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Recent XYZ studies at BESIII

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Despite being extensively studied since 2003, the XYZ states in the charmonium system do not have a clear interpretation. BESIII has recently collected additional data samples, which enables updated measurements and new searches for XYZ states. Five recent papers using these new data samples are presented. Included are measurements of $\sigma(e^+e^- \to \eta\psi(2S))$, $\sigma(e^+e^- \to \phi\Lambda\bar{\Lambda})$, $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$, $\sigma(e^+e^- \to D_s^{*+}D_{sJ}^- + c.c.)$, $\sigma(e^+e^- \to \pi^+\pi^-\pi^0\eta_c)$, $\sigma(e^+e^- \to \pi^+\pi^-\eta_c)$, and $\sigma(e^+e^- \to \gamma\pi^0\eta_c)$. The analysis for $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ observes the $Y(4660)$ for the first time at BESIII.

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1. Introduction

The $\chi_{c1}(3872)$ (a.k.a. $X(3872)$) discovered by Belle in 2003 [1] was the first state in the charmonium region that did not fit into the predicted charmonium spectrum. LHCb determined the state has $J^{PC} = 1^{++}$ [2] and a width assuming a Breit-Wigner lineshape of $\Gamma = 1.39 \pm 0.24 \pm 0.10$ MeV [3], which is narrower than expected for a charmonium state over $D\bar{D}$ threshold. The measured mass is also lower than expected for the $\chi_{c1}(2P)$ state. Measurements of $\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\rho J/\psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$ [4] and $\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\rho J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$ [5] by BESIII show that the $X(3872)$ decays to isovector and isosinglet states at about the same rate, which is not expected for a pure charmonium state. Its mass agrees within statistical uncertainties with $D^*\bar{D}$ threshold, which has prompted molecular and four-quark interpretations for the $X(3872)$.

Further studies in the charmonium region found that there is an overabundance of vector meson states. The vector states that do not match a predicted charmonium state are called Y states. These Y states can be produced directly in e^+e^- collisions, so the masses and widths of the Y states can be determined by fitting measured e^+e^- cross section values. Using this method, BESIII was able to resolve the single $Y(4260)$ in $e^+e^- \to \pi^+\pi^- J/\psi$ into the $Y(4230)$ and the $Y(4320)$ [6].

In addition to the $X(3872)$ and Y states, a study of $e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII found a charged charmonium-like structure in $Z_c(3900)^\pm \to \pi^\pm J/\psi$ [7]. BESIII found the neutral partner in $e^+e^- \to \pi^0\pi^0 J/\psi$ in $Z_c(3900)^0 \to \pi^0 J/\psi$ [8]. Further studies at BESIII found a new $Z_c(4020)^\pm$ in $\pi^\pm h_c$ [9], and the neutral partner $Z_c(4020)^0$ in $\pi^0 h_c$ [10]. Since these states form isovectors, they cannot be simple $c\bar{c}$ states, and must have at least a four-quark content.

The discovery of XYZ states in the charmonium region has prompted BESIII to take more data in the center-of-mass (E_{cm}) region between 4.15 and 5.0 GeV to search for new decays of existing states, as well as to search for new XYZ states. The BESIII detector is located at the Beijing Electron Positron Collider (BEPCII) [11], where it records symmetric e^+e^- collisions and covers 93% of the 4π solid angle for charged particles and photons. This is an excellent environment to study XYZ states because they are produced nearly at rest and there are relatively small backgrounds levels. This allows BESIII to reconstruct complicated decay modes of these states. The remainder of the paper is dedicated to the most recent studies on the XYZ states at BESIII.

2. $e^+e^- \to \eta\psi(2S)$

BESIII has measured $\sigma(e^+e^- \to \eta J/\psi)$, and observed significant $Y(4230)$ and $Y(4390)$ signals. This analysis measures $\sigma(e^+e^- \to \eta\psi(2S))$ [12], where the same Y states are expected to contribute. Using data corresponding to an integrated luminosity of 5.25 fb^{-1} collected between 4.236 and 4.600 GeV, the process $e^+e^- \to \eta\psi(2S)$ is observed with a total significance of 4.9σ. The measured cross section values are shown in Figure 1a. The statistical uncertainties of the cross section are too large to make a conclusion about any resonant structure.

3. $e^+e^- \to \phi\Lambda\bar{\Lambda}$

Models predict a $[cs][\bar{c}\bar{s}]$ state at 4330 ± 70 MeV/c^2 [13]. If this predicted state is the $Y(4230)$, this interpretation would explain why the decay $Y(4230) \to \pi^+\pi^- J/\psi$ is dominated by

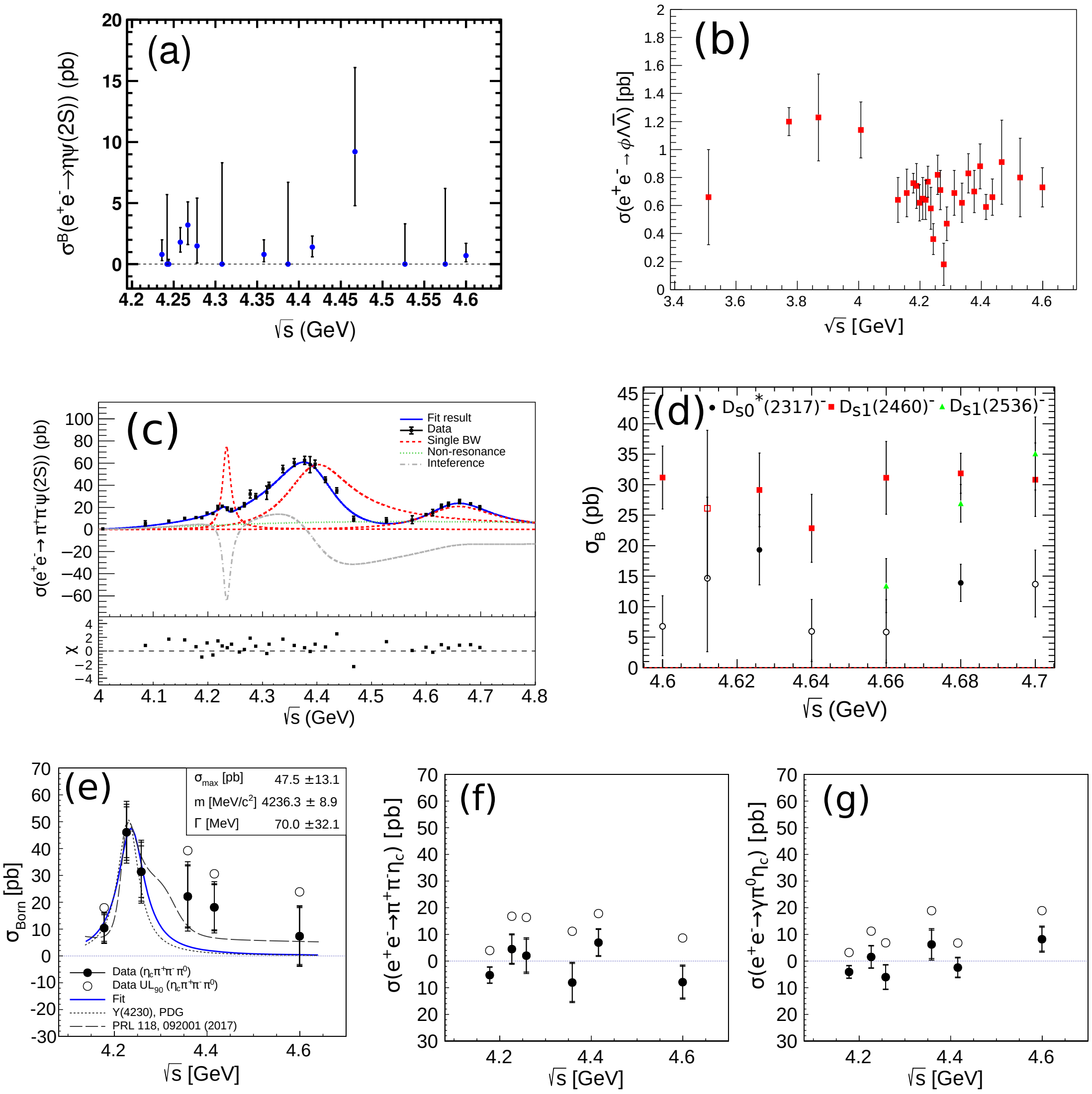

Figure 1: Measured values for $\sigma(e^+e^- \to \eta\psi(2S))$ (a), $\sigma(e^+e^- \to \phi\Lambda\bar{\Lambda})$ (b), $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ (c), $\sigma(e^+e^- \to D_s^{*+}D_{sJ}^- + \text{c.c.})$ (d), $\sigma(e^+e^- \to \pi^+\pi^-\pi^0\eta_c)$ (e), $\sigma(e^+e^- \to \pi^+\pi^-\eta_c)$ (f), and $\sigma(e^+e^- \to \gamma\pi^0\eta_c)$ (g).

$f_0(980) \to \pi^+\pi^-$. Since $e^+e^- \to \phi\Lambda\bar{\Lambda}$ has a final state that contains strange and anti-strange quarks, the $[cs][\bar{c}\bar{s}]$ state should decay to this final state. Figure 1b shows the measured cross section values for this process, and it is the first observation of this process between 3.51 and 4.6 GeV [14]. Due to the large statistical uncertainties, the structure of the cross section cannot be investigated.

4. High Precision Update of $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$

BESIII previously published the measurement of $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ in 2017 and found significant signals for the $Y(4230)$ and $Y(4390)$. Since then, more data has been collected between

4.23 and 4.36 GeV, and new data samples between 4.6 and 4.7 GeV have been collected. The measured cross sections in the updated data samples are consistent with the 2017 result and include significant $Y(4230)$ [4.0σ], $Y(4390)$ [16.1σ], and $Y(4660)$ [8.1σ] signals [15]. One of the four fit solutions is shown in Figure 1c. This is the first time the $Y(4660)$ has been observed at BESIII.

5. Measurements of $\sigma(e^+e^- \to D_s^{*+}D_{sJ}^-$+c.c.)

The $D_{s0}^*(2317)^-$ and $D_{s1}(2460)^-$ both have masses below their predicted values, which makes them candidates for exotic states. This analysis measures $\sigma(e^+e^- \to D_s^{*+}D_{sJ}^-)$ by fitting the signals in the recoil mass spectrum of the D_s^{*+} [16]. The measured cross section values are shown in Figure 1d. The fit at 4.68 GeV has a significant signal for all three D_{sJ}^- states. The measured cross section values show no evidence of resonant structures.

6. Measurements of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$, $\pi^+\pi^-\eta_c$, and $\gamma\pi^0\eta_c$

Previous Z_c states have been found in systems of a pion plus a charmonium state, with masses near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds. This analysis looks for a new Z_c state near $D\bar{D}$ that would decay to $\pi\eta_c$ [17]. No Z_c signals are found, so upper limits are placed on the cross sections based on several mass and width assumptions for the hypothetical Z_c state.

Figure 1 shows the measured cross section values for $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ (e), $e^+e^- \to \pi^+\pi^-\eta_c$ (f), and $e^+e^- \to \gamma\pi^0\eta_c$ (g). The latter two final states have measured cross section values consistent with zero. The measured cross section for $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ is fit with a Breit-Wigner, and the extracted parameters are consistent with production through the $Y(4230)$.

7. Summary

In summary, BESIII is very active in searches for new decay modes of XYZ states in the charmonium region. The most recently collected data is between 4.6 and 4.95 GeV, which has already been used to observe the $Y(4660)$. An accelerator upgrade is planned for 2024, which will increase the luminosity by up to a factor of 3, and will increase the maximum center-of-mass energy to 5.6 GeV. This will give the experiment access to more charmed baryons, and the capability to search for new Y states at higher energies.

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