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XYZ at BESIII

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Abstract: With 5.1 fb^{-1} of data taken at $\sqrt{s}=3.8\sim4.6$ GeV, BESIII made a significant contribution to the study of charmonium-like states, i.e., the XYZ states. 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; initial state radiation (ISR); exoitic

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BESIII 上 XYZ 的研究

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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.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

0 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

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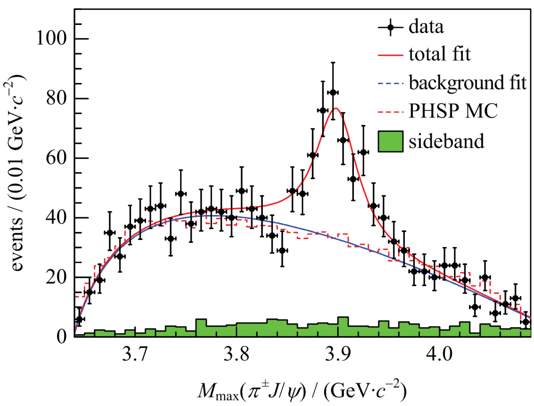
on these data samples.

1 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 (3 899.0±3.6±4.9) MeV/c^2 and a width of (46±10±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±3.3±7.5)%.



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.

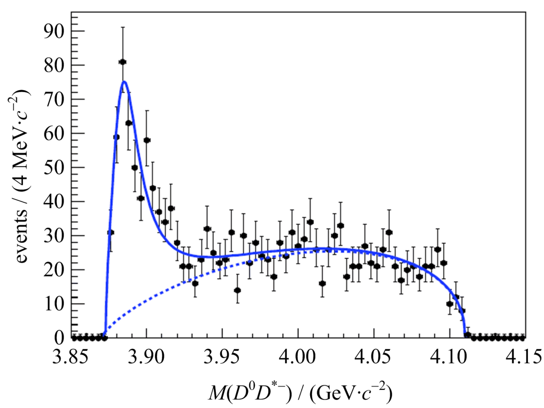
Fig. 1 Unbinned maximum likelihood fit to the distribution of the $M_{max}(\pi^\pm J/\psi)$

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 to 4.42 GeV[11]. The mass and width were measured to be (3 894.8±2.3±3.2) MeV/c^2 and (29.6±8.2±8.2) 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 $e^+e^-\to\pi^0\pi^0 J/\psi$ 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.

2 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 (3 883.9±1.5±4.2) MeV/c^2 and (24.8±3.3±11.0) 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±6.6±22.0) 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



The curves show the best fits.

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

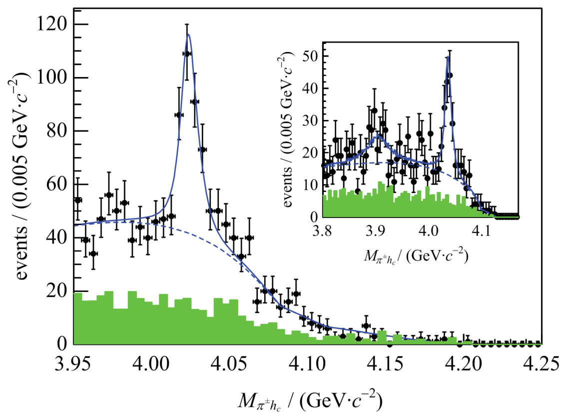
shift the results. A spin-parity quantum number determination for $Z_c(3900)$ would provide an additional test of this possibility.

Assuming the $Z_c(3885)$ structure is caused by $Z_c(3900)$, we obtain $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)}=6.2\pm 1.1\pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold, e. g., $\Gamma(\psi(3770)\to D\bar{D})/\Gamma(\psi(3770)\to\pi^+\pi^- J/\psi)=482\pm 84$[13] and $\Gamma(\psi(4040)\to D^{(*)}\bar{D}^{(*)})/\Gamma(\psi(4040)\to \eta J/\psi)=192\pm 27$[14]. This suggests very different dynamics in the $Y(4260)-Z_c(3900)$ system.

3 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 $3.518\ \mathrm{GeV}/c^2 < M(\gamma\eta_c) < 3.538$, 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. Fig. 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.

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. Fig. 3 shows the fitted results. The mass and width of $Z_c(4020)$ were measured to be



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.

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 $M_{\pi^\pm h_c}$ distributions at 4.23 and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$

$(4\,022.9\pm 0.8\pm 2.7)$ 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 $e^+e^-\to\pi^0\pi^0 h_c$ 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 $(4\,023.9\pm 2.2\pm 3.8)$ 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 $\pi^0 h_c$ 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.

4 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 $(137\pm9\pm15)$ 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 $(4\,026.3\pm2.6\pm3.7)$ MeV/c^2 and $(24.8\pm5.6\pm7.7)$ 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 $0.65\pm0.09\pm0.06$.

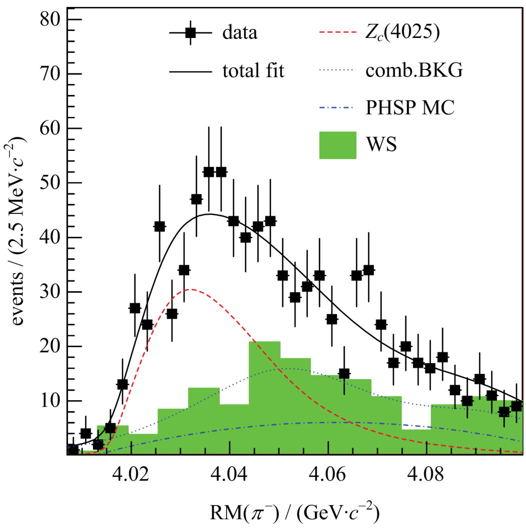


Fig. 4 Unbinned maximum likelihood fit to the $\pi^{\mp}$ recoil mass spectrum in $e^+e^-\to(D^*\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s}$ =4.26 GeV

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 $(4\,025.5^{+2.0}_{-4.7}\pm3.1)$ MeV/c^2 and $\Gamma=(23.0\pm6.0\pm1.0)$ 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 $(61.6\pm8.2\pm9.0)$ pb at 4.23 GeV and $(43.4\pm8.0\pm5.4)$ 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 $Z_c(4025)^{\pm}$.

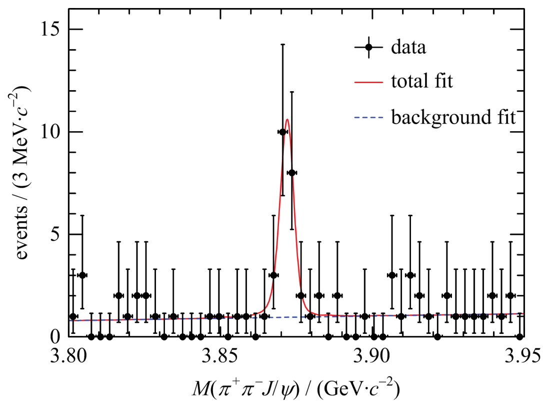
As the $Z_c(4025)$ parameters agree to within 1.5σ with those of $Z_c^{\pm}(4020)$, it is very probable that they are the same state. As the results for $Z_c(4025)^{\pm}$ are only from data at 4.26 GeV, extending the analysis to 4.23 GeV and 4.36 GeV will probably provide a definite answer.

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

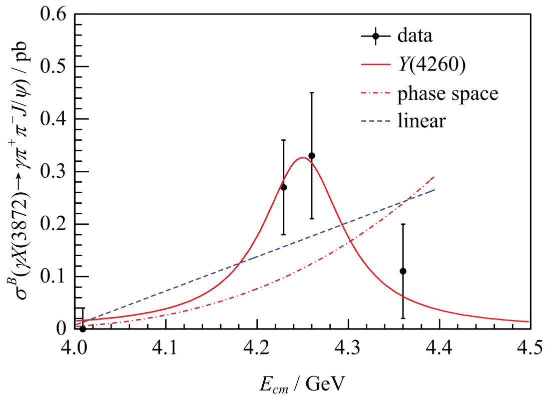
BESIII observed $e^+e^-\to\gamma X(3872)\to\gamma\pi^+\pi^-J/\psi$, with J/ψ reconstructed through its decays into lepton pairs (e^+e^- or $\mu^+\mu^-$)[19]. The $M(\pi^+\pi^-J/\psi)$ distribution (summed over all energy points), as shown in Fig. 5, was fitted to extract the mass and signal yield of $X(3872)$. 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. Fig. 5 (top) shows the fitting result: the measured mass of $X(3872)$ was $(3\,871.9\pm0.7\pm0.2)$ 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.

The Born-order cross-section was measured, and the results are listed in Tab. 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



Dots with error bars are data, the curves are the fit results.



Dots with error bars are data.

Fig. 5　Top: fit to the $M(\pi^+\pi^- J/\psi)$ distribution. Bottom: fit to $\sigma^B[e^+e^-\to\gamma X(3872)]\times\mathscr{B}[X(3872)\to\pi^+\pi^- J/\psi]$ 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)

Tab. 1　The product of the Born cross section $\sigma^B(e^+e^-\to\gamma X(3872))$ and $\mathscr{B}(X(3872)\to\pi^+\pi^- J/\psi)$ at different energy points

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

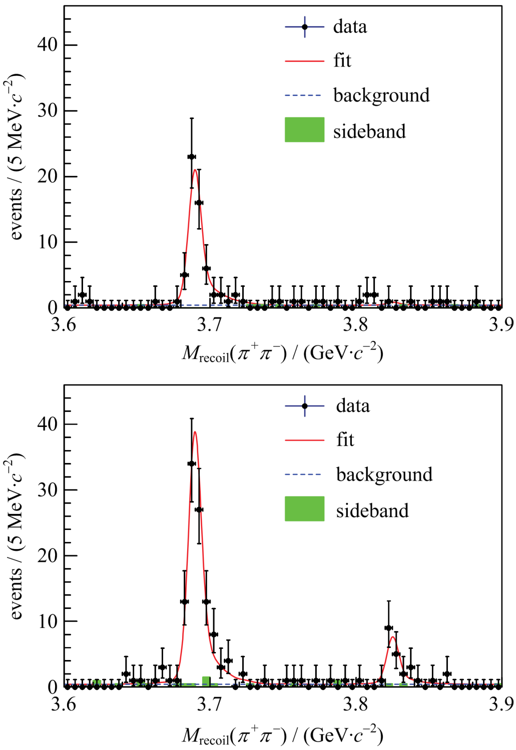
【Note】 The upper limits are given at 90% C. L.

to PDG[13] values), linear continuum, or $E1$-transition phase space ($\propto E_\gamma^3$) term. Fig. 5 (bottom) shows all the fitting results, which imply that χ^2/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 $\sigma^B[e^+e^-\to\gamma X(3872)]\cdot BF[X(3872)\to\pi^+\pi^- J/\psi]/\sigma^B(e^+e^-\to\pi^+\pi^- J/\psi)=(5.2\pm1.9)\times10^{-3}$, 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] (We take 5% from the range presented in the paper of $2.3\%<B[X(3872)\to\pi^+\pi^- J/\psi]<6.6\%$ at 90% C. L.), then $\mathscr{R}=\frac{BF[Y(4260)\to\gamma X(3872)]}{BF(Y(4260)\to\pi^+\pi^- J/\psi)}\sim0.1$.

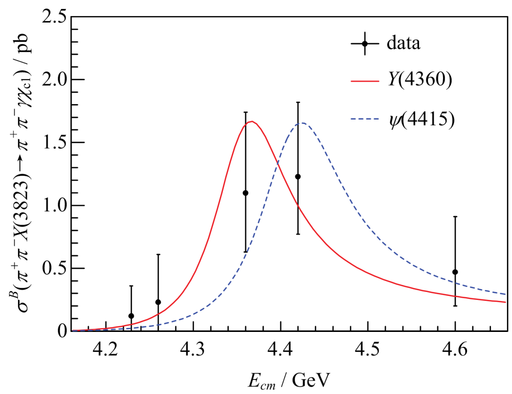
6　Observation of $\psi(1^3D_2)$

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]. Fig. 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±1.3±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 $\sigma^B(e^+e^-\to\pi^+\pi^- X(3823))\cdot\mathscr{B}(X(3823)\to\gamma\chi_{c1},\gamma\chi_{c2})$ 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]. Fig. 7 shows the fitting results, both the $Y(4360)$ and $\psi(4415)$ hypotheses are accepted at a 90% C. L.



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. 6 Simultaneous fit to the $M_{recoil}(\pi^+\pi^-)$ distribution of $\gamma\chi_{c1}$ events (top) and $\gamma\chi_{c2}$ events (bottom), respectively



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.

Fig. 7 Comparison of the energy-dependent cross sections of $\sigma^B[e^+e^- \to \pi\pi X(3823)] \cdot \mathscr{B}(X(3823) \to \gamma\chi_{c1})$ to the $Y(4360)$ and $\psi(4415)$ line shapes

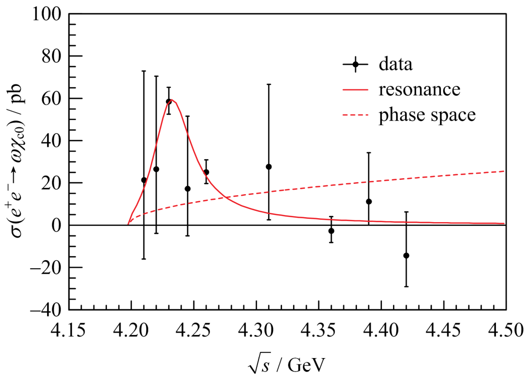
The $X(3823)$ resonance is a good candidate for the $\psi(1^3D_2)$ charmonium state. According to potential models[24-25], the D-wave charmonium states are expected to be within a mass range of 3.82～3.85 GeV. The $1^1D_2 \to \gamma\chi_{c1}$ transition is forbidden because of C-parity conservation, and the amplitude for $1^3D_3 \to \gamma\chi_{c1}$ is expected to be small[26]. The mass of $\psi(1^3D_2)$ is in the 3.810～3.840 GeV/c^2 range predicted by several phenomenological calculations[27]. 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[27-28]. From the cross-section measurement, we obtain the ratio $\frac{\mathscr{B}[X(3823)\to\gamma\chi_{c2}]}{\mathscr{B}[X(3823)\to\gamma\chi_{c1}]} < 0.42$ at the 90% C. L., which also agrees with expectations for the $\psi(1^3D_2)$ state[28].

7 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[29]. The Born cross-sections were measured to be $(55.4\pm6.0\pm5.9)$ 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. [30]. By assuming the $\omega\chi_{c0}$ signals coming from a single resonance, the $\Gamma_{ee}\mathscr{B}(\omega\chi_{c0})$, mass, and width of the resonance are fitted to be $(2.7\pm0.5\pm0.4)$ eV, $(4\,230\pm8\pm6)$ MeV/c^2, and $(38\pm12\pm2)$ 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 $Y(4260)$.

Using data samples collected at energies of 3.81～4.60 GeV, BESIII analyzed $e^+e^- \to$



Dots with error bars are the dressed cross sections.

The uncertainties are statistical only.

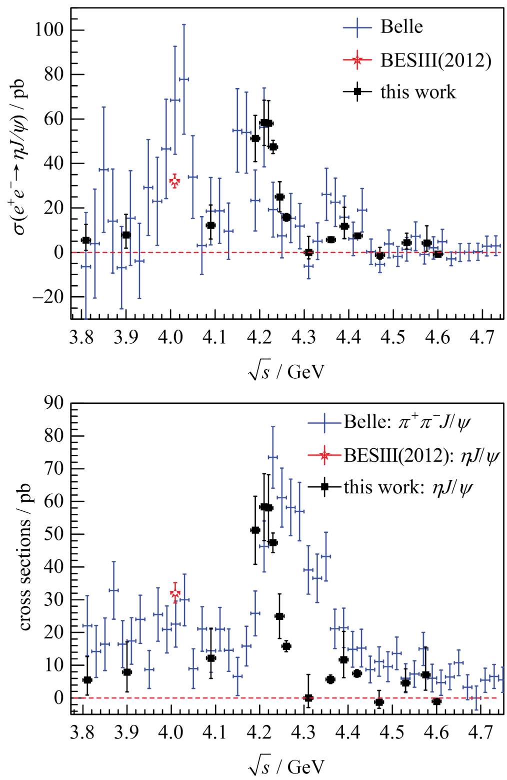
Fig. 8 Fit to $\sigma(e^+e^-\to\omega\chi_{c0})$ with a resonance (solid curve), or a phase space term (dot-dashed curve)

$\eta J/\psi$[31]. 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[14,32] 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 $\sqrt{s}=4.1\sim4.6$ 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.

8 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 achieve a systematic understanding of the nature of the XYZ states.



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.

Fig. 9 A comparison of the measured Born cross sections of $e^+e^-\to\eta J/\psi$ to those of the previous measurements[14,32] (top), and to those of $e^+e^-\to\pi^+\pi^- J/\psi$ from Belle[9]

References

[1] BRAMBILLA N, EIDELMAN S, HELTSLEY B K, et al. Heavy quarkonium: Progress, puzzles, and opportunities[J]. Eur Phys J C, 2011, 71: 1534.

[2] AUBERT B, BARATE R, BOUTIGNY D, et al. Observation of abroad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26 GeV/c^2 [J]. Phys Rev Lett, 2005, 95: 142001.

[3] HE Q, INSLER J, MURAMATSU H, et al. Confirmation of the Y(4260) resonance production in initial state radiation[J]. Phys Rev D, 2006, 74: 091104.

[4] YUAN C Z, SHEN C P, WANG P, et al. Measurement of $e^+e^-\to\pi^+\pi^- J/\psi$ cross-section via initial state radiation at Belle[J]. Phys Rev Lett, 2007, 99: 182004.

[5] MO X H, LI G, YUAN C Z, et al. Determining the upper limit of Γ_{ee} for the Y(4260)[J]. Phys Lett B,

2006, 640:182.

[6] ABLIKIM M, ACHASOV M N, AI X C, et al. Measurements of the center-of-mass energies at BESIII via the di-muon process [J]. Chin Phys C, 2016, 40(6):063001.

[7] ABLIKIM M, ACHASOV M N, AI X C, et al. 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 [EB/OL]. (2015-03-11) [2015-11-01]. http://arxiv. org/abs/1503.03408.

[8] ABLIKIM M, ACHASOV M N, AI X C, et al. Observation of a charged charmoniumlike structure in $e^+e^-\to\pi^+\pi^- J/\psi$ at $\sqrt{s}$=4.26 GeV[J]. Phys Rev Lett, 2013, 110:252001.

[9] LIU Z Q, SHEN C P, YUAN C Z, et al. Study of $e^+e^-\to\pi^+\pi^- J/\psi$ and observation of a charged charmoniumlike state at Belle [J]. Phys Rev Lett, 2013, 110: 252002.

[10] XIAO T, DOBBS S, TOMARADZE A, et al. 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 $\sqrt{s}$=4 170 MeV[J]. Phys Lett B, 2013, 72:366-370.

[11] ABLIKIM M, ACHASOV M N, AI XC, et al. Observation of $Z_c(3900)^0$ in $e^+e^-\to\pi^0\pi^0 J/\psi$[J]. Phys Rev Lett, 2015, 115: 112003.

[12] ABLIKIM M, ACHASOV M N, ALBAYRAK O, et al. Observation of a charged $(D\overline{D}^*)^{\pm}$ mass peak in $e^+e^-\to\pi D\overline{D}^*$ at $\sqrt{s}$=4.26 GeV [J]. Phys Rev Lett, 2014, 112: 022001.

[13] OLIVE K A, AGASHE K, AMSLER C, et al. Review of particle physics [J]. Chin Phys C, 2014, 38(09): 090001.

[14] ABLIKIM M, ACHASOV M N, AMBROSE D J, et al. Observation of $e^+e^-\to\eta J/\psi$ at center-of-mass energy $\sqrt{s}$= 4.009 GeV [J]. Phys Rev D, 2012, 86: 071101.

[15] ABLIKIM M, ACHASOV M N, ALBAYRAK O, et al. Observation of a charged charmoniumlike structure Z_c(4020) and search for the Z_c(3900) in $e^+e^-\to\pi^+\pi^- h_c$ [J]. Phys Rev Lett, 2013, 111: 242001.

[16] ABLIKIM M, ACHASOV M N, AI X C, et al. Observation of $e^+e^-\to\pi^0\pi^0 h_c$ and a neutral charmoniumlike structure $Z_c(4020)^0$ [J]. Phys Rev Lett, 2014, 113: 212002.

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

[18] ABLIKIM M, ACHASOV M N, AI X C, et al. Observation of a neutral charmoniumlike state $Z_c(4025)^0$ in $e^+e^-\to(D^*\overline{D}^*)^0\pi^0$ [EB/OL]. (2015-10-08)[2015-11-01]. http://arxiv. org/abs/1507.02404.

[19] ABLIKIM M, ACHASOV M N, AI X C, et al. Observation of $e^+e^-\to\gamma X(3872)$ at BESIII[J]. Phys Rev Lett, 2014, 11:092001.

[20] CHAO K T, HE Z G, LI D, et al. Search for $C=+$ charmonium states in $e^+e^-\to\gamma+X$ at BEPCII/BESIII [EB/OL]. (2013-10-31)[2015-11-01]. http://arxiv. org/abs/1310.8597.

[21] YUAN C Z. Exotic Hadrons[EB/OL]. (2009-11-08)[2015-11-01]. http://arxiv. org/abs/0910.3138.

[22] ABLIKIM M, ACHASOV M N, AI X C, et al. Observation of the $\psi(1^3D_2)$ State in $e^+e^-\to\pi^+\pi^-\gamma\chi_{c1}$ at BESIII[J]. Phys Rev Lett, 2015, 115: 011803.

[23] BHARDWAJ V, MIYABAYASHI K, ADACHI I, et al. Evidence of a new narrow resonance decaying to $\chi_{c1}\gamma$ in $B\to\chi_{c1}\gamma K$ [J]. Phys Rev Lett, 2013, 111: 032001.

[24] EICHTEN E, GOTTFRIED K, KINOSHITA T, et al. Charmonium: The Model[J]. Phys Rev D, 1978, 17:3090.

[25] EICHTEN E, GOTTFRIED K, KINOSHITA T, et al. Erratum: Charmonium: The model [J]. Phys Rev D, 1980, 21:313.

[26] BARNES T, GODFREYS, SWANSON E S. Higher charmonia[J]. Phys Rev D, 2005, 72:054026.

[27] GODFREY S, ISGURN. Mesons in a relativized quark model with chromodynamics [J]. Phys Rev D, 1985, 32: 189.

[28] QIAO C F, YUAN F, CHAO K T. Crucial test for color-octet production mechanism in Z^0 decays [J]. Phys Rev D, 1997, 55:4001.

[29] ABLIKIM M, ACHASOV M N, AI X C, et al. Study of $e^+e^-\to\omega\chi_{cJ}$ at center of mass energies from 4.21 to 4.42 GeV[J]. Phys Rev Lett, 2015, 114:092003.

[30] DAI L Y, SHI M, TANG G Y, et al. Nature of $X(4260)$[J]. Phys Rev D, 2015, 92: 014020.

[31] ABLIKIM M, ACHASOV M N, AI X C, et al. 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[J]. Phys Rev D, 2015, 91:112005.

[32] WANG X L, HAN Y L, YUAN C Z, et al. Observation of $\psi(4040)$ and $\psi(4160)$ decay into $\eta J/\psi$ [J]. Phys Rev D, 2013, 87: 051101.