RECENT RESULTS ON CHARMONIUM-LIKE (EXOTIC) XYZ STATES AT THE BESIII/BEPCII EXPERIMENT IN BEIJING/CHINA*

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With about 12 fb^{-1} collected XYZ data sets, BESIII continues the exploration of the exotic charmonium-like states. In this paper, recent results on the measurements of the spin-parity determination of $Z_c(3900)$, as well as on line-shapes of $e^+e^- \to J/\psi\,\pi\pi, h_c\pi\pi, \psi(2S)\,\pi^0\pi^0/\pi^+\pi^-$, and $\pi^+D^0D^{*-}$ from open charm are discussed. Also, the recent observation of $e^+e^- \to \phi\chi_{c1/2}$ at $\sqrt{(s)} = 4.6$ GeV is reported.

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1. Introduction

In the charmonium region, the $c\bar{c}$ charmonium states can successfully be described using potential models. All the predicted states have been observed with the expected properties beneath the open-charm threshold, and excellent agreement is achieved between theory and experiment. Above the open-charm threshold, however, there are still many predicted states that have not yet been discovered and, surprisingly, quite some unexpected states have been observed since 2003. Interesting examples of these so-called (exotic) charmonium-like XYZ states are the $X(3872)$ observed by Belle [1], the vector states $Y(4260)$ and $Y(4360)$, both discovered by BaBar using the initial-state radiation (ISR) [2,3], and the charged state $Z_c(3900)^\pm$ discovered by BESIII [4], shortly after confirmed by Belle [5], that is a manifestly exotic state; for a recent overview, see *e.g.* [6].

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The Beijing Spectrometer (BES) at the Beijing Electron–Positron Collider (BEPC) in China started initially in 1989, and the BESIII/BEPCII experiment [7] is the latest incarnation that began operation in March 2008 after major upgrades were finalised.

The multi-purpose detector allows for coverage of a broad hadron physics programme, including not only charmonium and open-charm spectroscopy but also electromagnetic form factor as well as R scan measurements and many others. We have collected the world largest data sets in the τ-charm mass region. Among those are unique high-luminosity data sets to explore the still unexplained XYZ states of in total more than 5 fb^{-1} accumulated above 3.8 GeV.

2. Recent major results on charmonium-like exotic XYZ states

With BESIII/BEPCII conventional as well as charmonium-like (exotic) XYZ states can be studied. In the e^+e^- annihilation, we have direct access to vector Y states ($J^{PC} = 1^{--}$) that are produced at unprecedented statistics. Moreover, we can study charged as well as neutral Z_c states indirectly produced (together with recoil particles), whereas X states are accessible via radiative decays, see *e.g.* [8].

2.1. Spin-parity determination of the $Z_c(3900)$ *and* $Z_c(3885)$

The discovery of the $Z_c(3900)^{\pm}$ state is due to the charge in combination with the mass a strong hint for the first four-quark state being observed. After observation of the neutral partner $Z_c(3900)^0 \to J/\psi\pi^0$ [9], confirming earlier evidence reported by CLEO-c [10], a $Z_c(3900)^{\pm,0}$ isospin triplet seems to be established. Furthermore, also a second isospin triplet $Z_c(4020)^{\pm,0}$ has meanwhile been established in the BESIII data [11, 12], also consistent with others [13, 14]. Despite this remarkable progress, the nature of these states is still unclear and the question is whether the different decays the Z_c states have been observed in (hidden *versus* open charm) are decay modes of the same state.

Therefore, the spin-parity J^P of $Z_c(3885)^{\pm} \to D\bar{D}^{*\pm}$ has been studied in terms of the angular distribution $|\cos\theta_\pi|$ between the bachelor pion and the beam axis of the detection efficiency-corrected signal event yields (Fig. 1). Based on a single D-tag analysis (Fig. 1, left) of data taken at 4.26 GeV, $J^P = 1^+$ was determined [15], and later re-confirmed at higher significance in a double D-tag analysis based on data at 4.23 GeV and 4.26 GeV (Fig. 1, right) [16]. Recently, also the spin-parity of the $Z_c(3900)^{\pm} \to J/\psi\pi^{\pm}$ system has been studied in an amplitude analysis (Fig. 2), including a simultaneous fit to the data sets at 4.23 GeV and 4.26 GeV [17]. Not only the $J^P = 1^+$ assignment for this state is significantly favoured by the data, but also the pole mass of $(3881.2 \pm 4.2_{\rm stat} \pm 52.7_{\rm syst})$ MeV$/c^2$ is found to be consistent with that of the $Z_c(3885)^{\pm}$ from the open charm channel [16], and this holds also for the ratio $\mathcal{B}(Z_c^{\pm} \to D\bar{D}^{*\pm})/\mathcal{B}(Z_c^{\pm} \to J/\psi\pi^{\pm})$ of about 6.2 ± 2.9.

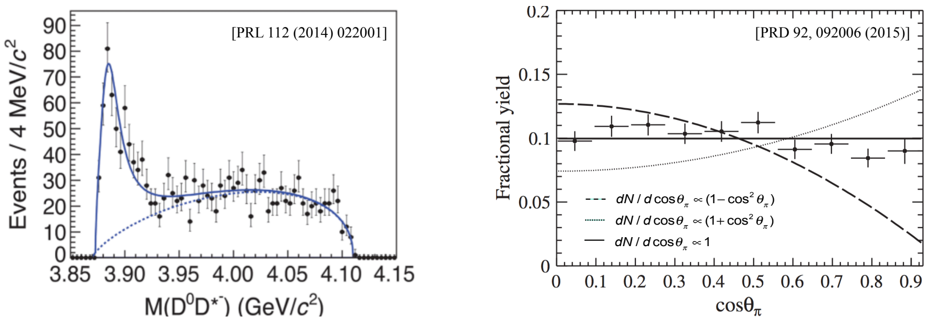

Fig. 1. Results on the charged Z_c state observed in open charm decays. Left: Observation of $Z_c(3885)^{\pm} \to D\bar{D}^{*\pm}$ at $\sqrt{s} = 4.26$ GeV (525 pb^{-1}). Right: Angular distribution $|\cos\theta_{\pi}|$ in comparison to different J^P assumptions based on data sets at $\sqrt{s} = 4.23$, 4.26 GeV (1.9 fb^{-1}).

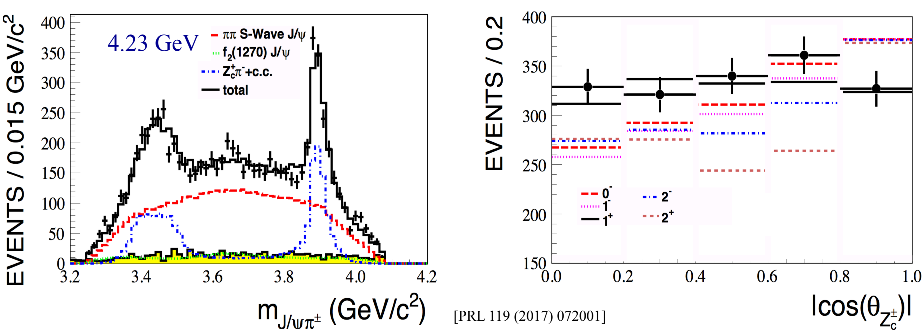

Fig. 2. Results on the charged Z_c states observed in hidden charm decays. Left: Amplitude analysis result for $Z_c(3900)^{\pm} \to J/\psi\pi^{\pm}$ based on data sets at $\sqrt{s} = 4.23$ GeV (similar at 4.26 GeV). Right: Angular distribution of the $Z_c(3900)^{\pm}$ polar angle $|\cos\theta_{Z_c}|$ in comparison to various J^P assumptions from a simultaneous fit to two data sets at $\sqrt{s} = 4.23, 4.26$ GeV.

In conclusion, it seems that these two Z_c states at 3.9 GeV$/c^2$ are indeed the same object observed in different decay modes. Clearly, also further decay channels via other charmonia than J/ψ and h_c, like *e.g.* η_c [18], need to be investigated, and possible multiplets need to be completed also by high-spin states, which can only be accessed by future experiments such as PANDA/FAIR [19].

2.2. Line-shapes of $J/\psi\pi^+\pi^-$, $h_c\pi\pi$, $\psi(2S)\,\pi^0\pi^0/\pi^+\pi^-$ and $\pi^+D^0D^{*-}$

The $Y(4260)$ and $Y(4360)$ were discovered decaying to $J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$, respectively [2, 3]. Based on increased statistics, the $Y(4260)$ appears with a somewhat asymmetric shape [20]. The Belle experiment confirmed the $Y(4260) \to J/\psi\pi^+\pi^-$. In contradiction to the BaBar result, they claimed a lower mass peak, the "$Y(4008)$", to be needed in addition in order to describe the data [21]. A simultaneous fit to the BESIII high-precision energy-dependent cross-section measurements for $\sigma(e^+e^- \to J/\psi\pi^+\pi^-)$ of the high luminosity XYZ (8.2 fb^{-1}) and low luminosity R-scan (0.8 fb^{-1}) data sets [22], resolves two resonance structures at high statistical significance ($> 7\sigma$) in the $Y(4260)$ region, whereas a $Y(4008)$ appears not to be present. It should be emphasised that while the $Y(4260)$ is observed with a significantly smaller width ($\Gamma = 44.1 \pm 3.8$ MeV$/c^2$) at smaller mass ($m = 4220$ MeV$/c^2$), the second resonance (with $m = 4326.8 \pm 10.0$ MeV$/c^2$, $\Gamma = 98.2^{+25.4}_{-19.6}$ MeV$/c^2$) is (within errors) consistent with the $Y(4360)$, which is here firstly observed in the decay to $J/\psi\pi^+\pi^-$. Previously, it was only seen in $\psi(2S)\pi^+\pi^-$ [3, 23].

Before coming back to e^+e^- production of the $\psi(2S)\pi^+\pi^-$, the recent BESIII result on $h_c\pi^+\pi^-$ production [24] should be mentioned and noted, providing evidence for two resonant structures at 4.22 GeV$/c^2$ ($m = (4218.4 \pm 4.0 \pm 0.9)$ MeV$/c^2$ and $\Gamma = (66.0 \pm 0.9 \pm 0.4)$ MeV$/c^2$) and at 4.39 GeV$/c^2$ ($m = (4391.6 \pm 6.3 \pm 1.0)$ MeV$/c^2$, $\Gamma = (139.5 \pm 16.1 \pm 0.6)$ MeVc^2) that we call $Y(4220)$ and $Y(4390)$. They are observed at a statistical significance of more than 10σ over the one resonance assumption.

The Belle result on e^+e^- production of $\psi(2S)\pi^+\pi^-$ (Fig. 3, left) shows clear indication of $Y(4360)$ and $Y(4660)$, both decaying to $\psi(2S)\pi^+\pi^-$ [23]. However, no evidence for the $Y(4260)$ is found in the data ($< 3\sigma$), and it was thus omitted from their best fit. The new $\psi(2S)\pi^+\pi^-$ production cross-section result by BESIII [25] is compared to the ones from BaBar and Belle in Fig. 3, right. The BESIII measurement confirms the $Y(4360)$ line shape reported previously, and from our fit with three coherent Breit–Wigner functions, we observe for the first time $Y(4220) \to \psi(2S)\pi^+\pi^-$ and again $Y(4390)$, which are both consistent in the resonance parameters (m, Γ) with the two structures that we observe in $h_c\pi^+\pi^-$ [24].

In the region of these both states, we studied also possible intermediate states using an unbinned maximum-likelihood fit to the Dalitz plots (Fig. 4), in which the parameterisation comprises two coherent sums of resonant and non-resonant production. At 4.42 GeV, including an intermediate state of $(m, \Gamma) = (4032.1 \pm 2.4, 26.1 \pm 5.3)$ MeV$/c^2$ improves significantly (9.2σ) the fit description of the data, consistent with a clearly visible narrow structure in $m(\psi(2S)\pi)$ at this $E_{\rm cms}$ (Fig. 4, top right). At 4.36 GeV, no obvious structure is visible but a cluster of events at low $m(\pi\pi)$. At the two lower

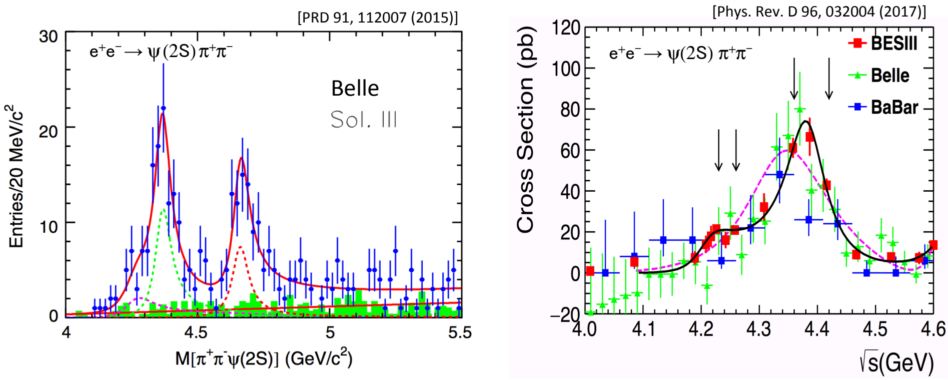

Fig. 3. Left: The reconstructed $\psi(2S)\pi^+\pi^-$ invariant mass from Belle shows clear indications of the $Y(4360)$ and $Y(4660)$, however, no evidence for the $Y(4260)$ resonance. Right: Comparison of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ cross-section shape as measured at BESIII to those provided by BaBar and Belle — the $Y(4360)$ line shape is found to be in consistency for the three different experiments. The arrows indicate the four BESIII high luminosity XYZ data sets.

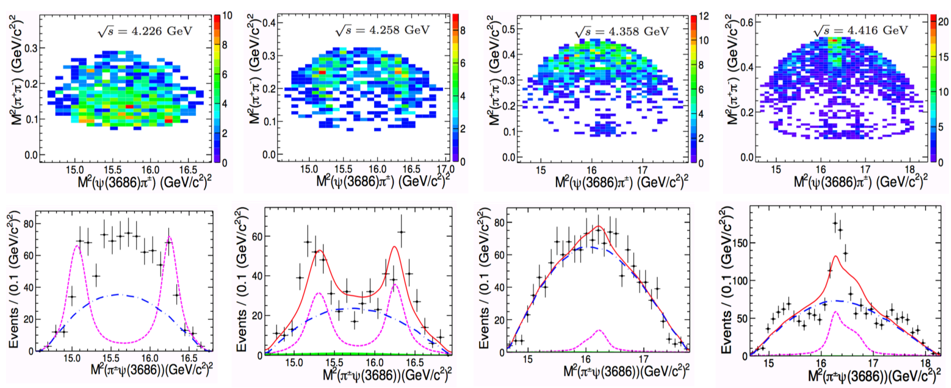

Fig. 4. Top: Dalitz plots $m^2(\pi\pi)$ *vs.* $m^2(\psi(2S)\pi)$ at the four $E_{\rm cms}$ = 4.23, 4.26, 4.36 and 4.42 GeV indicated in Fig. 3. Bottom: Projections of the Dalitz plots to $m^2(\psi(2S)\pi)$ with the fit result overlaid. Both figures taken from [25].

$E_{\rm cms}$ (Fig. 4, top left), *i.e.* in the region of $Y(4220)$, two accumulations of events at about 3.9 and 4.03 GeV$/c^2$, respectively, are visible at 4.26 GeV, whereas at 4.23 GeV, no structure is clearly seen and the $m(\pi\pi)$ distribution appears very different from that at 4.26 GeV. It should be noted that possible intermediate states of 3.9 and 4.03 GeV$/c^2$ at 4.26 GeV would have kinematic reflections at each other's masses, and at 4.23 GeV, a possible $Z_c(4030)$ state would be rather close to the kinematical border, so that no obvious distinct structure would be expected to be visible here. In the fits at 4.36 and 4.26 GeV$/c^2$, the resonance parameters of the intermediate Z_c-like state were fixed to those obtained at 4.42 GeV$/c^2$, resulting in a statistical significance of 3.6σ and 9.6σ, respectively. Even though, also at 4.42 GeV$/c^2$, the data is not described sufficiently, the confidence level improves to about 50%, when applying an additional cut of $m(\pi\pi) > 0.3$ GeV$/c^2$.

Even though there are still unresolved discrepancies (model *vs.* data), we might have observed a Z_c-like intermediate state of a mass of about $m = 4030$ MeV$/c^2$. A similar analysis of the neutral counter part, $e^+e^- \to \psi(2S)\pi^0\pi^0$, delivers similar structures and results of the corresponding Dalitz plot analysis [26]. Higher statistics data and theoretical input are needed to improve and sort out the present discrepancies in describing the significant sub-structures in the $\psi(2S)\pi\pi$ system.

In conclusion for the vector Y states, we observe two structures, $Y(4220)$ and $Y(4390)$, consistently in the decays to $c\bar{c}\pi\pi$, involving the three charmonia J/ψ, h_c and $\psi(2S)$ and, interestingly, we observe these two Y states also being consistent in the resonance parameters as well as in the preliminary open charm analysis of $e^+e^- \to D^0D^*\pi$ (Fig. 5, bottom).

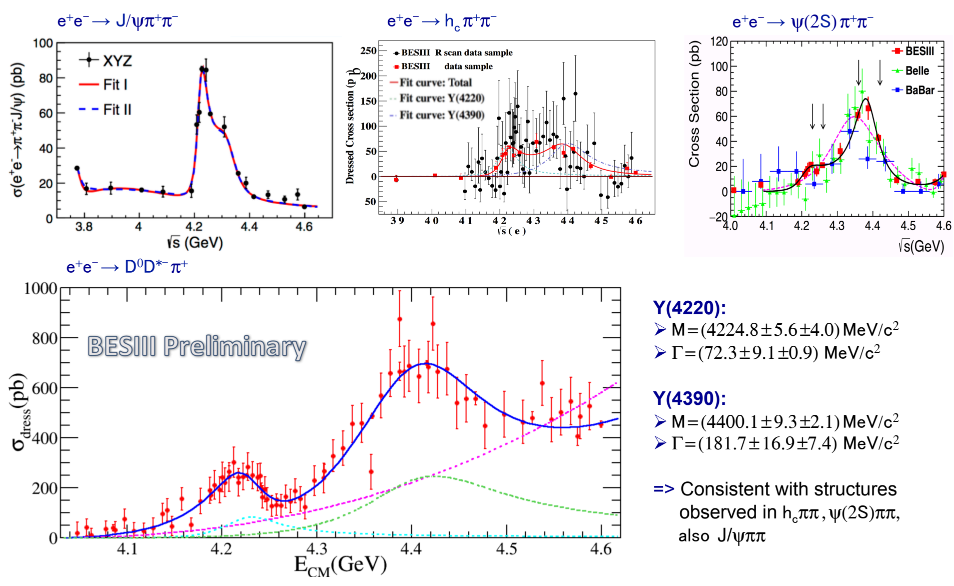

Fig. 5. Cross-section measurements of direct $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$ production, resolving consistently the $Y(4220)$ and $Y(4390)$ states (top) that are also observed in the open charm decay to $D^0D^*\pi$ (bottom).

3. Conclusions and outlook

The BESIII/BEPCII experiment has been successfully operating since 2008. Given the world largest data set in the τ-charm region, it offers unique possibilities for investigations of the XYZ spectrum. We have the first two Z_c isospin triplets established, the $X(3872)$ for the first time observed in radiative decays [27], and we have recently published precision measurements of production cross section in the Y energy range, resolving for the first time structures overseen in previous measurements. Similarly to the X and Z_c states, we find these Y states also decaying to $DD^*\pi$. As an outlook, BESIII is continuing to collect data, helping and needed to further resolve the XYZ puzzle.

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