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# Latest $XYZ$ results from $e^+e^-$ colliders

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**Abstract.** We present the recent progress on the charmonium-like states (or called $XYZ$ states) from electron-positron colliders, including the results from BESIII, CLEO-c, BaBar and Belle. This talk covers the observation of $X(3872)$ from radiative decay of the $Y(4260)$, the updated results of $Y$ states from initial state radiation (ISR) process of $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ and also cross section measurement of $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \omega\chi_{c0}$, and the observation of charged and neutral charmonium-like states ($Z_c$s).

## 1 Introduction

In the quark model, the mesons are composed from one quark and anti-quark, while baryons are composed from three quarks. But these are the lowest configurations, the hadrons with other configurations are not excluded. People believe that there are hadrons with no quarks (glue ball), with excited gluon (hybrid) or with more than three quarks (multi-quark state) [1]. Starting from the two B-factories, i.e., BaBar at SLAC and Belle at KEK, a large number of charmonium-like states were observed in the final states of a charmonium and light hadrons. These states could be the charmonium states, but they also have some strange properties, which makes them more like exotic states.

In this talk, the recent results on observation of $X(3872)$ from radiative decay of $Y(4260)$, the new information of $Y$ states, the observations of $Z_c$ states. The results are mainly from electron-positron colliders including BESIII, CLEO-c, BaBar and Belle experiments. The BESIII and CLEO-c detector are working at charmonium region, the data taken can be used directly. While the two B-factories are working at the bottomonium region, the data taken there can be used to study charmonium states if an ISR photon which can lower the center of mass energy (CM) exist, or through B decays.

## 2 New information on $X(3872)$

The $X(3872)$ was first observed by Belle collaboration in $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ [2]. Since its discovery, it has stimulated a lot of interest about its nature both from theoretical and experimental side. Combining the observation of $X(3872) \to \gamma J/\psi$ at BaBar and Belle and the angular analysis at CDF and LHCb experiments, the spin parity of the $X(3872)$ was determined to be $J^P = 1^{++}$ [3]. Thus it could also be produced through radiative transition from the vector charmonium or charmonium-like states.

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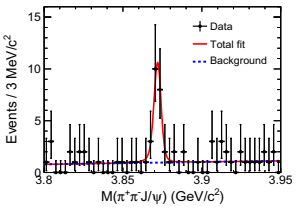


**Figure 1.** Fit to the summed $\pi^+\pi^- J/\psi$ invariant mass spectrum. Dots with error bars are data, and the curves are the best fit.

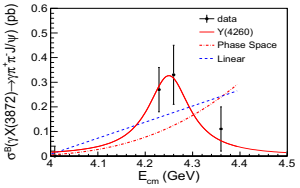


**Figure 2.** The fit to $\sigma^B[e^+e^- \to \gamma X(3872)] \times \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]$ with a $Y(4260)$ resonance, a linear continuum, or a $E1$-transition phase space term.

### 2.1 Observation of $X(3872)$ in $e^+e^- \to \gamma X(3872)$

The process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ has been studied at BESIII experiment, with the $J/\psi$ reconstructed using its decay into lepton pairs $J/\psi \to e^+e^-$, or $\mu^+\mu^-$ [4]. The analysis was performed by using the data samples collected at the CM energy $\sqrt{s}$ = 4.009, 4.230, 4.260, and 4.360 GeV.

The $\pi^+\pi^- J/\psi$ invariant mass spectrum was used to extract the mass and signal yields of the $X(3872)$. Figure. 1 shows the $\pi^+\pi^- J/\psi$ invariant mass spectrum summed over all the energy points and the best fit results. Obvious $X(3872)$ was observed with a statistical significance of $6.3\sigma$, the mass of the $X(3872)$ was measured to be $(3872.1 \pm 0.8 \pm 0.3)$ MeV/$c^2$. The product of the Born cross section times the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ as a function of CM energy are shown in Fig. 2 in dots with error bars. The cross section suggests that the $X(3872)$ might come from the radiative transition of $Y(4260)$. Taking the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ measured by BESIII [5] into account and assuming the branching fraction $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = 5\%$, the fraction $\mathcal{R} = \frac{\sigma^B[e^+e^- \to \gamma X(3872)]}{\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)}$ is about 11%, which is a relatively large decay width.

## 3 The $Y$ states

The $Y$-states in charmonium system are mainly observed at B-factories via ISR process. The $Y(4260)$ was observed by BaBar collaboration in the $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ process, and confirmed by CLEO [10] and Belle [11] experiments using the same method. Beside $Y(4260)$, in Belle data, another broad structure (called $Y(4008)$) near 4.008 GeV was observed. In the $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ process, BaBar collaboration found a structure around 4.32 GeV [12], while Belle observed two structures at 4.36 and 4.66 GeV in the same process [13]. Using full data sample, both BaBar and Belle experiments updated their analysis of $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ [14, 15] and $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ [16]. The $Y(4660)$ resonance was confirmed by BaBar experiment, while the discrepancy at $Y(4008)$ between two experiments still exist. The foresee study at BESIII using data samples the this energy region may help to clarify this issue. The data samples collected with BESIII detector from 3.81 to 4.42 GeV are used to study to the $Y$-states in the $e^+e^- \to \pi^+\pi^- h_c$ [17] and $e^+e^- \to \omega\chi_{c0}$ process [18].

### 3.1 Update of $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$

The updated analysis of $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ at BaBar experiment using 520 fb$^{-1}$ data collected at or near the $\Upsilon(nS)(n = 2, 3, 4)$ was reported recently [16]. Two resonant structures were observed in the mass distribution of $\pi^+\pi^-\psi(2S)$. The parameters of $Y(4360)$ and $Y(4660)$ were determined by


**Figure 3.** The $\pi^+\pi^-\psi(2S)$ mass spectrum from Belle measurement (dots with error bars) and the fits with sum of two (left) or three (right) BW functions.

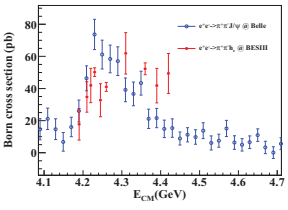


**Figure 4.** The Born cross section of $e^+e^- \to \pi^+\pi^- h_c$ from BESIII experiment, and those of $e^+e^- \to \pi^+\pi^- J/\psi$ from Belle experiment.

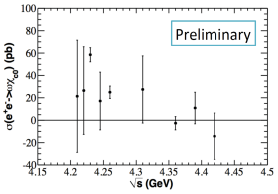


**Figure 5.** The Born cross section of $e^+e^- \to \omega\chi_{c0}$ at different energy points from 4.21 to 4.42 GeV.

fitting to the mass distribution corresponding to the $\psi(2S) \to \pi^+\pi^- J/\psi$ decay mode. The parameters yield are consistent with Belle measurement [13], the $Y(4660)$ observed by Belle experiment was confirmed.

Using 980 fb$^{-1}$ data sample, Belle Collaboration also updated the analysis of $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ with the same two decay modes of $\psi(2S)$ as used in BaBar paper [19]. Fitting to the mass spectrum of $\pi^+\pi^-\psi(2S)$ summed over two decay modes with two coherent Breit-Wigner (BW) functions, the result shows in Fig. 3. The mass of the two structures are about 20 MeV smaller than previous Belle results [13]. Since there were some events accumulated around the mass region of $Y(4260)$, the fit with $Y(4260)$ included was also performed (right panel of Fig. 3). The significance of $Y(4260)$ was estimated to be $2.1\sigma$ with parameters fixed to the latest measurement from Belle [14].

### 3.2 Cross section of $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \omega\chi_{c0}$

BESIII studied the process of $e^+e^- \to \pi^+\pi^- h_c$ using data samples taken at 13 energy points from 3.90 to 4.42 GeV [17]. The $h_c$ was reconstructed through its electric-dipole (E1) transition $h_c \to \gamma\eta_c$, while $\eta_c$ was reconstructed using 16 of its hadronic decay modes.

Figure 4 shows the Born cross sections of $e^+e^- \to \pi^+\pi^- h_c$ at each energy points (solid dots with error bars) and also the comparison with $\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)$ from Belle experiment [14]. The $\sigma^B(e^+e^- \to \pi^+\pi^- h_c)$ are at the same order of magnitude as $\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)$, but with a difference line shape. There is a broad structure at high energy with a possible local maximum at around 4.23 GeV. Since the $Y(4260)$ was established from the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$, the different line shape $e^+e^- \to \pi^+\pi^- h_c$ makes the understanding of $Y$ states more complicate.

Based on data samples collected at 9 CM energy points from 4.21 to 4.42 GeV, the production of $e^+e^- \to \omega\chi_{cJ}(J = 0,\ 1,\ 2)$ was studied at BESIII experiment [18]. $e^+e^- \to \omega\chi_{c0}$ was observed for

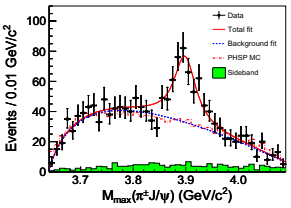


**Figure 6.** The $M_{\max}(\pi^{\pm}J/\psi)$ distribution and best fit from BESIII.

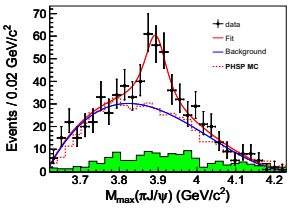


**Figure 7.** The $M_{\max}(\pi^{\pm}J/\psi)$ distribution and best fit from Belle.

the first time at 4.23 and 4.26 GeV. Here $\omega$ was reconstructed using its decay into $\pi^+\pi^-\pi^0$ final state, $\chi_{c0}$ was reconstructed via $\pi^+\pi^-$ and $K^+K^-$ decays. Figure 5 shows the cross section of $e^+e^- \to \omega\chi_{c0}$ at different energy points, the cross section peaks at 4.23 GeV, which indicates the enhancement of $\omega\chi_{c0}$ does not arise from $Y(4260)$.

## 4 Observation of charged charmonium-like states

The most important thing to identify an exotic state is to find a clear signature of it compared with the conventional meson states. The charged charmonium-like state is the most promising candidate for the exotic hadrons since it contains at least four quarks thus could not be a conventional meson.

In the study of $e^+e^- \to \pi^+\pi^- J/\psi$ process at CM energies around 4.26 GeV, the BESIII and Belle experiments observed a charged charmonium-like state, the $Z_c(3900)$ in the $\pi^{\pm}J/\psi$ mass spectrum [5, 14], which was confirmed with CLEO-c data at a CM energy of 4.17 GeV [20]. Shortly after, BESIII observed a charged $Z_c(3885)$ state in $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ [21], a charged $Z_c(4025)$ state in $e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$ [22], and a charged and neutral $Z_c(4020)$ state in $e^+e^- \to \pi^{\pm,0}(\pi^{\mp,0}h_c)$ [17, 23]. These states contain at least four quarks, carry electric charge and close to the threshold. The observation of these states may indicate a new class of hadrons has been observed.

### 4.1 Observation of the $Z_c(3900)$ and $Z_c(3885)$

In the study of the $e^+e^- \to \pi^+\pi^- J/\psi$ process using a 525 pb$^{-1}$ data sample taken at $\sqrt{s} = 4.26$ GeV, BESIII experiment observed a structure near 3.9 GeV (named as $Z_c(3900)$) in the invariant mass spectrum of $\pi^{\pm}J/\psi$ with a statistical significance larger than $8\sigma$. An unbinned maximum likelihood fit to the distribution of $M_{\max}(\pi^{\pm}J/\psi)$, with possible interference neglected, as shown in Fig. 6, determined the mass and width of $Z_c(3900)$ to be $(3899.0 \pm 3.6 \pm 4.9)$ MeV/$c^2$ and $(46 \pm 10 \pm 20)$ MeV, respectively. The production ratio was measured to be $R = \frac{\sigma(e^+e^- \to \pi^{\pm}Z_c^{\mp}(3900) \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$

Using ISR method, the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ was measured from 3.8 to 5.5 GeV at Belle experiment. Selecting the events around $Y(4260)$ resonance, the intermediate states in $Y(4260) \to \pi^+\pi^- J/\psi$ decays were investigated [14]. Similar structure around 3.9 GeV was observed in the $\pi^{\pm}J/\psi$ mass spectrum (named as $Z_c(3900)^+$) with significance larger than $5.2\sigma$. Fitting to the $M_{\max}(\pi^{\pm}J/\psi)$ mass spectrum determined the mass to be $(3894.5 \pm 6.6 \pm 4.5)$MeV/$c^2$ and the width to be $(63 \pm 24 \pm 26)$ MeV. Figure. 7 shows the $M_{\max}(\pi^{\pm}J/\psi)$ mass distribution and also the best fit result.

Since the mass of $Z_c(3900)$ is close to the $D\bar{D}^*$ mass threshold, BESIII experiment performed a study of the process $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ using the same data sample at 4.26 GeV [21] with partial reconstruction technique. In the recoil mass of the bachelor $\pi^{\pm}$, an enhancement (called $Z_c(3885)$) was

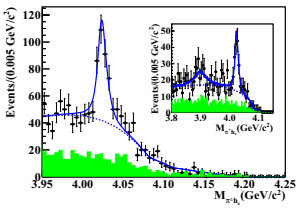

**Figure 8.** Sum of the simultaneous fit to the $M_{\pi^\pm h_c}$ distributions at 4.23, 4.26, and 4.36 GeV.

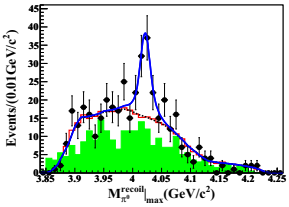

**Figure 9.** Sum of the simultaneous fit to the $M_{\max}(\pi^0 h_c)$ distributions at 4.23, 4.26, and 4.36 GeV.

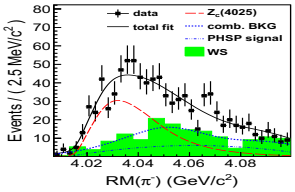


**Figure 10.** Fit to the $\pi^-$ recoil mass spectrum from $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ process at 4.26 GeV.

observed. Fits to the mass spectrum with a mass-dependent-width BW function, the pole mass and width were determined to be $M = (3885.9 \pm 1.5 \pm 4.2)$ MeV/$c^2$ and $\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV. The product of the Born cross section times the branching fraction of $Z_c(3885) \to D\bar{D}^*$ was measured to be $(83.5 \pm 6.6 \pm 22.0)$ pb. Assuming the $Z_c(3885)$ and the $Z_c(3900)$ are the same state, the ratio of partial decay widths was determined to be $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium state above the open charm threshold. In the analysis, the quantum number of $Z_c(3885)$ has been studied by examining the pole angle distribution of the bachelor pion. The efficiency corrected fractional signal yield as a function of $|\cos\theta_\pi|$ from date agrees well with the flat expectation for $J^P = 1^+$.

### 4.2 Observation of the $Z_c(4020)$ and $Z_c(4025)$

In the process of $e^+e^- \to \pi^+\pi^- h_c$, BESIII experiment also analysed the Dalitz plot of $\pi^+\pi^- h_c$ system at 4.23, 4.26, and 4.36 GeV. A structure around 4.02 GeV was observed in the $\pi^\pm h_c$ invariant mass spectrum (named as $Z_c(4020)$) [17].

A simultaneous fit to the $\pi^\pm h_c$ mass spectrum in the three energy points using the same signal function with common mass and with was shown in Fig. 8. The fit yields a mass of $(4022.9 \pm 0.8 \pm 2.7)$ MeV/$c^2$ and a width of $(7.9 \pm 2.7 \pm 2.6)$ MeV with the statistical significance larger than $8.9\sigma$. The $Z_c(4020)$ is close to the $D^*\bar{D}^*$ mass threshold, and similar to the $Z_c(3900)$, it contains more than just a pair of charm quarks. The $Z_c(3900)$ is not significant in this process, adding a $Z_c(3900)$ with mass and width fixed to the BESIII measurement [5] in the fit, resulted in a statistical significant of $2.1\sigma$(see inset of Fig. 8). The upper limits at 90% C.L. on the production cross section were determined to be $\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c) < 13$ pb at 4.23 GeV and $< 11$ pb at 4.26 GeV. The cross section at 4.260 GeV is lower than that of $Z_c(3900) \to \pi^\pm J/\psi$ [5].

In the similar process, $e^+e^- \to \pi^0\pi^0 h_c$, with $h_c$ reconstructed by the same final states as in $e^+e^- \to \pi^+\pi^- h_c$ process, the neutral partner of $Z_c(4020)$ was investigated at BESIII experiment using the same data samples at 4.23, 4.26 and 4.36 GeV. An obvious peak around 4.02 GeV was observed in the $\pi^0 h_c$ mass spectrum, as shown in Fig. 9. Apply a simultaneous fit to the $M_{\max}(\pi^0 h_c)$ mass spectrum in the three energy points with width of $Z_c(4020)$ fixed to the value measured in the charged channel, the mass of neutral $Z_c(4020)$ was determined to be $4023.6 \pm 2.2 \pm 3.9$ MeV, which is consistent with the charged $Z_c(4020)$. The significance of neutral $Z_c(4020)$ is large than $5\sigma$.

BESIII experiment also performed a study of $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ process using 827 pb$^{-1}$ data at 4.26 GeV with partial reconstruction technique. In the recoil mass spectrum of the bachelor $\pi^\pm$ (see Fig. 10), a structure near the $(D^*\bar{D}^*)^\pm$ threshold was observed (denoted as $Z_c(4025)$). Fitting to the mass spectrum using unbinned maximum likelihood method yields a mass of $(4026.3 \pm 2.6 \pm 3.7)$

MeV/$c^2$, and a width of (24.8 ± 5.6 ± 7.7) MeV. The Born cross section of $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ was calculated to be (139 ± 9 ± 15) pb.

A series of charged charmoniu-like states have been observed or confirmed recently. These states all contain at least four quarks and close to the threshold. Besides these common features, the natures of these states are still not clear, the understanding of these states and the similar states in the bottomonium system may help to develop the QCD at non-perturbative region.

## 5 Summary

Dramatic progress has been made in the charmonium-like states from different experiments. Using full data samples, both B-factories updated their analysis about the charmonium-like states, some of them were confirmed while discrepancies still exist. BESIII experiment started to make effort to the charmonium-like states. Using scan data samples from 3.81 to 4.42 GeV, a various processes have been studies at BESIII. The observation of charged $Z_c$ states together with other $Z$ states may indicate one kind of new hadrons has been observed. With more data taken at XYZ region at BESIII experiment in short term and more statistics at Belle II experiment, which is under construction, more results will surely improve the understanding of these states.

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