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Recent results from hadron spectroscopy at BESIII

M. Albrecht on behalf of the BESIII Collaboration
Ruhr-Universitaet Bochum - Bochum, Germany

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Summary. — Recent results in the field of hadron spectroscopy from the BESIII experiment, operated at the Beijing Electron Positron Collider II (BEPCII), are highlighted. Apart from the world's largest data samples at center-of-mass energies corresponding to the J/ψ, ψ' and $\psi(3770)$ resonances, the BESIII Collaboration has recently recorded various data sets at and around the $Y(4260)$. The latter provide a unique opportunity to study the nature of the yet unsatisfactorily explained XYZ-states. Furthermore, several observations around the $p\bar{p}$ threshold in the light hadron sector are discussed.

1. – Introduction

In recent years, the BESIII Collaboration has recorded various data samples from e^+e^- collisions in the energy region between 2.0 and 4.6 GeV, which include a scan in the region between 2.0 and 3.0 GeV, huge data samples at energies corresponding to the three lightest vector-charmonia (1.3 billion J/ψ decays, 450 million $\psi(2S)$ decays and $2.9\,\text{fb}^{-1}$ of data at the $\psi(3770)$ mass), as well as multiple data sets at higher energies. These include about $3\,\text{fb}^{-1}$ of data at an energy of 4.18 GeV, 104 scan points in the region between 3.85 and 4.59 GeV, which amount to a total of $0.8\,\text{fb}^{-1}$, and a series of data sets recorded between 3.81 and 4.6 GeV with individual sample sizes varying between $50\,\text{pb}^{-1}$ and $1.1\,\text{fb}^{-1}$ and a total size of more than $4\,\text{fb}^{-1}$ for detailed studies of the XYZ states [1]. Using these data samples, referred to as XYZ data samples in the following, new measurements of the exclusive $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$ and $\pi^+\pi^- h_c$ cross sections were performed, which provide a useful insight into the direct production of $J^{PC} = 1^{--}$ Y-states. Radiative and hadronic transitions from these Y-states are then used to shed light onto the X-, and charged, charmonium-like Z-states. Furthermore, the J/ψ and $\psi(2S)$ samples provide the possibility to perform high-statistics measurements in the light hadron sector. Here, a recent analysis of the radiative J/ψ decay into $\gamma_{\text{rad}}\eta'\pi^+\pi^-$ is presented. A significant distortion of the cross section is observed in the vicinity of the $p\bar{p}$ threshold, which might be related to the presence of the so-called $X(1835)$ state.

2. – The Y-states: Exclusive cross section measurements

In 2005 the BaBar experiment observed a resonant structure in the invariant $J/\psi\pi^+\pi^-$ mass at about 4.26 GeV/c^2 using the initial state radiation process [2]. The enhancement was interpreted as a resonance and was called $Y(4260)$. The Belle experiment was able to confirm the existence of this structure shortly after [3], and both experiments published updates of their analyses a few years later, exploiting the full statistics that the B-factories had recorded by then [4,5]. In the high-statistics Belle analysis, another state had to be introduced to properly describe the data, which was called $Y(4008)$. Using the high statistics XYZ and scan data-sets recorded by BESIII, we were able to perform a direct measurement of the e^+e^- cross section into final states including a charmonium resonance. This new data reveals that the structure in the $\pi^+\pi^-J/\psi$ final state appears to be more complicated and cannot be described by a single resonance. However, the deviation from the shape of a single resonance appears on the high mass side of the $Y(4260)$ instead of the low mass side. The structure can be described with two peaks, one with a mass of $4222.0 \pm 3.1 \pm 1.4\,\mathrm{MeV}/c^2$ and a width of $44.1 \pm 4.3 \pm 2.0\,\mathrm{MeV}$ and the second one with a mass of $4320.0 \pm 10.4 \pm 7.0\,\mathrm{MeV}/c^2$ and a width of $101.4^{+23.4}_{-19.7}$ $\pm 10.2\,\mathrm{MeV}$ [6].

When exchanging the J/ψ with a $\psi(2S)$ in this reaction, the measured cross section shows a very different behaviour: While there is no narrow structure near 4.26 GeV/c^2 visible, a resonant behaviour is observed roughly 100 MeV/c^2 higher. The latest BESIII data for this reaction is in very good agreement with previous observations by BaBar and Belle (see fig. 1, bottom left) and the observed structure is usually interpreted as the $Y(4360)$. Finally, the reaction involving an h_c resonance in the final state was studied. A picture similar to the $\pi^+\pi^-J/\psi$ channel seems to emerge: The observed cross section shows a much more complex behavior than previously expected. Again, it can be parameterized using two structures instead of one, whereas the lower one has a mass of $4218.4 \pm 4.0 \pm 0.9\,\mathrm{MeV}/c^2$ and a width of $66.0 \pm 9.0 \pm 0.4\,\mathrm{MeV}$, while the higher one is located at a mass of $4391.6 \pm 6.3 \pm 1.0\,\mathrm{MeV}/c^2$ and has a width of $139.5 \pm 16.1 \pm 0.6\,\mathrm{MeV}$ [7]. The cross section is displayed in the bottom right plot of fig. 1.

3. – The X-states

The first discovered and probably best-studied of the XYZ states is the $X(3872)$. It is a narrow state, that was discovered in 2003 by the Belle experiment in the reaction $B \to KX(3872) \to K(\pi^+\pi^-J/\psi)$ [8]. This state was confirmed in other production and decay modes and its quantum numbers have been determined to be $J^{PC} = 1^{++}$ [9], however its nature is still controversially discussed. Using the high statistics data sets recorded at $\sqrt{s} = 4009, 4229, 4260$ and 4360 MeV, BESIII recently observed the $X(3872)$ for the first time in the process $e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$, with a significance of 6.3σ (see fig. 2, left) [10]. The resonance parameters were measured to be $M = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$ and $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL), which is in good agreement with the Belle results. Apart from the observation, BESIII studied the energy dependent $e^+e^- \to \gamma X(3872)$ cross section, which gives a strong hint towards a possible production of the $X(3872)$ through the decay of a Y-state around 4.2–4.3 GeV, as can be seen in fig. 2. However, more data is needed to make a clear statement.

Another very interesting state in the same mass region is the so-called $X(3823)$, which was also first observed by Belle in 2013 [11]. Belle observed this state in the process $B \to KX(3823) \to K\chi_{c1}\gamma$ with a significance of 3.8σ. A particularly interesting

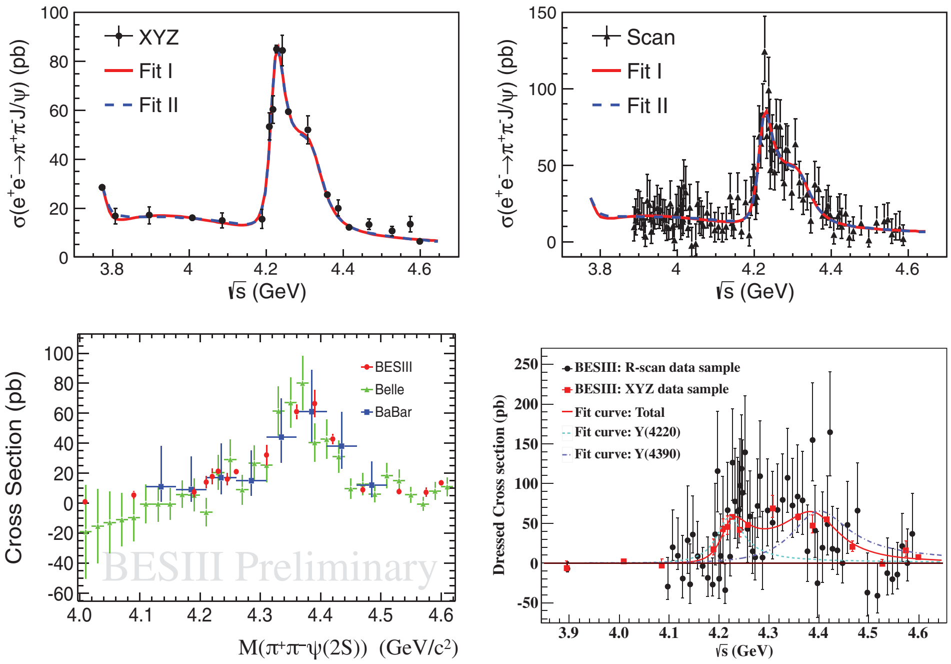

Fig. 1. – $e^+e^- \to \pi^+\pi^- J/\psi$ cross section for BESIII high statistics XYZ data sets (top left) and a larger number of low statistics data sets (top right) [6]. The bottom row plots show the $e^+e^- \to \pi^+\pi^-\psi(2S)$ (left) and $e^+e^- \to \pi^+\pi^- h_c$ (right) [7] cross section measurements. The red data points represent the high statistics XYZ data samples, while the black points correspond to the scan data points.

feature of this narrow resonance is, that its mass is consistent with expectations from potential model predictions for the yet unobserved $\psi_2(1^3D_2)$ conventional charmonium state. With the BESIII data sets the existence of the $X(3823)$ could be confirmed. Based on the samples recorded at center-of-mass energies of $4229, 4260, 4360, 4420$ and $4600\,\mathrm{MeV}$, a signal of the $X(3823)$ was observed with a significance of 6.2σ in the process $e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\chi_{c1}\gamma$ [12]. As for the previously presented study of the $X(3872)$, also here the energy dependent cross section was extracted. Again, the

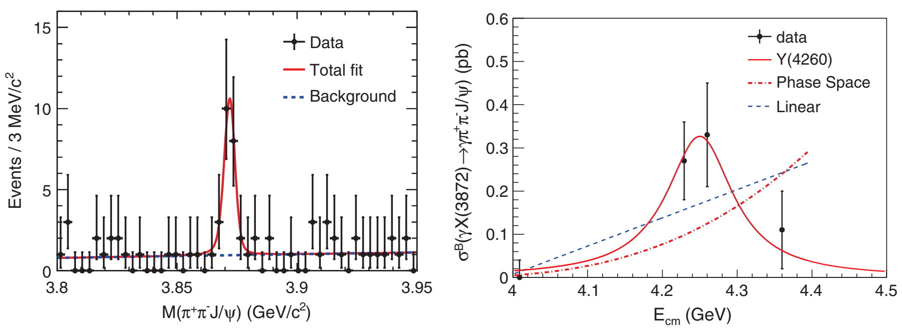

Fig. 2. – First observation of the $X(3872)$ in $e^+e^- \to \gamma X(3872) \to \gamma(\pi^+\pi^- J/\psi)$ (left) and energy dependent cross section of the process $e^+e^- \to \gamma X(3872)$ [10].

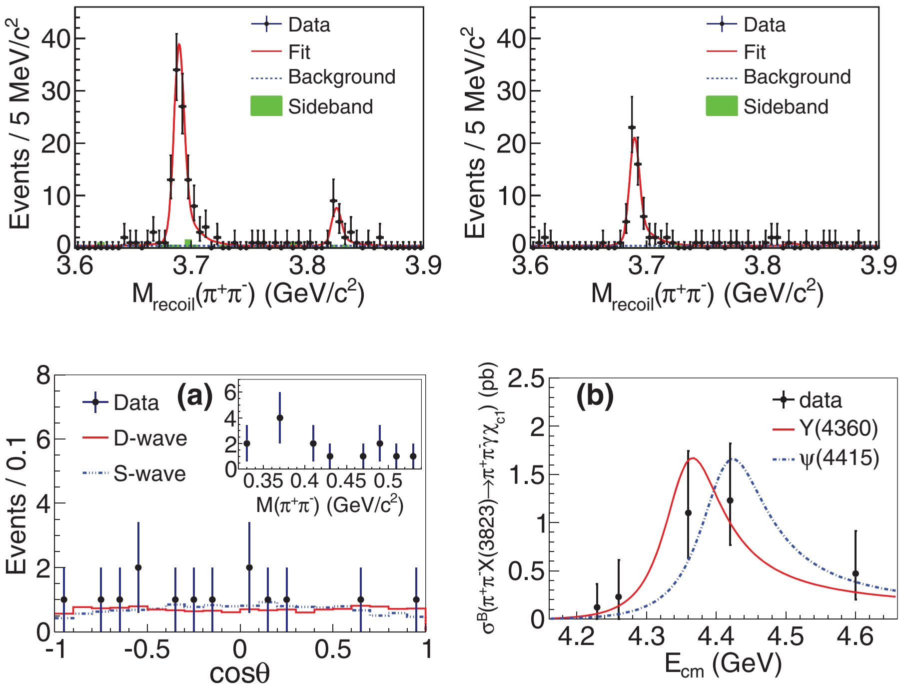

Fig. 3. – Top row: $\pi\pi$-recoil mass spectra for the final states $\pi^+\pi^-\chi_{c1}\gamma$ (left) and $\pi^+\pi^-\chi_{c2}\gamma$ (right). A clear signal of the $X(3823)$ is observed in the χ_{c1} channel. Bottom row: Scattering angle of the $(X3823)$ together with MC-expectations for S- and D-wave (left) and energy dependent $e^+e^- \to \pi^+\pi^-X(3823)$ cross section (right). Two fits corresponding to the $Y(4360)$ (red) and the $\psi(4415)$ (blue) were performed [12].

shape hints towards a production of the $X(3823)$ state through the decay of a resonance with a mass of roughly $4.4\,\mathrm{GeV}/c^2$. However, fits to this energy dependent cross section with different parameterizations do not allow to distinguish between the $Y(4360)$ and the $\psi(4415)$ (see fig. 3). The bottom left plot in fig. 3 shows the scattering angle of the $X(3823)$ as extracted from data (black points), overlayed with expectations for D- and S-wave from Monte Carlo simulations. Given the current statistics, the data is consistent with both hypotheses and more data is needed to determine the properties of the $X(3823)$.

4. – The Z-states

In 2013, BESIII discovered a resonant structure in the $J/\psi\pi^\pm$ invariant mass in the process $e^+e^- \to \pi^+\pi^-J/\psi$ at $\sqrt{s} = 4.26\,\mathrm{GeV}$ with a significance of more than 8σ [13]. Since this resonance is charged, and it obviously decays into $c\bar{c}$, it must contain four quarks. The resonance is located very close to the $D\overline{D^*}$-threshold and has been confirmed by Belle [5] and CLEOc [14] shortly after its first observation at BESIII. Therefore, this is the first four-quark state, that has been observed by more than one experiment. After this discovery, we present an updated analysis based on $1.92\,\mathrm{fb}^{-1}$ of data recorded at $\sqrt{s} = 4.23$ and $4.26\,\mathrm{GeV}$ with the aim to determine the J^P quantum numbers of the $Z_c(3900)^\pm$ using a partial wave analysis. The partial wave fit contains several resonances

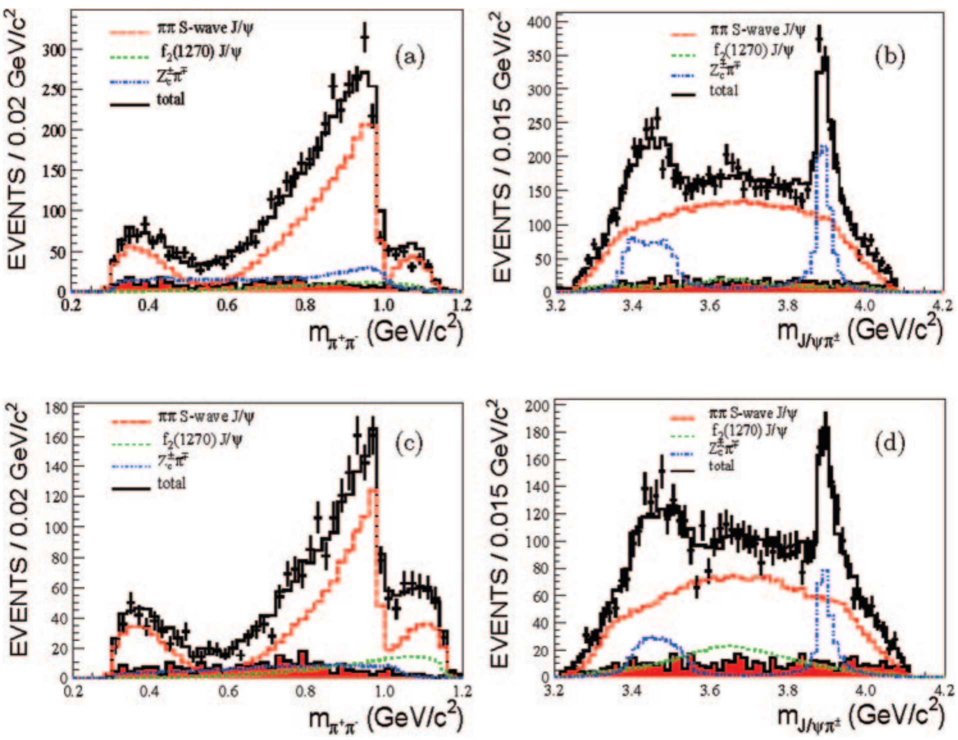

Fig. 4. – Projection of the best PWA fit and its individual components to the $\pi^+\pi^-$ (left) and $J/\psi\pi^\pm$ (right) invariant mass distributions. The upper row shows the plots for data taken at $\sqrt{s} = 4.23\,\text{GeV}$, while the lower represents the data taken at $\sqrt{s} = 4.26\,\text{GeV}$ (PRELIMINARY).

to describe the scalar $(\pi\pi)_S$-wave component, the $Z_c^\pm$ resonance in the $J/\psi\pi^\pm$ system as well as a non-resonant $\pi^+\pi^- J/\psi$ component. As for the scalar resonances in the $\pi\pi$ system, the σ_0, $f_0(980)$, $f_2(1270)$ and the $f_0(1370)$ were included. For the J^P quantum-number assignment of the $Z_c^\pm$ state, the possibilities $0^-, 1^-, 1^+, 2^-$ and 2^+ are tested and this resonance is also parameterized using a Flatté line shape. The projections of the fit and its individual components to the $\pi\pi$ and $J/\psi\pi^\pm$ invariant mass are displayed in fig. 4 for both data sets that were used.

The use of the Flatté line shape allows to account for the coupling of the $Z_c^\pm$ to the $D\overline{D}^*$ channel. The ratio of the coupling constants for the $J/\psi\pi^\pm$ and the $D\overline{D}^*$ channels is taken from the BESIII measurement [15]. The preliminary result of this study is that an assignment of $J^P = 1^+$ for the $Z_c^\pm$ resonance is preferred over other quantum number assignments with a statistical significance of $> 7.3\sigma$. Furthermore, the pole mass and width of the $Z_c^\pm$ are $M = (3887.0 \pm 0.8 \pm 10.0)\,\text{MeV}/c^2$ and $\Gamma = (45.2 \pm 4.8 \pm 16.8)\,\text{MeV}$, respectively, when using a Flatté line shape parameterization.

5. – The $X(1835)$: Structures at and around the $p\bar{p}$ threshold

The huge data samples recorded by BESIII at the mass of the J/ψ and $\psi(2S)$ allow for detailed studies of exclusively reconstructed subsamples of various different channels involving resonances decaying into light hadrons. Also in this field, several peculiarities have been observed and the BESIII analyses, past and ongoing, provide valuable input for the interpretation and the understanding of the observed phenomena. One such phenomenon is the observation of structures (peaks and dips) in cross sections and anomalous line shapes in the vicinity of the $p\bar{p}$ threshold in various different channels.

The BESII experiment first observed a strong enhancement at the $p\bar{p}$ threshold in the reaction $J/\psi \to \gamma p\bar{p}$ [16], which was later confirmed by BESIII [17] as well as CLEO [18] in $\psi(2S)$ decays. This structure, which was called $X(p\bar{p})$ throughout the literature, was then attested to have a spin-parity of $J^P = 0^-$ by BESIII [19].

Apart from this enhancement in the channels containing an antiproton-proton pair, a number of structures were observed in various different channels, mostly —but not exclusively— from radiative J/ψ decays. Also here, the BESII experiment was the first to observe a peaking structure in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ channel [20], which was named $X(1835)$ and confirmed by BESIII in the same channel [21]. Furthermore, similar structures and enhancements were observed in $J/\psi \to \gamma K_S^0 K_S^0 \eta$ [22], $J/\psi \to \omega\eta\pi^+\pi^-$ [23], $J/\psi \to \gamma\omega\phi$ [24] and $J/\psi \to \gamma 3(\pi^+\pi^-)$ [25]. The multitude of these findings led to a number of possible explanations by theorists, several of which also present the possibility, that the $p\bar{p}$ threshold-enhancement and the structures found in other channels are originating from the same source. If a significant coupling of a resonance located at $\sim 1830\,\mathrm{MeV}/c^2$ to $p\bar{p}$ is given, then this should be visible as a dip in the measured intensity of the channel under study. This drop would be expected exactly at the position of the $p\bar{p}$ threshold and is caused by the intensity that is leaking to the newly opened $p\bar{p}$ decay channel of the resonance. Therefore, the line shape of the $\eta'\pi^+\pi^-$ invariant mass in the process $J/\psi \to \gamma\eta'\pi^+\pi^-$ was studied at BESIII with high statistics.

A sudden drop of the intensity in the $\eta'\pi^+\pi^-$ invariant mass is indeed observed and different models were fitted to the data in order to properly describe the distorted line shape [26]. Two fit models delivered very similar overall fit qualities, so that they are both presented as possible solutions. In the first scenario, displayed in fig. 4, left, the shape is described with a single resonance, the $X(1835)$, which is parameterized using a Flatté formula. A significant coupling to the $p\bar{p}$ channel is needed, in order to obtain a good fit with this model. For the second fit model, shown in the right plot of fig. 4, the

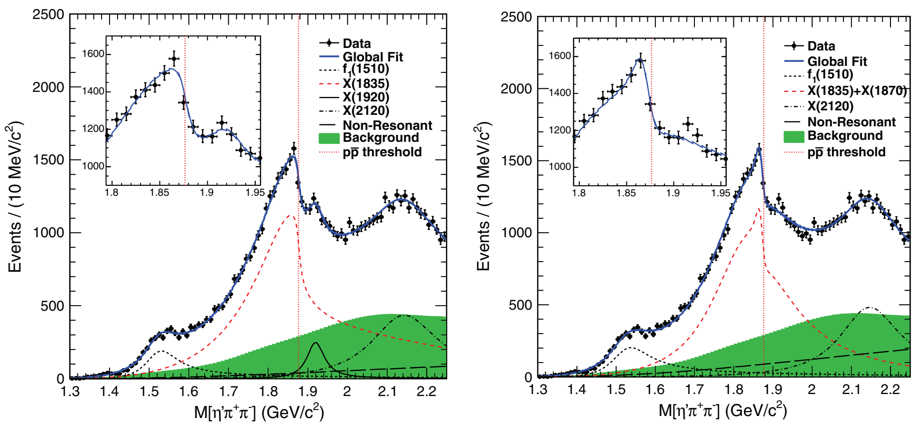

Fig. 5. – Fit to the invariant $\eta'\pi^+\pi^-$ mass in the reaction $J/\psi \to \gamma\eta'\pi^+\pi^-$ using one resonance near the $p\bar{p}$ threshold, the $X(1835)$, which is parameterized using a Flatté formula (left) as well as a second fit to the same data in which two interfering resonances were included. Both fits yield similar qualities [26].

line shape was instead parameterized with two heavily interfering resonances. While the lower lying resonance needs to have a large width on the order of 250 MeV, the second one is situated right at the $p\overline{p}$ threshold and is extremely narrow ($\Gamma \approx 13\,\mathrm{MeV}$).

Although it is not possible with current statistics to distinguish between the two models, the presence of states right above or slightly below the $p\overline{p}$ threshold which cause the observed distortion, suggest that either one of these states is not a conventional meson, but rather a molecule-like state, or a loosely bound $p\overline{p}$ state. Similarly, the line shape must also be studied with high statistics samples in other channels such as $J/\psi \to \gamma K_S^0 K_S^0 \eta$ to shed light on the nature of the $X(1835)$.

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