



# Study of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle

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The cross section for  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  between 3.8 and 5.5 GeV is measured with a  $967\text{ fb}^{-1}$  data sample collected by the Belle detector at or near the  $Y(nS)$  ( $n = 1, 2, \dots, 5$ ) resonances. The  $Y(4260)$  state is observed, and its resonance parameters are determined. In addition, an excess of  $\pi^+\pi^-J/\psi$  production around 4 GeV is observed. This feature can be described by a Breit-Wigner parametrization with properties that are consistent with the  $Y(4008)$  state that was previously reported by Belle. In a study of  $Y(4260) \rightarrow \pi^+\pi^-J/\psi$  decays, a structure is observed in the  $M(\pi^\pm J/\psi)$  mass spectrum with  $5.2\sigma$  significance, with mass  $M = (3894.5 \pm 6.6 \pm 4.5)\text{ MeV}/c^2$  and width  $\Gamma = (63 \pm 24 \pm 26)\text{ MeV}/c^2$ , where the errors are statistical and systematic, respectively. This structure can be interpreted as a new charged charmoniumlike state.

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The  $Y(4260)$  state was first observed by the BABAR Collaboration in the initial-state-radiation (ISR) process  $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$  [1] and then confirmed by the CLEO [2] and Belle experiments [3] using the same

technique. Subsequently, a charged  $Z(4430)^\pm$  charmoniumlike state was reported in the  $\pi^\pm\psi(2S)$  invariant mass spectrum of  $B \rightarrow K\pi^\pm\psi(2S)$  [4] and two  $Z^\pm$  states were observed in the  $\pi^\pm\chi_{c1}$  invariant mass distribution of

$B \rightarrow K \chi_{c1} \pi^+$  [5]. Motivated by the striking observations of charged charmoniumlike [4,5] and bottomoniumlike states [6], we investigate the existence of similar states as intermediate resonances in  $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$  decays.

After the initial observations of the  $Y(4260)$  [1–3], CLEO collected  $13.2 \text{ pb}^{-1}$  of  $e^+e^-$  data at  $\sqrt{s} = 4.26 \text{ GeV}$  and investigated 16 possible  $Y(4260)$  decay modes with charmonium or light hadrons in the final state [7]. An ISR analysis by the Belle experiment with  $548 \text{ fb}^{-1}$  of data collected at or near  $\sqrt{s} = 10.58 \text{ GeV}$  [8] showed a significant  $Y(4260)$  signal as well as an excess of  $\pi^+ \pi^- J/\psi$  event production near 4 GeV that could be described by a broad Breit-Wigner (BW) parametrization—the so-called  $Y(4008)$ . Recently, the BABAR Collaboration reported an updated ISR analysis with  $454 \text{ fb}^{-1}$  of data and a modified approach for the background description [9]; the  $Y(4260)$  state was observed with improved significance, but the  $Y(4008)$  structure was not confirmed. Instead, they attributed the structure below the  $Y(4260)$  to exponentially falling non-resonant  $\pi^+ \pi^- J/\psi$  production.

In this Letter, we report cross section measurements for  $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$  between 3.8 and 5.5 GeV, and a search for structures in the  $\pi^+ \pi^- J/\psi$ ,  $\pi^\pm J/\psi$ , and  $\pi^+ \pi^-$  systems. The results are based on the full Belle data sample with an integrated luminosity of  $967 \text{ fb}^{-1}$  collected at or near the  $Y(nS)$  resonances ( $n = 1, 2, \dots, 5$ ). The Belle detector operated at the KEKB asymmetric-energy  $e^+e^-$  collider [10] and is described in detail elsewhere [11]. We use the PHOKHARA [12] program to generate signal Monte Carlo (MC) events and determine experimental efficiencies. The results reported here supersede those of Ref. [8], wherein a subset of the Belle data sample was used.

The event selection is described in Ref. [8]. We require four well reconstructed charged tracks with zero net

charge. For each charged track, a likelihood  $\mathcal{L}_X$  is formed from different detector subsystems for particle hypothesis  $X \in \{e, \mu, \pi, K, p\}$ . Tracks with a likelihood ratio  $\mathcal{R}_K = (\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)) < 0.4$  are identified as pions with an efficiency of about 95%. Similar ratios are also defined for lepton-pion discrimination [13]. For electrons from  $J/\psi \rightarrow e^+e^-$ , one track should have  $\mathcal{R}_e > 0.95$  and the other track  $\mathcal{R}_e > 0.05$ . For muons from  $J/\psi \rightarrow \mu^+ \mu^-$ , at least one track should have  $\mathcal{R}_\mu > 0.95$ ; in cases where the other track has no muon identification, in order to suppress misidentified muon tracks, the polar angles of the two muon tracks in the  $\pi^+ \pi^- \mu^+ \mu^-$  center-of-mass (c.m.) frame must satisfy  $|\cos\theta_\mu| < 0.7$ . Events with  $\gamma$  conversions are removed by requiring  $\mathcal{R}_e < 0.75$  for the  $\pi^+ \pi^-$  candidate tracks. Furthermore, in  $J/\psi \rightarrow e^+e^-$ , such events are further reduced by requiring the invariant mass of the  $\pi^+ \pi^-$  candidate pair to be larger than  $0.32 \text{ GeV}/c^2$ . Events with a total energy deposit in the electromagnetic calorimeter above 9 GeV are removed in the  $J/\psi \rightarrow e^+e^-$  mode because the MC simulation of the trigger efficiency for these Bhabha-like events does not accurately reproduce the data. There is only one combination of  $\pi^+ \pi^- \ell^+ \ell^-$  ( $\ell = e, \mu$ ) in each event after the above selections.

Candidate ISR events are identified by the requirement  $|M_{\text{rec}}^2| < 2.0 (\text{GeV}/c^2)^2$ , where  $M_{\text{rec}}^2 = (P_{\text{c.m.}} - P_{\pi^+} - P_{\pi^-} - P_{\ell^+} - P_{\ell^-})^2$  and  $P_i$  represents the four-momentum of the corresponding particle or composite in the  $e^+e^-$  c.m. frame. Clear  $J/\psi$  signals are observed in both the  $J/\psi \rightarrow e^+e^-$  and  $\mu^+ \mu^-$  modes. We define the  $J/\psi$  signal region as  $3.06 \text{ GeV}/c^2 < M(\ell^+ \ell^-) < 3.14 \text{ GeV}/c^2$  (the mass resolution for lepton pairs being about  $20 \text{ MeV}/c^2$ ), and  $J/\psi$  mass sidebands as  $2.91 \text{ GeV}/c^2 < M(\ell^+ \ell^-) < 3.03 \text{ GeV}/c^2$  or  $3.17 \text{ GeV}/c^2 < M(\ell^+ \ell^-) < 3.29 \text{ GeV}/c^2$ , which are three times as wide as the signal region.

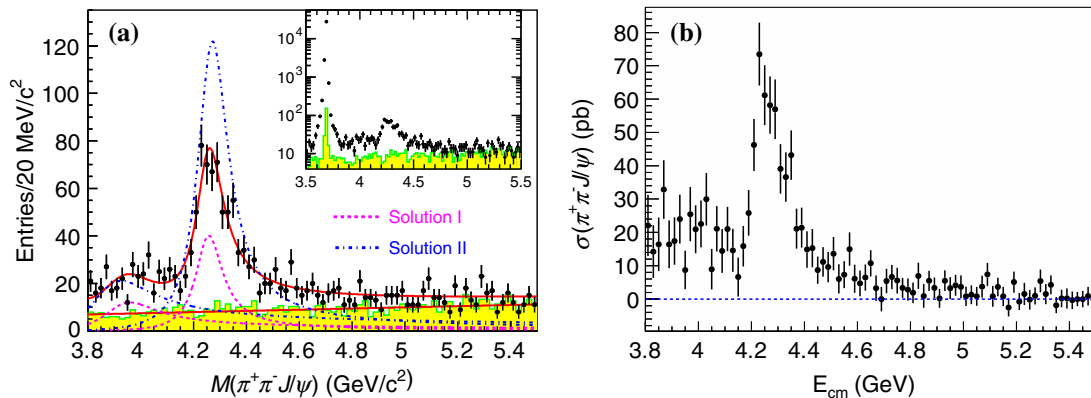


FIG. 1 (color online). (a) Invariant mass distributions of  $\pi^+ \pi^- \ell^+ \ell^-$ . Points with error bars are data, and the shaded histograms are the normalized  $J/\psi$  mass sidebands. The solid curves show the total best fit with two coherent resonances and contribution from background. The dashed curves are for solution I, while the dotted-dashed curves are for solution II. The inset shows the distributions on a logarithmic vertical scale. The large peak around  $3.686 \text{ GeV}/c^2$  is the  $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$  signal. (b) Cross section of  $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$  after background subtraction. The errors are statistical only.

Figure 1(a) shows the  $\pi^+\pi^-\ell^+\ell^-$  invariant mass [14] distributions after all of these selection requirements are applied. Also shown in this figure are the background estimates evaluated using the normalized  $J/\psi$ -mass sidebands. Two enhancements—the  $Y(4008)$  and the  $Y(4260)$ —above  $3.8 \text{ GeV}/c^2$  are observed, consistent with the results of Ref. [8] but in disagreement with those of Ref. [9]. Other possible background sources not included in the sidebands are found to be small from MC simulation [7]; these include (1)  $\pi^+\pi^-J/\psi$  with  $J/\psi$  decays into final states other than lepton pairs and (2)  $XJ/\psi$ , with  $X$  not being a  $\pi^+\pi^-$  pair, such as  $K^+K^-$  or  $\pi^+\pi^-\pi^0$ . Non-ISR production of  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  final states, such as  $e^+e^- \rightarrow \gamma\gamma^*\gamma^* \rightarrow \gamma\rho^0J/\psi$ , is also estimated to be small [15]. Figure 1(b) shows the measured cross sections for  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ , where the error bars are statistical only.

Systematic uncertainties of the cross section measurement are found to be 7.9% and 7.3% for the  $e^+e^-$  and  $\mu^+\mu^-$  modes, respectively. The particle identification uncertainties, measured from pure  $\psi(2S)$  events in the same data sample, are 4.7% and 3.6% for the  $e^+e^-$  and  $\mu^+\mu^-$  modes, respectively. Tracking efficiency uncertainties are estimated to be 3.3% for both  $e^+e^-$  and  $\mu^+\mu^-$  modes in the momentum and angular regions of interest for signal events. The uncertainties associated with the choice of the  $J/\psi$  mass window and  $|M_{\text{rec}}^2|$  requirements are also estimated using pure  $\psi(2S)$  events. It is found that MC efficiencies are higher than data by  $(4.5 \pm 0.4)\%$  in the  $e^+e^-$  mode and  $(4.1 \pm 0.2)\%$  in the  $\mu^+\mu^-$  mode. The differences in efficiencies are corrected and the uncertainties in the correction factors are incorporated into the systematic errors. Overall, together with the  $|M_{\text{rec}}^2|$  requirements, these uncertainties contribute 0.6% for the  $e^+e^-$  mode and 0.3% for the  $\mu^+\mu^-$  mode within the  $J/\psi$  mass window. Belle measures luminosity with a precision of 1.4% using wide-angle Bhabha events. The PHOKHARA generator calculates ISR with 0.1% accuracy [12]. The dominant uncertainties due to the MC generator are from three-body decay dynamics. MC simulation with modified  $\pi^+\pi^-$  invariant mass distributions weighted according to data distributions yields a 2% to 5% efficiency difference compared with a phase space  $\pi^+\pi^-$  mass spectrum model. Thus, we conservatively use 5% as the systematic error due to the approximations made in the MC event generator. According to MC simulation, the off-line trigger efficiency for four-track events of the studied topology exceeds 99%. A 1.0% systematic error is included for the trigger uncertainty. The uncertainty of  $\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-) = \mathcal{B}(J/\psi \rightarrow e^+e^-) + \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$  is 1.0% [16].

As a validation of our analysis, we also measure the ISR  $\psi(2S)$  production rate using the same selection criteria. The cross sections are  $(14.12 \pm 0.18 \pm 0.85)$  and  $(15.13 \pm 0.11 \pm 0.79)$  pb at  $\sqrt{s} = 10.58 \text{ GeV}$  [17] for the  $e^+e^-$  and  $\mu^+\mu^-$  modes, respectively. Our measurement agrees

within errors with the prediction of  $(14.25 \pm 0.26)$  pb [18] using the world-average resonance parameters [16].

An unbinned maximum likelihood fit is performed to the  $\pi^+\pi^-J/\psi$  mass spectrum above  $3.8 \text{ GeV}/c^2$ . As there are two enhancements observed, as shown in Fig. 1(a), we use the same fit strategy as in Ref. [8]. Two coherent BW functions ( $R_1, R_2$ ) are used to describe the  $Y(4008)$  and  $Y(4260)$  structures, assuming there is no continuum production of  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ . In the fit, the background term is fixed at the level obtained from a linear fit to the sideband data. The solid curves in Fig. 1(a) show the fit results. There are two solutions of equal optimum fit quality. The masses and widths of the resonances are the same for the two solutions; the partial widths to  $e^+e^-$  and the relative phase between the two resonances are different (see Table I) [19]. The fit quality is estimated using the reduced  $\chi^2$  statistic; we obtain  $\chi^2/ndf = 101.6/84$ , corresponding to a confidence level of 9.3%. Systematic uncertainties in the extracted values of the resonance parameters arise from the absolute energy scale, the detection efficiency, background estimation, and the parametrization of the resonance models. The absolute energy uncertainty is estimated from the  $\psi(2S)$  mass fit. Uncertainty in the detection efficiency does not affect the mass and width measurements, but could affect the measurement of the partial width to  $e^+e^-$ . Systematic uncertainties associated with the background contribution are estimated by varying the background level by  $\pm 1\sigma$  in the fit. Resonance parametrization is studied by changing the  $Y(4260)$  BW function from a parametrization with a constant width to another with a three-body phase-space-dependent function. The interference between the two resonances,  $Y(4260)$  and  $Y(4008)$ , depends on the structure of the  $\pi^+\pi^-J/\psi$  amplitude, which can be different for the two resonances. We conservatively estimate possible systematic effects by performing a fit without the interference between the  $Y(4008)$  and the  $Y(4260)$  and taking the difference compared to results with interference as the

TABLE I. Results of the fits to the  $\pi^+\pi^-J/\psi$  mass spectrum with two coherent resonances.  $M(R_i)$ ,  $\Gamma_{\text{tot}}(R_i)$  and  $\Gamma_{ee}\mathcal{B}(R_i \rightarrow \pi^+\pi^-J/\psi)$ ,  $i = 1, 2$  represent the mass (in  $\text{MeV}/c^2$ ), total width (in  $\text{MeV}/c^2$ ) and product of the branching ratio for the decay into  $\pi^+\pi^-J/\psi$  and the  $e^+e^-$  partial width (in  $\text{eV}/c^2$ ) for the two resonances, respectively. The parameter  $\phi$  (in degrees) is the relative phase between the two resonances. The first and second errors are statistical and systematic, respectively.

Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\text{tot}}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \rightarrow \pi^+\pi^-J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\text{tot}}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \rightarrow \pi^+\pi^-J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
$\phi$	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$



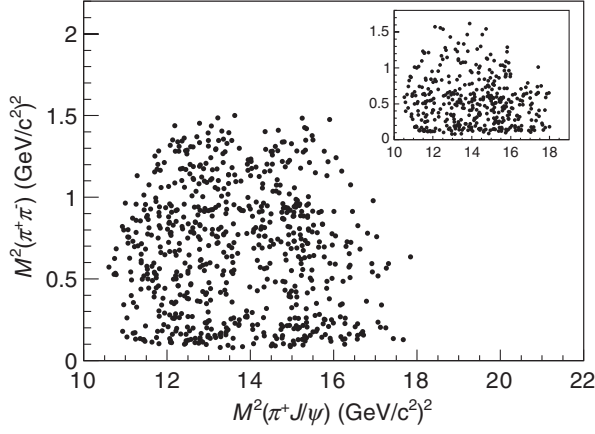


FIG. 2. Dalitz plot for  $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$  decays for  $4.15 \text{ GeV}/c^2 < M(\pi^+ \pi^- J/\psi) < 4.45 \text{ GeV}/c^2$ . The inset shows background events from the  $J/\psi$ -mass sidebands (not normalized).

corresponding systematic error. All of these contributions are summarized in Table I. The measured mass, width, and the product  $\Gamma_{ee} \mathcal{B}(R_1 \rightarrow \pi^+ \pi^- J/\psi)$  are consistent within statistics with the previous results [8,20].

Figure 2 shows the Dalitz plot for events in the  $Y(4260)$  signal region ( $4.15 \text{ GeV}/c^2 < M(\pi^+ \pi^- J/\psi) < 4.45 \text{ GeV}/c^2$ ), where we observe structures in the  $\pi^+ \pi^-$  and  $\pi^+ J/\psi$  systems. The inset is for the events in the  $J/\psi$ -mass sidebands, where no obvious structures are observed in the non- $\pi^+ \pi^- J/\psi$  background events.

Figure 3 shows a projection of the  $M(\pi^+ \pi^-)$ ,  $M(\pi^+ J/\psi)$ , and  $M(\pi^- J/\psi)$  invariant mass distributions for events in the  $Y(4260)$  signal region. Background contributions are estimated from the normalized  $J/\psi$  mass sidebands. There are  $f_0(980)$ ,  $f_0(500)$ , and nonresonant  $S$ -wave amplitudes in the  $\pi^+ \pi^-$  mass spectrum. In the  $\pi^\pm J/\psi$  mass spectrum, there is a significant peak around  $3.9 \text{ GeV}/c^2$  [called the  $Z(3900)^\pm$  hereafter], that we interpret as evidence for an exotic charmoniumlike state, decays into  $\pi^\pm J/\psi$ ; the broader peak near  $3.5 \text{ GeV}/c^2$  is a reflection of the  $Z(3900)^\pm$ , as confirmed by MC

simulation. The pure  $\pi^+ \pi^-$   $S$ -wave amplitudes that describe the  $\pi^+ \pi^-$  invariant mass distribution well cannot reproduce the structure at  $3.9 \text{ GeV}/c^2$  in the  $\pi^\pm J/\psi$  mass spectra, as shown in Fig. 3 with the open histograms.

An unbinned maximum likelihood fit is performed to the distribution of  $M_{\max}(\pi J/\psi)$ , the maximum of  $M(\pi^+ J/\psi)$  and  $M(\pi^- J/\psi)$ . The signal shape is parametrized as an  $S$ -wave BW function convolved with a Gaussian whose mass resolution is fixed at the MC-estimated value of  $7.4 \text{ MeV}$ , and the background is approximated by a cubic polynomial. The mass-dependent efficiency is also included in the fit. Figure 4 shows the fit results. The fit yields  $159 \pm 49 \pm 7 \text{ } Z(3900)^\pm$  events, with a mass of  $(3894.5 \pm 6.6 \pm 4.5) \text{ MeV}/c^2$  and a width of  $(63 \pm 24 \pm 26) \text{ MeV}/c^2$ , where the errors are statistical and systematic, respectively. The largest contributions to the systematic uncertainties arise from the parametrization of the signal and background shapes, the mass resolution and mass calibrations. The statistical significance of the  $Z(3900)^\pm$  state is found to be  $5.5\sigma$  in the nominal fit, and is larger than  $5.2\sigma$  in all alternate fits used for systematic checks with different background shapes, fit ranges and BW resonant models. The significance is calculated by comparing the logarithmic likelihoods with and without the  $Z(3900)^\pm$  signal, and including the change of the number of parameters in the fits. From the signal yields and the MC-simulated efficiencies, we obtain the ratio of the production rates  $(\mathcal{B}[Y(4260) \rightarrow Z(3900)^\pm \pi^\pm] \mathcal{B}[Z(3900)^\pm \rightarrow \pi^\pm J/\psi]) / \mathcal{B}[Y(4260) \rightarrow \pi^+ \pi^- J/\psi] = (29.0 \pm 8.9)\%$ , where the error is statistical only [21]. We test the hypothesis that interference between the  $S$  and  $D$  waves in the  $\pi^+ \pi^-$  system might produce a structure similar to the enhancement observed in data. Although the statistics do not allow us to fully explore the Dalitz plot via an amplitude analysis, we find that these partial waves alone cannot produce a  $\pi^\pm J/\psi$  invariant mass peak near  $3.9 \text{ GeV}/c^2$  [22]. Inclusion of a  $Z(3900)^\pm$  with the mass and width determined above significantly improves the agreement between predicted and observed Dalitz plot distributions.

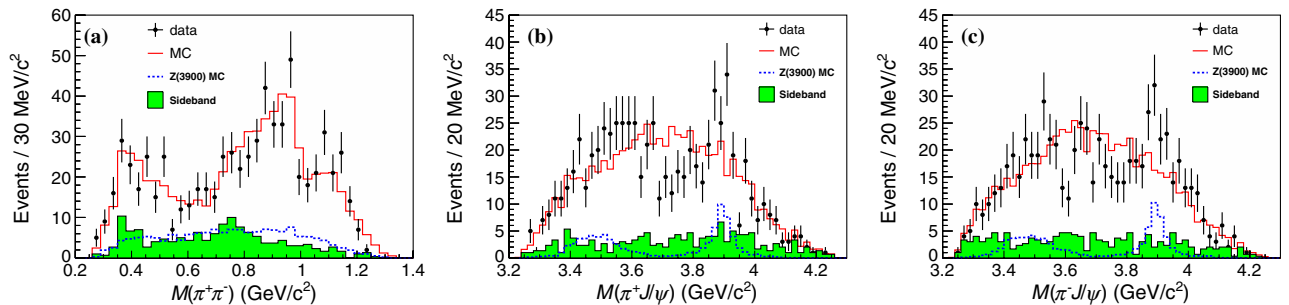


FIG. 3 (color online). Invariant mass distributions of (a)  $\pi^+ \pi^-$ , (b)  $\pi^+ J/\psi$ , and (c)  $\pi^- J/\psi$  for events in the  $Y(4260)$  signal region. Points with error bars represent data, shaded histograms are normalized background estimates from the  $J/\psi$ -mass sidebands, solid histograms represent MC simulations of  $\pi^+ \pi^-$  amplitudes [22] (normalized  $J/\psi$ -mass sideband events added) and dashed histograms are MC simulation results for a  $Z(3900)^\pm$  signal.

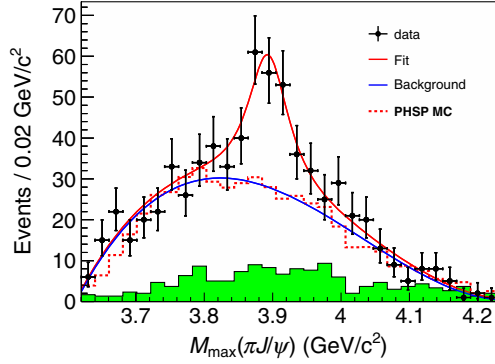


FIG. 4 (color online). Unbinned maximum likelihood fit to the distribution of the  $M_{\max}(\pi J/\psi)$ . Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space (PHSP) distribution and the shaded histogram is the non- $\pi^+\pi^-J/\psi$  background estimated from the normalized  $J/\psi$  sidebands.

In summary, the cross section of  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  is measured from 3.8 to 5.5 GeV. The  $Y(4260)$  resonance is observed and its resonant parameters are determined. In addition, the  $Y(4008)$  state is confirmed. The intermediate states in  $Y(4260) \rightarrow \pi^+\pi^-J/\psi$  decays are also investigated. A  $Z(3900)^\pm$  state with a mass of  $(3894.5 \pm 6.6 \pm 4.5)$  MeV/ $c^2$  and a width of  $(63 \pm 24 \pm 26)$  MeV/ $c^2$  is observed in the  $\pi^\pm J/\psi$  mass spectrum with a statistical significance larger than  $5.2\sigma$ . This state is close to the  $D\bar{D}^*$  mass threshold; however, no enhancement is observed near the  $D^*\bar{D}^*$  mass threshold. As the  $Z(3900)^\pm$  state has a strong coupling to charmonium and is charged, we conclude it cannot be a conventional  $c\bar{c}$  state.

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*Note added.*—Recently, we became aware of a Letter from the BESIII Collaboration [23] that also reports on the  $Z(3900)^\pm$  at the same time.

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- [20] A smaller systematic error is obtained because we no longer use a BW with a phase-space-dependent total width to parametrize  $R_1$ .
- [21] The fraction of  $Z(3900)^\pm$  events is obtained from a one-dimensional fit to the  $M_{\max}(\pi J/\psi)$  distribution without

including possible interference with other amplitudes. For a more precise determination of this fraction, a full partial wave analysis with more statistics would be required.

- [22] We perform a partial wave analysis with  $f_0(500)$ ,  $f_0(980)$ , nonresonant  $S$  wave, and  $f_2(1270)$  amplitudes, and find
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