Precise Measurement of the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV


Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.118.092001

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2017

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.118.092001

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Precise Measurement of the $e^+e^- \to \pi^+\pi^-J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV

092001 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

(BESIII Collaboration)

1Institute of High Energy Physics, Beijing 100049, People’s Republic of China
2Beihang University, Beijing 100191, People’s Republic of China
3Beijing Institute of Petrochemical Technology, Beijing 102617, People’s Republic of China
4Bochum Ruhr-University, D-44780 Bochum, Germany
5Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
6Central China Normal University, Wuhan 430079, People’s Republic of China
7China Center of Advanced Science and Technology, Beijing 100190, People’s Republic of China
8COMSATS Institute of Information Technology, Lahore, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan
9G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia
10GSI Helmholtzzentrum for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany
11Guangxi Normal University, Guilin 541004, People’s Republic of China
12Guangxi University, Nanning 530004, People’s Republic of China
13Hangzhou Normal University, Hangzhou 310036, People’s Republic of China
14Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
15Henan Normal University, Xinxing 453007, People’s Republic of China
16Henan University of Science and Technology, Luoyang 471003, People’s Republic of China
17Huangshan College, Huangshan 245000, People’s Republic of China
18Indiana University, Bloomington, Indiana 47405, USA
19INFN Laboratori Nazionali di Frascati, I-00044, Frascati, Italy;
20INFN and University of Perugia, I-06100, Perugia, Italy
21INFN Sezione di Ferrara, I-44122, Ferrara, Italy;
22Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany
23Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia
24Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany
25KVI-CART, University of Groningen, NL-9747 AA Groningen, The Netherlands
26Lanzhou University, Lanzhou 730000, People’s Republic of China
27Liaoning University, Shenyang 110036, People’s Republic of China
28Nanjing Normal University, Nanjing 210023, People’s Republic of China
29Nanjing University, Nanjing 210093, People’s Republic of China
30Nankai University, Tianjin 300071, People’s Republic of China
31Peking University, Beijing 100871, People’s Republic of China
32Penn State University, University Park, Pennsylvania 16802, USA
33Purdue University, West Lafayette, Indiana 47907, USA
34Purdue University, West Lafayette, Indiana 47907, USA
35Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
36Shanxi University, Taiyuan 030006, People’s Republic of China
37Sichuan University, Chengdu 610064, People’s Republic of China
38Soochow University, Suzhou 215006, People’s Republic of China
39Sun Yat-Sen University, Guangzhou 510275, People’s Republic of China
40Tsinghua University, Beijing 100084, People’s Republic of China
41University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
42University of Hawaii, Honolulu, Hawaii 96822, USA
43University of Minnesota, Minneapolis, Minnesota 55455, USA
44University of Rochester, Rochester, New York 14627, USA
45University of Science and Technology Liaoning, Anshan 114051, People’s Republic of China
46University of Science and Technology of China, Hefei 230026, People’s Republic of China
47University of Science and Technology of China, Hefei 230026, People’s Republic of China
48University of South China, Hengyang 421001, People’s Republic of China

092001-2
The process $e^+e^-\rightarrow \pi^+\pi^-J/\psi$ at center-of-mass (c.m.) energies between 3.8 and 5.0 GeV was first studied by the $BABAR$ experiment using an initial-state-radiation (ISR) technique [1], and a new structure, the $Y(4260)$, was reported with a mass around 4.26 GeV/$c^2$. This observation was immediately confirmed by the CLEO [2] and Belle experiments [3] in the same process. In addition, the Belle experiment reported an accumulation of events at around 4 GeV, which was called $Y(4008)$ later. Although the $Y(4008)$ state is still controversial—a new measurement by the $BABAR$ experiment does not confirm it [4], while an updated measurement by the Belle experiment still supports its existence [5]—the observation of the $Y$ states has stimulated substantial theoretical discussions on their nature [6,7].

Being produced in $e^+e^-$ annihilation, the $Y$ states have quantum numbers $J^{PC}=1^{--}$. However, unlike the known $1^{--}$ charmonium states in the same mass range, such as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ [8], which decay predominantly into open charm final states $[D^+\bar{D}^0]$, the $Y$ states show strong coupling to hidden-charm final states $[D^+(\bar{D}^0)]$, together with the newly observed resonant structures in $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ [9], the $Y(4260)$ state is reported by the observations of the states $Y(4360)$ and $Y(4660)$ in $e^+e^-\rightarrow \pi^+\pi^-\psi(2S)$ [10], together with the newly observed resonant structures in $e^+e^\rightarrow \omega\chi_{c0}$ [11] and $e^+e^-\rightarrow \pi^+\pi^-h_c$ [12], overpopulates the vector charmonium spectrum predicted by potential models [13]. All of this indicates that the $Y$ states may not be conventional charmonium states, and they are good candidates for new types of exotic particles, such as hybrids, tetraquarks, or meson molecules [6,7].

The $Y(4260)$ state was once considered a good hybrid candidate [14], since its mass is close to the value predicted by the flux tube model for the lightest hybrid charmonium $[15]$. Recent lattice calculations also show a $1^{--}$ hybrid charmonium could have a mass of $4285\pm14$ MeV/$c^2$ [16] or $4333(2)$ GeV/$c^2$ [17]. Meanwhile, the diquark-antidiquark tetraquark model predicts a wide spectrum of states which can also accommodate the $Y(4260)$ [18]. Moreover, the mass of $Y(4260)$ is near the mass threshold of $D^+_sD^0\bar{s}$, $D^0\bar{D}^*$, and $J_0(980)J/\psi$, and $Y(4260)$ was supposed to be a meson molecule candidate of these meson pairs [19,20]. A recent observation of a charged charmoniumlike state $Z_{c}(3900)$ by BESIII [21], Belle [5], and CLEO data [22] seems to favor the $DD_1$ meson pair option [19]. Another possible interpretation describes the $Y(4260)$ as a heavy charmonium ($J/\psi$) being bound inside light hadronic matter—hadrocharmonium [23]. To better identify the nature of the $Y$ states and distinguish various models, more precise experimental measurements, including the production cross section and the mass and width of the $Y$ states, are essential.

In this Letter, we report a precise measurement of the $e^+e^\rightarrow \pi^+\pi^-J/\psi$ cross section at $e^+e^-$ c.m. energies from 3.77 to 4.60 GeV, using a data sample with an integrated luminosity of 9.05 fb$^{-1}$ [24] collected with the BESIII detector operating at the BEPCII storage ring [25]. The $J/\psi$ candidate is reconstructed with its leptonic decay modes ($\mu^+\mu^-$ and $e^+e^-$). The data sample used in this measurement includes two independent data sets. A high luminosity data set (dubbed “XYZ data”) contains more than 40 pb$^{-1}$ at each c.m. energy with a total integrated luminosity of 8.2 fb$^{-1}$, which dominates the precision of this measurement, and a low luminosity data set (dubbed “scan data”) contains about 7–9 pb$^{-1}$ at each c.m. energy with a total integrated luminosity of 0.8 fb$^{-1}$.
The integrated luminosities are measured with Bhabha events with an uncertainty of 1% [24]. The c.m. energy of each data set is measured using dimuon events, with an uncertainty of ±0.8 MeV [26].

The BESIII detector is described in detail elsewhere [25]. The GEANT4-based [27] Monte Carlo (MC) simulation software package BOOST [28], which includes the geometric description of the BESIII detector and the detector response, is used to optimize event selection criteria, determine the detection efficiency, and estimate the backgrounds. For the signal process, we generate 60 000 $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ events at each c.m. energy of the XYZ data, and an extrapolation is performed to the scan data with nearby c.m. energies. At $e^+e^-$ c.m. energies between 4.189 and 4.358 GeV, the signal events are generated according to the Dalitz plot distributions obtained from the data set at corresponding c.m. energy, since there is significant $\chi_c(3900)$ production [5,21,22]. At other c.m. energies, signal events are generated using an EVTGEN [29] phase space model. The $J/\psi$ decays into $\mu^+\mu^-$ and $e^+e^-$ with the same branching fractions [8]. The ISR is simulated with KKM [30], and the maximum ISR photon energy is set to correspond to a 3.72 GeV/c² production threshold of the $\pi^+\pi^-J/\psi$ system. Final-state radiation (FSR) is simulated with PHOTOS [31]. Possible background contributions are estimated with KKM-generated inclusive MC samples $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma$, $\gamma_{\text{ISR}}J/\psi$, $\gamma_{\text{ISR}}\psi(2S)$, and $q\bar{q}$ with $q = u, d, s, c$ with comparable integrated luminosities to the XYZ data.

Events with four charged tracks with zero net charge are selected. For each charged track, the polar angle in the drift chamber must satisfy $|\cos \theta| < 0.93$, and the point of closest approach to the $e^+e^-$ interaction point must be within ±10 cm in the beam direction and within 1 cm in the plane perpendicular to the beam direction. Taking advantage of the fact that pions and leptons are kinematically well separated in the signal decay, charged tracks with momenta larger than 1.06 GeV/c in the laboratory frame are assumed to be leptons, and the others are assumed to be pions. We use the energy deposited in the electromagnetic calorimeter (EMC) to separate electrons from muons. For both muon candidates, the deposited energy in the EMC is required to be less than 0.35 GeV, while for both electrons, it is required to be larger than 1.1 GeV. To avoid systematic errors due to unstable operation, the muon system is not used here. Each event is required to have one $\pi^+\pi^-e^+e^-$ ($\ell = e$ or $\mu$) combination.

To improve the momentum and energy resolution and to reduce the background, a four-constraint kinematic fit is applied to the event with the hypothesis $e^+e^- \rightarrow \pi^+\pi^-e^+e^-$, which constrains the total four-momentum of the final state particles to that of the initial colliding beams. The $\chi^2$/n.d.f. of the kinematic fit is required to be less than 60/4.

To suppress radiative Bhabha and radiative dimuon ($e^+e^- \rightarrow \gamma e^+e^-/\mu^+\mu^-$) backgrounds associated with photon conversion to an $e^+e^-$ pair which subsequently is misidentified as a $\pi^+\pi^-$ pair, the cosine of the opening angle of the pion-pair (cos $\theta_{\pi^+\pi^-}$) candidates is required to be less than 0.98 for both $J/\psi \rightarrow \mu^+\mu^-$ and $e^+e^-$ events. For $J/\psi \rightarrow e^+e^-$ events, since there are more abundant photon sources from radiative Bhabha events, we further require the cosine of the opening angles of both pion-electron pairs (cos $\theta_{e^+e^-}$) to be less than 0.98. These requirements remove almost all of the Bhabha and dimuon background events, with an efficiency loss of less than 1% for signal events.

After imposing the above selection criteria, a clear $J/\psi$ signal is observed in the invariant mass distribution of the lepton pairs [$M(\ell^+\ell^-)$]. The mass resolution of the $M(\ell^+\ell^-)$ distribution is estimated to be $(3.7\pm0.2)$ MeV/c² for $J/\psi \rightarrow \mu^+\mu^-$ and $(3.9\pm0.3)$ MeV/c² for $J/\psi \rightarrow e^+e^-$ in data for the range of c.m. energies investigated in this study. The $J/\psi$ mass window is defined as $3.08 < M(\ell^+\ell^-) < 3.12$ GeV/c². In order to estimate the non-$J/\psi$ background contribution, we also define the $J/\psi$ mass sideband as $3.00 < M(\ell^+\ell^-) < 3.06$ GeV/c² and $3.14 < M(\ell^+\ell^-) < 3.20$ GeV/c², which is 3 times as wide as the signal region. The dominant background comes from $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) processes, such as $e^+e^- \rightarrow \pi^+\pi^-e^+e^-$, and $q\bar{q}$ events form a smooth distribution in the $J/\psi$ signal region, their contribution is estimated by the $J/\psi$ mass sideband. Contributions from backgrounds related with charm quark production, such as $e^+e^- \rightarrow J/\psi g$ [32], $D^{(*)}\bar{D}^{(*)}$, and other open-charm mesons, are estimated to be negligible according to MC simulation studies.

In order to determine the signal yields, we make use of both fitting and counting methods on the $M(\ell^+\ell^-)$ distribution. In the XYZ data, each data set contains many signal events, and an unbinned maximum likelihood fit to the $M(\ell^+\ell^-)$ distribution is performed. We use a MC simulated signal shape convolved with a Gaussian function (with standard deviation 1.9 MeV, which represents the resolution difference between the data and the MC simulation) as the signal probability density function (PDF) and a linear term for the background. For the scan data, due to the low statistics, we directly count the number of events in the $J/\psi$ signal region and that of the normalized background events in the $J/\psi$ mass sideband and take the difference as the signal yields.

The cross section of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at a certain $e^+e^-$ c.m. energy $\sqrt{s}$ is calculated using

$$\sigma(\sqrt{s}) = \frac{N_{\text{sig}}^{\psi}}{\mathcal{L}_{\text{int}}(1 + \delta) e \mathcal{B}},$$

where $N_{\text{sig}}^{\psi}$ is the number of signal events, $\mathcal{L}_{\text{int}}$ is the integrated luminosity of data, $1 + \delta$ is the ISR correction factor, $e$ is the detection efficiency, and $\mathcal{B}$ is the branching fraction of $J/\psi \rightarrow e^+e^-$ [8]. The ISR correction factor is
calculated using the KKMC [30] program. To get the correct ISR photon energy distribution, we use the $\sqrt{s}$-dependent cross section line shape of the $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ process, i.e., $\sigma(\sqrt{s})$, to replace the default one of KKMC. Since $\sigma(\sqrt{s})$ is what we measure in this study, the ISR correction procedure needs to be iterated, and the final results are obtained when the iteration converges. Figure 1 shows the measured cross section $\sigma(\sqrt{s})$ from both the XYZ data and scan data (numerical results are listed in Supplemental Material [33]).

To study the possible resonant structures in the $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ process, a binned maximum likelihood fit is performed simultaneously to the measured cross section $\sigma(\sqrt{s})$ of the XYZ data with Gaussian uncertainties and the scan data with Poisson uncertainties. The PDF is parameterized as the coherent sum of three Breit-Wigner functions, together with an incoherent $\psi (3770)$ component which accounts for the decay of $\psi (3770) \rightarrow \pi^+ \pi^- J/\psi$, with $\psi (3770)$ mass and width fixed to PDG [8] values. Because of the lack of data near the $\psi (3770)$ resonance, it is impossible to determine the relative phase between the $\psi (3770)$ amplitude and the other amplitudes. The amplitude to describe a resonance $R$ is written as

$$A(\sqrt{s}) = \frac{M \sqrt{12\pi \Gamma e^{-e-\Gamma_{tot}} B_R}}{\sqrt{s} - M^2 + i M \Gamma_{tot}} \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M)}} e^{i \phi},$$

(2)

where $M$, $\Gamma_{tot}$, and $\Gamma_{e^+e^-}$ are the mass, full width, and electronic width of the resonance $R$, respectively; $B_R$ is the branching fraction of the decay $R \rightarrow \pi^+ \pi^- J/\psi$; $\Phi(\sqrt{s})$ is the phase space of the three-body decay $R \rightarrow \pi^+ \pi^- J/\psi$ [8]; and $\phi$ is the phase of the amplitude. The fit has four solutions with equally good fit quality [34] and identical masses and widths of the resonances (listed in Table I), while the phases and the product of the electronic widths with the branching fractions are different (listed in Table II). Figure 1 shows the fit results. The resonance $R_1$ has a mass and width consistent with that of $Y(4008)$ observed by Belle [5] within 1.0$\sigma$ and 2.9$\sigma$, respectively.

The resonance $R_2$ has a mass 4222.0 $\pm$ 3.1 MeV/c$^2$, which agrees with the average mass, 4251 $\pm$ 9 MeV/c$^2$ [8], of the $Y(4260)$ peak [1–5] within 3.0$\sigma$. However, its measured width is much narrower than the average width, 120 $\pm$ 12 MeV [8], of the $Y(4260)$. We also observe a new resonance $R_3$. The statistical significance of $R_3$ is estimated to be 7.9$\sigma$ (including systematic uncertainties) by comparing the change of $\Delta(-2 \ln L) = 74.9$ with and without the $R_3$ amplitude in the fit and taking the change of number of degree of freedom $\Delta$ n.d.f. = 4 into account. The fit quality is estimated using a $\chi^2$-test method, with $\chi^2$/n.d.f. = 93.6/110. Fit models taken from previous experiments [1–5] are also investigated and are ruled out with a confidence level equivalent to more than 5.4$\sigma$.

As an alternative description of the data, we use an exponential [35] to model the cross section near 4 GeV as in Ref. [4] instead of the resonance $R_1$. The fit results are shown as dashed lines in Fig. 1. This model also describes the data very well. A $\chi^2$ test to the fit quality gives $\chi^2$/n.d.f. = 93.2/111. Thus, the existence of a resonance near 4 GeV, such as the resonance $R_1$ or the $Y(4008)$ resonance [3], is not necessary to explain the data. The fit has four solutions with equally good fit quality [34] and

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(R_1)$</td>
<td>3812.6$^{+61.9}_{-86.6}$ (⋯)</td>
</tr>
<tr>
<td>$\Gamma_{tot}(R_1)$</td>
<td>476.9$^{+79.4}_{-64.8}$ (⋯)</td>
</tr>
<tr>
<td>$M(R_2)$</td>
<td>4222.0 $\pm$ 3.1 (4220.9 $\pm$ 2.9)</td>
</tr>
<tr>
<td>$\Gamma_{tot}(R_2)$</td>
<td>44.1 $\pm$ 4.3 (44.1 $\pm$ 3.8)</td>
</tr>
<tr>
<td>$M(R_3)$</td>
<td>4320.0 $\pm$ 10.4 (4326.8 $\pm$ 10.0)</td>
</tr>
<tr>
<td>$\Gamma_{tot}(R_3)$</td>
<td>101.4$^{+25.3}<em>{-19.7}$ (98.2$^{+25.4}</em>{-19.6}$)</td>
</tr>
</tbody>
</table>

TABLE I. The measured masses and widths of the resonances from the fit to the $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ cross section with three coherent Breit-Wigner functions. The numbers in the brackets correspond to a fit by replacing $R_1$ with an exponential describing the continuum. The errors are statistical only.
TABLE II. The values of $\Gamma_{e^+e^-}B(R \to \pi^+\pi^-J/\psi)$ (in eV) from a fit to the $e^+e^- \to \pi^+\pi^-J/\psi$ cross section. $\phi_1$ and $\phi_2$ (in degrees) are the phase of the resonance $R_2$ and $R_3$, and the phase of resonance $R_1$ (or continuum) is set to 0. The numbers in the brackets correspond to the fit by replacing resonance $R_1$ with an exponential to describe the continuum. The errors are statistical only.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
<th>Solution III</th>
<th>Solution IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{e^+e^-}B(\psi(3770) \to \pi^+\pi^-J/\psi)$</td>
<td>0.5 ± 0.1 (0.4 ± 0.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{e^+e^-}B(R_1 \to \pi^+\pi^-J/\psi)$</td>
<td>8.8 ± 1.5 (1.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{e^+e^-}B(R_2 \to \pi^+\pi^-J/\psi)$</td>
<td>13.3 ± 1.4 (12.0 ± 1.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{e^+e^-}B(R_3 \to \pi^+\pi^-J/\psi)$</td>
<td>21.1 ± 3.9 (17.9 ± 3.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi_1$</td>
<td>−58 ± 11 (−33 ± 8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>−156 ± 5 (−132 ± 3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

identical masses and widths of the resonances (listed in Table I), while the phases and the product of the electronic widths with the branching fractions are different (listed in Table II). We observe the resonance $R_2$ and the resonance $R_3$ again. The statistical significance of resonance $R_3$ in this model is estimated to be 7.6$\sigma$ (including systematic uncertainties) [$\Delta(-2 \ln L) = 70.7, \Delta n.d.f. = 4$] using the same method as above.

The systematic uncertainty for the cross section measurement mainly comes from uncertainties in the luminosity, efficiencies, radiative correction, background shape, and branching fraction of $J/\psi \to \ell^+\ell^-$. The integrated luminosities of all the data sets are measured using large angle Bhabha scattering events, with an uncertainty of 1% [24]. The uncertainty in the tracking efficiency for high momentum leptons is 1% per track. Pions have momenta that range from 0.1 to 1.06 GeV/c, and their momentum-weighted tracking efficiency uncertainty is also 1% per track. For the kinematic fit, we use a similar method as in Ref. [36] to improve the agreement of the $\chi^2$ distribution between the data and MC simulation, and the systematic uncertainty for the kinematic fit is estimated to be 0.6% (1.1%) for $\mu^+\mu^−$ ($e^+e^−$) events. For the MC simulation of signal events, we use both the $\pi^\pm Z_e(900)\mp$ model [5,21,22] and the phase space model to describe the $e^+e^- \to \pi^+\pi^-J/\psi$ process. The efficiency difference between these two models is 3.1%, which is taken as systematic uncertainty due to the decay model.

The efficiencies for the other selection criteria, the trigger simulation, the event start time determination, and the FSR simulation, are quite high (>99%), and their systematic errors are estimated to be less than 1%. In the ISR correction procedure, we iterate the cross section measurement until $(1 + \delta)e$ converges. The convergence criterion is taken as the systematic uncertainty due to the ISR correction, which is 1%. We obtain the number of signal events by either fitting or counting events in the $M(\ell^+\ell^-)$ distribution. The background shape is described by a linear distribution. Varying the background shape from a linear shape to a second-order polynomial causes a 1.6% (2.1%) difference for the $J/\psi$ signal yield for the $\mu^+\mu^−$ ($e^+e^−$) mode, which is taken as the systematic uncertainty for the background shape. The branching fraction of $J/\psi \to \ell^+\ell^−$ is taken from PDG [8], and the errors are 0.6% for both $J/\psi$ decay modes. Assuming all the sources of systematic uncertainty are independent, the total systematic uncertainties are obtained by adding them in quadrature, resulting in 5.7% for the $\mu^+\mu^−$ mode and 5.9% for the $e^+e^−$ mode.

In both fit scenarios to the $e^+e^- \to \pi^+\pi^-J/\psi$ cross section, we observe the resonance $R_2$ and $R_3$. Since we cannot distinguish the two scenarios from the data, we take the difference in mass and width as the systematic uncertainties, i.e., 1.1 (6.8) MeV/c$^2$ for the mass and 0.0 (3.2) MeV for the width of $R_2$ ($R_3$). The absolute c.m. energies of all the data sets were measured with dimuon events, with an uncertainty of ±0.8 MeV. Such a kind of common uncertainty will propagate only to the masses of the resonances with the same amount, i.e., ±0.8 MeV/c$^2$. In both fits, the $\psi(3770)$ amplitude was added incoherently. The possible interference effect of the $\psi(3770)$ component was investigated by adding it coherently in the fit with various phases. The largest deviation of the resonant parameters between the fits with and without interference for the $\psi(3770)$ amplitude is taken as a systematic error, which is 0.3 (1.3) MeV/c$^2$ for the mass and 2.0 (9.7) MeV for the width of the $R_2$ ($R_3$) resonance. Assuming all the systematic uncertainties are independent, we get the total systematic uncertainties by adding them in quadrature, which is 1.4 (7.0) MeV/c$^2$ for the mass and 2.0 (10.2) MeV for the width of $R_2$ ($R_3$), respectively.

In summary, we perform a precise cross section measurement of $e^+e^- \to \pi^+\pi^-J/\psi$ for c.m. energies from $\sqrt{s} = 3.77$ to 4.60 GeV. Two resonant structures are observed, one with a mass of (4222.0 ± 3.1 ± 1.4) MeV/c$^2$ and a width of (44.1 ± 4.3 ± 2.0) MeV and the other with a mass of (4320.0 ± 10.4 ± 7.0) MeV/c$^2$ and a width of (101.4 ± 25.3 ± 10.2) MeV, where the first errors are statistical and the second ones are systematic. The first resonance agrees with the $Y(4260)$ resonance reported...
by BABAR, CLEO, and Belle [1–5]. However, our measured width is much narrower than the $Y(4260)$ average width [8] reported by previous experiments. This is thanks to the much more precise data from BESIII, which results in the observation of the second resonance. The second resonance is observed for the first time in the process $e^+e^- \rightarrow \pi^+\pi^-J/\psi$. Its statistical significance is estimated to be larger than 7.6σ. The second resonance has a mass and width comparable to the $Y(4360)$ resonance reported by Belle and BABAR in $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ [10]. If we assume it is the same resonance as the $Y(4360)$, we observe a new decay channel of $Y(4360) \rightarrow \pi^+\pi^-J/\psi$ for the first time. Finally, we cannot confirm the existence of the $Y(4008)$ resonance [3,5] from our data, since a continuum term also describes the cross section near 4 GeV equally well.

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts No. 11235011, No. 11325244, No. 11335008, and No. 11425524; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); the Collaborative Innovation Center for Particles and Interactions (CICPI); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts No. U1232201 and No. U1332201; CAS under Contracts No. KJCX2-YW-N29 and No. KJCX2-YW-N45; 100 Talents Program of CAS; National 100 Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Collaborative Research Center Contracts No. CRC 1044 and No. FOR 2359; Seventh Framework Programme of the European Commission under Marie Curie International Incoming Fellowship Grant Agreement No. 627240; Istituto Nazionale di Fisica Nucleare, Italy; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532257; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contract No. U1532258; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; NSFC under Contract No. 11275266; The Swedish Research Council; U.S. Department of Energy under Contracts No. DE-FG02-05ER41374, No. DE-SC-0010504, No. DE-SC0012069, and No. DESC0010118; U.S. National Science Foundation; University of Groningen (RuG) and the Helmholtzzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

*Corresponding author.
zqliu@ihep.ac.cn

[a] Also at State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People’s Republic of China.
[b] Also at Bogazici University, 34342 Istanbul, Turkey.
[c] Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.
[d] Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk, 634050, Russia.
[e] Also at the Novosibirsk State University, Novosibirsk, 630090, Russia.
[f] Also at the NRC “Kurchatov Institute,” PNPI, 188300, Gatchina, Russia.
[g] Also at University of Texas at Dallas, Richardson, TX 75083, USA.
[h] Also at Istanbul Arel University, 34295 Istanbul, Turkey.
[i] Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.
[j] Also at Institute of Nuclear and Particle Physics, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, People’s Republic of China.


[35] $p_0 e^{-p_1(\sqrt{s}-M_{th})} \Phi(\sqrt{s})$, where $p_0$ and $p_1$ are free parameters, $M_{th} = 2m_\pi + m_{J/\psi}$ is the mass threshold of the $\pi^+\pi^-J/\psi$ system, and $\Phi(\sqrt{s})$ is the phase space factor.