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Exotics at BESIII

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Abstract. Using the 1.31×10^{10} J/ψ events and the data above open charm collected at BESIII detector, we studied and observed a lot of exotics, including $X(3872), X(3823), Y(2175), Y(4140), Z_c(3900), Z_c(4020)$, and so on. Some of them are confirmed, some of them are observed for the first time, and some of them are searched, but with no obvious signal.

1 Introduction

The exotics are quite different from the common hadrons though they are not forbidden by QCD theory. The study on these exotics is very helpful to understand the nature of hadrons. A lots of exotics, some of them are called X, Y, and Z states, are observed in different experiments. However, our understanding to these exotics is quite limited. For example, the Y(4260) is discovered in ISR process $e^+e^- \to \gamma\pi^+\pi^+ J/\psi$, and despite its subsequent observation, its nature has remained a mystery. Considering that its mass above open charm and its strong coupling to $\pi^+\pi^+ J/\psi$, it is regarded as a non-conventional state of charmonium.

In this paper, we report the study on X, Y, and Z states at BESIII detector.

2 X states

2.1 $X(3872)$

The $X(3872)$ was first observed 10 years ago by Belle [1] in $B^+ \to K^\pm\pi^+\pi^+ J/\psi$ decays; it subsequently confirmed by several other experiments [2–4]. Its J^{PC} is determined to be 1^{++} by other decay modes and angular information. In order to understand the puzzle of $Y(4260)$ and $Y(4360)$, an investigation of their other decay processes, such as their radiative decay to the low lying charmonium or charmoniumlike states is important. The process of $Y(4260)/Y(4360) \to \gamma X(3872)$ is unique due to the exotic feature of $X(3872)$ and $Y(4260)$ or $Y(4360)$ resonances. We study the process of $e^+e^- \to \gamma X(3872), X(3872) \to \pi^+\pi^+ J/\psi, J/\psi \to l^+l^-$ ($l^+l^- = e^+e^-$ or $\mu^+\mu^-$) using the data collected at $\sqrt{s}$=4.009 GeV and 4.42 GeV. Figure 1 (top-left) shows the fit to $M_{\pi^+\pi^+ J/\psi}$ with sum of all energies. A clear X(3872) signal is seen with a statistical significance of 6.3σ. The product of the Born-order cross section times the branching fraction of $X(3872) \to \pi^+\pi^+ J/\psi$ is calculated at 4 energies. Figure 1 (bottom-left) shows the fit to the energy-dependent Born cross section with a Y(4260) resonance, a linear continuum, or a E1-transition phase space. The Y(4260) resonance describes better than the other two options.

2.2 $X(3823)$

The lightest charmonium state above $D\bar{D}$ is $\psi(3770)$, which is currently defined as 1^3D_1 state [5]. Until now, there have been no definitive observations its two D-wave spin-triplet partner states. i.e., 1^3D_2 and 1^3D_3 states. Phenomenological models predict that the 1^3D_2 charmnium state has large decay widths to $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$. Recently, the Belle Collaboration reported evidence for a narrow resonance $X(3823) \to \gamma\chi_{c1}$ in B meson decays with 3.8σ significance and mass $3823.1 \pm 1.8 \pm 0.7$ MeV/c^2, and suggested that this is a good candidate for the 1^3D_2 charmonium state [6]. We performed search for the production of the 1^3D_2 state via the process $e^+e^- \to \pi^+\pi^-X$, using 4.67 fb^{-1} data at $\sqrt{s}$ =4.19-4.60 GeV. The 1^3D_2 candidates are reconstructed in their $\gamma\chi_{c1,2}$ decay modes. Figure 1 (top-left) shows the fit to $M_{recoil}(\pi^+\pi^-)$ of $\gamma\chi_{c1,2}$, respectively. The statistical significance of the $X(3823)$ signal in $\gamma\chi_{c1}$ mode is estimated to be 6.2σ. For the $\gamma\chi_{c2}$ mode, we don't observe an $X(3823)$ signal. The $X(3823)$ is a candidate for the 1^3D_2 charmonium state with $J^{PC} = 2^{--}$. The product of the Born-order cross section and the branching ratio of $X(3823) \to \gamma\chi_{c1,2}$ is calculated. We fit the energy-dependent cross sections of $e^+e^- \to \pi^+\pi^-X(3823)$ with the $Y(4360)$ shape or the $\psi(4415)$ shape with their resonance parameters fixed to the PDG values. Figure 1 (bottom-right) shows the fit results. Due to the low statistics, we accept both the $Y(4360)$ and $\psi(4415)$ hypotheses at 90% C.L.

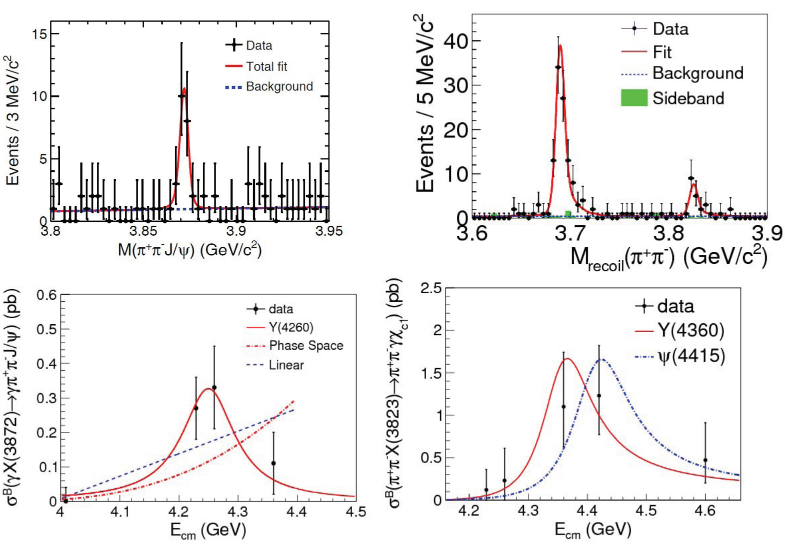

Figure 1. (top-left) $X(3872)$ signal. (top-right) $X(3823)$ signal. (bottom-left) Born cross-section of $e^+e^- \to \gamma X(3872)$. (bottom-right) Born cross-section of $e^+e^- \to \gamma X(3823)$

3 Y state

3.1 $Y(2175)$

The $Y(2175)$ was first observed by the *BABAR* experment [7] in the $e^+e^- \to \gamma_{ISR}\phi f_0(980)$ process. It was later confirmed by the BESII experiment in $J/\psi \to \eta\phi f_0(980)$ decays [8] and other experiments. Since the $Y(2175)$ has $J^{PC} = 1^{--}$, one speculates whether it may be an s-quark counterpart to the

$Y(4260)$. A number of different interpretations have been proposed for the $Y(2175)$. The confirmation and study of the $Y(2175)$ in $J/\psi \to \eta\phi\pi^+\pi^-$ with a large data sample is necessary for clarifying its nature. Figure 2 (left) shows the fit results to $\phi f_0(980)$ invariant mass spectrum. The solid curve is the overall fit projection and a clear $Y(2175)$ signal is seen [9]. Its mass and width are determined to be $M = 2200 \pm 6$ MeV/c^2 and $\Gamma = 104 \pm 15$ MeV, respectively.

3.2 $Y(4140)$

The CDF experiment observed the $Y(4140)$ in the decay of $B^+ \to \phi J/\psi K^+$ with a statistical significance greater than 5σ [10]. However, this new state was not confirmed by the Belle and LHCb collaborations, but confirmed by CMS and D0 Collaborations. The $Y(4140)$ is the first charmoniumlike state decaying into two vector mesons consisting of $c\bar{c}$ and $\Sigma^0\bar{\Sigma}^0$ pairs. Since the $\phi J/\psi$ system has positive C-parity, and can be searched for through radiative transitions of $Y(4260)$ or other 1^{--} charmonium or charmoniumlike states. Here, we report a search for the radiative transition $Y(4260) \to \gamma Y(4140) \to \gamma\phi J/\psi$ with the data collected at $\sqrt{s} = 4.23, 4.26$, and 4.36 GeV. As a result, no obvious signal is found in $\phi J/\psi$ mass spectrum (see Fig. 2 (right)) and the upper limit is given [11].

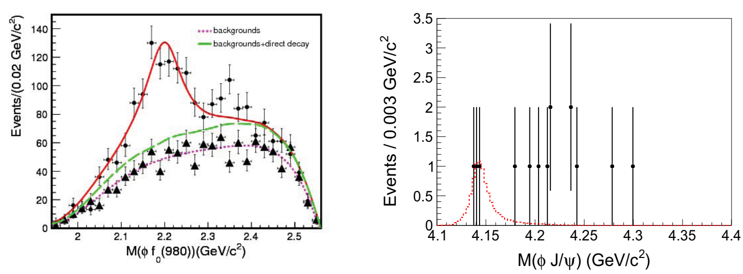

Figure 2. (left) The invariant mass of $\phi f_0(980)$ in $J/\psi \to \pi^+\pi^-\phi\eta$. (right) The invariant mass of $\phi J/\psi$ in $e^+e^- \to \gamma K^+K^-J/\psi$.

3.3 $e^+e^- \to \omega\chi_{cJ}$

The authors of Ref. [12] predict a sizeable coupling between the $Y(4260)$ and the $\omega\chi_{c0}$ channel by the considering the threshold effect that plays a role in reducing the decay rates into open-charm channels. By adopting the spin rearrangement scheme in the heary quark limit and the experimental information, Ref. [13] predicts the ratio of the decays $Y(4260) \to \omega\chi_{cJ}(J = 0, 1, 2)$ to be 4:3:5.

Enhancements can be seen in the line shapes of $\omega\chi_{c0}$ mode. It is fitted with a phase-space modified BW function, and the fit results for the structure parameters are $\Gamma_{ee}\mathcal{B}(\omega\chi_{c0}) = (2.8 \pm 0.5 \pm 0.4)$ eV, $M = (4226 \pm 8 \pm 6)$ MeV/c^2, and $\Gamma_t = (39 \pm 12 \pm 2)$ MeV, where M, Γ_{ee}, Γ_t are mass, total width, e^+e^- partial for the potential Y state. In the $e^+e^- \to \omega\chi_{c2}$ cross section, an enhancement is seen around 4.146 GeV, so we use a coherent sum of the $\psi(4415)$ BW function and a phase-space term to fit the cross section. There are two solutions, constructive and destructive [14]. The cross section of $e^+e^- \to \omega\chi_{c1}$ seems to be raising near 4.6 GeV. The different line shapes observed for $\omega\chi_{cJ}$ might indicate that the production mechanism is different.

4 Z states

4.1 $Z_c(3900)$ and $Z_c(3885)$

The nature of $Y(4260)$ has remained a mystery since its discovery. Unlike other charmonium states with the same quantum numbers and in the same mass region, the $Y(4260)$ state does not have a natural place within the quark model of charmonium. Furthermore, it shows strong coupling to the $\pi^+\pi^+ J/\psi$ final state, but relatively small coupling to open charm decay modes. A similar situation has recently become apparent in the bottomonium system above the $b\bar{b}$ threshold. The observed substructure in these two decay modes indicates the possible existence of charged bottomniumlike state [15], which must have a t least four constituent quarks. By analogy, this suggests there may exist interesting substructure in the $Y(4260) \to \pi^+\pi^+ J/\psi$ process in the charmonium region. Figure 3 (left) shows the distribution of $M_{max}(\pi^\pm J/\psi)$, the larger one of the two mass combinations $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$ in each event. A clear structure near 3.9 GeV is seen An unbinned maximum likelihood fit yields a mass of (3899.0 ± 3.6) MeV/c^2, and a width of (46 ± 10) MeV [16]. Later a search of its neutral isospin partner, $Z_c(3900)^0$, was also performed in $e^+e^- \to \pi^0\pi^0 J/\psi$ process in BESIII [17]. The $Z_c(3900)^0$ mass and width values with statistical and systematic errors are consistent with the charged $Z_c(3900)^\pm$. Meanwhile, we also calculated the Born cross section of $e^+e^- \to \pi^+\pi^+ J/\psi$ at different energies. Compared with the measured Born cross sections of $e^+e^- \to \pi^+\pi^+ J/\psi$ by Belle, we found that the ratio between charged and neutral is consistent with the isospin symmetry expectation for resonances

A peculiar feature of $Y(4260)$ is the absence of any apparent corresponding structure in the cross sections for $e^+e^- \to D^{(*)}\bar{D}^{(*)}(\pi)$ in the same energy region. This implies a partial-width lower-limit of $\Gamma(Y(4260) \to \pi^+\pi^+ J/\psi) > 1$ MeV that is 1 order of magnitude larger than is typical for conventional charmonium meson transitions, and indicates that the $Y(4260)$ is probably not a conventional quarkonium state. The mass of observed $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^+ J/\psi$ is 24 MeV/c^2 above the $D\bar{D}^*$ mass threshold, which is suggestive of a virtual $D\bar{D}^*$ moleculelike structure, i.e., a charmed-sector analogy of the $Z_b(10650)$. We observed a peak in the $(D\bar{D}^*)^-$ invariant mass distribution in $e^+e^- \to \pi^+(D\bar{D}^*)^-$ annihilation events at $\sqrt{s}$=4.26 GeV [18]. Figure 3 (right) shows the distribution of D^0D^{*-} invariant masses. There is a distinct peak near the $m_D + m_{\bar{D}^*}$ mass threshold. The solid curves show the fit results and the dashed curves show the non-resonant background. The $Z_c(3885)$ signal significance for each fit is greater than 18σ. Later, its neutral isospin partner is also observed in the processes $e^+e^- \to D^+D^{*-}\pi^0$ +c.c. and $e^+e^- \to D^0\bar{D}^{*0}\pi^0$+ c.c. at $\sqrt{s}$ =4.226 and 4.257 GeV [19]. The fitted mass and width to the enhancement in neutral mode are very consistent with those of the charged $Z_c(3885)$. Meanwhile, we also determined the ratio, $\mathcal{R} = \mathcal{B}_{D^+D^{*-}}/\mathcal{B}_{D^0\bar{D}^{*0}}$ to be 0.96 ± 0.18, which is very close to the expectation value from isospin conservation.

Assuming the $Z_c(3885)$ structure is due to the $Z_c(3900)$, the ratio of partial decay widths is determined to be $(\Gamma(Z_c(3885) \to D\bar{D}^*)/\Gamma(Z_c(3900) \to \pi J/\psi)) = 6.2 \pm 1.1 \pm 2.7$. This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold. This suggests the influence of very different dynamics in the $Y(4260) - Z_c(3900)$ system.

4.2 $Z_c(4025)$ and $Z_c(4020)$

The mass of observed $Z_b(10610)$ and $Z_b(10650)$ at the Belle experiment [15] are close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively, which supports a molecular interpretation of Z_b's as $B\bar{B}^*$ and $B^*\bar{B}^*$ bound states. One intriguing suggestion is to look for corresponding particles in the charmonium sector. As anticipated, a charged charmoniumlike structure, $Z_c(3900)$, has been observed in the $\pi^\pm J/\psi$ mass spectrum by three experiments. Therefore, a search of Z_c candidates via their direct decays

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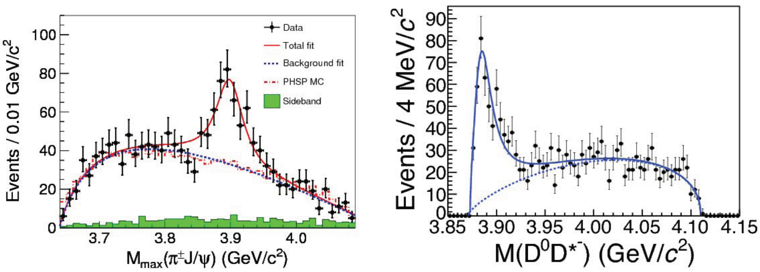

Figure 3. (left) The invariant mass of $\pi^{\pm}J/\psi$ in $e^+e^- \to \pi^+\pi^+J/\psi$. (right) The invariant mass of $D^0\bar{D}^{*-}$ in $e^+e^- \to \pi^+D^0\bar{D}^{*-}$.

into $D^*\bar{D}^*$ pairs is strongly motivated. We study the process $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{mp}$ at a center-of-mass energy $\sqrt{s}$=4.26 GeV, where $(D^*\bar{D}^*)$ refers to the sum of the $D^{*+}\bar{D}^{*0}$ and its charge conjugate $\bar{D^{*+}}D^{*0}$ states. Here, we use a partial reconstruction technique to identify the $D^{*+}\bar{D}^{*0}\pi^-$ final states This technique requires that only the pi^- from the primary decay (denoted as the bachelor π^-), the D^+ decaying from $D^{*+} \to D^+\pi^0$, and at least one soft π^0 from D^{*+} or $\bar{D}^{*0}$ decay are reconstructed. By reconstructing the D^+ particle the charges of its other particle D^{*+} and the bachelor π^- can be unambiguously identified. Therefore, possible combinatoric backgrounds are suppressed with respect to the signals. Figure 4 (left) shows the recoil mass of bachelor π^- with the events in $D^{*+}\bar{D}^{*0}$ mass region. An enhancement near $D^{*+}\bar{D}^{*0}$ threshold is seen [20]. We assume that this enhancement is due to a particle, Labeled as $Z_c(4025)^+$, and parameterized its line shape by the product of an S-wave BW shape and a phase space factor. An unbinned maximum likelihood fit to the π^- recoil mass spectrum yields the mass $m = (4026.3 \pm 2.6)$ MeV/c^2 and $\Gamma = (24.8 \pm 5.6)$ MeV. Later its neutral isospin partner, $Z_c(4025)^0$ is also observed in $e^+e^- \to (D^*\bar{D}*)\pi^0$. A clear enhancement near $D^*\bar{D}^*$ mass threshold is seen. A simultaneous unbinned maximum likelihood fit yields the pole position $m_{pole} = (4025.5^{+2.0}_{-4.7})$ MeV/c^2 and width at pole $\Gamma_{pole} = (23.0 \pm 6.0)$ MeV [21], which are consistent with those of the charged $Z_c(4025)$.

After the report of the observation of charged $Z_c(4025)$, someone points that it may couple to $\pi^{\pm}h_c$. Thus it can be searched for in $e^+e^- \to \pi^+\pi^-h_c$. We present such a search at 13 energies from 3.900 to 4.420 GeV. Here, the h_c is reconstructed via its electric-dipole transition $h_c \to \gamma\eta_c$ with η_c decays to 16 exclusive hadronic final states. Figure 4 (right) shows the fit to the invariant mass of $M_{\pi^{\pm}h_c}$ (two entries per event) distribution. The fit yields a mass of (4020 ± 0.8) MeV/c^2 and a width of (7.9 ± 2.7) MeV. We also tried to add a $Z_c(3900)$ with the mass and width fixed to the measured value. It is found that the statistical significance of $Z_c(3900)$ is 2.9σ. Later, with similar technique, we observed the neutral charmoniumlike state $Z_c(4020)^0$ in $e^+e^- \to \pi^0\pi^0h_c$ process [23]. An unbinned maximum likelihood fit with the fixed width to its charged partner yields a $Z_c(4020^0$ mass of 4023.9 ± 2.2 MeV/c^2, which agrees with that of its charged partner. We also measured the Born cross section of $e^+e^- \to \pi\pi h_c$ and $e^+e^- \to \pi Z_c$ for charged and neutral modes. No obvious isospin violation are found for both processes.

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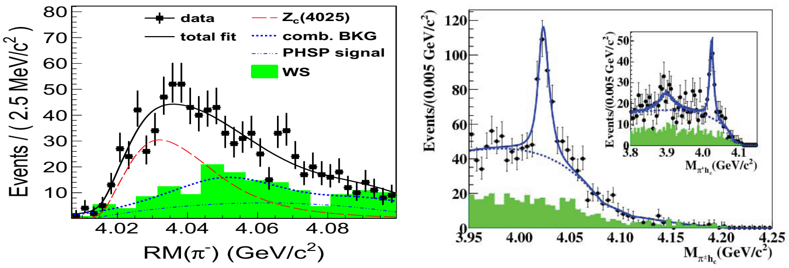

Figure 4. (left) The recoil mass of π^- in $e^+e^- \to (D^*\bar{D}^*)^+\pi^-$. (right) The recoil mass of $\pi^\pm$ in $e^+e^- \to \pi^+\pi^-h_c$.

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