XYZ states at Belle*

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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 them after the running of the B-factories. In this report, I present the most recent results on the XYZ states at Belle, including (1) X states: the first observation of $B^0 \to X(3872)K^+\pi^-$ and evidence for $B^+ \to X(3872)K^0\pi^+$; search for the X_b state; (2) Y states: the updated results for the $Y(4360)$ and $Y(4660)$ and cross section measurements of $e^+e^- \to K^+K^-J/\psi$ and $\gamma\chi_{cJ}$; (3) Z states: the evidence for the $Z_c(4050)^\pm \to \pi^\pm\psi(2S)$; search for the Z_{cs} in $e^+e^- \to K^+K^-J/\psi$.

Key words: XYZ, exotic states, Belle

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1 Introduction

It has been prospering for dozen years that lots of charmoniumlike states, the so-called "XYZ" particles [1, 2], were observed by many Collaborations, like Belle, BaBar, and BESIII. 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. Especially the charged charmoniumlike state $Z_c(3900)$ was observed by BESIII [3] and Belle [4] experiments in 2013 in $J/\psi\pi^\pm$ system of $e^+e^- \to \pi^+\pi^-J/\psi$ at center-of-mass (CM) energies around 4.26 GeV and very recently the two exotic structures, denoted as pentaquark states of $P_c(4380)^+$ and $P_c(4450)^+$, in the $J/\psi p$ system in $\Lambda_b^0 \to J/\psi K^- p$ were observed by LHCb [5].

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]. It is a long history of searching for all these kinds of states, however, no solid conclusion was reached until the recent discovery of tetraquark and pentaquark states.

Here, I present some most recent results on the XYZ states from the Belle experiment.

2 X states

More than a decade ago, the Belle Collaboration discovered the $X(3872)$ state [6] in the exclusive reconstruction of $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$. Considerable effort by both experimentalists and theorists has been invested to clarify its nature. As a result, we know precisely its mass (3871.69±0.17) MeV/c^2 [7], have a stringent limit on its width (less than 1.2 MeV at 90% confidence level (C.L.)) [8] and have a definitive J^{PC} assignment of 1^{++} determined by LHCb [9]. 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 [10]. Eventually both BaBar [11] and Belle [12] 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 the quantum numbers of $X(3872)$ ($I^G(J^{PC}) = 0^+(1^{++})$) also suggested that it is possibly a candidate of $\chi_{c1}(2P)$. 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. More experimental information on the production and decays of the $X(3872)$ will shed additional light on its nature.

Based on 711 fb^{-1} of data containing 772×10^6 $B\bar{B}$ events, Belle searched for the $X(3872)$ production via the $B^0 \to X(3872)K^+\pi^-$ and $B^+ \to X(3872)K_S^0\pi^+$ decay modes, where the $X(3872)$ decays to $J/\psi\pi^+\pi^-$ [13].

B candidates were selected using two kinematic variables: the energy difference $\Delta E = E_B - E_{\rm beam}$ and the beam-energy constrained mass $M_{\rm bc} = (\sqrt{E_{\rm beam}^2 - p_B^2c^2})/c^2$, where $E_{\rm beam}$ is the beam energy and E_B and p_B are the energy and magnitude of momentum, respectively, of the candidate B meson, all calculated in the e^+e^- CM frame. To extract the signal yield of $B \to X(3872)(\to J/\psi\pi^+\pi^-)K\pi$, a two-dimensional

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(2D) unbinned extended maximum likelihood fit to the ΔE and $M_{J/\psi\pi\pi}$ distributions was performed after all the event selections. For the signal, the ΔE distribution is parametrized by the sum of a Crystal Ball and a Gaussian function while the $M_{J/\psi\pi\pi}$ distribution is modeled using the sum of two Gaussians having a common mean. The 2D probability distribution function (PDF) is a product of the individual one-dimensional PDFs.

For the $B^0 \to X(3872)K^+\pi^-$ decay mode, a 2D fit is performed. Figure 1 shows the signal-enhanced projection plots for the $B^0 \to X(3872)K^+\pi^-$ decay mode. The curves show the signal (red long-dashed curve) and the background components (black dash-dotted line for the component peaking in $M_{J/\psi\pi\pi}$ but nonpeaking in ΔE, green dashed line for the one peaking in ΔE but nonpeaking in $M_{J/\psi\pi\pi}$, and magenta long dash-dotted line for combinatorial background) as well as the overall fit (blue solid curve). The number of signal for $B^0 \to X(3872)K^+\pi^-$ is 116 ± 19, corresponding to a significance of 7.0σ. The product of branching fractions is measured to be $\mathcal{B}(B^0 \to X(3872)K^+\pi^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (7.9 \pm 1.3(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-6}$.

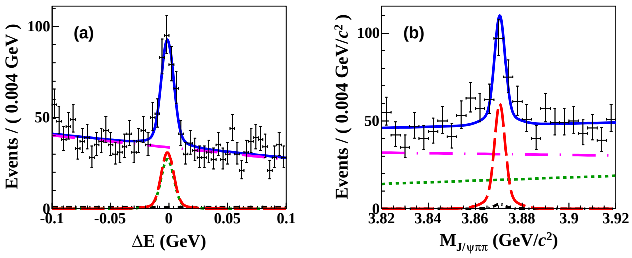

Fig. 1. Projections of the $(\Delta E,\, M_{J/\psi\pi\pi})$ fit for the $B^0 \to X(3872)K^+\pi^-$ decay mode.

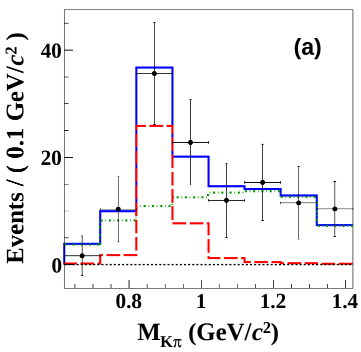

Fig. 2. Fit to the $M_{K\pi}$ distribution for the $B^0 \to X(3872)K^+\pi^-$ decay mode.

To obtain the pure $M_{K\pi}$ distribution, a similar 2D fit to ΔE and $M_{J/\psi\pi\pi}$ in each bin of $M_{K\pi}$ was performed. All parameters of the signal PDFs for $M_{J/\psi\pi\pi}$ and ΔE distributions are fixed from the previous 2D fit to all events. Then a χ^2 fit to the $M_{K\pi}$ distribution using $K^*(892)^0$ and $(K^+\pi^-)_{\rm NR}$ components was done, where the histogram PDFs were obtained from MC samples directly. The possible interference between the $K^*(892)$ and nonresonant component was not considered due to the small statistics. The resulting fit result is shown in Fig. 2. The curves show the $B^0 \to X(3872)K^*(892)^0$ (red long-dashed lines), $B^0 \to X(3872)(K^+\pi^-)_{\rm NR}$ (green dot-dashed lines), as well as the overall fit (blue solid lines). We obtain 38 ± 14 (82 ± 21) signal events for the $B^0 \to X(3872)K^*(892)^0$ ($B^0 \to X(3872)(K^+\pi^-)_{\rm NR}$) decay mode and a corresponding product of branching fractions of $\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.0 \pm 1.5(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{-6}$. The ratio of branching fractions is

$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)} = 0.34 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.}).$$

In contrast to $B^0 \to \psi' K^+\pi^-$, $B^0 \to X(3872)K^*(892)^0$ does not dominate in the $B^0 \to X(3872)K^+\pi^-$.

The decays $B^+ \to X(3872)K^0\pi^+$ were also analyzed using the same method. The projections of the 2D fit are shown in Fig. 3. The representations of the curves match those in Fig. 1. The number of fitted signal events is 35 ± 10, corresponding to a 3.7σ significance. The product of branching fractions is $\mathcal{B}(B^+ \to X(3872)K^0\pi^+) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (10.6 \pm 3.0(\text{stat.}) \pm 0.9(\text{syst.})) \times 10^{-6}$.

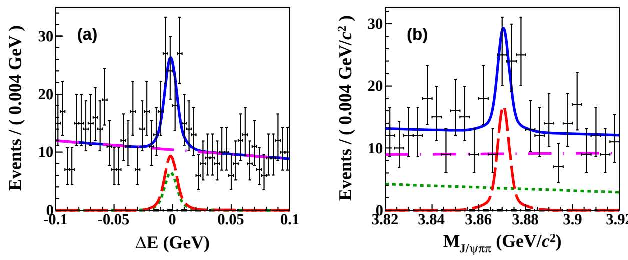

Fig. 3. Projections of the $(\Delta E,\, M_{J/\psi\pi\pi})$ fit for the $B^\pm \to X(3872)K^0_S\pi^\pm$ decay mode.

It is very natural to search for a similar $X(3872)$ 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 [14] and those involving a molecular interpretation [15–17]. 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 [18]. 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 [16, 19]. So Belle did a search for an X_b signal decaying to $\omega\Upsilon(1S)$ in $e^+e^- \to \gamma X_b$ at a CM energy of 10.867 GeV [20].

Figure 4 shows the final $\omega\Upsilon(1S)$ invariant mass distribution with the requirement of $M(\pi^+\pi^-\pi^0)$ within the ω signal region; the X_b is searched for 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 $e^+e^- \to \omega\chi_{bJ}$ $(J=0,\ 1,\ 2)$ and the shaded histogram is from the normalized ω mass sideband. No obvious X_b signal is observed after applying all the event selection criteria.

An unbinned extended maximum likelihood fit to the $\omega\Upsilon(1S)$ mass distribution is applied, where the signal shape is obtained from MC simulation and the background is parameterized as a first-order polynomial. From the fit, the number of X_b signal events is $-0.4{\pm}2.0$ with a mass at 10.6 GeV/c^2. The upper limit on the yield of the X_b signal events is 4.0 at 90% C.L. with systematic uncertainty included. The dashed histogram in Fig. 4 shows the upper limit on the yield of X_b signal events. The product branching fraction is determined to be $\mathcal{B}(\Upsilon(5S)\to\gamma X_b)\mathcal{B}(X_b\to\omega\Upsilon(1S)) < 2.9{\times}10^{-5}$ at 90% C.L.

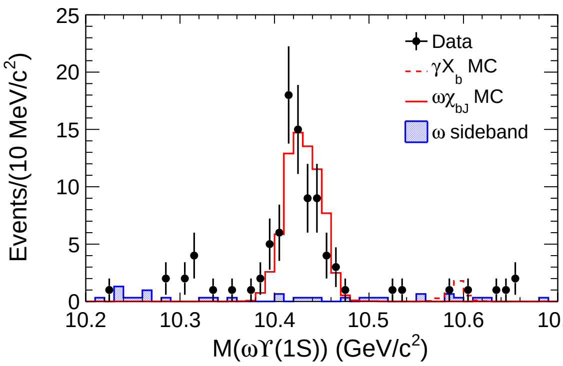

Fig. 4. The $\omega\Upsilon(1S)$ invariant mass distribution. The components shown are described in the text.

3 Y states

The $Y(4260)$ state was first observed by BaBar in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-J/\psi$ [21] and then confirmed by the CLEO [22] and Belle experiments [23] using the same technique. 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 $Y(4008)$ [24].

Later, the BaBar Collaboration reported an updated ISR analysis with 454 fb^{-1} of data and a modified approach for the background description [25]; the $Y(4260)$ state was observed with improved significance, but the $Y(4008)$ structure was not confirmed. Instead, they attributed the structure below the $Y(4260)$ to exponentially falling non-resonant $\pi^+\pi^-J/\psi$ production. In 2013, the Belle Collaboration 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 [4].

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 $Y(4360)$) [26], while Belle observed two resonant structures at 4.36 and 4.66 GeV/c^2, denoted as the $Y(4360)$ and $Y(4660)$ [27]. 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 [28].

Very recently, to characterize more precisely the properties of the $Y(4360)$ and $Y(4660)$, Belle updated the $e^+e^- \to \pi^+\pi^-\psi(2S)$ process with the full Belle data 980 fb^{-1} [29]. Figure 5 shows the invariant mass distribution of $\pi^+\pi^-\psi(2S)$ from the updated measurement. Fitting the mass spectrum of $\pi^+\pi^-\psi(2S)$ with two coherent Breit-Wigner (BW) functions, there are two solutions with identical mass and width but different couplings to electron-positron pairs: $M_{Y(4360)} = (4347\pm6\pm3)$ MeV/c^2, $\Gamma_{Y(4360)} = (103\pm9\pm5)$ MeV, $M_{Y(4660)} = (4652\pm10\pm8)$ MeV/c^2, $\Gamma_{Y(4660)} = (68\pm11\pm1)$ MeV; and $\mathcal{B}[Y(4360)\to\pi^+\pi^-\psi(2S)]\cdot\Gamma^{e^+e^-}_{Y(4360)} = (10.9\pm0.6\pm0.7)$ eV and $\mathcal{B}[Y(4660)\to\pi^+\pi^-\psi(2S)]\cdot\Gamma^{e^+e^-}_{Y(4660)} = (8.1\pm1.1\pm0.5)$ eV for one solution; or $\mathcal{B}[Y(4360)\to\pi^+\pi^-\psi(2S)]\cdot\Gamma^{e^+e^-}_{Y(4360)} = (9.2\pm0.6\pm0.6)$ eV and $\mathcal{B}[Y(4660)\to\pi^+\pi^-\psi(2S)]\cdot\Gamma^{e^+e^-}_{Y(4660)} = (2.0\pm0.3\pm0.2)$ eV for the other. Here, the first errors are statistical and the second systematic.

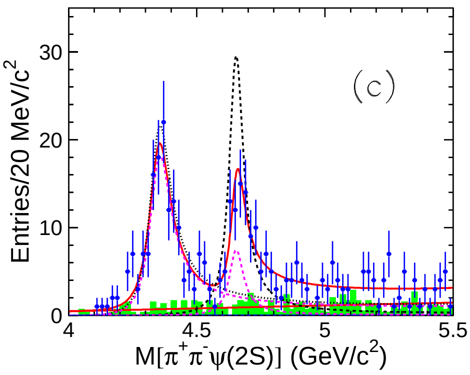

Fig. 5. The $\pi^+\pi^-\psi(2S)$ invariant-mass distributions and the simultaneous fit results described in the text.

Belle also noticed there are a few 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 also performed. But the signal significance of the $Y(4260)$ is only 2.4σ.

Using a data sample of 673 fb^{-1}, Belle has observed abundant $e^+e^- \to K^+K^-J/\psi$ signal events [30]. There is one very broad structure in the K^+K^-J/ψ mass spectrum; fits using either a single BW function, or the $\psi(4415)$ plus a second BW function yield resonant parameters that are very different from those of the currently tabulated excited ψ states. To examine possible resonant structures in the cross section of the process $e^+e^- \to K^+K^-J/\psi$ as well as in the $K^{\pm}J/\psi$ and K^+K^- systems, Belle updated measurement of the cross sections for $e^+e^- \to K^+K^-J/\psi$ between threshold and 6.0 GeV/c^2 with an integrated luminosity of 980 fb^{-1} [31].

Figure 6 shows the measured cross sections for $e^+e^- \to K^+K^-J/\psi$. The maximum likelihood fit was performed to fit the K^+K^-J/ψ invariant mass spectrum using two different parameterizations of the signal shape: (1) a single BW function plus a background term; (2) a coherent sum of a BW function and a $\psi(4415)$ component with mass and width fixed at their world average values plus a background term. The goodness of the fit ($\chi^2/ndf = 39/13 = 3.0$ for model (1) and $\chi^2/ndf = 30/11 = 2.7$ for model (2)) is marginal. Thus, these two models can not describe the data well with the increased statistics.

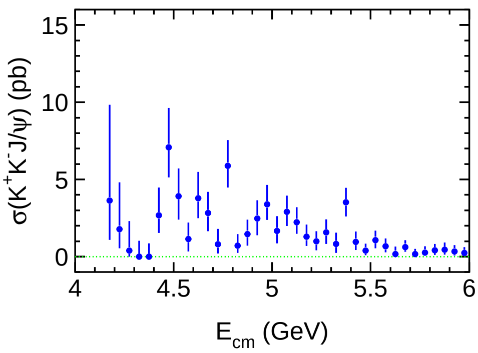

Fig. 6. The measured $e^+e^- \to K^+K^-J/\psi$ cross sections for CM energies up to 6.0 GeV.

In order to improve the understanding of the nature of vector charmoniumlike states and search for more new states, Belle studied $e^+e^- \to \gamma\chi_{cJ}$ process using ISR events with χ_{cJ} reconstructed via $\gamma J/\psi$ [32]. The integrated luminosity used in this analysis is 980 fb^{-1}.

After all the event selections, no significant signal is observed in either $\gamma\chi_{c1}$ or $\gamma\chi_{c2}$ mode in $M(\gamma\gamma J/\psi)$ distributions for $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ candidate events as well as the sum of them. The measured upper limits on the cross sections are shown in Fig. 7 and are around a few pb to a few tens of pb.

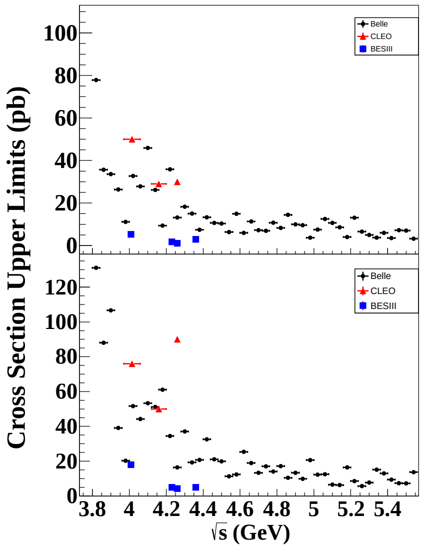

Fig. 7. Measured upper limits on the $e^+e^- \to \gamma\chi_{cJ}$ cross sections at the 90% C.L. for χ_{c1} (top) and χ_{c2} (bottom). The solid dots show the Belle measurements, the solid triangles are the results from CLEO and the blue squares are from BESIII.

4 Z states

After the charged charmoniumlike state $Z_c(3900)$ observed by BESIII and Belle experiments, BESIII and Belle also observed a series of charged Z_c states including $Z_c(4020)$, $Z_c(4200)$, and $Z_c(4430)$. 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 with a pair of charm-anticharm quarks and a pair of light quarks, molecular states of two charmed mesons, or other configurations.

To find more similar charged states, Belle checked the $\pi^{\pm}\psi(2S)$ system in the updated $e^+e^- \to \pi^+\pi^-\psi(2S)$ analysis [29]. There is an excess evident at around 4.05 GeV/c^2 in the $\pi^{\pm}\psi(2S)$ invariant-mass distributions in the $Y(4360)$ subsample defined as $4.0 < M_{\pi^+\pi^-\psi(2S)} <$ 4.5 GeV/c^2. An unbinned maximum-likelihood fit is performed on the distribution of $M_{\max}(\pi^{\pm}\psi(2S))$, the maximum of $M(\pi^+\psi(2S))$ and $M(\pi^-\psi(2S))$. The excess is parameterized with a BW function and the non-resonant non-interfering background with a second-order polynomial function. The fit yields a mass of $(4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV/c^2, a width of $(45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV and a 3.5σ significance, as shown in Fig. 8. This evident structure is called $Z_c(4050)$.

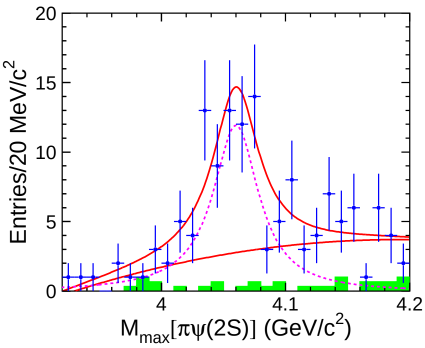

Fig. 8. The distribution of $M_{\max}(\pi^{\pm}\psi(2S))$ from $Y(4360)$-subsample decays. The points with error bars represent the data; the histogram is the normalized sidebands; the solid curve is the best fit and the dashed curve is the signal.

A strange partner of the $Z_c(3900)^{\pm}$, called Z_{cs}, may exist in the above scenarios. The mass of a $J^P = 1^+$ $D_s\bar{D}^*$ molecular state was first predicted [33] using QCD sum rules with $M(Z_{cs}) = (3.97 \pm 0.08)$ GeV$/c^2$, which is very close to the $D_s^+\bar{D}^{*0}$ threshold of 3.976 GeV$/c^2$. Using the same QCD sum rules, the authors of Ref. [34] calculated the decay widths of the Z_{cs}^+ to K^+J/ψ, $K^{*+}\eta_c$, $D_s^+\bar{D}^{*0}$ and $\bar{D}^0D_s^{*+}$, assuming the Z_{cs} to be a tetraquark state. Such a state is also predicted in the single-kaon emission model [35].

Belle tried to search for such a Z_{cs} state in $J/\psi K^{\pm}$ system in the updated process $e^+e^- \to K^+K^-J/\psi$ [31]. The $M(K^+J/\psi)$ and $M(K^-J/\psi)$ invariant mass distributions are investigated. No obvious structures were observed in the $J/\psi K^{\pm}$ system. A larger data sample is necessary to obtain more information about possible intermediate structures.

5 summary

In summary, I give a review of some recent results on XYZ from Belle experiment. With more and more exotic states discovered, especially the recent candidate tetraquark and pentaquark states, a new hadron spectroscopy is being revealed.

Although there have been great progress in the study of the XYZ states, especially Belle and BESIII are still producing more exciting results, 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 50ab^{-1} data sample, the future is very promising.

References

1 N. Brambilla *et al.*, Eur. Phys. J. C **74**, 2981 (2014).
2 N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
3 M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013).
4 Z. Q. Liu *et al.* (Belle Collaboration), Phys. Rev. Lett. **110**, 252002 (2013).
5 A. Raij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 072001 (2015).
6 S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
7 K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).
8 S.K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).
9 R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 222001 (2013).
10 E.S. Swanson, Phys. Lett. B **598**, 197 (2004); E.S. Swanson, Phys. Rep. **429**, 243 (2006).
11 B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **77**, 011102 (2008).
12 T. Aushev *et al.* (Belle Collaboration), Phys. Rev. D **81**, 031103 (2010).
13 A. Bala *et al.* (Belle Collaboration), Phys. Rev. D **91**, 051101(R) (2015).
14 A. Ali, C. Hambrock, I. Ahmed and M. J. Aslam, Phys. Lett. B **684**, 28 (2010).
15 N. A. Tornqvist, Z. Phys. C **61**, 525 (1994).
16 F.-K. Guo, C. Hidalgo-Duque, J. Nieves and M. P. Valderrama, Phys. Rev. D **88**, 054007 (2013).
17 M. Karliner and S. Nussinov, JHEP **1307**, 153 (2013).
18 S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **727**, 57 (2013).
19 F. -K. Guo, U. -G. Meißner and W. Wang, Eur. Phys. J. C **74**, 3063 (2014).
20 X. H. He *et al.* (Belle Collaboration), Phys. Rev. Lett. **113**, 142001 (2014).
21 B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).
22 Q. He *et al.* (CLEO Collaboration), Phys. Rev. D**74**, 091104(R) (2006).
23 K. Abe *et al.* (Belle Collaboration), hep-ex/0612006.
24 C. Z. Yuan *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 182004 (2007).
25 J. P. Lees *et al.* (BaBar Collaboration), Phys. Rev. D **86**, 051102(R) (2012).
26 B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **98**, 212001 (2007).
27 X. L. Wang *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 142002 (2007).
28 B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **89**, 111103 (2014).
29 X. L. Wang *et al.* (Belle Collaboration), Phys.Rev. D **91**, 112007 (2015).
30 C. Z. Yuan *et al.* (Belle Collaboration), Phys. Rev. D **77**,

011105(R) (2008).
31 C. P. Shen *et al.* (Belle Collaboration), Phys. Rev. D **89**, 072015 (2014).
32 Y. L. Han *et al.* (Belle Collaboration), Phys. Rev. D **92**, 012011 (2015).
33 S. H. Lee, M. Nielsen and U. Wiedner, Jour. Korean Phys. Soc. **55**, 424 (2009).
34 J. M. Dias, X. Liu and M. Nielsen, Phys. Rev. D **88**, 096014 (2013).
35 D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. Lett. **110**, 232001 (2013).