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Recent results of XYZ study at BESIII

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Summary. — Recent progress on the exotic and charmonium-like states from the BESIII experiment is presented, including a series of studies of Y states via cross section line-shape measurements, and the spin parity determination of the $Z_c(3900)$.

1. – Introduction

In the quark model [1], conventional hadrons are divided into two categories: the quark-antiquark mesons and three-quark baryons. However, Quantum Chromodynamics (QCD) allows the existence of states beyond conventional hadrons, referred to as exotic states, such as glueball, hybrids, multi-quark states (states consisting of more than 3 quarks). The study of exotic states is important for our understanding of QCD. Despite extensive experimental searches, no unambiguous candidates for any of these exotic configurations have been identified. On the other hand, a number of new particles in the charmonium mass region are observed and show different features from normal charmonium states. They might be good candidates for exotic states, such as the X states (non-1^- charmonium-like states), the Y states (1^- charmonium-like states) and the charged Z_c states.

In the Y family, $Y(4260)$ has gathered a lot of attention, and has been studied intensively. As a state above the open-charm threshold, it is only observed in hidden-charm decay channels, not like other conventional vector charmonium. From the cross section measurements of inclusive hadronic and open-charm processes, there is no enhancement around the peak of $Y(4260)$. For the hidden-charm channels, such as πZ_c, $\gamma X(3872)$ and $\omega\chi_{c0}$, the enhancement is very clear, indicating that these channels are due to $Y(4260)$ decays. From previous measurements of $e^+e^- \to \pi^+\pi^- J/\psi$, the line shape of $Y(4260)$ is

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not exactly a symmetric Breit-Wigner, but with a possible fine structure. These observations indicate that the $Y(4260)$ mass region is far from being well understood. With more data collected at BESIII, we can measure this region with more hidden and open-charm channels.

2. – Data samples at BESIII

The BESIII experiment operating at the Beijing Electron Positron Collider II (BEPCII) started to take data in 2009. Since the end of 2012, the experiment has accumulated about $12\,\mathrm{fb}^{-1}$ data samples with center of mass energy above 4 GeV yielding fruitful results on (exotic) charmonium spectroscopy. We have several large data samples (referred to as XYZ sample) and about 100 sub-samples (R-scan data) with about $7\,\mathrm{pb}^{-1}$ for each energy point.

3. – The study of Y states

In the past decade, a series of new vector charmonium-like states have been observed, such as the $Y(4260)$ and $Y(4360)$. Many theoretical interpretations have been proposed to understand the nature of the Y states. Recently, BESIII analysed the process $e^+e^- \to \pi^+\pi^- J/\psi$ [2] and found that the previously reported $Y(4260)$ state actually consists of two structures. In the process $e^+e^- \to \pi^+\pi^- h_c$ [3], there are also two structures between 4.2 and 4.4 GeV. The lower mass state, referred to as $Y(4220)$, has a mass consistent with the lower mass state observed in $e^+e^- \to \pi^+\pi^- J/\psi$. The higher mass state, referred to as $Y(4390)$, does not match any known vector states. To have a better understanding of the region around $Y(4260)$ mass, more processes are investigated. In this paper, five analyses are presented.

3˙1. *Line shape measurement of* $e^+e^- \to \pi\pi\psi(3686)$. – Using $5.1\,\mathrm{fb}^{-1}$ of data collected at 16 center-of-mass energy points from 4.008 to 4.6 GeV, the cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$ is measured [4]. In this analysis, $\psi(3686)$ is reconstructed with two decay modes: $\psi(3686) \to \pi^+\pi^- J/\psi$ and $\psi(3686) \to \text{neutrals} + J/\psi$. Here "neutrals" refers to $\pi^0\pi^0$, π^0, η and $\gamma\gamma$. The measured cross section is shown in fig. 1 (left). The dots (red) are the results obtained in this analysis, the triangles (green) and squares (blue) are from Belle [5] and BaBar's [6] latest updated results, respectively. The solid curve is the fit to BESIII results with the coherent sum of three Breit-Wigner functions. Two relative phase angles are free parameters in the fit. The dashed curve (pink) is the fit to BESIII results with the coherent sum of two Breit-Wigner functions without the $Y(4220)$ hypothesis. The arrows mark the locations of four energy points with large luminosities. Compared to the previous experimental results, the results in this analysis are in good agreement with those from BaBar and Belle, however, with significantly improved precision.

To study possible resonant structures in this process, a binned χ^2 fit is applied to describe the cross section line shape. A fit with three coherent Breit-Wigner functions is performed. The parameters of two resonances, the $Y(4220)$ and $Y(4390)$, are determined to be $M = 4209 \pm 7.4 \pm 1.4\,\mathrm{MeV}/c^2$ and $\Gamma = 80.1 \pm 24.6 \pm 2.9\,\mathrm{MeV}/c^2$ for the $Y(4220)$, and $M = 4383.8 \pm 4.2 \pm 0.8\,\mathrm{MeV}/c^2$ and $\Gamma = 84.2 \pm 12.5 \pm 2.1\,\mathrm{MeV}/c^2$ for the $Y(4390)$. The significance of the $Y(4220)$ is 5.8 σ, determined by a comparison with a fit without the $Y(4220)$ hypothesis. Both the $Y(4220)$ and $Y(4390)$ are consistent with the vector resonances observed in $e^+e^- \to \pi^+\pi^- h_c$.

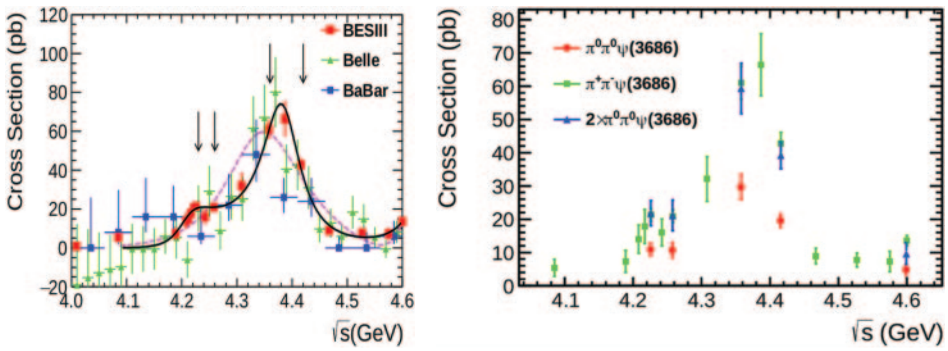

Fig. 1. – (left) Born cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$. The solid curve is the fit to BESIII results with three Breit-Wigner functions. The dashed curve is the fit with two Breit-Wigner functions without the $Y(4220)$ hypothesis. The arrows mark the location of four energy points with large luminosities. (Right) Born cross section of $e^+e^- \to \pi^0\pi^0\psi(3686)$ at 4.226, 4.258, 4.416, 4.600 GeV, respectively. The dots are the results obtained in this analysis, the triangles are twice the results and squares are the Born cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$ from BESIII.

As a cross check, the cross section of $e^+e^- \to \pi^0\pi^0\psi(3686)$ is measured at $\sqrt{s} = 4.226$, 4.258, 4.358, 4.416, 4.600 GeV, respectively [7]. As shown in fig. 1 (right), the dots (red) are the results obtained in this analysis, and the squares (blue) are the Born cross section of $e^+e^- \to \pi^+\pi^-\psi(3686)$ from ref. [4]. To compare to the charged process, the cross section of $e^+e^- \to \pi^0\pi^0\psi(3686)$ is multiplied by 2, as shown with the triangles (red). We can see that the cross section of $e^+e^- \to \pi^0\pi^0\psi(3686)$ is consistent to be half of those of $e^+e^- \to \pi\pi\psi(3686)$ with the expectation from isospin symmetry.

3·2. *Line shape measurement of* $e^+e^- \to K\bar{K}J/\psi$. – The process $e^+e^- \to K\bar{K}J/\psi$ is studied at $\sqrt{s}$ from 4.189 to 4.600 GeV [8]. The Born cross sections for $e^+e^- \to K^+K^-J/\psi$ and $K^0_SK^0_SJ/\psi$ are measured as a function of the center-of-mass energy, as shown in fig. 2. The cross sections of these two channels are consistent with the prediction from isospin symmetry. The energy dependence of the cross section for $e^+e^- \to K^+K^-J/\psi$ is different from that of $\pi^+\pi^-J/\psi$ in the region around $Y(4260)$ [2].

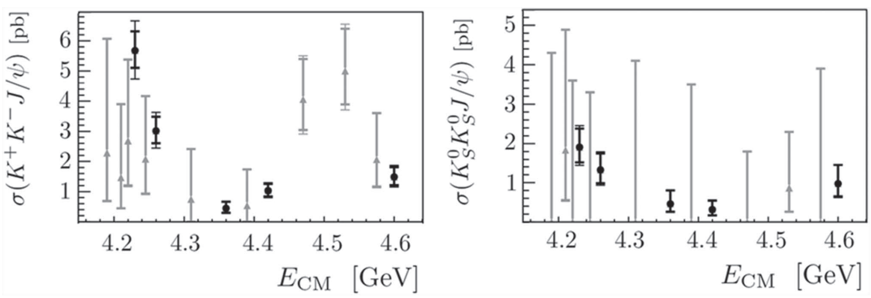

Fig. 2. – The cross sections of $\sigma(K^+K^-J/\psi)$ (left) and $\sigma(K^0_SK^0_SJ/\psi)$ (right). The black circular points are for data sets with high integrated luminosities; the gray triangular points are for the smaller data sets.

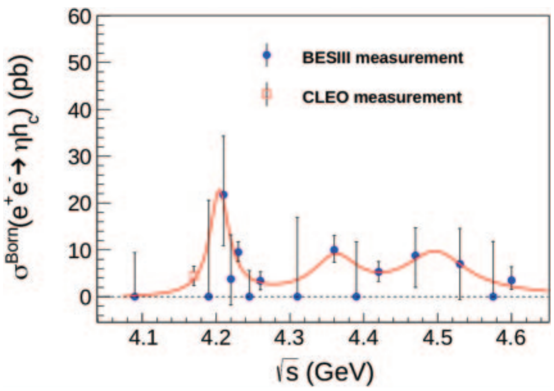

Fig. 3. – Fit to the cross section of $e^+e^- \to \eta h_c$ as a function of the center of mass energies.

3·3. *Measurement of* $e^+e^- \to \eta h_c$. – The process $e^+e^- \to \eta h_c$ is investigated at $\sqrt{s}$ from 4.085 to 4.600 GeV at BESIII [9]. Significant signals are observed at the center-of-mass energy 4.226 GeV for the first time, and the Born cross section is measured to be $9.5^{+2.2}_{-2.0} \pm 2.7$ pb. Evidence for ηh_c is observed at 4.358 GeV.

Figure 3 shows the energy dependent Born cross sections from this measurement. Taking into acount the CLEO measurement at 4.17 GeV [10], the cross section from 4.085 to 4.600 GeV is parameterized as the coherent sum of three Breit-Wigner functions, as shown by the solid line in fig. 3. In the fit, the parameters of the Breit-Wigner around 4.36 GeV are fixed to those of the $Y(4360)$ [11] while the other two Breit-Wigner functions are left free in the fit. The fitted parameters of the first one have a mass of $4204 \pm 6\,\text{MeV}/c^2$ and a width of 32 ± 22 MeV. Its mass is close to that observed in $\pi^+\pi^- J/\psi$, $\pi^+\pi^- h_c$ and $\pi^+\pi^- \psi(3686)$.

3·4. *Open-charm process* $e^+e^- \to \pi^+ D^0 D^{*-}$. – To understand the $Y(4260)$, a study of an open-charm process $e^+e^- \to \pi^+ D^0 D^{*-}$ is performed. This process could be strongly

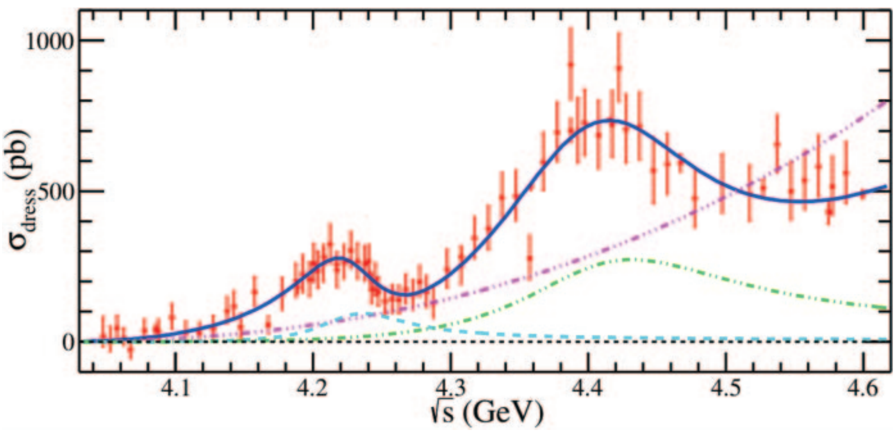

Fig. 4. – Fit to the cross section of $e^+e^- \to \pi^+ D^0 D^{*-}$ as a function of the center of mass energies.

enhanced since it is above the $D\bar{D}_1$ threshold [12]. Figure 4 shows the measured cross sections between 4.05 to 4.60 GeV. A clear enhancement around 4.23 GeV and a broad structure around 4.4 GeV are observed. To interpret the line-shape, a fit with two coherent Breit-Wigner functions is performed. The mass and width for the first structure are $4228.6 \pm 4.1 \pm 5.0\,\mathrm{MeV}/c^2$ and $77.1 \pm 6.8 \pm 2.7\,\mathrm{MeV}/c^2$, and for the second one are $4404.6 \pm 7.4 \pm 4.8\,\mathrm{MeV}/c^2$ and $191.7 \pm 13.0 \pm 15.1\,\mathrm{MeV}/c^2$ respectively. The first structure is consistent with the structure observed in the above processes, and consistent with the prediction of a $D\bar{D}_1(2420)$ molecule [12].

4. – Determination of spin and parity of the $Z_c(3900)$

In 2013, BESIII discovered a charged charmonium-like state $Z_c(3900)$ decaying into $\pi^\pm J/\psi$ by studying the process $e^+e^- \to \pi^+\pi^- J/\psi$ with a $525\,\mathrm{pb}^{-1}$ data sample at 4.26 GeV [13]. The mass and width of this state are determined to be $(3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$ and $(46 \pm 10 \pm 20)\,\mathrm{MeV}/c^2$, respectively. This state cannot be a conventional charmonium state, since it carries electric charge. The minimal quark content is a four quark combination.

Using a $1092\,\mathrm{pb}^{-1}$ data sample at 4.23 GeV and $827\,\mathrm{pb}^{-1}$ data at 4.26 GeV, the spin and parity of the $Z_c(3900)$ are determined employing a partial wave analysis with the helicity-covariant method. A simultaneous fit is performed to the two data sets. The fit results shown in fig. 5 indicate that process is dominated by the $\pi\pi$ S-wave resonances

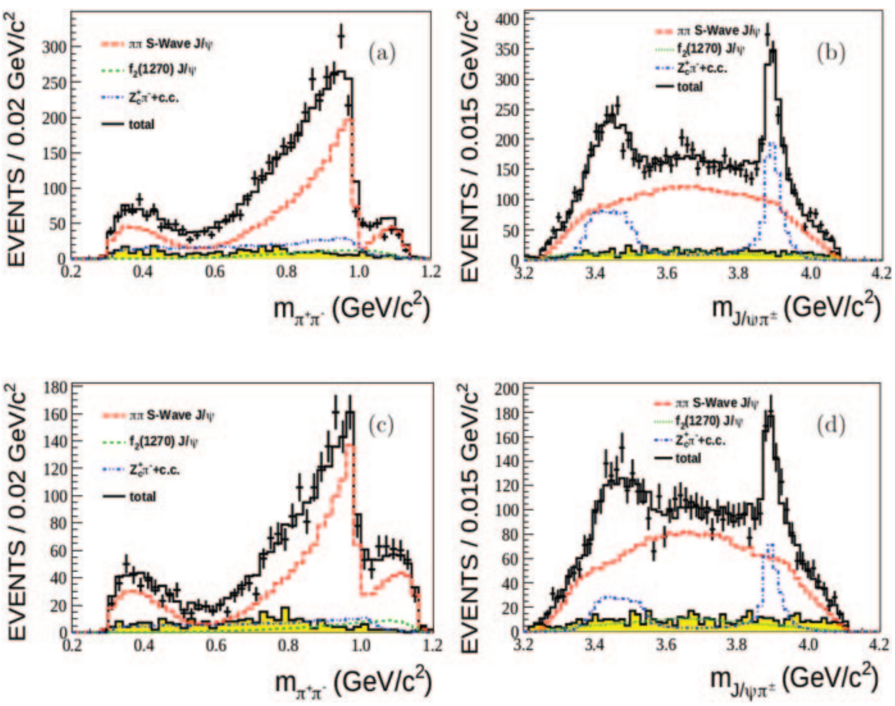

Fig. 5. – Projections to $m_{\pi^+\pi^-}$ ((a), (c)) and $m_{J/\psi\pi^\pm}$ ((b), (d)) of the fit results with $J^P = 1^+$ for the Z_c at $\sqrt{s} = 4.23\,\mathrm{GeV}$ ((a), (b)) and 4.26 GeV ((c), (d)). The points with error bars are data, and the black histograms are the fit results including backgrounds. The shaded histogram denotes backgrounds.

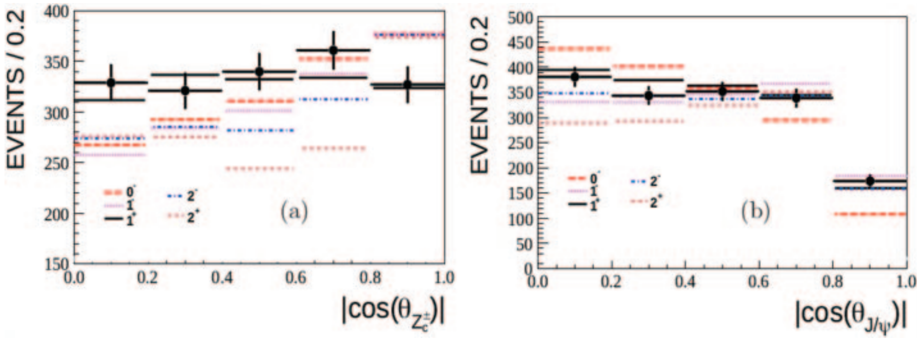

Fig. 6. – (a) Polar angle distribution of Z_c, (b) helicity angle distribution of J/ψ. The dots with error bars show the combined data with requirement $m_{J/\psi\pi^{\pm}}$ in the range of (3.86, 3.92) GeV/c^2, and compared to the total fit results with different J^P hypotheses.

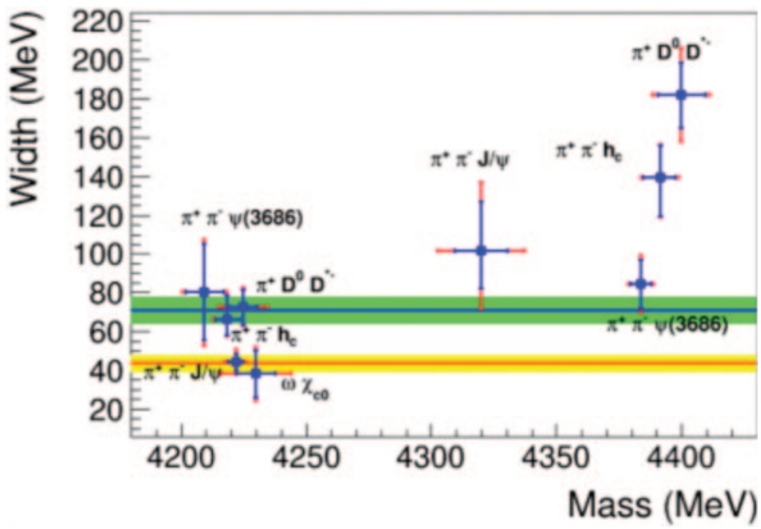

Fig. 7. – A summary of the measured mass and width from different processes.

(red histogram). The contribution of the Z_c state is shown in the blue histogram. The fit results, using different assumptions for the Z_c spin and parity, are compared with the experimental data, as shown in fig. 6. The distribution indicates that data favors a spin parity assignment of 1^+ for the $Z_c^{\pm}$ [14].

5. – Summary

The $Z_c(3900)$, discovered in the process of $e^+e^- \to \pi^+\pi^- J/\psi$, is investigated with more data collected at BESIII. With an amplitude analysis, the spin parity of this state is determined to be 1^+.

For the Y states, a series of studies has been performed via the measurement of cross section line-shapes, including the process $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^- h_c$, $\pi\pi\psi(3686)$, KKJ/ψ, ηh_c and $\pi^+ D^0 D^{*-}$. In these processes, a structure with mass around 4220 MeV/c^2, denoted as $Y(4220)$, is observed. At a mass around 4.4 GeV/c^2, structures are also observed. Figure 7 shows a summary of the observed structures in these processes. For the structure around 4220 MeV, the masses are well consistent between different channels, while the widths have a larger difference.

With more data at BESIII, more channels will be investigated and the nature of the structure at 4220 MeV will become clearer and clearer.

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