

Test of CP Symmetry in the Neutral Decays of Λ via $J/\psi \rightarrow \Lambda \bar{\Lambda}$

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Using $(10\,087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a full angular analysis is carried out on the process $J/\psi \rightarrow \Lambda \bar{\Lambda} \rightarrow n\pi^0 \bar{p}\pi^+ + \text{c.c.}$ The decay parameters α_0 for $\Lambda \rightarrow n\pi^0$ and $\bar{\alpha}_0$ for $\bar{\Lambda} \rightarrow \bar{n}\pi^0$ are measured to be $0.668 \pm 0.007 \pm 0.002$ and $-0.677 \pm 0.007 \pm 0.003$, respectively, yielding the most precise test for CP symmetry of neutral decays of Λ , $A_{CP}^0 = (\alpha_0 + \bar{\alpha}_0)/(\alpha_0 - \bar{\alpha}_0)$, to be $-0.006 \pm 0.007 \pm 0.002$. The ratios α_0/α_- and $\bar{\alpha}_0/\alpha_+$ are determined to be $0.884 \pm 0.013 \pm 0.006$ and $0.885 \pm 0.013 \pm 0.004$, where α_- and α_+ are the decay parameters of $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$, respectively. The ratios, found to be smaller than unity by more than 5σ , confirm the presence of the $\Delta I = 3/2$ transition in the Λ and $\bar{\Lambda}$ decays, which is expected to improve the theoretical calculations for isospin amplitudes, and A_{CP} , in hyperon decays. In all results, the first and second uncertainties are statistical and systematic, respectively.

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The violation of the combined charge-conjugation (C) and spatial parity (P) symmetries, known as CP violation, is a key ingredient in explaining the observed matter-antimatter asymmetry of the Universe through baryogenesis [1]. Despite accommodating CP violation via the Kobayashi-Maskawa phase [2,3], the standard model (SM) fails to explain the baryon asymmetry of the Universe [4]. Its predicted CP violation is at least 10 orders of magnitude too small. Experimental evidence for CP violation has been found in K [5], B [6,7], and D [8] meson systems, and the Λ_b^0 baryon system [9], all these measurements are consistent with the SM predictions. Therefore, to resolve the baryogenesis puzzle, additional sources of CP violation beyond the SM must be considered. Hyperon decays, in particular, provide a sensitive probe for such effects [10,11].

In the two-body hadronic decays of spin 1/2 hyperons, CP violation arises from the interference between parity-conserving (P -wave) and parity-violating (S -wave) amplitudes with differing CP -odd weak phases, where the S and P wave are the relative orbital momentum between the final state particles [12]. In these decays, the angular distribution of the daughter baryon is given by $1 + \alpha_Y \mathbf{P}_Y \cdot \hat{\mathbf{p}}_d$, where α_Y is the hyperon decay parameter, $\mathbf{P}_Y$ is the hyperon polarization vector, and $\hat{\mathbf{p}}_d$ is the unit vector along the daughter baryon momentum in the hyperon rest frame.

A CP asymmetry observable is defined as $A_{CP} = (\alpha_Y + \alpha_{\bar{Y}})/(\alpha_Y - \alpha_{\bar{Y}})$, where α_Y and $\alpha_{\bar{Y}}$ denote the decay parameters of the hyperon and antihyperon, respectively. A nonzero A_{CP} indicates CP violation.

Within the SM, phenomenological studies based on different scenarios [10,11,13] predict an extremely small CP asymmetry in the Λ two-body hadronic decay, $|A_{CP}^{\text{SM}}| \leq 3 \times 10^{-5}$. In contrast, several beyond SM theories predict significantly larger values, e.g. $|A_{CP}^{\text{MSM}}| \leq 10^{-4}$ with minimal extensions of the SM (MSM) [14], $|A_{CP}^{\text{CMPC}}| \leq 7 \times 10^{-4}$ with chromomagnetic-penguin contributions (CMPC) [15], $|A_{CP}^{\text{SUSY}}| \leq 10^{-3}$ with supersymmetric models (SUSY) [16], and $|A_{CP}^{\text{DM}}| \leq 1.6 \times 10^{-3}$ with dark matter models (DM) [17]. The main limitation in the precision of the theoretical predictions arises from the well known S/P -wave puzzle in hyperon two-body hadronic decays, where the S - and P -wave amplitudes cannot be simultaneously described within leading-order chiral perturbation theory [18,19]. Improved precision in the decay parameters can help resolve this puzzle. Such measurements can also sharpen the status of the $\Delta I = 1/2$ rule in the spin 1/2 hyperon sector [20,21], in comparison to kaon decays $K \rightarrow \pi\pi$ [22,23] where the $\Delta I = 3/2$ transitions are strongly suppressed relative to the $\Delta I = 1/2$ ones [24,25]. With increasing experimental precision, $\Delta I = 3/2$ contributions can no longer be neglected [26] and must be included in theoretical calculations of A_{CP} .

Recently, BESIII has performed a series of precision studies of two-body hadronic decays [26–33]. The decay parameters of the charged Λ decay mode $\Lambda \rightarrow p\pi^-$ (α_-) and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ (α_+) were measured with the highest precision in the decay sequence $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ [28]. For the neutral decay modes of Λ , α_0 for $\Lambda \rightarrow n\pi^0$ and $\bar{\alpha}_0$ for

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$\bar{\Lambda} \rightarrow \bar{n}\pi^0$ were measured in the decay sequence $J/\psi \rightarrow \Xi^-\Xi^+ \rightarrow \Lambda(\rightarrow n\pi^0)\pi^-\bar{\Lambda}(\rightarrow \bar{p}\pi^+)\pi^+$ and its charge conjugated channel [26]. $\bar{\alpha}_0$ was also measured in $J/\psi \rightarrow \Lambda(\rightarrow p\pi^+)\bar{\Lambda}(\rightarrow \bar{n}\pi^0)$ based on 1.3 billion J/ψ events [27], but its precision is poor due to limited statistics. However, the uncertainties in α_0 and $\bar{\alpha}_0$ remain substantially larger than those for the charged modes, motivating further improvement. The decay $J/\psi \rightarrow \Lambda(\rightarrow n\pi^0)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ and its charge conjugated channel offer larger signal yields compared to the previous mode $J/\psi \rightarrow \Xi^-\Xi^+$. Although the reduced quantum correlation and polarization in this channel partly offsets the statistical advantage, it still provides a pathway toward more precise measurements of α_0 and $\bar{\alpha}_0$.

In this Letter, we present a full angular analysis of the decay $J/\psi \rightarrow \Lambda(\rightarrow n\pi^0)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ and its charge conjugate, based on $(10\,087 \pm 44) \times 10^6$ J/ψ events [34] collected with the BESIII detector. The transverse polarization of Λ and $\bar{\Lambda}$ together with their spin correlation [27,28], allow the angular distributions of both production and decay processes to be described by an extended helicity formalism [35]. Unless otherwise indicated, the $\bar{\Lambda} \rightarrow \bar{n}\pi^0$ mode is implicitly included throughout this text.

The BESIII experiment provides a unique platform to study hyperon production and decay properties in e^+e^- annihilation to a $\Lambda\bar{\Lambda}$ pair via the intermediate J/ψ resonance. The decay chain $J/\psi \rightarrow \Lambda(\rightarrow n\pi^0)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ is characterized by five angles $\xi = (\theta_\Lambda, \theta_n, \phi_n, \theta_{\bar{p}}, \phi_{\bar{p}})$ and the four parameters $\omega = (\alpha_{J/\psi}, \Delta\Phi, \alpha_0, \alpha_+)$, where θ_Λ is the polar angle of Λ in the center-of-mass (c.m.) system of J/ψ , and (θ_n, ϕ_n) , $(\theta_{\bar{p}}, \phi_{\bar{p}})$ are the polar and azimuthal angles of the neutron and anti-proton in their respective mother's rest frames, defined in a right-handed system [35]. Two real parameters, $\alpha_{J/\psi}$ and $\Delta\Phi$, are defined as the function of the helicity amplitude modulus and the helicity phase difference of $J/\psi \rightarrow \Lambda\bar{\Lambda}$ [35]. Then the nonzero $\Delta\Phi$ indicates the presence of a transverse polarization between Λ and $\bar{\Lambda}$, which is perpendicular to the production plane [36]. The α_0 and α_+ are the decay parameters of $\Lambda \rightarrow n\pi^0$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$, respectively. The joint angular distribution of the decay is given by [35]

$$\begin{aligned} \mathcal{W}(\xi; \omega) = & \mathcal{F}_0(\xi) + \alpha_{J/\psi} \mathcal{F}_5(\xi) + \alpha_0 \alpha_+ [\mathcal{F}_1(\xi) \\ & + \sqrt{1 - \alpha_{J/\psi}^2} \cos(\Delta\Phi) \mathcal{F}_2(\xi) - \alpha_{J/\psi} \mathcal{F}_6(\xi)] \\ & + \sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) [-\alpha_0 \mathcal{F}_3 + \alpha_+ \mathcal{F}_4], \quad (1) \end{aligned}$$

where the angular functions $\mathcal{F}_i(\xi)$ ($i = 0, 1, \dots, 6$) are described in Ref. [37]. In Eq. (1), the $\alpha_0 \alpha_+$ terms arise from $\Lambda - \bar{\Lambda}$ spin correlations, while the α_0 and α_+ terms reflect the transverse polarization of Λ and $\bar{\Lambda}$, respectively.

Details of the BESIII detector are given in Refs. [38,39]. The corresponding simulation, analysis framework, and

software are presented in Refs. [40–44]. The Monte Carlo (MC) samples were generated with Geant4-based [45] software, which models the electron-positron collisions, particle decays, and detector response. A generic J/ψ MC sample, with statistics matching the data, was used to study the potential background contribution. To eliminate experimental bias, the analysis was performed blindly: the central values of all parameters to be measured were kept hidden [46] until the procedure is finalized. Signal MC samples were used to validate the analysis approaches and to study the systematic effects.

Two oppositely charged tracks are detected in the main drift chamber (MDC). The $\bar{p}$ and π^+ candidates are primarily selected as in Ref. [47]. A discrepancy between data and MC simulation is observed in the $\bar{\Lambda}$ polar angle distribution, mainly due to the trigger efficiency in the endcap region. To minimize this effect, we require the absolute value of the cosine of the $\bar{p}$ polar angle must be less than 0.8. The $\bar{\Lambda}$ candidate is reconstructed from the $\bar{p}$ and π^+ tracks via a vertex fit [48], and its invariant mass must lie within five times its resolution, where the mass resolution is determined in bins of the $\bar{\Lambda}$ polar angle. The decay length of the reconstructed $\bar{\Lambda}$ is required to be positive. To suppress backgrounds from $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$, $\Sigma^0 \bar{\Lambda}$, $\gamma \Lambda \bar{\Lambda}$, and $\gamma \eta_c$, which include a $\bar{\Lambda}$ in their final state, we furthermore require $|M_{\bar{\Lambda}}^{\text{rec}} - m_{\Lambda}| < 3\sigma_{\bar{\Lambda}}^{\text{rec}}$. Here, m_{Λ}

refers to the nominal mass of Λ [49] and $M_{\bar{\Lambda}}^{\text{rec}} = \sqrt{(E_{\text{cm}} - E_{\bar{\Lambda}})^2/c^4 - P_{\bar{\Lambda}}^2/c^2}$ is the recoiling mass of the $\bar{\Lambda}$, obtained from the c.m. energy E_{cm} , as well as the energy $E_{\bar{\Lambda}}$ and momentum $P_{\bar{\Lambda}}$ of the $\bar{\Lambda}$ candidate from the vertex fit. The resolution $\sigma_{\bar{\Lambda}}^{\text{rec}}$ is determined in bins of the $\bar{\Lambda}$ polar angle.

At least two photon candidates are required in the electromagnetic calorimeter (EMC). Neutral showers in the EMC are primarily selected as in Ref. [26]. To veto the showers from neutron (anti-neutron) interaction in the EMC, since the angle between neutron (anti-neutron) and $\Lambda(\bar{\Lambda})$ is very small (less than 7°), the photon candidates should be separated from the $\Lambda(\bar{\Lambda})$ momentum direction by more than 10° (15°), where the $\Lambda(\bar{\Lambda})$ momentum direction is opposite to that of $\bar{\Lambda}(\Lambda)$. To further suppress the neutron-induced shower, a boosted decision tree (BDT) classifier [50] is constructed using shower shape variables including deposited energy, number of hits, second moment, Zernike moments, and deposition shape [26]. Photons matched to truth information in signal MC are treated as signal, while others are treated as background. A requirement on the BDT output > 0.15 (0.10) is applied to ensure 90% signal efficiency, with a corresponding 55% (45%) background rejection efficiency. The π^0 candidates are reconstructed with a photon pair by performing a kinematic fit constraining their invariant mass to the π^0 nominal mass. In case of multiple π^0 candidates from combinatorial effects,

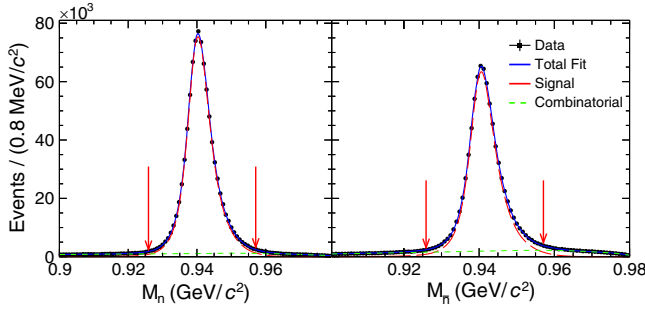


FIG. 1. Distributions of the missing masses corresponding to the neutron mass for $\Lambda \rightarrow n\pi^0$ (left) and antineutron mass for $\bar{\Lambda} \rightarrow \bar{n}\pi^0$ (right). The blue solid curve represents the total fit result. The red dashed and green dotted lines denote the signal shape and the combinatorial background contributions, respectively. The red arrows indicate the signal region.

the one with the smallest kinematic fit χ^2 is retained, requiring $\chi^2 < 100$.

Because of the limited detection efficiency for neutrons and antineutrons, they are not reconstructed directly. Instead, their four momenta are inferred as $\mathbf{P}_n = \mathbf{P}_\Lambda - \mathbf{P}_{\pi^0}$, where $\mathbf{P}_n$, $\mathbf{P}_\Lambda$, and $\mathbf{P}_{\pi^0}$ are the four momenta of neutron, Λ and π^0 candidate, respectively. To improve the resolution, the momentum and energy of Λ are set to $\vec{p}_\Lambda = -\hat{p}_{\bar{\Lambda}} \sqrt{E_{\text{cm}}^2/c^2/4 - m_\Lambda^2 c^2}$ and $E_\Lambda = E_{\text{cm}}/2$, respectively, where $\hat{p}_{\bar{\Lambda}}$ is the momentum direction of the $\bar{\Lambda}$ in the e^+e^- rest frame. The neutron is identified by the invariant mass calculated from $\mathbf{P}_n$, which shows a clear peak near the nominal neutron mass with low background (Fig. 1). Studies of MC samples and data in the sideband of the neutron mass distribution show that background in the signal region mainly arises from signal candidates with misreconstructed π^0 candidates, i.e., combinatorial background. The combinatorial background does not peak in the neutron invariant mass distribution. The other backgrounds, stemming from processes with one or two extra photons in the final state [51], contribute less than 0.5% and are neglected in the nominal analysis.

To extract the production and decay parameters, a simultaneous fit on the joint angular distribution is performed on the selected events in the neutron/anti-neutron invariant mass signal range $[0.926, 0.957]$ GeV/c^2 , with the production parameters $\alpha_{J/\psi}$ and $\Delta\Phi$ shared between the two charge conjugated channels. Correlations between the angles, arising due to the reconstruction, are taken into account in this full five-dimensional fit. In the fit, the probability density function for the i th event with angles ξ_i is parameterized with the four parameters ω ,

$$\mathcal{P}(\xi_i; \omega) = \mathcal{W}(\xi_i; \omega) \varepsilon(\xi_i) / \mathcal{N}(\omega), \quad (2)$$

where $\varepsilon(\xi_i)$ refers to the detection efficiency and the normalization factor $\mathcal{N}(\omega)$ is obtained by $\mathcal{N}(\omega) = (1/M) \sum_{j=1}^M [\mathcal{W}(\xi_j; \omega) / \mathcal{W}(\xi_j; \omega_{\text{gen}})]$ with a signal MC

sample generated with known parameters ω_{gen} [26,28] and the sample size M , similar to that in Ref. [26]. The sum runs over all M signal MC events, corresponding to 50 times the data yield. The log-likelihood function for N selected candidates is

$$\mathcal{S} = - \sum_{i=1}^N \ln \mathcal{P}(\xi_i; \omega) + \frac{N_{\text{bkg}}}{N_{\text{miss}}} \sum_i^{N_{\text{miss}}} \ln \mathcal{P}(\xi_i; \omega), \quad (3)$$

where the second term accounts for the contribution from the combinatorial background, estimated using N_{miss} MC-simulated background events. While these simulations describe well the data in missing-mass sideband regions, their large statistics assure modelling of correlations between the angular and mass observables. To determine the background yield N_{bkg} , unbinned maximum likelihood fits are carried out on the distributions of the neutron invariant mass, as shown in Fig. 1. In the fit, the signal is modeled with an MC-simulated shape convolved with a Gaussian function to account for the resolution difference between data and MC simulation, while the combinatorial background is modeled by the shape from the corresponding MC sample. The fit yields 872450 ± 982 signal events with 42925 ± 293 background events for the decay $\Lambda \rightarrow n\pi^0$, and 759770 ± 963 signal events with 74567 ± 379 background events for the decay $\bar{\Lambda} \rightarrow \bar{n}\pi^0$.

The parameters ω are determined by a maximum likelihood fit, minimizing $\mathcal{S}$ with the TMinuit [52] package. The parameter $\alpha_{J/\psi}$ is fixed to the value reported in Ref. [28], a consequence of the data-MC discrepancy in θ_Λ . The fit results including the production and decay parameters, the CP asymmetry $A_{CP}^- = (\alpha_- + \alpha_+) / (\alpha_- - \alpha_+)$ and $A_{CP}^0 = (\alpha_0 + \bar{\alpha}_0) / (\alpha_0 - \bar{\alpha}_0)$, the average decay parameters $\langle \alpha_0 \rangle = (\alpha_0 - \bar{\alpha}_0) / 2$ and $\langle \alpha_- \rangle = (\alpha_- - \alpha_+) / 2$, as well as the ratios α_0 / α_- and $\bar{\alpha}_0 / \alpha_+$ are summarized in Table I. The details of fit results projected onto the five angles are provided in the Supplementary Material [53]. The moment μ , defined as

$$\mu(\cos \theta_\Lambda) = \frac{m}{N} \sum_{i=1}^{N_k} \left(\sin \theta_n^i \sin \phi_n^i + \sin \theta_{\bar{p}}^i \sin \phi_{\bar{p}}^i \right), \quad (4)$$

is proportional to the product of the Λ transverse polarization and its decay asymmetry parameters, which reads [28],

$$\mu(\cos \theta_\Lambda) = \frac{\alpha_0 - \alpha_+}{2} \frac{1 + \alpha_{J/\psi} \cos^2 \theta_\Lambda}{3 + \alpha_{J/\psi}} P_y(\theta_\Lambda), \quad (5)$$

$$P_y(\theta_\Lambda) = \frac{\sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) \cos \theta_\Lambda \sin \theta_\Lambda}{1 + \alpha_{J/\psi} \cos^2 \theta_\Lambda}, \quad (6)$$

TABLE I. Summary of the measured parameters. The first uncertainties are statistical and the second ones systematic. The correlation coefficients are $\rho(\alpha_0, \bar{\alpha}_0) = -0.005$ and $\rho(\alpha_-, \alpha_+) = -0.026$.

Parameter	This Letter	Previous result
$\Delta\Phi$ (rad)	$0.748 \pm 0.006 \pm 0.004$	$0.7521 \pm 0.0042 \pm 0.0066$ [28]
α_-	$0.756 \pm 0.008 \pm 0.003$	$0.7519 \pm 0.0036 \pm 0.0024$ [28]
α_+	$-0.764 \pm 0.008 \pm 0.001$	$-0.7559 \pm 0.0036 \pm 0.0030$ [28]
α_0	$0.668 \pm 0.007 \pm 0.002$	$0.670 \pm 0.009^{+0.009}_{-0.008}$ [26]
$\bar{\alpha}_0$	$-0.677 \pm 0.007 \pm 0.003$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$ [26]
A_{CP}^-	$-0.005 \pm 0.007 \pm 0.002$	$-0.0025 \pm 0.0046 \pm 0.0012$ [28]
A_{CP}^0	$-0.006 \pm 0.007 \pm 0.002$	$0.001 \pm 0.009^{+0.005}_{-0.007}$ [26]
$\langle\alpha_0\rangle$	$0.672 \pm 0.005 \pm 0.002$	...
$\langle\alpha_-\rangle$	$0.760 \pm 0.006 \pm 0.002$	$0.7542 \pm 0.0010 \pm 0.0024$ [28]
α_0/α_-	$0.884 \pm 0.013 \pm 0.006$	$0.877 \pm 0.015^{+0.014}_{-0.010}$ [26]
$\bar{\alpha}_0/\alpha_+$	$0.885 \pm 0.013 \pm 0.004$	$0.863 \pm 0.014^{+0.012}_{-0.008}$ [26]

where $P_y(\theta_\Lambda)$ represents the transverse polarization of Λ . The quantity is evaluated across $m = 40$ bins in $\cos\theta_\Lambda$. For each bin k , containing N_k events, the index i denotes the i -th event within it. Comparison of the data with the phase-space (PHSP) MC sample reveals a significant polarization of the Λ hyperons in $J/\psi \rightarrow \Lambda\bar{\Lambda}$ decays, as shown in Fig. 2, where $\alpha_{J/\psi}$, $\Delta\Phi$ and decay parameters are set to 0 of the PHSP MC and values measured in the data of the signal MC, respectively.

The sources of systematic uncertainties are separated into four categories: event reconstruction, background estimation, fit method, and residual data/MC discrepancy. For event reconstruction, the effects from p , $\bar{p}$, and $\pi^\pm$ tracking, particle identification, and $\Lambda/\bar{\Lambda}$ reconstruction are evaluated with a control sample of $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$. The π^0 reconstruction efficiency is studied with $J/\psi \rightarrow \Sigma^+(\rightarrow p\pi^0)\bar{\Sigma}^-(\rightarrow \bar{p}\pi^0)$, which

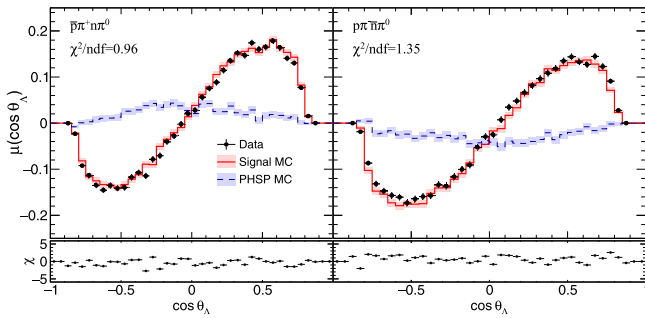


FIG. 2. Distributions of $\mu(\cos\theta_\Lambda)$ as a function of $\cos\theta_\Lambda$. The dots with error bars are data, the red solid lines are the signal MC sample and the blue dashed line represent the distributions without polarization from the PHSP MC sample. The red and blue bands indicate the statistical uncertainties of signal MC and PHSP MC samples, respectively. The distribution of $\chi = (\mu_{\text{data}} - \mu_{\text{MC}}) / \sqrt{\sigma^2(\mu_{\text{data}}) + \sigma^2(\mu_{\text{MC}})}$ is shown at the bottom, where μ_{data} and μ_{MC} are the moments of data and signal MC sample, σ is the corresponding statistical uncertainty.

has a final-state topology similar to the signal. Selection-related effects, such as the polar angle requirement of $\bar{p}$, the neutron invariant mass window, and the χ^2 of the π^0 kinematic fit, are estimated by varying their values around the nominal ones and repeating the fits. Background-related uncertainties are evaluated in two ways: a $\pm 1\sigma$ variation of the combinatorial background yield in the fit, and the inclusion of the dominant neglected background term, as determined from MC simulation, in an alternative fit. The uncertainty of fit method includes the fit procedure and fixed parameter $\alpha_{J/\psi}$. The former is tested with 50 sets of toy MC samples generated using the best-fit parameters. Since the input and output are consistent within statistical fluctuations, no additional uncertainty is assigned to the fit procedure. The latter is studied by repeating the fit with $\alpha_{J/\psi}$ randomly varied within one standard deviation for 100 iterations. The standard deviation of the output is assigned as the corresponding uncertainty. Finally, the residual data/MC discrepancy is evaluated by reweighting the MC to match the $\bar{\Lambda}$ polar-angle distribution in data; the shift in the fitted result is taken as the associated uncertainty. The absolute contributions from various sources are summarized in Table II. The total systematic uncertainty for each parameter is obtained by summing these individual contributions in quadrature.

Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, we perform a full angular analysis of the decay $J/\psi \rightarrow \Lambda(\rightarrow n\pi^0)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ and its charge conjugated mode. The neutral decay parameters α_0 and $\bar{\alpha}_0$ are consistent with previous measurements [26,27], with precisions improved by 43% and 27%, respectively. Compared with the Ref. [27], owing to the innovative selection strategy, our results yield a factor of 2.3 enhancement in selection efficiency. Compared with the Ref. [26], thanks to fewer selection conditions and numerous efficiency corrections, our systematic uncertainties have been significantly improved, corresponding to a factor of 4.3 improvement in α_0 and 2.3 improvement for $\bar{\alpha}_0$. We also

TABLE II. Absolute systematic uncertainties of the measured parameters (in units of 10^{-3}).

Parameter	Event reconstruction	Background estimation	Fit method	Data/MC discrepancy	Total
$\Delta\Phi$ (rad)	1.3	2.7	2.3	2.1	4.3
α_-	1.9	1.8	0.3	0.9	2.8
α_+	0.9	0.7	0.3	0.3	1.2
α_0	1.6	0.4	0.6	0.6	1.9
$\bar{\alpha}_0$	2.4	0.4	0.6	2.0	3.2
A_{CP}^-	1.5	0.8	0.0	0.8	1.9
A_{CP}^0	2.0	0.1	0.1	1.0	2.2
$\langle\alpha_0\rangle$	1.1	0.4	0.6	1.3	1.9
$\langle\alpha_-\rangle$	0.9	1.2	0.3	0.3	1.6
α_0/α_-	5.0	2.7	0.5	1.8	5.9
$\bar{\alpha}_0/\alpha_+$	3.4	1.2	0.4	2.2	4.3

determine $\Delta\Phi$ and the charged decay parameters α_- and α_+ , establishing nonzero polarization in $J/\psi \rightarrow \Lambda\bar{\Lambda}$, which are all consistent with the previous results [26–28,30]. The derived CP asymmetries A_{CP}^- and A_{CP}^0 are consistent with zero, with A_{CP}^0 obtained at the highest precision to date (29% improvement). The ratios of the Λ decay parameters between the isospin conjugated decay modes α_0/α_- and $\bar{\alpha}_0/\alpha_+$, deviate from unity by 8.1σ and 8.5σ , respectively, confirming the $\Delta I = 3/2$ contributions. Combining the averages of $\langle\alpha_0\rangle$, $\langle\alpha_-\rangle$, the decay rates $\Gamma(\Lambda \rightarrow p\pi^-)$, $\Gamma(\Lambda \rightarrow n\pi^0)$ [49] and the $N - \pi$ scattering phase shift [54], the ratio of $\Delta I = 3/2$ to $\Delta I = 1/2$ transitions in the S wave and P wave can be determined [10,55]. Building upon previous work [26], this analysis achieves the most precise measurement of neutral decays of Λ to date. It also demonstrates the necessity of including $\Delta I = 3/2$ amplitudes.

Notably, our measurement of the CP asymmetry in Λ decays remains consistent with zero. Future colliders such as STCF, which is expected to produce a data sample of $10^{12} J/\psi$ events [56], enable more precise determinations of the CP asymmetry. The substantial reduction in systematic uncertainties achieved in this analysis will be valuable for studies of potential systematic sources at STCF.

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Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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