Measurement of absolute branching fraction of the inclusive decay $\Lambda^+_c \to \Lambda + X$
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 $\Lambda_c^+ \rightarrow \Lambda + X$ to be $B(\Lambda_c^+ \rightarrow \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$ 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 $A_{CP} \equiv \frac{B(\Lambda_c^+ \rightarrow \Lambda + X) - B(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)}{B(\Lambda_c^+ \rightarrow \Lambda + X) + B(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)} = (2.1^{+7.9}_{-6.6} \pm 1.4)\%$, a statistically limited result with no evidence of CP violation.

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The inclusive decay $\Lambda^+_c \rightarrow \Lambda + X$, where $X$ means any possible final state particles, is mediated by the $c \rightarrow s$ Cabibbo-favored (CF) transition that dominates the decays of the $\Lambda^+_c$ [3]. As the $\Lambda^+_c$ is the lightest charmed baryon, the decay rate of the $\Lambda^+_c \rightarrow \Lambda + X$ 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 non-perturbative QCD region [3]. For instance, the $\Lambda^+_c \rightarrow \Lambda + X$ decay rate is an essential input in the experimental calculations of the lifetimes of charmed baryons, whose current theoretical results largely deviate from the input experimental measurements [3]. Furthermore, better understanding of the quark structure and decay dynamics in the $\Lambda^+_c \rightarrow \Lambda + X$ benefits the research on heavier charmed baryons [4, 5]. Especially for those lesser-known charmed baryons with double- or triple-charm quarks, an improved and calibrated theoretical prediction on the $c \rightarrow s$ decay vertex is crucial for guiding experimental search [5]. As the observation of the $\Xi^{++}$ at LHCb [10], such as the observation of the $\Xi^{++}$ 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 [11–12]. The average of their results gives $B(\Lambda^+_c \rightarrow \Lambda + X) = (35 \pm 11)\%$ [3], 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 $\chi^2/ndf = 4.1/2$ and a low confidence level of 0.126 [3]. 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 $\Lambda$ in PDG is $(24.5 \pm 2.1)\%$ [3]. The difference between the inclusive and exclusive rates will point out the size of as yet unknown decays, which requires high precision measurement of $B(\Lambda^+_c \rightarrow \Lambda + X)$. In addition, precise knowledge of $B(\Lambda^+_c \rightarrow \Lambda + X)$ provides an essential input for exploring the decays of $b$-flavored hadrons involving a $\Lambda^+_c$ 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 [13]. The impressive agreement on CP violation among the results from the $s$-quark and $b$-quark sectors [13, 16], calls for further checks in the less tested area of $c$-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 [17–19]. In this analysis, we search for direct CP violation by measuring the charge asymmetry of this inclusive decay $A_{CP} \equiv \frac{B(\Lambda_c^+ \rightarrow \Lambda + X) - B(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)}{B(\Lambda_c^+ \rightarrow \Lambda + X) + B(\bar{\Lambda}_c^- \rightarrow \bar{\Lambda} + X)}$.

The data used in this Letter comprise an integrated luminosity of 567 pb$^{-1}$ [21], corresponding to about $1.0 \times 10^5 \Lambda^+_c\Lambda^-_c$ pairs [22]. The data set was collected with the BESIII detector at the center-of-mass energy $\sqrt{s} = 4.6$ GeV. At this energy, the $\Lambda^+_c\Lambda^-_c$ pairs are produced near the production threshold with no additional hadrons, providing a clean environment for studying $\Lambda^+_c$ decays. By analyzing the data with the double-tag (DT) method [23], we perform the first measurement of the absolute BF for the inclusive decay $\Lambda^+_c \rightarrow \Lambda + X$. 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. [24]. The response of the experimental apparatus is simulated with a GEANT4-based [25] Monte Carlo (MC) simulation package. The reactions in $e^+e^-$ annihilations are generated by KKMC [26] and EvtGen [27], with initial-state radiation (ISR) effects [28] and final-state radiation (FSR) effects [29] 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 ($\Lambda^+_c$), the ISR-produced $\psi$ states and quantum electrodynamics processes. The $\Lambda^+_c$ is set to decay to all possible final states based on the BFs from the Particle Data Group (PDG) [30].

To study the signal $\Lambda^+_c \rightarrow \Lambda + X$ with the DT method, we first select the anti-particle $\Lambda^-_c$ by the two decay modes, $\bar{\Lambda}^+_c \rightarrow pK^0_S$ and $\bar{\Lambda}^+_c \rightarrow pK^+\pi^-$. The yield of
the tag mode $i$, $N_{\text{tag}}^{i}$, is given by

$$N_{\text{tag}}^{i} = 2 \cdot N_{\Lambda^{+} \bar{\Lambda}^{-}}^{i} \cdot B_{\text{sig}}^{i} \cdot \varepsilon_{\text{tag}}^{i},$$

(1)

where $N_{\Lambda^{+} \bar{\Lambda}^{-}}^{i}$ is the number of $\Lambda^{+} \bar{\Lambda}^{-}$ pairs in the data sample, while $B_{\text{sig}}^{i}$ and $\varepsilon_{\text{tag}}^{i}$ are the BF and detection efficiency for the tag mode $i$. Then we search for a $\Lambda$ among the remaining tracks. The number of the inclusive decays of $\Lambda^{\pm} \rightarrow \Lambda + X$ in the presence of the tag mode $i$, $N_{\text{sig}}^{i}$, is given by

$$N_{\text{sig}}^{i} = 2 \cdot N_{\Lambda^{+} \bar{\Lambda}^{-}}^{i} \cdot B_{\text{sig}}^{i} \cdot \varepsilon_{\text{sig}}^{i},$$

(2)

where $B_{\text{sig}}$ and $\varepsilon_{\text{sig}}$ are the BF and reconstruction efficiency for the inclusive decay $\Lambda^{\pm} \rightarrow \Lambda + X$. Here we assume that the reconstruction efficiency $\varepsilon_{\text{sig}}$ is independent of the tag mode, so the DT efficiency is given by $\varepsilon_{\text{sig}}^{i} \approx \varepsilon_{\text{tag}}^{i} \cdot \varepsilon_{\text{sig}}^{i}$. From Eq. 1 and Eq. 2 we determine the BF of the signal process by

$$B_{\text{sig}} = \frac{(\sum N_{\text{sig}}^{i})/\varepsilon_{\text{sig}}}{\sum N_{\text{tag}}^{i}},$$

(3)

The efficiency for detecting $\Lambda$ as a function of momentum and polar angle is determined from data with a control sample of $J/\psi$ decays. Due to lacking knowledge of the phase space distribution of the inclusive decay $\Lambda^{\pm} \rightarrow \Lambda + X$, we re-weight the $\Lambda$ efficiencies according to the momentum and polar angle distributions of $\Lambda$ in the DT signals. Therefore, the signal BF is calculated by

$$B_{\text{sig}} = \frac{\sum j ((\sum_{i} N_{\text{tag}}^{i})/\varepsilon_{\text{tag}}^{i})}{\sum_{i} N_{\text{tag}}^{i}} = \frac{\sum j (N_{\text{sig}}^{i}/\varepsilon_{\text{sig}}^{i})}{\sum_{i} N_{\text{tag}}^{i}},$$

(4)

where $j = 1, 2, \ldots$ is the index for the intervals of $\Lambda$ weighting kinematics, and $N_{\text{sig}}^{i}$ is the sum of DT signal yields in the two tag modes within the $j$-th 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 $\theta$ 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 $\Lambda$. 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 $L(p) > L(K)$ and $L(p) > L(\pi)$, while kaons and pions are discriminated from each other by requiring $L(K) > L(\pi)$ or $L(\pi) > L(K)$, respectively. To improve efficiency, no PID requirements are imposed on the charged pion candidates from the decays of $\Lambda$ or $K_{S}^{0}$.

The $K_{S}^{0}$ and $\Lambda$ candidates are reconstructed through their dominant decays $K_{S}^{0} \rightarrow \pi^{+} \pi^{-}$ and $\Lambda \rightarrow p \pi^{+}$. The distances of closest approach of the two candidate charged tracks to the IP must be within $\pm$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 $\chi^{2}$ 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 $\Lambda$ 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 momenta of the $\pi^{+} \pi^{-}$ and $p \pi^{-}$ combinations are used in the further analysis. To select $K_{S}^{0}$ and $\Lambda$ candidates, the invariant masses of $\pi^{+} \pi^{-}$ and $p \pi^{-}$ are required to be in the range $487 < M_{\pi^{+} \pi^{-}} < 511 \text{ MeV}/c^{2}$ and $1111 < M_{p \pi^{-}} < 1121 \text{ MeV}/c^{2}$, respectively.

To distinguish the tagged $\Lambda^{-}$ 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, $\Delta E \equiv E_{\Lambda^{-}} - E_{\text{beam}}$, where $E_{\Lambda^{-}}$ is the measured energy of the tagged $\Lambda^{-}$ candidate and $E_{\text{beam}}$ is the beam energy. To suppress combinatorial backgrounds, the mode-dependent $\Delta E$ requirements listed in Table I corresponding to $\pm 2.5$ times the resolutions of the fitted $\Delta E$ peaks, are imposed on the tagged $\Lambda^{-}$ candidates. The second is the beam-constrained mass of the tagged $\Lambda^{-}$ candidate, $M_{\text{BC}} \equiv \sqrt{E_{\text{beam}}^{2} - |\vec{p}_{\Lambda^{-}}|^{2}} \cdot c^{2}/c^{2}$, where $\vec{p}_{\Lambda^{-}}$ represents the momentum of the $\Lambda^{-}$ candidate. Figure I shows the $M_{\text{BC}}$ distributions of the two tag modes, showing clear $\Lambda^{-}$ signals at the expected mass. Studies based on MC show that the peaking backgrounds in the tag modes are negligible. Maximum likelihood fits are performed on these $M_{\text{BC}}$ distributions to obtain the yields of tagged $\Lambda^{-}$. The backgrounds are parameterized by an ARGUS function [31] with endpoint fixed to the beam energy. The signals are described by the MC-simulated shapes convoluted with 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 from the total event yields, we obtain the yields of the single tagged $\Lambda^{-}$, as listed in Table I.

Then we search for a $\Lambda$ candidate among the remaining

| Tag mode $i$ | $\Delta E$ (GeV) | $M_{\text{BC}}$ (GeV/$c^{2}$) | $N_{\text{tag}}^{i}$ |
|-------------|-----------------|-----------------|-----------------|
| $\Lambda^{-} \rightarrow p K_{S}^{0}$ | $[-0.021, 0.019]$ | $[2.282, 2.300]$ | $6088 \pm 85$ |
| $\Lambda^{-} \rightarrow p K^{+} \pi^{-}$ | $[-0.020, 0.015]$ | $1220 \pm 37$ | |

Table I. Requirements on $\Delta E$, $M_{\text{BC}}$ and resulting yields $N_{\text{tag}}^{i}$ for the tagged $\Lambda^{-}$ in data. The uncertainty of $N_{\text{tag}}^{i}$ is statistical only.
FIG. 1. Fits to the $M_{BC}$ distributions of the candidate events for (a) $\Lambda_c^- \to \pi^0 K_S^0$ and (b) $\Lambda_c^- \to \pi^- K^+ \pi^-$ in data. The thick dots stand for the data. The solid curves denote the total fits, while the dotted lines represent the background. The arrows show the signal regions. The description of the fits is given in the text.

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.

The efficiencies for detecting a $\Lambda$ candidate are estimated from the control samples $J/\psi \to \Lambda \bar{X}$ and $J/\psi \to \pi K^+ \Lambda$, which are selected from a $J/\psi$ on-peak data sample consisting of $(1310.6 \pm 7.0) \times 10^6$ $J/\psi$ decays [32]. In each kinematic interval, the data-driven efficiency is calculated based on a “tag-and-probe” technique. For $J/\psi \to \Lambda \bar{X}$, a $\Lambda$ is tagged in an event, while for $J/\psi \to \pi K^+ \Lambda$, two charged tracks identified as a proton and a kaon are selected. The missing $\Lambda$ is identified by limiting the missing mass within $[1.067, 1.155]$ GeV/c$^2$ for $J/\psi \to \Lambda \bar{X}$ and $[1.093, 1.139]$ GeV/c$^2$ for $J/\psi \to \pi K^+ \Lambda$. In the tagged event, we search for a $\Lambda$ 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 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 $N_{sig}^{\Lambda}$ from Table II and the numbers of $N_{sig}^{\Lambda}$ and $\varepsilon_j^{\Lambda}$ from Table II into Eq. (3), we determine the BF of $\Lambda_0^{+} \to \Lambda + X$ to be $B(\Lambda_0^{+} \to \Lambda + X) = (38.2^{+2.8}_{-2.3})\%$. 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 $\Lambda_0^{+} \to \Lambda + X$ is obtained by comparing the separate BFs of the charge conjugate decays, which are $B(\Lambda_0^{+} \to \Lambda + X) = (39.4^{+4.7}_{-3.4})\%$ and $B(\Lambda_0^{+} \to \bar{\Lambda} + X) = (37.8^{+3.8}_{-3.6})\%$. The yields and efficiencies of $\Lambda_0^{+} \to \Lambda + X$ and $\bar{\Lambda}_0^{+} \to \Lambda + X$ can be found in the supplemental material [33]. The $CP$ asymmetry is determined to be $A_{CP} = (2.1^{+2.0}_{-6.6})\%$, where the uncertainty is statistical only.

The $CP$ asymmetry 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 $\Lambda$ control samples bring uncertainty to the $\Lambda$ efficiency, which is estimated by a weighted right-mean-square (RMS) of the statisti-
Table III. Summary of the relative systematic uncertainties for the BF of $\Lambda^+_c \rightarrow \Lambda + X$.

| Source                             | Relative uncertainty (%) |
|------------------------------------|--------------------------|
| Statistics of the control sample   | 0.6                      |
| $\Lambda$ 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 $\Lambda^+_c \rightarrow \Lambda + X$ to be $\mathcal{B}(\Lambda^+_c \rightarrow \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$. The precision of the BF is improved by a factor of 4 compared to previous measurements. This inclusive rate is larger than the exclusive rate of $(24.5\pm2.1)\%$ in PDG, which indicates that more than one third of the $\Lambda^+_c$ decays to $\Lambda$ remain unobserved in experiment. Furthermore, we search for direct $CP$ violation in this decay for the first time. The $CP$ asymmetry is measured to be $\mathcal{A}_{CP} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$. The precision is limited by statistical uncertainty and no evidence for $CP$ violation is found.

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[33] See Supplemental Materials at [URL will be inserted by the publisher] for a summary of the yields of $\Lambda^+ \rightarrow \Lambda + X$ and $\bar{\Lambda}^- \rightarrow \bar{\Lambda} + X$, as well as the reconstruction efficiencies of $\Lambda$ and $\bar{\Lambda}$.
### TABLE IV. Signal yields and detection efficiencies of the inclusive \( \Lambda \) and \( \bar{\Lambda} \) in each \((p, |\cos\theta|)\) interval. The errors here reflect only statistical uncertainties.

| \( p \) (GeV/c) | \( N_{\text{sig}, \Lambda} \) | \( \text{[cos}\theta]\) | \( N_{\text{sig}, \bar{\Lambda}} \) | \( \text{[cos}\theta]\) |
|---------------|----------------|------------|----------------|------------|
| \([0.0, 0.3]\) | \(4.5 \pm 3.7\) | \([-2.4, 3.0]\) | \(5.9 \pm 4.4\) | \(-3.1\) |
| \([0.3, 0.5]\) | \(26.8 \pm 7.2\) | \([-5.9, 5.0]\) | \(44.7 \pm 8.3\) | \(11.5 \pm 6.0\) |
| \([0.5, 0.7]\) | \(46.8 \pm 8.3\) | \([-7.2, 7.9]\) | \(30.8 \pm 7.1\) | \(30.8 \pm 7.1\) |
| \([0.7, 0.9]\) | \(21.5 \pm 6.0\) | \([-4.8, 4.0]\) | \(21.0 \pm 6.0\) | \(17.9 \pm 5.9\) |
| \([0.9, 1.1]\) | \(3.0 \pm 3.2\) | \([-1.8, 2.7]\) | \(4.0 \pm 3.4\) | \(4.5 \pm 3.7\) |

| \( p \) (GeV/c) | \( \varepsilon_{12}^{\text{incl}, \Lambda}\) (%) | \( \text{[cos}\theta]\) | \( \varepsilon_{12}^{\text{incl}, \bar{\Lambda}}\) (%) | \( \text{[cos}\theta]\) |
|---------------|----------------|------------|----------------|------------|
| \([0.0, 0.3]\) | \(7.98 \pm 0.53\) | \(8.25 \pm 0.52\) | \(7.75 \pm 0.44\) | \(3.85 \pm 0.27\) |
| \([0.3, 0.5]\) | \(30.38 \pm 0.55\) | \(29.38 \pm 0.55\) | \(27.01 \pm 0.48\) | \(15.53 \pm 0.32\) |
| \([0.5, 0.7]\) | \(35.92 \pm 0.47\) | \(35.91 \pm 0.49\) | \(34.14 \pm 0.47\) | \(20.49 \pm 0.36\) |
| \([0.7, 0.9]\) | \(40.15 \pm 0.70\) | \(39.30 \pm 0.72\) | \(36.51 \pm 0.71\) | \(24.05 \pm 0.75\) |
| \([0.9, 1.1]\) | \(41.34 \pm 0.20\) | \(40.70 \pm 0.19\) | \(38.38 \pm 0.17\) | \(30.72 \pm 0.16\) |