

Measurement of the branching fractions of the Cabibbo-favored decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ and search for $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$

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Based on e^+e^- collision data corresponding to an integrated luminosity of about 4.5 fb^{-1} collected at center-of-mass energies between 4599.53 and 4698.82 MeV with the BESIII detector, the absolute branching fraction of the Cabibbo-favored decay $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ is measured to be $(3.12 \pm 0.46 \pm 0.15) \times 10^{-3}$. Combined with a previous measurement from the BESIII Collaboration, the branching fraction of the decay $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ is calculated to be $(3.07 \pm 0.26 \pm 0.13) \times 10^{-3}$. The decay $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ is observed for the first time with a statistical significance of 6.6σ , and its branching fraction is determined to be $(3.70 \pm 0.60 \pm 0.21) \times 10^{-3}$. In addition, a search for the decay $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ is performed, and its branching fraction is determined to be $(0.80_{-0.24}^{+0.28} \pm 0.16) \times 10^{-3}$, corresponding to an upper limit of 1.28×10^{-3} at a 90% confidence level. These measurements provide new information that can be used to distinguish between theoretical models.

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I. INTRODUCTION

Hadronic decays of charmed baryons serve as an ideal laboratory to understand the weak and strong interactions in the charm sector [1]. The branching fractions (BFs) of charmed baryon decays can provide essential input for constraining theoretical models [2]. Decay amplitudes of charmed baryons can be separated into factorizable terms, allowing for the independent treatment of the strong and weak components, and nonfactorizable terms, for which it is difficult to calculate the interplay between the two components [3,4]. The external W -emission diagram is predominantly factorizable, while internal W -emission and W -exchange diagrams incorporate nonfactorizable terms, which contribute to the heightened complexity of theoretical calculations for charmed baryon decays.

Numerous theoretical models and approaches have been developed to study charmed baryon decays. One possibility, a model-independent approach based on SU(3) flavor symmetry, has been proposed to describe these decays, incorporating nonfactorizable effects [5]. While SU(3) symmetry is only approximate, it is a powerful tool for extracting valuable information from the quark transitions in charmed baryon decays. Improved measurements of

charmed baryon decays will be essential for further testing the SU(3) symmetry assumption.

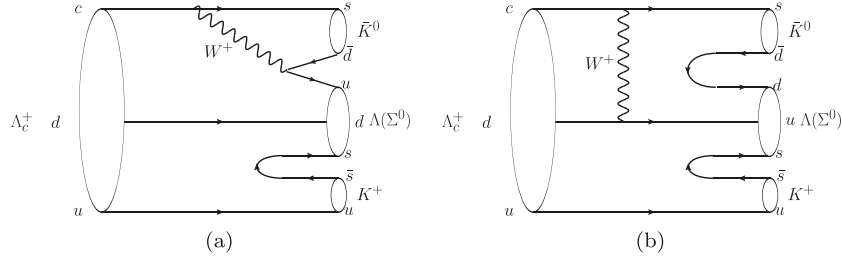
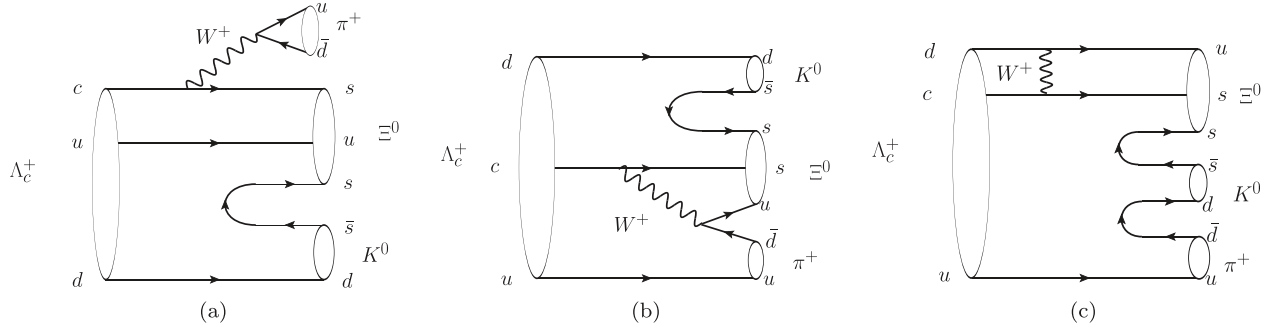
The ground state of the charmed baryon Λ_c^+ was first observed at the Mark II experiment in 1979 [6]. Since 2014, BESIII has accumulated a large data sample at the $\Lambda_c^+ \bar{\Lambda}_c^-$ threshold. Based on these data, the BESIII experiment reported a series of BFs of exclusive decays of the Λ_c^+ baryon [7–18]. Several new decay modes were discovered, and the precision of BFs for the known decay modes has also been significantly improved. However, decay processes involving two or three strange hadrons in the final state have rarely been studied. A comparison between the BFs of the inclusive and summed exclusive decay channels of $\Lambda_c^+ \rightarrow \Lambda X$ [19,20] and $\Lambda_c^+ \rightarrow K_S^0 X$ [21], where X means all possible final state particles, shows that there is still room for unmeasured decay channels involving two or three strange hadrons.

The decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ are predominantly characterized by the $c \rightarrow s$ transition but involve more than one strange hadron. The topology diagrams illustrating the three decay modes are displayed in Figs. 1 and 2. Predictions for the BFs of these decay modes by SU(3) flavor symmetry or by the statistical isospin model are listed in Table I alongside the averaged results from the Particle Data Group (PDG) [20]. Further measurements of the BFs of these decays are needed to help confirm the predictions of SU(3) flavor symmetry and to offer valuable information for further theoretical studies [5].

In this analysis, we conduct precise measurements of the absolute BFs of $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, and

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FIG. 1. Topological diagrams of $\Lambda_c^+ \rightarrow \Lambda(\Sigma^0)K_S^0 K^+$. (a) Internal W -emission. (b) W -exchange.FIG. 2. Topological diagrams of $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$. (a) External W -emission. (b) Internal W -emission. (c) W -exchange.

we search for $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ by employing the double-tag (DT) method [25]. Our analysis uses electron-positron collision data samples collected at seven center-of-mass energies (E_{cm}) ranging from 4599.53 to 4698.82 MeV by the BESIII detector [26]. These data samples correspond to an integrated luminosity of 4.5 fb^{-1} [26], as detailed in Table II. Throughout this paper, charge conjugation is always implied.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [27] records symmetric e^+e^- collisions provided by the BEPCII storage ring [28], in the center-of-mass energy ranging from 1.85 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved in 2023 at a center-of-mass energy of $\sqrt{s} = 3.773 \text{ GeV}$. BESIII has collected large data samples in this energy

region [29]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and is comprised of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke, which is segmented into layers and instrumented with resistive plate counter modules for muon identification. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution of the TOF in the barrel region is 68 ps, while that in the end-cap region is 110 ps. The end-cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time

TABLE I. The theoretical predictions and experimental results for the BFs of $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$.

	$\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$	$\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$	$\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$
Geng <i>et al.</i> [5]	$(2.85 \pm 0.55) \times 10^{-3}$	$(2.50 \pm 0.50) \times 10^{-3}$	$(4.35 \pm 0.85) \times 10^{-2}$
Cen <i>et al.</i> [22]	$(2.90 \pm 0.50) \times 10^{-3}$	$(0.14 \pm 0.05) \times 10^{-3}$	$(2.20 \pm 0.40) \times 10^{-2}$
Geng <i>et al.</i> [23]	$(2.73 \pm 0.49) \times 10^{-3}$	$(1.27 \pm 0.48) \times 10^{-4}$	$(4.85 \pm 1.65) \times 10^{-3}$
Statistical isospin model [24]	...	...	$(3.10 \pm 0.30) \times 10^{-3}$
PDG value [20]	$(2.80 \pm 0.55) \times 10^{-3}$	...	...
This work	$(3.12 \pm 0.46 \pm 0.15) \times 10^{-3}$	$(0.80^{+0.28}_{-0.24} \pm 0.16) \times 10^{-3}$	$(3.70 \pm 0.60 \pm 0.21) \times 10^{-3}$

TABLE II. Center-of-mass energies and luminosities of the data samples used in this work.

E_{cm} (MeV)	Luminosity (pb^{-1})
$4599.53 \pm 0.07 \pm 0.74$	$586.9 \pm 0.1 \pm 3.9$
$4611.86 \pm 0.12 \pm 0.32$	$103.8 \pm 0.1 \pm 0.6$
$4628.00 \pm 0.06 \pm 0.32$	$521.5 \pm 0.1 \pm 2.8$
$4640.91 \pm 0.06 \pm 0.38$	$552.4 \pm 0.1 \pm 2.9$
$4661.24 \pm 0.06 \pm 0.29$	$529.6 \pm 0.1 \pm 2.8$
$4681.92 \pm 0.08 \pm 0.29$	$1669.3 \pm 0.2 \pm 8.8$
$4698.82 \pm 0.10 \pm 0.39$	$536.4 \pm 0.1 \pm 2.8$

resolution of 60 ps [30–32]. About 85% of the $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs are produced in data taken after this upgrade. More detailed descriptions can be found in Refs. [27,28].

High-statistics Monte Carlo (MC) simulation samples for the annihilation of e^+e^- are produced with the KKMC generator [33] by incorporating the initial-state radiation (ISR) effects and the beam-energy spread. The inclusive MC sample, which consists of $\Lambda_c^+ \bar{\Lambda}_c^-$ events, $D_{(s)}^{(*)}$ production, ISR return to the lower-mass ψ states, and the continuum processes $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$), is generated to determine the single-tag (ST) detection efficiency and estimate the potential background. All particle decays are modeled with EvtGen [34,35] using BF's either taken from the PDG [20], when available, or otherwise estimated with Lundcharm [36]. Furthermore, exclusive DT-signal MC events, where the $\bar{\Lambda}_c^-$ decays into any of the tag modes and the Λ_c^+ decays into any of the signal modes are used to determine the DT detection efficiencies. The Born cross sections are taken into account when producing the MC sample of $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs [37]. The simulated $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ signal MC samples are modeled uniformly distributed in phase space (PHSP), and the resulting angular, momentum, and two-body invariant mass distributions of the final-state particles are in good

agreement with the data. For the signal simulated sample of $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, the key kinematic distributions mentioned above have been reweighted to agree with those of data. All final tracks are fed into a Geant4-based detector simulation package, which includes the geometric description of the BESIII detector and also generates showers [38,39].

III. EVENT SELECTION

We first reconstruct a $\bar{\Lambda}_c^-$ baryon candidate, referred to as the ST candidate, using one of the twelve exclusive decay modes listed in Table III. Then, we reconstruct the signal decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, referred to as the DT candidates, in the system recoiling against the $\bar{\Lambda}_c^-$ ST candidate. The DT events are selected using a partial reconstruction technique, as described below. The selection criteria for the $\bar{\Lambda}_c^-$ ST candidates of the twelve tag modes are the same as those described in Ref. [40].

For $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, we search for a candidate K_S^0 and K^+ , while for $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, a candidate K_S^0 and π^+ are reconstructed. The K_S^0 particle candidate is formed by combining two oppositely charged tracks, which satisfy $|\cos \theta| < 0.93$ (where the angle θ is defined with respect to the z axis, which is the symmetry axis of the MDC), and their distances of closest approach to the interaction point (IP) are required to be within ± 20 cm along the beam direction. No additional requirements are made for particle identification (PID) and distance in the transverse plane for the two tracks. To veto backgrounds from the miscombination of pions, the two daughter tracks from the K_S^0 are required to originate from a common decay vertex by applying a vertex fit, and the χ^2 of the vertex fit must be less than 100. Furthermore, since the K_S^0 has a relatively long lifetime, the decay vertex is required to be separated from the IP by a distance of at least twice the corresponding uncertainty (σ_L) of the decay length (L).

TABLE III. ST yield (N_i^{ST}) of 12 modes from 4599.53 to 4698.82 MeV. The uncertainty is statistical only.

Mode	4599.53 MeV	4611.86 MeV	4628.00 MeV	4640.91 MeV	4661.24 MeV	4681.92 MeV	4698.82 MeV
$\bar{p} K_S^0$	1277 ± 36	239 ± 16	1062 ± 35	1116 ± 36	1119 ± 35	3376 ± 61	958 ± 33
$\bar{p} K^+ \pi^-$	6806 ± 91	1166 ± 39	5969 ± 89	6337 ± 90	5938 ± 86	17508 ± 147	5167 ± 80
$\bar{p} K_S^0 \pi^0$	606 ± 34	127 ± 17	624 ± 36	609 ± 36	594 ± 36	1785 ± 63	471 ± 34
$\bar{p} K_S^0 \pi^- \pi^+$	613 ± 34	106 ± 16	517 ± 33	560 ± 35	537 ± 33	1511 ± 57	462 ± 31
$\bar{p} K^+ \pi^- \pi^0$	2197 ± 78	364 ± 34	1615 ± 69	1662 ± 72	1700 ± 73	5111 ± 128	1389 ± 74
$\bar{\Lambda} \pi^-$	757 ± 28	123 ± 11	682 ± 29	712 ± 29	668 ± 27	2074 ± 48	538 ± 25
$\bar{\Lambda} \pi^- \pi^0$	1743 ± 56	302 ± 23	1474 ± 54	1639 ± 55	1491 ± 51	4380 ± 88	1301 ± 49
$\bar{\Lambda} \pi^- \pi^+ \pi^-$	768 ± 36	139 ± 15	595 ± 33	756 ± 37	780 ± 36	2059 ± 61	639 ± 34
$\bar{\Sigma}^0 \pi^-$	520 ± 26	102 ± 13	419 ± 24	452 ± 25	454 ± 25	1398 ± 42	0371 ± 22
$\bar{\Sigma}^- \pi^0$	320 ± 25	73 ± 10	267 ± 23	303 ± 25	298 ± 25	879 ± 43	251 ± 24
$\bar{\Sigma}^- \pi^- \pi^+$	1186 ± 49	218 ± 22	1094 ± 49	1094 ± 50	1066 ± 49	3027 ± 88	956 ± 48
$\bar{p} \pi^- \pi^+$	598 ± 47	155 ± 22	524 ± 45	559 ± 48	590 ± 48	1596 ± 80	459 ± 47

Tracks satisfying the above requirements are assigned as the π^+ and π^- candidates from the K_S^0 decay. The fitted momenta of the $\pi^+\pi^-$ combinations are utilized in the subsequent analysis. The invariant mass of the $\pi^+\pi^-$ combination $M(\pi^+\pi^-)$ must lie in the mass range $487 \text{ MeV}/c^2 < M(\pi^+\pi^-) < 511 \text{ MeV}/c^2$, corresponding to a window of about 3 times the resolution. If multiple K_S^0 particle candidates are reconstructed in the event, the one with the maximum L/σ_L is chosen. We have neglected the exchange of the two K_S^0 candidates in the $\Lambda_c^+\bar{\Lambda}_c^-$ events, since it is found to be negligible based on the inclusive MC sample, and the background contribution is represented by a flat distribution.

An additional charged particle is selected, with the requirements that the track must satisfy $|\cos\theta| < 0.93$ and have a distance of closest approach to the IP less than 10 cm along the beam axis and less than 1 cm in the perpendicular plane. This particle is identified as a kaon or a pion candidate by comparing the likelihoods $\mathcal{L}$ with the different hypotheses calculated by the energy loss in the MDC and the flight time measured by the TOF system, where the requirement for K is $\mathcal{L}(K) > \mathcal{L}(\pi)$, and that for π is $\mathcal{L}(\pi) > \mathcal{L}(K)$.

IV. DATA ANALYSIS

The beam-constrained mass $M_{\text{BC}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}|^2/c^2}$ is utilized to identify the $\bar{\Lambda}_c^-$ ST candidates, where $E_{\text{beam}} = \sqrt{s}/2$ represents the average value of the e^+ and e^- beam energies, and $\vec{p}$ corresponds to the momentum of $\bar{\Lambda}_c^-$ candidates in the center-of-mass system of the e^+e^- collision. The M_{BC} of reconstructed $\bar{\Lambda}_c^-$ ST candidates is expected to peak around the $\bar{\Lambda}_c^-$ nominal mass, which is approximately 2.286 GeV. The energy difference $\Delta E \equiv E - E_{\text{beam}}$ of the $\bar{\Lambda}_c^-$ ST candidates is used to improve the signal purity, where E represents the total energy of the reconstructed $\bar{\Lambda}_c^-$ candidates. The corresponding

requirement for the energy difference is in accordance with the criteria outlined in Ref. [40]. In the case of multiple $\bar{\Lambda}_c^-$ ST candidates in an event, the best $\bar{\Lambda}_c^-$ candidate is selected by choosing the one with the minimal $|\Delta E|$. The M_{BC} distribution for the twelve ST modes in the data sample is consistent with Ref. [40]. Each mode has a distinct signal peak around the $\bar{\Lambda}_c^-$ nominal mass. The unbinned maximum-likelihood fit is performed for the M_{BC} distribution to determine the ST yield, which aligns with the fit strategy reported in Ref. [40]. Candidates within the M_{BC} signal region (2.275, 2.310) GeV/ c^2 are retained for further analysis. The ST efficiencies are determined by analyzing the inclusive MC sample. The ST yields and detection efficiencies of the twelve modes at the seven energy points are presented in Tables III and IV, respectively.

For the decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, the kinematic variable $M_{\text{miss}} \equiv \sqrt{E_{\text{miss}}^2/c^4 - |\vec{p}_{\text{miss}}|^2/c^2}$ is used to search for the Λ , Σ^0 , and Ξ^0 candidates, respectively. The E_{miss} and $\vec{p}_{\text{miss}}$ are calculated by $E_{\text{miss}} \equiv E_{\text{beam}} - E_{\text{rec}}$ and $\vec{p}_{\text{miss}} \equiv \vec{p}_{\Lambda_c^+} - \vec{p}_{\text{rec}}$, where E_{rec} and $\vec{p}_{\text{rec}}$ are the energy and momentum of the reconstructed final-state particles other than $\bar{\Lambda}_c^-$ in the e^+e^- center-of-mass system. The E_{beam} is used to replace the energy of the Λ_c^+ candidate to improve the resolution. The Λ_c^+ baryon momentum $\vec{p}_{\Lambda_c^+}$ is calculated as $\vec{p}_{\Lambda_c^+} \equiv -\hat{p}_{\text{tag}} \sqrt{E_{\text{beam}}^2/c^2 - m_{\Lambda_c^+}^2}$, where $\hat{p}_{\text{tag}}$ is the momentum direction of the $\bar{\Lambda}_c^-$ ST candidate and $m_{\Lambda_c^+}$ is the nominal mass of the Λ_c^+ [20]. No significant peaking background contribution is observed in studies of the inclusive MC sample and the data sample within the M_{BC} and $M(K_S^0)$ sideband region. The M_{miss} distributions from the data sample, after combining all seven energy points and twelve tag modes, are depicted in Figs. 3 and 4. In Fig. 3, the two peaks around the nominal masses of the Λ and Σ^0 represent the $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$

TABLE IV. ST detection efficiency (ϵ_i^{ST} , in %) of 12 modes from 4599.53 to 4698.82 MeV. The uncertainty is statistical only.

Mode	4599.53 MeV	4611.86 MeV	4628.00 MeV	4640.91 MeV	4661.24 MeV	4681.92 MeV	4698.82 MeV
$\bar{p} K_S^0$	56.1 ± 0.2	53.7 ± 0.5	52.2 ± 0.2	51.1 ± 0.2	49.6 ± 0.2	48.6 ± 0.1	47.5 ± 0.2
$\bar{p} K^+ \pi^-$	51.5 ± 0.1	51.0 ± 0.2	49.9 ± 0.1	49.2 ± 0.1	48.2 ± 0.1	47.1 ± 0.1	46.3 ± 0.1
$\bar{p} K_S^0 \pi^0$	23.0 ± 0.2	22.2 ± 0.4	21.0 ± 0.2	21.0 ± 0.2	20.1 ± 0.2	19.7 ± 0.1	18.9 ± 0.2
$\bar{p} K_S^0 \pi^- \pi^+$	23.5 ± 0.2	21.9 ± 0.5	20.9 ± 0.2	21.1 ± 0.2	20.2 ± 0.2	20.7 ± 0.1	19.5 ± 0.2
$\bar{p} K^+ \pi^- \pi^0$	20.6 ± 0.1	19.9 ± 0.2	19.0 ± 0.1	18.4 ± 0.1	18.1 ± 0.1	17.8 ± 0.1	17.5 ± 0.1
$\bar{\Lambda} \pi^-$	48.4 ± 0.3	46.9 ± 0.6	43.7 ± 0.3	43.1 ± 0.3	41.7 ± 0.3	41.3 ± 0.2	39.4 ± 0.3
$\bar{\Lambda} \pi^- \pi^0$	21.6 ± 0.1	19.8 ± 0.2	19.4 ± 0.1	19.4 ± 0.1	18.9 ± 0.1	18.2 ± 0.1	17.9 ± 0.1
$\bar{\Lambda} \pi^- \pi^+ \pi^-$	15.6 ± 0.1	13.6 ± 0.3	14.1 ± 0.1	14.4 ± 0.1	14.1 ± 0.1	13.9 ± 0.1	14.6 ± 0.1
$\bar{\Sigma}^0 \pi^-$	29.4 ± 0.2	26.6 ± 0.6	27.6 ± 0.2	26.6 ± 0.2	26.3 ± 0.2	25.9 ± 0.1	24.3 ± 0.2
$\bar{\Sigma}^- \pi^0$	23.7 ± 0.3	22.6 ± 0.6	23.8 ± 0.3	25.0 ± 0.3	23.2 ± 0.3	22.5 ± 0.2	22.2 ± 0.3
$\bar{\Sigma}^- \pi^- \pi^+$	25.4 ± 0.1	25.5 ± 0.3	24.0 ± 0.1	23.7 ± 0.1	23.2 ± 0.1	22.1 ± 0.1	22.2 ± 0.1
$\bar{p} \pi^- \pi^+$	64.3 ± 0.3	62.7 ± 0.8	62.4 ± 0.4	60.4 ± 0.4	60.2 ± 0.4	53.6 ± 0.2	55.9 ± 0.4

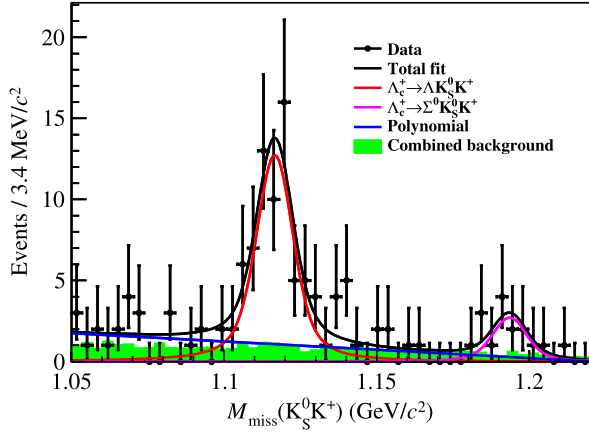


FIG. 3. Fit result of the $M_{\text{miss}}(K_S^0 K^+)$ distribution. The points with error bars are data. The solid black line is a sum of fit functions. The red and pink solid lines are the $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and $\Sigma^0 K_S^0 K^+$ signal shapes, respectively. The blue solid line is the polynomial function, and the green shaded histogram is the simulated background contribution derived from the inclusive MC sample.

decays, respectively, while Fig. 4 shows the $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ decay. The Λ , Σ^0 , and Ξ^0 signal shapes are modeled by individual MC-derived shapes convolved with a Gaussian function with free parameters. Since no peaking background contribution is observed, a linear function is used to describe the total background contributions, which includes $q\bar{q}$ events from continuum hadron production in e^+e^- annihilation and $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs from $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ events, excluding the corresponding signal processes. The fitted signal yields for the decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ are 67.7 ± 10.1 ,

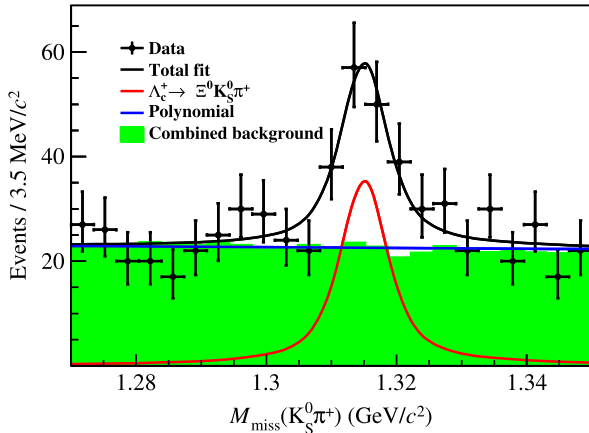


FIG. 4. Fit result of the $M_{\text{miss}}(K_S^0 \pi^+)$ distribution. The points with error bars are data. The black solid line is a sum of fit functions. The red solid line is the $\Xi^0 K_S^0 \pi^+$ signal shape. The blue solid line represents the polynomial function for the background, and the green shaded histogram is the simulated background contribution derived from the inclusive MC sample.

$13.1^{+4.6}_{-3.9}$ and 125.4 ± 20.2 , respectively, where the uncertainty is statistical. The statistical significances are 9.4σ , 3.4σ , and 6.6σ for the signal modes $\Lambda K_S^0 K^+$, $\Sigma^0 K_S^0 K^+$, and $\Xi^0 K_S^0 \pi^+$, respectively, and are estimated by comparing the fit likelihoods with and without including the signal components. The BF of the signal decays are calculated as

$$\mathcal{B} = \frac{N^{\text{DT}}}{\sum_{ij} N_{ij}^{\text{ST}} \cdot (\epsilon_{ij}^{\text{DT}} / \epsilon_{ij}^{\text{ST}}) \cdot \mathcal{B}_{\text{int}}}, \quad (1)$$

where i and j are the different ST modes and center-of-mass energies of the data samples. The value N^{DT} is the total DT yield of each ST mode and center-of-mass energy. $\mathcal{B}_{\text{int}}$ is the BF of $K_S^0 \rightarrow \pi^+ \pi^-$, which is $(69.2 \pm 0.05)\%$, as quoted by the PDG [20]. The values N_{ij}^{ST} , $\epsilon_{ij}^{\text{ST}}$, and $\epsilon_{ij}^{\text{DT}}$ represent the ST yield and efficiency, and the DT efficiency, respectively, where the latter is obtained by using the corresponding exclusive DT signal MC samples. The efficiencies $\epsilon_{i,j}^{\text{ST}}$, $\epsilon_{i,j}^{\text{DT}}$ for the twelve tag modes for each center-of-mass energy are presented in Tables IV–VII. The corresponding BF results are summarized in Table I. Since the $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ decay has a relatively low statistical significance, the upper limit on the BF is set at the 90% confidence level based on the Bayesian approach with a flat prior [41–44]. The upper limit is determined to be 1.28×10^{-3} , as shown in Fig. 5. Corresponding systematic uncertainties are taken into account in the estimation of the upper limit. The additive uncertainties, represented by the M_{miss} fit in Table VIII, are addressed by varying the DT fit method, and the most conservative upper limit is chosen. The multiplicative uncertainties are used to smear the likelihood distribution by a value of 8.6%.

V. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainty for the BF measurements include track and K_S^0 reconstruction, PID, the M_{miss} fit, the quoted intermediate BF of the K_S^0 , determination of the $\bar{\Lambda}_c^-$ ST yields, choice of the MC model, and generated MC statistics.

The systematic uncertainties from the tracking reconstruction and PID of the charged kaon and pion are 1%, as quoted from Ref. [40]. The systematic uncertainty due to the fitted DT yields is estimated by altering the shape of the signal and background candidates in the fit of the M_{miss} distribution. For the description of the signal shape, the MC derived curve is convolved with a double Gaussian function, while the background shape is changed from a first-order polynomial function to a MC derived shape. For the K_S^0 reconstruction, the systematic uncertainty due to the efficiency difference between MC and data samples is estimated using a control sample of the decays $J/\psi \rightarrow K_S^0 K^\pm \pi^\mp$. The efficiency of K_S^0 reconstruction is recalculated based on

TABLE V. DT efficiencies of $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ ($\epsilon_{i,\Lambda K_S^0 K^+}^{\text{DT}}$, in %) for 12 tag modes at various energy points. The uncertainty is statistical only.

Mode	4599.53 MeV	4611.86 MeV	4628.00 MeV	4640.91 MeV	4661.24 MeV	4681.92 MeV	4698.82 MeV
$\bar{p} K_S^0$	15.01 ± 0.18	13.68 ± 0.17	13.33 ± 0.17	13.21 ± 0.17	12.83 ± 0.17	12.86 ± 0.17	12.34 ± 0.17
$\bar{p} K^+ \pi^-$	13.98 ± 0.12	12.79 ± 0.12	12.41 ± 0.12	12.61 ± 0.12	12.61 ± 0.12	12.20 ± 0.12	12.00 ± 0.12
$\bar{p} K_S^0 \pi^0$	5.89 ± 0.11	5.23 ± 0.10	5.23 ± 0.10	5.39 ± 0.10	5.27 ± 0.10	4.96 ± 0.10	5.09 ± 0.10
$\bar{p} K_S^0 \pi^- \pi^+$	5.42 ± 0.11	4.59 ± 0.11	4.38 ± 0.10	4.52 ± 0.10	4.49 ± 0.10	4.39 ± 0.10	04.40 ± 0.10
$\bar{p} K^+ \pi^- \pi^0$	5.37 ± 0.10	4.82 ± 0.09	5.02 ± 0.09	4.99 ± 0.09	4.76 ± 0.09	4.42 ± 0.09	4.50 ± 0.09
$\bar{\Lambda} \pi^-$	12.45 ± 0.26	11.28 ± 0.25	10.80 ± 0.25	10.92 ± 0.25	10.73 ± 0.24	10.45 ± 0.24	10.56 ± 0.24
$\bar{\Lambda} \pi^- \pi^0$	5.31 ± 0.08	4.63 ± 0.07	4.62 ± 0.07	4.52 ± 0.07	4.57 ± 0.07	4.37 ± 0.07	4.19 ± 0.07
$\bar{\Lambda} \pi^- \pi^+ \pi^-$	3.43 ± 0.09	2.92 ± 0.08	3.17 ± 0.08	3.02 ± 0.08	2.97 ± 0.08	3.12 ± 0.08	2.97 ± 0.08
$\bar{\Sigma}^0 \pi^-$	7.75 ± 0.21	7.58 ± 0.21	6.72 ± 0.20	7.00 ± 0.20	6.73 ± 0.20	6.65 ± 0.20	6.35 ± 0.19
$\bar{\Sigma}^- \pi^0$	6.42 ± 0.20	6.52 ± 0.20	6.29 ± 0.20	5.71 ± 0.19	5.99 ± 0.19	5.61 ± 0.18	5.76 ± 0.19
$\bar{\Sigma}^- \pi^- \pi^+$	6.90 ± 0.11	6.30 ± 0.10	6.20 ± 0.10	6.18 ± 0.10	6.04 ± 0.10	5.97 ± 0.10	5.54 ± 0.10
$\bar{p} \pi^- \pi^+$	15.50 ± 0.48	14.59 ± 0.47	14.45 ± 0.47	14.14 ± 0.46	13.83 ± 0.45	13.14 ± 0.45	13.22 ± 0.45

TABLE VI. DT efficiencies of $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ ($\epsilon_{i,\Sigma^0 K_S^0 K^+}^{\text{DT}}$, in %) for 12 tag modes at various energy points. The uncertainty is statistical only.

Mode	4599.53 MeV	4611.86 MeV	4628.00 MeV	4640.91 MeV	4661.24 MeV	4681.92 MeV	4698.82 MeV
$\bar{p} K_S^0$	10.97 ± 0.16	10.08 ± 0.15	9.89 ± 0.15	9.93 ± 0.15	9.69 ± 0.15	9.75 ± 0.15	9.52 ± 0.15
$\bar{p} K^+ \pi^-$	10.31 ± 0.11	9.30 ± 0.10	9.40 ± 0.10	9.39 ± 0.10	9.20 ± 0.10	9.21 ± 0.10	9.18 ± 0.10
$\bar{p} K_S^0 \pi^0$	4.45 ± 0.09	3.94 ± 0.09	3.94 ± 0.09	3.94 ± 0.09	3.92 ± 0.09	3.87 ± 0.09	3.90 ± 0.09
$\bar{p} K_S^0 \pi^- \pi^+$	3.89 ± 0.10	3.18 ± 0.09	3.04 ± 0.09	3.18 ± 0.09	3.17 ± 0.09	3.27 ± 0.09	3.07 ± 0.09
$\bar{p} K^+ \pi^- \pi^0$	4.13 ± 0.09	3.69 ± 0.08	3.71 ± 0.08	3.68 ± 0.08	3.74 ± 0.08	3.56 ± 0.08	3.46 ± 0.08
$\bar{\Lambda} \pi^-$	9.52 ± 0.23	8.20 ± 0.22	8.06 ± 0.21	8.04 ± 0.21	7.54 ± 0.21	7.78 ± 0.21	7.90 ± 0.21
$\bar{\Lambda} \pi^- \pi^0$	3.85 ± 0.06	3.49 ± 0.06	3.46 ± 0.06	3.52 ± 0.06	3.38 ± 0.06	3.37 ± 0.06	3.37 ± 0.06
$\bar{\Lambda} \pi^- \pi^+ \pi^-$	2.56 ± 0.07	2.12 ± 0.07	2.04 ± 0.07	2.26 ± 0.07	2.44 ± 0.07	2.25 ± 0.07	2.35 ± 0.07
$\bar{\Sigma}^0 \pi^-$	6.16 ± 0.19	5.04 ± 0.17	5.01 ± 0.17	5.01 ± 0.17	5.23 ± 0.18	5.02 ± 0.17	4.70 ± 0.17
$\bar{\Sigma}^- \pi^0$	5.10 ± 0.18	4.84 ± 0.17	4.86 ± 0.17	4.51 ± 0.17	4.61 ± 0.17	4.13 ± 0.16	4.45 ± 0.17
$\bar{\Sigma}^- \pi^- \pi^+$	5.07 ± 0.09	4.73 ± 0.09	4.67 ± 0.09	4.57 ± 0.09	4.47 ± 0.09	4.56 ± 0.09	4.49 ± 0.09
$\bar{p} \pi^- \pi^+$	11.08 ± 0.42	10.78 ± 0.41	11.14 ± 0.42	11.36 ± 0.43	9.93 ± 0.40	11.09 ± 0.42	9.92 ± 0.39

TABLE VII. DT efficiencies of $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ ($\epsilon_{i,\Xi^0 K_S^0 \pi^+}^{\text{DT}}$, in %) for 12 tag modes at various energy points. The uncertainty is statistical only.

Mode	4599.53 MeV	4611.86 MeV	4628.00 MeV	4640.91 MeV	4661.24 MeV	4681.92 MeV	4698.82 MeV
$\bar{p} K_S^0$	21.98 ± 0.21	19.03 ± 0.20	19.95 ± 0.20	20.17 ± 0.20	20.26 ± 0.20	20.95 ± 0.21	20.62 ± 0.20
$\bar{p} K^+ \pi^-$	19.65 ± 0.14	18.18 ± 0.14	18.53 ± 0.14	18.58 ± 0.14	18.62 ± 0.14	18.87 ± 0.14	18.75 ± 0.14
$\bar{p} K_S^0 \pi^0$	8.69 ± 0.13	7.74 ± 0.12	7.82 ± 0.12	7.83 ± 0.12	7.85 ± 0.12	7.94 ± 0.12	7.89 ± 0.12
$\bar{p} K_S^0 \pi^- \pi^+$	7.23 ± 0.13	6.45 ± 0.12	6.58 ± 0.13	6.62 ± 0.13	6.63 ± 0.13	6.79 ± 0.13	6.71 ± 0.13
$\bar{p} K^+ \pi^- \pi^0$	8.25 ± 0.12	8.06 ± 0.12	8.07 ± 0.12	8.08 ± 0.12	8.09 ± 0.12	8.10 ± 0.12	8.10 ± 0.12
$\bar{\Lambda} \pi^-$	17.96 ± 0.30	15.68 ± 0.29	16.45 ± 0.29	16.65 ± 0.29	16.71 ± 0.30	17.32 ± 0.30	17.03 ± 0.30
$\bar{\Lambda} \pi^- \pi^0$	7.90 ± 0.09	7.19 ± 0.09	7.40 ± 0.09	7.44 ± 0.09	7.47 ± 0.09	7.61 ± 0.09	7.54 ± 0.09
$\bar{\Lambda} \pi^- \pi^+ \pi^-$	4.86 ± 0.10	4.35 ± 0.10	4.47 ± 0.10	4.50 ± 0.10	4.51 ± 0.10	4.65 ± 0.10	4.58 ± 0.10
$\bar{\Sigma}^0 \pi^-$	11.77 ± 0.26	11.62 ± 0.26	11.63 ± 0.26	11.65 ± 0.26	11.65 ± 0.26	11.65 ± 0.26	11.64 ± 0.26
$\bar{\Sigma}^- \pi^0$	9.76 ± 0.24	8.74 ± 0.23	8.96 ± 0.23	9.02 ± 0.23	9.04 ± 0.23	9.26 ± 0.23	9.15 ± 0.23
$\bar{\Sigma}^- \pi^- \pi^+$	9.98 ± 0.13	9.39 ± 0.12	9.52 ± 0.12	9.57 ± 0.13	9.57 ± 0.12	9.74 ± 0.13	9.66 ± 0.13
$\bar{p} \pi^- \pi^+$	21.31 ± 0.54	21.05 ± 0.54	21.08 ± 0.54	21.08 ± 0.54	21.11 ± 0.54	21.14 ± 0.54	21.14 ± 0.54

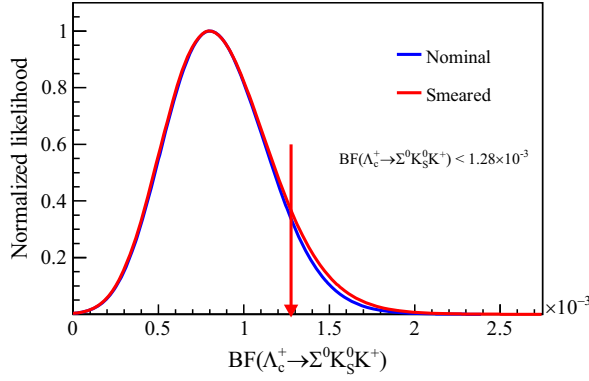


FIG. 5. Normalized likelihood distribution versus the BF of $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$. The blue solid line is the nominal distribution. The red solid line is the smeared distribution with systematic uncertainties considered. The red arrow represents the final upper limit result.

$$\epsilon' = \frac{1}{N} \sum_{i=1}^n \left(\frac{\epsilon^{\text{data}}(P_i)}{\epsilon^{\text{MC}}(P_i)} \right), \quad (2)$$

where ϵ' is the reweighted detection efficiency of the K_S^0 obtained from a control sample of the decays $J/\psi \rightarrow K_S^0 K^\pm \pi^\mp$ of data or simulated samples, respectively, depending on the K_S^0 momentum, P . The value N is the total number of events in the MC sample, while n is the selected number of signal events. The uncertainty is determined by comparing the nominal BF result and the BF with recalculated efficiency. The BF of $K_S^0 \rightarrow \pi^+ \pi^-$ is $(69.20 \pm 0.05)\%$, quoted from the PDG [20], which contributes to a relative systematic uncertainty of 0.1%. The uncertainty from the $\bar{\Lambda}_c^-$ ST yield is estimated by varying the mass range and the signal and background shapes in the fit of the M_{BC} distribution. To estimate the uncertainty from the MC model, the distributions of the simulated sample are reweighted to agree with the data distributions. The mass distribution of $K_S^0 K^+$, ΛK^+ , and ΛK_S^0 for the decay $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ and the mass distributions of $K_S^0 K^+$, $\Sigma^0 K^+$, and $\Sigma^0 K_S^0$ for the decay $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ obtained from the M_{BC} sideband subtraction method are used to reweight the PHSP signal MC distributions. In the case of the decay $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$, the mass distribution of $K_S^0 \pi^+$, $\Xi^0 \pi^+$, and $\Xi^0 K_S^0$ obtained using the S -weights method [45] is utilized to reweight the PHSP signal MC distributions. The difference of BF between the nominal and reweighted samples is assigned as a systematic uncertainty. The uncertainty from the statistical fluctuation $\Delta_{\text{sys}}^{\text{MC}}$ of the MC sample is estimated to be 0.3% for the signal decay modes, according to

$$\Delta_{\text{sys}}^{\text{MC}} = \frac{\sqrt{\sum_j (N_j^{\text{ST}} \Delta \epsilon^j)^2}}{\sum_j N_j^{\text{ST}} \epsilon^j}, \quad (3)$$

TABLE VIII. Relative systematic uncertainties (in %) for the BF measurements.

Source	$\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$	$\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$	$\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$
Tracking	1.0	1.0	1.0
PID	1.0	1.0	1.0
M_{miss} fit	2.1	17.6	0.8
K_S^0 reconstruction	2.6	3.8	1.6
$\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$	0.1	0.1	0.1
$\bar{\Lambda}_c^-$ ST yields	0.7	1.2	1.2
MC model	2.9	7.5	5.1
MC statistics	0.3	0.3	0.3
Total	4.7	19.6	5.7

where j is the energy point, N_j^{ST} is a sum of ST yields from all tag modes at each energy point j , $\epsilon^j =$

$\sum_i \left(\frac{N_{ij}^{\text{ST}}}{\epsilon_{i,j}^{\text{ST}}} \cdot \epsilon_{i,j}^{\text{DT}} \right) / \sum_i N_{ij}^{\text{ST}}$ is the reduction efficiency, and $\Delta \epsilon^j$ is the corresponding error.

Assuming that all the sources are uncorrelated, the total systematic uncertainties of the three decay modes are obtained by adding each of the sources in quadrature, as listed in Table VIII.

VI. SUMMARY

The three Cabibbo-favored decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ are studied by analyzing a 4.5 fb $^{-1}$ data sample at seven center-of-mass energy points varying from 4599.53 to 4698.82 MeV. The BFs of the decays $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$, and $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ are measured to be $(3.12 \pm 0.46 \pm 0.15) \times 10^{-3}$, $(0.80^{+0.28}_{-0.24} \pm 0.16) \times 10^{-3}$, and $(3.70 \pm 0.60 \pm 0.21) \times 10^{-3}$, respectively, where the first uncertainty is statistical and the second is systematic. The BF upper limit of the decay $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ is determined for the first time and is set to be 1.28×10^{-3} at the 90% confidence level. The measured BF of the decay $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$ is consistent with the PDG value $(2.80 \pm 0.55) \times 10^{-3}$ with improved precision. This result is also consistent with the previous BESIII measurement [46] and the theoretical predictions [5,22]. The combination with the previous BESIII measurement [46] gives the average BF of the decay $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$, $(3.07 \pm 0.26 \pm 0.13) \times 10^{-3}$, taking into account the small overlap between the signal samples in the two analyses.

The decay $\Lambda_c^+ \rightarrow \Xi^0 K_S^0 \pi^+$ is observed for the first time, and the measured BF is about 1 order of magnitude lower than the theoretical predictions [5,22], but it is consistent with the statistical isospin model calculation [24] and the theoretical prediction incorporating the contribution of the $H(15)$ [23]. The BF upper limit of the decay $\Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+$ is consistent with Ref. [22], but it is incompatible

with Ref. [5]. These discrepancies motivate further investigations to enhance our understanding of the Λ_c^+ decays involving more than one strange hadron in the final state. All the results are dominated by the statistical uncertainty. Larger datasets are planned to be collected near the $\Lambda_c^+ \bar{\Lambda}_c^-$ threshold in the upcoming years [47] and will allow for further investigation and will deepen our knowledge of the decay mechanisms of charmed baryons.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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