

Search for $\psi_0(4360) \rightarrow \eta\psi(2S)$ through the process $e^+e^- \rightarrow \eta\eta\psi(2S)$ M. Ablikim *et al.*^{*}
(BESIII Collaboration)

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Using data samples corresponding to an integrated luminosity of 0.9 fb^{-1} collected with the BESIII detector operating at the BEPCII storage ring at the center-of-mass energies of 4.84, 4.92, and 4.95 GeV, we search for the exotic charmoniumlike state with quantum numbers $J^{PC} = 0^{--}$, $\psi_0(4360)$, in the process $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$. No significant signal of the $\psi_0(4360)$ resonance state is observed. Upper limits on $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) \cdot \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$ and $\sigma(e^+e^- \rightarrow \eta\eta\psi(2S))$ at the 90% confidence level are determined for each energy point.

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I. INTRODUCTION

Since the discovery of the $X(3872)$ [1], many charmoniumlike states, including the $Y(4260)$, $Y(4660)$, $T_{c\bar{c}1}(3900)$, and $T_{c\bar{c}}(4020)$ states, have been observed by the BABAR [2], Belle [3], and BESIII experiments [4,5]. They exhibit unconventional properties that are difficult to accommodate within the framework of the conventional quark model [6]. These states are collectively referred to as XYZ particles and regarded as promising candidates for exotic hadronic states. A wide range of theoretical interpretations have been proposed, including compact tetraquarks [7,8], hadronic molecules [9–12], hybrids [13–17], hadrocharmonium states [18,19], and admixtures of the conventional quarkonium and the hadronic molecule [20].

Among the various XYZ states observed in experiment, the vector charmoniumlike states with $J^{PC} = 1^{--}$ (known as Y states) have attracted particular attention. In addition to the three well-established charmonium states $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, several other experimentally observed states, such as $Y(4260)$, overpopulate the conventional charmonium spectrum above the open-charm threshold predicted by potential model [21]. The $Y(4260)$ state was discovered via the process $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ by the BABAR experiment [2] using the initial-state radiation (ISR) process and was subsequently confirmed by the CLEO [22] and Belle experiments [23]. The BESIII Collaboration performed a dedicated scan on the process $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ [24] and found two structures $Y(4230)$

[also known as $\psi(4230)$] and $Y(4360)$ [also known as $\psi(4360)$]. Furthermore, structures similar to the $\psi(4230)$ and $\psi(4360)$ have been observed in various processes [25–35]. However, the parameters of these two resonances, as measured in different processes, are in tension with each other [36]. Despite the diversity of proposed interpretations, including hybrid [13–15], hadrocharmonium [18,19], conventional charmonium [37,38], and bound systems [39], the hadronic molecular picture provides a compelling framework. Within this picture, the $\psi(4230)$, $\psi(4360)$, and $\psi(4415)$ can be understood as molecular configurations dominated by the $D\bar{D}_1$, $D\bar{D}_1(2420)$, and $D\bar{D}_2$ components, respectively [11,40–44].

Recently, based on the molecular scenarios, an exotic charmoniumlike state with quantum numbers $J^{PC} = 0^{--}$, denoted as $\psi_0(4360)$ [45], has been predicted as a bound system of $D^*\bar{D}_1(2420)$. The mass and width of this state are predicted to be $(4366 \pm 18) \text{ MeV}/c^2$ and less than 10 MeV, respectively. It can be searched for in the process $e^+e^- \rightarrow \eta\psi_0(4360)$ and distinguished from 1^{--} charmonium vector states by the distinctly different angular distribution of the outgoing η meson. Observation of a 0^{--} molecule would play a crucial role in inferring the internal structure of the vector mesons in the mass range between 4.2 and 4.5 GeV/c^2 and in understanding the nature of other exotic hadronic states, such as Z_c [4,5,46] and P_c [47,48] states.

In this analysis, we search for the processes $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$ using data samples collected at three center-of-mass (c.m.) energies ($\sqrt{s}$): 4.84, 4.92, and 4.95 GeV, corresponding to a total integrated luminosity of 0.9 fb^{-1} . This analysis is performed using a partial reconstruction method, where one η is reconstructed via its decay to $\gamma\gamma$, while the other η is left unreconstructed and treated inclusively. The $\psi(2S)$ candidate is reconstructed with $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, where J/ψ is reconstructed by its leptonic decays, $J/\psi \rightarrow e^+e^-$ and

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

$J/\psi \rightarrow \mu^+\mu^-$, referred to as the ee -mode and $\mu\mu$ -mode, respectively.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector [49] records symmetric e^+e^- collisions provided by the BEPCII storage ring [50] in the c.m. 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 $\sqrt{s} = 3.773 \text{ GeV}$. BESIII has collected large data samples in this energy region [51]. 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 (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 solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules muon counter (MUC) 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 plastic scintillator 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 all data used in this analysis [52–54].

Monte Carlo (MC) simulated samples produced with Geant4-based [55] software, 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 ISR in the e^+e^- annihilations with the generator KKMC [56]. The inclusive MC sample includes the production of open-charm processes, the ISR production of vector charmonium(like) states, and the continuum processes incorporated in KKMC [56]. All particle decays are modeled with EvtGen [57] using branching fractions either taken from the Particle Data Group (PDG) [58], when available, or otherwise estimated with Lundcharm [59,60]. Final-state radiation from charged final-state particles is incorporated using Photos [61].

Signal MC samples for the process $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$ are generated considering a cascade two-body P-wave process. The angular distribution of the cascade products follows a $1 - \cos^2 \theta$ dependence at each c.m. energy. The mass and width of $\psi_0(4360)$ are set to be 4366 MeV/ c^2 and 10 MeV, respectively, based on the prediction [45]. MC samples for the process $e^+e^- \rightarrow \eta\eta\psi(2S)$ without a $\psi_0(4360)$ intermediate state are generated using a phase-space (PHSP) model at each c.m. energy. To reproduce the physical process, η mesons are allowed to decay inclusively in the MC simulation according to their known branching fractions, while a partial

reconstruction strategy is adopted in the analysis, where one η meson is reconstructed via $\gamma\gamma$ and another η is not explicitly reconstructed. The decay $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ is generated by the vector to $\pi\pi$ vector model (JPIPI), and the subsequent decays $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ are processed by the vector to lepton pair model (VLL) with calling Photos [61] to take possible final-state radiation into account, where all the JPIPI, VLL, and Photos are included in the EvtGen program [57].

III. EVENT SELECTION

To improve the selection efficiency, a partial reconstruction method is used for the signal processes $e^+e^- \rightarrow \eta\eta\psi(2S)$ and $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$, where only one η decaying to two photons is selected. Candidate events are required to have four charged tracks with zero net charge and at least two photon candidates.

Charged tracks detected in the MDC are required to be within a polar angle (θ) range of $|\cos \theta| < 0.93$, where θ is defined with respect to the z -axis, which is the symmetry axis of the MDC. For each track, the distance of closest approach to the interaction point (IP) must be less than 10 cm along the z -axis, $|V_z|$, and less than 1 cm in the transverse plane, $|V_{xy}|$. The pions and the leptons from the $\psi(2S)$ and J/ψ decay are kinematically well separated. Tracks with momenta larger than 1.0 GeV/ c are assigned as leptons from the J/ψ decay; otherwise, they are identified as pions from the $\psi(2S)$ decay. The leptons ($\ell^+\ell^-$, $\ell = e$ or μ) from the J/ψ decay with energy deposited in the EMC larger than 1.0 GeV are identified as electrons, while those with less than 0.4 GeV are identified as muons.

Photon candidates are identified as isolated showers in the EMC. The deposited energy of each shower must be greater than 25 MeV in the barrel region ($|\cos \theta| < 0.80$) and greater than 50 MeV in the end-cap region ($0.86 < |\cos \theta| < 0.92$). To exclude showers that originate from charged tracks, the opening angle between the position vectors for the EMC shower and the closest charged track's incident point on the EMC inner surface, measured from the IP, must be greater than 10° . To suppress electronic noise and showers unrelated to the event, the difference between the EMC time and the event start time is required to be within $[0, 700] \text{ ns}$.

In order to improve the mass resolution, a one-constraint (1C) kinematic fit is performed by constraining the η candidate reconstructed from a $\gamma\gamma$ pair to its nominal mass [58]. The other η decays inclusively and is not reconstructed, but is instead treated as a missing particle. To further suppress background contributions, the invariant mass of the $\gamma\gamma$ pair before the 1C kinematic fit is required to be within the range of $[499.5, 576.9] \text{ MeV}/c^2$. This mass window is optimized using the Punzi figure of merit

(FOM) [62], defined as $\epsilon/(1.5 + \sqrt{B})$, where ϵ is the signal efficiency obtained from the signal MC samples and B is the number of background events estimated from the dominant background process $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$ discussed in Sec. IV. If there is more than one combination in an event, the one with minimum χ^2 of 1C kinematic fit (χ^2_{1C}) value is retained. For the $\mu\mu$ -mode, we require at least one muon candidate to have a hit depth in the MUC greater than 30 cm to suppress the pion-to-muon misidentification.

For the two η candidates in this analysis, the η reconstructed from $\gamma\gamma$ is denoted as η_1 , while η_2 refers to the particle treated inclusively. The mass of η_2 is determined from the recoil against the selected $\eta_1\psi(2S)$ system after the 1C kinematic fit, defined as $M_{\eta_1\psi(2S)}^{\text{recoil}} = \sqrt{(\sqrt{s} - E_{\eta_1\psi(2S)})^2 - |\vec{p}_{\eta_1\psi(2S)}|^2}$, where $E_{\eta_1\psi(2S)}$ and $\vec{p}_{\eta_1\psi(2S)}$ are the energy and momentum of the selected $\eta_1\psi(2S)$ candidate in the c.m. system, respectively. To reduce the impact of detector resolution on $M(\ell^+\ell^-)$, the corrected mass of η_2 is obtained as $M(\eta_2) = M_{\eta_1\psi(2S)}^{\text{recoil}} + M(\ell^+\ell^-) - M(J/\psi)$, where $M(J/\psi)$ denotes the nominal masses of the J/ψ from the PDG [58], and $M(\ell^+\ell^-)$ is the invariant mass of the lepton pair. A similar correction is applied to the invariant mass of $\pi^+\pi^-J/\psi$, which is defined as $M(\pi^+\pi^-J/\psi) = M(\pi^+\pi^-\ell^+\ell^-) + M(\ell^+\ell^-) - M(J/\psi)$, in order to reduce the detector resolution effect originating from $M(\ell^+\ell^-)$.

The signal region for η_2 states is defined as [516.3, 579.5] MeV/ c^2 , which is optimized using the Punzi FOM [62] in the same way as for the η_1 candidate. The invariant mass of the lepton pair $M(\ell^+\ell^-)$ is required to lie within [3040.0, 3140.8] MeV/ c^2 , which is also optimized using the Punzi FOM [62] following the same method as for the η candidates, to identify the J/ψ . The $\psi(2S)$ signal region is determined from the signal MC as $\pm 3\sigma$ (where σ is the mass resolution) around the nominal mass value, corresponding to the range [3678.3, 3693.5] MeV/ c^2 .

IV. BORN CROSS SECTION MEASUREMENT

A. $e^+e^- \rightarrow \eta\eta\psi(2S)$

After applying the above requirements, the remaining background is mainly from $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$ events. The number of expected background events in the $\psi(2S)$ signal region is estimated using

$$N_{\text{bkg}} = \mathcal{L}(1 + \delta_{\text{ISR}}^{\text{bkg}})(1 + \delta_{\text{VP}})\epsilon_{\text{bkg}}\mathcal{B}_{\text{bkg}}\sigma_{\text{bkg}}, \quad (1)$$

where σ_{bkg} is the measured Born cross section of $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$ [63], $\mathcal{L}$ is the integrated luminosity at each energy point, ϵ_{bkg} represents the detection efficiency of the background process after applying the signal selection, and $\mathcal{B}_{\text{bkg}}$ is the product of branching fraction of the intermediate states taken from the PDG [58]. The factor $(1 + \delta_{\text{ISR}}^{\text{bkg}})$ accounts for the ISR correction quoted from Ref. [63], and $(1 + \delta_{\text{VP}})$ is the vacuum polarization (VP) correction factor [64], which depends only on the c.m. energy and is therefore universal for all processes. The numbers of background events are estimated to be 0.10, 0.05, and 0.02 at the three energy points.

Figure 1 presents the distributions of the η_2 and $\pi^+\pi^-J/\psi$ invariant masses for the process $e^+e^- \rightarrow \eta\eta\psi(2S)$ for the combined datasets. No significant $\psi(2S)$ signal is observed. The signal yield (N_{sig}) is obtained by subtracting the estimated background from the observed number of events in the $\psi(2S)$ signal region, i.e. $N_{\text{sig}} = N_{\text{obs}} - N_{\text{bkg}}$. The upper limits on the numbers of signal events are calculated at the 90% confidence level (CL) using a frequentist method. This method, described in Ref. [65], incorporates an unbounded profile-likelihood treatment for multiplicative systematic uncertainties and is implemented via TROLKE [66] within the ROOT framework [67], where the numbers of signal and background events follow Poisson statistics and the efficiencies are modeled with Gaussian distributions.

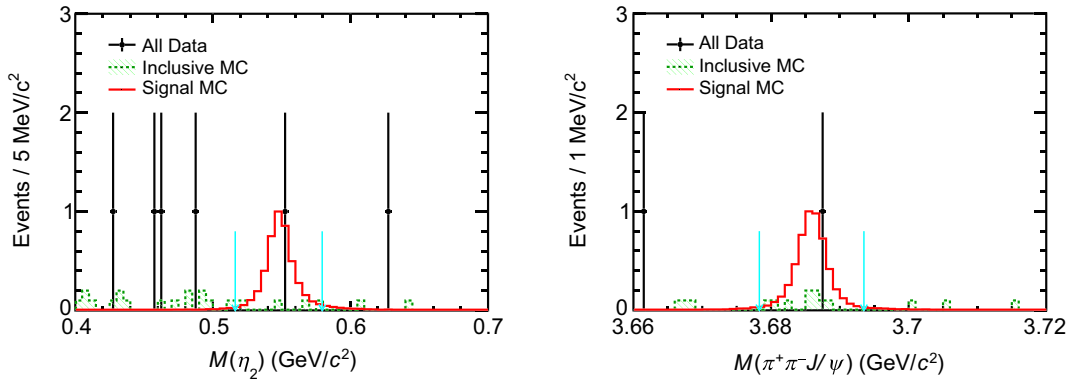


FIG. 1. Distributions of $M(\eta_2)$ and $M(\pi^+\pi^-J/\psi)$ combined from all c.m. energies. The black dots with error bars denote the real data, the green dashed histograms denote the inclusive MC simulation, and the red histograms correspond to the signal MC simulation of $e^+e^- \rightarrow \eta\eta\psi(2S)$. The blue vertical lines indicate the signal regions of η_2 and $\psi(2S)$.

TABLE I. Numerical results for the process $e^+e^- \rightarrow \eta\eta\psi(2S)$ at each c.m. energy, where $\sqrt{s}$ is the c.m. energy, $\mathcal{L}$ is integrated luminosity, N_{obs} is the number of events in the $\psi(2S)$ signal region, N_{sig} is the calculated signal yield in the $\psi(2S)$ signal region, N^{UL} is the upper limit of signal yield at the 90% CL, $(1 + \delta_{\text{ISR}}^{\text{sig}})$ is the ISR correction factor, $(1 + \delta_{\text{VP}})$ is the vacuum polarization factor, ϵ is the detection efficiency, σ^{Born} is the Born cross section (first uncertainty statistical, second systematic), and σ^{UL} is the upper limit on σ^{Born} at the 90% CL after taking into account systematic uncertainty.

$\sqrt{s}$ (MeV)	$\mathcal{L}(\text{pb}^{-1})$	N_{obs}	N_{sig}	N^{UL}	$(1 + \delta_{\text{ISR}}^{\text{sig}})$	$(1 + \delta_{\text{VP}})$	$\epsilon(\%)$	σ^{Born} (pb)	σ^{UL} (pb)
4843.07	525.16	0	$0.0^{+1.0}_{-0.0}$	<2.0	0.706	1.056	10.7	$0.0^{+1.1}_{-0.0}$	<2.3
4918.02	207.82	0	$0.0^{+1.0}_{-0.0}$	<2.0	0.750	1.056	9.7	$0.0^{+2.9}_{-0.0}$	<6.0
4950.93	159.28	1	$1.0^{+1.4}_{-0.7}$	<3.6	0.762	1.056	9.5	$3.9^{+5.5}_{-2.7} \pm 0.2$	<15

The Born cross section of $e^+e^- \rightarrow \eta\eta\psi(2S)$ is calculated with

$$\sigma(e^+e^- \rightarrow \eta\eta\psi(2S)) = \frac{N_{\text{sig}}}{\mathcal{L}(1 + \delta_{\text{ISR}}^{\text{sig}})(1 + \delta_{\text{VP}})\mathcal{B}_{\psi(2S)}(\epsilon_e\mathcal{B}_e + \epsilon_\mu\mathcal{B}_\mu)}. \quad (2)$$

Here, N_{sig} is the number of signal events, $(1 + \delta_{\text{ISR}}^{\text{sig}})$ is the ISR correction factor obtained from a quantum electrodynamics calculation [68] using the KKMC generator [56], assuming that the cross section follows the line shape of a three-body PHSP model, and ϵ_e and ϵ_μ are the detection efficiencies for the ee -mode and $\mu\mu$ -mode from the signal MC simulation, respectively. $\mathcal{B}_{\psi(2S)}$ is the branching fraction for $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, and $\mathcal{B}_e$ and $\mathcal{B}_\mu$ are the branching fractions of the decays $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$, respectively. The numerical results for each data sample are listed in Table I.

B. $\psi_0(4360) \rightarrow \eta\psi(2S)$

A search for the charmoniumlike state $\psi_0(4360)$ is performed via the process $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$. Based on MC study, the η originating from $\psi_0(4360)$ has higher momentum than the η produced

directly from e^+e^- collision. Therefore, the $\psi_0(4360)$ candidate is reconstructed from the $\eta_h\psi(2S)$ system, where η_h denotes the higher-momentum candidate between η_1 and η_2 , and its mass is defined as $M(\eta_h\psi(2S))$. The $\psi_0(4360)$ signal region is chosen as $[4310.8, 4416.4]$ MeV/ c^2 , corresponding to $\pm 3\sigma$ around the $\psi_0(4360)$ nominal mass, where σ is the standard deviation. After applying the $\psi_0(4360)$ mass window requirement, no significant signal remains. The number of expected background events in $\psi_0(4360)$ signal region is also estimated with Eq. (1). The numbers of background events are estimated to be 0.05 and 0.02 at the two energy points. Figure 2 shows the $\eta_h\psi(2S)$ invariant mass distributions for data and MC samples of the processes $e^+e^- \rightarrow \eta\psi_0(4360)$ with $\psi_0(4360) \rightarrow \eta\psi(2S)$ at c.m. energies 4.92 and 4.95 GeV. No significant $\psi_0(4360)$ candidates are found. Therefore, the same method as previously described is employed to calculate upper limits on the numbers of signal events for these processes.

The product of the Born cross section and branching fraction, $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) \cdot \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$, at each c.m. energy is calculated using a similar equation as shown in Eq. (2). The ISR correction factor $(1 + \delta_{\text{ISR}})$ is obtained using the same method as the $e^+e^- \rightarrow \eta\eta\psi(2S)$ process, assuming the cross section follows the line shape of a P-wave two-body process. The numbers used in the

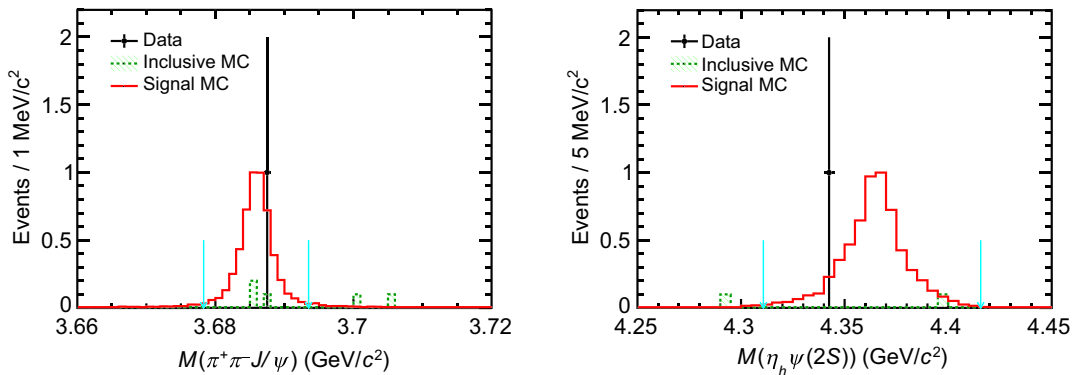


FIG. 2. Distributions of $M(\pi^+\pi^-J/\psi)$ and $M(\eta_h\psi(2S))$ at the c.m. energies of 4.92 and 4.95 GeV. The black dots with error bars denote data, the green dashed histograms denote the inclusive MC, and the red histograms denote the signal MC simulation of $e^+e^- \rightarrow \eta\psi_0(4360)$. The blue solid lines mark the signal regions of $\psi(2S)$ and $\psi_0(4360)$.

TABLE II. Numerical results for the process $e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi(2S)$ at each c.m. energy, where $\sqrt{s}$ is the c.m. energy, $\mathcal{L}$ is integrated luminosity, N^{UL} is the upper limit on the number of signal events at the 90% CL, $(1 + \delta_{\text{ISR}})$ is the ISR correction factor, $(1 + \delta_{\text{VP}})$ is the vacuum polarization factor, ϵ is the detection efficiency, $\sigma^{\text{UL}} \cdot \mathcal{B}$ is the upper limit on $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) \cdot \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$ at the 90% CL after taking into account systematic uncertainty.

$\sqrt{s}$ (MeV)	$\mathcal{L}(\text{pb}^{-1})$	N^{UL}	$(1 + \delta_{\text{ISR}}^{\text{sig}})$	$(1 + \delta_{\text{VP}})$	$\epsilon(\%)$	$\sigma^{\text{UL}} \cdot \mathcal{B}$ (pb)
4918.02	207.82	<2.0	0.676	1.056	9.6	<6.8
4950.93	159.28	<3.6	0.687	1.056	9.8	<16

calculation and corresponding upper limits at the 90% CL for each energy point are listed in Table II.

V. SYSTEMATIC UNCERTAINTY ESTIMATION

Systematic uncertainties in the cross section measurements of the processes $e^+e^- \rightarrow \eta\eta\psi(2S)$ and $e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi(2S)$ are from the luminosity measurement, the tracking of charged tracks, the photon detection, the 1C kinematic fit, the η , J/ψ and $\psi(2S)$ mass windows, the $\psi_0(4360)$ mass window, the input line shape, the generator model, the input branching fractions, and the background estimation. The systematic uncertainties related to $\sigma(e^+e^- \rightarrow \eta\eta\psi(2S))$ and $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) \cdot \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$ for each c.m. energy are summarized in Table III, where the total systematic uncertainty is calculated as a sum in quadrature of all sources of uncertainties, assuming they are independent.

The systematic uncertainties in the determination of the upper limits of the cross sections are classified as either additive or multiplicative terms. The additive uncertainties originate from the background estimation. The resulting

upper limits are determined, and the most conservative upper limit is taken as the final result. The multiplicative systematic uncertainties are considered in the calculations of the upper limits by using TROLKE.

The integrated luminosity is measured using Bhabha events with an uncertainty of 0.6% [69].

The uncertainty of the pion tracking is estimated to be 1.0% per pion based on the study of $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ [70]. The uncertainty of the tracking for high-momentum leptons is assigned to be 1.0% per track according to the study of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ with $J/\psi \rightarrow \ell^+\ell^-$ [71]. The total systematic uncertainty from the tracking of all charged tracks is assigned to be 4.0%.

The uncertainty due to the photon detection is determined by using the control sample of $J/\psi \rightarrow \rho^0\pi^0$ and found to be 1.0% per photon [72]. In this work, candidate events are required to have at least two photons, and only two good photon candidates are retained for further analysis. The probability of reconstructing two photons is estimated from the photon multiplicity distribution, and the corresponding systematic uncertainty associated with photon detection is determined to be 1.0%.

The uncertainty due to the kinematic fit is estimated by correcting the helix parameters of charged tracks according to the method described in Ref. [73]. The difference in detection efficiencies obtained from the MC samples with and without this correction is taken as the uncertainty.

The systematic uncertainty of the MUC selection is estimated with the control sample of $e^+e^- \rightarrow \mu^+\mu^-$ [74]. The difference in efficiencies between data and MC simulation, which is 1.1%, is taken as the systematic uncertainty.

The uncertainties for the selection of η , J/ψ and $\psi(2S)$ mass windows are estimated using the control sample of $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$, $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ at c.m. energies of 4.348, 4.377, and 4.416 GeV. The detection efficiency of the control samples at these three points is 8.5%, 8.0%, and 8.0%, respectively. And the signal yield in the $\psi(2S)$ signal region with statistical uncertainty is 113 ± 12 , 109 ± 12 , and 171 ± 15 , respectively. The $\psi(2S)$ is reconstructed in the final state of $\pi^+\pi^-J/\psi$ with $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$, and one π^0 is reconstructed from a photon pair, while the other π^0 is treated inclusively. The π^0 signal is fitted with a signal MC shape convolved with a Gaussian

TABLE III. Systematic uncertainties (in %) in the cross section measurements. The first values in brackets are for the process $e^+e^- \rightarrow \eta\eta\psi(2S)$, and the second are for the process $e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi(2S)$. Centered dots indicate that a systematic effect is not applicable.

Dataset	4.843	4.918	4.951
Integrated luminosity	(0.6, ...)	(0.6, 0.6)	(0.6, 0.6)
Tracking	(4.0, ...)	(4.0, 4.0)	(4.0, 4.0)
Photon detection	(1.0, ...)	(1.0, 1.0)	(1.0, 1.0)
1C kinematic fit	(1.0, ...)	(1.1, 0.9)	(0.7, 0.9)
MUC requirement	(1.1, ...)	(1.1, 1.1)	(1.1, 1.1)
η_1 mass window	(0.1, ...)	(0.1, 0.1)	(0.1, 0.1)
η_2 mass window	(0.1, ...)	(0.1, 0.1)	(0.1, 0.1)
J/ψ mass window	(0.3, ...)	(0.3, 0.3)	(0.3, 0.3)
$\psi(2S)$ mass window	(0.1, ...)	(0.1, 0.1)	(0.1, 0.1)
$\psi_0(4360)$ mass window	(..., ...)	(..., 5.4)	(..., 4.6)
ISR and generator	(2.8, ...)	(1.8, 1.8)	(1.4, 1.4)
MC statistics	(0.9, ...)	(0.9, 0.9)	(0.9, 0.9)
Branching fractions	(1.5, ...)	(1.5, 1.5)	(1.5, 1.5)
Background	(0.0, ...)	(0.0, 0.0)	(0.2, 0.2)
Sum	(5.5, ...)	(5.1, 7.4)	(4.9, 6.8)

function, whose parameters are left free in the fit. This allows the resolution difference between data and MC simulation to be determined. The resolution difference obtained for π^0 is assumed to be representative of that for η , as both are reconstructed via similar methods. The MC simulated shape of η is smeared with the Gaussian function to improve data-MC consistency. The resulting difference in selection efficiencies before and after smearing is taken as the systematic uncertainty associated with the η mass window requirement. The uncertainties for the J/ψ and $\psi(2S)$ mass windows are estimated using the same method.

The uncertainty from the $\psi_0(4360)$ mass window is estimated by varying the window boundaries by $\pm 1\sigma$, and the largest change in efficiency is taken as the uncertainty.

The systematic uncertainty associated with the ISR factor and MC generator models is considered simultaneously. The signal MC samples of the processes $e^+e^- \rightarrow \eta\eta\psi(2S)$ and $e^+e^- \rightarrow \eta\psi_0(4360)$ are generated using a three-body PHSP model and a P-wave two-body process, respectively. Since the production threshold for $\eta\psi_0(4360)$ lies above $\sqrt{s} = 4.84$ GeV, we consider two scenarios at this energy: the mass of the hypothetical charmoniumlike state (ψ_0) is set to 4234 and 4295 MeV/ c^2 , corresponding to the kinematic boundaries of the $\eta\psi_0$ system. For the other two c.m. energy points, we take the mass of $\psi_0(4360)$ as 4366 MeV/ c^2 . The largest difference in $(1 + \delta_{\text{ISR}}^{\text{sig}}) \times \epsilon$ between the two signal MC processes is taken as the uncertainty.

The uncertainty due to finite MC statistics is obtained by $\frac{1}{\sqrt{N}} \sqrt{\frac{(1-\epsilon)}{\epsilon}}$, where ϵ is the detection efficiency and N is the total number of the generated MC events. Given that we generate 100 000 MC events at each energy point, this corresponds to an uncertainty of approximately 0.9%.

The branching fractions quoted from the PDG [58] for $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow e^+e^-$, and $J/\psi \rightarrow \mu^+\mu^-$ are $(34.69 \pm 0.34)\%$, $(5.971 \pm 0.032)\%$, and $(5.961 \pm 0.033)\%$, respectively. Since we generate signal MC events allowing both η 's to decay inclusively, the uncertainty from the branching fraction of $\eta \rightarrow \gamma\gamma$ $[(39.36 \pm 0.18)\%]$ is also included. The sum in quadrature of the individual contributions, 1.5%, is assigned as the total systematic uncertainty due to the quoted branching fractions.

The number of expected background events is estimated according to the measured cross sections using Eq. (1). The cross sections for the background processes are increased by their corresponding uncertainties, and the corresponding change in the signal yield is computed. The difference of the signal cross sections due to this change is taken as the uncertainty of the background estimation.

VI. SUMMARY

In summary, the process $e^+e^- \rightarrow \eta\eta\psi(2S)$ has been searched for using data at the c.m. energies of 4.84,

4.92, and 4.95 GeV. No significant signal is observed, and upper limits on $\sigma(e^+e^- \rightarrow \eta\eta\psi(2S))$ at the 90% CL are provided. The numerical results of cross sections are given in Table I. No 0^{--} molecular candidate $\psi_0(4360)$ is observed at the c.m. energies of 4.92 and 4.95 GeV. Upper limits on $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) \cdot \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$ at the 90% CL are provided in Table II. The threshold of $\eta\psi_0(4360)$ production is about 4.9 GeV; it may be highly suppressed at the current BESIII experiment due to the limited phase space. At the upcoming BEPCII-U upgrade [75], which has an energy up to 5.6 GeV and has a higher luminosity than the current BEPCII, the studies in this article can be further performed with higher energy and larger statistics data samples.

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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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M. Ablikim,¹ M. N. Achasov,^{4,e} P. Adlarson,⁸¹ X. C. Ai,⁸⁷ C. S. Akondi,^{31a,31b} R. Aliberti,³⁹ A. Amoroso,^{80a,80c} Q. An,^{77,64,a} Y. H. An,⁸⁷ Y. Bai,⁶² O. Bakina,⁴⁰ H.-R. Bao,⁷⁰ X. L. Bao,⁴⁹ M. Barbagiovanni,^{80c} V. Batzskaya,^{1,48} K. Begzsuren,³⁵ N. Berger,³⁹ M. Berlowski,⁴⁸ M. B. Bertani,^{30a} D. Bettoni,^{31a} F. Bianchi,^{80a,80c} E. Bianco,^{80a,80c} A. Bortone,^{80a,80c} I. Boyko,⁴⁰ R. A. Briere,⁵ A. Brueggemann,⁷⁴ D. Cabiati,^{80a,80c} H. Cai,⁸² M. H. Cai,^{42,m,n} X. Cai,^{1,64} A. Calcaterra,^{30a} G. F. Cao,^{1,70} N. Cao,^{1,70} S. A. Cetin,^{68a} X. Y. Chai,^{50,j} J. F. Chang,^{1,64} T. T. Chang,⁴⁷ G. R. Che,⁴⁷ Y. Z. Che,^{1,64,70} C. H. Chen,¹⁰ Chao Chen,¹ G. Chen,¹ H. S. Chen,^{1,70} H. Y. Chen,²⁰ M. L. Chen,^{1,64,70} S. J. Chen,⁴⁶ S. M. Chen,⁶⁷ T. Chen,^{1,70} W. Chen,⁴⁹ X. R. Chen,^{34,70} X. T. Chen,^{1,70} X. Y. Chen,^{12,i} Y. B. Chen,^{1,64} Y. Q. Chen,¹⁶ Z. K. Chen,⁶⁵ J. Cheng,⁴⁹ L. N. Cheng,⁴⁷ S. K. Choi,¹¹ X. Chu,^{12,j} G. Cibinetto,^{31a} F. Cossio,^{80c} J. Cotte-Meldrum,⁶⁹ H. L. Dai,^{1,64} J. P. Dai,⁸⁵ X. C. Dai,⁶⁷ A. Dbeyssi,¹⁹ R. E. de Boer,³ D. Dedovich,⁴⁰ C. Q. Deng,⁷⁸ Z. Y. Deng,¹ A. Denig,³⁹ I. Denisenko,⁴⁰ M. Destefanis,^{80a,80c} F. De Mori,^{80a,80c} E. Di Fiore,^{31a,31b} X. X. Ding,^{50,j} Y. Ding,⁴⁴ Y. X. Ding,³² Yi. Ding,³⁸ J. Dong,^{1,64} L. Y. Dong,^{1,70} M. Y. Dong,^{1,64,70} X. Dong,⁸² M. C. Du,¹ S. X. Du,⁸⁷ Shaoxu Du,^{12,i} X. L. Du,^{12,i} Y. Q. Du,⁸² Y. Y. Duan,⁶⁰ Z. H. Duan,⁴⁶ P. Egorov,^{40,c} G. F. Fan,⁴⁶ J. J. Fan,²⁰ Y. H. Fan,⁴⁹ J. Fang,^{1,64} Jin Fang,⁶⁵ S. S. Fang,^{1,70} W. X. Fang,¹ Y. Q. Fang,^{1,64,a} L. Fava,^{80b,80c} F. Feldbauer,³ G. Felici,^{30a} C. Q. Feng,^{77,64} J. H. Feng,¹⁶ L. Feng,^{42,m,n} Q. X. Feng,^{42,m,n} Y. T. Feng,^{77,64} M. Fritsch,³ C. D. Fu,¹ J. L. Fu,⁷⁰ Y. W. Fu,^{1,70} H. Gao,⁷⁰ Y. Gao,^{77,64} Y. N. Gao,^{50,j} Y. Y. Gao,³² Yunong Gao,²⁰ Z. Gao,⁴⁷ S. Garbolino,^{80c} I. Garzia,^{31a,31b} L. Ge,⁶² P. T. Ge,²⁰ Z. W. Ge,⁴⁶ C. Geng,⁶⁵ E. M. Gersabeck,⁷³ A. Gilman,⁷⁵ K. Goetzen,¹³ J. Gollub,³ J. B. Gong,^{1,70} J. D. Gong,³⁸ L. Gong,⁴⁴ W. X. Gong,^{1,64} W. Gradl,³⁹ S. Gramigna,^{31a,31b} M. Greco,^{80a,80c} M. D. Gu,⁵⁵ M. H. Gu,^{1,64} C. Y. Guan,^{1,70} A. Q. Guo,³⁴ H. Guo,⁵⁴ J. N. Guo,^{12,i} L. B. Guo,⁴⁵ M. J. Guo,⁵⁴ R. P. Guo,⁵³ X. Guo,⁵⁴ Y. P. Guo,^{12,i} Z. Guo,^{77,64} A. Guskov,^{40,c} J. Gutierrez,²⁹ J. Y. Han,^{77,64} T. T. Han,¹ X. Han,^{77,64} F. Hanisch,³ K. D. Hao,^{77,64} X. Q. Hao,²⁰ F. A. Harris,⁷¹ C. Z. He,^{50,j} K. K. He,^{17,46} K. L. He,^{1,70} F. H. Heinsius,³ C. H. Heinz,³⁹ Y. K. Heng,^{1,64,70} C. Herold,⁶⁶ P. C. Hong,³⁸ G. Y. Hou,^{1,70} X. T. Hou,^{1,70} Y. R. Hou,⁷⁰ Z. L. Hou,¹ H. M. Hu,^{1,70} J. F. Hu,^{61,1} Q. P. Hu,^{77,64} S. L. Hu,^{12,i} T. Hu,^{1,64,70} Y. Hu,¹ Y. X. Hu,⁸² Z. M. Hu,⁶⁵ G. S. Huang,^{77,64} K. X. Huang,⁶⁵ L. Q. Huang,^{34,70} P. Huang,⁴⁶ X. T. Huang,⁵⁴ Y. P. Huang,¹ Y. S. Huang,⁶⁵ T. Hussain,⁷⁹ N. Hüsken,³⁹ N. in der Wiesche,⁷⁴ J. Jackson,²⁹ Q. Ji,¹ Q. P. Ji,²⁰ W. Ji,^{1,70} X. B. Ji,^{1,70} X. L. Ji,^{1,64} Y. Y. Ji,¹ L. K. Jia,⁷⁰ X. Q. Jia,⁵⁴ D. Jiang,^{1,70} H. B. Jiang,⁸² S. J. Jiang,¹⁰ X. S. Jiang,^{1,64,70} Y. Jiang,⁷⁰ J. B. Jiao,⁵⁴ J. K. Jiao,³⁸ Z. Jiao,²⁵ L. C. L. Jin,¹ S. Jin,⁴⁶ Y. Jin,⁷² M. Q. Jing,^{1,70} X. M. Jing,⁷⁰ T. Johansson,⁸¹ S. Kabana,³⁶ X. L. Kang,¹⁰ X. S. Kang,⁴⁴ B. C. Ke,⁸⁷ V. Khachatryan,²⁹ A. Khokkaz,⁷⁴ O. B. Kolcu,^{68a} B. Kopf,³ L. Kröger,⁷⁴ L. Krümmel,³ Y. Y. Kuang,⁷⁸ M. Kuessner,³ X. Kui,^{1,70} N. Kumar,²⁸ A. Kupsc,^{48,81} W. Kühn,⁴¹ Q. Lan,⁷⁸ W. N. Lan,²⁰ T. T. Lei,^{77,64} M. Lellmann,³⁹ T. Lenz,³⁹ C. Li,⁵¹ C. H. Li,⁴⁵ C. K. Li,⁴⁷ Chunkai Li,²¹ Cong Li,⁴⁷

D. M. Li,⁸⁷ F. Li,^{1,64} G. Li,¹ H. B. Li,^{1,70} H. J. Li,²⁰ H. L. Li,⁸⁷ H. N. Li,^{61,1} H. P. Li,⁴⁷ Hui Li,⁴⁷ J. N. Li,³² J. S. Li,⁶⁵ J. W. Li,⁵⁴ K. Li,¹ K. L. Li,^{42,m,n} L. J. Li,^{1,70} Lei Li,⁵² M. H. Li,⁴⁷ M. R. Li,^{1,70} M. T. Li,⁵⁴ P. L. Li,⁷⁰ P. R. Li,^{42,m,n} Q. M. Li,^{1,70} Q. X. Li,⁵⁴ R. Li,^{18,34} S. Li,⁸⁷ S. X. Li,⁸⁷ S. Y. Li,⁸⁷ Shanshan Li,^{27,k} T. Li,⁵⁴ T. Y. Li,⁴⁷ W. D. Li,^{1,70} W. G. Li,^{1,a} X. Li,^{1,70} X. H. Li,^{77,64} X. K. Li,^{50,j} X. L. Li,⁵⁴ X. Y. Li,^{1,9} X. Z. Li,⁶⁵ Y. Li,²⁰ Y. G. Li,⁷⁰ Y. P. Li,³⁸ Z. H. Li,⁴² Z. J. Li,⁶⁵ Z. L. Li,⁸⁷ Z. X. Li,⁴⁷ Z. Y. Li,⁸⁵ C. Liang,⁴⁶ H. Liang,^{77,64} Y. F. Liang,⁵⁹ Y. T. Liang,^{34,70} G. R. Liao,¹⁴ L. B. Liao,⁶⁵ M. H. Liao,⁶⁵ Y. P. Liao,^{1,70} J. Libby,²⁸ A. Limphirat,⁶⁶ C. C. Lin,⁶⁰ C. X. Lin,³⁴ D. X. Lin,^{34,70} T. Lin,¹ B. J. Liu,¹ B. X. Liu,⁸² C. Liu,³⁸ C. X. Liu,¹ F. Liu,¹ F. H. Liu,⁵⁸ Feng Liu,⁶ G. M. Liu,^{61,1} H. Liu,^{42,m,n} H. B. Liu,¹⁵ H. M. Liu,^{1,70} Huihui Liu,²² J. B. Liu,^{77,64} J. J. Liu,²¹ K. Liu,^{42,m,n} K. Y. Liu,⁴⁴ Ke Liu,²³ Kun Liu,⁷⁸ L. Liu,⁴² L. C. Liu,⁴⁷ Lu Liu,⁴⁷ M. H. Liu,³⁸ P. L. Liu,⁵⁴ Q. Liu,⁷⁰ S. B. Liu,^{77,64} T. Liu,¹ W. M. Liu,^{77,64} W. T. Liu,⁴³ X. Liu,^{42,m,n} X. K. Liu,^{42,m,n} X. L. Liu,^{12,i} X. P. Liu,^{12,i} X. Y. Liu,⁸² Y. Liu,^{42,m,n} Y. B. Liu,⁴⁷ Yi Liu,⁸⁷ Z. A. Liu,^{1,64,70} Z. D. Liu,⁸³ Z. L. Liu,⁷⁸ Z. Q. Liu,⁵⁴ Z. X. Liu,¹ Z. Y. Liu,⁴² X. C. Lou,^{1,64,70} H. J. Lu,²⁵ J. G. Lu,^{1,64} X. L. Lu,¹⁶ Y. Lu,⁷ Y. H. Lu,^{1,70} Y. P. Lu,^{1,64} Z. H. Lu,^{1,70} C. L. Luo,⁴⁵ J. R. Luo,⁶⁵ J. S. Luo,^{1,70} M. X. Luo,⁸⁶ T. Luo,^{12,i} X. L. Luo,^{1,64} Z. Y. Lv,²³ X. R. Lyu,^{70,q} Y. F. Lyu,⁴⁷ Y. H. Lyu,⁸⁷ F. C. Ma,⁴⁴ H. L. Ma,¹ Heng Ma,^{27,k} J. L. Ma,^{1,70} L. L. Ma,⁵⁴ L. R. Ma,⁷² Q. M. Ma,¹ R. Q. Ma,^{1,70} R. Y. Ma,²⁰ T. Ma,^{77,64} X. T. Ma,^{1,70} X. Y. Ma,^{1,64} Y. M. Ma,³⁴ F. E. Maas,¹⁹ I. MacKay,⁷⁵ M. Maggiora,^{80a,80c} S. Maity,³⁴ S. Malde,⁷⁵ Q. A. Malik,⁷⁹ H. X. Mao,^{42,m,n} Y. J. Mao,^{50,j} Z. P. Mao,¹ S. Marcello,^{80a,80c} A. Marshall,⁶⁹ F. M. Melendi,^{31a,31b} Y. H. Meng,⁷⁰ Z. X. Meng,⁷² G. Mezzadri,^{31a} H. Miao,^{1,70} T. J. Min,⁴⁶ R. E. Mitchell,²⁹ X. H. Mo,^{1,64,70} B. Moses,²⁹ N. Yu. Muchnoi,^{4,e} J. Muskalla,³⁹ Y. Nefedov,⁴⁰ F. Nerling,^{19,g} H. Neuwirth,⁷⁴ Z. Ning,^{1,64} S. Nisar,^{33,b} Q. L. Niu,^{42,m,n} W. D. Niu,^{12,i} Y. Niu,⁵⁴ C. Normand,⁶⁹ S. L. Olsen,^{11,70} Q. Ouyang,^{1,64,70} S. Pacetti,^{30b,30c} X. Pan,⁶⁰ Y. Pan,⁶² A. Pathak,¹¹ Y. P. Pei,^{77,64} M. Pelizaeus,³ G. L. Peng,^{77,64} H. P. Peng,^{77,64} X. J. Peng,^{42,m,n} Y. Y. Peng,^{42,m,n} K. Peters,^{13,g} K. Petridis,⁶⁹ J. L. Ping,⁴⁵ R. G. Ping,^{1,70} S. Plura,³⁹ V. Prasad,³⁸ L. Pöpping,³ F. Z. Qi,¹ H. R. Qi,⁶⁷ M. Qi,⁴⁶ S. Qian,^{1,64} W. B. Qian,⁷⁰ C. F. Qiao,⁷⁰ J. H. Qiao,²⁰ J. J. Qin,⁷⁸ J. L. Qin,⁶⁰ L. Q. Qin,¹⁴ L. Y. Qin,^{77,64} P. B. Qin,⁷⁸ X. P. Qin,⁴³ X. S. Qin,⁵⁴ Z. H. Qin,^{1,64} J. F. Qiu,¹ Z. H. Qu,⁷⁸ J. Rademacker,⁶⁹ C. F. Redmer,³⁹ A. Rivetti,^{80c} M. Rolo,^{80c} G. Rong,^{1,70} S. S. Rong,^{1,70} F. Rosini,^{30b,30c} Ch. Rosner,¹⁹ M. Q. Ruan,^{1,64} N. Salone,^{48,s} A. Sarantsev,^{40,f} Y. Schelhaas,³⁹ M. Schernau,³⁶ K. Schoenning,⁸¹ M. Scodreggio,^{31a} W. Shan,²⁶ X. Y. Shan,^{77,64} Z. J. Shang,^{42,m,n} J. F. Shangguan,¹⁷ L. G. Shao,^{1,70} M. Shao,^{77,64} C. P. Shen,^{12,i} H. F. Shen,^{1,9} W. H. Shen,⁷⁰ X. Y. Shen,^{1,70} B. A. Shi,⁷⁰ Ch. Y. Shi,^{85,d} H. Shi,^{77,64} J. L. Shi,^{8,r} J. Y. Shi,¹ M. H. Shi,⁸⁷ S. Y. Shi,⁷⁸ X. Shi,^{1,64} H. L. Song,^{77,64} J. J. Song,²⁰ M. H. Song,⁴² T. Z. Song,⁶⁵ W. M. Song,³⁸ Y. X. Song,^{50,j,o} Zirong Song,^{27,k} S. Sosio,^{80a,80c} S. Spataro,^{80a,80c} S. Stansilaus,⁷⁵ F. Stieler,³⁹ M. Stolte,³ S. S. Su,⁴⁴ G. B. Sun,⁸² G. X. Sun,¹ H. Sun,⁷⁰ H. K. Sun,¹ J. F. Sun,²⁰ K. Sun,⁶⁷ L. Sun,⁸² R. Sun,⁷⁷ S. S. Sun,^{1,70} T. Sun,^{56,h} W. Y. Sun,⁵⁵ Y. C. Sun,⁸² Y. H. Sun,³² Y. J. Sun,^{77,64} Y. Z. Sun,¹ Z. Q. Sun,^{1,70} Z. T. Sun,⁵⁴ H. Tabaharizato,¹ C. J. Tang,⁵⁹ G. Y. Tang,¹ J. Tang,⁶⁵ J. J. Tang,^{77,64} L. F. Tang,⁴³ Y. A. Tang,⁸² Z. H. Tang,^{1,70} L. Y. Tao,⁷⁸ M. Tat,⁷⁵ J. X. Teng,^{77,64} J. Y. Tian,^{77,64} W. H. Tian,⁶⁵ Y. Tian,³⁴ Z. F. Tian,⁸² I. Uman,^{68b} E. van der Smagt,³ B. Wang,⁶⁵ Bin Wang,¹ Bo Wang,^{77,64} C. Wang,^{42,m,n} Chao Wang,²⁰ Cong Wang,²³ D. Y. Wang,^{50,j} H. J. Wang,^{42,m,n} H. R. Wang,⁸⁴ J. Wang,¹⁰ J. J. Wang,⁸² J. P. Wang,³⁷ K. Wang,^{1,64} L. L. Wang,¹ L. W. Wang,³⁸ M. Wang,⁵⁴ Mi Wang,^{77,64} N. Y. Wang,⁷⁰ S. Wang,^{42,m,n} Shun Wang,⁶³ T. Wang,^{12,i} T. J. Wang,⁴⁷ W. Wang,⁶⁵ W. P. Wang,³⁹ X. F. Wang,^{42,m,n} X. L. Wang,^{12,i} X. N. Wang,^{1,70} Xin Wang,^{27,k} Y. Wang,¹ Y. D. Wang,⁴⁹ Y. F. Wang,^{1,9,70} Y. H. Wang,^{42,m,n} Y. J. Wang,^{77,64} Y. L. Wang,²⁰ Y. N. Wang,⁴⁹ Yanning Wang,⁸² Yaqian Wang,¹⁸ Yi Wang,⁶⁷ Yuan Wang,^{18,34} Z. Wang,^{1,64} Z. L. Wang,² Z. Q. Wang,^{12,i} Z. Y. Wang,^{1,70} Zhi Wang,⁴⁷ Ziyi Wang,⁷⁰ D. Wei,⁴⁷ D. H. Wei,¹⁴ D. J. Wei,⁷² H. R. Wei,⁴⁷ F. Weidner,⁷⁴ H. R. Wen,³⁴ S. P. Wen,¹ U. Wiedner,³ G. Wilkinson,⁷⁵ M. Wolke,⁸¹ J. F. Wu,^{1,9} L. H. Wu,¹ L. J. Wu,²⁰ Lianjie Wu,²⁰ S. G. Wu,^{1,70} S. M. Wu,⁷⁰ X. W. Wu,⁷⁸ Z. Wu,^{1,64} H. L. Xia,^{77,64} L. Xia,^{77,64} B. H. Xiang,^{1,70} D. Xiao,^{42,m,n} G. Y. Xiao,⁴⁶ H. Xiao,⁷⁸ Y. L. Xiao,^{12,i} Z. J. Xiao,⁴⁵ C. Xie,⁴⁶ K. J. Xie,^{1,70} Y. Xie,⁵⁴ Y. G. Xie,^{1,64} Y. H. Xie,⁶ Z. P. Xie,^{77,64} T. Y. Xing,^{1,70} D. B. Xiong,¹ C. J. Xu,⁶⁵ G. F. Xu,¹ H. Y. Xu,² Q. J. Xu,¹⁷ Q. N. Xu,³² T. D. Xu,⁷⁸ X. P. Xu,⁶⁰ Y. Xu,^{12,i} Y. C. Xu,⁸⁴ Z. S. Xu,⁷⁰ F. Yan,²⁴ L. Yan,^{12,i} W. B. Yan,^{77,64} W. C. Yan,⁸⁷ W. H. Yan,⁶ W. P. Yan,²⁰ X. Q. Yan,^{12,i} Y. Y. Yan,⁶⁶ H. J. Yang,^{56,h} H. L. Yang,³⁸ H. X. Yang,¹ J. H. Yang,⁴⁶ R. J. Yang,²⁰ X. Y. Yang,⁷² Y. Yang,^{12,i} Y. H. Yang,⁴⁷ Y. M. Yang,⁸⁷ Y. Q. Yang,¹⁰ Y. Z. Yang,²⁰ Youhua Yang,⁴⁶ Z. Y. Yang,⁷⁸ Z. P. Yao,⁵⁴ M. Ye,^{1,64} M. H. Ye,^{9,a} Z. J. Ye,^{61,1} Junhao Yin,⁴⁷ Z. Y. You,⁶⁵ B. X. Yu,^{1,64,70} C. X. Yu,⁴⁷ G. Yu,¹³ J. S. Yu,^{27,k} L. W. Yu,^{12,i} T. Yu,⁷⁸ X. D. Yu,^{50,j} Y. C. Yu,⁸⁷ Yongchao Yu,⁴² C. Z. Yuan,^{1,70} H. Yuan,^{1,70} J. Yuan,³⁸ Jie Yuan,⁴⁹ L. Yuan,² M. K. Yuan,^{12,i} S. H. Yuan,⁷⁸ Y. Yuan,^{1,70} C. X. Yue,⁴³ Ying Yue,²⁰ A. A. Zafar,⁷⁹ F. R. Zeng,⁵⁴ S. H. Zeng,⁶⁹ X. Zeng,^{12,i} Y. J. Zeng,^{1,70} Yujie Zeng,⁶⁵ Y. C. Zhai,⁵⁴ Y. H. Zhan,⁶⁵ B. L. Zhang,^{1,70} B. X. Zhang,^{1,a} D. H. Zhang,⁴⁷ G. Y. Zhang,²⁰ Gengyuan Zhang,^{1,70} H. Zhang,^{77,64} H. C. Zhang,^{1,64,70} H. H. Zhang,⁶⁵ H. Q. Zhang,^{1,64,70} H. R. Zhang,^{77,64} H. Y. Zhang,^{1,64} Han Zhang,⁸⁷ J. Zhang,⁶⁵ J. J. Zhang,⁵⁷ J. L. Zhang,²¹ J. Q. Zhang,⁴⁵ J. S. Zhang,^{12,i} J. W. Zhang,^{1,64,70} J. X. Zhang,^{42,m,n} J. Y. Zhang,¹ J. Z. Zhang,^{1,70} Jianyu Zhang,⁷⁰ Jin Zhang,⁵²

Jiyuan Zhang,^{12,i} L. M. Zhang,⁶⁷ Lei Zhang,⁴⁶ N. Zhang,³⁸ P. Zhang,^{1,9} Q. Zhang,²⁰ Q. Y. Zhang,³⁸ Q. Z. Zhang,⁷⁰ R. Y. Zhang,^{42,m,n} S. H. Zhang,^{1,70} S. N. Zhang,⁷⁵ Shulei Zhang,^{27,k} X. M. Zhang,¹ X. Y. Zhang,⁵⁴ Y. Zhang,¹ Y. T. Zhang,⁸⁷ Y. H. Zhang,^{1,64} Y. P. Zhang,^{77,64} Yu Zhang,⁷⁸ Z. Zhang,³⁴ Z. D. Zhang,¹ Z. H. Zhang,¹ Z. L. Zhang,³⁸ Z. X. Zhang,²⁰ Z. Y. Zhang,⁸² Zh. Zh. Zhang,²⁰ Zhilong Zhang,⁶⁰ Ziyang Zhang,⁴⁹ Ziyu Zhang,⁴⁷ G. Zhao,¹ J.-P. Zhao,⁷⁰ J. Y. Zhao,^{1,70} J. Z. Zhao,^{1,64} L. Zhao,¹ Lei Zhao,^{77,64} M. G. Zhao,⁴⁷ R. P. Zhao,⁷⁰ S. J. Zhao,⁸⁷ Y. B. Zhao,^{1,64} Y. L. Zhao,⁶⁰ Y. P. Zhao,⁴⁹ Y. X. Zhao,^{34,70} Z. G. Zhao,^{77,64} A. Zhemchugov,^{40,c} B. Zheng,⁷⁸ B. M. Zheng,³⁸ J. P. Zheng,^{1,64} W. J. Zheng,^{1,70} W. Q. Zheng,¹⁰ X. R. Zheng,²⁰ Y. H. Zheng,^{70,q} B. Zhong,⁴⁵ C. Zhong,²⁰ H. Zhou,^{39,54,p} J. Q. Zhou,³⁸ S. Zhou,⁶ X. Zhou,⁸² X. K. Zhou,⁶ X. R. Zhou,^{77,64} X. Y. Zhou,⁴³ Y. X. Zhou,⁸⁴ Y. Z. Zhou,²⁰ A. N. Zhu,⁷⁰ J. Zhu,⁴⁷ K. Zhu,¹ K. J. Zhu,^{1,64,70} K. S. Zhu,^{12,i} L. X. Zhu,⁷⁰ Lin Zhu,²⁰ S. H. Zhu,⁷⁶ T. J. Zhu,^{12,i} W. D. Zhu,^{12,i} W. J. Zhu,¹ W. Z. Zhu,²⁰ Y. C. Zhu,^{77,64} Z. A. Zhu,^{1,70} X. Y. Zhuang,⁴⁷ M. Zhuge,⁵⁴ J. H. Zou,¹ and J. Zu³⁴

(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*Chengdu University of Technology, Chengdu 610059, People's Republic of China*

⁹*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*

¹⁰*China University of Geosciences, Wuhan 430074, People's Republic of China*

¹¹*Chung-Ang University, Seoul 06974, Republic of Korea*

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, Xinxiang 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*Hengyang Normal University, Hengyang 421001, People's Republic of China*

²⁵*Huangshan College, Huangshan 245000, People's Republic of China*

²⁶*Hunan Normal University, Changsha 410081, People's Republic of China*

²⁷*Hunan University, Changsha 410082, People's Republic of China*

²⁸*Indian Institute of Technology Madras, Chennai 600036, India*

²⁹*Indiana University, Bloomington, Indiana 47405, USA*

^{30a}*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*

^{30b}*INFN Sezione di Perugia, I-06100 Perugia, Italy*

^{30c}*University of Perugia, I-06100 Perugia, Italy*

^{31a}*INFN Sezione di Ferrara, I-44122 Ferrara, Italy*

^{31b}*University of Ferrara, I-44122 Ferrara, Italy*

³²*Inner Mongolia University, Hohhot 010021, People's Republic of China*

³³*Institute of Business Administration, Karachi 75270, Pakistan*

³⁴*Institute of Modern Physics, Lanzhou 730000, People's Republic of China*

³⁵*Institute of Physics and Technology, Mongolian Academy of Sciences, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia*

³⁶*Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica 1000000, Chile*

³⁷*Jiangsu Ocean University, Lianyungang 222000, People's Republic of China*

³⁸*Jilin University, Changchun 130012, People's Republic of China*

³⁹*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*

⁴⁰*Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*

- ⁴¹*Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*
- ⁴²*Lanzhou University, Lanzhou 730000, People's Republic of China*
- ⁴³*Liaoning Normal University, Dalian 116029, People's Republic of China*
- ⁴⁴*Liaoning University, Shenyang 110036, People's Republic of China*
- ⁴⁵*Nanjing Normal University, Nanjing 210023, People's Republic of China*
- ⁴⁶*Nanjing University, Nanjing 210093, People's Republic of China*
- ⁴⁷*Nankai University, Tianjin 300071, People's Republic of China*
- ⁴⁸*National Centre for Nuclear Research, Warsaw 02-093, Poland*
- ⁴⁹*North China Electric Power University, Beijing 102206, People's Republic of China*
- ⁵⁰*Peking University, Beijing 100871, People's Republic of China*
- ⁵¹*Qufu Normal University, Qufu 273165, People's Republic of China*
- ⁵²*Renmin University of China, Beijing 100872, People's Republic of China*
- ⁵³*Shandong Normal University, Jinan 250014, People's Republic of China*
- ⁵⁴*Shandong University, Jinan 250100, People's Republic of China*
- ⁵⁵*Shandong University of Technology, Zibo 255000, People's Republic of China*
- ⁵⁶*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
- ⁵⁷*Shanxi Normal University, Linfen 041004, People's Republic of China*
- ⁵⁸*Shanxi University, Taiyuan 030006, People's Republic of China*
- ⁵⁹*Sichuan University, Chengdu 610064, People's Republic of China*
- ⁶⁰*Soochow University, Suzhou 215006, People's Republic of China*
- ⁶¹*South China Normal University, Guangzhou 510006, People's Republic of China*
- ⁶²*Southeast University, Nanjing 211100, People's Republic of China*
- ⁶³*Southwest University of Science and Technology, Mianyang 621010, People's Republic of China*
- ⁶⁴*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*
- ⁶⁵*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*
- ⁶⁶*Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand*
- ⁶⁷*Tsinghua University, Beijing 100084, People's Republic of China*
- ^{68a}*Turkish Accelerator Center Particle Factory Group, Istinye University, 34010 Istanbul, Turkey*
- ^{68b}*Near East University, Nicosia, North Cyprus, 99138, Mersin 10, Turkey*
- ⁶⁹*University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom*
- ⁷⁰*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
- ⁷¹*University of Hawaii, Honolulu, Hawaii 96822, USA*
- ⁷²*University of Jinan, Jinan 250022, People's Republic of China*
- ⁷³*University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom*
- ⁷⁴*University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany*
- ⁷⁵*University of Oxford, Keble Road, Oxford OX13RH, United Kingdom*
- ⁷⁶*University of Science and Technology Liaoning, Anshan 114051, People's Republic of China*
- ⁷⁷*University of Science and Technology of China, Hefei 230026, People's Republic of China*
- ⁷⁸*University of South China, Hengyang 421001, People's Republic of China*
- ⁷⁹*University of the Punjab, Lahore-54590, Pakistan*
- ^{80a}*University of Turin and INFN, University of Turin, I-10125 Turin, Italy*
- ^{80b}*University of Eastern Piedmont, I-15121 Alessandria, Italy*
- ^{80c}*INFN, I-10125 Turin, Italy*
- ⁸¹*Uppsala University, Box 516, SE-75120 Uppsala, Sweden*
- ⁸²*Wuhan University, Wuhan 430072, People's Republic of China*
- ⁸³*Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an, Shaanxi 710049, People's Republic of China*
- ⁸⁴*Yantai University, Yantai 264005, People's Republic of China*
- ⁸⁵*Yunnan University, Kunming 650500, People's Republic of China*
- ⁸⁶*Zhejiang University, Hangzhou 310027, People's Republic of China*
- ⁸⁷*Zhengzhou University, Zhengzhou 450001, People's Republic of China*

^aDeceased.^bAlso at Bogazici University, 34342 Istanbul, Turkey.^cAlso at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.^dAlso at the Functional Electronics Laboratory, Tomsk State University, Tomsk 634050, Russia.^eAlso at the Novosibirsk State University, Novosibirsk 630090, Russia.^fAlso at the NRC "Kurchatov Institute," PNPI, 188300 Gatchina, Russia.

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

^hAlso 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.

ⁱAlso 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.

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

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

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

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

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

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

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

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

^rAlso at Applied Nuclear Technology in Geosciences Key Laboratory of Sichuan Province, Chengdu University of Technology, Chengdu 610059, People's Republic of China.

^sCurrently at University of Silesia in Katowice, Institute of Physics, 75 Pulku Piechoty 1, 41-500 Chorzow, Poland.