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XVth Quark Confinement and the Hadron Spectrum

Exotic states in the quarkonium sector

— status and perspectives

Chang-Zheng Yuan[1,2,*]

[1]Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing, China
[2]University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing, China

Abstract. The discovery of hadronic states beyond the conventional two-quark meson and three-quark baryon picture in the last two decades is one of the most amazing accomplishments in fundamental physics research. Many experiments contributed to this field despite of the original goals of the design. We review the experimental progress on the study of the quarkoniumlike states — states with at least one heavy quark-antiquark pair and possible light quarks, also known as XYZ states. We give a general review and then focus on the new experimental results on the $X(3872)$ and its bottom-quark partner X_b, the $X(3960)$, the $Y(4260)$, $Y(4500)$, $Y(4660)$, and $Y(10750)$, and the charged charmonium-like Z_c and Z_{cs} states. The observations suggest that we did observe hadronic molecules and we also observed hadronic states with some other quark configurations. Possible further studies at the existing and future facilities are briefly discussed.

1 Introduction

Hadron spectroscopy is a field of frequent discoveries and surprises, and the theoretical difficulties in understanding the strong interaction in the color-confinement regime make the field even more fascinating. The tremendous data collected by the BaBar, Belle, BESIII, LHCb, and other experiments and improved theoretical tools developed to analyze the experimental data result in rapid progress of the field [1–4].

In the conventional quark model, mesons are composed of one quark and one anti-quark, while baryons are composed of three quarks. However, many quarkoniumlike states were discovered at two B-factories BaBar and Belle [5] in the first decade of the 21st century. Whereas some of these are good candidates of quarkonium states, such as the $\eta_c(2S)$, $\psi_2(3823)$, $h_b(2P)$, many other states have exotic properties, which may indicate that exotic states, such as multi-quark state, hadronic molecule, or hybrid, have been observed [1–4].

BaBar and Belle experiments finished their data taking in 2008 and 2010, respectively, and the data are still used for various physics analyses. BESIII [6] and LHCb [7] experiments started data taking and contributed to the study of the XYZ particles since 2008. Most of the discoveries of the such states were made at these four experiments.

Figure 1 shows the history of the discovery of the heavy exotic states, started from the observation of the $X(3872)$ in 2003 [8]. In this brief review, we show some recent experimental results on these particles, and we focus on those states with exotic properties, including the $X(3872)$, $Y(4260)$, $Z_c(3900)$, and their siblings.

*e-mail: yuancz@ihep.ac.cn

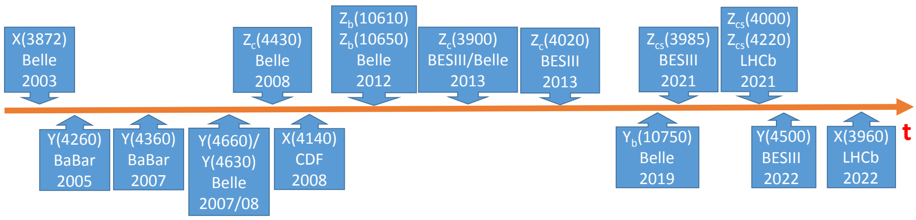

Figure 1. Discovery of heavy exotic states from experiments.

2 The X states

The $X(3872)$ was observed in 2003 by the Belle experiment [8], and it was confirmed later by CDF [9] and $D0$ [10] experiments in $p\bar{p}$ collision. After almost 20 years' study, we know this state much better than any of the other similar states. The bottomonium equivalent of the $X(3872)$, X_b, was searched for but not observed, and there are other X states observed recently, such as the $X(3960)$ in its decay into $D_s^+ D_s^-$.

2.1 Resonance parameters of the $X(3872)$

The mass of the $X(3872)$ has been measured as 3871.65 ± 0.06 MeV [11], which is lower than the mass threshold of $\bar{D}^0 D^{*0}$, 3871.69 ± 0.11 MeV, by 0.04 ± 0.12 MeV, to be compared with the binding energy of the deuteron of 2.2 MeV. If the $X(3872)$ is a molecule of $\bar{D}^0 D^{*0}$, its size will be larger than 5 fm, much larger than the size of a typical hadron.

The width measurements are less precise and model dependent since the $X(3872)$ is very narrow and the mass resolution of the experiments is usually much larger than the intrinsic width. Fitting the $\pi^+\pi^- J/\psi$ invariant mass distribution with a Breit-Wigner function, LHCb reported a width of about 1 MeV (the mass resolution is 2.4–3.0 MeV); and the fit with a Flatté function with constraints from other measurements yields a FWHM of 0.22 MeV which depends strongly on the $X(3872) \to \bar{D}^0 D^{*0}$ coupling [12, 13]. Although the statistics are low at BESIII experiments, the high efficiencies of reconstructing all the $X(3872)$ decays modes and the very good mass resolution in the $\bar{D}^0 D^{*0}$ mode (< 1 MeV) make it possible to measure the line shape of the $X(3872)$ state [14].

2.2 Production of the $X(3872)$

Production of the $X(3872)$ has been reported in many different kinds of processes, in B and B_s meson decays, in Λ_b baryon decays, in $p\bar{p}$ and pp collisions, and in e^+e^- annihilation [15]. Recently, evidence for $X(3872)$ production in $PbPb$ and two-photon collisions, and observation of $e^+e^- \to \omega X(3872)$ were reported, whereas no hint of direct production of the $X(3872)$ in e^+e^- annihilation was observed.

CMS experiment reported a 4.2σ signal of the $X(3872)$ in $PbPb$ collision at 5.02 TeV [16], and it is interesting to note that its production rate relative to the $\psi(2S)$ is much larger than in the pp collision at 7 and 8 TeV, although the uncertainty is large. If this is confirmed, this is a supplemental information to understand the nature of this state.

Belle experiment searched for the $X(3872)$ in $\gamma\gamma^*$ fusion [17] and observed three $X(3872)$ candidates, where the expected background is 0.11 ± 0.10 events, with a significance of 3.2σ.

Since we know that the $X(3872)$ has $J^{PC} = 1^{++}$, it cannot be produced in two real-photon collision, the production requires at least one of the photons is virtual.

BESIII experiment reported observation of $e^+e^- \to \omega X(3872)$ with 4.7 fb^{-1} data at center-of-mass (CM) energies from 4.66 to 4.95 GeV, 24 $X(3872)$ signal events are observed with a significance of 7.5σ, including both the statistical and systematic uncertainties [18]. The $X(3872)$ signal and the cross section as a function of CM energy are shown in Fig. 2. Although not very conclusive, it seems that the $\omega X(3872)$ signal comes from a resonance decay with a mass of about 4.75 GeV and a peak cross section of around 14 pb.

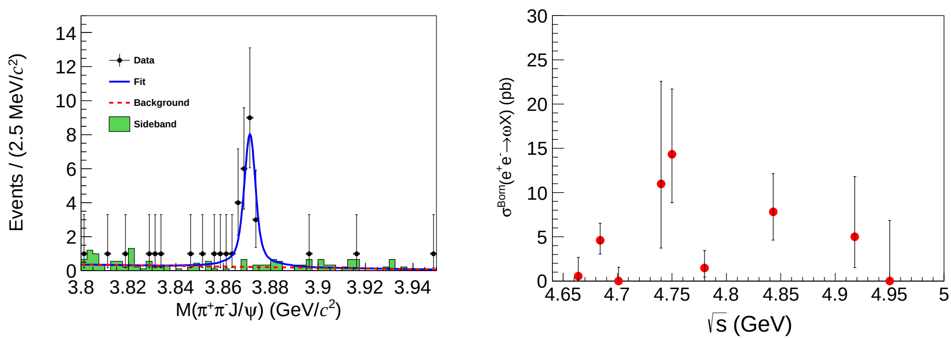

Figure 2. The $X(3872)$ signal recoiling against ω in e^+e^- annihilation (left panel) and cross sections of $e^+e^- \to \omega X(3872)$ (right panel) from BESIII experiment [18].

BESIII experiment searched for $e^+e^- \to X(3872)$ by taking data at a CM energy corresponds to exactly the $X(3872)$ mass and at a few energies in the vicinity of the $X(3872)$ [19] and measure the cross sections for the process $e^+e^- \to \pi^+\pi^- J/\psi$ (see Fig. 3). No enhancement of the cross section is observed at the $X(3872)$ peak and an upper limit is determined to be $\Gamma_{ee} \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 7.5 \times 10^{-3}$ eV at the 90% confidence level, and with the $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ from PDG [11] as input, an upper limit on the electronic width Γ_{ee} of $X(3872)$ is obtained to be < 0.32 eV at the 90% confidence level. Since the process $e^+e^- \to \chi_{c1}$ has been observed (see right panel of Fig. 3) by the BESIII experiment [20], it is only a matter of sensitivity of the experiment to observe $e^+e^- \to X(3872)$ since both χ_{c1} and $X(3872)$ have the same quantum numbers ($J^{PC} = 1^{--}$) and the expected electronic width of the $X(3872)$ is at the same level as the χ_{c1}. Although not significant, the lower cross section at the $X(3872)$ peak than in the nearby energies may indicate interference between $e^+e^- \to X(3872)$ and non-resonant $e^+e^- \to \rho J/\psi$ [21, 22] amplitudes.

2.3 Decays of the $X(3872)$

The total production rate of the $X(3872)$ in B decays was measured by reconstructing a B^- and a charged kaon from B^+ decays and checking the recoiling mass of the B^-K^+ system. BaBar observed a small peak, corresponding to a 3.0σ significance at the $X(3872)$ signal region, and measured the branching fraction of $B^+ \to K^+X(3872)$ as $(2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$ [23]. Belle did the same analysis, but the signal is less significant and the resulting branching fraction is $(1.2 \pm 1.1 \pm 0.1) \times 10^{-4}$ and the signal significance is 1.1σ [24]. Although the signals are not very significant, we know this process must exist because this state has been observed in its many exclusive decays. One can use these measurements combined with other information, such as the product branching fractions and the ratio of the branching fractions, to determine

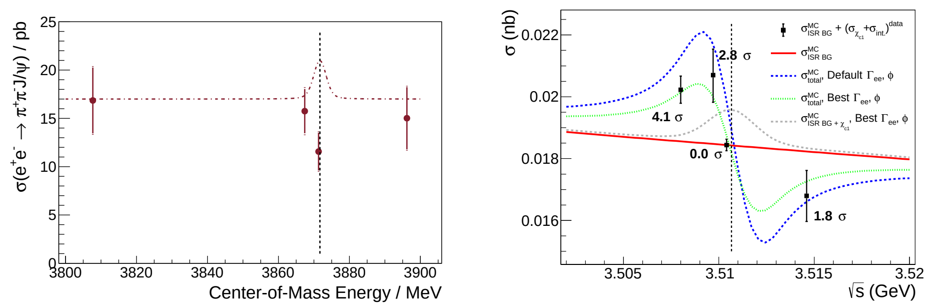

Figure 3. Cross sections of $e^+e^- \to \pi^+\pi^- J/\psi$ in the vicinity of the $X(3872)$ (left panel, [19]) and those of $e^+e^- \to \gamma\chi_{c1}$ in the vicinity of the χ_{c1} (right panel, [20]).

the decay branching fractions of the $X(3872)$, including its decays to open charm final states, hadronic transitions, and radiative transitions. There could be a small branching fraction to light hadrons, but no experiment has observed any of them.

The authors of Ref. [25] did a global fit to the currently available experimental measurements of the product branching fractions and the ratios of the branching fractions. It is found that the branching fraction of open charm decay is around 50% and that of each hadronic transition is at a few per cent level, there is still around one-third of the $X(3872)$ decays unknown. A few searches for the new decay modes of the $X(3872)$ were reported recently, and more will be searched for in the future experiments like BESIII and Belle II.

BESIII searched for $X(3872) \to \pi^0\chi_{c0}$ and $\pi^+\pi^-\chi_{c0}$ with 9.9 fb^{-1} data at CM energies between 4.15 and 4.30 GeV [26]. No signals are observed and the upper limits at the 90% C.L. are determined as $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^-J/\psi)} < 3.6$, $\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^-J/\psi)} < 0.56$, and $\frac{\mathcal{B}(X(3872)\to\pi^0\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^-J/\psi)} < 1.7$.

Belle reported a search for $X(3872) \to \pi^+\pi^-\pi^0$ in $B^\pm \to K^\pm X(3872)$ and $B^0 \to K^0_S X(3872)$ decays [27]. No signal is observed and the 90% credible upper limits are set for two different models of the decay processes: if the decay products are distributed uniformly in phase space, $\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0) < 1.3\%$; if $M(\pi^+\pi^-)$ is concentrated near the mass of the $D\bar{D}$ pair in the process $X(3872) \to D^0\bar{D}^{*0} + c.c. \to D\bar{D}\pi^0 \to \pi^+\pi^-\pi^0$, $\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0) < 1.2 \times 10^{-3}$.

LHCb reported a detailed analysis of the $m_{\pi^+\pi^-}$ distribution of $X(3872) \to \pi^+\pi^- J/\psi$, contributions from $\omega \to \pi^+\pi^-$ and its interference with $\rho^0 \to \pi^+\pi^-$ are observed with high significance and the isospin-violating effect in $X(3872)$ decays is measured with improved precision [28].

One still very confusing decay mode is $X(3872) \to \gamma\psi(2S)$. There have been four different measurements. The BaBar experiment claimed 3.5σ evidence of this mode and a production rate relative to $X(3872) \to \gamma J/\psi$ is 3.4 ± 1.4 [29], but Belle failed to find significant signal and the ratio was measured to be less than 2.1 at the 90% C.L. [30]. Three years later, LHCb did the same analysis and the found a 4.4σ signal with a ratio of 2.46 ± 0.81 [31], but a recent BESIII measurement found no signal and a much stringent upper limit of the ratio is determined to be 0.59 at the 90% C.L. [14]. We have four experiments here, two claimed evidence and the other two observed nothing. So it is still not clear whether this channel, $X(3872) \to \gamma\psi(2S)$, exists, or if it exists, how small the branching fraction is.

2.4 X_b, bottomonium equivalent of the $X(3872)$

Belle II experiment collected data at CM energies 10.701, 10.745, and 10.805 GeV and combined with the Belle data at 10.653 GeV to search for the bottomonium equivalent of the $X(3872)$ state, X_b, decaying into $\omega\Upsilon(1S)$ [32]. No significant signal is observed for X_b masses between 10.45 and 10.65 GeV (Fig. 4).

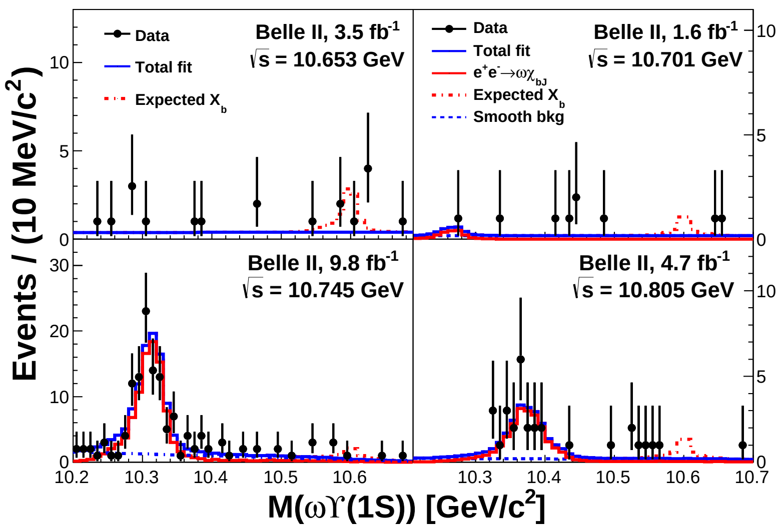

Figure 4. Invariant mass distributions of $\omega\Upsilon(1S)$ from Belle and Belle II data at $\sqrt{s} = 10.653$, 10.701, 10.745, and 10.805 GeV [32]. The red dash-dotted histograms are from simulated events $e^+e^- \to \gamma X_b(\to \omega\Upsilon(1S))$ with the X_b mass fixed at 10.6 GeV and yields fixed at the upper limit values.

2.5 Observation of the $X(3960)$

LHCb did an amplitude analysis of the $B^+ \to D_s^+ D_s^- K^+$ decay using proton-proton collision data collected at CM energies of 7, 8 and 13 TeV [33]. About 360 signal events are identified, and a near-threshold peaking structure, $X(3960)$, is observed in the $D_s^+ D_s^-$ invariant-mass spectrum with significance greater than 12σ. The mass, width and the quantum numbers of the structure are measured to be $3956 \pm 5 \pm 10$ MeV, $43 \pm 13 \pm 8$ MeV, and $J^{PC} = 0^{++}$, respectively. Further investigation is needed to understand the nature of this state.

Such a state could be produced in the radiative transitions of the Y and excited ψ states such as the $\psi(4040)$, $\psi(4160)$, $Y(4260)$, $\psi(4415)$. It can be searched for with the large data samples at BESIII experiment.

3 The Y states

3.1 The charmoniumlike Y states

The Y states were discovered in the initial state radiation (ISR) in the B-factory experiments, and they have $J^{PC} = 1^{--}$. So these state can also be produced directly in e^+e^- annihilation

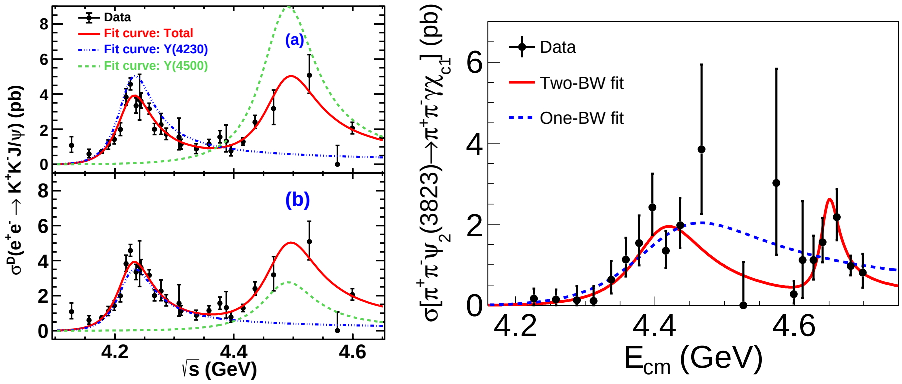

Figure 5. Fits to $\sigma(e^+e^- \to K^+K^-J/\psi)$ (Left panel, [39]) and $\sigma[e^+e^- \to \pi^+\pi^-\psi_2(3823)] \times \mathcal{B}[\psi_2(3823) \to \gamma\chi_{c1}]$ (right panel, [43]).

experiment like BESIII. In this case, much larger statistics are achieved and these states, the $Y(4260)$, $Y(4360)$, $Y(4660)$, and so on, are measured with improved precision.

The $Y(4260)$ was observed in 2005 by BaBar experiment [34] and the most precise measurement is from the BESIII experiment [35] (an update of the analysis reported in Ref. [36]). By doing a high luminosity energy scan in the vicinity of the $Y(4260)$, BESIII found the peak of the $Y(4260)$ is much lower (so now named the $Y(4230)$) than that from previous measurements and the width is narrow, and there is a high mass shoulder with a mass of 4.3 GeV if fitted with a BW function. Since then, more new decay modes of the $Y(4230)$ were observed including $\pi^+\pi^-h_c$, $\omega\chi_{c0}$, $\pi\bar{D}D^* + c.c.$, K^+K^-J/ψ, and so on, and no significant $Y(4230)$ was observed in $e^+e^- \to \pi^+\pi^-D^+D^-$ process [37] from a recent BESIII measurement.

A global fit [38] to four modes ($\pi^+\pi^-J/\psi$, $\pi^+\pi^-h_c$, $\omega\chi_{c0}$, and $\pi\bar{D}D^* + c.c.$) was performed, and the mass of the $Y(4230)$ as 4230 ± 6 MeV and the width of 56 ± 8 MeV are determined. It is interesting to point out that the mass of this resonance is quite close to the threshold of $D_s^{*+}D_s^{*-}$ which is 4224 MeV. Since there are more $Y(4230)$ decay modes observed ($\pi^+\pi^-\psi(2S)$, $\eta_c\pi^+\pi^-\pi^0$, K^+K^-J/ψ, and so on), this combined fit can be updated with more channels.

Recently, the cross sections of $e^+e^- \to K^+K^-J/\psi$ at CM energies from 4.1 to 4.6 GeV are measured at the BESIII [39]. Two resonant structures are observed in the line shape of the cross sections (see Fig. 5). The mass and width of the first structure are measured to be $(4225.3 \pm 2.3 \pm 21.5)$ MeV and $(72.9 \pm 6.1 \pm 30.8)$ MeV, respectively. They are consistent with those of the established $Y(4230)$. The second structure is observed for the first time with a statistical significance greater than 8σ, denoted as the $Y(4500)$. Its mass and width are determined to be $(4484.7 \pm 13.3 \pm 24.1)$ MeV and $(111.1 \pm 30.1 \pm 15.2)$ MeV, respectively. The product of the electronic partial width with the decay branching fraction $\Gamma(Y(4230) \to e^+e^-)\mathcal{B}(Y(4230) \to K^+K^-J/\psi)$ is found to be $1.35 \pm 0.14 \pm 0.07$ eV or $0.41 \pm 0.08 \pm 0.13$ eV. This state is consistent with a vector charmonium state in the 5S-4D mixing scheme [40], a heavy-antiheavy hadronic molecule [41], or a $(cs\bar{c}\bar{s})$ tetraquark state [42].

For the state at 4.66 GeV, it was observed in $e^+e^- \to \pi^+\pi^-\psi(2S)$ by Belle [44], and confirmed by BaBar [45]. The peak position is at around 4.66 GeV, thus it is called the $Y(4660)$. There is another state observed in $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ by the Belle experiment [46], but the peak is at around 4.63 GeV, although the error is large. It is not clear whether these two states are the same or whether there are two states in this energy region.

BESIII data on $e^+e^- \to \pi^+\pi^-\psi(2S)$ mode from 4.0 to 4.7 GeV confirmed the Belle and BaBar observations with much improved precision [47], BESIII has data now covering from threshold to 4.95 GeV, comparable precision as at 4.6 GeV is expected at high energies, so we expect better measurement of the $Y(4660)$ state from BESIII soon.

BESIII measured the product of the $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ cross section and the branching fraction $\mathcal{B}[\psi_2(3823) \to \gamma\chi_{c1}]$ at CM energies from 4.23 to 4.70 GeV [43]. For the first time, resonance structure is observed in the cross section line shape of $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ with significances exceeding 5σ (see Fig. 5). A fit to data with two coherent Breit-Wigner resonances modeling the $\sqrt{s}$-dependent cross section yields $M(R_1) = 4406.9 \pm 17.2 \pm 4.5$ MeV, $\Gamma(R_1) = 128.1 \pm 37.2 \pm 2.3$ MeV, and $M(R_2) = 4647.9 \pm 8.6 \pm 0.8$ MeV, $\Gamma(R_2) = 33.1 \pm 18.6 \pm 4.1$ MeV. Though weakly disfavored by the data, a single resonance with $M(R) = 4417.5 \pm 26.2 \pm 3.5$ MeV, $\Gamma(R) = 245 \pm 48 \pm 13$ MeV is also possible to interpret data. Within current uncertainties, the parameters of structures in the two-resonance fit are similar to the $Y(4360)$ and $Y(4660)$ states reported in $\pi^+\pi^-\psi(2S)$ [44, 45]. Assuming the observed structures correspond to these resonances, this will be the second decay channel of the $Y(4660)$ state after more than 15 years of its discovery.

Belle reported measurements of two open-charm final states. There is a very beautiful peak observed at around 4.63 GeV in $D_s^+D_{s1}(2536)^- + c.c.$ mode and the signal significance is 5.9σ [48]. The signal in $D_s^+D_{s2}(2573)^- + c.c.$ mode is not so significant, is only 3.4σ [49].

If we put all these information together, we can find that the peak position is about 4.65 GeV in $\pi^+\pi^-\psi(2S)$ and $\pi^+\pi^-\psi_2(3823)$ modes, and that in open charm baryon and meson pair final states is below 4.65 GeV, There are differences from different final states. We need more measurements to really understand the structures in this mass region.

3.2 The bottomoniumlike $Y(10750)$

A Belle study of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1,\ 2,\ 3$) revealed the existence of a new vector bottomoniumlike state, the $Y(10750)$, with a mass of $(10752.7 \pm 5.9^{+0.7}_{-1.1})$ MeV and width $(35.5^{+17.6+3.9}_{-11.3-3.3})$ MeV [50]. However, this state is at exactly the position of a dip in the total cross section of $e^+e^- \to b\bar{b}$ [51]. This indicates that the dip is very likely produced by the interference between a resonance and a smooth background amplitudes.

To understand the $Y(10750)$ better, Belle II experiment accumulated data at CM energies 10.701, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 fb^{-1} of integrated luminosity, respectively. Belle II reported the first observation [32] of $e^+e^- \to \omega\chi_{bJ}(1P)$ ($J = 1,\ 2$) signals and by combining the Belle II data with Belle results at $\sqrt{s} = 10.867$ GeV, Belle II found that the energy dependencies of the cross sections for $e^+e^- \to \omega\chi_{b1,b2}(1P)$ are consistent with the shape of the $\Upsilon(10750)$ state (shown in Fig. 6). By fitting the energy dependence of the cross sections for $e^+e^- \to \omega\chi_{b1}$ and $\omega\chi_{b2}$, one obtains $\Gamma_{ee}\mathcal{B}(\Upsilon(10750) \to \omega\chi_{b1}$ and $\omega\chi_{b2})$ in the range 0.20–2.9 and 0.05–2.0 eV, respectively.

4 Charged quarkonium states

These include the Z_c, Z_b, and also the Z_{cs} states. Since these states decay into final states with one pair of heavy quarks and charged, there must be at least four quarks in their configurations.

The $Z_c(3900)$ discovered by BESIII [52] and Belle [53] is quite close to the $\bar{D}D^*$ threshold, and the $Z_c(4020)$ discovered by BESIII is quite close to the $\bar{D}^*D^*$ threshold [54], while

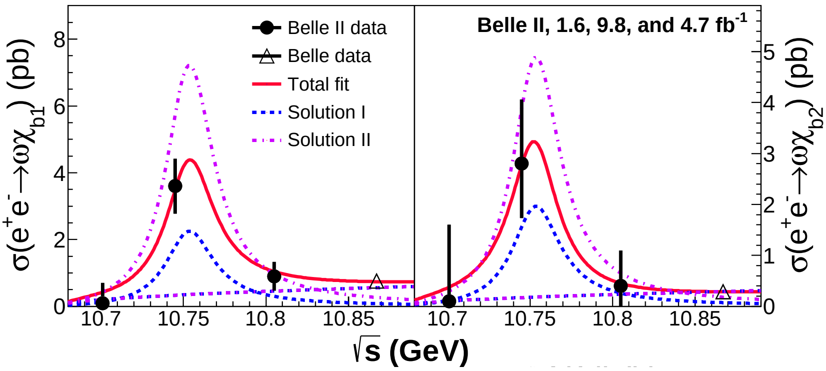

Figure 6. Energy dependence of the cross sections for $e^+e^- \to \omega\chi_{b1}$ (left panel) and $e^+e^- \to \omega\chi_{b2}$ (right panel) [32]. Curves show the fit results and various components of the fit function.

the $Z_c(4430)$ discovered by the Belle [55] is not quite close to any of the open charm threshold. In the bottom sector, The $Z_b(10610)$ and $Z_b(10650)$ discovered by Belle [56] are close to the $\bar{B}B^*$ and $\bar{B}^*B^*$ thresholds, respectively.

These states have been observed for some time. Recent studies try to search for states with one of the four quarks replaced by a different quark, for example, the Z_{cs} states with quark content $c\bar{c}u\bar{s}$ or $c\bar{c}d\bar{s}$. There are three different measurements, one from Belle in $e^+e^- \to K^+K^-J/\psi$ [57], another from BESIII in $e^+e^- \to K(DD_s^* + D^*D_s)$ [58, 59], and the third from LHCb in $B^+ \to J/\psi K^+\phi$ [60].

No significant signal was observed in Belle data of ISR production of $e^+e^- \to K^+K^-J/\psi$ [57]. BESIII announced observation of a near-threshold structure $Z_{cs}(3985)$ in the K^+ recoil-mass spectrum in $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$ [58] with a mass of 3983 MeV and a width of about 10 MeV and evidence for its neutral partner in the K_S^0 recoil-mass spectrum in $e^+e^- \to K_S^0(D_s^-D^{*+} + D_s^{*-}D^+)$ [59] (see Fig. 7). LHCb reported two resonances decaying into $K^\pm J/\psi$, the $Z_{cs}(4000)$ with a mass of 4003 MeV and a width of about 131 MeV, and the $Z_{cs}(4220)$ with a mass of 4216 MeV and a width of about 233 MeV [60].

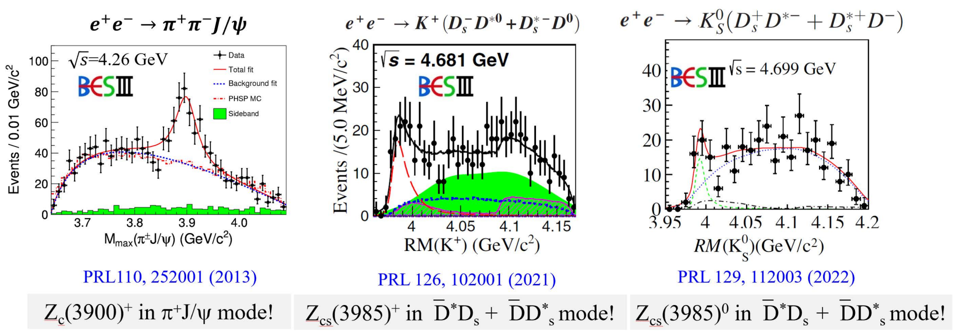

Figure 7. The $Z_c(3900)$ (left panel, [52]), $Z_{cs}(3985)^+$ (middle panel, [58]), and $Z_{cs}(3985)^0$ (right panel, [59]) signals observed in BESIII experiment.

The widths of the $Z_{cs}(3985)$ and $Z_{cs}(4000)$ are quite different, so they could not be the same state. Maybe one of them is the strange partner of the $Z_c(3900)$ with the d quark replaced with an s quark. These may suggest the existence of a $J^P = 1^+$ nonet similar to the lowest lying pseudoscalar nonet (see Fig. 8), and the states correspond to η and η' need to be further searched for.

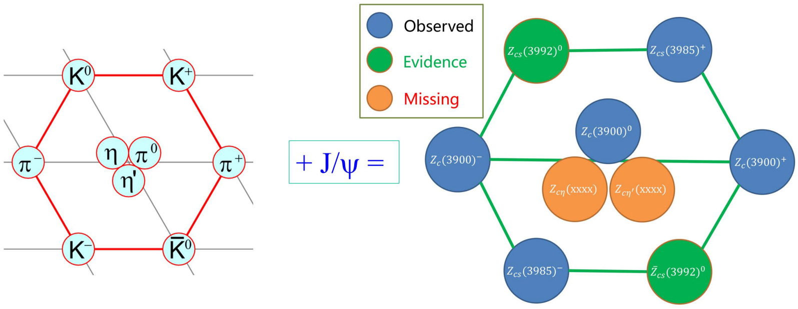

Figure 8. The similarity of the pseudoscalar nonet and the $J^P = 1^+$ Z_c nonet.

5 Perspectives

Although Belle and BaBar have ended their data taking for more than 10 years, there are still analyses ongoing with the existing data samples.

BESIII has produced a considerable amount of information about the XYZ and the conventional charmonium states [61]. In addition, there are data that are still being analyzed and more data that will be accumulated at other CM energies [62, 63]. Analyses with these additional data samples will provide improved understanding of the XYZ states, especially the $X(3872)$, $Y(4260)$, $Z_c(3900)$, and $Z_c(4020)$. The maximum CM energy accessible at BEPCII was upgraded from 4.6 to 5.0 GeV in 2019, and 5.6 fb^{-1} of data were accumulated in the 2019-20 and 2020-21 running periods, with more data planned for the future. This enables a full coverage of the $Y(4660)$ [44] resonance and a search for possible higher mass vector mesons and states with other quantum numbers, as well as improved measurements of their properties. A further upgrade of the accelerator will enable an energy coverage up to 5.6 GeV and with a factor of 3 improvement of the luminosity at above 4.7 GeV [64]. This will enable a study of the CM energy region 4.7 to 5.6 GeV that was not well investigated due to lack of data [65]. It will take about 3 years to prepare the upgraded components and half a year for installation starting from summer 2024, and commissioning is planed in early 2025.

At the same time, the B-factory experiments will supply substantial information on these states and possibly discover more [66, 67]. At the LHCb, in addition to the 9 fb^{-1} of data at 7, 8, and 13 TeV that have been used for most of their published analyses, 50 fb^{-1} more data are being accumulated in run3 which was started in summer 2022 and at 13.6 TeV [66]. The huge statistics at LHCb and very low background after tagging the long lifetime b-hadrons make many searches and precision studies possible. The study of final states with photons and π^0 will be very challenging at LHCb, an alternative way of photon detection of using gamma-conversion will help but with a considerable drop of efficiency.

Belle II [67] has collected 424 fb^{-1} of data by mid-2022, and will accumulate 50 ab^{-1} data at the $\Upsilon(4S)$ peak by the end of 2035 [68]. These data samples can be used to study the XYZ and charmonium states in many different ways [5], among which ISR can produce events in the same energy range covered by the BESIII. A 50 ab^{-1} Belle II data sample will correspond to about 250 fb^{-1} of data for e^+e^- collision energy between 4 and 5 GeV. Similar statistics will be available for modes like $e^+e^- \to \pi^+\pi^- J/\psi$ at Belle II and BESIII (after considering the fact that Belle II has lower efficiency). Belle II has the advantage that data at different energies will be accumulated at the same time, making the analysis much simpler than at BESIII. Belle II is unique in studying the bottomoniumlike states by doing energy scan above the $\Upsilon(4S)$ peak up to about 11 GeV, the maximum energy SuperKEKB can reach.

The PANDA Experiment at the Facility for Antiproton and Ion Research (FAIR) is under construction and may start commissioning of the experiment in 2027 [69]. It will be able to study charmoniumlike exotic states via $p\bar{p}$ annihilation. The momentum range of the antiproton beam is 1–15 GeV and the peak luminosity is 2×10^{31} cm$^{-2}s^{-1}$ (Phase 1+2) and 2×10^{32} cm$^{-2}s^{-1}$ (Phase 3). The extremely good precision of the beam energy measurement will enable very precise line shape scan of the narrow resonances like $X(3872)$ [70].

There are two super τ-charm factories being proposed, the STCF in China [71] and the SCT in Russia [72]. Both machines would run at CM energies of up to 5 GeV or higher with a peak luminosity of 10^{35} cm^{-2}s^{-1} which is a factor of 100 improvement over the BEPCII. These would enable systematic studies of the charmoniumlike XYZ states with unprecedented precision.

6 Summary

If we summarize these quarkoniumlike hadrons, we find that some of them are quite close to the thresholds of two heavy flavor mesons, like the $X(3872)$ ($\bar{D}^0 D^{*0}$), $Y(4220)$ ($D_s^{*+} D_s^{*-}$ or $\bar{D} D_1$), $Z_c(3900)^+$ ($\bar{D}^0 D^{*+}$), $Z_c(4020)^+$ ($\bar{D}^{*0} D^{*+}$), $Z_{cs}(3985)^+$ or $Z_{cs}(4003)^+$ ($\bar{D}^0 D_s^{*+}$), $Z_b(10610)^+$ ($\bar{B}^0 B^{*+}$), $Z_b(10650)^+$ ($\bar{B}^{*0} B^{*+}$); and some other states are not close to such thresholds, such as the $Y(4360)$, $Y(4500)$, $Y(4660)$, $Z_c(4430)^+$, and $Z_{cs}(4220)^+$. These may suggest that we did observe the hadronic molecules close to thresholds and we also observed hadronic states with some other quark configurations like compact tetraquark states and so on.

It is expected that more results will be produced by the Belle II, BESIII, LHCb, and other experiments. Theoretical efforts are also essential for understanding these new particles.

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