were assumed to include all events in the suspected  $p\pi$  regions

For the decay studied by M. Ebert [14], [15] an upper limit on  $\overline{B}^0 \to \Sigma_c^+(2455)\overline{p}$  was found giving a ratio

$$\frac{\overline{B}^0 \to \overline{p} \Lambda_c^+}{\overline{B}^0 \to \overline{p} \Sigma_c^+(2455)} < 1.148 \tag{A.23}$$

Comparing the measured result in eq. A.23 to the diquark prediction (1.3) would suggest a possible branching fraction just near the observed upper limit. However no hints for a signal have been seen for  $\overline{B}^0 \to \overline{p} \Sigma_c^+(2455)$ 

For the decay studied in this work only decay cascades originating from a baryon-antibaryon pair as  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{\Delta^0}$  can be compared to some predictions. The diquark prediction suggests branching fractions for  $B \to \Sigma_c \overline{\Delta}$  modes comparable or larger than the measured two body mode  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$ . However, because of the widths of  $\Delta$  resonances and the small branching fraction seen for  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$ , no clear signal is expected for modes as predicted in eq. 1.5 or in  $\frac{\overline{B}^0 \to u(cd)\overline{u}(\overline{ud}): \Delta_c^+ \overline{p}}{\overline{B}^0 \to u(cd)\overline{u}(\overline{ud}): \Sigma_c^+ \overline{\Delta^+}} = 2.211_{\text{nonlocal pair}} | = 4.554_{\text{local pair}}$  from [24].

Consequently this analysis covers only intermediate states with  $\Sigma_c$  resonances and further intermediate states have to be left for following studies.

A more recent pole model [71] gives an explicit prediction on the branching fraction ratio from the decays  $B^- \to \Lambda_c^+ \overline{p} \rho^-$  and  $B^- \to \Lambda_c^+ \overline{p} \pi^-$ . Here the one pion final state is compared to an excited meson final state

$$\frac{\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \rho^{-}\right)}{\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-}\right)} = 2.6 \tag{A.24}$$

If the prediction in eq. A.24 could be adapted to the related  $\overline{B}^0$  decays (without an in-detail isospin analysis), a substantial contribution would be expected from intermediate states with excited mesons. However, in no significant signal from  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \rho^0(770)$  could be identified in this analysis.

Furthermore, the decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  and  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  can be compared to study contributions to the decay amplitudes from different isospin diagrams. While  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$  can have decay amplitudes with isospins  $I_{...\pi^0} = \frac{1}{2}$  and  $I_{...\pi^0} = \frac{3}{2}$  (figures A.1(a) and A.1(b)),  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  can only have decay amplitudes with an isospin of  $I_{...\pi^-} = \frac{3}{2}$  (figures A.1(c) and A.1(d)). With the assumption of  $I = \frac{3}{2}$ amplitudes dominating, one would expect a branching fraction ratio in the order of  $\frac{\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0}{B^- \to \Lambda_c^+ \overline{p} \pi^-} = \frac{2}{3}$ . The measured ratios

$$\frac{\Gamma\left(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0\right)}{\Gamma\left(B^- \to \Lambda_c^+ \overline{p} \pi^-\right)} = 0.61 \pm 0.09_{\mathsf{stat+sys}} \tag{A.25}$$

$$\frac{\Gamma\left(B^0 \to \Lambda_c^+ \bar{p} \pi^0\right)}{\Gamma\left(B^- \to \Lambda_c^+ \bar{p} \pi^-\right)_{\text{nonresonant}}} = 0.80 \pm 0.11_{\text{stat+sys}}$$
(A.26)

$$\frac{\Gamma\left(\overline{B}^{0} \to \Sigma_{c}^{+} \overline{p}\right)}{\Gamma\left(B^{-} \to \Sigma_{c}^{0} \overline{p}\right)} < 0.73 \tag{A.27}$$

are all in agreement with the assumption of  $\frac{3}{2}$  within the uncertainties. Here, the conclusion can be drawn that contributions with isospins  $I = \frac{3}{2}$  dominate the decay amplitude.



Figure A.1:  $\overline{B}{}^0/B^- \to \Lambda_c^+ \overline{p} \pi^0/\pi^-$ : Comparison of different isospin options

## $B \to \Lambda_c^+ \overline{p} \pi \pi$

CLEO reports for the charged B four body decay  $B^-\to \Lambda_c^+ \overline{p} \pi^+ \pi^0~[31]$ 

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{0}\right)_{\text{CLEO}} = \left(4.2 \pm 1.3 \pm 0.4 \pm 1.0_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \tag{A.28}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-} \pi^{0}\right)_{\text{CLEO}} = \left(18.1 \pm 2.9 \begin{array}{c} +2.2 \\ -1.6 \end{array} \pm 4.7_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4}$$
(A.29)

for the neutral B four body decay  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  CLEO found [31]

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\right)_{\text{CLEO}} = \left(3.7 \pm 0.8 \pm 0.7 \pm 0.8_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \tag{A.30}$$

$$\mathcal{B}\left(\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+\right)_{\text{CLEO}} = \left(2.2 \pm 0.6 \pm 0.4 \pm 0.5_{\mathcal{B}\left(\Lambda_c^+\right)}\right) \cdot 10^{-4} \tag{A.31}$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-}\right)_{\text{CLEO}} = \left(16.7 \pm 1.9 \begin{array}{c} +1.9 \\ -1.6 \end{array} \pm 4.3_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.32}$$

Belle found [70]

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\right)_{\text{Belle}} = \left(2.38 \begin{array}{c} +0.63 \\ -0.55 \end{array} \pm 0.41 \pm 0.62_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \left[5.3\sigma\right]$$
(A.33)

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2520)\overline{p}\pi^{-}\right)_{\text{Belle}} = \left(1.63 \begin{array}{c} +0.57\\ -0.51 \end{array} \pm 0.28 \pm 0.42_{\mathcal{B}(\Lambda_{c}^{+})}\right) \cdot 10^{-4} \left[1.63\sigma\right] \quad (A.34)$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}\right)_{\text{Belle}} = \begin{pmatrix} 0.84 & +0.42 \\ -0.35 & \pm 0.14 \pm 0.22_{\mathcal{B}(\Lambda_{c}^{+})} \end{pmatrix} \cdot 10^{-4} [2.6\sigma] \quad (A.35)$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{0}(2520)\overline{p}\pi^{+}\right)_{\text{Belle}} = \left(0.48 \begin{array}{c} +0.26\\ -0.19 \end{array} \pm 0.08 \pm 0.12_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \left[1.2\sigma\right]$$
(A.36)

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-}\right)_{\text{Belle}} = \left(11.0 \begin{array}{c} +1.2\\ -1.2 \end{array} \pm 1.9 \pm 2.9_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.37}$$

 $B \to \Lambda_c^+ \overline{p} \pi \pi \pi$ 

CLEO measured for the charged B five body decay  $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^+ \pi^-$  [31]

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}\pi^{-}\right)_{\text{CLEO}} = \left(4.4 \pm 1.2 \pm 0.5 \pm 1.1_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-4} \tag{A.38}$$

$$\mathcal{B}\left(B^{-} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}\pi^{-}\right)_{\text{CLEO}} = \left(2.8 \pm 0.9 \pm 0.5 \pm 0.7_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.39}$$

$$\mathcal{B}\left(B^{-} \to \Lambda_{c}^{+} \overline{p} \pi^{-} \pi^{+} \pi^{-}\right)_{\text{CLEO}} = \left(16.7 \pm 2.5 \begin{array}{c} +2.4 \\ -1.9 \end{array} \pm 4.3_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-4} \tag{A.40}$$

 $\overline B{}^0 \to \Lambda_c^+ \overline p \pi^+ K^-$ 

At BABAR T. Leddig made the first observation of the mode  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ K^-$  [30], [72], [73] which could decay similar to the  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+$  mode but suppressed in first order by  $W \to us$  (figure A.2). Except for an annihilation diagram, this decay can proceed via similar diagrams as  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+$  via internal W radiations of type 2 or via an external W radiation (compare figures 1.2 and following).

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \bar{K}^{*0}\right)_{\text{BABAR}} = \left(1.60 \pm 0.61 \pm 0.12 \pm 0.42_{\mathcal{B}}(\Lambda_{c}^{+})\right) \cdot 10^{-5} \left[2.7\sigma\right] \tag{A.41}$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}K^{-}\right)_{BABAR} = \left(1.11 \pm 0.30 \pm 0.09 \pm 0.29_{\mathcal{B}(\Lambda_{c}^{+})}\right) \cdot 10^{-5} \left[4.3\sigma\right] \quad (A.42)$$

$$\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} K^{-}\right)_{\text{BABAR}} = \left(4.33 \pm 0.82 \pm 0.31 \pm 1.13_{\mathcal{B}\left(\Lambda_{c}^{+}\right)}\right) \cdot 10^{-5} \tag{A.43}$$

In the measurement by T. Leddig (A.43) the ratio from the resonant decays is compatible (within the uncertainties) to a simple expectation with a suppression factor of  $\left|\frac{V_{us}}{V_{ud}}\right|^2 = 0.0536 \pm 0.0020$  [4], while the non-resonant ratio deviates with more than  $2\sigma$ :

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\pi^{+}K^{-}\right)}{\mathcal{B}\left(\overline{B}^{0} \to \Lambda_{c}^{+}\overline{p}\pi^{+}\pi^{-}\right)} = 0.038 \pm 0.009 \tag{A.44}$$

$$\frac{\mathcal{B}\left(\overline{B}^{0} \to \Sigma_{c}^{++} \overline{p} K^{-}\right)}{\overline{B}^{0} \to \Sigma_{c}^{++} \overline{p} \pi^{-}} = 0.048 \pm 0.009 \tag{A.45}$$

although the number of first order graphs for  $\overline{B}{}^0 \to \Sigma_c^{++} \overline{p} \pi^-$  compared to  $\overline{B}{}^0 \to \Sigma_c^{++} \overline{p} K^-$  could suggest a smaller ratio.



Figure A.2:  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} K^- \pi^+ \longleftrightarrow \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+$ 

## A.2 BABAR tracking and PID lists

The particle track reconstruction at BABAR were categorized by different quality criteria. For the main track selectors raw data from the sub-detectors were used. Table A.1 lists the available track quality lists and their quality criteria.

Similar, the particle identification of a given track is categorized by quality criteria. Table A.2 lists the criteria for a given track to be sorted in one of the the likelihood-based PID lists.

Table A.1: Tracking reconstruction criteria. Tracking criteria before 2006 are noted as "old", since 2006 definitions for GoodTracksLoose and GoodTracksTight are identical [74].

Tracking lists	$ heta_{lab}$	$[\stackrel{p_{lab}}{\text{GeV}/c}]$	DCH Hits	$\begin{bmatrix} z_{Doca} \\ [cm] \end{bmatrix}$	$\begin{array}{c} xy_{Doca} \ [cm] \end{array}$	$P(\chi^2)$	$ [ \stackrel{p_t}{\text{GeV}/c} ] $
ChargedTracks	-	_	-	-	-	> 0	-
GoodTracksVeryLoose	$0.410 \dots 2.54$	$0 \dots 10$	0	< 2.5	< 1.5	> 0	-
${\tt GoodTracksVeryLoose}_{old}$	$0.410 \dots 2.54$	010	0	< 10	< 1.5	> 0	-
GoodTracksLoose	$0.410 \dots 2.54$	010	-	< 2.5	< 1.5	> 0	> 0.05
${\tt GoodTracksLoose}_{old}$	$0.410 \dots 2.54$	010	12	< 10	< 1.5	> 0	> 0.1
GoodTracksTight	$0.410 \dots 2.54$	010	-	< 2.5	< 1.5	> 0	> 0.05
${\tt GoodTracksTight}_{old}$	$0.410 \dots 2.54$	010	20	< 3	< 1	> 0	> 0.1

Table A.2: Particle identification lists for kaons  $\mathcal{L}_K$ , pions  $\mathcal{L}_{\pi}$  and protons  $\mathcal{L}_p$ . For some lists a minimum momentum or a veto on the electron PID list eLHTight is required. For veryTight requirements also a veto on the muon hypothesis muMicroVeryTight is made.

PID lists	$rac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$	$rac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_p}$	$rac{\mathcal{L}_p}{\mathcal{L}_p + \mathcal{L}_\pi}$	Momentum or veto on eLHTight	muMicroVeryTight
pLHVeryLoose	-	< 0.75	> 0.5	-	-
pLHLoose	-	< 0.3	> 0.5	$p < 0.75 \mathrm{GeV}/c$ or $veto$	-
pLHTight	-	< 0.2	> 0.75	$p < 0.75 \mathrm{GeV}/c$ or $veto$	-
pLHVeryTight	-	< 0.1	> 0.96	p < 0.75 GeV/c  or  veto	veto
KLHNotPion	> 0.2	-	-	-	-
KLHVeryLoose	> 0.5	> 0.018	-	$p < 0.40 \mathrm{GeV}/c$ or $veto$	-
KLHLoose	> 0.8176	> 0.018	-	$p < 0.40 \mathrm{GeV}/c$ or $veto$	-
KLHTight	> 0.9	> 0.2	-	$p < 0.40 \mathrm{GeV}/c$ or $veto$	-
KLHVeryTight	> 0.5	> 0.018	-	p < 0.40 GeV/c  or  veto	veto
piLHVeryLoose	< 0.98	-	< 0.98	-	-
piLHLoose	< 0.82	-	< 0.98	veto	-
piLHTight	< 0.5	-	< 0.98	veto	-
piLHVeryTight	< 0.2	-	< 0.5	veto	veto

### A.3 Reconstruction software

The data selection and the analysis itself were performed with the following release and added packages/tags

• Software release: analysis-50 (24.3.2)

- package: BetaCoreTools chcheng-20080829
- package: BetaMiniUser V00-04-05
- package: BetaPid V00-12-07
- package: CompositionFactory V01-05-07
- package: FilterTools V00-20-39
- package: PDT V00-07-00
- package: PidDchSvtDrcCalib V00-04-11
- package: SimCondAlias V00-02-12

### A.4 Monte-Carlo datasets

In addition to side-band events from data and to generic Monte-Carlo event simulations, background sources were searched for and studied in specific Monte-Carlo simulated modes. Table A.3 lists the Monte-Carlo produced modes, that were requested, since they were similar to the signal decays  $B \to \Lambda_c^+ \overline{p} X$ , e.g. with higher or smaller multiplicity.

Table A.4 lists the modes studied in Monte-Carlo simulations, which have the form  $B \to Dp\overline{p} X$ . Some of these decays were found to contribute as significant background, since the final state particles could be rearranged and fake a signal decay.

Table A.3: Monte-Carlo: background Monte-Carlo modes with  $\Lambda_c$  or  $\Sigma_c$ . For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data and including the branching fraction of the reconstructed  $\Lambda_c^+$  decay  $(N_{B\overline{B}} \sim 462 \cdot 10^6 \text{ and } \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.05 \text{ from } [4]).$ 

mode	decay	produced events	$\times$ on-peak
SP-5084	$B^- \to \Lambda_c^+ \overline{p} \pi^-$	1745000	359.7
SP-6973	$B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$	350000	54.1
SP-6974	$B^- \to \Sigma_c^0(2455)\overline{p}, \ \Sigma_c^0(2455) \to \Lambda_c^+\pi^-$	350000	409.5
SP-6975	$B^- \to \Sigma_c^0(2520)\overline{p}, \ \Sigma_c^0(2520) \to \Lambda_c^+\pi^-$	350000	> 561.2
SP-6976	$B^- \to \Sigma_c^0(2800)\overline{p}, \ \Sigma_c^0(2800) \to \Lambda_c^+\pi^-$	350000	-
SP-6977	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^0$	350000	> 25.7
SP-6978	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$	350000	721.5
SP-6986	$B^- \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \pi^+$	350000	6.6
SP-6987	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \pi^0$	350000	> 3.0
SP-7186	$\overline{B}{}^0 \to \Sigma_c^+(2455)\overline{p}, \ \Sigma_c^+(2455) \to \Lambda_c^+\pi^0$	175000	-
SP-7187	$\overline{B}{}^0 \to \Sigma_c^+(2520)\overline{p}, \ \Sigma_c^+(2520) \to \Lambda_c^+\pi^0$	175000	-
SP-7188	$\overline{B}{}^0 \to \Sigma_c^+(2800)\overline{p}, \ \Sigma_c^+(2800) \to \Lambda_c^+\pi^0$	175000	-
SP-8935	$B^- \to \Sigma_c^+(2455)\overline{p}\pi^-, \ \Sigma_c^+(2455) \to \Lambda_c^+\pi^0$	650000	-
SP-8936	$B^- \to \Sigma^0_c(2455)\overline{p}\pi^0, \ \Sigma^0_c(2455) \to \Lambda^+_c\pi^-$	650000	63.9
SP-8937	$B^- \to \Sigma_c^+(2520)\overline{p}\pi^-, \ \Sigma_c^+(2520) \to \Lambda_c^+\pi^0$	650000	-
SP-8938	$B^- \to \Sigma^0_c(2520)\overline{p}\pi^0, \ \Sigma^0_c(2520) \to \Lambda^+_c\pi^-$	650000	> 201.0
SP-10096	$B^- \to \Sigma_c^+(2800)\overline{p}\pi^-, \ \Sigma_c^+(2800) \to \Lambda_c^+\pi^0$	429000	-
SP-10160	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \rho, \ \rho \to \pi^+ \pi^-$	21700	-
SP-10161	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p}  ho, \ \rho \to \pi^0 \pi^0$	21700	-
SP-10162	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^0 \pi^0$	21700	-
SP-10163	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} f_2 (1270), \ f_2 \to \pi^+ \pi^-$	21700	-
SP-10164	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} f_2 (1270), \ f_2 \to \pi^0 \pi^0$	21700	-
SP-10165	$\overline{B}{}^0 \to \Lambda^+_c \overline{p} K^0_s, \ K^0_s \to \pi^+ \pi^-$	21700	-
SP-10166	$\overline{B}{}^0 \to \Lambda_c^+ \overline{p} K_s^0, \ K_s^0 \to \pi^0 \pi^0$	21700	-
SP-10167	$\overline{B}{}^0 \to \Sigma_c^+(2455)\overline{p}\pi^0, \ \Sigma_c^+(2455) \to \Lambda_c^+\pi^0$	21700	-
SP-10168	$\overline{B}^0 \to \Sigma_c^+(2520)\overline{p}\pi^0, \ \Sigma_c^+(2520) \to \Lambda_c^+\pi^0$	21700	-
SP-10169	$\overline{B}{}^0 \to \Sigma_c^+(2800)\overline{p}\pi^0, \ \Sigma_c^+(2800) \to \Lambda_c^+\pi^0$	21700	-

Table A.4: Monte-Carlo: background Monte-Carlo modes with  $D^0$  or  $D^+$ . For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data including the branching fraction of the reconstructed  $D^{+}_{(*)}$  decays  $(N_{B\overline{B}} \sim 462 \cdot 10^6 \text{ and } (D^{+}_{*} \rightarrow D^{+}_{*} \pi^{\pm}), BR(D^{+}_{*} \rightarrow \dots)$  from [4] and [25]).

mode	decay	produced events	$\times$ on-peak
SP-8016	$\overline{B}{}^0 \to D^0 p \overline{p}, \ D^0 \to K^- \pi^+$	392000	213.8
SP-8017	$\overline{B}{}^0 \to D^0 p \overline{p}, \ D^0 \to K^- \pi^+ \pi^0$	392000	59.8
SP-8018	$\overline{B}{}^0 \to D^0 p \overline{p}, \ D^0 \to K^- \pi^+ \pi^- \pi^+$	392000	102.7
SP-8019	$\overline{B}{}^0 \to D^0 p \overline{p}, \ D^0 \to K^0_S \pi^+ \pi^-$	392000	278.2
SP-8020	$\overline{B}{}^0 \to D^{*0} p \overline{p}, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^- \pi^+$	392000	374.8
SP-8021	$\overline{B}{}^0 \to D^{*0} p \overline{p}, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^- \pi^+ \pi^0$	392000	104.9
SP-8022	$\overline{B}{}^0 \to D^{*0} p \overline{p}, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^- \pi^+ \pi^- \pi^+$	392000	180.0
SP-8023	$\overline{B}{}^0 \to D^{*0} p \overline{p}, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^0_s \pi^+ \pi^-$	392000	487.6
SP-8028	$\overline{B}{}^0 \to D^+ p \overline{p} \pi^-, \ D^+ \to K^- \pi^+ \pi^+$	392000	27.7
SP-8029	$\overline{B}{}^0 \to D^+ p \overline{p} \pi^-, \ D^+ \to K^0_S \pi^+$	392000	176.2
SP-8030	$\overline{B}{}^0 \to D^+ p \overline{p} \pi^-, \ D^+ \to K^- K^+ \pi^+$	392000	26.5
SP-8031	$\overline{B}{}^0 \to D^{*+} p \overline{p} \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^- \pi^+$	392000	70.8
SP-8032	$\overline{B}{}^0 \to D^{*+} p \overline{p} \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^- \pi^+ \pi^0$	392000	19.8
SP-8033	$\overline{B}{}^0 \to D^{*+} p \overline{p} \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^- \pi^+ \pi^- \pi^+$	392000	34.0
SP-8034	$\overline{B}{}^0 \to D^{*+} p \overline{p} \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^0_S \pi^+ \pi^-$	392000	92.1
SP-8035	$\overline{B}{}^0 \to D^0 p \overline{p} \pi^+ \pi^-, \ D^0 \to K^- \pi^+$	392000	72.9
SP-8036	$\overline{B}{}^0 \to D^0 p \overline{p} \pi^+ \pi^-, \ D^0 \to K^- \pi^+ \pi^0$	392000	20.4
SP-8037	$\overline{B}{}^0 \to D^0 p \overline{p} \pi^+ \pi^-, \ D^0 \to K^- \pi^+ \pi^- \pi^+$	392000	35.0
SP-8038	$\overline{B}{}^0 \to D^0 p \overline{p} \pi^+ \pi^-, \ D^0 \to K^0_{\scriptscriptstyle S} \pi^+ \pi^-$	392000	94.9
SP-8039	$\overline{B}{}^0 \to D^{*0} p \overline{p} \pi^+ \pi^-, \ D^{*0} \to D^0 \pi^0; \ D^0 \to K^- \pi^+$	392000	184.5
SP-8040	$\overline{B}{}^0 \to D^{*0} p \overline{p} \pi^+ \pi^-, \ D^{*0} \to D^0 \pi^0; \ D^0 \to K^- \pi^+ \pi^0$	392000	51.6
SP-8041	$\overline{B}{}^0 \to D^{*0} p \overline{p} \pi^+ \pi^-, \ D^{*0} \to D^0 \pi^0; \ D^0 \to K^- \pi^+ \pi^- \pi^+$	392000	88.6
SP-8042	$\overline{B}{}^0 \to D^{*0} p \overline{p} \pi^+ \pi^-, \ D^{*0} \to D^0 \pi^0; \ D^0 \to K^0_{\scriptscriptstyle S} \pi^+ \pi^-$	392000	240.0
SP-8055	$B^- \to D^0 p \overline{p} \pi^-, \ D^0 \to K^- \pi^+$	261000	39.0
SP-8056	$B^- \to D^0 p \overline{p} \pi^-, \ D^0 \to K^- \pi^+ \pi^0$	261000	10.9
SP-8057	$B^- \to D^0 p \overline{p} \pi^-, \ D^0 \to K^- \pi^+ \pi^+ \pi^-$	261000	18.8
SP-8058	$B^- \to D^0 p \overline{p} \pi^-, \ D^0 \to K^0_S \pi^+ \pi^-$	261000	50.8
SP-8059	$B^- \to D^{*0} p \overline{p} \pi^-, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^- \pi^+$	261000	62.9
SP-8060	$B^- \to D^{*0} p \overline{p} \pi^-, \ D^{*0} \to, D^0 \pi^0, \ D^0 \to K^- \pi^+ \pi^0$	261000	17.6
SP-8061	$B^- \to D^{*0} p \overline{p} \pi^-, \ D^{*0} \to D^0 \pi^0, \ D^0 \to K^- \pi^+ \pi^- \pi^+$	261000	30.2
SP-8062	$B^- \to D^{*0} p \overline{p} \pi^-, \ D^{*0} \to, D^0 \pi^0, \ D^0 \to K^0_{_S} \pi^+ \pi^-$	261000	81.8
SP-8067	$B^- \to D^+ p \overline{p} \pi^- \pi^-, \ D^+ \to K^- \pi^+ \pi^+$	261000	36.9
SP-8068	$B^- \to D^+ p \overline{p} \pi^- \pi^-, \ D^+ \to K^0_S \pi^+$	261000	234.7
SP-8069	$B^- \to D^+ p \overline{p} \pi^- \pi^-, \ D^+ \to K^- K^+ \pi^+$	261000	35.3
SP-8070	$B^- \to D^{*+} p \overline{p} \pi^- \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to \overline{K^- \pi^+}$	261000	115.3
SP-8071	$B^- \to D^{*+} p \overline{p} \pi^- \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^- \pi^+ \pi^0$	261000	32.3
SP-8072	$B^- \to D^{*+} p \overline{p} \pi^- \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^- \pi^+ \pi^- \pi^+$	261000	55.4
SP-8073	$B^- \to D^{*+} p \overline{p} \pi^- \pi^-, \ D^{*+} \to D^0 \pi^+; \ D^0 \to K^0_s \pi^+ \pi^-$	261000	150.0

# A.5 $\Lambda_c^+$ mass related measurements

In this section supplementary information can be found on the study of the  $\Lambda_c^+$  mass in the six BABAR data taking runs, and on the impact of different  $\Lambda_c^+$  selection constraints on the  $\overline{B}^0$ -candidates.

## A.5.1 Run-dependent $\Lambda_c^+$ mass fits

To search for run dependent effects on the  $\Lambda_c^+$  mass,  $\Lambda_c^+$ -candidates  $m (pK^-\pi^+)$  were reconstructed in each run 1-6 separately. The results are given in figure A.3 and in table A.5. Within the uncertainties no run-dependence was seen. Thus, a mean  $\Lambda_c^+$  mass over all six runs was assumed.



Figure A.3:  $\Lambda_c$  mass:  $m(pK^-\pi^+)$  for runs 1 -6 fitted with a Gaussian for signal and a 2nd order polynomial for background. The fits'  $\Lambda_c^+$  masses are given in table A.5.

run	$\Lambda_c^+$ mass
1	$(2.28560 \pm 0.00047) \text{ GeV}/c^2$
2	$(2.28558 \pm 0.00025) \text{ GeV}/c^2$
3	$(2.28558 \pm 0.00036) \text{ GeV}/c^2$
4	$(2.28562 \pm 0.00022) \text{ GeV}/c^2$
5	$(2.28555 \pm 0.00018) \text{ GeV}/c^2$
6	$(2.28546 \pm 0.00023) \text{ GeV}/c^2$

Table A.5:  $\Lambda_c$  mass: Masses from fitting  $m(pK^-\pi^+)$  for runs 1 -6 with a Gaussian for signal and a 2nd order polynomial for background.  $m(pK^-\pi^+)$  distributions are shown in figure A.3.

### A.5.2 Influence of $\Lambda_c^+$ mass constraints and cut regions on the number of $\overline{B}{}^0$

#### Fits on $m_{inv}$ for different $\Lambda_c^+$ constraints and cuts

To study the influence of different hypotheses for constraining a  $\Lambda_c^+$  mass on a resulting *B*-candidate,  $\Lambda_c^+$  candidates were fitted with the different mass hypothesis as mass constraint. On a subset of run 1-6 data using the R22d-V08 LambdaC skim  $\Lambda_c^+$  candidates were formed in  $m (pK^-\pi^+)$ . The  $\Lambda_c^+$ -candidate was then used to form a  $\overline{B}^0$ -candidate with the remaining  $\overline{B}^0$  daughters for the mode  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ . In the fit using TreeFitter a mass constraint was applied on the  $\Lambda_c^+$  candidate.

This was done for the mass hypothesis  $m(\Lambda_c^+) = 2.2849 \text{ GeV}/c^2$ ,  $m(\Lambda_c^+) = 2.2856 \text{ GeV}/c^2$  and without a mass assumption and mass constraint.  $\Lambda_c^+$  candidates were used to form a  $\overline{B}^0$  candidate if their pre-fit masses were in between  $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$ , i.e. symmetric around the MC mass hypothesis, or  $m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$ , i.e. symmetric around the shifted  $\Lambda_c^+$  mass fitted in data.

The  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  distributions were fitted assuming a Gaussian for signal and a first-order polynomial for background. The resulting numbers of *B* signal candidates and widths are given in tables A.6 and A.7. The fits are shown in figures A.4 to A.9.

Furthermore, the study was repeated with different signal PDFs to exclued a bias from the chosen signal shape. Two fit series were done assuming a double Gaussian as signal shape and a first order polynomial for background and fits using only a polynomial for background and excluding the signal region. The results with their the dependency on the  $\Lambda_c^+$  selection were compatible.

The shift of the  $\Lambda_c^+$  mass cut has no significant influence on the number  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  signal events or the width of the signal within the uncertainties. However, with an unconstraint  $\Lambda_c^+$  mass the uncertainties on the  $\overline{B}^0$  width and number of events rose, showing the benefit of including the a priori knowledge of the  $\Lambda_c^+$  mass.

#### Differences in $m_{inv}$ for different $\Lambda_c^+$ constraints and cuts

As sub-study the differences between the events reconstructed with the different  $\Lambda_c^+$  selection options were studied in the invariant  $\overline{B}^0$  mass. Figures A.10, A.11 and A.12 show the differences in  $m_{inv}$  between applying a cut on  $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$  and  $m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$  for the  $\Lambda_c^+$ candidate mass constraint to  $2.2849 \text{ GeV}/c^2$ ,  $2.2856 \text{ GeV}/c^2$  and no mass constraint, respectively. Within uncertainties no plot shows a significant deviation and the binwise differences scatter randomly around zero. However, each two subtracted histograms are naturally correlated resulting in estimating to large uncertainties.

Figures A.13, A.14 and A.15 show the difference in  $m_{inv}$  between applying a  $\Lambda_c^+$  mass constraint of 2.2849 GeV/ $c^2$  and 2.2856 GeV/ $c^2$ , between a mass constraint of 2.2856 GeV/ $c^2$  and no mass constraint and between no mass constraint and a mass constraint of 2.2849 GeV/ $c^2$ , respectively, for  $\Lambda_c^+$  candidates in the range  $m(\Lambda_c^+) \in (2.2727, 2.2977)$  GeV/ $c^2$ .

In figure A.13 a overshot followed by an undershot in the difference of events derives from the shifted energy of the  $\Lambda_c^+$  daughter due to the different mass constraints. Constraining the  $\Lambda_c^+$  to 2.2849 GeV/ $c^2$ 

Table A.6:  $m_{inv}$ :  $\overline{B}^0$  signal events from the invariant mass for different  $\Lambda_c^+$  mass hypothesis and  $m(pK^-\pi^+)$  cut regions fitted with a single Gaussian for signal and a first order polynomial for background.

$\Lambda_c^+$ mass constraint	$m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$	$m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$
$m(\Lambda_c^+) = 2.2849 \text{GeV}/c^2$	$4147.04 \pm 109.266$	$4129.50 \pm 109.077$
$m\left(\Lambda_{c}^{+}\right) = 2.2856 \mathrm{GeV}/c^{2}$	$4121.64 \pm 109.126$	$4114.35 \pm 109.171$
$m\left(\Lambda_{c}^{+} ight)$ no constraint	$4329.00 \pm 118.081$	$4275.79 \pm 117.585$

Table A.7:  $m_{inv}$ :  $\overline{B}^0$  signal widths from fitted invariant mass for different  $\Lambda_c^+$  mass hypothesis and  $m (pK^-\pi^+)$  cut regions.

$\Lambda_c^+$ mass constraint	$m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$	$m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$
$m(\Lambda_c^+) = 2.2849 \text{GeV}/c^2$	$0.00857 \pm 0.00026$	$0.00857 \pm 0.00026$
$m\left(\Lambda_c^+\right) = 2.2856 \mathrm{GeV}/c^2$	$0.00854 \pm 0.00027$	$0.00856 \pm 0.00027$
$m\left( \Lambda_{c}^{+} ight)$ no constraint	$0.01045 \pm 0.00032$	$0.01037 \pm 0.00032$

the resulting  $\overline{B}^0$  mother has a smaller invariant mass compared to the same  $\overline{B}^0$  with the  $\Lambda_c^+$  constraint to 2.2856 GeV/ $c^2$ .

The undershot-overshot-undershot structure in figure A.14 results from the broader  $\overline{B}^0$  peak in  $m_{inv}$  for unconstraint  $\Lambda_c^+$  daughters compared to a more narrow structure for  $\overline{B}^0$  with  $\Lambda_c^+$  daughters constraint to 2.2856 GeV/ $c^2$ . Obviously, a consistent  $\Lambda_c^+$  selection was necessary. Therefore, all  $\Lambda_c^+$ -candidates from events in data or Monte-Carlo were constraint and selected only with their corresponding criteria.



Figure A.4:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were constraint to  $m(\Lambda_c^+) = 2.2849 \,\text{GeV}/c^2$ and had to have a mass within  $m(\Lambda_c^+) \in$  $(2.272, 2.297) \,\text{GeV}/c^2$ .



Figure A.6:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were constraint to  $m(\Lambda_c^+) = 2.2856 \text{ GeV}/c^2$ and had to have a mass within  $m(\Lambda_c^+) \in$  $(2.272, 2.297) \text{ GeV}/c^2$ .



Figure A.8:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were not constraint to a certain mass but had to have a mass within  $m(\Lambda_c^+) \in (2.272, 2.297)$  GeV/ $c^2$ .



500

Figure A.5:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were constraint to  $m(\Lambda_c^+) = 2.2849 \,\text{GeV}/c^2$ and had to have a mass within  $m(\Lambda_c^+) \in$  $(2.2727, 2.2977) \,\text{GeV}/c^2$ .



Figure A.7:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were constraint to  $m(\Lambda_c^+) = 2.2856 \text{ GeV}/c^2$ and had to have a mass within  $m(\Lambda_c^+) \in$  $(2.2727, 2.2977) \text{ GeV}/c^2$ .



Figure A.9:  $m_{inv}$  :  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  fitted with a Gaussian for signal and a first order polynomial for background.  $\Lambda_c^+$  daughters were not constraint to a certain mass but had to have a mass within  $m(\Lambda_c^+) \in (2.2727, 2.2977)$  GeV/ $c^2$ .



Figure A.10:  $m_{inv}$ : Difference in  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  with  $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$  and  $m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$  for  $\Lambda_c^+$  constraint to 2.2849 GeV/c^2.



Figure A.12:  $m_{inv}$ : Difference in  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  with  $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$  and  $m(\Lambda_c^+) \in (2.2727, 2.2977) \text{ GeV}/c^2$  for  $\Lambda_c^+$  constraint without mass constraint.



Figure A.14:  $m_{inv}$ : Difference in  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  between  $\Lambda_c^+$  constraint to 2.2856 GeV/ $c^2$  and  $\Lambda_c^+$  unconstraint for  $m(\Lambda_c^+) \in (2.2727, 2.2977)$  GeV/ $c^2$ .



5.3 5.35

 $m_{inv}$  :

5.4 5.45

 $m_{inv} \left[ GeV/c^2 \right]$ 

Difference

in

5.2 5.25

Figure A.11:

 $\frac{dn}{dm_{inv}} \left[ \frac{1}{2 \text{ MeV/c}^2} \right]$ 



Figure A.13:  $m_{inv}$ : Difference in  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  between  $\Lambda_c^+$  constraint to 2.2849 GeV/ $c^2$  and constraint to 2.2856 GeV/ $c^2$  for  $m(\Lambda_c^+) \in (2.2727, 2.2977)$  GeV/ $c^2$ .



Figure A.15:  $m_{inv}$ : Difference in  $m_{inv}$   $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$  between  $\Lambda_c^+$  unconstraint and constraint to 2.2849 GeV/ $c^2$  for  $m(\Lambda_c^+) \in (2.2727, 2.2977)$  GeV/ $c^2$ .

## A.6 $m\left(\Lambda_{c}^{+}\pi^{\pm}\right)$ distributions in signal and side band regions

The plots in figure A.16 show zooms to the  $m(\Lambda_c^+\pi^{\pm})$  distributions from events from the  $m_{inv}$  and  $m_{\rm ES}$  signal region. The for  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  the lower plots show the side band subtracted distributions; here the scaled distribution from the  $m_{inv}$  side bnd and  $m_{\rm ES}$  signal band region were subtracted from the signal region distribution. Clearly visible are the  $\Sigma_c^{++}$  (2455) resonances, while a signal for a  $\Sigma_c$  (2520) resonance is only apparent in  $m(\Lambda_c^+\pi^+)$ . Due to the fine binning signals for a broad  $\Sigma_c$  (2800) are hard to spot here.

The distributions in  $m(\Lambda_c^+\pi^+)$  from the various regions are shown in figures A.17 and A.18. In figure A.17 the sub-side-bands in  $m_{inv}$  III<sub>a</sub> and III<sub>b</sub> were subsumed to the combined region III. In figure A.18 the distributions from the individual side-bands III<sub>a</sub> and III<sub>b</sub> are shown. The equivalent distributions in  $m(\Lambda_c^+\pi^-)$  are shown in figures A.19 and A.20. In the various side band distributions contributions of combinatorial events with  $\Sigma_c$  resonances are visible. However, contributions differ when comparing  $\Sigma_c^{++}$  and  $\Sigma_c^0$  resonances as well as compared between  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) contributions.



Figure A.16:  $m(\Lambda_c^+\pi^\pm)$ : Detailed view of the lower  $m(\Lambda_c^+\pi^\pm)$  masses as from figure 3.8. The plots show for  $m(\Lambda_c^+\pi^+)$  (uper two plots) and  $m(\Lambda_c^+\pi^-)$  (lower two plots) the distributions from the  $m_{inv}$  and  $m_{\rm ES}$ signal region and the side band subtracted distribution.  $\Sigma_c$  (2455,2520) signal regions are denoted as dashed lines (see definitions in table 3.8).



Figure A.17:  $m(\Lambda_c^+\pi^+)$ : distributions for events in I)  $m_{inv}$  &  $m_{\rm ES}$  signal bands, II)  $m_{inv}$  signal &  $m_{\rm ES}$  side band region, III) combined  $m_{inv}$  side bands &  $m_{\rm ES}$  signal band, IV) combined  $m_{inv}$  &  $m_{\rm ES}$  side bands



Figure A.18:  $m(\Lambda_c^+\pi^+)$ : distributions for events in I)  $m_{inv}$  side band 1 &  $m_{\rm ES}$  signal band, II)  $m_{inv}$  side band 2 &  $m_{\rm ES}$  signal band, III)  $m_{inv}$  side band 1 &  $m_{\rm ES}$  side band, VI)  $m_{inv}$  side band 2 &  $m_{\rm ES}$  side band


Figure A.19:  $m(\Lambda_c^+\pi^-)$ : distributions for events in I)  $m_{inv}$  &  $m_{\rm ES}$  signal bands, II)  $m_{inv}$  signal &  $m_{\rm ES}$  side band region, III) combined  $m_{inv}$  side bands &  $m_{\rm ES}$  signal band, IV) combined  $m_{inv}$  &  $m_{\rm ES}$  side bands



Figure A.20:  $m(\Lambda_c^+\pi^-)$ : distributions for events in I)  $m_{inv}$  side band 1 &  $m_{\rm ES}$  signal band, II)  $m_{inv}$  side band 2 &  $m_{\rm ES}$  signal band, III)  $m_{inv}$  side band 1 &  $m_{\rm ES}$  side band, VI)  $m_{inv}$  side band 2 &  $m_{\rm ES}$  side band 2 &  $m_{\rm E$ 

## A.7 Plots from $\overline{B}{}^0 \to \Sigma_c^0 \overline{p} \pi^+$ Monte-Carlo simulated events

Since the Monte-Carlo simulation uses the same phase space model for generating the decays  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  and  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$ , the distributions of the differently charged resonant modes are nearly equivalent. For completeness figures, A.21-A.23 show the relevant distributions in  $m_{inv}:m(\Lambda_c^+\pi^\pm)$ ,  $m_{inv}$ ,  $m_{\rm ES}$  and  $m(\Lambda_c^+\pi^\pm)$  for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  simulated events and for  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  Monte-Carlo events in figures A.24-A.26.



Figure A.21: SP-6981:  $m_{inv}: m(\Lambda_c^+\pi^{\pm})$  from  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  signal Monte-Carlo. The upper plot shows the signal event distribution in  $m_{inv}: m(\Lambda_c^+\pi^-)$ , the middle plot  $m_{inv}: m(\Lambda_c^+\pi^-)$  more in detail, the lower plot the adjoint  $m_{inv}: m(\Lambda_c^+\pi^+)$  distribution.



Figure A.22:  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  Monte Carlo:  $m_{inv}$  from  $m_{\rm ES}$  signal band,  $m_{\rm ES}$  from  $m_{inv}$  signal band and the  $m_{inv}{}:m_{\rm ES}$  plane



 $m(\Lambda_c^+\pi^+)$  [GeV/c<sup>2</sup>]

 $m(\Lambda_{c}^{+}\pi)$  [GeV/c<sup>2</sup>]

which when the head of the strength of the str



Figure A.24:  $m_{inv}: m\left(\Lambda_c^+\pi^\pm\right)$  from  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  signal Monte-Carlo. The upper plot shows the signal event distribution in  $m_{inv}: m\left(\Lambda_c^+\pi^-\right)$ , the middle plot  $m_{inv}: m\left(\Lambda_c^+\pi^-\right)$  more in detail, the lower plot the adjoint  $m_{inv}: m\left(\Lambda_c^+\pi^+\right)$  distribution.



Figure A.25:  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  Monte-Carlo:  $m_{inv}$  from  $m_{\rm ES}$  signal band,  $m_{\rm ES}$  from  $m_{inv}$  signal band and the  $m_{inv}:m_{\rm ES}$  plane

Figure A.26:  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$  Monte-Carlo:  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$  distributions from  $m_{inv}$  and  $m_{\rm ES}$  signal region

 $m(\Lambda_c^{\scriptscriptstyle +}\pi^{\scriptscriptstyle +})\left[GeV/c^2\right]$ 

 $m(\Lambda_{c}^{+}\pi^{-})$  [GeV/c<sup>2</sup>]

## A.8 Combinatorial background

In studies of generic Monte-Carlo simulated events it was found, that events from reactions  $e^+e^- \rightarrow u\overline{u}, d\overline{d}, s\overline{s}$  pose no threat at all.

After applying all constraints during reconstruction (table 3.4), no background contribution is expected from uds events, i.e.  $e^+e^- \rightarrow u\overline{u}$ ,  $e^+e^- \rightarrow d\overline{d}$  or  $e^+e^- \rightarrow s\overline{s}$ . Figure A.27 shows all unscaled events from the complete uds Monte-Carlo dataset (see table 4.2) after reconstruction. Scaled onto luminosity no significant contribution is present. As visible in the unscaled distributions from uds Monte-Carlo events only about 20 events would contribute in the signal region, which translate to about  $\sim 6$  events scaled on-peak.

From events from the reaction  $e^+e^- \rightarrow c\overline{c}$  only about 100 scaled events were expected to contribute to the signal region at all. As visible in figure A.28 they do not distribute in a peaking structure in any of the signal variables were therefore not considered a threat and were absorbed in the general combinatorial background.

### A.8.1 Combinatorial background with $\Sigma_c$ resonances

Events from combinatorial background but with true  $\Sigma_c$  resonances were studied in data in side bands and in Monte-Carlo simulations of specific decays.

In the different side band regions signals of  $\Sigma_c^{+0}$  (2455,2520) resonances are visible on-top the combinatorial background as visible in figure A.29. However, the evidences for  $\Sigma_c^{++}$  (2520) resonances in combinatorial background events are less significant, probably due to the larger width.

Monte-Carlo simulations for decays  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$  were studied as high luminosity samples. Figure A.30 shows the distributions in the  $m_{inv}:m(\Lambda_c^+\pi^\pm)$  planes and figure A.31 shows projections onto the axes. Clearly visible are the signals in  $m(\Lambda_c^+\pi^-)$  while in other variables these events distribute as combinatorial background



Figure A.27: Generic *uds* Monte-Carlo unscaled: upper row:  $m_{\text{ES}}$ ,  $m_{inv}$ ; middle row  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\text{ES}}$ - $m_{inv}$  signal region); lower row  $m_{inv}$ :  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\text{ES}}$  signal band)



Figure A.28: Generic  $c\bar{c}$  Monte-Carlo unscaled: upper row:  $m_{\rm ES}$ ,  $m_{inv}$ ; middle row  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$ - $m_{inv}$  signal region); lower row  $m_{inv}$ :  $m(\Lambda_c^+\pi^+)$ ,  $m(\Lambda_c^+\pi^-)$  (from  $m_{\rm ES}$  signal band)



Figure A.29:  $m(\Lambda_c^+\pi^\pm)$  from data side bands: left column  $m(\Lambda_c^+\pi^+)$ , right column  $m(\Lambda_c^+\pi^-)$ ; top down:  $m_{inv}$  signal- $m_{\rm ES}$  side band region (II),  $m_{inv}$  side- $m_{\rm ES}$  signal region (III),  $m_{inv}$  - $m_{\rm ES}$  side band region (IV)



Figure A.30:  $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$ :Monte-Carlo simulated background events with true  $\Sigma_c^0(2455, 2520)$  in the  $m_{inv}:m(\Lambda_c^+\pi^-)$  plane for the  $m_{\rm ES}$  signal region (upper plot) and  $m_{\rm ES}$  side band region (lower plot)



Figure A.31: Example for true  $\Sigma_c$  background Monte-Carlo: left column  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ , right column  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$ ; top down:  $m_{\rm ES}$ ,  $m_{inv}$ ,s;  $m(\Lambda_c^+\pi^+)$  (from  $m_{inv}$  - $m_{\rm ES}$  signal region),  $m(\Lambda_c^+\pi^-)$  (from  $m_{inv}$  - $m_{\rm ES}$  signal region).

## A.8.2 Fitting combinatorial background in $m\left(\Lambda_{c}^{+}\pi^{\pm}\right)$

The robustness of equations 3.13 and 3.18 as PDF for combinatorial background in  $m(\Lambda_c^+\pi^{\pm})$  was tested on toy Monte-Carlo. Since the *composition* of combinatorial background in data is not known, Monte-Carlo toy mixtures were composed of signal Monte-Carlo without resonances in  $m(\Lambda_c^+\pi^+)$  or in  $m(\Lambda_c^+\pi^-)$ . Several Monte-Carlo modeled modes were added with random weights and were fitted with a  $\chi^2$ -fit. The toy Monte-Carlo sets were composed of:

$$0.91 \times \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \frac{m(\Lambda_c^+ \pi^+)}{MC} + 0.38 \times \overline{B}{}^0 \to \Sigma_c^{++} (2455) \overline{p} \pi^- \frac{m(\Lambda_c^+ \pi^-)}{MC}$$

$$+ 0.51 \times \overline{B}{}^0 \to \Sigma_c^0 (2520) \overline{p} \pi^+ \frac{m(\Lambda_c^+ \pi^+)}{MC}$$
(A.46)

shown in figure A.32(a) and of

$$0.14 \times \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \frac{m(\Lambda_c^+ \pi^+)}{MC} + 0.65 \times \overline{B}{}^0 \to \Sigma_c^{++} (2455) \overline{p} \pi^- \frac{m(\Lambda_c^+ \pi^-)}{MC}$$

$$+ 0.32 \times \overline{B}{}^0 \to \Lambda_c^+ \Delta^{--} \pi^+ \frac{m(\Lambda_c^+ \pi^+)}{MC} + 0.24 \times \overline{B}{}^0 \to \Lambda_c^+ \Delta^{--} \pi^+ \frac{m(\Lambda_c^+ \pi^-)}{MC}$$

$$(A.47)$$

shown in figure A.32(b). Both Monte-Carlos were successful fitted in  $m(\Lambda_c^+\pi^{\pm})$ , table A.8 gives the found paratements. As visible in figure A.32(b), the fit was not able to describe the distribution perfectly between  $\sim 3.0 \text{ GeV}/c^2$  and 3.4  $\text{GeV}/c^2$ . This was taken into account, by limiting the fit for the signal yield measurements in  $m(\Lambda_c^+\pi^{\pm})$  to  $2.625 \text{ GeV}/c^2$ .



Figure A.32:  $m(\Lambda_c^+\pi^\pm)$ : Mixture of  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ , respectively, from signal SP modes with random scaling each.

Toy MC	Parameter	$\mathbf{Fit}$
eq. A.46	$a'_{\sigma}$	$0.00286 \pm 0.00014$
	$b'_{\sigma}$	$-0.0186 \pm 0.0009$
	$c'_{\sigma}$	$0.0381 \pm 0.0013$
eq. A.47	$a_{\sigma}^{\prime\prime}$	$0.00275 \pm 0.00013$
	$b_{\sigma}^{\prime\prime}$	$-0.0179 \pm 0.0008$
	$c''_{\sigma}$	$0.0374 \pm 0.0013$

Table A.8: Results of fitting the Gaussian width in  $m_{inv}$  in subranges of  $m(\Lambda_c^+\pi^\pm)$ .

## A.9 Decays with a $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$ final state

## A.9.1 Background studies on $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$ and $B^- \to \Sigma_c^+ (2800) \overline{p} \pi^-$

The resonant decays  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  were dangerous due to their low momentum pions, that could be interchanged with a correctly charged pion from the other B. However, the non-resonant decay  $B^- \to \Lambda_c^+ \overline{p}\pi^- \pi^0$  posed no danger, since the mis-reconstructed events distribute broadly of all relevant variables as visible in figure A.33. Also the resonant decay via a  $\Sigma_c^+(2800)$  resonances does not fake a signal in one of the signal variables and ranges as visible in figure A.34. Here, the the broader  $\Sigma_c$  (2800) structures

Therefore, both modes were assumed to be absorbed into combinatoril background.



Figure A.33: Non-resonant  $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$  background Monte-Carlo: upper row:  $m_{inv}, m_{\rm ES}$ ; middle row (from  $m_{inv}$  - $m_{\rm ES}$  signal region)  $m(\Lambda_c^+ \pi^+), m(\Lambda_c^+ \pi^-)$ , lower row  $m_{inv}:m(\Lambda_c^+ \pi^+), m_{inv}:m(\Lambda_c^+ \pi^-)$ .

## A.9.2 $B^- \rightarrow \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ in $m_{inv}$

The shape of  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  events in  $m_{inv}$  were fitted in Monte-Carlo. For events from the  $\Sigma_c^{++}(2455)$  signal sub-region in  $m(\Lambda_c^+\pi^+)$  the invariant B mass  $m_{inv}$  was fitted with a Gaussian for signal and a first order polynomial for background. Since the branching fraction from  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  has not been measured yet and since  $\mathcal{B}(B^- \to \Sigma_c^+(2455)\overline{p}\pi^-) = (4.4 \pm 1.8) \cdot 10^{-4}$  was affected by a large uncertainty, the influence of the potential background sources was tested by including successively their PDFs from Monte-Carlo in the fit on data. The shapes were fixed and only the scaling was allowed to float. As visible in figure A.35 and in the signal yields given in table A.9, especially between assumptions on an existence or on a non-existence of  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  have large effects on the signal mode yield. In  $m_{inv}$  the one-dimensional fit could not distinguish properly between combinatorial background and  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  events; also in  $m(\Lambda_c^+\pi^+)$   $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  events appear similar to  $\overline{B}^0 \to \Sigma_c^{+}(2520)\overline{p}\pi^-$  could be made, one-dimensional fits in  $m_{inv}$  or in  $m(\Lambda_c^+\pi^\pm)$  for a signal yield extraction had to be discarded.

Furthermore, no justifiable predictions on the branching fraction on  $B^- \to \Sigma_c^+ \overline{p} \pi^-$  could be deduced from the already measured decays via  $\Sigma_c^{++}$  or  $\Sigma_c^0$  baryons. Especially, since the branching fractions tend to differ significantly, e.g. the large branching ratio  $\mathcal{B}\left(\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-\right) = (1.4 \pm 0.1 \pm 0.2 \pm 0.3) \cdot 10^{-4}$ compared with the result for the neutral mode  $\mathcal{B}\left(\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+\right) < 0.38 \cdot 10^{-4}$  [6]



Figure A.34:  $B^- \to \Sigma_c^+(2800)\overline{p}\pi^-$  background Monte-Carlo: upper row: left  $m_{inv}:m(\Lambda_c^+\pi^+)$ , right  $m_{inv}:m(\Lambda_c^+\pi^-)$ ; middle row: left  $m_{\rm ES}$ , right  $m_{inv}$ ; lower row: from the  $m_{inv}:m_{\rm ES}$  signal region: left  $m(\Lambda_c^+\pi^+)$ , right  $m(\Lambda_c^+\pi^-)$ 



Figure A.35:  $m_{inv}$ : signal fit with and without signal PDFs for  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  with fixed shape parameters from Monte-Carlo and free floating scaling.

Table A.9:  $m_{inv}$ : signal fit with and without signal PDFs for  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$  with fixed shape parameters from Monte-Carlo and free floating scaling.

PDF	N
—	$545.867 \pm 40.7737$
$\Sigma_{c}^{+}(2455)$	$519.475 \pm 39.3748$
$\Sigma_{c}^{+}(2520)$	$430.59 \pm 44.3423$
$\Sigma_c^+(2455, 2520)$	$444.93 \pm 45.394$

# A.10 Background from events with similar or the same final state particles

On the search for background events with dangerous peak-like structures in the signal variables, Monte-Carlo simulated events were studied for suspected decay modes.

## A.10.1 Background from $B \to D^{(*)+/0} p \overline{p} X$ events

Figure A.36 shows the distributions of Monte-Carlo simulated events for  $\overline{B}^0 \to D^0 p \overline{p} \pi^+ \pi^-$ ;  $D^0 \to K^- \pi^+$ in  $m\left(K_{D^0}^- \pi_{D^0/\overline{B}^0}^+\right)$  from the signal region in  $m_{inv}$  and  $m_{\rm ES}$ . Here, two permutations are possible for a  $m\left(K^-\pi^+\right)$  combination with the  $\pi^+$  either mis-reconstructed as  $\Lambda_c^+$ -daughter or as  $\overline{B}^0$ -daughter. Due to the mass cuts on  $\Lambda_c^+$ , the contributions from the permutation  $m\left(K_{A_c^+}^- \pi_{A_c^+}^+\right)$  would not appear as peaking background. The decay cascade  $\overline{B}^0 \to D^{*+} p \overline{p} \pi^-$ ,  $D^{*+} \to D^0 \pi^+$ ,  $D^0 \to K^- \pi^+$  is as intermediate resonant decay to  $\overline{B}^0 \to D^0 p_{\overline{B}^0} \overline{p}_{\overline{B}^0} \pi_{\overline{B}^0}^+ \pi_{\overline{B}^0}^-$  similar as recombined peaking background in the signal distributions. Figures A.37 and A.38 show the distributions in the signal variables  $m_{\rm ES}$ ,  $m_{inv}$  and  $m\left(\Lambda_c^+\pi^+\right)$ , where these events tend to appear signal-like.

Further Monte-Carlo simulations of the form  $B \to D^{(*)+/0} p\overline{p} X$  were studied, if they could contribute as background peaking in one or more signal variables. Figures A.39 to A.43 show the distributions in  $m_{\rm ES}$ from the studied decays. The modes with a signal like structure were taken into account; all remaining decays were assumed to contribute only as combinatorial background.



Figure A.36:  $m\left(K_{D^0}^-\pi_{D^0/\overline{B}^0}^+\right)$  from Monte-Carlo simulated  $\overline{B}^0 \to D^0 p \overline{p} \pi^+ \pi^-$ ;  $D^0 \to K^- \pi^+$  without  $D_0^+$  veto

# A.10.2 Background from $\overline{B}{}^0 \to (c\overline{c})_{\text{charmonium}} + X$ events with $(c\overline{c}) \to p\overline{p} [\pi^+\pi^-]$

Final state particles of some decays with charmonia can be rearranged to form the signal mode.  $\overline{B}^0$  mesons decays with the same final state particles can have the form  $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} \pi^+ \pi^-$  or  $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0}$ . The



Figure A.37: Monte-Carlo events:  $\overline{B}^0 \to D^{*+}p\overline{p}\pi^-$ ;  $D^{*+} \to D^0\pi^+$ ;  $D^0 \to K^-\pi^+$  without  $D^+_0$  veto:  $m_{\rm ES}$ ,  $m_{inv}$  and  $m_{inv}$ :  $m_{\rm ES}$  plane.  $m_{inv}$  was fitted with a Gaussian for the peak and a second order polynomial for background.



Figure A.38: Monte-Carlo events:  $\overline{B}^0 \to D^{*+}p\overline{p}\pi^-$ ;  $D^{*+} \to D^0\pi^+$ ;  $D^0 \to K^-\pi^+$  without  $D^+_0$  veto: left row  $m(\Lambda_c^+\pi^+)$  and  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane, right row  $m(\Lambda_c^+\pi^-)$  and  $m_{inv}:m(\Lambda_c^+\pi^-)$  plane

charmonium can decay further into two baryons, either  $(c\overline{c}) \to p\overline{p}$  or  $(c\overline{c}) \to p\overline{p}\pi^+\pi^-$ . The  $\overline{K}^{*0}$  decays dominantly via  $\overline{K}^{*0} \to K^-\pi^+$ . The final state particles  $\overline{B}^0 \to p_{(c\overline{c})}\overline{p}_{(c\overline{c})}K^-_{\overline{K}^{*0}}\pi^+_{\overline{K}^{*0}}\pi^+_{\overline{B}^0/(c\overline{c})}\pi^-_{\overline{B}^0/(c\overline{c})}$  can be reordered to the signal decay final state configuration  $\overline{B}^0 \to \left[p_{(c\overline{c})}K^-_{\overline{K}^{*0}}\pi^+_{\overline{K}^{*0}}\right]_{\sim A_c^+}\overline{p}_{(c\overline{c})}\pi^+_{\overline{B}^0/(c\overline{c})}\pi^-_{\overline{B}^0/(c\overline{c})}$ . The branching ratios for B



Figure A.39:  $\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$  without  $D_0^+$  veto from Monte-Carlo modes SP-8016-8033 (See table A.4 for the specific mode reference) without vetos on  $D^0$  or  $D^+$  masses.



Figure A.40:  $\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$  without  $D_0^+$  veto from Monte-Carlo modes SP-8034-8053 (See table A.4 for the specific mode reference) without vetos on  $D^0$  or  $D^+$  masses.

decay into possible charmonia jpsi(1S), psi(2S),  $\chi_{c1}(1P)$  and the charmonia branching ratios into baryons are given in table A.10. The daughter baryons carry most of the momentum and energy of the initial  $\overline{B}^0$ and charmonium and lie in extreme regions of the phase space. To approximate the maximum number of contributing events an pessimistic large upper reconstruction efficiency of 0.1% was assumed. The numbers of expected background events based on this assumption are listed in table A.11.

In data no signals of  $J/\psi(1S), \psi(2S), \chi_{c1}(1P)$  were found in the  $m\left(p_{A_c^+}\overline{p}_{\overline{B}^0}\right)$  or  $m\left(p_{A_c^+}\overline{p}_{\overline{B}^0}\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0}^-\pi_{\overline{B}^0}^+\pi_{\overline{B}^0$ 



Figure A.41:  $\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$  without  $D_0^+$  veto from Monte-Carlo modes SP-8073-8091 (See table A.4 for the specific mode reference) without vetos on  $D^0$  or  $D^+$  masses.



Figure A.42:  $\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$  without  $D_0^+$  veto from Monte-Carlo modes SP-8092-8110 (See table A.4 for the specific mode reference) without vetos on  $D^0$  or  $D^+$  masses.

distributions as shown in figures A.44 and A.45. Therefore, it is assumed that for background from charmonium modes no vetoes were necessary; a systematic uncertainty was taken into account.



Figure A.43:  $\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$  without  $D_0^+$  veto from Monte-Carlo modes SP-8111-8120 (See table A.4 for the specific mode reference) without vetos on  $D^0$  or  $D^+$  masses.

Table A.10:  $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} [\pi^+\pi^-]$ :  $\mathcal{B}$  for  $\overline{B}^0$  decays into charmonium states with proton daughters.

$\overline{B}^0$ mode	$(c\overline{c})$ mode
$\mathcal{B}\left[\overline{B}^0 \to J/\psi(1S)\overline{K}^{*0}\right] = (1.33 \pm 0.06) \cdot 10^{-3}$	$\mathcal{B}\left[J/\psi\left(1S\right) \to p\overline{p}\pi^{+}\pi^{-}\right] = (6.0 \pm 0.5) \cdot 10^{-3}$
$\mathcal{B}\left[\overline{B}{}^{0} \to J/\psi\left(1S\right)\overline{K}{}^{*0}\pi^{+}\pi^{-}\right] = \left(6.6 \pm 2.2\right) \cdot 10^{-4}$	$\mathcal{B}\left[J\!/\!\psi\left(1S\right) \to p\overline{p}\right] = (2.17 \pm 0.07) \cdot 10^{-3}$
$\mathcal{B}\left[\overline{B}{}^0 \to \psi(2S)\overline{K}{}^{*0}\right] = (7.2 \pm 0.8) \cdot 10^{-4}$	$\mathcal{B}[J/\psi(2S) \to p\overline{p}\pi^{+}\pi^{-}] = (6.0 \pm 0.5) \cdot 10^{-3}$
$\mathcal{B}\left[\overline{B}^0 \to \chi_{c1}(1P)\overline{K}^{*0}\right] = (3.2 \pm 0.6) \cdot 10^{-4}$	$\mathcal{B}[\chi_{c1}(1P) \to p\overline{p}\pi^+\pi^-] = (2.1 \pm 0.7) \cdot 10^{-3}$

Table A.11:  $\overline{B}{}^0 \to (c\overline{c}) \overline{K}{}^{*0} [\pi^+\pi^-]$ : Expected events with an assumed upper reconstruction efficiency of  $\epsilon_{\sim wc} = 0.1\%$  and  $\mathcal{B} \left[ \overline{K}{}^{*0} \to K^-\pi^+ \right] = {}^2/{}_3$ 

$\overline{B}^0$ mode	expected events
$\overline{B}{}^{0} \to J/\psi(1S)\overline{K}{}^{*0}$	$\sim 2.5$
$\overline{B}{}^{0} \rightarrow J\!/\psi(1S)\overline{K}{}^{*0}\pi^{+}\pi^{-}$	$\sim 0.5$
$\overline{B}{}^0 \to \psi(2S) \overline{K}{}^{*0}$	$\sim 1.3$
$\overline{B}{}^0 \to \chi_{c1}(1P)\overline{K}{}^{*0}$	$\sim 0.2$



Figure A.44:  $\overline{B}^0 \rightarrow \left(p_{(c\overline{c})}\overline{p}_{(c\overline{c})}\right) K^-\pi^+\pi^+\pi^-$ :  $m\left(p_{A_c^+}\overline{p}_{\overline{B}^0}\right)$  distribution form the  $m_{\rm ES}$  and  $m_{inv}$  signal region with side bands substracted. Masses of charmonia are denoted.





### A.11 Fit verification on Monte-Carlo and side-band data

## A.11.1 Non- $\Sigma_c$ (2455,2520) $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ events

Similar to the one-dimensional fit verification of eq. 3.18 for distributions of non-resonant events in  $m(\Lambda_c^+\pi^{\pm})$  given in section A.8.2, the verification of the applicability of the two-dimensional PDF 3.20 for non- $\Sigma_c$  events decaying into the final state  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  was tested in fits on distributions of  $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ .

The applicability of the two-dimensional analytical PDF (eq. 3.20) for non- $\Sigma_c$  (2455,2520) signal contributions, i.e. all decays to the four-body final state without the signal  $\Sigma_c$  resonances (see section 3.8.3), was verified by fitting toy mixtures of Monte-Carlo simulated modes. Since the exact *composition* of non-resonant signal modes in data is not known yet and to test the robustness of the fit function, toy Monte-Carlo mixtures were produced from randomly weighted non-signal- $\Sigma_c$  (2455,2520) Monte-Carlo sets, for example a toy Monte-Carlo mixture of:

$$0.114 \times \overline{B}{}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{-})}{MC} + 0.263 \times \overline{B}{}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC}$$

$$+ 0.247 \times \overline{B}{}^{0} \to \Sigma_{c}^{++} (2455) \overline{p} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{-})}{MC} + 0.120 \times \overline{B}{}^{0} \to \Sigma_{c}^{0} (2520) \overline{p} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC}$$

$$+ 0.042 \times \overline{B}{}^{0} \to \Sigma_{c}^{++} (2800) \overline{p} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{-})}{MC} + 0.120 \times \overline{B}{}^{0} \to \Lambda_{c}^{+} \Delta^{--} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC}$$

$$+ 0.094 \times \overline{B}{}^{0} \to \Lambda_{c}^{+} \Delta^{--} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{-})}{MC}$$

$$(A.48)$$

The toy Monte-Carlo mixtures were fitted with PDF 3.20 in the range  $m_{inv} \in (5.26, 5.3) \text{ GeV}/c^2 \times m(\Lambda_c \pi) \in (2.425, 3.025) \text{ GeV}/c^2)$ . Figure A.46 shows the fit input and fit quality distributions for toy Monte-Carlo (eq. A.48). The input distribution in  $m(\Lambda_c^+\pi^{\pm})$  from toy Monte-Carlo is shown in the upper plot. The middle plot shows the bin-wise difference between the input from toy Monte-Carlo (eq. A.48) and the fitted PDF 3.20. The lower plot shows the  $\chi^2$ -distribution between the toy Monte-Carlo Carlo Carlo Carlo PDF per bin, i.e.

$$\chi_i^2 = \frac{\left(n_i^{in} - n_i^{fit}\right)^2}{n_i^{fit}}$$
(A.49)

All parameters were allowed to float including the quadratic polynomial parameterization for the with of the Gaussian in  $m_{inv}$  (see eq. 3.17). The PDF was successful to fit to the mixtures, as visible for the example in the difference- and  $\chi^2$ -plots fluctuating around zero. The fitted PDF is shown in figure A.47. Results from fitting this sample can be found in tables A.12 and A.13.

Because the polynomial parameters a, b, c of the Gaussian width were found highly correlated and because of the smaller statistics in data, for fits on data the linear and quadratic parameters a and bwere fixed to Monte-Carlo results and only the scaling parameter c was allowed to float. A systematic uncertainty was taken into account by varying the fixed linear and quadratic parameters a and b within the uncertainties. The maximal variation in the reconstructed event number of 0.12% was taken as systematic uncertainty.



Figure A.46:  $m_{inv}:m(\Lambda_c^+\pi^\pm)$ : fitted toy Monte-Carlo mixture (eq. A.48). The distribution was fitted with function 3.20. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.47:  $m_{inv}:m(\Lambda_c^+\pi^\pm)$ : PDF 3.20 fitted to toy Monte-Carlo mixture eq. A.48.

Table A.12: Non-resonant  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ : Correlation matrix from fitting the toy mixture given in subsection txt:NonResFitVerification with function 3.20.

	S	$\mu_{m_{inv}}$	$\sigma a m_{inv}$	$\sigma bm_{inv}$	$\sigma cm_{inv}$	$A_{m(\Lambda_c\pi)}$	$B_{m(\Lambda_c\pi)}$	$C_{m(\Lambda_c\pi)}$
S	1.000	0.022	0.048	-0.023	0.040	0.235	-0.882	-0.640
$\mu_{m_{inv}}$		1.000	0.009	-0.010	0.005	0.017	-0.022	-0.014
$\sigma a m_{inv}$			1.000	-0.958	0.994	-0.026	-0.098	-0.122
$\sigma bm_{inv}$				1.000	-0.981	0.024	0.086	0.127
$\sigma cm_{inv}$					1.000	-0.027	-0.093	-0.125
$PolyA_{m(\Lambda_c\pi)}$						1.000	-0.389	-0.504
$PolyB_{m(\Lambda_c\pi)}$							1.000	0.915
$PolyC_{m(\Lambda_c\pi)}$								1.000

Table A.13: Non-resonant  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ : Results from fitting the toy mixture given in subsection txt:NonResFitVerification with function 3.20.

Parameter	Fit Value
S	$187947\pm2113$
$\mu m_{inv}$	$5.27906 \pm 0.000023$
$\sigma a m_{inv}$	$0.1116\pm0.037$
$\sigma bm_{inv}$	$-0.4573 \pm 0.037$
$\sigma cm_{inv}$	$0.01137 \pm 0.0006$
$PolyA_{m(\Lambda_c\pi)}$	$0.0012 \pm 0.00013$
$PolyB_{m(\Lambda_c\pi)}$	$1.77\pm0.06$
$PolyC_{m(\Lambda_c\pi)}$	$-0.392 \pm 0.010$

### A.11.2 Combinatorial events with $\Sigma_c$ resonances

As described in section 3.8.2 combinatorial events with  $\Sigma_c$  baryons had to be separated from combinatorial events without resonances. These background events were described by the PDF given in eq. 3.17. To study these background contributions, Monte-Carlo data sets for the decays  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  and  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$  were used as high luminosity samples. These events distribute as combinatorial background in  $m_{inv}$  while they appear as  $\Sigma_c^0(2455,2520)$  signals in  $m(\Lambda_c^+\pi^-)$ . For Monte-Carlo events from  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  figures A.48 and A.49 show the fit results and the fitted

For Monte-Carlo events from  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  figures A.48 and A.49 show the fit results and the fitted PDF (eq. 3.17). For the  $\Sigma_c^0(2455)$  signal shape in  $m(\Lambda_c^+\pi^-)$  the effective mean and width were fixed to Monte-Carlo values from signal Monte-Carlo (see table 4.8). The fit was successful with a fit probability of  $P(\chi^2) = 0.000945565$ .

The fit was repeated with free floating shape parameters and converged successfully with  $P(\chi^2) = 0.451456$  The slope parameter  $A_{\Sigma_c^0(2455)}$  in  $m_{inv}$  were consistent in both fits and was nearly uncorrelated with any other parameter, which justified the separation ansatz in function 3.17.

Analogous to Monte-Carlo for  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^-$ , fits with fixed and free floating shape parameters were done with PDF eq. 3.17 on  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^-$  signal Monte-Carlo. With shape parameters for the  $\Sigma_c^0(2520)$  resonance fixed according to table 4.8 the fit converged successfully with  $P(\chi^2) = 0.0589243$ . The fit results are shown in figures A.50 and A.51. The fit with free floating shape parameters converged successfully with  $P(\chi^2) = 0.166899$ .

Also for fits to  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^-$  the slopes from fits with free floating parameters and fixed parameters were in good agreement with each other.



Figure A.48:  $\Sigma_c^0(2455)$  in combinatorial background: Fit to Monte-Carlo events from  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$  with function 3.17. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.49:  $\Sigma_c^0(2455)$  in combinatorial background: Fitted function 3.17 to Monte-Carlo events from  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ .



Figure A.50:  $\Sigma_c^0(2520)$  in combinatorial background: Fit to signal Monte-Carlo for  $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$  with function 3.17. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.51:  $\Sigma_c^0(2520)$  in combinatorial background: Fitted function 3.17 to signal Monte-Carlo for  $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ .

## A.11.3 $\Sigma_c$ (2455,2520) masses and widths

Figure A.52 shows the fits to  $4.4\mathchar`-4.7$ 



Figure A.52: Fits to side-band subtracted  $m\left(\Lambda_c^+\pi^\pm\right)$ 

### A.11.4 Combinatorial background fit verifications

To verify the PDFs for combinatorial backgrounds, distributions from side-band events in data and from generic Monte-Carlo events were studied. Since these distributions consist of combinatorial background (see section 3.8.1) and combinatorial background events with true  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) resonances (see sections 3.8.2 and A.11.2) the verification was done for the combined PDF, consisting of the PDFs for each of the three combinatorial background species.

161

Events from Monte-Carlo samples or from the side-band regions in  $m_{inv}$  were fitted with PDF (eq. 3.17) for  $\Sigma_c^{++}(2455)$  and  $\Sigma_c^{++}(2520)$  in combinatorial background. They were added to the global PDF combined with the PDF for *generic* combinatorial background (eq. 3.15).

#### Fits to generic $B^+B^-$ Monte-Carlo

As purely combinatorial background sample, generic Monte-Carlo for  $B^+B^-$  events was fitted<sup>2</sup>. Fits to generic  $B^+B^-$  Monte-Carlo are shown in figures A.53 and A.54 for  $m_{inv}:m(\Lambda_c^+\pi^-)$  and in figures A.55 and A.56 for  $m_{inv}:m(\Lambda_c^+\pi^+)$ . Both fits were successful with a fit probability of  $P(\chi^2) = 0.592697$  and  $P(\chi^2) = 0.437789$  (since the fits were performed as likelihood fits, the fit probabilities were calculated from the after the fit had convergenced). The fit results are given in tables A.14-A.16.

### Fits to generic $B^0\overline{B}^0$ Monte-Carlo

As sample of Monte-Carlo including combinatorial background and signal, generic  $B^0\overline{B}^0$  Monte-Carlo was fitted<sup>3</sup>. Results from fitting the  $m_{inv}: m(\Lambda_c^+\pi^+)$  plane are shown in figures A.59 and A.60. The fit was successful with a fit probability of  $P(\chi^2) = 0.199198$  (since the fits were performed as likelihood fits, the fit probabilities was calculated from the after the fit had convergenced). The fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  is shown in figures A.57 and A.58 and was successful with a fit probability of  $P(\chi^2) = 0.00465727$ . The fit results are given in tables A.18-A.21.

Here, the higher luminosity of generic  $B^0\overline{B}^0$  Monte-Carlo compared to data becomes noticeable as the signal decays start to *leak* into the side-bands.

#### Side-band fits in data

In data the side-band region in  $m_{inv}$  without signal events or peaking background events was studied. The fit region consisted of the two sub-regions  $m_{inv} \in (5.172, 5.228) \text{ GeV}/c^2, m(\Lambda_c^+\pi^{\pm}) \in (2.425, 3.025)$ and  $m_{inv} \in (5.324, 5.38) \text{ GeV}/c^2, m(\Lambda_c^+\pi^{\pm}) \in (2.425, 3.025)$  excluding the signal region in  $m_{inv}$ .

In the fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  the allowed floating range of the slope in  $m_{inv}$  was limited to a reasonable range, i.e.  $A_{\Sigma_c^0(2520)} \in (-100, 0.)$ , which included the slopes from fits to generic and signal Monte-Carlo events. This was necessary, since the PDF for combinatorial background with  $\Sigma_c^0(2520)$  resonances was not significant in the  $m_{inv}$ side bands (see projections in figure 3.19). The fit to the  $m_{inv}:m(\Lambda_c^+\pi^-)$ plane was successful with a fit probability of  $P(\chi^2) = 0.143947$ . In figure A.61 the input distribution from data is shown with the excluded signal region hatched; the difference between data and fit as well as the bin-wise  $\chi^2$  distribution of the fit are shown below. The fitted PDFs for all three combinatorial background species are shown in figure A.62 (the fit results are given in tables A.22-A.24).

The fit to the  $m_{inv}:m(\Lambda_c^+\pi^+)$  plane was successful with a fit probability of  $P(\chi^2) = 0.833455$ . The fit is shown in figures A.63 and A.64 (the fit results are given in tables A.23-A.25).

The background PDFs were able to describe the range of data and Monte-Carlo distributions. In particular, the shape of combinatorial background without  $\Sigma_c$  (2455,2520) resonances varied between data and Monte-Carlo samples and between  $m(\Lambda_c^+\pi^+)$  and  $m(\Lambda_c^+\pi^-)$ . For example compare the fitted

<sup>&</sup>lt;sup>2</sup>Generic  $B^+B^-$  Monte-Carlo: projections onto  $m_{inv}$ ,  $m\left(\Lambda_c^+\pi^+\right)$  and  $m\left(\Lambda_c^+\pi^-\right)$  are shown in figure 3.16 <sup>3</sup>Generic  $B^0\overline{B}^0$  Monte-Carlo: projections onto  $m_{inv}$ ,  $m\left(\Lambda_c^+\pi^+\right)$  and  $m\left(\Lambda_c^+\pi^-\right)$  are shown in figure 3.17

PDFs for non-resonant combinatorial background along  $m(\Lambda_c^+\pi^-)$  and  $m(\Lambda_c^+\pi^+)$  in the upper plots of figures A.54 and A.56 with their different maxima positions. The PDFs were flexible enough to adapt to each distribution. Hence, it was assumed that also the combinatorial background contributions in the full signal region could be described in a fit.

Table A.14: Combinatorial background: results from fitting generic  $B^+B^-$  MC (SP-1235) in  $m_{inv}:m(\Lambda_c^+\pi^-)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10, 0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{CombiBkg}$	$11.2 \pm 0.4$
$A^{m_{inv}}_{CombiBkg}$	$-1.7989 \pm 0.0003$
$A_{CombiBkq}^{m(\Lambda_c\pi)}$	$2.42\pm0.15$
$B_{CombiBkq}^{m(\Lambda_c\pi)}$	$0.534 \pm 0.025$
$S_{\Sigma_c(2455) Bkg}$	$11.6\pm1.7$
$A_{\Sigma_c(2455) Bkg}$	$-1.23\pm2.24$
$S_{\Sigma_c(2520) Bkg}$	$2.0\pm24.6$
$A_{\Sigma_c(2520) Bkg}$	$-3.58 \pm 1.58$

Table A.15: Combinatorial background: results from fitting generic  $B^+B^-$  MC (SP-1235) in  $m_{inv}:m(\Lambda_c^+\pi^+)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{CombiBkg}$	$7.57804 \pm 0.34$
$A_{CombiBkg}^{m_{inv}}$	$-0.17873 \pm 0.0004$
$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$3.37\pm0.12$
$B_{CombiBkq}^{m(\Lambda_c\pi)}$	$0.435 \pm 0.019$
$S_{\Sigma_c(2455) Bkg}$	$5.78 \pm 1.10$
$A_{\Sigma_c(2455) Bkg}$	$-9.2\pm2.7$
$S_{\Sigma_c(2520) Bkg}$	$128.6\pm46.7$
$A_{\Sigma_c(2520) Bkg}$	$-5.1 \pm 4.8$



Figure A.53:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  including the  $m_{inv}$  signal region in generic  $B^+B^-$ Monte-Carlo. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.54:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  including the  $m_{inv}$  signal region in generic  $B^+B^-$ Monte-Carlo. Plots from top-down: Combinatorial background,  $\Sigma_c^0(2455)$  in combinatorial background,  $\Sigma_c^0(2520)$  in combinatorial background



Figure A.55:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in generic  $B^+B^-$ Monte-Carlo. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.56:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in generic  $B^+B^-$ Monte-Carlo. Plots from top-down: Combinatorial background,  $\Sigma_c^{++}(2455)$  in combinatorial background,  $\Sigma_c^{++}(2520)$  in combinatorial background



Figure A.57:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  including the  $m_{inv}$  signal region in generic  $B^0\overline{B}^0$ Monte-Carlo. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.58:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  including the  $m_{inv}$  signal region in generic  $B^0\overline{B}^0$ Monte-Carlo. Plots from top-down: Combinatorial background,  $\Sigma_c^0(2455)$  in combinatorial background,  $\Sigma_c^0(2520)$  in combinatorial background



Figure A.59:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in generic  $B^0\overline{B}^0$ Monte-Carlo. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.60:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in generic  $B^0\overline{B}^0$ Monte-Carlo. Plots from top-down: Combinatorial background,  $\Sigma_c^{++}(2455)$  in combinatorial background,  $\Sigma_c^{++}(2520)$  in combinatorial background



Figure A.61:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  excluding the  $m_{inv}$  signal region in data. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.62:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  excluding the  $m_{inv}$  signal region in data. Plots from top-down: Combinatorial background,  $\Sigma_c^0(2455)$  in combinatorial background,  $\Sigma_c^0(2520)$  in combinatorial background

Table A.16: Combinatorial background: Correlation matrix from fitting generic  $B^+B^-$  MC (SP-1235) in  $m_{inv}:m(\Lambda_c^+\pi^-)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes allowed to assume only negative values (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{Combi\ Bkg}^{m(\Lambda_c\pi)}$	$B^{m(\Lambda_c\pi)}_{CombiBkg}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520) Bkg}$
$S_{CombiBkg}$	1.000	-0.824	-0.381	-0.160	0.002	0.063	0.079	0.218
$A^{m_{inv}}_{CombiBkg}$		1.000	-0.001	0.007	0.011	-0.074	0.037	-0.268
$A_{CombiBkg}^{m(\Lambda_c\pi)}$			1.000	0.874	0.231	-0.026	0.016	0.004
$B_{CombiBkg}^{m(\Lambda_c\pi)}$				1.000	0.352	-0.037	0.229	-0.003
$S_{\Sigma_c(2455) Bkg}$					1.000	-0.175	0.134	-0.005
$A_{\Sigma_c(2455) Bkg}$						1.000	-0.023	-0.012
$S_{\Sigma_c(2520) Bkg}$							1.000	-0.095
$A_{\Sigma_c(2520) Bkg}$								1.000

Table A.17: Combinatorial background: Correlation matrix from fitting generic  $B^+B^-$  MC (SP-1235) in  $m_{inv}:m(\Lambda_c^+\pi^+)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$B^{m(\Lambda_c\pi)}_{CombiBkg}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520) Bkg}$
$S_{Combi Bkg}$	1.000	-0.872	-0.348	-0.067	0.012	-0.395	0.171	0.337
$A_{CombiBkg}^{m_{inv}}$		1.000	-0.027	-0.105	-0.004	0.439	-0.052	-0.363
$A_{CombiBkg}^{m(\Lambda_c\pi)}$			1.000	0.831	0.144	-0.072	-0.106	-0.021
$B_{CombiBkg}^{m(\Lambda_c\pi)}$				1.000	0.268	-0.253	0.197	0.035
$S_{\Sigma_c(2455) Bkg}$					1.000	-0.068	0.120	0.021
$A_{\Sigma_c(2455) Bkg}$						1.000	-0.183	-0.074
$S_{\Sigma_c(2520) Bkg}$							1.000	0.085
$A_{\Sigma_c(2520) Bkg}$								1.000

Table A.18: Combinatorial background: results from fitting generic  $B^0\overline{B}^0$  MC (SP-1237) in  $m_{inv}:m(\Lambda_c^+\pi^-)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10, 0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{CombiBkg}$	$0.96\pm0.15$
$A_{CombiBkg}^{m_{inv}}$	$-0.1591 \pm 0.0046$
$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$3.36\pm0.23$
$B_{CombiBkg}^{m(\Lambda_c\pi)}$	$0.2279 \pm 0.0029$
$S_{\Sigma_c(2455) Bkg}$	$44.7\pm3.5$
$A_{\Sigma_c(2455) Bkg}$	$-3.2 \pm 0.9$
$S_{\Sigma_c(2520) Bkg}$	$193.5\pm32.0$
$A_{\Sigma_c(2520) Bkq}$	$-2.4 \cdot 10^{-14} \pm 0.33$

Table A.19: Combinatorial background: results from fitting generic  $B^0\overline{B}^0$  MC (SP-1237) in  $m_{inv}:m(\Lambda_c^+\pi^+)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10, 0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{CombiBkg}$	$28.1\pm0.7$
$A_{CombiBkg}^{m_{inv}}$	$-0.17559 \pm 0.00032$
$A_{CombiBkq}^{m(\Lambda_c\pi)}$	$2.439 \pm 0.08$
$B^{m(\Lambda_c\pi)}_{CombiBkg}$	$0.369 \pm 0.012$
$S_{\Sigma_c(2455) Bkg}$	$43.8\pm3.4$
$A_{\Sigma_c(2455) Bkg}$	$-9.2\pm7.2\cdot10^{-9}$
$S_{\Sigma_c(2520) Bkg}$	$345.3\pm96.2$
$A_{\Sigma_c(2520) Bkg}$	$-9.3 \pm 2.2 \cdot 10^{-10}$

Table A.20: Combinatorial background: Correlation matrix from fitting generic  $B^0\overline{B}^0$  MC (SP-1237) in  $m_{inv}:m(\Lambda_c^+\pi^-)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$B^{m(\Lambda_c\pi)}_{CombiBkg}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520) Bkg}$
$S_{CombiBkg}$	1.000	-0.955	-0.263	-0.134	-0.015	0.114	0.122	-0.010
$A_{CombiBkg}^{m_{inv}}$		1.000	0.023	0.017	0.025	-0.119	-0.056	0.006
$A_{CombiBkg}^{m(\Lambda_c\pi)}$			1.000	0.832	0.096	-0.001	-0.209	0.003
$B_{CombiBkq}^{m(\Lambda_c\pi)}$				1.000	0.238	0.008	0.012	-0.010
$S_{\Sigma_c(2455) Bkg}$					1.000	-0.036	0.088	-0.006
$A_{\Sigma_c(2455) Bkg}$						1.000	0.012	-0.002
$S_{\Sigma_c(2520) Bkg}$							1.000	-0.012
$A_{\Sigma_c(2520) Bkg}$								1.000

Table A.21: Combinatorial background: Correlation matrix from fitting generic  $B^0\overline{B}^0$  MC (SP-1237) in  $m_{inv}:m(\Lambda_c^+\pi^+)$  (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{Combi\ Bkg}^{m(\Lambda_c\pi)}$	$B_{CombiBkg}^{m(\Lambda_c\pi)}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520)Bkg}$
$S_{CombiBkg}$	1.000	-0.826	-0.388	-0.211	-0.050	-0.004	-0.061	0.003
$A^{m_{inv}}_{CombiBkg}$		1.000	-0.042	0.022	0.066	0.004	0.232	-0.003
$A_{CombiBkg}^{m(\Lambda_c\pi)}$			1.000	0.854	0.138	-0.002	-0.158	0.002
$B_{CombiBkg}^{m(\Lambda_c\pi)}$				1.000	0.253	-0.004	0.051	0.005
$S_{\Sigma_c(2455) Bkg}$					1.000	-0.000	0.094	0.000
$A_{\Sigma_c(2455) Bkg}$						-1.000	-0.008	1.003
$S_{\Sigma_c(2520) Bkg}$							1.000	0.009
$A_{\Sigma_c(2520) Bkg}$								-1.000


Figure A.63:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  excluding the  $m_{inv}$  signal region in data. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.64:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  excluding the  $m_{inv}$  signal region in data. Plots from top-down: Combinatorial background,  $\Sigma_c^{++}(2455)$  in combinatorial background,  $\Sigma_c^{++}(2520)$  in combinatorial background

Table A.22: Combinatorial background: results from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^-)$  in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{CombiBkg}$	$3.54\pm0.27$
$A_{CombiBkg}^{m_{inv}}$	$-0.1732 \pm 0.0011$
$A_{CombiBkq}^{m(\Lambda_c\pi)}$	$3.29\pm0.21$
$B_{CombiBka}^{m(\Lambda_c\pi)}$	$0.49\pm0.03$
$S_{\Sigma_c(2455) Bkg}$	$2.8\pm0.5$
$A_{\Sigma_c(2455) Bkg}$	$-5.6 \pm 1.9$
$S_{\Sigma_c(2520) Bkg}$	$8.8\pm6.0$
$A_{\Sigma_c(2520) Bkg}$	$-1.1 \cdot 10^{-11} \pm 2.8$

Table A.23: Combinatorial background: results from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^+)$  in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

Parameter	Fit Value
$S_{Combi Bkg}$	$3.33\pm0.22$
$A^{m_{inv}}_{CombiBkg}$	$-0.1730 \pm 0.0009$
$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$3.34\pm0.12$
$B_{CombiBkq}^{m(\Lambda_c\pi)}$	$0.424 \pm 0.020$
$S_{\Sigma_c(2455) Bkg}$	$6.6 \pm 1.4$
$A_{\Sigma_c(2455) Bkg}$	$-9.2 \pm 3.3$
$S_{\Sigma_c(2520) Bkg}$	$142.3\pm45.8$
$A_{\Sigma_c(2520) Bkg}$	$-9.1171 \pm 0.0009$

Table A.24: Combinatorial background: Correlation matrix from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^-)$  in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$B^{m(\Lambda_c\pi)}_{CombiBkg}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520) Bkg}$
$S_{CombiBkg}$	1.000	-0.877	-0.353	-0.144	0.001	0.096	0.161	0.003
$A^{m_{inv}}_{CombiBkg}$		1.000	0.007	-0.009	0.009	-0.108	-0.072	-0.003
$A_{CombiBkg}^{m(\Lambda_c\pi)}$			1.000	0.862	0.194	0.058	-0.057	-0.001
$B_{CombiBkg}^{m(\Lambda_c\pi)}$				1.000	0.323	0.097	0.165	-0.001
$S_{\Sigma_c(2455) Bkg}$					1.000	0.090	0.116	-0.003
$A_{\Sigma_c(2455) Bkg}$						1.000	0.039	0.001
$S_{\Sigma_c(2520) Bkg}$							1.000	-0.002
$A_{\Sigma_c(2520) Bkg}$								1.000

Table A.25: Combinatorial background: Correlation matrix from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^+)$  in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).

	$S_{CombiBkg}$	$A_{CombiBkg}^{m_{inv}}$	$A_{CombiBkg}^{m(\Lambda_c\pi)}$	$B_{CombiBkg}^{m(\Lambda_c\pi)}$	$S_{\Sigma_c(2455) Bkg}$	$A_{\Sigma_c(2455) Bkg}$	$S_{\Sigma_c(2520) Bkg}$	$A_{\Sigma_c(2520) Bkg}$
$S_{CombiBkg}$	1.000	-0.893	-0.856	-0.517	-0.068	0.041	-0.112	-0.021
$A^{m_{inv}}_{CombiBkg}$		1.000	0.712	0.721	0.138	-0.049	0.288	0.021
$A^{m(\Lambda_c\pi)}_{CombiBkg}$			1.000	0.641	0.084	-0.017	-0.135	0.023
$B_{CombiBkg}^{m(\Lambda_c\pi)}$				1.000	0.245	-0.009	0.218	0.016
$S_{\Sigma_c(2455) Bkg}$					1.000	-0.002	0.086	0.002
$A_{\Sigma_c(2455) Bkg}$						1.000	0.002	-0.000
$S_{\Sigma_c(2520) Bkg}$							1.000	-0.001
$A_{\Sigma_c(2520) Bkg}$								1.000

#### A.11.5 Fit verification for signal events with and without $\Sigma_c$ resonances

Toy signal Monte-Carlo mixtures were studied if non- $\Sigma_c$  (2455,2520) signal events and resonant signal events can be disentangled in a two-dimensional fit. The toy Monte-Carlo was composed of randomly chosen  $\Sigma_c$  (2455),  $\Sigma_c$  (2520) and non- $\Sigma_c$  (2455,2520) signal Monte-Carlo. The toy Monte-Carlos were studied to determine if the input numbers of the specific event types can be extracted by the fit.

Additionally, it was studied if the  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) signal extraction is influenced by  $\Sigma_c$  (2800) events. If the two lighter  $\Sigma_c$  resonances were fitted in a combined fit in the range  $m(\Lambda_c^+\pi^{\pm}) \in$  (2.425 - 2.625) GeV/ $c^2$ , the question arose if a separate fit PDF for  $\Sigma_c$  (2800) events could be necessary. Therefore, toy Monte-Carlo mixtures were created with and without  $\Sigma_c$  (2800) events.

Each toy mixture was fitted with the  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) signal histograms plus eq. 3.20 as PDF for non- $\Sigma_c$  (2455,2520) signal. The numbers of input  $\Sigma_c$  signal events and the fitted numbers are given in table A.26. All fitted event numbers are in agreement within  $1 \sigma$  with the input signal numbers. It is therefore assumed that  $\Sigma_c^{++}$  (2800) events do not influence lighter resonances, when the fit region is below the  $\Sigma_c^{++}$  (2800) resonance, i.e.  $m (\Lambda_c^+ \pi^{\pm}) < 2.625 \,\text{GeV}/c^2$ . As example, figures A.65 and A.66 show the fit to a toy Monte-Carlo with

$$0.58 \times \overline{B}{}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC} + 0.06 \times \overline{B}{}^{0} \to \Sigma_{c}^{++} (2455) \overline{p} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC} + 0.13 \times \overline{B}{}^{0} \to \Sigma_{c}^{0} (2455) \overline{p} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC} + 0.07 \times \overline{B}{}^{0} \to \Sigma_{c}^{++} (2520) \overline{p} \pi^{-} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC} + 0.08 \times \overline{B}{}^{0} \to \Sigma_{c}^{0} (2520) \overline{p} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC} + 0.09 \times \overline{B}{}^{0} \to \Sigma_{c}^{0} (2800) \overline{p} \pi^{+} \frac{m(\Lambda_{c}^{+} \pi^{+})}{MC}$$

(relative to the total event number). The fit was performed in the  $\Sigma_c$  (2455,2520) signal range  $m_{inv} \in (5.252, 5.308) \,\text{GeV}/c^2$  and  $m \left( \Lambda_c^+ \pi^+ \right) \in (2.425, 2.625) \,\text{GeV}/c^2$ 

Table A.26: Toy mixtures with and without  $\Sigma_c^{++}(2800)$  signal Monte-Carlo events were fitted. The headers give the number of  $\overline{B}^0 \to \Sigma_c^{+}(2455, 2520, 2800)\overline{p}\pi^{\mp}$  Monte-Carlo events added to the toy sample. The central column gives the number of fitted events for the  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$  modes given in the first column. The fit quality results are given in the right column.

$\Sigma_c$	$No_{\Sigma_c}$	$\frac{\chi^2/_{nDOF}}{P(\chi^2)}$
	$\Sigma_{c}^{++}(2455) \times 10238$	$+ \Sigma_{c}^{++}(2520) \times 13152$
$ \begin{array}{c} \Sigma_c \ (2455) \\ \Sigma_c \ (2520) \end{array} $	$\begin{array}{c} 10232.7 \pm 503.813 \\ 13108.3 \pm 892.095 \end{array}$	704.22 /630 0.0210428
$\Sigma_{c}^{++}(2455)$	$\times 10238 + \Sigma_c^{++}(252)$	$20) \times 13152 + \Sigma_c^{++}(2800) \times 15672$
$ \begin{array}{c} \Sigma_c (2455) \\ \Sigma_c (2520) \end{array} $	$\begin{array}{c} 10233.2\pm 503.49\\ 13091.3\pm 873.877\end{array}$	$\begin{array}{c} 708.453 \ / \ 630 \\ 0.0160509 \end{array}$

 $\Sigma_c^{++}(2455) \times 20638 + \Sigma_c^{++}(2520) \times 18697$ 

$\Sigma_c$ (2455)	$20538.7 \pm 344.727$	566.318 / 630
$\Sigma_c$ (2520)	$19007.3 \pm 652.688$	0.96707
$\Sigma_{c}^{++}(2455)$	$\times 20638 + \Sigma_c^{++}(252)$	$20) \times 18697 + \Sigma_c^{++}(2800) \times 31173$
$\Sigma_c$ (2455)	$20528.7 \pm 329.182$	584.867/630
$\Sigma_c$ (2520)	$19016.2 \pm 695.181$	0.900476



Figure A.65:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in a mixture of non- $\Sigma_c$  (2455,2520) signal Monte-Carlo and  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) signal Monte-Carlo. Plots from top-down: the input signal distribution, the difference between the input distribution and the fitted function, the bin-wise  $\chi^2$  distribution of the fit.



Figure A.66:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  including the  $m_{inv}$  signal region in a mixture of non- $\Sigma_c$  (2455,2520) signal Monte-Carlo and  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) signal Monte-Carlo. Plots from top-down:  $\Sigma_c^{++}(2455)$  signal,  $\Sigma_c^{++}(2520)$  signal, non- $\Sigma_c$  (2455,2520) signal.

## A.12 Resonant signal decay measurements in $m_{inv}m\left(\Lambda_c^+\pi^\pm ight)$

In this section additional information on the fit to data can be found.

### A.12.1 Fit to $m_{inv}:m\left(\Lambda_c^+\pi^-\right)$ for $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$

From the fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  figure A.67 shows to fitted PDFs, with the combinatorial background sources in the upper three plots and the three signal event classes in the lower plots. Supplementary to the fit's correlation matrix (eq. 5.2) the covariance matrix is given in table A.27.



Figure A.67: Fit for  $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$  in data: fit PDFs top - down: combinatorial background, combinatorial background with  $\Sigma_c^0(2455)$ , combinatorial background with  $\Sigma_c^0(2520)$ , MC signal histogram:  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ , MC signal histogram:  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ , non-resonant  $\overline{B}^0 \to \Lambda_c^+\overline{p}\pi^+\pi^-$ 

	$S_{CombiBka}$	$A_{CombiBka}^{m_{inv}}$	$A_{CombiBka}^{A_{c}\pi}$	$B_{CombiBka}^{Ac\pi}$	$S_{\Sigma_{\alpha}(2455)}Bka$	$A_{\Sigma_a(2455)Bka}$	$S_{\Sigma_{\alpha}(2520)Bka}$
	0 three larg	ComorBkg	Comorbidg	Comorbag	()g	= E((= :00) = ::g	()g
$S_{CombiBkq}$	$5.92563 \cdot 10^{6}$	-1.42173	-2669.91	-105.177	4699.68	401.172	60944.6
$A_{CombiBkq}^{\dot{m}_{inv}}$		$3.81018 \cdot 10^{-6}$	$6.64366 \cdot 10^{-5}$	$2.27358 \cdot 10^{-6}$	0.000604417	-0.000626078	-0.0107626
$A_{CombiBkq}^{\Lambda_C \pi}$			1.32594	0.0561997	-1.50117	-0.0682169	-29.3508
$B_{CombiBka}^{\Lambda_c \pi}$				0.00299548	0.123738	0.00233731	-1.11072
$S_{\Sigma_c(2455)Bkg}$					600.56	4.09823	156.775
$A_{\Sigma_c(2455)Bkg}$						4.10855	5.81963
$S_{\Sigma_c(2520)Bkg}$							3110.25
$A \Sigma_c (2520) B kg$							
$S_{\Sigma_{c}(2455)}$							
$S_{\Sigma_{c}(2520)}$							
$S_{NonResSignal}$							
$\sigma_{NonResSignal}$							
$C^{B_{NonResSignal}}$							
$C_{NonResSignal}$							

Table A.27:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Covariance matrix from fitting data. (Table I, continued in Table II A.28)

Table A.28:  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Covariance matrix from fitting data. (Table II, continued from Table I A.27)

	$A_{\Sigma_c(2520)Bkg}$	$S_{\Sigma_{c}(2455)}$	$S_{\Sigma_{c}(2520)}$	$S_{NonResSignal}$	$\sigma_{NonResSignal}$	$B_{NonResSignal}$	$C_{NonResSignal}$
$S_{CombiBkq}$	0.00155936	-1903.56	-7469.46	-478988	-0.0917421	3653.47	110.208
$A_{CombiBkq}^{m_{inv}}$	$4.04552 \cdot 10^{-9}$	-0.000167468	0.00166023	0.00857534	$-4.85444 \cdot 10^{-9}$	$-6.77876 \cdot 10^{-5}$	$-1.80477 \cdot 10^{-6}$
$A^{\Lambda_c \pi}_{CombiBkg}$	$-1.71019 \cdot 10^{-6}$	0.893529	3.46372	221.634	$2.83109 \cdot 10^{-5}$	-1.71913	-0.0565796
$B_{CombiBkq}^{\Lambda_c \pi}$	$-1.34414 \cdot 10^{-7}$	0.016194	0.118838	6.95508	$3.37216 \cdot 10^{-6}$	-0.0576185	-0.0026565
$S_{\Sigma_c(2455)Bkq}$	$-3.00639 \cdot 10^{-5}$	-159.79	-24.2621	-978.273	0.00102568	6.94444	0.0133476
$A_{\Sigma_c}(2455)Bkq$	$-7.0329 \cdot 10^{-7}$	-1.20118	-0.976251	-24.6798	$1.80222 \cdot 10^{-5}$	0.180764	0.00156624
$S_{\Sigma_c(2520)Bkq}$	0.000108651	-37.5232	-480.359	-3960.42	-0.000992175	33.0747	1.18844
$A_{\Sigma_c(2520)Bkq}$	$1.70839 \cdot 10^{-8}$	$3.77189 \cdot 10^{-7}$	$-1.42527 \cdot 10^{-5}$	0.000952639	$3.97869 \cdot 10^{-10}$	$-6.38272 \cdot 10^{-6}$	$-4.57414 \cdot 10^{-8}$
$S_{\Sigma_{c}(2455)}$		584.944	65.3834	2564.34	-0.00105785	-18.7678	-0.251765
$S_{\Sigma_{c}(2520)}$			739.37	5396.91	0.00259542	-44.0287	-1.39777
SNonResSignal				435961	0.0116648	-3287.16	-89.5115
σ <sub>Non</sub> ResSignal					$2.3794 \cdot 10^{-6}$	$8.44099 \cdot 10^{-5}$	$-6.47039 \cdot 10^{-6}$
$B_{NonResSignal}$						25.0671	0.722336
$C_{NonResSignal}$							0.0281768

## A.12.2 Fit to $m_{inv}:m\left(\Lambda_c^+\pi^+\right)$ for $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$

In addition to the correlation matrix 5.5 from the fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  for  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^$ the covariance matrix is given in table A.29. In figure A.68 the fitted PDFs for combinatorial background events and signal decays is shown. Figure A.69 shows the fitted contribution from non-SigmaCplpl/2455,2520) signal events as well as the contributions from  $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ , which are a specific background only for decays via  $\Sigma_c^{++}$  resonances.



Figure A.68: Fit for  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  in data: fit PDFs top - down: combinatorial background, combinatorial background with  $\Sigma_c^{++}(2455)$ , combinatorial background with  $\Sigma_c^{++}(2520)$ , MC signal histogram:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ , MC signal histogram:  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ , non-resonant  $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$ 

APPENDIX	
APPENDIX A.	

 $A^{m_{inv}}_{CombiBkg}$  $A^{\Lambda_c \pi}_{CombiBkg}$  $B^{A_c\pi}_{CombiBkg}$  $S_{CombiBkg}$  $S_{\Sigma_{c}(2455)Bkg}$  $^{A}\Sigma_{c}(2455)Bkg$  $S_{\Sigma_c(2520)Bkg}$  $A_{\Sigma_c(2520)Bkg}$  $S_{CombiBkg} \\ A_{CombiBkg}^{minv} \\ A_{c\pi} \\ CombiBkg \\ B_{Ac\pi} \\ CombiBkg \\ \sigma$  $3.47674 \cdot 10^{6}$ 9054.78 -0.000305327 0.415614-1044.34-46.67611653.28-1436.49 $2.53046 \cdot 10^{-6}$  $-5.33342 \cdot 10^{-5}$  $-2.50152 \cdot 10^{-11}$ -0.00074929 -0.00293471 -0.000911415 0.0341757 0.0309117  $8.37192 \cdot 10^{-8}$ 0.4980090.994290.578332-11.8166  $2.70642 \cdot 10^{-9}$ 0.002638590.2593190.0311116-0.697041 $9.73538 \cdot 10^{-7}$ 633.29 11.2046239.061 $S_{\Sigma_c(2455)Bkg}$  $_{4.03815\cdot 10}{}^{-7}$ 10.0024-8.84045  $A_{\varSigma_{c}(2455)Bkg}$  $-4.41043 \cdot 10^{-8}$  $s_{\varSigma_c(2520)Bkg}$ 2760.29 $4.64407 \cdot 10^{-13}$  $^{A}\varSigma_{c}(2520)Bkg$  $S \Sigma_c(2455)$  $S_{\Sigma_c(2520)}$  $S_{NonResSignal}$  $\sigma_{NonResSignal}$  $C_{NonResSignal}$  $S_{\Sigma_{c}(2455)}+$  $S_{\Sigma_{c}(2520)}+$ 

Table A.29:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Covariance matrix from fitting data. (Table I, continued in Table II A.29)

Table A.30:  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Covariance matrix from fitting data. (Table II, continued from Table I A.30)

	$S_{\Sigma_c(2455)}$	$S_{\Sigma_{c}(2520)}$	$S_{NonResSignal}$	$\sigma_{NonResSignal}$	$C_{NonResSignal}$	$S_{\Sigma_{c}(2455)}+$	$S_{\Sigma_{c}(2520)}+$
$S_{CombiBkg}$	10029.1	-198.099	66528.4	-0.17083	38.803	-16356.3	-86380.5
$A^{m_{inv}}_{CombiBkq}$	0.0033809	-0.00440557	0.0270519	$9.67074 \cdot 10^{-7}$	$7.40394 \cdot 10^{-6}$	-0.0765482	-0.00350986
$A^{\Lambda_c \pi}_{CombiBkq}$	-3.8238	1.35472	-32.5132	-0.00018905	-0.0190096	25.0385	21.9332
$B_{CombiBka}^{A_c\pi}$	-0.228598	0.0277066	-2.11726	$-1.16918 \cdot 10^{-5}$	-0.00155736	2.46582	1.6121
$S_{\Sigma_c(2455)Bkq}$	-226.304	-55.1928	-2.25182	-0.00791495	-0.0324104	395.806	34.9504
$A \Sigma_c (2455) B k q$	-11.0907	-1.93186	-12.3024	-0.00097472	0.00821282	0.440784	128.093
$S_{\Sigma_c(2520)Bkg}$	76.352	-669.757	1449.71	-0.00487973	0.771198	-610.186	-484.415
$A_{\Sigma_c(2520)Bkg}$	$-3.66813 \cdot 10^{-6}$	$9.01594 \cdot 10^{-7}$	$-8.55313 \cdot 10^{-6}$	$-1.04062 \cdot 10^{-10}$	-3.38066.10-9	$-4.51164 \cdot 10^{-6}$	$1.92569 \cdot 10^{-5}$
$S_{\Sigma_{c}(2455)}$	1041.62	173.862	210.669	0.00512754	0.418537	-317.917	-141.431
$S_{\Sigma_{c}(2520)}$		1457.95	-1319.4	0.0276322	-0.587124	-75.0382	-666.037
S <sub>NonResSianal</sub>			16749.2	0.0737694	12.8993	2070.92	-1101.93
$\sigma_{NonResSignal}$				$1.20414 \cdot 10^{-5}$	$-6.79743 \cdot 10^{-5}$	-0.0756583	-0.0714926
C <sub>NonResSignal</sub>					0.0137975	3.14603	-0.325042
$S_{\Sigma_{c}(2455)+}$						10868.7	-2280.87
$S_{\Sigma_{c}(2520)}+$							17600.5



Figure A.69: Fit for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$  in data: fit PDFs top - down: non-resonant  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-, B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$  background,  $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$  background

### A.13 $_{s}\mathcal{P}lots$

The  ${}_{s}\mathcal{P}lot$ -formalism proved to be a powerful tool to separate signal and background events. However, because of its limits, the  ${}_{s}\mathcal{P}lot$ -technique was used in this analysis only to correct Monte-Carlo simulated events with the presented weighting method and to the basic distributions of signal events. To implement a signal yield measurement using the  ${}_{s}\mathcal{P}lot$ -technique, a more elaborate study of the correlations between the discriminating variables and the projection variables would have been necessary.

#### A.13.1 Formalism

The  ${}_{s}\mathcal{P}lot$ -technique calculates for each signal or background signal class  $N_{s}$  the so-called  ${}_{s}\mathcal{W}eight {}_{s}w$ . To extract a specific signal class in a given variable, each event is weighted with the corresponding signal class's  ${}_{s}\mathcal{W}eight$ .

To calculate the  ${}_{s}Weights$ , a discriminating variable is necessary, where all signal classes can be distinguished, i.e. for each signal class a probability density  $f_{j}$  can be fitted and measure the number of events for each signal class. As for the side-band subtraction the PDF shapes have to be known a priori. After fitting the PDFs in the discriminating variable, the  ${}_{s}Weights$  can be calculated from the fit's covariance matrix  $V_{N}$ .

For a signal class j the sWeight can be calculated with

$${}_{s}w_{j} = \frac{\sum_{h=1}^{N_{s}} \mathbf{V}_{jh} f_{h}\left(x_{j}\right)}{\sum_{h=1}^{N_{s}} \hat{n}_{k} f_{h}\left(x_{j}\right)}$$
(A.50)

Since the  ${}_{s}\mathcal{P}lot$  formalism does not take correlations between shape variables and the number of events into account, one has to *know* the shape parameters for all *signal classes.*<sup>4</sup> In a straight-forward approach the shape variables and number of events are allowed to float in a first global fit. In a following fit the shape parameters are fixed to the found values, and only the numbers of events for each *signal class* are left floating.

Histograms in other variables than the discriminating variables for a specific signal class can be produced by weighting each event with the  $_{s}Weight$ .

In this measurement the variables to discriminate the signal classes were the  $m_{inv}:m(\Lambda_c^+\pi^+)$  and  $m_{inv}:m(\Lambda_c^+\pi^-)$  planes for the resonant decays and  $m_{inv}$  for the non- $\Sigma_c$  decays. The shape parameters of each signal class were fixed to the values found in the global fits described in the section 5.1. The fits were repeated with only the number of events left free floating for each signal class. From each fit  ${}_{s}Weights$  for the signal class were calculated from the covariance matrices.

#### A.13.2 Result of $_{s}\mathcal{P}lot$ fits in data

To calculate the *sWeights* all four signal fits were repeated with fixed shape parameters and with free floating number of events for each *signal class*. The shape parameters for the fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$  were taken from table 5.1. For the fit to  $m_{inv}:m(\Lambda_c^+\pi^-)$  the used shape parameter are given in table 5.4. For the fit to  $m_{inv}$  from region  $I_{\Sigma_c}$  the shape parameters were used given in table 5.7 and for the fit to  $m_{inv}$  from region  $I_{\Sigma_c}$  from table 5.11.

The results are given in table A.31 from fitting  $m_{inv}:m(\Lambda_c^+\pi^+)$ , in table A.32 from fitting  $m_{inv}:m(\Lambda_c^+\pi^-)$ , in table A.33 from fitting  $m_{inv}$  from region  $I_{\Sigma_c}$  and in table A.34 from fitting  $m_{inv}$  from region  $I_{\Sigma_c}$ .

#### A.13.3 Interpretation of $_{s}\mathcal{P}lot$ distributions

Decays into the three-body intermediate states with  $\Sigma_c$  resonances could proceed via initial two-baryon states (or two-meson initial states). For example states with resonant nucleons  $\overline{N}^*$  are conceivable.

<sup>&</sup>lt;sup>4</sup>The  ${}_{s}\mathcal{P}lot$ -technique requires that the discriminating variable and the variable for the  ${}_{s}\mathcal{P}lot$ -projection have to be uncorrelated. Since in this analysis the  ${}_{s}\mathcal{P}lot$ -technique was only used for the MC correction in a coarse binning and not for the actual signal yield measurements, the correlations between discriminating and  ${}_{s}\mathcal{P}lot$ ted variables were ignored.

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$2592.14 \ / \ 2592 \rightarrow 0.49553$
$N_{CombiBkg}$	$4817.38 \pm 178.142$
$N_{\Sigma_c(2455)Bkg}$	$109.032 \pm 26.1716$
$N_{\Sigma_c(2520)Bkg}$	$180.284 \pm 52.7974$
$N_{\Sigma_{c}(2455)}$	$722.571 \pm 34.0503$
$N_{\Sigma_{c}(2520)}$	$458.213 \pm 40.6846$
$N_{NonResSignal}$	$415.331 \pm 64.9539$
$N_{\Sigma_{c}(2455)^{+}}$	$164.345 \pm 94.3841$
$N_{\Sigma_{c}(2520)^{+}}$	$272.827 \pm 142.095$

Table A.31:  ${}_{s}\mathcal{P}lots$  from fit to  $m_{inv}:m(\Lambda_{c}^{+}\pi^{+})$ : Results from fitting with fixed shape parameters.

Table A.32:  ${}_{s}\mathcal{P}lots$  from fit to  $m_{inv}:m(\Lambda_{c}^{+}\pi^{-})$ : Results from fitting with fixed shape parameters.

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$2682.18 \; / \; 2594 \to 0.11126$
$N_{CombiBkg}$	$4751.22 \pm 93.7395$
$N_{\Sigma_c(2455)Bkg}$	$141.263 \pm 22.9949$
$N_{\Sigma_c(2520)Bkg}$	$63.3393 \pm 49.8174$
$N_{\Sigma_{c}(2455)}$	$346.595 \pm 24.1552$
$N_{\Sigma_c(2520)}$	$86.8203 \pm 25.5525$
$N_{NonResSignal}$	$500.252 \pm 48.6429$

However the possible nucleon resonances are quite broad and overlap. Figure A.70 sketches the distribution of such nucleon resonances in the  $m(\bar{p}\pi^+)$  distribution. To disentangle the possible intermediate states, one would have to perform a study of the angular distribution of the alleged  $N^*$  daughters  $\bar{p}\pi^+$ , which would need more statistics.

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$207.631 / 206 \rightarrow 0.455023$
$N^{Bkg}$	$3800.97 \pm 77.9493$
$N^{Signal}$	$540.52 \pm 49.7342$

Table A.33:  ${}_{s}\mathcal{P}lots$  from fit to  $m_{inv}$  from region  $I_{\Sigma_{c}}$ : Results from fitting with fixed shape parameters.

Table A.34:  ${}_{s}\mathcal{P}lots$  from fit to  $m_{inv}$  from region  $I_{\Sigma_c}$ : Results from fitting with fixed shape parameters.

Parameter	Value
$\chi^2/\mathrm{nDof}  ightarrow \mathrm{Prob}\left(\chi^2 ight)$	$190.076 \ / \ 206 \rightarrow 0.780132$
$N^{Bkg}$	$14218.6 \pm 130.292$
$N^{Signal}$	$1918.3 \pm 68.379$



Figure A.70: Sketch of distributions of nucleon resonances in  $m(\overline{p}\pi^+)$  according to the nominal values [4] overlayed to the  ${}_s\mathcal{P}lot$  distribution from  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$  in  $m(\overline{p}\pi^+)$ . The distributions are arbitrary scaled for an illustration of the possible intermediate states.

#### A.14 Reweighted reconstruction efficiencies

## A.14.1 $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+, \ \overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$

As outlined in section 6.2.1 for  $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ , the signal Monte-Carlo data sets for remaining resonant modes were -re-weighted as well.

As visible in figure 5.18 the  ${}_{s}\mathcal{P}lot$  distributions in  $m(\Lambda_{c}^{+}\overline{p}\pi^{-})$ ,  $m(\overline{p}\pi^{+})$  and  $m(\Lambda_{c}^{+}\pi^{-}\pi^{+})$  fluctuate for  ${}_{s}\mathcal{P}lot$ ted events from  $\overline{B}^{0} \to \Sigma_{c}^{0}(2520)\overline{p}\pi^{+}$ , whereas the insignificant signal/low statistics are to blame. The reconstruction efficiencies after each weighting step on signal Monte-Carlo are given in table A.35. The reconstruction efficiencies vary all within the statistical uncertainty. With weightings applied along all three invariant masses, the comparisons between invariant masses from re-weighted Monte-Carlo and the smoothed  ${}_{s}\mathcal{P}lots$  from data are shown in figure A.71(a). The weighted Monte-Carlo and data distributions are all consistent with each other.

The signal and therefore the  ${}_{s}\mathcal{P}lot$  distributions from  $\overline{B}{}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$  were more significant, which are shown in figure A.72(a). The reconstruction efficiencies after each weighting iteration are given in A.36.

For  $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  the  ${}_s\mathcal{P}lot$  and re-weighted Monte-Carlo distributions are shown in figure A.73(a). The reconstruction efficiencies are given in table A.37.

Table A.35:  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : reconstruction efficiencies, '×' denotes the weighting along the invariant-mass projection.

mode	$m\left(\Lambda_{c}^{+}\overline{p}\pi^{-}\right)$	$m\left(\overline{p}\pi^{+}\right)$	$m\left(\Lambda_c^+\pi^-\pi^+\right)$	ε	figure
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$				$0.1650 \pm 0.0014$	
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	×			$0.1624 \pm 0.0018$	
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	×	×		$0.1652 \pm 0.0026$	
$\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$	×	×	×	$0.1684 \pm 0.0030$	A.71(a)

Table A.36:  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : reconstruction efficiencies, '×' denotes the weighting along the invariant-mass projection.

mode	$m\left(\Lambda_{c}^{+}\overline{p}\pi^{+}\right)$	$m\left(\overline{p}\pi^{-}\right)$	$m\left(\Lambda_c^+\pi^-\pi^+\right)$	ε	figure
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$				$0.1482 \pm 0.0011$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	×			$0.1462 \pm 0.0012$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	×	×		$0.1443 \pm 0.0011$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$	×	×	×	$0.1451 \pm 0.0013$	A.72(a)

Table A.37:  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : reconstruction efficiencies, '×' denotes the weighting along the invariant-mass projection.

mode	$m\left(\Lambda_c^+ \overline{p}\pi^+\right)$	$m\left(\overline{p}\pi^{-}\right)$	$m\left(\Lambda_c^+\pi^-\pi^+\right)$	ε	figure
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$				$0.1747 \pm 0.0015$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	×			$0.1718 \pm 0.0016$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	×	×		$0.1759 \pm 0.0020$	
$\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$	×	×	×	$0.1702 \pm 0.0020$	A.73(a)



Figure A.71:  $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : invariant masses from signal MC ( $\blacksquare$ ) with correction weights from  ${}_s\mathcal{P}lots$  ( $\bullet$ ) applied.



Figure A.72:  $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : invariant masses from signal MC ( $\blacksquare$ ) with correction weights from  ${}_s\mathcal{P}lots$  ( $\bullet$ ) applied.



Figure A.73:  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : invariant masses from signal MC ( $\square$ ) with correction weights from  ${}_s\mathcal{P}lots$  ( $\bullet$ ) applied.

# A.14.2 Non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ reconstruction efficiency in regions $I_{\Sigma_c}$ and $II_{\Sigma_c}$

The non- $\Sigma_c$  (2455,2520) Monte-Carlo data set consisted of non-resonant  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  and  $\overline{B}^0 \to \Sigma_c^{++}(2800)\overline{p}\pi^-$  Monte-Carlo events. The events were weighted similarly to the resonant signal events, since the non- $\Sigma_c$  events were regarded as four-body decays, the weighting was done along all three- and two-body invariant masses.

The reweighted Monte-Carlo distributions are given in figure A.74 for events from region  $II_{\Sigma_c^0}$  and in figure A.75 for events from region  $I_{\Sigma_c}$ ; all weighted Monte-Carlo distributions comply with the  ${}_s\mathcal{P}lot$  distributions within their uncertainties. The consecutive reconstruction efficiencies are given in table A.38 for region  $II_{\Sigma_c}$  events and in table A.39 for events from region  $I_{\Sigma_c}$ .

Figure shows the comparison A.76 between data and an not-reweighted non-resonant Monte Carlo events  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  from region  $I_{\Sigma_c}$  scaled to the same integral. No clear evidence of a non-charmed resonance as a  $\rho 770 \to \pi^+ \pi^-$  or a  $\overline{p} \pi^\pm$ -resonance is evident. Within the uncertainties the distributions from data and the Monte-Carlo simulation are compatible with each other. Probably with more statistics a signal from  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \rho$  could be separated (and eliminate the uncertainty in the comparison due to the scaling of data and Monte-Carlo on the same integral, which overestimates combinatorial Monte-Carlo distribution to the data distribution in the range of a possible  $\rho(770)$ ).

Table A.38:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $II_{\Sigma_c}$ ): reconstruction efficiencies with consecutively applied weighting along the *B*-daughter invariant-mass combinations.

Weighting	ε
w/o	$0.17211 \pm 0.00052$
$m\left(\Lambda_{c}^{+}\pi^{+}\right)$	$0.16825 \pm 0.00060$
$m\left(\Lambda_{c}^{+}\pi^{-}\right)$	$0.16827 \pm 0.00059$
$m\left(\Lambda_{c}^{+}\overline{p}\pi^{+}\right)$	$0.16841 \pm 0.00067$
$m\left(\overline{p}\pi^{+}\pi^{-}\right)$	$0.16985 \pm 0.00070$
$m\left(\Lambda_c^+\pi^+\pi^-\right)$	$0.16951 \pm 0.00071$
$m\left(\Lambda_c^+ \overline{p}\pi^-\right)$	$0.17001 \pm 0.00069$
$m\left(\Lambda_c^+\overline{p}\right)$	$0.16896 \pm 0.00071$
$m\left(\pi^{-}\pi^{+}\right)$	$0.16917 \pm 0.00073$
$m\left(\overline{p}\pi^{+}\right)$	$0.16929 \pm 0.00075$
$m\left(\overline{p}\pi^{-}\right)$	$0.16877 \pm 0.00075$

Table A.39:  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $I_{\Sigma_c}$  without  $\Sigma_c^{++}$  (2455,2520) bands): reconstruction efficiencies with consecutively applied weighting along the *B*-daughter invariant-mass combinations.

Weighting	ε
w/o	$0.1184 \pm 0.0013$
$m\left(\Lambda_{c}^{+}\pi^{+}\right)$	$0.1075 \pm 0.0014$
$m\left(\Lambda_{c}^{+}\pi^{-}\right)$	$0.1049 \pm 0.0015$
$m\left(\Lambda_{c}^{+}\overline{p}\pi^{+}\right)$	$0.1068 \pm 0.0021$
$m\left(\overline{p}\pi^{+}\pi^{-}\right)$	$0.1089 \pm 0.0021$
$m\left(\Lambda_{c}^{+}\pi^{+}\pi^{-}\right)$	$0.1050 \pm 0.0022$
$m\left(\Lambda_{c}^{+}\overline{p}\pi^{-}\right)$	$0.1144 \pm 0.0060$
$m\left(\Lambda_{c}^{+}\overline{p}\right)$	$0.1112 \pm 0.0069$
$m\left(\pi^{-}\pi^{+}\right)$	$0.1142 \pm 0.0058$
$m\left(\overline{p}\pi^{+}\right)$	$0.1092 \pm 0.0034$
$m(\overline{p}\pi^{-})$	$0.1163 \pm 0.0072$



(c) non-charmed two-body masses

Figure A.74:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $II_{\Sigma_c}$ ): invariant masses from signal MC ( $\blacksquare$ ) with correction weights from  ${}_s\mathcal{P}lots$  ( $\bullet$ ) applied.



(c) non-charmed two-body masses

Figure A.75:  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $I_{\Sigma_c}$ ): invariant masses from signal MC ( $\blacksquare$ ) with correction weights from  ${}_s\mathcal{P}lots$  ( $\bullet$ ) applied.



Figure A.76:  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$  (region  $I_{\Sigma_c}$ ): Comparison between uncharmed two-body invariant masses invariant masses from signal MC ( $\blacksquare$ ) and  ${}_s\mathcal{P}lots$  from data (•). The histograms are scaled to the same integral

# List of Figures

1.1	Type A diagram: $Internal W$ boson exchange	6
1.2	Type 2 diagram: Internal W boson radiation producing a $\overline{u} d$ quark pair	6
1.3	Type 1 diagram: <i>External W</i> boson radiation producing a pion	6
1.4	Feynman diagram: External W boson radiation with an intermediate $\Sigma_c^{++}$ resonance.	
	$\Sigma_c^{++}$ resonances can also be formed by <i>internal</i> W interaction similar as in figure 1.5	6
1.5	Feynman diagram: Internal W boson exchange proceeding via a charmed $\Sigma_c^0$ resonance.	
	The $\Sigma_c^0$ resonances can only be formed by <i>internal</i> W interaction	6
1.6	$\Sigma_c^{++}$ production diagram: <i>internal</i> W radiation of type 2g	7
1.7	$\Sigma_c^0$ production diagram: <i>internal</i> W radiation of type 2a	7
1.8	$\Sigma_c^{++}$ production diagram: <i>external</i> W radiation of type 1	7
1.9	$\Sigma_c^0$ production diagram: <i>internal</i> W radiation of type 2b	7
1.10	$\Sigma_c^{++}$ production diagram: W exchange of type A	7
1.11	$\Sigma_c^0$ production diagram: W exchange of type A	7
1.12	Feynman diagram: Internal W boson exchange proceeding via a charmed $\Sigma_c^0$ resonance	
	and a nucleonic $N^*$ resonance, i.e. an initial two baryon state	8
1.13	Feynman diagram: Internal W boson exchange proceeding via a charmed $\Lambda_c^+$ resonance.	
	Note that for some excited $\Lambda_c^+$ baryons cascades via intermediate $\Sigma_c$ baryons are also	
	possible, i.e. $\Lambda_c^+(2593) \to \Sigma_c^{\circ}(2455)\pi^{\mp}$	8
1.14	Feynman diagram: Internal W boson exchange proceeding via a baryon-antibaryon pair	
	and a meson resonance which can decay into a $\pi^+\pi^-$ pair in the fin al state	8
1.15	Decay cascade: decays via $\Sigma_c$ resonances	8
1.16	Decay cascade: decay chains as in figure 1.15 possible for different excitations of $\Sigma_c^{++}$ (same	0
	for $\Sigma_c^0$	8
1.17	Decay cascade: baryon-antibaryon initial state cascading into the four body final state $(1 - 1)^{-1} + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 +$	0
1 10	(same for $\Sigma_c^*$ and for direct decay $\Lambda_c^+ \to \Lambda_c^+ \pi^- \pi^+$ )	8
1.18	class M: Initial meson-meson-like states with W-radiation. Due to the large off-shell W-	
	an effective four point term $1.18(c)$ . This gives an effective meson-meson-like initial decay	
	state before barvonization.	10
1.19	class M: Initial meson-meson-like states with W-exchange. Due to the large off-shell W-	10
1.10	mass the (type A) diagram 1.19(a) can be contracted into an effective four point term	
	1.19(b). This gives an effective meson-meson-like initial decay state before baryonization.	11
1.20	class M: Baryonization from initial meson-meson-like states: the baryonization takes place	
	in one of the initial mesons, resulting in three particles in the initial decay state: either a	
	baryonization involving the B-spectator quark $\bar{q}_{sp}$ in W-radiation diagrams 1.20(a), or a	
	baryonization without involvement of the <i>B</i> -spectator quark $\bar{q}_{sp}$ in <i>W</i> -radiation diagrams	
	1.20(b), or a baryonization in one of the initial mesons in W-exchange diagrams $1.20(c)$ .	11

1.21	class B: Arrangement of the initial quarks and W-daughters (type 2 diagram) to a diquark and antidiquark pair in figure 1.21(a) with the subsequent baryonization in figure 1.21(b) to comply with color-confinement. Figure 1.21(c) shows the arrangement for the exchange type (type A diagram). In both cases the initial decay state is a baryon-antibaryon pair. A three-body final state can be reached, if one of the baryons further fragments into a	
1.22	baryon-meson pair	11
1.23	$\Sigma_c$ resonances	$\frac{13}{15}$
2.1	Schematic view of the LINAC linear accelerator and PEP-II $e^+e^-$ storage rings. The BABAR detector is located at the interaction region (IR)	17
2.2	PEP-II/BABAR: Delivered and recorded luminosities at $\Upsilon(4S), \Upsilon(3S), \Upsilon(2S)$ and off-peak energies over the run time	18
2.3	SVT: Design and parameters	21
2.4	DCH: Design and parameters	22
2.5	DIRC: Design, location and principle of operation	23
2.6	EMC: Schematic section drawing	24
3.1	$\Lambda_c$ mass: $m(pK^-\pi^+)$ from runs 1-6 in data	31
3.2	$m_{inv}: m_{\rm ES}$ and $\Delta E: m_{\rm ES}:$ plots from $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ signal MC (SP-5076). In the upper plot, a correlation between $m_{\rm ES}$ and $\Delta E$ is visible by eye; a fit with 2D-Gaussian (eq. 3.9) found a correlation of $\rho_{\Delta E:m_{\rm ES}} = -0.2879 \pm 0.0028$ . In the lower plot, for $m_{inv}$ and $m_{\rm ES}$ no immediate correlation is noticeable; correlation; a fit with 2D-Gaussian found a correlation of $\rho_{m_{inv}:m_{\rm ES}} = -0.023 \pm 0.005$ . The nominal $B^0$ mass, $m_{\rm ES}$ and energy difference values are denoted as dashed lines.	34
3.3	Signal and side band regions in the $m_{\rm ES}$ - $m_{inv}$ -plane. The plane is divided into four bands,	
	side regions. The borders are given in table 3.6. $\dots$	36
3.4	$m_{\rm ES}$ - $m_{\rm inv}$ -plane from data after passing $\overline{B}^0$ selection cuts (see tables 3.3 and 3.4).	36
3.5	$m_{\rm ES}$ $m_{mv}$ plane from data diece passing D = selection cars (see dashed of $m_{\rm eS}$ ). The $m_{inv}$ : distribution for events in the $m_{\rm ES}$ signal region. Borders of the signal region in $m_{\rm esc}$ are given in rad, side band barders in deshed blue.	97
36	$m_{inv}$ are given in red, side band borders in dashed blue	37
5.0	are given in red; side band borders in dashed blue	37
3.7	$m_{inv} : m(\Lambda_c^+ \pi^+)$ : 2D distribution of events in the $m_{\rm ES}$ signal band in $m_{inv} : m(\Lambda_c^+ \pi^+)$ (upper plot) and $m_{inv} : m(\Lambda_c^+ \pi^-)$ (lower plot)	40
3.8	$m(\Lambda_c^+\pi^\pm)$ : distributions of invariant masses $m(\Lambda_c^+\pi^+)$ in the two upper plots and $m(\Lambda_c^+\pi^-)$ in the two lower plots. The upper $m(\Lambda_c^+\pi^\pm)$ distributions are events from the signal region $I$ with side-band region $III$ subtracted. The lower $m(\Lambda_c^+\pi^\pm)$ distributions show the original distribution from the $m_{\rm ES}$ - $m_{inv}$ signal region $I$ overlayed with scaled	
	side band III.	40
3.9	$m_{inv}: m(\Lambda_c^+\pi^{\pm})$ from $B^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ signal Monte-Carlo events: The upper plot shows the signal event distribution in $m_{inv}: m(\Lambda_c^+\pi^+)$ , the middle plot $m_{inv}: m(\Lambda_c^+\pi^+)$	
0.10	more in detail, the lower plot shows the $m_{inv}: m(\Lambda_c^+\pi^-)$ distribution	43
3.10	$B^{\circ} \rightarrow \mathcal{L}_{c}^{++}(2455)p\pi$ signal Monte-Carlo: $m_{inv}$ from $m_{\rm ES}$ signal band, $m_{\rm ES}$ from $m_{inv}$ signal band and the $m_{inv}$ mag plane	43
3 11	$\overline{B}^0 \rightarrow \Sigma^{++}(2455)\overline{n}\pi^-$ signal Monte-Carlo: $m(A^+\pi^+)$ and $m(A^+\pi^-)$ distributions from	40
0.11	$m_{inv}$ and $m_{\rm ES}$ signal region	43

3.12	$m_{inv}: m(\Lambda_c^+\pi^\pm)$ from $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ signal Monte-Carlo: The upper plot shows the signal event distribution in $m_{inv}: m(\Lambda_c^+\pi^+)$ , the middle plot $m_{inv}: m(\Lambda_c^+\pi^+)$ more in detail, the lower plot shows the $m_{inv}: m(\Lambda_c^+\pi^-)$ distribution	44
3.13	$\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ signal Monte-Carlo: $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : $m_{inv}$ from $m_{\rm ES}$ signal band, $m_{\rm ES}$ from $m_{inv}$ signal band and the $m_{inv}:m_{\rm ES}$ plane $\ldots \ldots \ldots$	44
3.14	$\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ signal Monte-Carlo: $\overline{B}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : $m(\Lambda_c^+\pi^+)$ and $m(\Lambda_c^+\pi^-)$ distributions from $m_{inv}$ and $m_{\rm ES}$ signal region	44
3.15	Comparisons in $m_{\rm ES}$ (left plot) and $m_{inv}$ (right plot) between the distributions from data and generic Monte-Carlo sets. The distributions from Monte-Carlo for generic <i>uds</i> -events, $c\overline{c}$ -events, $B^+B^-$ -events and $B^0\overline{B}^0$ -events where scaled on the On-peak luminosity [38] and stacked onto each other. Signal decays were not removed from $B^0\overline{B}^0$ Monte-Carlo	46
3.16	Generic $B^+B^-$ Monte-Carlo event distributions (not scaled onto luminosity): upper row:	
	$m_{\rm ES}, m_{inv}$ ; second row $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ - $m_{inv}$ signal region); third row detailed $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ - $m_{inv}$ signal region); lower row $m_{inv}$ : $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ signal band)	48
3.17	Generic $B^0\overline{B}^0$ Monte-Carlo event distributions (not scaled onto luminosity): up-	
	per row: $m_{\text{ES}}$ , $m_{inv}$ ; second row $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\text{ES}}$ - $m_{inv}$ signal region); third row detailed $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\text{ES}}$ - $m_{inv}$ signal region); lower row $m_{inv}$ : $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\text{ES}}$ signal band). Signal mode components $(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-; \to \Sigma_c^0 \overline{p} \pi^-; \to \Sigma_c^0 \overline{p} \pi^+; \to \Lambda_c^+ \overline{p} \rho/f_2; \to \Lambda_c^+ \Delta \pi^-)$ are removed. No vetoes on $D^0$ or $D^+$ background are applied here; the signal peak remains from modes $\overline{B}^0 \to D^0/D^+ p\overline{p} + n \cdot \pi$ .	49
3.18	Data: $m(\Lambda_c^+\pi^+)$ distributions from $m_{inv}$ side band. plots top-down: $m(\Lambda_c^+\pi^+)$ from left $m_{inv}$ side-band $[m_{inv} \in (5.17, 5.23) \text{ GeV}/c^2]$ , $m(\Lambda_c^+\pi^+)$ from right $m_{inv}$ side-band $[m_{inv} \in (5.322, 5.382) \text{ GeV}/c^2]$ , $m(\Lambda_c^+\pi^+)$ from both $m_{inv}$ side-bands combined	50
3.19	Data: $m(\Lambda_c^+\pi^-)$ distributions from $m_{inv}$ side band. plots top-down: $m(\Lambda_c^+\pi^-)$ from left $m_{inv}$ side-band $[m_{inv} \in (5.17, 5.23) \text{ GeV}/c^2]$ , $m(\Lambda_c^+\pi^-)$ from right $m_{inv}$ side-band $[m_{inv} \in (5.322, 5.382) \text{ GeV}/c^2]$ , $m(\Lambda_c^+\pi^-)$ from both $m_{inv}$ side-bands combined $\ldots \ldots$	50
3.20	Monte-Carlo events for $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$ background: left column $m_{inv}:m(\Lambda_c^+\pi^+)$ , right column $m_{inv}:m(\Lambda_c^+\pi^-)$ ; upper row $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ , lower row $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$ (from the $m_{\rm ES}$ signal band) $\ldots \ldots \ldots$	52
3.21	Width of $m_{inv}$ for non-resonant signal Monte-Carlo: The Monte-Carlo sample was divided in subranges in $m(\Lambda_c^+\pi^{\pm})$ . For each subrange $m_{inv}$ was fitted with a Gaussian for signal and a 1st order polynomial for background. The fitted widths are shown here and were fitted with a 2nd order polynomial. The fit results are given in table 3.9	54
3.22	$B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ background Monte-Carlo events: left column $m_{inv}:m(\Lambda_c^+\pi^+)$ , right column $m_{inv}:m(\Lambda_c^+\pi^-)$ ; upper row $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$ , lower row $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$	56
3.23	$m(\Lambda_c^+\pi^+)$ : arbitrary scaled Monte-Carlo distribution for $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ in $m(\Lambda_c^+\pi^+)$ overlayed by the distribution from data.	56
3.24	$m_{\rm ES}$ distribution from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ Monte-Carlo	56
3.25	$m_{inv}$ distribution from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ Monte-Carlo	56
3.26	Monte-Carlo for $\overline{B}^0 \to D^0/D^+p\overline{p} + n \cdot \pi$ without $D^+$ veto: $m_{\rm ES}$ , $m_{inv}$ and $m_{inv}:m_{\rm ES}$ distributions from $\overline{B}^0 \to D^0p\overline{p}$ ; $D^0 \to K^-\pi^+\pi^-\pi^+$ (a), from $\overline{B}^0 \to D^+p\overline{p}\pi^-$ ; $D^+ \to K^-\pi^+\pi^+$ (b) and from $\overline{B}^0 \to D^0p\overline{p}\pi^+\pi^-$ ; $D^0 \to K^-\pi^+$ (c)	59

- 3.29 Distributions in  $m(\Lambda_c^+\pi^\pm)$  before and after applying  $D^0/D^+$  vetoes. The upper row shows the events from signal Monte-Carlo for  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$  (a) and  $\overline{B}{}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ (b), the lower row for  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$  (c) and  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ (d). Shown are the the original  $\bullet$  and post-veto  $\circ$  and binwise relative signal reduction  $\bullet$  distributions. . . 61

		-
4.1	$m_{inv}$ : the $m_{inv}:m(\Lambda_c^+\pi^-)$ distribution in data was fitted with binned signal Monte-Carlo for $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ as signal PDF. The difference between the distribution and the fit result the $\Sigma_c^0(2455)$ signal region in $m(\Lambda_c^+\pi^-)$ was projected onto $m_{inv}$ . In the left figure (a) the signal PDF from Monte-Carlo simulated events was uncorrected, i.e. $m_{inv}(\overline{B}^0) = 5.279 \text{GeV}/c^2$ . In the right plot (b) the Monte-Carlo events were corrected before the histogram PDF was created from them, i.e. $m_{inv}(\overline{B}^0) = 5.2766 \text{GeV}/c^2$	67
4.2	Monte-Carlo to data mass shift: Comparison between the $m_{inv}$ distributions from uncorrected and corrected Monte-Carlo events plus the difference between both. Left: non-resonant SP-5076 $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ , right: resonant signal Monte-Carlo $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ .)	67
4.3	Monte-Carlo misalignment: difference in the $m_{inv}$ signal region between data and fit with $\Sigma_c^{++}$ (2455,2520) histograms from signal Monte-Carlo. The two-dimensional difference between data and fit result was projected onto $m(\Lambda_c^+\pi^{\pm})$ . No correction was applied onto the $\Sigma_c$ (2455) mass in Monte-Carlo.	69
4.4	Monte-Carlo misalignment: difference in the $m_{inv}$ signal region between data and fit with $\Sigma_c^{++}(2455,2520)$ histograms from signal Monte-Carlo. The 2D difference between data and fit result was projected onto $m(\Lambda_c^+\pi^{\pm})$ . The $\Sigma_c^{++}(2455)$ mass was corrected in $m(\Lambda_c^+\pi^{\pm})$ corrected for signal Monte-Carlo.	69
5.1	Fit for $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$ in data: plots from top - down: data distribution, difference between data and fit, bin-wise $\chi^2$ distribution. The projection of the difference and bin-wise $\chi^2$ distributions onto the axes is shown in figure 5.2	77
5.2	Fit for $\overline{B}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$ in data: upper row: projections onto $m(\Lambda_c^+\pi^-)$ and $m_{inv}$ of the difference between data and fit, lower row: projection of the bin-wise $\chi^2$ residuals onto the axes in the signal ranges, i.e. the bin-wise sums along the projections of the $\chi^2$ distribution in the signal region.	77
5.3	Fit for $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ in data: plots from top - down: data distribution, difference between data and fit, bin-wise $\chi^2$ distribution. The projection of the difference and bin-wise $\chi^2$ distributions onto the axes is shown in figure 5.4	80
5.4	Fit for $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ in data: upper row: projections of the difference between data and fit onto the axes, lower row: projection of the bin-wise $\chi^2$ residuals onto the axes in the signal ranges, i.e. the bin-wise sums along the projections of the $\chi^2$	0.0
	distribution in the signal region.	80

as hatched areas; the right plot (b) marks the vetoes against $\Sigma_c^{++}$ (2455, 2520) resonances as green bands	
as green bands	
Fits to $B \to \Sigma_c^+ (2455, 2520) p\pi$ signal Monte-Carlo in the $m_{inv}: m(\Lambda_c^+ \pi^+)$ fit region	83
$I_{\Sigma_c}$ . The left plot (a) shows $B^- \to \Sigma_c^+(2455)\overline{p}\pi^-$ fitted with a ouble Gaussian; the right	0.9
plot (b) shows $B \to \Sigma_c^+(2520)p\pi^-$ fitted with a single Gaussian	83
excluded $\Sigma_c^{0}$ (2455,2520) bands. Solid lines represent the fit including PDFs for $B^- \rightarrow \Sigma_c^+(2455,2520)\overline{p}\pi^-$ background with fixed parameters; dashed lines represent the fit	~ 4
including only signal and combinatorial background. $\dots \dots \dots$	84
Fit to the $m_{inv}$ distribution from data in the $m_{inv}$ : $m(\Lambda_c^+\pi^+)$ fit region $\Pi_{\Sigma_c}$	80
$B^{\circ} \rightarrow \Sigma_{c}^{+}(2455)p\pi$ : Dalitz plot in $\mathbf{m}^{-}(p\pi)$ : $\mathbf{m}^{-}(\Sigma_{c}^{+}(2455)\pi)$ . Events are from the $m_{inv}:m_{\rm ES}$ signal region and within the $\Sigma_{c}^{++}(2455)$ signal region in $m(\Lambda_{c}^{+}\pi^{+})$ ; combinatorial background and other $\overline{B}^{0} \rightarrow \Lambda^{+}\overline{n}\pi^{+}\pi^{-}$ signal events in the $\Sigma_{c}^{++}(2455)$	
signal region are not removed	88
$\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-}$ : projections on $m(\Sigma_{c}^{++}(2455)\pi^{-})$ for events in the $m_{inv}:m_{\rm ES}$ signal	
region and within the $\Sigma_c^{++}(2455)$ signal region in $m(\Lambda_c^+\pi^+)$ . The left plot is without side-band subtraction, the right plot has combinatorial background removed by side-band	
subtraction.	89
$B^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : projections on $m(\overline{p}\pi^-)$ for events in the $m_{inv}:m_{\rm ES}$ signal region	
and within the $\Sigma_c^{++}(2455)$ signal region in $m(\Lambda_c^+\pi^+)$ . The left plot is without side-band	00
subtraction, the right plot has combinatorial background removed by side-band subtraction. $\overline{R}^0 \rightarrow \Sigma^{\pm\pm}(2455)\overline{m}\pi^{\pm}$ ; projections on $m(\Sigma^{\pm\pm}2455)\overline{m}$ for events in the $m_{\pm}$ - $m_{\pi\pi}$ signal	09
$D \to Z_c$ (2455)p/ . projections on $m(Z_c = 2455)p$ ) for events in the $m_{inv}.m_{\rm ES}$ signal region and within the $\Sigma^{++}(2455)$ signal region in $m(\Lambda^+\pi^+)$ . The left plot is without	
side-band subtraction, the right plot has combinatorial background removed by side-band	
subtraction.	89
$\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : Dalitz plot in $m^2(\overline{p}\pi^+)$ : $m^2(\Sigma_c^{++}(2455)\pi^+)$ . Events are from the $m_{inv}:m_{\rm ES}$ signal region and within the $\Sigma_c^0(2455)$ signal region in $m(\Lambda_c^+\pi^+)$ ; combinatorial	
background and other $B^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ signal events in the $\Sigma_c^0(2455)$ signal region are not	00
removed $\overline{R}^0 \rightarrow \overline{\Gamma}^0(2455)\overline{m}\pi^+$ , projections on $m\left(\overline{\Gamma}^0(2455)\pi^+\right)$ for events in the maximum signal	90
$D \rightarrow Z_c(2455)p\pi$ . projections on $m(Z_c(2455)\pi)$ for events in the $m_{inv}.m_{\rm ES}$ signal region and within the $\Sigma^0(2455)$ signal region in $m(\Lambda^+\pi^-)$ . The left plot is without	
side-band subtraction, the right plot has combinatorial background removed by side-band	
subtraction.	91
$\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : projections on $m(\overline{p}\pi^+)$ for events in the $m_{inv}:m_{\rm ES}$ signal region	
and within the $\Sigma_c^0(2455)$ signal region in $m(\Lambda_c^+\pi^-)$ . The left plot is without side-band	01
subtraction, the right plot has combinatorial background removed by side-band subtraction. $\overline{P}^0 \rightarrow \Sigma^0(2455)\overline{w}^{\pm}$ , projections on $m(\Sigma^02455)\overline{w}$ for events in the maximum signal region	91
and within the $\Sigma_c 0(2455)$ signal region in $m(\Lambda^+\pi^-)$ . The left plot is without side-band	
subtraction, the right plot has combinatorial background removed by side-band subtraction.	91
$\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : sPlotted signal distributions in $m(\Lambda_c^+\overline{p}\pi^-), m(\overline{p}\pi^+)$ and $m(\Lambda_c^+\pi^-\pi^+)$ .	94
$\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : sPlotted signal distributions in $m(\Lambda_c^+\overline{p}\pi^-), m(\overline{p}\pi^+)$ and $m(\Lambda_c^+\pi^-\pi^+)$ .	94
$\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : sPlotted signal distributions in $m(\Lambda_c^+\overline{p}\pi^+), m(\overline{p}\pi^-)$ and	
$\underline{m}(\Lambda_c^+\pi^-\pi^+).$	95
$B^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : sPlotted signal distributions in $m(\Lambda_c^+\overline{p}\pi^+), m(\overline{p}\pi^-)$ and $m(\Lambda_c^+\pi^-\pi^+), \dots, \dots,$	95
$\overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{\mp}: \text{ comparison between } m\left(\Lambda_{c}^{+}\overline{p}\pi^{\pm}\right), m\left(\overline{p}\pi^{\pm}\right) \text{ and } m\left(\Lambda_{c}^{+}\pi^{+}\pi^{-}\right) \text{ from } s\mathcal{P}lotted \text{ decays } \overline{B}^{0} \to \Sigma_{c}^{++}(2455)\overline{p}\pi^{-} \text{ and } \overline{B}^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}.$	96
	If is to $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ signal Monte-Carlo in the $m_{inv}:m(A_c^+\pi^\pm)$ fit region $I_{S_c}$ . The left plot (a) shows $B^- \to \Sigma_c^+(255)\overline{p}\pi^-$ fitted with a ouble Gaussian; the right plot (b) shows $B^- \to \Sigma_c^+(2520)\overline{p}\pi^-$ fitted with a single Gaussian

5.22	$\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ (region $II_{\Sigma_c}$ ): ${}_s \mathcal{P}lot$ ted signal distributions of three-body <i>B</i> -daughter invariant masses	08
5.23	$\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ (region $II_{\Sigma_c}$ ): ${}_s \mathcal{P}lot$ ted signal distributions of two-body <i>B</i> -daughter invariant masses. The upper plot (a) shows the charmed two-body masses, the non-	90
5.24	charmed two-body masses are shown in the lower plot (b)	100
5.25	invariant masses. $\overline{B}^{0} \to \Lambda_{c}^{+} \overline{p} \pi^{+} \pi^{-}$ (region $I_{\Sigma_{c}}$ ): ${}_{s} \mathcal{P}lot$ ted signal distributions of two-body <i>B</i> -daughter invariant masses. The upper plot (a) shows the charmed two-body masses, the non-charmed two-body masses are shown in the lower plot (b)	101 102
6.1	$m(\Lambda_c^+\pi^\pm\overline{p})$ : comparison of signal distribution from Monte-Carlos ( $\circ$ ) $\overline{B}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ (a) and $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^-$ (b) and from side-band subtracted data ( $\times$ ) with $m(\Lambda_c^+\pi^\pm)$	
6.2	in the $\Sigma_c^{(\circ)}$ (2455) signal region. The histograms were scaled to the same integral $m(\overline{p}\pi^+)$ : comparison of the signal distribution from Monte-Carlo ( $\circ$ ) and from side-band subtracted data ( $\times$ ) with $m(\Lambda^+\pi^\pm)$ in the $\Sigma^0$ (2455) signal region. Both histograms were	104
6.3	scaled to the same integral	104
6.4	$\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+ \checkmark$	104
	$m \left(\Lambda_c^+ \overline{p} \pi^-\right)_{4.99 \text{GeV}/c^2, 5.09 \text{GeV}/c^2}$ in the lower plot (c)	109
A.1 A.2 A.3	$\overline{B}^{0}/B^{-} \to \Lambda_{c}^{+}\overline{p}\pi^{0}/\pi^{-}: \text{ Comparison of different isospin options } \dots $	122 124
A.4	polynomial for background. The fits' $\Lambda_c^+$ masses are given in table A.5	129
A.5	background. $\Lambda_c^+$ daughters were constraint to $m(\Lambda_c^+) = 2.2849 \text{ GeV}/c^-$ and had to have a mass within $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2$	132
A.6	background. $\Lambda_c^+$ daughters were constraint to $m(\Lambda_c^+) = 2.2849 \text{GeV}/c^2$ and had to have a mass within $m(\Lambda_c^+) \in (2.2727, 2.2977) \text{GeV}/c^2$	132
A.7	mass within $m(\Lambda_c^+) \in (2.272, 2.297) \text{ GeV}/c^2 \dots \dots$	132
A.8	mass within $m(\Lambda_c^+) \in (2.2727, 2.2977)$ GeV/ $c^2$	132
A.9	for background. $A_c^+$ daughters were not constraint to a certain mass but had to have a mass within $m(A_c^+) \in (2.272, 2.297)$ GeV/ $c^2$	132
A.10	mass within $m(\Lambda_c^+) \in (2.2727, 2.2977)$ GeV/ $c^2$	132
A.11	$(2.2727, 2.2977) \text{ GeV}/c^2 \text{ for } \Lambda_c^+ \text{ constraint to } 2.2849 \text{ GeV}/c^2 \dots \dots$	133
	(2.2727, 2.2977) GeV/ $c^2$ for $\Lambda_c^+$ constraint to 2.2856 GeV/ $c^2$ .	133

A.12 $m_{inv}$ : Difference in $m_{inv}$ $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$ with $m(\Lambda_c^+) \in (2.272, 2.297)$ GeV/ $c^2$ and $m(\Lambda_c^+) \in (2.2727, 2.2977)$ GeV/ $c^2$ for $\Lambda^+$ constraint without mass constraint	133
A.13 $m_{inv}$ : Difference in $m_{inv}$ ( $\Lambda_c^+ \overline{p} \pi^+ \pi^-$ ) between $\Lambda_c^+$ constraint to 2.2849 GeV/ $c^2$ and	100
constraint to 2.2856 GeV/ $c^2$ for $m(\Lambda_c^+) \in (2.2727, 2.2977)$ GeV/ $c^2$	133
A.14 $m_{inv}$ : Difference in $m_{inv}$ ( $\Lambda_c^{-}p\pi^{+}\pi^{-}$ ) between $\Lambda_c^{-}$ constraint to 2.2856 GeV/ $c^{-}$ and $\Lambda_c^{-}$ unconstraint for $m(\Lambda_c^{+}) \in (2.2727, 2.2977)$ GeV/ $c^{2}$	133
A.15 $m_{inv}$ : Difference in $m_{inv}$ $(\Lambda_c^+ \overline{p} \pi^+ \pi^-)$ between $\Lambda_c^+$ unconstraint and constraint to 2.2849 GeV/ $c^2$ for $m(\Lambda_c^+) \in (2.2727, 2.2977)$ GeV/ $c^2$ .	133
A.16 $m(\Lambda_c^+\pi^\pm)$ : Detailed view of the lower $m(\Lambda_c^+\pi^\pm)$ masses as from figure 3.8. The plots show for $m(\Lambda_c^+\pi^+)$ (uper two plots) and $m(\Lambda_c^+\pi^-)$ (lower two plots) the distributions from the $m_{inv}$ and $m_{\rm ES}$ signal region and the side band subtracted distribution. $\Sigma_c$ (2455,2520) signal regions are denoted as dashed lines (see definitions in table 3.8).	135
A.17 $m(\Lambda_c^+\pi^+)$ : distributions for events in I) $m_{inv}$ & $m_{\rm ES}$ signal bands, II) $m_{inv}$ signal & $m_{\rm ES}$ side band region, III) combined $m_{inv}$ side bands & $m_{\rm ES}$ signal band, IV) combined $m_{inv}$ for $m_{\rm ES}$ signal band, IV) combined $m_{inv}$ for $m_{\rm ES}$ signal bands.	126
A.18 $m (\Lambda_c^+ \pi^+)$ : distributions for events in I) $m_{inv}$ side band 1 & $m_{\rm ES}$ signal band, II) $m_{inv}$ side band 2 & $m_{\rm ES}$ signal band, III) $m_{inv}$ side band 1 & $m_{\rm ES}$ side band, VI) $m_{inv}$ side band	130
2 & $m_{\rm ES}$ side band	136
$m_{\rm ES}$ side band region, fff) combined $m_{inv}$ side bands & $m_{\rm ES}$ signal band, fV) combined $m_{inv}$ & $m_{\rm ES}$ side bands	137
band 2 & $m_{\rm ES}$ signal band, III) $m_{inv}$ side band 1 & $m_{\rm ES}$ side band, VI) $m_{inv}$ side band 2 & $m_{\rm ES}$ side band	137
A.21 SP-6981: $m_{inv} : m(\Lambda_c^+\pi^\pm)$ from $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ signal Monte-Carlo. The upper plot shows the signal event distribution in $m_{inv} : m(\Lambda_c^+\pi^-)$ , the middle plot $m_{inv} : m(\Lambda_c^+\pi^-)$	100
more in detail, the lower plot the adjoint $m_{inv} : m(\Lambda_c^+ \pi^+)$ distribution	138
band and the $m_{inv}:m_{\rm ES}$ plane	138
$m_{\rm ES}$ signal region	138
signal event distribution in $m_{inv} : m(\Lambda_c^+\pi^-)$ , the middle plot $m_{inv} : m(\Lambda_c^+\pi^-)$ more in detail, the lower plot the adjoint $m_{inv} : m(\Lambda_c^+\pi^+)$ distribution.	139
A.25 $B^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ Monte-Carlo: $m_{inv}$ from $m_{\rm ES}$ signal band, $m_{\rm ES}$ from $m_{inv}$ signal band and the $m_{inv}$ : $m_{\rm ES}$ plane	139
A.26 $B^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ Monte-Carlo: $m(\Lambda_c^+\pi^+)$ and $m(\Lambda_c^+\pi^-)$ distributions from $m_{inv}$ and $m_{\rm ES}$ signal region	139
A.27 Generic <i>uds</i> Monte-Carlo unscaled: upper row: $m_{\rm ES}$ , $m_{inv}$ ; middle row $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ - $m_{inv}$ signal region); lower row $m_{inv}$ : $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ signal band)	141
A.28 Generic $c\bar{c}$ Monte-Carlo unscaled: upper row: $m_{\rm ES}$ , $m_{inv}$ ; middle row $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from $m_{\rm ES}$ - $m_{inv}$ signal region); lower row $m_{inv}$ : $m(\Lambda_c^+\pi^+)$ , $m(\Lambda_c^+\pi^-)$ (from	1 11
$m_{\rm ES}$ signal band)	141
down: $m_{inv}$ signal- $m_{\rm ES}$ side band region (II), $m_{inv}$ side- $m_{\rm ES}$ signal region (III), $m_{inv}$ - $m_{\rm ES}$ side band region (IV)	142
A.30 $B^- \to \Sigma_c^0(2455, 2520)\overline{p}\pi^0$ : Monte-Carlo simulated background events with true $\Sigma_c^0(2455, 2520)$ in the $m_{inv}:m(\Lambda_c^+\pi^-)$ plane for the $m_{\rm ES}$ signal region (upper plot) and $m_{\rm ES}$ side band	))
region (lower plot)	142

A.31	Example for true $\Sigma_c$ background Monte-Carlo: left column $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$ , right	
	column $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$ ; top down: $m_{\rm ES}$ , $m_{inv}$ , s; $m(\Lambda_c^+\pi^+)$ (from $m_{inv}$ - $m_{\rm ES}$ signal	
	region), $m(\Lambda_c^+\pi^-)$ (from $m_{inv}$ - $m_{\rm ES}$ signal region)	143
A.32	$m(\Lambda_c^+\pi^\pm)$ : Mixture of $m(\Lambda_c^+\pi^+)$ and $m(\Lambda_c^+\pi^-)$ , respectively, from signal SP modes with	
	random scaling each	144
A.33	Non-resonant $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$ background Monte-Carlo: upper row: $m_{inv}, m_{\rm ES}$ ; middle	
	row (from $m_{inv}$ - $m_{\rm ES}$ signal region) $m(\Lambda_c^+\pi^+), m(\Lambda_c^+\pi^-)$ , lower row $m_{inv}:m(\Lambda_c^+\pi^+),$	
	$m_{inv}:m(\Lambda_c^+\pi^-)$ .	145
A.34	$B^- \to \Sigma_c^+(2800)\overline{p}\pi^-$ background Monte-Carlo: upper row: left $m_{inv}:m(\Lambda_c^+\pi^+)$ , right	
	$m_{inv}:m(\Lambda_c^+\pi^-)$ ; middle row: left $m_{\rm ES}$ , right $m_{inv}$ ; lower row: from the $m_{inv}:m_{\rm ES}$ signal	
	region: left $m(\Lambda_c^+\pi^+)$ , right $m(\Lambda_c^+\pi^-)$	146
A.35	$m_{inv}$ : signal fit with and without signal PDFs for $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ with fixed	
	shape parameters from Monte-Carlo and free floating scaling	146
A.36	$m\left(K_{D^0}^-\pi_{D^0}^+,\overline{p_0}\right)$ from Monte-Carlo simulated $\overline{B}^0 \to D^0 p \overline{p} \pi^+\pi^-; D^0 \to K^-\pi^+$ without	
	$D^{+}$ voto	1/8
1 97	Monte Carle evente: $\overline{D}^0$ , $D^{*+} = D^{*+}$ , $D^0 = U^{*+}$ , $D^0 = U^{*+}$ without $D^+$ veter	140
A.57	Monte-Carlo events: $D^+ \rightarrow D^- pp\pi^-$ ; $D^+ \rightarrow D^-\pi^+$ ; $D^+ \rightarrow K^-\pi^+$ without $D^-$ veto:	
	$m_{\rm ES}$ , $m_{inv}$ and $m_{inv}$ . $m_{\rm ES}$ plane. $m_{inv}$ was intred with a Gaussian for the peak and a second order polynomial for background	149
1 90	Monte Carlo quenta: $\overline{D}_{0}^{0} = D^{*+} \overline{D}_{-}^{} D^{*+} = D^{0-+} D^{0-+} D^{0-+} \overline{D}_{-}^{0-+} \overline{D}_{-}^{+}$ rete:	140
A.30	Monte-Carlo events: $D^* \to D^+ pp\pi^+$ ; $D^+ \to D^*\pi^+$ ; $D^* \to K^-\pi^+$ without $D^0$ veto: left row $m(A^+\pi^+)$ and $m_* : :m(A^+\pi^+)$ plane right row $m(A^+\pi^-)$ and $m_* ::m(A^+\pi^-)$	
	neutrow $m(n_c \pi)$ and $m_{inv}.m(n_c \pi)$ prane, right row $m(n_c \pi)$ and $m_{inv}.m(n_c \pi)$	1/0
1 20	$\overline{D}_{0}^{0} = D^{(*)+(0)} = V^{(*)} + D^{(*)} + C^{(*)} + C^{(*$	140
A.39	$B^{\circ} \rightarrow D^{(\circ)+/\circ}ppX$ without $D^{\circ}$ veto from Monte-Carlo modes SP-8016-8033 (See table	150
	A.4 for the specific mode reference) without vetos of $D^*$ or $D^+$ masses	100
A.40	$B^0 \to D^{(*)+/0} p \overline{p} X$ without $D^{\circ}$ veto from Monte-Carlo modes SP-8034-8053 (See table	
	A.4 for the specific mode reference) without vetos on $D^0$ or $D^+$ masses	150
A.41	$\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$ without $D_0^+$ veto from Monte-Carlo modes SP-8073-8091 (See table	
	A.4 for the specific mode reference) without vetos on $D^0$ or $D^+$ masses	151
A.42	$\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$ without $D_0^+$ veto from Monte-Carlo modes SP-8092-8110 (See table	
	A.4 for the specific mode reference) without vetos on $D^0$ or $D^+$ masses	151
A.43	$\overline{B}{}^0 \to D^{(*)+/0} p \overline{p} X$ without $D_0^+$ veto from Monte-Carlo modes SP-8111-8120 (See table	
	A.4 for the specific mode reference) without vetos on $D^0$ or $D^+$ masses	152
Δ 44	$\overline{B}^0 \rightarrow (n_{\rm c} \neg \overline{n}_{\rm c} \neg) K^- \pi^+ \pi^+ \pi^- m(n_{\rm c} \neg \overline{n}_{\rm c})$ distribution form the $m_{\rm EG}$ and $m_{\rm c}$ signal	
11.11	$p = \left( p_{(cc)} p_{(cc)} \right) \prod_{n=1}^{\infty} n n n n n n n n n n n n n n n n n n n$	152
	Tegion with side bands substracted. Masses of charmonia are denoted. $\ldots$	100
A.45	$B^{0} \rightarrow \left( p_{(c\overline{c})} \overline{p}_{(c\overline{c})} \pi^{+}_{(c\overline{c})} \pi^{-}_{(c\overline{c})} \right) K^{-} \pi^{+} : m \left( p_{A_{c}^{+}} \overline{p}_{\overline{B}^{0}} \pi^{+}_{\overline{B}^{0}} \pi^{-}_{\overline{B}^{0}} \right) \text{ distribution form the } m_{\text{ES}} \text{ and}$	
	$m_{inv}$ signal region with side bands substracted. Masses of charmonia are denoted	153
A.46	$m_{inv}:m(\Lambda_c^+\pi^{\pm})$ : fitted toy Monte-Carlo mixture (eq. A.48). The distribution was fitted	
	with function 3.20. Plots from top-down: the input signal distribution, the difference	
	between the input distribution and the fitted function, the bin-wise $\chi^2$ distribution of the	
	ht	155
A.47	$m_{inv}:m(\Lambda_c^+\pi^\pm)$ : PDF 3.20 fitted to toy Monte-Carlo mixture eq. A.48	155
A.48	$\Sigma_c^0(2455)$ in combinatorial background: Fit to Monte-Carlo events from $B^- \rightarrow D_c^0(2455)$	
	$\Sigma_c^0(2455)\overline{p}\pi^0$ with function 3.17. Plots from top-down: the input signal distribution, the	
	difference between the input distribution and the fitted function, the bin-wise $\chi^2$ distribu-	150
A 40		198
A.49	$\Sigma_c^{*}(2455)$ in combinatorial background: Fitted function 3.17 to Monte-Carlo events from $D^{-} = -\Sigma_c^{0}(2455) = 0$	150
	$D \rightarrow \angle_{c}^{c} (2400) p\pi^{\circ}$ .	198

A.50 $\Sigma_c^0(2520)$ in combinatorial background: Fit to signal Mowith function 3.17. Plots from top-down: the input s	nte-Carlo for $B^- \to \Sigma_c^0(2520)\overline{p}\pi^0$ signal distribution, the difference
between the input distribution and the fitted function, the fit.	he bin-wise $\chi^2$ distribution of the 159
A.51 $\Sigma_c^0(2520)$ in combinatorial background: Fitted function $B^- \to \Sigma_c^0(2455)\overline{p}\pi^0$	n 3.17 to signal Monte-Carlo for $159$
A.52 Fits to side-band subtracted $m(\Lambda_c^+\pi^{\pm})$	
A.53 $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^-)$ including the $m_i$ Monte-Carlo. Plots from top-down: the input signal dis	$a_{nv}$ signal region in generic $B^+B^-$ stribution, the difference between
the input distribution and the fitted function, the bin-wi A.54 $m_{inv}$ : $m(\Lambda_c^+\pi^-)$ : Fit to $m_{inv}$ : $m(\Lambda_c^+\pi^-)$ including the $m_i$ Monte-Carlo. Plots from top-down: Combinatorial backg	ise $\chi^2$ distribution of the fit 163 $n_v$ signal region in generic $B^+B^-$ ground, $\Sigma_c^0(2455)$ in combinatorial
background, $\Sigma_c^0(2520)$ in combinatorial background	
A.55 $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ including the $m_i$ Monte-Carlo. Plots from top-down: the input signal dis	$_{nv}$ signal region in generic $B^+B^-$ stribution, the difference between
the input distribution and the fitted function, the bin-wi	ise $\chi^2$ distribution of the fit 164
A.56 $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ including the $B^+B^-$ Monte-Carlo. Plots from top-down: Combinate combinatorial background $\Sigma_{++}^{++}(2520)$ in combinatorial	e $m_{inv}$ signal region in generic orial background, $\Sigma_c^{++}(2455)$ in
$\sqrt{57}$ m, $m(\Lambda^{\pm}\pi^{-})$ ; Fit to m, $m(\Lambda^{\pm}\pi^{-})$ including the m	signal ragion in gaparia $B^0\overline{B}^0$
A.57 $m_{inv}.m(\Lambda_c \pi^{-})$ . Fit to $m_{inv}.m(\Lambda_c \pi^{-})$ including the $m$ Monte-Carlo. Plots from top-down: the input signal dis the input distribution and the fitted function the bin-wi	$_{inv}$ signal region in generic $D D$ stribution, the difference between ise $\chi^2$ distribution of the fit 165
A.58 $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^-)$ including the $m$ Monte-Carlo. Plots from top-down: Combinatorial backg	$\Sigma_{inv}$ signal region in generic $B^0\overline{B}^0$ round, $\Sigma_{i}^0(2455)$ in combinatorial
background, $\Sigma_c^0(2520)$ in combinatorial background	$\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $165$
A.59 $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ including the $m$ Monte-Carlo. Plots from top-down: the input signal dis	$_{inv}$ signal region in generic $B^0\overline{B}^0$ stribution, the difference between
the input distribution and the fitted function, the bin-with $A = CO = (A + A) + CO = (A + A) +$	ise $\chi^2$ distribution of the fit 166
A.60 $m_{inv}:m(\Lambda_c \pi^+)$ : Fit to $m_{inv}:m(\Lambda_c \pi^+)$ including the $B^0\overline{B}^0$ Monte-Carlo. Plots from top-down: Combinatorial combinatorial background $\Sigma^{++}(2520)$ in combinatorial	e $m_{inv}$ signal region in generic orial background, $\Sigma_c^{++}(2455)$ in background
A.61 $m_{inv}$ : $m(\Lambda^+\pi^-)$ : Fit to $m_{inv}$ : $m(\Lambda^+\pi^-)$ excluding the m	$n_{inv}$ signal region in data. Plots
from top-down: the input signal distribution, the different	ace between the input distribution
and the fitted function, the bin-wise $\chi^2$ distribution of the	he fit. $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $\ldots$ $167$
A.62 $m_{inv}:m(\Lambda_c^+\pi^-)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^-)$ excluding the <i>n</i> from top-down: Combinatorial background, $\Sigma_c^0(2455)$	$n_{inv}$ signal region in data. Plots b) in combinatorial background,
$\Sigma_c^0(2520)$ in combinatorial background	
A.63 $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ excluding the m	$n_{inv}$ signal region in data. Plots
from top-down: the input signal distribution, the different and the fitted function, the bin wise $x^2$ distribution of the second sec	the between the input distribution
$\Delta 64 m_{\odot} - m(A^{+}\pi^{+})$ . Fit to $m_{\odot} - m(A^{+}\pi^{+})$ excluding the m	ne nt
from top-down: Combinatorial background, $\Sigma_c^{++}(2520)$ in combinatorial background	5) in combinatorial background, $173$
A.65 $m_{inv}:m(\Lambda^+_{+}\pi^+)$ : Fit to $m_{inv}:m(\Lambda^+_{+}\pi^+)$ including the	$m_{inv}$ signal region in a mixture
of non- $\Sigma_c$ (2455,2520) signal Monte-Carlo and $\Sigma_c$ (245	(55) and $\Sigma_c$ (2520) signal Monte-
Carlo. Plots from top-down: the input signal distribu	ition, the difference between the
input distribution and the fitted function, the bin-wise $\chi$	$\chi^2$ distribution of the fit 178
A.66 $m_{inv}:m(\Lambda_c^+\pi^+)$ : Fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ including the $m_{inv}:m(\Lambda_c^+\pi^+)$	$u_{inv}$ signal region in a mixture of
non- $\Sigma_c$ (2455,2520) signal Monte-Carlo and $\Sigma_c$ (2455) as Plots from top-down: $\Sigma^{\pm\pm}(2455)$ signal $\Sigma^{\pm\pm}(2520)$ sign	nd $\mathcal{L}_c$ (2520) signal Monte-Carlo.
$\Sigma_c = (2400) \text{ signal}, \Sigma_c = (2400) \text{ signal}, \Sigma_c = (2020) \text{ signal}$	$1101-2_{C}$ (2+00,2020) signal 170

A.67 Fit for $\overline{B}{}^0 \to \Sigma_c^0(2455, 2520)\overline{p}\pi^+$ in data: fit PDFs top - down: combinatorial background,	
combinatorial background with $\Sigma_c^0(2455)$ , combinatorial background with $\Sigma_c^0(2520)$ , MC	
signal histogram: $\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ , MC signal histogram: $\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ , non-	
resonant $\underline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^- \dots \dots$	179
A.68 Fit for $\overline{B}{}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ in data: fit PDFs top - down: combinatorial	
background, combinatorial background with $\Sigma_c^{++}(2455)$ , combinatorial background with	
$\Sigma_c^{++}(2520)$ , MC signal histogram: $B^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ , MC signal histogram: $B^0 \to \Sigma_c^{++}(2520)$	
$\Sigma_c^{++}(2520)\overline{p}\pi^-$ , non-resonant $B^0 \to \Lambda_c^+ \overline{p}\pi^+\pi^-$	181
A.69 Fit for $B^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^-$ in data: fit PDFs top - down: non-resonant $B^0 \to$	
$\Lambda_c^+ \overline{p} \pi^+ \pi^-, B^- \to \Sigma_c^+ (2455) \overline{p} \pi^- \text{ background}, B^- \to \Sigma_c^+ (2520) \overline{p} \pi^- \text{ background} \ldots \ldots$	183
A.70 Sketch of distributions of nucleon resonances in $m(\overline{p}\pi^+)$ according to the nominal values [4]	
overlayed to the ${}_{s}\mathcal{P}lot$ distribution from $B^{0} \to \Sigma_{c}^{0}(2455)\overline{p}\pi^{+}$ in $m(\overline{p}\pi^{+})$ . The distributions	
are arbitrary scaled for an illustration of the possible intermediate states.	186
A.71 $B^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : invariant masses from signal MC ( $\square$ ) with correction weights from	
$_{s}\mathcal{P}lots$ (•) applied.	188
A.72 $B^0 \rightarrow \Sigma_c^{++}(2455)\overline{p}\pi^-$ : invariant masses from signal MC ( $\square$ ) with correction weights from	
$_{s}\mathcal{P}lots$ (•) applied.	188
A.73 $B^0 \rightarrow \Sigma_c^{++}(2520)\overline{p}\pi^-$ : invariant masses from signal MC ( $\square$ ) with correction weights from	100
$s\mathcal{P}lots$ (•) applied.	189
A.74 $B^{\circ} \to \Lambda_c^+ p \pi^+ \pi^-$ (region $\Pi_{\Sigma_c}$ ): invariant masses from signal MC ( $\blacksquare$ ) with correction	101
weights from $_{s}Plots$ (•) applied.	191
A. (5 $B^{\circ} \to \Lambda_c^{\circ} p \pi^+ \pi^-$ (region $I_{\Sigma_c}$ ): invariant masses from signal MO ( $\square$ ) with correction weights	100
$\operatorname{Irom}_{s} \mathcal{P}lots(\bullet) \text{ applied.} \dots \dots$	192
A. (6 $B^{\circ} \to \Lambda_c^{\circ} p \pi^+ \pi^-$ (region $I_{\Sigma_c}$ ): Comparison between uncharmed two-body invariant masses	
invariant masses from signal MU ( $\square$ ) and $_{s}$ Plots from data ( $\bullet$ ). The histograms are scaled	109
	193

## List of Tables

1.1	Meson properties [4].	3
1.2	Baryon properties [4]	4
1.3	Branching fractions from decays $B \to D^{(*)} p \overline{p} (n \cdot \pi) [2, 3, 25 - 29])$ .	14
1.4	Summary of the recent measurements of branching ratios of decays $B \to \Lambda_c^+ \overline{p} (n \cdot \pi)$ and similar decays with charmed/stranged baryons.	14
2.1	PEP-II: pair production cross sections at the on-peak cms energy $\sqrt{s} = 10.58 \text{ GeV} [35] [36].$	18
3.1	$\Lambda_c$ skim: Conditions for an event to be included in the $\Lambda_c$ skim for the decay $\Lambda_c^+ \to p K^- \pi^+$ . $\Lambda_c$ -candidates were reconstructed with a vertex fit in the invariant mass $m (p K^- \pi^+)$ , for which the potential $\Lambda_c$ -daughters had to pass soft particle ientification criteria	28
3.2	Event preselection: Tracking and PID requirements for $\overline{B}^0$ and $\Lambda_c^+$ daughters	29
3.3	Event reconstruction: Cuts on $\Lambda_c^+$ candidates during event reconstruction and event selection on ROOT ntuple level.	32
3.4	Event reconstruction: Cuts on $\overline{B}^0$ -candidates. Shifts between masses from $\Lambda_c$ generated in Monte-Carlo simulations and $\Lambda_c$ in data were taken into account.	32
3.5	Constraint acceptances for background and signal decay simulated Monte-Carlo events for consecutively applied cuts. For signal Monte-Carlo $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ events with with positively mapped signal events ( <i>truthmatched</i> ) was used, i.e. including the efficiency of the truthmatching algorithm. Efficiencies of $\overline{B}^0$ signal event selections in $m_{\rm ES}$ and $m_{inv}$ are given in table 3.7. Efficiencies of vetoes on $\overline{B}^0 \to D^0/D^+ p\overline{p} (n \cdot \pi)$ are discussed in detail in table 3.11 in section 3.8.5.	32
3.6	Definitions for signal and side bands in the $m_{\text{ES}}$ - $m_{inv}$ -plane. The bands and regions are shown in figure 3.3.	37
3.7	Constraint acceptances for generic background and signal Monte-Carlo for consecutively applied selection windows in $m_{\rm ES}$ and $m_{inv}$ after passing the constraints given in table 3.5. Truthmatched non-resonant $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ signal Monte-Carlo events were used, i.e. including the efficiency of the truthmatching algorithm (see footnote 3).	37
3.8	$\Sigma_c$ : Borders for the $\Sigma_c$ (2455, 2520) signal regions in $m(\Lambda_c^+\pi^+)$ and $m(\Lambda_c^+\pi^-)$	39

3.9	Width of $m_{inv}$ for non-resonant signal Monte-Carlo: Results of fitting the Gaussian width in $m_{inv}$ in subranges of $m(\Lambda_c^+\pi^{\pm})$ in a mixture of non-resonant signal Monte-Carlo composed of $0.38 \times \text{SP} - 5076 + 0.25 \times \text{SP} - 6980 + 0.12 \times \text{SP} - 6983 + 0.04 \times \text{SP} - 6984 + 0.24 \times \text{SP} - 6989$ . The fit is shown in figure 3.9 with ( $\chi^2 = 5.744$ , $ndf = 14$ ) $[P(\chi^2) = 0.9725]$ .	54
3.10	$\overline{B}^0 \to D^0/D^+p\overline{p} + n \cdot \pi$ : reconstruction efficiencies in the signal decay reconstruction, measured branching fractions [2], [25], $D^0/D^+$ branching ratios [57] and expected contributions to $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ without vetoes.	58
3.11	$D^0/\text{Dp}$ Veto signal reduction and remaining background events (expecting about 1.7 background events in total).	58
4.1	Data sets of Monte-Carlo simulated events. For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data and including the branching fraction of the reconstructed $\Lambda_c^+$ decay $(N_{B\overline{B}} \sim 462 \cdot 10^6, \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.05 \text{ from [4]})$ .	63
4.2	Monte-Carlo simulated event: generic background Monte-Carlo data sets	64
4.3	Invariant mass distributions in data and resonant Monte-Carlo for $\overline{B}^0 \to \Sigma_c^{+, 0} \overline{p} \pi^{\mp}$ ; the distributions were fitted with a single Gaussian for signal and a polynomial for background. In data the $\Lambda_c^+$ mass was constrained to the Monte-Carlo generator mass 2.2849 GeV/ $c^2$ , to the fitted mass in data 2.2856 GeV/ $c^2$ and without a constraint, the $\Lambda_c^+$ mass cuts were chosen correspondingly. In Monte-Carlo the $\Lambda_c^+$ mass was constrained to the Monte-Carlo generator mass.	66
4.4	$\Sigma_c^{++}$ (2455): Fitted Breit-Wigner masses in $m(\Lambda_c^+\pi^{\pm})$ from data and Monte-Carlo events.	70
4.5	$\Sigma_c^{++}(2455)$ : Fitted Breit-Wigner widths in $m(\Lambda_c^+\pi^{\pm})$ from data and Monte-Carlo events.	70
4.6	$\Sigma_c^{++}(2520)$ : Fitted Breit-Wigner masses in $m(\Lambda_c^+\pi^{\pm})$ from data and Monte-Carlo events.	70
4.7	$\Sigma_c^{++}(2520)$ : Fitted Breit-Wigner widths in $m(\Lambda_c^+\pi^{\pm})$ from data and Monte-Carlo events.	70
4.8	$\Sigma_c^{++}$ (2455,2520): Widths and (corrected) masses from Monte-Carlo used as shape parameters in fits to data and Monte-Carlo. The uncorrected values from $\Sigma_c^{++}$ (2455) in Monte-Carlo are given for comparison.	70
5.1	$m_{inv}:m(\Lambda_c^+\pi^-)$ : results from fitting data (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	75
5.2	$m_{inv}:m(\Lambda_c^+\pi^-)$ : Correlation matrix from fitting data (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). (Table I, continued in Table II 5.3)	76

5.3	$m_{inv}:m(\Lambda_c^+\pi^-)$ : Correlation matrix from fitting data. (Table II, continued from Table I 5.2)	76
5.4	$m_{inv}:m(\Lambda_c^+\pi^+)$ : results from fitting data (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ )).	78
5.5	$m_{inv}:m(\Lambda_c^+\pi^+)$ : Correlation matrix from fitting data (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). (Table I, continued in Table II 5.6)	79
5.6	$m_{inv}:m(\Lambda_c^+\pi^+)$ : Correlation matrix from fitting data. (Table II, continued from Table I 5.5)	79
5.7	Fit results for fitting the $m_{inv}$ distribution from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ signal Monte- Carlos in the $m_{inv}:m(\Lambda_c^+\pi^\pm)$ fit region $I_{\Sigma_c}$ .	83
5.8	Fit results for fitting the $m_{inv}$ distribution from data in the $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ fit region $I_{\Sigma_c}$ without $\Sigma_c^{+}$ (2455,2520) bands. Three fits were performed to estimate the systmatic uncertainty of the $\Sigma_c^+$ contribution, due to their large uncertainty. The first fit was performed excluding $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ PDFs. The second fit was performed including background from $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ with fixed PDF parameters. The third fit was repeated with $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ PDFs while the number of $\Sigma_c^+$ events was overestimated by a factor of 2. The covariance matrix from fitting with $\Sigma_c^+$ -PDFs is given in table 5.9. The fits are shown in figure 5.7.	84
5.9	Covariance matrix for fitting the $m_{inv}$ distribution from data in the $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ fit region $I_{\Sigma_c}$ without $\Sigma_c^{0}(2455,2520)$ bands and including background PDFs for $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$ . The $B^- \to \Sigma_c^+(2455,2520)\overline{p}\pi^-$ shape parameters were fixed to Monte-Carlo values (table 5.7), the number $\Sigma_c^+$ of events were fixed to the scaled number from the two-dimensional fit to $m_{inv}:m(\Lambda_c^+\pi^+)$ in data with respect to the $\Sigma_c$ (2455,2520) vetoes (table 5.12). Fit results are given in the middle column in table 5.8. The fit is shown in figure 5.7.	85
5.10	Covariance matrix for fitting the $m_{inv}$ distribution from data in the $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ fit region $II_{\Sigma_c}$ .	85
5.11	Fit results for fitting the $m_{inv}$ distribution from data in the $m_{inv}:m(\Lambda_c^+\pi^{\pm})$ fit region $II_{\Sigma_c}$ .	85
5.12	Measured signal yields of resonant $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$ modes without efficiency corrections applied.	86
5.13	Measured signal yields of non- $\Sigma_c$ contributions to $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ without efficiency corrections applied for the sub-regions $I_{\Sigma_c}$ and $II_{\Sigma_c}$ as shown in figures 5.1.3.3	86
6.1	$\overline{B}^0 \to \Sigma_c^0(2455)\overline{p}\pi^+$ : reconstruction efficiencies without and with applying weights from	

data  $_{s}\mathcal{Plots}, '\times'$  denotes the weighting along the invariant-mass projection. . . . . . . . 106

6.2	Branching fractions of resonant and non- $\Sigma_c$ (2455,2520) decays into $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ after efficiency corrections without systematic uncertainties. The subscript symbol $_{\Lambda_c^+}$ denotes the uncertainty on $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ [4]. Events from resonant $\Sigma_c$ (2455,2520) modes were vetoed in the fit to the $m_{inv}$ distribution from events in region <i>I</i> . The uncertainty on the total branching fraction for all decays into the final state $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ includes the small correlations between the $\Sigma_c$ (2455) and $\Sigma_c$ (2520) signal event yields (see tables 5.2 and 5.5).	108
6.3	PID systematic uncertainties: number of signal events from non-resonant signal Monte- Carlo $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ reconstructed (1) without PID tweaking and (2) with PID tweaking settings.	110
6.4	Combinatorial background shape: Relative signal yield variation with respect to the variation of the phase space end point $e_{psb}^{up}$ in eq. 3.12.	111
6.5	Summary of systematic uncertainties for $non-\Sigma_c \ \overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ , resonant $\overline{B}{}^0 \to \Sigma_c(2455) \overline{p} \pi^{\pm}$ and resonant $\overline{B}{}^0 \to \Sigma_c(2520) \overline{p} \pi^{\pm}$ decays	113
6.6	Branching fractions of the resonant decays $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520)\overline{p}\pi^{\mp}$ and non- $\Sigma_c$ (2455,2520) decays $\overline{B}^0 \to \Lambda_c^+ \overline{p}\pi^+ \pi^- \dots \dots$	113
A.1	Tracking reconstruction criteria. Tracking criteria before 2006 are noted as " $_{old}$ ", since 2006 definitions for GoodTracksLoose and GoodTracksTight are identical [74]	125
A.2	Particle identification lists for kaons $\mathcal{L}_K$ , pions $\mathcal{L}_{\pi}$ and protons $\mathcal{L}_p$ . For some lists a minimum momentum or a veto on the electron PID list eLHTight is required. For veryTight requirements also a veto on the muon hypothesis muMicroVeryTight is made.	125
A.3	Monte-Carlo: background Monte-Carlo modes with $\Lambda_c$ or $\Sigma_c$ . For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data and including the branching fraction of the reconstructed $\Lambda_c^+$ decay $(N_{B\overline{B}} \sim 462 \cdot 10^6$ and $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = 0.05$ from [4]).	127
A.4	Monte-Carlo: background Monte-Carlo modes with $D^0$ or $D^+$ . For measured decays the last column gives the ratio of produced Monte-Carlo events compared to the recorded on-peak data including the branching fraction of the reconstructed $D^{0}_{+(*)}$ decays $(N_{B\overline{B}} \sim 462 \cdot 10^6 \text{ and } (D^{0}_{+*} \rightarrow D^{0}_{+} \pi^{\pm}), BR(D^{0}_{+} \rightarrow \ldots)$ from [4] and [25]).	128
A.5	$\Lambda_c$ mass: Masses from fitting $m (pK^-\pi^+)$ for runs 1 -6 with a Gaussian for signal and a 2nd order polynomial for background. $m (pK^-\pi^+)$ distributions are shown in figure A.3.	130
A.6	$m_{inv}$ : $\overline{B}^0$ signal events from the invariant mass for different $\Lambda_c^+$ mass hypothesis and $m (pK^-\pi^+)$ cut regions fitted with a single Gaussian for signal and a first order polynomial for background.	131
A.7	$m_{inv}$ : $\overline{B}^0$ signal widths from fitted invariant mass for different $\Lambda_c^+$ mass hypothesis and $m(pK^-\pi^+)$ cut regions.	131
A.8	Results of fitting the Gaussian width in $m_{inv}$ in subranges of $m(\Lambda_c^+\pi^{\pm})$	144
A.9	$m_{inv}$ : signal fit with and without signal PDFs for $B^- \to \Sigma_c^+(2455, 2520)\overline{p}\pi^-$ with fixed shape parameters from Monte-Carlo and free floating scaling.	147
A.10 $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} [\pi^+\pi^-]$ : $\mathcal{B}$ for $\overline{B}^0$ decays into charmonium states with proton daughters.	152	
---	-----------	
A.11 $\overline{B}^0 \to (c\overline{c}) \overline{K}^{*0} [\pi^+\pi^-]$ : Expected events with an assumed upper reconstruction efficiency of $\epsilon_{\sim wc} = 0.1\%$ and $\mathcal{B} \left[ \overline{K}^{*0} \to K^-\pi^+ \right] = {}^2/{}_3 \ldots \ldots$	152	
A.12 Non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ : Correlation matrix from fitting the toy mixture given in subsection txt:NonResFitVerification with function 3.20.	156	
A.13 Non-resonant $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ : Results from fitting the toy mixture given in subsection txt:NonResFitVerification with function 3.20.	156	
A.14 Combinatorial background: results from fitting generic $B^+B^-$ MC (SP-1235) in $m_{inv}:m(\Lambda_c^+\pi^-)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	162	
A.15 Combinatorial background: results from fitting generic $B^+B^-$ MC (SP-1235) in $m_{inv}:m(\Lambda_c^+\pi^+)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	162	
A.16 Combinatorial background: Correlation matrix from fitting generic $B^+B^-$ MC (SP-1235) in $m_{inv}:m(\Lambda_c^+\pi^-)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes allowed to assume only negative values (-10, 0) and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	168	
A.17 Combinatorial background: Correlation matrix from fitting generic $B^+B^-$ MC (SP-1235) in $m_{inv}:m(\Lambda_c^+\pi^+)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	169	
A.18 Combinatorial background: results from fitting generic $B^0\overline{B}^0$ MC (SP-1237) in $m_{inv}:m(\Lambda_c^+\pi^-$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	.) 170	
A.19 Combinatorial background: results from fitting generic $B^0\overline{B}^0$ MC (SP-1237) in $m_{inv}:m(\Lambda_c^+\pi^+$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	.) 170	
A.20 Combinatorial background: Correlation matrix from fitting generic $B^0\overline{B}^0$ MC (SP-1237) in $m_{inv}:m(\Lambda_c^+\pi^-)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in $(-10,0)$ and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	171	
A.21 Combinatorial background: Correlation matrix from fitting generic $B^0\overline{B}^0$ MC (SP-1237) in $m_{inv}:m(\Lambda_c^+\pi^+)$ (for $\Sigma_c$ (2455,2520) background the slopes and offsets of the polynomials in $m_{inv}$ were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ).	172	

- A.24 Combinatorial background: Correlation matrix from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^-)$ in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). 175
- A.25 Combinatorial background: Correlation matrix from fitting to side-bands in  $m_{inv}:m(\Lambda_c^+\pi^+)$ in data (for  $\Sigma_c$  (2455,2520) background the slopes and offsets of the polynomials in  $m_{inv}$  were allowed to float only in limited ranges with the slopes in (-10,0) and the yield larger than zero following the fits on the Monte-Carlo simulation for  $B^- \to \Sigma_c^0 \overline{p} \pi^0$ ). 176
- A.26 Toy mixtures with and without  $\Sigma_c^{++}(2800)$  signal Monte-Carlo events were fitted. The headers give the number of  $\overline{B}^0 \to \Sigma_c^{++}(2455, 2520, 2800)\overline{p}\pi^{\mp}$  Monte-Carlo events added to the toy sample. The central column gives the number of fitted events for the A.27  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Covariance matrix from fitting data. (Table I, continued in Table II A.28) 180 A.28  $m_{inv}:m(\Lambda_c^+\pi^-)$ : Covariance matrix from fitting data. (Table II, continued from Table I A.29  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Covariance matrix from fitting data. (Table I, continued in Table II A.29) 182 A.30  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Covariance matrix from fitting data. (Table II, continued from Table I A.31 <sub>s</sub>  $\mathcal{P}lots$  from fit to  $m_{inv}:m(\Lambda_c^+\pi^+)$ : Results from fitting with fixed shape parameters. . . . 185 A.32  $_{s}\mathcal{P}lots$  from fit to  $m_{inv}:m(\Lambda_{c}^{+}\pi^{-})$ : Results from fitting with fixed shape parameters. . . 185 A.33 <sub>s</sub> $\mathcal{P}lots$  from fit to  $m_{inv}$  from region  $I_{\Sigma_c}$ : Results from fitting with fixed shape parameters. 186 A.34  $_{s}\mathcal{P}lots$  from fit to  $m_{inv}$  from region  $I_{\Sigma_{c}}$ : Results from fitting with fixed shape parameters. 186 A.35  $\overline{B}{}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+$ : reconstruction efficiencies, '×' denotes the weighting along the A.36  $\overline{B}{}^0 \to \Sigma_c^{++}(2455)\overline{p}\pi^-$ : reconstruction efficiencies, '×' denotes the weighting along the A.37  $\overline{B}{}^0 \to \Sigma_c^{++}(2520)\overline{p}\pi^-$ : reconstruction efficiencies, '×' denotes the weighting along the

A.38 $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$ (region $II_{\Sigma_c}$ ): reconstruction efficiencies with consecutively applied	
weighting along the $B$ -daughter invariant-mass combinations. $\ldots \ldots \ldots \ldots \ldots \ldots$	190
$4 \approx \overline{20}$ $4 + \overline{2} + \overline{2} (2 + \overline{2} + 1) + \overline{20} + (2 + \overline{2} + 2) + 1)$	
A.39 $B^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ (region $I_{\Sigma_c}$ without $\Sigma_c^{-0}$ (2455,2520) bands): reconstruction efficiencies	
with consecutively applied weighting along the <i>B</i> -daughter invariant-mass combinations.	190

## Bibliography

- Albrecht, H. and others. Measurement of inclusive baryon production in B meson decays. Z. Phys., C56:1-6, 1992. http://www.slac.stanford.edu/spires/find/hep/www?j=ZEPYA,C56,1.
- [2] The BABAR Collaboration: B. Aubert and et al. Observation and study of baryonic B decays:  $B \to D^{(*)} p \overline{p}, D^{(*)} p \overline{p} \pi, D^{(*)} p \overline{p} \pi \pi$ . 2009.
- [3] T.M. Hong. Hadronic b → c decays at BaBar. The 2009 Europhysics Conference on High Energy Physics, 2009. http://indico.ifj.edu.pl/MaKaC/contributionDisplay.py?contribId= 969&sessionId=2&confId=11.
- [4] C. Amsler et al. Review of particle physics. Phys. Lett., B667:1, 2008.
- [5] N. Gabyshev and H. Kichimi and Belle Collaboration. Study of Exclusive B decays to Charmed Baryons. *Physical Review D*, 66:091102, 2002. {doi:10.1103/PhysRevD.66.091102}.
- [6] K. S. Park and H. Kichimi and for the Belle Collaboration. Study of the charmed baryonic decays B<sup>0</sup> → Σ<sup>++</sup><sub>c</sub> pπ<sup>-</sup> and B<sup>0</sup> → Σ<sup>0</sup><sub>c</sub> pπ<sup>+</sup>. Physical Review D, 75:011101, 2007. doi:10.1103/PhysRevD. 75.011101.
- [7] H. Albrecht et al. Observation of the charmed baryon  $\Lambda_c$  in  $e^+e^-$  annihilation at 10 GeV. *Phys. Lett.*, B207:109, 1988.
- [8] Glen D. Crawford et al. Measurement of baryon production in B meson decay. *Phys. Rev.*, D45:752– 770, 1992.
- [9] H. Albrecht et al. Observations of  $A_c^+$  semileptonic decay. *Phys. Lett.*, B269:234–242, 1991.
- [10] T. Bergfeld et al. Study of the decay lambda(c)+  $\rightarrow$  Lambda lepton+ lepton- neutrino. *Phys. Lett.*, B323:219–226, 1994.
- [11] Bernard Aubert et al. The BaBar detector. Nucl. Instrum. Meth., A479:1–116, 2002.
- [12] B. Aubert et al. Measurements of  $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p})$  and  $\mathcal{B}(B^- \to \Lambda_c^+ \bar{p}\pi^-)$  and Studies of  $\Lambda_c^+ \pi^-$ Resonances. *Phys. Rev.*, D78:112003, 2008.
- [13] S. Majewski. Study of  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  and  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$ . BABAR Analysis Document 1670, 2007.
- [14] Aubert, Bernard *et all.* Observation of the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$ . *Phys. Rev. D*, 82(3):031102, Aug 2010.
- [15] M. Ebert. Study of Decay  $B \to \Lambda_c^+ \overline{p}\pi$ . BABAR Analysis Document **1691 v10**, 2009.
- [16] Pivk, Muriel and Le Diberder, Francois R. "Plot: a statistical tool to unfold data distributions. Nucl. Instrum. Meth., A555:356-369, 2005.

- [17] J. F. Donoghue, E. Golowich, and Barry R. Holstein. Dynamics of the standard model. Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 2:1–540, 1992.
- [18] R. Waldi. Phenomenological considerations on B meson decays into baryons. BABAR Analysis Document, 2032, 2008.
- [19] R. Mizuk et al. Observation of an isotriplet of excited charmed baryons decaying to  $\Lambda_c^+\pi$ . Phys. Rev. Lett., 94:122002, 2005.
- [20] Mahiko Suzuki. Partial waves of baryon antibaryon in three-body B meson decay. J. Phys., G34:283– 298, 2007.
- [21] Martin J. Savage and Mark B. Wise. SU(3) predictions for nonleptonix B meson decays to charmed baryons. Nucl. Phys., B326:15, 1989.
- [22] Martin J. Savage and Roxanne P. Springer. SU(3) PPredictions for Charmed Baryon decays. Phys. Rev., D42:1527–1543, 1990.
- [23] Martin J. Savage and Mark B. Wise. SU(3) Predictions for Nonleptonic B Meson Decays. Phys. Rev., D39:3346, 1989.
- [24] P. Ball and Hans Gunter Dosch. Branching ratios of exclusive decays of bottom mesons into baryon anti-baryon pairs. Z. Phys., C51:445–454, 1991. Uses techniques presented in [77] and [76].
- [25] T.M. Hong. Observation and measurement of the branching fractions of  $B \to D^{(*)}pp$ ,  $+\pi$ , and  $+\pi\pi$ . BABAR Analysis Document **933**, 2009.
- [26] T.M. Hong. Branching fractions of  $B \to D^{(*)}pp, +\pi$ , and  $+\pi\pi$ . BABAR Analysis Document **2150**, 2009.
- [27] T.M. Hong. Kinematic distributions of  $B \to D^{(*)}p\overline{p}$ ,  $+\pi$ , and  $+\pi\pi$ . BABAR Analysis Document **2155**, 2009.
- [28] T.M. Hong. Observation and study of ten B decays to  $D^{(*)}p\overline{p}(\pi)(\pi)D(*)$ . BABAR Analysis Document **2166**, 2009.
- [29] T.M. Hong. First observation and study of ten *B* decays to  $D^{(*)}p\overline{p}(\pi)(\pi)D(^*)$ . BABAR Analysis Document **2210**, 2009.
- [30] Bernard Aubert et al. Observation of the baryonic B-decay  $\overline{B}{}^0 \rightarrow \Lambda_c^+ \overline{p} K^- \pi^+$ . Phys. Rev., D80:051105, 2009.
- [31] S. A. Dytman et al. Measurement of exclusive B decays to final states containing a charmed baryon.
  ((B)). Phys. Rev., D66:091101, 2002.
- [32] Bernard Aubert et al. Measurement of the Branching Fraction and Lambda-bar Polarization in  $B^0 \to \overline{\Lambda}_c^- p \pi^-$ . Phys. Rev., D79:112009, 2009.
- [33] Bernard Aubert et al. Study of  $e^+e^- \to \Lambda\bar{\Lambda}$ ,  $\Lambda\bar{\Sigma}^0$ ,  $\Sigma^0\bar{\Sigma}^0$  using initial state radiation with BABAR. *Phys. Rev.*, D76:092006, 2007.
- [34] PEP-II: An Asymmetric B Factory. Conceptual Design Report. June 1993. SLAC-418. http: //www.slac.stanford.edu/spires/find/hep/www?r=SLAC-418.
- [35] P. F. Harrison, ed. and Helen R. Quinn, ed. The BABAR physics book: Physics at an asymmetric B factory. Papers from Workshop on Physics at an Asymmetric B Factory (BaBar Collaboration Meeting), Rome, Italy, 11-14 Nov 1996, Princeton, NJ, 17-20 Mar 1997, Orsay, France, 16-19 Jun 1997 and Pasadena, CA, 22-24 Sep 1997.

- [36] Bernard Aubert et al. A measurement of the total width, the electronic width, and the mass of the  $\Upsilon(10580)$  resonance. *Phys. Rev.*, D72:032005, 2005.
- [37] Bernard Aubert et al. The first year of the BaBar experiment at PEP-II. 2000.
- [38] ed. Harrison, P. F. and ed. Quinn, Helen R. The BABAR physics book: Physics at an asymmetric B factory. Papers from Workshop on Physics at an Asymmetric B Factory (BABAR Collaboration Meeting), Rome, Italy, 11-14 Nov 1996, Princeton, NJ, 17-20 Mar 1997, Orsay, France, 16-19 Jun 1997 and Pasadena, CA, 22-24 Sep 1997.
- [39] E. Varnes et al. Report of the tracking efficiency task force. BABAR Analysis Document **324** (2002).
- [40] C. Roat [BABAR Tracking Group]. Candidate lists and maps in the micro database. http://www.slac.stanford.edu/BFROOT/www/doc/workbook/eventstore/nanomicrosummary/ Micro/CandLists.html.
- [41] A. Roodman [BABAR PID Group]. Description of the lh selectors. http://www.slac.stanford. edu/BFROOT/www/Physics/Tools/Pid/Hadrons/Description\_of\_the\_LH\_selectors.html.
- [42] T. Brandt [BABAR PID Group]. Pid-selectors in beta. http://www.slac.stanford.edu/BFROOT/ www/Physics/Tools/Pid/PidSelectors/index.html#general.
- [43] N. Metropolis and S. Ulam. The Monte Carlo Method. J. Am. Stat. As, 44:335–341, 1949.
- [44] D. J. Lange. The EvtGen particle decay simulation package. Nucl. Instrum. Meth., A462:152–155, 2001.
- [45] Torbjorn Sjostrand. High-energy physics event generation with PYTHIA 5.7 and JETSET 7.4. Comput. Phys. Commun., 82:74–90, 1994.
- [46] Torbjorn Sjostrand, Leif Lonnblad, and Stephen Mrenna. PYTHIA 6.2: Physics and manual. 2001.
- [47] T. Sjostrand. The PYTHIA and JETSET programs. Prepared for Particles & Fields 92: 7th Meeting of the Division of Particles Fields of the APS (DPF 92), Batavia, Illinois, 10-14 Nov 1992.
- [48] E. Richter-Was. QED bremsstrahlung in semileptonic B and leptonic tau decays. Phys. Lett., B303:163-169, 1993.
- [49] S. Agostinelli et al. GEANT4: A simulation toolkit. Nucl. Instrum. Meth., A506:250–303, 2003.
- [50] C. Hearty. Hadronic Event Selection and B-Counting for Inclusive Charmonium Measurements. BABAR Analysis Document **30**, 2000.
- [51] C. Hearty. Measurement of the Number of Upsilon(4S) Mesons Produced in Run 1 (B Counting). BABAR Analysis Document 134, 2001.
- [52] R. Brun and F. Rademakers. ROOT: An object oriented data analysis framework. Nucl. Instrum. Meth., A389:81–86, 1997.
- [53] R. Brun, F. Rademakers, and S. Panacek. ROOT, an object oriented data analysis framework. Prepared for CERN School of Computing (CSC 2000), Marathon, Greece, 17-30 Sep 2000.
- [54] W. Dunwoodie. Simple Observations on B Bbar Kinematics. http://www.slac.stanford.edu/ ~wmd/bbkinematics/kinematics.note, compare also [75].
- [55] S. Eidelman et al. Review of particle physics. Phys. Lett., B592:1, 2004. comment: included since the  $\Lambda_c$  mass used in MC generation and for default mass constraining  $\Lambda_c$  candidates at BABAR is taken from this volume.

- [56] B. Aubert and The BABAR Collaboration. A Precision Measurement of the A<sub>c</sub> Baryon Mass. *Physical Review D*, 72:052006, 2005. {doi:10.1103/PhysRevD.72.052006}, http://www. springerlink.com/content/x67055u7t0344320/fulltext.pdf.
- [57] W. M. Yao et al. Review of particle physics. J. Phys., G33:1-1232, 2006.
- [58] R. Waldi J. Smith, A. Soffer. Recommendation for Exclusiv B Reconstruction. BABAR Note, 497, 1999. http://www.slac.stanford.edu/BFROOT/www/doc/BaBarNotes/BaBarNotes/ BaBar497.ps.gz.
- [59] M. Artuso et al. Measurement of the Masses and Widths of the  $\Sigma_c^{++}$  and  $\Sigma_c^0$  Charmed Baryons. *Phys. Rev.*, D65:071101, 2002.
- [60] R. Ammar et al. First observation of the  $\Sigma_c^{*+}$  baryon and a new measurement of the  $\Sigma_c^{+}$  mass. *Phys. Rev. Lett.*, 86:1167–1170, 2001.
- [61] J. M. Link et al. Measurement of natural widths of  $\Sigma_c^0$  and  $\Sigma_c^{++}$  baryons. *Phys. Lett.*, B525:205–210, 2002.
- [62] Albrecht, H. and others. Search for hadronic  $b \rightarrow u$  decays. *Phys. Lett.*, B241:278–282, 1990.
- [63] B. Petersen. Measurement of the  $\Lambda_c$  mass. BABAR Analysis Document 1087 v5, 2005.
- [64] B. Petersen. Measurement of the  $\Lambda_c^+$  baryon mass. BABAR Analysis Document 1175 v16, 2005.
- [65] R. H. Dalitz. Decay of  $\tau$  mesons of known charge. Phys. Rev., 94:1046–1051, 1954.
- [66] Tracking Efficiency Task Force. BABAR Charged Particles Reconstruction. {http://www.slac. stanford.edu/BFROOT/www/Physics/Tools/Pid/PID\_Systematics.html}.
- [67] BABAR PID-group. PID Systematic Errors. {http://www.slac.stanford.edu/BFROOT/www/ Physics/TrackEfficTaskForce/TrackingTaskForce-2007-R22.html}.
- [68] N. Gabyshev et al. Observation of  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p}$  decay. Phys. Rev. Lett., 90:121802, 2003.
- [69] N. Gabyshev et al. Study of decay mechanisms in  $B^- \to \Lambda_c^+ \overline{p} \pi^-$  decay and observation of anomalous structure in the  $\Lambda_c^+ \overline{p}$  system. *Phys. Rev. Lett.*, 97:242001, 2006.
- [70] N. Gabyshev et al. Study of exclusive B decays to charmed baryons at Belle. ((B)). Phys. Rev., D66:091102, 2002.
- [71] Hai-Yang Cheng and Kwei-Chou Yang. Charmful baryonic B decays  $\overline{B}^0 \to \Lambda_c^+ \overline{p}$  and  $\overline{B} \to \Lambda_c^+ \overline{p}\pi (\rho)$ . *Phys. Rev.*, D65:054028, 2002.
- [72] T. Leddig. Study of the decay  $\overline{B}^0 \to \Lambda_c^+ \overline{p} K^- \pi^+$ . BABAR Analysis Document **2149 v07**, 2009.
- [73] T. Leddig. Observation of the baryonic B-decay  $\overline{B}{}^0 \to \Lambda_c^+ \overline{p} K^- \pi^+$ . BABAR Analysis Document **2161** v10, 2009.
- [74] Charged Particle AWG. New BtaCandidate Lists. http://www.slac.stanford.edu/BFROOT/www/ Physics/Charged.html#Lists.
- [75] William T. Ford. Choice of Kinematic Variables in B Meson Reconstruction. BABAR Analysis Document, 53, 2000.
- [76] Hans Gunter Dosch, M. Jamin, and Stephan Narison. Baryon masses and flavor symmetry breaking of chiral condensates. *Phys. Lett.*, B220:251, 1989.

- [77] Hans Gunter Dosch, M. Jamin, and B. Stech. Diquarks, QCD sum rules and weak decays. Z. Phys., C42:167, 1989.
- [78] Manfred Bauer, B. Stech, and M. Wirbel. Exclusive Nonleptonic Decays of D, D<sup>\*</sup>, and B Mesons. Z. Phys., C34:103, 1987.
- [79] PYTHIA Manual. Widths. http://cepa.fnal.gov/psm/simulation/mcgen/lund/pythia\_ manual/pythia6.3/pythia6301/node192.html, 2005-0711.
- [80] Bernard Aubert et al. A study of  $\overline{B} \to \Xi_c \Lambda_c^-$  and  $\overline{B} \to \Lambda_c^+ \Lambda_c^- \overline{K}$  decays at BABAR. *Phys. Rev.*, D77:031101, 2008.
- [81] Bernard Aubert et al. A Study of e+ e- —; p anti-p using initial state radiation with BABAR. Phys. Rev., D73:012005, 2006.
- [82] M. Artuso et al. Observation of new states decaying into Lambda/c+ pi- pi+. Phys. Rev. Lett., 86:4479-4482, 2001.

## Danksagung

An dieser Stelle möchte ich mich bei allen Bedanken, die mich, direkt oder indirekt, bei der Erstellung dieser Arbeit unterstützt haben.

Insbesondere möchte ich mich bei Priv.-Doz. Dr. Roland Waldi und Prof. Dr. Henning Schröder für ihre hervorragend Betreuung und Geduld mit mir bedanken. Sie haben mir die Teilnahme am *BABAR*-Experiment überhaupt erst ermöglicht und mir Einblicke in die vielen Bereiche der Physik und darüber hinaus gewährt haben.

Dazu möchte ich Herrn Priv.-Doz. Dr. Roland Waldi und Herrn Prof. Dr. Achim Denig danken, dass sie sich bereit erklärten, als Gutachter dieser Arbeit zu fungieren.

Ich möchte mich auch bei meinen Studienkollegen Chris, Christian, Marcus, Oliver und Sebastian in der Elementarteilchenphysik-Arbeitsgruppe der Universität Rostock bedanken, mit denen ich immer physikspezifische und physikunspezifische Diskussionen führen konnte. Ganz besonders möchte ich Torsten danken, der mich all die Zeit als Büronachbarn verkraften musste und der mir mit seiner Geduld und seinem physikalischen wie freundschaftlichen Sachverstand immer weiterhalf.

Diese Arbeit wäre ohne die Vielzahl an Kollegen bei *BABAR* nicht möglich gewesen, die überall verstreut am gelingen dieses erfolgreichen Experimentes mitgearbeitet haben.

Ich möchte mich auch bei meinen Freunden bedanken, die mich wärend dieser Zeit begleitet haben: den Mitgliedern der Mensatruppe Enno, Thomas, Thomas und Patrice sowie Bianka, Dennis, Dörte, Gertrud und allen, die ich vergessen habe.

Und zu guter Letzt gilt natürlich mein besonderer Dank meiner Familie.

## Doktoranden-Erklärung gemäß §4 Absatz 1 Buchstaben g und h der Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Rostock

Die Arbeit wurde am Institut für Physik an der Universität Rostock unter der wissenschaftlichen Betreuung von Priv.-Doz. Dr. Roland Waldi angefertigt.

Ich gebe folgende Erklärung ab:

- 1. Die Gelegenheit zum vorliegenden Promotionsvorhaben ist mir nicht kommerziell vermittelt worden. Insbesondere habe ich keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen/Betreuer für die Anfertigung von Dissertationen sucht oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.
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Rostock, den 1. März 2011

Thomas Hartmann

## Errata

The following corrections were applied:

- Section 6.5 eq. 6.22 and in section 7: corrected the upper limit on  $\mathcal{B}(\overline{B}^0 \to \Sigma_c^0(2520)\overline{p}\pi^+)$ .
- Added the total branching fraction of the combined modes in section 6.3 in table 6.2 and in section 6.5 in table 6.6.
- Moved the interpretation of  ${}_{s}\mathcal{P}lotted$  invariant mass combinations  $\overline{B}^{0}$ -daughter from decays via  $\Sigma_{c}^{0}{}^{++}$  resonances from subsections 5.2.1.1 for  $\overline{B}^{0} \to \Sigma_{c}^{0}\overline{p}\pi^{+}$  and 5.2.1.3 for  $\overline{B}^{0} \to \Sigma_{c}^{++}\overline{p}\pi^{-}$  into a combined interpretation as subsection 5.2.2.
- Included in subsection 6.4 a systematic uncertainty on the weighting of the Monte-Carlo data with the  $_{s}\mathcal{P}lot$  projected data as described in chapter 6.
- Included subsection 1.1.3 for an overview of the relevant hadrons in the analysis.
- Added in section 6.5 an annotation on the differences in the branching ratios between decays with  $\Sigma_c$  (2455) and  $\Sigma_c$  (2520) baryons.
- Added my thanks to the referees.