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Measurement of the branching fraction $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)$ at CDF

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We report an analysis of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay in a data sample collected by the CDF II detector at the Fermilab Tevatron corresponding to 2.4 fb^{-1} of integrated luminosity. We reconstruct the currently largest samples of the decay modes $\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$ (with $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$), $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$ (with $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$), $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$ (with $\Sigma_c(2455)^{++} \to \Lambda_c^+\pi^+$), and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ (with $\Sigma_c(2455)^0 \to \Lambda_c^+\pi^-$) and measure the branching fractions relative to the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ branching fraction. We measure the ratio $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = 3.04 \pm 0.33(\mathrm{stat})^{+0.70}_{-0.55}(\mathrm{syst})$ which is used to derive $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-) = (26.8^{+11.9}_{-11.2}) \times 10^{-3}$.

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I. INTRODUCTION

Due to the high b-quark mass, weak decays of baryons containing a b quark are a good testing ground of some approximations in quantum chromodynamics (QCD) calculations, such as heavy-quark effective theory (HQET) [1]. Alternatively, when using such calculations, the Λ_b^0 may provide a determination of the Cabibbo-Kobayashi-Maskawa (CKM) couplings with systematic uncertainties different from the determinations from the decays of B mesons [2]. While the B mesons are well studied, less is known about the Λ_b^0 baryon. Only nine decay modes of the Λ_b^0 have been observed so far, with the sum of their measured branching fractions of the order of only 0.1 and with large uncertainties on the measurements [3]. While theoretical predictions are available for the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ branching fraction [4], no prediction is currently available for the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay mode. LHCb recently reported the measurement of the ratio of branching fractions $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = 1.43 \pm 0.16(\mathrm{stat}) \pm 0.13(\mathrm{syst})$ [5].

This paper reports a study of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay mode and is especially distinguished by the high yields and high precision measurement of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ resonant contributions, the following decay modes:

$$\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-,$$

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$\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$,

$\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$,

$\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$.

We measure the branching fraction of each resonant decay mode relative to the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decay mode, and the ratio of branching fractions $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$. The measurement is performed using a sample of $p\overline{p}$ collisions corresponding to 2.4 fb^{-1} integrated luminosity collected by CDF II between February 2002 and May 2007. We reconstruct Λ_b^0 decays from particles whose trajectory projections in the plane transverse to the beamline do not intersect the beamline (displaced tracks). The signal yields of interest are extracted by fitting mass differences to minimize the effect of systematic uncertainties. As a crosscheck, we repeat the analysis on the reference decay modes $B^0 \to D^-\pi^+\pi^-\pi^+$ and $B^0 \to D^-\pi^+$.

The structure of the paper is as follows. Section II describes the detector systems relevant to this analysis. Event selection and $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidate reconstruction are described in Sec. III. In Sec. IV we present the signal yields. In Sec. V we describe the evaluation of the detector acceptance and the relative branching fraction measurements, while in Sec. VI the systematic uncertainties are discussed. Final results are reported in Sec. VII.

II. THE CDF II DETECTOR AND TRIGGER

The CDF II detector is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors. The components relevant to this analysis are briefly described here. A more detailed description can be found elsewhere [6]. A silicon microstrip detector (SVX and ISL) [7] and a cylindrical drift chamber (COT) [8] immersed in a 1.4 T solenoidal magnetic field allow the reconstruction of charged particle trajectories in the pseudorapidity [9] range $|\eta| < 1.0$ [10]. The SVX detector consists of microstrip sensors arranged in six cylindrical shells around the beamline with radii between 1.5 and 10.6 cm, and with a total z coverage of 90 cm. The first SVX layer, also referred to as the L00 detector, is made of single-sided sensors mounted on the beryllium beam pipe. The remaining five SVX layers are made of double-sided sensors and divided into three contiguous five-layer sections along the beam direction z. The two additional silicon layers of the ISL help to link tracks in the COT to hits in the SVX. The COT has 96 measurement layers between 40 and 137 cm in radius, organized into alternating axial and $\pm 2^\circ$ stereo superlayers. The charged particle transverse momentum resolution is $\sigma_{p_T}/p_T \simeq 0.07\%\, p_T$ (GeV/c), and the resolution on the transverse distance of closest approach of the particle trajectory to the beamline (impact parameter, d_0) is $\approx$40 μm, including a $\approx$30 μm contribution from the beamline.

Candidate events for this analysis are selected by a three-level on-line event selection system (trigger). At level 1, charged particles are reconstructed in the COT axial superlayers by a hardware processor, the Extremely Fast Tracker (XFT) [11]. Two charged particles are required with transverse momenta $p_T \geq 2$ GeV/c. At level 2, the Silicon Vertex Trigger (SVT) [12] associates SVX $r-\phi$ position measurements with XFT tracks. This provides a precise measurement of the track impact parameter d_0. We select b-hadron candidates by requiring two SVT tracks with 120 μm $\leq d_0 \leq$ 1000 μm. To reduce background from light-quark jet pairs, the two trigger tracks are required to have an opening angle in the transverse plane $2^\circ \leq \Delta\phi \leq 90^\circ$. The tracks must also satisfy the requirement $L_T > 200$ μm, where L_T is defined as the distance in the transverse plane from the beam line to the two-track intersection point, projected onto the two-track momentum vector. The level 1 and 2 trigger requirements are then confirmed at trigger level 3, where the event is fully reconstructed.

III. EVENT RECONSTRUCTION

The search for $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates begins with the reconstruction of the Λ_c^+ using the three-body decay $\Lambda_c^+ \to pK^-\pi^+$ [13]. Three tracks, assumed to be a kaon, a proton, and a pion, with a total charge of +1, are fit to a common vertex. No particle identification is used in this analysis. All particle hypotheses consistent with the candidate decay chain are considered. Additional selection criteria (cuts) are applied on fit probability ($P(\chi^2(\Lambda_c^+)) > 10^{-5}$), transverse momentum ($p_T(\Lambda_c^+) > 4.0$ GeV/c), and transverse decay length relative to the beamline ($L_T(\Lambda_c^+) > 200$ μm). We also require $p_T(p) > p_T(\pi^+)$, to suppress random-track combinatorial background. The reconstructed Λ_c^+ mass ($m(\Lambda_c^+)$) distribution is comparable to the one reported in Ref. [14]. The reconstructed Λ_c^+ mass is required to be close to the known Λ_c^+ mass (2.240 - 2.330 GeV/c^2) [3]. Since mass differences are used to search for the resonances, no mass constraint is applied in the Λ_c^+ reconstruction. The $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ ($\Lambda_b^0 \to \Lambda_c^+\pi^-$) candidate is reconstructed by performing a fit to a common vertex of the reconstructed Λ_c^+ and three (one) additional tracks, assumed to be pions, with $p_T > 0.4$ GeV/c, and a total charge of −1. For all the possible track pairs out of the six (four) tracks that form the Λ_b^0 candidate, we require the difference between the z coordinate of the points of closest approach of the two tracks to the beam to be less than 5 cm. Additional cuts on the Λ_b^0 candidate fit probability ($P(\chi^2(\Lambda_b^0)) > 10^{-4}$), transverse momentum ($p_T(\Lambda_b^0) > 6.0$ GeV/c), transverse decay length relative to the beamline ($L_T(\Lambda_b^0) > 200$ μm), and Λ_c^+ transverse decay length relative to the beamline ($L_T(\Lambda_c^+) > 200$ μm) and to the Λ_b^0 vertex ($L_T(\Lambda_c^+$ from $\Lambda_b^0) > -200$ μm) are applied. We also require that the transverse momentum of the pion produced in the

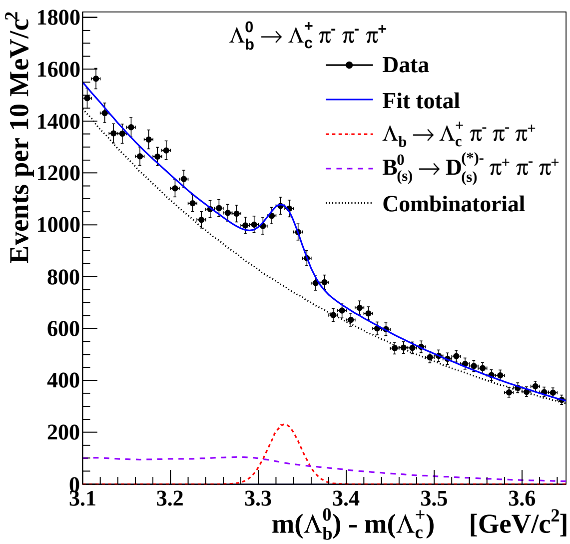
Λ_c^+ decay is larger than the transverse momentum of the same-charge pion produced in the Λ_b^0 decay, which considerably reduces the combinatorial background due to the larger boost of the pion produced in the Λ_c^+ decay. To improve the purity of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ signal, we optimize the analysis cuts to maximize the signal significance $\mathcal{S}/\sqrt{\mathcal{S}+\mathcal{B}}$. The number of $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ candidates $\mathcal{S}$ and the number of background events $\mathcal{B}$ are estimated in data by performing a fit of the $m(\Lambda_b^0)$ distribution. This procedure determines the final selection criteria: $p_T(\Lambda_b^0) > 9.0$ GeV/c, $L_T(\Lambda_b^0)/\sigma_{L_T(\Lambda_b^0)} > 16$, $d_0(\Lambda_b^0) < 70$ μm, and $\Delta R(\pi^-\pi^+\pi^-) < 1.2$, where $d_0(\Lambda_b^0)$ is the impact parameter of the reconstructed Λ_b^0 candidate relative to the beamline and $\Delta R(\pi^-\pi^+\pi^-)$ is the maximum $\sqrt{\Delta\eta^2 + \Delta\phi^2}$ distance between the two pions in each of the three possible pairs of pions. We verified that by splitting the data sample in two independent samples, the optimization procedure yields the same final selection criteria when applied separately to the two samples, and that the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ yield is evenly distributed. This ensures that our optimization procedure does not introduce a bias on the branching fraction measurement. To reduce possible systematic effects in the estimate of the reconstruction efficiency due to Monte Carlo simulation model inaccuracy, the same selection cuts optimized for $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ are also applied to the selection of the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ signal, except for the $\Delta R(\pi^-\pi^+\pi^-)$ cut.

IV. DETERMINATION OF THE SIGNAL YIELDS

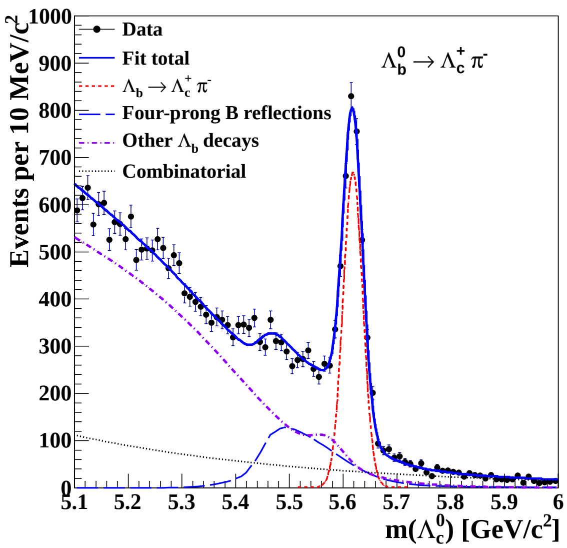
Figure 1(a) shows the distribution of the difference between the reconstructed Λ_b^0 and Λ_c^+ masses, $m(\Lambda_b^0) - m(\Lambda_c^+)$, of the selected $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ candidates with the fit projection overlaid. A significant signal of $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ is visible centered approximately at 3.330 GeV/c^2. Backgrounds include misreconstructed multibody b-hadron decays (physics background) and random combinations of charged particles that accidentally meet the selection requirements (combinatorial background). We use an unbinned extended maximum-likelihood fit to estimate the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ signal yield. The signal peak is modeled with a Gaussian, with mean and width left floating in the fit. The combinatorial background is modeled with an exponential function of $m(\Lambda_b^0) - m(\Lambda_c^+)$ with floating slope and normalization. The distribution of the main physics backgrounds, due to the $B_{(s)}^0 \to D_{(s)}^{(*)-}\pi^+\pi^-\pi^+$ decay modes, are derived from simulation and included in the fit with fixed shape and floating normalization. The $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ yield estimated by the fit of the data is 1087$\pm$101 candidates, the world's largest sample currently available of this decay mode. Figure 1(b) shows the Λ_b^0 mass distribution of the selected $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The Λ_b^0 mass distribution is described by several components: the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ Gaussian signal, a combinatorial background, reconstructed B mesons that pass the $\Lambda_c^+\pi^-$ selection criteria, partially reconstructed Λ_b^0 decays (*e.g.* $\Lambda_b^0 \to \Lambda_c^+ l^-\bar{\nu}_l$), and fully reconstructed Λ_b^0 decays other than $\Lambda_c^+\pi^-$ (*e.g.* $\Lambda_b^0 \to \Lambda_c^+K^-$). Also in this case the distributions of physics backgrounds are derived from simulation and included in the fit with fixed shapes and floating normalization, as detailed in Ref. [15]. The $\Lambda_b^0 \to \Lambda_c^+\pi^-$ yield estimated by the fit of the data is 3052$\pm$78 candidates.

In the reconstructed $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ sample we searched for the resonant decay modes: $\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$, $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$, $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$, and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$. The available energy transferred to the decay products in the decays of the charmed baryons ($\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Sigma_c(2455)^{++}$, and $\Sigma_c(2455)^0$) into Λ_c^+ is small. Therefore the differences of the reconstructed masses $m(\Lambda_c^{*+}) - m(\Lambda_c^+)$, $m(\Sigma_c(2455)^{++}) - m(\Lambda_c^+)$, and $m(\Sigma_c(2455)^0) - m(\Lambda_c^+)$ are determined with better resolution than the masses of the charmed baryons, since the mass resolution of the Λ_c^+ signal and most of the mass systematic uncertainties cancel in the difference. Figure 2(a) shows the $m(\Lambda_c^{*+}) - m(\Lambda_c^+)$ distribution, for $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ candidates with mass in a $\pm 3\sigma$ range ($\pm$57 MeV/c^2) around the Λ_b^0 mass. The $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ signals are clearly visible. Although there are two possible Λ_c^{*+} candidates for each $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay, only the candidate made with the π^- with lower p_T has a value of $m(\Lambda_c^{*+}) - m(\Lambda_c^+)$ in the mass region where the $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ signals are expected. The $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ signal yields are estimated with an unbinned extended maximum-likelihood fit. The $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ signals are modeled with two non-relativistic Breit-Wigner functions convolved with the same Gaussian resolution function, since the mass difference between the two resonances is tiny. The background is modeled by a linear function. The $\Lambda_c(2595)^+$ natural width is mass dependent to take into account the threshold effects, as reported in Ref. [14], the $\Lambda_c(2625)^+$ natural width and the width of the Gaussian resolution function are free parameters of the fit. Table I reports the estimated signal yields and significances, evaluated by means of the likelihood ratio test, $LR \equiv L/L_{bck}$, where L and L_{bck} are the likelihood of the signal and no signal hypotheses, respectively [16].

Figures 2(b) and 2(c) show the $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution restricted to candidates with $m(\Lambda_c^{*+}) - m(\Lambda_c^+) <$ 0.325 GeV/c^2 and 0.325$<$ $m(\Lambda_c^{*+}) - m(\Lambda_c^+) <$ 0.360 GeV/c^2, respectively, i.e. compatible with the $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ expected signals. Each signal is modeled with a Gaussian function, with floating mean and width. The combinatorial background is modeled with an exponential function with floating slope and normalization, and the physics background, which is mainly due to semileptonic $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+ l^-\overline{\nu}_l$ decays, is derived from simulation and introduced in the fit with fixed shape and floating normalization. We verified that the



(a)



(b)

FIG. 1: The reconstructed invariant mass spectra after applying all the selection criteria: (a) the mass difference $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ candidates; (b) the $m(\Lambda_b^0)$ distribution of the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates.

$\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$ yields estimated by fitting the $m(\Lambda_b^0) - m(\Lambda_c^+)$ distributions are compatible with the yields reported in Table I with lower significance.

To extract the $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$ and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ signals, the contributions due to the $\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$ decay modes are removed by applying the veto requirement $m(\Lambda_c^{*+}) - m(\Lambda_c^+) > 0.380$ GeV/c^2. In Fig. 3(a) and 3(b) the resulting $m(\Sigma_c(2455)^{++}) - m(\Lambda_c^+)$ and $m(\Sigma_c(2455)^0) - m(\Lambda_c^+)$ distributions are shown. Prominent $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ signals are visible. While there is only one $\Sigma_c(2455)^{++}$ candidate for each $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay, two $\Sigma_c(2455)^0$ candidates are possible. Also in this case, only the candidate made with the π^- with lower p_T is in the $\Sigma_c(2455)^0$ mass region. The $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ signals are modeled with non-relativistic Breit-Wigner functions convolved with a Gaussian resolution function, with the addition of an empirical background [17, 18]. The $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ natural widths are Gaussian constrained to the world average values [3], while the width of the Gaussian resolution function is determined to be 1 MeV/c^2 from larger statistics samples of $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ in the Λ_b^0 lower mass region and is fixed in the fit. The effect of this approximation is taken into account in the systematic uncertainties. The estimated $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$ and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ yields and significances are reported in Table I.

In Fig. 3(c) and 3(d) the $m(\Lambda_b^0) - m(\Lambda_c^+)$ distributions are shown restricted to candidates with 0.160 $< m(\Sigma_c(2455)^{++,0}) - m(\Lambda_c^+) <$ 0.176 GeV/c^2, where the $\Sigma_c(2455)^{++}$ and $\Sigma_c(2455)^0$ signals are contained. The Λ_b^0 signal is modeled with a Gaussian distribution, with floating mean and width, while the combinatorial background is an exponential function with floating slope and normalization. We verified that the $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$ and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ yields estimated by fitting the $m(\Lambda_b^0) - m(\Lambda_c^+)$ distributions are compatible with the yields reported in Table I with lower significance. The fitted masses and widths of the four resonances are in agreement with the world averages [3] and the recent CDF II measurements [14].

TABLE I: Yields and significances of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay modes. The quoted uncertainty is statistical only.

Λ_b^0 decay mode	Yield	Significance(σ)
$\Lambda_c(2595)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	46.0 ± 8.2	6.2
$\Lambda_c(2625)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	135 ± 15	>8
$\Sigma_c(2455)^{++}\pi^-\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	110 ± 19	6.6
$\Sigma_c(2455)^0\pi^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	36 ± 11	3.4
$\Lambda_c^+\pi^-\pi^+\pi^-$(other)	790 ± 100	>8

The residual Λ_b^0 signal (named $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$(other)) is selected by applying the cuts $m(\Lambda_c^{*+}) - m(\Lambda_c^+) > 0.380$ GeV/c^2 and $m(\Sigma_c(2455)^{++,0}) - m(\Lambda_c^+) > 0.190$ GeV/c^2 to remove the contribution due to the resonant decay modes (Fig. 4). This residual Λ_b^0 signal is likely due to a combination of the $\Lambda_b^0 \to \Lambda_c^+ a_1(1260)^-$, $\Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-$ with non-resonant $\rho^0\pi^-$ (i.e. not produced by a $a_1(1260)^-$ decay), and non-resonant $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay modes, in unknown proportions. A fit is performed with a Gaussian function, with floating mean and width to model the signal, an exponential function with floating slope and normalization to model the combinatorial background, and a physics background due to the $B^0_{(s)} \rightarrow D^{(*)-}_{(s)}\pi^+\pi^-\pi^+$ decay modes, derived from simulation and included in the fit with fixed shape and floating normalization. The resulting yield is 790±100 candidates (Table I). The unknown composition of the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$(other) sample is taken into account as a source of systematic uncertainty.

V. MEASUREMENT OF THE RATIO OF BRANCHING FRACTIONS $\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-)$

We measure the following ratio of branching fractions:

$$\frac{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-)} =$$

$$= \sum_i \frac{N(\Lambda^0_b \rightarrow i \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)}{N(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-)}\frac{\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-}}{\epsilon_i}, \quad (1)$$

where N are the measured signal yields reported in Table I, and the sum on the intermediate "i" states includes $\Lambda_c(2595)^+\pi^-$, $\Lambda_c(2625)^+\pi^-$, $\Sigma_c(2455)^{++}\pi^-\pi^-$, $\Sigma_c(2455)^0\pi^+\pi^-$, and $\Lambda^+_c\pi^-\pi^+\pi^-$(other). In the last state, we assume equal proportions of the three decay modes $\Lambda^0_b \rightarrow \Lambda^+_c a_1(1260)^-$, $\Lambda^0_b \rightarrow \Lambda^+_c\rho^0\pi^-$, and non-resonant $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$. To convert event yields into relative branching fractions, we apply the corrections $\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-}/\epsilon_i$ for the various trigger and offline selection efficiencies of the decay modes $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-$ and $\Lambda^0_b \rightarrow i \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$. All corrections are determined from the detailed detector simulation. The BGENERATOR program produces samples of specific B hadron decays according to measured p_T and rapidity spectra [19]. Decays of b and c hadrons and their daughters are simulated using the EVTGEN package [20]. The geometry and response of the detector components are simulated with the GEANT software package [21] and simulated events are processed with a full simulation of the CDF II detector and trigger. The resulting estimated corrections $\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-}/\epsilon_i$ are 4.70 ± 0.10, 4.66 ± 0.10, 5.28 ± 0.11, and 18.49 ± 0.66, respectively, for the $\Lambda_c(2595)^+\pi^-$, $\Lambda_c(2625)^+\pi^-$, $\Sigma_c(2455)^{++}\pi^-\pi^-$, and $\Sigma_c(2455)^0\pi^+\pi^-$ decay modes. For the $\Lambda^+_c\pi^-\pi^+\pi^-$(other) decay mode a correction factor equal to 9.16 ± 0.14 is obtained by averaging the relative efficiencies of the three intermediate states $\Lambda^0_b \rightarrow \Lambda^+_c a_1(1260)^-$, $\Lambda^0_b \rightarrow \Lambda^+_c\rho^0\pi^-$, and non-resonant $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$.
With a similar method, we also measure the ratios of the branching fractions of the intermediate resonances contributing to $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$,

$$\frac{\mathcal{B}(\Lambda^0_b \rightarrow j \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)} =$$

$$= \frac{N(\Lambda^0_b \rightarrow j \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)}{\sum_i N(\Lambda^0_b \rightarrow i \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)\frac{\epsilon_j}{\epsilon_i}}. \quad (2)$$

VI. SYSTEMATIC UNCERTAINTIES

The dominant sources of systematic uncertainty are the unknown relative fractions of $\Lambda^0_b \rightarrow \Lambda^+_c a_1(1260)^-$, $\Lambda^0_b \rightarrow \Lambda^+_c\rho^0\pi^-$, and non-resonant $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$, which affect the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$(other) decay mode efficiency, and the unknown Λ^0_b production and Λ^+_c decay polarizations, which affect the estimate of all the ϵ_i and $\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-}$ efficiencies. The correction $\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-}/\epsilon_{\Lambda^0_b\rightarrow\Lambda^+_c\pi^-\pi^+\pi^-(\text{other})}$ has an average value of 9.16 and varies between a minimum of 7.4 and a maximum of 11.6, obtained in the extreme cases in which the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$(other) sample is assumed to be entirely composed of $\Lambda^0_b \rightarrow \Lambda^+_c a_1(1260)^-$ or non-resonant $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$, respectively. The dependence of $\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-)$ on the fraction of $\Lambda^0_b \rightarrow \Lambda^+_c a_1(1260)^-$ and $\Lambda^0_b \rightarrow \Lambda^+_c\rho^0\pi^-$ in the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-$(other) sample is shown in Fig. 5. The difference between the values computed with the average and the minimum (maximum) efficiency correction, respectively, is taken as an estimate of the lower (upper) associated systematic uncertainty.

The unpolarized Λ^0_b and Λ^+_c simulation samples are used to obtain the central values of the efficiency corrections. For the study of the systematic uncertainties, angular distributions in simulation are reweighted according to all possible combinations of the Λ^0_b production polarization states along the normal to the production plane, with the Λ^+_c polarization states. The Λ^0_b polarization and the Λ^+_c polarizations are both taken to vary independently in the range ±1. We assume the extreme scenarios where both the Λ^0_b and Λ^+_c baryons are 100% polarized and we recompute the efficiency corrections assuming the four possible Λ^0_b and Λ^+_c polarization combinations. The difference in the efficiency corrections between the simulation with reweighted angular distributions and the simulation with unpolarized Λ^0_b and Λ^+_c is used to determine the associated systematic uncertainty. These two sources of systematic uncertainty account for approximately 98% of the total systematic uncertainty on the measurement of the relative branching fraction $\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda^0_b \rightarrow \Lambda^+_c\pi^-)$. Other systematic errors stem from the uncertainties on the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-$ background shapes; on the Cabibbo suppressed decay mode contributions, which affect the estimate of the signal yields; on the Monte Carlo simulation of the signal decay modes (limited sample statistics, trigger emulation, and Λ^0_b production transverse momentum distribution), which affect the estimate of the efficiency corrections. The contributions due to the uncertainties on the Σ^{++}_c and Σ^0_c signal and background shapes, the Λ^+_c and Λ^{*+}_c branching fractions, and the Λ^0_b and Λ^+_c lifetimes are negligible.

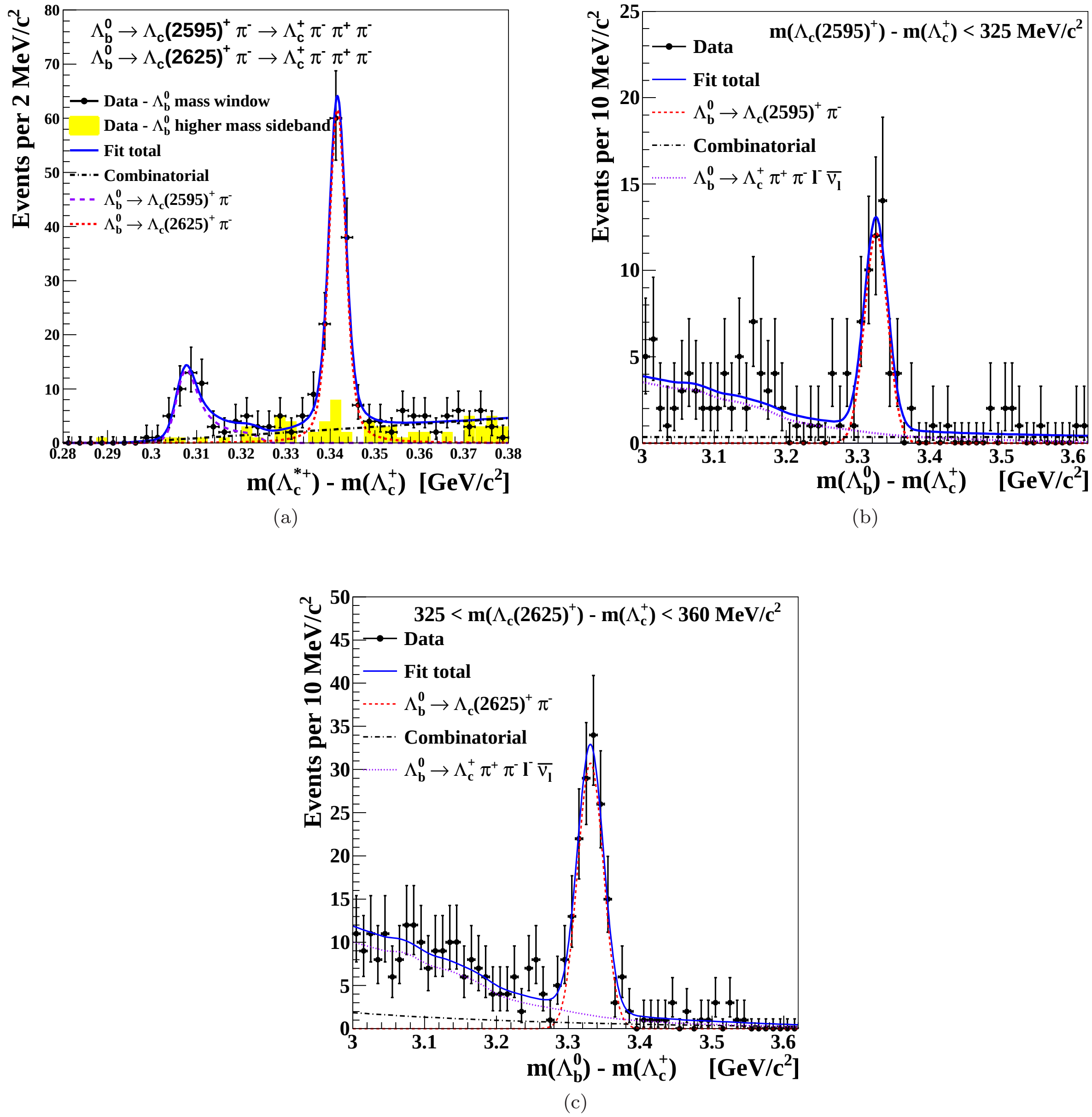


FIG. 2: The $\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$ signals: (a) $m(\Lambda_c^{*+}) - m(\Lambda_c^+)$ distribution for candidates in a $\pm 3\sigma$ range (± 57 MeV/c^2) around the Λ_b^0 mass; (b) $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution restricted to candidates in the region $m(\Lambda_c^{*+}) - m(\Lambda_c^+) < 0.325$ GeV/c^2; (c) $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution restricted to candidates in the region $0.325 < m(\Lambda_c^{*+}) - m(\Lambda_c^+) < 0.360$ GeV/c^2.

As a cross-check of the analysis, we also measure the relative branching fraction $\mathcal{B}(B^0 \to D^-\pi^+\pi^-\pi^+)/\mathcal{B}(B^0 \to D^-\pi^+)$, using the same data sample and vertex reconstruction procedure developed for the Λ_b^0 analysis. We apply the same optimized cuts to the B^0 candidates, with the additional request to have a D^- candidate with mass within ± 22 MeV/c^2 of the known mass of D^- [3]. We estimate $B^0 \to D^-\pi^+\pi^-\pi^+$ and $B^0 \to D^-\pi^+$ yields of 431 ± 32 and 1352 ± 44 candidates, respectively. Our measurement $\mathcal{B}(B^0 \to D^-\pi^+\pi^-\pi^+)/\mathcal{B}(B^0 \to D^-\pi^+) = 3.06 \pm 0.25(\text{stat})$ is in good agreement with the value calculated from the measured absolute branching fractions of the B^0 decay modes reported in Ref. [3].

TABLE II: Measured branching fractions relative to the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decay mode (second column). Absolute branching fractions (third column) are derived by normalizing to the known value $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = (8.8 \pm 3.2) \times 10^{-3}$ [22]. The first quoted uncertainty is statistical, the second is systematic, and the third is due to the uncertainty on the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ branching fraction.

Λ_b^0 decay mode	Relative $\mathcal{B}$ to $\Lambda_b^0 \to \Lambda_c^+\pi^-$	Absolute $\mathcal{B}(10^{-3})$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-) \cdot \mathcal{B}(\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-)$	$(7.1 \pm 1.3 \pm 0.6) \cdot 10^{-2}$	$0.62 \pm 0.11 \pm 0.05 \pm 0.23$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-) \cdot \mathcal{B}(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)$	$(20.6 \pm 2.4^{+1.4}_{-1.5}) \cdot 10^{-2}$	$1.81 \pm 0.21^{+0.12}_{-0.13} \pm 0.66$
$\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-) \cdot \mathcal{B}(\Sigma_c(2455)^{++} \to \Lambda_c^+\pi^+)$	$(19.0 \pm 3.3 \pm 1.1) \cdot 10^{-2}$	$1.67 \pm 0.29 \pm 0.10 \pm 0.61$
$\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-) \cdot \mathcal{B}(\Sigma_c(2455)^0 \to \Lambda_c^+\pi^-)$	$(21.5 \pm 6.5^{+4.5}_{-2.9}) \cdot 10^{-2}$	$1.89 \pm 0.57^{+0.40}_{-0.26} \pm 0.69$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(\text{other}))$	$2.36 \pm 0.32^{+0.68}_{-0.53}$	$20.8 \pm 2.8^{+6.0}_{-4.7} \pm 7.6$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)$	$3.04 \pm 0.33^{+0.70}_{-0.55}$	$26.8 \pm 2.9^{+6.2}_{-4.8} \pm 9.7$

VII. RESULTS

We measure the relative branching ratio of $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decays to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} = 3.04 \pm 0.33(\text{stat})^{+0.70}_{-0.55}(\text{syst}).$$

The relative branching fractions of the intermediate states contributing to $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ with respect to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ are reported in Table II. The absolute branching fractions are derived by normalizing to the known value $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = (8.8 \pm 3.2) \times 10^{-3}$ [22].

To compare our result with the recent LHCb measurement [5] of $1.43 \pm 0.16(\text{stat}) \pm 0.13(\text{syst})$, we assume the composition of the admixture to be 2/3 $\Lambda_b^0 \to \Lambda_c^+ a_1(1260)^-$ and 1/3 $\Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-$, and use the overall $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ yield and a global efficiency correction to compute $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$, as in the LHCb analysis. This results in a value of $2.55 \pm 0.25(\text{stat})^{+0.82}_{-0.27}(\text{syst})$, which is inconsistent with the LHCb result at the level of 2.6 Gaussian standard deviations.

We also measure the relative branching fractions of the intermediate resonances contributing to the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay (Table III). These results are of comparable or higher precision than existing measurements.

VIII. CONCLUSION

In summary, we reconstruct the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ decay mode and the $\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$, $\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$, $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$, and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ resonant decay modes in CDF II data corresponding to 2.4 fb^{-1} of integrated luminosity. We measure the branching fraction of the resonant decay modes relative to the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ branching fraction. We also measure $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = 3.04 \pm 0.33(\text{stat})^{+0.70}_{-0.55}(\text{syst})$. Using the known value of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$ [22] we find $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-) = (26.8 \pm 2.9(\text{stat})^{+6.2}_{-4.8}(\text{syst}) \pm 9.7(\text{norm})) \times 10^{-3}$, where the third quoted uncertainty arises from the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ normalization uncertainty.

IX. ACKNOWLEDGMENTS

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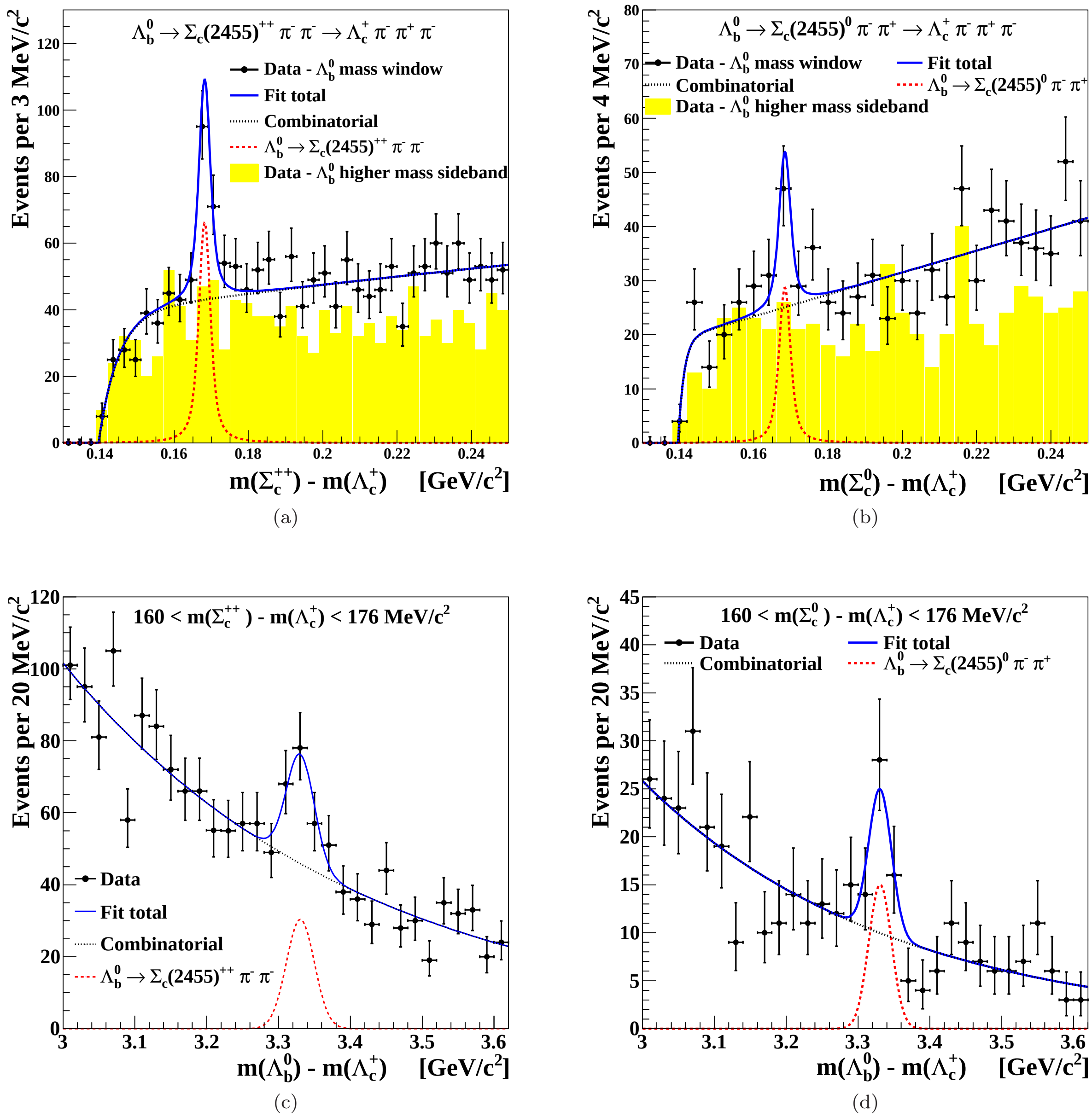

FIG. 3: The $\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-$ and $\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-$ signals: (a) $m(\Sigma_c(2455)^{++}) - m(\Lambda_c^+)$ distribution for candidates in a $\pm 3\sigma$ range (± 57 MeV/c^2) around the Λ_b^0 mass; (b) $m(\Sigma_c(2455)^0) - m(\Lambda_c^+)$ distribution for candidates in a $\pm 3\sigma$ range around the Λ_b^0 mass; (c) $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution restricted to candidates in the region $0.160 < m(\Sigma_c(2455)^{++}) - m(\Lambda_c^+) < 0.176$ GeV/c^2; (d) $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution restricted to candidates in the region $0.160 < m(\Sigma_c(2455)^0) - m(\Lambda_c^+) < 0.176$ GeV/c^2.

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TABLE III: Measured branching fractions of the resonant decay modes relative to $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$. The first quoted uncertainty is statistical, the second is systematic.

Λ_b^0 decay mode	Relative $\mathcal{B}(10^{-2})$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-) \cdot \mathcal{B}(\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-)$	$2.3 \pm 0.5 \pm 0.4$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-) \cdot \mathcal{B}(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)$	$6.8 \pm 1.0 \pm 1.3$
$\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^-) \cdot \mathcal{B}(\Sigma_c(2455)^{++} \to \Lambda_c^+\pi^+)$	$6.2 \pm 1.2 \pm 1.3$
$\mathcal{B}(\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-) \cdot \mathcal{B}(\Sigma_c(2455)^0 \to \Lambda_c^+\pi^-)$	$7.1 \pm 2.1^{+1.5}_{-1.3}$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-(\text{other}))$	$77.6 \pm 3.0^{+4.0}_{-4.1}$

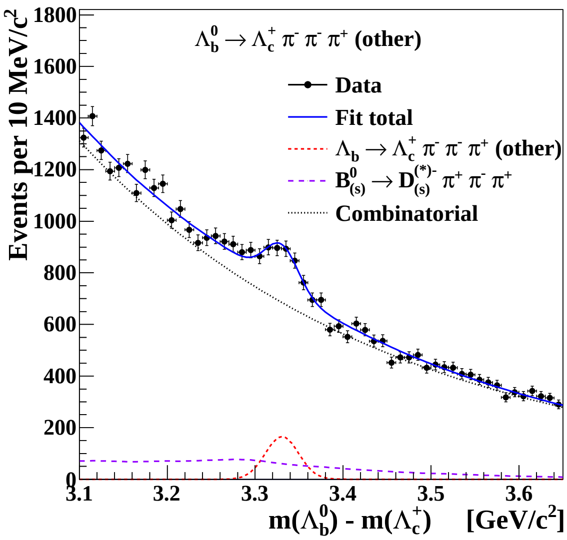

FIG. 4: The $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$(other) signal after vetoing the resonant decay modes: $m(\Lambda_b^0) - m(\Lambda_c^+)$ distribution.

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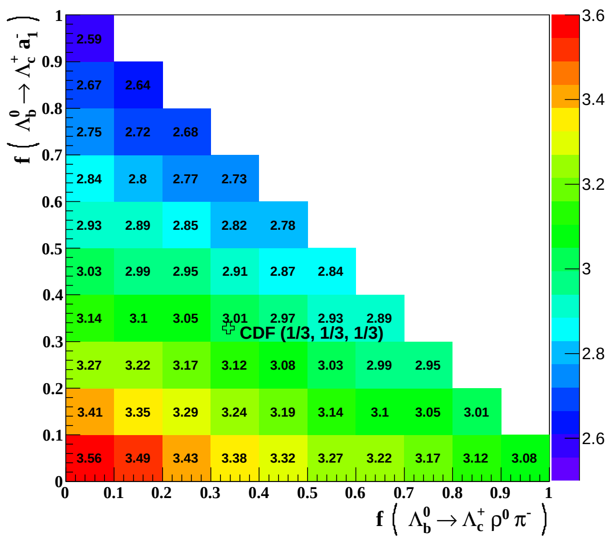

FIG. 5: $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$ (color scale) as a function of the assumed fractions of $\Lambda_b^0 \to \Lambda_c^+ a_1^-$ and $\Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-$ in the composition of the $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$(other) sample. The central value of the ratio is overlaid in each bin. The fraction of non-resonant $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$ is equal to $1 - f\left(\Lambda_b^0 \to \Lambda_c^+ a_1^-\right) - f\left(\Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-\right)$. The cross represents the composition chosen for the present measurement assuming equal proportions of $\Lambda_b^0 \to \Lambda_c^+ a_1^-$, $\Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-$ and non-resonant $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$.