

Search for $\Lambda - \bar{\Lambda}$ oscillation in $J/\psi \rightarrow \Lambda \bar{\Lambda}$ decay

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Using $(10087 \pm 44) \times 10^6$ J/ψ decays collected by the BESIII detector at the BEPCII collider, we search for baryon number violation via $\Lambda - \bar{\Lambda}$ oscillation in the decay $J/\psi \rightarrow \Lambda \bar{\Lambda}$. No evidence for $\Lambda - \bar{\Lambda}$ oscillation is observed. The upper limit on the time-integrated probability of $\Lambda - \bar{\Lambda}$ oscillation is estimated to be 1.4×10^{-6} , corresponding to an oscillation parameter less than 2.1×10^{-18} GeV at 90% confidence level.

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I. INTRODUCTION

The existence of baryon number violation is a fundamental question in particle physics [1,2]. This phenomenon plays a crucial role in explaining the observed matter-antimatter asymmetry in the Universe. The asymmetry could be a result of three conditions pointed out originally by Sakharov [3]: existence of Charge (C) or Charge-Parity (CP) violation; baryon number violating interactions; and the existence of out-of-thermal-equilibrium conditions in the early Universe. CP violation has been extensively studied in both noncollider and collider experiments. The violation of baryon number implies the instability of the proton and the atomic nucleus, which would occur on a timescale comparable to the lifetime of the Universe [4]. In many theoretical models, baryon number is not a natural exact symmetry [1,2,5–7]. For example, in some grand unified theories, protons can decay to light quarks in a variety of ways. This mechanism simultaneously breaks the conservation of baryon number (B) and lepton number (L) while keeping their difference $B - L$ constant [8]. Moreover, if neutrinos are Majorana particles with small masses [9], this would imply the presence of $\Delta(B - L) = 2$ interactions, thereby suggesting the existence of nucleon-antinucleon ($n - \bar{n}$) oscillation [10]. Many experiments have been carried out to search for $n - \bar{n}$ oscillation and the lower limit for the $n - \bar{n}$ oscillation time is currently 8.6×10^7 s with a 90% confidence level [11–13]. However, few results have been reported related to hyperons. Recently, the BESIII Collaboration published experimental results on $\Lambda - \bar{\Lambda}$ oscillation using the decay $J/\psi \rightarrow pK^- \bar{\Lambda} + \text{c.c.}$ (Hereinafter, “c.c.” is used to indicate the

inclusion of the charge-conjugate process for all relevant processes throughout the paper.) The upper limit for the oscillation parameter was reported to be $\delta m_{\Lambda \bar{\Lambda}} < 3.8 \times 10^{-18}$ GeV at the 90% confidence level [14].

To investigate $\Lambda - \bar{\Lambda}$ oscillation, we search for the presence of $J/\psi \rightarrow \Lambda \Lambda + \text{c.c.}$ starting with the coherent production of $\Lambda \bar{\Lambda}$ pairs in the decay $J/\psi \rightarrow \Lambda \bar{\Lambda}$ [15]. The time evolution of $\Lambda - \bar{\Lambda}$ oscillation can be described by a Schrödinger-like equation,

$$i \frac{\partial}{\partial t} \begin{pmatrix} \Lambda(t) \\ \bar{\Lambda}(t) \end{pmatrix} = M \begin{pmatrix} \Lambda(t) \\ \bar{\Lambda}(t) \end{pmatrix}, \quad (1)$$

where M is Hermitian matrix, defined as

$$M = \begin{pmatrix} m_{\Lambda} - \Delta E_{\Lambda} & \delta m_{\Lambda \bar{\Lambda}} \\ \delta m_{\Lambda \bar{\Lambda}} & m_{\bar{\Lambda}} - \Delta E_{\bar{\Lambda}} \end{pmatrix}, \quad (2)$$

and $\delta m_{\Lambda \bar{\Lambda}}$ is the transition mass between the Λ and $\bar{\Lambda}$ during oscillation, $m_{\Lambda}(m_{\bar{\Lambda}})$ is the nominal mass of the $\Lambda(\bar{\Lambda})$ baryon, and $\Delta E_{\Lambda/\bar{\Lambda}}$ is the energy split due to an external magnetic field. After considering the magnetic field (1.0 T) in the interaction region of the BESIII detector, the magnetic moment of the Λ and the flight length of the Λ , $\Delta E_{\Lambda/\bar{\Lambda}}$ is neglected in our case [14]. The oscillation rate, $P(\bar{\Lambda}, t)$, of generating a $\bar{\Lambda}$ with a beam of free Λ after time t can be written as

$$P(\bar{\Lambda}, t) = \sin^2(\delta m_{\Lambda \bar{\Lambda}} \cdot t) e^{-t/\tau_{\Lambda}}, \quad (3)$$

where t is the time when the oscillation is observed, and $\tau_{\Lambda} = (2.632 \pm 0.02) \times 10^{-10}$ s is the mean lifetime of the Λ [8].

The time-integrated oscillation probability of $\Lambda \rightarrow \bar{\Lambda}$ is given by

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$$P(\bar{\Lambda}) = \frac{\int_0^\infty \sin^2(\delta m_{\Lambda\bar{\Lambda}} \cdot t) e^{-t/\tau_\Lambda} dt}{\int_0^\infty e^{-t/\tau_\Lambda} dt}. \quad (4)$$

Then the oscillation parameter $\delta m_{\Lambda\bar{\Lambda}}$ can be deduced as

$$\delta m_{\Lambda\bar{\Lambda}} = \sqrt{\frac{P(\Lambda)}{2\tau_\Lambda^2}}. \quad (5)$$

In this paper, using $(10087 \pm 44) \times 10^6 J/\psi$ decays [16], accumulated at the center-of-mass energy of $\sqrt{s} = 3.097$ GeV with the BESIII detector, we report the $\Lambda - \bar{\Lambda}$ oscillation parameter based on the $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ process for the first time.

II. BESIII DETECTOR AND DATASET

The BESIII detector [17] records symmetric e^+e^- collisions provided by the BEPCII storage ring [18] in the center-of-mass energy range from 1.85 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [19]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a beam pipe, a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight (TOF) system, and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The magnetic field was 0.9 T in 2012, which affects 10.8% of the total J/ψ data. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region is 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [20].

Simulated data samples produced with a Geant4-based [21] Monte Carlo (MC) package, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and initial state radiation in the e^+e^- annihilations with the generator KKMC [22]. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [22]. All particle decays are modelled with EvtGen [23] using branching fractions (BFs) either taken from the Particle Data Group (PDG) [8], when available, or otherwise estimated with LUNDCHARM [24]. Final state radiation (FSR) from charged final state particles is

incorporated using the PHOTOS package [25]. For the signal process and oscillation process, we generate $1 \times 10^7 J/\psi \rightarrow \Lambda\bar{\Lambda}$ MC samples and $1 \times 10^6 J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ MC samples, respectively, considering the polarization and decay parameters measured in Ref. [26]. Additionally, exclusive MC samples for the main peaking background, $J/\psi \rightarrow \Lambda\bar{\Sigma}^0 + \text{c.c.}$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}\gamma$, are generated accordingly.

III. EVENT SELECTION

In this analysis, we fully reconstruct the $\Lambda/\bar{\Lambda}$ with $p\pi^-/\bar{p}\pi^+$ in the processes $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ We designate the events from the decay $J/\psi \rightarrow \Lambda\bar{\Lambda}$ as *right sign* (RS) events, and the ones from $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ as *wrong sign* (WS) events. Therefore, the final states in RS and WS decays are $p\bar{p}\pi^+\pi^-$ and $pp\pi^-\pi^-/\bar{p}\bar{p}\pi^+\pi^+$, respectively.

In the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ process, charged tracks must be well reconstructed in the MDC, with $|\cos\theta| < 0.93$, where θ is defined with respect to the symmetry axis of the MDC, referred to as the z axis. Events with at least four selected charged tracks are retained for further analysis. Based on MC simulation, the proton and pion from the Λ decay are well separated kinematically. The charged tracks with momentum less than 0.5 GeV are taken as pion candidates, while the other tracks are regarded as protons if their particle identification (PID) hypothesis of proton probability is higher than other particle hypotheses. PID for charged tracks combines measurements of the energy deposited in the MDC (dE/dx) and the flight time in the TOF to form likelihoods $\mathcal{L}(h)$ ($h = K, \pi, p$) for each hadron h hypothesis.

The $\Lambda/\bar{\Lambda}$ is reconstructed by looping over all $p\pi^-/\bar{p}\pi^+$ combinations, and a vertex fit is performed to each combination, ensuring that the $p\pi^-/\bar{p}\pi^+$ particles should originate from common decay vertexes. The position at which the Λ decays into a proton and a pion is referred to as the decay vertex, while the point where the Λ originated is referred to as the production vertex, determined by reconstructing the electron-positron interaction point using events from Bhabha scattering. The mass windows for the Λ and $\bar{\Lambda}$ selection are set to be within $\pm 3\sigma$, where $\sigma = 1.8$ MeV is the mass resolution of the Λ obtained from the fit to the invariant mass distribution of $p\pi^-$ in the signal MC sample. All $\Lambda/\bar{\Lambda}$ candidates are retained for further analysis.

A four-constraint (4C) kinematic fit, imposing energy-momentum conservation, is performed under the hypothesis of $J/\psi \rightarrow \Lambda\bar{\Lambda}$ to suppress background and improve the kinematic resolution [27]. If more than one $\Lambda\bar{\Lambda}$ pair is found, the one with the minimum χ_{4C}^2 value is retained. To improve the significance of the signal, the χ_{4C}^2 requirement is optimized using a figure-of-merit method: $\frac{S}{\sqrt{S+B}}$, where S and B are the numbers of signal and background events

from signal MC and inclusive MC samples, respectively. The nominal criterion is set as $\chi_{4C}^2 < 50$.

In the decay $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$, the selection criteria are identical to those applied in the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ process, with the exception that the p/π^- (\bar{p}/π^+) candidate should not be shared among multiple reconstructed Λ ($\bar{\Lambda}$) in an event. The detection efficiencies of $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ are determined to be 34.3% and 34.4% respectively.

IV. SIGNAL EXTRACTION

The MC sample for the WS channel was generated assuming complete $\Lambda - \bar{\Lambda}$ oscillation, with the oscillation rate $P(\bar{\Lambda}, t)$ set to 1. Consequently, only the decay rate of $\bar{\Lambda}$ was considered in the simulation. To match the actual detection efficiency, the oscillation effects of Λ , as described in Eq. (3), should be convolved with the decay rate of $\bar{\Lambda}$ to construct a combined oscillation-decay rate distribution as a function of the $\bar{\Lambda}$ decay vertex position. Using this distribution as the weight, the corrected detection efficiency for the WS channel is obtained by summing the re-weighted detection efficiency, which varies with the $\bar{\Lambda}$ decay vertex position.

Since the $P(\bar{\Lambda}, t)$ is a function of the $\delta m_{\Lambda\bar{\Lambda}}$, one of the results of this measurement, an iterative process in the efficiency correction is necessary to account for the dependence on $\delta m_{\Lambda\bar{\Lambda}}$. However, simulation studies indicate that for $\delta m_{\Lambda\bar{\Lambda}}$ values below 10^{-15} GeV (which is significantly larger than the magnitude of the upper limit of 10^{-18} GeV), variations in $\delta m_{\Lambda\bar{\Lambda}}$ have a negligible effect on the distribution of $P(\bar{\Lambda}, t)$. As a result, this simplifies the efficiency correction process, and does not affect the final results, including the upper limits. After applying the aforementioned efficiency correction, the corrected detection efficiency for the WS channel is found to be 14.9%.

The background is estimated using the inclusive MC, exclusive MC, and data samples collected at $\sqrt{s} = 3.773$ GeV. For the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ process, the ratio of the estimated background to the signal is about 0.2% in the signal region, including peaking background and non-peaking background. The main peaking background sources are $J/\psi \rightarrow \bar{\Sigma}^0\Lambda + \text{c.c.}$, $J/\psi \rightarrow \Lambda\bar{\Lambda}\gamma$, and $J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow \pi^+\pi^-p\bar{p}\gamma/e^-\bar{\nu}_e\pi^+p\bar{p}/\mu^-\bar{\nu}_\mu\pi^+p\bar{p}$ ($\pi^+\pi^-p\bar{p}\gamma/e^+\nu_e\pi^-\bar{p}p/\mu^+\nu_\mu\pi^-\bar{p}p$). These peaking backgrounds are simulated individually and normalized according to the branching fractions taken from the PDG [8]. Only 605 ± 27 events survive, corresponding to $(2.00 \pm 0.09) \times 10^{-4}$ of the signal events in the data, which is treated as negligible. With the data collected at $\sqrt{s} = 3.773$ GeV, the continuum contribution is studied. Assuming the cross section of the continuum process is proportional to $1/s$, the number of continuum background events, $N_{3.097}^{\text{cont}}$, is normalized to the J/ψ center-of-mass energy using

$$N_{3.097}^{\text{cont}} = N_{3.773}^{\text{obs}} \times f_{\text{norm}}, \quad (6)$$

$$f_{\text{norm}} = \frac{\mathcal{L}_{3.097}}{\mathcal{L}_{3.773}} \times \frac{3.773^2}{3.097^2}. \quad (7)$$

Here $\mathcal{L}_{3.097}$ and $\mathcal{L}_{3.773}$ are the integrated luminosities of the data samples taken at $\sqrt{s} = 3.097$ GeV and 3.773 GeV, respectively, corresponding to 2962.7 pb^{-1} [28] and 2931.8 pb^{-1} [29], and f_{norm} is the normalization factor, which is calculated to be 1.5. After the normalization, the number of continuum background events is calculated to be 402 ± 25 , corresponding to $(1.3 \pm 0.8) \times 10^{-4}$ of the signal events and is also neglected. For the process $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$, no events from either the inclusive MC or the data samples survive the event selection.

A simultaneous fit of the Λ and $\bar{\Lambda}$ mass spectrum is performed to determine the signal yield of $J/\psi \rightarrow \Lambda\bar{\Lambda}$. The invariant mass $M_{p\pi^-}/M_{\bar{p}\pi^+}$ is obtained using the reconstructed momenta of the two charged tracks after passing all criteria. The probability density functions of the signal distributions are derived from simulation, and are convolved with a Gaussian function with floating width to account for the resolution difference between experimental data and MC simulation. The background shape is described by the parametrization of the non-peaking background simulation in the inclusive MC sample. The fit range is [1.1, 1.13] GeV and the signal region is [1.11, 1.121] GeV. Figure 1 shows the fit result. The signal yield for the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ decay is determined to be 3123264 ± 1767 events.

V. UPPER LIMIT CALCULATION

Since no signal or background events are found in the search for $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$, a maximum likelihood estimator, based on the extended profile likelihood method [30], is constructed. The numbers of signal and background events are assumed to follow a Poisson distribution, and the detection efficiency is determined with an associated uncertainty, which is modeled as a Gaussian distribution. The likelihood is defined as

$$\mathcal{L} = \mathcal{P}(\mathbf{N}_{\text{WS}}^{\text{UL}}; N_{\text{WS}}^{\text{obs}} \cdot \epsilon_{\text{WS}} + \mathbf{N}_{\text{bkg}}) \otimes \mathcal{G}(\epsilon_{\text{WS}}; \epsilon_{\text{WS}}, \sigma_{\epsilon_{\text{WS}}}) \otimes \mathcal{P}(\mathbf{N}_{\text{bkg}}; N_{\text{bkg}}), \quad (8)$$

where $N_{\text{WS}}^{\text{obs}}$ and N_{bkg} are the observed number of signal events and background events in $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ decay, respectively; ϵ_{WS} is the detection efficiency, and its standard deviation $\sigma_{\epsilon_{\text{WS}}}$ is derived from the systematic uncertainties that have already been canceled out of common sources, which will be introduced later in the text.

The upper limit on the number of events, $\mathbf{N}_{\text{WS}}^{\text{UL}}$, for $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$, is determined to be 13.0 at the

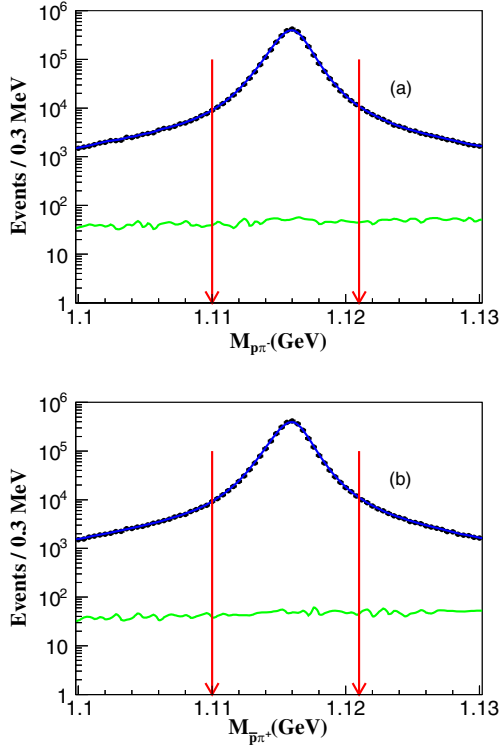


FIG. 1. Fits to the mass distributions of (a) $M_{p\pi^-}$ and (b) $M_{\bar{p}\pi^+}$ (GeV) in $J/\psi \rightarrow \Lambda\bar{\Lambda}$ in data, shown in log scale, where the filled circles with error bars are data, the blue solid lines represent the results of the fits, the green solid lines show the background contributions, and the arrows in the figure show the edges of the signal region.

90% confidence level. According to Eq. (4), the probability of $\Lambda - \bar{\Lambda}$ oscillation in $J/\psi \rightarrow \Lambda\bar{\Lambda}$, denoted as $P(\Lambda)$, can be expressed as

$$P(\Lambda) = \frac{\mathcal{B}(J/\psi \rightarrow \Lambda\Lambda + \text{c.c.})}{\mathcal{B}(J/\psi \rightarrow \Lambda\bar{\Lambda})} < \frac{N_{\text{WS}}^{\text{NUL}}}{N_{\text{RS}}^{\text{obs}}/\epsilon_{\text{RS}}} = 1.4 \times 10^{-6}, \quad (9)$$

where $\mathcal{B}(J/\psi \rightarrow \Lambda\Lambda + \text{c.c.})$ is shorthand for $\mathcal{B}(J/\psi \rightarrow \Lambda\bar{\Lambda}^{\text{oscillating}} \Lambda\Lambda + \text{c.c.})$, representing the BF for the WS channel, and $\mathcal{B}(J/\psi \rightarrow \Lambda\bar{\Lambda})$ is for the RS channel.

As a result, the upper limit of the oscillation parameter $\delta m_{\Lambda\bar{\Lambda}}$ is calculated to be less than 2.1×10^{-18} GeV.

VI. SYSTEMATIC UNCERTAINTY

In this measurement, the systematic uncertainties from the total number of J/ψ events, tracking efficiencies, and PID efficiencies cancel. The remaining systematic uncertainties are mainly from Λ reconstruction, the signal shape, fit range, and kinematic fit.

The combined systematic uncertainty from p and π tracking efficiencies and the Λ reconstruction efficiency has been estimated using a control sample of $J/\psi \rightarrow \bar{p}K^+\Lambda$. This uncertainty is 0.6% per reconstructed Λ [31].

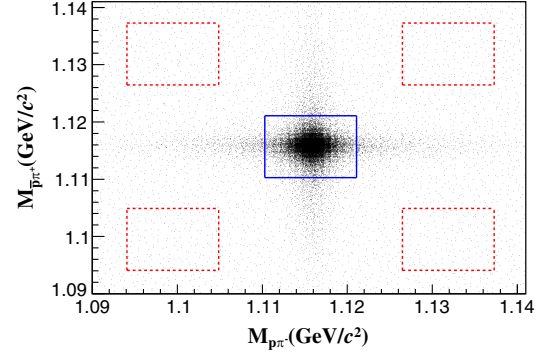


FIG. 2. The 2D sideband scatter plot of the Λ and $\bar{\Lambda}$ mass distributions from the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ data sample, where the box within the blue solid lines is the $\Lambda\bar{\Lambda}$ signal region, and the boxes bound by the red dashed lines are the sideband regions.

The uncertainty of the signal shape is estimated by using an alternative shape modeled with a Breit-Wigner function convolved with a double Gaussian function. The difference in the signal yield between the two approaches, 0.1%, is taken as the uncertainty of the signal shape.

The uncertainty arising from the mass window regions is determined through a study of the resolutions of both data and MC, with a value of 0.1%. Furthermore, the stability of the mass windows is studied by varying the range from $[1.110, 1.121]$ GeV to $[1.109, 1.120]$ GeV and $[1.111, 1.122]$ GeV. The maximum deviation observed is 0.6%.

The uncertainty due to unknown nonpeaking backgrounds is estimated by replacing the number of background events obtained from the inclusive MC sample with the estimated number from data. The estimated number of background events is obtained by using the two-dimensional sideband method. The sideband range is shown in Fig. 2, and the average number of events within the four red boxes is calculated as the estimated number of background events. The final systematic uncertainty for the fit procedure is less than 0.1% and can be safely neglected.

The uncertainty arising from the 4C kinematic fit is estimated by using the track parameter correction method [32]. The difference between the efficiencies with and without correction is taken as the systematic uncertainty. The correction factors for p and \bar{p} are determined based on a control sample of $J/\psi \rightarrow pK^-\bar{\Lambda} + \text{c.c.}$ and $\psi(3686) \rightarrow pK^-\bar{\Lambda} + \text{c.c.}$, and the π^+ and π^- are obtained based on the decay $\psi(3686) \rightarrow K^+K^-\pi^+\pi^-$ [33]. The uncertainties caused by the kinematic fit for $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$ are all determined to be 0.7%.

The uncertainty arising from misidentifying RS events as WS events is estimated using MC matching and found to be negligible.

The systematic uncertainties are listed in Table I. Each source of systematic uncertainty is treated as independent, and they are summed in quadrature.

TABLE I. Systematic uncertainties (in %) in the measurement of each channel after cancellation of common sources.

Source	$J/\psi \rightarrow \Lambda\bar{\Lambda}$	$J/\psi \rightarrow \Lambda\Lambda + \text{c.c.}$
Λ reconstruction	0.6	0.6
Kinematic fit	0.7	0.7
Mass windows	0.1	0.1
Signal shape	0.1	...
Mis-ID	Ignore	Ignore
Background shape	Ignore	...
Total	0.9	0.9

VII. SUMMARY

In summary, based on $(10087 \pm 44) \times 10^6$ J/ψ events at $\sqrt{s} = 3.097$ GeV collected with the BESIII detector, a search for $\Lambda - \bar{\Lambda}$ oscillation is carried out in the decay $J/\psi \rightarrow \Lambda\bar{\Lambda}$, yielding no evidence. Consequently, upper limits at a 90% confidence level are established for the time-integrated probability of $\Lambda - \bar{\Lambda}$ oscillation and the oscillation parameter, set at $P(\Lambda) < 1.4 \times 10^{-6}$ and $\delta m_{\Lambda\bar{\Lambda}} < 2.1 \times 10^{-18}$ GeV respectively. This corresponds to an oscillation time limit of $\tau_{\text{osc}} > 3.1 \times 10^{-7}$ s ($\tau_{\text{osc}} = 1/\delta m_{\Lambda\bar{\Lambda}}$). In comparison to the recent BESIII result [14], $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18}$ GeV, we have imposed more stringent constraints on the upper limits of the corresponding parameters.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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