

Search for CP violation in $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ via $D \rightarrow K_S^0\pi^0$

M. Ablikim *et al.*^{*}
(BESIII Collaboration)



(Received 25 August 2025; accepted 7 November 2025; published 18 February 2026)

Utilizing data samples of electron-positron collisions recorded with the BESIII detector at the center of mass energy of 3.773 GeV, corresponding to an integrated luminosity of 20.28 fb⁻¹, we report the first search for the CP forbidden process $e^+e^- \rightarrow \psi(3773) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$. No significant signal is observed. We set the upper limit on the observed cross section to be 7.37 fb, and the upper limit on the joint branching fraction of the C-odd correlated neutral D pair $\mathcal{B}[(D^0\bar{D}^0)_{\text{C-odd}} \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)] < 2.04 \times 10^{-6}$ at the 90% confidence level.

DOI: [10.1103/dwlf-f4jn](https://doi.org/10.1103/dwlf-f4jn)

I. INTRODUCTION

The phenomenon of CP violation remains one of the least understood aspects of particle physics. Over the past 60 years, CP violation has been detected in several processes involving the K , B , and D meson systems. The recent observation of CP violation [1] in the charm quark sector is stimulating a wide discussion to understand its nature. Identifying the sources of CP violation, whether within or beyond the Standard Model (SM), requires an accurate study performed across various processes.

As suggested in Refs. [2–4], a variety of neutral D decays, including the semileptonic decays, the hadronic CP and non- CP eigenstates, and the CP -forbidden states, provide an environment to obtain additional observations of CP violation, since they serve to clarify the ambiguities in current theoretical estimates and to shed some light on the dynamics of the $D^0 - \bar{D}^0$ mixing [5], of the subsequent $K^0 - \bar{K}^0$ mixing [6], searching for possible sources of new physics beyond the SM. It is notable that the interference between these sources could potentially enhance the overall CP violation and affect the cross section [2,4], from which $D^0 - \bar{D}^0$ mixing could be accessed. One possible hadronic CP eigenstate in D^0 decays is the $K_S^0\pi^0$ final state. In the SM, the decays $D^0 \rightarrow \bar{K}^0\pi^0$ and $D^0 \rightarrow K^0\pi^0$ and their CP -conjugate processes are Cabibbo favoured and doubly Cabibbo suppressed, respectively. Both occur only through the tree-level quark diagrams, as illustrated in Fig. 1. The Kobayashi-Maskawa CP violating phase, interference

between Cabibbo-favoured and doubly Cabibbo-suppressed diagrams, and the double-mixing from $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$, generate rich opportunities for studying CP violation [2,7,8] and create an ideal platform for exploration.

Furthermore, the $D^0\bar{D}^0$ pairs produced in e^+e^- annihilations originate from a virtual photon with quantum numbers $J^{PC} = 1^{--}$, and while the two daughter D mesons have spin-0, the initial virtual photon has spin-1. This results in the production of a P-wave two-meson system, which ensures that the two D mesons must have opposite C $\times$ P. This is known as the Einstein-Podolsky-Rosen (EPR) correlation [9,10].

According to CP conservation, Bose-Einstein statistics and the resulting EPR correlation, the process $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ is forbidden since the final states share the same CP numbers, and thus violate

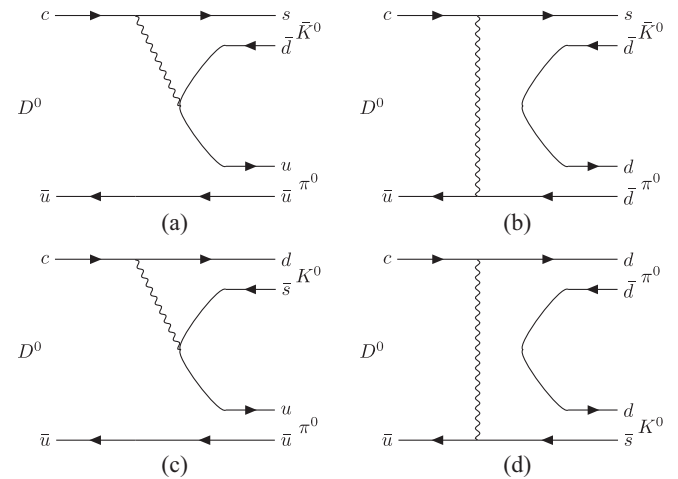


FIG. 1. Feynman diagrams for (a), (b) Cabibbo-favoured process $D^0 \rightarrow \bar{K}^0\pi^0$ and (c), (d) doubly Cabibbo-suppressed $D^0 \rightarrow K^0\pi^0$ at tree-level [4].

^{*}Full author list given at the end of the article.

the correlation. However, in the classical interpretation, the EPR correlation is entirely violated, with the D mesons decaying independently with their own branching fractions (BFs). The expected number of produced events in the classical picture is given by

$$N_{\text{classical}} = N_{D^0\bar{D}^0} \mathcal{B}_{D^0} \mathcal{B}_{\bar{D}^0}, \quad (1)$$

where $N_{D^0\bar{D}^0}$ is the total number of $D^0\bar{D}^0$ pairs produced in data, $\mathcal{B}_{D^0}(\mathcal{B}_{\bar{D}^0}) = (1.240 \pm 0.022)\%$ is the BF of $D^0 \rightarrow K_S^0\pi^0$ ($\bar{D}^0 \rightarrow K_S^0\pi^0$) [11].

In this paper, we search for the $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ process at $\sqrt{s} = 3.773$ GeV. We use the data sample collected by BESIII at $\sqrt{s} = 3.773$ GeV, corresponding to an integrated luminosity of 20.28 fb^{-1} [12]. In the collected data sample, with Eq. (1), about 11000 events of the $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ process are expected from a classical point of view [13], allowing one to test the CP violation and the EPR correlation at 10^{-4} level. We set an upper limit on the observed cross section and on the joint branching fraction of C-odd correlated neutral D pair $\mathcal{B}[(D^0\bar{D}^0)_{\text{C-odd}} \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)]$ at the 90% confidence level (CL). Here, the subscript in $(D^0\bar{D}^0)_{\text{C-odd}}$ denotes the two neutral D mesons are in C-odd correlation and have opposite $C \times P$. To avoid possible bias, a semiblind analysis by using a subsample of the data, corresponding to an integrated luminosity of 2.93 fb^{-1} , is performed. Throughout this paper, charge conjugation is always implied.

II. DETECTOR AND DATASETS

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 $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [16]. 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 plastic scintillator 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 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/ c 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 was 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 83% of the data used in this analysis [17].

Simulated Monte-Carlo (MC) samples produced with GEANT4-based [18] software, which includes the geometric description of the BESIII detector and the detector response, are used to determine the detection efficiency and to estimate the background contributions. The simulation includes the beam energy spread and initial state radiation (ISR) in the e^+e^- annihilation modeled with the generator KKMC [19]. The inclusive MC samples, which are divided into 40 subsamples with the same size as the data sample, are used to study the background contributions. This sample includes the production of open charm processes, the ISR production of vector charmonium(-like) states, and the continuum processes incorporated in KKMC. The known decay modes are modeled with EVTGEN [20] using world averaged BF values [11], and the remaining unknown decays from the charmonium states with LUNDCHARM [21]. Final state radiation from charged final state particles is incorporated with PHOTOS [22]. The signal detection efficiencies and signal shapes are obtained from signal MC simulation.

III. DATA ANALYSIS

In this analysis, K_S^0 and π^0 candidates are reconstructed via $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$ decays, respectively. The observed cross section σ_{obs} of the process $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ is given by

$$\sigma_{\text{obs}} = \frac{N_{\text{obs}}}{L \times \epsilon \times \mathcal{B}_{\text{sub}}}, \quad (2)$$

and the joint branching fraction of the C-odd correlated $D^0\bar{D}^0$ is given by

$$\begin{aligned} \mathcal{B}[(D^0\bar{D}^0)_{\text{C-odd}} \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)] \\ = \frac{N_{\text{obs}}}{N_{D^0\bar{D}^0} \times \epsilon \times \mathcal{B}_{\text{sub}}}, \end{aligned} \quad (3)$$

where N_{obs} is the number of observed signal events, L is the total integrated luminosity of the data, ϵ is the efficiency for the event reconstruction, and $\mathcal{B}_{\text{sub}}$ is the BF of the subdecay, given as $\mathcal{B}_{\text{sub}} = \mathcal{B}_{K_S^0}^2 \times \mathcal{B}_{\pi^0}^2$, where $\mathcal{B}_{K_S^0}$ and $\mathcal{B}_{\pi^0}$ are the BFs of $K_S^0 \rightarrow \pi^+\pi^-$ and $\pi^0 \rightarrow \gamma\gamma$, respectively.

The signal process $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ is searched using the double-tag method [23–25]. In this method, two D mesons which decay through the $K_S^0\pi^0$ channel in the same event are simultaneously reconstructed. The final state $K_S^0\pi^0$ is reconstructed with the K_S^0 and π^0 candidates satisfying the selections detailed below.

Photon candidates are identified using isolated clusters in the EMC. The EMC time is required to be within (0, 700) ns

from the event start time in order to suppress fake photons due to electronic noise or e^+e^- beam background. The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$), where θ is the polar angle with respect to the z axis, which is the symmetry axis of the MDC. The π^0 candidates are reconstructed through the $\pi^0 \rightarrow \gamma\gamma$ decay, with at least one photon in the barrel region. The two-photon invariant mass is required to be in the range (0.115, 0.150) GeV/c^2 . A 1C kinematic fit is performed constraining $M_{\gamma\gamma}$ to the π^0 known mass [11], and the χ^2 of the fit must be less than 50.

Charged tracks detected in the MDC are required to be within a polar angle range of $|\cos\theta| < 0.93$. Each K_S^0 candidate is reconstructed from two oppositely charged tracks whose distance of closest approach to the interaction point along the z axis is less than 20 cm. These tracks are assumed to be pions. They are constrained to originate from a common vertex and are required to have an invariant mass within (0.450, 0.550) GeV/c^2 . The decay length of the K_S^0 candidate is required to be greater than twice the vertex resolution away from the IP. The quality of the vertex fit is ensured by requiring $\chi^2 < 100$.

Signal D meson pairs are reconstructed from two pairs of K_S^0 and π^0 mesons. For each D meson candidate, we define the beam energy difference (ΔE) as

$$\Delta E = E_D - E_{\text{beam}}, \quad (4)$$

where E_D is the energy of the reconstructed D meson and E_{beam} is the beam energy, and we require ΔE to be within $(-0.042, 0.072)$ GeV. We define the distance from the left and right edges of the signal region to the most probable beam energy difference value, ΔE_m , as $3\sigma_L$ and $3\sigma_R$, respectively, and define the ΔE significance ($\sigma_{\Delta E}$) for the D meson as

$$\sigma_{\Delta E} = \begin{cases} \frac{|\Delta E - \Delta E_m|}{\sigma_L}, & \Delta E < \Delta E_m, \\ \frac{|\Delta E - \Delta E_m|}{\sigma_R}, & \Delta E > \Delta E_m, \end{cases} \quad (5)$$

For a candidate D meson pair, the $\sigma_{\Delta E}$ of the two D mesons are added up as “total $\sigma_{\Delta E}$.” For multiple candidate pairs, the one with the least “total $\sigma_{\Delta E}$ ” is kept for further analysis.

The dominant background is composed of events with $D^0(\bar{D}^0) \rightarrow \pi^+\pi^-\pi^0$ decays. To estimate this background, the invariant masses of the K_S^0 candidates are checked. Figure 2 shows the two-dimensional $\pi^+\pi^-$ invariant mass distribution for both D meson sides in the same event. We define the K_S^0 signal region as (0.487, 0.511) GeV/c^2 , and the sideband regions as (0.455, 0.479) and (0.519, 0.543) GeV/c^2 . We define Region I, corresponding to the signal region, where both $\pi^+\pi^-$ combinations lie in the K_S^0 signal region. Region II is defined with either one of the

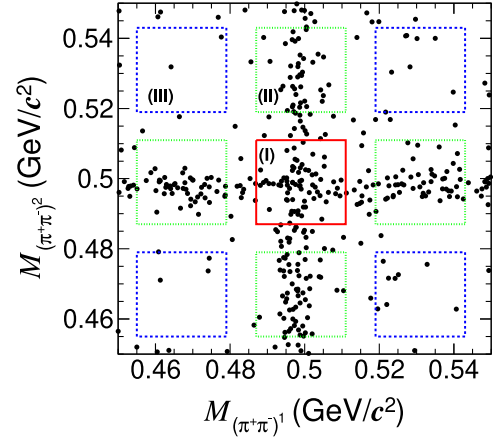


FIG. 2. Two-dimensional $\pi^+\pi^-$ invariant mass distribution for the K_S^0 candidates from the two D mesons in data (the order is arbitrary). The red solid box defines Region I, the green dotted box Region II, and the blue dashed box Region III.

$\pi^+\pi^-$ combinations in the K_S^0 signal region and the other in the K_S^0 sideband regions. The Region III has both the $\pi^+\pi^-$ combinations located in the K_S^0 sideband regions. Signal events are expected to peak in Region I, the $D^0 \rightarrow \pi^+\pi^-\pi^0$ background events are expected to distribute mainly in Region I and Region II, and other flat background events distribute in all the regions.

We use the beam-constrained mass M_{BC} to identify D mesons in the three regions, defined as

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2 c^2}, \quad (6)$$

where E_{beam} is the beam energy and $\vec{p}_D$ is the three-momentum of the reconstructed D meson.

The D meson yield is acquired by a two-dimensional (2D) fit to the M_{BC}^1 versus M_{BC}^2 distribution of two D mesons in the same event, where the order of the D mesons is arbitrary. The probability density function used in the fit comprises four components: “Signal” describes candidates where both D mesons are correctly reconstructed; “BKGI” and “BKGI” denote the background where only one D meson is correctly reconstructed; “BKGI” describes the background that diagonally populates the 2D distributions.

Specifically, the four components are constructed as follows:

$$\begin{aligned} \text{Signal: } & S_1 \times S_2, \\ \text{BKGI: } & S_1 \times f_2, \\ \text{BKGI: } & f_1 \times S_2, \\ \text{BKGI: } & f_{1+2} \times S_{1-2}. \end{aligned}$$

Here, 1 and 2 correspond to the two dimensions of the 2D fit. The S_i are Gaussian functions that describe the signal D shape, while f_i are ARGUS functions [26] that characterize the combinatorial background. The subscript i denotes the argument of the functions.

Finally, by fitting the M_{BC} distributions of the events within the three Regions defined in Fig. 2, three D signal

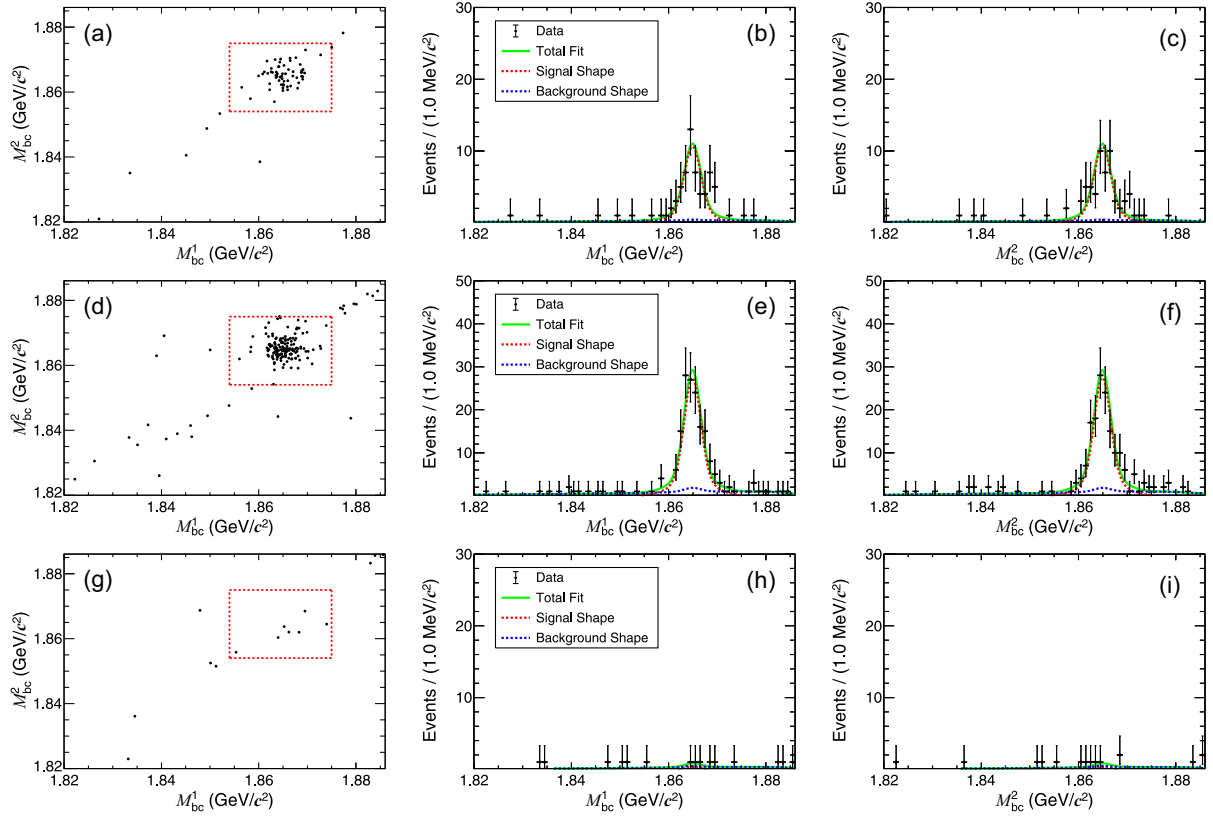


FIG. 3. M_{BC} distributions of the reconstructed D mesons. The first, second, and third rows correspond to events in Regions I, II, and III, respectively. These Regions are shown in Fig. 2; (a), (d), and (g) are the 2D distributions of M_{BC} for two D mesons in the same event, where the red dashed squares refer to the D signal region; (b), (e), and (h) are the M_{BC} distributions and fit result projections on one of the two D meson, while (c), (f), and (i) are for the other D meson. The order of D mesons is arbitrary.

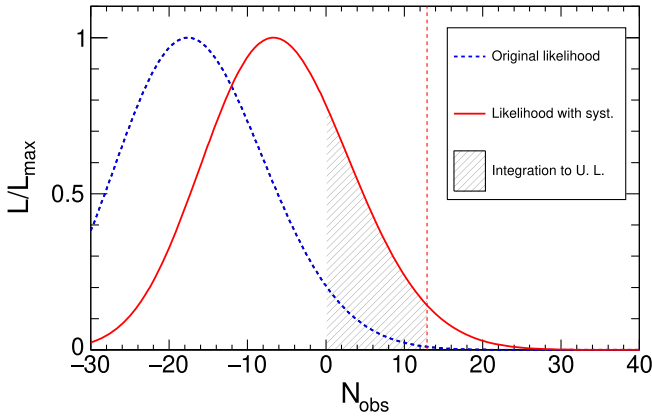


FIG. 4. Likelihood distributions as a function of N_{obs} of the data sample. The results obtained with and without incorporating the systematic uncertainties are shown as red solid and blue dashed curves, respectively. The dashed red line shows the result corresponding to the 90% CL. A flat prior for N_{obs} from 0 to infinity is assumed. The shaded area shows the integration above zero to the upper limit.

yields are obtained as $N^{(\text{I})} = 53 \pm 8$, $N^{(\text{II})} = 144 \pm 12$ and $N^{(\text{III})} = 2 \pm 2$. Notice that Region II (Region III) refers to all the green (blue) dashed square regions. The fit results are shown in Fig. 3. Assuming the background is flat, the background in Region I can be estimated as $N_{\text{bkg}} = \frac{1}{2}N^{(\text{II})} - \frac{1}{4}N^{(\text{III})} = 72 \pm 6$. The observed signal yield is determined to be $N_{\text{obs}} = N^{(\text{I})} - N_{\text{bkg}} = -19 \pm 10$. The selection efficiency ϵ is estimated to be $(18.44 \pm 0.10)\%$ from the signal MC sample. Since no significant signal is observed, an upper limit of N_{obs} is determined with the Bayesian approach, as shown in Fig. 4. The upper limit at the 90% CL is 12.9, which is incorporated with the systematic uncertainties described in the next Section. This leads to an upper limit of observed cross section $\sigma_{\text{sig}} < 7.37 \text{ fb}$ using Eq. (2). The method to incorporate systematic uncertainty is discussed in the next Section.

IV. SYSTEMATIC UNCERTAINTY

The systematic uncertainties on this measurement are summarized in Table I and are classified into multiplicative

TABLE I. Estimated multiplicative and additive systematic uncertainties.

Multiplicative	
Source	σ_ϵ (%)
K_S^0 reconstruction	1.5
π^0 reconstruction	1.7
ΔE signal region	1.3
MC statistics	0.2
Luminosity	0.5
Intermediate BF	0.2
Total	2.7
Additive	
Source	N_{add}
Signal shape	3.5
Background shape	0.0
N_{obs} estimation	10.3
Total	10.9

terms σ_ϵ , proportional to the measured BF, and additive terms N_{add} , independent of the measured BF. The multiplicative uncertainties are from the efficiency determination and the quoted BFs. The uncertainty from K_S^0 and π^0 reconstruction is studied from the control samples $D^0 \rightarrow K_S^0\pi^0$, $D^0 \rightarrow K_S^0\pi^0\pi^0$, $D^0 \rightarrow K_S^0\pi^0\pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+\pi^0$, extracted from the same data sample [12]. The uncertainty from the ΔE signal region selection is estimated by fitting the ΔE signal with a double-Gaussian function, and then using the $\pm 3\sigma$ range as an alternative signal region; the resulting change in N_{obs} is taken as the related uncertainty. The uncertainty due to the size of the MC sample is assigned as the statistical uncertainties related to the number of generated events. The uncertainty for luminosity is quoted from Ref. [12], and the uncertainty for the intermediate BFs is quoted from Particle Data Group (PDG) [11]. By adding these uncertainties in quadrature, the total uncertainty σ_ϵ is estimated to be 2.7%.

The additive uncertainties directly affect the total number of observed signal events N_{obs} . The total additive uncertainty N_{add} is estimated to be about 11 events. The uncertainty from the choice of the signal shape is obtained by altering the nominal signal shape S_i from a Gaussian function to a simulated signal shape, and the difference in N_{obs} is considered as the related uncertainty. The uncertainty from the choice of the background shape is estimated in a similar way by changing the function f_i with the simulated shape, and is found to be negligible. The uncertainty from the N_{obs} estimation, including the background subtraction, is studied using 40 inclusive MC samples with the same size of the data sample; the obtained values of N_{obs} are fitted with a Gaussian function and we obtain as mean value 0.3 ± 1.2 and as standard deviation

7.7 ± 0.9 . To be conservative, we consider the sum of the mean value and standard deviation, together with their uncertainties, as the uncertainty from the N_{obs} estimation.

V. RESULTS

The multiplicative systematic uncertainty is incorporated in the calculation of the upper limit following the prescriptions of Refs. [27,28], as

$$L(N_{\text{obs}}) \propto \int_0^1 L\left(N_{\text{obs}} \frac{\epsilon'}{\epsilon}\right) \exp\left[\frac{-(\epsilon'/\epsilon - 1)^2}{2(\sigma_\epsilon)^2}\right] d\epsilon', \quad (7)$$

where $L(N_{\text{obs}})$ is the likelihood distribution as a function of the assumed observed signal number N_{obs} ; ϵ' is the expected efficiency and ϵ is the MC-estimated efficiency. To take into account the additive systematic uncertainty, the updated likelihood is then shifted upward according to the number of additive uncertainty events N_{add} . The blue dashed and red solid curves in Fig. 4 show the original and the modified likelihood distributions, respectively.

The upper limit on N_{obs} at the 90% CL, obtained by integrating the resulting curve from zero to 90%, is $N_{\text{obs}} < 12.9$. It gives an upper limit of the observed cross section $\sigma_{\text{obs}}(e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)) < 7.37 \text{ fb}$, and of the joint branching fraction $\mathcal{B}[(D^0\bar{D}^0)_{\text{C-odd}} \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)] < 2.04 \times 10^{-6}$ at $\sqrt{s} = 3.773 \text{ GeV}$.

VI. CONCLUSION

Using data taken at $\sqrt{s} = 3.773 \text{ GeV}$ corresponding to an integrated luminosity of 20.28 fb^{-1} , recorded by the BESIII detector, we perform the first search for $e^+e^- \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ following a semiblind analysis. The quantum-correlated process $e^+e^- \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)$ is forbidden by CP conservation, and only allowed via $D^0 - \bar{D}^0$ mixing and $K^0 - \bar{K}^0$ mixing mechanism in the secondary decays, and interference between them. In this analysis, we establish the upper limit on the observed cross section $\sigma_{\text{obs}}(e^+e^- \rightarrow D^0\bar{D}^0 \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)) < 7.37 \text{ fb}$; additionally, the joint branching fraction is constrained to $\mathcal{B}[(D^0\bar{D}^0)_{\text{C-odd}} \rightarrow (K_S^0\pi^0)(K_S^0\pi^0)] < 2.04 \times 10^{-6}$, both at the 90% CL and at $\sqrt{s} = 3.773 \text{ GeV}$. This is the first exploration on the joint branching fraction and cross section of EPR correlated neutral D pair. This method can be generalized to study other EPR correlated systems like $e^+e^- \rightarrow D^0\bar{D}^{*0}$ [29], and the result provides crucial information for the CP violation of neutral D meson and helps eliminate or set theoretical boundaries to potential new physics effect in charm physics [4]. In the future, by studying the interference between different CP violation sources and existing CP violation results in neutral K mesons, more accurate cross section measurements will be able to bring a deeper insight into the $D^0 - \bar{D}^0$ mixing parameters, and finally reveal the nature of this broken symmetry.

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 No. 2023YFA1606000, No. 2023YFA1606704; National Natural Science Foundation of China (NSFC) under Contracts No. 11635010, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264, No. 12192265, No. 12221005, No. 12225509, No. 12235017, No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; The Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under

Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174, No. 2021.0299; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; Swedish Research Council under Contract No. 2019.04595; U.S. Department of Energy under Contract No. DE-FG02-05ER41374. This work is supported in part by the National Natural Science Foundation of China under Grant No. 12342502.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

-
- [1] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **122**, 211803 (2019).
 - [2] H. Y. Cheng, Z. H. Guo *et al.*, [arXiv:2502.08907](#); D. Friday, E. Gersabeck, A. Lenz, and M. L. Piscopo, [arXiv:2506.15584](#).
 - [3] I. I. Bigi and H. Yamamoto, *Phys. Lett. B* **349**, 363 (1995).
 - [4] Z. Z. Xing, *Phys. Rev. D* **55**, 196 (1997).
 - [5] Z. Z. Xing, *Chin. Phys. C* **32**, 483 (2008).
 - [6] G. D'Ambrosio *et al.* (KLOE Collaboration), *J. High Energy Phys.* **12** (2006) 011.
 - [7] D. Wang, F. S. Yu, and H. N. Li, *Phys. Rev. Lett.* **119**, 181802 (2017); F. S. Yu, W. J. Song, and Q. Qin, *Phys. Rev. D* **110**, L031301 (2024).
 - [8] W. Bernreuther, *Lect. Notes Phys.* **591**, 237 (2002).
 - [9] I. I. Bigi, A. I. Sanda, and B. Winstein, *Am. J. Phys.* **69**, 1287 (2001).
 - [10] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777 (1935).
 - [11] S. Navas *et al.* (Particle Data Group), *Phys. Rev. D* **110**, 030001 (2024).
 - [12] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **48**, 123001 (2024).
 - [13] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **42**, 083001 (2018).
 - [14] M. Ablikim *et al.* (BESIII Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010).
 - [15] C. H. Yu *et al.*, *Proceedings of IPAC2016, Busan, Korea* (2016), [10.18429/JACoW-IPAC2016-TUYA01](#).
 - [16] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **44**, 040001 (2020).
 - [17] X. Li *et al.*, *Radiat. Detect. Technol. Methods* **1**, 13 (2017); Y. X. Guo *et al.*, *Radiat. Detect. Technol. Methods* **1**, 15 (2017); P. Cao *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **953**, 163053 (2020).
 - [18] S. Agostinelli *et al.* (GEANT4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
 - [19] S. Jadach, B. F. L. Ward, and Z. Was, *Phys. Rev. D* **63**, 113009 (2001).
 - [20] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001); R. G. Ping, *Chin. Phys. C* **32**, 599 (2008).
 - [21] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, *Phys. Rev. D* **62**, 034003 (2000); R. L. Yang *et al.*, *Chin. Phys. Lett.* **31**, 061301 (2014).
 - [22] E. Richter-Was, *Phys. Lett. B* **303**, 163 (1993).
 - [23] R. M. Baltrusaitis *et al.* (MARK-III Collaboration), *Phys. Rev. Lett.* **56**, 2140 (1986).
 - [24] B. C. Ke, J. Koponen, H. B. Li, and Y. Zheng, *Annu. Rev. Nucl. Part. Sci.* **73**, 285 (2023).
 - [25] H. B. Li and X. R. Lyu, *Natl. Sci. Rev.* **8**, nwab181 (2021).
 - [26] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **241**, 278 (1990).
 - [27] K. Stenson, [arXiv:physics/0605236](#).
 - [28] X. X. Liu, X. R. Lyu, and Y. S. Zhu, *Chin. Phys. C* **39**, 103001 (2015).
 - [29] D. Cronin-Hennessy *et al.* (CLEO Collaboration), *Phys. Rev. D* **80**, 072001 (2009).
-

M. Ablikim¹, M. N. Achasov^{4,b}, P. Adlarson⁷⁷, X. C. Ai⁸², R. Aliberti³⁶, A. Amoroso^{76a,76c}, Q. An^{73,59,a},
Y. Bai⁵⁸, O. Bakina³⁷, Y. Ban^{47,c}, H.-R. Bao⁶⁵, V. Batozskaya^{1,45}, K. Begzsuren³³, N. Berger³⁶, M. Berowski⁴⁵,
M. Bertani^{29a}, D. Bettoni^{30a}, F. Bianchi^{76a,76c}, E. Bianco^{76a,76c}, A. Bortone^{76a,76c}, I. Boyko³⁷, R. A. Briere⁵,
A. Brueggemann⁷⁰, H. Cai⁷⁸, M. H. Cai^{39,d,e}, X. Cai^{1,59}, A. Calcaterra^{29a}, G. F. Cao^{1,65}, N. Cao^{1,65},
S. A. Cetin^{63a}, X. Y. Chai^{47,c}, J. F. Chang^{1,59}, G. R. Che⁴⁴, Y. Z. Che^{1,65,59}, C. H. Chen⁹, Chao Chen⁵⁶,
G. Chen¹, H. S. Chen^{1,65}, H. Y. Chen²¹, M. L. Chen^{1,65,59}, S. J. Chen⁴³, S. L. Chen⁴⁶, S. M. Chen⁶²,
T. Chen^{1,65}, X. R. Chen^{32,65}, X. T. Chen^{1,65}, X. Y. Chen^{12,f}, Y. B. Chen^{1,59}, Y. Q. Chen¹⁶, Z. Chen²⁵,
Z. J. Chen^{26,g}, Z. K. Chen⁶⁰, S. K. Choi¹⁰, X. Chu^{12,f}, G. Cibinetto^{30a}, F. Cossio^{76c}, J. Cottee-Meldrum⁶⁴,
J. J. Cui⁵¹, H. L. Dai^{1,59}, J. P. Dai⁸⁰, A. Dbeyssi¹⁹, R. E. de Boer³, D. Dedovich³⁷, C. Q. Deng⁷⁴, Z. Y. Deng¹,
A. Denig³⁶, I. Denysenko³⁷, M. Destefanis^{76a,76c}, F. De Mori^{76a,76c}, B. Ding^{68,1}, X. X. Ding^{47,c}, Y. Ding⁴¹,
Y. Ding³⁵, Y. X. Ding³¹, J. Dong^{1,59}, L. Y. Dong^{1,65}, M. Y. Dong^{1,65,59}, X. Dong⁷⁸, M. C. Du¹, S. X. Du⁸²,
S. X. Du^{12,f}, Y. Y. Duan⁵⁶, P. Egorov^{37,h}, G. F. Fan⁴³, J. J. Fan²⁰, Y. H. Fan⁴⁶, J. Fang^{1,59}, J. Fang⁶⁰,
S. S. Fang^{1,65}, W. X. Fang¹, Y. Q. Fang^{1,59}, R. Farinelli^{30a}, L. Fava^{76b,76c}, F. Feldbauer³, G. Felici^{29a},
C. Q. Feng^{73,59}, J. H. Feng¹⁶, L. Feng^{39,d,e}, Q. X. Feng^{39,d,e}, Y. T. Feng^{73,59}, M. Fritsch³, C. D. Fu¹, J. L. Fu⁶⁵,
Y. W. Fu^{1,65}, H. Gao⁶⁵, X. B. Gao⁴², Y. Gao^{73,59}, Y. N. Gao^{47,c}, Y. N. Gao²⁰, Y. Y. Gao³¹, S. Garbolino^{76c},
I. Garzia^{30a,30b}, L. Ge⁵⁸, P. T. Ge²⁰, Z. W. Ge⁴³, C. Geng⁶⁰, E. M. Gersabeck⁶⁹, A. Gilman⁷¹, K. Goetzen¹³,
J. D. Gong³⁵, L. Gong⁴¹, W. X. Gong^{1,59}, W. Gradl³⁶, S. Gramigna^{30a,30b}, M. Greco^{76a,76c}, M. H. Gu^{1,59},
Y. T. Gu¹⁵, C. Y. Guan^{1,65}, A. Q. Guo³², L. B. Guo⁴², M. J. Guo⁵¹, R. P. Guo⁵⁰, Y. P. Guo^{12,f}, A. Guskov^{37,h},
J. Gutierrez²⁸, K. L. Han⁶⁵, T. T. Han¹, F. Hanisch³, K. D. Hao^{73,59}, X. Q. Hao²⁰, F. A. Harris⁶⁷, K. K. He⁵⁶,
K. L. He^{1,65}, F. H. Heinsius³, C. H. Heinz³⁶, Y. K. Heng^{1,65,59}, C. Herold⁶¹, P. C. Hong³⁵, G. Y. Hou^{1,65},
X. T. Hou^{1,65}, Y. R. Hou⁶⁵, Z. L. Hou¹, H. M. Hu^{1,65}, J. F. Hu^{57,i}, Q. P. Hu^{73,59}, S. L. Hu^{12,f}, T. Hu^{1,65,59},
Y. Hu¹, Z. M. Hu⁶⁰, G. S. Huang^{73,59}, K. X. Huang⁶⁰, L. Q. Huang^{32,65}, P. Huang⁴³, X. T. Huang⁵¹,
Y. P. Huang¹, Y. S. Huang⁶⁰, T. Hussain⁷⁵, N. Hüsken³⁶, N. in der Wiesche⁷⁰, J. Jackson²⁸, Q. Ji¹, Q. P. Ji²⁰,
W. Ji^{1,65}, X. B. Ji^{1,65}, X. L. Ji^{1,59}, Y. Y. Ji⁵¹, Z. K. Jia^{73,59}, D. Jiang^{1,65}, H. B. Jiang⁷⁸, P. C. Jiang^{47,c},
S. J. Jiang⁹, T. J. Jiang¹⁷, X. S. Jiang^{1,65,59}, Y. Jiang⁶⁵, J. B. Jiao⁵¹, J. K. Jiao³⁵, Z. Jiao²⁴, S. Jin⁴³, Y. Jin⁶⁸,
M. Q. Jing^{1,65}, X. M. Jing⁶⁵, T. Johansson⁷⁷, S. Kabana³⁴, N. Kalantar-Nayestanaki⁶⁶, X. L. Kang⁹,
X. S. Kang⁴¹, M. Kavatsyuk⁶⁶, B. C. Ke⁸², V. Khachatryan²⁸, A. Khoukaz⁷⁰, R. Kiuchi¹, O. B. Kolcu^{63a},
B. Kopf³, M. Kuessner³, X. Kui^{1,65}, N. Kumar²⁷, A. Kupsc^{45,77}, W. Kühn³⁸, Q. Lan⁷⁴, W. N. Lan²⁰,
T. T. Lei^{73,59}, M. Lellmann³⁶, T. Lenz³⁶, C. Li^{73,59}, C. Li⁴⁸, C. Li⁴⁴, C. H. Li⁴⁰, C. K. Li²¹, D. M. Li⁸²,
F. Li^{1,59}, G. Li¹, H. B. Li^{1,65}, H. J. Li²⁰, H. N. Li^{57,i}, Hui Li⁴⁴, J. R. Li⁶², J. S. Li⁶⁰, K. Li¹, K. L. Li²⁰,
K. L. Li^{39,d,e}, L. J. Li^{1,65}, Lei Li⁴⁹, M. H. Li⁴⁴, M. R. Li^{1,65}, P. L. Li⁶⁵, P. R. Li^{39,d,e}, Q. M. Li^{1,65}, Q. X. Li⁵¹,
R. Li^{18,32}, S. X. Li¹², T. Li⁵¹, T. Y. Li⁴⁴, W. D. Li^{1,65}, W. G. Li^{1,a}, X. Li^{1,65}, X. H. Li^{73,59}, X. L. Li⁵¹,
X. Y. Li^{1,8}, X. Z. Li⁶⁰, Y. Li²⁰, Y. G. Li^{47,c}, Y. P. Li³⁵, Z. J. Li⁶⁰, Z. Y. Li⁸⁰, H. Liang^{73,59}, Y. F. Liang⁵⁵,
Y. T. Liang^{32,65}, G. R. Liao¹⁴, L. B. Liao⁶⁰, M. H. Liao⁶⁰, Y. P. Liao^{1,65}, J. Libby²⁷, A. Limphirat⁶¹, C. C. Lin⁵⁶,
D. X. Lin^{32,65}, L. Q. Lin⁴⁰, T. Lin¹, B. J. Liu¹, B. X. Liu⁷⁸, C. Liu³⁵, C. X. Liu¹, F. Liu¹, F. H. Liu⁵⁴,
Feng Liu⁶, G. M. Liu^{57,i}, H. Liu^{39,d,e}, H. B. Liu¹⁵, H. H. Liu¹, H. M. Liu^{1,65}, Huihui Liu²², J. B. Liu^{73,59},
J. J. Liu²¹, K. Liu^{39,d,e}, K. Liu⁷⁴, K. Y. Liu⁴¹, Ke Liu²³, L. C. Liu⁴⁴, Lu Liu⁴⁴, M. H. Liu^{12,f}, P. L. Liu¹,
Q. Liu⁶⁵, S. B. Liu^{73,59}, T. Liu^{12,f}, W. K. Liu⁴⁴, W. M. Liu^{73,59}, W. T. Liu⁴⁰, X. Liu^{39,d,e}, X. Liu⁴⁰,
X. K. Liu^{39,d,e}, X. L. Liu^{12,f}, X. Y. Liu⁷⁸, Y. Liu^{39,d,e}, Y. Liu⁸², Y. Liu⁸², Y. B. Liu⁴⁴, Z. A. Liu^{1,65,59},
Z. D. Liu⁹, Z. Q. Liu⁵¹, X. C. Lou^{1,65,59}, F. X. Lu⁶⁰, H. J. Lu²⁴, J. G. Lu^{1,59}, X. L. Lu¹⁶, Y. Lu⁷, Y. H. Lu^{1,65},
Y. P. Lu^{1,59}, Z. H. Lu^{1,65}, C. L. Luo⁴², J. R. Luo⁶⁰, J. S. Luo^{1,65}, M. X. Luo⁸¹, T. Luo^{12,f}, X. L. Luo^{1,59},
Z. Y. Lv²³, X. R. Lyu^{65,j}, Y. F. Lyu⁴⁴, Y. H. Lyu⁸², F. C. Ma⁴¹, H. L. Ma¹, J. L. Ma^{1,65}, L. L. Ma⁵¹, L. R. Ma⁶⁸,
Q. M. Ma¹, R. Q. Ma^{1,65}, R. Y. Ma²⁰, T. Ma^{73,59}, X. T. Ma^{1,65}, X. Y. Ma^{1,59}, Y. M. Ma³², F. E. Maas¹⁹,
I. MacKay⁷¹, M. Maggiora^{76a,76c}, S. Malde⁷¹, Q. A. Malik⁷⁵, H. X. Mao^{39,d,e}, Y. J. Mao^{47,c}, Z. P. Mao¹,
S. Marcello^{76a,76c}, A. Marshall⁶⁴, F. M. Melendi^{30a,30b}, Y. H. Meng⁶⁵, Z. X. Meng⁶⁸, G. Mezzadri^{30a},
H. Miao^{1,65}, T. J. Min⁴³, R. E. Mitchell²⁸, X. H. Mo^{1,65,59}, B. Moses²⁸, N. Yu. Muchnoi^{4,b}, J. Muskalla³⁶,
Y. Nefedov³⁷, F. Nerling^{19,k}, L. S. Nie²¹, I. B. Nikolaev^{4,b}, Z. Ning^{1,59}, S. Nisar^{11,l}, Q. L. Niu^{39,d,e}, W. D. Niu^{12,f},
C. Normand⁶⁴, S. L. Olsen^{10,65}, Q. Ouyang^{1,65,59}, S. Pacetti^{29b,29c}, X. Pan⁵⁶, Y. Pan⁵⁸, A. Pathak¹⁰,
Y. P. Pei^{73,59}, M. Pelizaeus³, H. P. Peng^{73,59}, X. J. Peng^{39,d,e}, Y. Y. Peng^{39,d,e}, K. Peters^{13,k}, K. Petridis⁶⁴

J. L. Ping⁴², R. G. Ping^{1,65}, S. Plura³⁶, V. Prasad³⁵, F. Z. Qi¹, H. R. Qi⁶², M. Qi⁴³, S. Qian^{1,59}, W. B. Qian⁶⁵, C. F. Qiao⁶⁵, J. H. Qiao²⁰, J. J. Qin⁷⁴, J. L. Qin⁵⁶, L. Q. Qin¹⁴, L. Y. Qin^{73,59}, P. B. Qin⁷⁴, X. P. Qin^{12,f}, X. S. Qin⁵¹, Z. H. Qin^{1,59}, J. F. Qiu¹, Z. H. Qu⁷⁴, J. Rademacker⁶⁴, C. F. Redmer³⁶, A. Rivetti^{76c}, M. Rolo^{76c}, G. Rong^{1,65}, S. S. Rong^{1,65}, F. Rosini^{29b,29c}, Ch. Rosner¹⁹, M. Q. Ruan^{1,59}, N. Salone⁴⁵, A. Sarantsev^{37,m}, Y. Schelhaas³⁶, K. Schoenning⁷⁷, M. Scodeggio^{30a}, K. Y. Shan^{12,f}, W. Shan²⁵, X. Y. Shan^{73,59}, Z. J. Shang^{39,d,e}, J. F. Shangguan¹⁷, L. G. Shao^{1,65}, M. Shao^{73,59}, C. P. Shen^{12,f}, H. F. Shen^{1,8}, W. H. Shen⁶⁵, X. Y. Shen^{1,65}, B. A. Shi⁶⁵, H. Shi^{73,59}, J. L. Shi^{12,f}, J. Y. Shi¹, S. Y. Shi⁷⁴, X. Shi^{1,59}, H. L. Song^{73,59}, J. J. Song²⁰, T. Z. Song⁶⁰, W. M. Song³⁵, Y. J. Song^{12,f}, Y. X. Song^{47,c,n}, S. Sosio^{76a,76c}, S. Spataro^{76a,76c}, F. Stielor³⁶, S. S. Su⁴¹, Y. J. Su⁶⁵, G. B. Sun⁷⁸, G. X. Sun¹, H. Sun⁶⁵, H. K. Sun¹, J. F. Sun²⁰, K. Sun⁶², L. Sun⁷⁸, S. S. Sun^{1,65}, T. Sun^{52,o}, Y. C. Sun⁷⁸, Y. H. Sun³¹, Y. J. Sun^{73,59}, Y. Z. Sun¹, Z. Q. Sun^{1,65}, Z. T. Sun⁵¹, C. J. Tang⁵⁵, G. Y. Tang¹, J. Tang⁶⁰, J. J. Tang^{73,59}, L. F. Tang⁴⁰, Y. A. Tang⁷⁸, L. Y. Tao⁷⁴, M. Tat⁷¹, J. X. Teng^{73,59}, J. Y. Tian^{73,59}, W. H. Tian⁶⁰, Y. Tian³², Z. F. Tian⁷⁸, I. Uman^{63b}, B. Wang¹, B. Wang⁶⁰, Bo Wang^{73,59}, C. Wang^{39,d,e}, C. Wang²⁰, Cong Wang²³, D. Y. Wang^{47,c}, H. J. Wang^{39,d,e}, J. J. Wang⁷⁸, K. Wang^{1,59}, L. L. Wang¹, L. W. Wang³⁵, M. Wang⁵¹, M. Wang^{73,59}, N. Y. Wang⁶⁵, S. Wang^{12,f}, T. Wang^{12,f}, T. J. Wang⁴⁴, W. Wang⁶⁰, W. Wang⁷⁴, W. P. Wang^{36,73,59,p}, X. Wang^{47,c}, X. F. Wang^{39,d,e}, X. J. Wang⁴⁰, X. L. Wang^{12,f}, X. N. Wang¹, Y. Wang⁶², Y. D. Wang⁴⁶, Y. F. Wang^{1,8,65}, Y. H. Wang^{39,d,e}, Y. J. Wang^{73,59}, Y. L. Wang²⁰, Y. N. Wang⁷⁸, Y. Q. Wang¹, Yaqian Wang¹⁸, Yuan Wang^{18,32}, Z. Wang^{1,59}, Z. L. Wang², Z. Q. Wang^{12,f}, Z. Y. Wang^{1,65}, D. H. Wei¹⁴, H. R. Wei⁴⁴, F. Weidner⁷⁰, S. P. Wen¹, Y. R. Wen⁴⁰, U. Wiedner³, G. Wilkinson⁷¹, M. Wolke⁷⁷, C. Wu⁴⁰, J. F. Wu^{1,8}, L. H. Wu¹, L. J. Wu²⁰, Lianjie Wu²⁰, S. G. Wu^{1,65}, S. M. Wu⁶⁵, X. Wu^{12,f}, X. H. Wu³⁵, Y. J. Wu³², Z. Wu^{1,59}, L. Xia^{73,59}, X. M. Xian⁴⁰, B. H. Xiang^{1,65}, D. Xiao^{39,d,e}, G. Y. Xiao⁴³, H. Xiao⁷⁴, Y. L. Xiao^{12,f}, Z. J. Xiao⁴², C. Xie⁴³, K. J. Xie^{1,65}, X. H. Xie^{47,c}, Y. Xie⁵¹, Y. G. Xie^{1,59}, Y. H. Xie⁶, Z. P. Xie^{73,59}, T. Y. Xing^{1,65}, C. F. Xu^{1,65}, C. J. Xu⁶⁰, G. F. Xu¹, H. Y. Xu², M. Xu^{73,59}, Q. J. Xu¹⁷, Q. N. Xu³¹, T. D. Xu⁷⁴, W. Xu¹, W. L. Xu⁶⁸, X. P. Xu⁵⁶, Y. Xu^{12,f}, Y. C. Xu⁷⁹, Z. S. Xu⁶⁵, F. Yan^{12,f}, H. Y. Yan⁴⁰, L. Yan^{12,f}, W. B. Yan^{73,59}, W. C. Yan⁸², W. H. Yan⁶, W. P. Yan²⁰, X. Q. Yan^{1,65}, H. J. Yang^{52,o}, H. L. Yang³⁵, H. X. Yang¹, J. H. Yang⁴³, R. J. Yang²⁰, T. Yang¹, Y. Yang^{12,f}, Y. F. Yang⁴⁴, Y. H. Yang⁴³, Y. Q. Yang⁹, Y. X. Yang^{1,65}, Y. Z. Yang²⁰, M. Ye^{1,59}, M. H. Ye^{8,a}, Z. J. Ye^{57,i}, Junhao Yin⁴⁴, Z. Y. You⁶⁰, B. X. Yu^{1,65,59}, C. X. Yu⁴⁴, G. Yu¹³, J. S. Yu^{26,g}, L. Q. Yu^{12,f}, M. C. Yu⁴¹, T. Yu⁷⁴, X. D. Yu^{47,c}, Y. C. Yu⁸², C. Z. Yuan^{1,65}, H. Yuan^{1,65}, J. Yuan³⁵, J. Yuan⁴⁶, L. Yuan², S. C. Yuan^{1,65}, X. Q. Yuan¹, Y. Yuan^{1,65}, Z. Y. Yuan⁶⁰, C. X. Yue⁴⁰, Ying Yue²⁰, A. A. Zafar⁷⁵, S. H. Zeng⁶⁴, X. Zeng^{12,f}, Y. Zeng^{26,g}, Y. J. Zeng⁶⁰, Y. J. Zeng^{1,65}, X. Y. Zhai³⁵, Y. H. Zhan⁶⁰, A. Q. Zhang^{1,65}, B. L. Zhang^{1,65}, B. X. Zhang¹, D. H. Zhang⁴⁴, G. Y. Zhang²⁰, G. Y. Zhang^{1,65}, H. Zhang^{73,59}, H. Zhang⁸², H. C. Zhang^{1,65,59}, H. H. Zhang⁶⁰, H. Q. Zhang^{1,65,59}, H. R. Zhang^{73,59}, H. Y. Zhang^{1,59}, J. Zhang⁸², J. Zhang⁶⁰, J. J. Zhang⁵³, J. L. Zhang²¹, J. Q. Zhang⁴², J. S. Zhang^{12,f}, J. W. Zhang^{1,65,59}, J. X. Zhang^{39,d,e}, J. Y. Zhang¹, J. Z. Zhang^{1,65}, Jianyu Zhang⁶⁵, L. M. Zhang⁶², Lei Zhang⁴³, N. Zhang⁸², P. Zhang^{1,8}, Q. Zhang²⁰, Q. Y. Zhang³⁵, R. Y. Zhang^{39,d,e}, S. H. Zhang^{1,65}, Shulei Zhang^{26,g}, X. M. Zhang¹, X. Y. Zhang⁴¹, X. Y. Zhang⁵¹, Y. Zhang¹, Y. Zhang⁷⁴, Y. T. Zhang⁸², Y. H. Zhang^{1,59}, Y. M. Zhang⁴⁰, Y. P. Zhang^{73,59}, Z. D. Zhang¹, Z. H. Zhang¹, Z. L. Zhang³⁵, Z. L. Zhang⁵⁶, Z. X. Zhang²⁰, Z. Y. Zhang⁷⁸, Z. Y. Zhang⁴⁴, Z. Z. Zhang⁴⁶, Zh. Zh. Zhang²⁰, G. Zhao¹, J. Y. Zhao^{1,65}, J. Z. Zhao^{1,59}, L. Zhao¹, L. Zhao^{73,59}, M. G. Zhao⁴⁴, N. Zhao⁸⁰, R. P. Zhao⁶⁵, S. J. Zhao⁸², Y. B. Zhao^{1,59}, Y. L. Zhao⁵⁶, Y. X. Zhao^{32,65}, Z. G. Zhao^{73,59}, A. Zhemchugov^{37,h}, B. Zheng⁷⁴, B. M. Zheng³⁵, J. P. Zheng^{1,59}, W. J. Zheng^{1,65}, X. R. Zheng²⁰, Y. H. Zheng^{65,j}, B. Zhong⁴², C. Zhong²⁰, H. Zhou^{36,51,p}, J. Q. Zhou³⁵, J. Y. Zhou³⁵, S. Zhou⁶, X. Zhou⁷⁸, X. K. Zhou⁶, X. R. Zhou^{73,59}, X. Y. Zhou⁴⁰, Y. X. Zhou⁷⁹, Y. Z. Zhou^{12,f}, A. N. Zhu⁶⁵, J. Zhu⁴⁴, K. Zhu¹, K. J. Zhu^{1,65,59}, K. S. Zhu^{12,f}, L. Zhu³⁵, L. X. Zhu⁶⁵, S. H. Zhu⁷², T. J. Zhu^{12,f}, W. D. Zhu^{12,f}, W. J. Zhu¹, W. Z. Zhu²⁰, Y. C. Zhu^{73,59}, Z. A. Zhu^{1,65}, X. Y. Zhuang⁴⁴, J. H. Zou¹, and J. Zu^{73,59}

(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*Bochum Ruhr-University, D-44780 Bochum, Germany*
- ⁴*Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*
- 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*China University of Geosciences, Wuhan 430074, People's Republic of China*
- ¹⁰*Chung-Ang University, Seoul, 06974, Republic of Korea*
- ¹¹*COMSATS University Islamabad,
Lahore Campus, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan*
- ¹²*Fudan University, Shanghai 200433, People's Republic of China*
- ¹³*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*
- ¹⁴*Guangxi Normal University, Guilin 541004, People's Republic of China*
- ¹⁵*Guangxi University, Nanning 530004, People's Republic of China*
- ¹⁶*Guangxi University of Science and Technology, Liuzhou 545006, People's Republic of China*
- ¹⁷*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*
- ¹⁸*Hebei University, Baoding 071002, People's Republic of China*
- ¹⁹*Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany*
- ²⁰*Henan Normal University, Xinxian 453007, People's Republic of China*
- ²¹*Henan University, Kaifeng 475004, People's Republic of China*
- ²²*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*
- ²³*Henan University of Technology, Zhengzhou 450001, People's Republic of China*
- ²⁴*Huangshan College, Huangshan 245000, People's Republic of China*
- ²⁵*Hunan Normal University, Changsha 410081, People's Republic of China*
- ²⁶*Hunan University, Changsha 410082, People's Republic of China*
- ²⁷*Indian Institute of Technology Madras, Chennai 600036, India*
- ²⁸*Indiana University, Bloomington, Indiana 47405, USA*
- ^{29a}*INFN Laboratori Nazionali di Frascati, INFN Laboratori Nazionali di Frascati,
I-00044, Frascati, Italy;*
- ^{29b}*INFN Laboratori Nazionali di Frascati, INFN Sezione di Perugia, I-06100, Perugia, Italy;*
- ^{29c}*INFN Laboratori Nazionali di Frascati, University of Perugia, I-06100, Perugia, Italy*
- ^{30a}*INFN Sezione di Ferrara, INFN Sezione di Ferrara, I-44122, Ferrara, Italy;*
- ^{30b}*INFN Sezione di Ferrara, University of Ferrara, I-44122, Ferrara, Italy*
- ³¹*Inner Mongolia University, Hohhot 010021, People's Republic of China*
- ³²*Institute of Modern Physics, Lanzhou 730000, People's Republic of China*
- ³³*Institute of Physics and Technology, Mongolian Academy of Sciences,
Peace Avenue 54B, Ulaanbaatar 13330, Mongolia*
- ³⁴*Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile*
- ³⁵*Jilin University, Changchun 130012, People's Republic of China*
- ³⁶*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*
- ³⁷*Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*
- ³⁸*Justus-Liebig-Universitaet Giessen,
II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*
- ³⁹*Lanzhou University, Lanzhou 730000, People's Republic of China*
- ⁴⁰*Liaoning Normal University, Dalian 116029, People's Republic of China*
- ⁴¹*Liaoning University, Shenyang 110036, People's Republic of China*
- ⁴²*Nanjing Normal University, Nanjing 210023, People's Republic of China*
- ⁴³*Nanjing University, Nanjing 210093, People's Republic of China*
- ⁴⁴*Nankai University, Tianjin 300071, People's Republic of China*
- ⁴⁵*National Centre for Nuclear Research, Warsaw 02-093, Poland*
- ⁴⁶*North China Electric Power University, Beijing 102206, People's Republic of China*
- ⁴⁷*Peking University, Beijing 100871, People's Republic of China*
- ⁴⁸*Qufu Normal University, Qufu 273165, People's Republic of China*
- ⁴⁹*Renmin University of China, Beijing 100872, People's Republic of China*
- ⁵⁰*Shandong Normal University, Jinan 250014, People's Republic of China*
- ⁵¹*Shandong University, Jinan 250100, People's Republic of China*
- ⁵²*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*

- ⁵³*Shanxi Normal University, Linfen 041004, People's Republic of China*
⁵⁴*Shanxi University, Taiyuan 030006, People's Republic of China*
⁵⁵*Sichuan University, Chengdu 610064, People's Republic of China*
⁵⁶*Soochow University, Suzhou 215006, People's Republic of China*
⁵⁷*South China Normal University, Guangzhou 510006, People's Republic of China*
⁵⁸*Southeast University, Nanjing 211100, People's Republic of China*
⁵⁹*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
⁶⁰*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
⁶¹*Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand*
⁶²*Tsinghua University, Beijing 100084, People's Republic of China*
^{63a}*Turkish Accelerator Center Particle Factory Group, Istinye University, 34010, Istanbul, Turkey;*
^{63b}*Turkish Accelerator Center Particle Factory Group, Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey*
⁶⁴*University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom*
⁶⁵*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
⁶⁶*University of Groningen, NL-9747 AA Groningen, The Netherlands*
⁶⁷*University of Hawaii, Honolulu, Hawaii 96822, USA*
⁶⁸*University of Jinan, Jinan 250022, People's Republic of China*
⁶⁹*University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*
⁷⁰*University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany*
⁷¹*University of Oxford, Keble Road, Oxford OX13RH, United Kingdom*
⁷²*University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
⁷³*University of Science and Technology of China, Hefei 230026, People's Republic of China*
⁷⁴*University of South China, Hengyang 421001, People's Republic of China*
⁷⁵*University of the Punjab, Lahore-54590, Pakistan*
^{76a}*University of Turin and INFN, University of Turin, I-10125, Turin, Italy;*
^{76b}*University of Turin and INFN, University of Eastern Piedmont, I-15121, Alessandria, Italy;*
^{76c}*University of Turin and INFN, INFN, I-10125, Turin, Italy*
⁷⁷*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
⁷⁸*Wuhan University, Wuhan 430072, People's Republic of China*
⁷⁹*Yantai University, Yantai 264005, People's Republic of China*
⁸⁰*Yunnan University, Kunming 650500, People's Republic of China*
⁸¹*Zhejiang University, Hangzhou 310027, People's Republic of China*
⁸²*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

^aDeceased.

^bAlso at the Novosibirsk State University, Novosibirsk, 630090, Russia.

^cAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China.

^dAlso at MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, People's Republic of China.

^eAlso at Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, People's Republic of China.

^fAlso at Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443, People's Republic of China.

^gAlso at School of Physics and Electronics, Hunan University, Changsha 410082, China.

^hAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.

ⁱAlso at Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China.

^jAlso at Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China.

^kAlso at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.

^lAlso at the Department of Mathematical Sciences, IBA, Karachi 75270, Pakistan.

^mAlso at the NRC "Kurchatov Institute," PNPI, 188300, Gatchina, Russia.

ⁿAlso at Ecole Polytechnique Federale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

^oAlso at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China.

^pAlso at Helmholtz Institute Mainz, Staudinger Weg 18, D-55099 Mainz, Germany.