

Cross section measurement of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ from $\sqrt{s} = 4.008$ GeV to 4.951 GeV

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



(Received 6 January 2026; accepted 17 March 2026; published 25 June 2026)

Using data samples with a total integrated luminosity of 22.1 fb⁻¹ at center-of-mass energies between 4.008 and 4.951 GeV collected with the BESIII detector, the cross sections of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ process are measured. The obtained cross sections are found to be approximately one-half of those of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$, consistent with the isospin symmetry expectation. A coherent fit to the dressed cross sections is performed, with the $Y(4230)$ parameters fixed at the values measured in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$. The significances of the $Y(4390)$ and $Y(4660)$ are both larger than 5σ , and their masses and widths are consistent with the previous measurement in the $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ process.

DOI: 10.1103/98g1-t98b

I. INTRODUCTION

Over the past two decades, a series of charmoniumlike states with $J^{PC} = 1^{--}$, referred to as the Y states, have been discovered and confirmed by numerous experiments. As exotic state candidates, the Y states cannot be easily accommodated within the conventional quark model [1] and their internal properties remain controversial. Besides the conventional charmonium interpretation, various other theoretical models have been proposed to understand Y states, including hybrid mesons, meson molecules, hadrocharmonia, and tetraquarks, but none of them has been proven conclusive to date [2–6]. Therefore, comprehensive studies of their production and decay patterns [7,8], as well as precise measurements of their resonant parameters from different experiments, are highly desired to provide critical information to explore the nature of the Y states.

Among all Y states, the $Y(4230)$ and $Y(4390)$, previously known as $Y(4260)$ and $Y(4360)$, were first observed by the *BABAR* and *Belle* experiments with the initial-state radiation (ISR) technique in the processes of $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ [9–12] and $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(3686)$ [13–16], respectively. With high-statistics data samples collected by the BESIII experiment, the $Y(4260)$ and $Y(4360)$ were observed in several decay modes and measured with improved precision. Furthermore, it was

found that $Y(4260)$ consists of two resonant structures, $Y(4230)$ and $Y(4320)$ [17]. The $Y(4230)$ was also observed in the processes $e^+e^- \rightarrow \pi^0\pi^0J/\psi$ [18], $e^+e^- \rightarrow K_S^0K_S^0J/\psi$ [19], $e^+e^- \rightarrow K^+K^-J/\psi$ [20], $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [21,22], $e^+e^- \rightarrow \pi^+\pi^-h_c$ [23], $e^+e^- \rightarrow \omega\chi_{c0}$ [24,25], $e^+e^- \rightarrow \pi^+D^0D^{*-}$ [26], and $e^+e^- \rightarrow \eta J/\psi$ [27,28]. The $Y(4390)$ was observed in the processes $e^+e^- \rightarrow \pi^+\pi^-h_c$ [23], $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$ [29], and $e^+e^- \rightarrow \eta J/\psi$ [27,28]. Although there are many experimental studies of $Y(4230)$ and $Y(4390)$ with high precision, the resonance parameters from various processes are different, which needs further investigation. Analogous to the $Y(4230)$ and $Y(4390)$, the $Y(4660)$ was first observed by *Belle* and *BABAR* with the ISR process of $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(3686)$ [14–16] and was also observed and confirmed by the BESIII experiment in the processes $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [22] and $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$ [29].

The possible existence of Y states in the $\pi^0\pi^0\psi(3686)$ final states has been investigated by the BESIII experiment in Ref. [30]. However, no resonancelike structures were observed in the cross section line shape due to the limited data statistics. In this paper, an updated analysis of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ at center-of-mass (c.m.) energies ($\sqrt{s}$) between 4.008 and 4.951 GeV is performed. The data samples used in this analysis were collected with the BESIII detector at the BEPCII collider with an integrated luminosity of 22.1 fb⁻¹, including the data samples used in the previous analysis [30]. The much larger data samples used in this analysis allow us to search for possible Y states in the $\pi^0\pi^0\psi(3686)$ final state. In this analysis, the $\psi(3686)$ is reconstructed via its decay to $\pi^+\pi^-J/\psi$, the J/ψ is reconstructed via $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e/\mu$), and the π^0 is reconstructed via $\pi^0 \rightarrow \gamma\gamma$.

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

II. DESCRIPTION OF BEPCII AND THE BESIII DETECTOR

The BESIII detector [31] records symmetric e^+e^- collisions provided by the BEPCII collider [32] 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 $\sqrt{s} = 3.773 \text{ GeV}$. BESIII has collected large data samples in this energy region [33–35]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The 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 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 [36–38], which benefits 76.5% of the data used in this analysis.

Monte Carlo (MC) simulated data samples produced with a Geant4-based [39] software package, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam energy spread and ISR in the e^+e^- annihilation with the generator KKMC [40]. 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 [40]. All particle decays are modelled with EvtGen [41,42] using branching fractions either taken from the Particle Data Group (PDG) [43] when available, or otherwise estimated with Lundcharm [44,45]. Final-state radiation (FSR) from charged final-state particles is incorporated using the Photos package [46]. Signal MC samples of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ are generated with the amplitude model from the partial wave analysis (PWA) in Ref. [22].

III. EVENT SELECTION

The event selection criteria are designed to ensure reliable identification of the final-state particles and proper reconstruction of the event. Good 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. 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

plane perpendicular to the z axis $|V_{xy}|$. Photon candidates are identified using isolated showers in the EMC. The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or more than 50 MeV in the end cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10 deg as measured from the IP. To suppress electronic noise and showers unrelated to the collision event, the difference between the EMC time and the event start time is required to be within [0, 700] ns.

The detailed MC study indicates the pions and leptons of signal are well separated kinematically. Therefore, the charged tracks with momenta above 1.1 GeV/ c are assigned to be leptons, while those with momenta below 0.75 GeV/ c are pions. Electron and muon are separated by using the deposited energy (E) in the EMC, i.e., both electron and positron must satisfy $E/p > 0.7$, while both muons must satisfy $E < 0.45 \text{ GeV}$, where p is the momentum of charged tracks measured by the MDC. Signal candidates are required to have a pair of charged pions with zero net charge and a lepton pair with the same flavor and opposite charge.

To improve the resolution and suppress the background, a four-constraint (4C) kinematic fit imposing energy-momentum conservation under the hypothesis of $e^+e^- \rightarrow \gamma\gamma\gamma\pi^+\pi^-\ell^+\ell^-$ is performed, and $\chi^2_{4C} < 120$ is required. For events with more than four photons, the combination with the smallest χ^2_{4C} is retained. The four selected photons are combined into two π^0 candidates by minimizing $(M(\gamma_1\gamma_2) - M_{\pi^0})^2 + (M(\gamma_3\gamma_4) - M_{\pi^0})^2$, where $M(\gamma_i\gamma_j)$ is the invariant mass of two photons and M_{π^0} is the π^0 nominal mass quoted from the PDG [43]. Both π^0 candidates are further required to satisfy $|M(\gamma_i\gamma_j) - M_{\pi^0}| < 20 \text{ MeV}/c^2$, which is larger than five times the π^0 mass resolution. In order to improve the mass resolution, a seven-constraint (7C) kinematic fit with the additional mass constraints on the two π^0 's and J/ψ candidates to their nominal masses is carried out. The particle kinematics information updated by the 7C kinematic fit is used in the following analysis, and the $\psi(3686)$ candidate is reconstructed from the $\ell^+\ell^-$ pair and charged pion pair.

IV. EXTRACTION OF THE BORN CROSS SECTIONS

From the studies of inclusive and exclusive MC samples, it is found that the main background is from the process $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ with the subsequent decay $\psi(3686) \rightarrow \pi^0\pi^0 J/\psi$, which has the same final state as the signal. As shown in the two-dimensional distributions of $M(\pi^+\pi^-\ell^+\ell^-)$ versus $M(\pi^0\pi^0\ell^+\ell^-)$ for data at c.m. energies with high statistics in Fig. 1, there are two bands corresponding to the signal (the vertical one) and

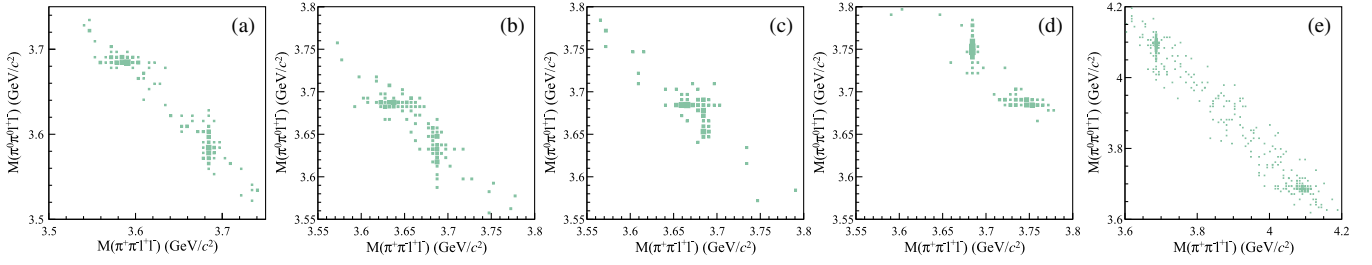


FIG. 1. Distributions of $M(\pi^+\pi^-\ell^+\ell^-)$ versus $M(\pi^0\pi^0\ell^+\ell^-)$ for high-statistics datasets taken at $\sqrt{s} =$ (a) 4.1784 GeV, (b) 4.2263 GeV, (c) 4.2580 GeV, (d) 4.3374 GeV, and (e) 4.6819 GeV.

background (the horizontal one) events. For datasets around $\sqrt{s} = 4.26$ GeV, the signal and background bands partially overlap due to the similar kinematic distributions of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs. Therefore, the background events are included in the fit when extracting signal yields for those datasets in the $\sqrt{s}$ range from 4.1989 to 4.3583 GeV.

The signal yields at the different c.m. energies are extracted by performing unbinned maximum likelihood fits on the $M(\pi^+\pi^-\ell^+\ell^-)$ distribution. In these fits, the fit ranges are chosen according to the background situation. The signal shapes are described with the exclusive MC-simulated shape convolved with a Gaussian function, which accounts for the resolution difference between data and MC simulation. Among the different datasets, the widths of the Gaussian functions are all fixed to the values obtained from simultaneous fits for four high-statistics datasets taken at $\sqrt{s} = 4.1784, 4.3774, 4.4156, 4.6819$ GeV. The shapes for the main background process $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ with the subsequent decay $\psi(3686) \rightarrow \pi^0\pi^0 J/\psi$ and other nonpeaking background are described by the MC-simulated shapes and first-order polynomial functions, respectively. The fits to the $M(\pi^+\pi^-\ell^+\ell^-)$ distributions for high-statistics datasets are shown in Fig. 2.

The Born cross section is determined by the formula

$$\sigma^B = \frac{N_{\text{sig}}}{\mathcal{L}_{\text{int}} \cdot (1 + \delta^{\text{ISR}}) \cdot \frac{1}{|1 - \Pi|^2} \cdot \mathcal{B} \cdot \epsilon}, \quad (1)$$

where N_{sig} is the number of signal events obtained from the fit to the $M(\pi^+\pi^-\ell^+\ell^-)$ distribution, $\mathcal{L}_{\text{int}}$ is the integrated luminosity, $1 + \delta^{\text{ISR}}$ is the ISR correction factor, $\frac{1}{|1 - \Pi|^2}$ is the vacuum polarization correction factor taken from Ref. [47], $\mathcal{B}$ is the branching fraction of the subsequent decay quoted from the PDG [43], and ϵ is the detection efficiency. The ISR correction factor and the detection efficiency are estimated using the signal MC samples. An iterative weight method [48] is used to consider the influence of the cross section line shape and to estimate the ISR correction factor. The relationship between the dressed cross section and the Born cross section is given by $\sigma^D = \sigma^B / |1 - \Pi|^2$.

For those low-statistics datasets with the signal significance less than 3σ , the cross section upper limits are estimated using the Bayesian method [49]. As an example, the likelihood distribution at $\sqrt{s} = 4.0076$ GeV is shown in Fig. 3. With a uniform prior probability density function, the Bayesian upper limit at 90% confidence level (CL) is estimated by integrating the likelihood distribution from zero to the upper limit, which gives 90% of the total area.

The Born cross sections for each c.m. energy and other related quantities used in the Born cross section calculation are summarized in Table I. A comparison of the cross section line shapes between $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ from this work and previous work [30] and that from $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [22] is shown in Fig. 4. Similar resonant structures are observed in the cross section line shapes of both processes.

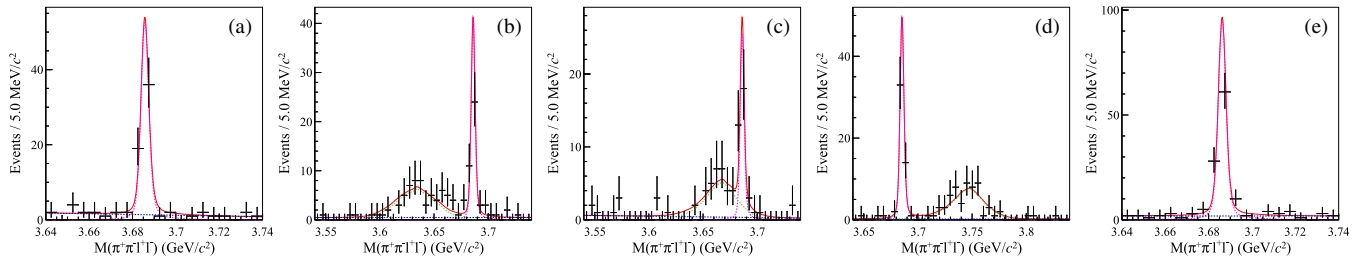


FIG. 2. Fits to the $M(\pi^+\pi^-\ell^+\ell^-)$ distributions for high-statistics datasets taken at $\sqrt{s} =$ (a) 4.1784 GeV, (b) 4.2263 GeV, (c) 4.2580 GeV, (d) 4.3374 GeV, and (e) 4.6819 GeV. The black dots with error bars are data, the red solid lines are the fit results, the dashed-red lines are the signal components, the dashed-green lines are the background components, and the dashed-blue lines are the nonpeaking background components.

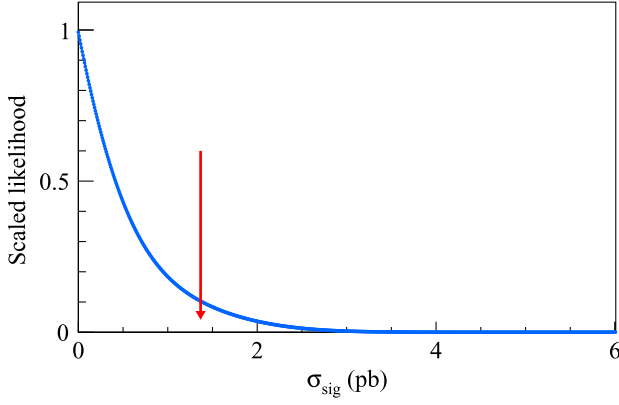


FIG. 3. The scaled likelihood distribution, normalized to its maximum value, as a function of the cross section at $\sqrt{s} = 4.0076$ GeV. The red arrow indicates the upper limit at the 90% confidence level.

V. FIT TO THE DRESSED CROSS SECTIONS

To study the possible resonant structures in the process $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$, an extended maximum likelihood fit is performed to the dressed cross sections at different c.m. energies. For datasets with high statistics in Table I, the cross section is expected to follow an asymmetric Gaussian distribution G_i . Following Ref. [23], G_i is defined as

$$G_i(\sigma_i^{\text{fit}}(\sqrt{s})) = \frac{1}{\delta_i \sqrt{2\pi}} e^{-\frac{(\sigma_i^{\text{fit}}(\sqrt{s}) - \sigma_i)^2}{2\delta_i^2}},$$

$$\delta_i = \begin{cases} \delta_i^{\text{negative}} & \sigma_i^{\text{fit}}(\sqrt{s}) < \sigma_i \\ \delta_i^{\text{positive}} & \sigma_i^{\text{fit}}(\sqrt{s}) \geq \sigma_i \end{cases}, \quad (2)$$

where $\sigma_i^{\text{fit}}(\sqrt{s})$ is the theoretical cross section as defined in Eq. (4), σ_i is the measured cross section of the i th data point, and δ_i is the statistical uncertainty, which is set to $\delta_i^{\text{negative}}$ and $\delta_i^{\text{positive}}$ for the cross section below and above the measured value, respectively. For the low-statistics datasets, the corresponding cross section likelihood distributions, which are parametrized as $L(\sigma_i^{\text{fit}}(\sqrt{s}))$ with double-Gaussian function as shown in Fig. 3, are used to describe the cross section distributions in the fit. The total likelihood function is defined as the product of the likelihood functions of all datasets, which is

$$L = \prod_{i=1}^{N_1=31} G_i(\sigma_i^{\text{fit}}) \cdot \prod_{j=1}^{N_2=10} L_j(\sigma_j^{\text{fit}}), \quad (3)$$

where N_1 and N_2 are the numbers of data points with and without sufficient statistics, respectively.

The cross section line shape of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ is consistent with that of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [22] and three resonant structures are observed there. Therefore, a model

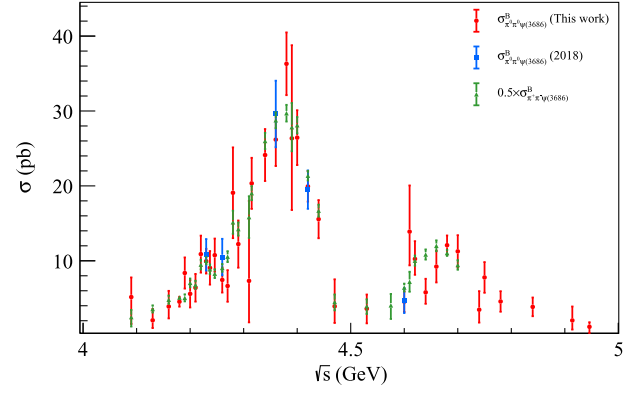


FIG. 4. The comparison of the cross section line shapes. The red dots are results from this work; the blue squares are results of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ from Ref. [30]; the green triangles are results of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ from Ref. [22]. The cross sections of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ have been multiplied by 0.5 for better comparison between the two processes.

including the coherent sum of three resonant structures $Y(4230)$, $Y(4390)$, and $Y(4660)$ as well as the continuum is used to describe the cross section,

$$\sigma^{\text{fit}}(\sqrt{s}) = \left| \sum_k e^{i\phi_k} \cdot BW_k(s) + e^{i\phi_{\text{cont}}} \cdot \psi_{\text{cont}} \right|^2, \quad (4)$$

where BW_k is the Breit-Wigner function for the k th resonance, the ψ_{cont} is the nonresonant function, and the ϕ_k and ϕ_{cont} are the corresponding phase relative to the $Y(4390)$. The BW_k is defined as

$$BW_k(s) = \frac{M_k}{\sqrt{s}} \frac{\sqrt{12\pi\Gamma_k^{\text{tot}}\Gamma_k^{ee}\mathcal{B}_k}}{s - M_k^2 + iM_k\Gamma_k^{\text{tot}}} \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M_k)}}, \quad (5)$$

where M_k , Γ_k^{tot} , Γ_k^{ee} , and $\mathcal{B}_k$ are the mass, total width, the partial width coupling to e^+e^- , and the branching fraction of the k th resonance, respectively. The $\Phi(\sqrt{s})$ is the standard phase space factor [43]. The continuum part is parametrized as

$$\psi_{\text{cont}} = \frac{a}{(\sqrt{s})^n} \sqrt{\Phi(\sqrt{s})} \quad (6)$$

with the free parameters a and n .

With the above model, the fit to the dressed cross sections is performed by maximizing the likelihood function L . The statistical significance of the resonant structures is estimated by comparing the likelihood values of the fits with and without the corresponding resonant structures included. The resultant significances of the resonant structures are 1.9σ , 11.4σ , and 5.7σ for $Y(4230)$, $Y(4390)$, and $Y(4660)$, respectively. Since the significance of $Y(4230)$ is not substantial, the parameters of $Y(4230)$

TABLE I. For each c.m. energy $\sqrt{s}$, the following quantities are listed: the integrated luminosity $\mathcal{L}_{\text{int}}$, the ISR correction factor $1 + \delta^{\text{ISR}}$, the vacuum polarization correction factor $\frac{1}{|1-\Pi|^2}$, the selection efficiency ϵ , the signal yield N_{sig} , the Born cross section σ^{B} , the ratio of the cross sections between $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ and that of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ denoted as R , and the cross section upper limit σ^{UP} at the 90% CL. The first uncertainties are statistical, and the second are systematic.

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\text{int}}$ (pb $^{-1}$)	$1 + \delta^{\text{ISR}}$	$\frac{1}{ 1-\Pi ^2}$	$\epsilon(\%)$	N_{sig}	σ^{B} (pb)	R	σ^{UP} (pb)
4.0076	482.0	0.682	1.044	12.50	—	—	—	1.3
4.0855	52.86	0.766	1.051	11.20	$1.0^{+0.5}_{-0.7} \pm 0.1$	$5.2^{+2.6}_{-3.6} \pm 0.3$	$1.04^{+0.66}_{-0.90} \pm 0.07$	20.2
4.1285	401.5	0.781	1.052	10.75	$3.0^{+2.2}_{-1.5} \pm 0.2$	$2.1^{+1.5}_{-1.0} \pm 0.1$	$0.29^{+0.22}_{-0.15} \pm 0.02$	4.8
4.1574	408.7	0.787	1.053	10.86	$5.8^{+3.1}_{-2.4} \pm 0.4$	$3.9^{+2.1}_{-1.6} \pm 0.2$	$0.41^{+0.22}_{-0.17} \pm 0.03$	—
4.1784	3194.5	0.789	1.054	11.18	$54.5^{+7.9}_{-7.9} \pm 3.5$	$4.5^{+0.7}_{-0.7} \pm 0.3$	$0.45^{+0.07}_{-0.07} \pm 0.03$	—
4.1888	570.03	0.789	1.056	11.48	$18.4^{+4.6}_{-4.6} \pm 1.2$	$8.4^{+2.1}_{-2.1} \pm 0.5$	$0.83^{+0.22}_{-0.22} \pm 0.05$	—
4.1989	526.0	0.788	1.056	11.58	$11.4^{+3.7}_{-3.7} \pm 0.7$	$5.6^{+1.8}_{-1.8} \pm 0.4$	$0.40^{+0.13}_{-0.13} \pm 0.03$	—
4.2091	572.05	0.785	1.057	11.06	$13.6^{+3.9}_{-3.9} \pm 1.0$	$6.4^{+1.9}_{-1.9} \pm 0.5$	$0.47^{+0.14}_{-0.14} \pm 0.04$	—
4.2186	569.2	0.778	1.056	11.69	$24.1^{+5.5}_{-5.5} \pm 1.8$	$10.9^{+2.5}_{-2.5} \pm 0.8$	$0.57^{+0.14}_{-0.14} \pm 0.04$	—
4.2263	1100.9	0.766	1.056	11.82	$42.3^{+7.0}_{-7.0} \pm 3.2$	$9.9^{+1.6}_{-1.6} \pm 0.8$	$0.50^{+0.09}_{-0.09} \pm 0.04$	—
4.2357	530.3	0.786	1.056	11.53	$18.6^{+4.6}_{-4.6} \pm 1.4$	$9.1^{+2.2}_{-2.2} \pm 0.7$	$0.51^{+0.13}_{-0.13} \pm 0.04$	—
4.2436	593.98	0.859	1.056	11.17	$26.1^{+5.4}_{-5.4} \pm 2.0$	$10.8^{+2.2}_{-2.2} \pm 0.8$	$0.65^{+0.14}_{-0.14} \pm 0.05$	—
4.2580	828.4	0.834	1.054	12.01	$26.4^{+6.0}_{-6.0} \pm 2.0$	$7.5^{+1.7}_{-1.7} \pm 0.6$	$0.41^{+0.10}_{-0.10} \pm 0.03$	—
4.2668	531.1	0.820	1.053	11.83	$14.5^{+4.6}_{-4.6} \pm 1.1$	$6.6^{+2.1}_{-2.1} \pm 0.5$	$0.31^{+0.10}_{-0.10} \pm 0.02$	—
4.2777	175.7	0.809	1.053	12.17	$14.1^{+4.5}_{-4.5} \pm 1.1$	$19.1^{+6.1}_{-6.1} \pm 1.5$	$0.63^{+0.21}_{-0.21} \pm 0.05$	—
4.2879	502.4	0.803	1.053	11.02	$23.1^{+6.0}_{-6.0} \pm 1.8$	$12.2^{+3.1}_{-3.1} \pm 0.9$	$0.43^{+0.11}_{-0.11} \pm 0.03$	—
4.3079	45.08	0.795	1.052	12.23	$1.4^{+2.0}_{-1.0} \pm 0.1$	$7.3^{+10.7}_{-5.5} \pm 0.5$	$0.23^{+0.34}_{-0.18} \pm 0.02$	18.9
4.3121	501.2	0.794	1.052	11.97	$41.1^{+6.9}_{-6.9} \pm 2.9$	$20.3^{+3.4}_{-3.4} \pm 1.5$	$0.53^{+0.09}_{-0.09} \pm 0.04$	—
4.3374	505.0	0.788	1.051	12.44	$50.7^{+7.3}_{-7.3} \pm 3.6$	$24.1^{+3.5}_{-3.5} \pm 1.7$	$0.46^{+0.07}_{-0.07} \pm 0.03$	—
4.3583	543.9	0.791	1.051	13.15	$62.9^{+8.5}_{-8.5} \pm 4.5$	$26.2^{+3.5}_{-3.5} \pm 1.9$	$0.46^{+0.06}_{-0.06} \pm 0.03$	—
4.3774	522.7	0.807	1.051	12.44	$81.0^{+9.3}_{-9.3} \pm 5.8$	$36.3^{+4.2}_{-4.2} \pm 2.6$	$0.61^{+0.07}_{-0.07} \pm 0.04$	—
4.3874	55.57	0.826	1.051	12.78	$6.6^{+3.1}_{-2.4} \pm 0.5$	$26.4^{+12.4}_{-9.6} \pm 1.9$	$0.47^{+0.23}_{-0.18} \pm 0.03$	—
4.3965	507.8	0.848	1.051	12.22	$59.1^{+8.2}_{-8.2} \pm 3.8$	$26.4^{+3.7}_{-3.7} \pm 1.7$	$0.47^{+0.07}_{-0.07} \pm 0.03$	—
4.4156	1090.7	0.913	1.052	12.28	$103.7^{+10.5}_{-10.5} \pm 6.6$	$19.9^{+2.0}_{-2.0} \pm 1.3$	$0.47^{+0.05}_{-0.05} \pm 0.03$	—
4.4362	569.9	1.008	1.054	11.22	$42.8^{+7.0}_{-7.0} \pm 2.7$	$15.6^{+2.5}_{-2.5} \pm 1.0$	$0.47^{+0.08}_{-0.08} \pm 0.03$	—
4.4671	111.09	1.168	1.055	10.13	$2.2^{+2.0}_{-1.2} \pm 0.1$	$3.9^{+3.6}_{-2.2} \pm 0.3$	$0.43^{+0.41}_{-0.27} \pm 0.03$	11.1
4.5271	112.12	1.367	1.054	8.37	$2.0^{+1.0}_{-1.1} \pm 0.1$	$3.6^{+1.9}_{-1.9} \pm 0.2$	$0.46^{+0.26}_{-0.28} \pm 0.03$	9.8
4.5745	48.93	1.248	1.054	9.20	—	—	—	8.1
4.5995	586.9	1.123	1.055	10.26	$13.1^{+3.9}_{-3.9} \pm 1.0$	$4.5^{+1.4}_{-1.4} \pm 0.4$	$0.35^{+0.11}_{-0.11} \pm 0.03$	—
4.6119	103.65	1.060	1.055	10.63	$6.9^{+3.1}_{-2.2} \pm 0.5$	$13.9^{+6.2}_{-4.5} \pm 1.1$	$0.96^{+0.46}_{-0.36} \pm 0.07$	—
4.6280	521.53	0.986	1.054	11.28	$25.3^{+5.8}_{-5.2} \pm 2.0$	$10.2^{+2.4}_{-2.1} \pm 0.8$	$0.51^{+0.12}_{-0.11} \pm 0.04$	—
4.6409	551.65	0.939	1.054	12.13	$15.5^{+4.8}_{-4.1} \pm 1.2$	$5.8^{+1.8}_{-1.5} \pm 0.5$	$0.27^{+0.09}_{-0.07} \pm 0.02$	—
4.6612	529.43	0.889	1.054	12.98	$24.0^{+5.5}_{-5.5} \pm 1.9$	$9.2^{+2.1}_{-2.1} \pm 0.7$	$0.38^{+0.09}_{-0.09} \pm 0.03$	—
4.6819	1667.39	0.877	1.054	13.33	$100.3^{+10.8}_{-10.8} \pm 7.8$	$12.1^{+1.3}_{-1.3} \pm 0.9$	$0.55^{+0.06}_{-0.06} \pm 0.04$	—
4.6988	535.54	0.898	1.055	13.71	$31.7^{+6.1}_{-6.1} \pm 2.5$	$11.3^{+2.2}_{-2.2} \pm 0.9$	$0.60^{+0.12}_{-0.12} \pm 0.05$	—
4.7397	163.87	1.020	1.055	12.65	$3.1^{+2.2}_{-1.6} \pm 0.2$	$3.5^{+2.5}_{-1.7} \pm 0.3$	—	8.0
4.7501	366.55	1.057	1.055	12.48	$16.0^{+4.2}_{-4.2} \pm 1.2$	$7.8^{+2.0}_{-2.0} \pm 0.6$	—	—
4.7805	511.47	1.160	1.055	11.81	$13.7^{+4.1}_{-4.1} \pm 1.1$	$4.6^{+1.4}_{-1.4} \pm 0.4$	—	—
4.8431	525.16	1.317	1.056	9.64	$10.9^{+3.5}_{-3.5} \pm 0.8$	$3.9^{+1.2}_{-1.2} \pm 0.3$	—	—
4.9180	207.82	1.424	1.056	8.73	$2.2^{+2.1}_{-1.4} \pm 0.2$	$2.0^{+1.9}_{-1.2} \pm 0.2$	—	5.5
4.9509	159.28	1.451	1.056	8.45	$1.0^{+0.5}_{-0.7} \pm 0.1$	$1.2^{+0.6}_{-0.8} \pm 0.1$	—	4.2

TABLE II. Results of the fits to the $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ dressed cross sections, where the first uncertainties are statistical and the second are systematic.

Parameter	Solution I	Solution II	Solution III	Solution IV
$M(Y4230)$ (MeV/ c^2)		4234.4 (fixed)		
$\Gamma^{\text{tot}}(Y4230)$ (MeV)		17.6 (fixed)		
$\mathcal{B}\Gamma^{ee}(Y4230)$ (eV)	$0.81 \pm 0.07 \pm 0.37$	$0.02 \pm 0.01 \pm 0.01$	$0.87 \pm 0.08 \pm 0.43$	$0.02 \pm 0.01 \pm 0.01$
$M(Y4390)$ (MeV/ c^2)		$4383.0 \pm 8.6 \pm 1.9$		
$\Gamma^{\text{tot}}(Y4390)$ (MeV)		$117.4 \pm 20.7 \pm 4.8$		
$\mathcal{B}\Gamma^{ee}(Y4390)$ (eV)	$3.18 \pm 1.21 \pm 0.57$	$2.92 \pm 1.07 \pm 0.36$	$9.90 \pm 1.42 \pm 0.76$	$9.03 \pm 1.22 \pm 0.09$
$M(Y4660)$ (MeV/ c^2)		$4684.0 \pm 17.3 \pm 1.9$		
$\Gamma^{\text{tot}}(Y4660)$ (MeV)		$119.5 \pm 47.1 \pm 9.1$		
$\mathcal{B}\Gamma^{ee}(Y4660)$ (eV)	$0.80 \pm 0.73 \pm 0.14$	$0.79 \pm 0.70 \pm 0.13$	$5.36 \pm 1.60 \pm 0.39$	$5.31 \pm 1.58 \pm 0.23$
$\phi_{(Y4230)}$ (rad)	2.03 ± 0.25	6.14 ± 0.41	1.23 ± 0.18	5.35 ± 0.52
$\phi_{(Y4660)}$ (rad)	5.99 ± 0.40	5.93 ± 0.40	5.28 ± 0.46	5.22 ± 0.46
ϕ_{cont} (rad)	3.87 ± 0.36	3.69 ± 0.33	2.23 ± 0.27	2.06 ± 0.24
$a(\times 10^5)$	4.2 ± 9.5	3.3 ± 8.0	5.3 ± 22.8	4.9 ± 22.6
n	8.7 ± 1.8	8.6 ± 1.8	8.9 ± 3.6	8.9 ± 3.6

are fixed to the values from the measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [22], while the parameters of $Y(4390)$ and $Y(4660)$ are free in the fit. By scanning three relative phases, four solutions are found with similar fit quality and identical masses and widths of $Y(4390)$ and $Y(4660)$. The fit results are shown in Table II and Fig. 5.

VI. SYSTEMATIC UNCERTAINTIES

A. Systematic uncertainties of the cross section measurement

Several sources of systematic uncertainties are considered in the cross section measurement. Due to the limited

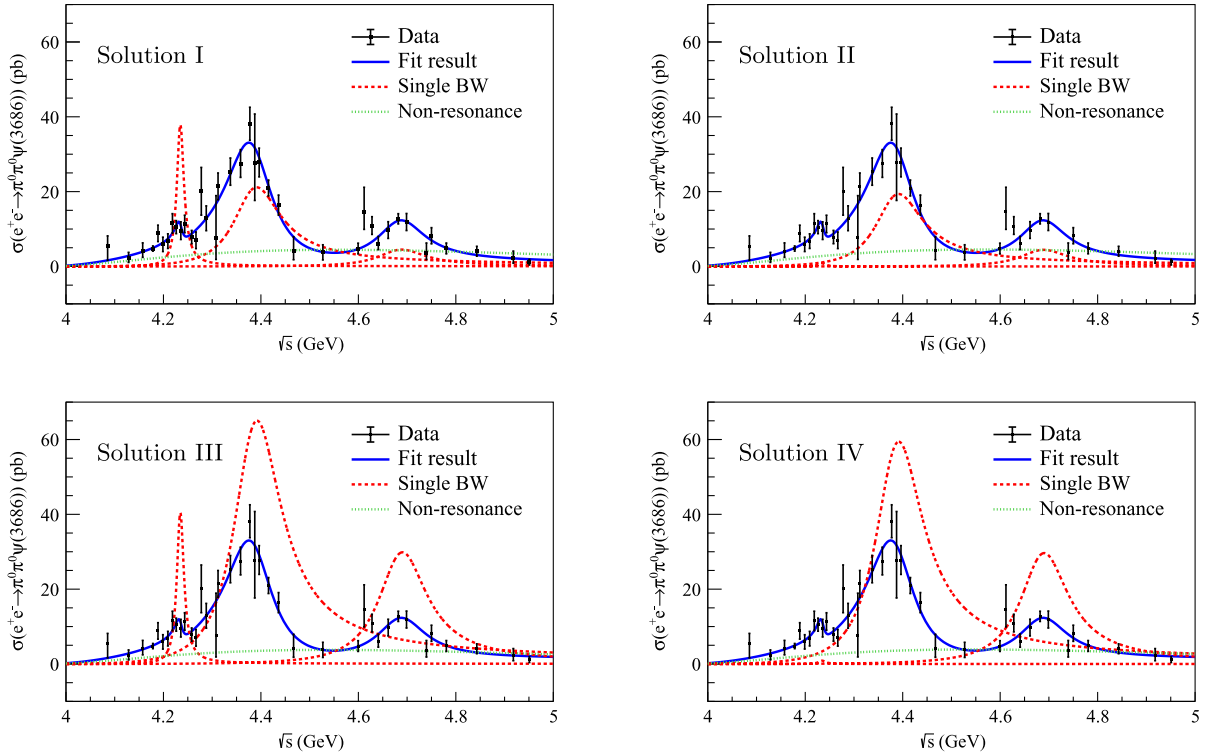


FIG. 5. Fits to dressed cross sections of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ with four solutions as summarized in Table II. The black dots with error bars are the measured dressed cross sections, the blue-solid curves are the best fit results, the red-dashed lines represent individual resonant structures, and the green-dashed lines are the continuum components.

statistics of some datasets, those with low statistics are estimated with the nearest high-statistics datasets ($\sqrt{s} = 4.1784, 4.2263, 4.3583, 4.4156, 4.6819$ GeV).

The uncertainty of the integrated luminosity is 1.0% [50–52]. The uncertainties of the branching fractions from the intermediate decays $\pi^0 \rightarrow \gamma\gamma$ (0.034%), $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ (0.34%), and $J/\psi \rightarrow \ell^+\ell^-$ (0.045%) are taken from the PDG [43]. The uncertainties of the charged track reconstruction and particle identification are both 1.0% for each charged track [53,54], and 4.0% is assigned. The uncertainty of the photon detection is 1.0% per photon [55], and 4.0% is assigned for two π^0 mesons. The uncertainty of the radiative correction includes two parts. The first one stems from the precision of the ISR calculation in the generator KKMC [56], which is 0.5%. The other one is from $(1 + \delta^{\text{ISR}})$ and ϵ in Eq. (1), relying on the input line shape of cross sections. To estimate the uncertainty, the $(1 + \delta^{\text{ISR}}) \cdot \epsilon$ is evaluated for 100 times by varying the input line shape within the uncertainties and the covariance matrix obtained from the nominal cross section line shape fit. The standard deviation of the $(1 + \delta^{\text{ISR}}) \cdot \epsilon$ distribution is taken as the systematic uncertainty of the radiative correction. The uncertainty associated with the J/ψ mass requirement is estimated by smearing the $M(\ell^+\ell^-)$ distribution of the MC sample with a Gaussian function, which represents the resolution difference between data and MC simulation, and the resulting signal efficiency variation is taken as the systematic uncertainty. The same procedure is applied to the π^0 mass requirement to estimate the related systematic uncertainty. For the systematic uncertainty from the kinematic fit, the helix parameters of the charged tracks are corrected to make the pull distribution of MC sample more consistent with the data and the signal efficiency is re-evaluated, and the resultant difference is taken as the uncertainty. To estimate the systematic uncertainty of the MC modeling, the signal efficiency is reevaluated using 200 regenerated MC samples in which the PWA parameters are varied within their uncertainties, while taking into account the correlations among these parameters through their full covariance matrix. The standard deviation of the signal efficiency distribution is taken as the systematic uncertainty. The systematic uncertainties related to the fit procedure are estimated by replacing the first-order polynomial function by a second-order polynomial function for the background shape and varying the resolution of the convolved Gaussian function for the signal shape by one standard deviation. Following the “Barlow-test” method in Refs. [57,58], the systematic uncertainty related to the fit range is found to be negligible. The uncertainties from the other selections, trigger simulation, event start time determination, and FSR simulation and other sources are conservatively taken as 1.0%. All the systematic uncertainties are summarized in Table III. Assuming all sources of systematic uncertainties are independent, the total uncertainties in the cross section measurement are obtained

TABLE III. The summary of the relative systematic uncertainties (in unit of %) at different energy points from different sources. The L_{int} denotes integral luminosity, $\mathcal{B}$ denotes branching fraction, and Track I and Track II denote charged and neutral tracks, respectively.

$\sqrt{s}$ (GeV)	4.1784	4.2263	4.3583	4.4156	4.6819
$L_{\text{int}}^{\text{a}}$	1.0	1.0	1.0	1.0	1.0
$\mathcal{B}^{\text{a}}$	1.0	1.0	1.0	1.0	1.0
Track I ^a	4.0	4.0	4.0	4.0	4.0
Track II ^a	4.0	4.0	4.0	4.0	4.0
ISR correction	0.9	2.3	1.2	1.8	3.7
J/ψ mass	0.6	0.6	0.2	0.1	0.8
π^0 mass	0.4	0.6	0.2	0.1	0.1
Kinematic fit	0.5	0.5	0.4	0.5	0.4
MC model	1.2	1.9	1.0	1.3	1.7
Signal shape	0.6	0.5	0.5	0.2	0.6
Background shape	0.0	0.1	0.0	0.2	0.2
Others ^a	1.0	1.0	1.0	1.0	1.0
Total	6.2	6.7	6.2	6.3	7.2

^aThe sources are the common systematic uncertainties for all the energy points.

by summing the individual uncertainties in quadrature, which range from 6.2% to 7.2%.

B. Systematic uncertainties of resonant parameter measurement

The systematic uncertainties of the resonant parameters from the fit to the cross section line shape are as follows. The systematic uncertainty associated with the collision energy is conservatively estimated to be 0.8 MeV [59,60]. It is common for all data samples and causes a global shift for the masses of the resonances. The uncertainty due to the energy spread is estimated by convolving the fit probability density function with a Gaussian function with a resolution of 1.6 MeV, which is the energy spread determined by the beam energy measurement system [61]. The uncertainty from the statistical uncertainties of the cross sections is estimated by incorporating the correlated and uncorrelated systematic uncertainties of the measured cross sections in the fit following the likelihood construction method in Ref. [28]. In the nominal fit, the mass and width of $Y(4230)$ are fixed to the values from Ref. [22]. To estimate the relevant systematic uncertainty, the mass and width of $Y(4230)$ are varied within their uncertainties. The resultant differences of each parameter are taken as the systematic uncertainties. To estimate the uncertainty related to the parametrization of the nonresonant part in the fit model, the nonresonant part in Eq. (4) is replaced by a function of $\psi_{\text{cont}} = \sqrt{\Phi(\sqrt{s})}e^{-p_0 u}p_1$ in Refs. [11,17] with p_0 and p_1 as free parameters, and $u = \sqrt{s} - (2M(\pi^\pm) + M(\psi(3686)))$. The cross section line shape fit is performed with the above scenario individually, and the resulting differences are taken as the systematic uncertainties as

TABLE IV. The summary of absolute systematic uncertainties of resonant parameters in the fit to the cross sections of the $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ process, including the c.m. energy $\sqrt{s}$, the energy spread (Ene. spread), the fit model, the parameters of $Y(4230)$, and the systematic uncertainty in the cross section measurement (Cross section). The ... represents that the uncertainty is negligible.

Source	Solution	$\sqrt{s}$	Ene. spread	Model	$Y(4230)$	Cross section	Total
$M(Y(4390))$ (MeV/ c^2)	-	0.8	0.0	0.4	1.5	0.4	1.9
$\Gamma(Y(4390))$ (MeV)	-	...	0.0	0.8	4.7	0.8	4.8
$M(Y(4660))$ (MeV/ c^2)	-	0.8	0.0	0.1	0.4	1.7	1.9
$\Gamma(Y(4660))$ (MeV)	-	...	0.0	3.0	5.5	6.6	9.1
$\mathcal{B}\Gamma^{e^+e^-}(Y(4230))$ (eV)	I	...	0.00	0.00	0.37	0.00	0.37
	II	...	0.00	0.00	0.01	0.00	0.01
	III	...	0.00	0.00	0.43	0.00	0.43
	IV	...	0.00	0.00	0.01	0.00	0.01
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	I	...	0.00	0.10	0.55	0.10	0.57
	II	...	0.00	0.08	0.34	0.09	0.36
	III	...	0.01	0.06	0.76	0.02	0.76
	IV	...	0.01	0.02	0.08	0.01	0.09
$\mathcal{B}\Gamma^{e^+e^-}(Y(4660))$ (eV)	I	...	0.00	0.05	0.09	0.09	0.14
	II	...	0.00	0.05	0.09	0.08	0.13
	III	...	0.01	0.14	0.33	0.15	0.39
	IV	...	0.01	0.12	0.11	0.15	0.23

shown in Table IV. The total systematic uncertainty is obtained by quadratically summing the individual systematic uncertainties in quadrature, under the assumption that they are uncorrelated.

VII. CONCLUSIONS

The cross sections of the process $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ are measured at c.m. energies between 4.008 and 4.951 GeV using data samples with a total integrated luminosity of 22.1 fb⁻¹ collected with the BESIII detector operating at the BEPCII. The measured cross sections are found to be approximately one-half of those of the charged channel $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ [22], which are consistent with the expectation from isospin symmetry.

The dressed cross sections are fitted with a coherent sum of three resonant structures, $Y(4230)$, $Y(4390)$, and $Y(4660)$, as well as the same nonresonant component as used in the charged channel. The statistical significances of $Y(4390)$ and $Y(4660)$ are larger than 5σ , which confirm the existence of these two states in the $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$ process. The mass and width of $Y(4390)$ are measured to be $4383.0 \pm 8.6 \pm 1.9$ MeV/ c^2 , $117.4 \pm 20.7 \pm 4.8$ MeV, and those of $Y(4660)$ are $4684.0 \pm 17.3 \pm 1.9$ MeV/ c^2 , $119.5 \pm 47.1 \pm 9.1$ MeV, where the first uncertainties are statistical and the second are systematic. The parameters of the resonant structures are consistent with the results from the charged channel within uncertainties. The results from this work provide valuable information for the studies of the charmoniumlike states and the nature of the XYZ particles.

ACKNOWLEDGMENTS

The BESIII Collaboration thanks the staff of BEPCII [62], the IHEP computing center, and the supercomputing center of the University of Science and Technology of China (USTC) for their strong support. This work is supported in part by National Key R&D Program of China under Contracts No. 2025YFA1613900, No. 2023YFA1609400, No. 2023YFA1606000, and No. 2023YFA1606704; National Natural Science Foundation of China (NSFC) under Contracts No. 12122509, No. 12105276, 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, and No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the Strategic Priority Research Program of Chinese Academy of Sciences under Contract No. XDA0480600; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U2032111; 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; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174 and 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; STFC (United Kingdom); Swedish Research Council under Contract

No. 2019.04595; and U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] T. Barnes, S. Godfrey, and E. S. Swanson, *Phys. Rev. D* **72**, 054026 (2005).
 - [2] H. Chen, W. Chen, X. Liu, and S. Zhu, *Phys. Rep.* **639**, 1 (2016).
 - [3] F. K. Guo, C. Hanhart, U. G. Meißner, Q. Wang, Q. Zhao, and B. S. Zou, *Rev. Mod. Phys.* **90**, 015004 (2018).
 - [4] N. Brambilla *et al.*, *Phys. Rep.* **873**, 1 (2020).
 - [5] Z. G. Wang, *Front. Phys. (Beijing)* **21**, 016300 (2026).
 - [6] D. Chen, X. Liu, and T. Matsuki, *Phys. Rev. D* **93**, 034028 (2016).
 - [7] X. Wang, X. Liu, and Y. Gao, *arXiv:2502.15117*.
 - [8] S. Nakamura, X. H. Li, H. P. Peng, Z. T. Sun, and X. R. Zhou, *Phys. Rev. D* **112**, 054027 (2025).
 - [9] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **95**, 142001 (2005).
 - [10] C. Z. Yuan *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 182004 (2007).
 - [11] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **86**, 051102 (2012).
 - [12] Z. Q. Liu *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **110**, 252002 (2013); **111**, 019901(E) (2013).
 - [13] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **98**, 212001 (2007).
 - [14] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **89**, 111103 (2014).
 - [15] X. L. Wang *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 142002 (2007).
 - [16] X. L. Wang *et al.* (Belle Collaboration), *Phys. Rev. D* **91**, 112007 (2015).
 - [17] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **118**, 092001 (2017).
 - [18] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **102**, 012009 (2020).
 - [19] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **107**, 092005 (2023).
 - [20] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **46**, 111002 (2022).
 - [21] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **96**, 032004 (2017); **99**, 019903(E) (2019).
 - [22] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **104**, 052012 (2021).
 - [23] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **118**, 092002 (2017).
 - [24] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **114**, 092003 (2015).
 - [25] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **99**, 091103 (2019).
 - [26] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **122**, 102002 (2019).
 - [27] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **102**, 031101 (2020).
 - [28] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **109**, 092012 (2024).
 - [29] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **129**, 102003 (2022).
 - [30] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **97**, 052001 (2018).
 - [31] M. Ablikim *et al.* (BESIII Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 345 (2010).
 - [32] C. Yu *et al.*, in *Proceedings of the 7th International Particle Accelerator Conference*, Vol. IPAC2016 (JACoW, Geneva, Switzerland, 2016).
 - [33] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **44**, 040001 (2020).
 - [34] J. Lu, Y. Xiao, and X. Ji, *Radiat. Detect. Technol. Methods* **4**, 337 (2020).
 - [35] J. W. Zhang *et al.*, *Radiat. Detect. Technol. Methods* **6**, 289 (2022).
 - [36] X. Li *et al.*, *Radiat. Detect. Technol. Methods* **1**, 13 (2017).
 - [37] Y. X. Guo *et al.*, *Radiat. Detect. Technol. Methods* **1**, 15 (2017).
 - [38] P. Cao *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **953**, 163053 (2020).
 - [39] S. Agostinelli *et al.* (Geant4 Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
 - [40] S. Jadach, B. F. L. Ward, and Z. Wąs, *Phys. Rev. D* **63**, 113009 (2001).
 - [41] D. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
 - [42] R. G. Ping, *Chin. Phys. C* **32**, 599 (2008).
 - [43] S. Navas *et al.* (Particle Data Group), *Phys. Rev. D* **110**, 030001 (2024).
 - [44] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, *Phys. Rev. D* **62**, 034003 (2000).
 - [45] R. L. Yang, R. G. Ping, and H. Chen, *Chin. Phys. C* **31**, 061301 (2014).
 - [46] E. Barberio, B. van Eijk, and Z. Wąs, *Comput. Phys. Commun.* **66**, 115 (1991).
 - [47] S. Actis *et al.*, *Eur. Phys. J. C* **66**, 585 (2010).

- [48] W. Sun, T. Liu, M. Jing, L. Wang, B. Zhong, and W. Song, *Front. Phys. (Beijing)* **16**, 64501 (2021).
- [49] G. D'Agostini, *Rep. Prog. Phys.* **66**, 1383 (2003).
- [50] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **46**, 113003 (2022).
- [51] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **39**, 093001 (2015).
- [52] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **46**, 113002 (2022).
- [53] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **110**, 252001 (2013).
- [54] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **83**, 112005 (2011).
- [55] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. D* **81**, 052005 (2010).
- [56] R. G. Ping, *Chin. Phys. C* **38**, 083001 (2014).
- [57] R. Barlow, [arXiv:hep-ex/0207026](https://arxiv.org/abs/hep-ex/0207026).
- [58] M. Ablikim *et al.* (BESIII Collaboration), *Nature (London)* **606**, 64 (2022).
- [59] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **40**, 063001 (2016).
- [60] M. Ablikim *et al.* (BESIII Collaboration), *Chin. Phys. C* **45**, 103001 (2021).
- [61] E. V. Abakumova *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **659**, 21 (2011).
- [62] <https://cstr.cn/31109.02.BEPC>.

M. Ablikim¹, M. N. Achasov^{4,d}, P. Adlarson⁸¹, X. C. Ai⁸⁶, R. Aliberti³⁹, A. Amoroso^{80a,80c}, Q. An^{77,64,a}, Y. Bai⁶², O. Bakina⁴⁰, Y. Ban^{50,i}, H.-R. Bao⁷⁰, V. Batozskaya^{1,48}, K. Begzsuren³⁵, N. Berger³⁹, M. Berowski⁴⁸, M. B. Bertani^{30a}, D. Bettoni^{31a}, F. Bianchi^{80a,80c}, E. Bianco^{80a,80c}, A. Bortone^{80a,80c}, I. Boyko⁴⁰, R. A. Briere⁵, A. Brueggemann⁷⁴, H. Cai⁸², M. H. Cai^{42,l,m}, X. Cai^{1,64}, A. Calcaterra^{30a}, G. F. Cao^{1,70}, N. Cao^{1,70}, S. A. Cetin^{68a}, X. Y. Chai^{50,i}, J. F. Chang^{1,64}, T. T. Chang⁴⁷, G. R. Che⁴⁷, Y. Z. Che^{1,64,70}, C. H. Chen¹⁰, Chao Chen⁶⁰, G. Chen¹, H. S. Chen^{1,70}, H. Y. Chen²¹, M. L. Chen^{1,64,70}, S. J. Chen⁴⁶, S. M. Chen⁶⁷, T. Chen^{1,70}, X. R. Chen^{34,70}, X. T. Chen^{1,70}, X. Y. Chen^{12,h}, Y. B. Chen^{1,64}, Y. Q. Chen¹⁶, Z. K. Chen⁶⁵, J. C. Cheng⁴⁹, L. N. Cheng⁴⁷, S. K. Choi¹¹, X. Chu^{12,h}, G. Cibinetto^{31a}, F. Cossio^{80c}, J. Cotte-Meldrum⁶⁹, H. L. Dai^{1,64}, J. P. Dai⁸⁴, X. C. Dai⁶⁷, A. Dbeyssi¹⁹, R. E. de Boer³, D. Dedovich⁴⁰, C. Q. Deng⁷⁸, Z. Y. Deng¹, A. Denig³⁹, I. Denisenko⁴⁰, M. Destefanis^{80a,80c}, F. De Mori^{80a,80c}, X. X. Ding^{50,i}, Y. Ding⁴⁴, Y. X. Ding³², J. Dong^{1,64}, L. Y. Dong^{1,70}, M. Y. Dong^{1,64,70}, X. Dong⁸², M. C. Du¹, S. X. Du⁸⁶, S. X. Du^{12,h}, X. L. Du⁸⁶, Y. Y. Duan⁶⁰, Z. H. Duan⁴⁶, P. Egorov^{40,c}, G. F. Fan⁴⁶, J. J. Fan²⁰, Y. H. Fan⁴⁹, J. Fang^{1,64}, J. Fang⁶⁵, S. S. Fang^{1,70}, W. X. Fang¹, Y. Q. Fang^{1,64,a}, L. Fava^{80b,80c}, F. Feldbauer³, G. Felici^{30a}, C. Q. Feng^{77,64}, J. H. Feng¹⁶, L. Feng^{42,l,m}, Q. X. Feng^{42,l,m}, Y. T. Feng^{77,64}, M. Fritsch³, C. D. Fu¹, J. L. Fu⁷⁰, Y. W. Fu^{1,70}, H. Gao⁷⁰, Y. Gao^{77,64}, Y. N. Gao^{50,i}, Y. N. Gao²⁰, Y. Y. Gao³², Z. Gao⁴⁷, S. Garbolino^{80c}, I. Garzia^{31a,31b}, L. Ge⁶², P. T. Ge²⁰, Z. W. Ge⁴⁶, C. Geng⁶⁵, E. M. Gersabeck⁷³, A. Gilman⁷⁵, K. Goetzen¹³, J. D. Gong³⁸, L. Gong⁴⁴, W. X. Gong^{1,64}, W. Gradl³⁹, S. Gramigna^{31a,31b}, M. Greco^{80a,80c}, M. D. Gu⁵⁵, M. H. Gu^{1,64}, C. Y. Guan^{1,70}, A. Q. Guo³⁴, J. N. Guo^{12,h}, L. B. Guo⁴⁵, M. J. Guo⁵⁴, R. P. Guo⁵³, X. Guo⁵⁴, Y. P. Guo^{12,h}, A. Guskov^{40,c}, J. Gutierrez²⁹, T. T. Han¹, F. Hanisch³, K. D. Hao^{77,64}, X. Q. Hao²⁰, F. A. Harris⁷¹, C. Z. He^{50,i}, K. L. He^{1,70}, F. H. Heinsius³, C. H. Heinz³⁹, Y. K. Heng^{1,64,70}, C. Herold⁶⁶, P. C. Hong³⁸, G. Y. Hou^{1,70}, X. T. Hou^{1,70}, Y. R. Hou⁷⁰, Z. L. Hou¹, H. M. Hu^{1,70}, J. F. Hu^{61,k}, Q. P. Hu^{77,64}, S. L. Hu^{12,h}, T. Hu^{1,64,70}, Y. Hu¹, Z. M. Hu⁶⁵, G. S. Huang^{77,64}, K. X. Huang⁶⁵, L. Q. Huang^{34,70}, P. Huang⁴⁶, X. T. Huang⁵⁴, Y. P. Huang¹, Y. S. Huang⁶⁵, T. Hussain⁷⁹, N. Hüskens³⁹, N. in der Wiesche⁷⁴, J. Jackson²⁹, Q. Ji¹, Q. P. Ji²⁰, W. Ji^{1,70}, X. B. Ji^{1,70}, X. L. Ji^{1,64}, X. Q. Jia⁵⁴, Z. K. Jia^{77,64}, D. Jiang^{1,70}, H. B. Jiang⁸², P. C. Jiang^{50,i}, S. J. Jiang¹⁰, X. S. Jiang^{1,64,70}, J. B. Jiao⁵⁴, J. K. Jiao³⁸, Z. Jiao²⁵, L. C. L. Jin¹, S. Jin⁴⁶, Y. Jin⁷², M. Q. Jing^{1,70}, X. M. Jing⁷⁰, T. Johansson⁸¹, S. Kabana³⁶, X. L. Kang¹⁰, X. S. Kang⁴⁴, B. C. Ke⁸⁶, V. Khachatryan²⁹, A. Khoukaz⁷⁴, O. B. Kolcu^{68a}, B. Kopf³, L. Kröger⁷⁴, M. Kuessner³, X. Kui^{1,70}, N. Kumar²⁸, A. Kupsc^{48,81}, W. Kühn⁴¹, Q. Lan⁷⁸, W. N. Lan²⁰, T. T. Lei^{77,64}, M. Lellmann³⁹, T. Lenz³⁹, C. Li⁵¹, C. Li⁴⁷, C. H. Li⁴⁵, C. K. Li²¹, D. M. Li⁸⁶, F. Li^{1,64}, G. Li¹, H. B. Li^{1,70}, H. J. Li²⁰, H. L. Li⁸⁶, H. N. Li^{61,k}, Hui Li⁴⁷, J. R. Li⁶⁷, J. S. Li⁶⁵, J. W. Li⁵⁴, K. Li¹, K. L. Li^{42,l,m}, L. J. Li^{1,70}, Lei Li⁵², M. H. Li⁴⁷, M. R. Li^{1,70}, P. L. Li⁷⁰, P. R. Li^{42,l,m}, Q. M. Li^{1,70}, Q. X. Li⁵⁴, R. Li^{18,34}, S. X. Li¹², Shanshan Li^{27,j}, T. Li⁵⁴, T. Y. Li⁴⁷, W. D. Li^{1,70}, W. G. Li^{1,a}, X. Li^{1,70}, X. H. Li^{77,64}, X. K. Li^{50,i}, X. L. Li⁵⁴, X. Y. Li^{1,9}, X. Z. Li⁶⁵, Y. Li²⁰, Y. G. Li⁷⁰, Y. P. Li³⁸, Z. H. Li⁴², Z. J. Li⁶⁵, Z. X. Li⁴⁷, Z. Y. Li⁸⁴, C. Liang⁴⁶, H. Liang^{77,64}, Y. F. Liang⁵⁹, Y. T. Liang^{34,70}, G. R. Liao¹⁴, L. B. Liao⁶⁵, M. H. Liao⁶⁵, Y. P. Liao^{1,70}, J. Libby²⁸, A. Limphirat⁶⁶, D. X. Lin^{34,70}, L. Q. Lin⁴³, T. Lin¹, B. J. Liu¹, B. X. Liu⁸², C. X. Liu¹, F. Liu¹, F. H. Liu⁵⁸

Feng Liu⁶, G. M. Liu^{61,k}, H. Liu^{42,l,m}, H. B. Liu¹⁵, H. M. Liu^{1,70}, Huihui Liu²², J. B. Liu^{77,64}, J. J. Liu²¹,
 K. Liu^{42,l,m}, K. Liu⁷⁸, K. Y. Liu⁴⁴, Ke Liu²³, L. Liu⁴², L. C. Liu⁴⁷, Lu Liu⁴⁷, M. H. Liu³⁸, P. L. Liu¹,
 Q. Liu⁷⁰, S. B. Liu^{77,64}, W. M. Liu^{77,64}, W. T. Liu⁴³, X. Liu^{42,l,m}, X. K. Liu^{42,l,m}, X. L. Liu^{12,h}, X. Y. Liu⁸²,
 Y. Liu^{42,l,m}, Y. Liu⁸⁶, Y. B. Liu⁴⁷, Z. A. Liu^{1,64,70}, Z. D. Liu¹⁰, Z. Q. Liu⁵⁴, Z. Y. Liu⁴², X. C. Lou^{1,64,70},
 H. J. Lu²⁵, J. G. Lu^{1,64}, X. L. Lu¹⁶, Y. Lu⁷, Y. H. Lu^{1,70}, Y. P. Lu^{1,64}, Z. H. Lu^{1,70}, C. L. Luo⁴⁵, J. R. Luo⁶⁵,
 J. S. Luo^{1,70}, M. X. Luo⁸⁵, T. Luo^{12,h}, X. L. Luo^{1,64}, Z. Y. Lv²³, X. R. Lyu^{70,p}, Y. F. Lyu⁴⁷, Y. H. Lyu⁸⁶,
 F. C. Ma⁴⁴, H. L. Ma¹, Heng Ma^{27,j}, J. L. Ma^{1,70}, L. L. Ma⁵⁴, L. R. Ma⁷², Q. M. Ma¹, R. Q. Ma^{1,70},
 R. Y. Ma²⁰, T. Ma^{77,64}, X. T. Ma^{1,70}, X. Y. Ma^{1,64}, Y. M. Ma³⁴, F. E. Maas¹⁹, I. MacKay⁷⁵, M. Maggiora^{80a,80c},
 S. Malde⁷⁵, Q. A. Malik⁷⁹, H. X. Mao^{42,l,m}, Y. J. Mao^{50,i}, Z. P. Mao¹, S. Marcello^{80a,80c}, A. Marshall⁶⁹,
 F. M. Melendi^{31a,31b}, Y. H. Meng⁷⁰, Z. X. Meng⁷², G. Mezzadri^{31a}, H. Miao^{1,70}, T. J. Min⁴⁶, T. Mineeva⁸⁷,
 R. E. Mitchell²⁹, X. H. Mo^{1,64,70}, B. Moses²⁹, N. Yu. Muchnoi^{4,d}, J. Muskalla³⁹, Y. Nefedov⁴⁰, F. Nerling^{19,f},
 H. Neuwirth⁷⁴, Z. Ning^{1,64}, S. Nisar^{33,b}, Q. L. Niu^{42,l,m}, W. D. Niu^{12,h}, Y. Niu⁵⁴, C. Normand⁶⁹, S. L. Olsen^{11,70},
 Q. Ouyang^{1,64,70}, S. Pacetti^{30b,30c}, X. Pan⁶⁰, Y. Pan⁶², A. Pathak¹¹, Y. P. Pei^{77,64}, M. Pelizaes³, H. P. Peng^{77,64},
 X. J. Peng^{42,l,m}, Y. Y. Peng^{42,l,m}, K. Peters^{13,f}, K. Petridis⁶⁹, J. L. Ping⁴⁵, R. G. Ping^{1,70}, S. Plura³⁹, V. Prasad³⁸,
 F. Z. Qi¹, H. R. Qi⁶⁷, M. Qi⁴⁶, S. Qian^{1,64}, W. B. Qian⁷⁰, C. F. Qiao⁷⁰, J. H. Qiao²⁰, J. J. Qin⁷⁸, J. L. Qin⁶⁰,
 L. Q. Qin¹⁴, L. Y. Qin^{77,64}, P. B. Qin⁷⁸, X. P. Qin⁴³, X. S. Qin⁵⁴, Z. H. Qin^{1,64}, J. F. Qiu¹, Z. H. Qu⁷⁸,
 J. Rademacker⁶⁹, C. F. Redmer³⁹, A. Rivetti^{80c}, M. Rolo^{80c}, G. Rong^{1,70}, S. S. Rong^{1,70}, F. Rosini^{30b,30c},
 Ch. Rosner¹⁹, M. Q. Ruan^{1,64}, N. Salone^{48,q}, A. Sarantsev^{40,e}, Y. Schelhaas³⁹, K. Schoenning⁸¹,
 M. Scodeggio^{31a}, W. Shan²⁶, X. Y. Shan^{77,64}, Z. J. Shang^{42,l,m}, J. F. Shangguan¹⁷, L. G. Shao^{1,70}, M. Shao^{77,64},
 C. P. Shen^{12,h}, H. F. Shen^{1,9}, W. H. Shen⁷⁰, X. Y. Shen^{1,70}, B. A. Shi⁷⁰, H. Shi^{77,64}, J. L. Shi^{8,r}, J. Y. Shi¹,
 S. Y. Shi⁷⁸, X. Shi^{1,64}, H. L. Song^{77,64}, J. J. Song²⁰, M. H. Song⁴², T. Z. Song⁶⁵, W. M. Song³⁸, Y. X. Song^{50,i,n},
 Zirong Song^{27,j}, S. Sosio^{80a,80c}, S. Spataro^{80a,80c}, S. Stansilaus⁷⁵, F. Stieler³⁹, S. S. Su⁴⁴, G. B. Sun⁸², G. X. Sun¹,
 H. Sun⁷⁰, H. K. Sun¹, J. F. Sun²⁰, K. Sun⁶⁷, L. Sun⁸², R. Sun⁷⁷, S. S. Sun^{1,70}, T. Sun^{56,g}, W. Y. Sun⁵⁵,
 Y. C. Sun⁸², Y. H. Sun³², Y. J. Sun^{77,64}, Y. Z. Sun¹, Z. Q. Sun^{1,70}, Z. T. Sun⁵⁴, C. J. Tang⁵⁹, G. Y. Tang¹,
 J. Tang⁶⁵, J. J. Tang^{77,64}, L. F. Tang⁴³, Y. A. Tang⁸², L. Y. Tao⁷⁸, M. Tat⁷⁵, J. X. Teng^{77,64}, J. Y. Tian^{77,64},
 W. H. Tian⁶⁵, Y. Tian³⁴, Z. F. Tian⁸², I. Uman^{68b}, B. Wang¹, B. Wang⁶⁵, Bo Wang^{77,64}, C. Wang^{42,l,m},
 C. Wang²⁰, Cong Wang²³, D. Y. Wang^{50,i}, H. J. Wang^{42,l,m}, J. Wang¹⁰, J. J. Wang⁸², J. P. Wang³⁷, K. Wang^{1,64},
 L. L. Wang¹, L. W. Wang³⁸, M. Wang⁵⁴, M. Wang^{77,64}, N. Y. Wang⁷⁰, S. Wang^{42,l,m}, Shun Wang⁶³,
 T. Wang^{12,h}, T. J. Wang⁴⁷, W. Wang⁶⁵, W. P. Wang³⁹, X. Wang^{50,i}, X. F. Wang^{42,l,m}, X. L. Wang^{12,h},
 X. N. Wang^{1,70}, Xin Wang^{27,j}, Y. Wang¹, Y. D. Wang⁴⁹, Y. F. Wang^{1,9,70}, Y. H. Wang^{42,l,m}, Y. J. Wang^{77,64},
 Y. L. Wang²⁰, Y. N. Wang⁴⁹, Y. N. Wang⁸², Yaqian Wang¹⁸, Yi Wang⁶⁷, Yuan Wang^{18,34}, Z. Wang^{1,64},
 Z. Wang⁴⁷, Z. L. Wang², Z. Q. Wang^{12,h}, Z. Y. Wang^{1,70}, Ziyi Wang⁷⁰, D. Wei⁴⁷, D. H. Wei¹⁴, H. R. Wei⁴⁷,
 F. Weidner⁷⁴, S. P. Wen¹, U. Wiedner³, G. Wilkinson⁷⁵, M. Wolke⁸¹, J. F. Wu^{1,9}, L. H. Wu¹, L. J. Wu²⁰,
 Lianjie Wu²⁰, S. G. Wu^{1,70}, S. M. Wu⁷⁰, X. W. Wu⁷⁸, Y. J. Wu³⁴, Z. Wu^{1,64}, L. Xia^{77,64}, B. H. Xiang^{1,70},
 D. Xiao^{42,l,m}, G. Y. Xiao⁴⁶, H. Xiao⁷⁸, Y. L. Xiao^{12,h}, Z. J. Xiao⁴⁵, C. Xie⁴⁶, K. J. Xie^{1,70}, Y. Xie⁵⁴,
 Y. G. Xie^{1,64}, Y. H. Xie⁶, Z. P. Xie^{77,64}, T. Y. Xing^{1,70}, C. J. Xu⁶⁵, G. F. Xu¹, H. Y. Xu², M. Xu^{77,64}, Q. J. Xu¹⁷,
 Q. N. Xu³², T. D. Xu⁷⁸, X. P. Xu⁶⁰, Y. Xu^{12,h}, Y. C. Xu⁸³, Z. S. Xu⁷⁰, F. Yan²⁴, L. Yan^{12,h}, W. B. Yan^{77,64},
 W. C. Yan⁸⁶, W. H. Yan⁶, W. P. Yan²⁰, X. Q. Yan^{12,h}, Y. Y. Yan⁶⁶, H. J. Yang^{56,g}, H. L. Yang³⁸, H. X. Yang¹,
 J. H. Yang⁴⁶, R. J. Yang²⁰, Y. Yang^{12,h}, Y. H. Yang⁴⁶, Y. Q. Yang¹⁰, Y. Z. Yang²⁰, Z. P. Yao⁵⁴, M. Ye^{1,64},
 M. H. Ye^{9,a}, Z. J. Ye^{61,k}, Junhao Yin⁴⁷, Z. Y. You⁶⁵, B. X. Yu^{1,64,70}, C. X. Yu⁴⁷, G. Yu¹³, J. S. Yu^{27,j},
 L. W. Yu^{12,h}, T. Yu⁷⁸, X. D. Yu^{50,i}, Y. C. Yu⁸⁶, Y. C. Yu⁴², C. Z. Yuan^{1,70}, H. Yuan^{1,70}, J. Yuan³⁸, J. Yuan⁴⁹,
 L. Yuan², M. K. Yuan^{12,h}, S. H. Yuan⁷⁸, Y. Yuan^{1,70}, C. X. Yue⁴³, Ying Yue²⁰, A. A. Zafar⁷⁹, F. R. Zeng⁵⁴,
 S. H. Zeng⁶⁹, X. Zeng^{12,h}, Yujie Zeng⁶⁵, Y. J. Zeng^{1,70}, Y. C. Zhai⁵⁴, Y. H. Zhan⁶⁵, Shunan Zhang⁷⁵,
 B. L. Zhang^{1,70}, B. X. Zhang^{1,a}, D. H. Zhang⁴⁷, G. Y. Zhang²⁰, G. Y. Zhang^{1,70}, H. Zhang^{77,64}, H. Zhang⁸⁶,
 H. C. Zhang^{1,64,70}, H. H. Zhang⁶⁵, H. Q. Zhang^{1,64,70}, H. R. Zhang^{77,64}, H. Y. Zhang^{1,64}, J. Zhang⁶⁵,
 J. J. Zhang⁵⁷, J. L. Zhang²¹, J. Q. Zhang⁴⁵, J. S. Zhang^{12,h}, J. W. Zhang^{1,64,70}, J. X. Zhang^{42,l,m}, J. Y. Zhang¹,
 J. Z. Zhang^{1,70}, Jianyu Zhang⁷⁰, L. M. Zhang⁶⁷, Lei Zhang⁴⁶, N. Zhang³⁸, P. Zhang^{1,9}, Q. Zhang²⁰,
 Q. Y. Zhang³⁸, R. Y. Zhang^{42,l,m}, S. H. Zhang^{1,70}, Shulei Zhang^{27,j}, X. M. Zhang¹, X. Y. Zhang⁵⁴, Y. Zhang¹

Y. Zhang⁷⁸, Y. T. Zhang⁸⁶, Y. H. Zhang^{1,64}, Y. P. Zhang^{77,64}, Z. D. Zhang¹, Z. H. Zhang¹, Z. L. Zhang³⁸,
 Z. L. Zhang⁶⁰, Z. X. Zhang²⁰, Z. Y. Zhang⁸², Z. Y. Zhang⁴⁷, Z. Z. Zhang⁴⁹, Zh. Zh. Zhang²⁰, G. Zhao¹,
 J. Y. Zhao^{1,70}, J. Z. Zhao^{1,64}, L. Zhao¹, L. Zhao^{77,64}, M. G. Zhao⁴⁷, S. J. Zhao⁸⁶, Y. B. Zhao^{1,64}, Y. L. Zhao⁶⁰,
 Y. X. Zhao^{34,70}, Z. G. Zhao^{77,64}, A. Zhemchugov^{40,c}, B. Zheng⁷⁸, B. M. Zheng³⁸, J. P. Zheng^{1,64}, W. J. Zheng^{1,70},
 X. R. Zheng²⁰, Y. H. Zheng^{70,p}, B. Zhong⁴⁵, C. Zhong²⁰, H. Zhou^{39,54,o}, J. Q. Zhou³⁸, S. Zhou⁶, X. Zhou⁸²,
 X. K. Zhou⁶, X. R. Zhou^{77,64}, X. Y. Zhou⁴³, Y. X. Zhou⁸³, Y. Z. Zhou^{12,h}, A. N. Zhu⁷⁰, J. Zhu⁴⁷, K. Zhu¹,
 K. J. Zhu^{1,64,70}, K. S. Zhu^{12,h}, L. X. Zhu⁷⁰, Lin Zhu²⁰, S. H. Zhu⁷⁶, T. J. Zhu^{12,h}, W. D. Zhu^{12,h}, W. J. Zhu¹,
 W. Z. Zhu²⁰, Y. C. Zhu^{77,64}, Z. A. Zhu^{1,70}, X. Y. Zhuang⁴⁷ and J. H. Zou¹

(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, 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, 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, University Road, 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*

- ⁴³Liaoning Normal University, Dalian 116029, People's Republic of China
⁴⁴Liaoning University, Shenyang 110036, People's Republic of China
⁴⁵Nanjing Normal University, Nanjing 210023, People's Republic of China
⁴⁶Nanjing University, Nanjing 210093, People's Republic of China
⁴⁷Nankai University, Tianjin 300071, People's Republic of China
⁴⁸National Centre for Nuclear Research, Warsaw 02-093, Poland
⁴⁹North China Electric Power University, Beijing 102206, People's Republic of China
⁵⁰Peking University, Beijing 100871, People's Republic of China
⁵¹Qufu Normal University, Qufu 273165, People's Republic of China
⁵²Renmin University of China, Beijing 100872, People's Republic of China
⁵³Shandong Normal University, Jinan 250014, People's Republic of China
⁵⁴Shandong University, Jinan 250100, People's Republic of China
⁵⁵Shandong University of Technology, Zibo 255000, People's Republic of China
⁵⁶Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
⁵⁷Shanxi Normal University, Linfen 041004, People's Republic of China
⁵⁸Shanxi University, Taiyuan 030006, People's Republic of China
⁵⁹Sichuan University, Chengdu 610064, People's Republic of China
⁶⁰Soochow University, Suzhou 215006, People's Republic of China
⁶¹South China Normal University, Guangzhou 510006, People's Republic of China
⁶²Southeast University, Nanjing 211100, People's Republic of China
⁶³Southwest University of Science and Technology, Mianyang 621010, People's Republic of China
⁶⁴State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China
⁶⁵Sun Yat-Sen University, Guangzhou 510275, People's Republic of China
⁶⁶Suranaree University of Technology, University Avenue 111, Nakhon Ratchasima 30000, Thailand
⁶⁷Tsinghua 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
⁶⁹University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, England, United Kingdom
⁷⁰University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
⁷¹University of Hawaii, Honolulu, Hawaii 96822, USA
⁷²University of Jinan, Jinan 250022, People's Republic of China
⁷³University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom
⁷⁴University of Muenster, Wilhelm-Klemm-Strasse 9, 48149 Muenster, Germany
⁷⁵University of Oxford, Keble Road, Oxford OX13RH, United Kingdom
⁷⁶University of Science and Technology Liaoning, Anshan 114051, People's Republic of China
⁷⁷University of Science and Technology of China, Hefei 230026, People's Republic of China
⁷⁸University of South China, Hengyang 421001, People's Republic of China
⁷⁹University 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
⁸¹Uppsala University, Box 516, SE-75120 Uppsala, Sweden
⁸²Wuhan University, Wuhan 430072, People's Republic of China
⁸³Yantai University, Yantai 264005, People's Republic of China
⁸⁴Yunnan University, Kunming 650500, People's Republic of China
⁸⁵Zhejiang University, Hangzhou 310027, People's Republic of China
⁸⁶Zhengzhou University, Zhengzhou 450001, People's Republic of China
⁸⁷University of La Serena, Av. Raúl Bitrán 1305, La Serena, Chile

^aDeceased.

^bAlso at Bogazici University, 34342 Istanbul, Turkey.

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

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

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

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

^gAlso 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.

^hAlso 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.

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

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

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

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

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

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

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

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

^qCurrently at Silesian University in Katowice, Chorzow, 41-500, Poland.

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