Search for $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$

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Using data samples of $(10087 \pm 44) \times 10^6$ J/ψ events and $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected with the BESIII detector at the BEPCII collider, we search for the CP violating decays $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$. No significant signals are observed over the expected background yields. The upper limits on their branching fractions are set as $\mathcal{B}(J/\psi \to K_S^0 K_S^0) < 4.7 \times 10^{-9}$ and $\mathcal{B}(\psi(3686) \to K_S^0 K_S^0) < 1.1 \times 10^{-8}$ at the 90% confidence level. These results improve the previous limits by a factor of three for $J/\psi \to K_S^0 K_S^0$ and two orders of magnitude for $\psi(3686) \to K_S^0 K_S^0$.

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I. INTRODUCTION

Experimental studies of the decays of vector charmonium states ψ [$\psi = J/\psi$ or $\psi(3686)$] to final states consisting of identical bosons, such as $K_S^0 K_S^0$, serve to test various symmetry principles and conservation laws in the Standard Model. First, studies of these decays are helpful to test Bose symmetry [1], which implies that a state composed of identical bosons remains unchanged under exchange of any two particles. The $K_S^0 K_S^0$ final state is forbidden in the ψ decays by Bose-Einstein statistics. Studies of these decays therefore provide valuable data to validate Bose symmetry. Second, investigations of these decays are valuable to search for potential violation of CP symmetry beyond the one present in neutral kaon oscillations. The branching fractions of the possible CP violating decays $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$, arising from $K^0 - \bar{K}^0$ oscillations, are predicted to be $(1.94 \pm 0.20) \times 10^{-9}$ for J/ψ and $(0.56 \pm 0.08) \times 10^{-9}$ for $\psi(3686)$ [2,3]. Third, studies of these decays are also important to test the CPT symmetry, which is a general feature of Lorentz-invariant local quantum field theories with a hermitian Hamiltonian. However, some quantum gravity models imply a violation of CPT symmetry. In the $K_S^0 K_S^0$ decay channel, this violation may be quantified with a complex parameter $\omega \sim 10^{-3}$ [4–6]. This parameter can be constrained using the ratio of the branching fractions of J/ψ or $\psi(3686)$ into $K_S^0 K_S^0$ and $K_S^0 K_L^0$.

Additionally, the $K_S^0 K_S^0$ states from ψ decays are sensitive to test quantum nonlocality versus Einstein–Podolsky-Rosen (EPR) locality [7]. EPR locality within a two-state system of massive particles allows a nonzero yield of $K_S^0 K_S^0$ states from the spacelike separated coherent quantum system of neutral kaons. The corresponding branching fractions of $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$ are predicted to be $(5.5 \pm 1.0) \times 10^{-6}$ and $(2.1 \pm 0.3) \times 10^{-6}$ [8], respectively, after considering potential CP violation and kaon regeneration. Quantum nonlocality, on the other hand, completely forbids these decays. Searching for these decays can thus provide experimental data for testing the EPR argument.

Experimentally, the MARKIII Collaboration reported the first search for $J/\psi \to K_S^0 K_S^0$ by using 2.7 million J/ψ events in 1985, and set an upper limit to its branching fraction at 5.2×10^{-6} at the 90% confidence level (CL) [9]. The BES experiment searched for $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$ with 58 million J/ψ events and 14 million $\psi(3686)$ events, yielding upper limits of 1.0×10^{-6} and 4.6×10^{-6} at the 95% CL [10], respectively. In 2009 and 2012, the BESIII Collaboration searched for $J/\psi \to K_S^0 K_S^0$ in 1.3 billion J/ψ events and set an upper limit of 1.4×10^{-8} at the 90% CL [11].

In this paper, we search for the CP violating decays $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$ with $(10087 \pm 44) \times 10^6$ J/ψ events [12] and $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events [13] accumulated by the BESIII detector. The data sample statistics are approximately 7.7 times and 190 times larger than previous studies for J/ψ and $\psi(3686)$ [10,11], respectively. To avoid potential bias, a semiblind analysis is carried out using a randomly selected 10% of the full dataset. This subset serves to evaluate the background level, verify consistency between the data and simulation samples, and validates the analysis strategy. The final results are then

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derived with the full dataset by applying the established analysis strategy.

II. BESIII EXPERIMENT AND MONTE CARLO SIMULATION

The BESIII detector [14] records symmetric e^+e^- collisions provided by the BEPCII storage ring [15] in the center-of-mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of $1.1\times10^{33}\ \mathrm{cm^{-2}\,s^{-1}}$ achieved at $\sqrt{s}=3.773$ GeV.

The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a time-of-flight system (TOF), 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. 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 $1\ \mathrm{GeV}/c$ is 0.5%, and the $\mathrm{d}E/\mathrm{d}x$ 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 plastic scintillator 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, which benefits 87% of the J/ψ data and 83% of the $\psi(3686)$ data used in this analysis [16].

Simulated data samples produced with a Geant4-based [17,18] Monte Carlo (MC) package, which includes the geometric description [19,20] 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 [21].

The inclusive MC sample, consisting of 1.001×10^{10} J/ψ events, includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC. The inclusive MC sample consisting of 2.7×10^9 $\psi(3686)$ events includes the production of the $\psi(3686)$ resonance, the initial state radiation production of the J/ψ, and the continuum processes incorporated in KKMC. All particle decays are modeled with EvtGen [22,23] using branching fractions either taken from the Particle Data Group (PDG) [24], when available, or otherwise estimated with Lundcharm [25,26]. Final-state radiation from charged final-state particles is incorporated using the PHOTOS package [27]. To estimate the detection efficiencies, the signal decays $J/\psi\to K^0_SK^0_S$ and $\psi(3686)\to K^0_SK^0_S$ are generated with the VSS model, which describes the decay of a vector particle into two scalar particles [22,23]. The $K^0_S\to\pi^+\pi^-$ decays are modeled by the uniform phase space.

III. EVENT SELECTION

Having chosen $K^0_S\to\pi^+\pi^-$, the final states of both decays are $\pi^+\pi^-\pi^+\pi^-$. At least four charged particles with zero net charge are required to satisfy the polar angle condition $|\cos\theta|<0.93$, where θ is defined with respect to the z-axis, which is the symmetry axis of the MDC. The particle identification (PID) for charged tracks is performed by combining the measurements of the specific ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) in the MDC and the flight time in the TOF to form likelihoods $L(h)$ ($h=p,\ K,\ \pi$) for each hadron h hypothesis. Charged tracks are identified as pions when the pion hypothesis has the greatest likelihood.

Each K^0_S candidate is reconstructed from two oppositely charged tracks assigned as π^+ and π^-. They are constrained to originate from a common vertex and are required to have an invariant mass within $|M_{\pi^+\pi^-}-M_{K^0_S}|<18\ \mathrm{MeV}/c^2$ and $30\ \mathrm{MeV}/c^2$ for $J/\psi\to K^0_SK^0_S$ and $\psi(3686)\to K^0_SK^0_S$, where $M_{K^0_S}$ is the K^0_S nominal mass [24]. The decay length of the K^0_S candidate away from the interaction point is required to be greater than twice the vertex resolution. The momenta of $\pi^+\pi^-$ are required to be within $(1.40, 1.55)\ \mathrm{GeV}/c$ and $(1.70, 1.84)\ \mathrm{GeV}/c$ for $J/\psi\to K^0_SK^0_S$ and $\psi(3686)\to K^0_SK^0_S$, respectively. If there is more than one combination of two K^0_S candidates, the one with the lowest sum of χ^2 from the second vertex fit [28] is selected.

A four-constraint (4C) kinematic fit with energy and momentum conservation is performed for all possible final state combinations. To suppress the background from $\psi\to\gamma K^0_SK^0_S$, we require $\chi^2_{K^0_SK^0_S}<\chi^2_{\gamma K^0_SK^0_S}$. Events satisfying $\chi^2_{4\mathrm{C}}<15$ and $\chi^2_{4\mathrm{C}}<30$ are kept for J/ψ and $\psi(3686)$ decays, respectively. To suppress the background from $\psi(3686)\to\pi^+\pi^-J/\psi$, $J/\psi\to\ell^+\ell^-(\ell=e,\mu)$ due to the misidentification of leptons and pions, the mass of any combination of $\pi^+\pi^-$ pair is required to be less than $3\ \mathrm{GeV}/c^2$.

The signal region is defined as

$$\sqrt{(p_{K^0_{S1}}-p_0)^2+(p_{K^0_{S2}}-p_0)^2}<5\sigma, \qquad (1)$$

where the $p_{K^0_{S1}}$ and $p_{K^0_{S2}}$ are the momenta of the two K^0_S in the ψ rest frame with a central value p_0 determined by fitting the corresponding signal MC samples. The K^0_S momentum resolution σ from the signal MC sample is the weighted average of the standard deviations of two Gaussian functions with the same mean. The σ values are $1.2\ \mathrm{MeV}/c$ for $J/\psi\to K^0_SK^0_S$ and $1.7\ \mathrm{MeV}/c$ for $\psi(3686)\to K^0_SK^0_S$. The number of signal events is obtained by counting the remaining events within the signal region. After applying the above selection criteria, the detection efficiencies of $J/\psi\to K^0_SK^0_S$ and $\psi(3686)\to K^0_SK^0_S$ are determined to be $(23.22 \pm 0.02)\%$ and $(20.14 \pm 0.02)\%$, respectively.

IV. BACKGROUND ANALYSIS

The backgrounds for $\psi \to K_S^0 K_S^0$ are dominated by other ψ hadronic decays and the continuum process.

Studies of the J/ψ inclusive MC sample show that the main backgrounds for $J/\psi \to K_S^0 K_S^0$ are from $J/\psi \to \gamma K_S^0 K_S^0$ and $J/\psi \to \pi^+\pi^-\pi^+\pi^-$. An exclusive MC sample of $J/\psi \to \gamma K_S^0 K_S^0$ is generated using the amplitude analysis generator [29] which provides the best agreement to data according to preliminary results from a mass-dependent analysis. Other exclusive MC samples of $J/\psi \to \pi^+\pi^-\pi^+\pi^-$, $J/\psi \to K^*(892)^0 \bar{K}^0 + \text{c.c.}$ and $J/\psi \to K_S^0 K_L^0$ are generated with the EvtGen models to estimate the background. Study of the $\psi(3686)$ inclusive MC sample shows that only a few background events survive after applying all selection criteria. Large exclusive MC samples of $\psi(3686) \to K_S^0 K_L^0$, $\psi(3686) \to \gamma\chi_{c0,2}$ ($\chi_{c0,2} \to K_S^0 K_S^0$), $\psi(3686) \to \rho^0\pi^+\pi^-$, $\psi(3686) \to K^*(892)^0 \bar{K}^0 + \text{c.c.}$, $\psi(3686) \to \gamma K_S^0 K_S^0$, and $\psi(3686) \to \pi^+\pi^- J/\psi (J/\psi \to \ell^+\ell^-)$ are generated to estimate the background. According to the branching fractions from the PDG [24], the total numbers of J/ψ and $\psi(3686)$ events as well as the detection efficiencies determined with each exclusive MC sample, the total normalized background yields are 6.1 ± 1.9 for $J/\psi \to K_S^0 K_S^0$ and 6.7 ± 3.6 for $\psi(3686) \to K_S^0 K_S^0$.

The continuum background for $J/\psi \to K_S^0 K_S^0$ is studied by using a sample of 168.3 pb^{-1} collision data taken at $\sqrt{s} = 3.08$ GeV; the continuum contribution for $\psi(3686) \to K_S^0 K_S^0$ is investigated by analyzing a data sample of 473.19 pb^{-1} taken at $\sqrt{s} = 3.65$ GeV and 2.93 fb^{-1} of events collected at $\sqrt{s} = 3.773$ GeV [30]. The contribution from the continuum process is estimated with $N_{\text{cont}}^{\text{obs}} \times f_c$, where $N_{\text{cont}}^{\text{obs}}$ is the number of events in the 2D K_S^0 momentum signal region for each dataset, and f_c denotes the scale factor that, taking into account the energy dependence of the cross section, is calculated as

$$f_c = \frac{\mathcal{L}_\psi}{\mathcal{L}_{\text{cont}}} \cdot \frac{s_{\text{cont}}}{s_\psi}, \qquad (2)$$

where $\mathcal{L}_\psi$ and s_ψ are the corresponding integrated luminosity and the square of the center-of-mass energy for J/ψ or $\psi(3686)$, the values of $\mathcal{L}_\psi$ are 2962.72 pb^{-1} [12] and 3877.05 pb^{-1} [13], respectively; $\mathcal{L}_{\text{cont}}$ and s_{cont} are the values for the data sample collected at $\sqrt{s} = 3.08$, 3.65, or 3.773 GeV, respectively. No event survives in the signal region for any dataset.

The decays $\psi \to K_S^0 K_L^0$, followed by the CP violating decay $K_L^0 \to \pi^+\pi^-$, could pose an irreducible source of background events that cannot be distinguished from signal decays. However, given the momenta of the ψ decay daughters and the effective detector volume in which we reconstruct the neutral Kaon decay to $\pi^+\pi^-$, the effective decay rate of this contribution is several orders of magnitude smaller than the upper limits derived in this analysis; these decays can therefore be safely neglected at the current level of precision.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the branching fraction measurements are from the total number of ψ events, the quoted branching fraction, tracking of charged particles, PID, the 4C kinematic fit, and the K_S^0 reconstruction.

The uncertainties of the total numbers of J/ψ and $\psi(3686)$ events are 0.4% [12] and 0.5% [13], respectively. The uncertainty of the quoted $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ from the PDG [24] is 0.2% for two K_S^0 mesons.

The control sample $J/\psi \to \pi^+\pi^-\pi^0$ is used to study the MDC tracking and PID uncertainties of charged pions. The difference in the tracking efficiencies between data and MC simulation is assigned as 0.5% for each charged pion. Therefore, the systematic uncertainty due to the MDC tracking efficiency is 2.0% for four tracks in J/ψ and $\psi(3686)$ decays. The differences in two-dimensional (momentum versus polar angle) PID efficiencies between data and MC simulation of the control samples are assigned as the systematic uncertainties for four charged pions. The resulting values are 2.7% for $J/\psi \to K_S^0 K_S^0$ and 2.5% for $\psi(3686) \to K_S^0 K_S^0$.

The control sample $\psi(3686) \to \pi^+\pi^- K_S^0 K_S^0$ is used to study the correction factors for the helix parameters of charged tracks from the K_S^0 decays. The correction factors are determined from the pull distributions of data and MC simulation [31]. The difference of signal efficiencies before and after helix correction is taken as the systematic uncertainty of the 4C kinematic fit. They are 6.2% for $J/\psi \to K_S^0 K_S^0$ and 1.8% for $\psi(3686) \to K_S^0 K_S^0$.

The systematic uncertainty from the K_S^0 reconstruction is estimated by using the control samples $J/\psi \to K_S^0 K_L^0$ and $\psi(3686) \to K_S^0 K_L^0$. Two charged pions are selected using PID and the angle between them is required to be within [15°, 50°]. To improve the purity, EMC shower variables are used to distinguish signal and background with a graph neural network [32] model on the recoil side of the $\pi^+\pi^-$ system. The differences in the K_S^0 reconstruction efficiencies between data and MC simulation are taken as the systematic uncertainties, which are 5.2% for $J/\psi \to K_S^0 K_S^0$ and 7.6% for $\psi(3686) \to K_S^0 K_S^0$. These control samples are also used to verify the consistency between data and MC, with good agreement observed.

Table I lists the systematic uncertainties from all sources. Assuming that each source is independent, the total systematic uncertainties are obtained by summing these uncertainties in quadrature.

TABLE I. Relative systematic uncertainties (in %) in the branching fraction measurements.

Source	$J/\psi \to K_S^0 K_S^0$	$\psi(3686) \to K_S^0 K_S^0$
N_ψ	0.4	0.5
$\mathcal{B}^{\rm PDG}(K_S^0 \to \pi^+\pi^-)$	0.2	0.2
Tracking	2.0	2.0
PID	2.7	2.5
4C kinematic fit	6.2	1.8
K_S^0 reconstruction	5.2	7.6
Total	8.8	8.5

VI. RESULTS

After unblinding all data, four candidate events for $J/\psi \to K_S^0 K_S^0$ and one event for $\psi(3686) \to K_S^0 K_S^0$ are observed in the corresponding signal region, as shown in Fig. 1. As estimated in Sec. IV, no significant signal events are observed over the expected numbers of background events. A maximum likelihood estimator, extended from the profile likelihood approach [33], is used to determine the upper limits on the branching fractions. The likelihood function depends on the parameter of interest $\mathcal{B}(\psi \to K_S^0 K_S^0)$ and the nuisance parameters $\boldsymbol{\theta} = (\epsilon_{\rm sig}, N_{\rm bkg})$. The likelihood function is defined as

$$\mathcal{L}(\mathcal{B}(\psi \to K_S^0 K_S^0), \boldsymbol{\theta}) = P\left(N_{\rm obs}, \mathcal{B}(\psi \to K_S^0 K_S^0) \cdot N_\psi \cdot \mathcal{B}^2_{K_S^0 \to \pi^+\pi^-} \cdot \epsilon_{\rm sig} + \sum_i N_{{\rm bkg},i}\right) \cdot \prod_i P\left(N^{\rm exp}_{{\rm bkg},i}, N_{{\rm bkg},i}\right) \cdot G\left(\epsilon^{\rm MC}_{\rm sig}, \epsilon_{\rm sig}, \sigma_{\epsilon^{\rm MC}_{\rm sig}}\right), \quad (3)$$

where the number of observed events $N_{\rm obs}$ is assumed to follow a Poisson distribution (P). Here, the detection efficiency $\epsilon_{\rm sig}$ follows a Gaussian distribution (G) with mean value $\epsilon^{\rm MC}_{\rm sig}$ and uncertainty $\sigma_{\epsilon^{\rm MC}_{\rm sig}}$, which are determined from signal MC samples and systematic uncertainties studies. The number of background events $N_{\rm bkg}$ obeys a Poisson distribution (P) with expected value $N^{\rm exp}_{\rm bkg}$, which is determined from the background study. The subscript i represents all background types, including those from ψ decay and continuum. The number of ψ events N_ψ, is obtained from an analysis of the inclusive J/ψ [$\psi(3686)$] sample [12,13].

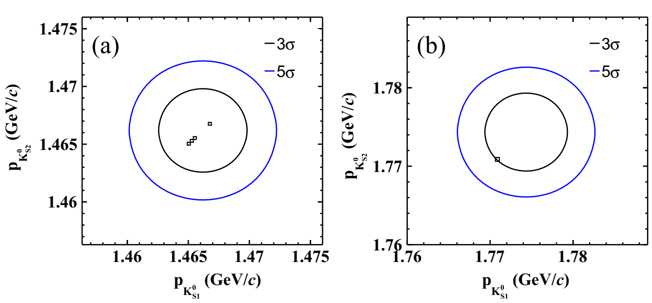

FIG. 1. Two-dimensional K_S^0 momentum distributions for (a) $J/\psi \to K_S^0 K_S^0$ and (b) $\psi(3686) \to K_S^0 K_S^0$. The black and blue circles correspond to 3σ and 5σ determined from the individual signal MC samples, respectively.

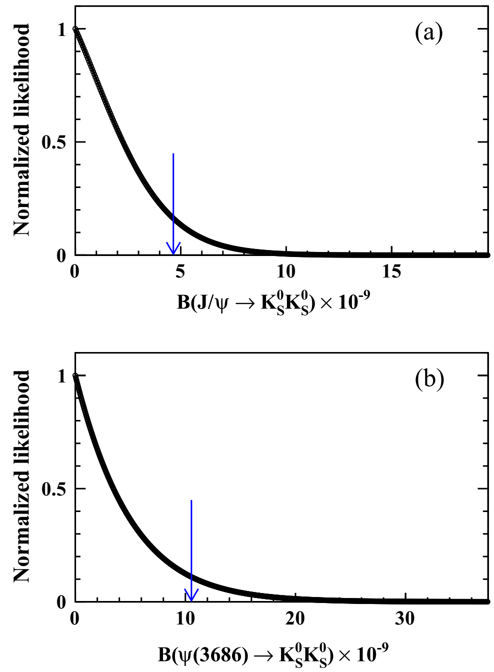

FIG. 2. The normalized likelihood distributions for (a) $J/\psi \to K_S^0 K_S^0$ and (b) $\psi(3686) \to K_S^0 K_S^0$. The blue arrows indicate the 90% CL upper limits.

Figure 2 shows the likelihood curves for $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$. We implicitly use a flat prior for the branching fraction in the determination of the upper limits. After integrating the likelihood distributions with all factors included, the upper limits of the branching fractions at the 90% CL after considering systematic uncertainties are determined to be $\mathcal{B}(J/\psi \to K_S^0 K_S^0) < 4.7 \times 10^{-9}$ and $\mathcal{B}(\psi(3686) \to K_S^0 K_S^0) < 1.1 \times 10^{-8}$ as listed in Table II.

VII. SUMMARY

Using $(10087 \pm 44) \times 10^6$ J/ψ events and $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected by the BESIII detector, we have searched for the *CP* violating decays $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$. A semiblind analysis finds no significant excess in the datasets with respect to the expected background yields. The upper limits on their branching fractions at the 90% CL are determined to be $\mathcal{B}(J/\psi \to K_S^0 K_S^0) < 4.7 \times 10^{-9}$ and $\mathcal{B}(\psi(3686) \to K_S^0 K_S^0) < 1.1 \times 10^{-8}$, where the systematic uncertainties have been taken into account. The results improve the

TABLE II. The observed yields in data (N_{obs}), estimated background yield ($N_{\mathrm{bkg}}^{\mathrm{exp}}$), detection efficiencies ($\epsilon_{\mathrm{sig}}^{\mathrm{MC}}$) and their uncertainties ($\sigma_{\epsilon_{\mathrm{sig}}^{\mathrm{MC}}}$) including both statistical and systematic uncertainties, and the upper limits on branching fractions of $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$. All upper limits are set at the 90% CL.

Channel	$J/\psi \to K_S^0 K_S^0$	$\psi(3686) \to K_S^0 K_S^0$
N_{obs}	4	1
$N_{\mathrm{bkg}}^{\mathrm{exp}}$	6.1 ± 1.9	6.7 ± 3.6
$\epsilon_{\mathrm{sig}}^{\mathrm{MC}}$	23.22%	20.14%
$\sigma_{\epsilon_{\mathrm{sig}}^{\mathrm{MC}}}$	2.04%	1.71%
$\mathcal{B}_{\mathrm{UL}}$	4.7×10^{-9}	1.1×10^{-8}

previous best limits [10,11] by a factor of three for $J/\psi \to K_S^0 K_S^0$ and two orders of magnitude for $\psi(3686) \to K_S^0 K_S^0$, which can be used to constrain new physics parameters. Experimental results have already excluded the EPR locality expectations [8]. These upper limits reach the level of the CP violation expectations [2] and could provide experimental evidence for further theoretical studies. Using the ratio of the branching fractions of J/ψ and $\psi(3686)$ into $K_S^0 K_S^0$ and $K_S^0 K_L^0$ [24], the CPT violation parameter $|\omega|$ is estimated to be $(4.91 \pm 0.14) \times 10^{-3}$ and $(1.44 \pm 0.04) \times 10^{-2}$ for the respective upper limits of $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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