

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

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We study the decay  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ , reconstructing the  $\Lambda_c^+$  baryon in the  $pK^- \pi^+$  mode, using a data sample of  $467 \times 10^6$   $B\bar{B}$  pairs collected with the *BABAR* detector at the PEP-II storage rings at SLAC. We measure branching fractions for decays with intermediate  $\Sigma_c$  baryons to be  $\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-] = (21.3 \pm 1.0 \pm 1.0 \pm 5.5) \times 10^{-5}$ ,  $\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-] = (11.5 \pm 1.0 \pm 0.5 \pm 3.0) \times 10^{-5}$ ,  $\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+] = (9.1 \pm 0.7 \pm 0.4 \pm 2.4) \times 10^{-5}$ , and  $\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+] = (2.2 \pm 0.7 \pm 0.1 \pm 0.6) \times 10^{-5}$ , where the uncertainties are statistical, systematic, and due to the uncertainty on the  $\Lambda_c^+ \rightarrow pK^- \pi^+$  branching fraction, respectively. For decays without  $\Sigma_c(2455)$  or  $\Sigma_c(2520)$  resonances, we measure  $\mathcal{B}[\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-]_{\text{non-}\Sigma_c} = (79 \pm 4 \pm 4 \pm 20) \times 10^{-5}$ . The total branching fraction is determined to be  $\mathcal{B}[\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-]_{\text{total}} = (123 \pm 5 \pm 7 \pm 32) \times 10^{-5}$ . We examine multibody mass combinations in the resonant three-particle  $\Sigma_c \bar{p} \pi$  final states and in the four-particle  $\Lambda_c^+ \bar{p} \pi^+ \pi^-$  final state, and observe different characteristics for the  $\bar{p} \pi$  combination in neutral versus doubly-charged  $\Sigma_c$  decays.

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## I. INTRODUCTION

Decays of  $B$  mesons into final states with baryons account for  $(6.8 \pm 0.6)\%$  [1] of all  $B$  meson decays. Notwithstanding their significant production rate, the baryon production mechanism in  $B$  meson decays is poorly understood. Theoretical models of  $B$  meson baryonic decays are currently limited to rough estimates of the branching fractions and basic interpretations of the decay mechanisms [2–6]. Additional experimental information may help to clarify the underlying dynamics.

In this paper, we present a measurement of the  $B$ -

meson baryonic decay<sup>1</sup>  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ . The  $\Lambda_c^+$  baryon is observed through its decays to the  $pK^- \pi^+$  final state. The study is performed using a sample of  $e^+e^-$  annihilation data collected at the mass of the  $\Upsilon(4S)$  resonance with the *BABAR* detector at the SLAC National Accelerator Laboratory. We include a study of the production of this final state through intermediate  $\Sigma_c^{++}$  and  $\Sigma_c^0$  resonances. The *sPlot* technique [7] is used to examine multibody mass combinations within the  $\Sigma_c \bar{p} \pi$  final states. We account for background from sources such as  $B \rightarrow D p \bar{p}$  ( $n\pi$ ) and  $B^- \rightarrow \Sigma_c^+ \bar{p} \pi^-$ , which were not considered in previous studies [8, 9]. In addition, we extract the four-body non-resonant branching fraction and examine two- and three-body mass combinations within the four-body  $\Lambda_c^+ \bar{p} \pi^+ \pi^-$  final state. The  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  decay has previously been studied by the CLEO [8] and Belle [9] Collaborations using data samples of  $9.17 \text{ fb}^{-1}$  of  $357 \text{ fb}^{-1}$ , respectively. The present work represents the first study of this decay mode from *BABAR*.

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<sup>1</sup> The use of charge conjugate decays is implied throughout this paper.

Section II provides a brief description of the *BABAR* detector and data sample. The basic event selection procedure is described in Sec. III. Section IV presents the method used to extract results for channels that proceed via intermediate  $\Sigma_c$  baryons. The corresponding results for channels that do not proceed via  $\Sigma_c$  baryons are presented in Sec. V. Section VI presents the method used to determine signal reconstruction efficiencies, Sec. VII the branching fraction results, Sec. VIII the evaluation of systematic uncertainties, and Sec. IX the final results. A summary is given in Sec. X.

## II. *BABAR* DETECTOR AND DATA SAMPLE

The data sample used in this analysis was collected with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  storage ring at SLAC. PEP-II operates with a 9 GeV  $e^-$  and a 3.1 GeV  $e^+$  beam resulting in a center-of-mass energy equal to the  $\Upsilon(4S)$  mass of 10.58 GeV/ $c^2$ . The collected data sample contains  $467 \times 10^6$   $B\bar{B}$  pairs, which corresponds to an integrated luminosity of 426 fb $^{-1}$ .

The *BABAR* detector [10] measures charged-particle tracks with a five-layer double-sided silicon vertex tracker (SVT) surrounded by a 40-layer drift chamber (DCH). Charged particles are identified using specific ionization energy measurements in the SVT and DCH, as well as Cherenkov radiation measurements in an internally reflecting ring imaging Cherenkov detector (DIRC). These detectors are located within the 1.5 T magnetic field of a superconducting solenoid.

Using information from the SVT, the DCH, and the DIRC for a particular track, the probability for a given particle hypothesis is calculated from likelihood ratios. The identification efficiency for a proton is larger than 90% with the probability of misidentifying a kaon or pion as a proton between 3% and 15% depending on the momentum. For a kaon, the identification efficiency is 90% with the probability of misidentifying a pion or proton as a kaon between 5% and 10%. The identification efficiency for a pion is larger than 95% with the probability of misidentifying a kaon or proton as a pion between 5% and 30%.

Monte Carlo (MC) simulated events are produced with an  $e^+e^- \rightarrow B\bar{B}$  event simulation based on the *EvtGen* program [11] and an  $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$  event simulation based on the *JETSET* program [12]. Generated events are processed in a *GEANT4* [13] simulation of the *BABAR* detector. MC-generated events are studied for generic background contributions as well as for specific signal and background modes. Baryonic  $B$  meson decays are generated assuming that their daughters are distributed uniformly in phase space.

## III. EVENT SELECTION

The signal mode is reconstructed in the decay chain  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  with  $\Lambda_c^+ \rightarrow p K^- \pi^+$ . All final state particles are required to have well defined tracks in the SVT and DCH. Kaons and protons, as well as pions from the  $\Lambda_c^+$  decay, are required to pass likelihood selectors based on information from the SVT, DCH, and DIRC. For pion candidates from the  $\bar{B}^0$  decay, a well reconstructed track is required.

To form a  $\Lambda_c^+$  candidate, the  $p$ ,  $K^-$ , and  $\pi^+$  candidates are fitted to a common vertex and a  $\chi^2$  probability greater than 0.1% is required for the vertex fit. To form a  $\bar{B}^0$  candidate, the  $\Lambda_c^+$  candidate is constrained to its nominal mass value and combined with an antiproton and two pions with opposite charge. The mass constraint value differs between events from data and MC. For the MC events a nominal  $\Lambda_c^+$  mass of  $m_{\Lambda_c^+}^{\text{MC}} = 2284.9$  MeV/ $c^2$  is chosen; this corresponds to the mass value used in the MC generation and to the value from fits to reconstructed MC events. For data,  $\chi^2$  fits are performed on the  $m(pK^-\pi^+)$  invariant mass distribution to find the nominal  $\Lambda_c^+$  mass. The fits are performed for each of the six distinct *BABAR* run periods. The results are found to vary between  $m_{\Lambda_c^+}^{\text{data}} = (2285.55 \pm 0.18)$  MeV/ $c^2$  and  $m_{\Lambda_c^+}^{\text{data}} = (2285.62 \pm 0.22)$  MeV/ $c^2$ , where the uncertainties are statistical. All invariant mass values are found to be consistent. The average result  $m_{\Lambda_c^+}^{\text{data}} = 2285.6$  MeV/ $c^2$  is used as the nominal value for the mass constraint in data.

Only candidates within a 25 MeV/ $c^2$  mass window centered on the nominal  $\Lambda_c^+$  mass  $m_{\Lambda_c^+}^{\text{data}}$  (or  $m_{\Lambda_c^+}^{\text{MC}}$  for simulated events) are retained. The entire decay chain is refitted requiring that the direct  $\bar{B}^0$  daughters originate from a common vertex and that the  $\chi^2$  probability for the  $\bar{B}^0$  vertex fit exceeds 0.1%.

The decays  $B \rightarrow D p \bar{p}$  ( $n\pi$ ) with  $n = 1, 2$ , which are described in more detail in section IV A, can contribute a signal-like background through rearrangement of the final-state particles and are denoted ‘‘peaking background’’ in the following. To suppress these events, symmetric vetoes of  $\pm 20$  MeV/ $c^2$  around the nominal  $D^0$  and  $D^+$  mass values [1] are applied in the distributions of the invariant masses  $m\left([K^-\pi^+]_{\Lambda_c^+} [\pi^-\pi^+]_{\bar{B}^0}\right)$ ,  $m\left([K^-\pi^+]_{\Lambda_c^+} [\pi^+]_{\bar{B}^0}\right)$ , and  $m\left([K^-\pi^+]_{\Lambda_c^+}\right)$ , where subscripts denote the mother candidate of the particles.

To separate  $\bar{B}^0$  signal events from combinatorial background, two variables are used. The  $\bar{B}^0$  invariant mass is defined as  $m_{\text{inv}} = \sqrt{E_{\bar{B}^0}^2 - \mathbf{p}_{\bar{B}^0}^2}$  with the four-momentum vector of the  $\bar{B}^0$  candidate ( $E_{\bar{B}^0}, \mathbf{p}_{\bar{B}^0}$ ) measured in the laboratory frame. The energy-substituted mass is defined in the laboratory frame as  $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_{\bar{B}^0})^2 / E_i^2 - \mathbf{p}_{\bar{B}^0}^2}$  with  $\sqrt{s}$  the center-of-mass energy and  $(E_i, \mathbf{p}_i)$  the four-momentum vector

of the initial  $e^+e^-$  system measured in the laboratory frame. For both variables, genuine  $\bar{B}^0$  decays are centered at the  $\bar{B}^0$  meson mass. In MC, these variables exhibit a negligible correlation for genuine  $\bar{B}^0$  mesons.

To suppress combinatorial background,  $\bar{B}^0$  candidates are required to satisfy  $m_{\text{ES}} \in [5.272, 5.285]$   $\text{GeV}/c^2$ . Figure 1 shows the  $m_{\text{inv}}$  distribution after applying all of the above selection criteria. The dashed lines show sideband regions  $m_{\text{inv}} \in [5.170, 5.230]$  and  $m_{\text{inv}} \in [5.322, 5.382]$ , used to study background characteristics; both sideband regions are combined into a single sideband region.

The analysis is separated into two parts: I) the

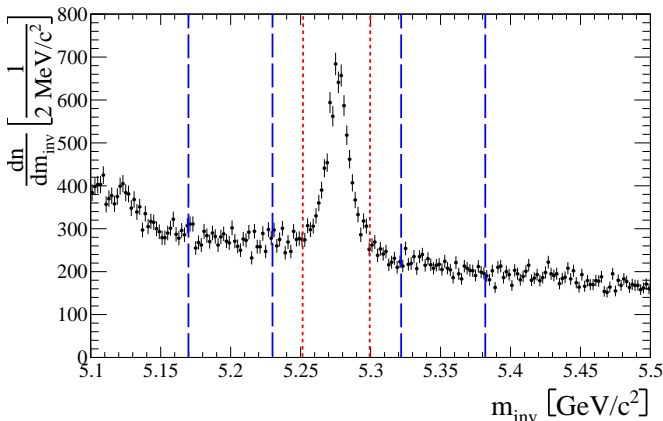


FIG. 1: Distribution of the invariant mass  $m_{\text{inv}}$  ( $\Lambda_c^+ \bar{p} \pi^+ \pi^-$ ) for events with  $m_{\text{ES}}$  in the region  $[5.272, 5.285]$   $\text{GeV}/c^2$ . The red dotted lines indicate the signal region and the blue dashed lines the sideband regions. Higher multiplicity modes, such as  $B \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \pi$ , appear for  $m_{\text{inv}} < 5.14$   $\text{GeV}/c^2$ .

measurement of the four signal decays via intermediate  $\Sigma_c(2455, 2520)$  resonances, i.e.,  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$ ,  $\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$ ,  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$ , and  $\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$ , and II) the measurement of all other decays into the four-body final state  $\Lambda_c^+ \bar{p} \pi^+ \pi^-$ , which are denoted as *non- $\Sigma_c$  signal events* in the following.

#### IV. $\bar{B}^0 \rightarrow \Sigma_c^{++} \bar{p} \pi^\mp$ ANALYSIS

Decays via resonant intermediate states with  $\Sigma_c$  resonances are studied in the two-dimensional planes spanned by  $m_{\text{inv}}$  and the invariant  $\Sigma_c$  candidate invariant mass  $m(\Lambda_c^+ \pi^+)$  for decays with  $\Sigma_c(2455, 2520)^{++}$  and  $m(\Lambda_c^+ \pi^-)$  for decays with  $\Sigma_c(2455, 2520)^0$ . In the following the like-sign  $\Lambda_c \pi$  invariant mass is denoted as  $m_{++}$  and the opposite-sign invariant mass as  $m_{+-}$ . If both invariant masses are referred to, we use the notation  $m_{\pm\pm}$ . For intermediate  $\Sigma_c(2455, 2520)^{+,0}$  states,  $\mathcal{B}[\Sigma_c \rightarrow \Lambda_c^+ \pi] \approx 100\%$  is assumed [1].

We perform fits in both planes  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$  to extract the signal yields for the decays via the  $\Sigma_c$  resonances. Background contributions are vetoed when feasible. We distinguish between different signal

and remaining background contributions by using separate probability density functions (PDF) for each signal and background component. We use analytical PDFs as well as discrete histogram PDFs. The PDFs are validated using data from the sideband regions and from MC samples. The different, combined PDFs are fitted to the  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$  planes and the resulting covariance matrices of the fits are used to calculate *sPlot* [7] distributions of signal events.

Figures 2(a) and 2(b) show the  $m_{++}$  and  $m_{+-}$  distributions, respectively, after applying the selection criteria as described in Sec. III. Signal contributions from the  $\Sigma_c(2455)^{++}$ ,  $\Sigma_c(2520)^{++}$ , and  $\Sigma_c(2455)^0$  resonances are observed and a contribution from events with a  $\Sigma_c(2800)^{++}$  resonance is visible. The doubly-charged  $\Sigma_c^{++}$  resonances are seen to contribute larger numbers of events than the neutral  $\Sigma_c^0$  resonances. The resonant structures sit on top of combinatorial background and peaking background events as well as non- $\Sigma_c$  signal events. The latter are distributed in  $m(\Lambda_c^+ \pi^\pm)$  like combinatorial background events.

#### A. Background sources

The main source for combinatorial background events is other  $B$  decays, while 20% originate from  $e^+e^- \rightarrow c\bar{c}$  events. Combinatorial events do not exhibit peaking structures in the distributions of the signal variables under study. In contrast, other sources of background do exhibit peaking structures, and are treated separately.

##### 1. $B \rightarrow D p \bar{p} (n\pi)$

Decays of the type  $B \rightarrow D p \bar{p} (n\pi)$  with  $D \rightarrow K^- (m\pi)$ , where  $n + m = 3$ , can have the same final state particles as signal decays. Rearrangement of the final state particles can yield a fake  $\Lambda_c^+$  candidate, while the  $\bar{B}^0$  candidate is essentially a genuine  $\bar{B}^0$  suppressed only by the  $\Lambda_c^+$  selection. Because these events represent fully reconstructed genuine  $B$ -meson decays, they are distributed like signal events in the  $m_{\text{inv}}$  and  $m_{\text{ES}}$  variables. Table I shows the relevant decay modes and their misreconstruction rate as signal. Furthermore, these events can also be misreconstructed as higher  $\Sigma_c$  resonances in the  $\Lambda_c^+ \pi$  invariant masses. Figure 3 shows the distributions of the MC-simulated background modes in the  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$  planes. Additionally,  $\bar{B}^0 \rightarrow D^+ \bar{p} \bar{p} \pi^-$  events with  $D^+ \rightarrow K^- \pi^+ \pi^+$  have a minimum invariant mass in  $m_{++}$  of  $m(D^+ p) \approx 2.808$   $\text{GeV}/c^2$  and can introduce background in the study of events with intermediate  $\Sigma_c(2800)^{++}$  resonances.

From the misreconstruction efficiency determined from signal MC events and scaled with the measured branching fractions [14],  $167 \pm 20$  background events are expected to contribute as signal. To suppress these events, veto regions are set to 20  $\text{MeV}/c^2$  around the nominal

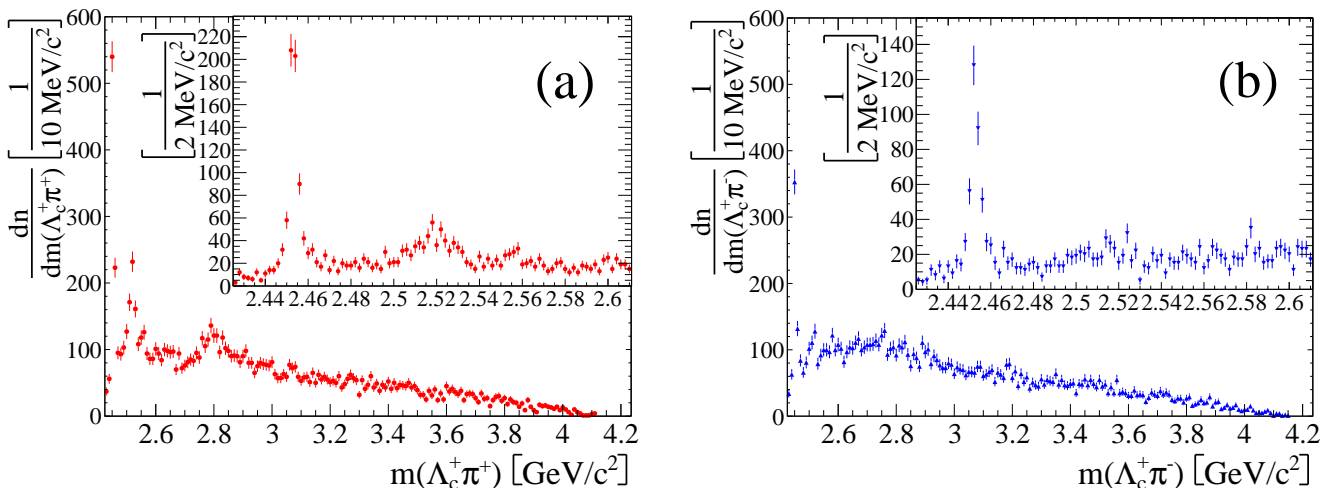


FIG. 2: Event distributions in  $m(\Lambda_c^+\pi^+)$  (a) and  $m(\Lambda_c^+\pi^-)$  (b) for events in the signal region of Fig. 1. The inserts show the low invariant mass regions.

$D^0$  and  $D^+$  masses [1] in  $m(K^-\pi^+)$ ,  $m(K^-\pi^+\pi^+)$ , and  $m(K^-\pi^+\pi^+\pi^-)$ , with the resulting suppression rates given in table I. A systematic uncertainty is assigned to account for the remaining background events. No distortions are found in other variables due to the vetoes. Note that  $\bar{B}^0 \rightarrow D^0 p \bar{p} \pi^+ \pi^-$  events with  $D^0 \rightarrow K^-\pi^+$  rearranged to  $\bar{B}^0 \rightarrow [\pi^-\pi^+\bar{p} [p]_{\bar{B}^0} [K^-\pi^+]_{D^0}]_{\text{fake } \Lambda_c^+}$  do not contribute peaking background because the selection requirement on  $m(pK^-\pi^+)_{\Lambda_c^+}$  effectively vetoes these events.

### 2. $\bar{B}^0 \rightarrow (c\bar{c}) \bar{K}^{*0} \pi^+ \pi^-$

Decays via charmonia, such as  $\bar{B}^0 \rightarrow (c\bar{c}) \bar{K}^{*0} \pi^+ \pi^-$  with  $(c\bar{c}) \rightarrow p\bar{p}$  and  $\bar{K}^{*0} \rightarrow K^-\pi^+$ , or  $\bar{B}^0 \rightarrow (c\bar{c}) \bar{K}^{*0}$  with  $(c\bar{c}) \rightarrow p\bar{p}\pi^+\pi^-$ , can also produce the same final state particles as signal events. We observe no indication of such contributions in data in the relevant combinations of  $\bar{B}^0$  daughters or in signal MC events when scaling the misreconstruction efficiencies with the measured branching fractions [1]. We neglect these events, but assign a corresponding systematic uncertainty (see Sec. VIII).

### 3. $B^- \rightarrow \Sigma_c^+ \bar{p} \pi^-$

Events from  $B^- \rightarrow \Sigma_c^+ \bar{p} \pi^-$  decays with  $\Sigma_c(2455)^+ \rightarrow \Lambda_c^+ \pi^0$  or  $\Sigma_c(2520)^+ \rightarrow \Lambda_c^+ \pi^0$  are found to have a signal-like shape in  $m_{\text{inv}}$  and  $m_{++}$ . Because of the low-momentum  $\pi^0$  daughters in the  $\Sigma_c(2455, 2520)^+$  center-of-mass systems, fake  $\Sigma_c(2455, 2520)^+$  can be generated by replacing the  $\pi^0$  with a  $\pi^+$  from the  $B^+$ . Figure 4 shows the distributions of MC-generated events. These events cluster in the  $m_{\text{inv}}$  signal region as well

as in  $m_{++}$  in the  $\Sigma_c(2455)^{++}$  and  $\Sigma_c(2520)^{++}$  signal regions. A correlation between  $m_{\text{inv}}$  and  $m_{++}$  is apparent. No significant structures are found in MC-generated events with nonresonant  $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^0$  or with  $B^- \rightarrow \Sigma_c(2800)^+ \bar{p} \pi^-$  events due to the softer momentum constraints on the  $\pi^0$ .

### 4. Combinatorial background with genuine $\Sigma_c$ events

In both MC and data-sideband events, combinatorial background events with genuine  $\Sigma_c(2455, 2520)^{+,0}$  resonances are found to be distributed differently than purely combinatorial background events without  $\Sigma_c$  resonances. These events produce a signal-like structure in  $m_{++}$  or  $m_{+-}$ , but are distributed in  $m_{\text{inv}}$  similarly to purely combinatorial background. However, since combinatorial background events with genuine  $\Sigma_c(2455, 2520)^{+,0}$  resonances scale differently in  $m_{\text{inv}}$  than purely combinatorial background events, no simple combined PDF can be constructed. Thus, both combinatorial background sources are treated as separate background classes.

### 5. $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ events without a $\Sigma_c$ signal

Events also appear as background in the  $m_{+\pm}$  distribution when they contain decays into the four-body final state  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ , not via the signal  $\Sigma_c$  resonance. For example, decays such as  $\bar{B}^0 \rightarrow \Sigma_c^{++} \bar{p} \pi^-$  are distributed as background to  $\bar{B}^0 \rightarrow \Sigma_c^0 \bar{p} \pi^+$  events in  $m_{+-}$  but as signal in  $m_{\text{inv}}$ . Therefore, decays to  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  not cascading via the signal resonance are included as a background class.



TABLE I: Efficiencies for reconstructing  $\bar{B}^0 \rightarrow Dp\bar{p}$  ( $n\pi$ ) events as signal decays by rearranging the final-state particles in signal-like combinations. In the fake signal reconstruction, the subscript particles denote the actual mother. The quantity  $n_{\text{expected}}$  gives the number of fake signal events without the  $D$ -meson veto (see text),  $\varepsilon_{\text{Cut}}$  gives the efficiencies of the vetoes, and  $n_{\text{remaining}}$  gives the expected number of remaining fake events in the signal regions after applying the vetoes. The  $\bar{B}^0 \rightarrow Dp\bar{p}$  ( $n\pi$ ) branching fractions are taken from Ref. [14] and the  $D^0/D^+$  branching fractions from Ref. [1].

Decay mode	Fake signal	$\varepsilon_{\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-}$	$n_{\text{expected}}$	$\varepsilon_{\text{Cut}}$	$n_{\text{remaining}}$
$\bar{B}^0 \rightarrow D^0 p \bar{p}$ $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	$\bar{B}_{\text{fake}}^0 \rightarrow [\bar{p} [p]_{\bar{B}^0} [K^- \pi^+]_{\text{fake } \Lambda_c^+} \pi^- \pi^+]_{D^0}$	$(6.79 \pm 0.19) \times 10^{-3}$	26.0	99.3%	0.3
$\bar{B}^0 \rightarrow D^+ p \bar{p} \pi^-$ $D^+ \rightarrow K^- \pi^+ \pi^+$	$\bar{B}_{\text{fake}}^0 \rightarrow [\pi^- \bar{p} [p]_{\bar{B}^0} [K^- \pi^+]_{\text{fake } \Lambda_c^+} \pi^+]_{D^+}$	$(7.28 \pm 0.17) \times 10^{-3}$	103.0	98.8%	1.0
$\bar{B}^0 \rightarrow D^0 p \bar{p} \pi^+ \pi^-$ $D^0 \rightarrow K^- \pi^+$	$\bar{B}_{\text{fake}}^0 \rightarrow [\pi^- \bar{p} [p \pi^+]_{\bar{B}^0} [K^-]_{\text{fake } \Lambda_c^+} \pi^+]_{D^0}$	$(4.19 \pm 0.15) \times 10^{-3}$	22.5	96.9%	0.2
$\bar{B}^0 \rightarrow D^{*+} p \bar{p} \pi^+$ $D^{*+} \rightarrow D^0 \pi^+$ $D^0 \rightarrow K^- \pi^+$	$\bar{B}_{\text{fake}}^0 \rightarrow [\pi^- \bar{p} [p]_{\bar{B}^0} [K^- [\pi^+]_{D^{*+}}]_{\text{fake } \Lambda_c^+} \pi^+]_{D^0}$	$(2.44 \pm 0.12) \times 10^{-3}$	13.4	96.9%	0.1

## B. Fit Strategy

The signal yields of resonant decays are determined in binned maximum-likelihood fits to the two-dimensional distributions  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$ . Since background events from  $B^- \rightarrow \Sigma_c^+ \bar{p} \pi^-$  decays are distributed similarly to signal events in all examined variables, one-dimensional measurements of the signal yield will not suffice. By extracting the signal yield in the  $m_{\text{inv}} : m_{+\pm}$  plane, we exploit the fact that the distributions of  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p} \pi^-$  events are more correlated in these variables than signal events.

### 1. Type of PDFs

Signal and background sources are divided into two classes of probability density functions. Background sources without significant correlations between  $m_{\text{inv}}$  and  $m_{+\pm}$  are described with analytical PDFs; independent analytical PDFs are used for each of the two variables and a combined two-dimensional PDF is formed by multiplication of the one-dimensional functions. Signal and background sources with correlations between  $m_{\text{inv}}$  and  $m_{+\pm}$  are described with binned histogram PDFs  $H_i = S_i \cdot h_i(m_{\text{inv}}, m_{+\pm})$ . For each source, a histogram  $h_i(m_{\text{inv}}, m_{+\pm})$  is generated from MC events, which takes correlations into account by design. Each histogram  $h_i$  is scaled with a parameter  $S_i$ , which is allowed to float in the fit. Histogram PDFs are used for all resonant signal decays and peaking background decays  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p} \pi^-$ .

In the fits to the two-dimensional distributions, the integrals of the analytical PDFs for each bin are calculated. Table II lists the PDFs and indicates whether they are included in the fit to  $m_{\text{inv}} : m_{++}$  for  $\bar{B}^0 \rightarrow \Sigma_c^{++} \bar{p} \pi^-$  events or in the fit to  $m_{\text{inv}} : m_{+-}$  for  $\bar{B}^0 \rightarrow \Sigma_c^0 \bar{p} \pi^+$  events.

### 2. Histogram PDF verification

When using a histogram PDF in fits, results prove to be sensitive to differences between data events and MC-generated events. As a cross-check, the projections onto  $m_{\text{inv}}$  are compared between data and MC simulation. The distributions are fitted using a Gaussian function to describe signal events. The means differ between data and MC by  $\Delta = (2.30 \pm 0.25) \text{ MeV}/c^2$ . The mass shift does not depend on the  $\Lambda_c^+$  candidate selection or on  $m_{+\pm}$ . The most probable explanation for the difference is an underestimation of the SVT material in the simulation, as studied in detail in Ref. [15]. Baryonic decays are especially affected by this issue, since heavier particles such as protons suffer more from such an underestimation compared to lighter particles. In each MC event, the baryon momenta  $|\vec{p}_{p, \Lambda_c^+}|$  and  $|\vec{p}_{p, \bar{B}^0}|$  are therefore increased by  $2.30 \text{ MeV}/c$  and the particle energy is adjusted accordingly.

In the  $m_{+\pm}$  distributions, the means of the masses of the  $\Sigma_c(2455)^{+,+0}$  baryons differ between data and MC by  $\Delta m = (0.441 \pm 0.095) \text{ MeV}/c^2$ . This effect originates from outdated  $\Sigma_c(2455)$  mass inputs in the MC generation, and so this shift is not covered by the correction for detector density.  $\Sigma_c(2455)$  events are especially sensitive to such mass differences due to their narrow width. The effect is taken into account by shifting each MC event in  $m_{+\pm}$  by  $+0.441 \text{ GeV}/c^2$ . The fully corrected data sets are used to generate the histogram PDFs employed in the fits to data.

### 3. Combinatorial background PDF

The combinatorial background is described by the PDF  $\text{BG}_{\text{Combi Bkg}}$  term given in Table II. It consists of

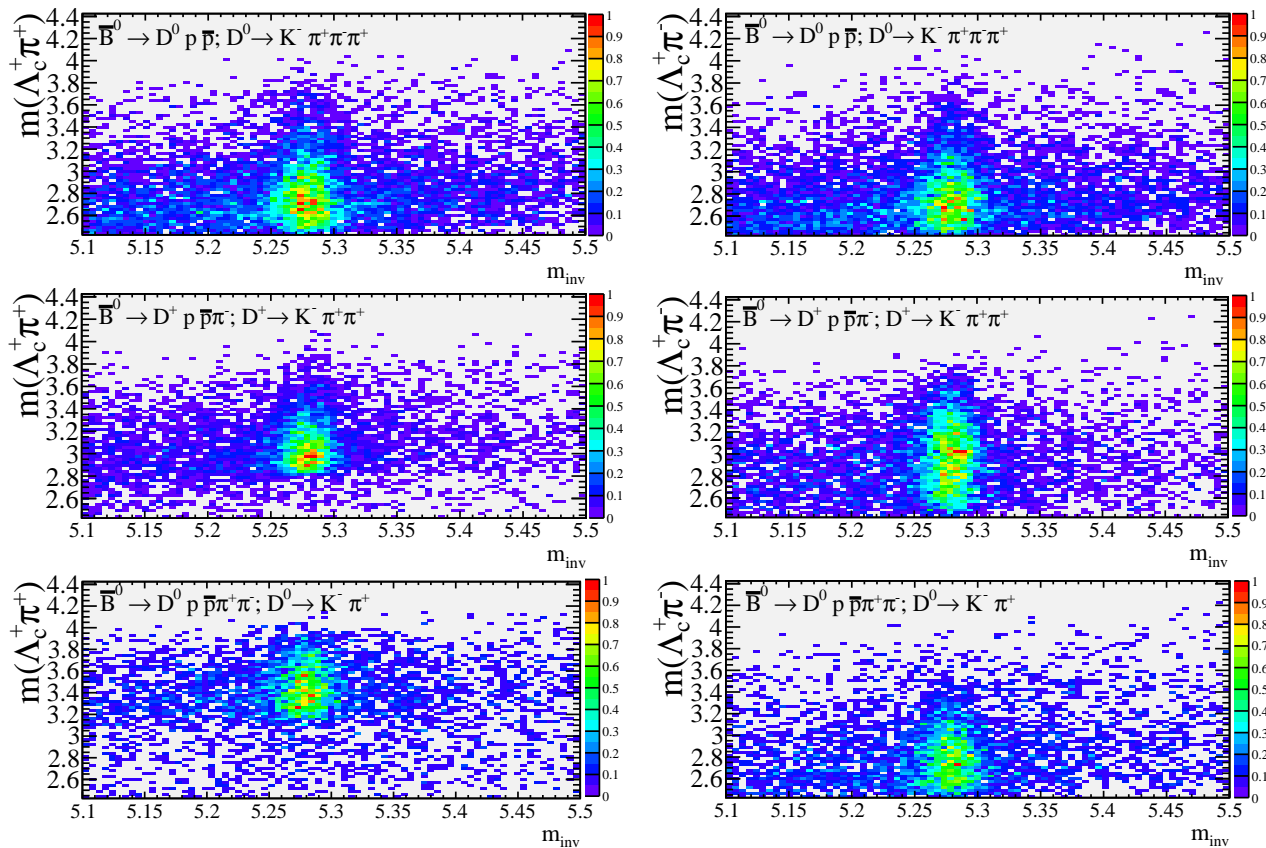


FIG. 3: Simulated events with  $\bar{B}^0 \rightarrow D p \bar{p} (n\pi)$  decays misidentified as signal decays in the  $m_{\text{inv}} : m_{++}$  plane (left column) and  $m_{\text{inv}} : m_{+-}$  plane (right column). The MC-generated events are reconstructed as  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ . The color scale indicates the relative contents of a bin compared to the maximally occupied bin (color online).

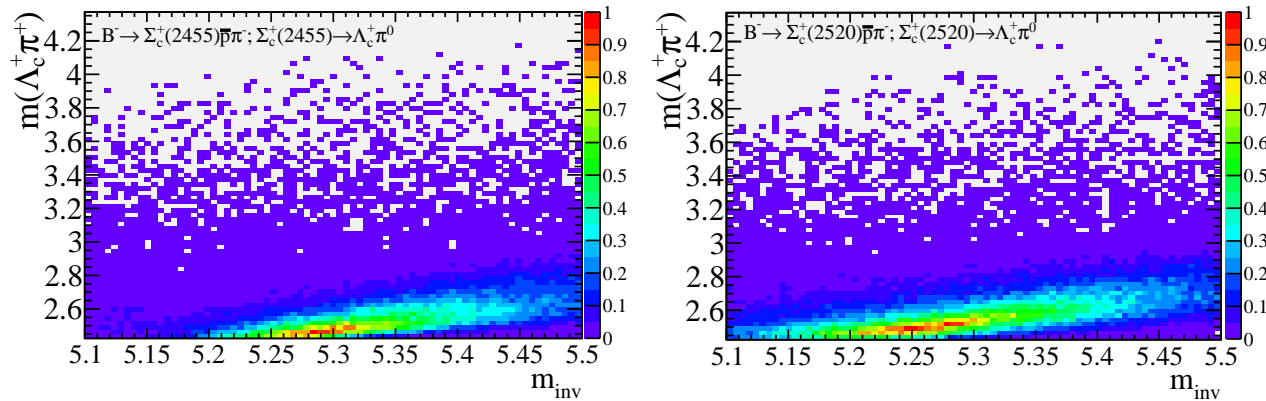


FIG. 4: Simulated events with  $B^- \rightarrow \Sigma_c(2455)^+ \bar{p} \pi^-$  (left) and  $B^- \rightarrow \Sigma_c(2520)^+ \bar{p} \pi^-$  (right) decays, where  $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^0$  decays are reconstructed as  $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^+$ ; these events accumulate in the signal regions of  $m_{\text{inv}}$  and in  $m_{++}$ . The MC-generated events are reconstructed as  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ . The color scale indicates the relative contents of a bin compared to the maximally occupied bin (color online).

two separable functions: for  $m_{\text{inv}}$  we use a first-order Chebyshev polynomial  $X_{\text{Combi Bkg w } \Sigma_c}^{\text{Chebyshev}}(m_{\text{inv}}; b)$  with a slope parameter  $b$  and for  $m_{\pm\pm}$  a phenomenological func-

tion,

$$Y_{\text{Combi Bkg}}(m_{\pm\pm}; p, q; e_{\text{up}}, e_{\text{low}}) = (c - m_{\pm\pm})^p \cdot (m_{\pm\pm} - e_{\text{low}})^q \cdot e_{\text{up}}. \quad (1)$$

The upper and lower phase-space boundaries in  $m_{+\pm}$  are constants  $e_{\text{low}} = 2.4249 \text{ GeV}/c^2$  and  $e_{\text{up}} = 4.215 \text{ GeV}/c^2$ . The phenomenological constant  $c = 4.108 \text{ GeV}/c^2$  is obtained from MC and, for estimating a systematic uncertainty, varied within the values found in MC. The exponent terms  $p$  and  $q$  are allowed to float in the fits to MC and data. In Table II,  $S_{\text{Combi Bkg}}$  is the overall scaling parameter of the combinatorial background PDF.

#### 4. Combinatorial background with genuine $\Sigma_c$ PDF

Combinatorial background events with genuine  $\Sigma_c$  resonances are described by uncorrelated functions in  $m_{\text{inv}}$  and  $m_{+\pm}$ . A first-order Chebyshev polynomial  $X_{\text{Combi Bkg w } \Sigma_c}^{\text{Chebyshev}}(m_{\text{inv}}; b)$  in  $m_{\text{inv}}$  is multiplied by a non-relativistic Breit-Wigner function in  $m_{+\pm}$ ,

$$\text{BW}_{\text{Combi Bkg w } \Sigma_c}(m_{+\pm}; \mu, \Gamma) = \frac{1}{\pi \cdot \left[ (m_{+\pm} - \mu)^2 + \left(\frac{\Gamma}{2}\right)^2 \right]}, \quad (2)$$

with mean  $\mu$ , width  $\Gamma$ , and an overall scaling factor  $S_{\text{Combi Bkg w } \Sigma_c}$ , to form a two-dimensional PDF ( $\text{BG}_{\text{Combi Bkg w } \Sigma_c}$  in Table II) in  $m_{+\pm}$ .

The PDFs for combinatorial background with and without genuine  $\Sigma_c$  resonances are validated using studies with MC events and from fits to data within the  $m_{\text{inv}}$  sidebands of the  $m_{\text{inv}} : m_{+\pm}$  planes.

#### 5. non- $\Sigma_c$ $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$

Events with  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  decays but without signal  $\Sigma_c$  resonances are described by the product of a phenomenological function in  $m_{+\pm}$ ,

$$Y_{\text{non-}\Sigma_c}(m_{+\pm}; n, p, q, r; e_{\text{up}}) = (m_{+\pm} - r) \cdot [m_{+\pm}]^p \cdot (e_{\text{up}} - m_{+\pm})^q, \quad (3)$$

and a Gaussian function  $X_{\text{non-}\Sigma_c}(m_{\text{inv}}; \mu, \sigma)$  in  $m_{\text{inv}}$ . Fits to mixtures of MC samples (denoted as *toy MC mixtures*) are used to validate the combined two-dimensional PDF ( $\text{BG}_{\text{non-}\Sigma_c}^{\text{Gauss}}$  in Table II). This procedure is designed to take into account the fact that  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  decays without signal  $\Sigma_c$  resonances can proceed via various other intermediate states besides direct decays into the four-body final state. Since the true composition of  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  decays without signal  $\Sigma_c$  resonances is unknown, toy MC sets are created by combining randomly chosen numbers of MC events with completely nonresonant signal decays, signal decays with intermediate non- $\Sigma_c$  resonances such as  $N^*$  or  $\rho$ , and signal decays with non-signal  $\Sigma_c$  resonances.

In the fits to toy MC samples, a quadratic dependency on  $m_{+\pm}$  of the signal-Gaussian width in  $m_{\text{inv}}$  is observed. This is taken into account by parameterizing the width as

$\sigma(m_{+\pm}; a_\sigma, b_\sigma, c_\sigma) = c_\sigma \cdot [a_\sigma \cdot m_{+\pm}^2 + b_\sigma \cdot m_{+\pm} + 1]$ . In fits to data, the width parameters are fixed to the values obtained from fits to MC; a systematic uncertainty on the shape is included by varying the parameters within the parameter range obtained from fits to toy MC.

Global PDFs for fits to  $m_{\text{inv}} : m_{++}$  and to  $m_{\text{inv}} : m_{+-}$  are formed from sums over the signal and background PDFs as listed in Table II. The global PDFs are validated on toy MC samples of randomly chosen numbers of events from the signal and background classes.

### C. Fit Results

Maximum likelihood fits to data distributions in the  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$  planes are performed in the range  $m_{\text{inv}} \in [5.17, 5.38] \text{ GeV}/c^2$  and  $m_{+\pm} \in [2.425, 2.625] \text{ GeV}/c^2$ , covering the regions of  $\Sigma_c(2455)$  and  $\Sigma_c(2520)$  resonances.<sup>2</sup>

The fit to  $m_{\text{inv}} : m_{+-}$  converges with  $\chi^2/\text{ndf} = 2807/2697$ . Figure 5 shows the projection of the two-dimensional fit onto the  $m_{\text{inv}}$  axis. The fitted PDFs are shown as stacked histograms and are overlaid with the distribution in data. The projection onto the  $m_{+-}$  axis is shown in Fig. 6.

In the  $m_{\text{inv}} : m_{++}$  plane, the fit converges with  $\chi^2/\text{ndf} = 2592/2695$ . The two-dimensional fit results are shown in Fig. 7 for the projection onto  $m_{\text{inv}}$  and in Fig. 8 for the projection onto  $m_{++}$ .

The measured signal yields are given in Table III.

### D. Signal event distributions

The distributions of signal events in variables other than those shown in Figs. 5-8 are extracted using the *sPlot* technique [7]. We use the covariance matrices from the fits to the signal and background PDFs to calculate per-event weights for each signal and background source. The weights represent the probability of an event to originate from one of the signal or background classes. We use these weights to generate histograms in Dalitz variables of the  $\Sigma_c \bar{p} \pi$  three-body systems.

In Fig. 9(a),  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  events are seen to exhibit a sharp enhancement just above the threshold in the  $m(\Sigma_c(2455)^0 \pi^+)$  distribution; however, there is insufficient information to reliably identify the  $\Lambda_c(2595)^+$

<sup>2</sup> Larger  $m_{+\pm}$  masses are omitted because of uncertainties on the  $\Sigma_c(2800)$  mass values. In a study of the related decay  $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$  [17], a significant difference in the mass is measured for the  $\Sigma_c(2800)^0$  resonances with  $m(\Sigma_c(2800)^0) = (2.846 \pm 0.008) \text{ GeV}/c^2$  compared to the world averaged mass  $m(\Sigma_c(2800)^0)_{\text{PDG}} = (2.802^{+0.004}_{-0.007}) \text{ GeV}/c^2$  [1]. Thus, the histogram PDF approach based on MC simulations is not feasible for  $\Sigma_c(2800)$ , since the input mass value is necessary for the MC generation.

TABLE II: The PDF types for signal and background sources as defined in Sec. IV B (see text for details). In the second column,  $S_i$  denote scaling factors,  $h_i$  histograms, and  $X_i$ ,  $Y_i$ ,  $BW_i$  analytical functions as described in the text. The third and fourth columns indicate in which global fit to the planes  $m_{\text{inv}} : m_{++}$  or  $m_{\text{inv}} : m_{+-}$  a particular PDF is included.

Mode	PDF	$m_{\text{inv}} : m_{++}$	$m_{\text{inv}} : m_{+-}$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$	$H_{\Sigma_c(2455)^{++}} = S_{\Sigma_c(2455)^{++}} \cdot h_{\Sigma_c(2455)^{++}}$	✓	
$\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$	$H_{\Sigma_c(2520)^{++}} = S_{\Sigma_c(2520)^{++}} \cdot h_{\Sigma_c(2520)^{++}}$	✓	
$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$	$H_{\Sigma_c(2455)^0} = S_{\Sigma_c(2455)^0} \cdot h_{\Sigma_c(2455)^0}$		✓
$\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$	$H_{\Sigma_c(2520)^0} = S_{\Sigma_c(2520)^0} \cdot h_{\Sigma_c(2520)^0}$		✓
$B^- \rightarrow \Sigma_c(2455)^+ \bar{p} \pi^-$	$BG_{\Sigma_c(2455)^+} = S_{\Sigma_c(2455)^+} \cdot h_{\Sigma_c(2455)^+}$	✓	
$B^- \rightarrow \Sigma_c(2520)^+ \bar{p} \pi^-$	$BG_{\Sigma_c(2520)^+} = S_{\Sigma_c(2520)^+} \cdot h_{\Sigma_c(2520)^+}$	✓	
Combinatorial background	$BG_{\text{Combi Bkg}} = S_{\text{Combi Bkg}}$		
	$\times Y_{\text{Combi Bkg}}(m_{\pm\pm}; p, q; e_{\text{up}}, e_{\text{low}})$	✓	✓
	$\times X_{\text{Combi Bkg}}^{\text{Chebyshev}}(m_{\text{inv}}; b)$		
Combinatorial background with genuine $\Sigma_c$	$BG_{\text{Combi Bkg w } \Sigma_c} = S_{\text{Combi Bkg w } \Sigma_c}$		
	$\times BW_{\text{Combi Bkg w } \Sigma_c}(m_{\pm\pm}; \mu, \Gamma)$	✓	✓
	$\times X_{\text{Combi Bkg w } \Sigma_c}^{\text{Chebyshev}}(m_{\text{inv}}; b)$		
non- $\Sigma_c$ $B^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$	$BG_{\text{non-}\Sigma_c} = S_{\text{non-}\Sigma_c}$		
	$\times Y_{\text{non-}\Sigma_c}(m_{\pm\pm}; p, q, r; e_{\text{psb}})$	✓	✓
	$\times X_{\text{non-}\Sigma_c}^{\text{Gauss}}(m_{\text{inv}}; \mu, \sigma [m_{\pm\pm}; a_\sigma, b_\sigma, c_\sigma])$		

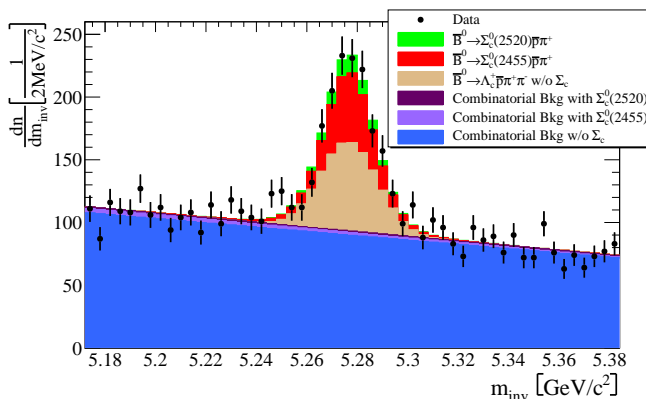


FIG. 5: Result of the fit to the  $m_{\text{inv}} : m_{+-}$  plane projected onto the  $m_{\text{inv}}$  axis. The data are shown as points with error bars; the fitted signal and background PDFs are overlaid as stacked histograms.

or  $\Lambda_c(2625)^+$  states. In Fig. 9(b), signal events from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  accumulate in  $m(\Sigma_c(2455)^0 \bar{p})$  only for values larger than  $3.8 \text{ GeV}/c^2$ , clearly ruling out an enhancement at baryon-antibaryon invariant mass threshold, which has been seen in other decays [14, 16–19]. Different behavior is observed in Fig. 9(c) where  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  events accumulate significantly only for masses  $m(\bar{p} \pi^+) < 1.8 \text{ GeV}/c^2$ . Possible sources for this structure could be  $\Delta$  baryons or  $N^*$  nucleon resonances decaying to  $\bar{p} \pi^+$ . However, due to

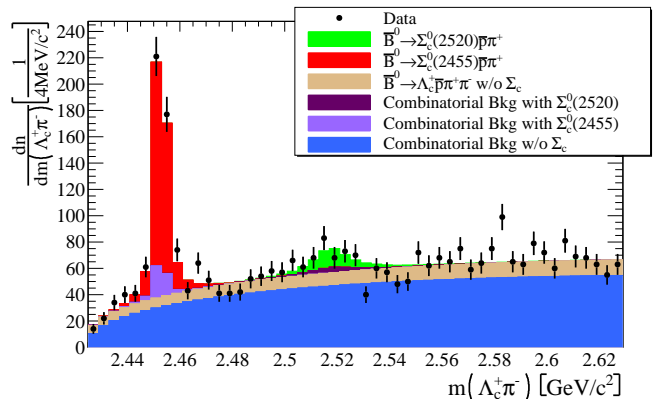


FIG. 6: Result of the fit to the  $m_{\text{inv}} : m_{+-}$  plane projected onto the  $m_{+-}$  axis. The data are shown as points with error bars; the fitted signal and background PDFs are overlaid as stacked histograms.

the overlap of possible broad baryon resonances, we cannot come to a conclusion on specific modes.

The corresponding distributions for  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  events exhibit different behavior. In the  $m(\Sigma_c^{++} \pi^-)$  distribution of Fig. 10(a), no enhancement in the threshold region is visible while a bump at around  $2.9 \text{ GeV}/c^2$  may be due to additional contributions from intermediate  $\Lambda_c(2880)^+$  and/or  $\Lambda_c(2940)^+$  resonances. In the  $m(\Sigma_c(2455)^{++} \bar{p})$  distribution of Fig. 10(b), events with masses below

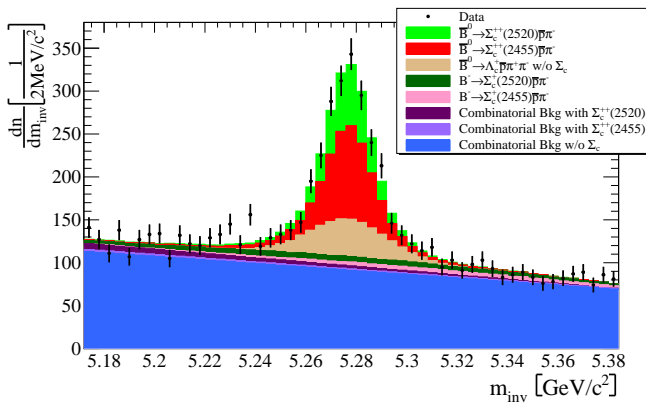


FIG. 7: Result of the fit to the  $m_{\text{inv}} : m_{++}$  plane projected onto the  $m_{\text{inv}}$  axis. The data are shown as points with error bars; the fitted signal and background PDFs are overlaid as stacked histograms.

TABLE III: Signal yields without efficiency correction from the fits to the  $m_{\text{inv}} : m_{+\pm}$  planes. The uncertainties are statistical.

Mode	Signal yield
$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$	$347 \pm 24$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$	$87 \pm 27$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$	$723 \pm 32$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$	$458 \pm 38$
$B^- \rightarrow \Sigma_c(2455)^+ \bar{p} \pi^-$	$164 \pm 104$
$B^- \rightarrow \Sigma_c(2520)^+ \bar{p} \pi^-$	$273 \pm 133$

$3.8 \text{ GeV}/c^2$  contribute prominently, in contrast to the corresponding  $m(\Sigma_c(2455)^0 \bar{p})$  distribution of Fig. 9(b), making  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  decays more similar to other baryonic decays [14, 16–19]. In Fig. 10(c), events from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  are distributed in  $m(\bar{p} \pi^-)$  without an obvious structure, unlike events from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  in  $m(\bar{p} \pi^+)$  in Fig. 9(c).

The distributions from  $\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$  in Fig. 11 are similar to the distributions from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  events shifted to higher invariant masses.

Due to the relatively small event yield for  $\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$  decays, the corresponding  $sPlots$  are not conclusive, and are therefore not presented.

## V. NON- $\Sigma_c$ $B^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ ANALYSIS

The rates of events decaying into the  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  final state without intermediate  $\Sigma_c(2455, 2520)^{++}$  or  $\Sigma_c(2455, 2520)^0$  resonances are determined in one-dimensional fits to  $m_{\text{inv}}$ . The non- $\Sigma_c$  signal yield compo-

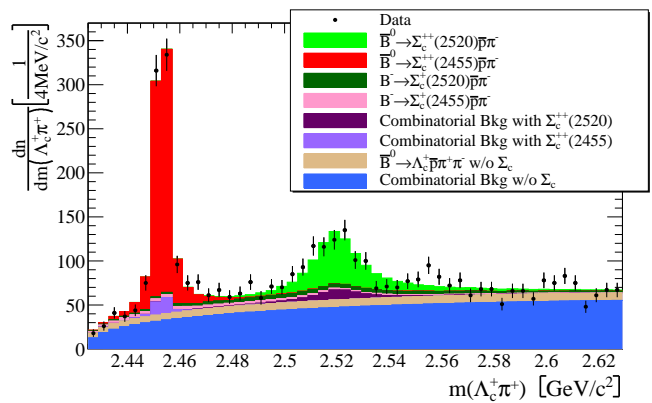


FIG. 8: Result of the fit to the  $m_{\text{inv}} : m_{++}$  plane projected onto the  $m_{++}$  axis. The data are shown as points with error bars; the fitted signal and background PDFs are overlaid as stacked histograms.

nents measured in the fits to  $m_{\text{inv}} : m_{++}$  and  $m_{\text{inv}} : m_{+-}$  are not used, since these yields are correlated.

### A. Fit strategy and results

The data are divided into two sets: subset  $m_{\text{inv}}^I$  with  $m_{++} < 2.625 \text{ GeV}/c^2$  and  $m_{+-} < 2.625 \text{ GeV}/c^2$ , and subset  $m_{\text{inv}}^{II}$  with  $m_{++} \geq 2.625 \text{ GeV}/c^2$  and  $m_{+-} \geq 2.625 \text{ GeV}/c^2$ . Thus, potential contributions of  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p} \pi^-$  are confined to the  $m_{\text{inv}}^I$  subset. In  $m_{\text{inv}}^I$ , resonant signal events  $\bar{B}^0 \rightarrow \Sigma_c(2455, 2520)^{+,0} \bar{p} \pi^\mp$  are excluded by requiring  $m(\Lambda_c^+ \pi^\pm)$  to lie outside  $[2.447, 2.461] \text{ GeV}/c^2$  and  $[2.498, 2.538] \text{ GeV}/c^2$ .

In the fit of the distribution of  $m_{\text{inv}}^I$ , background from  $B^- \rightarrow \Sigma_c(2455)^+ \bar{p} \pi^-$  decays is taken into account using a double-Gaussian PDF consisting of two single-Gaussian functions with different means and widths. The shape parameters are fixed to values obtained from signal MC, and the signal yield is fixed to the yield measured in the fit to  $m_{\text{inv}} : m_{++}$  (Table III). Similarly, background from  $B^- \rightarrow \Sigma_c(2520)^+ \bar{p} \pi^-$  events is described by a single-Gaussian PDF with fixed shape parameters from MC and the yield fixed to the fitted yield in  $m_{\text{inv}} : m_{++}$ . Combinatorial background is described with a linear function in  $m_{\text{inv}}$ . Signal event contributions are described with a double Gaussian with a shared mean; the parameters are allowed to float. In the distribution of  $m_{\text{inv}}^{II}$ , the fit is performed with a first-order polynomial for background and a double Gaussian with shared mean for signal, since no peaking background is expected here.

The fits are shown in Fig. 12 and the yields are given in Table IV.

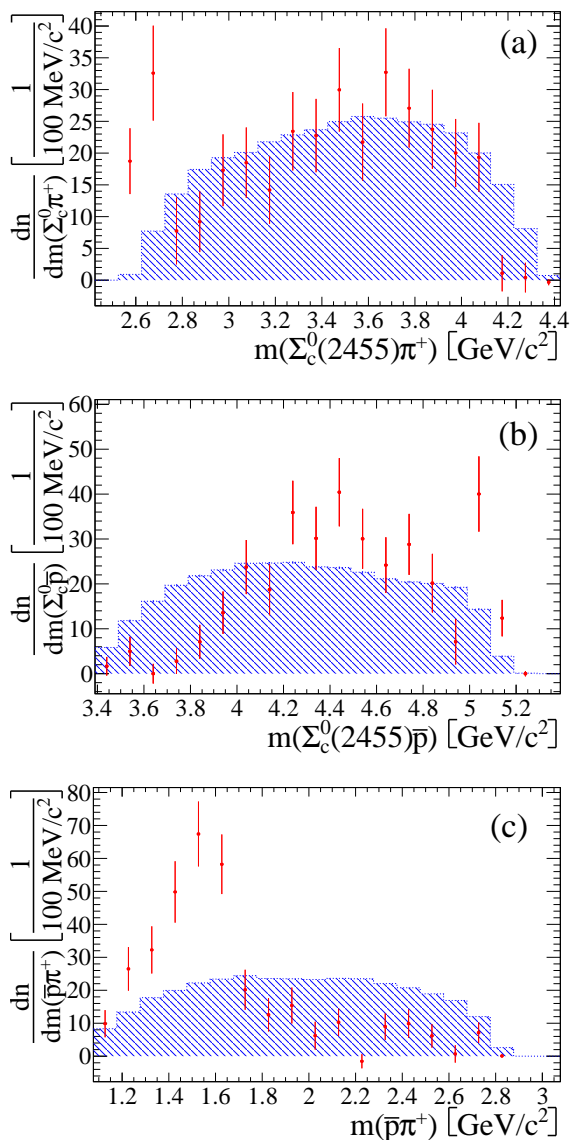


FIG. 9: Invariant mass distributions from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  signal events extracted with the *sPlot* method. Data points are displayed in comparison with the distribution of reconstructed phase-space generated  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  MC events scaled to the same number of entries (shaded histograms).

TABLE IV: Signal yields without efficiency correction for decays without intermediate  $\Sigma_c(2455, 2520)^{+,+0}$  resonances. The first uncertainty is the statistical uncertainty. The second uncertainty for  $m_{\text{inv}}^I$  denotes the uncertainty on the contribution due to  $B^- \rightarrow \Sigma_c^+ \bar{p} \pi^-$ .

Region	Signal yield
$m_{\text{inv}}^I$	$810 \pm 88 \pm 38$
$m_{\text{inv}}^{II}$	$1918 \pm 91$

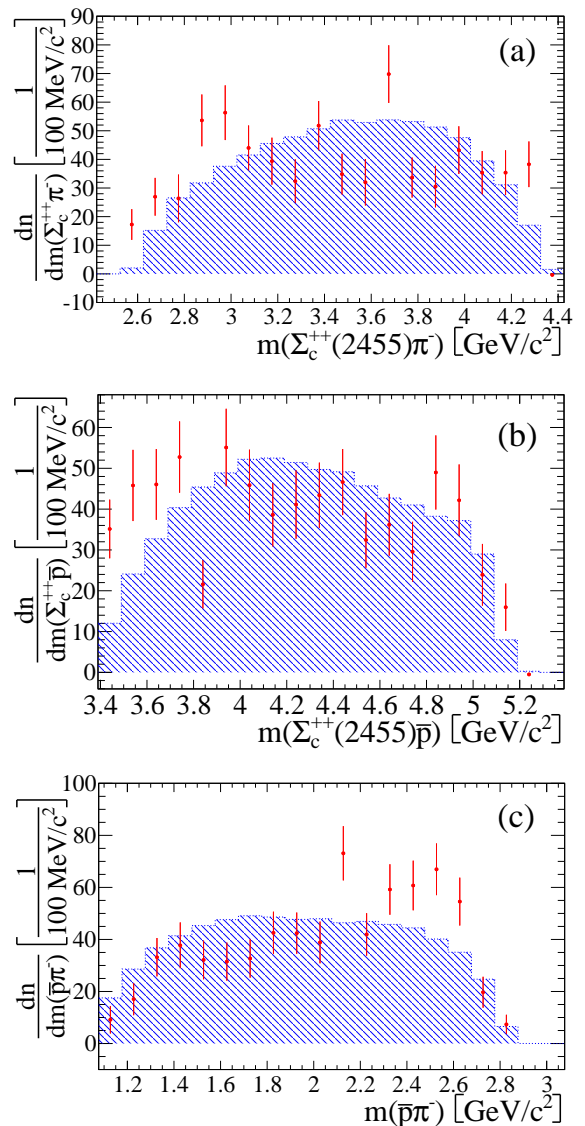


FIG. 10: Invariant mass distributions from  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  signal events extracted with the *sPlot* method. Data points are displayed in comparison with the distribution of reconstructed phase-space generated  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  MC events scaled to the same number of entries (shaded histograms).

## B. Signal event distributions

Figures 13 and 14 show the combined *sPlots* for non- $\Sigma_c \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  events from the fits to  $m_{\text{inv}}^I$  and  $m_{\text{inv}}^{II}$ .<sup>3</sup> In the  $m(\Lambda_c^+ \pi^+)$  distribution of Fig. 13(a), the contribution from intermediate  $\Sigma_c(2800)^{++}$  baryons is

<sup>3</sup> The fixed background contributions from  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p} \pi^-$  are taken into account in the *sPlot* weight calculations, following the method described in appendix B of Ref. [7].

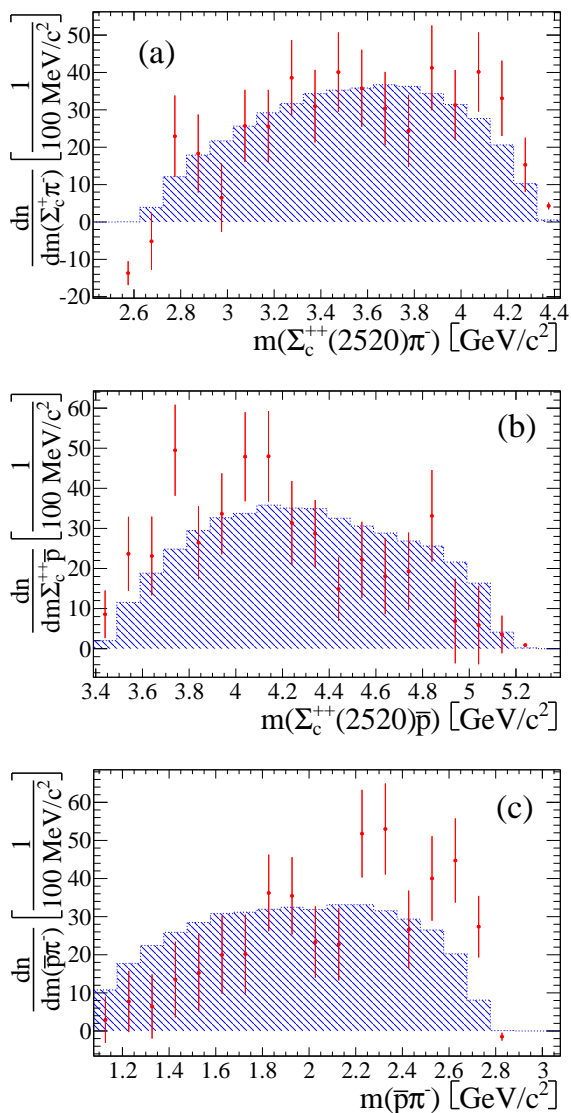


FIG. 11: Invariant mass distributions from  $\bar{B}^0 \rightarrow \Sigma_c(2520)^{++}\bar{p}\pi^-$  signal events extracted with the *sPlot* method. Data points are displayed in comparison with the distribution of reconstructed phase-space generated  $\bar{B}^0 \rightarrow \Sigma_c(2520)^{++}\bar{p}\pi^-$  MC events scaled to the same number of entries (shaded histograms).

clearly apparent. The corresponding distribution in  $m(\Lambda_c^+\pi^-)$  is shown in Fig. 13(b); here the isospin related  $\Sigma_c(2800)^0$  baryon is less significant. Note that the vetoes on low-mass  $\Sigma_c$  resonances appear as gaps in the distributions. We do not attempt to explicitly measure intermediate states with  $\Sigma_c(2800)$  baryons with the present approach. As described in footnote 2, significantly differing masses of  $\Sigma_c(2800)$  resonances have been observed in related  $B \rightarrow \Lambda_c^+\bar{p}\pi$  decays [16, 17], which could originate, amongst other possibilities, from different angular momentum states with similar masses or from contamination due to  $B \rightarrow Dp\bar{p}(n\pi)$  decays. Since the present approach uses *a priori* information on the masses and

widths to generate MC-based PDFs, histogram PDFs cannot be applied for states with uncertain masses or widths.

In the distribution of  $m(\bar{p}\pi^-)$  in Fig. 13(c), differences are seen compared to the distribution of  $m(\bar{p}\pi^+)$  in Fig. 13(d), with events accumulating in  $m(\bar{p}\pi^-)$  at values near the lower phase-space boundary, suggesting contributions from decays via  $\bar{\Delta}^{--}$ . Such a structure does not contribute to  $m(\bar{p}\pi^+)$ . The  $m(\pi^+\pi^-)$  distribution in Fig. 13(e) suggests an intermediate  $\rho(770)$  resonance. However, the data are not sufficiently precise to allow a definite conclusion. The  $m(\Lambda_c^+\bar{p})$  distribution in Fig. 13(f) shows some enhancement in the baryon-antibaryon mass near threshold, though less strongly than in other measurements with baryonic final states, e.g., those of Ref. [17]. A conclusive interpretation of the  $m(\Lambda_c^+\bar{p})$  result is difficult, because the MC distribution uses all events in the allowed phase space to avoid a possible bias, averaging over all possible structures. Furthermore, the projections onto the axes of the Dalitz space for the four-final-state-particle system make it difficult to identify reflections from resonances in other invariant masses.

The three-body mass distributions are shown in Fig. 14. Here, we do not observe structures in lower invariant-mass ranges that could hint at resonances, e.g., excited  $\Lambda_c$  baryons in  $m(\Lambda_c^+\pi^+\pi^-)$ . Negative values near the upper phase space boundary are artifacts of the *sPlot* method. On one hand, the discriminating variables are presumed to be uncorrelated with the variable being projected; however, this presumption is not a good approximation for a three-body system when the discriminating variable is  $m_{\text{inv}}$ . On the other hand, the *sPlot* technique does not account for physical constraints, such that signal and background weights are calculated without consideration of negative event numbers.

## VI. EFFICIENCY

The efficiency of the reconstruction is determined separately for each resonant signal mode and for the non- $\Sigma_c$  signal decays. Since signal MC events are generated uniformly in phase space, the observed decay dynamics are not reproduced. To avoid bias from phase-space-dependent reconstruction efficiencies, the MC samples are iteratively reweighted according to the *sPlot* histograms  $\mathcal{N}[m_{ab}]_{\text{data}}$  of invariant masses for each signal class from the  $B$  meson daughters  $a$  and  $b$  for all combinations of daughters.

In the initial step  $i = 1$ , the weight is calculated from the *sPlot* histogram and the signal MC histogram  $\mathcal{N}[m_{ab}]_{\text{MC}}^{i=1}$  as  $w^{i=1}[m_{ab}] = \mathcal{N}[m_{ab}]_{\text{data}} / \mathcal{N}[m_{ab}]_{\text{MC}}^{i=1}$  and applied to each signal MC event. In iteration step  $n$ , weights are calculated accordingly from the reweighted signal MC from iteration  $n - 1$  for invariant mass  $m_{bc}$  with  $w_{bc} = \mathcal{N}[m_{bc}]_{\text{data}} / \mathcal{N}[m_{bc}]_{\text{MC}}^{n-1}$ . In the following, the signal MC events are weighted by  $w_{bc}$ . Since the MC

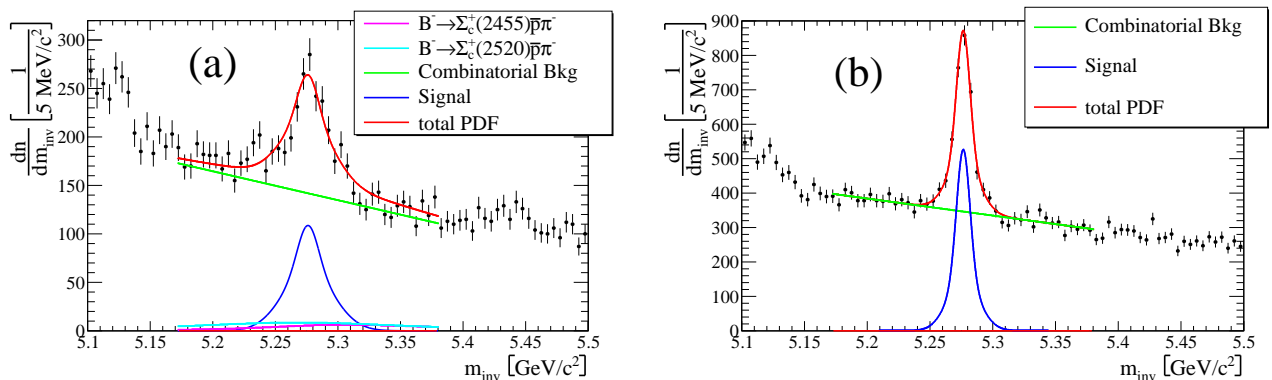


FIG. 12: Fits to  $m_{\text{inv}}$  distributions of events decaying into the four-body final state  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  without intermediate  $\Sigma_c(2455, 2520)^{++0}$  resonances. In (a) events originate from subset  $m_{\text{inv}}^I$  excluding the  $\Sigma_c(2455, 2520)^{++0}$  signal regions in  $m(\Lambda_c^+ \pi^\pm)$  and taking background from  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p} \pi^-$  into account. In (b) the events originate from subset  $m_{\text{inv}}^{II}$ .

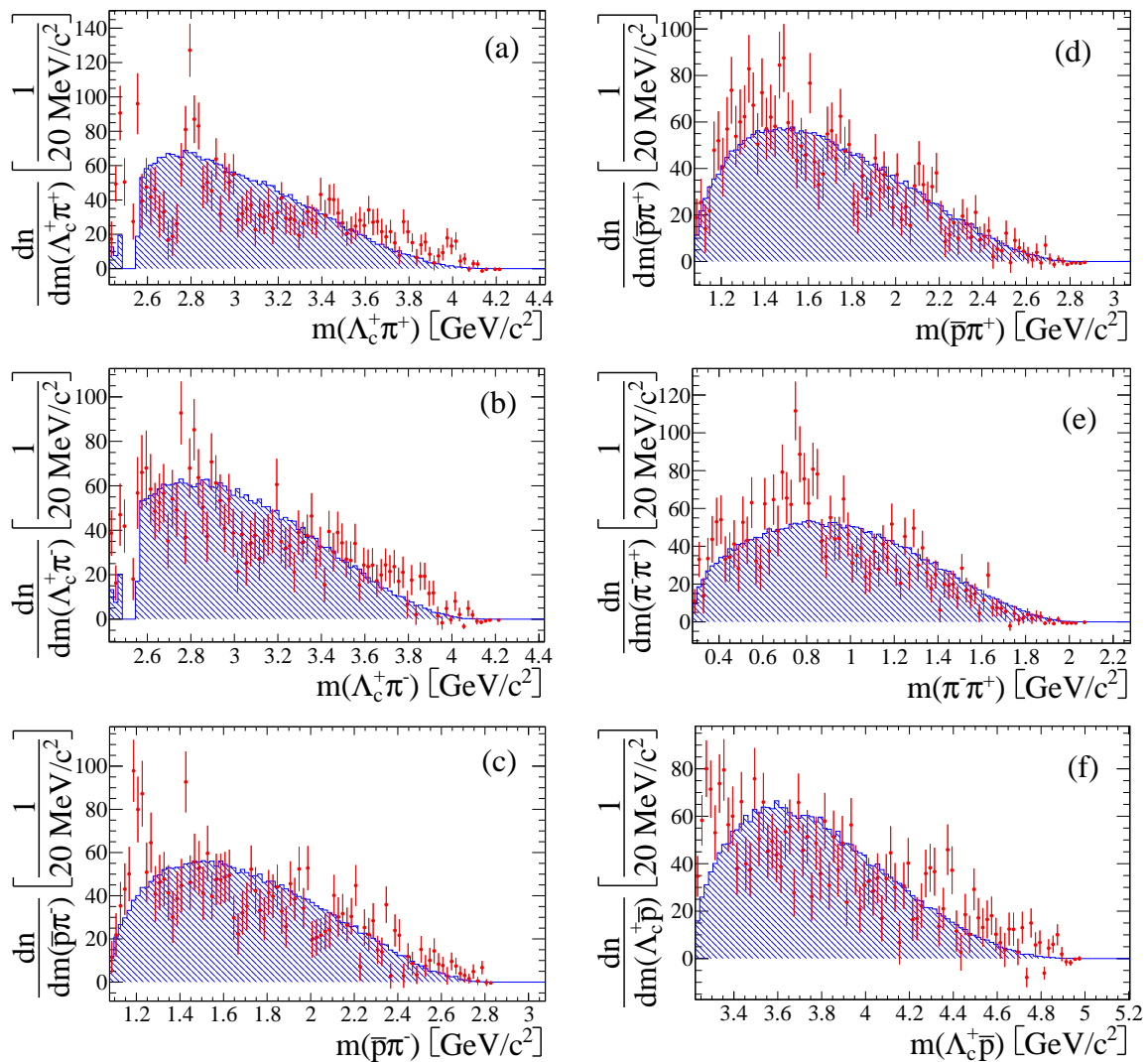


FIG. 13: Two-body invariant mass distributions for  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  signal events from the combined subsets  $m_{\text{inv}}^I$  and  $m_{\text{inv}}^{II}$  extracted with the *sPlot* method.  $\Sigma_c$  resonances are vetoed in the respective invariant masses. Data points are displayed in comparison with the distribution of reconstructed phase-space generated  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  MC events scaled to the same number of entries (shaded histograms).



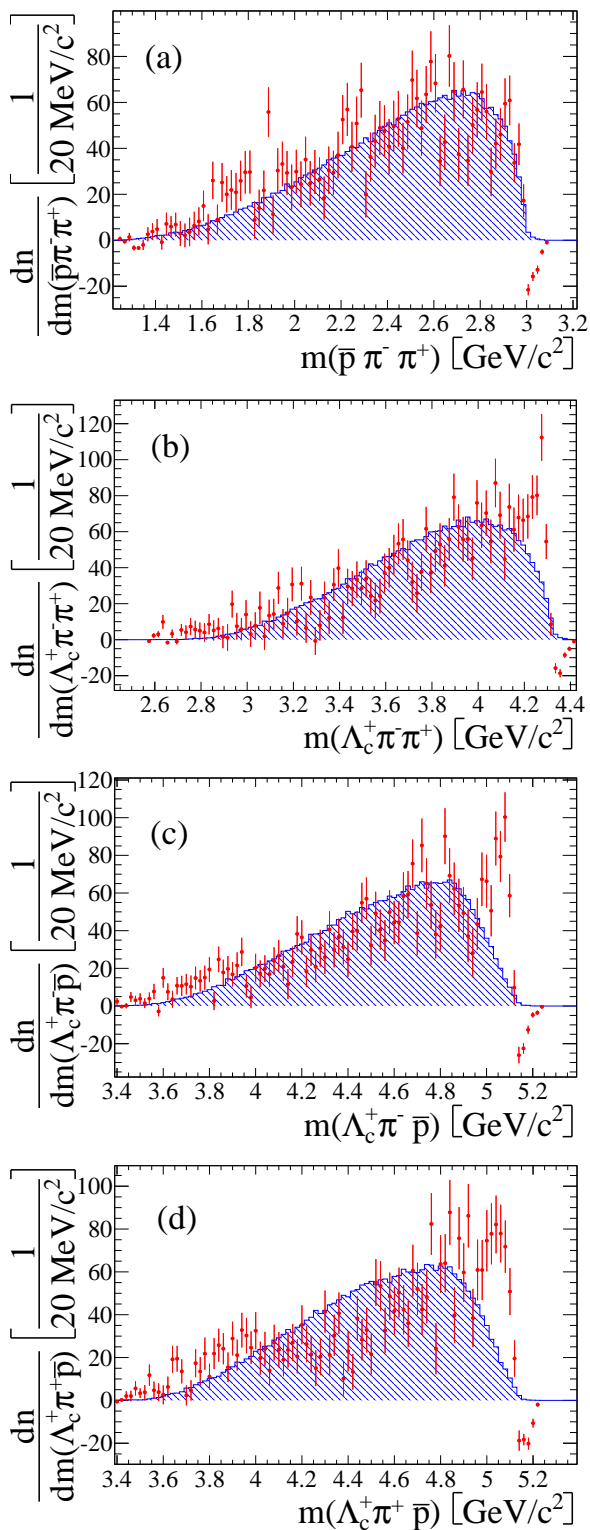


FIG. 14: Three-body invariant mass distributions for  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  signal events from the combined subsets  $m_{\text{inv}}^I$  and  $m_{\text{inv}}^{II}$  extracted with the  $sPlot$  method. Data points are displayed in comparison with the distribution of reconstructed phase-space generated  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  MC events scaled to the same number of entries (shaded histograms).

event values processed in step  $n$  originate from weighting the MC events in the previous step  $n - 1$ , the effective weight is  $w^n = w^{n-1} \cdot w_{bc}$ . Negative  $sPlot$  entries are set to zero to avoid nonphysical weightings.

The reconstruction efficiency is determined after each step by determining the number of reconstructed events from a  $\chi^2$  fit to the reweighted signal MC distribution in  $m_{\text{inv}}$  and from the sum of the weighted generated events. When the reconstruction efficiencies in the last steps of one cycle through all  $B$  daughter combinations are compatible with each other within the uncertainties, we assume that the reconstruction efficiency has converged and stop the iteration. The reconstruction efficiencies are listed in Table V. The differences between unweighted and weighted efficiencies vary between 2.1% for  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  and 7.9% for  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$ .

TABLE V: Reconstruction efficiencies for each signal event class, after reweighting signal MC events according to  $sPlot$  distributions.

Mode/region	Reconstruction efficiency
$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$	$(16.4 \pm 0.3)\%$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$	$(16.8 \pm 0.3)\%$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$	$(14.5 \pm 0.1)\%$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$	$(17.0 \pm 0.2)\%$
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi_{m_{\text{inv}}}^-$	$(11.6 \pm 0.7)\%$
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi_{m_{\text{inv}}}^{II}$	$(16.9 \pm 0.1)\%$

## VII. BRANCHING FRACTIONS

The product branching fractions  $\mathcal{B}$  are calculated for each signal mode  $i$  with

$$\mathcal{B} \left[ \bar{B}^0 \rightarrow [\Lambda_c^+ \pi^\pm]_{\Sigma_c} \bar{p} \pi^\mp \right]_i \cdot \mathcal{B} [\Lambda_c^+ \rightarrow p K^- \pi^+] = \frac{N_i}{N_{B\bar{B}}} \cdot \frac{1}{\varepsilon_i} \quad (4)$$

where  $N_i$  is the sum of signal-event numbers (Tables III and IV),  $\varepsilon_i$  the reconstruction efficiency (Table V), and  $N_{B\bar{B}}$  the number  $N(\Upsilon(4S))$  of  $\Upsilon(4S)$  decays; we assume that  $\frac{N(\Upsilon(4S) \rightarrow B^0 \bar{B}^0)}{N(\Upsilon(4S))} = 0.50$ . For an integrated luminosity of  $\mathcal{L} = 426 \text{ fb}^{-1}$ ,  $N_{B\bar{B}} = (467.36 \pm 0.11 \pm 5.14) \times 10^6$ , where the uncertainties are statistical and systematic.  $\Sigma_c$  resonances are assumed to decay exclusively into a  $\Lambda_c^+ \pi$  pair:  $\mathcal{B} [\Sigma_c(2455, 2520)^{++} \rightarrow \Lambda_c^+ \pi^\pm] \approx 100\%$  [1]. After accounting for the reconstruction efficiencies, the number of events from the two non- $\Sigma_c(2455, 2520)$  decay measurements are summed and their statistical uncertainties are added in quadrature.

### VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties applying to all modes, such as the uncertainty on  $N_{B\bar{B}}$ , as well as systematic uncertainties specific only to certain modes, are considered. Table VI lists the relative systematic uncertainties  $u_x = \frac{\delta N_x}{N_x}$  for each uncertainty  $x$ . Systematic uncertainties on the reconstruction efficiency of the six charged final-state tracks are added linearly to obtain a total tracking uncertainty. One of the largest systematic uncertainties originates from the particle identification efficiencies. The uncertainties are evaluated using MC events, with corrections derived from control samples in the data. In addition, MC events are examined without corrections. The relative difference in the particle identification efficiencies with and without the corrections defines the uncertainty. As discussed above,  $\bar{B}^0 \rightarrow Dp\bar{p}(n\pi)$  decays and decays through charmonia states  $\bar{B}^0 \rightarrow (c\bar{c})\bar{K}^{*0}[\pi^+\pi^-]$  can yield the same combination of final-state particles as signal events. Based on the known branching fractions [1], a total of at most 4.5 events from these two event classes are expected to satisfy the signal selection criteria. Here, a conservative reconstruction efficiency of  $\varepsilon = 0.1\%$  is assumed, overestimating the measured efficiencies in signal MC. The corresponding systematic uncertainty ( $B \rightarrow D + X, c\bar{c} + X$ ) is set equal to 100% of the corresponding estimated background in line 4 of Table I, for each mode separately.

Only resonant decays are affected by an uncertainty on the shape of non- $\Sigma_c$   $B^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-$  events in the  $m_{\text{inv}}: m_{\pm\pm}$  planes. The parameters on the signal width are varied individually by one standard deviation and the maximum deviation in the event yield is taken as the systematic uncertainty (labeled “nonres.shape” in Table VI). For the shape of combinatorial background, a systematic uncertainty is determined by varying in the PDF the constant describing the end point of the phase space,  $e_{\text{up}}$ . Fits are repeated with the constant moved from the nominal upper phase-space limit towards the upper end of the fit region in 0.2 GeV/ $c^2$  steps. The maximal deviations in the fitted signal event yields are taken as the systematic uncertainty, labeled “Combi Bkg shape”. An uncertainty, labeled “Eff. Corr.”, on the efficiency-calculation weighting is evaluated after completing a cycle through all daughter combinations for each mode. The values converge and are within the statistical uncertainties for all modes after one full cycle, except for  $\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p}\pi^+$ . For this mode, the efficiencies differ by 1.9% with a statistical uncertainty of 1.8% and the difference is taken as additional systematic uncertainty.

A systematic uncertainty, labeled “ $B^-(I+II)$ ”, on the contribution of  $B^- \rightarrow \Sigma_c(2455, 2520)^+ \bar{p}\pi^-$  events to the non- $\Sigma_c$   $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-$  yields is calculated by repeating fits to the  $m_{\text{inv}}^I$  distribution assuming no contribution and overestimating the found contribution by a factor of two. The maximum deviation of 38 events is included as systematic uncertainty.

### IX. RESULTS

Table VII lists the measured branching fractions for each mode. Due to the large uncertainty on  $\mathcal{B}[\Lambda_c^+ \rightarrow pK^-\pi^+]$ , its systematic uncertainty is given separately. The uncertainties on the total branching fraction of all  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-_{\text{total}}$  decays are added quadratically when uncorrelated and linearly when correlated.

Because the  $\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p}\pi^+$  signal has less than three standard deviations significance, we also report a 90% confidence level (CL) upper limit for this channel. The upper limit is determined using Bayesian methods, with statistical and systematic uncertainties added in quadrature. We do not include the uncertainty on  $\mathcal{B}[\Lambda_c^+ \rightarrow pK^-\pi^+]$  in the systematic uncertainty of the upper limit, but factor out the branching ratio based on the results of Ref. [1]. Assuming a Gaussian distribution, the 90% integral of the physically meaningful region  $\mathcal{B} \geq 0$  yields

$$\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p}\pi^+] \cdot \frac{\mathcal{B}[\Lambda_c^+ \rightarrow pK^-\pi^+]}{0.05} < 3.10 \times 10^{-5} \quad (5)$$

at 90% confidence level.

Resonant decays via  $\Sigma_c(2455, 2520)$  baryons provide a large contribution to the four-body final state. The ratios of decays via  $\Sigma_c$  resonances in comparison to the largest such mode,  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-$ , are

$$\frac{\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p}\pi^+]}{\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-]} = 0.425 \pm 0.036, \quad (6)$$

$$\frac{\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p}\pi^-]}{\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-]} = 0.541 \pm 0.052, \quad (7)$$

while the fraction of all decays that proceed via the  $\Sigma_c(2455)^+ \bar{p}\pi^-$  mode is

$$\frac{\mathcal{B}[\bar{B}^0 \rightarrow \Sigma_c(2455)^+ \bar{p}\pi^-]}{\mathcal{B}[\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-]_{\text{total}}} = 0.1739 \pm 0.047. \quad (8)$$

In these three results, systematic uncertainties common to numerator and denominator cancel, and only the systematic uncertainties specific to each mode are added in quadrature. The three-body intermediate states have comparable branching fractions to the non-resonant three body decays  $B \rightarrow \Lambda_c^+ \bar{p}\pi$  [8, 9, 16, 17, 20].

The measured branching fractions are in good agreement with previous measurements from Belle [9].

### X. SUMMARY

We observe the decay  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-$ , study the intermediate decays via  $\Sigma_c(2455)^{++}$ ,  $\Sigma_c(2520)^{++}$ ,  $\Sigma_c(2455)^0$ , and  $\Sigma_c(2520)^0$  resonances, and measure their branching fractions (Table VII). Yields for events

TABLE VI: Summary of relative systematic uncertainties  $u_i = \frac{\delta N_i}{N_i}$  in [%] for non- $\Sigma_c$   $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ , resonant  $\bar{B}^0 \rightarrow \Sigma_c(2455) \bar{p} \pi^\pm$ , and resonant  $\bar{B}^0 \rightarrow \Sigma_c(2520) \bar{p} \pi^\pm$  decays. The total systematic uncertainties, added in quadrature, are given in the last row.

Uncertainties $u_i$ [%]	non- $\Sigma_c$	$\Sigma_c(2455)^0$	$\Sigma_c(2455)^{++}$	$\Sigma_c(2520)^0$	$\Sigma_c(2520)^{++}$
$N_{B\bar{B}}$	1.1	1.1	1.1	1.1	1.1
Tracking	1.2	1.2	1.2	1.2	1.2
PID	4.3	4.3	4.3	4.3	4.3
$B \rightarrow D + X, c\bar{c} + X$	0.1	0.5	0.5	0.5	0.5
nonres. shape		0.1	0.1	0.4	0.4
Combi Bkg shape		0.001	0.001	0.7	0.7
Eff. Corr.				0.1	
$B^- (I + II)$	1.8				
$\sqrt{\sum u_i^2}$	4.9	4.6	4.6	4.7	4.7

TABLE VII: Branching fractions of the resonant decays  $\bar{B}^0 \rightarrow \Sigma_c(2455, 2520)^{+,0} \bar{p} \pi^\mp$  and non- $\Sigma_c(2455, 2520)$  decays  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  where the first uncertainty is statistical, the second systematic and the third due to the uncertainty on the  $\mathcal{B}[\Lambda_c^+ \rightarrow p K^- \pi^+]$  branching fraction.

Mode/region	$\mathcal{B}[\bar{B}^0] \cdot \mathcal{B}[\Lambda_c^+ \rightarrow p K^- \pi^+]$	$[10^{-6}]$	$\mathcal{B}[\bar{B}^0]$	$[10^{-5}]$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$	$(4.5 \pm 0.3 \pm 0.2)$		$(9.1 \pm 0.7 \pm 0.4 \pm 2.4)$	
$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$	$(10.7 \pm 0.5 \pm 0.5)$		$(21.3 \pm 1.0 \pm 1.0 \pm 5.5)$	
$\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$	$(1.1 \pm 0.4 \pm 0.1)$		$(2.2 \pm 0.7 \pm 0.1 \pm 0.6)$	
$\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$	$(5.8 \pm 0.5 \pm 0.3)$		$(11.5 \pm 1.0 \pm 0.5 \pm 3.0)$	
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-_{\text{non-}\Sigma_c}$	$(39.2 \pm 2.2 \pm 1.9)$		$(79 \pm 4 \pm 4 \pm 20)$	
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-_{\text{total}}$	$(61.3 \pm 2.4 \pm 3.7)$		$(123 \pm 5 \pm 7 \pm 32)$	

decaying to  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  without intermediate  $\Sigma_c(2455, 2520)^{+,0}$  resonances are obtained from one-dimensional fits in  $m_{\text{inv}}$ , taking information from fits to  $m_{\text{inv}}: m_{+\pm}$  into account. For all decay modes, we show the *sPlot* distributions of the signal, and we observe significant differences between decays into  $\Sigma_c^{++} \bar{p} \pi^-$  and  $\Sigma_c^0 \bar{p} \pi^+$  final states.

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