XYZ at BESIII *

Jingzhi Zhang[1)], Changzheng Yuan (for the BESIII Collaboration)
Institute of High Energy Physics, Beijing 100049, People's Republic of China

Abstract: With 5.1 fb^{-1} of data taken at $\sqrt{s}$=3.8 – 4.6 GeV, BESIII made a significant contribution to the study of charmonium-like states, i.e., the XYZ states. In this talk, we review the results of observations of the Z_c states, the $X(3872)$ in e^+e^- annihilation, and charmonium $\psi(1^3D_2)$ state, as well as measurements of the cross-sections of $\omega\chi_{cJ}$ and $\eta J/\psi$.

Key words: charmonium-like, ISR, exoitic

PACS: 14.40.Rt, 13.25.Gv, 13.66.Bc

BESIII上XYZ 的研究

张景芝[1)]，苑长征（BESIII合作组）

中国科学院高能物理研究所，北京100049，中国

摘　要:
通过分析质心系能量为3.8~4.6 GeV的5.1 fb^{-1}数据，BESIII在类粲偶素（即XYZ）的研究上取得了重要成果。在报告中，我们回顾了Z_c的发现，$X(3872)$在e^+e^-湮灭中的产生，粲偶素$\psi(1^3D_2)$的发现，以及$\omega\chi_{cJ}$和$\eta J/\psi$过程界面的测量。

关键词：类粲偶素，初态辐射，奇异态

1 Introduction

In recent years, charmonium physics gained renewed strong interest from both theorists and experimentalists, due to the observation of charmonium-like states [1]. These states do not fit in the conventional charmonium spectroscopy, and could be exotic states that lie outside the quark model. Y(4260) was first seen by BaBar as a peak in the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at enter-of-mass energy of 4.26 GeV [2]. It was subsequently confirmed by CLEO [3] and Belle [4]. Its production via the electron and positron annihilation process requires the quantum numbers of the Y(4260) to be $J^{pc} = 1^{--}$. The absence of any apparent corresponding structure in the cross sections for $e^+e^- \to D^{(*)}D^{(*)}(\pi)$ [5] indicates that the Y(4260) is probably not a conventional quarkonium state. To study the charmonium(-like) states above 4 GeV, and to establish the relationship between the charmonium-like states and higher excited charmonium states, BESIII has collected in total 5.1 fb^{-1} data [6, 7] during 2013 and 2014 above 3.8 GeV. The results presented in this talk are based on these data samples.

2 Observation of $Z_c(3900)$

BESIII studied the $e^+e^- \to \pi^+\pi^- J/\psi$ process at a center-of-mass energy of 4.26 GeV using a 525 pb^{-1} data sample [8]. A structure at around 3.9 GeV/c^2 was observed in the $\pi^\pm J\psi$ mass spectrum with a statistical significance larger than 8σ, which is referred to as the $Z_c(3900)$. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum, shown in Fig. 1, neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. The associated production ratio was measured to be $R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$.

Received 30 Nov. 2015
* Supported by National Natural Science Foundation of China (11235011,11475187)
1) E-mail: jingzhi@ihep.ac.cn

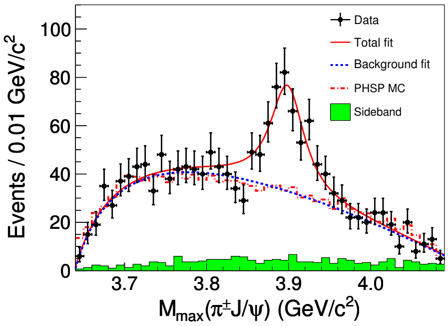


Fig. 1. Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi^{\pm}J/\psi)$. Points with error bars are for data, the curves are the fit results, the dashed histograms are the phase space distributions and the shaded histograms are the non-$\pi^+\pi^-J/\psi$ background estimated from the normalized J/ψ sidebands.

The $Z_c(3900)$ state was confirmed shortly after by Belle [9] and CLEO-c [10] using the initial state radiation (ISR) method. The measured mass and width agreed very well with the BESIII measurements.

A neutral state $Z_c(3900)^0 \to \pi^0 J/\psi$ with a significance of 10.4σ was observed at BESIII in $e^+e^- \to \pi^0\pi^0 J/\psi$ with center-of-mass energy ranges from 4.19–4.42 GeV [11]. The mass and width were measured to be $(3894.8\pm2.3\pm3.2)$ MeV$/c^2$ and $(29.6\pm8.2\pm8.2)$ MeV, respectively. This state is interpreted as the neutral partner of the $Z_c(3900)^{\pm}$, as it decays to $\pi^0 J/\psi$ and its mass is close to that of $Z_c(3900)^{\pm}$. This is in agreement with the previously reported 3.5σ evidence for $Z_c(3900)^0$ in the CLEO-c data [10]. The measured Born cross-sections of $e^+e^-\to\pi^0\pi^0J/\psi$ were about half of those for $e^+e^-\to\pi^+\pi^-J/\psi$ measured in the Belle experiment [9], which is consistent with the isospin symmetry expectation.

3 Observation of $Z_c(3885)$

With the data sample at $\sqrt{s}$ = 4.26 GeV, BESIII studied $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$. A structure (referred to as $Z_c(3885)$) was observed in the $(D\bar{D}^*)^{\pm}$ invariant mass distribution [12], as seen in Fig. 2. When fitted to a mass-dependent-width Breit-Wigner (BW) function, the pole mass and width were determined to be $(3883.9\pm1.5\pm4.2)$ MeV$/c^2$ and $(24.8\pm3.3\pm11.0)$ MeV, respectively. The angular distribution of the $Z_c(3885)$ system favors a $J^P = 1^+$ assignment for the structure and disfavors 1^- or 0^-. The production rate was measured to be $\sigma(e^+e^-\to\pi^{\mp}Z_c(3885)^{\pm})\times BF(Z_c(3885)^{\pm}\to(D\bar{D}^*)^{\pm}) = (83.5\pm6.6\pm22.0)$ pb. The mass and width of $Z_c(3885)$ are 2σ and 1σ, respectively, below those of $Z_c(3900)$, as observed by the BESIII and Belle experiments. However, neither fit considers the possibility of interference with a coherent non-resonant background, which could shift the results. A spin-parity quantum number determination for $Z_c(3900)$ would provide an additional test of this possibility.

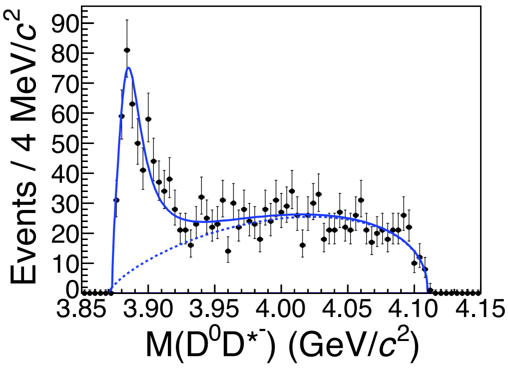


Fig. 2. Fit to the $M(D^0D^{*-})$ distribution for selected events at $\sqrt{s}=4.26$ GeV. The curves show the best fits.

Assuming the $Z_c(3885)$ structure is caused by $Z_c(3900)$, we obtain $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to\pi J/\psi)} = 6.2\pm1.1\pm2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold, e.g., $\Gamma(\psi(3770)\to D\bar{D})/\Gamma(\psi(3770)\to\pi^+\pi^-J/\psi) = 482\pm84$ [13] and $\Gamma(\psi(4040)\to D^{(*)}\bar{D}^{(*)})/\Gamma(\psi(4040)\to\eta J/\psi) = 192\pm27$ [14]. This suggests very different dynamics in the $Y(4260)$-$Z_c(3900)$ system.

4 Observation of $Z_c(4020)$

BESIII measured [15] $e^+e^-\to\pi^+\pi^-h_c$ cross-sections at center-of-mass energies of 3.90–4.42 GeV. Intermediate states were studied by examining the Dalitz plot of selected $\pi^+\pi^-h_c$ candidate events. The h_c signal was selected using $3.518 < M(\gamma\eta_c) < 3.538$ GeV$/c^2$, and $\pi^+\pi^-h_c$ samples of 859 events at 4.23 GeV, 586 events at 4.26 GeV, and 469 events at 4.36 GeV were obtained with purities of 65%. Although there are no clear structures in the $\pi^+\pi^-$ system, there is clear evidence for an exotic charmonium-like structure in the $\pi^{\pm}h_c$ system in the Dalitz plot. Figure 3 shows the projection of the $M(\pi^{\pm}h_c)$ distribution for the signal events, as well as the background events estimated from normalized h_c mass sidebands. There is a significant peak at around 4.02 GeV$/c^2$ ($Z_c^{\pm}(4020)$), and there are also some events at around 3.9 GeV$/c^2$ (inset of Fig. 3), which could be $Z_c(3900)$. The individual datasets at $\sqrt{s}$ = 4.23, 4.26, and 4.36 GeV show similar structures.

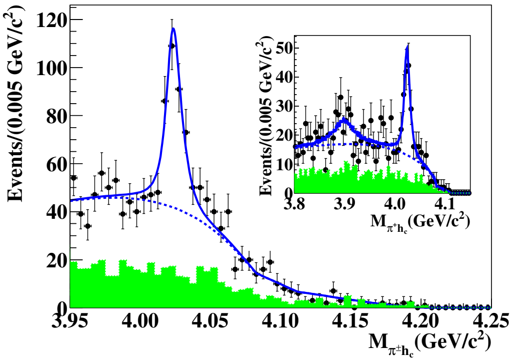


Fig. 3. Sum of the simultaneous fits to the $M(\pi^{\pm}h_c)$ distributions at 4.23, 4.26, and 4.36 GeV in the BESIII data; the inset plot shows the sum of the simultaneous fit to the $M_{\pi^+h_c}$ distributions at 4.23 and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit; and the dotted curves the backgrounds from the fit.

An unbinned maximum likelihood fit was applied to the $M(\pi^{\pm}h_c)$ distribution summed over the 16 η_c decay modes. The data at 4.23, 4.26, and 4.36 GeV were fitted simultaneously to the same signal function with common mass and width. Figure 3 shows the fitted results. The mass and width of $Z_c(4020)$ were measured to be $(4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2 and $(7.9 \pm 2.7 \pm 2.6)$ MeV, respectively. The statistical significance of the $Z_c(4020)$ signal was found to be greater than 8.9σ.

Adding $Z_c(3900)$ with the mass and width fixed to the BESIII measurements [8], the fit is improved somewhat. But the statistical significance is only 2.1σ (see the inset of Fig. 3). At the 90% confidence level (C.L.), the upper limits on the production cross-sections are set to $\sigma(e^+e^- \to \pi^{\pm}Z_c^{\mp}(3900) \to \pi^+\pi^-h_c) < 13$ pb at 4.23 GeV and < 11 pb at 4.26 GeV. These are lower than those of $Z_c(3900) \to \pi^{\pm}J/\psi$ [8].

BESIII also observed $e^+e^- \to \pi^0\pi^0h_c$ at $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV [16]. The measured Born cross-sections were about half of those for $e^+e^- \to \pi^+\pi^-h_c$, which agree with expectations based on isospin symmetry within systematic uncertainties. A narrow structure with a mass of $(4023.9 \pm 2.2 \pm 3.8)$ MeV/c^2 (in fit, the width was fixed to that measured in the $e^+e^- \to \pi^+\pi^-h_c$ process [15] due to low statistics) was observed in the π^0h_c mass spectrum. This structure is most likely the neutral isospin partner of the charged $Z_c(4020)$ observed in the $e^+e^- \to \pi^+\pi^-h_c$ process [15]. This observation indicates that there are no anomalously large isospin violations in $\pi\pi h_c$ and $\pi Z_c(4020)$ systems.

5 Observation of $Z_c(4025)$

We studied [17] the $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ process at 4.26 GeV using 827 pb^{-1} of data. Based on a partial reconstruction technique, the Born cross-section was measured to be $(137 \pm 9 \pm 15)$ pb. A structure near the $(D^*\bar{D}^*)^{\pm}$ threshold in the $\pi^{\mp}$ recoil mass spectrum was observed in Fig. 4, and this is denoted as $Z_c(4025)$. The measured mass and width of the structure were $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2 and $(24.8 \pm 5.6 \pm 7.7)$ MeV, respectively, from the fit with a constant-width BW function for the signal. The associated production ratio $\frac{\sigma(e^+e^- \to Z_c^{\pm}(4025)\pi^{\mp} \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})}{\sigma(e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})}$ was determined to be $0.65 \pm 0.09 \pm 0.06$.

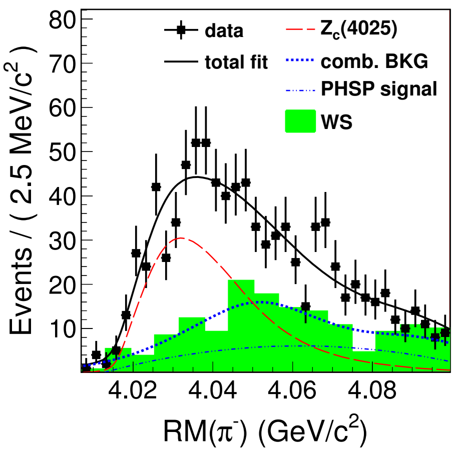


Fig. 4. Unbinned maximum likelihood fit to the $\pi^{\mp}$ recoil mass spectrum in $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s} = 4.26$ GeV,

Using data at $\sqrt{s} = 4.23$ and 4.26 GeV, a structure was observed in the π^0 recoil mass spectrum in the $e^+e^- \to D^{*0}\bar{D}^{*0}(D^{*+}D^{*-})\pi^0$ process [18]. Assuming that the enhancement is due to a neutral state decaying to $D^*\bar{D}^*$, the mass and width of its pole position were determined to be $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c^2 and $\Gamma = (23.0 \pm 6.0 \pm 1.0)$ MeV, respectively. The Born cross-section $\sigma(e^+e^- \to Z_c(4025)^0\pi^0 \to (D^{*0}\bar{D}^{*0} + D^{*+}D^{*-})\pi^0)$ was measured to be $(61.6 \pm 8.2 \pm 9.0)$ pb at 4.23 GeV and $(43.4 \pm 8.0 \pm 5.4)$ pb at 4.26 GeV. The ratio $\frac{\sigma(e^+e^- \to Z_c(4025)^0\pi^0 \to (D^*\bar{D}^*)^0\pi^0)}{\sigma(e^+e^- \to Z_c(4025)^+\pi^- \to (D^*\bar{D}^*)^+\pi^-)}$ is compatible with unity at $\sqrt{s} = 4.26$ GeV, which is expected from isospin symmetry. In addition, $Z_c(4025)^0$ has a mass and width that are very close to those of $Z_c(4025)^{\pm}$, which couples to $(D^*\bar{D}^*)^{\pm}$. Therefore, the observed $Z_c(4025)^0$ state is a good candidate for the isospin partner of $Z_c(4025)^{\pm}$.

As the $Z_c(4025)$ parameters agree to within 1.5 σ with those of $Z_c^{\pm}(4020)$, it is very probable that they are the same state. As the results for $Z_c(4025)^{\pm}$ are only from data at 4.26 GeV, extending the analysis to

4.23 GeV and 4.36 GeV will probably provide a definite answer.

6 Observation of $Y(4260) \to \gamma X(3872)$

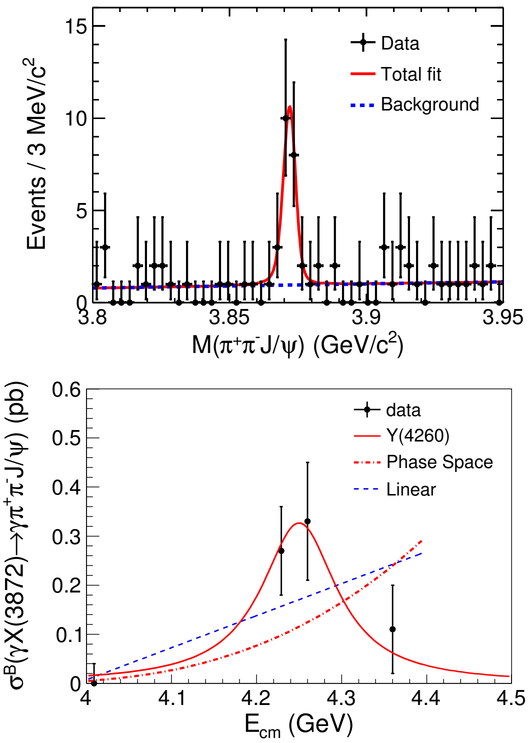


Fig. 5. Top: fit to the $M(\pi^+\pi^-J/\psi)$ distribution. Dots with error bars are data, the curves are the fit results. Bottom: fit to $\sigma^B[e^+e^- \to \gamma X(3872)] \times \mathcal{B}[X(3872) \to \pi^+\pi^-J/\psi]$ with a $Y(4260)$ resonance (red solid curve), a linear continuum (blue dashed curve), or an $E1$-transition phase space term (red dotted-dashed curve). Dots with error bars are data.

BESIII observed $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^-J/\psi$, with J/ψ reconstructed through its decays into lepton pairs (e^+e^- or $\mu^+\mu^-$) [19]. The $M(\pi^+\pi^-J/\psi)$ distribution (summed over all energy points), as shown in Fig. 5 (top), was fitted to extract the mass and signal yield of $X(3872)$. The ISR $\psi(2S)$ signal was used to calibrate the absolute mass scale and to extract the resolution difference between the data and a Monte Carlo (MC) simulation. Figure 5 (top) shows the fitting result: the measured mass of $X(3872)$ was $(3871.9 \pm 0.7 \pm 0.2)$ MeV/c^2. From a fit with a floating width, we obtain a width of $(0.0^{+1.7}_{-0.0})$ MeV, or less than 2.4 MeV at the 90% C.L. The statistical significance of $X(3872)$ is 6.3σ.

Table 1. The product of the Born cross section $\sigma^B(e^+e^- \to \gamma X(3872))$ and $\mathcal{B}(X(3872) \to \pi^+\pi^-J/\psi)$ at different energy points. The upper limits are given at 90% C.L.

$\sqrt{s}$ (GeV)	$\sigma^B[e^+e^- \to \gamma X] \cdot \mathcal{B} \to \pi\pi J/\psi)$ (pb)
4.009	$0.00 \pm 0.04 \pm 0.01$ or < 0.11
4.229	$0.27 \pm 0.09 \pm 0.02$
4.260	$0.33 \pm 0.12 \pm 0.02$
4.360	$0.11 \pm 0.09 \pm 0.01$ or < 0.36

The Born-order cross-section was measured, and the results are listed in Table 1. For 4.009 and 4.36 GeV data, since the $X(3872)$ signal is not significant, upper limits on the production rates are given at the 90% C.L. The measured cross-sections at around 4.26 GeV are an order of magnitude higher than the NRQCD calculation of continuum production [20], which may suggest the $X(3872)$ events come from resonance decays.

The energy-dependent cross-sections were fitted with a $Y(4260)$ resonance (parameters fixed to PDG [13] values), linear continuum, or $E1$-transition phase space ($\propto E_\gamma^3$) term. Figure 5 (bottom) shows all the fitting results, which imply that $\chi^2/\mathrm{ndf} = 0.49/3$ (C.L. = 92%), 5.5/2 (C.L. = 6%), and 8.7/3 (C.L. = 3%) for a $Y(4260)$ resonance, linear continuum, and phase space distribution, respectively. Thus, the $Y(4260)$ resonance describes the data better than the other two options. These observations strongly support the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$. The $Y(4260) \to \gamma X(3872)$ process could be another previously unseen decay mode of the $Y(4260)$ resonance.

Combining the above with the $e^+e^- \to \pi^+\pi^-J\psi$ cross-section measurement at $\sqrt{s} = 4.26$ GeV from BESIII [8], we obtain $\sigma^B[e^+e^- \to \gamma X(3872)] \cdot BF[X(3872) \to \pi^+\pi^-J/\psi]/\sigma^B(e^+e^- \to \pi^+\pi^-J/\psi) = (5.2 \pm 1.9) \times 10^{-3}$, under the assumption that $X(3872)$ and $\pi^+\pi^-J/\psi$ are only produced from $Y(4260)$ decays. If we take $BF[X(3872) \to \pi^+\pi^-J/\psi] = 5\%$ [21], then $\mathcal{R} = \frac{BF[Y(4260) \to \gamma X(3872)]}{BF(Y(4260) \to \pi^+\pi^-J/\psi)} \sim 0.1$.

7 Observation of $\psi(1^3D_2)$

BESIII observed $X(3823)$ in the $e^+e^- \to \pi^+\pi^-X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$ process with a statistical significance of 6.2σ in data samples at center-of-mass energies of $\sqrt{s}$ =4.23, 4.26, 4.36, 4.42, and 4.60 GeV [22]. Figure 6 shows the fitting results to $\pi\pi$ recoil mass distributions for events in the χ_{c1} and χ_{c2} signal regions. The fit yields 19 ± 5 $X(3823)$ signal events in the $\gamma\chi_{c1}$ mode, with a measured mass of $X(3823)$ of $(3821.7 \pm 1.3 \pm 0.7)$ MeV/c^2, where the first error is statistical and the second systematic. For the $\gamma\chi_{c2}$ mode, no significant $X(3823)$ signal was observed, and an upper limit on its production rate could be determined. The limited statistics do not allow a measurement of the intrinsic width of $X(3823)$. From a fit using the BW function (with a floating width) convolved with Gaussian resolution, it can be determined that $\Gamma[X(3823)] < 16$ MeV at the 90% C.L. (including systematic errors). This measurement agrees well with the values found by Belle [23]. The production cross-sections of $\sigma^B(e^+e^- \to \pi^+\pi^- X(3823)) \cdot \mathcal{B}(X(3823) \to \gamma\chi_{c1}, \gamma\chi_{c2})$ were also measured at these center-of-mass energies. The cross-sections of $e^+e^- \to \pi^+\pi^- X(3823)$ were fitted with the $Y(4360)$ shape or the $\psi(4415)$ shape, with their resonance parameters fixed to the PDG values [13]. Figure 7 shows the fitting results, both the $Y(4360)$ and $\psi(4415)$ hypotheses are accepted at a 90% C.L.

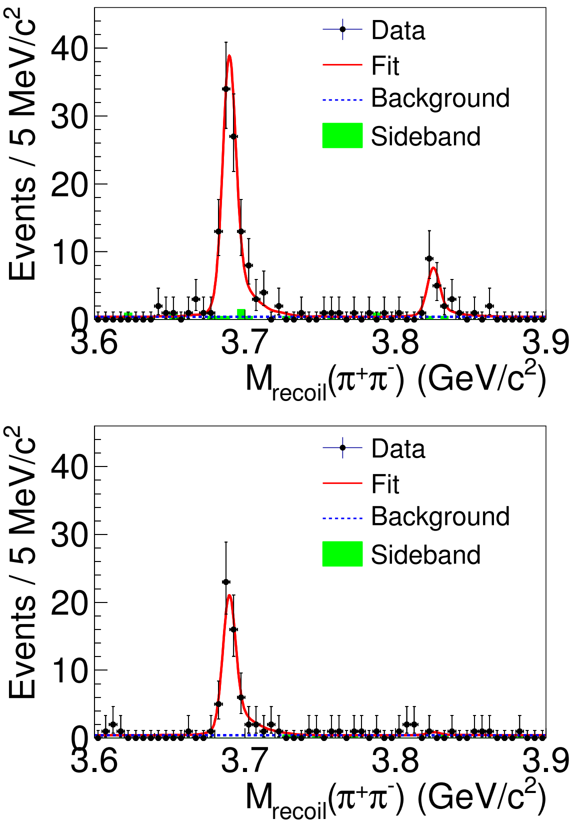


Fig. 6. Simultaneous fit to the $M_{\text{recoil}}(\pi^+\pi^-)$ distribution of $\gamma\chi_{c1}$ events (top) and $\gamma\chi_{c2}$ events (bottom), respectively. Dots with error bars are data, red solid curves are total fit, dashed blue curves are background, and the green shaded histograms are J/ψ mass sideband events.

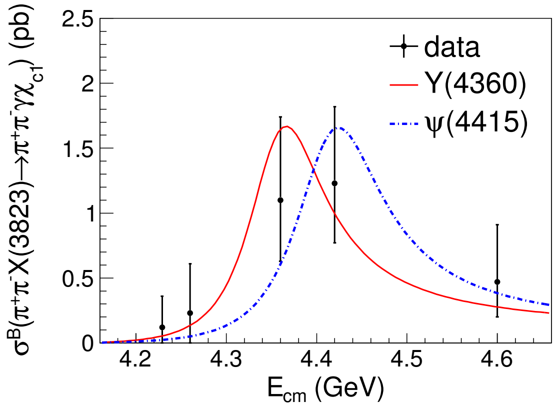


Fig. 7. Comparison of the energy-dependent cross sections of $\sigma^B[e^+e^- \to \pi\pi X(3823)] \cdot \mathcal{B}(X(3823) \to \gamma\chi_{c1})$ to the $Y(4360)$ and $\psi(4415)$ line shapes. Dots with error bars (statistical only) are data. The red solid (blue dashed) curve shows a fit with the $Y(4360)$ ($\psi(4415)$) line shape.

The $X(3823)$ resonance is a good candidate for the $\psi(1^3D_2)$ charmonium state. According to potential models [24], the D-wave charmonium states are expected to be within a mass range of 3.82 $\sim$ 3.85 GeV. The $1^1D_2 \to \gamma\chi_{c1}$ transition is forbidden because of C-parity conservation, and the amplitude for $1^3D_3 \to \gamma\chi_{c1}$ is expected to be small [25]. The mass of $\psi(1^3D_2)$ is in the 3.810 $\sim$ 3.840 GeV/c^2 range predicted by several phenomenological calculations [26]. In this case, the mass of $\psi(1^3D_2)$ was above the $D\bar{D}$ threshold but below the $D\bar{D}^*$ threshold. Because $\psi(1^3D_2) \to D\bar{D}$ violates parity, $\psi(1^3D_2)$ is expected to be narrow, in agreement with the observation, and $\psi(1^3D_2) \to \gamma\chi_{c1}$ is expected to be a dominant decay mode [26, 27]. From the cross-section measurement, we obtain the ratio $\frac{\mathcal{B}[X(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[X(3823)\to\gamma\chi_{c1}]} < 0.42$ at the 90% C.L., which also agrees with expectations for the $\psi(1^3D_2)$ state [27].

8 Observation of $e^+e^- \to \omega\chi_{c0}$

Based on data samples collected between $\sqrt{s} = 4.21$ and 4.42 GeV, the $e^+e^- \to \omega\chi_{c0}$ process was observed at $\sqrt{s} = 4.23$ and 4.26 GeV [28]. The Born cross-sections were measured to be $(55.4 \pm 6.0 \pm 5.9)$ and $(23.7\pm5.3\pm3.5)$ pb, respectively. For other energy points, no significant signals were found, and upper limits on the cross-section at the 90% C.L. were determined.

The data reveal a sizable $\omega\chi_{c0}$ production at around 4.23 GeV/c^2, as predicted in Ref. [29]. By assuming the $\omega\chi_{c0}$ signals come from a single resonance, the $\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})$, mass, and width of the resonance are fitted to be $(2.7 \pm 0.5 \pm 0.4)$ eV, $(4230 \pm 8 \pm 6)$ MeV/c^2, and $(38 \pm 12 \pm 2)$ MeV, respectively (shown in Fig. 8). The parameters are not consistent with the lineshape $Y(4260) \to \pi^+\pi^- J/\psi$ cross-section [2]. This suggests that the observed $\omega\chi_{c0}$ signals are unlikely to originate from $Y(4260)$.

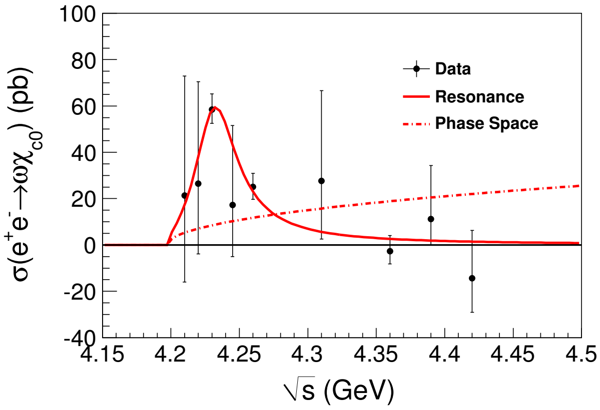
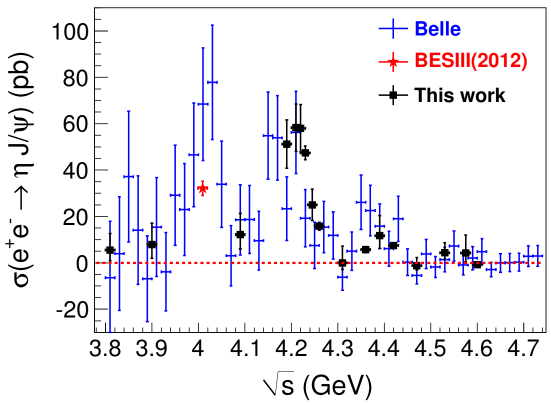


Fig. 8. Fit to $\sigma(e^+e^- \to \omega\chi_{c0})$ with a resonance (solid curve), or a phase space term (dot-dashed curve). Dots with error bars are the dressed cross sections. The uncertainties are statistical only.

8.1 Measurement of $e^+e^- \to \eta J/\psi$

Using data samples collected at energies of 3.81–4.60 GeV, BESIII analyzed $e^+e^- \to \eta J/\psi$ [30]. Statistically significant η signals were observed, and the corresponding Born cross-sections were measured. In addition, a search for the $e^+e^- \to \pi^0 J/\psi$ process observed no significant signals, and upper limits at the 90% C.L. on the Born cross-section were set.

A comparison of the Born cross-sections $\sigma(e^+e^- \to \eta J/\psi)$ in this measurement to previous results [14, 31] is shown in Fig. 9 (top), indicating very good agreement. The measured Born cross-sections were also compared to those of $e^+e^- \to \pi^+\pi^- J/\psi$ obtained from the Belle experiment [9], as shown in Fig. 9 (bottom). Different line shapes can be observed in these two processes, indicating that the production mechanism of $\eta J/\psi$ differs from that of $\pi^+\pi^- J/\psi$ in the vicinity of $\sqrt{s}$ = 4.1–4.6 GeV. This could indicate the existence of a rich spectrum of the Y states in this energy region with different coupling strengths to various decay modes.



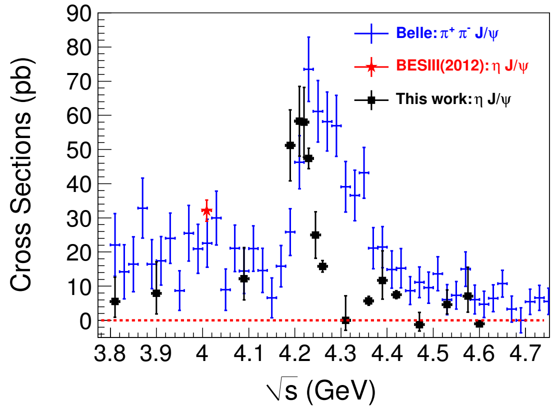


Fig. 9. A comparison of the measured Born cross sections of $e^+e^- \to \eta J/\psi$ to those of the previous measurements [14, 31] (top), and to those of $e^+e^- \to \pi^+\pi^- J/\psi$ from Belle [9]. In these two plots, the black square dots and the red star dots are the results of $\eta J/\psi$ obtained from BESIII. The blue dots are results of $\eta J/\psi$ (top) and $\pi^+\pi^- J/\psi$ (bottom) from Belle. The errors are statistical only for Belle's results, and are final combined uncertainties for BESIII's results.

9 Conclusion

With the world's largest data samples at the center-of-mass energies of 3.8–4.6 GeV, the BESIII experiment made a significant contribution to the study of the charmonium(-like) states. BESIII will continue to collect and analyse e^+e^- data in the energy region of the putative exotic states of charmonium. Efforts from other experiments, such as LHCb and PANDA, are important to enable a systematic understanding of the nature of the XYZ states.

References

1 N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer et al., "Heavy quarkonium: progress, puzzles, and opportunities" Eur. Phys. J. C71, 1534 (2011)

2 B. Aubert *et al.* [BaBar Collaboration], "Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26 GeV/c^2, Phys. Rev. Lett. **95**, 142001 (2005).

3 Q. He *et al.* [CLEO Collaboration], "Confirmation of the Y(4260) resonance production in ISR," Phys. Rev. D **74** (2006) 091104.

4 C. Z. Yuan *et al.* [Belle Collaboration], "Measurement of $e^+e^- \to \pi^+\pi^- J/\psi$ cross-section via initial state radiation at Belle," Phys. Rev. Lett. **99** 182004 (2007).

5 X. H. Mo, G. Li, C. Z. Yuan, K. L. He, H. M. Hu, J. H. Hu, P. Wang and Z. Y. Wang, Phys. Lett. B **640** (2006) 182

6 M. Ablikim *et al.* [BESIII Collaboration], "Measurements of the center-of-mass energies via the di-muon process at BESIII," to be submitted to Chin. Phys. C.

7 M. Ablikim *et al.* [BESIII Collaboration], "Precision measurement of the integrated luminosity of the data taken by BESIII at center of mass energies between 3.810 GeV and 4.600 GeV," arXiv:1503.03408 [hep-ex].

8 M. Ablikim *et al.* [BESIII Collaboration], "Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV," Phys. Rev. Lett. **110**, 252001 (2013).

9 Z. Q. Liu *et al.* [Belle Collaboration], "Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle," Phys. Rev. Lett. **110**, 252002 (2013).

10 T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, "Observation of the Charged Hadron $Z_c^{\pm}(3900)$ and Evidence for the Neutral $Z_c^0(3900)$ in $e^+e^- \to \pi\pi J/\psi$ at $\sqrt{s} = 4170$ MeV," Phys. Lett. B **727**, 366 (2013).

11 M. Ablikim *et al.* [BESIII Collaboration], "Observation of $Z_c^0(3900)$ in $e^+e^- \to \pi^0\pi^0 J/\psi$," Phys. Rev. Lett. **110**, 252001 (2013).

12 M. Ablikim *et al.* [BESIII Collaboration], "Observation of a charged $(D\bar{D}^*)^-$ mass peak in $e^+e^- \to \pi^+(D\bar{D}^*)^-$ at Ecm=4.26 GeV," Phys. Rev. Lett. **112**, 022001 (2014).

13 K. A. Olive *et al.* [Particle Data Group], "The Review of Particle Physics,", Chin. Phys. C **38**, 090001 (2014).

14 M. Ablikim *et al.* [BESIII Collaboration], "Observation of $e^+e^- \to \eta J/\psi$ at center-of-mass energy $sqrts = 4.009$ GeV," Phys. Rev. D **86**, 071101 (2012).

15 M. Ablikim *et al.* [BESIII Collaboration], "Observation of a charged charmoniumlike structure $Z_c(4020)$ and search for the $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- h_c$," Phys. Rev. Lett. **111**, 242001 (2013).

16 M. Ablikim *et al.* [BESIII Collaboration], "Observation of $e^+e^- \to \pi^0\pi^0 h_c$ and a Neutral Charmoniumlike Structure $Z_c(4020)^0$," Phys. Rev. Lett. **113**, no. 21, 212002 (2014).

17 M. Ablikim *et al.* [BESIII Collaboration], "Observation of a charged charmoniumlike structure in $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s} = 4.26$GeV," Phys. Rev. Lett. **112**, 132001 (2014).

18 M. Ablikim *et al.* [BESIII Collaboration], "Observation of a neutral charmoniumlike state $Z_c(4025)^0$ in $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$," arXiv:1507.02404 [hep-ex].

19 M. Ablikim *et al.* [BESIII Collaboration], "Observation of $e^+e^- \to \gamma X(3872)$ at BESIII," Phys. Rev. Lett. **112**, no. 9, 092001 (2014).

20 K. T. Chao, Z. G. He, D. Li and C. Meng, "Search for $C = +$ charmonium states in $e^+e^- \to \gamma + X$ at BEPCII/BESIII," arXiv:1310.8597 [hep-ph].

21 C. Z. Yuan (for the BES and Belle Collaborations), "Exotic Hadrons," arXiv:0910.3138 [hep-ex]. We take 5% from the range presented in the paper of $2.3\% < \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] < 6.6\%$ at 90% C.L.

22 M. Ablikim *et al.* [BESIII Collaboration], "Observation of the $\psi(1^3D_2)$ state in $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$ at BESIII," Phys. Rev. Lett. **115**, no. 1, 011803 (2015).

23 V. Bhardwaj *et al.* [Belle Collaboration], "Evidence of a new narrow resonance decaying to $\chi_{c1}\gamma$ in $B \to \chi_{c1}\gamma K$," Phys. Rev. Lett. **111**, no. 3, 032001 (2013).

24 E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, "Charmonium: The Model," Phys. Rev. D **17**, 3090 (1978) [Phys. Rev. D **21**, 313 (1980)].

25 T. Barnes, S. Godfrey and E. S. Swanson, "Higher charmonia," Phys. Rev. D **72**, 054026 (2005).

26 S. Godfrey and N. Isgur, "Mesons in a Relativized Quark Model with Chromodynamics," Phys. Rev. D **32**, 189 (1985).

27 C. F. Qiao, F. Yuan and K. T. Chao, "A Crucial test for color octet production mechanism in Z^0 decays," Phys. Rev. D **55**, 4001 (1997).

28 M. Ablikim *et al.* [BESIII Collaboration], "Study of $e^+e^- \to \omega\chi_{cJ}$ at center-of-mass energies from 4.21 to 4.42 GeV," Phys. Rev. Lett. **114**, no. 9, 092003 (2015).

29 L. Y. Dai, M. Shi, G. Y. Tang and H. Q. Zheng, "Nature of $X(4260)$," Phys. Rev. D **92**, no. 1, 014020 (2015).

30 M. Ablikim *et al.* [BESIII Collaboration], "Measurement of the $e^+e^- \to \eta J/\psi$ cross section and search for $e^+e^- \to \pi^0 J/\psi$ at center-of-mass energies between 3.810 and 4.600 GeV," Phys. Rev. D **91**, no. 11, 112005 (2015).

31 X. L. Wang *et al.* [Belle Collaboration], "Observation of $\psi(4040)$ and $\psi(4160)$ decay into $\eta J/\psi$," Phys. Rev. D **87**, no. 5, 051101 (2013).