IL NUOVO CIMENTO **47 C** (2024) 167
DOI 10.1393/ncc/i2024-24167-y

Colloquia: HADRON2023

Heavy meson spectroscopy results at BESIII

M. Scodeggio(*)
INFN, Sezione di Ferrara - Ferrara, Italy

received 21 December 2023

Summary. — Although the charmonium spectrum seems to be well investigated, charmonia can still be used as benchmarks to test QCD predictions, as these states lie in the transition region between perturbative and non-perturbative QCD. Despite the need for experimental confirmations, slowdowns arise from limited statistics of the production of non-vector states. Indeed, some charmonium states' masses, widths and brancing fractions are still far from being precisely known. Since 2009, BESIII has been scanning and investigating the energy range between 2.0 and 4.9 GeV. Thanks to its largest data sets of charmonium resonances (J/ψ, $\psi(2S)$, and $\psi(3770)$) in the world as well as other data sets at the centre-of-mass energies above 3.8 GeV, BESIII can overcome statistical limitations to shed light on open questions.

1. – Introduction

BESIII (BEijing Spectrometer III) is an e^+e^- collisions experiment, hosted at the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS) in Beijing, People's Republic of China. The leptonic beams are provided by the BEPCII (Beijing Electron Positron Collider II) storage ring, which operates in the centre-of-mass energy ($\sqrt{s}$) range from 2.0 to 4.9 GeV. Details on the sub-detectors and their performances can be found in ref. [1]. BESIII physics programme [2] covers charmonium(-like) and light hadron spectroscopy, charmed meson and baryon decays, tau lepton studies, Quantum ChromoDynamics (QCD) measurements, and new physics searches.

Since their discovery, charmonia have been fundamental tools for understanding the strong interaction and testing QCD. These resonances are indeed located in the transition region of perturbative (pQCD) and non-perturbative QCD. Due to the high mass of the constituent quarks, relativistic corrections can be neglected at the first order so that pQCD and effective field theory can be employed. Despite this, charmonium non-vector and above $D\bar{D}$-threshold states are partly unknown [3]. Moreover, since the discovery of

---

(*) On behalf the BESIII Collaboration.

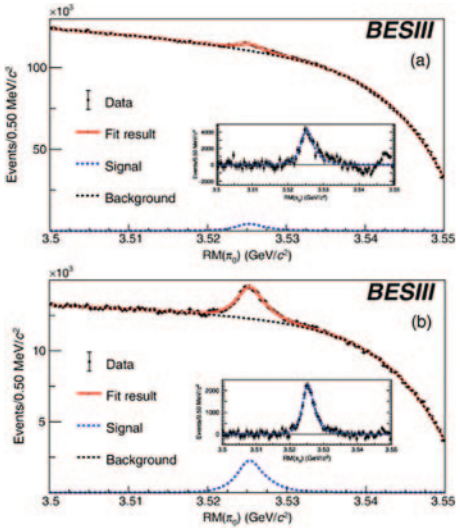

Fig. 1. – (Color online) Fits to the π^0 recoil mass spectra for the (a) inclusive and (b) tagged samples. Red solid lines denote the fit to the data, while the black dots with error bars are the data. The blue dashed lines represent the signal component and the black dashed lines are the background. Insets show the background-subtracted data with the signal shape overlaid.

$X(3872)$ [4], the charmonium spectrum became populated by a plethora of new states (namely, the XYZ exotic resonances) not fitting the potential model [5], pointing to some kind of link between conventional charmonia and these exotic states.

2. – Study of the $h_c(1^1P_1)$ meson via $\psi(2S) \to \pi^0 h_c$ decays at BESIII

The first presented work regards the $h_c(1^1P_1)$ meson, a pseudo-vector state whose knowledge is scarse, as only eleven decay modes have been observed and only one measurement of its width exists [3].

Using 448 million $\psi(2S)$ events, a search for the E1 $h_c \to \gamma\eta_c$ transition through the $\psi(2S) \to \pi^0 h_c$ decay was performed [6]. The work reports an updated determination of the $h_c(1^1P_1)$ resonance parameters (mass and width) and of the branching fractions of the involved decays. The h_c resonance was reconstructed via the π^0 recoil mass (RM(π^0)), either allowing the singlet state to decay inclusively or tagging the γ_{E1} of the $h_c \to \gamma\eta_c$ transition, as shown in fig. 1.

Being the signal-to-background ratio more favourable in the tagged data set (with respect to the inclusive one), this data sample was used to estimate the h_c resonance mass and width. The width, found to be $0.78^{+0.27}_{-0.24} \pm 0.12$ MeV, is the second estimate ever of this parameter. On the other hand, the h_c resonance mass measurement ($3525.32 \pm 0.06 \pm 0.15$ MeV/c^2) allowed updating the value of the $1P$ hyperfine mass splitting(1). Zero mass splitting ($\Delta_{hyp} = 0.03 \pm 0.06 \pm 0.15$ MeV/c^2) was observed with this measurement, as predicted by potential model calculations at leading order [7, 8].

---

(1) Defined as the difference of the h_c resonance mass and the center-of-gravity mass of the three $\chi_{cJ}(1^3P_J)$.

3. – Y's and ψ's

Using 20 energy points with an integrated luminosity of 11.3 fb^{-1} at $\sqrt{s}$ = [4.23, 4.70] GeV, ref. [9] studied the $\sigma(e^+e^- \to \pi^+\pi^-\psi_2(3823))$ cross-section and the $\psi_2(3823)$ resonance parameters. A partial reconstruction technique was employed to increase the event selection efficiency; one photon was allowed to be missing from the $\psi_2(3823) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi \to \gamma\gamma\ell^+\ell^-(\ell = e/\mu)$ decay chain. To estimate the $\psi_2(3823)$ resonance parameters and the total number of events, a simultaneous fit to the two data sets (the partial and the fully reconstructed ones) of the $\pi^+\pi^-$ recoil mass was performed. Mass (of which this work provides the most precise estimate up to date [3]) and width were found to be in agreement with the predictions for the charmonium $\psi_2(1^3D_2)$ state [10]. Normalising the total number of events by the reconstruction efficiency, luminosity, and the branching fraction of the $\psi_2(3823) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi \to \gamma\gamma\ell^+\ell^-$ decay chain, $\sigma(e^+e^- \to \pi^+\pi^-\psi_2(3823)))$ was obtained and studied. Two structures corresponding to the $Y(4360)$ and the $Y(4660)$ were found; the observation of the $Y(4660)$ in this hidden-charm channel challenges the $f_0(980)\psi(2S)$ hadron molecule interpretation [11] and the extended baryonium picture [12].

Similarly to what was presented above [9], the work of ref. [13] studied the $\sigma(e^+e^- \to \pi^0\pi^0\psi_2(3823))$ cross-section. The article provides the $\psi_2(3823)$ resonance parameters with a higher statistical uncertainty, but in agreement with the ones measured with the charged-pion counterpart. Considering isospin symmetry, the average cross-section of the neutral channel was found to be consistent with the charged one.

The two presented works allow to understand whether the $\psi_2(3823)$ particle is the $\psi_2(1^3D_2)$ charmonium state or not. The $\pi^+\pi^-$ system in the $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ process is expected to be S-wave, since the $\psi_2(3823)$ resonance is seen also in the $e^+e^- \to \pi^0\pi^0\psi_2(3823)$ channel. Hence, the relative orbital angular momentum (of the $\pi^+\pi^-$-$\psi_2(3823)$ system) should be 2, as mildly favoured by ref. [9] studies. Hence, the combination of these two studies supports the $J^{\mathrm{PC}} = 2^{--}$ assignment and the hypothesis that the $\psi_2(3823)$ particle is indeed the $\psi_2(1^3D_2)$ charmonium state.

4. – Looking at the light sector

The charmonium spectrum can also be inspected with high precision in the light sector, by probing charmonium gluon-rich processes.

Using 24 energy points at $\sqrt{s}$ = [4.0, 4.6] GeV, ref. [14] studied the $\sigma(e^+e^- \to \pi^+\pi^-\omega)$ cross-section. To estimate the Born cross-section a fit to the invariant mass of the ω decay products ($\pi^+\pi^-\pi^0$) was performed. The line shape of the Born cross-section was then studied and four different charmonium(-like) state amplitudes were tested (and shown in fig. 2); among the four hypotheses, two were found to have a significance greater than 3σ, the $\psi(4160)$ and the $Y(4220)$ states.

5. – Charming cross-sections

Data sets above the $D\bar{D}$-threshold can shed new light on charmonium decays and hint at possible connections between XYZ states and conventional charmonia.

5˙1. *Plain D mesons.* – Using 20 energy points at $\sqrt{s}$ = [4.19, 4.95] GeV, the study [15] focused on the D^+ ($\to K^-\pi^+\pi^+$) reconstruction to study the $\sigma(e^+e^- \to \pi^+\pi^-D^+D^-)$ cross-section. The fit to the $D^+\pi^+\pi^-$ invariant mass allows to obtain 20 Born cross-section points, the line-shape of which was fitted following four hypotheses, all containing

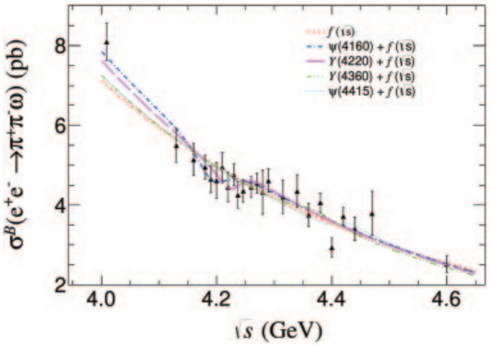

Fig. 2. – Fits to the $e^+e^- \to \pi^+\pi^-\omega$ Born cross-section. Data are represented by the filled triangles with error bars combining statistical and systematic uncertainties. The curves show the four tested fit hypotheses, $\psi(4160)$, $Y(4220)$, $Y(4360)$, and $\psi(4415)$.

the $\psi(4360)$ state. The most significant fit was obtained with an additional resonance above ~ 4.6 GeV. Moreover, by studying the D^+D^- system, the second evidence for the $\psi_3(1^3D_3)$ was found.

5·2. *Excited D mesons.* – With the same data set as above, ref. [16] studied the $\sigma(e^+e^- \to \pi^+D^{*0}D^{*-})$ cross-section, by reconstructing either the D^{*0} ($\to D^0\pi^0$) or the D^{*-} ($\to D^-\pi^0$). The cross-section was estimated by a simultaneous fit to the $\pi^+D^0\pi^0$ and $\pi^+D^-\pi^0$ recoil masses. The study of the $e^+e^- \to \pi^+D^{*0}D^{*-}$ line-shape, allowed to determine that 1) the measured electronic width of the $Y(4230)$ disfavours the hybrid interpretation [17], 2) finding the $Y(4500)$ in this channel is inconsistent with a hidden-strangeness tetraquark hypothesis [18], and 3) the $Y(4660)$ can decay into open-charm meson states.

5·3. *Strange D mesons.* – Using 20 energy points at $\sqrt{s} = [4.23,\ 4.95]$ GeV, the $\sigma(e^+e^- \to D_s^{*+}D_s^{*-})$ cross-section was studied semi-inclusively [19], by reconstructing either the D_s^{*+} ($\to \gamma K^+K^-\pi^+$) or the D_s^{*-} ($\to \gamma K^+K^-\pi^-$). The $\gamma K^+K^-\pi$ invariant mass allowed the extraction of the $e^+e^- \to D_s^{*+}D_s^{*-}$ line-shape. The fit of the line-shape, shown in fig. 3, found three structures with a significance greater than 5σ; the $\psi(4160)$, a candidate for the $\psi(2^3D_1)$ conventional charmonium, the $\psi(4415)$, a $\psi(4^3S_1)$ candidate, and the $Y(4793)$, a new possible 1^{--} state.

6. – Summary and conclusions

The BESIII Collaboration started taking data in 2008, and its physics reach has spanned a plethora of topics. This paper focuses on its most recent results on the charmonium spectrum. Thanks to its tuneable centre-of-mass energy in the charmonium range and leptonic beams, BESIII can be competitive even with smaller data sets. New data sets (*e.g.*, 2.7×10^9 of $\psi(2S)$ or $\sim$20 fb^{-1} of $\psi(3770)$) are currently being taken and analysed, hence more analyses will help the community to shed light on the charmonium(-like) states. Finally, an upgrade [2] of the BEPCII collider and the BESIII detector is under implementation to keep taking data beyond 2030. The upgraded BEPCII-U [20] will reach 2.8 GeV per beam, tripling its instantaneous luminosity at $\sqrt{s} \approx 4.7$ GeV

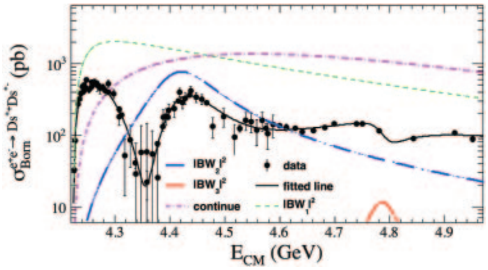

Fig. 3. – (Color online) Fit to the $e^+e^- \to D_s^{*+}D_s^{*-}$ Born cross-section. Data are black dots and the black solid line is the total fit. The green dashed line is the $\psi(4160)$ state, the blue dashed curve represents the $\psi(4415)$ resonance, and the new $Y(4793)$ candidate is the red dashed curve.

and the inner Multilayer Drift Chamber will be substituted by a triple cylindrical Gas Electron Multiplier (CGEM) [21].

REFERENCES

[1] Ablikim M. *et al.*, *Nucl. Instrum. Methods Phys. Res. Sec. A*, **614** (2010) 345.
[2] Ablikim M. *et al.*, *Chin. Phys. C*, **44** (2020) 040001.
[3] Zyla P. *et al.*, *PTEP*, **2020** (2020) 083C01.
[4] Choi S.-K. *et al.*, *Phys. Rev. Lett.*, **91** (2003) 262001.
[5] Brambilla N., Eidelman S., Hanhart C., Nefediev A., Shen C.-P., Thomas C. E., Vairo A. and Yuan C.-Z., *Phys. Rep.*, **873** (2020) 1.
[6] Ablikim M. *et al.*, *Phys. Rev. D*, **106** (2022) 072007.
[7] Kwong W., Rosner J. L. and Quigg C., *Annu. Rev. Nucl. Part. Sci.*, **37** (1987) 325.
[8] Lebed R. F. and Swanson E. S., *Phys. Rev. D*, **96** (2017) 056015.
[9] Ablikim M. *et al.*, *Phys. Rev. Lett.*, **129** (2022) 102003.
[10] Barnes T., Godfrey S. and Swanson E. S., *Phys. Rev. D*, **72** (2005) 054026.
[11] Guo F.-K., Hanhart C. and Meissner U.-G., *Phys. Lett. B*, **665** (2008) 26.
[12] Qiao C.-F., *J. Phys. G*, **35** (2008) 075008.
[13] Ablikim M. *et al.*, *JHEP*, **02** (2023) 171.
[14] Ablikim M. *et al.*, *JHEP*, **08** (2023) 159.
[15] Ablikim M. *et al.*, *Phys. Rev. D*, **106** (2022) 052012.
[16] Ablikim M. *et al.*, *Phys. Rev. Lett.*, **130** (2023) 121901.
[17] Chen Y., Chiu W.-F., Gong M., Gui L.-C. and Liu Z.-F., *Chin. Phys. C*, **40** (2016) 081002.
[18] Chiu T.-W. and Hsieh T.-H., *Phys. Rev. D*, **73** (2006) 094510.
[19] BESII Collobration (Ablikim M. *et al.*), arXiv: 2305.10789 [hep-ex] (2023).
[20] Geng H., Liu W., Qiu J., Xing J., Yu C. and Zhang Y., *Proceedings IPAC2021* (JACoW) 2021, p. 3756.
[21] BESII Collobration (Ablikim M. *et al.*), *Conceptual Design Report BESIII Cylindrical GEM Inner Tracker* (CERN) 2014.