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Recent empirical developments in the study and understanding of XYZ states

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Abstract. Exotic hadronic states beyond the conventional quark model (called charmoniumlike/bottomoniumlike states or XYZ particles) have been searched for and many candidates were proposed including glueballs, hybrids, multi-quark states, hadron molecules, etc. Dramatic progress was made in the study of the exotic states after the running of the two B-factories, i.e., Belle at KEK and BaBar at SLAC. In my review report, I present the most recent results on the study of the XYZ states from the BESIII, Belle, BaBar, LHCb, CMS experiments, etc., including (1) X states: the observation of the $X(3872)$ in $e^+e^- \to \gamma X(3872)$ at around 4.26 GeV; searches for the X_b state; (2) Y states including the updated results for the $Y(4008)$, $Y(4260)$, $Y(4360)$, $Y(4660)$, etc; (3) Z states including the observations of the $Z(4430)$, $Z_1(4050)$, $Z_2(4250)$, $Z_c(3900)$, $Z_c(4020)$, $Z_c(4200)$; the evidence for the $Z_c(4050)^\pm \to \pi^\pm\psi(2S)$; search for the Z_{cs} in $e^+e^- \to K^+K^-J/\psi$.

1 Introduction

It has been prospering for dozen years that lots of the "XYZ" particles mainly were observed by Belle, BaBar, and BESIII Collaborations. Most of them above the open charm threshold can not be described well by quark potential models, which decay into the final states containing a charmonium and light hadrons, but not open charm pairs with a detectable rate as expected [1, 2]. Their underlying exotic properties have been stimulating significant interests in theoretical studies, and indicate several possible popular interpretations such as tetraquarks, molecules, hybrids, hadrocharmonia, or glueballs [1, 2]. Here, I present the most recent results on the study of the "XYZ" states from the BESIII, Belle, BaBar, LHCb, CMS experiments, etc.

2 The X states

The unexpected observed $X(3872)$ in $M(\pi^+\pi^-J/\psi)$ distribution from $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ decays at Belle [3] in 2003 kicked off the research prelude of XYZ states. Later the $X(3872)$ was confirmed by BaBar [4], CDF [5], D0 [6], as well as LHCb [7]. The CDF group in particular demonstrated that the $\pi^+\pi^-$ pair tends to originate from a ρ decay [8]. Then Belle found evidence for the $\gamma J/\psi$ and $\pi^+\pi^-\pi^0 J/\psi$ decay modes with a significance of greater than 4σ [9]. Not only the former has been confirmed by BaBar [10, 11], but also a larger than 10σ significance signal was observed by LHCb

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[12]. In the latter the invariant mass distribution of $\pi^+\pi^-\pi^0$ indicated that the sub-threshold decay into $\omega J/\psi$ is dominated [9] with the rate comparable to that of the $\pi^+\pi^- J/\psi$ decay mode. However, the radiative decay, $X(3872) \to \gamma\psi(2S)$, had been puzzling for several years since Belle's upper limit [13] wasn't compatible with BaBar's measurement [11]. Until recently LHCb corroborated its existence with a better statistics [12]. Due to the close mass to $D^{*0}\bar{D}^0$ threshold, it was a considerable speculation from the beginning that the $X(3872)$ might be a molecule-like bound state of D^{*0} and $\bar{D}^0$ meson [14, 15]. Eventually both BaBar [16] and Belle [17] observed conspicuous signals of the $X(3872) \to D^{*0}\bar{D}^0$ process with an order of magnitude higher branching fraction than the $\pi^+\pi^- J/\psi$ mode. Moreover LHCb lately fixed the quantum numbers of $X(3872)$ to be $I^G(J^{PC}) = 0^+(1^{++})$, which suggested that it is possibly a candidate of $\chi_{c1}(2P)$ [18]. The generally accepted interpretation at present for the still-fascinating $X(3872)$ is a mixture of a charmonium state $\chi_{c1}(2P)$ and an S-wave $D^{*0}\bar{D}^0$ molecule.

About the $X(3872)$, BESIII recently gave some new information. BESIII measured the process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ at e^+e^- center-of-mass energies from $\sqrt{s} = 4.009$ GeV to 4.420 GeV [19]. The observed statistical significance of $X(3872)$ in the $M(\pi^+\pi^- J/\psi)$ distribution reaches 6.3σ. Figure 1(a) shows the energy-dependent cross section together with the fitted results with a $Y(4260)$ resonance, a linear continuum, or a $E1$-transition phase space term. The $Y(4260)$ resonance describes the data better than the other two options, which strongly supports the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$.

It is very natural to search for a similar state with $J^{PC} = 1^{++}$, called X_b, in the bottomonium system. The search for X_b supplies important information about the discrimination of a compact multiquark configuration and a loosely bound hadronic molecule configuration for the $X(3872)$. The existence of the X_b is predicted in both the tetraquark model [20] and those involving a molecular interpretation [21–23]. The CMS Collaboration ever searched for the X_b decaying to $\pi^+\pi^-\Upsilon(1S)$ based on a sample of pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.7fb^{-1} [24]. Figure 1(b) shows the $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution. Except the clear $\Upsilon(2S)$ signal, no evidence for an X_b signal was observed. However, unlike the $X(3872)$, whose decays exhibit large isospin violation, the X_b would decay preferably into $\pi^+\pi^-\pi^0\Upsilon(1S)$ rather than $\pi^+\pi^-\Upsilon(1S)$ if it exists [22, 25]. So Belle did a search for an X_b signal decaying to $\omega\Upsilon(1S)$ in $e^+e^- \to \gamma X_b$ at a center-of-mass energy of 10.867 GeV [26]. Figure 1(c) shows the $\omega\Upsilon(1S)$ invariant mass distribution in a range from 10.55 to 10.65 GeV/c^2. The dots with error bars are from data, the solid histogram is from the normalized contribution of $e^+e^- \to \omega\chi_{bJ}$ ($J = 0,\ 1,\ 2$). No obvious X_b signal is observed, and 90% confidence level upper limits on the product branching fraction $\mathcal{B}(\Upsilon(5S) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$ vary smoothly from 2.6×10^{-5} to 3.8×10^{-5} between 10.55 and 10.65 GeV/c^2.

3 The Y states

The $Y(4260)$ state was first observed by the BaBar Collaboration in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ [27] and then confirmed by the CLEO [28] and Belle experiments [29] using the same technique. After the initial observations of the $Y(4260)$ [27–29], CLEO collected 13.2 pb^{-1} of e^+e^- data at $\sqrt{s} = 4.26$ GeV and investigated 16 possible $Y(4260)$ decay modes with charmonium or light hadrons in the final state [30]. An ISR analysis by the Belle experiment with 548 fb^{-1} of data showed a significant $Y(4260)$ signal as well as a broad excess of $\pi^+\pi^- J/\psi$ event production near 4 GeV — the so-called $Y(4008)$ [31].

Later, the BaBar Collaboration reported an updated ISR analysis with 454 fb^{-1} of data and a modified approach for the background description [32]; the $Y(4260)$ state was observed with improved significance, but the $Y(4008)$ structure was not confirmed. Instead, they attributed the structure below

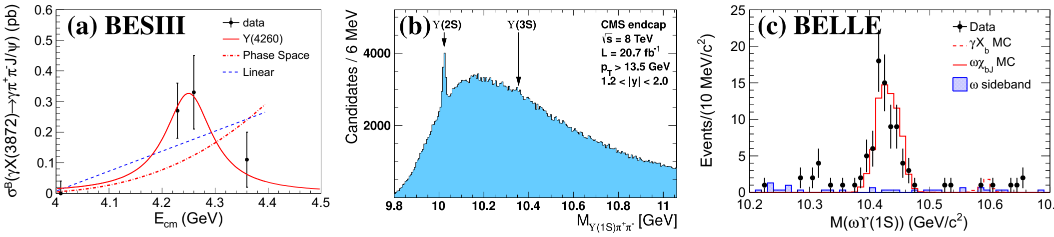

Figure 1. Recent results on the $X(3872)$ and its similar state in the bottomonium system X_b from BESIII, CMS and Belle. (a) The $\sigma^B[e^+e^- \to \gamma X(3872)] \times \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]$ distribution and fit results with different line shapes from BESIII; (b) The $M(\pi^+\pi^-\Upsilon(1S))$ distribution from CMS measurement; (c) The $\omega\Upsilon(1S)$ invariant mass distribution in $e^+e^- \to \gamma\omega\Upsilon(1S)$ from Belle measurement.

the $Y(4260)$ to exponentially falling non-resonant $\pi^+\pi^- J/\psi$ production, as shown in Fig. 2(a). Recently, the Belle Collaboration also updated the analysis of $e^+e^- \to \pi^+\pi^- J/\psi$ with a 967 fb^{-1} data sample. Not only the $Y(4260)$ state was observed clearly, but also the Y(4008) was confirmed [33], as shown in Fig. 2(b). The difference on the measured cross section from BaBar and Belle at around 4.01 GeV is large. A question on the existence of the $Y(4008)$ needs to be answered. Or are there more structures in this mass range ? At the moment, BESIII may use its accumulated large data sample at 4.01 GeV to check the cross section first. At BelleII, the $Y(4008)$ needs to be confirmed in the future.

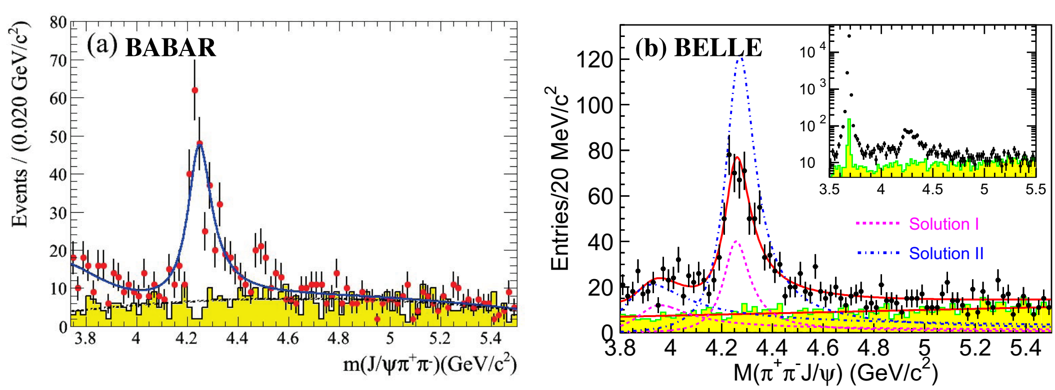

Figure 2. Invariant mass distributions of $\pi^+\pi^- J/\psi$ from BaBar and Belle measurements. Points with error bars are data, and the shaded histograms are the normalized J/ψ mass sidebands. The solid curves show the total best fits.

In an analysis of the $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ process, BaBar found a structure near 4.32 GeV/c^2 (called the $Y(4360)$) [34], while Belle observed two resonant structures at 4.36 and 4.66 GeV/c^2, denoted as the $Y(4360)$ and $Y(4660)$ [35]. Recently, BaBar updated their results on $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ analysis with its full data sample and confirmed the existence of the $Y(4660)$ state [36]. Figure 3(a) shows the invariant mass distribution of $\pi^+\pi^-\psi(2S)$ from the latest BaBar's measurement [36] together with that from previous Belle's measurement [35], where the $Y(4360)$ and $Y(4660)$ resonances are clear. Very recently, to characterize more precisely the properties of the $Y(4360)$ and $Y(4660)$, to better understand their nature, and to search for possible charged charmoniumlike states decaying into $\pi^{\pm}\psi(2S)$, Belle updated the $e^+e^- \to \pi^+\pi^-\psi(2S)$ process with the full Belle data 980fb^{-1} [37]. Figure 3(b) shows the invariant mass distribution of $\pi^+\pi^-\psi(2S)$ from the updated Belle's measurement and fit results with two coherent Breit-Wigner functions, one is for the $Y(4360)$ and the other is for the $Y(4660)$. The measured masses and widths are $M(Y(4360)) = (4374 \pm 6 \pm 3)$ MeV/c^2, $\Gamma(Y(4360)) = (103\pm9\pm5)$ MeV, $M(Y(4660)) = (4652\pm10\pm8)$ MeV/c^2, and $\Gamma(Y(4660)) = (68\pm11\pm1)$ MeV, respectively. Belle also noticed there are a number of events in the vicinity of the $Y(4260)$ mass, so an alternative fit with a coherent sum of $Y(4260)$, $Y(4360)$, and $Y(4660)$ amplitudes was performed. But the signal significance of the $Y(4260)$ is only 2.4σ. At BelleII, we need to redo this analysis to see if there is another new $Y(4260)$ decay mode.

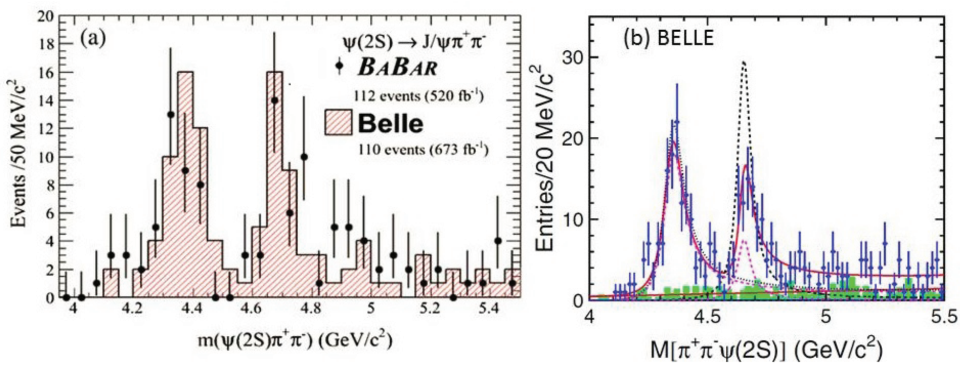

Figure 3. Invariant mass distributions of $\pi^+\pi^-\psi(2S)$ from BaBar and Belle measurements. Points with error bars are data. Two peaks are clear corresponding to the $Y(4360)$ and $Y(4660)$ resonances.

BESIII accumulated large data samples between 4.0 and 4.6 GeV for the study of the charmonium and charmoniumlike states. For the cross sections measurements to some processes, some results seem very interesting. For examples: (1) BESIII measured $e^+e^- \to \pi^+\pi^-h_c$ cross sections [38] at center-of-mass energies between 3.90 and 4.42 GeV. The measured cross sections of $\pi^+\pi^-h_c$ are of the same order of magnitude as those of the $e^+e^- \to \pi^+\pi^-J/\psi$, but with a different line shape. There is a broad structure at high energy with a possible local maximum at around 4.23 GeV. (2) Based on data samples collected at 9 center-of-mass energies from 4.21 to 4.42 GeV, BESIII searched for the production of $e^+e^- \to \omega\chi_{c0}$ [39], where χ_{c0} was reconstructed with $\pi^+\pi^-$ and K^+K^- decay modes. Figure 4(a) shows the Born cross sections of $e^+e^- \to \omega\chi_{c0}$, which were fitted with a $Y(4260)$ resonance or a phase space term. Assuming the $\omega\chi_{c0}$ signals come from a single resonance, the fitted mass and width of the resonance are $(4230 \pm 8 \pm 6)$ MeV/c^2 and $(38 \pm 12 \pm 2)$ MeV, respectively, and the statistical significance is more than 9σ. The position of this resonance is consistent with the $Y(4220)$ state observed in the cross section of $e^+e^- \to \pi^+\pi^-h_c$ [40]. It also indicates that the $Y(4260)$ signals observed in $e^+e^- \to \pi^+\pi^-J/\psi$ [27, 33] may have fine structures, and the lower mass structure at about 4230 MeV/c^2 has a sizable coupling to the $\omega\chi_{c0}$ channel as predicted in Ref. [41]. (3) BESIII searched for production of the ψ_2 state, called $X(3823)$, via the process $e^+e^- \to \pi^+\pi^-\psi_2$ [42], where the ψ_2 candidates were reconstructed in their $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ decay modes. The measured energy-dependent cross sections of $e^+e^- \to \pi^+\pi^-X(3823)$ are shown in Fig. 4(b), which were fitted with a $Y(4360)$ shape or a $\psi(4415)$ shape. Both fits can describe the data well due to the large statistical errors. For the above described processes, in the future at BelleII, they need to be rechecked to see if there are new vector charmoniumike states or new decay modes of the discovered Y states.

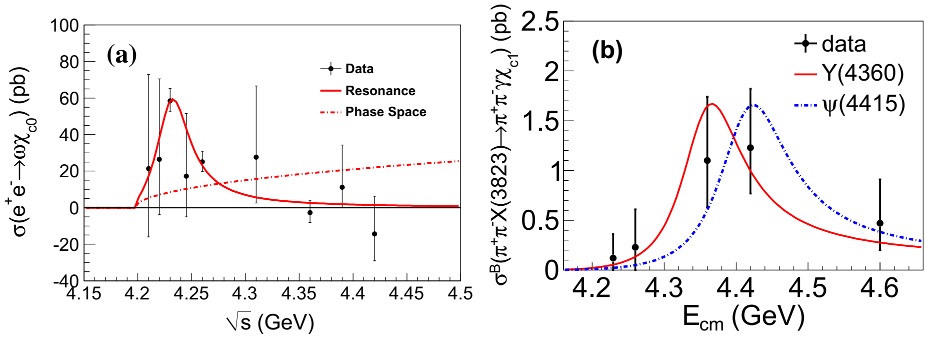

Figure 4. Fits to the distributions of (a) $\sigma(e^+e^- \to \omega\chi_{c0})$ with a resonance (solid curve), or a phase space term (dot-dashed curve) and (b) $\sigma(e^+e^- \to \pi^+\pi^- X(3823))$ with a $Y(4360)$ (solid curve), or a $\psi(4415)$ (dot-dashed curve) signal from BESIII measurements.

4 The Z states

The first observed Z state is the $Z(4430)^+$ discovered by Belle [43]. Based on the 657 million $B\bar{B}$ pairs collected at Belle, a distinct peak was observed in the $\psi(2S)\pi^\pm$ invariant mass distribution with the measured mass and width of $4433 \pm 4 \pm 2$ MeV/c^2 and 45^{+18+30}_{-13-13} MeV in $B \to K\psi(2S)\pi$ decays. At first, a simple Breit Wigner resonance shape was used to fit the $\psi(2S)\pi^\pm$ mass spectrum. The statistical significance is 6.5σ [43]. Very soon after that, however, BaBar did not observe any significant evidence for a $Z(4430)^-$ signal in the investigated $B^{-,0} \to J/\psi\pi^- K^{0,+}$ and $B^{-,0} \to \psi(2S)\pi^- K^{0,+}$ decays using a 413 fb^{-1} data sample [44]. They also found that each $J/\psi\pi$ or $\psi(2S)\pi$ mass distribution is well-described by the reflection of the measured $K\pi$ mass and angular distribution structures. To confirm the $Z(4430)^+$ discovery, Belle performed a Dalitz plot analysis of $B \to K\psi(2S)\pi$ decays based on the same data sample and confirmed the $Z(4430)^+$ signal with a mass $M = (4443^{+15-12}_{+19-13})$ MeV/c^2, width $\Gamma = (107^{+86-43)}_{+74-56})$ MeV, and significance of 6.4σ [45]. Later, a full amplitude analysis of $B^0 \to K^+\psi(2S)\pi^-$ decays was performed to constrain the spin and parity of the $Z(4430)^-$ based on a 711 fb^{-1} data sample. The $J^P = 1^+$ hypothesis is favored [46]. A four-dimensional fit of the decay amplitude was performed to the $B^0 \to K^+\psi(2S)\pi^-$ decays to search for resonant structures using pp collision data corresponding to 3fb^{-1} by LHCb [47]. LHCb found that the data cannot be described with $K^+\pi^-$ resonances alone and a highly significant $Z(4430)^- \to \psi(2S)\pi^-$ component is required, which is different from the BaBar's conclusion [44]. The spin-parity is determined unambiguously to be 1^+. Finally the first observed charged Z state, $Z(4430)^+$, was well established. For $Z(4430)^+$, besides the decay mode of $\psi(2S)\pi^+$, Belle also found another evidence for $Z(4430)^+ \to J/\psi\pi^+$ in $\bar{B}^0 \to K^- J/\psi\pi^+$ decays with an amplitude analysis based on a 711 fb^{-1} data sample [48]. In the future, at BelleII, the following task is to find the neutral $Z(4430)^0 \to \psi(2S)\pi^0$ and confirm the decay mode of $Z(4430)^+ \to J/\psi\pi^+$.

Motivated by the discovery of the $Z(4430)^+$, Belle continued to check the $\chi_{c1}\pi^+$ invariant mass distribution in exclusive $\bar{B}^0 \to K^-\chi_{c1}\pi^+$ decays based on $657 \times 10^6 B\bar{B}$ events [49]. From a Dalitz plot analysis, two resonance-like structures, called $Z_1(4050)^+$ and $Z_2(4250)^+$, were found with masses and widths of: $M_1 = (4051 \pm 14^{+20}_{-41})$ MeV/c^2, $\Gamma_1 = (82^{+21+47}_{-17-22})$ MeV, $M_2 = (4248^{+44+180}_{-29-35})$ MeV/c^2, and $\Gamma_2 = (177^{+54+316}_{-39-61})$ MeV. The significance of each of the $\chi_{c1}\pi^+$ structures exceeds 5σ [49]. However, BaBar did not find any evidence for the $Z_1(4050)^+$ and $Z_2(4250)^+$ in the same channel based on a 429 fb^{-1} data sample [50]. In the future, at BelleII, the urgent task is to confirm the existence of these two charged Z states in $\chi_{c1}\pi^+$ system.

In 2013, Belle and BESIII investigated the same $Y(4260) \to \pi^+\pi^- J/\psi$ decays at the same time to search for the intermediate resonance [33, 51]. Figure 5 shows the distributions of $M_{\max}(\pi^\pm J/\psi)$, the maximum of $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$, from Belle and BESIII measurements. Unbinned maximum likelihood fits are applied to the distributions of $M_{\max}(\pi^\pm J/\psi)$, where the signal shape is parameterized as an S-wave Breit-Wigner function convolved with a Gaussian with a mass resolution fixed at the MC simulated value. The measured masses are (3899.0±3.6±4.9) MeV/c^2 and (3894.5±6.6±4.5) MeV/c^2 and the measured widths are (46 ± 10 ± 20) MeV and (63 ± 24 ± 26) MeV/c^2 from BESIII and Belle, respectively. They are consistent with each other within the errors. The signal significance is greater than 5σ in both of the measurements. This state is close to the $D\bar{D}^*$ mass threshold. Recently, the neutral $Z_c(3900)$ was found in $e^+e^- \to \pi^0\pi^0 J/\psi$ [52], which established the isospin of $Z_c(3900)$ to be 1.

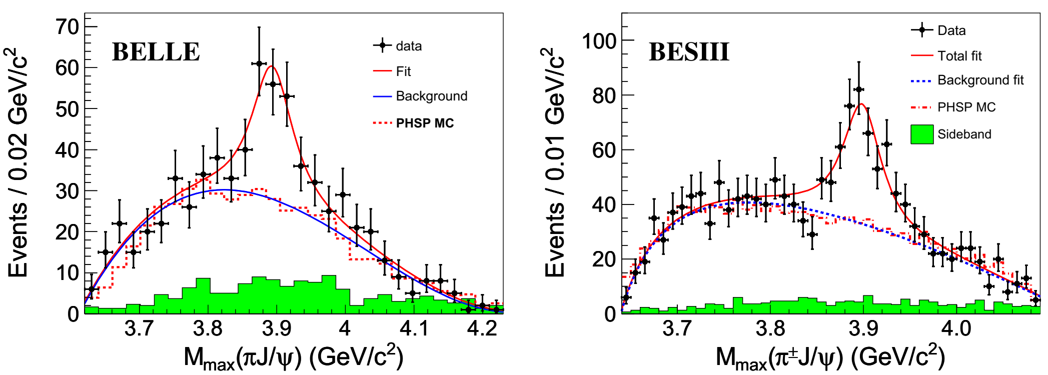

Figure 5. Unbinned maximum likelihood fits to the distributions of the $M_{\max}(\pi J/\psi)$ from Belle and BESIII experimental data. The solid curves are the best fits, the dashed histograms represent the results of phase space distribution and the shaded histograms are J/ψ sidebands.

The $Z_c(3900)$ mass is ~ 20 MeV/c^2 above the $D\bar{D}^*$ mass threshold, which is suggestive of a virtual $D\bar{D}^*$ molecule-like structure. So it is very nature to check the $(D\bar{D}^*)$ invariant mass distribution to see if there is a threshold enhancement. BESIII reported a study of the process $e^+e^- \to \pi^+(D\bar{D}^*)^-$ at Ecm=4.26 GeV using a 525pb^{-1} data sample. As expected, a distinct charged structure is observed in the $(D\bar{D}^*)$ invariant mass distribution, called the $Z_c(3885)$. The mass and width of the $Z_c(3885)$ are 2σ and 1σ, respectively, below those of the $Z_c(3900)$. The angular distribution of the $\pi Z_c(3885)$ system favors a $J^P = 1^+$ quantum number assignment [53]. PDG2014 has taken the $Z_c(3900)$ and $Z_c(3885)$ as the same state [54].

Replacing the J/ψ with the h_c, BESIII studied $e^+e^- \to \pi^+\pi^- h_c$ at 13 energies, and found a distinct structure at 4.02 GeV/c^2, referred to as $Z_c(4020)$, in the $\pi^\pm h_c$ mass spectrum. A fit to the $\pi^\pm h_c$ invariant mass spectrum results in a mass of (4022.9±0.8±2.7) MeV/c^2 and a width of (7.9±2.7±2.6) MeV [38]. Similarly, BESIII also studied the process $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ at a center-of-mass energy of 4.26 GeV using a 827pb^{-1} data sample. A structure near the $(D^*\bar{D}^*)^\pm$ threshold, denote as the $Z_c(4025)^\pm$, was observed [55]. The $Z_c(4025)$ and $Z_c(4020)$ should be from the same state. Without any surprise, the neutral $Z_c(4020)$ was found in $e^+e^- \to \pi^0\pi^0 h_c$ and the measured Born cross sections are about half of those of $e^+e^- \to \pi^+\pi^- h_c$ [56].

Table 1. Summary of the charged Z states discovered recently. The masses M (MeV/c^2) and widths Γ (MeV) are weighted averages of measurements with uncertainties added in quadrature. In the J^{PC} column, question marks indicate the educated guess or no information.

State	M	Γ	J^{PC}	Process (decay mode)	Experiment
$Z(4430)^+$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi(2S)\,\pi^+)$	Belle [43, 45, 46], LHCb [47]
				$B \to K + (J/\psi\,\pi^+)$	Belle [48]
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [49]
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [49]
$Z_c(3900)^+$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [51], Belle [33]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [53]
$Z_c(4020)^+$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [38]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [55]
$Z(4200)^+$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [48]
$Z_c(4050)^+$	4054 ± 4	45 ± 13	1^{+-}	$Y(4360) \to \pi^- + (\psi(2S)\pi^+)$	Belle [37]

To find more production modes for the $Z_c(3900)$, Belle did an amplitude analysis of $\bar{B}^0 \to K^- J/\psi\pi^+$ decays [48]. Unfortunately, no significant signal of the $Z_c(3900)$ was found. But a new charged charmoniumlike state $Z_c(4200)^+$ decaying to $J/\psi\pi^+$ was observed with a significance of 6.2σ. The mass and width of the $Z_c(4200)^+$ are 4196^{+31+17}_{-29-13} MeV/c^2 and $370^{+70+70}_{-70-132}$ MeV, respectively; the preferred assignment of the quantum numbers is $J^P = 1^+$ [48]. At BelleII, this state needs to be cross checked and confirmed.

Very recently, Belle updated the $e^+e^- \to \pi^+\pi^-\psi(2S)$ process via initial state radiation [37]. Evidence for a charged charmoniumlike structure at 4.05 GeV/c^2, denoted as the $Z_c(4050)$, was observed in the $\psi(2S)\pi^\pm$ intermediate state in the $Y(4360)$ decays. The measured mass and width are $(4054 \pm 3 \pm 1)$ MeV/c^2 and $(45 \pm 11 \pm 6)$ MeV [37]. More data from the BESIII and the BelleII experiments will enable a search with improved sensitivity.

Belle also tried to search for a strange partner of the $Z_c(3900)^\pm$, called the Z_{cs}, in $J/\psi K^\pm$ system in the process $e^+e^- \to K^+K^-J/\psi$ [57]. No obvious structures were observed in the $J/\psi K^\pm$ system. At BelleII, with much larger statistic, such searches should be continued.

Up to now, we have found a series of charged Z states. Table 1 gives the summary of the charged Z states discovered recently. As these Z state have strong couplings to charmonium and are charged, they cannot be conventional $c\bar{c}$ states. There have been a number of different interpretations, including tetraquark states, hadronic molecules, hadron-charmonium states and so on. These observations indicate one kind of the exotic states has been observed. The nature of these states have been discussed in many proposals, but no solid conclusion can be drawn. Searches for new decay modes and measuring their quantum numbers may provide further information that is useful for understanding the nature of them. There are also many open questions. For examples, may we observe more excited Z_c states ? Do the strange partners of the Z_c states exist ?

5 Summary

There have been great progress in the study of the XYZ states, especially Belle and BESIII are still producing more results. With more discoveries, we found we have more questions to answer. For examples:

- The $X(3872)$ and $X(3823)$ signals were observed by BESIII via $e^+e^- \to \gamma X(3872)$ and $\pi^+\pi^- X(3823)$ processes. Are the signals from resonances decays or continuum productions ? May other similar X states could be observed in similar processes ?
- Although the $Y(4260)$ has been well established, there is a possible local maximum at around 4.23 GeV in $e^+e^- \to \pi^+\pi^- J/\psi$ cross sections. Is the Y(4260) a single resonance? Is the $Y(4008)$ a real structure?
- In the updated $e^+e^- \to \pi^+\pi^-\psi(2S)$ analysis by Belle, there are a few events accumulating at around 4.26 GeV. With the $Y(4260)$ signal included, the signal significance is less than 3σ. Does the $Y(4260)$ decay to $\pi^+\pi^-\psi(2S)$? Are there any other decay modes ?
- There is a broad structure at high energy in the $e^+e^- \to \pi^+\pi^- h_c$ cross sections with a possible local maximum at around 4.23 GeV. How many structures are there ?
- Many charged Z_c states have been observed. Meanwhile, in the invariant mass distributions of the charm meson pairs, like $(D\bar{D}^*)^\pm$, $(D^*\bar{D}^*)^\pm$, some similar Z_c states were observed. Are they the same states ? What are the correlations between them ? Are there any Z_{cs} states ? Can the Z_c states decay into light hadrons ?
- BESIII recently measured cross sections for some processes including $\omega\chi_{cJ}$, $\pi^+\pi^- X(3823)$, $\gamma X(3872)$, $\eta J/\psi$, and so on. BESIII is also doing more channels, like $\eta' J/\psi$, $\eta\psi(2S)$, ηh_c, $\phi\chi_{cJ}$, etc. May we observe any new resonances ? What are the real line shapes for these channels ? Can any higher missing charmonium states, like $\psi(4S)$, η_{c2}, be observed in these decays ?

In the future at BelleII with a 50ab^{-1} data sample, most of the above questions can be answered. The physics behind them should be clear at that time. For some channels, we can even do partial wave analysis or amplitude analysis.

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