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# Overview of $XYZ$ states and tetraquarks

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Many hadronic states beyond the conventional quark model (called charmonium-like/bottomoniumlike states or $XYZ$ particles) were found during the past fourteen years. Their nature properties were proposed including glueballs, hybrids, multi-quark states, hadron molecules, etc. In this report, I present the most recent results on the $XYZ$ results from some experiments.

*The 15th International Conference on Flavor Physics & CP Violation*
*5-9 June 2017*
*Prague, Czech Republic*

[*]Speaker.

[†]Supported in part by National Natural Science Foundation of China (NSFC) under contract No. 11575017; the Ministry of Science and Technology of China under Contract No. 2015CB856701; and the CAS Center for Excellence in Particle Physics (CCEPP).

 

## 1. Introduction

During the past fourteen years many charmoniumlike and bottomoniumlike states, the so-called "$XYZ$" particles, have been reported in experiments by studying of $B$ decays, initial state radiation, double charmonium production, bottomonia decays, two-photon process, etc [1]. Most of them cannot be described well by quarkonium potential models and may be the good candidates of exotic states [1, 2, 3]. Their unusual properties have stimulated considerable theoretical interest and various interpretations have been proposed, including tetraquarks, molecules, hybrids, or hadrocharmonia [1, 3, 4]. To distinguish among these explanations, more experimental information is needed, such as additional production processes and/or more decay modes for these states.

## 2. The $X$ states

Fourteen years ago, the Belle Collaboration discovered the first $XYZ$ state, the $X(3872)$ [5] in $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$. Now we know precisely its mass (3871.69±0.17) MeV/$c^2$ [6], have a stringent limit on its width (less than 1.2 MeV at 90% confidence level) [7] and have a definitive $J^{PC}$ assignment of $1^{++}$ [8]. The observation of the $X(3872)$ revealed that the meson spectroscopy is far more complicated than the naive expectation of the quark model. Later the $X(3872)$ has been observed to decay to several other final states: $J/\psi\gamma$ [9], $\psi'\gamma$ [10], $J/\psi\pi^+\pi^-\pi^0$ [11] and $D^0\bar{D}^{*0}$ [12, 13]. Also it has been observed in the decay $B^0 \to X(3872)K^+\pi^-$ ($X(3872) \to J/\psi\pi^+\pi^-$) by Belle, where $B^0 \to X(3872)K^*(892)^0$ is not dominant [14], and in the process $e^+e^- \to \gamma X(3872)$ for the first time with a statistical significance of $6.3\sigma$ by BESIII using data samples at center-of-mass energies from 4.009 to 4.420 GeV [15].

Considerable efforts by both experimentalists and theorists have been invested to clarify its nature. The proximity of its mass to the $D^0$-$\bar{D}^{*0}$ threshold, along with its measured partial decay rates, suggests that it be a loosely bound "molecule" of $D^0$ and $\bar{D}^{*0}$ mesons [16] or an admixture of $D^0\bar{D}^{*0}$ with a charmonium ($c\bar{c}$) state [16, 17]. Some authors have advanced a QCD-tetraquark interpretation for the $X(3872)$, and predict the existence of charged- and $C$-odd partner states that are nearby in mass [18]. Experimental searches for charged- [7, 19] and $C$-odd [20, 21] partners report negative results. However, since these searches are restricted to states with narrow total widths, the published limits may not apply if the partner states access more decay channels and are thus broader.

More experimental information on the production and decays of the $X(3872)$ will shed additional light on its nature. It is therefore natural to search for a similar state with $J^{PC} = 1^{++}$ (called $X_b$) in the bottomonium system [22, 23]. 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 [24] and those involving a molecular interpretation [25, 26, 27]. The CMS Collaboration reported a null search for such a state in the $\pi^+\pi^-\Upsilon(1S)$ final state [28]. Using the 118 fb$^{-1}$ $\Upsilon(5S)$ data sample collected with Belle, the process $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S) \to \gamma\pi^+\pi^-\pi^0\ell^+\ell^-$ ($\ell = e$ or $\mu$) is used to search for the $X_b$ [29]. Figure 1 shows the $\omega\Upsilon(1S)$ invariant mass distribution with the requirement of $M(\pi^+\pi^-\pi^0)$ within the $\omega$ signal region. The dots with error bars are from data, where there is a structure at around 10.42 GeV/$c^2$. With the detailed studies, the structure is from the contribution of $e^+e^- \to \omega\chi_{bJ}$ $(J = 0,\ 1,\ 2)$ as compared with the solid histogram from MC simulations. The shaded histogram is from the normalized $\omega$ mass sideband. So no obvious $X_b$ signal is observed and the upper limit on the yield of the $X_b$ signal events is 4.0 at 90% C.L. The dashed histogram in Fig. 1 shows the upper limit on the yield of $X_b$ signal events.

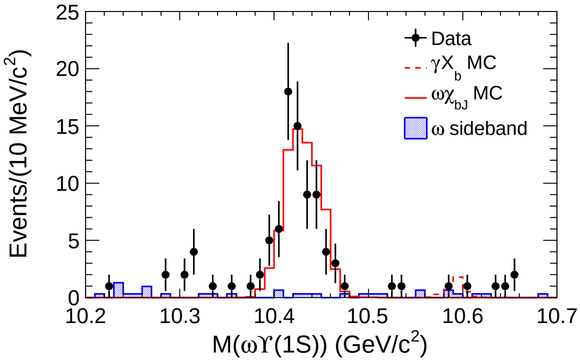


**Figure 1:** The $\omega\Upsilon(1S)$ invariant mass distribution. The dots with error bars are from data, the solid histogram is from the normalized contribution of $e^+e^- \to \omega\chi_{bJ}$ $(J = 0,\ 1,\ 2)$ from MC simulation and the shaded histogram is from normalized $\omega$ mass sideband events. The dashed histogram is from the MC signal sample $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S) \to \gamma\pi^+\pi^-\pi^0\ell^+\ell^-$ at $\sqrt{s} = 10.867$ GeV with $X_b$ mass fixed at 10.6 GeV/$c^2$ and yield fixed at the upper limit at 90% C.L.

In 2008 the CDF claimed a $3.8\sigma$ evidence for a near-threshold $X(4140) \to J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$ decays with $\Gamma = 11.7$ MeV [30]. Much larger widths are expected for charmonium states at this mass because of open flavor decay channels, which makes the observation of the $X(4140)$ received wide interest. It has been suggested that the $X(4140)$ structure could be a molecular state, a tetraquark state, a hybrid state or a rescattering effect. However, with much larger data sample LHCb did not see evidence for the narrow $X(4140)$ peak in the same $B$ decays [31]. Searches for the $X(4140)$ did not confirm its presence in analyses performed by the Belle [32, 33] (unpublished) and BaBar [34] experiments. Even so, the $X(4140)$ was observed by CMS with a $5\sigma$ significance [35]. Evidence for it was also reported by D0 ($3\sigma$) [36]. The D0 Collaboration claimed in addition a significant signal for prompt $X(4140)$ production in $p\bar{p}$ collisions [37]. The BESIII Collaboration did not find evidence for $X(4140) \to J/\psi\phi$ in $e^+e^- \to \gamma X(4140)$ [38].

In an updated analysis, the CDF Collaboration presented $3.1\sigma$ evidence for a second relatively narrow $J/\psi\phi$ peak near 4274 MeV/$c^2$ [39]. A second $J/\psi\phi$ mass peak was observed by the CMS Collaboration at a mass higher by $3.2\sigma$ [35]. To confirm the $X(4140)$, Belle did a two-photon analysis $\gamma\gamma \to J/\psi\phi$ [40]. Instead of observation of the $X(4140)$, Belle saw $3.2\sigma$ evidence for a narrow $J/\psi\phi$ peak at $4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV/$c^2$ [40]. In view of the complicated structures and confusing experimental situation concerning $J/\psi\phi$ system, LHCb did a full amplitude analysis of $B^+ \to K^+\phi J/\psi$ [41]. Figure 2 shows the $J/\psi\phi$ invariant mass distribution for the selected signal candidates, where four $J/\psi\phi$ structures, $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$, are needed [41]. So the structures in the $J/\psi\phi$ mass spectrum seem very rich, which needs to be revisited to confirm or deny the existence of these $X$ states at BelleII experiment in the near future.

The $X(3915)$ was observed by the Belle in $B \to J/\psi\omega K$ decays [42] with original name of $Y(3940)$. Subsequently, it was also observed by the BaBar in the same $B$ decay mode [11, 43] and

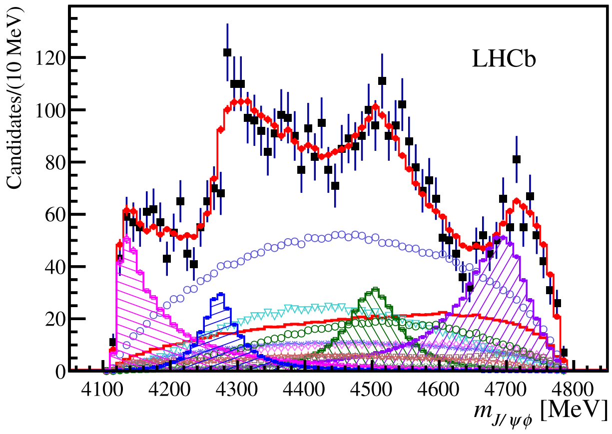


**Figure 2:** Distribution of $J/\psi\phi$ invariant mass (black data points) compared with the results of the full amplitude fit containing $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ contributions. The total fit is given by the red points with error bars. Individual fit components are also shown.

by both Belle [44] and BaBar [45] in the process $\gamma\gamma \to X(3915) \to J/\psi\omega$. The quantum numbers of the $X(3915)$ were measured to be $J^{PC} = 0^{++}$. As a result, the $X(3915)$ was identified as the $\chi_{c0}(2P)$ in the 2014 PDG tables. However, this assignment has some problems. For some reasons, please see Ref. [46]. As a result of these considerations, the $X(3915)$ is no longer identified as the $\chi_{c0}(2P)$ in the 2016 PDG tables. The nature of the $X(3915)$ is still unknown.

A unique process that is suitable for a search for the $\chi_{c0}(2P)$ and other charmonium states with positive $C$-parity is double-charmonium production in association with the $J/\psi$. The $X(3940)$ state was observed by Belle in the inclusive $e^+e^- \to J/\psi X$ spectrum and in the process $e^+e^- \to J/\psi D^*\bar{D}$ [47, 48], and the $X(4160)$ was observed in the process $e^+e^- \to J/\psi D^*\bar{D}^*$ [48].

Very recently, Belle performed a full amplitude analysis of the process $e^+e^- \to J/\psi D\bar{D}$ ($D$=$D^0$ or $D^+$) based on the 980 fb$^{-1}$ data sample [49]. A new charmoniumlike state $X^*(3860)$ that decays to $D\bar{D}$ is observed with a significance of $6.5\sigma$. Its mass is $(3862^{+26+40}_{-32-13})$ MeV/$c^2$ and width is $(201^{+154+88}_{-67-82})$ MeV. The $J^{PC} = 0^{++}$ hypothesis is favored over the $2^{++}$ hypothesis at the level of $2.5\sigma$. The measured $X^*(3860)$ mass is close to potential model expectations for the $\chi_{c0}(2P)$ so it is a better candidate for the $\chi_{c0}(2P)$ charmonium state than the $X(3915)$. Figure 3 shows the projection of the signal fit results onto $M_{D\bar{D}}$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with a new $X^*$ resonance ($J^{PC} = 0^{++}$) and the red dashed line is the fit with nonresonant amplitude only.

## 3. The $Y$ states

Among the new $XYZ$ states, there are many vector states with quantum numbers $J^{PC} = 1^{--}$ that are usually called $Y$ states, like the $Y(4260)$ [50], the $Y(4360)$ [51], and the $Y(4660)$ [52]. The $Y$-states show strong coupling to hidden-charm final states in contrast to the vector charmonium states in the same energy region ($\psi(4040)$, $\psi(4160)$, $\psi(4415)$) which couples dominantly to open-charm meson pairs. These $Y$ states are good candidates for new types of exotic parti-

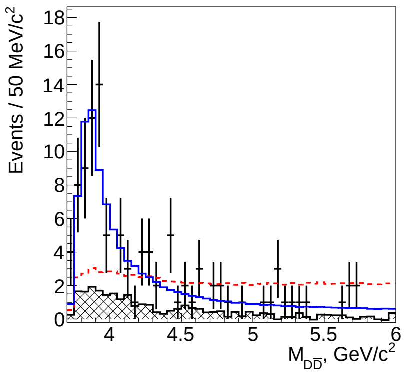


**Figure 3:** Projection of the signal fit results onto $M_{D\bar{D}}$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with a new $X^*$ resonance ($J^{PC} = 0^{++}$) and the red dashed line is the fit with nonresonant amplitude only.

cles and stimulated many theoretical interpretations, including tetraquarks, molecules, hybrids, or hadrocharmonia [1].

In 2013, BESIII reported the cross section measurement of $e^+e^- \to \pi^+\pi^- h_c$ at 13 center-of-mass (c.m.) energies from 3.9 to 4.2 GeV and found a resonant structure at around 4.22 GeV/$c^2$ [53]. A combined fit to the BESIII data together with the CLEO-c measurement at 4.17 GeV [54] results in a resonant structure, $Y(4220)$, with a mass of $(4216 \pm 18)$ MeV$/c^2$ and a width of $(39 \pm 32)$ MeV [55], different from any of the known $Y$ and excited $\psi$ states in this mass region [6].

In 2014, BESIII reported the cross section measurement of $e^+e^- \to \omega\chi_{c0}$ at 9 c.m. energies from 4.21 to 4.42 GeV. By assuming the $\omega\chi_{c0}$ signals come from a single resonance, BESIII reported a resonant structure with the mass and width of $(4230 \pm 8 \pm 6)$ MeV/$c^2$ and $(38 \pm 12 \pm 2)$ MeV, respectively, and the statistical significance is more than $9\sigma$ [56]. This structure is in good agreement with the $Y(4220)$ observed in $e^+e^- \to \pi^+\pi^- h_c$ [55], and combined fits assuming the structures at 4.22 GeV/$c^2$ are the same have been tried by the authors of Refs. [57, 58].

BESIII updated the measurements with higher energy data up to 4.6 GeV included, in both $e^+e^- \to \pi^+\pi^- h_c$ [59] and $\omega\chi_{c0}$ [60] processes. While the structure in $\omega\chi_{c0}$ mode was affected only slightly with the new measurements at high energies [60], in the $e^+e^- \to \pi^+\pi^- h_c$ mode, the $Y(4220)$ was observed with improved significance together with a new structure, the $Y(4390)$. The resonant parameters are $M = (4218.4 \pm 4.0 \pm 0.9)$ MeV/$c^2$ and $\Gamma = (66.0 \pm 9.0 \pm 0.4)$ MeV for the $Y(4220)$, and $M = (4391.6 \pm 6.3 \pm 1.0)$ MeV/$c^2$ and $\Gamma = (139.5 \pm 16.1 \pm 0.6)$ MeV for the $Y(4390)$ [59]. The updated cross sections of $e^+e^- \to \omega\chi_{c0}$ and $\pi^+\pi^- h_c$ are shown in Fig. 4.

The process $e^+e^- \to \pi^+\pi^- J/\psi$ at c.m. energies up to 5.0 GeV was first studied by BaBar, where the $Y(4260)$ was observed [50]. Belle measured the cross sections of $e^+e^- \to \pi^+\pi^- J/\psi$ at c.m. energies between 3.8 and 5.0 GeV and reported that $Y(4260)$ alone cannot describe the line shape satisfactorily [61]. Improved measurements with both BaBar [62] and Belle [63] full data samples confirmed the existence of non-$Y(4260)$ component in $e^+e^- \to \pi^+\pi^- J/\psi$ but the line shape was parametrized with different models. Recently, BESIII reported a precise measurement of $e^+e^- \to \pi^+\pi^- J/\psi$ cross sections at c.m. energies from 3.77 to 4.60 GeV shown in Fig. 4 using a 9 fb$^{-1}$ data sample [64]. While the nature of the events at around 4 GeV is still ambiguous, the dominant resonant structure, the so called $Y(4260)$, was found to have a mass of $(4222.0 \pm 3.1 \pm 1.4)$ MeV/$c^2$ and a width of $(44.1 \pm 4.3 \pm 2.0)$ MeV, in good agreement with the $Y(4220)$ observed in $e^+e^- \to \pi^+\pi^- h_c$ [59]. In addition, a new resonance with a mass of around 4.32 GeV/$c^2$ is needed to describe the high precision data.

BESIII also reported a measurement of the $e^+e^- \to D^0 D^{*-}\pi^+ + c.c.$ cross sections at c.m. energies from 4.05 to 4.60 GeV, which is a significant improvement over the previous measurement at Belle [65]. Two resonant structures in good agreement with the $Y(4220)$ and $Y(4390)$ observed in $\pi^+\pi^- h_c$ [59] are identified over a smoothly increasing non-resonant term which can be parametrized with a three-body phase space amplitude. The cross sections of $D^0 D^{*-}\pi^+ + c.c.$ are also shown in Fig. 4.

Considering the above features, i.e., there is a common structure at around 4.22 GeV/$c^2$, the authors in Ref. [66] performed a combined fit to the cross sections of $e^+e^- \to \omega\chi_{c0}$, $\pi^+\pi^- h_c$, $\pi^+\pi^- J/\psi$, and $D^0 D^{*-}\pi^+ + c.c.$ by applying constraints to the resonant parameters. The results of the combined fit are shown in Fig. 4, where the solid curves are the projections from the best fit and the dashed curves show the fitted resonance components from different solutions indicated in the top right corner in each plot. A mass $M = (4219.6 \pm 3.3 \pm 5.1)$ MeV/$c^2$ and a total width $\Gamma = (56.0 \pm 3.6 \pm 6.9)$ MeV for the $Y(4220)$ are obtained. Also the lower limit of its leptonic decay width is determined to be around 30 eV, which is close to the prediction from LQCD for a hybrid vector charmonium state for the $Y(4220)$ [67].

## 4. The Z states

After the charged charmoniumlike state $Z_c(3900)$ was observed by BESIII and Belle experiments [63, 68], BESIII and Belle have observed a series of charged $Z_c$ states including $Z_c(4020)$ [53], $Z_c(4200)$ [69], $Z_c(3885)$ [70], and $Z_c(4050)$ [71]. These states seem to indicate that a new class of hadrons has been observed. As there are at least four quarks within these $Z_c$ states, they have been interpreted either as tetraquark states, molecular states, or other configurations.

To determine the spin and parity of the $Z_c(3900)$, BESIII recently performed a partial wave analysis of the process $e^+e^- \to \pi^+\pi^- J/\psi$ using a data sample of 1.92 fb$^{?1}$ accumulated at $\sqrt{s}$ =4.23 and 4.26 GeV [72]. The $J^P = 1^+$ for the $Z_c(3900)$ are determined with a statistical significance larger than $7\sigma$ over other quantum numbers. The $Z_c(3900)$ mass is measured to be $M = (3901.5 \pm 2.7 \pm 38.0)$ MeV/$c^2$ in the parametrization of a Flatt$\acute{e}$-like formula.

Belle observed two charged bottomoniumlike resonances $Z_b(10610)$ and $Z_b(10650)$ in $e^+e^- \to \Upsilon(n\mathrm{S})\pi^+\pi^-$ $(n = 1,2,3)$ and $e^+e^- \to h_b(m\mathrm{P})\pi^+\pi^-$ $(m = 1,2)$ [73, 74]. Popular opinions regarded the $Z_b(10610)$ and $Z_b(10650)$ states might be loosely bound $B\bar{B}^*$ and $B^*\bar{B}^*$ systems, respectively. To confirm this, Belle reconstructed three-body $B^{(*)}\bar{B}^{(*)}\pi$ combinations using a data sample of 121.4 fb$^{-1}$ at $\Upsilon(5S)$ resonance [75], where the set of $B^+\bar{B}^0\pi^-$ and $B^-B^0\pi^+$ final states is referred to as $BB\pi$; the set of $B^+\bar{B}^{*0}\pi^-$, $B^-B^{*0}\pi^+$, $B^0B^{*-}\pi^+$ and $\bar{B}^0B^{*+}\pi^-$ final states is referred to as $BB^*\pi$; and the set of $B^{*+}\bar{B}^{*0}\pi^-$ and $B^{*-}B^{*0}\pi^+$ final states is denoted as $B^*B^*\pi$. In the missing mass distribution of $B\pi$, peaks corresponding to the $BB^*\pi$ and $B^*B^*\pi$ signals are evident. Three models are used to fit the $M_{\rm miss}(\pi)$ distributions: only the $Z_b(10610)$ [$Z_b(10650)$] amplitude [Model-0], an

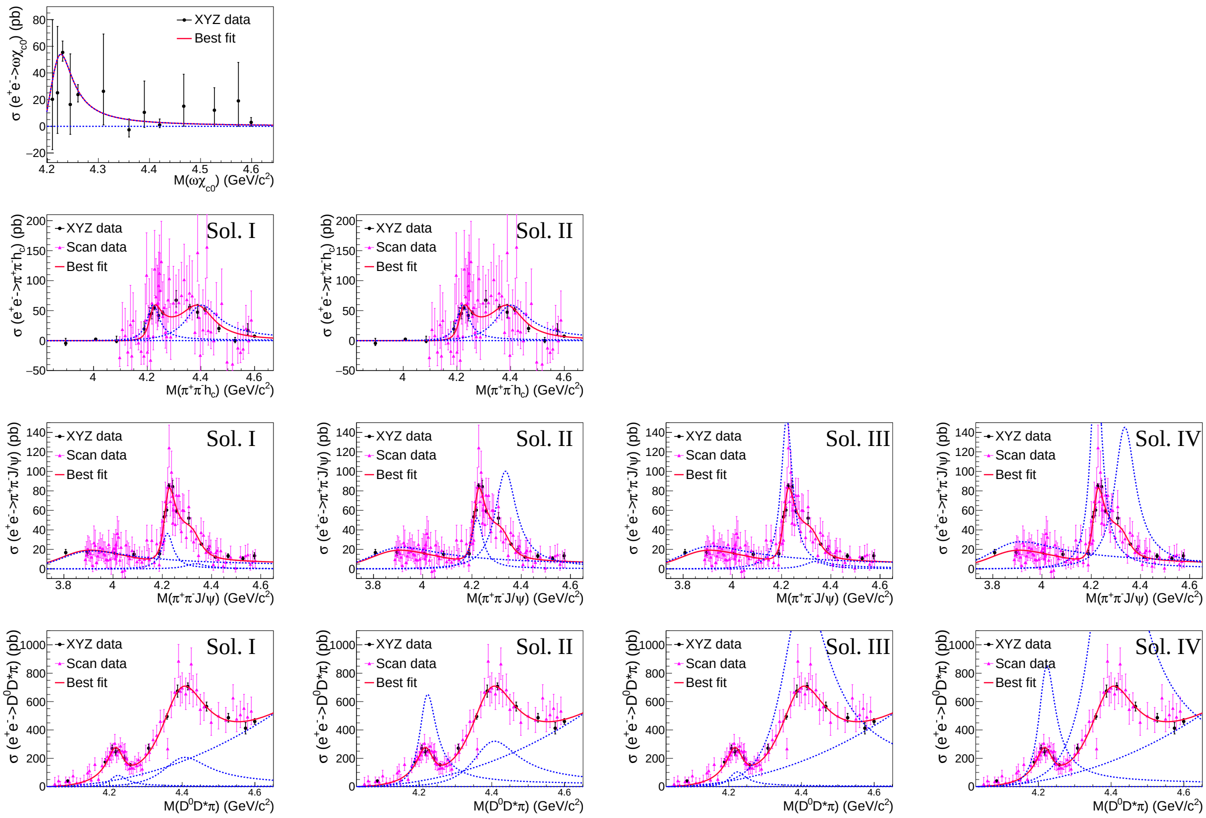


**Figure 4:** The results of the combined fit to $e^+e^- \to \omega\chi_{c0}$, $\pi^+\pi^-h_c$, $\pi^+\pi^-J/\psi$, and $D^0D^{*-}\pi^+ + c.c.$ (from the top to the bottom row). The dots and the triangles with errors bars are data from BESIII. The solid curves are the projections from the best fit. The dashed curves show the fitted resonance components from different solutions indicated in the top right corner in each plot.

additional possible non-resonant component [Model-1], and a combination of two $Z_b$ amplitudes [Model-2]. The fit to the $BB^*\pi$ data with Model-0 gives $10605 \pm 6$ MeV/$c^2$ and $25 \pm 7$ MeV for the $Z_b(10610)$ mass and width, respectively, and the fit to the $B^*B^*\pi$ data gives $10648 \pm 13$ MeV/$c^2$ and $23 \pm 8$ MeV for the $Z_b(10650)$ mass and width, respectively. Assuming that the $Z_b(10610)$ and $Z_b(10650)$ are saturated by the already observed $\Upsilon(n\mathrm{S})\pi$, $h_b(m\mathrm{P})\pi$, and $B^*B^{(*)}$ channels, the decay rates are summarized in Table 1.

## 5. Conclusion

In summary, there have been great progresses in the study of the $XYZ$ states, especially Belle and BESIII are still producing more exciting results. However, we found we have more questions to answer. Further studies along this line may strengthen our understanding of how strong interaction works at low energy and thus a better understanding of the matters around us. The Belle II experiment is going to take data in 2018. With a 50 ab$^{-1}$ data sample by 2024, the future is very promising.

**Table 1:** Branching fractions for the $Z_b^+(10610)$ and $Z_b^+(10650)$ decays.

| Channel | Fraction, % | |
|---|---|---|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.60 \pm 0.17 \pm 0.07$ | $0.17 \pm 0.06 \pm 0.02$ |
| $\Upsilon(2S)\pi^+$ | $4.05 \pm 0.81 \pm 0.58$ | $1.38 \pm 0.45 \pm 0.21$ |
| $\Upsilon(3S)\pi^+$ | $2.40 \pm 0.58 \pm 0.36$ | $1.62 \pm 0.50 \pm 0.24$ |
| $h_b(1P)\pi^+$ | $4.26 \pm 1.28 \pm 1.10$ | $9.23 \pm 2.88 \pm 2.28$ |
| $h_b(2P)\pi^+$ | $6.08 \pm 2.15 \pm 1.63$ | $17.0 \pm 3.74 \pm 4.1$ |
| $B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$ | $82.6 \pm 2.9 \pm 2.3$ | $-$ |
| $B^{*+}\bar{B}^{*0}$ | $-$ | $70.6 \pm 4.9 \pm 4.4$ |

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