



October 2, 2013

New results on XYZ states from e^+e^- experiments

CHANG-ZHENG YUAN¹

*Institute of High Energy Physics
Chinese Academy of Sciences, Beijing 100049, China*

In this talk, we present the recent study on the charmoniumlike states from the e^+e^- colliders, including BESIII, Belle, BaBar, and CLEOc. The talk covers the $X(3872)$ from the $Y(4260)$ radiative transition, the Y states from the initial-state-radiation processes and from $e^+e^- \rightarrow \pi^+\pi^-h_c$, and the charged Z_c states.

PRESENTED AT

The 6th International Workshop on Charm Physics
(CHARM 2013)
Manchester, UK, 31 August – 4 September, 2013

¹This work was supported in part by the Ministry of Science and Technology of China under Contract No. 2009CB825203, and National Natural Science Foundation of China (NSFC) under Contracts Nos. 10825524, 10935008, and 11235011.

1 Introduction

In the quark model, mesons are composed from one quark and one anti-quark, while baryons are composed from three quarks. Although no solid calculation shows hadronic states with other configurations must exist in QCD, people believe hadrons with no quark (glueball), with excited gluon (hybrid), or with more than three quarks (multi-quark state) should exist. Since a proton and a neutron can be bounded to form a deuteron, it is also believed that other mesons can also be bounded to form molecules.

It is a long history of searching for all these kinds of states, however, no solid conclusion was reached until recently on the existence of any one of them, except deuteron.

At the B -factories, BaBar and Belle, lots of new states (called charmoniumlike states or XYZ particles) have been observed in the final states with a charmonium and some light hadrons. All these states populate in the charmonium mass region. They could be candidates for charmonium states, however, there are also strange properties shown from these states, these make them more like exotic states rather than conventional mesons [1]. The BESIII [2] experiment at the BEPCII collider started data taking since 2009, and lots of data were accumulated at the peak of the narrow vector charmonium resonances as well as above 4 GeV, these data make the study of the XYZ states possible.

In this talk, we present the most recent results on the study of the $X(3872)$ from the $Y(4260)$ radiative transition, the Y states from initial-state-radiation (ISR) processes and from e^+e^- annihilation, and the charged Z_c states. The results are from the BESIII [2], Belle, BaBar, and CLEOc experiments.

2 Observation of the $Y(4260) \rightarrow \gamma X(3872)$ [3]

The $X(3872)$ was observed by Belle in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays ten years ago [4]. It was confirmed subsequently by several other experiments [5, 6, 7]. Since its discovery, the $X(3872)$ state has stimulated special interest for its nature. Both BaBar and Belle observed $X(3872) \rightarrow \gamma J/\psi$ decay, which supports $X(3872)$ being a C-even state [8, 9]. The CDF and LHCb experiments determined the spin-parity of the $X(3872)$ being $J^P = 1^+$ [10, 11], and CDF experiment also found that the $\pi^+\pi^-$ system was dominated by a $\rho^0(770)$ resonance [12].

Being near $D\bar{D}^*$ mass threshold, the $X(3872)$ was interpreted as a good candidate for a hadronic molecule or a tetraquark state [1]. Currently, $X(3872)$ was only observed in B meson decays and hadron collisions. Since the quantum number of $X(3872)$ is $J^{PC} = 1^{++}$, it could be produced through the radiative transition of the excited vector charmonium or charmoniumlike states such as the ψ s and the Y s.

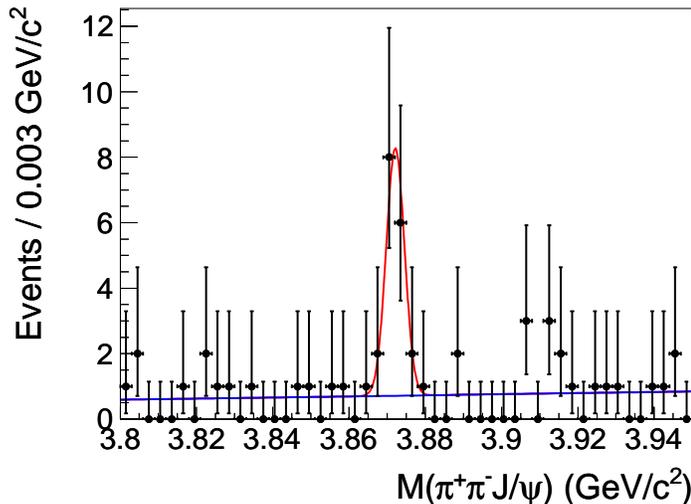


Figure 1: Fit the $M(\pi^+\pi^-J/\psi)$ distribution with MC simulated histogram convolving a Gaussian function for signal and a linear background term. Dots with error bars are data, the curves are the best fit.

BESIII reported the observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\pi^+\pi^-J/\psi$, with J/ψ reconstructed through its decays into lepton pairs ($\ell^+\ell^- = e^+e^-$ or $\mu^+\mu^-$). The analysis is performed with the data samples collected with the BESIII detector taken at e^+e^- central-of-mass (CM) energies from $\sqrt{s} = 4.009$ GeV to 4.420 GeV [13].

The $M(\pi^+\pi^-J/\psi)$ distribution (summed over all energy points) is fitted to extract the mass and signal yield of the $X(3872)$. An Monte Carlo (MC) simulated signal histogram convolving a Gaussian function which represents the difference between data and MC simulation is taken as the signal shape, and a linear term is used for the background. The ISR $\psi(3686)$ signal is used to calibrate the absolute mass scale and to extract the resolution difference between data and MC simulation. Figure 1 shows the fit result, the measured mass of $X(3872)$ is $M[X(3872)] = (3872.1 \pm 0.8 \pm 0.3)$ MeV/ c^2 . The statistical significance of $X(3872)$ is 5.3σ , estimated by comparing the difference of log-likelihood value with and without $X(3872)$ signal in the fit, and taking the change of number-of-degree-of-freedom into consideration.

The Born-order cross section is calculated using $\sigma^B = \frac{N^{\text{obs}}}{\mathcal{L}_{\text{int}}(1+\delta)\epsilon\mathcal{B}}$, where N^{obs} is the number of observed events obtained from the fit to the $M(\pi^+\pi^-J/\psi)$ distribution, \mathcal{L}_{int} is integrate luminosity, ϵ is selection efficiency, \mathcal{B} is branching ratio of $J/\psi \rightarrow \ell^+\ell^-$ and $(1 + \delta)$ is the radiative correction factor. The results are listed in Table 1. For 4.009 GeV and 4.360 GeV data, since the $X(3872)$ signal is not significant, upper limits on the production rates are given at 90% C.L.

The observation suggests that the $X(3872)$ might be from the radiative transition

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

\sqrt{s} (GeV)	$\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi)$ (pb)
4.009	< 0.12
4.229	$0.32 \pm 0.15 \pm 0.02$
4.260	$0.35 \pm 0.12 \pm 0.02$
4.360	< 0.39

of the $Y(4260)$. Combining with the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ cross section measurement at $\sqrt{s} = 4.260$ GeV from BESIII [14], one obtains $\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi] / \sigma^B(e^+e^- \rightarrow \pi^+\pi^-J/\psi) = (5.6 \pm 2.0) \times 10^{-3}$, under the assumption that $X(3872)$ produced only from $Y(4260)$ radiative decays. If one takes $\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi] = 5\%$ [15], then $\mathcal{R} = \frac{\sigma^B[e^+e^- \rightarrow \gamma X(3872)]}{\sigma^B(e^+e^- \rightarrow \pi^+\pi^-J/\psi)} \sim 11\%$. The measured relative large production rate near 4.26 GeV shows a similar tendency to the model dependent calculation [16].

3 More information on the Y states

The study of charmonium states via ISR at the B -factories has proven to be very fruitful. In the process $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$, the BaBar experiment observed the $Y(4260)$ [17]. This structure was also observed by the CLEO [18] and Belle experiments [19] with the same technique; moreover, there is a broad structure near 4.008 GeV in the Belle data. In an analysis of the $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$ process, BaBar found a structure at around 4.32 GeV [20], while the Belle observed two resonant structures at 4.36 GeV and 4.66 GeV [21]. Recently, BaBar updated $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$ analysis with the full data sample, and confirmed the $Y(4660)$ state [22]; while the update of the $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ from both the BaBar and Belle experiments still show differences at the $Y(4008)$ mass region [23, 24].

BESIII experiment reported the cross section of $e^+e^- \rightarrow \pi^+\pi^-h_c$ final state with 13 energy points between 3.81 and 4.42 GeV [13], together with the CLEOc measurement at 4.17 GeV [25], the data indicate the existence of a narrow structure at around 4.22 GeV.

3.1 Confirmation of the $Y(4660)$ [22]

The BaBar experiment study the process $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ with ISR events. The data were recorded with the BaBar detector at center-of-mass energies at and

near the $\Upsilon(nS)$ ($n = 2, 3, 4$) resonances and correspond to an integrated luminosity of 520 fb^{-1} . They investigate the $\pi^+\pi^-\psi(2S)$ mass distribution from 3.95 to 5.95 GeV, and measure the center-of-mass energy dependence of the associated $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ cross section. The mass distribution exhibits evidence of two resonant structures. A fit to the $\pi^+\pi^-\psi(2S)$ mass distribution corresponding to the decay mode $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ yields a mass value of $4340 \pm 16 \pm 9 \text{ MeV}/c^2$ and a width of $94 \pm 32 \pm 13 \text{ MeV}$ for the $Y(4360)$, and for the $Y(4660)$ a mass value of $4669 \pm 21 \pm 3 \text{ MeV}/c^2$ and a width of $104 \pm 48 \pm 10 \text{ MeV}$. The results are in good agreement with the Belle measurement [21] and confirm the $Y(4660)$ observed by the Belle experiment.

3.2 Measurement of $e^+e^- \rightarrow \pi^+\pi^-h_c$

BESIII studied $e^+e^- \rightarrow \pi^+\pi^-h_c$ at 13 CM energies from 3.900 to 4.420 GeV [13]. The data samples and the results are listed in Table 2. In the studies, the h_c is reconstructed via its electric-dipole (E1) transition $h_c \rightarrow \gamma\eta_c$ with $\eta_c \rightarrow X_i$, where X_i signifies 16 exclusive hadronic final states: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^\pm\pi^\mp$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$. Here K_S^0 is reconstructed from its $\pi^+\pi^-$ decays, and the π^0 and η from their $\gamma\gamma$ final states.

Table 2: $e^+e^- \rightarrow \pi^+\pi^-h_c$ cross sections (or upper limits at the 90% confidence level). The third errors are from the uncertainty in $\mathcal{B}(h_c \rightarrow \gamma\eta_c)$ [26].

\sqrt{s} (GeV)	\mathcal{L} (pb^{-1})	$n_{h_c}^{\text{obs}}$	$\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c)$ (pb)
3.900	52.8	< 2.3	< 8.3
4.009	482.0	< 13	< 5.0
4.090	51.0	< 6.0	< 13
4.190	43.0	8.8 ± 4.9	$17.7 \pm 9.8 \pm 1.6 \pm 2.8$
4.210	54.7	21.7 ± 5.9	$34.8 \pm 9.5 \pm 3.2 \pm 5.5$
4.220	54.6	26.6 ± 6.8	$41.9 \pm 10.7 \pm 3.8 \pm 6.6$
4.230	1090.0	646 ± 33	$50.2 \pm 2.7 \pm 4.6 \pm 7.9$
4.245	56.0	22.6 ± 7.1	$32.7 \pm 10.3 \pm 3.0 \pm 5.1$
4.260	826.8	416 ± 28	$41.0 \pm 2.8 \pm 3.7 \pm 6.4$
4.310	44.9	34.6 ± 7.2	$61.9 \pm 12.9 \pm 5.6 \pm 9.7$
4.360	544.5	357 ± 25	$52.3 \pm 3.7 \pm 4.8 \pm 8.2$
4.390	55.1	30.0 ± 7.8	$41.8 \pm 10.8 \pm 3.8 \pm 6.6$
4.420	44.7	29.1 ± 7.3	$49.4 \pm 12.4 \pm 4.5 \pm 7.6$

The resulting cross sections are of the same order of magnitude as those of the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ measured by BESIII [14] and other experiments [23, 24], but with

a different line shape (see Fig. 2). There is a broad structure at high energy with a possible local maximum at around 4.23 GeV. Together with the measurement at 4.17 GeV by the CLEOc experiment [25], $\sigma = (15.6 \pm 2.3 \pm 1.9 \pm 3.0)$ pb, the cross sections are fit to extract the possible resonant structures.

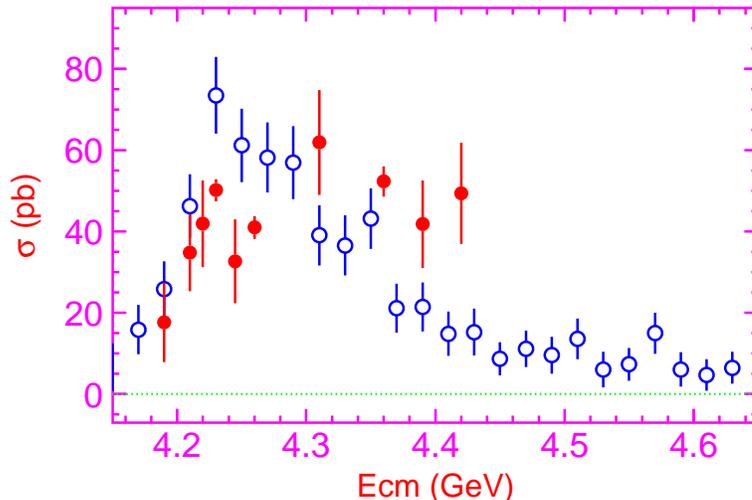


Figure 2: The comparison between the cross sections of $e^+e^- \rightarrow \pi^+\pi^-h_c$ from BE-SIII (dots with error bars) and those of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ from Belle (open circles with error bars). The errors are statistical only.

As the line shape at above 4.42 GeV is unknown, it is not clear whether the large cross section at high energy will decrease or not. Assuming the cross section follows the three-body phase space and there is a narrow resonance at around 4.2 GeV, we fit the cross sections with the coherent sum of two amplitudes, a constant and a constant width relativistic Breit-Wigner (BW) function. The fit indicates the existence of a resonance (called $Y(4220)$ hereafter) with a mass of (4216 ± 7) MeV/ c^2 and width of (39 ± 17) MeV, and the goodness-of-the-fit is $\chi^2/\text{ndf} = 11.04/9$, corresponding to a confidence level of 27%. There are two solutions for the $\Gamma_{e^+e^-} \times \mathcal{B}(Y(4220) \rightarrow \pi^+\pi^-h_c)$ which are (3.2 ± 1.5) eV and (6.0 ± 2.4) eV. Fitting the cross sections without the $Y(4220)$ results in a very bad fit, $\chi^2/\text{ndf} = 72.75/13$, corresponding to a confidence level of 2.5×10^{-10} . The statistical significance of the $Y(4220)$ is calculated to be 7.1σ comparing the two χ^2 s obtained above and taking into account the change of the number-of-degree-of-freedom. Figure 3 (left panel) shows the final fit with the $Y(4220)$.

Assuming the cross section decreases at high energy, we fit the cross sections with the coherent sum of two constant width relativistic BW functions. The fit indicates the existence of the $Y(4220)$ with a mass of (4230 ± 10) MeV/ c^2 and width of (12 ± 36) MeV, as well as a broad resonance, the $Y(4290)$, with a mass of $(4293 \pm$

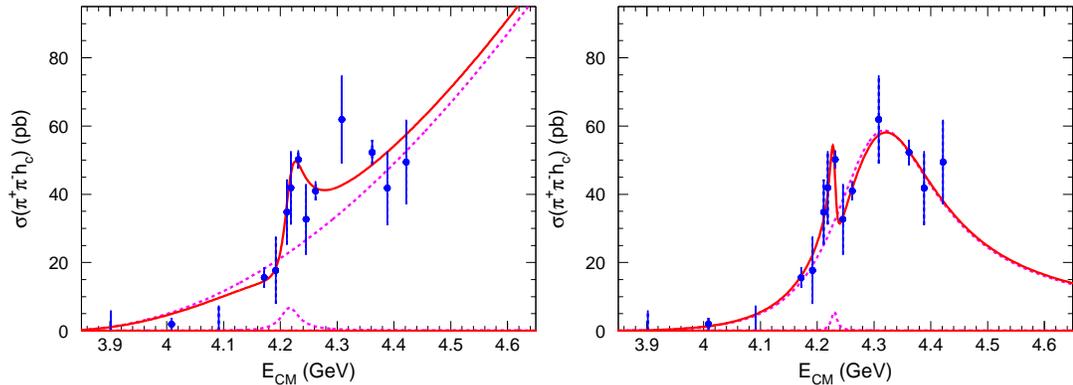


Figure 3: The fit to the cross sections of $e^+e^- \rightarrow \pi^+\pi^-h_c$ from BESIII and CLEOc (dots with error bars). Solid curves show the best fits, and the dashed ones are individual component. Left panel is the fit with the coherent sum of a phase space amplitude and a BW function, and the right panel is the coherent sum of two BW functions.

9) MeV/c^2 and width of (222 ± 67) MeV. The goodness-of-the-fit is $\chi^2/\text{ndf} = 1.81/7$, corresponding to a confidence level of 97%. There are two solutions for the $\Gamma_{e^+e^-} \times \mathcal{B}(Y(4220)/Y(4290) \rightarrow \pi^+\pi^-h_c)$ which are (0.07 ± 0.07) eV/ (16.1 ± 2.2) eV and (2.7 ± 4.9) eV/ (19.0 ± 5.9) eV. Fitting the cross sections without the $Y(4220)$ results in a much worse fit, $\chi^2/\text{ndf} = 30.65/11$, corresponding to a confidence level of 1.3×10^{-3} . The statistical significance of the $Y(4220)$ is calculated to be 4.5σ comparing the two χ^2 s obtained above and taking into account the change of the number-of-degree-of-freedom. Figure 3 (right panel) shows the final fit with the $Y(4220)$ and $Y(4290)$.

From the two fits showed above, we conclude that there must be a narrow structure at around $4.22 \text{ GeV}/c^2$ with a width at 10–50 MeV level, although we are not sure if there is a broad resonance at $4.29 \text{ GeV}/c^2$. More measurements from the BESIII experiments at CM energies above 4.42 GeV will certainly tell which of the above two fits is more meaningful, and more precise data at around the $Y(4220)$ peak will also be crucial to extract the resonant parameters of it more precisely.

There are thresholds of $\overline{D}D_1$ [27], $\omega\chi_{cJ}$ [28, 29], $D_s^{*+}D_s^{*-}$ at the $Y(4220)$ mass region, these make the identification of the nature of this structure very complicated. It is worth to point out that the lattice QCD calculations indicate that the charmonium-hybrid lies in the mass region of these two Y states [30] and the $c\bar{c}$ tend to be in a spin-singlet state. Such a state may couple to a spin-singlet charmonium state such as h_c strongly, this makes the $Y(4220)$ and/or $Y(4290)$ good candidates for the charmonium-hybrid states.

4 Observation of charged charmoniumlike states

In the study of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at CM energies around 4.26 GeV, the BESIII [14] and Belle [24] experiments observed a charged charmoniumlike state, the $Z_c(3900)$, which was confirmed shortly after with CLEO data at a CM energy of 4.17 GeV [31]. As there are at least four quarks within the $Z_c(3900)$, it is interpreted either as a tetraquark state, $D\bar{D}^*$ molecule, hadro-quarkonium, or other configuration. More recently, BESIII observed a charged $Z_c(4025)$ state in $e^+e^- \rightarrow \pi^\pm(D^*\bar{D}^*)^\mp$ [32] and a charged $Z_c(4020)$ state in $e^+e^- \rightarrow \pi^\pm(\pi^\mp h_c)$ [13]. These states seem to indicate that a new class of hadrons has been observed.

4.1 Observation of the $Z_c(3900)$ [14, 24]

BESIII experiment studied the process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at a CM energy of 4.260 GeV using a 525 pb^{-1} data sample [14]. A structure at around $3.9 \text{ GeV}/c^2$ is observed in the $\pi^\pm J/\psi$ mass spectrum with a statistical significance larger than 8σ , which is referred to as the $Z_c(3900)$. If interpreted as a new particle, it is unusual in that it carries an electric charge and couples to charmonium. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum (see Fig. 4), neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2$ and a width of $(46 \pm 10 \pm 20) \text{ MeV}$. Its production ratio is measured to be $R = \frac{\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$.

At Belle experiment, the cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ is measured from 3.8 GeV to 5.5 GeV using ISR method. The $Y(4260)$ resonance is observed and its resonant parameters are determined. The intermediate states in $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decays are also investigated [24]. A $Z_c(3900)$ state with a mass of $(3894.5 \pm 6.6 \pm 4.5) \text{ MeV}/c^2$ and a width of $(63 \pm 24 \pm 26) \text{ MeV}/c^2$ is observed in the $\pi^\pm J/\psi$ mass spectrum (see Fig. 4) with a statistical significance larger than 5.2σ .

The $Z_c(3900)$ was confirmed shortly after with CLEOc data at a CM energy of 4.17 GeV [31], the mass and width agree with the BESIII and Belle measurements very well.

This state is close to the $D\bar{D}^*$ mass threshold. As the $Z_c(3900)$ state has a strong coupling to charmonium and is charged, it cannot be a conventional $c\bar{c}$ state. However, its nature is unknown.

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

BESIII experiment measured $e^+e^- \rightarrow \pi^+\pi^- h_c$ cross sections at CM energies between 3.90 and 4.42 GeV and analyzed the Dalitz plot of $\pi^+\pi^- h_c$ system. A narrow structure very close to the $(D^*\bar{D}^*)^\pm$ threshold with a mass of $(4022.9 \pm 0.8 \pm 2.7) \text{ MeV}/c^2$ and a width of $(7.9 \pm 2.7 \pm 2.6) \text{ MeV}$ is observed in the $\pi^\pm h_c$ mass spectrum [13]. This structure couples to charmonium and has an electric charge, which is suggestive of

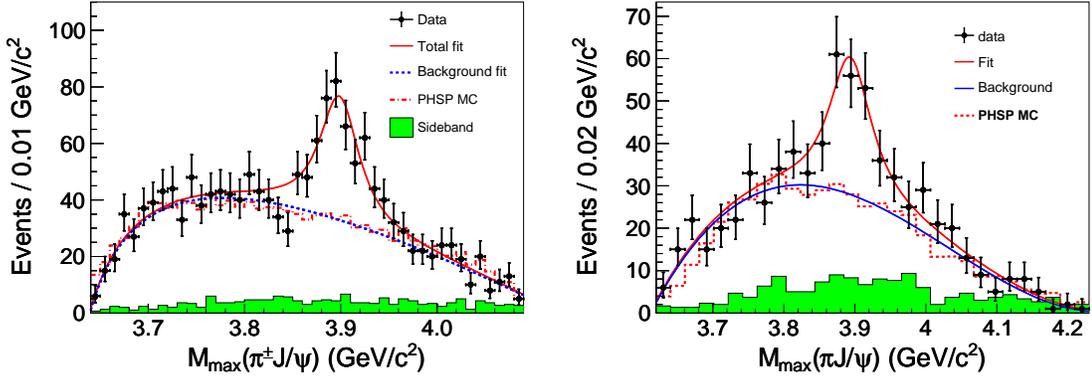


Figure 4: Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$ (left panel from BESIII and right panel from Belle). Points with error bars are data, the curves are the best fit, the dashed histograms are the phase space distributions and the shaded histograms are the non- $\pi^+\pi^-J/\psi$ background estimated from the normalized J/ψ sidebands.

a state containing more quarks than just a charm and an anti-charm quark, as the $Z_c(3900)$ observed in the $\pi^\pm J/\psi$ system [14, 24, 31]. BESIII experiment does not find a significant signal for $Z_c(3900) \rightarrow \pi^\pm h_c$ and the production cross section is found to be smaller than 11 pb at the 90% C.L. at 4.26 GeV, which is lower than that of $Z_c(3900) \rightarrow \pi^\pm J/\psi$ [14].

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

The $Z_c(4020)$ parameters agree within 1.5σ of those of the $Z_c(4025)$. Currently one cannot tell whether they are the same state. Further study is needed.

5 Summary

In summary, there are lots of charmoniumlike states observed in charmonium mass region but many of them show properties different from the naive expectation of conventional charmonium states. The BESIII experiment is now producing results on these XYZ states. The observation of the charged charmonium states, $Z_c(3900)$,

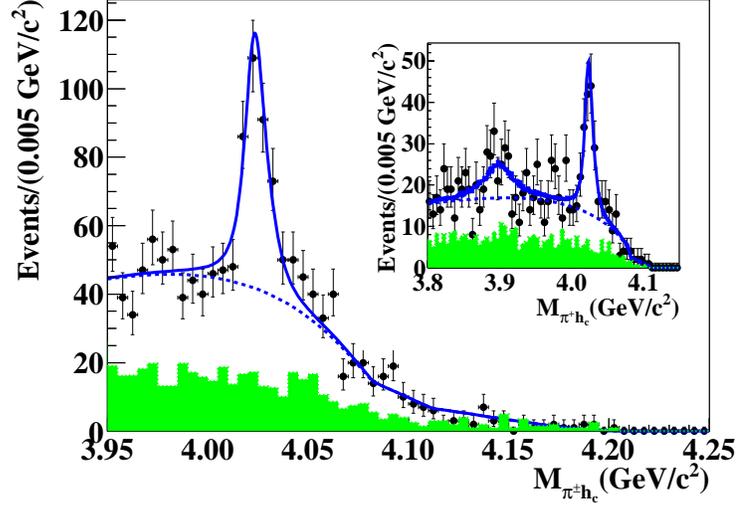


Figure 5: Sum of the simultaneous fits to the $M_{\pi^{\pm}h_c}$ distributions at 4.23 GeV, 4.26 GeV, and 4.36 GeV; the inset shows the sum of the simultaneous fit to the $M_{\pi^+h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

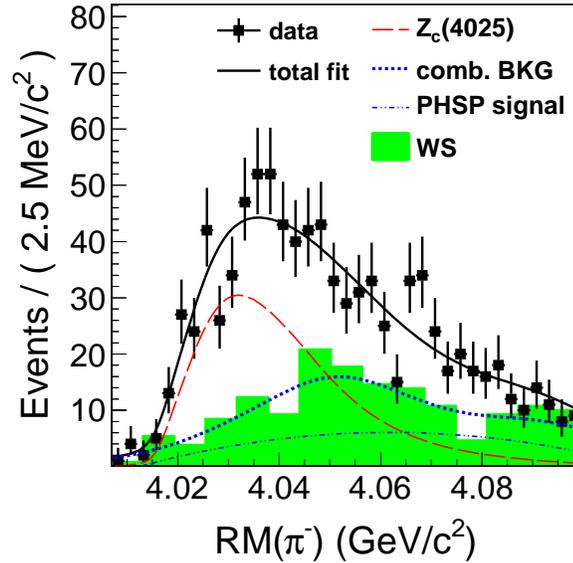


Figure 6: Unbinned maximum likelihood fit to the π^{\mp} recoil mass spectrum in $e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^{\mp}$.

$Z_c(4020)$, and $Z_c(4025)$, may indicate one kind of the exotic states has been observed.

In the near future, BESIII experiment [2] will accumulate more data for further study; the Belle II experiment [33] under construction, with about 50 ab^{-1} data accumulated, will surely improve our understanding of all these states.

ACKNOWLEDGEMENTS

We thank the organizers for their invitation to give the review talk and congratulate the organizers for a very successful workshop.

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