Precision measurements of decay parameters and CP asymmetry in $\Lambda$ decays
Shulei Zhang, X. D. Zhang, X. M. Zhang, X. Y. Zhang, X. Y. Zhang, Y. Zhang, Y. T. Zhang, Y. H. Zhang, Yan Zhang, Y. Zhao, Z. H. Zhang, Z. Y. Zhang, Z. Y. Zhang, G. Zhao, J. Zhao, J. Y. Zhao, J. Z. Zhao, Lei Zhao, Ling Zhao, M. G. Zhao, Q. Zhao, S. J. Zhao, Y. B. Zhao, Y. X. Zhao, Z. G. Zhao, A. Zhemchugov, B. Zheng, J. P. Zheng, Y. H. Zheng, B. Zhong, C. Zhong, X. Zhong, H. Zhou, L. P. Zhou, X. Zhou, X. K. Zhou, X. R. Zhou, X. Y. Zhou, Y. Z. Zhou, J. Zhu, K. Zhu, K. J. Zhu, L. X. Zhu, S. H. Zhu, S. Q. Zhu, T. J. Zhu, W. J. Zhu, Y. C. Zhu, Z. A. Zhu, B. S. Zou, J. H. Zou

(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 Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
6 Central China Normal University, Wuhan 430079, People’s Republic of China
7 Central South University, Changsha 410083, People’s Republic of China
8 China Center of Advanced Science and Technology, Beijing 100190, People’s Republic of China
9 COMSATS University Islamabad, Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
10 Fudan University, Shanghai 200433, People’s Republic of China
11 G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
12 GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany
13 Guangxi Normal University, Guilin 541004, People’s Republic of China
14 Guangxi University, Nanning 530004, People’s Republic of China
15 Hangzhou Normal University, Hangzhou 310036, People’s Republic of China
16 Hebei University, Baoding 071002, People’s Republic of China
17 Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany
18 Henan Normal University, Xinxiang 453007, People’s Republic of China
19 Henan University of Science and Technology, Luoyang 471003, People’s Republic of China
20 Henan University of Technology, Zhengzhou 450001, People’s Republic of China
21 Huangshan College, Huangshan 245500, People’s Republic of China
22 Hunan Normal University, Changsha 410081, People’s Republic of China
23 Hunan University, Changsha 410082, People’s Republic of China
24 Indian Institute of Technology Madras, Chennai 600036, India
25 Indiana University, Bloomington, Indiana 47405, USA
26 INFN Laboratori Nazionali di Frascati, (A)INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy; (B)INFN Sezione di Perugia, I-06100, Perugia, Italy; (C)University of Perugia, I-06100, Perugia, Italy
27 INFN Sezione di Ferrara, (A)INFN Sezione di Ferrara, I-44122, Ferrara, Italy; (B)University of Ferrara, I-44122, Ferrara, Italy
28 Institute of Modern Physics, Lanzhou 730000, People’s Republic of China
29 Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13230, Mongolia
30 Jilin University, Changchun 130012, People’s Republic of China
31 Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
32 Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
33 Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
34 Lanzhou University, Lanzhou 730000, People’s Republic of China
35 Liaoning Normal University, Dalian 116029, People’s Republic of China
36 LiaoNing University, Shenyang 110036, People’s Republic of China
37 Nanjing Normal University, Nanjing 210023, People’s Republic of China
38 Nanjing University, Nanjing 210093, People’s Republic of China
39 Nankai University, Tianjin 300071, People’s Republic of China
40 National Centre for Nuclear Research, Warsaw 02-093, Poland
41 North China Electric Power University, Beijing 102206, People’s Republic of China
42 Peking University, Beijing 100871, People’s Republic of China
43 Qufu Normal University, Qufu 273165, People’s Republic of China
44 Shandong Normal University, Jinan 250014, People’s Republic of China
45 Shandong University, Jinan 250100, People’s Republic of China
46 Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
47 Shanxi Normal University, Linfen 041004, People’s Republic of China
48 Shanxi University, Taiyuan 030006, People’s Republic of China
49 Sichuan University, Chengdu 610064, People’s Republic of China
50 Soochow University, Suzhou 215006, People’s Republic of China
51 South China Normal University, Guangzhou 510006, People’s Republic of China
52 Southeast University, Nanjing 211100, People’s Republic of China
53 State Key Laboratory of Particle Detection and Electronics, Beijing 100039, Hefei 230026, People’s Republic of China
Based on 10 billion $J/\psi$ events collected in the BESIII experiment, the phase angle $\Delta \Phi$ associated with hyperon polarization in $\Lambda/\bar{\Lambda}$ production, and the decay parameters $\alpha_-$ for $\bar{\Lambda} \to p\pi^-$ and $\alpha_+$ for $\Lambda \to \bar{p}\pi^+$ are studied in the process $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$. The free parameters of the joint angular distribution are determined by means of a maximum likelihood fit, and the results are: $\Delta \Phi = 0.7521 \pm 0.0042 \pm 0.0080$, $\alpha_- = 0.7519 \pm 0.0036 \pm 0.0019$, and $\alpha_+ = -0.7559 \pm 0.0036 \pm 0.0029$. The average value of the $\Lambda$ decay parameter is $\alpha_{\text{ave}} = 0.7542 \pm 0.0010 \pm 0.0020$. The CP asymmetry observable $A_{\text{CP}} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$ is determined to be $-0.0025 \pm 0.0046 \pm 0.0011$, which is the most precise measurement in the strange baryon sector.

Although CP violation has been observed in the $K$ [1], $B$ [2, 3], and $D$ mesons [4, 5], our understanding of this process is still quite limited and there is currently no experimental evidence for CP violation in the strange baryon sector. Such a discovery could potentially shed new light on the matter-antimatter asymmetry in the universe. In spin-$\frac{1}{2}$ hyperon non-leptonic decays, the angular distribution of the daughter baryon is proportional to $(1 + \alpha_Y \hat{p}_Y \cdot \hat{p}_d)$ [6], where $\alpha_Y$ is the hyperon decay parameter, and $\hat{p}_Y$ and $\hat{p}_d$ are the hyperon polarization and the unit vector in the direction of the daughter baryon momentum, respectively, both in the hyperon rest frame. The CP asymmetry observable is defined by $A_{\text{CP}} = \frac{\alpha_Y + \alpha_+}{\alpha_Y - \alpha_-}$. The parameters $\alpha_Y$ and $\alpha_-$ are CP odd so that a non-zero $A_{\text{CP}}$ indicates CP violation. The Cabibbo-Kobayashi-Maskawa mechanism predicts an $A_{\text{CP}}$ value of $\sim 10^{-4}$ [7].

In 2019, using 1.3 billion $J/\psi$ events, the BESIII Collaboration determined the $\Lambda$ baryon decay parameter $\alpha_0 = 0.750 \pm 0.009 \pm 0.004$ [8], which was larger than the earlier PDG average value by more than five stan-
standard deviations. In the same year, Ref. [9] made an independent measurement of $\alpha_-$ from a set of polarization data measured in kaon photoproduction at CLAS. Their obtained value of $0.721 \pm 0.006 \pm 0.005$ [9] supported the BESIII result, but with a 2.3σ discrepancy. The previous BESIII analysis was based on 1.3 billion $J/\psi$ events, and we update these results here with data accumulated in 2017-2019 to a total sample of 10 billion $J/\psi$ events. We present improved measurements of the $\Lambda$ decay parameters and the CP asymmetry observable with increased precision. Compared with the previous BESIII analysis, the systematic uncertainties are studied in a comprehensive way to match the significant improvement of statistics. Figure 1(a) shows the Feynman diagram of $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$ and Fig. 1(b) shows the measurement reference system. Two real parameters, the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ angular distribution parameter $\alpha_{J/\psi}$ and the helicity phase difference $\Delta\Phi$, describe the angular distribution and polarization of the produced $\Lambda$ and $\bar{\Lambda}$ [10][15]. If the phase difference $\Delta\Phi$ is non-vanishing, the polarization of the $\Lambda$ and $\bar{\Lambda}$ will be oriented perpendicular to the production plane.

For the decay $\Lambda \rightarrow p\pi^-$, the angular distribution of the proton is $\frac{1}{4\pi} (1 + \alpha_+ P_n \cdot n)$, where $P_n$ is the polarization vector of the $\Lambda$, $n$ is the unit vector of the proton momentum in the $\Lambda$ rest frame, and $-1 \leq \alpha_+ \leq 1$ is the decay parameter which characterizes the degree of mixing of parity conserving and parity violating amplitudes [6]. The definition of the decay parameter $\alpha_+$ for $\Lambda \rightarrow p\pi^+$ follows an analogous convention [10]. The differential decay rate of $J/\psi \rightarrow \Lambda \rightarrow p\pi^- (\Lambda \rightarrow \bar{p}\pi^+)$ is proportional to [15]:

$$W(\xi; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+) = 1 + \alpha_{J/\psi} \cos^2 \theta_\Lambda$$

$$+ \alpha_- \alpha_+ \sin^2 \theta_\Lambda (n_{1,x}n_{2,x} - \alpha_{J/\psi}n_{1,y}n_{2,y}) + (\cos^2 \theta_\Lambda + \alpha_{J/\psi}) n_{1,z}n_{2,z}$$

$$+ \sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) \sin \theta_\Lambda \cos \theta_\Lambda (n_{1,x}n_{2,z} + n_{1,z}n_{2,x})$$

$$+ \sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) \sin \theta_\Lambda \cos \theta_\Lambda (\alpha_+ n_{1,y} + \alpha_- n_{2,y}),$$  \hspace{0.5cm} (1)

where $\hat{n}_1 (\hat{n}_2)$ is the unit vector in the direction of the proton (anti-proton) momentum in the $\Lambda$ ($\bar{\Lambda}$) rest frame. The components of these vectors are expressed using a right-handed coordinate system ($\hat{x}, \hat{y}, \hat{z}$) shown in Fig. 1(b). The $\hat{z}$ axis is taken along the $\Lambda$ momentum $p_\Lambda = -p_{\bar{\Lambda}} = p$ in the $e^+e^-$ center-of-mass system (CMS). The $\hat{y}$ axis is perpendicular to the production plane and oriented along the vector $k \times p$, where $k_{-} = -k_{+} = k$ is the electron beam momentum in the CMS. The scattering angle of the $\Lambda$ is given by $\cos \theta_\Lambda = p \cdot k$.

Each event is uniquely characterized by the kinematic variable $\xi = (\theta_\Lambda, \hat{n}_1, \hat{n}_2)$. The terms proportional to $\alpha_-\alpha_+$ in Eq. (1) represent the contribution from $\Lambda-\bar{\Lambda}$ spin correlations, and the terms proportional to $\alpha_-$ and $\alpha_+$ separately represent the contribution from the hyperon transverse polarization $P_y$, defined as:

$$P_y(\cos \theta_\Lambda) = \frac{\sqrt{1 - \alpha_{J/\psi}^2 \sin(\Delta\Phi) \cos \theta_\Lambda \sin \theta_\Lambda}}{1 + \alpha_{J/\psi} \cos^2 \theta_\Lambda}.$$  \hspace{0.5cm} (2)

The analysis presented here is based on the aforementioned sample of 10 billion $J/\psi$ events [17] collected at the BESIII detector [18][19]. A Monte Carlo (MC) simulation of $J/\psi$ samples is used to determine the detector efficiency, optimize the event selection, and estimate the background. The simulation is performed by the GEANT4 [20]-based BESIII Object Oriented Simulation Tool project [21], which includes the geometric description of the BESIII detector and the detector response. The MC event generators KKMC [22], BesEvtGen [23], and Lundcharm [24][25] are used to describe $J/\psi$ production together with known and unknown decay modes. For the signal process, $J/\psi \rightarrow \Lambda\bar{\Lambda}$, the parameters of the angular distribution are obtained from previous measurements [8]. For the dominant background channel $J/\psi \rightarrow \gamma\eta_c (\eta_c \rightarrow \Lambda\bar{\Lambda})$, the decay $J/\psi \rightarrow \gamma\eta_c$ is generated with an angular distribution of $1 + \cos^2 \theta_\gamma$ [26], where $\theta_\gamma$ is the angle between the photon and positron beam direction in the CMS, and another background channel $J/\psi \rightarrow \gamma\Lambda\bar{\Lambda}$ is described by the phase space model.

The $\Lambda$ and $\bar{\Lambda}$ baryons are reconstructed from their dominant hadronic decay mode, $\Lambda(\bar{\Lambda}) \rightarrow p\pi^-(\bar{p}\pi^+)$. Charged tracks detected in the Main Drift Chamber must satisfy $|\cos \theta(\gamma)| < 0.93$ for acceptance, where $\theta$ is the angle between the charged track and the positron beam direction (with the 11 mrad crossing angle removed). Events with at least four charged tracks are retained. Tracks with momentum larger than 0.5 GeV/$c$ are considered as proton candidates, otherwise as pion candidates. There are no further particle identification requirements. Vertex fits are performed by looping over all combinations with oppositely charged proton and pion candidates, constraining them to a common vertex. The pairs with vertex fit $\chi^2$ lower than 200 and decay length larger than 0 are regarded as $\Lambda/\bar{\Lambda}$ candidates. A four-momentum constrained kinematic fit (4C-fit) is applied to the $pp\pi^+\pi^-$ hypothesis, and events with a minimum $\chi^2$ lower than 60.
are selected as $J/\psi$ candidates.

The results of the fit to the $p\pi^-$ and $\bar{p}\pi^+$ invariant mass spectra are shown in Fig. 2, where the signal shape is described by the sum of four Gaussian functions and the background shape modeled by a first-order Chebyshev polynomial. The signal region obtained by fitting is $m_{p\pi^-} \in [1.111, 1.121]$ GeV/c$^2$. An inclusive MC sample of 10 billion $J/\psi$ events is used for studying potential backgrounds. After applying the same selection criteria as for the data and using the generic analysis tool TopoAna [27], the main backgrounds are divided into two types according to the shapes of $m_{p\pi^-}$ and $m_{\bar{p}\pi^+}$: (1) BKGI, non-peaking backgrounds, including $J/\psi \rightarrow p\pi^-\bar{p}e^+$, $\Delta^{++}p\pi^-$, $\Delta^{++}p\pi^+$, $\Delta^{++}/\Delta^{++}$; (2) BKGI, peaking backgrounds, including $J/\psi \rightarrow \gamma\Lambda\bar{\Lambda}$, $\gamma\eta_c(\eta_c \rightarrow \Lambda\bar{\Lambda})$. The number of non-peaking backgrounds is estimated by the two-dimensional signal regions of the $m_{p\pi^-}$ versus $m_{\bar{p}\pi^+}$ distribution from the data sample. The sideband regions are defined as $|m_{p\pi^-} - m_\Lambda| \in (0.009, 0.018)$ GeV/c$^2$, where $m_\Lambda = 1.1168$ GeV/c$^2$ is the fitted mean value of $m_{p\pi^-}$ and $m_{\bar{p}\pi^+}$ distributions from data. The yields of various peaking background sources are estimated by individual exclusive MC samples, then normalized to the data sample according to their branching fractions [28]. The final data sample contains 3231781 events including the estimated background yield of 3801 ± 63 events. The sample has a high purity of 99.9%.

Based on the joint angular distribution, a maximum likelihood fit with four free parameters ($\alpha_{J/\psi}$, $\Delta\Phi$, $\alpha_-$, and $\alpha_+$) is performed. The joint likelihood function is defined as:

$$
\mathcal{L} = \prod_{i=1}^{N} \mathcal{P}(\xi^i; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+)
$$

$$= \prod_{i=1}^{N} \mathcal{W}(\xi^i; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+) e(\xi^i) ,
$$

where $\mathcal{P}(\xi^i; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+)$ is the probability density function of $\xi^i = (\theta_\Lambda, \hat{n}_1, \hat{n}_2)$, the kinematic variable of event $i$, and $\mathcal{W}(\xi^i; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+)$ is given by Eq. (1). The detection efficiency is denoted by $e(\xi^i)$. The normalization factor $C^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} W(\xi^j; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+) e(\xi^j)$ is estimated with the $N_{MC}$ events generated with the phase space model, applying the same event selection criteria as for the data. To improve the accuracy of the normalization factor, we generate an MC sample about 100 times larger than the selected experimental data. We use the RooFit package [29] to determine the fit parameters from the function:

$$
S = -\ln \mathcal{L}_{\text{data}} + \ln \mathcal{L}_{\text{BKGI}} + \ln \mathcal{L}_{\text{BKGI+}} ,
$$

where $\mathcal{L}_{\text{data}}$ and $\mathcal{L}_{\text{BKGI}}$ are the likelihood function of events in the signal region and sideband regions, respectively. The $\mathcal{L}_{\text{BKGI+}}$ is the likelihood function of background events obtained by exclusive MC samples. The likelihood function of background event is same as data. The results of the maximum likelihood fit of data are given in Table 1 with the CP asymmetry observable given by $A_{CP} = (\alpha_+ - \alpha_-)/(\alpha_+ + \alpha_-)$, and the average value of the $\Lambda$ and $\Lambda$ decay parameters $\alpha_{avg} = (\alpha_- + \alpha_+)/2$. The correlation coefficient between $\alpha_-$ and $\alpha_+$ is $\rho(\alpha_- , \alpha_+) = 0.850$.

| Par. | This work | Previous results [8] |
|------|-----------|----------------------|
| $\alpha_{J/\psi}$ | 0.4748 ± 0.0022 ± 0.0024 | 0.461 ± 0.006 ± 0.007 |
| $\Delta\Phi$ | 0.7521 ± 0.0042 ± 0.0080 | 0.740 ± 0.010 ± 0.009 |
| $\alpha_-$ | 0.7519 ± 0.0036 ± 0.0019 | 0.750 ± 0.009 ± 0.004 |
| $\alpha_+$ | -0.7559 ± 0.0036 ± 0.0029 | -0.758 ± 0.010 ± 0.007 |
| $A_{CP}$ | -0.0025 ± 0.0046 ± 0.0011 | 0.006 ± 0.012 ± 0.007 |
| $\alpha_{avg}$ | 0.7542 ± 0.0010 ± 0.0020 | - |

The moment

$$
\mu(\cos(\theta_\Lambda)) = (m/N) \sum_{i=1}^{N_\Lambda} (n_{1,y}^{(i)} - n_{2,y}^{(i)}) ,
$$

where

FIG. 1. (a) Feynman diagram of the $\Lambda\bar{\Lambda}$ pair production in $e^+e^-$ annihilation. (b) A $J/\psi$ particle is produced after the collision of $e^+e^-$ and then rapidly decays into a $\Lambda\bar{\Lambda}$ pair. In the $e^+e^-$ CMS, $\theta_\Lambda$ denotes the angle between $\Lambda(\hat{n}_z)$ and the $e^-$ beam direction. The hyperons are polarized in the direction perpendicular to the production plane ($\hat{y}$).
which strongly depends on the Λ direction, is suited for
the observation of the hyperon polarization. Hereby, \( N \) is
the total number of events in the data set, and \( m = 100 \) is
the number of bins in \( \cos(\theta_\Lambda) \) for calculating the moment.
\( N_k \) denotes the number of events in the \( k \)-th \( \cos(\theta_\Lambda) \) bin.
The expected angular dependence of the moment for the
acceptance-corrected data reads

\[
\mu(\cos \theta_\Lambda) = \frac{\alpha_- - \alpha_+}{2} + \frac{1 + \alpha_{J/\psi} \cos^2 \theta_\Lambda}{3 + \alpha_{J/\psi}} P_y(\theta_\Lambda) . \tag{6}
\]

A significant transverse polarization of Λ and \( \bar{\Lambda} \) can be
seen in Fig. 3, in which the points with error bars are the
data, and the solid line is obtained from signal MC sample
generated by Eq. 1, where the input parameters are
taken from fit results. The data are consistent with the
fit results. To compare the fit results with the data, the
moments \( T_i, i = 1, \ldots, 5 \) can be extracted from Eq. 1:

\[
T_1 = \sum_{i=1}^{N_k} \left( \sin^2 \theta_\Lambda n_{1,x}^{(i)} n_{2,x}^{(i)} + \cos^2 \theta_\Lambda n_{1,x}^{(i)} n_{2,z}^{(i)} \right),
\]

\[
T_2 = \sum_{i=1}^{N_k} \sin \theta_\Lambda \cos \theta_\Lambda \left( n_{1,x}^{(i)} n_{2,z}^{(i)} + n_{1,z}^{(i)} n_{2,x}^{(i)} \right),
\]

\[
T_3 = \sum_{i=1}^{N_k} \sin \theta_\Lambda \cos \theta_\Lambda n_{1,y}^{(i)}, \tag{7}
\]

\[
T_4 = \sum_{i=1}^{N_k} \sin \theta_\Lambda \cos \theta_\Lambda n_{2,y}^{(i)},
\]

\[
T_5 = \sum_{i=1}^{N_k} \left( n_{1,z}^{(i)} n_{2,z}^{(i)} - \sin^2 \theta_\Lambda n_{1,y}^{(i)} n_{2,y}^{(i)} \right).
\]

The moments are again calculated for \( m = 100 \) bins in \( \cos \theta_\Lambda \). Figure 4 shows the distribution of the moments
versus \( \cos \theta_\Lambda \), where the black dots with error bars are the
data, and the red histograms are calculated using the
probability density function \( P(\xi^i, \alpha_{J/\psi}, \Delta \Phi, \alpha_-, \alpha_+) \)
with the parameters set to the global fit values. There
are some inconsistencies between data and MC simulation
in \( T_5 \). The impact of these inconsistencies on the fit
parameters is determined by making corrections to the
\( T_5 \) distribution in the phase space MC sample to better
match the data. The difference between the fit results
with and without this correction is negligible.

The systematic uncertainties in this analysis can be
divided into two categories: (A) the uncertainties from
event selection, including background estimation, tracking,
the Λ/\( \bar{\Lambda} \) vertex fit and kinematic fit; (B) the un-
certainty associated with the fit procedure. The uncer-
tainty from background is estimated by varying the in-
put background numbers by one standard deviation. The differences on the fitted parameters are taken as the sys-
tematic uncertainty. For the tracking and Λ/\( \bar{\Lambda} \) vertex fit
and kinematic fit, a correction to the MC efficiency is
made. We use control samples to get the efficiencies of
the data and MC simulation in tracking, Λ/\( \bar{\Lambda} \) vertex fit,
and kinematic fit, and use the data and MC difference.

FIG. 2. The fit results of invariant mass spectra of (a) \( p\pi^- \) and (b) \( \bar{p}\pi^+ \) from the data. The signal is described by the sum of
four Gaussian functions, the background by a first-order Chebyshev polynomial.

FIG. 3. Distribution of moment \( \mu(\cos \theta_\Lambda) \) versus \( \cos \theta_\Lambda \). The
points with error bars are the data, and the red histogram
is the signal MC sample with input parameters fixed to fit
results. The blue histogram shows the result from PHSP MC
sample. The distribution of \( \chi = (\mu_{\text{data}} - \mu_{\text{MC}})/\sigma(\mu_{\text{data}}) \) is
shown at the bottom, where \( \mu_{\text{data}} \) and \( \mu_{\text{MC}} \) are the moments
of data and signal MC sample. The \( \sigma(\mu_{\text{data}}) \) is the statistical
uncertainty of \( \mu_{\text{data}} \).
to calibrate the MC sample. The uncertainty due to the charged particle tracking efficiency has been investigated with a $J/\psi \rightarrow p\pi^-\bar{p}\pi^+$ control sample. The systematic uncertainties due to the $\Lambda$ and $\bar{\Lambda}$ vertex reconstruction and kinematic fits are estimated by a control sample $J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^-\bar{p}\pi^+$. In order to reduce the impact of statistical fluctuations, the fit with corrected MC sample is performed 100 times by varying the correction factor randomly within one standard deviation. The differences between the mean value of the fit results with corrections and the nominal fit are taken as the systematic uncertainties. The MC simulation is used to estimate the uncertainty of the fit method. The differences between the input and output values are regarded as systematic uncertainties. The absolute systematic uncertainties for various sources are summarized in Table II. The total systematic uncertainty of each parameter is obtained by summing the individual contributions in quadrature.

In summary, by analyzing 10 billion $J/\psi$ events, including 1.3 billion events used in our previous measurement [3], we report precision measurements of the angular distribution parameters of $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and the decay parameters of $\Lambda(\bar{\Lambda})$, with results given in Table II. The results are consistent with those in the previous analysis [8], however, with significantly improved precision. A clear transverse polarization is observed for the $\Lambda$ and $\bar{\Lambda}$ as shown in Fig. 3. The phase between helicity flip and helicity conserving transitions is determined to be $\Delta \Phi = 0.7521 \pm 0.0042 \pm 0.0080$, where the first uncertainty is statistical and the second one is systematic. The large value of the phase makes it possible to simultaneously determine the decay parameters of $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow \bar{p}\pi^+$ to be $\alpha_- = 0.7519 \pm 0.0036 \pm 0.0019$ and $\alpha_+ = 0.7559 \pm 0.0036 \pm 0.0029$, which represents the most precise measurements to date. Owing to the large correlation coefficient of the two decay parameters $\rho(\alpha_-, \alpha_+) = 0.850$, the average value of the $\Lambda$ decay parameter, $\alpha_{\text{avg}} = 0.7542 \pm 0.0010 \pm 0.0020$, has a much smaller statistical uncertainty than $\alpha_-$ and $\alpha_+$. The reported value of $\alpha_{\text{avg}}$ is relevant for charmed baryon and beauty baryon decays into final states involving $\Lambda$ [30–34].

Results of the $\Lambda$ decay parameter from different experiments are shown in Fig. 5. The $\alpha_-$ value obtained in this work agrees with the previous BESIII measurements [8] and the BESIII result extracted from the $J/\psi \rightarrow \Xi^-\Xi^+$ decay [35], but deviates from the CLAS result by $3.5\sigma$. In addition, we obtain the value of CP violation for the $\Lambda$ decay $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = \ldots$
ACKNOWLEDGMENTS

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 Contracts Nos. 2020YFA0406300, 2020YFA0406400; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11635010, 11735014, 11835012, 11935015, 11935016, 11935018, 11961141012, 12025210, 12025502, 12035009, 12035013, 12192260, 12192261, 12192262, 12192263, 12192264, 12192265; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1832207; CAS Key Research Program of Frontier Sciences under Contract No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; Polish National Science Centre under Contract 2019/35/O/ST2/02907; ERC under Contract No. 758462; European Union’s Horizon 2020 research and innovation programme under Marie Sklodowska-Curie grant agreement under Contract No. 894790; German Research Foundation DFG under Contracts Nos. 443159800, Collaborative Research Center CRC 1044, GRK 2149; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund: STFC (United Kingdom); The Royal Society, UK under Contracts Nos. DH140054, DH160214; The Swedish Research Council; U. S. Department of Energy under Contract No. DE-FG02-05ER41374.