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BESIII Collaboration; Kalantar-Nayestanaki, N.; Kappert, R.; Kavatsyuk, M.; Messchendorp, J.; Rodin, V.

Published in:
Physical Review Letters

DOI:
[10.1103/PhysRevLett.132.031801](https://doi.org/10.1103/PhysRevLett.132.031801)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2024

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

BESIII Collaboration, Kalantar-Nayestanaki, N., Kappert, R., Kavatsyuk, M., Messchendorp, J., & Rodin, V. (2024). First Measurement of the Decay Asymmetry in the Pure W -Boson-Exchange Decay $\Lambda c^+ \rightarrow \Xi 0 K^+$. *Physical Review Letters*, 132(3), Article 031801. <https://doi.org/10.1103/PhysRevLett.132.031801>

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First Measurement of the Decay Asymmetry in the Pure W -Boson-Exchange Decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$

M. Ablikim *et al.**
(BESIII Collaboration)

(Received 6 September 2023; accepted 30 November 2023; published 17 January 2024)

Based on 4.4 fb^{-1} of e^+e^- annihilation data collected at the center-of-mass energies between 4.60 and 4.70 GeV with the BESIII detector at the BEPCII collider, the pure W -boson-exchange decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$ is studied with a full angular analysis. The corresponding decay asymmetry is measured for the first time to be $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16(\text{stat}) \pm 0.03(\text{syst})$. This result reflects the noninterference effect between the S - and P -wave amplitudes. The phase shift between S - and P -wave amplitudes has two solutions, which are $\delta_p - \delta_s = -1.55 \pm 0.25(\text{stat}) \pm 0.05(\text{syst})$ rad or $1.59 \pm 0.25(\text{stat}) \pm 0.05(\text{syst})$ rad.

DOI: 10.1103/PhysRevLett.132.031801

Investigations of charmed baryon decay dynamics are essential for exploring the weak and strong interactions in the standard model (SM) of particle physics. The ground state of the singly charmed baryons Λ_c^+ was discovered in 1979 [1]. Many studies have since been made of the properties of charmed baryons, such as the decay branching fractions (BFs) and decay asymmetries. But experimental results of the decay asymmetries, which are sensitive to the different amplitudes in the decay dynamics, were only a few. Since 2014, there has been some progress on the weak hadronic decays of Λ_c^+ , $\Xi_c^{+,0}$, and Ω_c^0 , both experimentally and theoretically [2–4]. This provides crucial information about the properties of all of the singly charmed baryons and the searches for doubly charmed baryons (Ξ_{cc} and Ω_{cc}) [5]. Nonetheless, the understanding of the decay dynamics of charmed baryons is still limited, due to the lack of precision experimental measurements and the difficulties in the theoretical treatment of strong interaction effects.

Compared to heavy meson decays, charmed baryon decays have a significant dependence on nonfactorizable contributions from W -boson-exchange diagrams. However, these contributions cannot currently be calculated using theoretical approaches. Additionally, no experimental measurements exist for the decay asymmetries of W -boson-exchange hadronic decays. An example of such a process is the decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$, which can only be produced via a W -boson-exchange process as depicted in Fig. 1. Experimental measurements of the asymmetry parameters

of the decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$ can aid understanding of the internal dynamics and can also explore charge-parity (CP) violation in baryons [6].

Table I lists the theoretical calculations of the BF and asymmetry parameters of $\Lambda_c^+ \rightarrow \Xi^0 K^+$, as well as the experimental measurements of the BF. Various predictions of the BFs based on the covariant confined quark model (CCQM), the pole model, and current algebra (CA) in the 1990s are all smaller than the experimental results [2]. This is explained as a strong cancellation in the S - and P -wave amplitudes, corresponding to the $L = 0$ and $L = 1$ orbital angular momenta of the $\Xi^0 - K^+$ system, respectively. Moreover, the decay asymmetry parameter was predicted to be zero in these models owing to the vanishing S -wave amplitude [7–11]. This long-standing puzzle has recently experienced a renewed interest in the theoretical community [6,12,13], especially after the report of new BF measured by BESIII in 2018 [14]. To reproduce the relatively large experimental branching fraction of this decay, the authors of Ref. [6] adopted a variant of the CA approach and obtained a larger $\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+) \simeq 0.71\%$. This modification introduces a large positive decay asymmetry of 0.90, which is quite close to the calculations based on SU(3) symmetry [12,13]. However, regarding the

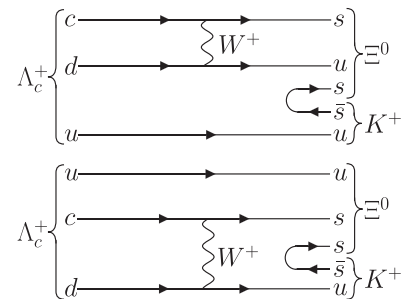


FIG. 1. Feynman diagrams for $\Lambda_c^+ \rightarrow \Xi^0 K^+$.

*Full author list given at the end of the Letter.

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TABLE I. Theoretical calculations and experimental measurements of the BF, $\alpha_{\Xi^0 K^+}$, $|A|$, $|B|$, and $\delta_p - \delta_s$ of $\Lambda_c^+ \rightarrow \Xi^0 K^+$. G_F is the Fermi constant. The superscript a denotes a model with SU(3) symmetry, while model b includes SU(3) symmetry-breaking effects. The PDG fit BF also includes a CLEO result on $\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+)/\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)$ [2].

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \rightarrow \Xi^0 K^+) (\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$|A| (\times 10^{-2} G_F \text{ GeV}^2)$	$|B| (\times 10^{-2} G_F \text{ GeV}^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	...	...	...
Xu (1992), Pole [8]	1.0	0	0	7.94	...
Żencaykowski (1994), Pole [9]	3.6	0	...	...	...
Ivanov (1998), CCQM [10]	3.1	0	...	...	...
Sharma (1999), CA [11]	1.3	0	...	...	...
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	...
Zou (2020), CA [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3) ^a [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	...
Zhong (2022), SU(3) ^b [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	...
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

significant enhancement of $\alpha_{\Xi^0 K^+}$ from 0 to about 0.9, the authors of Ref. [15] pointed out that the particular construction of the S -wave amplitude in Ref. [6] is not well justified. So experimental measurement of the asymmetry parameter of the decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$ will be crucial to test these calculations and confirm the vanishing S -wave contribution [15].

In the SM, the amplitude for a spin-1/2 baryon decaying into a spin-1/2 baryon and a spin-0 meson can be written as $\mathcal{M} = i\bar{u}_f(A - B\gamma_5)u_i$, where A and B are constants, and u_i and \bar{u}_f are spinors describing the initial and final baryons [8]. For the decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$, the decay asymmetry is defined by $\alpha_{\Xi^0 K^+} = 2\text{Re}(s^*p)/(|s|^2 + |p|^2)$, where $s = A$ and $p = |\vec{p}_{\Xi^0}|B/(E_{\Xi^0} + m_{\Xi^0})$; here E_{Ξ^0} and \vec{p}_{Ξ^0} are the energy and momentum of the Ξ^0 in the Λ_c^+ rest frame [2]. The effect of the S - and P -wave phase shift difference, $\delta_p - \delta_s$, is not well accounted for in the theoretical calculations of decay asymmetries. It can be extracted from experiments combined with the BF cited from the Particle Data Group (PDG) [2] and provides an important experimental parameter for the theoretical prediction of CP violation [16].

In this Letter, we present the first measurement of the decay asymmetry of $\Lambda_c^+ \rightarrow \Xi^0 K^+$ and its decay dynamic parameters ($|A|$, $|B|$, and $\delta_p - \delta_s$). A multidimensional angular analysis of the cascade-decay $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$, $\Lambda_c^+ \rightarrow \Xi^0 K^+$, $\Xi^0 \rightarrow \Lambda \pi^0$, and $\Lambda \rightarrow p \pi^-$ is performed using a technique similar to that used to measure the asymmetry parameters of $\Lambda_c^+ \rightarrow p K_S^0$, $\Lambda \pi^+$, $\Sigma^+ \pi^0$, and $\Sigma^0 \pi^+$ [17]. The data samples used in this analysis, with an integrated luminosity of 4.4 fb^{-1} , were collected at center-of-mass (CM) energies of 4.60 (587 pb^{-1}), 4.63 (522 pb^{-1}), 4.64 (552 pb^{-1}), 4.66 (529 pb^{-1}), 4.68 (1667 pb^{-1}), and 4.70 GeV (536 pb^{-1}) with the BESIII detector at the BEPCII collider [18–20]. The values in the parentheses are the corresponding luminosities. Details about BEPCII

as well as BESIII and its subdetectors can be found in Refs. [21–25]. Large data samples taken around the $\Lambda_c^+ \bar{\Lambda}_c^-$ production threshold allow one to measure decay asymmetry of low BF decays with the single-tag technique [26]. The low-background environment is more favorable to measure $\alpha_{\Xi^0 K^+}$ accurately. Charge-conjugate modes are always implied unless explicitly stated otherwise.

Simulated event samples produced with a GEANT4-based [27] Monte Carlo (MC) package, which provides the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. More details about simulations can be found in Ref. [28]. The phase space MC signal sample is generated uniformly over phase space, which is $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ followed by $\Lambda_c^+ \rightarrow \Xi^0 K^+$, $\Xi^0 \rightarrow \Lambda(\rightarrow p \pi^-)\pi^0(\rightarrow \gamma\gamma)$ and $\bar{\Lambda}_c^-$ decaying inclusively. For the signal MC sample, the signal process is generated by the helicity formalism using the decay asymmetry parameters measured in this Letter or cited from the PDG [2].

A detailed description of the selection criteria for charged tracks, showers, π^0 , and Λ candidates is provided in Ref. [28]. The only difference is the χ^2 of vertex fit, which constrains the daughter tracks $p \pi^-$ from Λ decays to a common originating vertex, imposed to be less than 20 in order to better suppress the background. The Ξ^0 candidates are formed by $\Lambda \pi^0$ combinations and the invariant mass $M_{\Lambda \pi^0}$ must be within the mass region (1.30, 1.33) GeV/ c^2 . The mass region is selected to be about three times the resolution.

Two kinematic variables, the energy difference $\Delta E \equiv E_{\Lambda_c^+} - E_{\text{beam}}$ and the beam-constrained mass $M_{\text{BC}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_{\Lambda_c^+}|^2/c^2}$, are defined to identify $\Lambda_c^+ \rightarrow \Xi^0 K^+$ candidates. Here, $E_{\Lambda_c^+}$ and $\vec{p}_{\Lambda_c^+}$ are the reconstructed energy and momentum of the Λ_c^+ candidates calculated in the e^+e^- rest frame, and E_{beam} is the average energy of the e^+ and e^- beams. All candidates are required to satisfy

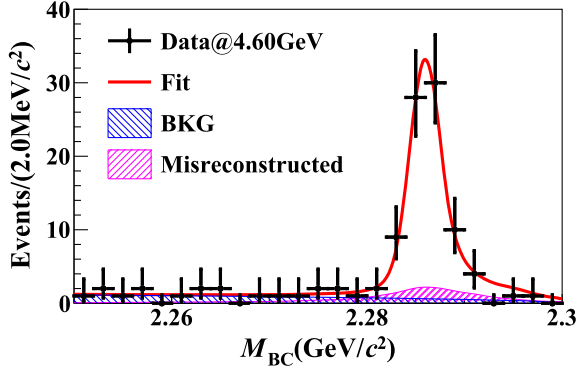


FIG. 2. Distribution of the M_{BC} fitting result at 4.60 GeV, and the corresponding signal yield is 70 ± 8 . Black points with error bars are data; the blue shaded region indicates the combinatorial background events and the pink shaded region is the misreconstructed signal events.

$|\Delta E| < 0.05$ GeV and $2.25 \text{ GeV}/c^2 < M_{BC} < E_{\text{beam}}$. If more than one candidate satisfies the above requirements, the one with minimal $|\Delta E|$ is kept. After applying these conditions, the M_{BC} distribution in data collected at 4.60 GeV is shown in Fig. 2. In the fit to this data, the correctly and misreconstructed signal shapes are modeled with the MC-simulated shape convolved with a Gaussian function representing the resolution difference between data and MC simulation, and the background shape is described by an ARGUS function [29]. Finally, 378 ± 21 signal events are obtained by combining the six energy points.

The decay asymmetry parameters are determined by analyzing the multidimensional angular distributions, where the full cascade-decay chain is considered. The joint angular formula is obtained using the helicity basis [30]. Figure 3 illustrates the definitions of the helicity angles for the three-level cascade decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$, $\Xi^0 \rightarrow \Lambda \pi^0$, and $\Lambda \rightarrow p \pi^-$ following the process of $e^+ e^- \rightarrow \gamma^* \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$. In the helicity frame of the $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$, θ_0 is the polar angle of the Λ_c^+ with respect to the e^+ beam axis in the $e^+ e^-$ CM system. For the $\Lambda_c^+ \rightarrow \Xi^0 K^+$ decay, ϕ_1 is the angle between the $e^+ \Lambda_c^+$ and $\Xi^0 K^+$ planes, and θ_1 is the polar angle of the Ξ^0 with respect to the direction of $\bar{\Lambda}_c^-$ evaluated in Λ_c^+ 's rest frame. For the $\Xi^0 \rightarrow \Lambda \pi^0$ decay, ϕ_2 is the angle between the $\Xi^0 K^+$ and $\Lambda \pi^0$ planes, and θ_2 is the polar angle of the Λ with respect to the direction of K^+ evaluated in Ξ^0 's rest frame. For the helicity angles describing the $\Lambda \rightarrow p \pi^-$ decay, ϕ_3 is the angle between the $\Lambda \pi^0$ and $p \pi^-$ planes, and θ_3 is the polar angle of the proton with respect to the direction of π^0 evaluated in Λ 's rest frame.

In Ref. [30], Δ_0 is defined as the phase shift between two individual helicity amplitudes, $\mathcal{H}_{\lambda_1, \lambda_2}$, for the Λ_c^+ production process $\gamma^*(\lambda_0) \rightarrow \Lambda_c^+(\lambda_1) \bar{\Lambda}_c^-(\lambda_2)$ with γ^* 's helicity $\lambda_0 = \pm 1$, and total helicities $|\lambda_1 - \lambda_2| = 0$ and 1, respectively. In the case where one-photon exchange dominates

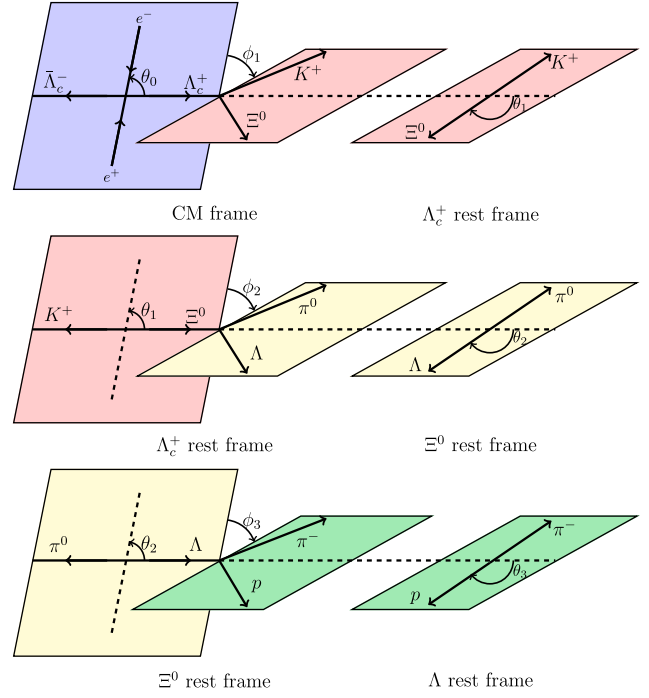


FIG. 3. Definitions of the helicity frames and related angles for $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$, $\Lambda_c^+ \rightarrow \Xi^0 K^+$, $\Xi^0 \rightarrow \Lambda \pi^0$, and $\Lambda \rightarrow p \pi^-$.

the production process, Δ_0 is also the phase between the electric and magnetic form factors of Λ_c^+ [33,34], and α_0 is the angular distribution parameter of Λ_c^+ defined by the helicity amplitude $\alpha_0 = (|\mathcal{H}_{1/2, -1/2}|^2 - 2|\mathcal{H}_{1/2, 1/2}|^2) / (|\mathcal{H}_{1/2, -1/2}|^2 + 2|\mathcal{H}_{1/2, 1/2}|^2)$. Similarly, the $\Lambda_c^+ \rightarrow \Xi^0 K^+$ decay is described by two parameters, $\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$, where the latter one is the phase shift between the two helicity amplitudes. The Lee-Yang parameters [30,35] can be obtained with the relations

$$\begin{aligned} \beta_{\Xi^0 K^+} &= \sqrt{1 - (\alpha_{\Xi^0 K^+})^2} \sin \Delta_{\Xi^0 K^+}, \\ \gamma_{\Xi^0 K^+} &= \sqrt{1 - (\alpha_{\Xi^0 K^+})^2} \cos \Delta_{\Xi^0 K^+}. \end{aligned} \quad (1)$$

In this analysis, the common free parameters ($\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$) describing the angular distributions for the six datasets are determined by a simultaneous unbinned maximum likelihood fit. The likelihood function is constructed from the joint probability density function (PDF) by

$$\mathcal{L}_{\text{total}} = \sum_{\text{energy}} \mathcal{L}_{\text{data}} = \prod_{i=1}^{N_{\text{data}}} f_s(\vec{\xi}_i). \quad (2)$$

Here, $f_s(\vec{\xi}_i)$ is the PDF of the signal process, N_{data} is the number of events in the data, and i is the event index. The signal PDF $f_s(\vec{\xi}_i)$ is formulated as

$$f_s(\vec{\xi}_i) = \frac{\epsilon(\vec{\xi}_i) |M(\vec{\xi}_i; \vec{\eta})|^2}{\int \epsilon(\vec{\xi}_i) |M(\vec{\xi}_i; \vec{\eta})|^2 d\vec{\xi}_i}, \quad (3)$$

where $\vec{\xi}_i$ denotes the kinematic angular observables ($\theta_{0,1,2,3}$ and $\phi_{1,2,3}$) and $\vec{\eta}$ denotes the free parameters ($\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$) to be determined. $M(\vec{\xi}_i; \vec{\eta})$ is the total amplitude [30] of all decay chains and $\epsilon(\vec{\xi}_i)$ is the detection efficiency parametrized in terms of the kinematic variables $\vec{\xi}_i$. The background contribution to the joint likelihood is subtracted according to the calculated likelihoods for the combinatorial background based on the inclusive MC simulation and for the misreconstructed signal events based on the signal MC simulation. The integration of the normalization factor is calculated with a large phase space MC sample as

$$\int \epsilon(\vec{\xi}_i) |M(\vec{\xi}_i; \vec{\eta})|^2 d\vec{\xi}_i = \frac{1}{N_{\text{gen}}} \sum_{k_{\text{MC}}}^{N_{\text{MC}}} |M(\vec{\xi}_{k_{\text{MC}}}; \vec{\eta})|^2, \quad (4)$$

where N_{gen} is the total number of the simulated phase space MC events, N_{MC} is the number of the phase space MC events surviving all selection criteria, and k_{MC} is the event index.

Using the MINUIT package [36], we minimize the negative logarithmic likelihood with background subtraction over the six data samples. Here, α_0 , Δ_0 , $\alpha_{\Lambda\pi^0}$, $\alpha_{\bar{\Lambda}\pi^0}$, $\Delta_{\Lambda\pi^0}$, and $\Delta_{\bar{\Lambda}\pi^0}$ are fixed to individual values measured by BESIII [37,38], where the α_0 and Δ_0 can be different at different energy points. $\alpha_{p\pi^-}$ and $\alpha_{\bar{p}\pi^+}$ are fixed to the values from the PDG [2]. In the fit, $\alpha_{\Xi^0 K^+}$ and $\Delta_{\Xi^0 K^+}$ are free parameters, and $\alpha_{\Xi^0 K^+} = -\alpha_{\Xi^0 K^-}$ and $\Delta_{\Xi^0 K^+} = -\Delta_{\Xi^0 K^-}$ as required under the CP invariance assumption. The projections of the best fit onto several variables are shown in Fig. 4. The data are compared with the MC events weighted by the nominal fitting result. From this fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16$ and $\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90$ rad. Hence, the other two Lee-Yang parameters are calculated to be $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58$, where the uncertainties are statistical only.

The systematic uncertainties arise mainly from the reconstruction of final state particles, which is studied with $J/\psi \rightarrow K_s^0 K^\pm \pi^\mp$ for kaon, $\Lambda_c^+ \rightarrow \Lambda X$ for Λ , $\psi(3686) \rightarrow J/\psi \pi^0 \pi^0$ and $e^+ e^- \rightarrow \omega \pi^0$ for π^0 . The systematic uncertainties for the ΔE requirement and M_{BC} signal regions are estimated by smearing the phase space MC samples using resolution parameters, and for the background subtraction by taking into account the background shape and size. The uncertainties from the quoted values of α_0 , Δ_0 , $\alpha_{\Lambda\pi^0}$, $\alpha_{\bar{\Lambda}\pi^0}$, $\Delta_{\Lambda\pi^0}$, $\Delta_{\bar{\Lambda}\pi^0}$, $\alpha_{p\pi^-}$, and $\alpha_{\bar{p}\pi^+}$ are estimated by Gaussian sampling considering their uncertainties and refit the angular distribution, and by taking the values in one time uncertainty of Gaussian fit as the uncertainties of this part. A further source of uncertainty is the fit bias, which is the difference before and after the correction from a pull distribution check. Systematic uncertainties from all

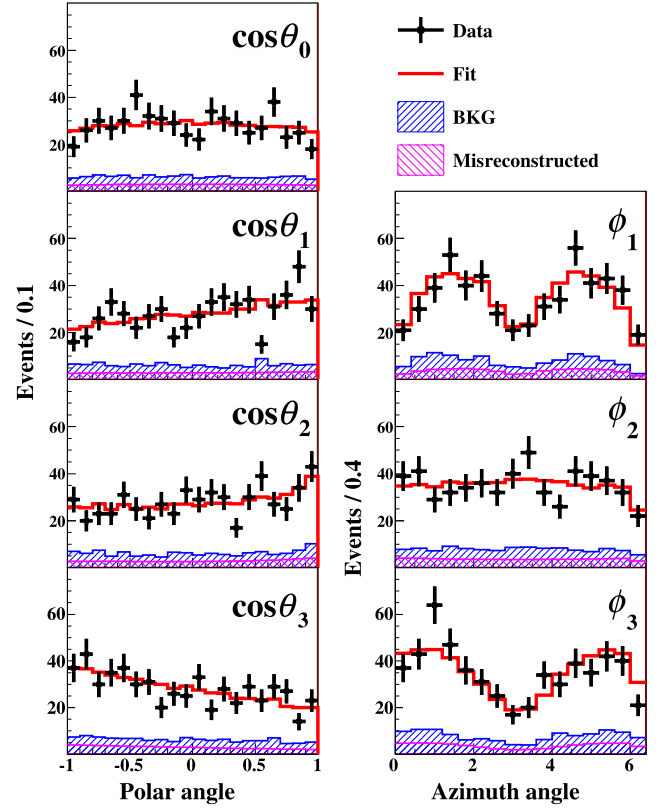


FIG. 4. Projections of the best fit onto various variables. Black points with error bars are data; red solid lines are phase space MC events reweighted by angular distribution formula, and represent the fitting result; the blue shaded region denotes the combinatorial background events and the pink shaded region is the misreconstructed signal events.

sources are combined in quadrature to calculate the total systematic uncertainties. All details of systematic uncertainties can be found in Ref. [30].

One has $\delta_p - \delta_s = \arctan(\sqrt{1 - \alpha_{\Xi^0 K^+}^2} \sin \Delta_{\Xi^0 K^+} / \alpha_{\Xi^0 K^+})$, and the derivation of $|A|$ and $|B|$ can be found in Ref. [30]. The study has uncovered two distinct physical solutions, with the first one characterized by $|A| = 1.6_{-1.6}^{+1.9}(\text{stat}) \pm 0.4(\text{syst})$ and $|B| = 18.3 \pm 2.8(\text{stat}) \pm 0.7(\text{syst})$, and the second one by $|A| = 4.3 \pm 0.7(\text{stat}) \pm 0.2(\text{syst})$ and $|B| = 6.7_{-6.7}^{+8.3}(\text{stat}) \pm 1.6(\text{syst})$.

In summary, by analyzing 4.4 fb^{-1} of $e^+ e^-$ annihilation data collected at the CM energies between 4.60 and 4.70 GeV with the BESIII detector, the pure W -boson-exchange decay $\Lambda_c^+ \rightarrow \Xi^0 K^+$ from the $e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ production has been studied. The decay asymmetry parameters are measured for the first time as $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16(\text{stat}) \pm 0.03(\text{syst})$ and $\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90(\text{stat}) \pm 0.17(\text{syst})$ rad. The other two Lee-Yang parameters are calculated to be $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69(\text{stat}) \pm 0.13(\text{syst})$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58(\text{stat}) \pm 0.11(\text{syst})$. The comparison between this Letter and theoretical predictions is

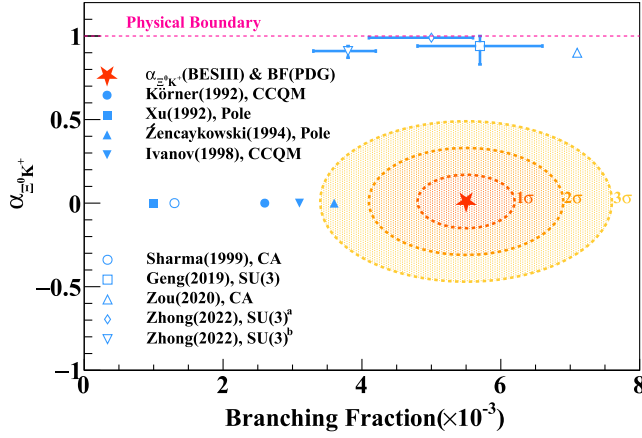


FIG. 5. Comparison between this Letter and theoretical predictions, where the branching fraction is taken from PDG (2022) [2]. The 1σ , 2σ , and 3σ contours correspond to 68.2%, 95.4%, and 99.7% confidence level, respectively. The blue symbols are theoretical predictions and the red star is the result from this Letter. The definitions of the superscripts a and b can be found in Table I and the theory acronyms are explained in the text.

shown in Fig. 5. Our measurement of $\alpha_{E^0 K^+}$ is in good agreement with zero, which is consistent with the theoretical predictions from the 1990s. The decay dynamics parameters $|A|$, $|B|$, and $\delta_p - \delta_s$ are derived. The value of $\delta_p - \delta_s$ has two solutions, which are $\delta_p - \delta_s = -1.55 \pm 0.25(\text{stat}) \pm 0.05(\text{syst})$ rad or $1.59 \pm 0.25(\text{stat}) \pm 0.05(\text{syst})$ rad. This is of great significance for decay asymmetries, as $\cos(\delta_p - \delta_s)$ measured in this Letter is close to zero, an effect that had not been anticipated in previous literature. This measurement resolves the long-standing puzzle and deepens our understanding of the strong dynamics in the charmed baryon sector.

P.-R. Li and X.-R. Lyu thank Hai-Yang Cheng, Fan-Rong Xu, and Fu-Sheng Yu for useful discussions. The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key R&D Program of China under Contract Nos. 2020YFA0406400 and 2020YFA0406300; National Natural Science Foundation of China (NSFC) under Contract Nos. 11635010, 11735014, 11835012, 11935015, 11935016, 11935018, 11961141012, 12022510, 12025502, 12035009, 12035013, 12061131003, 12192260, 12192261, 12192262, 12192263, 12192264, 12192265, 12221005, 12225509, 12235017; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1832207; CAS Key Research Program of Frontier Sciences under Contract Nos. QYZDJ-SSW-SLH003 and QYZDJ-SSW-SLH040; 100 Talents Program of CAS; Fundamental Research Funds for the

Central Universities, Lanzhou University, University of Chinese Academy of Sciences; the Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; European Union's Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement under Contract No. 894790; German Research Foundation DFG under Contract Nos. 443159800 and 455635585, Collaborative Research Center CRC 1044, FOR5327, GRK 2149; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; National Science Research and Innovation Fund (NSRF) via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation of Thailand under Contract No. B16F640076; Polish National Science Centre under Contract No. 2019/35/O/ST2/02907; the Swedish Research Council; and the U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

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M. Ablikim,¹ M. N. Achasov,^{5,b} P. Adlarson,⁷⁴ X. C. Ai,⁸⁰ R. Aliberti,³⁵ A. Amoroso,^{73a,73c} M. R. An,³⁹ Q. An,^{70,57} Y. Bai,⁵⁶ O. Bakina,³⁶ I. Balossino,^{29a} Y. Ban,^{46,g} V. Batzskaya,^{1,44} K. Begzsuren,³² N. Berger,³⁵ M. Berlowski,⁴⁴ M. Bertani,^{28a} D. Bettoni,^{29a} F. Bianchi,^{73a,73c} E. Bianco,^{73a,73c} A. Bortone,^{73a,73c} I. Boyko,³⁶ R. A. Briere,⁶ A. Brueggemann,⁶⁷ H. Cai,⁷⁵ X. Cai,^{1,57} A. Calcaterra,^{28a} G. F. Cao,^{1,62} N. Cao,^{1,62} S. A. Cetin,^{61a} J. F. Chang,^{1,57} T. T. Chang,⁷⁶ W. L. Chang,^{1,62} G. R. Che,⁴³ G. Chelkov,^{36,a} C. Chen,⁴³ Chao Chen,⁵⁴ G. Chen,¹ H. S. Chen,^{1,62} M. L. Chen,^{1,57,62} S. J. Chen,⁴² S. M. Chen,⁶⁰ T. Chen,^{1,62} X. R. Chen,^{31,62} X. T. Chen,^{1,62} Y. B. Chen,^{1,57} Y. Q. Chen,³⁴ Z. J. Chen,^{25,h} W. S. Cheng,^{73c} S. K. Choi,¹¹ X. Chu,⁴³ G. Cibinetto,^{29a} S. C. Coen,⁴ F. Cossio,^{73c} J. J. Cui,⁴⁹ H. L. Dai,^{1,57} J. P. Dai,⁷⁸ A. Dbeyssi,¹⁸ R. E. de Boer,⁴ D. Dedovich,³⁶ Z. Y. Deng,¹ A. Denig,³⁵ I. Denysenko,³⁶ M. Destefanis,^{73a,73c} F. De Mori,^{73a,73c} B. Ding,^{65,1} X. X. Ding,^{46,g} Y. Ding,⁴⁰ Y. Ding,³⁴ J. Dong,^{1,57} L. Y. Dong,^{1,62} M. Y. Dong,^{1,57,62} X. Dong,⁷⁵ M. C. Du,¹ S. X. Du,⁸⁰ Z. H. Duan,⁴² P. Egorov,^{36,a} Y. H. Y. Fan,⁴⁵ Y. L. Fan,⁷⁵ J. Fang,^{1,57} S. S. Fang,^{1,62} W. X. Fang,¹ Y. Fang,¹ R. Farinelli,^{29a} L. Fava,^{73b,73c} F. Feldbauer,⁴ G. Felici,^{28a} C. Q. Feng,^{70,57} J. H. Feng,⁵⁸ K. Fischer,⁶⁸ M. Fritsch,⁴ C. Fritsch,⁶⁷ C. D. Fu,¹ J. L. Fu,⁶² Y. W. Fu,¹ H. Gao,⁶² Y. N. Gao,^{46,g} Yang Gao,^{70,57} S. Garbolino,^{73c} I. Garzia,^{29a,29b} P. T. Ge,⁷⁵ Z. W. Ge,⁴² C. Geng,⁵⁸ E. M. Gersabeck,⁶⁶ A. Gilman,⁶⁸ K. Goetzen,¹⁴ L. Gong,⁴⁰ W. X. Gong,^{1,57} W. Gradl,³⁵ S. Gramigna,^{29a,29b} M. Greco,^{73a,73c} M. H. Gu,^{1,57} C. Y. Guan,^{1,62} Z. L. Guan,²² A. Q. Guo,^{31,62} L. B. Guo,⁴¹ M. J. Guo,⁴⁹ R. P. Guo,⁴⁸ Y. P. Guo,^{13,f} A. Guskov,^{36,a} T. T. Han,⁴⁹ W. Y. Han,³⁹ X. Q. Hao,¹⁹ F. A. Harris,⁶⁴ K. K. He,⁵⁴ K. L. He,^{1,62} F. H. H. Heinsius,⁴ C. H. Heinz,³⁵ Y. K. Heng,^{1,57,62} C. Herold,⁵⁹ T. Holtmann,⁴ P. C. Hong,^{13,f} G. Y. Hou,^{1,62} X. T. Hou,^{1,62} Y. R. Hou,⁶² Z. L. Hou,¹ H. M. Hu,^{1,62} J. F. Hu,^{55,i} T. Hu,^{1,57,62} Y. Hu,¹ G. S. Huang,^{70,57} K. X. Huang,⁵⁸ L. Q. Huang,^{31,62} X. T. Huang,⁴⁹ Y. P. Huang,¹ T. Hussain,⁷² N. Hüskens,^{27,35} W. Imoehl,²⁷ J. Jackson,²⁷ S. Jaeger,⁴ S. Janchiv,³² J. H. Jeong,¹¹ Q. Ji,¹ Q. P. Ji,¹⁹ X. B. Ji,^{1,62} X. L. Ji,^{1,57} Y. Y. Ji,⁴⁹ X. Q. Jia,⁴⁹ Z. K. Jia,^{70,57} H. J. Jiang,⁷⁵ P. C. Jiang,^{46,g} S. S. Jiang,³⁹ T. J. Jiang,¹⁶ X. S. Jiang,^{1,57,62} Y. Jiang,⁶² J. B. Jiao,⁴⁹ Z. Jiao,²³ S. Jin,⁴² Y. Jin,⁶⁵ M. Q. Jing,^{1,62} T. Johansson,⁷⁴ X. K.,¹ S. Kabana,³³ N. Kalantar-Nayestanaki,⁶³ X. L. Kang,¹⁰ X. S. Kang,⁴⁰ R. Kappert,⁶³ M. Kavatsyuk,⁶³ B. C. Ke,⁸⁰ A. Khoukaz,⁶⁷ R. Kiuchi,¹ R. Kliemt,¹⁴ O. B. Kolcu,^{61a} B. Kopf,⁴ M. Kuessner,⁴ A. Kupsc,^{44,74} W. Kühn,³⁷ J. J. Lane,⁶⁶ P. Larin,¹⁸ A. Lavania,²⁶ L. Lavezzi,^{73a,73c} T. T. Lei,^{70,k} Z. H. Lei,^{70,57} H. Leithoff,³⁵ M. Lellmann,³⁵ T. Lenz,³⁵ C. Li,⁴⁷ C. Li,⁴³ C. H. Li,³⁹ Cheng Li,^{70,57} D. M. Li,⁸⁰ F. Li,^{1,57} G. Li,¹ H. Li,^{70,57} H. B. Li,^{1,62} H. J. Li,¹⁹ H. N. Li,^{55,i} Hui Li,⁴³ J. R. Li,⁶⁰ J. S. Li,⁵⁸ J. W. Li,⁴⁹ K. L. Li,¹⁹ Ke Li,¹ L. J. Li,^{1,62} L. K. Li,¹ Lei Li,³ M. H. Li,⁴³ P. R. Li,^{38,j,k} Q. X. Li,⁴⁹ S. X. Li,¹³ T. Li,⁴⁹ W. D. Li,^{1,62} W. G. Li,¹ X. H. Li,^{70,57} X. L. Li,⁴⁹ Xiaoyu Li,^{1,62} Y. G. Li,^{46,g} Z. J. Li,⁵⁸ C. Liang,⁴² H. Liang,^{1,62} H. Liang,^{70,57} H. Liang,³⁴ Y. F. Liang,⁵³ Y. T. Liang,^{31,62} G. R. Liao,¹⁵ L. Z. Liao,⁴⁹ Y. P. Liao,^{1,62} J. Libby,²⁶ A. Limphirat,⁵⁹ D. X. Lin,^{31,62} T. Lin,¹ B. J. Liu,¹ B. X. Liu,⁷⁵ C. Liu,³⁴ C. X. Liu,¹ F. H. Liu,⁵² Fang Liu,¹ Feng Liu,⁷ G. M. Liu,^{55,i} H. Liu,^{38,j,k} H. M. Liu,^{1,62} Huanhuan Liu,¹ Huihui Liu,²¹ J. B. Liu,^{70,57} J. L. Liu,⁷¹ J. Y. Liu,^{1,62} K. Liu,¹ K. Y. Liu,⁴⁰ Ke Liu,²² L. Liu,^{70,57}

L. C. Liu,⁴³ Lu Liu,⁴³ M. H. Liu,^{13,f} P. L. Liu,¹ Q. Liu,⁶² S. B. Liu,^{70,57} T. Liu,^{13,f} W. K. Liu,⁴³ W. M. Liu,^{70,57} X. Liu,^{38,j,k}
 Y. Liu,^{38,j,k} Y. Liu,⁸⁰ Y. B. Liu,⁴³ Z. A. Liu,^{1,57,62} Z. Q. Liu,⁴⁹ X. C. Lou,^{1,57,62} F. X. Lu,⁵⁸ H. J. Lu,²³ J. G. Lu,^{1,57} X. L. Lu,¹
 Y. Lu,⁸ Y. P. Lu,^{1,57} Z. H. Lu,^{1,62} C. L. Luo,⁴¹ M. X. Luo,⁷⁹ T. Luo,^{13,f} X. L. Luo,^{1,57} X. R. Lyu,⁶² Y. F. Lyu,⁴³ F. C. Ma,⁴⁰
 H. L. Ma,¹ J. L. Ma,^{1,62} L. L. Ma,⁴⁹ M. M. Ma,^{1,62} Q. M. Ma,¹ R. Q. Ma,^{1,62} R. T. Ma,⁶² X. Y. Ma,^{1,57} Y. Ma,^{46,g} Y. M. Ma,³¹
 F. E. Maas,¹⁸ M. Maggiora,^{73a,73c} S. Malde,⁶⁸ Q. A. Malik,⁷² A. Mangoni,^{28b} Y. J. Mao,^{46,g} Z. P. Mao,¹ S. Marcello,^{73a,73c}
 Z. X. Meng,⁶⁵ J. G. Messchendorp,^{14,63} G. Mezzadri,^{29a} H. Miao,^{1,62} T. J. Min,⁴² R. E. Mitchell,²⁷ X. H. Mo,^{1,57,62}
 N. Yu. Muchnoi,^{5,b} J. Muskalla,³⁵ Y. Nefedov,³⁶ F. Nerling,^{18,d} I. B. Nikolaev,^{5,b} Z. Ning,^{1,57} S. Nisar,^{12,1} Y. Niu,⁴⁹
 S. L. Olsen,⁶² Q. Ouyang,^{1,57,62} S. Pacetti,^{28b,28c} X. Pan,⁵⁴ Y. Pan,⁵⁶ A. Pathak,³⁴ P. Patteri,^{28a} Y. P. Pei,^{70,57} M. Pelizaesus,⁴
 H. P. Peng,^{70,57} K. Peters,^{14,d} J. L. Ping,⁴¹ R. G. Ping,^{1,62} S. Plura,³⁵ S. Pogodin,³⁶ V. Prasad,³³ F. Z. Qi,¹ H. Qi,^{70,57} H. R. Qi,⁶⁰
 M. Qi,⁴² T. Y. Qi,^{13,f} S. Qian,^{1,57} W. B. Qian,⁶² C. F. Qiao,⁶² J. J. Qin,⁷¹ L. Q. Qin,¹⁵ X. P. Qin,^{13,f} X. S. Qin,⁴⁹ Z. H. Qin,^{1,57}
 J. F. Qiu,¹ S. Q. Qu,⁶⁰ C. F. Redmer,³⁵ K. J. Ren,³⁹ A. Rivetti,^{73c} V. Rodin,⁶³ M. Rolo,^{73c} G. Rong,^{1,62} Ch. Rosner,¹⁸
 S. N. Ruan,⁴³ N. Salone,⁴⁴ A. Sarantsev,^{36,c} Y. Schelhaas,³⁵ K. Schoenning,⁷⁴ M. Scodeggio,^{29a,29b} K. Y. Shan,^{13,f} W. Shan,²⁴
 X. Y. Shan,^{70,57} J. F. Shangguan,⁵⁴ L. G. Shao,^{1,62} M. Shao,^{70,57} C. P. Shen,^{13,f} H. F. Shen,^{1,62} W. H. Shen,⁶² X. Y. Shen,^{1,62}
 B. A. Shi,⁶² H. C. Shi,^{70,57} J. L. Shi,¹³ J. Y. Shi,¹ Q. Q. Shi,⁵⁴ R. S. Shi,^{1,62} X. Shi,^{1,57} J. J. Song,¹⁹ T. Z. Song,⁵⁸
 W. M. Song,^{34,1} Y. J. Song,¹³ Y. X. Song,^{46,g} S. Sosio,^{73a,73c} S. Spataro,^{73a,73c} F. Stieler,³⁵ Y. J. Su,⁶² G. B. Sun,⁷⁵ G. X. Sun,¹
 H. Sun,⁶² H. K. Sun,¹ J. F. Sun,¹⁹ K. Sun,⁶⁰ L. Sun,⁷⁵ S. S. Sun,^{1,62} T. Sun,^{1,62} W. Y. Sun,³⁴ Y. Sun,¹⁰ Y. J. Sun,^{70,57} Y. Z. Sun,¹
 Z. T. Sun,⁴⁹ Y. X. Tan,^{70,57} C. J. Tang,⁵³ G. Y. Tang,¹ J. Tang,⁵⁸ Y. A. Tang,⁷⁵ L. Y. Tao,⁷¹ Q. T. Tao,^{25,h} M. Tat,⁶⁸
 J. X. Teng,^{70,57} V. Thoren,⁷⁴ W. H. Tian,⁵⁸ W. H. Tian,⁵¹ Y. Tian,^{31,62} Z. F. Tian,⁷⁵ I. Uman,^{61b} S. J. Wang,⁴⁹ B. Wang,¹
 B. L. Wang,⁶² Bo Wang,^{70,57} C. W. Wang,⁴² D. Y. Wang,^{46,g} F. Wang,⁷¹ H. J. Wang,^{38,j,k} H. P. Wang,^{1,62} J. P. Wang,⁴⁹
 K. Wang,^{1,57} L. L. Wang,¹ M. Wang,⁴⁹ Meng Wang,^{1,62} S. Wang,^{13,f} S. Wang,^{38,j,k} T. Wang,^{13,f} T. J. Wang,⁴³ W. Wang,⁵⁸
 W. Wang,⁷¹ W. P. Wang,^{70,57} X. Wang,^{46,g} X. F. Wang,^{38,j,k} X. J. Wang,³⁹ X. L. Wang,^{13,f} Y. Wang,⁶⁰ Y. D. Wang,⁴⁵
 Y. F. Wang,^{1,57,62} Y. H. Wang,⁴⁷ Y. N. Wang,⁴⁵ Y. Q. Wang,¹ Yaqian Wang,^{17,1} Yi Wang,⁶⁰ Z. Wang,^{1,57} Z. L. Wang,⁷¹
 Z. Y. Wang,^{1,62} Ziyi Wang,⁶² D. Wei,⁶⁹ D. H. Wei,¹⁵ F. Weidner,⁶⁷ S. P. Wen,¹ C. W. Wenzel,⁴ U. Wiedner,⁴ G. Wilkinson,⁶⁸
 M. Wolke,⁷⁴ L. Wollenberg,⁴ C. Wu,³⁹ J. F. Wu,^{1,62} L. H. Wu,¹ L. J. Wu,^{1,62} X. Wu,^{13,f} X. H. Wu,³⁴ Y. Wu,⁷⁰ Y. J. Wu,³¹
 Z. Wu,^{1,57} L. Xia,^{70,57} X. M. Xian,³⁹ T. Xiang,^{46,g} D. Xiao,^{38,j,k} G. Y. Xiao,⁴² S. Y. Xiao,¹ Y. L. Xiao,^{13,f} Z. J. Xiao,⁴¹ C. Xie,⁴²
 X. H. Xie,^{46,g} Y. Xie,⁴⁹ Y. G. Xie,^{1,57} Y. H. Xie,⁷ Z. P. Xie,^{70,57} T. Y. Xing,^{1,62} C. F. Xu,^{1,62} C. J. Xu,⁵⁸ G. F. Xu,¹ H. Y. Xu,⁶⁵
 Q. J. Xu,¹⁶ Q. N. Xu,³⁰ W. Xu,^{1,62} W. L. Xu,⁶⁵ X. P. Xu,⁵⁴ Y. C. Xu,⁷⁷ Z. P. Xu,⁴² Z. S. Xu,⁶² F. Yan,^{13,f} L. Yan,^{13,f}
 W. B. Yan,^{70,57} W. C. Yan,⁸⁰ X. Q. Yan,¹ H. J. Yang,^{50,e} H. L. Yang,³⁴ H. X. Yang,¹ Tao Yang,¹ Y. Yang,^{13,f} Y. F. Yang,⁴³
 Y. X. Yang,^{1,62} Yifan Yang,^{1,62} Z. W. Yang,^{38,j,k} Z. P. Yao,⁴⁹ M. Ye,^{1,57} M. H. Ye,⁹ J. H. Yin,¹ Z. Y. You,⁵⁸ B. X. Yu,^{1,57,62}
 C. X. Yu,⁴³ G. Yu,^{1,62} J. S. Yu,^{25,h} T. Yu,⁷¹ X. D. Yu,^{46,g} C. Z. Yuan,^{1,62} L. Yuan,² S. C. Yuan,¹ X. Q. Yuan,¹ Y. Yuan,^{1,62}
 Z. Y. Yuan,⁵⁸ C. X. Yue,³⁹ A. A. Zafar,⁷² F. R. Zeng,⁴⁹ X. Zeng,^{13,f} Y. Zeng,^{25,h} Y. J. Zeng,^{1,62} X. Y. Zhai,³⁴ Y. C. Zhai,⁴⁹
 Y. H. Zhan,⁵⁸ A. Q. Zhang,^{1,62} B. L. Zhang,^{1,62} B. X. Zhang,¹ D. H. Zhang,⁴³ G. Y. Zhang,¹⁹ H. Zhang,⁷⁰ H. H. Zhang,⁵⁸
 H. H. Zhang,³⁴ H. Q. Zhang,^{1,57,62} H. Y. Zhang,^{1,57} J. Zhang,⁸⁰ J. J. Zhang,⁵¹ J. L. Zhang,²⁰ J. Q. Zhang,⁴¹ J. W. Zhang,^{1,57,62}
 J. X. Zhang,^{38,j,k} J. Y. Zhang,¹ J. Z. Zhang,^{1,62} Jianyu Zhang,⁶² Jiawei Zhang,^{1,62} L. M. Zhang,⁶⁰ L. Q. Zhang,⁵⁸ Lei Zhang,⁴²
 P. Zhang,^{1,62} Q. Y. Zhang,^{39,80} Shuihan Zhang,^{1,62} Shulei Zhang,^{25,h} X. D. Zhang,⁴⁵ X. M. Zhang,¹ X. Y. Zhang,⁴⁹
 Xuyan Zhang,⁵⁴ Y. Zhang,⁷¹ Y. Zhang,⁶⁸ Y. T. Zhang,⁸⁰ Y. H. Zhang,^{1,57} Yan Zhang,^{70,57} Yao Zhang,¹ Z. H. Zhang,¹
 Z. L. Zhang,³⁴ Z. Y. Zhang,⁷⁵ Z. Y. Zhang,⁴³ G. Zhao,¹ J. Zhao,³⁹ J. Y. Zhao,^{1,62} J. Z. Zhao,^{1,57} Lei Zhao,^{70,57} Ling Zhao,¹
 M. G. Zhao,⁴³ S. J. Zhao,⁸⁰ Y. B. Zhao,^{1,57} Y. X. Zhao,^{31,62} Z. G. Zhao,^{70,57} A. Zhemchugov,^{36,a} B. Zheng,⁷¹ J. P. Zheng,^{1,57}
 W. J. Zheng,^{1,62} Y. H. Zheng,⁶² B. Zhong,⁴¹ X. Zhong,⁵⁸ H. Zhou,⁴⁹ L. P. Zhou,^{1,62} X. Zhou,⁷⁵ X. K. Zhou,⁷ X. R. Zhou,^{70,57}
 X. Y. Zhou,³⁹ Y. Z. Zhou,^{13,f} J. Zhu,⁴³ K. Zhu,¹ K. J. Zhu,^{1,57,62} L. Zhu,³⁴ L. X. Zhu,⁶² S. H. Zhu,⁶⁹ S. Q. Zhu,⁴² T. J. Zhu,^{13,f}
 W. J. Zhu,^{13,f} Y. C. Zhu,^{70,57} Z. A. Zhu,^{1,62} J. H. Zou,¹ and J. Zu^{70,57}

(BESIII Collaboration)

¹*Institute of High Energy Physics, Beijing 100049, People's Republic of China*

²*Beihang University, Beijing 100191, People's Republic of China*

³*Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China*

⁴*Bochum Ruhr-University, D-44780 Bochum, Germany*

⁵*Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*

- ⁶Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
- ⁷Central China Normal University, Wuhan 430079, People's Republic of China
- ⁸Central South University, Changsha 410083, People's Republic of China
- ⁹China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China
- ¹⁰China University of Geosciences, Wuhan 430074, People's Republic of China
- ¹¹Chung-Ang University, Seoul 06974, Republic of Korea
- ¹²COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
- ¹³Fudan University, Shanghai 200433, People's Republic of China
- ¹⁴GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
- ¹⁵Guangxi Normal University, Guilin 541004, People's Republic of China
- ¹⁶Hangzhou Normal University, Hangzhou 310036, People's Republic of China
- ¹⁷Hebei University, Baoding 071002, People's Republic of China
- ¹⁸Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
- ¹⁹Henan Normal University, Xinxiang 453007, People's Republic of China
- ²⁰Henan University, Kaifeng 475004, People's Republic of China
- ²¹Henan University of Science and Technology, Luoyang 471003, People's Republic of China
- ²²Henan University of Technology, Zhengzhou 450001, People's Republic of China
- ²³Huangshan College, Huangshan 245000, People's Republic of China
- ²⁴Hunan Normal University, Changsha 410081, People's Republic of China
- ²⁵Hunan University, Changsha 410082, People's Republic of China
- ²⁶Indian Institute of Technology Madras, Chennai 600036, India
- ²⁷Indiana University, Bloomington, Indiana 47405, USA
- ^{28a}INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
- ^{28b}INFN Sezione di Perugia, I-06100 Perugia, Italy
- ^{28c}University of Perugia, I-06100 Perugia, Italy
- ^{29a}INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122 Ferrara, Italy
- ^{29b}University of Ferrara, I-44122 Ferrara, Italy
- ³⁰Inner Mongolia University, Hohhot 010021, People's Republic of China
- ³¹Institute of Modern Physics, Lanzhou 730000, People's Republic of China
- ³²Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia
- ³³Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile
- ³⁴Jilin University, Changchun 130012, People's Republic of China
- ³⁵Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
- ³⁶Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
- ³⁷Justus-Liebig-Universität Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
- ³⁸Lanzhou University, Lanzhou 730000, People's Republic of China
- ³⁹Liaoning Normal University, Dalian 116029, People's Republic of China
- ⁴⁰Liaoning University, Shenyang 110036, People's Republic of China
- ⁴¹Nanjing Normal University, Nanjing 210023, People's Republic of China
- ⁴²Nanjing University, Nanjing 210093, People's Republic of China
- ⁴³Nankai University, Tianjin 300071, People's Republic of China
- ⁴⁴National Centre for Nuclear Research, Warsaw 02-093, Poland
- ⁴⁵North China Electric Power University, Beijing 102206, People's Republic of China
- ⁴⁶Peking University, Beijing 100871, People's Republic of China
- ⁴⁷Qufu Normal University, Qufu 273165, People's Republic of China
- ⁴⁸Shandong Normal University, Jinan 250014, People's Republic of China
- ⁴⁹Shandong University, Jinan 250100, People's Republic of China
- ⁵⁰Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
- ⁵¹Shanxi Normal University, Linfen 041004, People's Republic of China
- ⁵²Shanxi University, Taiyuan 030006, People's Republic of China
- ⁵³Sichuan University, Chengdu 610064, People's Republic of China
- ⁵⁴Soochow University, Suzhou 215006, People's Republic of China
- ⁵⁵South China Normal University, Guangzhou 510006, People's Republic of China
- ⁵⁶Southeast University, Nanjing 211100, People's Republic of China
- ⁵⁷State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
- ⁵⁸Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
- ⁵⁹Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
- ⁶⁰Tsinghua University, Beijing 100084, People's Republic of China
- ^{61a}Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey
- ^{61b}Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey

- ⁶²University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
⁶³University of Groningen, NL-9747 AA Groningen, The Netherlands
⁶⁴University of Hawaii, Honolulu, Hawaii 96822, USA
⁶⁵University of Jinan, Jinan 250022, People's Republic of China
⁶⁶University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom
⁶⁷University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
⁶⁸University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
⁶⁹University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
⁷⁰University of Science and Technology of China, Hefei 230026, People's Republic of China
⁷¹University of South China, Hengyang 421001, People's Republic of China
⁷²University of the Punjab, Lahore-54590, Pakistan
^{73a}University of Turin and INFN, University of Turin, I-10125 Turin, Italy
^{73b}University of Eastern Piedmont, I-15121 Alessandria, Italy
^{73c}INFN, I-10125 Turin, Italy
⁷⁴Uppsala University, Box 516, SE-75120 Uppsala, Sweden
⁷⁵Wuhan University, Wuhan 430072, People's Republic of China
⁷⁶Xinyang Normal University, Xinyang 464000, People's Republic of China
⁷⁷Yantai University, Yantai 264005, People's Republic of China
⁷⁸Yunnan University, Kunming 650500, People's Republic of China
⁷⁹Zhejiang University, Hangzhou 310027, People's Republic of China
⁸⁰Zhengzhou University, Zhengzhou 450001, People's Republic of China

^aAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

^bAlso at the Novosibirsk State University, Novosibirsk 630090, Russia.

^cAlso at the NRC "Kurchatov Institute", PNPI, 188300 Gatchina, Russia.

^dAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

^eAlso at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China.

^fAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.

^gAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

^hAlso at School of Physics and Electronics, Hunan University, Changsha 410082, China.

ⁱAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.

^jAlso at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.

^kAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.

^lAlso at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan.