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Exotic hadrons at BESIII

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Summary. — The BESIII experiment at the electron positron collider BEPCII is successfully operating since 2008 and has collected large data samples in the tau-charm mass region. Selected recent results on XYZ studies at BESIII are reported. Thanks to the data samples of about 12 fb^{-1}, useful for this kind of studies, BESIII Collaboration continues the exploration of these intriguing charmonium-like states.

1. – Introduction

The Beijing Electron Spectrometer III (BESIII) detector is general purpose magnetic spectrometer, installed at the Beijing Electron Positron Collider II (BEPCII). BEPCII is a double ring e^+e^- collider, hosted at the Institute of High Energy Physics (IHEP) of Beijing (PRC) with a tunable beam energy from 1.0 to 2.3 GeV. The BESIII detector is a magnetic spectrometer composed by a helium gas based Main Drift Chamber (MDC), a plastic scintillator Time-Of-Flight (TOF) system, a CSI(Tl) ElectroMagnetic Calorimeter (EMC) and a muon detector (MUC) based on Resistive Plate Chambers, immersed in a 1.0 T magnetic field provided by a super-conducting solenoidal magnet. Further details can be found in ref. [1].

It reached its design luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ in April 2016. It is successfully operating since 2008 and has collected large data samples in the tau-charm mass region, including the world's largest data samples at the J/ψ and $\psi(2S)$ resonances. Beside dedicated data samples collected in the XYZ energy region (3.8–4.6 GeV) with a integrated luminosity of about 12 fb^{-1}, BESIII can profit, for this kind of analyses, of 104 energy points between 3.85 and 4.59 GeV (R scan) and about 20 energy points between 2.0 and 3.1 GeV. Next year major BEPCII upgrades are foreseen including the Top-Up injection, that will increase the data collected by 20–30% and the increasing of the maximum beam energy from 4.60 GeV to 4.70 GeV to explore a new energy region.

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In the last decade many unexpected states (XYZ states) have been discovered, mostly at B-factories, above the $D\overline{D}$ threshold in the higher mass charmonium spectrum. The conventional charmonium paradigm as simple quark-antiquark bound state is not fitted by several of them, stimulating various exotic hypotheses, *e.g.*, $c\bar{c}$ hybrids, glueballs, hadronic molecules, tetraquarks and hadrocharmonia. Up to now a firm and comprehensive conclusion about the nature of XYZ states has not been found.

They are commonly distinguished in three main groups: the Y states are the vector neutral states, those with isospin equal to 1 are the Z ones and all of the rest are called X.

The Y(4260) was first observed by BaBar in the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section [2] and subsequently confirmed by Cleo-c [3] and Belle [4]. Its production in electron-positron annihilations determines its quantum numbers to be $J^{pc} = 1^{--}$, while the absence of a similar structure in open charm channels suggest that it is not a conventional charmonium.

At BESIII, Y states can be produced directly in e^+e^- annihilations. Based on this, BESIII has started to reveal the connections of Y states with X and Z states via radiative or hadronic transition and, in the meanwhile, the cross section of various channels can be investigated as a function of the center-of-mass (c.m.) energy

2. – X states

The X(3872) was discovered by Belle in 2003 in $B^+ \to K^+J/\psi\pi^+\pi^-$ [5]. It was confirmed by BaBar, CDF, D0, LHCb [6]. It is very close to the $D^0\bar{D}^{*0}$ threshold and very narrow(<1.2 MeV/c^2). Its quantum numbers has been determined to be $J^{PC} = 1^{++}$ by LHCb. No isospin partners have been observed.

Much is now known about the X(3872), except exactly what it is.

BESIII observed for the first time the process $e^+e^- \to \gamma X(3872) \to \gamma J/\psi\pi^-\pi^+$ at center-of-mass energies from 4.009 to 4.420 GeV [7]. The result for the mass of X(3872) is $(3871.9 \pm 0.7 \pm 0.2)$ MeV/c^2, in agreement with previous determinations [8]. The product of the X(3872) production cross section and its branching fraction to $J/\psi\pi^-\pi^+$ has been found to be consistent with the expectation for the radiative transition process $Y(4260) \to \gamma X(3872)$.

It was the first connection between charmonium-like states. Since then, BESIII has collected a total of 9.0 fb^{-1} for 4.15 <ECM <4.30 GeV, 0.7 fb^{-1} for 4.00 <ECM <4.15 GeV and 2.8 fb^{-1} for 4.30 <ECM <4.60 GeV, opening opportunity to search for new decay modes of the X(3872).

2·1. $X(3872) \to \omega J/\psi$. – The hadronic molecule model predicts that the decay of $X(3872)$ in $\omega J/\psi$ is sensitive to its internal structure Previously, Belle and BaBar reported weak evidences for this decay [9].

We reported the study of the process $e^+e^- \to \gamma\omega J/\psi$, with $J/\psi \to l^+l^-(l = e, \mu)$ and $\omega \to \pi^+\pi^-\pi^0; \pi^0 \to \gamma\gamma$ [10]. Figure 1 shows the M($\omega J/\psi$) distribution from the full data set, based on data samples collected at center-of-mass (c.m.) energies from 4.008 to 4.600 GeV with a total integrated luminosity of about 11.6 fb^{-1}. A signal peak consistent with the X(3872) resonance is observed with additional evident structures above 3.9 GeV/c^2. In the unbinned maximum-likelihood fit of M($\omega J/\psi$), the signal probability density function (PDF) is the incoherent sum of three Breit-Wigner (BW) resonances (named as X(3872), X(3915), and X(3960), respectively), each convolved with a Gaussian resolution function with the X(3872) width set to 1.2 MeV [8]. The upper plot of

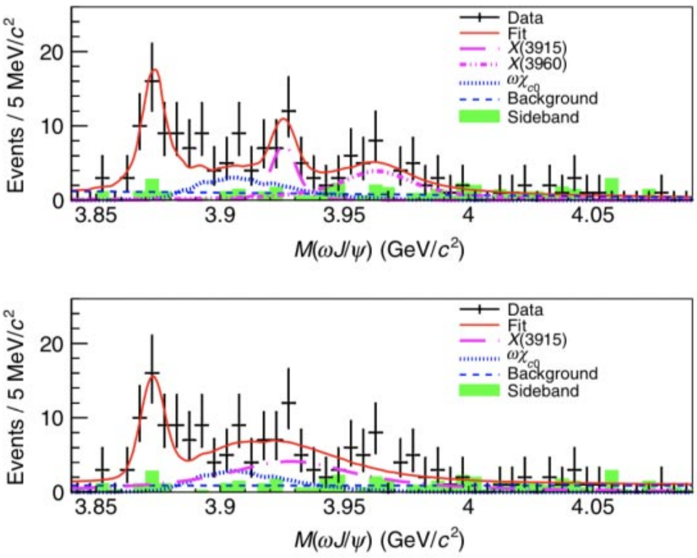

Fig. 1. – The distribution of the invariant mass of the $\omega J/\psi$ system with overlapped the results of an unbinned maximum-likelihood fit to data including, as signal, three BW resonances (up) and including two BW resonances (bottom).Dots with error bars are data, the red solid curves show the total fit [10].

fig. 1 shows the fit results and the extracted X(3872) mass agrees with its world average value within errors with a signal significance of 5.7σ, including systematic errors. The statistical significance of X(3915) and X(3960) are estimated to be 3.1σ and 3.4σ only. An alternative, shown in the bottom plot of fig. 1, consists in fitting with inco-

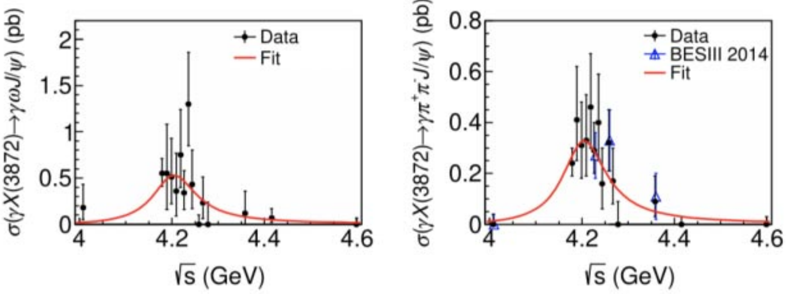

Fig. 2. – The measured cross section of times the branching fraction of $X(3872) \to \omega J/\psi$, in the left plot and $X(3872) \to \pi\pi J/\psi$ on the right, and a simultaneous fit to data with a single BW resonance [10].

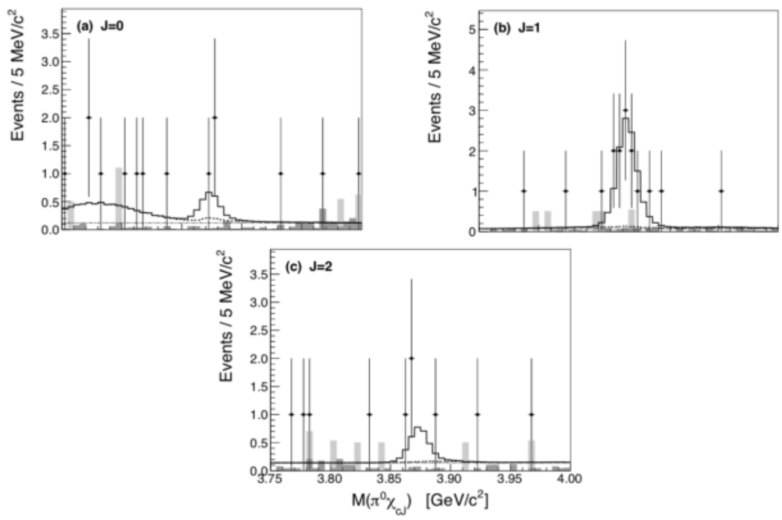

Fig. 3. – Distributions of M($\pi^0\chi_{cj}$), from the process for $e^+e^- \to \gamma X(3872); X(3872) \to \pi^0\chi_{cJ}$, being in (a) $J = 0$, in (b) $J = 1$, and in (c) $J = 2$ [12].

herent sum of only two Breit-Wigner (BW) resonances, X(3872) and X(3915), convolved each with a Gaussian resolution function, as PDF. In this case the signal significance of X(3872) is found to be larger than 5.1σ, including systematic errors. The statistical significance of X(3915) is estimated to be 6.9σ. Simultaneous maximum-likelihood fit on the $\sigma \times B(X(3872) \to \omega J/\psi$ and $\sigma \times B(X(3872) \to \pi\pi J/\psi()$ with a single Breit-Wigner resonance (denoted as Y(4200)) with free mass and width, is shown in fig. 2 and results in a relative decay ratio of $1.6^{+0.4}_{-0.3} \pm 0.2$, predicted about 60% by hadronic molecule model [11].

2˙2. $X(3872) \to \pi^0\chi_{c1}(1P)$. – We searched for the process $e^+e^- \to \gamma X(3872)$ and subsequent $X(3872) \to \pi^0\chi_{cJ}$ (for $J = 0, 1, 2$) using 9.0 fb^{-1} of e^+e^- collision data with center-of-mass energies between 4.15 and 4.30 GeV, collected by the BESIII detector [12]. Indeed, pionic transitions to χ_{cJ} have been proposed to be sensitive to the nature of $X(3872)$. If the X(3872) is a conventional charmonium state, transitions to the χ_{cJ} should be very small, with a partial width $\Gamma(X(3872) \to \pi^0\chi_{c1}) \sim 0.06$ keV, as predicted in ref. [13]. Instead, for tetraquark or molecular state hypotheses, these rates are expected to be sizable [13, 14]. In fig. 3 the distributions for M($\pi^0\chi_{cJ}$) with $J = 0, 1, 2$ are shown, fitted with a constant background function and a signal shape derived from signal MC simulation. In the M($\pi^0\chi_{c1}$) distribution, we found a X(3872) signal with a 5.2σ significance. This is the first observation of the process $X(3872) \to \pi^0\chi_{c1}(1P)$. No significant X(3872) signals are found in the other invariant mass distributions. Then we have determined the ratio between $\mathcal{B}(X(3872) \to \pi^0\chi_{c1}(1P))$ and $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$, normalizing to $e^+e^- \to \gamma X(3872)$, with $X(3872) \to \pi^+\pi^- J/\psi$, that results to be $0.88^{+0.33}_{-0.27}\pm0.10$. Using for $B(X(3872) \to \pi^+\pi^- J/\psi)$ a lower limit of 3.2% [8], that is obtained comparing exclusive [15] and inclusive [16] B^+ decays and a higher limit of 6.4%, by assuming all measured X(3872) decays add to less than 100%, $\mathcal{B}(X(3872) \to \pi_0\chi_{c1})$is about 3–6%. In ref. [13] $\Gamma(X(3872) \to \pi^0\chi_{c1})$ for a pure charmonium state is predicted

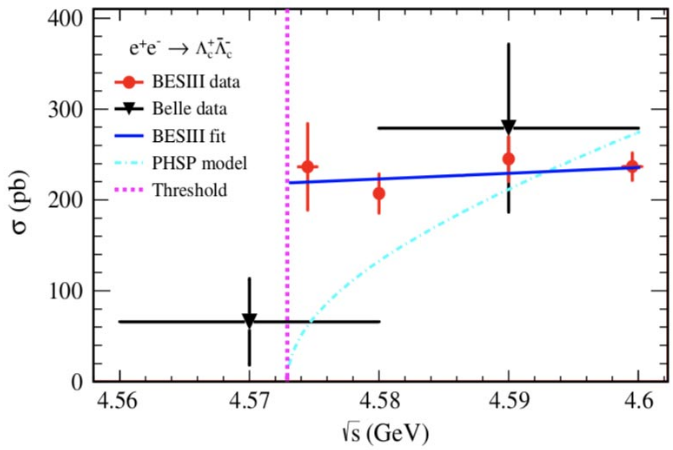

Fig. 4. – The cross section of $e^+e^- \to \Lambda_C\bar{\Lambda}_C$ is shown as a function of the center-of-mass energy for BESIII [22] and Belle [19]. The magenta dashed line represents the threshold.

to be 0.06 keV and combining this with our result, it would imply a total width of the X(3872) of 1.0–2.0 keV only, that is orders of magnitude smaller than what was found for all other observed charmonium states. Therefore, our measurement disfavors the $c\bar{c}$ interpretation of the X(3872).

3. – Y states

3˙1. $e^+e^- \to \Lambda_C\overline{\Lambda}_C$. – In the $e^+e^- \to p\bar{p}$ process, the BaBar Collaboration [17] observed a rapid rise of the cross section near threshold, followed by a plateau around 200 MeV above threshold, confirmed by BESIII [18]. It is of great interest to explore the production behavior of Λ_c, the lightest baryon containing the charm quark. Previously, the Belle Collaboration measured the cross section of $e^+e^- \to \gamma_{ISR}\Lambda_C\bar{\Lambda}_C$ using the initial-state radiation (ISR) technique, with significant errors on CME and cross section near threshold [19]. Ulf-G. Meißner *et al* [20] fit the Belle data with a resonance Y(4660), called X(4660), plus Final State Interaction at threshold, with $M = (4652.5 \pm 3.4)$ MeV and $\Gamma = (62.6 \pm 5.6)$ MeV for mass and width, compatible with the ones of the X(4660) resonance that have been established in the reaction $e^+e^- \to \pi^+\pi^-\psi(2S)$. The Y(4660) mass, so close to the threshold, favors its interpretation as a charmed baryonium [21].

In BESIII, using 10 decay Cabibbo-favored hadronic decay processes to reconstruct Λ_c, the cross section of $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ is measured at 4 energy points (4574.5, 4580.0, 4590.0 and 4599.5 MeV), with good detection efficiency at threshold thanks to weak decay [22]. Each mode will produce one measurement of the cross section, and the total cross section is obtained by weighted average. A sort of tension can be found near threshold between BESIII and Belle, as shown in fig. 4, that can be confirmed or not if BESIII will collect more data near threshold, eventually with energy points at larger values, with the BEPCII upgrades.

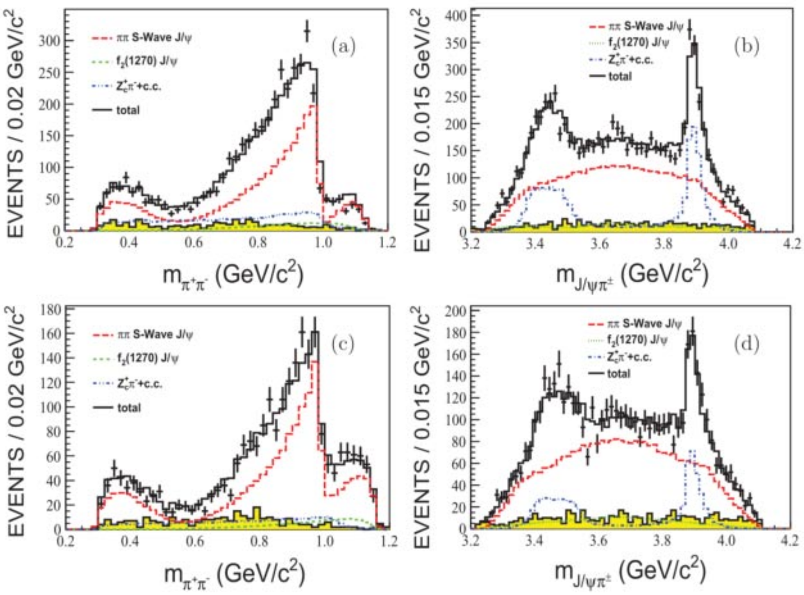

Fig. 5. – Projections to m($\pi^+\pi^-$) (a),(c) and m($J/\psi\pi$) (b),(d) of the fit results when J^P for the Z_c is set to 1^+, at center-of-mass energy of 4.23 GeV (a),(b) and 4.26 GeV (c),(d). The points with error bars are data, and the black histograms are the total fit results including backgrounds. The shaded histogram represent the backgrounds [27].

4. – Z states

In 2013, the BESIII Collaboration observed a new charged charmonium-like state [23], referred to as $Z_c(3900)$, in the $J/\psi\pi^{\pm}$ mass distribution in the $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ process, using a 525 pb^{-1} data sample collected at $\sqrt{s} = 4.260$ GeV. We measured a cross section of the process consistent with the Y(4260) production, finding a first connection between Y and Z states. This state was shortly afterwards confirmed by the Belle Collaboration in e^+e^- annihilations with radiative return to the Y(4260) [24] and in direct e^+e^- annihilations at 4.17 GeV in CLEO-c data [25]. This $Z_c(3900)$ couples strongly to charmonium and carries electric charge, so it should be at least a four-quark combination. Furthermore it is close to the $D\overline{D}^*$ threshold. Afterwards BESIII found its neutral isospin partner [26].

4·1. *Determination of J^P of Z_c(3900).* – Based on 1.92 fb^{-1} of data samples collected at 4.23 and 4.26 GeV, the Z_c state is studied with an amplitude fit to $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ channel [27]. In the nominal fit, the Z_c is assumed to have $J^P = 1^+$ with a line shape described with a Flatté-like formula that takes into account the fact that its decays are dominated by the final states $(D\overline{D}^*)^{\mp}$ [28] and $J/\psi\pi$ [23]. To describe the $\pi^+\pi^-$ mass spectrum, beside the non-resonant processes, four resonances are introduced: σ, $f_0(980)$, $f_2(1270)$ and $f_0(1370)$. The statistical significance of each of these states and the non-resonant process is estimated to be larger than 5σ. A simultaneous fit is performed to the two data sets in which the coupling constants are set as free parameters and are

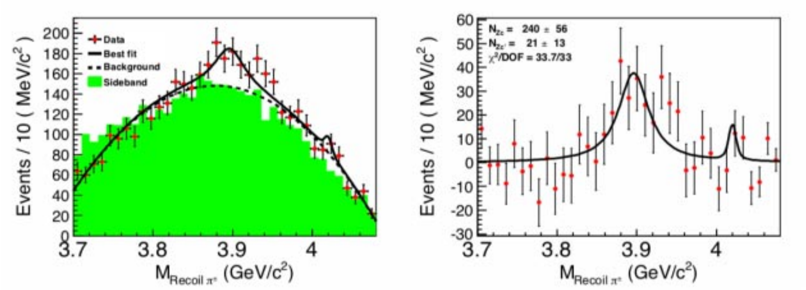

Fig. 6. – The $\pi^{\pm}$ recoiling mass distribution in $e^+e^- \to \pi^{\pm}\rho^{\mp}\eta_C$ at center-of-mass energy of 4.23 GeV and the fit the Z_c signal, plus a smooth background [30].

allowed to be different at the two energy points except for the common ones describing Z_c decays. The oppositely charged Z_c states, being isospin partners, have a common mass and coupling parameters. In fig. 5 the projections of the fit result with this quantum numbers for Z_c to m($\pi^+\pi^-$) and m($J/\psi\pi$) are shown. The significance of the $J^P = 1^+$ hypothesis is further examined using the hypothesis test. Its spin and parity have been determined to be 1^+ with a statistical significance larger than 7σ with respect to other quantum numbers.

4·2. *Evidence of* $Z_C \to \rho\eta_C$. – Theoretical expectations exist for the ratio (R) of branching fractions of $Z_c(')\to \rho\eta_C$ and $Z_c(') \to \pi J/\psi(\pi h_C)$ [29]. This can help in understanding the nature of these Z_C states, in particular between tetra-quark (Type-1) e molecule.

BESIII performed searches of $e^+e^- \to \pi^+\pi^-\pi^0\eta_C$ with intermediate states decay into $\rho\eta_C$, using data samples at 4.23, 4.26, and 4.36 GeV (η_C is reconstructed with 9 hadronic final states) [30]. A clear signal is observed at 4.23 GeV and $Z_c(3900/4020)^{\pm} \to \rho^{\pm}\eta_C$ are searched for. The recoiling mass of the remaining pion is shown in fig. 6 at 4.23 GeV. Here a $Z_c(3900)^{\pm}$ signal is found while there is no significant signal for $Z_c(4020)^{\pm}$. The invariant mass distribution for the $\rho\eta_c$ system is fitted with the contributions from $Z_c(3900)$ and $Z_c(4020)$ together with a smooth background, as shown in fig. 6, on the right. The $Z_c(3900)$ signals at other c.m. energies and the $Z_c(4020)$ signals at all the c.m. energies are not statistically significant. Using the results from ref. [31], the ratio R of the branching fractions of different $Z_c(3900)$ decays, previously introduced, is calculated to be 2.1 ± 0.8 at 4.23 GeV and less than 6.4 at $\sqrt{s} = 4.26$ GeV at the 90% C.L.. The theoretical predictions for this ratio vary depending on model assumptions and ranges from a few per cent to a few hundreds.

5. – Summary

BESIII achieved important results in the XYZ studies, based on a dedicated data-samples. We contribute to the lively discussion on the nature of this states searching for new ones, looking for connection and studying the cross sections as a function of the center-of-mass energies. BESIII is expected to run for 5 to 10 more years. Stay tuned for future results and future data takings.

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