

Precision Studies and Searches for CP Asymmetries in the Inclusive Decay $\Lambda_c^+ \rightarrow \Lambda X$

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(Received 28 February 2026; revised 10 August 2026; accepted 18 August 2026; published 24 September 2026)

Based on e^+e^- annihilation data collected with the BESIII detector at center-of-mass energies from 4.600 to 4.699 GeV, corresponding to an integrated luminosity of 4.5 fb^{-1} , we present the first measurement of the longitudinal polarization of Λ hyperon produced in the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$, where X denotes any allowed final states. The polarizations are determined to be $\mathcal{P}_\Lambda = -0.393 \pm 0.055_{\text{stat}} \pm 0.020_{\text{syst}}$ and $\mathcal{P}_{\bar{\Lambda}} = 0.288 \pm 0.056_{\text{stat}} \pm 0.017_{\text{syst}}$. A search for CP violation is performed using an asymmetry constructed from the Λ polarization and the $\Lambda \rightarrow p\pi^-$ decay asymmetry parameter, and $\mathcal{A}_{CP}^{\text{pol}} = 0.15 \pm 0.12_{\text{stat}} \pm 0.03_{\text{syst}}$ was obtained. Furthermore, an updated measurement of the absolute branching fraction is reported as $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda X) = (38.07 \pm 0.38_{\text{stat}} \pm 0.49_{\text{syst}})\%$, representing a fourfold precision improvement over the previous BESIII measurement. A search for CP violation in the decay rate yields $\mathcal{A}_{CP}^{\text{dir}} = (1.5 \pm 1.0_{\text{stat}} \pm 1.0_{\text{syst}})\%$. No evidence for CP violation is observed in this inclusive charm baryon decay. The subscripts ‘stat’ and ‘syst’ denote statistical and systematic uncertainties, respectively.

DOI: [10.1103/cxm9-mr48](https://doi.org/10.1103/cxm9-mr48)

The standard model (SM) is the most successful and well-tested theory in particle physics, offering a comprehensive framework for describing elementary particles and their fundamental interactions. However, it does not provide a quantitatively sufficient explanation for the observed matter-antimatter asymmetry of the universe. In 1967, Sakharov proposed that the violation of charge conjugation (C) and charge-parity (CP) symmetry is one of the necessary conditions to explain the baryon asymmetry of the universe [1]. Over the decades, CP violation (CPV) has been extensively studied in meson systems, first observed in neutral K decays and later established in the B and D sectors [2–5]. However, the observable universe is dominated by baryon asymmetry, suggesting that CPV in the baryon sector may play a qualitatively different and potentially critical role. Recently, the LHCb Collaboration reported the first observation of CPV in the b -baryon decay $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ [6], with the result consistent with SM predictions. By contrast, despite increasing statistics in various experiments, no evidence of CPV has been observed in the charm baryon sector. This is primarily because SM predictions for charm CP asymmetries are suppressed to the order of $\mathcal{O}(10^{-4}\text{--}10^{-3})$ [7], making such searches experimentally challenging.

As the lightest charm baryon, the Λ_c^+ serves as a cornerstone for studying weak decays, offering a unique window into the interplay of weak and strong interactions in the baryon sector [8,9]. Compared to mesons, the three-quark structure of baryons leads to a richer phenomenology in decay dynamics [10]. Among all studies, inclusive measurements are particularly valuable as they constrain the total decay width and quantify contributions from unmeasured channels. Currently, the sum of all measured exclusive decay modes of Λ_c^+ containing a Λ in the final state accounts for only $(33.59 \pm 1.09)\%$ of the total width [11]. By contrast, the inclusive branching fraction (BF) of $\Lambda_c^+ \rightarrow \Lambda X$ was measured by BESIII to be $(38.2_{-2.2}^{+2.8} \pm 0.9)\%$, utilizing a data sample corresponding to 586.9 pb^{-1} [12]. This discrepancy highlights the existence of undiscovered decay modes, but with limited precision. Thus a more accurate inclusive BF measurement is necessary.

Besides the branching fraction, baryon polarization in weak decays serves as a sensitive probe of parity-violating weak dynamics [8,13]. Previous searches for CPV in charm baryons have focused on exclusive modes, such as $\Lambda_c^+ \rightarrow \Lambda K^+$ and $\Lambda_c^+ \rightarrow \Sigma^0 K^+$ [14,15], with results indicating no CPV . While local asymmetries arising from interference in specific exclusive channels may cancel upon integration, a nonzero inclusive asymmetry would indicate a net, integrated difference in decay dynamics between baryons and antibaryons. This motivates inclusive CPV searches as a complementary approach, with the practical advantages of larger signal yields and reduced reliance on modeling individual subchannels [16]. The inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ has been proposed as a

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probe of net CPV in the baryon sector [16], for which SM effects are expected to be $\mathcal{O}(10^{-5}-10^{-4})$.

In this Letter, the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ is studied with a double tag (DT) method [17]. The $\bar{\Lambda}_c^-$ baryon is reconstructed in one of the eleven single tag (ST) modes ($\bar{p}K_S^0$, $\bar{p}K^+\pi^-$, $\bar{p}K_S^0\pi^0$, $\bar{p}K_S^0\pi^-\pi^+$, $\bar{p}K^+\pi^-\pi^0$, $\bar{\Lambda}\pi^-$, $\bar{\Lambda}\pi^-\pi^0$, $\bar{\Lambda}\pi^-\pi^+\pi^-$, $\bar{\Sigma}^0\pi^-$, $\bar{\Sigma}^-\pi^0$, and $\bar{\Sigma}^-\pi^-\pi^+$). Using e^+e^- annihilation data, corresponding to an integrated luminosity of 4.5 fb^{-1} , collected at center-of-mass energies between 4.600 and 4.699 GeV with the BESIII detector at BEPCII [18,19], we investigate CPV in decay and polarization-dependent CPV in the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ and report measurements of its BF and the longitudinal polarization of the Λ produced in this decay. Charge-conjugate processes are included unless otherwise stated.

Details about BESIII and BEPCII can be found in Refs. [20–25]. High-statistics inclusive Monte Carlo (MC) simulated samples for e^+e^- annihilation are generated with the KKMC generator [26] incorporating initial-state radiation (ISR) effects and the beam-energy spread. The inclusive MC sample, comprising $\Lambda_c^+\bar{\Lambda}_c^-$ events and hadronic processes such as $D_{(s)}^{(*)}$ 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 ST detection efficiency and estimate the potential background. All particle decays are modeled with EvtGen [27,28] using BFs either taken from the Particle Data Group (PDG) [11] or estimated with Lundcharm when available [29]. Final-state particles are propagated through a GEANT4 based detector simulation, which provides an accurate geometric description of the BESIII detector [30,31]. The Born cross sections are taken into account when generating $\Lambda_c^+\bar{\Lambda}_c^-$ pairs in inclusive MC samples [32]. Furthermore, signal MC samples are generated to determine the DT detection efficiencies, in which the $\bar{\Lambda}_c^-$ decays into any of the tag modes and the Λ_c^+ decays inclusively into the modes with a Λ in the final state. These samples incorporate amplitude models for the dominant multibody processes [33] (e.g.,

$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^0$) and account for angular distributions in two-body decays [34,35] (e.g., $\Lambda_c^+ \rightarrow \Lambda\pi^+$). To further improve the kinematic agreement between the signal MC sample and data, simulated events are reweighted using a boosted decision tree (BDT)-based algorithm [36]. The BDT is trained using the Λ momentum and its recoil invariant mass. The derived weights are then applied in the subsequent analysis.

The selection of ST $\bar{\Lambda}_c^-$ candidates follows the procedure described in Ref. [37]. The ST $\bar{\Lambda}_c^-$ candidates are reconstructed, and the ST yields are extracted from the beam-constrained mass, defined as $M_{BC} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}|^2/c^2}$, where E_{beam} is the beam energy and $\vec{p}$ is the $\bar{\Lambda}_c^-$ momentum in the center-of-mass system of the e^+e^- collision. After reconstructing a $\bar{\Lambda}_c^-$ through one of the eleven ST modes, a Λ candidate is searched among the remaining tracks via $\Lambda \rightarrow p\pi^-$, forming the DT candidate. The $p\pi^-$ tracks are constrained to originate from a common decay vertex by requiring the χ^2 of the vertex fit to be less than 100. Furthermore, the decay vertex is required to be separated from the interaction point of e^+e^- by a distance of at least twice the fitted vertex resolution. The squared Λ recoil invariant mass distribution for the background-subtracted data sample is shown in Appendix A, where a clear peak is observed near zero from the decay $\Lambda_c^+ \rightarrow \Lambda\pi^+$. To obtain the pure signal shape, a truth-matching procedure is applied to the signal MC samples on both the ST and DT sides. The matching angle θ_{match} , defined as the angle between the momentum vectors of a reconstructed particle and the corresponding generated particle, must satisfy $\theta_{\text{match}}(p) < 15^\circ$ and $\theta_{\text{match}}(\pi^-) < 25^\circ$ for the $p\pi^-$ pair from the Λ in the ST and DT sides, and $\theta_{\text{match}} < 10^\circ$ is required for other particles in the ST side. Otherwise, they are considered as “unmatched events.”

To obtain the BF, a two-dimensional (2D) simultaneous unbinned maximum likelihood fit is performed to the distribution of M_{BC} versus the invariant mass of $p\pi^-$ (M_Λ) at seven center-of-mass energy points, with all ST modes combined at each energy point. The signal is modeled

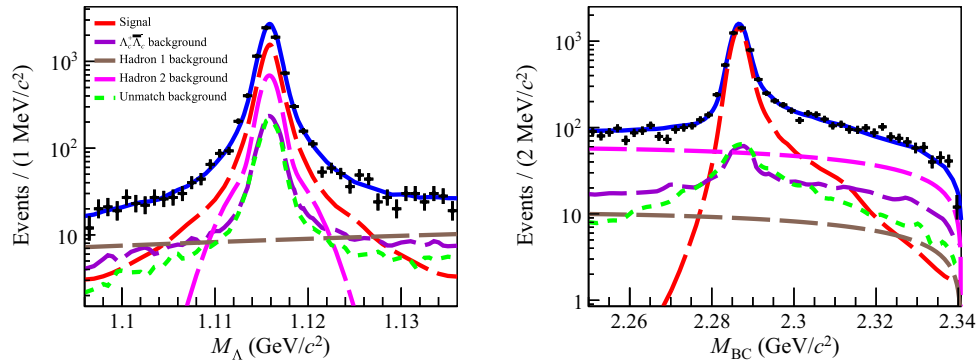


FIG. 1. Projections of the 2D simultaneous fit on the M_Λ versus M_{BC} distributions for the data taken at $\sqrt{s} = 4.682 \text{ GeV}$, where the vertical axis is shown on a logarithmic scale. Points with error bars are data, and the colored curves show the total fit and its individual components.

by the MC-simulated shape represented by the kernel estimation probability density function (PDF) [38] convolved with a Gaussian function with floating parameters to describe the detector resolution. The unmatched background is described using the shape taken from the signal MC samples. The ratio of matched to unmatched event numbers is fixed based on a study of the signal MC samples.

The background shape from $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ events is determined using inclusive MC samples, which are also used to fix the yield ratio between the signal and this background in the fit. The background from hadronic processes is classified into two categories: “Hadron 1,” which is combinatorial in both the M_Λ and M_{BC} distributions, and “Hadron 2,” which peaks in M_Λ distribution but remains combinatorial in M_{BC} distribution. To model these components, the M_{BC} distributions of both categories are described by ARGUS functions. For the distribution of M_Λ , “Hadron 1” is modeled by a polynomial function, whereas “Hadron 2” is described by a double Gaussian function. The shape parameters are determined by performing the 2D fit to M_Λ versus M_{BC} of the hadron MC samples at each energy point, with the ARGUS end points fixed to E_{beam} . The yields of both components are left as free parameters in the fit.

Figure 1 shows the fit result of the M_Λ versus M_{BC} distribution for data taken at $\sqrt{s} = 4.682$ GeV. The fit results displayed with linear vertical axes for all energies are shown in Supplemental Material [39]. In the fit, the BF of $\Lambda_c^+ \rightarrow \Lambda X$ is a common parameter at all energy points. The signal yields at each energy point are given as $N_j^{\text{DT}} = \mathcal{B} \sum_i N_{ij}^{\text{ST}} (\epsilon_{ij}^{\text{DT}} / \epsilon_{ij}^{\text{ST}}) \mathcal{B}_{\text{int}}$, where $\mathcal{B}$ is the BF of $\Lambda_c^+ \rightarrow \Lambda X$ and i and j represent the ST modes and different center-of-mass energy points, respectively. The factor $\mathcal{B}_{\text{int}}$ is the BF of $\Lambda \rightarrow p\pi^-$, which is $(64.1 \pm 0.5)\%$ [11]. N_{ij}^{ST} , $\epsilon_{ij}^{\text{ST}}$, and $\epsilon_{ij}^{\text{DT}}$ are the ST yields, ST efficiencies, and DT efficiencies, respectively. The ST yields and ST efficiencies are cited from Ref. [37] since we use the same reconstruction criteria for ST $\bar{\Lambda}_c^-$ candidates. The $\epsilon_{ij}^{\text{DT}}$ are estimated from the signal MC samples. Furthermore, control samples of $J/\psi \rightarrow \bar{p}K^+\Lambda$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$ are selected from both data and MC samples to study the Λ reconstruction efficiency. Correction factors, parameterized as a function of the Λ momentum and $\cos\theta$ (where θ is the polar angle), are derived from the Λ efficiency difference between data and MC samples. These factors are then applied to correct the DT signal MC samples based on the Λ kinematics in the decay $\Lambda_c^+ \rightarrow \Lambda X$. This correction results in a relative difference of $(1.4 \pm 0.6)\%$ between the corrected and uncorrected efficiencies. The corrected DT efficiencies for each energy point are summarized in Supplemental Material [39].

In the determination of the BFs, most systematic uncertainties from the ST side cancel out. The remaining systematic uncertainties arise from the Λ reconstruction, the

intermediate BF of $\Lambda \rightarrow p\pi^-$, the 2D fit, the ST $\bar{\Lambda}_c^-$ yield, the BDT reweighting procedure, the MC statistics, and the unmatched background. Further details are provided in Appendix B. Accounting for these uncertainties, the BF of $\Lambda_c^+ \rightarrow \Lambda X$, averaged over charge-conjugate modes, is determined to be $(38.07 \pm 0.38_{\text{stat}} \pm 0.49_{\text{syst}})\%$. The subscripts ‘stat’ and ‘syst’ denote statistical and systematic uncertainties, respectively. Applying the same procedure to the individual charge-conjugate modes, we determine the BFs for the $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$ decays to be $(38.35 \pm 0.53_{\text{stat}} \pm 0.69_{\text{syst}})\%$ and $(37.19 \pm 0.53_{\text{stat}} \pm 0.60_{\text{syst}})\%$, respectively. The ST yields, ST efficiencies, and DT efficiencies for the separate decays are summarized in Supplemental Material [39].

The longitudinal polarization of the Λ hyperon is extracted from the proton angular distribution in the decay $\Lambda_c^+ \rightarrow \Lambda X$ with $\Lambda \rightarrow p\pi^-$. The decay topology and the definition of the reference frames are illustrated in Fig. 2. As described in Ref. [16], the differential decay rate for this decay can be expressed in terms of a single helicity angle:

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 + \mathcal{P}_\Lambda \alpha_- \cos\theta_p, \quad (1)$$

where α_- is the decay asymmetry parameter for Λ in $\Lambda \rightarrow p\pi^-$. The helicity axis is defined along the Λ flight direction in the Λ_c^+ rest frame. The helicity angle, θ_p , is defined as the angle between the proton momentum and this axis, measured in the Λ rest frame. The parameter $\mathcal{P}_\Lambda$ denotes the longitudinal polarization of the Λ hyperon along the chosen helicity axis, averaged over all contributing $\Lambda_c^+ \rightarrow \Lambda X$ decay modes. For the charge-conjugate decay $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$, the α_- and $\mathcal{P}_\Lambda$ are replaced by α_+ and $\mathcal{P}_{\bar{\Lambda}}$, respectively.

A simultaneous unbinned maximum likelihood fit for the seven data samples is performed to determine the common parameters. The total effective log-likelihood function is given by $\ln \mathcal{L}_{\text{total}}^{\text{sig}} = \sum_{\text{energy}} \ln \mathcal{L}_{\text{energy}}^{\text{sig}}$. At each energy point, the background contribution is statistically subtracted at the log-likelihood level [33] according to

$$\ln \mathcal{L}_{\text{energy}}^{\text{sig}} = \kappa \left[\sum_{i \in S} \ln f_s(\theta_p^i; \eta) - \frac{1}{2} \sum_{i \in \text{AUB}} \ln f_s(\theta_p^i; \eta) - r \sum_{i \in D} \ln f_s(\theta_p^i; \eta) + \frac{r}{2} \sum_{i \in \text{CUE}} \ln f_s(\theta_p^i; \eta) \right]. \quad (2)$$

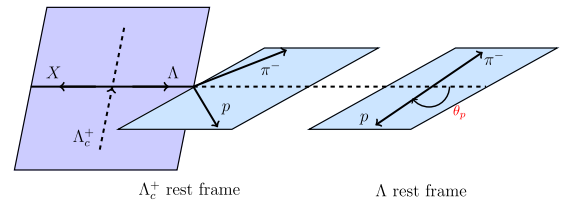


FIG. 2. Angular distribution of the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ and its subsequent decay $\Lambda \rightarrow p\pi^-$.

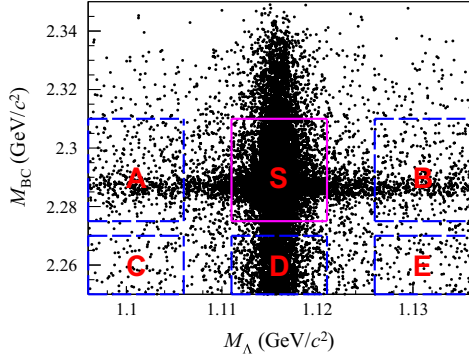


FIG. 3. Distribution of M_{BC} versus M_Λ in data taken at $\sqrt{s} = 4.682$ GeV. The Λ signal region is defined as $(1.111, 1.121)$ GeV/ c^2 , with sidebands taken as $(1.096, 1.106) \cup (1.126, 1.136)$ GeV/ c^2 , while the M_{BC} signal and sideband regions are chosen as $(2.275, 2.31)$ GeV/ c^2 and $(2.25, 2.27)$ GeV/ c^2 , respectively.

The factor $\kappa = \{N_S - (N_A + N_B)/2 - r[N_D - (N_C + N_E)/2]/[N_S + (N_A + N_B)/4 + r^2[N_D + (N_C + N_E)/4]]\}$ accounts for the event weights in the effective log-likelihood and corrects the parameter uncertainties following Refs. [33,40], where N_j is the data yield in region j ($j \in \{S, A, B, C, D, E\}$). As shown in Fig. 3, the box labeled S stands for the signal region, and boxes A , B , C , D , and E represent the 2D sideband regions. The background normalization ratio r between the M_{BC} sideband and signal regions is determined from the 2D simultaneous fit. The $\cos\theta_p$ distribution of the data sideband events is corrected for the difference between the background distributions in the signal and sideband regions, as determined from background MC samples including $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs, hadronic processes, and unmatched components. In the M_{BC} distribution, only the lower sidebands are used since the high side ISR tail contains signal events that would contaminate the background estimate. The PDF is formulated as $f_s(\theta_p^i; \eta) = \{[\epsilon(\theta_p^i)|M(\theta_p^i; \eta)|^2]/[\int \epsilon(\theta_p^i)|M(\theta_p^i; \eta)|^2 d\theta_p^i]\}$, where $M(\theta_p^i; \eta)$ is the angular distribution function

described in Eq. (1), $\epsilon(\theta_p^i)$ is the detection efficiency parameterized in terms of the kinematic variables θ_p^i , and η denotes the product $\mathcal{P}_\Lambda \alpha_-$ or $\mathcal{P}_{\bar{\Lambda}} \alpha_+$ to be determined. The integration of the normalization factor in the fitting procedure is calculated using a large BDT reweighted signal MC sample, with $\int \epsilon(\theta_p^i)|M(\theta_p^i; \eta)|^2 d\theta_p^i \propto (1/N_{\text{gen}}) \sum_{k_{\text{MC}}}^{N_{\text{MC}}} |M(\theta_p^{k_{\text{MC}}}; \eta)|^2$, where N_{gen} is the total number of the simulated signal MC events, N_{MC} is the number of the reweighted signal MC events surviving all selection criteria, and k_{MC} is the event index. The negative log-likelihood with background subtraction over the seven data samples is minimized using the MINUIT package [41]. Figure 4 shows the fit results for the decays $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$. For illustration, the corresponding background-subtracted and efficiency-corrected angular distributions are presented in Supplemental Material [39].

Systematic uncertainties from imperfect simulation and the measurement procedure can affect the determination of the products $\mathcal{P}_\Lambda \alpha_-$ and $\mathcal{P}_{\bar{\Lambda}} \alpha_+$. The relevant sources are the Λ reconstruction, the resolution differences between data and MC simulation, the background subtraction, the unmatched-background model, and the BDT reweighting procedure. These sources also apply to the Λ longitudinal polarizations $\mathcal{P}_\Lambda$ and $\mathcal{P}_{\bar{\Lambda}}$. The additional systematic uncertainty for the $\mathcal{P}_\Lambda$ and $\mathcal{P}_{\bar{\Lambda}}$ arises from the input parameters $\alpha_{-,+}$, which do not affect the products extracted directly from data. The BESIII inputs to the PDG averages of $\alpha_{-,+}$ are based on the J/ψ data and do not overlap with the data used in the present analysis. This uncertainty, estimated by Gaussian sampling according to the uncertainties of $\alpha_{-,+}$, is 1.0% for $\mathcal{P}_\Lambda$ and 0.7% for $\mathcal{P}_{\bar{\Lambda}}$. Further details are given in Appendix C. The measured products are $\mathcal{P}_\Lambda \alpha_- = -0.293 \pm 0.041_{\text{stat}} \pm 0.015_{\text{syst}}$ and $\mathcal{P}_{\bar{\Lambda}} \alpha_+ = -0.218 \pm 0.042_{\text{stat}} \pm 0.013_{\text{syst}}$. Using the PDG values $\alpha_- = 0.746 \pm 0.008$ and $\alpha_+ = -0.758 \pm 0.005$ [11], the Λ longitudinal polarizations are determined to be $\mathcal{P}_\Lambda = -0.393 \pm 0.055_{\text{stat}} \pm 0.020_{\text{syst}}$ and $\mathcal{P}_{\bar{\Lambda}} = 0.288 \pm 0.056_{\text{stat}} \pm 0.017_{\text{syst}}$, respectively.

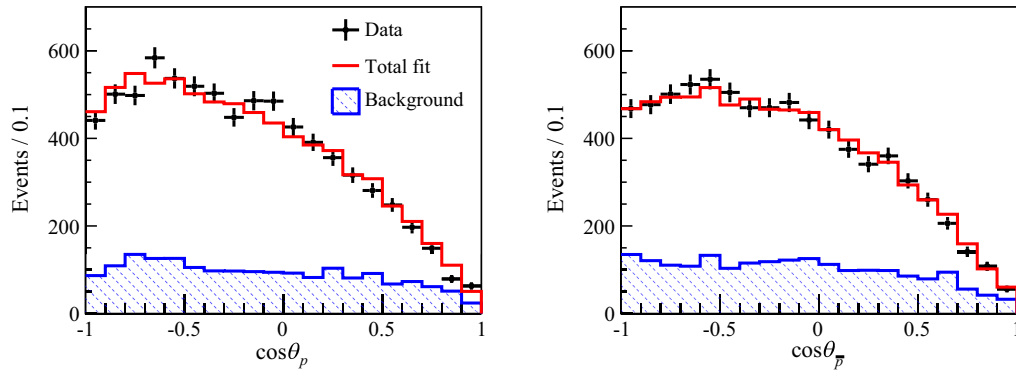


FIG. 4. Angular distributions for (left) $\Lambda_c^+ \rightarrow \Lambda X$ and (right) $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$, obtained by summing over the data samples of all the energy points. Points with error bars are data, the red lines are the fitting models, and the blue shaded areas are the background events of the 2D sideband region in data.

The CP asymmetry between $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$, defined as $\mathcal{A}_{CP}^{\text{dir}} \equiv [\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda X) - \mathcal{B}(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X)] / [\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda X) + \mathcal{B}(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X)]$, is determined to be $\mathcal{A}_{CP}^{\text{dir}} = (1.5 \pm 1.0_{\text{stat}} \pm 1.0_{\text{syst}})\%$. The CP asymmetry constructed from the products $\mathcal{P}_{\Lambda\alpha_-}$ and $\mathcal{P}_{\bar{\Lambda}\alpha_+}$, $\mathcal{A}_{CP}^{\text{pol}} \equiv (\mathcal{P}_{\Lambda\alpha_-} - \mathcal{P}_{\bar{\Lambda}\alpha_+}) / (\mathcal{P}_{\Lambda\alpha_-} + \mathcal{P}_{\bar{\Lambda}\alpha_+})$ provides access to polarization-dependent CPV in the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ and is measured to be $\mathcal{A}_{CP}^{\text{pol}} = 0.15 \pm 0.12_{\text{stat}} \pm 0.03_{\text{syst}}$. This is the first search for polarization-dependent CPV in the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$. The corresponding systematic uncertainty evaluations for $\mathcal{A}_{CP}^{\text{dir}}$ and $\mathcal{A}_{CP}^{\text{pol}}$ are summarized in Appendixes B and C, respectively.

In summary, using data corresponding to an integrated luminosity of 4.5 fb^{-1} , collected by BESIII at center-of-mass energies between 4.600 and 4.699 GeV, we report the first measurement of the longitudinal polarizations of Λ hyperon produced in inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$, which are determined to be $\mathcal{P}_{\Lambda} = -0.393 \pm 0.055_{\text{stat}} \pm 0.020_{\text{syst}}$ and $\mathcal{P}_{\bar{\Lambda}} = 0.288 \pm 0.056_{\text{stat}} \pm 0.017_{\text{syst}}$. These results provide detailed information that improves our understanding of the dynamics of charm baryon decay. The absolute BF of the inclusive decay $\Lambda_c^+ \rightarrow \Lambda X$ is determined to be $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda X) = (38.07 \pm 0.38_{\text{stat}} \pm 0.49_{\text{syst}})\%$, with precision improved by a factor of four over the previous BESIII measurement [12]. This more precise determination constrains the sum of known exclusive Λ_c^+ decay channels, thereby reducing the allowed phase space for yet-undiscovered modes and providing a clear target for future searches. By comparison with the measured exclusive processes containing a Λ in the final state listed in the PDG [11], it is found that $(4.48 \pm 1.25)\%$ of the exclusive decays remain unmeasured. Moreover, we measure the CP asymmetry in decay to be $\mathcal{A}_{CP}^{\text{dir}} = (1.5 \pm 1.0_{\text{stat}} \pm 1.0_{\text{syst}})\%$. The present analysis uses the data that includes the one used in the previous BESIII measurement and additional ST modes, and therefore the results of the BF and $\mathcal{A}_{CP}^{\text{dir}}$ supersede the previous BESIII results. We also perform the first search for the polarization-dependent CPV in this inclusive decay, obtaining $\mathcal{A}_{CP}^{\text{pol}} = 0.15 \pm 0.12_{\text{stat}} \pm 0.03_{\text{syst}}$. By searching for the CPV in inclusive mode, we provide a complementary constraint on a net CPV in $\Lambda_c^+ \rightarrow \Lambda X$ decay that survives after integration over all contributing subchannels, which is relevant for understanding the mechanisms underlying the baryon asymmetry of the universe. These results offer new insights to improve our understanding of CPV in charm baryons and the properties of inclusive decays.

Acknowledgments—The BESIII Collaboration thanks the staff of BEPCII [42] and the IHEP computing center for their strong support. This work is supported in part by the National Key R&D Program of China under Contracts No. 2023YFA1609400, No. 2023YFA1606000, and

No. 2023YFA1606704; the National Natural Science Foundation of China (NSFC) under Contracts No. 12105127, No. 12422504, No. 11635010, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264, No. 12192265, No. 12221005, No. 12225509, No. 12235017, No. 12342502, and No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the Strategic Priority Research Program of Chinese Academy of Sciences under Contract No. XDA0480600; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; Fundamental Research Funds for the Central Universities, Lanzhou University under Contracts No. lzujbky-2025-ytB01 and No. lzujbky-2023-stlt01; The Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174, No. 2021.0299, and No. 2023.0315; 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; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; STFC (United Kingdom); Swedish Research Council under Contract No. 2019.04595; and U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

Data availability—The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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End Matter

Appendix A: Plot for the squared Λ recoil invariant mass distribution—Figure 5 shows the squared Λ recoil invariant mass distribution of the weighted data sample. The clear peak above zero corresponds to the $\Lambda_c^+ \rightarrow \Lambda\pi^+$ decay.

Appendix B: Systematic uncertainties for the BF and $\mathcal{A}_{\text{CP}}^{\text{dir}}$ —The systematic uncertainty associated with the Λ reconstruction is derived from the uncertainty on the

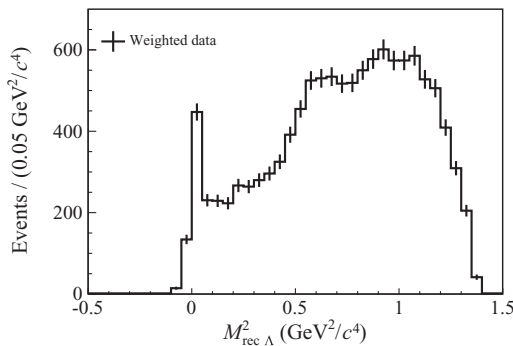


FIG. 5. Squared Λ recoil invariant mass distribution of the weighted data sample.

efficiency correction factor, which is estimated using the control samples $J/\psi \rightarrow \bar{p}K^+\Lambda$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$. Additionally, the uncertainty related to the intermediate BF of $\Lambda \rightarrow p\pi^-$ is taken from the PDG. For the 2D fit, systematic uncertainty is evaluated by varying the signal shape, including a convolution of the MC-simulated shape with a double-Gaussian function, and by varying the background shape and the ratio of the signal and $\Lambda_c^+\bar{\Lambda}_c^-$ background yields. Similarly, the uncertainty on the total ST $\bar{\Lambda}_c^-$ yield is assessed from variations of the signal and background shapes as well as the fit range in the M_{BC} fit. To evaluate the uncertainty from the BDT reweighting procedure, the BDT hyperparameters are varied, and the corresponding uncertainty is estimated from the resulting efficiency differences between the nominal and modified samples. Limited MC statistics contribute an additional uncertainty, quantified through sample size fluctuations. For the unmatched background, the corresponding uncertainty is assigned based on the deviation observed in the BF when relaxing the matching angle requirement.

The uncertainties of $\mathcal{A}_{\text{CP}}^{\text{dir}}$ are obtained by propagating the BF uncertainties for the decays $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$.

TABLE I. Systematic uncertainties (in percent) for the CP averaged and charge-conjugate BFs and $\mathcal{A}_{CP}^{\text{dir}}$, given as relative uncertainties for the BFs and absolute uncertainties for $\mathcal{A}_{CP}^{\text{dir}}$.

Source	CP average	ΛX	$\bar{\Lambda} X$	$\mathcal{A}_{CP}^{\text{dir}}$
Λ reconstruction	0.6	0.7	0.7	0.5
Intermediate BF	0.8	0.8	0.8	0.0
2D fit	0.4	0.9	0.6	0.4
ST $\bar{\Lambda}_c^-$ yield	0.4	0.5	0.6	0.4
BDT reweighting	0.1	0.1	0.1	0.0
MC statistics	0.2	0.3	0.3	0.2
Unmatched background	0.6	1.0	0.8	0.6
Total	1.3	1.8	1.6	1.0

In this propagation, the uncertainty associated with the intermediate BF of $\Lambda \rightarrow p\pi^-$ is treated as fully correlated since possible CPV in this decay is neglected and the same PDG value is used for both charge-conjugate modes. The contribution from the BDT reweighting procedure is also taken to be fully correlated because the same set of BDT hyperparameters is used in evaluating this effect for the two charge-conjugate modes. By contrast, the uncertainty associated with the Λ reconstruction is taken from the uncertainties of the efficiency correction factors, which are determined by the statistical precision of the respective control samples, and is therefore treated as uncorrelated. The remaining sources are evaluated independently using separate samples for the decays $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$ and are thus also treated as uncorrelated in the present analysis.

The total systematic uncertainty is taken as the quadratic sum of the individual contributions. The corresponding systematic uncertainties for the CP -averaged BF, the charge-conjugate BFs, and $\mathcal{A}_{CP}^{\text{dir}}$ are summarized in Table I.

Appendix C: Systematic uncertainties for the products $\mathcal{P}_{\Lambda\alpha_-}$ and $\mathcal{P}_{\bar{\Lambda}\alpha_+}$ and for $\mathcal{A}_{CP}^{\text{pol}}$ —The systematic uncertainty arising from the Λ reconstruction is evaluated using the control samples $J/\psi \rightarrow \bar{p}K^+\Lambda$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$. Correction factors extracted from these control samples are applied to the signal MC samples, modifying the θ_p -dependent efficiency used in the likelihood normalization and consequently leading to changes in the fit results. The systematic uncertainty for the differences in the M_{BC} and M_{Λ} resolutions between data and signal MC is evaluated by applying Gaussian smearing to the M_{BC} and M_{Λ} variables in the signal MC samples, using smearing parameters determined from fits to the corresponding distributions, and repeating the MC integration in the angular distribution fit. The systematic uncertainty associated with the BDT reweighting procedure is obtained by changing the BDT hyperparameters. For the background subtraction, we take into account the background shape and size. The

 TABLE II. Relative systematic uncertainties (in percent) for the products $\mathcal{P}_{\Lambda\alpha_-}$ and $\mathcal{P}_{\bar{\Lambda}\alpha_+}$ and for $\mathcal{A}_{CP}^{\text{pol}}$.

Source	$\mathcal{P}_{\Lambda\alpha_-}$	$\mathcal{P}_{\bar{\Lambda}\alpha_+}$	$\mathcal{A}_{CP}^{\text{pol}}$
Λ reconstruction	4.6	5.2	14.7
Resolution	0.3	0.3	1.4
BDT reweighting	0.5	0.3	0.5
Background size	1.5	1.4	6.9
Background shape	0.3	2.4	8.1
Unmatched background	1.0	1.0	4.9
Total	5.0	6.0	18.9

systematic uncertainty associated with the background shape is evaluated by replacing the data sideband sample with the background MC sample from the signal region. To assess the impact of the background size, the fits are repeated using alternative background yields derived from Gaussian sampling of the 2D fit parameters. By sampling the fit parameters under the assumption of a Gaussian distribution, we estimate the systematic uncertainty associated with the background size. The uncertainty is evaluated by combining the fitted Gaussian width and shift of the fitted Gaussian mean from the nominal value. In addition, to account for potential mismodeling of the unmatched background component, an alternative signal MC sample is generated using polarizations shifted by one statistical standard deviation from their nominal values, and the resulting variation is assigned as the corresponding systematic uncertainty.

The uncertainties of $\mathcal{A}_{CP}^{\text{pol}}$ are propagated from those of the products $\mathcal{P}_{\Lambda\alpha_-}$ and $\mathcal{P}_{\bar{\Lambda}\alpha_+}$. The contribution associated with the BDT reweighting procedure is treated as fully correlated, following the same treatment as for $\mathcal{A}_{CP}^{\text{dir}}$. The Λ reconstruction uncertainty is treated as partially correlated between the two charge-conjugate modes since the determination of the corresponding efficiency correction factors contain both common and channel-specific contributions. The common contributions arise from three correlated terms: the reconstruction of charged tracks, the particle identification, and the vertex fit; the channel-specific contributions come from two uncorrelated terms: the finite size of control samples and the extraction of yields. Therefore, a correlation coefficient of 60% is adopted when evaluating the uncertainty on $\mathcal{A}_{CP}^{\text{pol}}$. As a robustness check, the correlation coefficient is varied to 50% and 70%, and the final result remains unchanged at the quoted precision. For other contributions, the corresponding uncertainties are determined separately for the decays $\Lambda_c^+ \rightarrow \Lambda X$ and $\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} X$ and are therefore taken to be uncorrelated.

All systematic uncertainties are added in quadrature to calculate the total systematic uncertainties. The corresponding uncertainties for the products $\mathcal{P}_{\Lambda\alpha_-}$ and $\mathcal{P}_{\bar{\Lambda}\alpha_+}$ and for $\mathcal{A}_{CP}^{\text{pol}}$ are summarized in Table II.

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