Measurement of the Absolute Branching Fraction of the Inclusive Decay $\Lambda_c^+ \to \Lambda + X$

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(Received 31 March 2018; revised manuscript received 11 June 2018; published 7 August 2018)

Based on an e^+e^- collision data sample corresponding to an integrated luminosity of 567 pb^{-1} taken at the center-of-mass energy of $\sqrt{s} = 4.6$ GeV with the BESIII detector, we measure the absolute branching fraction of the inclusive decay $\Lambda_c^+ \to \Lambda + X$ to be $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.9)\%$ using the double-tag method, where X refers to any possible final state particles. In addition, we search for direct CP violation in the charge asymmetry of this inclusive decay for the first time, and obtain $\mathcal{A}_{CP} \equiv [\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)]/[\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)] = (2.1^{+7.0}_{-6.6} \pm 1.6)\%$, a statistically limited result with no evidence of CP violation.

DOI: 10.1103/PhysRevLett.121.062003

The inclusive decay $\Lambda_c^+ \to \Lambda + X$, where X means any possible final state particles, is mediated by the $c \to s$ Cabibbo-favored (CF) transition that dominates the decays of the Λ_c^+ [1–3]. As the Λ_c^+ is the lightest charmed baryon, the decay rate of the $\Lambda_c^+ \to \Lambda + X$ is important to calibrate the amplitude of the CF transition in the charmed baryon sector in theory, which suffers from a large uncertainty in the nonperturbative QCD region [3]. For instance, the $\Lambda_c^+ \to \Lambda + X$ decay rate is an essential input in the calculation of the lifetimes of charmed baryons, whose current theoretical results largely deviate from the experimental measurements [3–5]. Furthermore, better understanding of the quark structure and decay dynamics in the $\Lambda_c^+ \to \Lambda + X$ benefits the research on heavier charmed baryons [6,7]. Especially for those lesser-known charmed baryons with double- or triple-charm quarks, an improved and calibrated theoretical prediction on the $c \to s$ decay vertex is crucial for guiding experimental searches [8,9], such as the observation of the Ξ_{cc}^{++} at LHCb [10].

Measurements of the branching fraction (BF) of this decay were carried out only before 1992 by the SLAC Hybrid Facility Photon, Photon Emulsion, and CLEO Collaborations [11–13]. The average of their results gives $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (35 \pm 11)\%$ [5], with an uncertainty larger than 30%. The three individual measurements show big discrepancies, and their average in the Particle Data Group (PDG) gives a poor fit quality of $\chi^2/\mathrm{ndf} = 4.1/2$ and a low confidence level of 0.126 [5]. This is because they were not absolute measurements and substantial uncertainties could be underestimated. Hence, it is crucial to carry out an absolute measurement with improved precision. Furthermore, the sum of the BFs of the known exclusive decay final states involving the Λ in PDG is $(24.5 \pm 2.1)\%$ [5]. The difference between the inclusive and exclusive rates will point out the size of as yet unknown decays, which requires high precision measurement of $\mathcal{B}(\Lambda_c^+ \to \Lambda + X)$ [14]. In addition, precise knowledge of $\mathcal{B}(\Lambda_c^+ \to \Lambda + X)$ provides an essential input for exploring the decays of b-flavored hadrons involving a Λ_c^+ in the final states.

It has been confirmed that the Cabibbo-Kobayashi-Maskawa (CKM) mechanism embedded in the standard model (SM) is the main source of CP violation in the quark sector [15]. The impressive agreement on CP violation among the results from the s-quark and b-quark sectors [16,17], calls for further checks in the less tested area of the c-quark sector. The SM predictions for CP violation in the charm sector are tiny due to the hierarchical structure of the CKM matrix and the mass differences between the fermion generations. Any significant amount of CP violation would be an observation of physics beyond the SM, and therefore, the charmed baryon decays provide an opportunity to improve our knowledge on CP violation in and beyond the SM [18–21]. In this analysis, we search for direct CP violation by measuring the charge asymmetry of this inclusive decay $\mathcal{A}_{CP} \equiv [\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)]/[\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)]$.

The data used in this Letter comprise an integrated luminosity of $567\ \mathrm{pb}^{-1}$ [22], corresponding to about 1.0×10^5 $\Lambda_c^+\bar{\Lambda}_c^-$ pairs [23]. The data set was collected with the BESIII detector at the center-of-mass energy $\sqrt{s}=4.6$ GeV. At this energy, the $\Lambda_c^+\bar{\Lambda}_c^-$ pairs are produced near the production threshold with no additional hadrons, providing a clean environment for studying Λ_c^+ decays. By analyzing the data with the double-tag (DT) method [24], we perform the first measurement of the absolute BF for the inclusive decay $\Lambda_c^+\to\Lambda+X$. Throughout this Letter, charge-conjugate modes are implicitly assumed, unless explicitly stated.

Details about the features and capabilities of the BESIII detector can be found in Ref. [25]. The response of the experimental apparatus is simulated with a GEANT4-based [26] Monte Carlo (MC) simulation package. The reactions in e^+e^- annihilations are generated by KKMC [27] and EVTGEN [28], with initial-state radiation (ISR) effects [29] and final-state radiation (FSR) effects [30] included. To study backgrounds, optimize event selection criteria and validate data analysis method, an inclusive MC sample is produced at $\sqrt{s}=4.6$ GeV. This sample consists of pair production of charmed mesons (D and D_s) and baryons (Λ_c^+), the ISR-produced ψ states and quantum electrodynamics processes. The Λ_c^+ is set to decay to all possible final states based on the BFs (a sum larger than 85%) from the Particle Data Group (PDG) [31].

Given the use of implied charge conjugation in this Letter, we will describe the tag modes as coming from the anti-baryon and the inclusive mode from the baryon. With the DT method, the tag $\bar{\Lambda}_c^-$ is selected in either the $\bar{\Lambda}_c^-\to\bar{p}K_S^0$ or $\bar{\Lambda}_c^-\to\bar{p}K^+\pi^-$. The yield of the tag mode i, N_i^{tag}, is given by

$$N_i^{\mathrm{tag}}=2N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_i^{\mathrm{tag}}\varepsilon_i^{\mathrm{tag}}, \qquad (1)$$

where $N_{\Lambda_c^+\bar{\Lambda}_c^-}$ is the number of $\Lambda_c^+\bar{\Lambda}_c^-$ pairs in the data sample, while $\mathcal{B}_i^{\mathrm{tag}}$ and $\varepsilon_i^{\mathrm{tag}}$ are the BF and detection efficiency for the tag mode i. Then we search for a Λ among the remaining tracks. The number of the inclusive decays of $\Lambda_c^+\to\Lambda+X$ in the presence of the tag mode i, N_i^{sig}, is given by

$$N_i^{\mathrm{sig}}=2N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_i^{\mathrm{tag}}\mathcal{B}^{\mathrm{sig}}\varepsilon_i^{\mathrm{sig,tag}}, \qquad (2)$$

where $\mathcal{B}^{\mathrm{sig}}$ and $\varepsilon_i^{\mathrm{sig,tag}}$ are the BF of the inclusive decay $\Lambda_c^+\to\Lambda+X$ and the DT efficiency. Here we assume that the reconstruction efficiency of signal $\varepsilon^{\mathrm{sig}}$ is independent of the tag mode, so the DT efficiency is given by $\varepsilon_i^{\mathrm{sig,tag}}\approx\varepsilon^{\mathrm{sig}}\cdot\varepsilon_i^{\mathrm{tag}}$. From Eqs. (1) and (2) we can determine the BF of the signal process by

$$\mathcal{B}^{\mathrm{sig}}=\frac{(\sum_i N_i^{\mathrm{sig}})/\varepsilon^{\mathrm{sig}}}{\sum_i N_i^{\mathrm{tag}}}. \qquad (3)$$

Because of lacking knowledge of the phase space distribution of the inclusive decay $\Lambda_c^+\to\Lambda+X$, we follow a "data-driven" method. The model-independent efficiency for detecting a Λ as a function of momentum and polar angle is estimated from the control samples $J/\psi\to\Lambda\bar{\Lambda}$ and $J/\psi\to\bar{p}K^+\Lambda$, which are selected from a J/ψ on-peak data sample consisting of $(1310.6\pm7.0)\times10^6$ J/ψ decays [32]. Then we reweight the Λ efficiencies according to the momentum and polar angle distributions of Λ in the DT signals. Therefore, the signal BF is calculated by

$$\mathcal{B}^{\mathrm{sig}}=\frac{\sum_j((\sum_i N_{i,j}^{\mathrm{sig}})/\varepsilon_j^{\mathrm{sig}})}{\sum_i N_i^{\mathrm{tag}}}=\frac{\sum_j(N_{-,j}^{\mathrm{sig}}/\varepsilon_j^{\mathrm{sig}})}{\sum_i N_i^{\mathrm{tag}}}, \qquad (4)$$

where $j=1,2,\ldots$ is the index for the intervals of Λ weighting kinematics, and $N_{-,j}^{\mathrm{sig}}$ is the sum of DT signal yields in the two tag modes within the jth interval.

To select the candidate events, the charged tracks detected in the main drift chamber (MDC) are required to satisfy $|\cos\theta|<0.93$, where θ is the polar angle with respect to the direction of the e^+ beam. The distance of closest approach of the charged tracks to the run-averaged interaction point (IP) must be less than 10 cm along the beam axis and less than 1 cm in the perpendicular plane, except for those tracks used to reconstruct K_S^0 and Λ. Particle identification (PID) is achieved by combining the measurement of specific ionization (dE/dx) and time-of-flight information to compute likelihoods for different particle hypotheses. Protons are distinguished from pions and kaons with the likelihood requirements $\mathcal{L}(p)>\mathcal{L}(K)$ and $\mathcal{L}(p)>\mathcal{L}(\pi)$, while kaons and pions are discriminated from each other by requiring $\mathcal{L}(K)>\mathcal{L}(\pi)$ or $\mathcal{L}(\pi)>\mathcal{L}(K)$, respectively. To improve efficiency, no PID requirements are imposed on the charged pion candidates from the decays of Λ or K_S^0.

The K_S^0 and Λ candidates are reconstructed through their dominant decays $K_S^0\to\pi^+\pi^-$ and $\Lambda\to p\pi^-$. The distances of closest approach of the two candidate charged tracks to the IP must be within ±20 cm along the beam direction, with no requirements imposed in the perpendicular plane. The two charged tracks are constrained to originate from a common vertex by performing a vertex fit on the two tracks and requiring the χ^2 of the fit to be less than 100. A secondary vertex fit is performed on the daughter tracks of the surviving K_S^0 and Λ candidates, imposing the additional constraint that the momentum of the candidate points back to the IP. The decay vertex from this secondary vertex fit is required to be on the correct side of the IP and separated from the IP by a distance of at least twice its fitted resolution. The events with only one pair of charged tracks satisfying the above requirements are kept, and the fitted

TABLE I. Requirements on ΔE, M_{BC}, and resulting yields N_i^{tag} for the tagged $\bar{\Lambda}_c^-$ in data. The uncertainty of N_i^{tag} is statistical only.

Tag mode i	ΔE (GeV)	M_{BC} (GeV/c^2)	N_i^{tag}
$\bar{\Lambda}_c^- \to \bar{p}K_S^0$	$[-0.021, 0.019]$	[2.282, 2.300]	1220 ± 37
$\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$	$[-0.020, 0.015]$		6088 ± 85

momenta of the $\pi^+\pi^-$ and $p\pi^-$ combinations are used in the further analysis. To select K_S^0 and Λ candidates, the invariant masses of $\pi^+\pi^-$ and $p\pi^-$ are required to be in the range $487 < M_{\pi^+\pi^-} < 511$ MeV$/c^2$ and $1111 < M_{p\pi^-} < 1121$ MeV$/c^2$, respectively.

To distinguish the tagged $\bar{\Lambda}_c^-$ candidates from background, we define two variables in the e^+e^- rest frame that reflect the conservation of energy and momentum. The first is the energy difference, $\Delta E \equiv E_{\bar{\Lambda}_c^-} - E_{\mathrm{beam}}$, where $E_{\bar{\Lambda}_c^-}$ is the measured energy of the tagged $\bar{\Lambda}_c^-$ candidate and E_{beam} is the beam energy. To suppress combinatorial backgrounds, the mode-dependent ΔE requirements listed in Table I, corresponding to ± 2.5 times the resolutions of the fitted ΔE peaks, are imposed on the tagged $\bar{\Lambda}_c^-$ candidates. The second is the beam-constrained (BC) mass of the tagged $\bar{\Lambda}_c^-$ candidate, $M_{\mathrm{BC}} \equiv \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_{\bar{\Lambda}_c^-}|^2 c^2}/c^2$, where $\vec{p}_{\bar{\Lambda}_c^-}$ represents the momentum of the $\bar{\Lambda}_c^-$ candidate. Figure 1 shows the M_{BC} distributions of the two tag modes, showing clear $\bar{\Lambda}_c^-$ signals at the expected mass. Studies based on MC simulations show that the peaking backgrounds in the tag modes are negligible. Maximum likelihood fits are performed on these M_{BC} distributions to obtain the yields of tagged $\bar{\Lambda}_c^-$. The backgrounds are parametrized by an ARGUS function [33] with end point fixed to the beam energy. The signals are described by the MC-simulated shapes convoluted by Gaussian functions with free widths to account for the difference of resolutions between data and MC simulations. The yields for the background and signal are free parameters in the fits. By subtracting the number of events of the fitted backgrounds

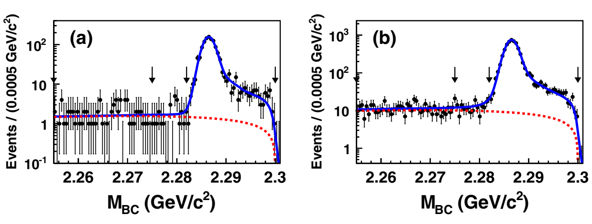

FIG. 1. Fits to the M_{BC} distributions of the candidate events for (a) $\bar{\Lambda}_c^- \to \bar{p}K_S^0$ and (b) $\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$ in data. The thick dots stand for the data. The solid curves denote the total fits, while the dotted lines represent the background. The left and right two arrows show the sideband and signal regions, respectively. The description of the fits is given in the text.

from the total event yields, we obtain the yields of the single tagged $\bar{\Lambda}_c^-$, as listed in Table I.

Then we search for a Λ candidate among the remaining tracks on the recoiling side of the tagged $\bar{\Lambda}_c^-$. The signal yield is determined from the distribution of M_{BC} versus the invariant mass of $p\pi^-$ system $M_{p\pi^-}$ by

$$N^{\mathrm{sig}} = N^S - \frac{N^A + N^B}{2} - f\left(N^D - \frac{N^C + N^E}{2}\right), \quad (5)$$

where N^S, N^A, N^B, N^C, N^D, and N^E represent the numbers of events observed in the regions of S, A, B, C, D. and E, as shown in Fig. 2. Here the backgrounds due to misreconstruction of Λ are assumed to be flat in the $M_{p\pi^-}$ distribution, which can be estimated from the events in regions A and B. While the peaking backgrounds in the $M_{p\pi^-}$ distribution, which are from non-Λ_c^+ decays with Λ correctly reconstructed, can be estimated using the sideband region of M_{BC}, namely, the regions C, D, and E. f is the fraction of non-Λ_c^+ signals under the M_{BC} peak over that in the sideband region of M_{BC}, which is evaluated to be 0.58 ± 0.06 from the fit to the combined M_{BC} distribution of data for the two tagging modes. We divide the data into 5×4 two-dimensional $(p, |\cos\theta|)$ intervals of Λ and obtain the net signal yield in each kinematic interval following Eq. (5), as listed in Table II.

In each kinematic interval, the data-driven efficiency is calculated based on a "tag-and-probe" technique. For $J/\psi \to \Lambda\bar{\Lambda}$, a $\bar{\Lambda}$ is tagged in an event, while for $J/\psi \to \bar{p}K^+\Lambda$, two charged tracks identified as a proton and a kaon are selected. The missing Λ is identified by limiting the missing mass within $[1.067, 1.155]$ GeV$/c^2$ for $J/\psi \to \Lambda\bar{\Lambda}$ and $[1.093, 1.139]$ GeV$/c^2$ for $J/\psi \to \bar{p}K^+\Lambda$. In the tagged event, we search for a Λ among the remaining tracks and take the detection rate as the efficiency. We partition the control samples into $(p, |\cos\theta|)$ intervals, and then determine the efficiency in each interval, as listed in

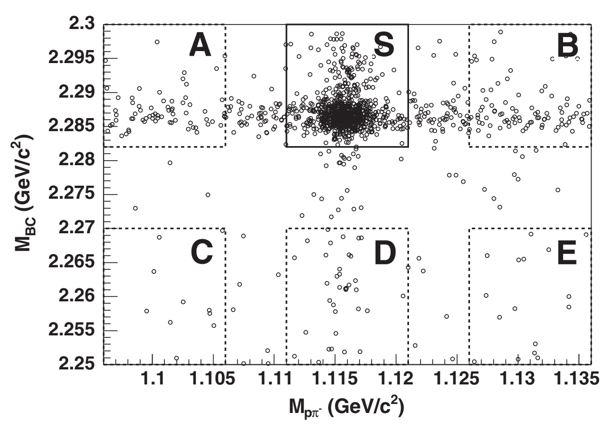

FIG. 2. Scatter plot of M_{BC} versus $M_{p\pi^-}$ of the DT candidates in data. The box labeled S stands for the signal region, while boxes A, B, C, D, and E denote the sideband regions.

TABLE II. Signal yield and detection efficiency of the inclusive Λ in each $(p, |\cos\theta|)$ interval. The uncertainties here are statistical only.

p (GeV/c)	$N^{\rm sig}_{-,j}$			
	$\|\cos\theta\|$			
	[0.00, 0.20)	[0.20, 0.40)	[0.40, 0.65)	[0.65, 1.00)
[0.0, 0.3)	$5.3^{+5.1}_{-3.8}$	$11.4^{+5.5}_{-4.2}$	$9.1^{+5.5}_{-4.2}$	$6.3^{+5.4}_{-4.0}$
[0.3, 0.5)	$59.8^{+9.9}_{-8.6}$	$41.6^{+8.9}_{-7.7}$	$71.9^{+10.7}_{-9.5}$	$33.1^{+8.7}_{-7.4}$
[0.5, 0.7)	$86.7^{+10.9}_{-9.7}$	$72.5^{+10.0}_{-8.8}$	$74.8^{+10.1}_{-9.0}$	$53.9^{+9.1}_{-7.9}$
[0.7, 0.9)	$40.4^{+7.8}_{-6.6}$	$28.3^{+6.8}_{-5.6}$	$44.0^{+8.1}_{-6.9}$	$38.4^{+7.9}_{-6.7}$
[0.9, 1.1)	$6.9^{+4.3}_{-3.0}$	$12.4^{+5.0}_{-3.7}$	$8.3^{+4.2}_{-2.9}$	$5.5^{+3.9}_{-2.6}$
p(GeV/c)	$\varepsilon^{\rm sig}_{j}(\%)$			
	$\|\cos\theta\|$			
	[0.00, 0.20)	[0.20, 0.40)	[0.40, 0.65)	[0.65, 1.00)
[0.0, 0.3)	8.28 ± 0.38	8.22 ± 0.37	8.01 ± 0.31	4.45 ± 0.21
[0.3, 0.5)	29.03 ± 0.37	28.28 ± 0.37	26.56 ± 0.33	14.98 ± 0.21
[0.5, 0.7)	35.43 ± 0.32	35.00 ± 0.33	33.25 ± 0.32	20.15 ± 0.25
[0.7, 0.9)	39.68 ± 0.47	39.27 ± 0.50	36.56 ± 0.50	23.80 ± 0.51
[0.9, 1.1)	40.82 ± 0.14	40.21 ± 0.14	37.76 ± 0.12	29.97 ± 0.11

Table II. For these efficiencies, the BF of the intermediate process $\Lambda \to p\pi^-$ has been included, and the uncertainties are statistical only. Inserting the numbers of $N^{\rm tag}_i$ from Table I, and the numbers of $N^{\rm sig}_{-,j}$ and $\varepsilon^{\rm sig}_j$ from Table II into Eq. (4), we determine the BF of $\Lambda_c^+ \to \Lambda + X$ to be $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.3})\%$. The reliability of the analysis method used in this work has been validated by analyzing the inclusive MC sample.

The CP asymmetry of the decay $\Lambda_c^+ \to \Lambda + X$ is obtained by comparing the separate BFs of the charge conjugate decays, which are $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (39.4^{+4.7}_{-3.4})\%$ and $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X) = (37.8^{+3.8}_{-2.9})\%$. The yields and efficiencies of $\Lambda_c^+ \to \Lambda + X$ and $\bar{\Lambda}_c^- \to \bar{\Lambda} + X$ can be found in the Supplemental Material [34]. The CP asymmetry is determined to be $\mathcal{A}_{CP} = (2.1^{+7.0}_{-6.6})\%$, where the uncertainty is statistical only.

In the BF measurement with the DT method, systematic uncertainties from the tag side mostly cancel. Other non-canceling systematic uncertainties, which are estimated relative to the measured BF, are discussed below. The limited statistics of the Λ control samples bring uncertainty to the Λ efficiency, which is estimated by a weighted root-mean-square (rms) of the statistical uncertainties for different $(p, |\cos\theta|)$ intervals given in Table II. In this analysis, the efficiency for reconstructing a $\bar{\Lambda}_c^-$ using the tag modes or finding a Λ in the Λ_c^+ side have been assumed to be independent of the multiplicities of the $\Lambda_c^+/\bar{\Lambda}_c^-$ sides. To evaluate the potential bias of this assumption, we use MC simulation to study the Λ efficiencies with 2 different tag modes, or the tag efficiencies with and without inclusion of non-Λ-involved Λ_c^+ decays in the signal side. We find the resultant changes on the Λ efficiency or tag efficiency are at the percent level, which are taken as the systematic uncertainties. The choice of kinematic intervals is varied and the resultant changes on the output BF are examined. The maximum change is quoted as the systematic uncertainty. The uncertainty due to the fitting procedure of tag yields is studied by altering the signal shape, fitting range, and end point of the ARGUS function. Potential bias of the background-subtraction procedure in Eq. (5) is studied by changing the boundaries of sideband regions and taking the largest difference in the resultant BF as the systematic uncertainty. All of the above systematic uncertainties are summarized in Table III and the total uncertainty is determined to be 2.3% as the sum in quadrature. For the charge asymmetry $\mathcal{A}_{CP}$, we assume that the systematic uncertainties for the channels of Λ and $\bar{\Lambda}$ are the same and completely uncorrelated.

TABLE III. Summary of the relative systematic uncertainties for the BF of $\Lambda_c^+ \to \Lambda + X$.

Source	Relative uncertainty (%)
Statistics of the control sample	0.6
Λ efficiency bias	1.1
Tag efficiencies bias	1.6
Choices of the intervals	0.5
Tag yields	0.9
Background subtraction	0.3
Total	2.3

In summary, by analyzing a data sample taken at $\sqrt{s} = 4.6$ GeV with the BESIII detector, we report the absolute BF of the inclusive decay of $\Lambda_c^+ \to \Lambda + X$ to be $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.9)\%$. The precision of the BF is improved by a factor of 4 compared to previous measurements [5]. This inclusive rate is larger than the exclusive rate of $(24.5 \pm 2.1)\%$ in PDG [5], which indicates that more than one-third of the Λ_c^+ decays to Λ remain unobserved in experiment. In addition, our result is 2.4σ larger than the value in Ref. [14], inferred from the known exclusive Λ-involved decay rates in the statistical isospin model. This indicates that there exist some large-rate decay types, which have not yet been observed. Furthermore, we search for direct CP violation in this decay for the first time. The CP asymmetry is measured to be $\mathcal{A}_{CP} = (2.1^{+7.0}_{-6.6} \pm 1.6)\%$. The precision is limited by statistical uncertainty and no evidence for CP violation is found.

The authors would like to thank Hai-Yang Cheng 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 Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts No. 11335008, No. 11425524, No. 11625523, No. 11635010, No. 11735014; 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 Contracts No. U1532257, No. U1532258, No. U1732263; CAS Key Research Program of Frontier Sciences under Contracts No. QYZDJ-SSW-SLH003, No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts No. Collaborative Research Center CRC 1044, No. FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; The Swedish Research Council; U.S. Department of Energy under Contracts No. DE-FG02-05ER41374, No. DE-SC-0010118, No. DE-SC-0010504, No. DE-SC-0012069; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt.

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