

## Observation of Resonance Structures in $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$ and Mass Measurement of $\psi_2(3823)$


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Using a data sample corresponding to an integrated luminosity of  $11.3 \text{ fb}^{-1}$  collected at center-of-mass energies from 4.23 to 4.70 GeV with the BESIII detector, we measure the product of the  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  cross section and the branching fraction  $\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}]$ . For the first time, resonance structure is observed in the cross section line shape of  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  with significances exceeding  $5\sigma$ . A fit to data with two coherent Breit-Wigner resonances modeling the  $\sqrt{s}$ -dependent cross section yields  $M(R_1) = 4406.9 \pm 17.2 \pm 4.5 \text{ MeV}/c^2$ ,  $\Gamma(R_1) = 128.1 \pm 37.2 \pm 2.3 \text{ MeV}$ , and  $M(R_2) = 4647.9 \pm 8.6 \pm 0.8 \text{ MeV}/c^2$ ,  $\Gamma(R_2) = 33.1 \pm 18.6 \pm 4.1 \text{ MeV}$ . Though weakly disfavored by the data, a single resonance with  $M(R) = 4417.5 \pm 26.2 \pm 3.5 \text{ MeV}/c^2$ ,  $\Gamma(R) = 245 \pm 48 \pm 13 \text{ MeV}$  is also

possible to interpret data. This observation deepens our understanding of the nature of the vector charmoniumlike states. The mass of the  $\psi_2(3823)$  state is measured as  $(3823.12 \pm 0.43 \pm 0.13)$  MeV/ $c^2$ , which is the most precise measurement to date.

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In the quark model, hadrons are strongly interacting, composite particles built from color-neutral combinations of quarks and antiquarks [1]. It was long thought that all observed hadrons fall into two classes only: baryons, composed of three quarks, and mesons, bound states of a quark-antiquark pair. The QCD theory describing the strong interaction also allowed for other color-neutral configurations, but there was no experimental evidence for such “exotic” hadrons.

This simple picture, however, has been challenged since 2003, when many new charmoniumlike states such as the  $\chi_{c1}(3872)$  [2],  $\psi(4260)$  [3], and  $Z_c(3900)$  [4,5] have been observed experimentally. These particles cannot easily be accommodated in the spectrum of conventional charmonium states and are widely considered to be promising candidates for QCD exotic hadrons [6,7]. Among them, the vector  $\psi$  states usually couple to hidden charm final states like  $J/\psi$ ,  $\psi(2S)$ , or  $h_c$  via dipion transitions, such as the  $\psi(4260) \rightarrow \pi^+\pi^-J/\psi$  [3,8,9],  $\psi(4360)/\psi(4660) \rightarrow \pi^+\pi^-\psi(2S)$  [10,11], and  $\psi(4390) \rightarrow \pi^+\pi^-h_c$  [12]. In addition, there are also vector states with mass above 4.6 GeV reported in  $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$  [13], and  $e^+e^- \rightarrow D_s^+D_{s1}^-(2536)/D_s^+D_{s2}^*(2573)^-$  processes [14]. At the moment, experimental information about these  $\psi$  states, especially for the high mass states is still quite limited. It is not clear whether  $\psi(4360)$  and  $\psi(4390)$  correspond to the same resonance or not. Above 4.6 GeV, the resonance parameters of vector states observed in hidden-charm and open-charm final states are not exactly the same. Whether there exists one or more resonances is a long-standing puzzle in the study of the vector charmoniumlike spectrum. To pin down these issues, new observations from experiment are urgently needed.

One of the vector states, the  $\psi(4660)$  resonance, was first observed by the Belle experiment [11] and later confirmed by the BABAR and BESIII experiments [15,16]. It remains, however, unclear what the exact nature is of the  $\psi(4660)$ . Possible interpretations of its internal structure include a hadronic molecule [17], a baryonium [18], or a compact tetraquark state [19]. For these theoretical models, the coupling of  $\psi(4660)$  to the  $\psi(2S)$  state with no or weak coupling to other charmonium states is an essential element. Therefore, a search for the decay of  $\psi(4660)$  to final state other than  $\psi(2S)$  in experiment helps to test various pictures for the  $\psi(4660)$  structure.

The  $D$ -wave charmonium state  $\psi_2(3823)$  [20,21] and  $\psi_3(3842)$  [22] were well established recently, and several decay modes of the  $\psi_2(3823)$  state are also observed [23].

It serves as a new probe to study the vector  $\psi$  states. We search for the dipion transition of  $\psi(4660)$  to  $\psi_2(3823)$ , which on the one hand helps establish the  $\psi(4660)$  state, and on the other hand sheds light on its internal structure. At the same time, the  $\psi_2(3823)$  mass is also precisely measured, which can be used to calibrate the parameters in the potential model [24], and finally greatly deepens our understanding of the dynamics of the  $c\bar{c}$  system.

In this Letter, we measure the  $\sqrt{s}$ -dependent production cross section of the process  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$ , and explore the resonance structures in the cross section line shape. The resonance parameters of the  $\psi_2(3823)$  state are measured as well. To increase the yield of signal events, a partial reconstruction approach is employed. We use a data sample corresponding to an integrated luminosity of  $11.3 \text{ fb}^{-1}$ , taken at center-of-mass (c.m.) energies from  $\sqrt{s} = 4.23$  to 4.70 GeV [25], with the BESIII detector [26] operating at the BEPCII storage ring [27]. The  $\psi_2(3823)$  candidates are reconstructed in their  $\gamma\chi_{c1}$  decay mode, with  $\chi_{c1} \rightarrow \gamma J/\psi$  and  $J/\psi \rightarrow \ell^+\ell^-$  ( $\ell = e$  or  $\mu$ ).

The BESIII detector is described in detail elsewhere [26,28]. A GEANT4-based [29] Monte Carlo (MC) simulation software package is used to optimize event selection criteria, determine the detection efficiency, and estimate the backgrounds. For the signal process, we generate 50 000  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  events at each c.m. energy using an EVTGEN [30] phase space model. Initial-state-radiation (ISR) is simulated with KKMC [31], where we use the  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  cross section measured from this analysis as input. The maximum ISR photon energy is set to correspond to the production threshold of the  $\pi^+\pi^-\psi_2(3823)$  system at 4.1 GeV/ $c^2$ . Final-state radiation is simulated with PHOTOS [32].

Events with four good charged tracks with net charge zero are selected as described in Ref. [21]. Electromagnetic showers identified as photon candidates must satisfy fiducial shower quality as well as timing requirements as described in Ref. [33]. For events with only one photon candidate ( $N_\gamma = 1$ ), assuming that only one of the two radiative photons is detected, we use a partial reconstruction strategy, i.e., allowing one missing photon ( $\gamma_{\text{miss}}$ ). The mass square of the missing photon candidate is required to be  $-0.07 < M_{\text{miss}}^2(\gamma) < 0.08 \text{ GeV}^2/c^4$  (with a signal efficiency  $> 99\%$ ), where the 4 momentum of  $\gamma_{\text{miss}}$  is computed from momentum conservation. To improve the momentum and energy resolution and to further reduce background, a one-constraint (1C) kinematic fit is performed under the hypothesis of  $\pi^+\pi^-\ell^+\ell^-\gamma_{\text{miss}}$  to the

initial  $e^+e^-$  c.m. system. The  $\chi^2/\text{ndf}$  of the kinematic fit is required to be less than 15/1. For multiphoton events ( $N_\gamma \geq 2$ ), we use the full reconstruction strategy as described in Ref. [21].

To reject radiative Bhabha and radiative dimuon ( $\gamma e^+e^-/\gamma\mu^+\mu^-$ ) background events with  $\gamma$  conversion ( $\gamma \rightarrow e^+e^-$ ), where the converted electrons are misidentified as pions, the cosine of the opening angle of the pion pairs is required to be less than 0.98. The background from  $e^+e^- \rightarrow \eta J/\psi$  with  $\eta \rightarrow \pi^+\pi^-\pi^0/\gamma\pi^+\pi^-$  is effectively rejected by the invariant mass requirement  $M(\gamma\gamma_{\text{miss}}\pi^+\pi^-) > 0.65 \text{ GeV}/c^2$ . In order to remove possible backgrounds from  $e^+e^- \rightarrow \gamma_{\text{ISR}}\psi(2S)$ ,  $e^+e^- \rightarrow \eta\psi(2S)$  with  $\eta \rightarrow \gamma\gamma$ , and  $e^+e^- \rightarrow \gamma\gamma\psi(2S)$  processes, the invariant mass of  $\pi^+\pi^-J/\psi$  is required to satisfy  $|M(\pi^+\pi^-J/\psi) - m[\psi(2S)]| > 7 \text{ MeV}/c^2$  [34,35].

According to a resolution of  $(14.2 \pm 0.5) \text{ MeV}$  from  $\psi(2S)$  data events for the  $M(\ell^+\ell^-)$  mass, the  $J/\psi$  signal region is defined as  $3.06 < M(\ell^+\ell^-) < 3.135 \text{ GeV}/c^2$ . To estimate non- $J/\psi$  backgrounds, we also define  $J/\psi$  mass sidebands as  $2.950 < M(\ell^+\ell^-) < 3.025 \text{ GeV}/c^2$  or  $3.170 < M(\ell^+\ell^-) < 3.245 \text{ GeV}/c^2$ . To reconstruct the  $\chi_{c1}$  candidate from the  $\psi_2(3823)$  decay, the 4 momenta of the two radiative photons after the 1C kinematic fit are boosted to the c.m. frame of the  $\psi_2(3823)$  system. The photon with the higher energy is used to reconstruct  $\chi_{c1}$ , while the lower-energy one is considered to originate from the  $\psi_2(3823)$  decay. MC simulation shows that the misassignment of the two photons is negligibly small ( $< 1\%$ ). The mass window of the reconstructed  $\chi_{c1}$  candidates is defined as  $3.48 < M(\gamma_H J/\psi) < 3.53 \text{ GeV}/c^2$  [34], with a signal efficiency of 96%.

The possible remaining backgrounds mainly come from  $e^+e^- \rightarrow (\eta'/\gamma\omega)J/\psi$ , with  $(\eta'/\omega) \rightarrow \gamma\gamma\pi^+\pi^-/\gamma\pi^+\pi^-$ , and  $\pi^+\pi^-\pi^+\pi^-(\pi^0/\gamma\gamma)$ . The  $e^+e^- \rightarrow (\eta'/\gamma\omega)J/\psi$  backgrounds are measured by BESIII using the same data set [36,37] and can be reliably simulated. The  $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-(\pi^0/\gamma\gamma)$  continuum background can be estimated by data in the  $J/\psi$  mass sidebands. All these background sources are found to be small, and only produce flat distributions in the  $\psi_2(3823)$  signal region.

To achieve better sensitivity, the one-photon events (partial reconstruction) and the multiphoton events (full reconstruction) are separated. Figure 1 shows the  $M^{\text{recoil}}(\pi^+\pi^-)$  distributions for data, where obvious  $\psi(2S)$  and  $\psi_2(3823)$  signal peaks are observed in both the one-photon and multiphoton events. Here,  $M^{\text{recoil}}(\pi^+\pi^-) = \sqrt{(P_{e^+e^-} - P_{\pi^+} - P_{\pi^-})^2}$  is the recoil mass of  $\pi^+\pi^-$ , where  $P_{e^+e^-}$  and  $P_{\pi^\pm}$  are the 4 momenta of the initial  $e^+e^-$  system and the reconstructed  $\pi^\pm$  candidates, respectively. For this expression, we use the  $\pi^\pm$  momenta without the kinematic fit correction because of the good resolution for low momentum pions according to MC simulation studies. A simultaneous unbinned extended

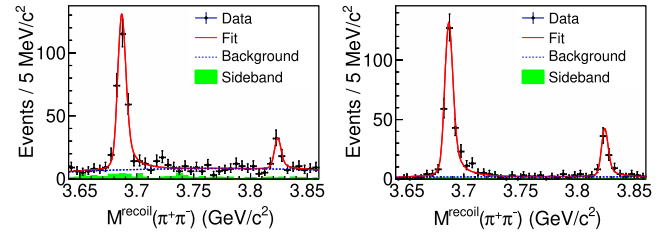


FIG. 1. Result of the simultaneous fit to the  $M^{\text{recoil}}(\pi^+\pi^-)$  distributions for one-photon events (left) and multiphoton events (right). Dots with error bars are the selected data, the red solid curves are fit results, the blue dashed curves are backgrounds, and the green shaded histograms are backgrounds estimated from  $J/\psi$  mass sideband events.

maximum likelihood fit to the two  $M^{\text{recoil}}(\pi^+\pi^-)$  distributions is performed to determine the parameters of the  $\psi_2(3823)$  state. In the fit, the signal probability density function (PDF) is represented by  $\psi(2S)$  and  $\psi_2(3823)$  (with input mass of  $3.823 \text{ GeV}/c^2$  and a zero natural width) MC simulated shapes, convolved with Gaussian functions with free mean  $\mu$  and width  $\sigma$  to account for the mass and resolution difference between data and MC simulation, respectively. The background shape is parametrized as a second-order polynomial.

The fit results, also shown in Fig. 1, yield  $M[\psi_2(3823)] = M[\psi_2(3823)]_{\text{input}} + \mu_{\psi_2(3823)} - \mu_{\psi(2S)} = 3823.12 \pm 0.43 \text{ MeV}/c^2$ , where  $M[\psi_2(3823)]_{\text{input}}$  is the input  $\psi_2(3823)$  mass in MC simulation;  $\mu_{\psi_2(3823)} = 1.02 \pm 0.43 \text{ MeV}/c^2$  and  $\mu_{\psi(2S)} = 0.90 \pm 0.22 \text{ MeV}/c^2$  are the mass shift values for the  $\psi_2(3823)$  and  $\psi(2S)$  shapes, respectively. The total number of  $\psi_2(3823)$  signal events determined from the fit is  $120.0 \pm 13.6$ . The statistical significance of the  $\psi_2(3823)$  signal is estimated to be  $13.4\sigma$ , by comparing the difference between the log-likelihood value [ $\Delta(\ln \mathcal{L}) = 96.6$ ] with or without the  $\psi_2(3823)$  signal in the fit and taking the change of the number of degrees of freedom ( $\Delta\text{ndf} = 4$ ) into account. We are not able to measure the intrinsic width of  $\psi_2(3823)$  precisely because of the limited data sample size. From a fit using a Breit-Wigner (BW) function (with a width parameter that is left free) convolved with a double Gaussian function as signal PDF for  $\psi_2(3823)$ , we set an upper limit of  $\Gamma[\psi_2(3823)] < 2.9 \text{ MeV}$  at the 90% confidence level (CL).

The product of the  $\sqrt{s}$ -dependent  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  cross section and the branching ratio of  $\psi_2(3823) \rightarrow \gamma\chi_{c1}$  is calculated as  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}] = [N^{\text{sig}}/\mathcal{L}_{\text{int}}\epsilon\mathcal{B}(1 + \delta)]$ , where  $N^{\text{sig}}$  is the number of  $\psi_2(3823) \rightarrow \gamma\chi_{c1}$  signal events obtained from a same fit ( $\sigma$  fixed to previous result) to the  $M^{\text{recoil}}(\pi^+\pi^-)$  distribution at a certain c.m. energy,  $\mathcal{L}_{\text{int}}$  is the integrated luminosity,  $\epsilon$  is the detection efficiency,  $\mathcal{B}$  is the branching fraction of  $\chi_{c1} \rightarrow \gamma J/\psi \rightarrow \gamma\ell^+\ell^-$ , and  $(1 + \delta)$  is the radiative correction factor, which depends on the cross section line shape of

TABLE I. Results of the fit to the distribution of  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}]$  with two coherent resonances. Here,  $M[R_i]$  and  $\Gamma_{\text{tot}}[R_i]$  represent the mass (in  $\text{MeV}/c^2$ ) and total width (in  $\text{MeV}$ ) of resonance  $R_i$ , respectively;  $\Gamma_{e^+e^-}\mathcal{B}_1^{R_i}\mathcal{B}_2$  is the product of the  $e^+e^-$  partial width (in  $\text{eV}/c^2$ ) and branching fraction of  $R_i \rightarrow \pi^+\pi^-\psi_2(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$  ( $i = 1, 2$ ). The parameter  $\phi$  (in degrees) is the relative phase between the two resonances. The first uncertainties are statistical and the second systematic.

Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\text{tot}}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\text{tot}}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
$\phi$	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

$e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$ . Since visible enhancements are observed near 4.40 and 4.65 GeV in the cross section line shape, the radiative correction factors are first obtained by modeling the line shape with two coherent BW resonances, and then iterated by updating the cross section measurement until this procedure converges, with a relative difference for  $(1 + \delta)\epsilon < 1\%$  between the last two iterations. The numerical results of the cross section measurement are listed in Supplemental Material [38].

To extract the resonance structures in  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]$ , a maximum likelihood fit using the coherent sum of two BW resonances to model the measured cross section is performed to data events in the  $\psi_2(3823)$  signal interval  $[3.815, 3.835]$   $\text{GeV}/c^2$ . The likelihood is constructed as that in Ref. [39]. There are two solutions with identical fit quality, and all resonance parameters from the fit are summarized in Table I. In addition, a fit with one single BW resonance to model the cross section yields  $M[R] = 4417.5 \pm 26.2$   $\text{MeV}/c^2$ ,  $\Gamma_{\text{tot}}[R] = 245 \pm 48$   $\text{MeV}$ ,  $\Gamma_{e^+e^-}\mathcal{B}_1\mathcal{B}_2 = 0.57 \pm 0.08$   $\text{eV}/c^2$ . The fit result is shown in Fig. 2. To discriminate the two resonances hypothesis ( $H_1$ ) from the one resonance hypothesis ( $H_0$ ) for the cross section interpretation, the likelihood ratio  $t = -2\ln(\mathcal{L}_{1\text{BW}}/\mathcal{L}_{2\text{BW}})$  is used as a test variable. We perform 2000 MC pseudoexperiments for both hypotheses and the corresponding  $t$  distributions are shown in Fig. 2. The  $t = 13.6$  from data is positive and slightly favors  $H_1$ . The  $p$  value to reject  $H_0$  is 8.2%, corresponding to a significance of  $1.7\sigma$ . Other possible continuum parametrizations of the cross section in the fit, such as a shape of three-body phase space,  $1/s^n$ , or a product of phase space with  $1/s^n$  are also tested, and they are not able to describe data well. The significance for the resonance hypothesis (with either one

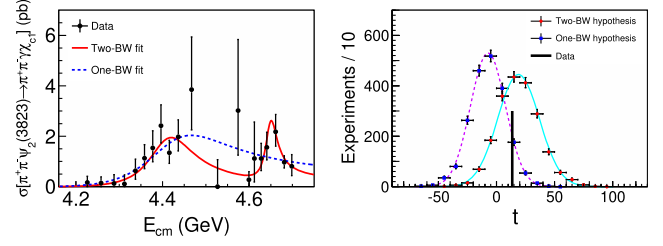


FIG. 2. Left panel: result of the fit to the  $\sqrt{s}$ -dependent cross section  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]$  times the branching ratio  $\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}]$ . Dots with error bars are data, and the red solid (blue dashed) curve shows the fit with two coherent resonances (one resonance). Right panel: the likelihood ratio  $t = -2\ln(\mathcal{L}_{1\text{BW}}/\mathcal{L}_{2\text{BW}})$  distribution from MC pseudoexperiments under two cross section hypothesis. Red dots (blue squares) with error bars are the two resonances (one resonance) hypothesis, and the black line shows data measurement.

or two resonances) over continuum is estimated to be greater than  $5\sigma$ .

The systematic uncertainties in the  $\psi_2(3823)$  mass measurement include those from the absolute mass scale, resolution, parametrization of the  $\psi_2(3823)$  signal and background shapes. In the  $\psi_2(3823)$  mass measurement, we use the  $\psi(2S)$  mass to calibrate the absolute mass scale. The uncertainty from the  $\psi(2S)$  mass measurement is therefore taken as the systematic uncertainty due to the absolute mass scale, which is  $0.12$   $\text{MeV}/c^2$ . To increase the  $\psi(2S)$  sample size and thus reduce the  $\psi(2S)$  mass uncertainty, we also employ  $\psi(2S) \rightarrow \gamma\chi_{c2}$  and  $\psi(2S) \rightarrow \eta J/\psi$  data events. The resolution difference between data and MC simulation is also estimated using the  $\psi(2S)$  events. Fixing the resolution from a free value to the one measured with  $\psi(2S)$  events, the mass difference for  $\psi_2(3823)$  in the fit is  $0.01$   $\text{MeV}/c^2$ . In the nominal fit, the signal PDF of  $\psi_2(3823)$  is parametrized as a MC simulated shape convolved with Gaussian resolution. A signal PDF parametrized as a BW convolved with Gaussian resolution is also tested, and the mass difference ( $0.03$   $\text{MeV}/c^2$ ) is taken as the systematic uncertainty from signal parametrization. Changing the background shape from a second-order polynomial to a linear term yields  $0.03$   $\text{MeV}/c^2$  mass difference associated with the background shape parametrization. Assuming that all the sources are independent, the total systematic uncertainty is calculated by adding them in quadrature, resulting in  $0.13$   $\text{MeV}/c^2$  for the  $\psi_2(3823)$  mass measurement. For the  $\psi_2(3823)$  width, we measure the upper limits with all of the above systematic uncertainty sources, and report the most conservative one.

The systematic uncertainties in the cross section measurement mainly come from luminosity measurement, efficiencies, kinematic fit, signal shape, background shape, decay model, radiative correction, branching ratios and MC sample size. The luminosity is measured using Bhabha

events, with an uncertainty of 1.0% [25]. The uncertainty in the tracking efficiency for high momentum leptons is 1.0% per track. Pions have momenta between 0.1 and 0.6 GeV/ $c$ , and the momentum-weighted uncertainty is 1.0% per track. By requiring at least one good photon candidate to be detected, the photon detection efficiency is very high and the uncertainty is negligible. The systematic uncertainty for the choice of  $J/\psi$  mass window is similar to that of Ref. [40], which is 1.6%. A track helix parameters correction method as discussed in Ref. [41] is applied to each MC simulated event during the 1C kinematic fit. The difference in detection efficiencies with or without corrections, 1.7%, is assigned as the systematic uncertainty from kinematic fit. The same sources of signal and background shape parametrizations as discussed for the  $\psi_2(3823)$  mass measurement would contribute 3.9% and 1.4% differences in the  $\psi_2(3823)$  signal events yields, which are taken as systematic uncertainties in the cross section measurement. We model the  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  process with  $L = 2$  between  $\pi^+\pi^-$  and  $\psi_2(3823)$  in the MC simulation. The efficiency difference between this model and a three-body phase space model is 1.8%. For the radiative correction, we take an alternative cross section line shape from one BW resonance model, and the difference for  $(1 + \delta)e$  to the nominal two BW resonances model is 5.0%. The uncertainties on the branching ratios for  $\chi_{c1} \rightarrow \gamma J/\psi$  (2.9%) and  $J/\psi \rightarrow \ell^+\ell^-$  (0.5%) are taken from PDG [35]. The uncertainty from MC sample size is 0.6%. Assuming that all the sources are independent, the total systematic uncertainty is calculated by adding them in quadrature, resulting in 8.8% for the cross section measurement.

The systematic uncertainties for the resonance parameters in the cross section fit come from absolute c.m. energy measurement, the cross section uncertainty, and the fit model. The c.m. energies of data sets taken in different time periods are measured with different methods. Shifting the c.m. energies of data sets taken in the same period globally (i.e., fully correlated) within uncertainties, we repeat the cross section fit. The deviations of the resonance parameters are taken as systematic uncertainties. The systematic uncertainties on the cross section measurements are common to all c.m. energies and are propagated to  $\Gamma_{e^+e^-}\mathcal{B}_1\mathcal{B}_2$  with the same amount. We quote 8.8% systematic uncertainty for  $\Gamma_{e^+e^-}\mathcal{B}_1\mathcal{B}_2$ . BW functions with constant full widths are used as the PDF in the cross section fit. We also use BW functions with  $\sqrt{s}$ -dependent full widths as the fit PDF, and the deviations of the resonance parameters between this fit and the nominal one are taken as systematic uncertainties from fit model. All these systematic contributions are listed in Supplemental Material [38]. Assuming all the sources are independent, the total systematic uncertainties are calculated by adding them in quadrature.

In summary, the product of the  $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$  cross section and the branching ratio of  $\psi_2(3823) \rightarrow \gamma\chi_{c1}$  is

measured with  $11.3 \text{ fb}^{-1}$  data collected with the BESIII detector at  $\sqrt{s} = 4.23$  to 4.70 GeV. For the first time, we observe resonance structure in the cross section line shape with a significance greater than  $5\sigma$ . A fit to data with a sum of two coherent BW resonances to model the cross section yields the masses and widths of both resonances as shown in Table I. Although weakly disfavored by data with  $1.7\sigma$ , a single resonance with a mass  $4417.5 \pm 26.2 \pm 3.5 \text{ MeV}/c^2$ , and a width  $245 \pm 48 \pm 13 \text{ MeV}$  is also possible to interpret data. Such a resonance has not been observed before. This is the first observation of vector  $\psi$  states decaying to  $D$ -wave charmonium state, which provides new insights about the  $\psi$  state wave functions. Considering that the measured  $e^+e^- \rightarrow \pi^+\pi^-\psi(3770)$  cross section is also relatively large near 4.4 GeV [42], this indicates that the coupling between the  $\psi$  states and  $D$ -wave charmonium might be popular, which should be taken into account when explaining the nature of these  $\psi$  states.

Within current uncertainties, the parameters of structures in the two resonances interpretation are similar to the  $\psi(4360)$  and  $\psi(4660)$  states reported in  $\pi^+\pi^-\psi(2S)$  [10,11]. Assuming the observed structures correspond to these resonances, this will be the second decay channel of the mysterious  $\psi(4660)$  state after more than 15 years of discovery. By comparing the measured cross section of  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]$  and  $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi(2S)]$  [16], we find  $\{\mathcal{B}[\psi(4660) \rightarrow \pi^+\pi^-\psi_2(3823)]/\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}]/\mathcal{B}[\psi(4660) \rightarrow \pi^+\pi^-\psi(2S)]\}$  reaches 10% level. Taking the branching fraction of  $\mathcal{B}[\psi_2(3823) \rightarrow \gamma\chi_{c1}] \sim 50\%$  [43] as input, we obtain the relative partial decay width  $\{\Gamma[\psi(4660) \rightarrow \pi^+\pi^-\psi_2(3823)]/\Gamma[\psi(4660) \rightarrow \pi^+\pi^-\psi(2S)]\} \sim 20\%$ . This sizable partial width poses a challenge to the  $f_0(980)\psi(2S)$  hadron molecule interpretation [17] for the  $\psi(4660)$  nature, which expects  $\psi(4660)$  predominantly decaying into  $f_0(980)\psi(2S)$ . The observed  $\psi(4660) \rightarrow \pi^+\pi^-\psi_2(3823)$  decay also differs from an extended baryonium picture [18] which explains the  $\psi(4660)$  as a  $\Sigma_c^0\bar{\Sigma}_c^0$  baryonium and speculates  $\psi(4660)$  is a first radial excitation in accordance with the  $n = 2$  radial quantum number of  $\psi(2S)$  and absent coupling to charmonium states with  $n = 1$ . A similar argument also appears in a diquark-antidiquark tetraquark explanation [19], which assigns the  $\psi(4660)$  as the radial excitation of the  $\psi(4260)$  (a  $P$ -wave tetraquark) based on the only observed decay  $\psi(4660) \rightarrow \pi^+\pi^-\psi(2S)$ . Our observation obviously deviates from this assignment.

We also measure the mass of the  $\psi_2(3823)$  state as  $M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13 \text{ MeV}/c^2$ , where the first uncertainty is statistical and the second systematic. The  $\psi_2(3823)$  width is studied, and an upper limit  $\Gamma[\psi_2(3823)] < 2.9 \text{ MeV}$  at the 90% CL is obtained. This is the most precise measurement of the  $\psi_2(3823)$  mass and the most stringent constraint on its width to

date, which will help to refine the parameters of potential models and significantly reduce the uncertainties (ca.  $\pm 50$  MeV) of the  $D$ -wave states predicted by the potential model [24].

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