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Connecting the XYZ States at BESIII

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Most states in the charmonium system can be successfully described as a simple bound system composed of a charm quark and anti-charm quark. The past decade, however, has seen the discovery of a number of new states (named the "XYZ" states) that do not fit within this model, and which perhaps point towards more complex systems. In December of 2012, the BESIII Collaboration undertook a new program to study these XYZ states of charmonium by directly producing the $Y(4260)$ and $Y(4360)$ states in electron-positron collisions. Since that time, BESIII has collected the world's largest samples of $Y(4260)$ and $Y(4360)$ decays, which will help us understand those states, but which has also led to a number of surprises. Here I review several recent discoveries from these data samples.

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1. Introduction: Directly Producing the Y(4260) and Y(4360) at BESIII

The quark model of charmonium (for example, [1]) – in which a state of charmonium is described as a charm quark bound to an anticharm quark in a particular configuration of internal spin (**S**), orbital angular momentum (**L**), total spin (**J**), and radial quantum numbers (n) – has been remarkably successful in describing the spectrum of experimentally observed states below $D\overline{D}$ threshold. At higher masses, however, many new states have been discovered that seem to point beyond this simple $c\bar{c}$ picture [2]. These include candidates for quark-antiquark states with excited gluonic fields (hybrid mesons), four-quark states (tetraquarks), and meson-meson molecules. These "XYZ" states, if understood, could thus open the door to spectroscopy beyond the quark model.

Somewhat ironically, the majority of these new states were discovered by the Belle and BaBar experiments using e^+e^- collisions in the bottomonium region. BESIII, on the other hand, is in a unique position in that it can use e^+e^- collisions in the charmonium region, provided by the Beijing Electron Positron Collider (BEPC), to directly produce the $Y(4260)$ or $Y(4360)$ states by simply tuning the center of mass energies to 4.26 or 4.36 GeV, respectively. Between December of 2012 and June of 2013, BESIII collected a total of 2.9 fb^{-1} of data in this energy region, with the largest samples being at $E_{CM} = 4.23$ (1054 pb^{-1}), 4.26 (806 pb^{-1}), and 4.36 GeV (523 pb^{-1}).

These energies have proved valuable not only for the production of the $Y(4260)$ and $Y(4360)$, but also for the production of "charged charmoniumlike states," the $Z_c(3900)$ and the $Z_c(4020)$, as well as radiative production of the $X(3872)$. The $Z_c(3900)$ and $Z_c(4020)$ are especially interesting because of their electric charge. Since a $c\bar{c}$ system is electrically neutral, these Z_c states must contain more quarks, and may be four-quark systems, or molecules composed of two two-quark systems. Figure 1 shows the spectrum of charmonium and illustrates a few of the processes that have been observed by BESIII.

The results shown below establish the existence of the charged $Z_c(3900)$ and $Z_c(4020)$ structures. Using an angular analysis of its D^*D decay the $Z_c(3900)$ is shown to have $J^P = 1^+$. The J^P of the $Z_c(4020)$ has not yet been determined. Amplitude analyses of the dominant reactions, especially $e^+e^- \to \pi^+\pi^- J/\psi$, are underway.

2. Five XYZ Observations from BESIII in 2013

2.1 The Charged $\mathbf{Z_c(3900)}$ in $\pi \mathbf{J}/\psi$

The $Y(4260)$ was originally discovered by BaBar [3], and later confirmed by Belle [4], in the Initial State Radiation (ISR) process $e^+e^-(\gamma_{ISR}) \to Y(4260) \to \pi^+\pi^- J/\psi$. BESIII confirmed the cross section for this process in early 2013 using 515 pb^{-1} of data at $E_{CM} = 4.26$ GeV, near the peak of the $Y(4260)$ [5]. But more interestingly, BESIII also found structure in the $\pi^\pm J/\psi$ subsystem. Fitting this structure, referred to as the $Z_c(3900)$, with a resonant lineshape (upper left of Fig. 2) resulted in a mass and width of $3899.0 \pm 3.6 \pm 4.9$ MeV/c^2 and $46 \pm 10 \pm 20$ MeV, respectively. Since the $Z_c(3900)$ contains $c\bar{c}$, but is also charged, it must contain at least four quarks.

2.2 Structure in Charged $\mathbf{D^*\bar{D} + c.c.}$

One possible clue for the interpretation of the $Z_c(3900)$ is that it has a mass very close to $D^*\bar{D}$ threshold. To investigate, BESIII analyzed the processes $e^+e^- \to \pi^- D^+ \bar{D}^{*0} + c.c.$ and $e^+e^- \to$

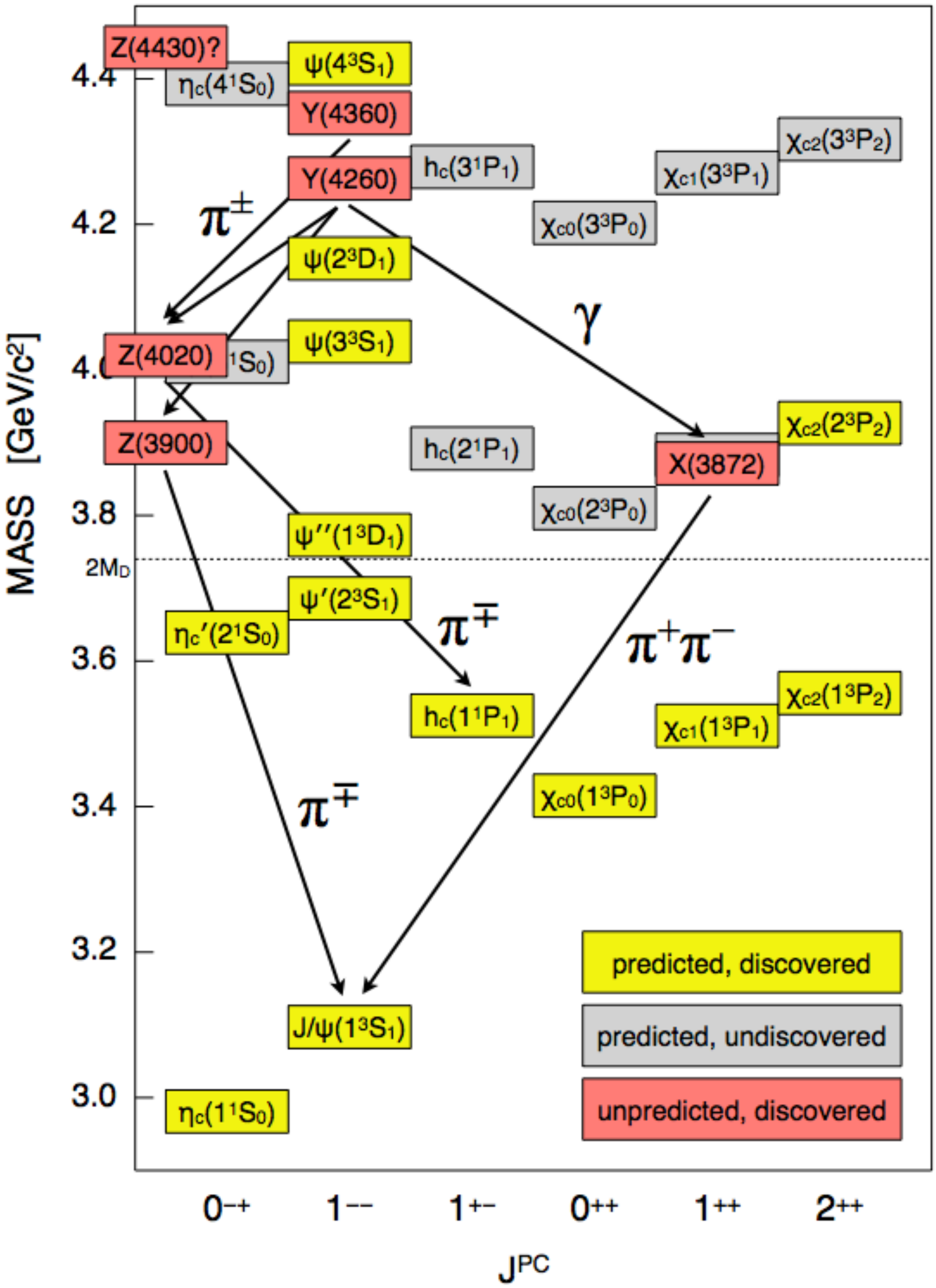

Figure 1: The charmonium system. The yellow and gray boxes represent states of charmonium as predicted by the quark model, where charmonium is treated as a bound system of a charm quark and anti-charm quark [1] – those in yellow have been experimentally discovered, while those in gray have not. The red boxes represent a sample of the so-called XYZ states of charmonium, which seem to point to configurations beyond the simple $c\bar{c}$ interpretation. The arrows mark transitions discussed in these proceedings.

$\pi^-\bar{D}^0 D^{*+} + c.c.$ at $E_{CM} = 4.26$ GeV [6]. Clear structure in the mass spectrum of both $D^+\bar{D}^{*0} + c.c.$ and $\bar{D}^0 D^{*+} + c.c.$ was found (middle left of Fig. 2). The measured mass and width were $3883.9 \pm 1.5 \pm 4.2$ MeV/c^2 and $24.8 \pm 3.3 \pm 11.0$ MeV, respectively. The mass and width are both slightly lower than those of the $Z_c(3900)$ in $\pi^\pm J/\psi$, but it is likely the structures are related.

2.3 The Charged $\mathbf{Z_c(4020)}$ in $\pi\mathbf{h_c}$

In previous work at CLEO-c, it was found that the process $e^+e^- \to \pi^+\pi^- h_c$ at $E_{CM} = 4.17$ GeV was unexpectedly similar in strength to $e^+e^- \to \pi^+\pi^- J/\psi$ [7]. At BESIII, it was found that the process $e^+e^- \to \pi^+\pi^- h_c$ also remained strong at higher center of mass energies [8]. But more surprisingly, a narrow structure was found in the $\pi^\pm h_c$ subsystem (upper right of Fig. 2). The mass and width of this structure, called the $Z_c(4020)$, were measured to be $4022.9 \pm 0.8 \pm 2.7$ MeV/c^2 and $7.9 \pm 2.7 \pm 2.6$ MeV, respectively. Like the $Z_c(3900)$, the $Z_c(4020)$ is charged and so must contain more quarks than just the $c\bar{c}$.

2.4 Structure in Charged $\mathbf{D^*\bar{D}^*}$

While the $Z_c(3900)$ is near $D^*\bar{D}$ threshold, the $Z_c(4020)$ is near $D^*\bar{D}^*$ threshold. Analyzing e^+e^- collisions at 4.26 GeV, BESIII found a structure decaying to $(D^*\bar{D}^*)^\pm$ in the process $e^+e^- \to \pi^\mp(D^*\bar{D}^*)^\pm$ (middle right of Fig. 2) [9]. The mass and width of this structure, $4026.3 \pm 2.6 \pm 3.7$ MeV/c^2 and $24.8 \pm 5.6 \pm 7.7$ MeV, respectively, are somewhat larger than those of the $Z_c(4020)$ in $\pi^\pm h_c$, but close enough to suggest a connection.

2.5 Observation of the X(3872)

One final surprise from the 2013 data was the observation of the $X(3872)$ in the process $e^+e^- \to \gamma X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$ (lower right of Fig. 2) [10]. This discovery presents a new way to access the $X(3872)$, which is still one of the least understood of the XYZ states. As briefly discussed below, the cross section of this process as a function of center of mass energy, while not conclusive, suggests this observation could arise from the process $Y(4260) \to \gamma X(3872)$.

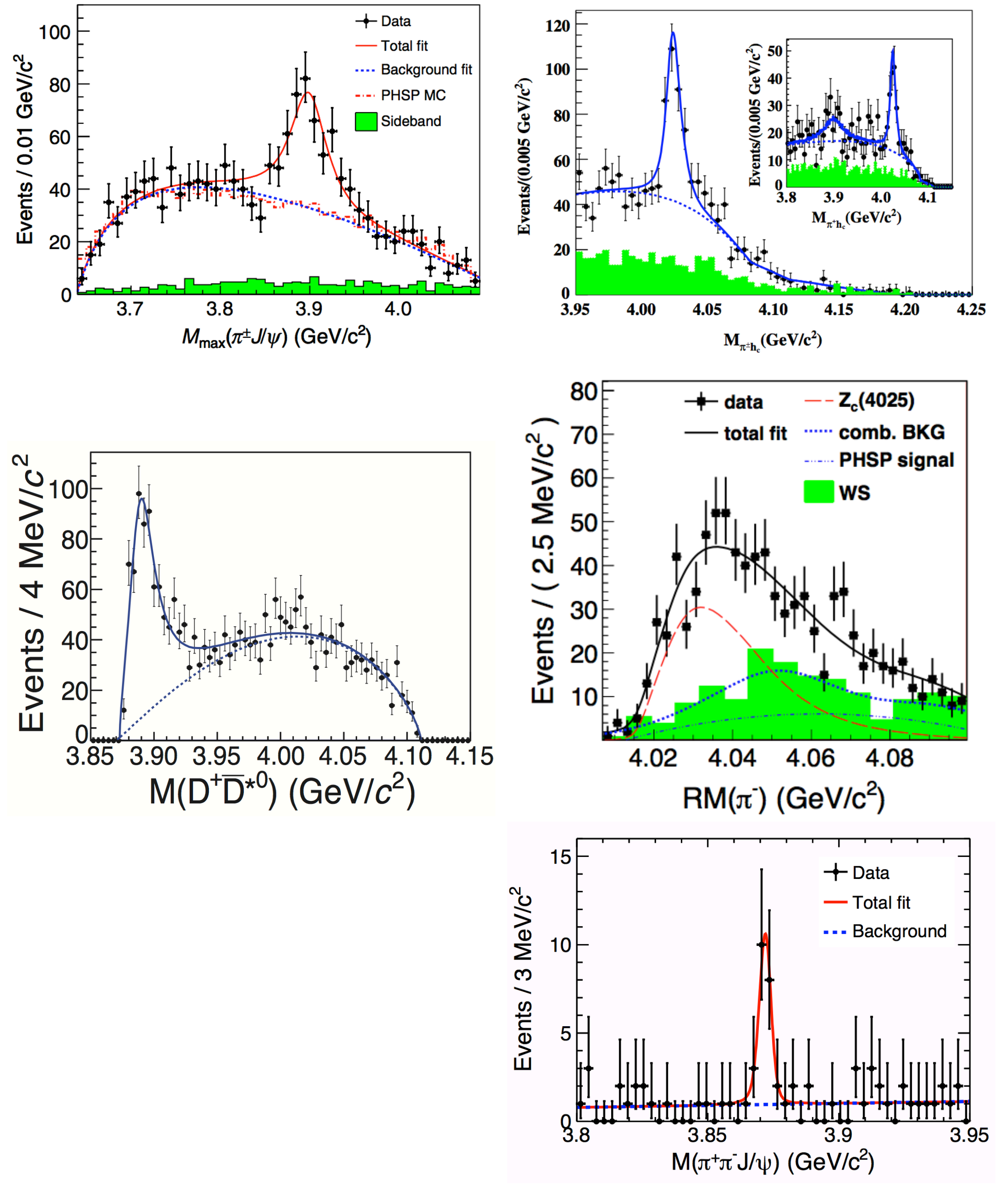

Figure 2: Five discoveries by the BESIII Experiment in 2013. (Upper Left) The $\mathbf{Z_c(3900)}$ produced in $e^+e^- \to \pi^{\mp}Z_c(3900)^{\pm}$ at $E_{CM} = 4.26$ GeV and decaying through $Z_c(3900)^{\pm} \to \pi^{\pm}J/\psi$ [5]. (Upper Right) The $\mathbf{Z_c(4020)}$ produced in $e^+e^- \to \pi^{\mp}Z_c(4020)^{\pm}$ at $E_{CM} = 4.23$, 4.26, and 4.36 GeV and decaying through $Z_c(4020)^{\pm} \to \pi^{\pm}h_c$ [8]. (Middle Left) **Structure in** $\mathbf{D^+\bar{D}^{*0} + c.c.}$ from the reaction $e^+e^- \to \pi^- D^+\bar{D}^{*0} + c.c.$ at $E_{CM} = 4.26$ GeV [6]. (Middle Right) **Structure in** $\mathbf{(D^*\bar{D}^*)^{\pm}}$ from the reaction $e^+e^- \to \pi^{\mp}(D^*\bar{D}^*)^{\pm}$ at $E_{CM} = 4.26$ GeV [9]. (Lower Right) The $\mathbf{X(3872)}$ produced in $e^+e^- \to \gamma X(3872)$ at $E_{CM} = 4.23$, 4.26, and 4.36 GeV and decaying through $X(3872) \to \pi^+\pi^- J/\psi$ [10].

3. Connections to the Y(4260) and Outlook

The fact that these five observations occur in e^+e^- collisions with center of mass energies near the mass of the $Y(4260)$ suggests that there may be an intimate connection between the $Y(4260)$ and the $Z_c(3900)$, the $Z_c(4020)$, and the $X(3872)$. Unfortunately, the BESIII data is not entirely conclusive in this regard. Figure 3 shows the cross sections of $e^+e^- \to \gamma X(3872)$ (top) and $e^+e^- \to \pi^+\pi^- h_c$ (bottom) as a function of center of mass energy. For the former, the shape of the cross section is more consistent with the $Y(4260)$ than other shapes, but the significance is low. In the latter, the cross section shows more physics is present than just $Y(4260) \to \pi^\pm Z_c(4020)^\mp$. A measurement of the production cross section of the $Z_c(3900)$ is still in progress.

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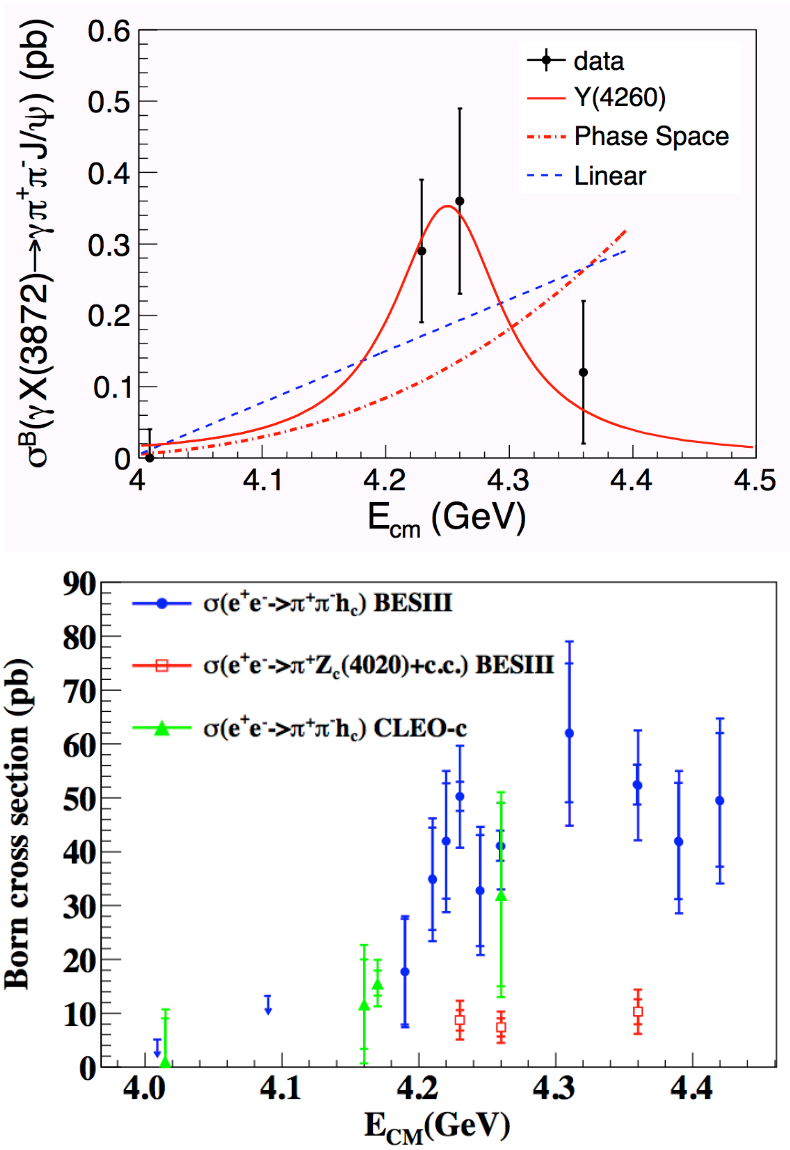

Figure 3: Connections to the $Y(4260)$. If a reaction originates from a $Y(4260)$ decay, the e^+e^- cross section as a function of center of mass energy should show structure consistent with the $Y(4260)$. (Top) The cross section for $e^+e^- \to \gamma X(3872)$. The cross section is more consistent with a $Y(4260)$ shape than phase space or a linear lineshape [10]. (Bottom) The cross sections for $e^+e^- \to \pi^+\pi^- h_c$ and $e^+e^- \to \pi^\pm Z_c(4020)^\mp$. The shape of the cross section is inconclusive, but appears to stay constant at higher energies [8].