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XYZ physics at BESIII

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Abstract. In this talk, we present the recent study on the charmonium-like states from the BESIII Collaboration based on large data samples above $D\bar{D}$ threshold. The observation of $X(3872)$ from the $Y(4260)$ radiative transition, the study of the Y states from the $e^+e^- \to \pi^+\pi^- h_c$ process, and the observation of the charged Z_c states are included .

1 Introduction

Starting from B-factories, new states with characteristics different from conventional mesons are observed in the final states with a charmonium and some light hadrons. Due to the strange properties they carry, these states are called charmonium-like states or XYZ states.

The BESIII [1] experiment at the BEPCII collider started to take data since 2009. From the end of 2012, the experiment accumulated a lot of data around the peaks of the vector charmonium resonances above 4.0 GeV at 14 energy points [2], making possible a study of the charmonium-like states.

In this talk, we present the recent results from the BESIII experiment about the $X(3872)$ from a radiative transition of $Y(4260)$, the Y states from e^+e^- annihilation, and the charged Z_c states.

2 Observation of $X(3872)$ in $e^+e^- \to \gamma X(3872)$ [3]

The $X(3872)$ was first observed by the Belle Collaboration in the B decays $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ with a mass close to the $D^0\bar{D}^{*0}$ threshold and a width smaller than 1.2 MeV [4]. Since its discovery, it has stimulated a lot of interest about its nature. Theoretically, it has been explained as a loosely bound hadronic molecule, a $\chi_{c2}(2P)$ candidate, a mixture of charmonium and mesonic-molecule, and other configurations [5]. Experimentally, both BaBar and Belle experiments observed $X(3872) \to \gamma J/\psi$, which suggests it being a C-even state [6, 7]. Recently the LHCb experiment determined the spin parity of the $X(3872)$ to be $J^P = 1^+$ by using the angular analysis [9].

Currently, $X(3872)$ was only observed in B meson decays and hadron collisions. Since its quantum numbers are $J^{PC} = 1^{++}$, it could also be produced through a radiative transition of the vector charmonium or charmonium-like states such as the ψs and Ys.

The process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ has been studied in the BESIII experiment, with the J/ψ reconstructed using its decay into lepton pairs $J/\psi \to e^+e^-$, or $\mu^+\mu^-$. The analysis is performed by using the data samples collected at the center-of-mass (c.m.) energies $\sqrt{s}$ = 4.009, 4.230, 4.260, and 4.360 GeV.

The $\pi^+\pi^- J/\psi$ invariant mass spectrum summed over all the energy points is used to extract the mass and signal yields of the $X(3872)$. The signal events are described with a Monte Carlo (MC) simulated signal histogram convolved with a Gaussian function which account for the resolution difference between data and MC simulation, while the background events are described with a linear function. The initial state radiation (ISR) $\psi(3686)$ signal is used to calibrate the absolute mass scale and extract the resolution difference between data and MC simulation. The fitted results are shown in Fig. 1, the measured mass of the $X(3872)$ is $(3872.1 \pm 0.8 \pm 0.3)\,\mathrm{MeV}/c^2$. The statistical significance of $X(3872)$ estimated to be 5.3 σ by comparing the difference of the log-likelihood value with and without the $X(3872)$ signal in the fit, and the change of the number of degrees of freedom is taken into consideration.

The product of the Born cross section and the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ is calculated from $\frac{N^{obs}}{\mathcal{L}_{int}(1+\delta)\epsilon\mathcal{B}}$, where N^{obs} is the number of signal events obtained from the fit to the $\pi^+\pi^- J/\psi$ mass spectrum, $\mathcal{L}_{int}$ is an integrated luminosity, $(1+\delta)$ is the radiative correction factor, ϵ is the selection efficiency, and $\mathcal{B}$ is the branching fraction of $J/\psi \to l^+l^-$. The results are listed in Table 1. For 4.009 GeV and 4.360 GeV data, since the $X(3872)$ signal is not significant, the upper limits at 90% confidence level (C.L.) are given.

The cross section as a function of c.m. energy suggests that the $X(3872)$ might come from the radiative transition of $Y(4260)$. Taking the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ measured by BESIII [10] into account and assuming the branching fraction $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = 5\%$ [11], the fraction $\mathcal{R} = \frac{\sigma^B[e^+e^- \to \gamma X(3872)]}{\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)}$ is calculated to be about

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Table 1. The number of $X(3872)$ events, radiative correction factor, detection efficiency, measured Born cross section $\sigma^B(e^+e^- \to \gamma X(3872))$ times $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ ($\sigma^B \cdot \mathcal{B}$, where the first errors are statistical and the second systematic), and ISR $\psi(3686)$ cross section ($\sigma^{\rm ISR}$ with statistical error only) at different energy points. The upper limits are given at the 90% C.L.

$\sqrt{s}$ (GeV)	$N^{\rm obs}$	ϵ (%)	$1+\delta$	$\sigma^B \cdot \mathcal{B}$ (pb)	$\sigma^{\rm ISR}$ (pb)
4.009	< 1.4	25.5	0.861	< 0.12	712 ± 29
4.229	9.6 ± 3.1	31.5	0.799	$0.29 \pm 0.10 \pm 0.02$	412 ± 14
4.260	8.7 ± 3.0	30.5	0.814	$0.36 \pm 0.13 \pm 0.03$	385 ± 16
4.360	< 5.1	21.1	1.023	< 0.39	309 ± 17

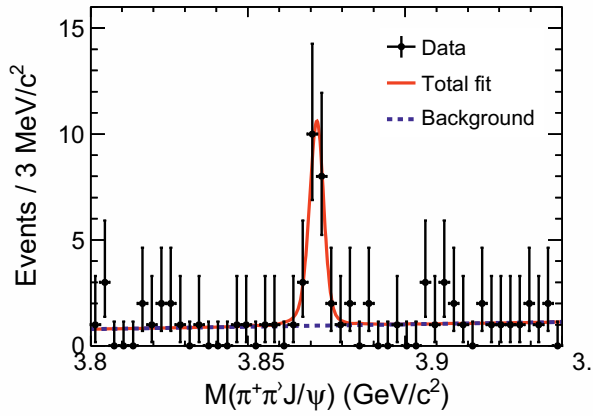

Figure 1. Fit to the summed $\pi^+\pi^- J/\psi$ invariant mass spectrum with MC simulated histogram convolved with a Gaussian function for signal and linear function for background. Dots with error bars are data, and the curves are the best fit.

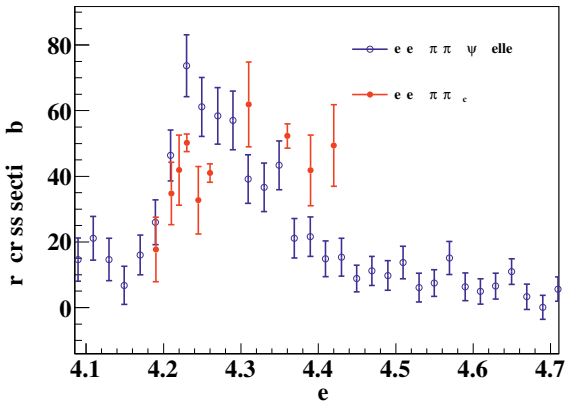

Figure 2. The comparison between the cross sections of $e^+e^- \to \pi^+\pi^- h_c$ from the BESIII experiment (solid dots with error bars), and those of $e^+e^- \to \pi^+\pi^- J/\psi$ from the Belle experiment (open circles with error bars).

11%. The measured relatively large decay width near 4.260 GeV is partly similar to model dependent calculations in Ref. [12]

3 The Y states

The Y-states in the charmonium system are mainly observed at the B-factories via ISR process. In the process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$, the Babar experiment observed the $Y(4260)$ [13]. This structure was also confirmed in the CLEO [14] and Belle experiments [15] using the same method. Besides, in Belle data, there is another broad structure near 4.008 GeV, which is called $Y(4008)$ in the Belle paper. In the process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(3686)$, BaBar found a structure around 4.32 GeV [16], while Belle observed two structures at 4.36 and 4.66 GeV [17]. The higher resonance was confirmed recently by the updated BaBar results [18]. The BESIII data samples taken at this region are also used to study to the Y-states in the $e^+e^- \to \pi^+\pi^- h_c$ process and $e^+e^- \to \pi^+\pi^- J/\psi$ process.

The $e^+e^- \to \pi^+\pi^- J/\psi$ process was studied at BESIII experiment using 525 pb^{-1} data taken at c.m. energy $\sqrt{s} = 4.260$ GeV with J/ψ reconstructed by its decay into lepton pair [10]. The Born cross section is measured to be $\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb, which is consistent with the result from both BaBar and Belle experiments. The cross section measurement at other energy points will help to clarify the difference between BaBar and Belle experiments around 4.008 GeV.

The $e^+e^- \to \pi^+\pi^- h_c$ process was observed by CLEO-c using 586 pb^{-1} e^+e^- collision data taken at 4.170 GeV [19]. Together with the scan data sample at other three energy regions, the CLEO-c result shows that the cross section of $e^+e^- \to \pi^+\pi^- h_c$ is comparable to the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$, and also hints to a rise in the $\pi^+\pi^- h_c$ cross section at 4.260 GeV.

BESIII studied this process using data samples taken at 13 energy points from 3.900 to 4.420 GeV [2]. The h_c is reconstructed through its electric-dipole (E1) transition $h_c \to \gamma\eta_c$, while η_c is reconstructed using 16 of its hadronic decay modes: $p\bar{p}$, $\pi^+\pi^- p\bar{p}$, $\pi^+\pi^- K^+K^-$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)K^+K^-$, $K^0_S K^\pm\pi^\mp$, $K^0_S K^\pm\pi^\mp\pi^+\pi^-$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$. Here K^0_S is reconstructed from its $\pi^+\pi^-$ decays, and the π^0 and η from its $\gamma\gamma$ final states. The data samples and Born cross sections are listed in Table 2.

Figure 2 shows the comparison of $\sigma^B(e^+e^- \to \pi^+\pi^- h_c)$ from this measurement and $\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)$ from the Belle experiment. The Born cross sections of $e^+e^- \to \pi^+\pi^- h_c$ are at the same order of magnitude as those of $e^+e^- \to \pi^+\pi^- J/\psi$, but with a difference line shape. There is a broad structure at high energy with a possible local maximum at around 4.23 GeV.

Table 2. $e^+e^- \to \pi^+\pi^- h_c$ cross sections (or upper limits at the 90% confidence level). The third errors are from the uncertainty in $\mathcal{B}(h_c \to \gamma\eta_c)$ [20].

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$n^{\rm obs}_{h_c}$	$\sigma(e^+e^- \to \pi^+\pi^- h_c)$ (pb)
3.900	52.8	< 2.3	< 8.3
4.009	482.0	< 13	< 5.0
4.090	51.0	< 6.0	< 13
4.190	43.0	8.8 ± 4.9	$17.7 \pm 9.8 \pm 1.6 \pm 2.8$
4.210	54.7	21.7 ± 5.9	$34.8 \pm 9.5 \pm 3.2 \pm 5.5$
4.220	54.6	26.6 ± 6.8	$41.9 \pm 10.7 \pm 3.8 \pm 6.6$
4.230	1090.0	646 ± 33	$50.2 \pm 2.7 \pm 4.6 \pm 7.9$
4.245	56.0	22.6 ± 7.1	$32.7 \pm 10.3 \pm 3.0 \pm 5.1$
4.260	826.8	416 ± 28	$41.0 \pm 2.8 \pm 3.7 \pm 6.4$
4.310	44.9	34.6 ± 7.2	$61.9 \pm 12.9 \pm 5.6 \pm 9.7$
4.360	544.5	357 ± 25	$52.3 \pm 3.7 \pm 4.8 \pm 8.2$
4.390	55.1	30.0 ± 7.8	$41.8 \pm 10.8 \pm 3.8 \pm 6.6$
4.420	44.7	29.1 ± 7.3	$49.4 \pm 12.4 \pm 4.5 \pm 7.6$

4 Observations of Z_c states

This year, four charged charmonium-like states were observed by BESIII, the $Z_c(3900)$, the $Z_c(4020)$, the $Z_c(3885)$, and the $Z_c(4025)$. These states have at least four quarks, carry electric charge and close to the threshold. The observation of these states seems to indicate that a new class of hadrons has been observed.

4.1 Observation of the $Z_c(3900)$ [10]

In the study of the process $e^+e^- \to \pi^+\pi^- J/\psi$ using a 525 pb^{-1} data sample taken at $\sqrt{s} = 4.260$ GeV, the BESIII experiment observed a structure near 3.9 GeV in the invariant mass spectrum of $\pi^\pm J/\psi$ with a statistical significance larger than 8σ. This structure, called as $Z_c(3900)$, was also observed in the Belle experiment [21] and shortly after confirmed by CLEO data with 586 pb^{-1} data taken at 4.170 GeV [22].

An unbinned maximum likelihood fit to the distribution of $M_{\rm max}(\pi^\pm J/\psi)$, as shown in Fig. 3, determined the mass and width to be $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and $(46 \pm 10 \pm 20)$ MeV, respectively. In the fit, the signal events are described by an S-wave Breit-Wigner (BW) function convolved with a Gaussian function with a mass resolution fixed at the MC simulated value. The phase space factor and the efficiency correction are also considered in fit, while the possible interference bewteen signal and background is neglected. The $Z_c(3900)^\pm$ signal yield from the fit is 307 ± 48, and the production ratio is calculated to be $R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(3900) \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.5)\%$

This state is close to the $D\bar{D}^*$ mass threshold, and can not be explained as a conventional charmonium state. After its observation, it is interpreted either as a tetraquark state, $D\bar{D}^*$ molecule, hadro-quarkonium, or other configurations, however its nature is still unclear.

4.2 Observation of the $Z_c(4020)$ [2]

In the process $e^+e^- \to \pi^+\pi^- h_c$, BESIII not only measured the cross section at c.m. energies between 3.900 and 4.420 GeV, but also analysed the Dalitz plot of the $\pi^+\pi^- h_c$ system at 4.230, 4.260, and 4.360 GeV. A structure around 4.02 GeV is observed in the $\pi^\pm h_c$ invariant mass spectrum, and there is also a hint of $Z_c(3900)$.

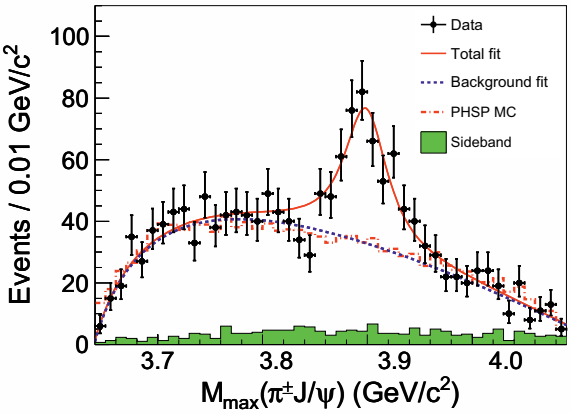

Figure 3. The $M_{\rm max}(\pi^\pm J/\psi)$ distribution and best fit. The dots with error bars are data; the red solid curve shows the best fit, and the blue dotted curve the background; the red dotted-dashed histogram shows the phase space distribution from MC simulation; and the green shaded histogram shows the normalised non-J/ψ background from J/ψ sideband.

A simultaneous fit to the $\pi^\pm h_c$ mass spectrum in the three energy points using the same signal function with common mass and width are shown in Fig. 4. The signal shape is parameterized as a constant width BW function convolved with a Gaussian with a mass resolution determined from data directly; while the background shape is parameterized as an ARGUS function. The phase space factor and the efficiency correction are also considered in the fit. The fit yields a mass of $(4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2 and a width of $(7.9 \pm 2.7 \pm 2.6)$ MeV. By comparing the fit likelihoods with and without the signal, the statistical significance of the $Z_c(4020)$ signal is calculated to be greater than 8.9σ. The $Z_c(4020)$ is close to the $D^*\bar{D}^*$ mass thresh-

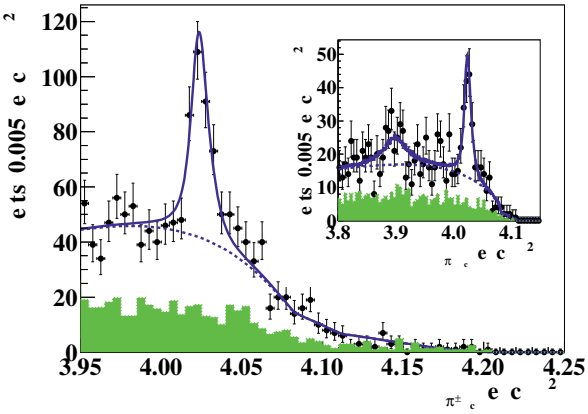

Figure 4. Sum of the simultaneous fits to the $M_{\pi^\pm h_c}$ distributions at 4.230, 4.260, and 4.36 GeV; the inset shows the sum of the simultaneous fit to the $M_{\pi^+ h_c}$ distributions at 4.230 and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

old, and similar to the $Z_c(3900)$, it contains more than just a pair of charm quarks.

Using the $Z_c(4020)^\pm$ signal yields from the fit, the cross section $\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^+\pi^- h_c)$ is calculated to be $(8.7 \pm 1.9 \pm 2.8 \pm 1.4)$ pb, $(7.4 \pm 1.7 \pm 2.1 \pm 1.2)$ pb, and $(10.3 \pm 2.3 \pm 3.1 \pm 1.6)$ pb at 4.230, 4.260, and 4.360 GeV, respectively. There is no siginificant $Z_c(3900)$ signal in the $\pi^\pm h_c$ mass spectrum, adding a $Z_c(3900)$ with mass and width fixed to the BESIII measurement [10] in the fit, results in a statistical significance of 2.1σ. The upper limits at 90% C.L. on the production cross section are determined to be $\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c) <$ 13 pb at 4.230 GeV and $<$ 11 pb at 4.260 GeV. The cross section at 4.260 GeV is lower than that of $Z_c(3900) \to \pi^\pm J/\psi$.

4.3 Observation of the $Z_c(3885)$ in the $D\bar{D}^*$ final state [23]

Using 525 pb^{-1} data taken at a c.m. energy of 4.260 GeV, BESIII experiment performed a study of the process $e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$. In order to include more signal events, a partial reconstruction technique is used in the analysis, which means only the bachelor $\pi^\pm$ and one final-state D meson are detected, the $\bar{D}^*$ is inferred from energy-momentum conservation. Here D^0 is reconstructed by its decay into the $K^-\pi^+$ final states, and D^+ from its $K^-\pi^+\pi^+$ decay.

In the recoil mass of the bachelor $\pi^\pm$, an enhancement, called $Z_c(3885)$is observed near the $D\bar{D}^*$ mass threshold, as shown in Fig. 5. Fits to the mass spectrum using a mass-dependent-width BW line-shape to model the signal and smooth threshold functions to represent the background. The combined mass and width (pole position) are $M = (3885.9 \pm 1.5 \pm 4.2)\,\mathrm{MeV}/c^2$ and $\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV, respectively, and the product of the Born cross section times the branching fraction of $Z_c(3885) \to D\bar{D}^*$ is calculated to be $(83.5 \pm 6.6 \pm 22.0)$ pb. Assuming the $Z_c(3885)$ observed here and the $Z_c(3900)$ observed in $\pi^+\pi^- J/\psi$ process are the same state, the ratio of partial decay widths is determined to be $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium state above the open charm threshold.

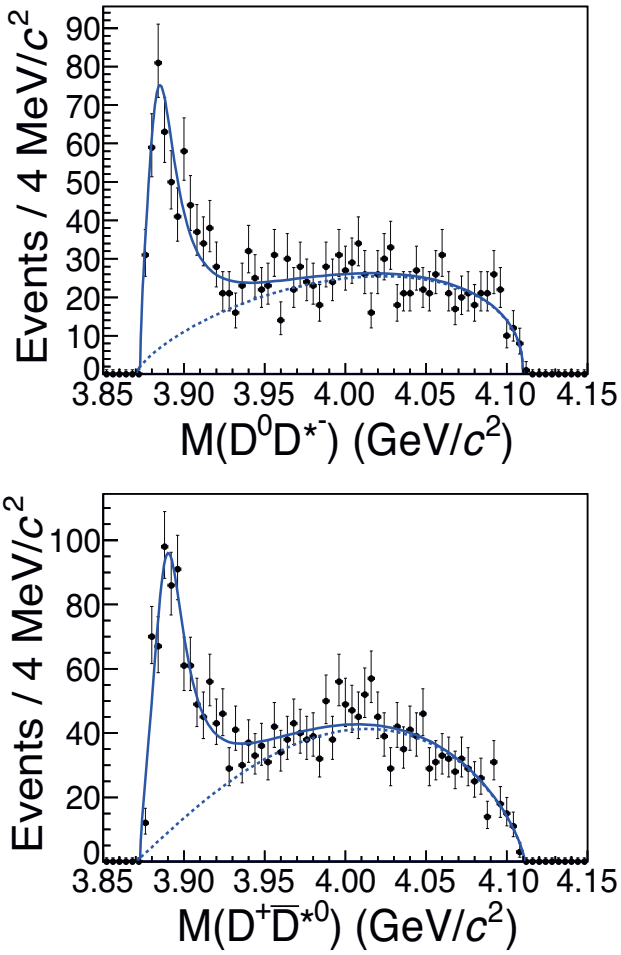

Figure 5. The $M(D^0D^{*-})$ and $M(D^+\bar{D}^{*0})$ distributions for selected events. The curves are the best fit results.

Besides, BESIII experiment also studied the quantum numbers of $Z_c(3885)$ by examining the pole angle distribution of the bachelor pion. Figure 6 shows the efficiency corrected fractional signal yield as a function of $|\cos\theta_\pi|$, together with the different J^P assumptions. The data agree well with the flat expectation for $J^P = 1^+$.

4.4 Observation of the $Z_c(4025)$ in the $D^*\bar{D}^*$ final state [24]

Using a similar partial reconstruction technique, BESIII also performed a study of the $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ process at a c.m. energy of 4.260 GeV using a 827 pb^{-1} data sample. Only the charged D meson and the bachelor pion are reconstructed, here the charged D meson is reconstructed by its decay into the $K\pi\pi$ final state. The candidate events

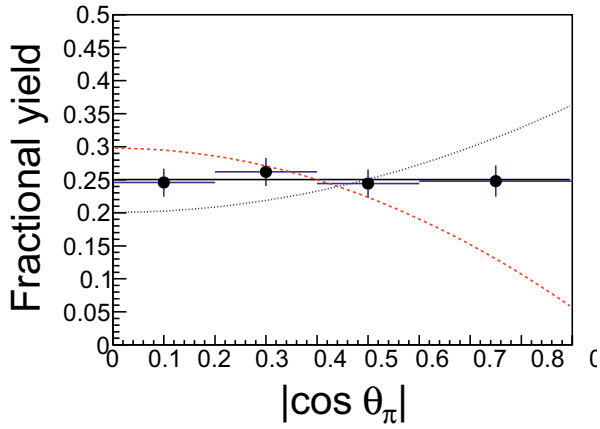

Figure 6. $(1/N_{tot})dN/d|\cos\theta_\pi|$ *versus* $|\cos\theta_\pi|$ for $Z_c(3885)$ events in data. The solid, dashed and dotted curves show expectations for $J^P = 1^+$, 0^-, and 1^-, respectively.

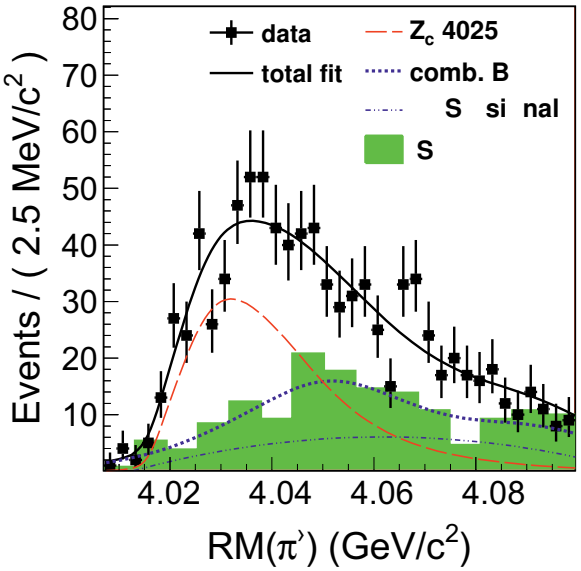

Figure 7. Unbinned maximum likelihood fit to the π^- recoil mass spectrum in data. Dots with error bars are data, solid curve is the best fit result.

are required to have at least one addtional π^0 reconstructed in the final states to further suppress backgrounds.

In the recoil mass spectrum of the bachelor $\pi^\pm$, a structure near the $(D^*\bar{D}^*)^\pm$ threshold which can not be explained by the phase space events and possible background events is observed, which is denoted as the $Z_c(4025)$. Figure 7 shows the mass distribution. Applying an unbinned maximum likelihood fit to the mass spectrum yields a mass of $(4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2, and a width of $(24.8 \pm 5.6 \pm 7.7)$ MeV. The Born cross section of $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ is calculated to be $(139 \pm 9 \pm 15)$ pb, and the production ratio $\frac{\sigma(e^+e^-\to Z_c^\pm(4025)\pi^\mp\to(D^*\bar{D}^*)^\pm\pi^\mp)}{\sigma(e^+e^-\to(D^*\bar{D}^*)^\pm\pi^\mp)}$ is determined to be $0.65 \pm 0.09 \pm 0.06$.

This year, BESIII experiment observed 4 charged charmonium-like states. Two of them are close to the $D\bar{D}^*$ mass threshold, and two of them are close to the $D^*\bar{D}^*$ mass threshold. In each class, the parameters of the two structures are consistent with each other within 2σ. Whether these four states are actually two states need further study.

5 Summary

In summary, BESIII started studying the XYZ particles. The $X(3872)$ has been observed from a radiative decay of a vector charmonium or charmonium-like state. Four charged charmonium states have been observed, $Z_c(3900)$, $Z_c(4020)$, $Z_c(3885)$, and $Z_c(4025)$, these states may indicate that a new type of hadrons has been observed. Using the current large data sample at several energy points, the cross section of $e^+e^- \to \pi^+\pi^- h_c$ has been measured, which is very different from that of $e^+e^- \to \pi^+\pi^- J/\psi$.

In the near future, BESIII experiment will take more data in the XYZ region, which will certainly improve our understanding of these states.

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