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Observation of $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ and evidence for $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$

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We report the first observation of the decay $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ with a significance of 8.7σ and evidence for the decay $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ with a significance of 3.8σ. The product $\mathcal{B}(B^+ \to \bar{\Xi}_c^0 \Lambda_c^+) \times \mathcal{B}(\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-)$ is measured to be $(4.8^{+1.0}_{-0.9} \pm 1.1 \pm 1.2) \times 10^{-5}$, and $\mathcal{B}(B^0 \to \bar{\Xi}_c^- \Lambda_c^+) \times \mathcal{B}(\bar{\Xi}_c^- \to \bar{\Xi}^+ \pi^- \pi^-)$ is measured to be $(9.3^{+3.7}_{-2.8} \pm 1.9 \pm 2.4) \times 10^{-5}$. The errors are statistical, systematic and the error of the $\Lambda_c^+ \to pK^-\pi^+$ branching fraction, respectively. The decay $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ is the first example of a two-body exclusive B^+ decay into two charmed baryons. The data used for this analysis was accumulated at the $\Upsilon(4S)$ resonance, using the Belle detector at the e^+e^- asymmetric-energy collider KEKB. The integrated luminosity of the data sample is equal to 357 fb^{-1}, corresponding to 386×10^6 $B\bar{B}$ pairs.

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A number of B-meson decay modes to final states containing baryons have been observed, including $b \to c\bar{u}d$ decays with either one final-state charmed meson (e.g. $B^0 \to \bar{D}^0 p\bar{p}$ [1]) or a charmed baryon (e.g. $B^+ \to \bar{\Lambda}_c^- p\pi^+$ [2]), and charmless baryonic decays [3] that proceed via $b \to s$ or $b \to u$ transitions. Two-body baryonic decay modes are found to have lower branching fractions than multibody modes and, in the latter, near-threshold enhancements are observed in the baryon-pair invariant mass spectra [4]. Some theoretical models attribute these phenomena to baryonic form factors that are large for multibody modes [5].

Recently Belle reported examples of new modes that proceed via $b \to c\bar{c}s$ transitions: $B^- \to J/\psi\Lambda\bar{p}$ [6] and $B \to \Lambda_c^+ \bar{\Lambda}_c^- K$ [7]. To date, however, nothing is experimentally known about two-body exclusive B decays to two charmed baryons, which would also proceed through $b \to c\bar{c}s$ transitions. An example of such a decay is $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, which would proceed via the tree quark-diagram shown in Fig. 1(a) [8]. The analogous two-body baryonic B decay proceeding via a $b \to c\bar{u}d$ transition, $B^0 \to \bar{\Lambda}_c^- p$, is shown in Fig. 1(b). The $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ decay mode, like $B \to \Lambda_c^+ \bar{\Lambda}_c^- K$, would produce a "wrong-sign" Λ_c^+, in contrast to all other known B decay modes that only have $\bar{\Lambda}_c^-$'s in the final state [9]. Recently the *BABAR* collaboration has measured the inclusive yield of (wrong-sign) Λ_c^+'s from B decays [10]. It was suggested that this type of B decay might be a substantial component of baryonic $b \to c\bar{c}s$ transitions and could have an important influence on the determination of the charm particle yield per B decay [11].

The Belle experiment has observed the $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ decay and measured its branching fraction to be $(2.19^{+0.56}_{-0.49} \pm 0.32 \pm 0.57) \times 10^{-5}$ [12], which is consistent with a theoretical prediction of $\sim 10^{-5}$ based on the pole model [13,14]. Such a value could also be expected for the branching fraction of $B \to \bar{\Xi}_c \Lambda_c^+$ decay from a simple comparison with the measured branching fraction of $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ decay (see Fig. 1). However, it is much smaller than those ($\sim 10^{-3}$) suggested by the diquark model [15] and QCD sum rules [16], the latter also predicting the same branching fraction for $B \to \bar{\Xi}_c \Lambda_c^+$. Therefore, experimental measurements of the branching fraction for $B \to \bar{\Xi}_c \Lambda_c^+$, together with the previous studies, can provide important information for coherent description of various B decays with baryons.

In this Letter we report the first observation of $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ and evidence for $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ decays. Charge conjugation is implied throughout the paper. The analysis is performed using data collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [17]. The data sample consists of 357 fb^{-1}, which corresponds to 386×10^6 $B\bar{B}$ pairs.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a

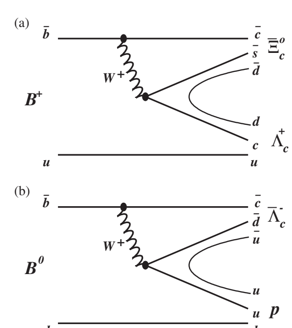

FIG. 1. The quark diagrams for the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ (a) and $B^0 \to \bar{\Lambda}_c^- p$ (b) decays.

50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [18]. Two different inner detector configurations were used. For the first sample of 152×10^6 $B\bar{B}$ pairs (Set I), a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 234×10^6 $B\bar{B}$ pairs (Set II), a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used [19]. We use GEANT-based Monte Carlo (MC) simulation to model the response of the detector and determine the efficiency [20].

We select charged pions, kaons and protons that originate from the region $dr < 1$ cm, $|dz| < 4$ cm, where dr and dz are the distances of closest approach to the interaction point in the plane perpendicular to the beam axis ($r - \phi$ plane) and along the beam direction, respectively. Pions, kaons and protons are identified using a likelihood ratio method, which combines information from the TOF system and ACC counters with dE/dx measurements in the CDC [21].

In this analysis we reconstruct the following decay modes: $\Xi_c^0 \to \Xi^- \pi^+$ and $\Lambda K^- \pi^+$, $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, $\Lambda_c^+ \to p K^- \pi^+$, $\Xi^- \to \Lambda \pi^-$ and $\Lambda \to p \pi^-$. For $\Lambda \to p \pi^-$, we fit the p and π tracks to a common vertex and require an invariant mass in a ± 5 MeV$/c^2$ interval around the Λ mass. The distance between the Λ decay vertex position and interaction point (IP) in the $r - \phi$ plane ($dr(\Lambda)$) is required to be greater than 0.05 cm and the angle α_Λ, between the Λ momentum and the vector pointing from the IP to the decay vertex, must satisfy $\cos\alpha_\Lambda > 0.995$ for the case of $\Xi_c^0 \to \Lambda K^- \pi^+$. We make no requirements on dr and $|dz|$ for tracks coming from $\Xi^- \to \Lambda \pi^-$ and $\Lambda \to p\pi^-$ decays. For $\Xi^- \to \Lambda \pi^-$, we fit the Λ trajectory and the π^- track to a common vertex and require a $\Lambda\pi^-$ invariant mass in a ± 5 MeV$/c^2$ interval around the Ξ^- mass. We require that the distance between the Ξ^- decay vertex position and IP in the $r - \phi$ plane be greater than 0.01 cm. For the Λ's coming from Ξ^- in the decay $\Xi_c^0 \to \Xi^- \pi^+$ we apply the requirements, $dr(\Lambda) > 0.5$ cm and $\cos\alpha_\Lambda > 0.0$. For Λ_c^+, Ξ_c^0 and Ξ_c^+ we use mass windows that are ± 15 MeV$/c^2$ around their nominal values. We use a large sample of inclusive Λ, Ξ^-, $\Xi_c^{+/0}$ and Λ_c^+ signals to verify that their mass peaks are well described by two Gaussians, corresponding to the core and tail of the distribution. The signal mass windows that we use correspond to approximately 4σ for the core and 2σ for the tail Gaussian. The MC studies of the inclusive Λ, Ξ^-, $\Xi_c^{+/0}$ and Λ_c^+ signals show agreement with data.

The B candidates (i.e. $\bar{\Xi}_c \Lambda_c^+$ combinations) are identified by their center of mass (c.m.) energy difference, $\Delta E = \Sigma_i E_i - E_{\rm beam}$, and their beam-energy constrained mass, $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - (\Sigma_i \vec{p}_i)^2}$, where $E_{\rm beam} = \sqrt{s}/2$ is the beam energy in the c.m. and $\vec{p}_i$ and E_i are the three-momenta and energies of the B candidate's decay products. We accept B candidates with $M_{\rm bc} > 5.2$ GeV$/c^2$ and $|\Delta E| < 0.2$ GeV. To suppress the continuum background, we require the normalized Fox-Wolfram moment [22] R_2 to be less than 0.5. We apply $|\cos\theta_B| < 0.85$ for the Ξ_c^0 reconstruction in the $\Lambda K^- \pi^+$ mode, to suppress the combinatorial background. Here θ_B is the polar angle of the B-meson direction in the c.m.

The ΔE and $M_{\rm bc}$ distributions for the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ candidates are shown in Figs. 2(a) and 2(b), where the two Ξ_c^0 modes are combined. We require $M_{\rm bc} > 5.272$ GeV$/c^2$ ($|\Delta E| < 0.025$ GeV) for the ΔE ($M_{\rm bc}$) projection [23]. The hatched histograms in Figs. 2(a) and 2(b) show the sum of normalized Λ_c^+ and $\bar{\Xi}_c^0$ mass sidebands [24] where no peaking structures are evident. The superimposed curves are the results of a two-dimensional binned maximum likelihood fit to the ΔE and $M_{\rm bc}$ distributions for the two Ξ_c^0 channels, simultaneously. For this fit, we constrain the ratio $\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ to the recent Belle measurement of $1.07 \pm 0.12 \pm 0.07$ [25]. To describe the signal we use Gaussians with means and widths fixed to the values obtained from MC. The backgrounds in ΔE and $M_{\rm bc}$ are parametrized by a first-

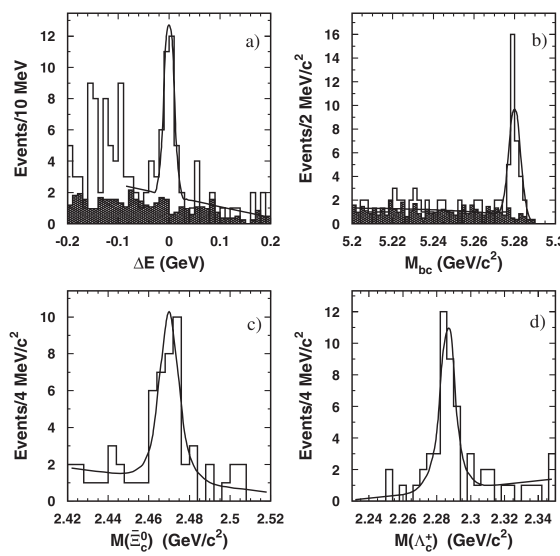

FIG. 2. ΔE (a) and $M_{\rm bc}$ (b) distributions for the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ candidates. The hatched histograms show the combined $\bar{\Xi}_c^0$ and Λ_c^+ mass sidebands normalized to the signal region. The excess around $\Delta E = -0.150$ GeV is due to the contributions from $B^{+/0} \to \bar{\Xi}_c^0 \Lambda_c^+ \pi^{0/-}$ and $B^{0/+} \to \bar{\Xi}_c^0 \Sigma_c^{0/+}$, $\Sigma_c^{0/+} \to \Lambda_c^+ \pi^{-/0}$ decays, where the pion is undetected. Therefore, we exclude this region from the fit. $\bar{\Xi}_c^0$ (c) and Λ_c^+ (d) mass distributions for the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ candidates taken from the B-signal region of $|\Delta E| < 0.025$ GeV and $M_{\rm bc} > 5.272$ GeV$/c^2$. For the $\bar{\Xi}_c^0$ (Λ_c^+) distribution we require Λ_c^+ ($\bar{\Xi}_c^0$) to be within ± 15 MeV$/c^2$ of the nominal mass. The overlaid curves are the fit results (see the text).

order polynomial and an ARGUS function [26], respectively. The fit gives a statistical significance of 8.7σ for the signal, where the statistical significance is defined as $\sqrt{-2\ln(L_0/L_{\max})}$, where L_0 and $L_{\max}$ are the likelihoods with the signal fixed at zero and at the fitted value, respectively. The region $\Delta E < -0.08$ GeV is excluded from the fit to avoid possible contributions from $B^{+/0} \to \bar{\Xi}_c^0 \Lambda_c^+ \pi^{0/-}$ and $B^{0/+} \to \bar{\Xi}_c^0 \Sigma_c^{0/+}$, $\Sigma_c^{0/+} \to \Lambda_c^+ \pi^{-/0}$ decays, where the pion is undetected. The same fitting procedure applied separately for the two Ξ_c^0 modes gives $12.4^{+4.2}_{-3.3}$ (6.8σ significance) and $16.9^{+4.8}_{-4.0}$ (5.9σ significance) events for $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ followed by $\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-$ and $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ followed by $\bar{\Xi}_c^0 \to \bar{\Lambda} K^+ \pi^-$, respectively.

As a cross-check of the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ signal, we select events in the B-signal region of $|\Delta E| < 0.025$ GeV and $M_{\rm bc} > 5.272$ GeV$/c^2$ for the two Ξ_c^0 modes and examine the Λ_c^+ and $\bar{\Xi}_c^0$ mass distributions [Fig. 2(c) and 2(d)]. For the Λ_c^+ ($\bar{\Xi}_c^0$) distribution we require $\bar{\Xi}_c^0$ (Λ_c^+) to be within ± 15 MeV$/c^2$ of the nominal mass. We then fit each distribution with two Gaussians for the signal and a first-order polynomial to describe the background. The widths and means of the Gaussians are fixed to the values obtained from the data as described above. The fitted signal yields of 32.6 ± 7.2 events for the Λ_c^+ and 29.4 ± 6.9 events for the $\bar{\Xi}_c^0$, are in good agreement with the total signal yield for $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, including the two Ξ_c^0 decay modes.

The $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ mode is an isospin partner of the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ mode. Therefore their branching fractions are expected to be of the same order of magnitude. The ΔE and $M_{\rm bc}$ distributions for the $\bar{B}^0 \to \bar{\Xi}_c^- \Lambda_c^+$ candidates are shown in Figs. 3(a) and 3(b). The superimposed curves are the results of a two-dimensional binned maximum likelihood fit to the ΔE versus $M_{\rm bc}$ distribution. The fit gives $8.3^{+3.3}_{-2.5}$ signal events. The signal significance is 3.8σ, taking into account the systematic uncertainty from the signal and background parameterization. The hatched histogram shows the sum of the normalized Λ_c^+ and $\bar{\Xi}_c^-$ mass sidebands. We apply the same procedure used for $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ to check the Λ_c^+ and $\bar{\Xi}_c^-$ signals as shown in Figs. 3(c) and 3(d). The fit gives 9.0 ± 3.0 events for the Λ_c^+ and 8.4 ± 2.8 events for the $\bar{\Xi}_c^-$. Both are in agreement with the $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ signal yield.

Table I summarizes the results of the fits for the B^+ and B^0 decays, the reconstruction efficiencies including the $\mathcal{B}(\Lambda \to p\pi^-)$, statistical significance of the signals and extracted products of branching fractions. Here we use $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3)\%$ [9] and assume equal fractions of charged and neutral B mesons produced in $\Upsilon(4S)$ decays.

The major sources of systematic error are the uncertainties in the tracking efficiency of 7% (1% per track), 11% in charged particle identification efficiency (1% for pion, 2% for kaon and 3% for proton), 5% in finding Λ, 6% in efficiency estimation due to MC statistics, 10% in the signal and background parameterization, and 13% in

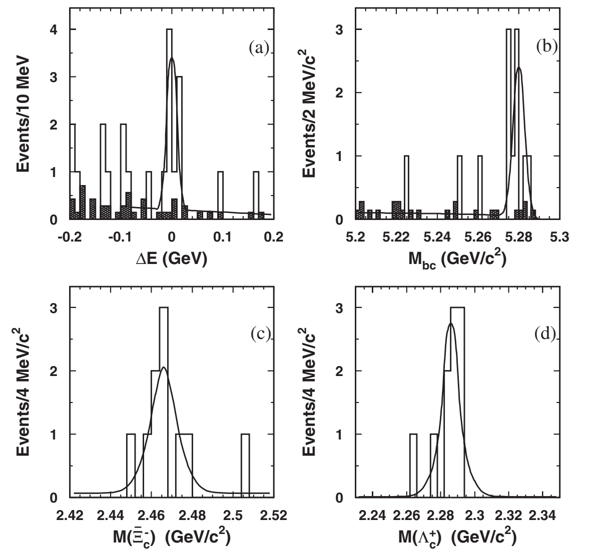

FIG. 3. ΔE (a) and $M_{\rm bc}$ (b) distributions for the $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ candidates. The hatched histograms show the combined $\bar{\Xi}_c^-$ and Λ_c^+ mass sidebands normalized to the signal region. $\bar{\Xi}_c^-$ (c) and Λ_c^+ (d) mass distributions for the $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ candidates taken from the B-signal region of $|\Delta E| < 0.025$ GeV and $M_{\rm bc} > 5.272$ GeV$/c^2$. For the $\bar{\Xi}_c^-$ (Λ_c^+) distribution we require Λ_c^+ ($\bar{\Xi}_c^-$) to be within ± 15 MeV$/c^2$ of the nominal mass. The overlaid curves are the fit results (see the text).

$\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$. Added in quadrature, these correspond to a total systematic error of 23% for $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ and 20% for $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$.

In summary, we report the first observation of the $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ decay mode and the first evidence for the $B^0 \to \bar{\Xi}_c^- \Lambda_c^+$ decay mode. The products of the branching fractions $\mathcal{B}(B^+ \to \bar{\Xi}_c^0 \Lambda_c^+) \times \mathcal{B}(\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-) = (4.8^{+1.0}_{-0.9} \pm 1.1 \pm 1.2) \times 10^{-5}$ and $\mathcal{B}(B^0 \to \bar{\Xi}_c^- \Lambda_c^+) \times \mathcal{B}(\bar{\Xi}_c^- \to \bar{\Xi}^+ \pi^- \pi^-) = (9.3^{+3.7}_{-2.8} \pm 1.9 \pm 2.4) \times 10^{-5}$ are measured with 8.7σ and 3.8σ significance, respectively. These results and Belle's recent observation of the $B \to \Lambda_c^+ \bar{\Lambda}_c^- K$ decays [7] are the first examples of B decays into two charmed baryons. The branching fraction obtained for $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ together with the theoretical predictions for $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ of $\sim$(0.9–2)% [27] result in $\mathcal{B}(B^+ \to \bar{\Xi}_c^0 \Lambda_c^+) \sim (2.4 - 5.3) \times 10^{-3}$. This can be compared with the theoretical prediction of 10^{-3} [16]. On the other hand, the Belle measurement of $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}) = (2.19^{+0.56}_{-0.49} \pm 0.32 \pm 0.57) \times 10^{-5}$ [12] is much smaller than the prediction of 4×10^{-4} of the same authors [16]. The very large experimental ratio of $\sim$100 for $\mathcal{B}(B \to \bar{\Xi}_c^0 \Lambda_c^+)/\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p})$ disagrees with the expectation that the branching fractions for two-body baryonic B decays proceeding via $b \to c\bar{c}s$ and $b \to c\bar{u}d$ transitions should be of the same order [16]. This measurement also indicates the absence of a coherent and unique theoretical description of two-body baryonic B-decays.

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TABLE I. Summary of the fit results, efficiencies, products of branching fractions and statistical significances. For the two $\bar{\Xi}_c^0$ modes of the B^+ decay the product of branching fractions is $\mathcal{B}(B^+ \to \bar{\Xi}_c^0 \Lambda_c^+) \times \mathcal{B}(\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-)$ since for $\bar{\Xi}_c^0 \to \bar{\Lambda} K^+ \pi^-$ we use the ratio $\mathcal{B}(\Xi_c^0 \to \Lambda K^- \pi^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ mentioned in the text. The uncertainties in the products of the branching ratios are statistical, systematic and the uncertainty of the $\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)$.

Decay Mode	Yield	Efficiency (%)	Product of $\mathcal{B}$'s (10^{-5})	Significance
$B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, $\bar{\Xi}_c^0 \to \bar{\Xi}^+ \pi^-$	$12.4^{+4.2}_{-3.3}$	1.14	$5.6^{+1.9}_{-1.5} \pm 1.1 \pm 1.5$	6.8σ
$B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, $\bar{\Xi}_c^0 \to \bar{\Lambda} K^+ \pi^-$	$16.9^{+4.8}_{-4.0}$	2.04	$4.0^{+1.1}_{-0.9} \pm 0.9 \pm 1.0$	5.9σ
$B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, simultaneous fit			$4.8^{+1.0}_{-0.9} \pm 1.1 \pm 1.2$	8.7σ
$B^0 \to \bar{\Xi}_c^- \Lambda_c^+$, $\bar{\Xi}_c^- \to \bar{\Xi}^+ \pi^- \pi^-$	$8.3^{+3.3}_{-2.5}$	0.46	$9.3^{+3.7}_{-2.8} \pm 1.9 \pm 2.4$	3.8σ

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