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Recent results on (exotic) charmonium spectroscopy

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1. Introduction

In the quark model, mesons are composed of a quark and a anti-quark; and baryons are composed of three quarks. Quantum chromodynamics (QCD) also predicts hadrons as glueball, hybrid and multiquark states. Searching for these exotic states is also an important topic for high energy experiments[1]. For charmonium below charm threshold, all states have been observed, and the charm anti-charm potential model describes the spectrum well. However, there are many missing states above charm threshold, and a large number of charmonium-like states are observed in final states with charmonium and light hadrons. It is clear that a number of the new states above the charm threshold do not fit into $c\bar{c}$ picture, and they have some strange properties, which makes them candidates exotic states.

In this talk, I present recent results in (exotic) charmonium spectroscopy. The updated Babar and Belle results on Y(4260) and Y(4008) in $\pi^+\pi^- J/\psi$; Y(4360) and Y(4660) in $\pi^+\pi^-\psi(2S)$ from initial state radiation (ISR) production and B decays; cross sections of $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \omega\chi_{c0}$ by the BESIII Collaboration; the latest study of charged and neutral Z_c states.

2. Y(4260) and Y(4008) in $\pi^+\pi^- J/\psi$

The Y(4260) was observed by the Babar collaboration in $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ [2], and confirmed by CLEO [3] and Belle experiments [4]. In Belle results, another broad structure near 4.008 GeV (denoted as Y(4008)) is observed besides the Y(4260). Using 454 fb^{-1} data sample at $\sqrt{s} = 10.58$GeV and 10.54GeV, The Babar collaboration has confirmed Y(4260) and explains events in low mass region as the tail of $\psi^{'}$ (shown in Fig. 1) [5]. Their results are also consistent with previous measurements. Based on 967 fb^{-1} dataset, Belle Collaboration published their results on the invariant mass of $\pi^+\pi^- J/\psi$ (shown in Fig. 1), and fitted the spectrum with two coherent resonances, Y(4008) is confirmed, parameters of Y(4260) and Y(4008) are also consistent with previous measurement [6]. The discrepancy on Y(4008) between BaBar and Belle still exists, studies at BESIII using data samples the this energy region may help to clarify.

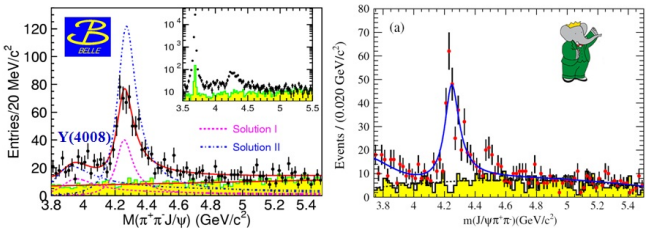

Figure 1: The invariant mass of $\pi^+\pi^- J/\psi$ by Belle collaboration and BaBar Collaboration

3. Y(4360) and Y(4660) in $\pi^+\pi^-\psi(2S)$

In $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$ process, BaBar collaboration finds a structure around 4.32GeV [7], while Belle collaboration observe two structures at 4.36GeV and 4.66GeV in the same process [8]. Using 520 fb^{-1} data collected at or near $\Upsilon(nS)(n = 2,3,4)$, BaBar collaboration update their

analysis [9]. Two structures are observed in the invariant mass of $\pi^+\pi^-\Psi(2S)$ (Fig.2), and measured parameters are consistent with the Belle measurement[8]. The Y(4660) observed by Belle collaboration is confirmed.

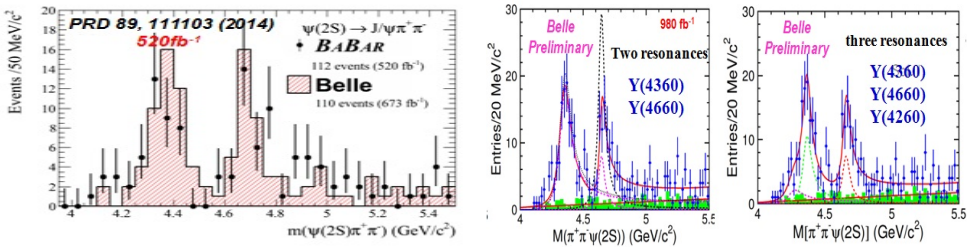

Figure 2: The invariant mass of $\pi^+\pi^-\psi(2S)$ by BaBar collaboration and Belle Collaboration

Using a 980 fb^{-1} data sample, the Belle collaboration updated their analysis. Fig.2 shows a fit to the mass spectrum of $\pi^+\pi^-\Psi(2S)$ with two coherent Breit-Wigner functions. The fitted mass of Y(4360) and Y(4660) are about 20 MeV smaller than previous Belle results [8]. Another fit with the Y(4260) included is also performed (figure 2), where the parameters of Y(4260) are fixed to the latest Belle measurement, The significance of the Y(4260) is 2.1σ.

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

Using 13 energy points between 3.90GeV and 4.42GeV, the BESIII Collaboration studied the cross section of $e^+e^- \to \pi^+\pi^- h_c$ [10], where h_c is reconstructed with $\gamma\eta_c$, and η_c is identified with 16 hadronic decay modes. Fig.3 present the Born cross section of $e^+e^- \to \pi^+\pi^- h_c$ at each energy points. The Born cross sections of $e^+e^- \to \pi^+\pi^- h_c$ are at same order of $e^+e^- \to \pi^+\pi^- J/\psi$, but with difference line shape. There is a broad structure at high energy, with a possible maximum around 4.23 GeV. Because Y(4260) was established from $\pi^+\pi^- J/\psi$, different line shape $\pi^+\pi^- h_c$ makes understanding of Y states more complicate.

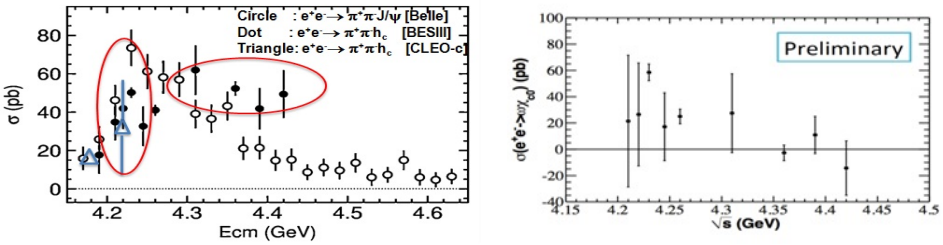

Figure 3: The cross section of $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \omega\chi_{c0}$ by BESIII collaboration

Using data samples at 9 energy points between 4.21 GeV and 4.42 GeV, BESIII Collaboration has measured the cross section of $e^+e^- \to \omega\chi_{cJ}(J = 0,1,2)$ [11]. Here ω is reconstructed with $\pi^+\pi^-\pi^0$ and χ_{c0} is identified with $\pi^+\pi^-$ and K^+K^-. The $e^+e^- \to \omega\chi_{c0}$ are observed for the first time at 4.23GeV and 4.26GeV. At other seven energy points, $e^+e^- \to \omega\chi_{c0}$ signal is not significant, and upper limits on cross section are determined. Fig.3 shows the cross section of $e^+e^- \to \omega\chi_{c0}$ as a function of the center of mass energy, where the cross section peaks around 4.23GeV.

5. Observation of charged charmonium-like states

The charged charmonium-like states are observed with a charmonium and charged light hadrons, hence they at least have four quarks, and could not be a conventional meson. Recent results on charmonium-like states are described in this section.

5.1 $Z_c^{\pm}(3900)$ and $Z_c^0(3900)$

Using 525 pb^{-1} data sets at $\sqrt{s} = 4.26$GeV, BESIII Collaboration studies $e^+e^- \to \pi^+\pi^- J/\psi$ process [12], and observes a charged charmoniumlike state (named as Zc(3900)) in the $\pi^{\pm}J/\psi$ mass spectrum, with a statistical significance larger than 8σ. An unbinned maximum likelihood fit to $M_{max}(\pi^{\pm}J/\psi)$ distribution is performed, as shown in Fig.4. . The fitted mass and width are $3899.0 \pm 3.6 \pm 4.9 MeV$ and $46 \pm 10 \pm 20 MeV$ respectively. This structure is confirmed by CLEO-c data at a center of mass energy of 4.17GeV [13], their fitted mass and width are $3886 \pm 4 \pm 2 MeV$ and $37 \pm 4 \pm 8 MeV$ respectively (shown in Fig.4).

The Belle Collaboration uses ISR production to study cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ between 3.8GeV and 5.5GeV. For events around Y(4260) resonance [14], similar structure is observed in $M_{max}(\pi^{\pm}J/\psi)$ spectrum, with a statistical signigicance larger than 5.2σ. Fitting to the $M_{max}(\pi^{\pm}J/\psi)$ spectrum determines mass and width to be $3886 \pm 4 \pm 2 MeV$ and $37 \pm 4 \pm 8 MeV$ separately. In summary, the fitted mass and width of $Z_c^{\pm}(3900)$ from BESIII, CLEO-c and Belle Collaboration are consistent.

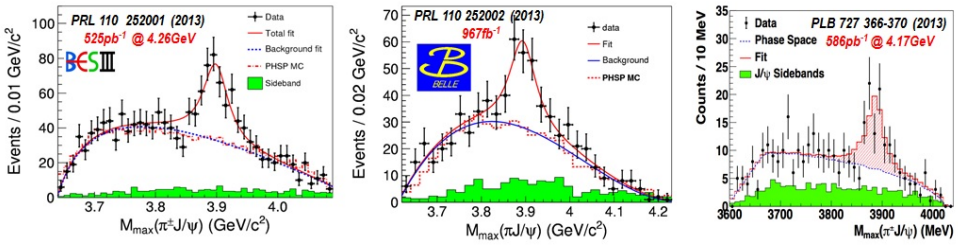

Figure 4: $\pi^{\pm}J/\psi$ mass spectrum in $e^+e^- \to \pi^+\pi^- J/\psi$ process by BESIII, Belle and CLEO-c collaboration, in ISR production by Belle collaboration.

BESIII Collaboration also studies $e^+e^- \to \pi^0\pi^0 J/\psi$ at $\sqrt{s}$ =4.23GeV, 4.26GeV and 4.36GeV, The structure around 3.9GeV (named as $Z_c^0(3900)$) is observed in invariant mass of $\pi^0 J/\Psi$, with a statistical significance 10.4σ. The mass and width of $Z_c^0(3900)$ are $3894.8 \pm 2.3 MeV/c^2$ and $29.6 \pm 8.2 MeV/c^2$ respectively. These results are consistent with that of Cleo-c data at $\sqrt{s} = 4.17 GeV$ [13].

5.2 $Z_c(3885)$ and $Z_c(4020)$

Since the mass of $Z_c(3900)$ is close to $D\bar{D}^*$ mass threshold, BESIII Collaboration studies process $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ at $\sqrt{s} = 4.26$GeV [15]. In order to improve the event selection efficiency, bachelor $\pi^{\pm}$ and one D meson are detected, The $\bar{D}^*$ is inferred from energy-momentum conservation. Fig.5 shows recoil mass of bachelor $\pi^{\pm}$, a structure (named as $Z_c(3885)$) is observed near $D\bar{D}^*$ mass threshold. The fitted mass and width are $3883.9 \pm 1.5 \pm 4.2$ MeV and $24.8 \pm 3.3 \pm 11.0$ MeV, which are about $2\sigma/1\sigma$ below those of $Z_c(3900)$. Assuming $Z_c(3885)$ and $Z_c(3900)$ are

the same state, The ratio $\Gamma(Z_c(3990) \to D\bar{D}^*)/\Gamma(Z_c(3990) \to \pi J/\psi) = 6.2 \pm 2.9$, which is smaller than typical value for conventional charmonium states. The signal yield as a function of bachelor $|\cos\theta_\pi|$ with a different J^P assumptions is displayed in Fig. 5, and experimental data agrees well with flat expectation with $J^P = 1^+$.

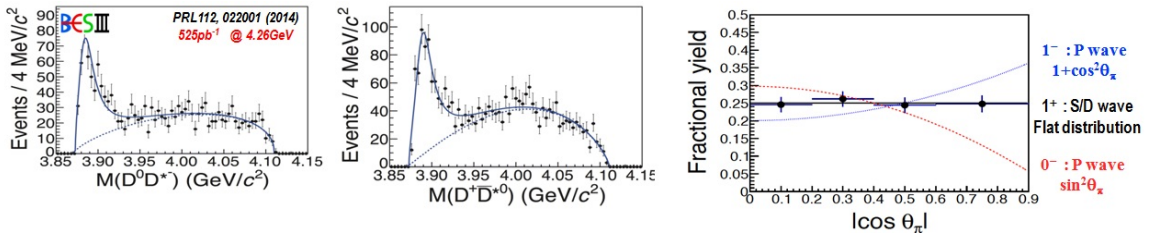

Figure 5: The $M(D^0D^{*-})$ and $M(D^+\bar{D}^{*0})$ spectrum for selected events, curves are best fit results. left plot describe signal yield as a function of bachelor $|\cos\theta_\pi|$ for $Z_c(3885)$ events.

The BESIII Collaboration studies process $e^+e^- \to \pi^+\pi^- h_c$ between 3.90GeV and 4.42GeV [10]. A structure around 4.02 GeV is observed in $\pi^\pm h_c$ mass spectrum, and is refered to as the Zc(4020). Fig.6 shows a simultaneous fit to $\pi^\pm h_c$ mass spectrum at 4.23GeV, 4.26GeV and 4.36GeV, and the fitting yields a mass of $(4022.9 \pm 0.8 \pm 2.7)$MeV and a width of $(7.9 \pm 2.7 \pm 2.6)$MeV with a statistical significance larger than 8.9σ. There is no significant evidence for $Z_c(3900) \to \pi^\pm h_c$ in fig.6.

BESIII Collaboration also performs a study of $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ at $\sqrt{s} = 4.26$GeV [16]. Only bachelor pion and charged D meson are detected in this analysis, in order to further suppress backgrounds, additional π^0 is required. Figure 6 shows a structure (named as $Z_c(4025)$) near the $D^*\bar{D}^*$ threshold in recoil mass of bachelor $\pi^\pm$, fitted mass and width are $(4026.3 \pm 2.6 \pm 3.7)$MeV and $(24.8 \pm 5.6 \pm 7.7)$MeV. Assuming $Z_c(4020)$ and $Z_c(4025)$ are same state, ratio $\Gamma(Z_c(4020) \to D^*\bar{D}^*)/\Gamma(Z_c(4020) \to \pi h_c) = 12 \pm 5$, is also not large compared to the conventional charmonium state above open charm threshold.

Fig. 6 also shows the cross section of $e^+e^- \to \pi^0\pi^0 h_c$, which is about half of $e^+e^- \to \pi^+\pi^- h_c$, and agrees with expectation of isospin symmetry. The neutral $Z_c(4020)^0$ is also observed in $\pi^0 h_c$ mass distribution. A simultaneous fit to 4.23GeV, 4.26GeV and 4.36GeV data with fixed width from $Z_c(4020)^\pm$, the fitted mass of $Z_c(4020)^0$ is $(4023.6 \pm 2.2 \pm 3.9)$MeV, and is consistent with that of the $Z_c(4020)^\pm$.

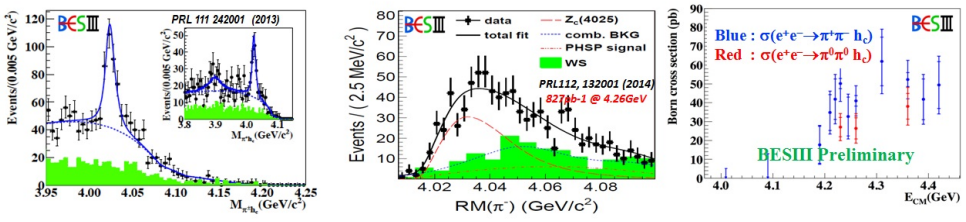

Figure 6: The invariant mass of $\pi^\pm J/\psi$ and $\pi^+\pi^-$ in $e^+e^- \to \pi^+\pi^- J/\psi$ process by BESIII collaboration

5.3 $Z_c(4430)$

The Belle Collaboration used the $B^0 \to \psi(2S)K\pi$ decay mode, and observed charged charmonium-like state $Z_c(4430)$ with a statistical significance 6.5σ. BaBar collaboration performed analysis in the same process, found data can be explained as the reflection of the K^* states, and Z(4430) was not confirmed. Belle Collaboration updated their analysis with a four dimensional (4D) amplitude analysis after taking into account effect of K^* states [17]. The $Z_c(4430)$ is observed with a much larger mass and a large width, its spin-parity is favoured to be $J^P = 1+$. LHCb Collobation confirmed $Z_c(4430)$ and established its spin parity to be 1^+ both with very high significance [18]. The mass and width measured are consistent with the latest Belle measurement [17].

Using $\bar{B}^0 \to J/\psi K^-\pi^+$ decays, Belle Collaboration performs an amplitude analysis in four dimensions [19], A new charged charmonium-like states $Z_c(4210)$ is observed in variant mass of $\pi J/\psi$ with a statistical significance 7.2σ, are shown in Fig.7. mass and width of $Z_c(4210)$ are 4196^{+31+17}_{-29-6} MeV and 370^{+70+70}_{-70-85} MeV respectively. The preferred assignment of quantum number is $J^P = 1^+$. The $Z_c(4430)$ is also found with statistical significance 4σ.

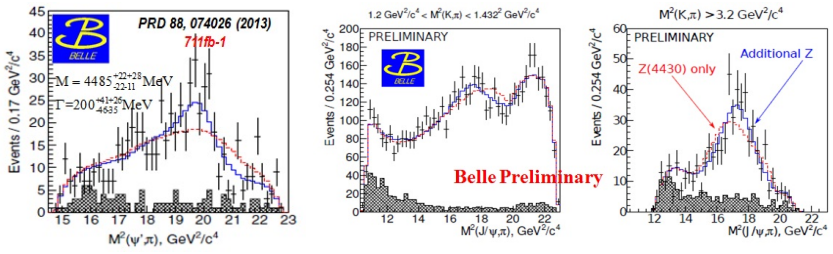

Figure 7: The invariant mass of $\pi\psi(2S)$ and $\pi J/\psi$ by Belle collaboration

6. Summary

During the past several years, large progress has been made on charmonium-like states from different experiments. Some states are confirmed, and some states still have discrepancies. In the near future, more data sets taken at XYZ region at BESIII experiment; larger dataset at Belle II experiment, are useful to understand charmonium-like states in detail, fruitful results from ATLAS/CMS/LHCb at LHC experiments are highly welcomed.

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