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Hadron Spectroscopy at BESIII

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Abstract. The BESIII experiment, hosted at the IHEP of Beijing, has collected the world largest data sample in the charmonium energy region. One of the most important physics goals of BESIII is the investigation of the QCD prediction. QCD can be accessed in a unique way by means of hadron spectroscopy, which was extensively studied and many important progresses were achieved in the last years. Charmonium decays provide an excellent scenario for studying nucleons, hyperons and their excited states, XYZ resonances, as well as light hadrons. Some of the most recent results for hadron spectroscopy from BESIII will be reported.

1 Introduction

Particles subject to the strong interaction are defined as hadrons. The hadronic states description is provided by the quark model [1]. The experimental results for the meson sector and for the ground state baryons are in a good agreement with this description, while the interpretation of the excited baryonic spectrum is much less clear. The strong interaction is described by the well estabilished QCD theory. In order to obtain a deep understanding of QCD, its predictions have to be searched for and properly investigated.

Hadron spectroscopy is a poweful tool to understand the quark structure of the particles, and the force which acts between them. This knowledge could be gained by searching for new hadronic states, and by a deep investigation of the light hadron sector. Studies performed in the charmonium energy range offer an appropriate playground to investigate the hadronic interactions, and complementary informations to the existing data.

2 The BESIII Experiment

The BESIII (BEijing Spectrometer III) [2], hosted on the BEPCII $e^+ e^-$ collider at the Institute of High Energy Physics (IHEP) in Beijing, with its excellent performances offers the appropriate scenario to support hadron spectroscopy studies. The Beijing Electron-Positron Collider II (BEPCII), with beam currents up to 0.93 A, has reached in 2016 its design Luminosity of $1{\cdot}10^{33}\text{cm}^{-2}\ \text{s}^{-1}$. The beam energy (from 1.0 up to 2.3 GeV) can be tuned according to the required center of mass energy, for example to pin the charmonium resonances down. The wide geometrical acceptance provided by the spectrometer, depicted in Fig.1, of about 93% of the solid angle is a consequence of its shell like structure. Departing from the interaction point, it hosts, inside a 1T solenoidal magnetic field, 43

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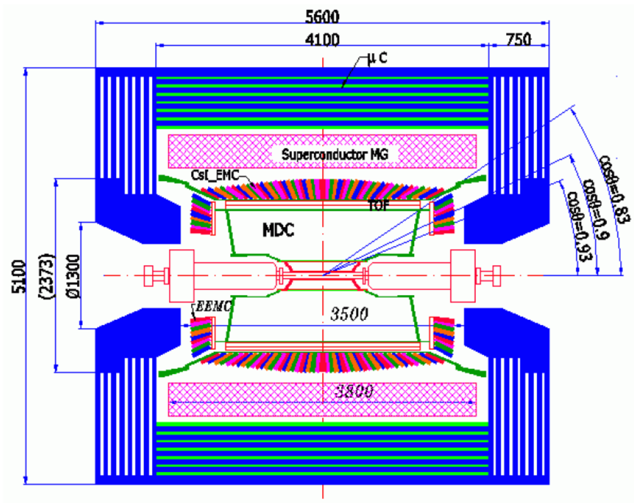

Figure 1. *View of the BESIII spectrometer [2].*

small-celled, helium-based main drift chamber (MDC) chambers for charged tracks reconstruction, a time-of-flight (TOF) system for particle identification, and an electromagnetic calorimeter (EMC) composed of 6240 CsI (Tl) crystals arranged in a cylindrical shape (barrel) plus two end-caps. A muon chamber (MUO) system, composed of resistive plate chambers (for a total of 1000 m^2) arranged in 9 layers in the barrel and 8 layers in the end-caps, is hosted in the semented magnet iron yoke.

The excellent performances provided by the BESIII spectrometer allowed to collect the world largest data sample of J/ψ, ψ(3686), and ψ(3770). Moreover, 1.3fb^{-1} of data were collected for the R scan, and 3.9fb^{-1} for the Y resonances studies.

3 X(1835) Studies

Since its discovery, the $X(1835)$ was subject of different speculations about its nature, in connection with its possible relationship with the anomaly seen at threshold in J/$\psi \rightarrow \gamma p\bar{p}$. The $X(1835)$ resonance was observed for the first time by the BESII experiment [3]. The high statistic data samples collected by the BESIII experiment gave the opportunity to further confirm the resonance and to have a deep insight into QCD dynamics, since possible interpretations include $p\bar{p}$ bound state [4], glueball [5], radial excitation of η' meson [6]. The lowest lying pseudoscalar glueball meson predicted by the Lattice QCD is expected to have a mass around 2.3 GeV/c^2 [7]. Its decay dynamics suggests that it may have properties in common with the η_c, of which one of the strongest decay channel is $\pi^+\pi^-\eta'$. For this reason, the $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ was subject of studies. As anticipated, those investigations were stimulated by an anomalous $p\bar{p}$ invariance mass enhancement at threshold, reported by BESII [8] and confirmed by BESIII [9, 10] in $J/\psi \rightarrow \gamma p\bar{p}$ and $\psi' \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^-\gamma p\bar{p}$ decays, respectively, and CLEO-c [11].

From the $\pi^+\pi^-\eta'$ invariant mass spectrum, shown in Fig.2, it was possible to notice two already known resonances, the $f_1(1510)$ and the $X(1835)$, and two new peaks defined as $X(2120)$ and $X(2370)$, which need to be included in the Partial Wave Analysis (PWA) performed to describe the experimental

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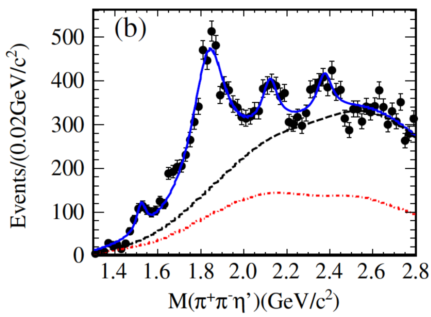

Figure 2. $\pi^+\pi^-\eta'$ *invariant mass spectrum [10].*

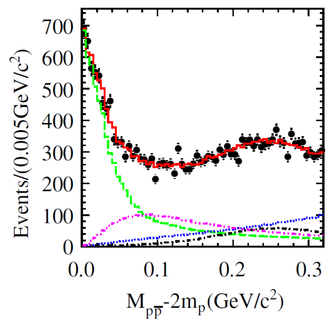

Figure 3. $p\bar{p}$ *threshold enhancement [12].*

data. The angular distribution of the radiative photon suggests the psuedoscalar nature of all those states.

In order to understand the nature of the $p\bar{p}$ threshold enhancement, a dedicated study was performed [12]. The invariant mass spectrum was investigated by means of PWA: the structure was described with a Breit-Wigner (BW) function (green), and $f_2(1910)$ (purple), $f_0(2100)$ (black), 0^{++} phase space (PS) (black), as shown in Fig.3, and a final state interaction (FSI) effect using the Juelich formulation [13] were included as well. Variation of the fit components were studied, and it was found that changes of the log-likelihood values and of the parameters of the $X(p\bar{p})$ were quite small. The mass of the $X(p\bar{p})$ was found to be consistent with the $X(1835)$, but with a significatively narrower width.

A similar enhancement was searched in $J/\psi \to \omega p\bar{p}$ [14] and $J/\psi \to \varphi p\bar{p}$ [15], where $\varphi \to K_S K_L$ or K^+K^-, final states. The decays $J/\psi \to \omega p\bar{p}$, $\varphi p\bar{p}$ restrict the isospin of the $p\bar{p}$ system and could clarify the role of the FSI. The Dalitz plot shows no significant signal close to the $p\bar{p}$ threshold, disfavoring a pure FSI effect giving rise to the $X(p\bar{p})$. The upper limits on the product of branching fractions were $B(J/\psi \to \omega X(p\bar{p}) \to \omega p\bar{p} < 3.7{\cdot}10^{-6}$ and $B(J/\psi \to \varphi X(p\bar{p}) \to \varphi p\bar{p} < 2.1{\cdot}10^{-7}$.

A clear $X(1835)$ signal was seen in $J/\psi \to \gamma K_S K_S \eta$ final state [16]. By means of the PWA method, the best fit to the data was obtained by including the three components: $X(1835)\eta \to f_0(980)\eta$, $X(1560)\eta \to f_0(980)\eta$, and a non-resonant $f_0(980)\eta$ component. A spin parity 0^{-+} was associated to all the components, althought a $J^P = 1^{++}$ for the non-resonant one cannot be excluded. The obtained results were consistent with the $J/\psi \to \gamma\pi^+\pi^-\eta'$ ones.

Further studies on the $J/\psi \to \omega\eta\pi^+\pi^-$ [17], $J/\psi \to \gamma\omega\varphi$ [18], and $J/\psi \to \gamma 3(\pi^+\pi^-)$ [19] final states investigated the $X(1840)$ and $X(1870)$ resonances. The PWA was performed with the tensor covariant amplitudes, and contributions from S-wave and P-wave were considered. The $X(1840)$ properties are in agreement with the $X(1835)$, but their width were found to be significantly different; it is now important to understand if they are the same particle or not. On the other hand, it has been reported that investigations on the $J/\psi \to \eta\varphi\pi^+\pi^-$ final state [20] did not show a remarkable presence of the $X(1835)$ and $X(1870)$ resonances.

In more recent studies on $J/\psi \to \gamma\pi^+\pi^-\eta'$ with the full statistic collected [21] by BESIII it was possible to observe a significant abrupt change in the slope of $\eta\pi^+\pi^-$ invariant mass distribution. The invariant mass spectrum lineshape around 1.85 GeV/c^2 might be characterized by means of two models. The first one takes the advantage of the Flatté formula to describe the opening of an additional decay mode, and a resonance at $X(1920)$ with a significance of 5.7σ has to be included (see Fig.4. The second model is based on the coherent sum of two BW amplitudes, the $X(1835)$ and a narrow

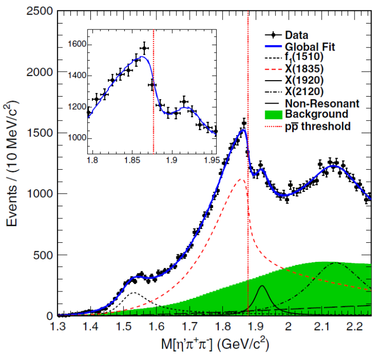

Figure 4. *Fit results from using the Flatté formula and the $X(1920)$ resonance [21].*

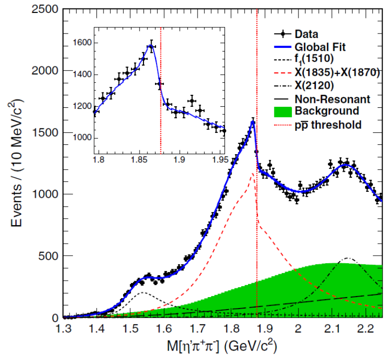

Figure 5. *Fit results from using a coherent sum of two Breit-Wigner amplitudes [21].*

$X(1870)$ (see Fig.5. Both models support the existence of a state, either a narrow state just below the $p\bar{p}$ mass threshold, or a broad state with strong couplings to $p\bar{p}$.

4 XYZ States

Below the $D\bar{D}$ threshold, the charmonium states could be properly described by the $c\bar{c}$ potential model. The scenario becomes more complex above the $D\bar{D}$ threshold: some of the predicted states were not found, while many new states were discovered. Thus the aim of BESIII searches was to estabilish the spectrum of those states and build a connection between them.

4.1 X States

The $\psi(3770)$ is the lightest charmonium state above the $D\bar{D}$ threshold, and it can be identified as the $1\,^3D_1$ state, as member of the D-wave spin-triplet. At the moment, there was no clear observation of the $1\,^3D_2$ and $1\,^3D_3$, the other two spin-triplet states. According to the phenomenological prediction, the $1\,^3D_2$ state should strongly couple to $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ final states. The narrow $X(3823)$ resonance, observed by BELLE in $X(3823 \to \gamma\chi_{c1})$ decay [22], was investigated as well by the BESIII experiment in $\gamma\chi_{c1,2}$ final states [23]. The analysis, performed at 5 different energy values, agreed with the BELLE discovery indicating the $X(3823)$ as a good candidate to be considered the $1\,^3D_2$ state, but no signal in $\gamma\chi_{c2}$ was found, as shown in Fig.6. The energy dependent cross section was fitted including the $Y(4360)$ or the $\psi(4415)$ line shapes: both hypothesis provide a reasonable description of the data.

4.2 Y States

The discovery of the Y resonances ($Y(4260)$, $Y(4360)$, $Y(4660)$) by BELLE and BABAR poses many questions in understanding their nature. They have relatively narrow widths and strong coupling to hidden-charm final states. The study of hadronic transitions to lower charmonia states together with lineshape measurements should allow us to investigate the different properties of those Y states. In order to deeply understand their nature, a complete PWA has to be performed.

One of the most recent results is the investigation of the $e^+e^- \to \eta(\pi^0)J/\psi$ reaction [24] in the energy range between 3.810 and 4.600 GeV. The measurement was performed at 17 different center

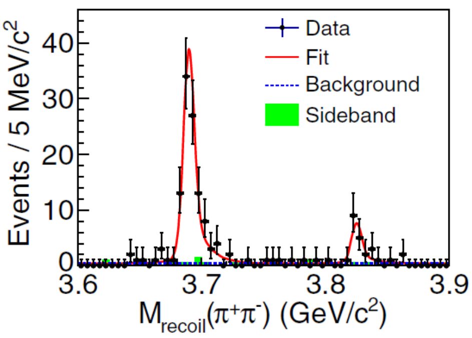

Figure 6. *Fit of the $\pi^+\pi^-$ recoil mass distribution of $\gamma\chi_{c1}$ (right) and $\gamma\chi_{c2}$ (left) events [23].*

of mass energies and a clear enhancement around 4.2 GeV was observed. The obtained cross sections, shown in Fig7, were compared with the previous measurements from BELLE [25] and BESIII [26], and are predicted to be strongly affected by open charm effects. This work provided the most precise measurements available in the litterature so far.

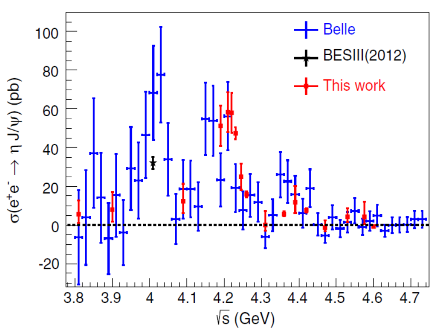

Figure 7. *Measured Born cross sections from the $e^+e^- \to \eta J/\psi$ final state [24].*

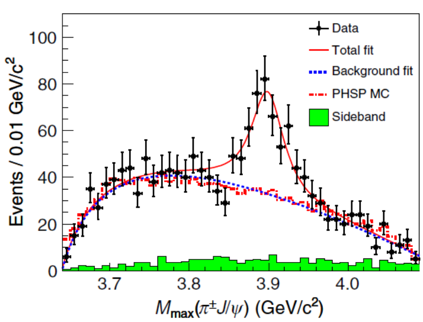

Figure 8. *Fit to the invaiant mass distribution of $\pi^\pm J/\psi$ [30].*

4.3 Z States

At the begining of 2013 a new charmonium like structure, the so called $Z_c(3900)$, was announced [27], then confirmed by BELLE [28] and CLEO-c [29]. The analysis was performed on the 515pb^{-1} data collected by BESIII at the center of mass energy of 4.260 GeV. The structure was observed with a significance higher than 8σ through its decay into a charged pion and a J/psi ($Z_c(3900)^\pm \to \pi^\pm J/\psi$), as shown in Fig.8, and its main carachteristic is that it is a charged state. The Z_c could be interpreted as tetraquark or as a hadronic molecule, so its nature is still under discussion.

Similar investigations, aimed to understand the Z_c nature were, performed for different final states. It was possible to discover the neutral partner of Z_c ($Z_c(3900)^0 \to \pi^0 J/\psi$) [30], allowing to complete the $Z_c(3900)$ triplet. Also the decay into open charm final states [31, 32] and its excited state, the $Z_c(4020)^0$ [32–34], were observed for the first time.

5 Baryonic States

Baryons are powerful tools to investigate the hadronic structure. The experimental data on ground baryonic states available in the literature are in good agreement with the quark model. Despite this, our knowledge becomes poor as soon as we investigate their excited states. For example, according to the prediction provided by the relativistic quark model [35] or to lattice QCD calculations [36] some resonances were not experimentally found and some others were unexpectedly observed. There is a huge effort from both theory and experiments devoted to obtain a clear comprehension of the baryonic scenario.

The data collected by BESIII can offer a complementary information by means of charmonium decays studies. In fact, in e^+e^- machines, like BEPCII, the baryon coupling to the conventional production channels (γ-nucleons) can be quite small, but the coupling between 3 gluon and baryons could be larger (ψ decays). The statistics collected by the BESIII experiment could be enough to improve our knowledge.

5.1 Hyperon Studies

The two lowest lying hyperon states were investigated by means of $\psi(3686)$ decays.

The $\psi(3686) \to \bar{p}K^+\Sigma$ decay was observed for the first time [37]. In order to improve our knowledge on hyperon properties, the $\bar{p}K^+\Lambda$ final state was investigated in the decay of χ_{cj}, abundantly produced from $\psi(3686)$ through radiative decays. In the analysis of the Dalitz plot of the χ_{c0}, as shown in Fig.9, a certain discrepancy between the phase space MC and the data due to the presence of an intermediate state, close to the $\bar{p}\Lambda$ threshold was observed [37].

In order to test QCD and its interplay with Perturbative-QCD, the $\Lambda\bar{\Sigma}^{\pm}\pi^{\mp}$ final state was investigated [38]. The experimental data, shown in Fig.10, depict clear clusters, indicating that this process is mediated by excited baryons. In order to determine the correct detection efficiency, a PWA was performed considering 16 possible intermediate states, which were described by a BW function. It was possible to measure for the first time the branching ratios for the $\psi(3686)$ decays into those final states.

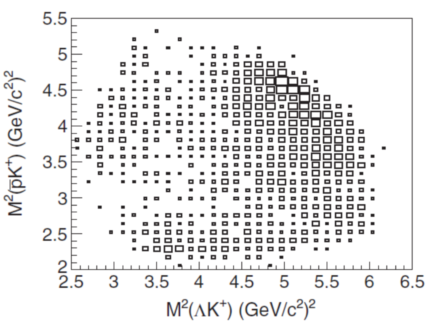

Figure 9. *Dalitz plot of $M^2(\bar{p}K^+)$ versus $M^2(\Lambda K^+)$ for χ_{c0} [37].*

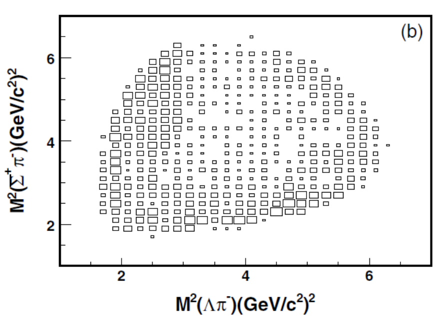

Figure 10. *Dalitz plot of $M^2(\Sigma^+\pi^-)$ versus $M^2(\Lambda\pi^-)$ [38].*

In the investigation of the $\psi(3686) \to (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$ [39], two structures in the invariant mass of the ΛK system at 1690 and 1820 MeV were observed with a significance of 4.9σ and 6.2σ, respectively. The structures, shown in Fig.11, were fitted with a Voigtian function, while the background was estimated with the Λ and Ξ sidebands (red and green), by means of the inclusive MonteCarlo (shaded blue), and the non-resonant contribution are shown by the blue line. The number of events collected was not enough to study the angular distributions and to assign a J^P value to those structures.

J/ψ and $\psi(3686)$ were exploited to reconstruct $\Xi^-\bar{\Xi}^+$ and $\Sigma(1385)^{\mp}\bar{\Sigma}(1385)^{\pm}$ final states by means of the single tag method [40]. The decay of $\psi(3686)$ into $\Sigma(1385)$, shown in Fig.12 was observed for the first time. Their angular distributions, proprtional to $1 + \alpha\cos^2\vartheta$, were investigated as well and it was found that α from J/ψ and $\psi(3686)$ has the same sign for the Ξ production, while it is opposite for the $\Sigma(1385)$ scenario. The obtained results are the most precise measurements available in the litterature.

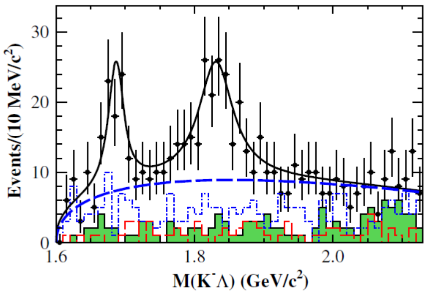

Figure 11. *$K^-\Lambda$ invariant mass distribution, with clear structures at 1690 and 1820 MeV [39].*

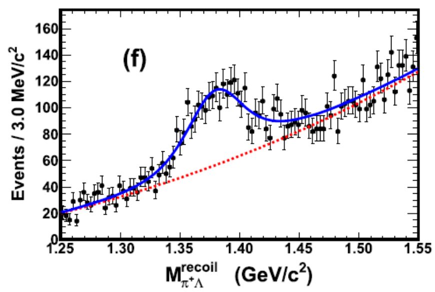

Figure 12. *$\Lambda\pi^+$ recoil mass spectrum for $\psi(3686) \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$ [40].*

6 Conclusions

Charmonium decays at BESIII have proven to be a powerful tool to investigate the hadron spectroscopy, spanning from light hadron to XYZ states and to the baryon resonances sector. The discoveries performed by BESIII are complementary to those coming from the existing data. BESIII is expected to provide a significant contribution exploiting the new and larger data samples which are foreseen to be collected in future.

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