Hadron Spectroscopy at BESIII

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Abstract. The BESIII experiment, located at the symmetric electron positron collider BEPCII in Beijing, is successfully operating since 2008 and has collected large data samples at center-of-mass energies in particular above 4 GeV in the past few years. The analysis of these samples has resulted in a number of surprising discoveries with respect to the “XYZ states”. In this talk, we highlight recent results of the hadron spectroscopy program, with a focus on new results in the XYZ energy region.

1. Introduction
The BESIII collaboration recorded various data samples of $e^+e^−$ collisions in the $\tau$-charm mass region in recent years. Apart from a scan in the 2.0 to 3.0 GeV region, large samples at energies corresponding to the masses of the three lightest vector-charmonia, namely the $J/\psi$ (1.3 billion events), $\psi(2S)$ (450 million events), and the $\psi(3770)$ (2.9 fb$^{-1}$) were recorded. In the energy region around 4.0 GeV a larger data set at an energy of 4.18 GeV (3 fb$^{-1}$), a scan including 104 samples between 3.85 and 4.59 GeV amounting to a total of 0.8 fb$^{-1}$, and a series of samples between 3.85 and 4.6 GeV with sample sizes between 50 pb$^{-1}$ and 1.1 fb$^{-1}$ are available. The latter have an accumulated size of more than 4 fb$^{-1}$ and enable detailed studies of the XYZ states. Since the $Y$ states carry the quantum numbers $J^{PC} = 1^{−−}$ they can be directly produced in $e^+e^−$ annihilations.

Using the data sets outlined above, we present precise measurements of the $e^+e^− \rightarrow \pi^+\pi^−J/\psi, \pi^+\pi^−(2S)$ and $\pi^+\pi^−h_c$ cross sections. Various candidates for $Y$ states are observed in these exclusive cross section measurements. Furthermore, the obtained results are compared to a very recent measurement of the $e^+e^− \rightarrow D^0D^{*−}\pi^+$ cross section. Two $Y$-state candidates are also observed in this open-charm channel. Finally, we present detailed results of a recent re-analysis of our data including a partial wave analysis to determine the spin-parity of the possibly exotic $Z_c(3900)$ state, which was observed in the $J/\psi\pi$ system already in 2013.

2. Precise cross-section measurements in the 4 – 4.6 GeV region
A resonant structure in the invariant $J/\psi\pi^+\pi^−$ mass at $\approx 4.26\text{ GeV}/c^2$ was observed by the BaBar experiment exploiting the Initial State Radiation process in 2005. The BaBar collaboration interpreted this structure as a resonance and called it $Y(4260)$ [1]. The observation was confirmed by the Belle experiment [2] and both collaborations published detailed updated analyses later [3],[4]. Additionally to the $Y(4260)$, Belle found evidence for another state in the updated high-statistics analysis. This state is situated on the low mass side of the resonant structure and was called the $Y(4008)$. This additional low mass state was however not seen
Figure 1. The top row plots show the $e^+e^-\rightarrow \pi^+\pi^- J/\psi$ cross section for the high statistics (left) and a larger number of low statistics BESIII data sets (right) [5]. The bottom row shows the $e^+e^-\rightarrow \pi^+\pi^- \psi(2S)$ (left) [6] and $e^+e^-\rightarrow \pi^+\pi^- h_c$ (right) [7] cross sections. Here, the square-shaped markers indicate the high-statistics data sets, while the circular ones correspond to the low statistics samples. (Figures coloured online)

by BaBar. Using the BESIII data samples we perform precise measurements of the $e^+e^-$ cross section into final states consisting of two charged pions and a $J/\psi$, $\psi(2S)$ or $h_c$. We observe, that the structure in the $\pi^+\pi^- J/\psi$ channel, which is commonly associated with the $Y(4260)$, indeed appears to be more complicated and cannot be described by a single resonance. In contrast to the results from Belle, the deviation appears on the high-mass side of the enhancement at 4.26 GeV/$c^2$ and we do not need an additional contribution on the low-mass side to describe the data. The asymmetric enhancement can be described using two peaks, one with a mass of $4222.0 \pm 3.1 \pm 1.4$ MeV/$c^2$ and a width of $44.1 \pm 4.3 \pm 2.0$ MeV and the second one with a mass of $4320.0 \pm 10.4 \pm 7.0$ MeV/$c^2$ and a width of $101.4^{+23.4}_{-19.7} \pm 10.2$ MeV [5].

The cross section shows a very different behavior when exchanging the $J/\psi$ with the $\psi(2S)$. We do not observe a significant structure at 4.26 GeV/$c^2$, however a resonant enhancement appears about 100 MeV/$c^2$ higher [6]. These findings are in very good agreement with previous observations by BaBar and Belle, where this structure was called the $\psi(4360)$. Finally, we studied the $e^+e^-\rightarrow \pi^+\pi^- h_c$ cross section where a picture very similar to the $\pi^+\pi^- J/\psi$ channel seems to emerge: a complex structure between 4.2 and 4.3 GeV/$c^2$ is observed (see Fig.1, bottom right) for which a solution containing two instead of one resonances is favored by the fit. A fit to all available BESIII data reveals a mass of $4218.4 \pm 4.0 \pm 0.9$ MeV/$c^2$ and a width of $66.0 \pm 9.0 \pm 0.4$ MeV for the lower state. The mass of the second state is determined to be $4391.6 \pm 6.3 \pm 1.0$ MeV/$c^2$ with a width of $139.5 \pm 16.1 \pm 0.6$ MeV [7]. Additionally to the findings in the channels containing charmonium resonances, we also observe resonant structures in open-charm channels which could be connected to the ones described above. A precise
measurement of the $e^+e^- \to \pi^+ D^0 D^{*-}$ cross section reveals two distinct and clearly visible structures (see Fig. 2) [8]. Using various different models to describe the data we obtained stable parameters for the mass and width of the lower lying enhancement which are determined to be 4228.6 ± 4.1 ± 5.9 MeV/$c^2$ and 77.1 ± 6.8 ± 6.9 MeV, respectively. These parameters are consistent with the previously observed $Y(4220)$ state. The situation is more complicated for the second enhancement, which seems not to stem from a single known resonance and could contain contributions from the $\psi(4415)$ and other resonances. Thus, we refrain from listing resonance parameters for this enhancement since a more sophisticated partial wave analysis will be needed to provide more insight into the origin of the enhancement.

3. Determination of spin-parity quantum numbers of the $Z_c(3900)$

Using the data sample recorded at a center-of-mass energy of 4.26 GeV BESIII reported the observation of a resonant structure in the $J/\psi \pi^\pm$ invariant mass with a significance of more than 8$\sigma$ in the process $e^+e^- \to \pi^+\pi^- J/\psi$ which was discussed in detail in the previous paragraph [9]. This resonance is charged and decays into $e\bar{e}$; thus, it is treated as a candidate for a four-quark state. The resonance is located very close to the $D\bar{D'}$ threshold and its observation was confirmed by the Belle experiment [4] and a group analyzing CLEO-c data [11]. Here, we present an updated analysis based on 1.92 fb$^{-1}$ of data recorded at center-of-mass energies of 4.23 and 4.26 GeV. Using these data samples, we perform a partial wave analysis to determine the spin and parity quantum numbers of the $Z_c(3900)$. The fits contain different resonances to describe the scalar ($\pi\pi$)$_S$-wave component, the $f_2(1270)$ tensor resonance, the resonant $Z_c^{\pm}$ as well as a non-resonant $\pi^+\pi^- J/\psi$ component. For the description of the ($\pi\pi$)$_S$-wave, the scalar resonances $\sigma_0$ (also called $f_0(600)$), $f_0(980)$ and $f_0(1370)$ were included in the fit. Different hypotheses for the $J^P$ quantum number assignment of the $Z_c$ are tested, namely 0$^-$, 1$^-$, 1$^+$, 2$^-$ and 2$^+$. Furthermore, the resonance was also parameterized using a Flatté line-shape to take the coupling to the $D\bar{D'}$ channel into account. The projections of the fit and its individual
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Figure 3. Projections to invariant $\pi^+\pi^-$ (left column) and $J/\psi\pi^\pm$ mass (right column) of the fit results with the quantum number assignment $J^P = 1^+$ for the $Z_c$. The upper row plots show the data recorded at $\sqrt{s} = 4.23$ GeV, while the lower row plots correspond to the $\sqrt{s} = 4.26$ GeV data sample. The points with error bars are data, and the black histograms are the total fit results including background [10]. (Figures coloured online)

components to the $\pi\pi$ and $J/\psi\pi^\pm$ invariant mass are displayed in Figure 3 for both data sets.

For the parameterization of the $Z_c$ using the Flatté line-shape, additional information about the coupling of the resonance to the two considered channels are necessary. Here, the ratio of the coupling constants for the $J/\psi\pi^\pm$ and $DD\bar{\Phi}$ channels from the previous BESIII measurements [12] were used. The result of this analysis reveals the quantum numbers $J^P = 1^+$ as the most probable assignment for the tetraquark-candidate $Z_c(3900)$. This assignment is preferred over all other tested hypotheses with a statistical significance larger than $7\sigma$. The differences between the individual $J^P$ assignments are clearly visible in the polar angle distribution of the $Z_c$ as well as in the helicity angle distribution of the $J/\psi$, which are shown in Figure 4. When the $Z_c$ is parametrized using the Flatté line-shape, we obtain a pole mass of $3881.2 \pm 4.2 \pm 52.7$ MeV/c$^2$ and a pole width of $51.8 \pm 4.6 \pm 36.0$ MeV.

4. Summary
The BESIII experiment is operating successfully since 2008 and has collected large data samples in the $\tau$-charm mass region. New data sets recorded at center-of-mass energies between 4 and 4.6 GeV enable us to perform detailed studies of the $XYZ$ states. BESIII is ideally suited to
explore the transitions and decays of Y states, since these can be directly produced in $e^+e^-$ annihilations. We performed precise cross section measurements in the Y energy range and observed e.g. the Y(4220) and Y(4390) in various hidden charm channels. Similar to the observations of the X and Z states, we observed candidates for Y states in an open charm channel ($\pi^+D^0\bar{D}^*-\pi^-D^*\bar{D}^0$) for the first time.

Additionally, BESIII started a campaign to determine the $J^P$ quantum numbers of the possibly exotic $Z_c$ states. From a partial wave analysis of the $\pi^+\pi^-J/\psi$ channel at $\sqrt{s} = 4.26$ and 4.36 GeV we determined the spin-parity quantum numbers of the $Z_c(3900)$ to be $J^P = 1^+$. 

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