Measurement of the branching fraction $B(\Lambda^0_b \rightarrow \Lambda^+ + \pi^-)$ at CDF

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We report an analysis of the \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^- \) 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 \( \Lambda_0^0 \to \Lambda_c(2595)^+\pi^- \) (with \( \Lambda_c(2595)^+ \to \Lambda_c^+ \pi^+ \pi^- \)), \( \Lambda_0^0 \to \Lambda_c^0(2625)^+\pi^- \) (with \( \Lambda_c^0(2625)^+ \to \Lambda_c^+ \pi^- \pi^- \)), \( \Lambda_0^0 \to \Sigma_c(2455)^0\pi^+\pi^- \) (with \( \Sigma_c(2455)^0 \to \Lambda_c^0 \pi^- \)) and measure the branching fractions relative to the \( \Lambda_c^+ \) branching fraction. We measure the ratio \( B(\Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^-)/B(\Lambda_0^0 \to \Lambda_c^+ \pi^-) = 3.04 \pm 0.33\text{(stat)}^{+0.34}_{-0.30}\text{(syst)} \) which is used to derive \( B(\Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^-) = (26.8 \pm 11.2) \times 10^{-3} \).

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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 \( \Lambda_0^0 \) 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 \( \Lambda_0^0 \) baryon. Only nine decay modes of the \( \Lambda_0^0 \) 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 \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \) branching fraction \[4\], no prediction is currently available for the \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^- \) decay mode. LHCb recently reported the measurement of the ratio of branching fractions \( B(\Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^-)/B(\Lambda_0^0 \to \Lambda_c^+ \pi^-) = 1.43 \pm 0.16\text{(stat)} \pm 0.13\text{(syst)} \) \[3\].

This paper reports a study of the \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^- \) decay mode and is especially distinguished by the high yields and high precision measurement of the \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \pi^0 \pi^- \) resonant contributions, the following decay modes:

\[ \Lambda_0^0 \to \Lambda_c(2595)^+\pi^- , \]
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 $B(\Lambda_b^0 \to \Lambda^+_c\pi^-\pi^+\pi^-)/B(\Lambda_b^0 \to \Lambda^+_c\pi^-)$. The measurement is performed using a sample of $p\bar{p}$ collisions corresponding to 2.4 fb$^{-1}$ integrated luminosity collected by CDF II between February 2002 and May 2007. We reconstruct $\Lambda_b^0$ 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 $\Lambda^0 \to \Sigma^+_c(2455)^+\pi^-\pi^-$ and $\Lambda^0 \to \Sigma^-_c(2455)^0\pi^+\pi^-$. 

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. A silicon microstrip detector (SVX and ISL) and a cylindrical drift chamber (COT) immersed in a 1.4 T solenoidal magnetic field allow the reconstruction of charged particle trajectories in the pseudorapidity range $|\eta| < 1.0$. 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 ±2° stereo superlayers. The charged particle transverse momentum resolution is $\sigma_{p_T}/p_T \approx 0.07%$ $p_T$ (GeV/c), and the resolution on the transverse distance of closest approach of the particle trajectory to the beamline (impact parameter, $d_0$) is $\approx 40 \mu m$, including a $\approx 30 \mu m$ 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). Two charged particles are required with transverse momenta $p_T > 2$ GeV/c. At level 2, the Silicon Vertex Trigger (SVT) 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 $120 \mu m \leq d_0 < 1000 \mu m$. 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 $L_T > 200 \mu m$, 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 $\Lambda^+_c$ using the three-body decay $\Lambda^+_c \to pK^-\pi^+$. 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 ($P(x^2(\Lambda^+_c)) < 10^{-5}$), transverse momentum ($p_T(\Lambda^+_c) > 4.0$ GeV/c), and transverse decay length relative to the beamline ($L_T(\Lambda^+_c) > 200 \mu m$). We also require $p_T(p) > p_T(\pi^+)$, to suppress random-track combinatorial background. The reconstructed $\Lambda^+_c$ mass (m($\Lambda^+_c$)) distribution is comparable to the one reported in Ref. 14. The reconstructed $\Lambda^+_c$ mass is required to be close to the known $\Lambda^+_c$ mass (2.240 - 2.330 GeV/c$^2$). Since mass differences are used to search for the resonances, no mass constraint is applied in the $\Lambda^+_c$ 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 $\Lambda^+_c$ 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 $\Lambda_b^0$ 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 $\Lambda_b^0$ candidate fit probability ($P(x^2(\Lambda_b^0)) < 10^{-4}$), transverse momentum ($p_T(\Lambda_b^0) > 6.0$ GeV/c), transverse decay length relative to the beamline ($L_T(\Lambda_b^0) > 200 \mu m$), and $\Lambda^+_c$ transverse decay length relative to the beamline ($L_T(\Lambda^+_c) > 200 \mu m$) and to the $\Lambda^+_c$ vertex ($L_T(\Lambda^+_c$ from $\Lambda_b^0) > -200 \mu m$) are applied. We also require that the transverse momentum of the pion produced in the
Λ⁺ decay is larger than the transverse momentum of the same-charge pion produced in the Λ⁺ decay, which considerably reduces the combinatorial background due to the larger boost of the pion produced in the Λ⁺ decay. To improve the purity of the Λ⁺ → Λ⁺π⁻π⁺π⁻ signal, we optimize the analysis cuts to maximize the signal significance S/√S + B. The number of Λ⁺ → Λ⁺π⁻π⁺π⁻ candidates S and the number of background events B are estimated in data by performing a fit of the m(Λ⁺) distribution. This procedure determines the final selection criteria: pT(Λ⁺) > 9.0 GeV/c, LRT(Λ⁺)/σ_LRT(Λ⁺) > 16, d0(Λ⁺) < 70 μm, and ΔR(π⁻π⁺π⁻) < 1.2, where d0(Λ⁺) is the impact parameter of the reconstructed Λ⁺ candidate relative to the beamline and ΔR(π⁻π⁺π⁻) is the maximum √(Δη² + Δφ²) 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 Λ⁺ → Λ⁺π⁻π⁺π⁻ 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 Λ⁺ → Λ⁺π⁻π⁺π⁻ are also applied to the selection of the Λ⁺ → Λ⁺π⁻ signal, except for the ΔR(π⁻π⁺π⁻) cut.

IV. DETERMINATION OF THE SIGNAL YIELDS

Figure 2(a) shows the distribution of the difference between the reconstructed Λ⁺ and Λ⁺ masses, m(Λ⁺) − m(Λ⁺), of the selected Λ⁺ → Λ⁺π⁻π⁺π⁻ candidates with the fit projection overlaid. A significant signal of Λ⁺ → Λ⁺π⁻π⁺π⁻ is visible centered approximately at 3.330 GeV/c². 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 Λ⁺ → Λ⁺π⁻π⁺π⁻ 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(Λ⁺) − m(Λ⁺) with floating slope and normalization. The distribution of the main physics backgrounds, due to the B⁺(S) → D⁺(S)π⁻π⁺π⁺ decay modes, are derived from simulation and included in the fit with fixed shape and floating normalization. The Λ⁺ → Λ⁺π⁻π⁺π⁻ yield estimated by the fit of the data is 1087±101 candidates, the world’s largest sample currently available of this decay mode. Figure 2(b) shows the Λ⁺ mass distribution of the selected Λ⁺ → Λ⁺π⁻ candidates. The Λ⁺ mass distribution is described by several components: the Λ⁺ → Λ⁺π⁻ Gaussian signal, a combinatorial background, reconstructed B mesons that pass the Λ⁺π⁻ selection criteria, partially reconstructed Λ⁺ decays (e.g. Λ⁺ → Λ⁺π⁻ l⁻νl), and fully reconstructed Λ⁺ decays other than Λ⁺π⁻ (e.g. Λ⁺ → Λ⁺ 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 Λ⁺ → Λ⁺π⁻ yield estimated by the fit of the data is 3052±78 candidates.

In the reconstructed Λ⁺ → Λ⁺π⁻π⁺π⁻ sample we searched for the resonant decay modes: Λ⁺ → Λ⁺(2595)⁺π⁻, Λ⁺ → Λ⁺(2625)⁺π⁻, Λ⁺ → Λ⁺(2595)⁺π⁻π⁻, and Λ⁺ → Λ⁺(2625)⁰. The available energy transferred to the decay products in the decays of the charmed baryons (Λ⁺(2595)⁺, Λ⁺(2625)⁺, Λ⁺(2595)⁰, and Λ⁺(2625)⁰) into Λ⁺ is small. Therefore the differences of the reconstructed masses m(Λ⁺(2595)⁺) − m(Λ⁺), m(Σ⁺(2455)⁰) − m(Λ⁺), and m(Σ⁺(2455)⁺) − m(Λ⁺) are determined with better resolution than the masses of the charmed baryons, since the mass resolution of the Λ⁺ signal and most of the mass systematic uncertainties cancel in the difference. Figure 2(a) shows the m(Λ⁺) distribution, for Λ⁺ → Λ⁺π⁻π⁺π⁻ candidates with mass in a ±3σ range around the Λ⁺ mass. The Λ⁺(2595)⁺ and Λ⁺(2625)⁺ signals are clearly visible. Although there are two possible Λ⁺ candidates for each Λ⁺ → Λ⁺π⁻π⁺π⁻ decay, only the candidate made with the π⁻ with lower pT has a value of m(Λ⁺) − m(Λ⁺) in the mass region where the Λ⁺(2595)⁺ and Λ⁺(2625)⁺ signals are expected. The Λ⁺(2595)⁺ and Λ⁺(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 Λ⁺(2595)⁺ signal yield is mass dependent to take into account the threshold effects, as reported in Ref. 11, the Λ⁺(2625)⁺ signal yield and the width of the Gaussian resolution function are free parameters of the fit. Table II reports the estimated signal yields and significances, evaluated by means of the likelihood ratio test, LR ≡ L/L_bck, where L and L_bck are the likelihood of the signal and no signal hypotheses, respectively.

Figures 2(b) and 2(c) show the m(Λ⁺) − m(Λ⁺) distribution restricted to candidates with m(Λ⁺) − m(Λ⁺) < 0.325 GeV/c² and 0.325 < m(Λ⁺) − m(Λ⁺) < 0.360 GeV/c², respectively, i.e. compatible with the Λ⁺(2595)⁺ and Λ⁺(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 Λ⁺ → Λ⁺π⁻π⁺l⁻νl decays, is derived from simulation and introduced in the fit with fixed shape and floating normalization. We verified that the
The residual $\Lambda_b^0$ signal is selected by applying the cuts $m(\Lambda^*_c) - m(\Lambda^+_b) > 0.380$ GeV/$c^2$ and $m(\Sigma_c(2455)^{++}) - m(\Lambda^+_c) > 0.190$ GeV/$c^2$ to remove the contribution due to the resonant decay modes (Fig. 3). This residual $\Lambda_b^0$ signal is likely due to a combination of the $\Lambda_b^0 \rightarrow \Lambda^*_b a_1(1260)^-$, $\Lambda_b^0 \rightarrow \Lambda^*_c \rho^0 \pi^-$ with non-resonant $\rho^0 \pi^-$ (i.e., not produced by a $a_1(1260)^-$ decay), and non-resonant $\Lambda_b^0 \rightarrow \Lambda^*_c \pi^- \pi^- \pi^-$ decay modes, in unknown proportions. A fit is performed with a Gaussian function, with floating mean and width to

- $m(\Lambda^*_c) - m(\Lambda^+_b)$ > 0.380 GeV/$c^2$.
- $m(\Sigma_c(2455)^{++}) - m(\Lambda^+_c)$ > 0.190 GeV/$c^2$
model the signal, an exponential function with floating slope and normalization to model the combinatorial background, and a physics background due to the $B_{(s)}^0 \rightarrow D_{(s)}^{(*)-} \pi^+ \pi^- \pi^+$ 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 $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$ (other) sample is taken into account as a source of systematic uncertainty.

V. MEASUREMENT OF THE RATIO OF BRANCHING FRACTIONS

$\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-)/\mathcal{B}(Λ_0^b \rightarrow Λ_c^+ π^-)$

We measure the following ratio of branching fractions:

$$\frac{\mathcal{B}(Λ_0^b \rightarrow Λ_c^+ π^- π^+ π^-)}{\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^-)} = \frac{\sum_i N(Λ_0^b \rightarrow i \rightarrow Λ_c^+ π^- π^+ π^-)}{N(Λ_b^0 \rightarrow Λ_c^+ π^-)} \epsilon_i$$

where $N$ are the measured signal yields reported in Table I and the sum on the intermediate “$i$” states includes $Λ_c(2595)^+ π^-$, $Λ_c(2625)^+ π^-$, $Σ_c(2455)^+ π^- π^-$, $Σ_c(2455)^0 π^+ π^-$, and $Λ_c^+ π^- π^+ π^-$(other). In the last state, we assume equal proportions of the three decay modes $Λ_b^0 \rightarrow Λ_c^+ a_1(1260)^-$, $Λ_b^0 \rightarrow Λ_c^+ ρ^0 π^-$, and non-resonant $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$. To convert event yields into relative branching fractions, we apply the corrections $\epsilon_{Λ_0^b→Λ_c^+ π^-}/\epsilon_i$ for the various trigger and offline selection efficiencies of the decay modes $Λ_0^b \rightarrow Λ_c^+ π^-$ and $Λ_b^0 \rightarrow i \rightarrow Λ_c^+ π^- π^+ π^-$. All corrections are determined from the detailed detector simulation. The Generador 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 $\epsilon_{Λ_0^b→Λ_c^+ π^-}/\epsilon_i$ are 4.70 ± 0.10, 4.66 ± 0.10, 5.28 ± 0.11, and 18.49 ± 0.66, respectively, for the $Λ_c(2595)^+ π^-$, $Λ_c(2625)^+ π^-$, $Σ_c(2455)^+ π^- π^-$, and $Σ_c(2455)^0 π^+ π^-$ decay modes. For the $Λ_c^+ π^- π^+ π^-$ (other) decay mode a correction factor equal to 9.16 ± 0.14 is obtained by averaging the relative efficiencies of the three intermediate states $Λ_0^b \rightarrow Λ_c^+ a_1(1260)^-$, $Λ_0^b \rightarrow Λ_c^+ ρ^0 π^-$, and non-resonant $Λ_0^b \rightarrow Λ_c^+ π^- π^+ π^-$. With a similar method, we also measure the ratios of the branching fractions of the intermediate resonances contributing to $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$,

$$\frac{\mathcal{B}(Λ_0^b \rightarrow j \rightarrow Λ_c^+ π^- π^+ π^-)}{\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-)} = \frac{\sum_i N(Λ_0^b \rightarrow j \rightarrow Λ_c^+ π^- π^+ π^-)}{N(Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-)} \epsilon_i.$$  

VI. SYSTEMATIC UNCERTAINTIES

The dominant sources of systematic uncertainty are the unknown relative fractions of $Λ_b^0 \rightarrow Λ_c^+ a_1(1260)^-$, $Λ_b^0 \rightarrow Λ_c^+ ρ^0 π^-$, and non-resonant $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$, which affect the $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$ (other) decay mode efficiency, and the unknown $Λ_b^0$ production and $Λ_c^+$ decay polarizations, which affect the estimate of all the $ε_i$ and $ε_{Λ_0^b→Λ_c^+ π^-}$ efficiencies. The correction $ε_{Λ_0^b→Λ_c^+ π^-}/ε_{Λ_b^0→Λ_c^+ π^- π^+ π^-}$ 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 $Λ_b^0$ is entirely composed of $Λ_b^0 \rightarrow Λ_c^+ a_1(1260)^-$ or non-resonant $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$, respectively. The dependence of $\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-)/\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^-)$ on the fraction of $Λ_b^0 \rightarrow Λ_c^+ a_1(1260)^-$ and $Λ_b^0 \rightarrow Λ_c^+ ρ^0 π^-$ in the $Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-$ (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 $Λ_b^0$ 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 $Λ_b^0$ production polarization states along the normal to the production plane, with the $Λ_c^+$ polarization states. The $Λ_b^0$ polarization and the $Λ_c^+$ polarizations are both taken to vary independently in the range ±1. We assume the extreme scenarios where both the $Λ_b^0$ and $Λ_c^+$ baryons are 100% polarized and we recompute the efficiency corrections assuming the four possible $Λ_b^0$ and $Λ_c^+$ polarization combinations. The difference in the efficiency corrections between the simulation with reweighted angular distributions and the simulation with unpolarized $Λ_b^0$ 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 $\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^- π^+ π^-)/\mathcal{B}(Λ_b^0 \rightarrow Λ_c^+ π^-)$. Other systematic errors stem from the uncertainties on the $Λ_b^0 \rightarrow Λ_c^+ π^-$ 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 $Λ_b^0$ production transverse momentum distribution), which affect the estimate of the efficiency corrections. The contributions due to the uncertainties on the $Σ_c^{++}$ and $Σ_c^+$ signal and background shapes, the $Λ_c^+$ and $Λ_c^+$ branching fractions, and the $Λ_b^0$ and $Λ_c^+$ lifetimes are negligible.
for the $\Lambda_c^0$ sample and vertex reconstruction procedure developed to the $\Lambda_c^0$ candidates, respectively. Our measurement of the $\Lambda_c^0 \rightarrow \Lambda_c(2595)^+ \pi^-$ signal in agreement with the value calculated from the measured absolute branching fractions of the $B^0$ decay modes reported in Ref. [3].

As a cross-check of the analysis, we also measure the relative branching fraction $B(B^0 \rightarrow D^- \pi^+ \pi^- \pi^+)/B(B^0 \rightarrow D^- \pi^+)$ using the same data sample and vertex reconstruction procedure developed for the $\Lambda_c^0$ analysis. We apply the same optimized cuts to the $B^0$ candidates, with the additional request to have a $D^-$ candidate with mass within $\pm 22$ MeV/c^2 of the known mass of $D^-$ [3]. We estimate $B(B^0 \rightarrow D^- \pi^+ \pi^- \pi^+)/B(B^0 \rightarrow D^- \pi^+) = 3.06 \pm 0.25$(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].
We also measure the relative branching fractions of the LHCb result at the level of 2.6 Gaussian standard deviations as in the LHCb analysis. This results in a value of $0.56_{-0.15}^{+0.12}$ for the branching fraction. To compare our result with the recent LHCb measurement, we reconstruct the $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^-$ decay mode (second column). Absolute branching fractions (third column) are derived by normalizing to the known value $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (8.8 \pm 3.2) \times 10^{-3}$ [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.

### VII. RESULTS

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

$$B(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-) = 3.04 \pm 0.33_{\text{stat}}^{+0.70}_{-0.53_{\text{syst}}}.$$  

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 $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (8.8 \pm 3.2) \times 10^{-3}$ [22].

To compare our result with the recent LHCb measurement of $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 1.43_{-0.13}^{+0.16}$ (stat) (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 branching ratio $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^- \pi^-$ yield and a global efficiency correction to compute $B(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-) / B(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$. As in the LHCb analysis, this results in a value for $B(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-) / B(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$, as in the LHCb measurement of $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 1.43_{-0.13}^{+0.16}$ (stat) (syst), which is inconsistent with our result at the level of 2.6 Gaussian standard deviations.

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

### VIII. CONCLUSION

In summary, we reconstruct the $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^- \pi^-$ 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 $\Lambda_b^0 \to \Sigma_c(2650)^0 \pi^+ \pi^-$ 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 $B(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-) / B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 3.04_{-0.53}^{+0.70}$ (syst). Using the known value of $B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 1.43_{-0.13}^{+0.16}$ (stat) (syst), we find $B(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-) = (26.8 \pm 2.9_{\text{stat}}^{+1.4}_{-0.8}(syst) \pm 9.7(norm)) \times 10^{-3}$, where the third quoted uncertainty arises from the $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^- \pi^-$ normalization uncertainty.

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[1] A. V. Manohar and M. B. Wise, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. 10, 1, (2000); N. Isgur, D. Scora, B. Grinstein, and M. B. Wise, Phys. Rev. D 39, 799 (1989).
[2] I. Dunietz, Z. Phys. C 56, 129 (1992).
[3] K. Nakamura et al. (Particle Data Group), J.Phys. G 37, 075021 (2010).
[4] A. K. Leibovich, Z. Ligeti, I. W. Stewart, and M. B. Wise,
FIG. 3: The $\Lambda_b^0 \rightarrow \Sigma_c(2455)^{++} \pi^- \pi^-$ and $\Lambda_b^0 \rightarrow \Sigma_c(2455)^0 \pi^+ \pi^-$ signals: (a) $m(\Sigma_c(2455)^{++}) - m(\Lambda^+_b)$ distribution for candidates in a $\pm 3\sigma$ range ($\pm 57$ MeV/$c^2$) around the $\Lambda_b^0$ mass; (b) $m(\Sigma_c(2455)^0) - m(\Lambda^+_b)$ distribution for candidates in a $\pm 3\sigma$ range around the $\Lambda_b^0$ mass; (c) $m(\Lambda_b^0) - m(\Lambda^+_b)$ distribution restricted to candidates in the region $0.160 < m(\Sigma_c(2455)^{++}) - m(\Lambda^+_b) < 0.176$ GeV/$c^2$; (d) $m(\Lambda_b^0) - m(\Lambda^+_b)$ distribution restricted to candidates in the region $0.160 < m(\Sigma_c(2455)^0) - m(\Lambda^+_b) < 0.176$ GeV/$c^2$. 

Phys. Lett. B 586, 337 (2004); H. Y. Cheng, Phys. Rev. D 56, 2799 (1997). 
[5] R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 84, 092001 (2011). 
[6] D. Acosta et al. (CDF Collaboration), Phys. Rev. D 71, 032001 (2005). 
[7] A. Sill et al., Nucl. Instrum. Methods A 447, 1 (2000). 
[8] T. Affolder et al., Nucl. Instrum. Methods A 526, 249 (2004). 
[9] The pseudorapidity is defined as $\eta = -\log\tan(\theta/2)$ where $\theta$ is the angle between the trajectory of the particle being considered and the undeflected beam direction. 
[10] CDF II uses a cylindrical coordinate system in which $\phi$ is the azimuthal angle, $r$ is the radius from the nominal beam line, and $z$ points in the proton beam direction, with the origin at the center of the detector. The transverse plane is the plane perpendicular to the $z$ axis. 
[11] E. Thomson et al., IEEE Trans. Nucl. Sci. 49, 1063 (2002). 
[12] B. Ashmanskas et al., Nucl. Instrum. Methods A 518, 532 (2004); L. Ristori, G. Punzi, Ann. Rev. Nucl. Part. Sci., 60, 595 (2010).
TABLE III: Measured branching fractions of the resonant decay modes relative to $\Lambda_0^b \rightarrow \Lambda_+^c \pi^- \pi^+ \pi^-$. The first quoted uncertainty is statistical, the second is systematic.

| $\Lambda_0^b$ decay mode                                                                 | Relative $\mathcal{B}(10^{-2})$ |
|----------------------------------------------------------------------------------------|----------------------------------|
| $B(\Lambda_0^b \rightarrow \Lambda_c(2595)^+ \pi^-) \cdot B(\Lambda_c(2595)^+ \rightarrow \Lambda^+_c \pi^- \pi^-)$ | $2.3 \pm 0.5 \pm 0.4$            |
| $B(\Lambda_0^b \rightarrow \Lambda_c(2625)^+ \pi^-) \cdot B(\Lambda_c(2625)^+ \rightarrow \Lambda^+_c \pi^- \pi^-)$ | $6.8 \pm 1.0 \pm 1.3$            |
| $B(\Lambda_0^b \rightarrow \Sigma_c(2455)^{++} \pi^- \pi^-) \cdot B(\Sigma_c(2455)^{++} \rightarrow \Lambda^+_c \pi^+)$ | $6.2 \pm 1.2 \pm 1.3$            |
| $B(\Lambda_0^b \rightarrow \Sigma_c(2455)^0 \pi^+ \pi^-) \cdot B(\Sigma_c(2455)^0 \rightarrow \Lambda^+_c \pi^-)$   | $7.1 \pm 2.1^{+1.5}_{-1.3}$      |
| $B(\Lambda_0^b \rightarrow \Lambda^+_c \pi^- \pi^+ \pi^- (\text{other}))$                     | $77.6 \pm 3.0^{+4.0}_{-4.1}$     |

FIG. 4: The $\Lambda_0^b \rightarrow \Lambda_+^c \pi^- \pi^+ \pi^-$ (other) signal after vetoing the resonant decay modes: $m(\Lambda_0^b) - m(\Lambda_+^c)$ distribution.

[13] Throughout this article, the inclusion of charge conjugate decays is implied.
[14] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 84, 012003 (2011).
[15] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 104, 102002 (2010).
[16] R. Royall, J. Amer. Stat. Assoc. 95, 760 (2000).
[17] R. Brun and F. Rademakers, Nucl. Instrum. Methods A 389, 81 (1997).
[18] I. Antcheva et al., Comput. Phys. Commun. 180, 2499 (2009).
[19] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B303, 607 (1998); Nucl. Phys. B327, 49 (1989); C. Peterson, D. Schlatter, I. Schmitt and P. M. Zerwas, Phys. Rev. D 27, 105 (1983).
[20] D. J. Lange, Nucl. Instrum. Methods A 462, 152 (2001).
[21] R. Brun, R. Hagelberg, M. Hansroul, and J. C. Lassalle, CERN-DD-78-2-REV, 1978 (unpublished).
[22] A. Abulencia et al. (CDF Collaboration), Phys. Rev. Lett. 98, 122002 (2007).
FIG. 5: \( \mathcal{B}(\Lambda^0_b \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)/\mathcal{B}(\Lambda^0_b \rightarrow \Lambda_c^+ \pi^-) \) (color scale) as a function of the assumed fractions of \( \Lambda^0_b \rightarrow \Lambda_c^+ a_1^- \) and \( \Lambda^0_b \rightarrow \Lambda_c^+ \rho^0 \pi^- \) in the composition of the \( \Lambda^0_b \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^- \) (other) sample. The central value of the ratio is overlaid in each bin. The fraction of non-resonant \( \Lambda^0_b \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^- \) is equal to \( 1 - f(\Lambda^0_b \rightarrow \Lambda_c^+ a_1^-) - f(\Lambda^0_b \rightarrow \Lambda_c^+ \rho^0 \pi^-) \). The cross represents the composition chosen for the present measurement assuming equal proportions of \( \Lambda^0_b \rightarrow \Lambda_c^+ a_1^- \), \( \Lambda^0_b \rightarrow \Lambda_c^+ \rho^0 \pi^- \) and non-resonant \( \Lambda^0_b \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^- \).