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# Recent Charmonium and Exotics Study at BESIII

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**Abstract.** Recent progress in charmonium and exotic states has been reported in this proceeding. Using the data samples collected by the BESIII experiment, the mass and width of $Y$ states have been extensively studied in hidden and open charm channels. The processes of $e^+e^- \to \eta h_c$, $e^+e^- \to \eta\psi(2S)$ and $e^+e^- \to \omega\chi_{c1(2)}$ are used in the search for new charmonium states. Additionally, new measurements of the X(3872) and the search for C-even states with radiative transition are presented.

## 1 Introduction

Charmonium, a bound state composed of a charm quark ($c$) and an anti-charm quark ($\bar{c}$), has been a significant focus of hadronic physics research since its discovery with the $J/\psi$ particle in 1974. The identification of the $J/\psi$ particle not only confirmed the existence of the charm quark but also provided crucial experimental evidence that advanced the quark model, thereby offering a deeper understanding of the strong interaction. Following this discovery, numerous other charmonium states, including various excited states and new resonances, were observed, each exhibiting distinctive properties such as narrow resonance peaks and specific decay modes. These features play a critical role in probing the non-perturbative regime of Quantum Chromodynamics (QCD).

In recent years, with advancements in experimental techniques and the accumulation of data from high-energy electron-positron colliders like BESIII and Belle, significant progress has been made in exploring exotic charmonium states beyond the traditional charmonium spectrum. These exotic states, including particles like $X(3872)$ and $Y(4260)$, exhibit characteristics that challenge the conventional quark model, suggesting the presence of new, non-traditional hadronic states. The study of both charmonium and exotic charmonium states not only enhances our understanding of QCD and quark model but also supplies possibilities for discovering new physics beyond the Standard Model.

## 2 Vector charmonium(-like) states

The $Y$ states, with $J^{PC} = 1^{--}$, could be directly generated in $e^+e^-$ collisions. Those states have been observed in the charmonium sector but with different properties. The first $Y$ state, $Y(4260)$, was discovered in 2005 by the BaBar collaboration with the initial state radiation

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(ISR) method [1]. In the invariant-mass spectrum of $\pi^+\pi^- J/\psi$, a broad resonance with a mass of about 4.26 GeV/$c^2$ is observed. Subsequently, this state was confirmed by the CLEO and Belle experiments with the ISR method [2, 3]. Since the mass of this resonance is above open charm thresholds, it is expected to decay into $D^{(*)}\bar{D}^{(*)}$ final states. However, we did not observe any decay coupling to the hadronic or open charm channels at that moment. Due to these properties, it suggests that $Y(4260)$ may be a hybrid meson or a tetraquark state. After the discovery of $Y(4260)$, the $Y(4360)$ was observed in the process of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$ by BaBar, with the similar properties with the $Y(4260)$ [4]. Using the same final state, Belle reported a new resonance, denoted as $Y(4660)$ [5]. The BESIII experiment has collected 46 data samples above the $D\bar{D}$ mass threshold with the luminosity of 22 fb$^{-1}$, which enables the detailed studies of those Y states with the scan method. With this method, many decay channels could be well reconstructed, even if the branching fractions are relatively lower than $\pi^+\pi^- J/\psi$ or $\pi^+\pi^-\psi(2S)$. For example, the $\pi^+\pi^- h_c$, $h_c \to \gamma\eta_c$ could be implemented in BESIII, despite $\eta_c$ were reconstructed with 16 light hadron final states. By fitting the lineshape of $\pi^+\pi^- h_c$, a new resonance, called $Y(4390)$, was observed with statistical significance over $10\sigma$ [6]. Besides the complicated final states, the precision of cross-section measurement could be improved significantly. Based on the cross sections of the $e^+e^- \to \pi^+\pi^- J/\psi$ from 3.77 to 4.6 GeV, we found the lineshape of $Y(4260)$ needs to be described by two resonances [7]. Based on this measurement, the $Y(4260)$ is renamed to be $Y(4230)$. Not only in the hidden charm final states but also in open charm channels, $\pi^+ D^0 \bar{D}^{*-}$ [8] and $\pi^+ D^{*0}\bar{D}^{*-}$ [9], the $Y(4230)$ were firstly observed in the BESIII experiment with scan method. In the following, we will present the recent progress for Y states in BESIII.

### 2.1 The cross section measurment of $e^+e^- \to \eta h_c$

The process $e^+e^- \to \eta h_c$ was initially observed by the BESIII experiment at $\sqrt{s} = 4.226$ GeV from 2012 to 2014 [10]. A potential resonance close to 4.200 GeV was observed in the energy-dependent cross section. Recently, the BESIII experiment collected additional data at c.m. energies ranging from 4.129 to 4.600 GeV. Those new data sets allow for an updated study of the $e^+e^- \to \eta h_c$ process, with $h_c \to \gamma\eta_c$ and $\eta \to \gamma\gamma$, leading to a significant improvement in our measurement of the cross section [11]. As shown in Fig. 1, the cross-section lineshape reveals a resonant structure around 4.200 GeV, with a statistical significance of $7\sigma$. The parameters of this resonance are determined to be $M = 4188.8 \pm 4.7 \pm 8.0\,\mathrm{MeV}/c^2$ and $\Gamma = 49 \pm 16 \pm 19\,\mathrm{MeV}$, where the first uncertainties are statistical and the second are systematic. This result is consistent with the parameters of $\psi(4160)$, and it is also not close to the $\psi(4230)$ observed from the $\pi^+\pi^- J/\psi$ process. Furthermore, our measurement is consistent with the mass of the $1^{--}$ hybrid charmonium state predicted by the BOEFT model [12], which is estimated to be $4.15 \pm 0.15$ GeV.

### 2.2 The cross section measurment of $e^+e^- \to \eta\psi(2S)$ and search for $\tilde{X}(3872)$

The BESIII experiment has made substantial progress in the study of charmonium states by investigating the process $e^+e^- \to \eta\psi(2S)$, following the observation of the Y(4230) in $e^+e^- \to \eta J/\psi$ and $e^+e^- \to \eta' J/\psi$. While the CLEO-c experiment previously searched for $e^+e^- \to \eta\psi(2S)$ at $\sqrt{s} = 4.260$ GeV without success, BESIII has achieved a breakthrough with a statistical significance of 4.9 standard deviations using 5.25 fb$^{-1}$ of data collected between 4.236 and 4.600 GeV. BESIII is now updating cross-section measurements with additional data at higher energies. Furthermore, the experiment is also exloring the $\widetilde{X}(3872)$ state, which was identified by COMPASS with $J^{PC} = 1^{++}$ and a mass of 3860 MeV/c$^2$, as a potential partner to $X(3872)$ [13]. The search for $\widetilde{X}(3872)$ is performed via $e^+e^- \to \eta\widetilde{X}(3872)$,

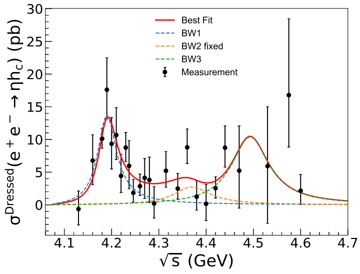


**Figure 1.** Result of the fit to the $\sqrt{s}$-dependent cross section $\sigma^{\text{Dressed}}(e^+e^- \to \eta h_c)$. Dots with error bars are data, and the red solid curve shows the fit with three resonances. The dashed curves show the three individual resonances.

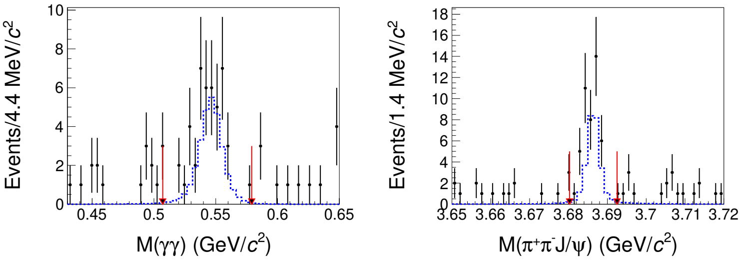


**Figure 2.** The invariant mass of $\gamma\gamma$ distribution in the $\psi(2S)$ mass window (left) and the invariant mass of $\pi^+\pi^- J/\psi$ distribution in the $\eta$ mass window for the full data set (right). The blue dashed histograms represent the signal MC distributions.

with $\widetilde{X}(3872)$ decaying to $\pi^+\pi^- J/\psi$. The data analysis, which covers center-of-mass energies from 4.288 to 4.951 GeV, includes precise measurements of energy and luminosity and reconstructs the signal processes through the decays of $\psi(2S)$ and $\widetilde{X}(3872)$, as well as $\eta \to \gamma\gamma$ [14]. Due to limited statistics, upper limits on cross sections at different energy points are provided at 90% C.L. Combining these results, a significant signal of $e^+e^- \to \eta\psi(2S)$ can be seen in Fig. 2. There are 79 observed events and 27 expected background events, yielding a P-value of $5.9 \times 10^{-16}$ for the background-only hypothesis and a statistical significance exceeding $5\sigma$ based on 14.2 fb$^{-1}$. No significant signal for $\widetilde{X}(3872)$ is found, and upper limits on the cross sections of $e^+e^- \to \eta\widetilde{X}(3872)[\widetilde{X}(3872) \to \pi^+\pi^- J/\psi]$ at 90% C.L. are set, consistent across different width hypotheses.

### 2.3 The observations of $\omega\chi_{c1}$ and $\omega\chi_{c2}$

In this analysis, we investigate the processes $e^+e^- \to \omega\chi_{c1,2}$ using data collected by the BESIII experiment across a center-of-mass energy range from 4.308 to 4.951 GeV [15]. This study extends previous observations of $e^+e^- \to \omega\chi_{c1}$ at $\sqrt{s} = 4.600$ GeV and $e^+e^- \to \omega\chi_{c2}$ at $\sqrt{s} = 4.420$ GeV by providing the first detailed measurements of the cross-section lineshapes for these processes over a broader energy region. The $\chi_{c1,2}$ was reconstructed via their decay

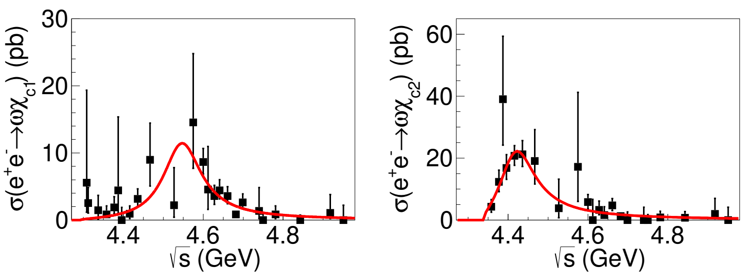


**Figure 3.** Fits to the cross sections of $e^+e^- \to \omega\chi_{c1}$ (left) and $e^+e^- \to \omega\chi_{c2}$ (right) with one single resonce.

modes $\chi_{c1,2} \to \gamma J/\psi, J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$), and the $\omega$ meson identified through its decay $\omega \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$. This comprehensive analysis reveals non-trivial features in the cross-section lineshapes, indicating the potential resonant structures. As shown in Fig. 3, a new resonance in the $e^+e^- \to \omega\chi_{c1}$ process is observed with a mass significantly higher than similar structures reported in other processes. Meanwhile, the lineshape of $e^+e^- \to \omega\chi_{c2}$ is consistent with the known $\psi(4415)$ state. These results provide valuable insights into the nature of these resonances and highlight the need for further precision measurements to enhance our understanding of their underlying physics.

## 3 Decays of X(3872)

The study of $X(3872)$ resonance has attracted significant attention since its discovery due to its unique properties, which challenge the conventional charmonium model. In 2003, the Belle experiment observed this state in the decay of $B^\pm \to K^\pm X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$ [16]. This state has a mass very close to the $D^0\bar{D}^{*0}$ threshold, leading to various interpretations, including that of a tetraquark, a molecular state, or a hybrid meson. The narrow width of the $X(3872)$ and its quantum numbers $J^{PC} = 1^{++}$ add to the complexity of its classification, making it a compelling subject for both experimental and theoretical investigations. If $X(3872)$ is the conventional charmonium state $\chi_{c1}(2P)$, the process of $X(3872) \to \pi^+\pi^-\chi_{c1}$ should be the main decay mode, and the process of $X(3872) \to \pi^0\chi_{c1}$ would be suppressed. However, by assuming the nature of $X(3872)$ as a shallow bound state of $D^0\bar{D}^{*0}$, the one-pion transition rate would be increased. Therefore, the process of two pion transition to $\chi_{c1}$ is searched for in BESIII experiment with 15 energy points from 4.16 to 4.34 GeV [17]. The $\chi_{c1}$ candidates are reconstructed with $\gamma J/\psi$, with subsequently $J/\psi \to l^+l^-$. Considering the soft pions, we require the final states with 3 or 4 tracks to increase the detection efficiency. The simultaneous fit is performed to the recoil mass of radiative photon for 3-track and 4-track events as shown in Fig. 4. Since no signal is observed in the recoil mass distribution, the upper limit is estimated at each c. m. energy. The relative ratio of decay width $\frac{\Gamma[X(3872)\to\chi_{c1}\pi^0]}{\Gamma[X(3872)\to\chi_{c1}\pi^+\pi^-]}$ is greater than 5, which is two orders of magnitude greater than that expected under pure charmonium $2^3P_1$ assumption for the $X(3872)$.

Another new $X(3872)$ decay mode is the radiative transition $X(3872) \to \gamma\psi_2(3823)$, which is predicted under the assumption that $X(3872)$ is a excited spin-triplet state, $\chi_{c1}(2P)$. Such decay channel is searched for the first time by BESIII with the data collected at the

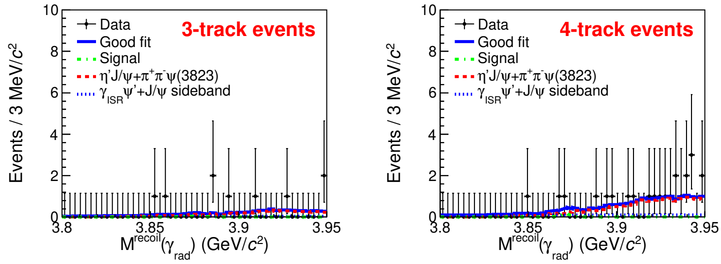


**Figure 4.** The simultaneous fit to the recoil mass spectrum. Dots with error bars are data. The blue solid curves represent the total fit. The green dash-dotted curves show the signal contributions.

energy region from 4.178 to 4.278 GeV [18]. No signal is observed, and the upper limit on the branching fraction is set to indicate the $X(3872)$ is not a pure $\chi_{c1}(2P)$ state.

## 4 Radiative transition in search for C-even states

In the above study, the $X(3872)$ is generated through the radiative transition process of $e^+e^- \to \gamma X(3872)$. Considering the quamtum number of $X(3872)$ equals to $1^{--}$, it is allowed to be produced in $e^+e^-$ collisions via two-photon fusion [19, 20]. Although the two-photon production is suppressed, the $e^+e^- \to e^+e^-\pi^+\pi^- J/\psi$ is searched in Belle experiment, and an evidence of $X(3872)$ is found [21]. Ultizing the data samples collected in the $\chi_{c1}$ mass region, BESIII experiment observed the C-even resonance, $\chi_{c1}$, in $e^+e^-$ annilation for the first time [22]. In this analysis, the interference between the continuum process and the signal channel is important to extract the signal yields. The electronic width of the $\chi_{c1}$ is determined to be $\Gamma_{ee} = (0.12^{+0.13}_{-0.08})$ eV through the fitting of the cross sections at 4 energy points. Motivated by those findings, the directly formation of $X(3872)$ in $e^+e^-$ collision is searched for in BESIII [23]. Four data samples were collected to implement this analysis. One is at the peak of $X(3872)$, while others are taken at off-resonance regions. The $X(3872)$ is reconstructed with final states $\pi^+\pi^- J/\psi$ with $J/\psi \to l^+l^-$. By fitting the invariant mass of $l^+l^-$, the signal yields are extracted, and the cross sections are determined considering the efficiencies and luminosities. By fitting the line shape of the cross sections at four energy points, the corresponding parameters are determined as shown in Fig. 5. Since no obvious signal is observed, the upper limit on $\Gamma_{ee} \times \mathcal{B}$ is determined to be $7.5 \times 10^{-3}$ eV at the 90 % C.L., with an improvement of a factor of about 17 compared to the previous limit.

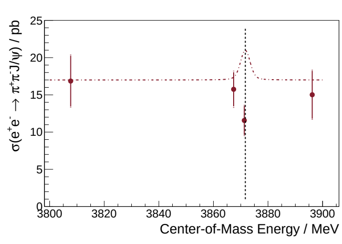


**Figure 5.** Cross section of $e^+e^- \to \pi^+\pi^- J/\psi$. The dashed vertical line indicates the peak position of $X(3872)$ and the dot-dashed curve illustrates the expected line-shape.

To search for C-even charmonium-(like) states, the radiative transition process of $e^+e^- \to \gamma D_s^\pm D_s^{*\mp}$ has been studied with the data sample collected at 4.681 GeV with the luminosity of 1667.39 pb$^{-1}$ [24]. The $D_s^*$ is reconstructed with $\gamma D_s$ modes, and the $D_s$ is reconstructed with two decay models: $D_s \to K^+K^-\pi$ and $K_S^0 K$, here $K_S^0$ is required to decay into two charged pions. We found that the main background is from $e^+e^- \to (\gamma_{ISR})D_s^\pm D_s^{*\mp}$. There is no significant signal in the invariant mass spectrum of $D_s^\pm D_s^{*\mp}$. Therefore, based on the spin, mass and width assumptions for different charmonium states, the upper limits on cross sections are determined, as listed in Tab. 1.

**Table 1.** The upper limits of Born cross section of $e^+e^- \to \gamma X$ times the branching fraction of $X \to D_s^\pm D_s^{*\mp}$ at 90% C.L. for each candidate $C$-even state. Here, $N_{\rm sig}$, $N_{\rm sig}^{\rm UL}$, and $\bar{\epsilon}$ are the number of signal events, the upper limit on the number of signal events, and the average detection efficiency, respectively. "Significance" represents statistical significance. "$\sigma^{\rm UL} \cdot \mathcal{B}$ with sys." stands for the upper limits of the cross section times the branching ratio with systematic uncertainties.

| | $\eta_{c2}(2D)$ | $\chi_{c1}(3P)$ | $\chi_{c2}(3P)$ | $X(4080)$ | $X(4217)$ | $X(4279)$ |
|---|---|---|---|---|---|---|
| $N_{\rm sig}^{\rm UL}$ | 6.7 | 16.3 | 18.7 | 2.4 | 7.6 | 19.6 |
| $N_{\rm sig}$ | $-5.6^{+4.2}_{-3.2}$ | $9.8^{+5.2}_{-4.4}$ | $13.0^{+4.5}_{-3.9}$ | $-0.9^{+0.3}_{-0.2}$ | $2.3^{+3.0}_{-2.4}$ | $13.8^{+4.5}_{-3.8}$ |
| $\bar{\epsilon}$ ($10^{-4}$) | 3.73 | 3.48 | 3.26 | 4.21 | 3.50 | 3.11 |
| Significance ($\sigma$) | 1.3 | 2.6 | 3.1 | – | 0.9 | 3.3 |
| $\sigma^{\rm UL} \cdot \mathcal{B}$ with sys. (pb) | 13.3 | 36.3 | 45.5 | 4.1 | 15.7 | 51.7 |

## 5 Summary

In summary, the properties of vector states have been extensively studied through various processes, including open charm, hidden charm, and light hadronic final states. The $Y(4230)$ has been observed in 10 different decay modes, revealing rich structures in the cross-section line shapes above 4.3 GeV. However, more data samples are required, particularly around 4.5 GeV and 4.7 GeV, to better understand these structures. In contrast, no evident structures have been observed in processes involving light hadrons. The current strategies, which rely on simple formulas to fit cross-sections, have proven insufficient for providing a unified picture of these vector states. This indicates the need for a joint effort and improved modeling techniques, such as combined fits using the K-matrix formalism. Additionally, interference effects must be properly accounted for in these analyses. The new decay modes of $X(3872)$ have also been investigated, and future studies may benefit from direct electron-positron annihilation processes to further explore these phenomena.

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