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Measurements of the branching fractions of $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays at Belle

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Using the entire data sample of 980 fb^{-1} collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, we present measurements of the branching fractions of the Cabibbo-favored decays $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$. Taking the decay $\Xi_c^0 \rightarrow \Xi^- \pi^+$ as the normalization mode, we measure the branching fraction ratio $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.229 \pm 0.008 \pm 0.012$ with improved precision, and measure the branching fraction ratios $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.038 \pm 0.006 \pm 0.004$ and $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = 0.123 \pm 0.007 \pm 0.010$ for the first time. Taking into account the branching fraction of the normalization mode, the absolute branching fractions are determined to be $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0) = (3.27 \pm 0.11 \pm 0.17 \pm 0.73) \times 10^{-3}$, $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) = (0.54 \pm 0.09 \pm 0.06 \pm 0.12) \times 10^{-3}$, and $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-) = (1.76 \pm 0.10 \pm 0.14 \pm 0.39) \times 10^{-3}$. The first and second uncertainties above are statistical and systematic, respectively, while the third ones arise from the uncertainty of the branching fraction of $\Xi_c^0 \rightarrow \Xi^- \pi^+$.

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I. INTRODUCTION

Charmed baryons provide a unique laboratory to study the subtle interplay of the strong and weak interactions. Recently, there have been several major breakthroughs in the experimental study of the Ξ_c^0 baryon. Belle has presented the first measurement of the absolute branching fraction $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$ [1], so that the branching fractions of other decay channels of Ξ_c^0 can be determined from ratios of branching fractions. The branching fractions of

the semileptonic decays $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$ and $\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu$ have been measured to be $(1.31 \pm 0.04 \pm 0.07 \pm 0.38)\%$ and $(1.27 \pm 0.06 \pm 0.10 \pm 0.37)\%$ [2], where the uncertainties are statistical, systematic, and from $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$, respectively. The corresponding branching fraction ratio $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \mu^+ \nu_\mu)$ is 1.03 ± 0.09 , which is consistent with the expectation of lepton flavor universality. Very recently, the branching fractions and asymmetry parameters of the Cabibbo-favored (CF) decays $\Xi_c^0 \rightarrow \Lambda \bar{K}^{*0}$, $\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^{*0}$, and $\Xi_c^0 \rightarrow \Sigma^+ K^{*-}$ have been measured for the first time [3].

Theoretical calculations for the two-body hadronic weak decays $\Xi_c^0 \rightarrow B + P$ have been performed using dynamical models [4] and $SU(3)_F$ flavor symmetry methods [5,6], where B and P represent light baryons and pseudoscalar mesons. In hadronic weak decays of charmed baryons, nonfactorizable contributions from inner W -emission and

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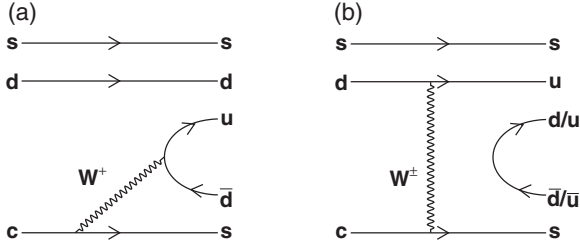


FIG. 1. Feynman diagrams from (a) internal W -emission for $\Xi_c^0 \rightarrow \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0$ decays and (b) W -exchange for $\Xi_c^0 \rightarrow \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0 / \Sigma^+ K^-$ decays.

W -exchange topological diagrams play an essential role and cannot be neglected, in contrast with their negligible effects in heavy meson decays [7]. Figure 1 shows the Feynman diagrams from internal W -emission for $\Xi_c^0 \rightarrow \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0$ decays and W -exchange for $\Xi_c^0 \rightarrow \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0 / \Sigma^+ K^-$ decays as examples. In Ref. [4], the authors found that the factorizable and nonfactorizable terms in both the S - and P -wave amplitudes of the decay $\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^0$ interfere destructively, resulting in a small branching fraction. On the other hand, the interference in the decay $\Xi_c^0 \rightarrow \Lambda \bar{K}^0$ is found to be constructive. The decay $\Xi_c^0 \rightarrow \Sigma^+ K^-$ proceeds only through purely non-factorizable diagrams, and it allows us to check the importance of such decay diagrams. The branching fractions of $\Xi_c^0 \rightarrow \Lambda \bar{K}^0$, $\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays predicted by different theoretical models are listed in Table I.

The ratio of the branching fraction of $\Xi_c^0 \rightarrow \Lambda K_S^0$ relative to that of $\Xi_c^0 \rightarrow \Xi^- \pi^+$ has been measured to be $0.21 \pm 0.02 \pm 0.02$ by Belle using a 140 fb^{-1} data sample [8]. In this paper, we measure the branching fraction ratio $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ to improve the precision, and present the first measurements of the branching fraction ratios $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ and $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-) / \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ using the entire data sample of 980 fb^{-1} collected with the Belle detector. Charge-conjugate modes are also implied unless otherwise stated throughout this paper.

II. THE DATA SAMPLE AND THE BELLE DETECTOR

This analysis is based on data recorded at or near the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and $\Upsilon(5S)$ resonances by the Belle detector [9,10] at the KEKB asymmetric-energy e^+e^- collider [11,12]. The total data sample corresponds to an integrated luminosity of 980 fb^{-1} [10]. The detector is described in detail elsewhere [9,10].

Monte Carlo (MC) simulated signal events are generated using EVTGEN [13] to optimize the signal selection criteria and calculate the reconstruction efficiencies.

TABLE I. The predicted branching fractions in units of 10^{-3} for the CF decays $\Xi_c^0 \rightarrow \Lambda \bar{K}^0 / \Sigma^0 \bar{K}^0 / \Sigma^+ K^-$ based on dynamical model calculations and $SU(3)_F$ flavor symmetry approaches.

Modes	Zou <i>et al.</i> [4]	Geng <i>et al.</i> [5]	Zhao <i>et al.</i> [6]
$\Xi_c^0 \rightarrow \Lambda \bar{K}^0$	13.3	10.5 ± 0.6	8.3 ± 5.0
$\Xi_c^0 \rightarrow \Sigma^0 \bar{K}^0$	0.4	0.8 ± 0.8	7.9 ± 4.8
$\Xi_c^0 \rightarrow \Sigma^+ K^-$	7.8	5.9 ± 1.1	22.0 ± 5.7

Events for the $e^+e^- \rightarrow c\bar{c}$ production are generated using PYTHIA [14] with a specific Belle configuration, where one of the two charm quarks hadronizes into a Ξ_c^0 baryon. The $\Xi_c^0 \rightarrow \Lambda K_S^0 / \Sigma^0 K_S^0 / \Sigma^+ K^-$ decays are generated using a phase space model. The simulated events are processed with a detector simulation based on GEANT3 [15]. Inclusive MC samples of $\Upsilon(1S, 2S, 3S)$ decays, $\Upsilon(4S) \rightarrow B^+ B^- / B^0 \bar{B}^0$, $\Upsilon(5S) \rightarrow B_{(s)}^{(*)} \bar{B}_{(s)}^{(*)}$, and $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) at center-of-mass (c.m.) energies of 9.460, 10.024, 10.355, 10.520, 10.580, and 10.867 GeV corresponding to the total integrated luminosity of data are used to check possible peaking backgrounds and to verify the event selection criteria.

III. COMMON EVENT SELECTION CRITERIA

The selection of the photon candidates as well as the particle identifications (PID) of kaon, pion, and proton are performed using the same methods as in Ref. [3]. Furthermore, the impact parameters of kaons with respect to the interaction point (IP) are required to be less than 0.2 cm and 1.0 cm perpendicular to, and along the beam direction, respectively.

The K_S^0 candidates are first reconstructed from pairs of oppositely charged tracks, which are treated as pions, with a production vertex significantly separated from the IP, and then selected using an artificial neural network [16,17]. The Λ candidates are reconstructed via $\Lambda \rightarrow p\pi^-$ decays. The invariant masses of the K_S^0 and Λ candidates are required to be within $9.5 \text{ MeV}/c^2$ and $3.5 \text{ MeV}/c^2$ of the corresponding nominal masses [18] ($> 95\%$ signal events are retained), respectively.

For the $\Sigma^0 \rightarrow \Lambda\gamma$ reconstruction, the selected Λ candidate is combined with a photon to form a Σ^0 candidate. The energy of the photon is required to exceed 130 MeV in the laboratory frame to suppress combinatorial backgrounds. This criterion is optimized by maximizing the figure-of-merit $N_{\text{sig}} / \sqrt{N_{\text{sig}} + N_{\text{bkg}}}$, where N_{sig} is the number of expected signal events of $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay, and N_{bkg} is the number of background events in the normalized Ξ_c^0 sidebands in data. N_{sig} is obtained from the following formula

$$N_{\text{sig}} = \varepsilon(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) \times \frac{N^{\text{obs}}(\Xi_c^0 \rightarrow \Xi^- \pi^+)}{\varepsilon(\Xi_c^0 \rightarrow \Xi^- \pi^+)} \times \frac{\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) \mathcal{B}(\Sigma^0 \rightarrow \Lambda \gamma) \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) \mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-)},$$

where $\varepsilon(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)$ and $\varepsilon(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ are the reconstruction efficiencies of $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ and $\Xi_c^0 \rightarrow \Xi^- \pi^+$ decays; $N^{\text{obs}}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ is the number of observed $\Xi_c^0 \rightarrow \Xi^- \pi^+$ signal events in data; $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) = 2.0 \times 10^{-4}$ is the branching fraction of $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay predicted by dynamical model calculations [4], $\mathcal{B}(\Sigma^0 \rightarrow \Lambda \gamma) = 100\%$, $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (69.20 \pm 0.05)\%$, $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = (1.43 \pm 0.32)\%$ [18], and $\mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-) = (99.887 \pm 0.035)\%$ [18]. The optimized selection criterion is the same using the assumed branching fractions from the above-mentioned theoretical predictions.

The $\Sigma^+ \rightarrow p \pi^0$ reconstruction is performed as follows [19]. Photon pairs are kept as π^0 candidates. The reconstructed invariant mass of the π^0 candidates is required to be within 15 MeV/ c^2 of the π^0 nominal mass [18], corresponding to approximately twice the resolution. To reduce the combinatorial backgrounds, the momentum of the π^0 in the $e^+ e^-$ c.m. frame is required to exceed 0.3 GeV/ c , which is optimized using the same method that was used for the energy of photon from the Σ^0 decay [20]. Combinations of π^0 candidates and protons are made using those protons with a significantly large (> 1 mm) distance of closest approach to the IP. Then, taking the IP as the point of origin of the Σ^+ , the sum of the proton and π^0 momenta is taken as the momentum vector of the Σ^+ candidate. The intersection of this trajectory with the reconstructed proton trajectory is then found and this position is taken as the decay location of the Σ^+ baryon. The π^0 is then refit using this location as its point of origin. Only those combinations with the decay location of the Σ^+ indicating a positive Σ^+ pathlength are retained.

The ΛK_S^0 , $\Sigma^0 K_S^0$, or $\Sigma^+ K^-$ combinations are made to form Ξ_c^0 candidates with their daughter tracks fitted to a common vertex. The helicity angle of Ξ_c^0 candidates is required to be $|\cos \theta(\Xi_c^0)| < 0.75$ to suppress the combinatorial background, where $\theta(\Xi_c^0)$ is the angle between the $\Lambda/\Sigma^0/\Sigma^+$ momentum vector and the boost direction from the laboratory frame in the Ξ_c^0 rest frame. To reduce combinatorial backgrounds, especially from B -meson decays, the scaled momentum $x_p = p_{\Xi_c^0}^*/p_{\text{max}}$ is required to be larger than 0.55. Here, $p_{\Xi_c^0}^*$ is the momentum of Ξ_c^0 candidates in the $e^+ e^-$ c.m. frame, and $p_{\text{max}} = \frac{1}{c} \sqrt{E_{\text{beam}}^2 - M_{\Xi_c^0}^2 c^4}$, where E_{beam} is the beam energy in the $e^+ e^-$ c.m. frame and $M_{\Xi_c^0}$ is the invariant mass of Ξ_c^0 candidates. All these selection criteria are optimized using the same method that was used for the energy of photon from the Σ^0 decay [20,21].

IV. BRANCHING FRACTIONS OF $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, AND $\Xi_c^0 \rightarrow \Sigma^+ K^-$ DECAYS

For the reference channel $\Xi_c^0 \rightarrow \Xi^- (\rightarrow \Lambda \pi^-) \pi^+$, except for the scaled momentum x_p and the Λ selection criteria, all other selection criteria are similar to those used in Ref. [2]. The required x_p value and the Λ selection criteria of the reference channel are the same as those of the signal channels. Figure 2 shows the invariant mass distribution of $\Xi^- \pi^+$ with $x_p > 0.55$ from data, together with the results of an unbinned extended maximum-likelihood fit. In the fit, the signal shape of Ξ_c^0 candidates is parametrized by a double-Gaussian function with different mean values, and the background shape is described by a first-order polynomial. The parameters of signal and background shapes are free. The fit result is displayed in Fig. 2 along with the pull $(N_{\text{data}} - N_{\text{fit}})/\sigma_{\text{data}}$ distribution, where σ_{data} is the uncertainty on N_{data} , and the fitted signal yield of $\Xi_c^0 \rightarrow \Xi^- \pi^+$ decay in data is 40539 ± 315 .

After applying the aforementioned event selection criteria, the invariant mass distributions of $p \pi^-$, $\Lambda \gamma$, and $p \pi^0$ from the decays $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ in data are shown in Figs. 3(a)–3(c), together with the results of unbinned extended maximum-likelihood fits described below. There are significant Λ , Σ^0 , and Σ^+ signals observed in the Ξ_c^0 signal region, defined as a window of ± 20 MeV/ c^2 around the Ξ_c^0 nominal mass [18] ($\sim 2.5\sigma$). In the fits, the signal shapes of Λ and Σ^+ candidates are described by double-Gaussian functions with different mean values, and the signal shape of Σ^0 is described by a Crystal-Ball function [22]. The backgrounds are parametrized by a first-order polynomial function for the $p \pi^-$ mass spectrum, and second-order polynomial functions for the $\Lambda \gamma$ and $p \pi^0$ mass spectra. The blue solid curves show the best-fit results, and the blue dashed curves represent the fitted backgrounds. The

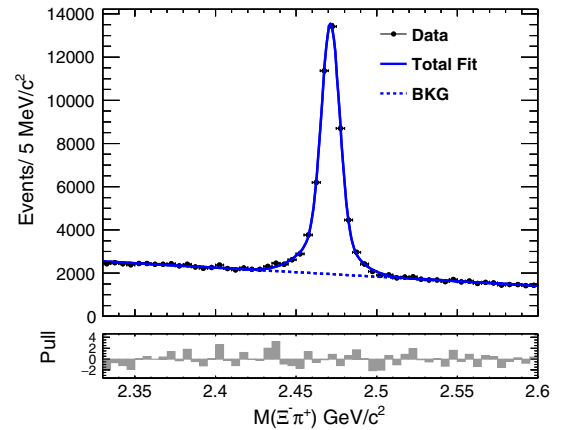


FIG. 2. The invariant mass distribution of $\Xi^- \pi^+$ from data. The points with error bars represent the data, the blue solid curve shows the best-fit result, and the blue dashed curve represents the fitted background.

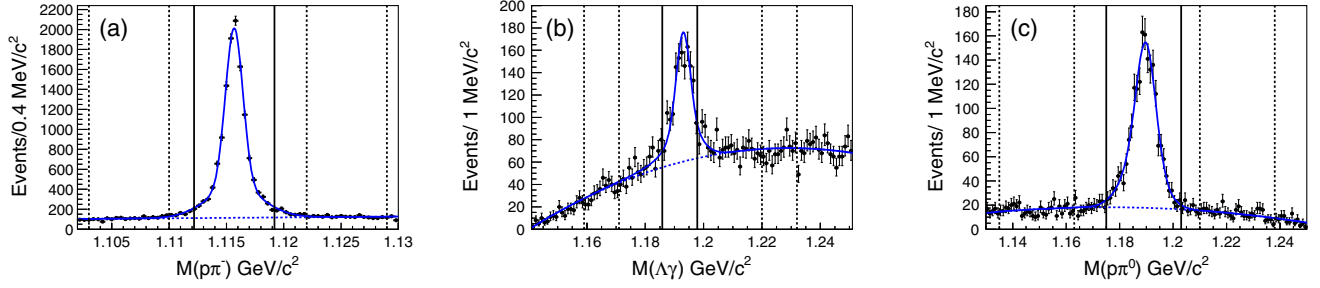


FIG. 3. The invariant mass distributions of (a) $p\pi^-$, (b) $\Lambda\gamma$, and (c) $p\pi^0$ candidates from the decays $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ in the Ξ_c^0 signal region in data. The points with error bars represent the data, the blue solid curves show the best-fit results, and the blue dashed curves are the fitted backgrounds. The vertical solid lines represent the required signal regions, and the vertical dashed lines show the defined sidebands.

reduced χ^2 values of the fits are $\chi^2/\text{nfd} = 1.20, 1.23$, and 0.73 for $M(p\pi^-)$, $M(\Lambda\gamma)$, and $M(p\pi^0)$ distributions, respectively, where $\text{nfd} = 63, 106$, and 112 are the corresponding numbers of degrees of freedom. The ratios of mass resolutions of Λ , Σ^0 , and Σ^+ candidates between the MC simulations and data are found to be $\sigma_{\text{MC}}/\sigma_{\text{data}} = 93\%, 90\%$, and 92% , respectively. The signal regions of Λ , Σ^0 , and Σ^+ candidates are defined as $|M(p\pi^-) - m(\Lambda)| < 3.5 \text{ MeV}/c^2$, $-7 \text{ MeV}/c^2 < M(\Lambda\gamma) - m(\Sigma^0) < 5 \text{ MeV}/c^2$, and $|M(p\pi^0) - m(\Sigma^+)| < 14 \text{ MeV}/c^2$ with corresponding efficiencies of approximately $95\%, 83\%$, and 98% , respectively. Here, $m(i)$ denotes the nominal mass of particle i [18]. The above required signal regions are optimized using the same method that was used for the energy of the photon from the Σ^0 decay. We define the Λ , Σ^0 , and Σ^+ sideband regions as $1.103 \text{ GeV}/c^2 < M(p\pi^-) < 1.110 \text{ GeV}/c^2$ or $1.122 \text{ GeV}/c^2 < M(p\pi^-) < 1.129 \text{ GeV}/c^2$, $1.159 \text{ GeV}/c^2 < M(\Lambda\gamma) < 1.171 \text{ GeV}/c^2$ or $1.220 \text{ GeV}/c^2 < M(\Lambda\gamma) < 1.232 \text{ GeV}/c^2$, and $1.135 \text{ GeV}/c^2 < M(p\pi^0) < 1.163 \text{ GeV}/c^2$ or $1.210 \text{ GeV}/c^2 < M(p\pi^0) < 1.238 \text{ GeV}/c^2$, respectively, which are twice as wide as the corresponding signal regions. The vertical solid lines indicate the required Λ , Σ^0 , and Σ^+ signal regions, and the vertical dashed lines represent the defined Λ , Σ^0 , and Σ^+ sideband regions.

The scatter plots of $M(p\pi^-)$ versus $M(p\pi^- K_S^0)$, $M(\Lambda\gamma)$ versus $M(\Lambda\gamma K_S^0)$, and $M(p\pi^0)$ versus $M(p\pi^0 K^-)$ from data are shown in Figs. 4(a)–4(c). From the plots, significant $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays are observed.

Figure 5 shows the invariant mass spectra of ΛK_S^0 , $\Sigma^0 K_S^0$, and $\Sigma^+ K^-$ from data. The cyan shaded histograms indicate events from the normalized Λ , Σ^0 , and Σ^+ sidebands, respectively. There are no evident peaking backgrounds found in the normalized sidebands or in the inclusive MC samples. To extract the Ξ_c^0 signal yields from the two-body decays $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$, we perform an unbinned extended maximum-likelihood fit to each distribution. The signal shapes of Ξ_c^0 candidates are described by double-Gaussian functions with different mean values, where the parameters are floated for $\Xi_c^0 \rightarrow \Lambda K_S^0$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays and are fixed to those obtained from the fit to the corresponding simulated signal distribution for $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay. The backgrounds are parametrized by second-order polynomial functions with free parameters. The fit results are displayed in Fig. 5 along with the pull distributions, and the corresponding reduced χ^2 values of the fits are $\chi^2/\text{nfd} = 1.12, 1.44$, and 1.21 , respectively, where $\text{nfd} = 46, 51$, and 46 are the corresponding numbers of degrees of freedom. The fitted mean values of Ξ_c^0 candidates in $\Xi_c^0 \rightarrow \Lambda K_S^0$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$

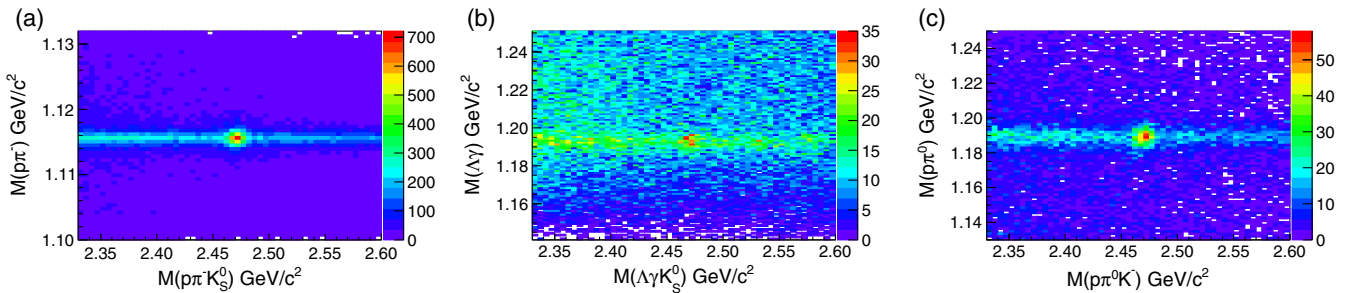


FIG. 4. The scatter plots of (a) $M(p\pi^-)$ versus $M(p\pi^- K_S^0)$, (b) $M(\Lambda\gamma)$ versus $M(\Lambda\gamma K_S^0)$, and (c) $M(p\pi^0)$ versus $M(p\pi^0 K^-)$ from the selected $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ candidates in data.

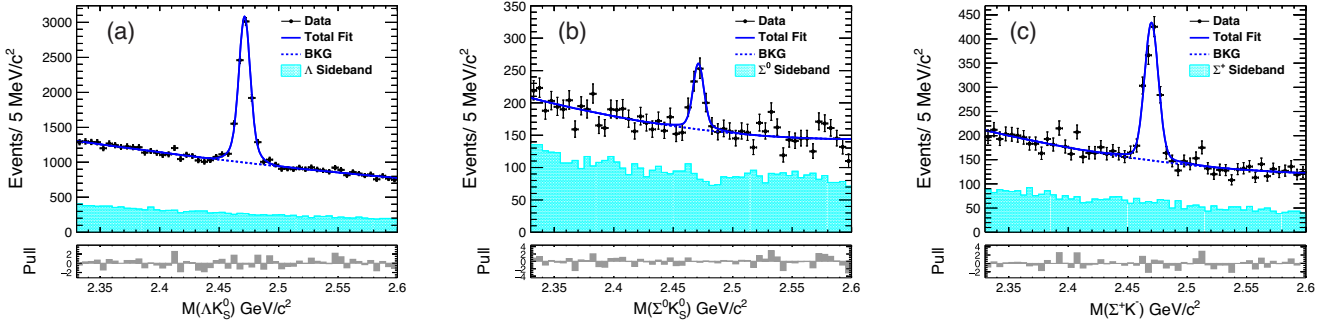


FIG. 5. The invariant mass distributions of (a) ΛK_S^0 , (b) $\Sigma^0 K_S^0$, and (c) $\Sigma^+ K^-$ from data. The points with error bars represent the data, the blue solid curves show the best-fit results, and the blue dashed curves show the fitted backgrounds. The cyan histograms represent events from the normalized Λ , Σ^0 , and Σ^+ sidebands.

decays are consistent with the Ξ_c^0 nominal mass [18], and the fitted signal yields of $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays in data are listed in Table II. The statistical significances of $\Xi_c^0 \rightarrow \Lambda K_S^0$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays are greater than 10σ . The statistical significance of $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay is 8.5σ calculated using $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_0$ and $\mathcal{L}_{\max}$ are the maximized likelihoods without and with a signal component, respectively.

The branching fraction ratios of the decays $\Xi_c^0 \rightarrow \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-$ relative to that of $\Xi_c^0 \rightarrow \Xi^- \pi^+$ are calculated from the following formulas

$$\frac{\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0)}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = \frac{N_{\Lambda K_S^0}^{\text{obs}} \epsilon_{\Xi^- \pi^+} \mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-)}{N_{\Xi^- \pi^+}^{\text{obs}} \epsilon_{\Lambda K_S^0} \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)} = 0.229 \pm 0.008(\text{stat}) \pm 0.012(\text{syst}),$$

$$\frac{\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = \frac{N_{\Sigma^0 K_S^0}^{\text{obs}} \epsilon_{\Xi^- \pi^+}}{N_{\Xi^- \pi^+}^{\text{obs}} \epsilon_{\Sigma^0 K_S^0}} \times \frac{\mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-)}{\mathcal{B}(\Sigma^0 \rightarrow \Lambda \gamma) \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)} = 0.038 \pm 0.006(\text{stat}) \pm 0.004(\text{syst}),$$

and

TABLE II. Summary of the fitted signal yields N^{obs} and reconstruction efficiencies ϵ . All the uncertainties here are statistical only.

Modes	N^{obs}	ϵ (%)
$\Xi_c^0 \rightarrow \Lambda K_S^0$	5574 ± 180	20.05 ± 0.08
$\Xi_c^0 \rightarrow \Sigma^0 K_S^0$	279 ± 41	6.03 ± 0.04
$\Xi_c^0 \rightarrow \Sigma^+ K^-$	889 ± 50	5.15 ± 0.04
$\Xi_c^0 \rightarrow \Xi^- \pi^+$	40539 ± 315	23.24 ± 0.10

$$\frac{\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-)}{\mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)} = \frac{N_{\Sigma^+ K^-}^{\text{obs}} \epsilon_{\Xi^- \pi^+}}{N_{\Xi^- \pi^+}^{\text{obs}} \epsilon_{\Sigma^+ K^-}} \times \frac{\mathcal{B}(\Xi^- \rightarrow \Lambda \pi^-) \mathcal{B}(\Lambda \rightarrow p \pi^-)}{\mathcal{B}(\Sigma^+ \rightarrow p \pi^0) \mathcal{B}(\pi^0 \rightarrow \gamma \gamma)} = 0.123 \pm 0.007(\text{stat}) \pm 0.010(\text{syst}).$$

Here, $N_{\Lambda K_S^0}^{\text{obs}}$, $N_{\Sigma^0 K_S^0}^{\text{obs}}$, $N_{\Sigma^+ K^-}^{\text{obs}}$, and $N_{\Xi^- \pi^+}^{\text{obs}}$ are the fitted signal yields in decays $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, $\Xi_c^0 \rightarrow \Sigma^+ K^-$, and $\Xi_c^0 \rightarrow \Xi^- \pi^+$, respectively; $\epsilon_{\Lambda K_S^0}$, $\epsilon_{\Sigma^0 K_S^0}$, $\epsilon_{\Sigma^+ K^-}$, and $\epsilon_{\Xi^- \pi^+}$ are the corresponding reconstruction efficiencies, which are obtained from the signal MC simulations and are listed in Table II. The efficiency correction factors of 95.5% and 95.4% from the required Σ^0 signal region and PID of π^+ are included for $\epsilon_{\Sigma^0 K_S^0}$ and $\epsilon_{\Xi^- \pi^+}$, respectively, which are discussed in Sec. V. Branching fractions $\mathcal{B}(\Sigma^+ \rightarrow p \pi^0) = (51.57 \pm 0.30)\%$, $\mathcal{B}(\pi^0 \rightarrow \gamma \gamma) = (98.823 \pm 0.034)\%$, and $\mathcal{B}(\Lambda \rightarrow p \pi^-) = (63.9 \pm 0.5)\%$ are taken from Particle Data Group [18].

V. SYSTEMATIC UNCERTAINTIES

There are several sources of systematic uncertainties for the measurements of branching fractions, including detection-efficiency-related uncertainties, the branching fractions of intermediate states, as well as the overall fit uncertainties. Note that the uncertainties from detection-efficiency-related sources and the branching fractions of intermediate states partially cancel in the ratio to the reference mode.

The detection-efficiency-related uncertainties include those from tracking efficiency, PID efficiency, K_S^0 reconstruction efficiency, Λ reconstruction efficiency, photon reconstruction efficiency, π^0 reconstruction efficiency, and the uncertainty related to the required Σ^0 signal region. Based on a study of $D^{*+} \rightarrow \pi^+ D^0 (\rightarrow K_S^0 \pi^+ \pi^-)$ decay, the tracking efficiency uncertainty is evaluated to be 0.35% per track. Using the $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$, and $\Lambda \rightarrow p \pi^-$

control samples, the PID uncertainties are estimated to be 1.6% per kaon and 3.5% per proton. The uncertainties associated with K_S^0 , Λ , and π^0 reconstruction efficiencies are found to be 2.23% [23], 3.0% [24], and 2.25% [25], respectively. The efficiency uncertainty in the photon reconstruction is 2.0% per photon, according to a study of radiative Bhabha events. For the reference channel $\Xi_c^0 \rightarrow \Xi^-(\rightarrow \Lambda\pi^-)\pi^+$, the PID efficiency uncertainties of π^+ from the Ξ_c^0 decay and π^- from the Ξ^- decay are considered separately, because π^+ has a larger momentum. The PID efficiency ratio between the data and MC simulation of π^+ is found to be $\epsilon_{\text{data}}/\epsilon_{\text{MC}} = (95.4 \pm 0.7)\%$, and then we take 95.4% and 0.7% as an efficiency correction factor and PID uncertainty for π^+ ; the PID efficiency ratio between the data and MC simulation of π^- is found to be $\epsilon_{\text{data}}/\epsilon_{\text{MC}} = (99.5 \pm 0.8)\%$, and 1.3% is taken as the PID uncertainty of π^- . We assume that $\Xi_c^0 \rightarrow \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-$ decays are isotropic in the rest frame of Ξ_c^0 , and a phase space model is used to generate signal events. For the $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay, the $M(\Sigma^0)$ resolution discrepancy between data and MC simulation brings an efficiency correction factor 95.5% and systematic uncertainty 0.5% because of the required Σ^0 signal region. For the $\Xi_c^0 \rightarrow \Lambda K_S^0$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays, the uncertainties of the required Λ and Σ^+ signal regions are less than 1%. For the measurements of $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0)$ and $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)$, the uncertainties from tracking and Λ reconstruction efficiencies mostly cancel by the reference channel. Assuming these uncertainties are independent and adding them in quadrature, the final detection-efficiency-related uncertainties are obtained, as listed in Table III.

For the measurements of $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0)$ and $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0)$, the uncertainties from $\mathcal{B}(\Xi^- \rightarrow \Lambda\pi^-)$ and $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$ are 0.035% and 0.072% [18], which are small and neglected. For the measurement of $\mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-)$, the uncertainties from $\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)$ and $\mathcal{B}(\Lambda \rightarrow p\pi^-)$ are 0.6% and 0.8% [18], which are added in quadrature as the total uncertainty from branching fractions of intermediate states.

The systematic uncertainties associated with the background shape, fit range, and mass resolution are considered as follows. The order of the background polynomial is

TABLE III. Relative systematic uncertainties (%) for the measurements of branching fractions of $\Xi_c^0 \rightarrow \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-$. The uncertainty of 22.4% on $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+)$ [18] is treated as an independent systematic uncertainty.

Sources	$\Xi_c^0 \rightarrow \Lambda K_S^0$	$\Xi_c^0 \rightarrow \Sigma^0 K_S^0$	$\Xi_c^0 \rightarrow \Sigma^+ K^-$
Detection efficiency	3.1	3.7	5.9
Branching fraction	< 0.1	< 0.1	1.0
Fit uncertainty	4.0	10.5	5.9
Sum in quadrature	5.1	11.1	8.4

changed from second to first or third, and the average deviation compared to the nominal fit result is taken as the systematic uncertainty related to the background shape, which are 3.26%, 9.11%, and 5.20% for $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays, respectively. The fit range is changed by $\pm 20 \text{ MeV}/c^2$, and the average deviation compared to the nominal fit result is taken as the systematic uncertainty related to the fit range, which are 1.67%, 2.14%, and 2.31% for $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays, respectively. For $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ decay, the signal shape of Ξ_c^0 is replaced by a Gaussian function with a free resolution convolved with the fixed signal shape from signal MC simulation: the difference in the number of signal events, 4.32%, is taken as the systematic uncertainty related to the mass resolution. The fit uncertainty of the reference mode is estimated using the same method as was used for the signal modes, and the uncertainties associated with the background shape and fit range are determined to be 1.54% and 0.57%, respectively. For each mode, all the above uncertainties are summed in quadrature to obtain the total systematic uncertainty due to the fit. Finally, the fit uncertainties of signal and reference modes are added in quadrature to give the total fit uncertainty for each signal mode.

Assuming all the sources are independent and adding them in quadrature, the total systematic uncertainties are obtained. All the systematic uncertainties are summarized in Table III.

VI. SUMMARY

In summary, using the entire data sample of 980 fb $^{-1}$ integrated luminosity collected with the Belle detector, we study $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decay modes. The ratios of the branching fractions of $\Xi_c^0 \rightarrow \Lambda K_S^0$, $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$, and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ relative to that of $\Xi_c^0 \rightarrow \Xi^-\pi^+$ are measured to be $0.229 \pm 0.008(\text{stat}) \pm 0.012(\text{syst})$, $0.038 \pm 0.006(\text{stat}) \pm 0.004(\text{syst})$, and $0.123 \pm 0.007(\text{stat}) \pm 0.010(\text{syst})$, respectively. The measured branching fraction ratio $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0)/\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+)$ is consistent with the previously measured value of $0.21 \pm 0.02(\text{stat}) \pm 0.02(\text{syst})$ [8] with much improved precision and supersedes the previous result. Taking $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+) = (1.43 \pm 0.32)\%$ [18], the absolute branching fractions are determined to be

$$\begin{aligned}\mathcal{B}(\Xi_c^0 \rightarrow \Lambda K_S^0) &= (3.27 \pm 0.11 \pm 0.17 \pm 0.73) \times 10^{-3}, \\ \mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 K_S^0) &= (0.54 \pm 0.09 \pm 0.06 \pm 0.12) \times 10^{-3}, \\ \mathcal{B}(\Xi_c^0 \rightarrow \Sigma^+ K^-) &= (1.76 \pm 0.10 \pm 0.14 \pm 0.39) \times 10^{-3},\end{aligned}$$

where the uncertainties are statistical, systematic, and from $\mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+)$, respectively. The branching fractions of $\Xi_c^0 \rightarrow \Sigma^0 K_S^0$ and $\Xi_c^0 \rightarrow \Sigma^+ K^-$ decays, which are measured for the first time, are of the same order of magnitude as the

theoretical predictions in Refs. [4,5], but an order of magnitude smaller than the predicted values in Ref. [6]. All these measured branching fractions are in the same order of magnitude as the theoretical predictions [4–6]. The measured ratios of the branching fractions among the three decay modes are consistent with the theoretical predictions based on $SU(3)_F$ flavor symmetry approaches within the theoretical uncertainties [5,6], but contradict those predicted by dynamical model calculations [4].

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