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# $XYZ$ states at BESIII

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Using the $e^+e^-$ annihilation data collected above 4.0 GeV with the BESIII detector, we observed the decay $Y(4260) \to \gamma X(3872)$, and found evidence for $X(3823)$ in $e^+e^- \to \pi^+\pi^-\chi_{c1}$, and hints of $Y(4140)$ in $e^+e^- \to \gamma\phi J/\psi$. Cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^- h_c$, $\pi^+\pi^-\psi(2S)$ and $\pi^+ D^0 D^{*-}$ are measured, and two resonance structures are observed near 4.2 and 4.4 GeV, which can be understood as $Y(4260)$ and $Y(4360)$ states. Charged multiquark states of $Z_c(3900)$ and $Z_c(4020)$ were observed in $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+ D^0 D^{*-}$ and $e^+e^- \to \pi^+\pi^- h_c$, $\pi^+ D^{0*} D^{*-}$ processes, respectively. Their neutral partners were also observed, thus the isospin vector is established. The spin and parity of $Z_c(3900)^{\pm}$ is determined as $1^+$, distinguishing from other hypotheses with statistical significance larger than $7\sigma$.

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## 1. Introduction

In the conventional quark model, mesons are made of quark and antiquark pairs, while baryons are made of three (anti-)quarks. Due to the non-abelian properties of quantum chromodynamics (QCD), gluons are allowed to interact with themselves, forming glueballs. Much effort has been devoted to search for glueballs, but no state is established in experiments. Besides this, QCD also predicts the existence of hybrid states, which have an additional gluon component in mesons or baryons, and multiquark states, which have more than three constituent quarks bound in a resonance.

Search for these kinds of unconventional (or exotic) states has continued for many years. There are some multiquark state candidates suggested in the sector of light quark mesons, but they are controversial in the physics community. In 2003, the Belle collaboration reported for the first time an exotic resonance, $X(3872)$ observed in the $B^{\pm} \to X(3872)K^{\pm},\ X(3872) \to \pi^{+}\pi^{-}J/\psi$ decay. It exhibits some exotic properties. It has mass very close to the threshold of the $D^0\bar{D}^{*0}$ mode, but it has an extremely narrow decay width, less than 1.2 MeV. After that, many exotic states, dubbed $XYZ$ sates, are reported in the Belle and BaBar experiments, the LHC experiments and the BESIII experiments.

Compared to the $B$ factory, the $\tau$-charm factory provides us a laboratory to study the production mechanism of $XYZ$ states. Either in continuum production or subsequent hadronic production, it conserves the PC parity and (or) G parity. This obviously provides information on the determination of $XYZ$ quantum numbers. BEPCII/BESIII has accumulated many data sets above 4 GeV with large integrated luminosity. In this talk, I present the BESIII measurement results on the $XYZ$ states with these data sets.

## 2. $X$ states

### 2.1 $X(3872)$ state

The first exotic state, $X(3872)$, established in experiments was reported by the Belle Collaboration in 2003 for the first time [1]. They found an extremely narrow structure in the spectrum of $\pi^{+}\pi^{-}J/\psi$ in the $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays. The most interesting thing is that it has a mass very close to the $D^0\bar{D}^{*0}$ threshold, but the decay width is less than 1.2 MeV. This behaviour is quite different from the charmonium decays with mass above the open charm threshold.

The BESIII Collaboration searched for the $X(3872)$ state with data sets taken at $\sqrt{s} = 4009$, 4229, 4260 and 4360 MeV via the process $e^{+}e^{-} \to \gamma X(3872),\ X(3872) \to \pi^{+}\pi^{-}J/\psi$ [2]. They $X(3872)$ state was observed in the combination of four data sets in the $m_{\pi^{+}\pi^{-}J/\psi}$ mass distribution as shown in Fig. 1 (a), and the mass was measured to be 3871.9$\pm$0.7$\pm$0.2 MeV. Cross sections at these points were measured as shown in Fig. 1 (b). The lineshape can be explained with the resonance $Y(4260)$ [see Fig. 1 (b)]. This indicates that the $X(3872)$ state has strong coupling with the $Y(4260)$, which implies that the two exotic states share much commonality in nature.

### 2.2 $X(3823)$ state

The $X(3823)$ state was reported by the Belle Collaboration for the first time in 2013 [3]. They observed a structure in the $\gamma\chi_{c1}$ mass distribution in the $B^{\pm} \to \gamma\chi_{c1}K^{\pm}$ decays with significance

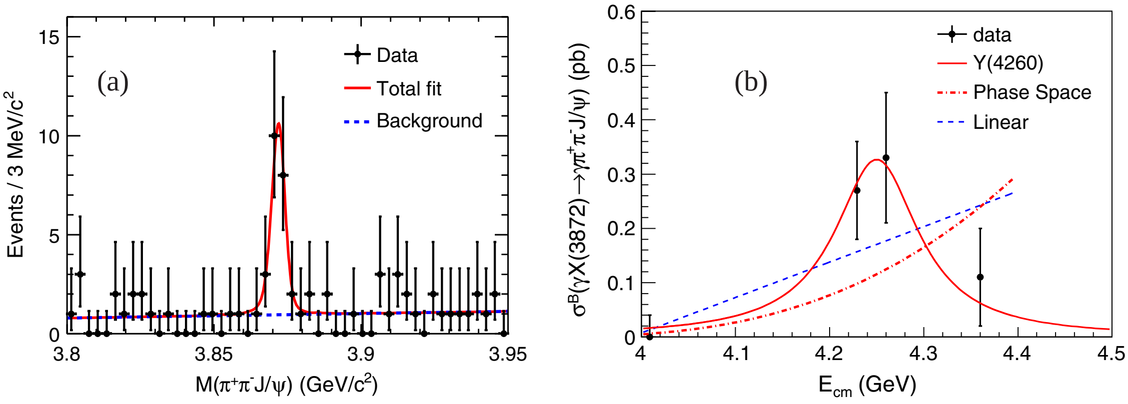



**Figure 1:** (a) Invariant mass distribution of $\pi^+\pi^- J/\psi$ in the process $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ for the combined four data sets, (b) distributions of measured cross section.

$3.8\sigma$. Now it is identified with a charmonium state with $J^{PC} = 1^{--}$, but its width is determined to be less than 12 MeV at the 90% confidence level. They also searched for it in the $\gamma\chi_{c2}$ final state, but no signals were observed.

The BESIII Collaboration searched for it in the process $e^+e^- \to \pi^+\pi^- X(3823)$, $X(3823) \to \gamma\chi_{c1}$ with data sets taken at $\sqrt{s} = 4230$, 4260, 4360, 4420 and 4600 MeV [4]. The combined mass distribution recoiling against $\pi^+\pi^-$ is shown in Fig. 2 (a), where the $\psi(3686)$ state is clearly seen, and the $X(3823)$ is observed with mass determined to be $M = 3821.7 \pm 1.3 \pm 0.7$ MeV. The cross sections at these energies are measured as shown in Fig. 2 (b).

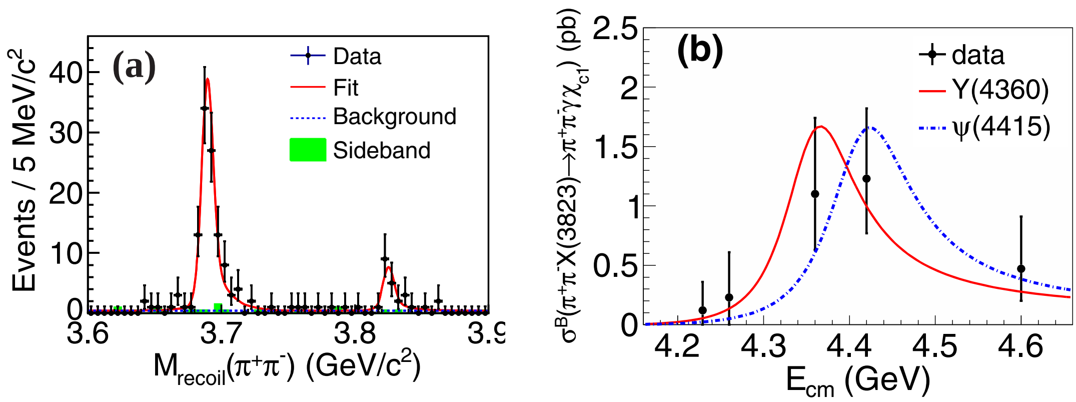



**Figure 2:** (a) The mass distribution recoiling $\pi^+\pi^-$, and (b) the measured cross sections.

### 2.3 $X(4140)$ state

First evidence of $X(4140)$ was reported by the CDF Collaboration in 2009 [5]. They reported a $\phi J/\psi$ threshold enhancement in the decay $B^+ \to K^+\phi J/\psi$ with significance of $3.8\sigma$. However, searches for this state in other experiments are controversial. The D0, Belle, and CMS experiments measured mass and width without consistency. The LHCb Collaboration observed this state with significance of 8.4$\sigma$, and the partial wave analysis identified it as a $J^{PC} = 1^{++}$ state.

The BESIII Collaboration searched for this state in the process $e^+e^- \to \gamma\phi J/\psi$ using data sets taken at $\sqrt{s} = 4230$, 4260 and 4360 MeV [6]. The $\phi$ mesons are reconstructed with $K^+K^-$, $K_S^0K_L$ and $\pi^+\pi^-\pi^0$ decays, and the $J/\psi$ decays are reconstructed with $e^+e^-$ and $\mu^+\mu^-$ decays. No signals are observed, and the upper limits of cross sections for $e^+e^- \to \gamma X(4140)$ process are set at 90% confidence level. The ratio $R = \frac{e^+e^- \to \gamma X(4140)}{e^+e^- \to \gamma X(3872)}$ is determined to be $R \sim 0.1$ at energies $\sqrt{s}$ =4.23 and 4.26 GeV.

## 3. $Y$ states

### 3.1 $Y(4260)$ and $Y(4360)$ state

The $Y(4260)$ state was observed for the first time by the BaBar Collaboration in the initial state radiation (ISR) process $e^+e^- \to \gamma_{ISR}Y(4260)$, $Y(4260) \to \pi^+\pi^- J/\psi$ [7], and then confirmed by the Belle [8] and CLEO [9] experiments. The weighted mass and width are $M(Y(4260)) = 4259 \pm 9$ MeV and $\Gamma(Y(4260)) = 120 \pm 12$ MeV. Then BaBar searched for the decays $Y(4260) \to \pi^+\pi^-\psi'$ in the ISR process, and they got a strong peak near 4.32 GeV. This peak is not comparable with the measured $Y(4260)$ mass and width. Belle used a large data sample to study this peak and confirmed it, dubbing it as $Y(4360)$. The current PDG values of $Y(4360)$ mass and width are $M(Y(4360)) = 4346 \pm 6$ MeV and $\Gamma(Y(4360)) = 102 \pm 12$ MeV.

The $Y$ states are allowed to couple to virtual photons and are directly produced from the $e^+e^-$ annihilation events. The $\tau$-charm factory is also the $Y$ factory. The scan data sets around the $Y$ mass region are an ideal laboratory to study $Y$ states. The cross section for the $e^+e^- \to \eta J/\psi$ process [10] is measured above 3.8 GeV as shown in Fig. 3 (a), where a hint of narrow structure around 4.2 GeV is seen. A similar hint is also indicated in the cross section distribution for the $e^+e^- \to \omega\chi_{c0}$ process [11] (see Fig.3 (b)). A naive fit with a Breit-Wigner yields mass and width inconsistent with the $Y(4260)$ resonance.

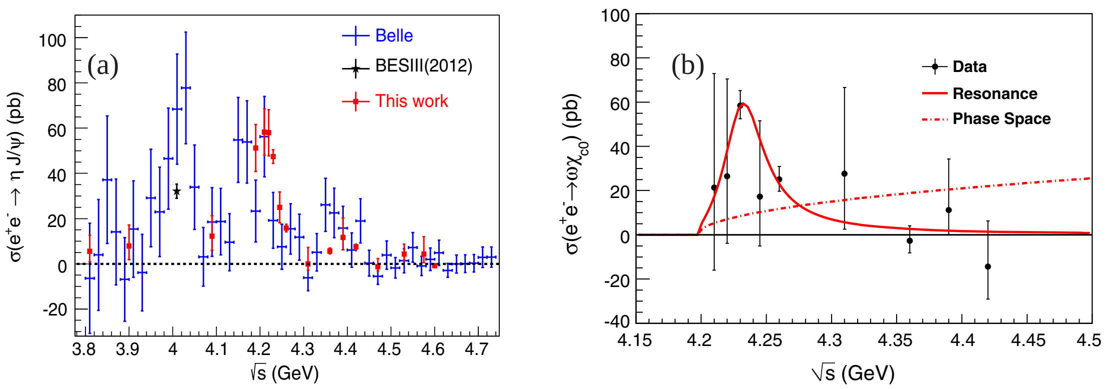



**Figure 3:** (a) The cross section distributions for $e^+e^- \to \eta\phi$, measured by BESIII experiments (red), and (b) the cross section for $e^+e^- \to \omega\chi_{c0}$.

The cross section distributions within 4.2∼4.4 GeV are further studied in the process $e^+e^- \to \pi^+\pi^- J/\psi$ [12]. Figure 4 (a) shows the measured cross sections with $XYZ$ data samples; each has integrated luminosity larger than 80 pb$^{-1}$; and Fig. 4 (b) with $R$ scan data samples, each has luminosity about $8 \sim 9$ pb$^{-1}$. Obviously, it fails to be described with a single resonance. A simultaneous fit with two Breit-Wigner resonances yields masses and widths

$$M_1 = 4222 \pm 4 \text{ MeV}, \ \Gamma_1 = 44 \pm 5 \text{ MeV},$$
$$M_2 = 4320 \pm 13 \text{ MeV}, \ \Gamma_2 = 101^{+27}_{-22} \text{ MeV}.$$

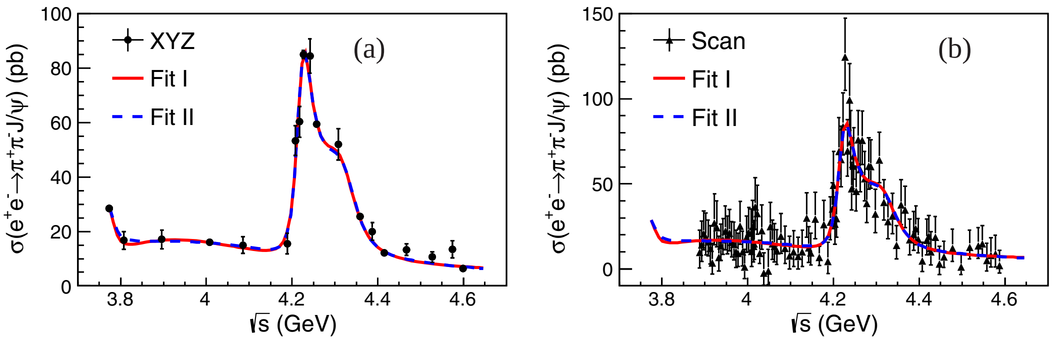
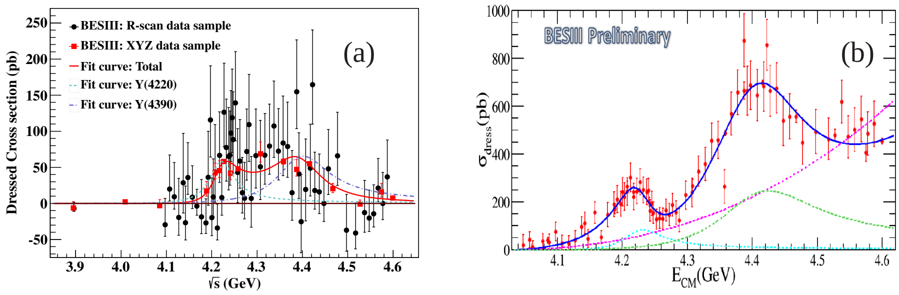


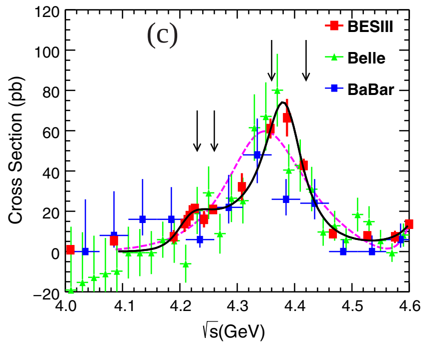

**Figure 4:** (a) The cross section distributions for the $e^+e^- \to \pi^+\pi^- J/\psi$ process using $XYZ$ data samples, and (b) the cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ using $R$ scan data samples.

Cross sections between $\sqrt{s} = 4.0 \sim 4.4$ GeV are also measured for the $e^+e^- \to \pi^+\pi^- h_c$ [13], $\pi^\pm(D^0\bar{D}^*)^\mp$, $\pi^+\pi^-\psi'$ [14] processes as shown in Fig. 5. The lineshapes of these processes show two peaks in the region $3.2 \sim 4.5$ GeV. The two resonance parameters are measured in these processes, and the results are given in Table 1. These two resonances can be understood simply as the established resonances $Y(4260)$ and $Y(4360)$ in the ISR processes. The scan data sets have better energy resolution than that in the ISR measurements, so that they can be identified in the same decay mode.

**Table 1:** Masses and widths of the vector charmonium states observed from different processes at BESIII in the mass region between 4.2 and 4.4 GeV/$c^2$. The subscript 1 or 2 denotes the lower mass state or higher mass state.

| Process | $M_1$ (MeV/$c^2$) | $\Gamma_1$ (MeV) | $M_2$ (MeV/$c^2$) | $\Gamma_2$ (MeV) |
|---|---|---|---|---|
| $e^+e^- \to \omega\chi_{c0}$ | $4230 \pm 8 \pm 6$ | $38 \pm 12 \pm 2$ [11] | | |
| $e^+e^- \to \pi^+\pi^- J/\psi$ | $4220.0 \pm 3.1 \pm 1.4$ | $44.1 \pm 4.3 \pm 2.0$ | $4320.0 \pm 10.4 \pm 7.0$ | $101.4^{+25.3}_{-19.7} \pm 10.2$[12] |
| $e^+e^- \to \pi^+\pi^- h_c$ | $4218.4^{+5.5}_{-4.5} \pm 0.9$ | $66.0^{+12.3}_{-8.3} \pm 0.4$ | $4391.5^{+6.3}_{-6.8} \pm 1.0$ | $139.5^{+16.2}_{-20.6} \pm 0.6$ [13] |
| $e^+e^- \to \pi^+D^0D^{*-} + c.c$ | $4224.8 \pm 5.6 \pm 4.0$ | $72.3 \pm 9.1 \pm 0.9$ | $4400.1 \pm 9.3 \pm 2.1$ | $181.7 \pm 16.9 \pm 7.4$ |
| $e^+e^- \to \pi^+\pi^-\psi(3686)$ | $4209.5 \pm 7.4 \pm 1.4$ | $80.1 \pm 24.6 \pm 2.9$ | $4383.8 \pm 4.2 \pm 0.8$ | $84.2 \pm 12.5 \pm 2.1$ [14] |




(a) Cross section distribution for the $e^+e^- \to \pi^+\pi^- h_c$ process, (b) $e^+e^- \to \pi^\pm(D^0\bar{D}^*)^\mp$ process, (c) $e^+e^- \to \pi^+\pi^-\psi'$ process. Here points with errors denote data, solid curve denotes the fit results with two resonance Breit-Wigners.

**Figure 5:** Measurement of cross sections for different exclusive processes.

### 3.2 $Y(4660)$ state

The $Y(4600)$ state was observed for the first time by Belle Collaboration when searching for the $Y(4260)$ in the ISR process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi'$ [15] with a significance of $5.8\sigma$, and then confirmed by BaBar Collaboration in the same ISR process [16]. In addition, Belle also reported a peak with similar mass and width in the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass in $e^+e^- \to \gamma_{\rm ISR}\Lambda_c^+\bar{\Lambda}_c^-$ events. The current PDG average of Belle and BaBar mass and width measurements are $M = 4643 \pm 9$ MeV and $\Gamma = 72 \pm 11$ MeV.

The BESIII Collaboration measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ with four scanning data sets above the $\Lambda_c^+\bar{\Lambda}_c^-$ mass threshold [17] as shown in Fig. 6. A striking feature is that the cross sections are almost distributed at the same value from the $\Lambda_c^+\bar{\Lambda}_c^-$ mass threshold up to 4.6 GeV, and the cross section near the threshold is enhanced. The center-of-mass energy of BEPCII will be upgraded from 4.6 to 4.9 GeV, and the full lineshape of the $Y(4660)$ will be measured.

## 4. $Z_c$ states

### 4.1 $Z_c(3900)$ state

Using the 525 pb$^{-1}$ data taken at $\sqrt{s} = 4.26$ GeV, the BESIII Collaboration searched for the decays $e^+e^- \to \pi^+\pi^- J/\psi$ in 2013, and a narrow structure was observed in the $\pi^\pm J/\psi$ invariant mass distribution [18]. A fit using a Breit-Wigner to represent the peak and a phase space lineshape to represent the nonresonant contribution gives a mass and width of $M = 3899.0 \pm 6.1$ MeV and $\Gamma = 46 \pm 22$ MeV, as shown in Fig. 7 (a). Due to decays to $\pi^\pm J/\psi$ final sates, it is at least made

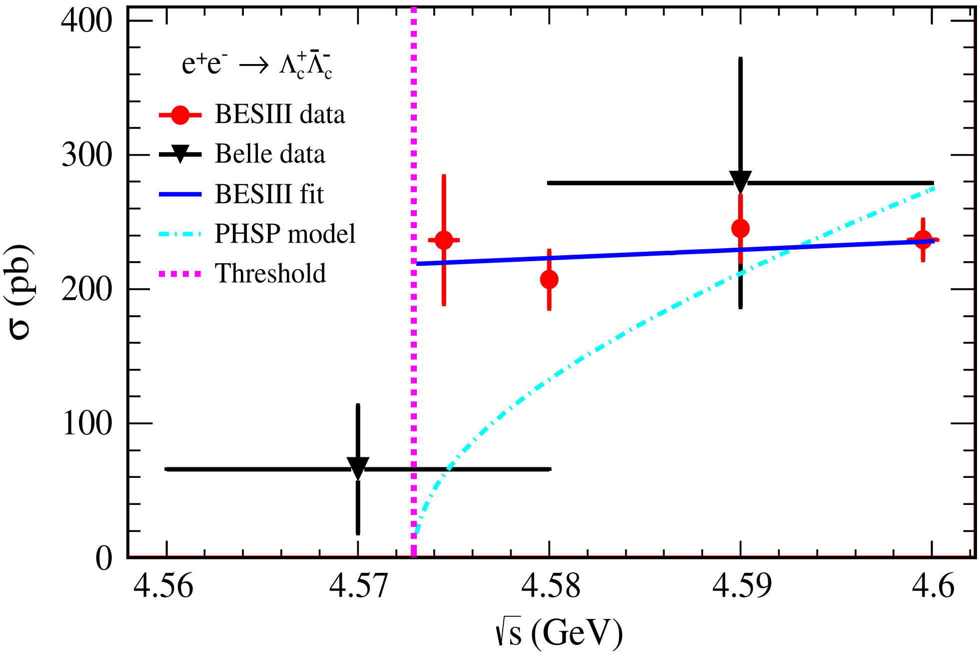



**Figure 6:** The cross section for $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ process. The blue solid curve shows the Born cross section used to estimate the ISR factor, the dash-dotted cyan curve denotes the prediction of the phase-space model.

of two charm quarks ($c\bar{c}$) and two charged light quarks ($u\bar{d}$ or $d\bar{u}$). They dubbed it the $Z_c(3900)^{\pm}$ state, and it was confirmed in the Belle [19] and CLEOc [20] data. The neutral $Z_c$ state was also observed in the $e^+e^- \to \pi^0\pi^0 J/\psi$ process [21] (see Fig. 7 (b)). Its isospin $I = 1$ was established in experiment.

An interesting thing is that the mass of $Z_c(3900)$ is above and very close to the $D^{*\pm}D^0$ or $D^{*0}D^{\pm}$ mass threshold. Its open charm decay was subsequently searched for in the $e^+e^- \to \pi^+D^0D^{*-}$ events in the same data, and a very strong threshold enhancement was observed in the $D^0D^{*-}$ invariant mass distribution [22] as shown in Fig. 7 (c), and its isospin partner was also observed in the $e^+e^- \to \pi^0(D\bar{D}^*)^0$ events [23] (see Fig. 7 (d)). The solid curve in the figure shows the results of fit with a threshold modified Breit-Wigner to represent the peak and a phase space shape to represent backgrounds. The average of mass and width in the two modes is determined to be $M = 3883.9 \pm 4.5$ MeV and $\Gamma = 24.8 \pm 12.0$ MeV. Due to very close proximity to the threshold of $(D\bar{D}^*)^{\pm}$ final states, the decay is expected to be dominated by the $S$-wave component. Thus the peak should have quantum numbers of the spin and parity $J^P = 1^+$. The analysis of the angular distribution for the bachelor pion gets a result consistent with the expectation.

Since the mass and width of the $D\bar{D}^*$ threshold enhancement are inconsistent with that observed in the $Z_c(3900) \to \pi^{\pm}J/\psi$ mode within statistical uncertainty, determination of $J^P$ quantum numbers in the $\pi^+\pi^-J/\psi$ events is crucial to interpret the two structures as the same state decaying into $(D\bar{D}^0)^{\pm}$ and $\pi^{\pm}J/\psi$ final states. A partial wave analysis was performed using the 1.92 fb$^{-1}$

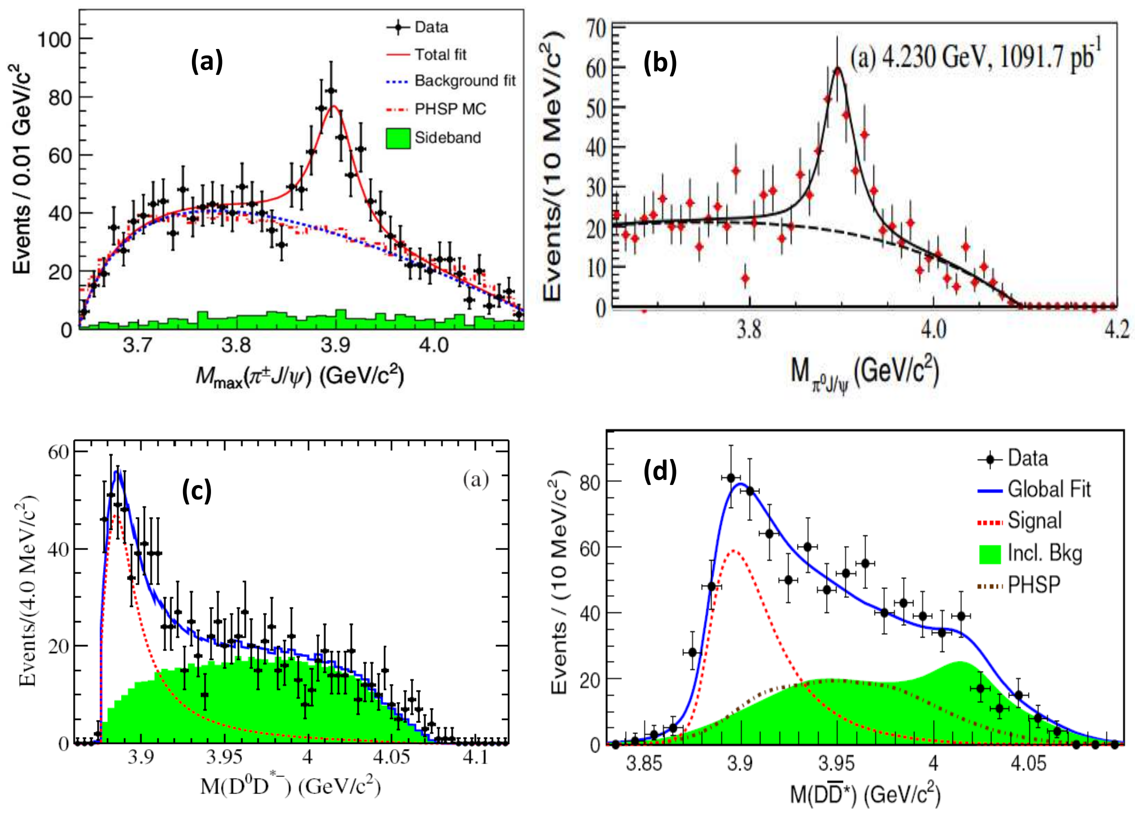



**Figure 7:** Observation of $Z_c(3900)$ in (a) $e^+e^- \to \pi^+\pi^- J/\psi$, (b) $e^+e^- \to \pi^0\pi^0 J/\psi$, (c) $e^+e^- \to \pi^+(D^0 D^{*-})$, (d) $e^+e^- \to \pi^0(D\bar{D}^*)^0$. Points with error bars are data, and solid curves are the total fit results.

data sets taken at $\sqrt{s} = 4.23$ and 4.26 GeV. The data events are described with the $Z_c$ peak and $\pi\pi$-$S$ and $D$ waves. Results of a simultaneous fit to the two data sets are shown in Fig. 8. The $J^P$ quantum numbers of $Z_c(3900)^{\pm}$ state are determined to be $1^+$ with statistical significance large than $7\sigma$ [24]. To resolve the mass and width inconsistency in the $Z_c(3900) \to (D\bar{D}^*)^{\pm}$ and $\pi^{\pm}J/\psi$ modes, a coupled channel analysis is necessary to perform a simultaneous fit to the $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ and $\pi^+\pi^- J/\psi$ events.

## 4.2 $Z_c(4020)$ state

Using the 13 data sets with center-of-mass energies between $3.9 \sim 4.42$ GeV, the BESIII Collaboration searched for the precess $e^+e^- \to \pi^+\pi^- h_c$, where the $h_c$ candidate is reconstructed with the decay $h_c \to \gamma\eta_c$, and $\eta_c$ reconstructed in 16 exclusive hadronic decay modes. In the $\pi^{\pm}h_c$ invariant mass distributions, a distinct structure with mass near 4020 MeV was observed [25] as shown in Fig. 9. A fit with a signal Breit-Wigner (assuming $J^P = 1^+$) and a smooth background shape gives the mass and width of $M = 4022.9 \pm 2.8$ MeV and $\Gamma = 7.9 \pm 3.7$ MeV. The statistical significance of this narrow structure is about $9\sigma$. A neutral isopin partner of $Z_c(4020)$ was also searched for and observed in the $e^+e^- \to \pi^0\pi^0 h_c$ events in the data sets taken at $\sqrt{s} = 4.23,\ 4.26$ and 4.36 GeV. Figure 9 (b) shows results of fit to the $\pi^0 h_c$ invariant mass distribution [26], using a

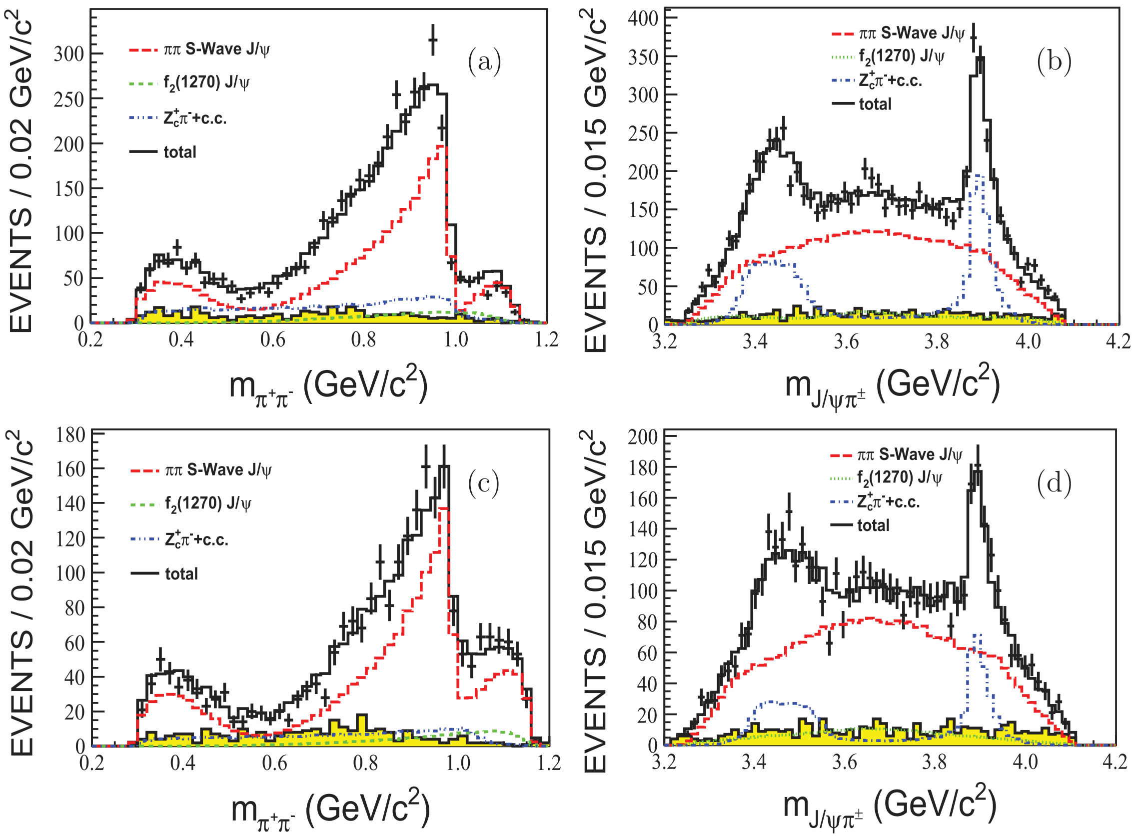



**Figure 8:** Projections to $m_{\pi^+\pi^-}$ (a, c) and $m_{J/\psi\pi^\pm}$ (b, d) of the fit results with $J^P = 1^+$ for the $Z_c$, at $\sqrt{s} = 4.23$ GeV (a, b) and $\sqrt{s} = 4.26$ GeV (c, d). The points with error bars are data, and the black histograms are the total fit results including backgrounds. The shaded histogram denotes backgrounds. The contributions from the $\pi^+\pi^-$ $S$-wave $J/\psi$, $f_2(1270)J/\psi$, and $Z_c^\pm\pi^\mp$, are shown in the plots. The $\pi^+\pi^-$ $S$-wave resonances include the $\sigma$, $f_0(980)$ and $f_0(1370)$. Plots (b) and (d) are filled with two entries ($m_{J/\psi\pi^+}$ and $m_{J/\psi\pi^-}$) per event..

signal Breit-Wigner to represent the $Z_c(4020)$, with mass and width fixed to the measurements of the charged $Z_c(4020)$.

The mass of $Z_c(4020)$ is about 5 MeV above the $(D^*\bar{D}^*)^\pm$ mass threshold. Its decays into open charm modes were searched for in the $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\pm$ [27] and $\pi^0(D^*\bar{D}^*)^0$ [28] events, and strong enhancements near the $(D^*\bar{D}^*)^{\pm,0}$ threshold were observed as shown in Fig. 9 (c) and (d). The solid black curve in Fig. 9 (c) shows the results of a fit to the data points that includes an efficiency weighted S-wave BW function (long dashes), the combinatoric background shape (short dashes) scaled to represent the non-resonant background under the peak. The fit returns a 13$\sigma$ signal with mass and width $M = 4026.3 \pm 4.5$ MeV and $\Gamma = 24.8 \pm 9.5$ MeV. Figure 9 (d) shows results of a fit to the $(D^*\bar{D}^*)^0$ mass distribution. The peak is represented with a threshold-modified Breit-Wigner, and the pole mass and width were determined to be $M = 4025.5^{+2.0}_{-4.7} \pm 3.1$ MeV and $\Gamma = 43.4 \pm 8.0 \pm 5.4$ MeV.

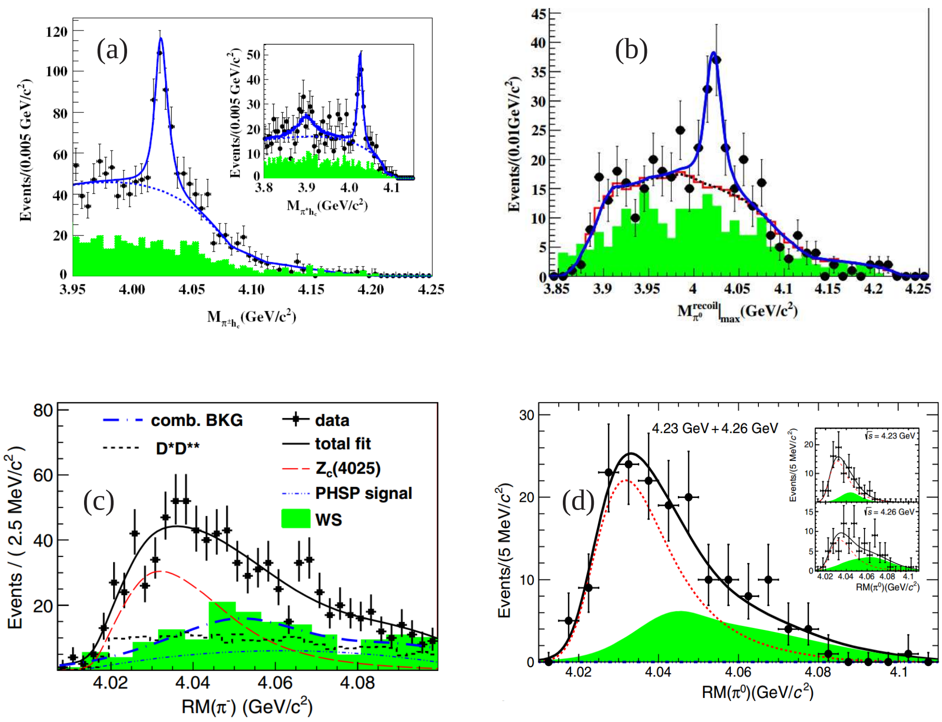



**Figure 9:** Observation of the $Z_c(4020)$ state in the processes (a) $e^+e^- \to \pi^+\pi^-h_c$, the inset shows evidence of the $Z_c(3900)$ contribution in the $m_{\pi^+h_c}$ distribution; (b) $e^+e^- \to \pi^0\pi^0h_c$, (c) $e^+e^- \to \pi^\mp(D^*\bar{D}^*)^\pm$ and (d) $e^+e^- \to \pi^0(D^*\bar{D}^*)^0$, the inset shows the recoiling mass distribution of $\pi^0$ for the two data sets at 4.23 and 4.26 GeV. Points with error bars are data, solid curves are total fit results, and shaded histograms show backgrounds.

## 5. Summary

Observation of charmonium-like states opens a new window for the study of multiquark dynamics. Using the data sets above 4.0 GeV, we observed the decay $Y(4260) \to \gamma X(3872)$, and found evidence for $X(3823)$ in $e^+e^- \to \pi^+\pi^-\chi_{c1}$, and hints of $Y(4140)$ in $e^+e^- \to \gamma\phi J/\psi$. Cross sections for $e^+e^- \to \pi^+\pi^-J/\psi$, $\pi^+\pi^-h_c$, $\pi^+\pi^-\psi(2S)$ and $\pi^+D^0D^{*-}$ are measured, and two resonance structures are observed near 4.2 and 4.4 GeV, which can be understood as $Y(4260)$ and $Y(4360)$ states. Charged multiquark states of $Z_c(3900)$ and $Z_c(4020)$ were observed in $e^+e^- \to \pi^+\pi^-J/\psi$, $\pi^+D^0D^{*-}$ and $e^+e^- \to \pi^+\pi^-h_c$, $\pi^+D^{0*}D^{*-}$ processes, respectively. Their neutral partners were also observed, thus the isospin vector is established. The spin and parity of $Z_c(3900)^\pm$ is determined as $1^+$ to distinguish against other hypothesis with statistical significance large than $7\sigma$. These studies indicate that the BEPCII/BESIII is an efficient $Y$-factory, and more data taking is under consideration for improved $XYZ$ studies.

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