Charmonium-like States at BESIII

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Abstract. Using e^+e^- annihilation data taken by the BESIII detector, several searches for charmonium-like states were performed: In $e^+e^- \to D_s^{*+}D_s^{*-}$ using datasets with center-of-mass energies of 4.23 GeV to 4.95 GeV corresponding to a total integrated luminosity of 15.67 fb^{-1}, three peaks around 4.19 GeV, 4.41 GeV and 4.79 GeV were observed. In $e^+e^- \to D^{*0}D^{*-}\pi^+$ at 4.19 GeV to 4.95 GeV corresponding to $\mathcal{L}_{\text{int}} = 17.9\,\text{fb}^{-1}$, three peaks at 4.20 GeV, 4.47 GeV and 4.67 GeV were identified. And in $\psi(3770) \to \gamma\eta\eta', \gamma\pi^+\pi^- J/\psi$ with $\mathcal{L}_{\text{int}} = 2.93\,\text{fb}^{-1}$ an upper limit on the production of a scalar partner of the $\chi_{c1}(3872)$ was determined.

1 Introduction

Since the discovery of the J/ψ meson [1, 2] the charmonium energy region has been an active area of research and below the $D\bar{D}$ threshold the spectrum is experimentally and theoretically well understood. Above the threshold, however, many states predicted by the quark model are yet to be observed experimentally. In addition, several states have been found in this energy region, which show properties that are unexpected for charmonium states. The first of these charmonium-like states is the $\chi_{c1}(3872)$ meson [3] which lies directly at the $D^0\bar{D}^{0*}$ threshold and which is considered to be a $D^0\bar{D}^{0*}$ molecule [4]. Under this assumption, inter alia, a scalar partner χ_{c0} of this state was predicted in [5, 6], whereby the mass was determined to be around 3700 MeV/c^2. This state is searched for by BESIII in the radiative decay $\psi(3770) \to \gamma\chi_{c0}(3700)$ with $\chi_{c0}(3700) \to \eta\eta'$ and $\chi_{c0}(3700) \to \pi^+\pi^- J/\psi$ [7].

In addition to the particles with unexpected properties for charmonia, supernumerary states with quantum numbers $J^{PC} = 1^{--}$ were found. Established examples for these are the $\psi(4230), \psi(4360)$ and $\psi(4660)$ [8]. There are, however, many more states which were often only seen by single experiments or only in single decays and additional theoretical and experimental input is needed to clear up the picture. As these states lie above the $D^0\bar{D}^0$ threshold, decays with continuous quark lines are favored by the OZI rule [9–11] and are therefore searched for by BESIII e.g. in $e^+e^- \to D^{*0}D^{*-}\pi^+$ [12] and $e^+e^- \to D_s^{*+}D_s^{*-}$ [13].

The BESIII detector [14] records symmetric e^+e^- collisions provided by the BEPCII storage ring [15] in the center-of-mass energy range from 2.0 GeV to 4.95 GeV, with a peak luminosity of $1 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$ achieved at $\sqrt{s} = 3.77$ GeV. Details about the detector can be found in [14].

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2 Search for a scalar partner of the $\chi_{c1}(3872)$

The search for a scalar partner of the $\chi_{c1}(3872)$ [7] was performed using the BESIII datasets taken at the $\psi(3770)$ resonance corresponding to an integrated luminosity of $\mathcal{L}_{\text{int}} = 2.93\,\text{fb}^{-1}$ [16, 17]. Here a $\chi_{c0}(3700)$ produced in the radiative decay $\psi(3770) \to \gamma\chi_{c0}(3700)$ with subsequent decays $\chi_{c0}(3700) \to \eta\eta'$ and $\chi_{c0}(3700) \to \pi^+\pi^- J/\psi$ was searched for.

In the $\chi_{c0}(3700) \to \eta\eta'$ analysis the η is reconstructed in its decay to two photons and the η' decays to $\gamma\pi^+\pi^-$. After applying event selection criteria on the invariant masses of the η and η' candidates, as well as on the χ^2 of a kinemtic fit and on unwanted π^0 background only one event remains in the region of interest as can be seen in Figure 1. Using a Bayesian method [18] the upper limit on the product branching ratio $\mathcal{B}_{\eta\eta'} = \mathcal{B}(\psi(3770) \to \gamma\chi_{c0}) \cdot \mathcal{B}(\chi_{c0} \to \eta\eta')$ is determined at the 90% confidence level for different masses of the χ_{c0}. The resulting upper limits lie in the range of 0.9×10^{-5} to 1.9×10^{-5} and exclude the theoretical predictions in [19] for masses of the χ_{c0} smaller than $3730\,\text{MeV}/c^2$.

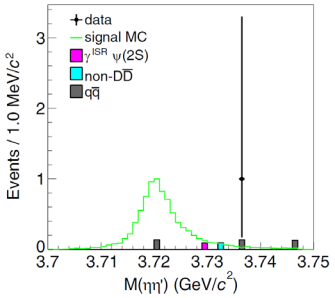

Figure 1. Invariant mass spectrum of the $\eta\eta'$ system in the $\psi(3770) \to \gamma\eta\eta'$ analysis of data (black) compared with a signal Monte Carlo simulation with $m_{\chi_{c0}} = 3720\,\text{MeV}/c^2$ (green). In addition expected background contributions estimated by Monte Carlo Simulations are shown as filled histograms [7].

In the $\chi_{c0}(3700) \to \pi^+\pi^- J/\psi$ analysis the J/ψ gets reconstructed in its decays to e^+e^- and $\mu^+\mu^-$. After reduction of the main background contributions coming from Bhabha scattering and initial state radiation (ISR) events no significant χ_{c0} contribution can be seen in the $\pi^+\pi^- J/\psi$ invariant mass spectra (see Figure 2). To extract an upper limit for the product branching ratio $\mathcal{B}_{\pi^+\pi^- J/\psi} = \mathcal{B}(\psi(3770) \to \gamma\chi_{c0}) \cdot \mathcal{B}(\chi_{c0} \to \pi^+\pi^- J/\psi)$ a simultaneous unbinned maximum likelihood to the $\pi^+\pi^- J/\psi$ spectra is performed using different mass hypotheses. Using these fits the likelihood profiles are extracted, from which the upper limits at the 90% confidence level are determined. These lie in the range of 0.9×10^{-5} to 3.4×10^{-5} and, together with an independent determination of the branching ratio of the decay $\psi(3770) \to \gamma\chi_{c0}$, might give important information on the isospin violation in these molecule-like systems, assuming the χ_{c0} to be a $D\bar{D}$ molecule with a mass below that of the $\psi(3770)$ charmonium [5].

3 Search for charmonium-like states with $J^{PC} = 1^{--}$ in $e^+e^- \to D^{*0}D^{*-}\pi^+$

Using 86 data samples with center-of-mass energies of 4.19 GeV to 4.95 GeV corresponding to an integrated luminosity of $\mathcal{L}_{\text{int}} = 17.9\,\text{fb}^{-1}$ [20–22] BESIII searched for the reaction $e^+e^- \to D^{*0}D^{*-}\pi^+$ using a semi-inclusive method, where only the $D^{*0}(\to D^0\pi^0)$ or the $D^{*-}(\to D^-\pi^0)$ and the π^+ are reconstructed [12]. Here, the D^0 decays to $K^-\pi^+$, $K^-\pi^+(\pi^0 \to \gamma\gamma)$ or $K^-\pi^+\pi^+\pi^-$ and the D^- decays to $K^+\pi^-\pi^-$.

The number of observed events N_D^{obs} is extracted by a simultaneous fit to the $D^{*0}\pi^+$ and $D^{*-}\pi^+$ recoil mass spectra which can be seen in Figure 3. From this the dressed cross section

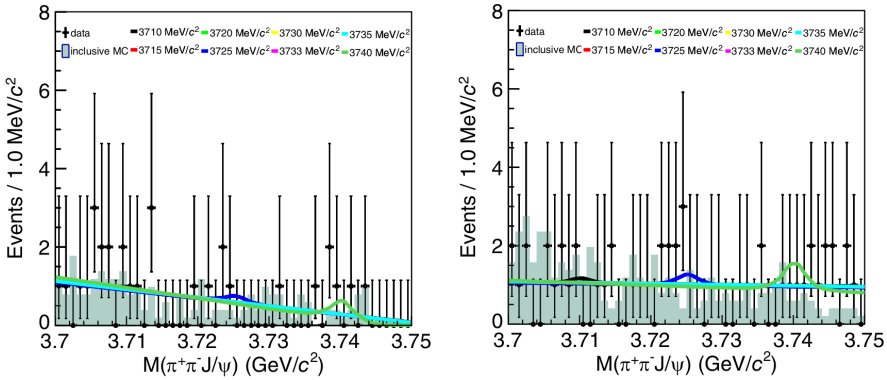

Figure 2. Invariant mass spectra of $\pi^+\pi^- J/\psi$ with $J/\psi \to e^+e^-$ (left) and $J/\psi \to \mu^+\mu^-$ (right) for data (black) in the mass region of interest. The fits with different mass assumptions of the χ_{c0} are also shown and the results of a MC simulation of the background is shown as a filled histogram [7].

σ_{dressed} gets calculated via

$$\sigma_{\text{dressed}} = \frac{N_D^{\text{obs}}}{\mathcal{L}_{\text{int}} \varepsilon_D \mathcal{B}_D (1 + \delta_{\text{ISR}})}. \tag{1}$$

Here, ε_D is the efficiency which is taken from a MC simulation, $\mathcal{B}_D$ is the product of the branching ratios of the appearing D^*, D and π^0 mesons and δ_{ISR} is a correction factor for ISR radiation which is determined using an iterative weighting method for the MC simulation [23].

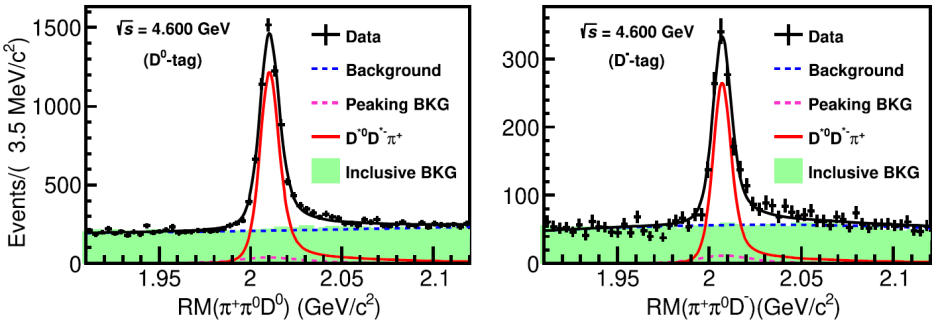

Figure 3. Recoil mass spectra of $\pi^+\pi^0 D^0$ (left) and $\pi^+\pi^0 D^-$ (right) for data (black points with error bars) and a background MC sample (green filled histogram). The result of the simultaneous fit is shown in black, the signal contribution in red, the smooth background in blue and the combinatorial peaking background in pink [12].

The determined dressed cross sections[1] are displayed in Figure 4, which show enhancements around 4.5 GeV and 4.7 GeV. A significance test shows that an additional state around

[1] A detailed list of the determined cross sections at each center-of-mass energy, including all the quantities needed to calculate them can be found in the supplemental material of [12].

4.25 GeV is needed to describe the cross section. The cross section is fitted by a coherent sum of a continuum contribution and three Breit-Wigner (BW) amplitudes. The fit yields eight mathematically ambiguous solutions [24] with different values for the the product of the electronic width of the state and its branching ratio to $D^{*0}D^{*-}\pi^+$ as well as the relative phases.

The fitted mass $m = (4209.6 \pm 7.6)\,\mathrm{MeV}/c^2$ and width $\Gamma = (81.6 \pm 20.0)\,\mathrm{MeV}$ of the lowest state are compatible with the $\psi(4230)$ [8] within 2σ. Together with the result of the combined fit on multiple $\psi(4230)$ decay modes in [25] the lower limit on its electronic width becomes $\Gamma_{ee} > (41.2 \pm 4.5)\,\mathrm{eV}$, which is at the edge of the prediction from lattice QCD for a hybrid interpretation of this state [26]. For the second state the fit gives a mass of $m = (4469.1 \pm 26.5)\,\mathrm{MeV}/c^2$ and a width of $\Gamma = (246.3 \pm 37.9)\,\mathrm{MeV}$ which is compatible with the $\psi(4500)$ seen in $e^+e^- \to K^+K^-J/\psi$ [27] and the ratio of the two decay branching ratios $\mathcal{B}(\psi(4500) \to D^{*0}D^{*-}\pi^+)/\mathcal{B}(\psi(4500) \to K^+K^-J/\psi)$ is inconsistent with a hidden-strangeness tetraquark [28, 29]. The highest lying state has a mass of $m = (4675.3 \pm 29.8)\,\mathrm{MeV}/c^2$ and a width of $\Gamma = (218.3 \pm 73.5)\,\mathrm{MeV}$ which are inside of 2σ of the $\psi(4660)$ [8].

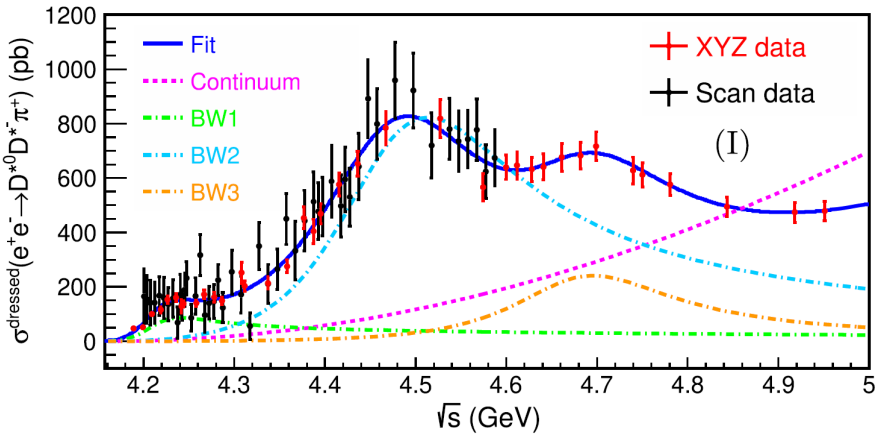

Figure 4. Determined dressed cross sections of the reaction $e^+e^- \to D^{*0}D^{*-}\pi^+$ for the 86 data samples divided into the XYZ data samples with high integrated luminosities in red and the scan data samples with smaller luminosities in black. One of the eight fits is shown as a blue line, the continuum contribution is shown in pink and the three BW contributions are green, light blue and orange [12].

4 Search for charmonium-like states with $J^{PC} = 1^{--}$ in $e^+e^- \to D_s^{*+}D_s^{*-}$

BESIII searched for the reaction $e^+e^- \to D_s^{*+}D_s^{*-}$ using 76 data samples with an integrated luminosity of $\mathcal{L}_{\mathrm{int}} = 15.7\,\mathrm{fb}^{-1}$ [20, 22, 30] with a semi-inclusive method, by only reconstructing either the D_s^{*+} or the D_s^{*-} with $D_s^{*\pm} \to D_s^{\pm}\gamma$ and $D_s^{\pm} \to K^+K^-\pi^{\pm}$ [13].

Detailed studies of the remaining background showed peaking background coming from the reaction $e^+e^- \to \gamma_{\mathrm{ISR}}D_s^{\pm}D_s^{*\mp}$, which was subtracted from the determined number of observed events. These were determined by a fit to the $\gamma KK\pi$ invariant mass spectrum, which is presented in Figure 5. The cross sections are then calculated according to Equation (1) using again an iterative method to determine the efficiency and ISR correction factor [23].

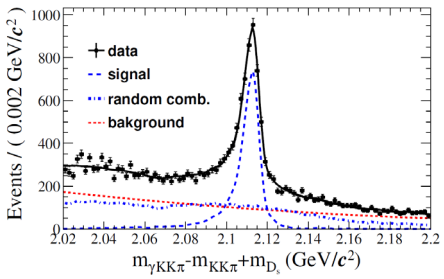

Figure 5. Invariant mass spectrum of all $\gamma KK\pi$ combinations for data as black dots with uncertainties. Also shown is the total fit in black, the signal contribution as the dashed blue line, a contribution coming from random combinations as the blue dot-dashed curve and an additional smooth background as the red dashed curve [13].

The resulting cross sections[2] are presented in Figure 6, which are fitted by a coherent sum of three P-wave BW amplitudes and a two-body P-wave phase space term whereby the significance of the third BW around 4.8 GeV was determined to be 5.9σ. The fit gives three solutions with similar fit quality, masses and widths, but significantly different magnitudes and phases. As the fit model used here is just a simple model of a sum of three Breit-Wigner amplitudes, which is known to violate unitarity, in the future more sophisticated models, e.g. using a K-Matrix approach like in [35], should be tested.

The mass and width of the lightest state are determined as $m = (4186.8 \pm 31.3)\,\mathrm{MeV}/c^2$ and $\Gamma = (55 \pm 55)\,\mathrm{MeV}$, respectively. These are consistent with the $\psi(4230)$ [8] or the $\psi(4160)$, which was seen in the inclusive cross section for $e^+e^- \to$ hadrons [31] and in $B^- \to K^-\mu^+\mu^-$ [32] and which is a candidate for the $\psi(2D)$ charmonium state. For the second BW contribution the mass of $m = (4414.6 \pm 7.0)\,\mathrm{MeV}/c^2$ is consistent with the mass of the $\psi(4415)$ [8], which is a candidate for the $\psi(4S)$ charmonium. The width of $\Gamma = (122.5 \pm 11.1)\,\mathrm{MeV}$, however, is nearly 3σ larger. The heaviest state with $m = (4793.3 \pm 11.5)\,\mathrm{MeV}/c^2$ and $\Gamma = (27 \pm 35)\,\mathrm{MeV}$ is compatible with the evidence for the $\psi(4710)$ seen in $e^+e^- \to K^0_S K^0_S J/\psi$ [33] and $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [34] and is a candidate for the $\psi(5S)$ charmonium state.

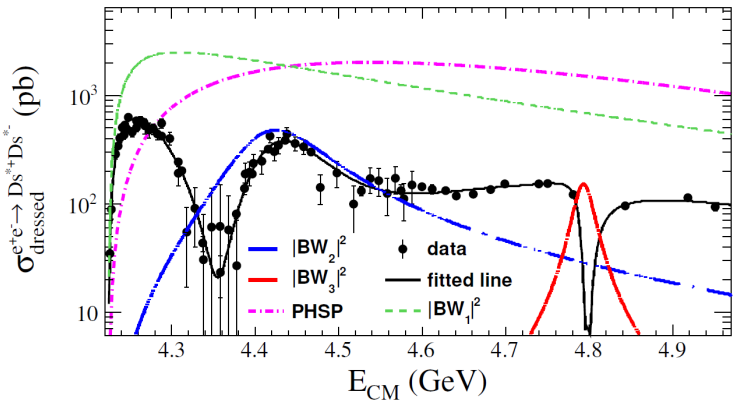

Figure 6. Dressed cross sections of the reaction $e^+e^- \to D_s^{*+}D_s^{*-}$ as black points with uncertainties. The total fit is shown as the black curve, the phase space contribution as the pink curve and the three BW contributions as the green, blue and red curve [13].

[2] A detailed table of the determined cross sections can be found in the supplemental material of [13].

5 Conclusion and outlook

The large datasets taken by the BESIII experiment at known charmonium resonances as well as in regions where additional states have been found facilitate the search for charmonium-like states with all possible quantum numbers. In this note three of these searches were presented, which give important information on the spectrum of charmonium-like states. In the future sophisticated theoretical models are needed to describe the line shape of e.g. the $J^{PC} = 1^{--}$ states in a coherent way, as it is done in the bottomonium region [35].

The BESIII experiment is still actively taking data in the charmonium region. Additionally, in the future BEPCII will be upgraded in 2024 to allow measurements at center-of-mass energies of up to 5.6 GeV searching for even heavier charmonium-like states.

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