

Observations of the singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ at Belle and Belle II

The Belle and Belle II collaborations

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ABSTRACT: Using data samples of 983.0 fb^{-1} and 427.9 fb^{-1} accumulated with the Belle and Belle II detectors operating at the KEKB and SuperKEKB asymmetric-energy e^+e^- colliders, singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ are observed for the first time. The ratios of branching fractions of $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ relative to that of $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ are measured to be

$$\begin{aligned}\frac{\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} &= (2.47 \pm 0.16 \pm 0.07)\%, \\ \frac{\mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} &= (1.56 \pm 0.14 \pm 0.09)\%, \\ \frac{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} &= (4.13 \pm 0.26 \pm 0.22)\%.\end{aligned}$$

Multiplying these values by the branching fraction of the normalization channel, $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = (2.9 \pm 1.3)\%$, the absolute branching fractions are determined to be

$$\begin{aligned}\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0) &= (7.16 \pm 0.46 \pm 0.20 \pm 3.21) \times 10^{-4}, \\ \mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+) &= (4.52 \pm 0.41 \pm 0.26 \pm 2.03) \times 10^{-4}, \\ \mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+) &= (1.20 \pm 0.08 \pm 0.07 \pm 0.54) \times 10^{-3}.\end{aligned}$$

The first and second uncertainties above are statistical and systematic, respectively, while the third ones arise from the uncertainty in $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$.

KEYWORDS: e^+e^- Experiments

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1 Introduction

The study of charmed baryons is valuable for exploring the subtle interplay between the strong and weak interactions. In hadronic weak decays of charmed baryons, nonfactorizable contributions from the internal W -emission and W -exchange diagrams play an essential role and cannot be neglected. This is unlike the situation in heavy meson decay where they are negligible [1]. In particular, there exist decay channels that receive only nonfactorizable contributions, such as $\Lambda_c^+ \rightarrow \Xi^0 K^+$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$. Therefore, studying nonfactorizable effects is critical for understanding the dynamics of charmed baryon decays.

In the last few years, there has been a significant advance in the experimental and theoretical studies of hadronic weak decays of anti-triplet charmed baryons (Λ_c^+ , Ξ_c^0 , and Ξ_c^+) [1, 2]. Notably, the absolute branching fractions of $\Xi_c^0 \rightarrow \Xi^-\pi^+$ and $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ have been measured by Belle to be $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+) = (1.80 \pm 0.50(\text{stat.}) \pm 0.14(\text{syst.}))\%$ [3] and $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = (2.86 \pm 1.21(\text{stat.}) \pm 0.38(\text{syst.}))\%$ [4]. Most measurements of Ξ_c^0 and Ξ_c^+ branching fractions are measured relative to these two decay modes. The measurements of these absolute branching fractions have sparked renewed interest in the study of Ξ_c^0 and Ξ_c^+ decays [5–11]. Comprehensive and precise experimental measurements are essential to test different theoretical models and illuminate the decay mechanisms of anti-triplet charmed baryons. Theoretical calculations for the two-body hadronic weak decays of Ξ_c^+ have been performed based on dynamical model calculations [12] and $\text{SU}(3)_F$ flavor symmetry methods [13–22]. However, most of these decay channels have not yet been measured experimentally, especially the singly Cabibbo-suppressed decay modes. Figure 1 shows the typical decay diagrams for the singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow p\bar{K}^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$. Note that the decay $\Xi_c^+ \rightarrow p\bar{K}^0$ cannot proceed via an external W -emission diagram and so it occurs solely through nonfactorizable diagrams. Thus, measuring this decay enables a direct evaluation of the significance of nonfactorizable contributions in Ξ_c^+ decay. The branching fractions of these three decay channels are predicted by different theoretical models to cover the range of 10^{-4} to 10^{-3} [12–22].

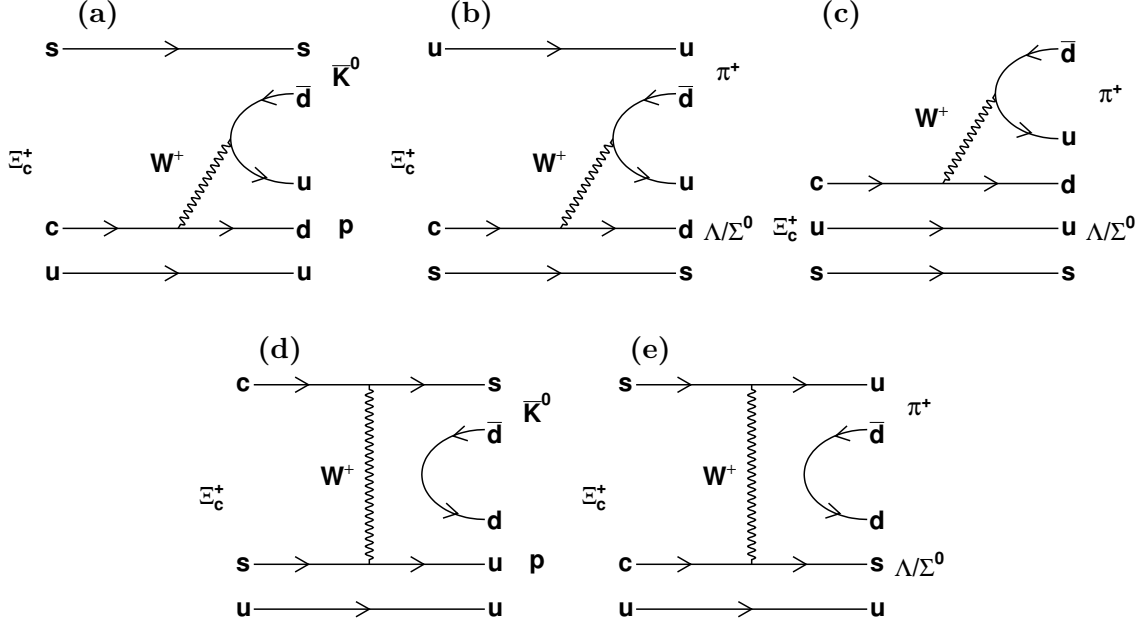


Figure 1. Representative decay diagrams for (a,b) internal W -emission, (c) external W -emission, and (d,e) W -exchange contributions for the singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow p \bar{K}^0$, $\Xi_c^+ \rightarrow \Lambda \pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0 \pi^+$.

In this paper, we study the singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow p \bar{K}_S^0$, $\Xi_c^+ \rightarrow \Lambda \pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0 \pi^+$ for the first time. Using $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ as the normalization channel, we measure the ratios of branching fractions of $\Xi_c^+ \rightarrow p \bar{K}_S^0$, $\Xi_c^+ \rightarrow \Lambda \pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0 \pi^+$ relative to that of $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$. This analysis is based on data samples of 983.0 fb^{-1} [23] and 427.9 fb^{-1} [24] accumulated with the Belle and Belle II detectors operating at the KEKB and SuperKEKB asymmetric-energy e^+e^- colliders, respectively. Charge-conjugate modes are included throughout the paper.

2 The Belle and Belle II detectors and data samples

The Belle detector [25], which operated between 1999 and 2010 at the KEKB asymmetric-energy e^+e^- collider [26, 27], was a large cylindrical solid-angle magnetic spectrometer that consisted of a silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter composed of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return equipped with resistive plate chambers located outside the coil is instrumented to detect K_L^0 mesons and to identify muons. The detector is described in detail elsewhere [25].

The Belle II detector [28] is located at the interaction point (IP) of the SuperKEKB asymmetric-energy e^+e^- collider [29], and has been collecting data since 2019. The Belle II detector is based on the Belle detector but contains several new subsystems, as well as substantial upgrades to others. The innermost subdetector is the vertex detector (VXD) which includes two inner layers of pixel sensors and four outer layers of double-sided silicon microstrip

sensors. Charged particle momenta and charges are measured by a new large-radius, helium-ethane, small-cell CDC, which also offers charged-particle-identification information through a measurement of specific ionization. A Cherenkov-light angle and time-of-propagation (TOP) detector surrounding the CDC provides charged-particle identification in the central detector volume, supplemented by proximity-focusing, aerogel, ring-imaging Cherenkov (ARICH) detectors in the forward region with respect to the electron beam. The Belle CsI(Tl) crystal electromagnetic calorimeter, the Belle solenoid and iron flux return are reused in the Belle II detector. The electromagnetic calorimeter readout electronics have been upgraded and the instrumentation in the flux return to identify K_L^0 mesons and muons has been replaced.

This measurement uses data recorded at center-of-mass (c.m.) energies at or near the $\Upsilon(nS)$ ($n = 1, 2, 3, 4, 5$) resonances by the Belle detector, and at or near the $\Upsilon(4S)$ and at $\sqrt{s} = 10.75$ GeV by the Belle II detector. The data samples correspond to integrated luminosities of 983.0 fb^{-1} [23] and 427.9 fb^{-1} [24] with Belle and Belle II, respectively.

Monte Carlo (MC) signal events are generated using EvtGen [30] and used to optimize signal selection criteria and calculate the reconstruction efficiencies. Continuum $e^+e^- \rightarrow c\bar{c}$ events are generated using PYTHIA6 [31] for Belle and PYTHIA8 [32] and KKMC [33] for Belle II, where one of the two charm quarks hadronizes into a Ξ_c^+ baryon. The decays $\Xi_c^+ \rightarrow pK_S^0/\Lambda\pi^+/\Sigma^0\pi^+/\Xi^-\pi^+\pi^+$ are generated using a phase space model. The effect of final-state radiation is taken into account in the simulation using the PHOTOS package [34]. The simulated signal events are processed with detector simulations based on GEANT3 [35] for the Belle detector and GEANT4 [36] for the Belle II detector.

Inclusive MC samples of $\Upsilon(1S, 2S, 3S)$ decays, $\Upsilon(4S) \rightarrow B\bar{B}$, $\Upsilon(5S) \rightarrow B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}$, and $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) at c.m. energies of 10.520, 10.580, and 10.867 GeV are used to optimize signal selection criteria and study the composition of backgrounds in the Belle analysis, corresponding to twice the integrated luminosity of the Belle data. In the Belle II analysis, we use inclusive MC samples of $e^+e^- \rightarrow q\bar{q}$ at c.m. energies of 10.520, 10.580 and 10.750 GeV and $\Upsilon(4S) \rightarrow B\bar{B}$ corresponding to four times the integrated luminosity of the Belle II data, to optimize signal selection criteria and study the backgrounds [37].

3 Event selection criteria

We reconstruct the decay modes $\Xi_c^+ \rightarrow pK_S^0$, $\Lambda\pi^+$, $\Sigma^0\pi^+$, and $\Xi^-\pi^+\pi^+$, followed by the decays $K_S^0 \rightarrow \pi^+\pi^-$, $\Sigma^0 \rightarrow \Lambda\gamma$, $\Xi^- \rightarrow \Lambda\pi^-$, and $\Lambda \rightarrow p\pi^-$. We use the Belle II analysis software framework (BASF2) to reconstruct the events at Belle and Belle II [38]. The Belle II data are directly processed with this framework, while the tracks and clusters in the processed Belle data are converted to BASF2 format using the B2BII software package [39]. After conversion, the same reconstruction software is applied to both data samples. The event selection criteria described below are optimized by maximizing the figure of merit $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkg}}}$. Here, N_{sig} represents the number of expected $\Xi_c^+ \rightarrow pK_S^0/\Lambda\pi^+/\Sigma^0\pi^+$ signal events, based on the branching fraction predicted in ref. [12], and N_{bkg} denotes the number of background events in the Ξ_c^+ signal region, obtained from the inclusive MC samples and scaled by the ratio of yields between data and inclusive MC in the normalized Ξ_c^+ sideband regions. The optimal selection criteria are not significantly dependent on the choice of theoretically predicted branching fractions. The signal region for the Ξ_c^+ is defined as

$|M(pK_S^0/\Lambda\pi^+/\Sigma^0\pi^+) - m_{\Xi_c^+}| < 20 \text{ MeV}/c^2$ (approximately 3 standard deviations, σ), and the sideband regions are defined as $32 \text{ MeV}/c^2 < |M(pK_S^0/\Lambda\pi^+/\Sigma^0\pi^+) - m_{\Xi_c^+}| < 52 \text{ MeV}/c^2$. Here and throughout this paper, m_i represents the known mass of the particle i [2]. We apply nearly identical event selection criteria in the Belle and Belle II analyses unless otherwise stated.

The impact parameters of charged tracks, except for those of the decay products of K_S^0 , Λ , and Ξ^- , measured with respect to the e^+e^- IP, are required to be less than 0.2 cm perpendicular to the z -axis and less than 1 cm parallel to it. The z -axis is defined as the central solenoid axis with the positive direction toward the e^- beam, common to both the Belle and Belle II detectors. For the particle identification (PID) of a charged track, information from different detector subsystems, including specific ionization in the CDC, time measurement in the TOF (TOP), and the response of the ACC (ARICH) of Belle (Belle II), is combined to form a likelihood ratio, $\mathcal{R}(h|h') = \mathcal{L}(h)/[\mathcal{L}(h) + \mathcal{L}(h')]$, where $\mathcal{L}(h^{(i)})$ is the likelihood of the charged track being a hadron $h^{(i)} = p, K$, or π as appropriate. Tracks with $\mathcal{R}(p|K) > 0.6$ and $\mathcal{R}(p|\pi) > 0.6$ are identified as proton candidates; charged pion candidates must satisfy $\mathcal{R}(\pi|K) > 0.6$ with an average efficiency of 91% (90%) in Belle (Belle II), while 6% (7%) of kaons are misidentified as pions. To suppress backgrounds from low-momentum protons and pions, we require the momentum of the proton in the laboratory frame to be greater than 1.1 GeV/ c for the $\Xi_c^+ \rightarrow pK_S^0$ mode and the pion momentum to be greater than 0.6 GeV/ c and 0.4 GeV/ c for the $\Xi_c^+ \rightarrow \Lambda\pi^+$ and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ modes, respectively.

The K_S^0 candidates are first reconstructed from pairs of oppositely charged tracks, which are treated as pions. In the Belle analysis, we use an artificial neural network [40] based on two sets of input variables [41] to select the K_S^0 candidates. In the Belle II analysis, the significance of flight distance ($L_{\text{fl}}/\sigma_{L_{\text{fl}}}$) of K_S^0 is required to be greater than 10 to suppress combinatorial backgrounds. Here and below, the flight distance (L_{fl}) of a particle is calculated as the projection of the displacement vector, which joins its production and decay vertices, onto the direction of its momentum. The corresponding uncertainty ($\sigma_{L_{\text{fl}}}$) is calculated by propagating the uncertainties in the vertex positions and momenta. The signal region of the reconstructed K_S^0 candidates is defined as $|M(\pi^+\pi^-) - m_{K_S^0}| < 10 \text{ MeV}/c^2$ ($\sim 3\sigma$).

The Λ candidates are reconstructed via the decay $\Lambda \rightarrow p\pi^-$. In the Belle analysis, we select Λ candidates using Λ -momentum-dependent criteria based on four parameters: the distance between the two daughter tracks along the z -axis at their closest approach; the minimum distance between the daughter tracks and the IP in the transverse plane; the angular difference between the Λ flight direction and the direction between the IP and the Λ decay vertex in the transverse plane; and the flight length of the Λ in the transverse plane. In the Belle II analysis, the significance of the flight distance of the Λ is required to be $L_{\text{fl}}/\sigma_{L_{\text{fl}}} > 10$ to suppress combinatorial backgrounds. The signal region of the reconstructed Λ candidates is defined as $|M(p\pi^-) - m_{\Lambda}| < 3.5 \text{ MeV}/c^2$ ($\sim 3\sigma$).

An ECL cluster is used as a photon candidate if it is not consistent with the extrapolated path of any charged track. To suppress background from neutral hadrons, we require $E(3 \times 3)/E(5 \times 5) \geq 85\%$ where $E(n \times n)$ is the energy contained in an $n \times n$ crystal region centered on the crystal with the highest energy (for Belle II only, the outer corner crystals are not included). The photon energy must exceed 80 MeV in the laboratory frame to further

suppress the combinatorial backgrounds. The selected photon candidate is then combined with a Λ candidate to form a Σ^0 candidate. The signal region of the reconstructed Σ^0 candidates is defined as $|M(\Lambda\gamma) - m_{\Sigma^0}| < 6 \text{ MeV}/c^2$ ($\sim 2\sigma$).

In the reconstruction of $\Xi^- \rightarrow \Lambda\pi^-$, the selected Λ candidate is combined with a π^- to form a Ξ^- candidate. The π^- is not required to satisfy any PID criteria as the expected kinematics of the Ξ^- signal gives sufficient discrimination, but its transverse momentum must exceed $50 \text{ MeV}/c$ to eliminate background from low-momentum pions. Additionally, the distance from the IP to the Ξ^- decay vertex must be less than that to the Λ decay vertex. A vertex fit is applied to the entire Ξ^- decay chain [42], including subsequent decay products, with the $p\pi^-$ invariant mass constrained to the known Λ mass [2]. The signal region of the reconstructed Ξ^- candidates is defined as $|M(\Lambda\pi^-) - m_{\Xi^-}| < 6 \text{ MeV}/c^2$ ($\sim 3\sigma$).

The pK_S^0 , $\Lambda\pi^+$, $\Sigma^0\pi^+$, and $\Xi^-\pi^+\pi^+$ combinations are used to form Ξ_c^+ candidates. A vertex-fitting algorithm is applied to the entire decay chain, incorporating mass constraints for the intermediate states and ensuring that the Ξ_c^+ originates from the IP [42]. The goodness-of-fit χ^2 is required to be less than 20 for the $\Xi_c^+ \rightarrow pK_S^0/\Lambda\pi^+/\Sigma^0\pi^+$ modes and less than 100 for the $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ mode. The significance of the Ξ_c^+ flight distance is required to be greater than 1.5 (3.0) for the Belle (Belle II) analysis. This criterion suppresses a significant number of background events, particularly in the Belle II data which benefits from the superior vertex resolution of the Belle II VXD detector and the smaller beam spot of SuperKEKB.

To reduce combinatorial backgrounds, especially from B -meson decays, the scaled momentum $x_p = p_{\Xi_c^+}^*/p_{\text{max}}$ is required to be larger than 0.55 in both Belle and Belle II analyses. Here, $p_{\Xi_c^+}^*$ is the momentum of Ξ_c^+ candidates in the e^+e^- c.m. frame, and $p_{\text{max}} = \frac{1}{c}\sqrt{E_{\text{beam}}^2 - M_{\Xi_c^+}^2 c^4}$, where E_{beam} is the beam energy in the e^+e^- c.m. frame and $M_{\Xi_c^+}$ is the invariant mass of Ξ_c^+ candidates. Finally, if there are multiple Ξ_c^+ candidates in an event, all the combinations are retained for further analysis. The fractions of events that have multiple candidate events in signal MC simulations for Belle (Belle II) are 0.2% (0.3%), 0.4% (0.7%), 2.7% (2.8%), and 2.0% (1.6%) for the $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, $\Xi_c^+ \rightarrow \Sigma^0\pi^+$, and $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ decay modes, respectively. These values are consistent with the multiple candidate rates observed in the data.

4 Branching fractions of $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ decays

After applying all the selection criteria described above, the invariant mass spectra of $\Xi^-\pi^+\pi^+$ from the reconstructed $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ candidates in Belle and Belle II data are shown in figures 2(a) and 2(b), respectively. To extract the yield of $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ signal events, we perform an unbinned extended maximum-likelihood fit to the $M(\Xi^-\pi^+\pi^+)$ distributions. In the fit, a double-Gaussian function is used as the signal probability density function (PDF) for the Ξ_c^+ candidates, while the combinatorial background PDF is parametrized by a second-order polynomial. All parameters of the signal and combinatorial background PDFs are free in the fit. The pull distributions, defined as $(N_{\text{data}} - N_{\text{fit}})/\sqrt{N_{\text{data}}}$, are also shown in figure 2, where N_{data} represents the number of entries in each bin from data and N_{fit} is the number of events in each bin according to the fit. The fitted $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ signal yields in Belle and Belle II data are listed in table 1.

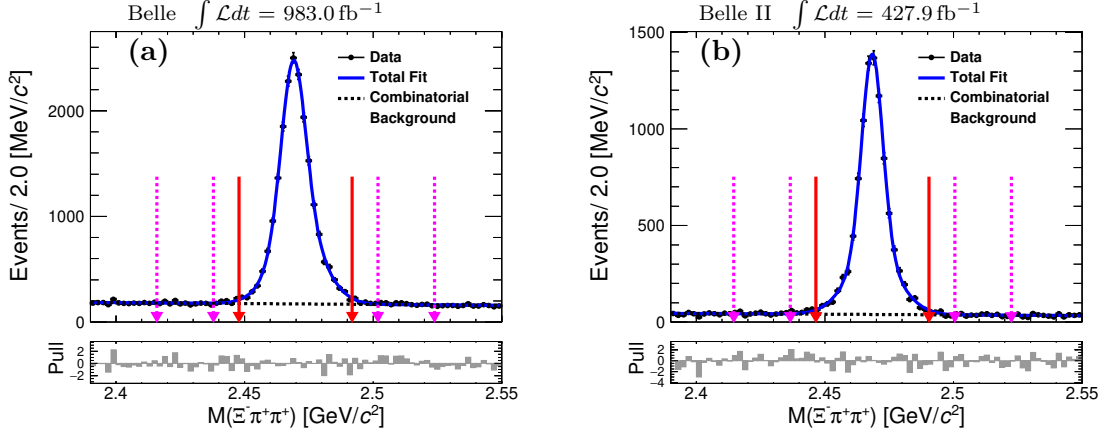


Figure 2. The invariant mass spectra of $\Xi^- \pi^+ \pi^+$ from the reconstructed $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ candidates in (a) Belle and (b) Belle II data. The points with error bars represent the data, the solid blue curves show the best-fit results, and the dashed black curves represent the fitted combinatorial backgrounds. The solid red arrows indicate the defined Ξ_c^+ signal region: $|M(\Xi^- \pi^+ \pi^+) - m_{\Xi_c^+}| < 22 \text{ MeV}/c^2 (\sim 3\sigma)$, and the dashed magenta arrows denote the defined sideband regions: $32 \text{ MeV}/c^2 < |M(\Xi^- \pi^+ \pi^+) - m_{\Xi_c^+}| < 54 \text{ MeV}/c^2$.

For the three-body decay $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$, the reconstruction efficiency can vary across the phase space, as visualized in a Dalitz plot [43]. Figures 3(a) and 3(b) show the Dalitz plots of $M_H^2(\Xi^- \pi^+)$ versus $M_L^2(\Xi^- \pi^+)$ from Belle and Belle II data in the Ξ_c^+ signal region, after subtracting the normalized Ξ_c^+ sideband events. Here, the $\Xi^- \pi^+$ combination with a higher (lower) invariant mass is labeled as $M_H^2(\Xi^- \pi^+)$ ($M_L^2(\Xi^- \pi^+)$). We divide the Dalitz plot into 20×30 bins and then apply a bin-by-bin correction for efficiency. The reconstruction efficiency averaged over the Dalitz plot is determined by the formula

$$\varepsilon^{\text{corr}} = \frac{\sum_i N_{s,i}}{\sum_j \left(\frac{N_{s,j}}{\varepsilon_j} \right)}, \quad (4.1)$$

where i and j index all bins; $N_{s,i(j)}$ denotes the number of signal events in the $i(j)^{\text{th}}$ -bin in data; ε_j is the reconstruction efficiency from signal MC simulation for the j^{th} -bin. The term $N_{s,i}$ is calculated using $N_i^{\text{tot}} - N_{\text{SR}}^{\text{bkg}} f_i^{\text{bkg}}$, where N_i^{tot} is the number of total events in the i^{th} -bin of the Dalitz plot in data, $N_{\text{SR}}^{\text{bkg}}$ is the number of fitted background events in the Ξ_c^+ signal region in data, and f_i^{bkg} is the fraction of background in the i^{th} -bin, with $\sum_i f_i^{\text{bkg}} = 1$. These fractions are obtained from the Dalitz plot of events in the normalized Ξ_c^+ sideband regions in data. The average reconstruction efficiencies for the $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ decay are listed in table 1.

Figure 4 shows the invariant mass spectra of pK_S^0 , $\Lambda\pi^+$, and $\Sigma^0\pi^+$ from Belle and Belle II data. Significant signal yields are observed for all three decays, in both Belle and Belle II data. In addition, there are identified feed-down backgrounds with shoulder-like shapes on the lower mass sides of the $M(\Lambda\pi^+)$ and $M(\Sigma^0\pi^+)$ distributions in both datasets. In the $M(\Lambda\pi^+)$ distribution, the feed-down background is attributed to the $\Xi_c^+ \rightarrow \Sigma^0(\rightarrow \Lambda\gamma)\pi^+$ decay with a

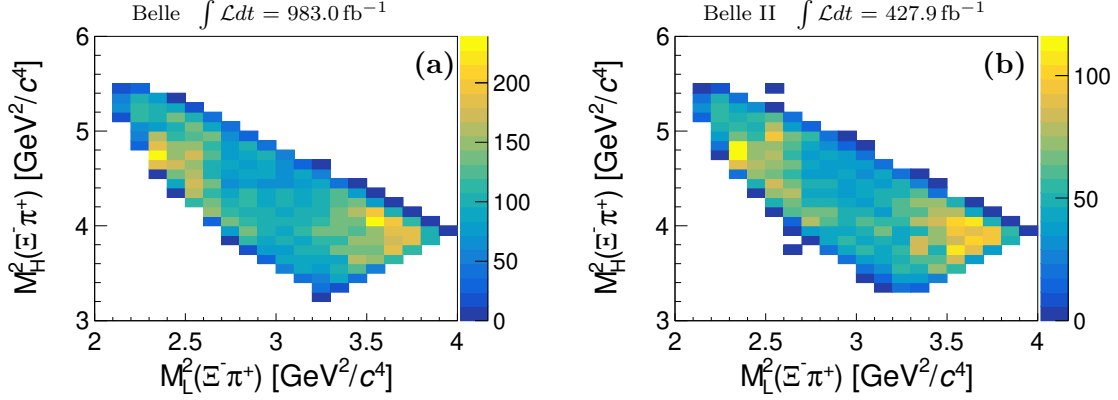


Figure 3. Dalitz plots of the reconstructed $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ candidates from (a) Belle and (b) Belle II data in the Ξ_c^+ signal region with the normalized Ξ_c^+ sideband events subtracted.

missing photon, while in the $M(\Sigma^0 \pi^+)$ distribution, it originates from a $\Lambda_c^+ \rightarrow \Lambda \pi^+$ decay combined with a random photon, as identified in the study of inclusive MC samples using the TopoAna package [37].

To extract the signal yields for $\Xi_c^+ \rightarrow p K_S^0$, $\Lambda \pi^+$, and $\Sigma^0 \pi^+$ in data, we perform unbinned extended maximum-likelihood fits to the $M(p K_S^0)$, $M(\Lambda \pi^+)$, and $M(\Sigma^0 \pi^+)$ distributions. The signal shapes for Ξ_c^+ candidates are modeled by double-Gaussian functions with different mean values, and the fraction and parameters of the tail Gaussian, which represents the broader part of the distribution, are fixed to those obtained from the corresponding signal MC simulation. The combinatorial backgrounds are parametrized by a second-order polynomial for the $M(p K_S^0)$ distribution, and first-order polynomials for the $M(\Lambda \pi^+)$, and $M(\Sigma^0 \pi^+)$ distributions. The shapes of the feed-down backgrounds are represented by nonparametric (multi-dimensional) kernel-estimated probability density functions [44], derived from the signal MC simulations. The fit results are displayed in figure 4 along with the pull distributions, and the fitted signal yields are summarized in table 1. The statistical significances of all decay channels are greater than 10σ in both Belle and Belle II data, except for the $\Xi_c^+ \rightarrow \Lambda \pi^+$ decay in Belle data, which has a statistical significance of 7.6σ . These significances are calculated using $-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})$ [45], accounting for the difference in the number of degrees of freedom ($\Delta \text{ndf} = 3$), where $\mathcal{L}_0$ and $\mathcal{L}_{\max}$ are the maximized likelihoods without and with a signal component, respectively.

The ratios of branching fractions of $\Xi_c^+ \rightarrow p K_S^0/\Lambda \pi^+/\Sigma^0 \pi^+$ relative to that of $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ are calculated separately for Belle and Belle II data using the formulas

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow p K_S^0)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)} = \frac{N^{\text{fit}}(\Xi_c^+ \rightarrow p K_S^0) \varepsilon(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-) \mathcal{B}(\Lambda \rightarrow p \pi^-)}{N^{\text{fit}}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \varepsilon(\Xi_c^+ \rightarrow p K_S^0) \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)}, \quad (4.2)$$

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Lambda \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)} = \frac{N^{\text{fit}}(\Xi_c^+ \rightarrow \Lambda \pi^+) \varepsilon(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-)}{N^{\text{fit}}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \varepsilon(\Xi_c^+ \rightarrow \Lambda \pi^+)}, \quad (4.3)$$

and

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)} = \frac{N^{\text{fit}}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+) \varepsilon(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-)}{N^{\text{fit}}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) \varepsilon(\Xi_c^+ \rightarrow \Sigma^0 \pi^+) \mathcal{B}(\Sigma^0 \rightarrow \Lambda \gamma)}, \quad (4.4)$$

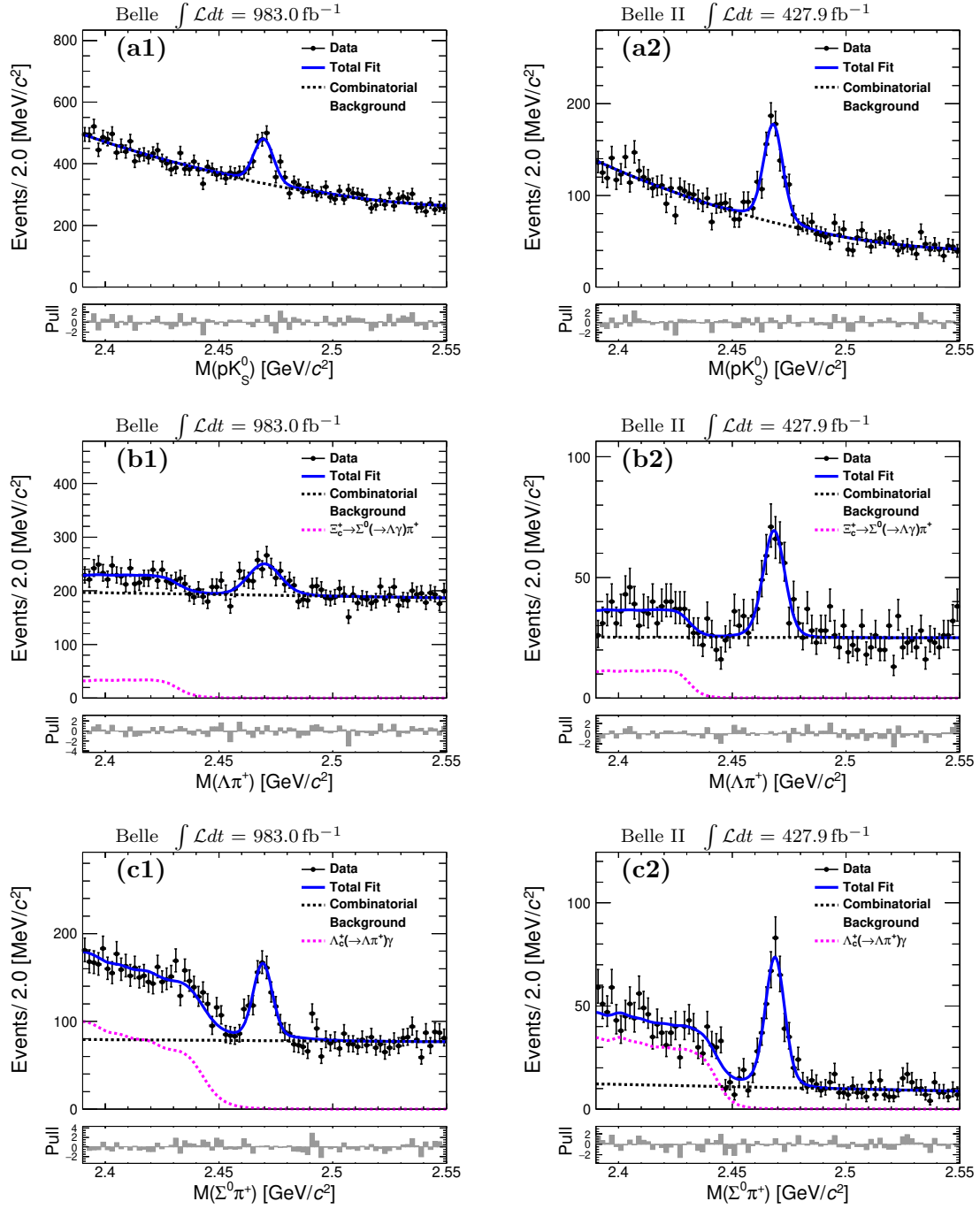


Figure 4. The invariant mass spectra of (a) pK_S^0 , (b) $\Lambda\pi^+$, and (c) $\Sigma^0\pi^+$ in (1) Belle and (2) Belle II data. The points with error bars are the data, the solid blue curves show the best-fit results, and the dashed black curves represent the fitted combinatorial backgrounds. In the $M(\Lambda\pi^+)$ and $M(\Sigma^0\pi^+)$ distributions, the dashed magenta curves are the fitted feed-down backgrounds from the $\Xi_c^+ \rightarrow \Sigma^0(\rightarrow \Lambda\gamma)\pi^+$ and $\Lambda_c^+ \rightarrow \Lambda\pi^+\gamma$ decays, respectively.

Mode	Belle		Belle II	
	N^{fit}	ε (%)	N^{fit}	ε (%)
$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$	17657 ± 160	3.63 ± 0.03	8970 ± 106	4.61 ± 0.03
$\Xi_c^+ \rightarrow p K_S^0$	917 ± 103	7.39 ± 0.04	608 ± 45	11.30 ± 0.04
$\Xi_c^+ \rightarrow \Lambda \pi^+$	530 ± 88	6.35 ± 0.04	275 ± 30	9.62 ± 0.03
$\Xi_c^+ \rightarrow \Sigma^0 \pi^+$	537 ± 57	2.78 ± 0.03	359 ± 27	4.33 ± 0.03

Table 1. Summary of the fitted signal yields (N^{fit}) and reconstruction efficiencies (ε). All the uncertainties here are statistical only. The efficiencies for Belle II are higher than those for Belle. This is mostly due to the different requirements for the significance of the flight distance of Ξ_c^+ . This improvement is due to the superior vertex resolution of the Belle II VXD detector and the smaller beam spot of SuperKEKB, enabling Belle II to achieve a larger efficiency while effectively excluding more backgrounds.

where $N^{\text{fit}}(\Xi_c^+ \rightarrow p K_S^0)$, $N^{\text{fit}}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$, $N^{\text{fit}}(\Xi_c^+ \rightarrow \Lambda \pi^+)$, and $N^{\text{fit}}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)$ are the numbers of fitted $\Xi_c^+ \rightarrow p K_S^0$, $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$, $\Xi_c^+ \rightarrow \Lambda \pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0 \pi^+$ signal events in data summarized in table 1; $\varepsilon(\Xi_c^+ \rightarrow p K_S^0)$, $\varepsilon(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$, $\varepsilon(\Xi_c^+ \rightarrow \Lambda \pi^+)$, and $\varepsilon(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)$ are the corresponding reconstruction efficiencies listed in table 1; and $\mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-) = (99.887 \pm 0.035)\%$, $\mathcal{B}(\Lambda \rightarrow p \pi^-) = (64.2 \pm 0.5)\%$, $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (69.20 \pm 0.05)\%$, and $\mathcal{B}(\Sigma^0 \rightarrow \Lambda \gamma) = 100\%$ are taken from the Particle Data Group [2]. The reconstruction efficiencies of signal channels are obtained from simulation using the ratio $N_{\text{sel.}}/N_{\text{gen.}}$, where $N_{\text{sel.}}$ and $N_{\text{gen.}}$ are the numbers of true signal events surviving the selection criteria and generated events, respectively. The calculated branching fraction ratios are summarized in table 2.

We combine the ratios of branching fractions and uncertainties measured at Belle and Belle II using the formulas in ref. [46]

$$r = \frac{r_1 \sigma_2^2 + r_2 \sigma_1^2}{\sigma_1^2 + \sigma_2^2 + (r_1 - r_2)^2 \epsilon_r^2}, \quad (4.5)$$

and

$$\sigma = \sqrt{\frac{\sigma_1^2 \sigma_2^2 + (r_1^2 \sigma_2^2 + r_2^2 \sigma_1^2) \epsilon_r^2}{\sigma_1^2 + \sigma_2^2 + (r_1 - r_2)^2 \epsilon_r^2}} \quad (4.6)$$

where r_i , σ_i , and ϵ_r are the branching fraction ratio, uncorrelated uncertainty, and relative correlated systematic uncertainty from each data sample, respectively. The correlated systematic uncertainty includes branching fractions of intermediate states and the background shape in the fit, while the efficiency-related uncertainty is treated as uncorrelated. All the uncorrelated and correlated uncertainties are listed in table 3. The combined branching fraction ratios are summarized in table 2, where the first and second uncertainties are statistical and systematic, respectively. The systematic uncertainties are discussed in detail below.

5 Systematic uncertainties

Sources of systematic uncertainties in the measurements of the branching fraction ratios include those associated with efficiency, the branching fractions of intermediate states, and the

	Belle	Belle II	Combined
$\frac{\mathcal{B}(\Xi_c^+ \rightarrow p K_S^0)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$	$(2.36 \pm 0.27 \pm 0.08)\%$	$(2.56 \pm 0.19 \pm 0.11)\%$	$(2.47 \pm 0.16 \pm 0.07)\%$
$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Lambda \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$	$(1.72 \pm 0.29 \pm 0.11)\%$	$(1.47 \pm 0.16 \pm 0.09)\%$	$(1.56 \pm 0.14 \pm 0.09)\%$
$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$	$(3.97 \pm 0.42 \pm 0.23)\%$	$(4.26 \pm 0.33 \pm 0.24)\%$	$(4.13 \pm 0.26 \pm 0.22)\%$

Table 2. The ratios of branching fractions of $\Xi_c^+ \rightarrow p K_S^0 / \Lambda \pi^+ / \Sigma^0 \pi^+$ relative to that of $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$, where the first and second uncertainties are statistical and systematic, respectively.

Sources	$\frac{\mathcal{B}(\Xi_c^+ \rightarrow p K_S^0)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$		$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Lambda \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$		$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)}$	
	Belle	Belle II	Belle	Belle II	Belle	Belle II
Tracking	0.7	0.7	0.7	0.7	0.7	0.7
Particle identification	0.1	0.2	0.1	0.1	0.1	0.1
K_S^0 reconstruction	0.8	2.6	...	...	...	...
Λ reconstruction	0.5	0.3	0.3	0.2	0.3	0.2
Photon reconstruction	...	...	...	...	2.0	1.1
Mass resolution	0.2	0.2	0.4	0.5	0.7	0.8
Dalitz efficiency correction	1.3	1.5	1.3	1.5	1.3	1.5
Branching fraction	0.8	0.8	0.0	0.0	0.0	0.0
Fit Uncertainty	2.5	2.5	5.9	5.9	5.1	5.1
Sum in quadrature	3.2	4.1	6.1	6.2	5.7	5.5

Table 3. Relative systematic uncertainties (%) in the measurements of branching fraction ratios. The uncertainties due to intermediate branching fractions and fit uncertainty are common to Belle and Belle II; the other uncertainties are independent.

fit procedure. Note that some uncertainties from efficiency-related sources and the branching fractions of intermediate states cancel when taking the ratio to the normalization mode. Table 3 summarizes these systematic uncertainties, with the total uncertainty calculated as the quadratic sum of the uncertainties from each source.

The systematic uncertainty of the efficiency determination includes effects due to the detection efficiency of the daughter particles, the mass window used for the intermediate state, and the averaging of the efficiency across the Dalitz plot of the normalization mode. Based on the table of the detection efficiency ratios between data and MC ($r_\epsilon = \epsilon_{\text{data}} / \epsilon_{\text{MC}}$) from the control sample, we build 1000 r_ϵ tables for both the signal and normalization modes by randomly fluctuating r_ϵ in each bin according to its uncertainty and calculate $\bar{r}_\epsilon$ for each. We take the mean values from the distributions of $\bar{r}_\epsilon^{\text{sig.}}$ and $\bar{r}_\epsilon^{\text{nor.}}$ as the efficiency correction factors of the signal and normalization modes, respectively, and the root-mean-square value from the distribution of $\bar{r}_\epsilon^{\text{sig.}} / \bar{r}_\epsilon^{\text{nor.}}$ as the systematic uncertainty in the measurement of the branching fraction ratio. The efficiency correction factors and uncertainties include those from track-finding efficiency, obtained from the control samples of $D^{*+} \rightarrow D^0 (\rightarrow K_S^0 \pi^+ \pi^-) \pi^+$ at

Belle and $\bar{B}^0 \rightarrow D^{*+}(\rightarrow D^0\pi^+)\pi^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ at Belle II; charged pion identification, obtained from the control samples of $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ at Belle and $K_S^0 \rightarrow \pi^+\pi^-$ at Belle II; proton identification, obtained from the $\Lambda \rightarrow p\pi^-$ control sample at Belle and Belle II; K_S^0 reconstruction, obtained from the control samples of $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^0)\pi^+$ at Belle and $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ at Belle II; Λ reconstruction, obtained for the control samples of $\Lambda \rightarrow p\pi^-$ at Belle and $\Lambda_c^+ \rightarrow \Lambda(\rightarrow p\pi^-)\pi^+$ at Belle II; and photon reconstruction, obtained from control samples of radiative Bhabhas at Belle and radiative muon-pairs at Belle II. The PID uncertainties listed in table 3 include the proton and two-pion identification uncertainties in the measurement of $\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$ and three-pion identification uncertainties in the measurements of $\mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$ and $\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$. For the Λ reconstruction, the momentum distributions of Λ of the signal modes $\Xi_c^+ \rightarrow \Lambda\pi^+$ and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ and the normalization mode overlap in most regions, but there are still some differences. Therefore, we treat the efficiency correction factors for the signal and normalization modes separately, along with a systematic uncertainty that includes the proton identification uncertainty, using the same method mentioned above. The uncertainty due to the mass window requirement for the intermediate state is calculated based on the difference between the selected signal fractions in the simulation and data. For the reference mode $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$, the signal efficiency is corrected across the Dalitz plot. The selected Ξ_c^+ sideband regions may influence the efficiency. To account for this, we shift the Ξ_c^+ sideband regions by $\pm 5 \text{ MeV}/c^2$, and the average deviation in efficiency compared to the nominal value is taken as the systematic uncertainty. We assume that the decays $\Xi_c^+ \rightarrow pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$ are isotropic in the rest frame of the Ξ_c^+ , and a phase space model is employed to generate signal MC events. Since the efficiency-corrected $\cos\theta_{\text{hel}}$ distributions are consistent with those in the MC signal distributions at the generator level, where θ_{hel} represents the helicity angle between the momentum of the daughter baryon ($p/\Lambda/\Sigma^0$) and the opposite of the boost direction of the c.m. system, the systematic uncertainty associated with the model of signal MC generation can be neglected. We weight the signal MC samples according to the efficiency-corrected x_p distribution of the normalization mode from data to ensure good agreement between data and MC. The efficiency-corrected x_p distribution is obtained by fitting the $M(\Xi^-\pi^+\pi^+)$ distribution in each x_p bin of data, while accounting for the efficiency in each bin.

For the measurement of $\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$, the uncertainties from $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$, $\mathcal{B}(\Xi^- \rightarrow \Lambda\pi^-)$, and $\mathcal{B}(\Lambda \rightarrow p\pi^-)$ are 0.072%, 0.035%, and 0.78% [2], respectively. These uncertainties are combined in quadrature to obtain the total uncertainty from the branching fractions of intermediate states. For the measurements of $\mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$ and $\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+)/\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$, the uncertainty from $\mathcal{B}(\Xi^- \rightarrow \Lambda\pi^-)$ is only 0.035% [2].

The systematic uncertainty associated with the fit procedure is evaluated by changing the background PDF to a higher-order polynomial or a lower-order polynomial, and the average deviation from the nominal fit result is taken as the systematic uncertainty. Here, the uncertainty from the background PDF is treated as correlated, and extracted from a simultaneous fit to Belle and Belle II data. We estimate the fit uncertainties for both the signal and normalization modes separately, and the uncertainty for the normalization mode

is determined to be 0.9%. Finally, the fit uncertainties of the signal and normalization modes are added in quadrature to obtain the total fit uncertainty.

6 Result and discussion

In summary, we report the first observations of the singly Cabibbo-suppressed decays $\Xi_c^+ \rightarrow pK_S^0$, $\Xi_c^+ \rightarrow \Lambda\pi^+$, and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$, each with a signal significance greater than 10σ , using the combined data samples of 983.0 fb^{-1} and 427.9 fb^{-1} collected by the Belle and Belle II detectors. The ratios of branching fractions of the $\Xi_c^+ \rightarrow pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$ decays relative to that of $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ are measured to be

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} = (2.47 \pm 0.16 \pm 0.07)\%,$$

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} = (1.56 \pm 0.14 \pm 0.09)\%,$$

and

$$\frac{\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+)}{\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)} = (4.13 \pm 0.26 \pm 0.22)\%.$$

Taking $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = (2.9 \pm 1.3)\%$ [4], the absolute branching fractions are determined to be

$$\mathcal{B}(\Xi_c^+ \rightarrow pK_S^0) = (7.16 \pm 0.46 \pm 0.20 \pm 3.21) \times 10^{-4},$$

$$\mathcal{B}(\Xi_c^+ \rightarrow \Lambda\pi^+) = (4.52 \pm 0.41 \pm 0.26 \pm 2.03) \times 10^{-4},$$

and

$$\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0\pi^+) = (1.20 \pm 0.08 \pm 0.07 \pm 0.54) \times 10^{-3}.$$

where the uncertainties are statistical, systematic, and from $\mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$, respectively.

Figure 5 presents comparisons of the measured absolute branching fractions of $\Xi_c^+ \rightarrow pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$ decays in this work with the theoretical predictions [12–22]. The χ^2 values for the predicted branching fractions in refs. [13, 22] compared to the experimental measured results for each of these three decay modes are all less than 4. The measured absolute branching fractions of $\Xi_c^+ \rightarrow pK_S^0$ and $\Xi_c^+ \rightarrow \Sigma^0\pi^+$ are lower than the central values predicted by most theoretical papers. However, the measured absolute branching fraction of $\Xi_c^+ \rightarrow \Lambda\pi^+$ is consistent with all theoretical predictions within 2σ .

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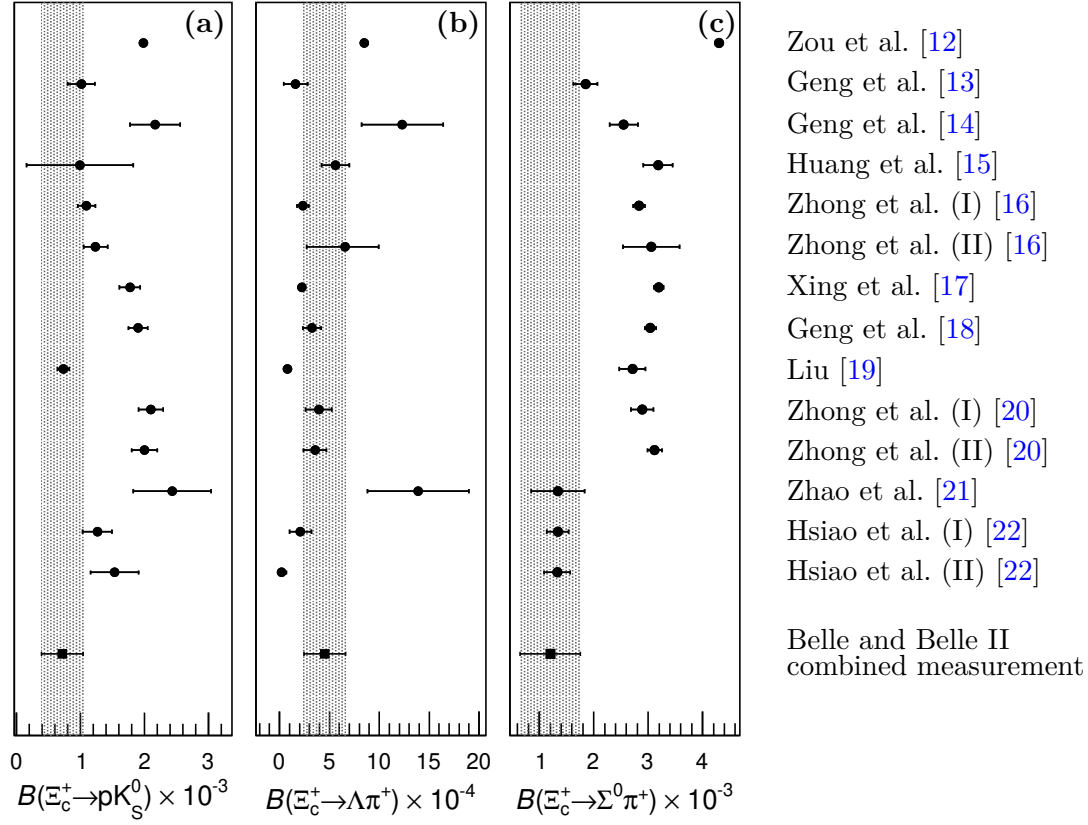


Figure 5. Comparisons of the measured (a) $\mathcal{B}(\Xi_c^+ \rightarrow p K_S^0)$, (b) $\mathcal{B}(\Xi_c^+ \rightarrow \Lambda \pi^+)$, and (c) $\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^0 \pi^+)$ with theoretical predictions [12–22]. The dots and error bars represent the central values and uncertainties of the theoretical predictions, respectively. The dots without error bars indicate that no theoretical uncertainty is available. The squares and error bars denote the measured central values and uncertainties in this work. For refs. [16, 22], (I) indicates the predicted value based on the $SU(3)_F$ flavor symmetry, while (II) takes into account the breaking of $SU(3)_F$ flavor symmetry. For ref. [20], (I) and (II) represent the predicted values derived from the topological diagrammatic approach and the irreducible $SU(3)_F$ approach, respectively.

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