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Recent results for the BESIII experiment

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Summary. — Since 2009, the BESIII experiment collected data in the center-of-energy range from 2 to 4.6 GeV, thus making it a unique environment to cover a broad range of physics topics. In this paper a selection of the recent BESIII results on the still mysterious XYZ states, hadron spectroscopy, as well as a very brief review on the charm and Λ_c physics are reported.

1. – Introduction

BESIII is a third generation of the Beijing Spectrometer operating at the second generation of the Beijing Electron Positron Collider BEPCII at the Institute of High Energy Physics (IHEP) in Beijing, Cina. The BESIII detector has a cylindrical geometry with a solid angle coverage of 93% of 4π, and consists of several main components. A main drift chamber (MDC) of 43 layers is used for the reconstruction of charged tracks and to measure the specific ionization ($\mathrm{d}E/\mathrm{d}x$) for particles identification (PID). It provides a momentum resolution of 0.5% at a momentum of 1 GeV/c in a magnetic field of 1 T. A time-of-flight system (TOF) is used to measure the flight time of charged particles with a time resolution of 80 ps (110 ps) in the barrel (end caps). An electromagnetic calorimeter (EMC) consisting of 6240 CsI(Tl) crystals arranged into a cylindrical structure and two end caps is used to measure the energy of photons and electrons, with a resolution of 2.5% (5.0%) in the barrel (end caps) for photon/electron with an energy of 1 GeV. A solenoidal superconducting magnet outside the EMC provides a magnetic field of about 1 T in the central tracking region of the detector. The iron flux return of the magnet is instrumented with about 1000 m^2 of resistive plate muon counter (MUC) arranged in nine layers in the barrel and eight layers in the end caps, used for the identification of muons with momentum greater than 0.5 GeV/c. More details can be found in ref. [1].

(*) On behalf of the BESIII Collaboration.

From 2009, BESIII has accumulated a wide set of physics data ranging from the center of mass (c.m.) of 2 GeV to 4.6 GeV, and the largest world sample collected at J/ψ , $\psi(2S)$, and $\psi(3770)$ that allows to deeply investigate the charmonium energy range. In this paper a selection of the latest BESIII results is reported as follows: in sect. **2** the results on the XYZ states are summarized, an overview on the light hadron spectroscopy is discussed in sect. **3**, while some hints on charm and Λ_c physics are summarized in sect. **4**.

2. – XYZ states

In the last years, many fruitful BESIII results about the XYZ states have attracted the interest of the physics community, both from an experimental and theoretical point of view. In the Quantum Chromodynamics (QCD) approach unconventional states, such as multi-quark states, molecules, hybrid states and glueballs, are also allowed to exist and their observation can be considered as a direct test of QCD. In particular, all charmonium states below the open charm threshold have been observed experimentally, and the observed spectra is consistent with the prediction of the $c\bar{c}$ potential model. Above the open charm threshold, instead, many expected charmonium states are not discovered, while other unexpected states are observed. These new states have properties that differ from the conventional charmonium, and are so called charmonium-like or XYZ states.

From 2011, BESIII has accumulated an integrated luminosity of about $5\,\text{fb}^{-1}$ in the energy range from 3.8 and 4.6 GeV, which allows to search for new decay modes of both charmonium and charmonium-like states in order to investigate their nature. A short summary of the Z_c and Y states observed at BESIII is reported below.

2˙1. *Z_c states at BESIII*. – Few years ago, BESIII reported the discovery of a new charged resonance, called $Z_c(3900)$, in the process $J/\psi \to \pi^+\pi^- J/\psi$ with a significance of 10σ [2]. Its mass and width are obtained from a fit to the invariant mass of $\pi^\pm J/\psi$, and determined to be $(3899.0 \pm 3.6 \pm 4.9)\,\text{MeV}/c^2$ and $(46 \pm 10 \pm 20)$ MeV, respectively. Since it decays to J/ψ and a charged pion, it implies that the $Z_c(3900)^\pm$ must contain at least four quarks, a $c\bar{c}$ pair plus a light quark $q\bar{q}$ pair, and hence it is an exotic state candidate. This resonance is also observed by Belle [3] and confirmed using CLEO-c data [4]. The neutral isospin partner $Z_c(3900)^0$ was observed in the $\pi^0 J/\psi$ invariant mass at the c.m.

TABLE I. – *Summary of Z_c states observed by the BESIII experiment.*

Decay channel	Z_c state	Mass (MeV/c^2)	Width (MeV)	Ref.
$e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$	$Z_c(3885)^\pm$	$3882.2 \pm 1.1 \pm 1.5$	$26.5 \pm 1.7 \pm 2.1$	[7]
$e^+e^- \to \pi^0(D\bar{D}^*)^0$	$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	[8]
$e^+e^- \to \pi^+\pi^- J/\psi$	$Z_c(3900)^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	[2]
$e^+e^- \to \pi^0\pi^0 J/\psi$	$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 3.2$	$29.6 \pm 8.2 \pm 8.2$	[5]
$e^+e^- \to \pi^+\pi^- h_c$	$Z_c(4020)^\pm$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	[9]
$e^+e^- \to \pi^0\pi^0 h_c$	$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed at $Z_c(4020)^\pm$	[10]
$e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$	$Z_c(4025)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	[11]
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$	$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	[12]

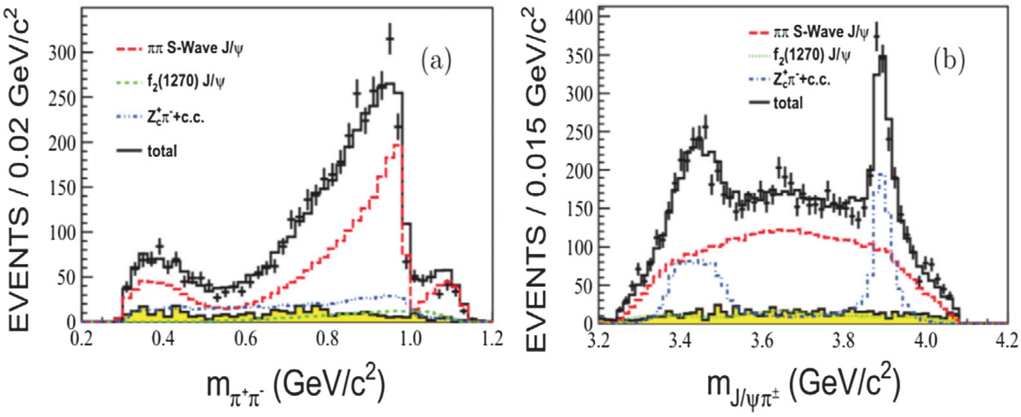

Fig. 1. – Projection to $m_{\pi^+\pi^-}$ and $m_{J/\psi\pi^\pm}$ of the fit results with $J^P = 1^+$ for the Z_c at $\sqrt{s} = 4.23$. Points with error bars are data and the black histograms are the total fit results including backgrounds. The contributions from $\pi^+\pi^-$ S-wave J/ψ (dashed line), $f_2(1270)J/\psi$ (dotted line), and $Z_c(3900)^\pm\pi^\mp$ (dash-dotted line) are shown in the plots. The $\pi^+\pi^-$ S-wave resonances include σ, $f_0(980)$, and $f_0(1370)$.

energies $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV by BESIII [5], where the mass and the width are summarized in table. I. More recently, a partial wave analysis (PWA) based on a sample of 1.92 fb^{-1} accumulated at $\sqrt{s} = 4.23$ and 4.26 GeV is used to determine the spin parity of the $Z_c(3900)$ in the process $e^+e^- \to \pi^+\pi^- J/\psi$ [6]. Figure 1 shows the projections of the fit results obtained at $\sqrt{s} = 4.23$. The mass and width are determined from a simultaneous fit to the two data sets, and they are found to be consistent with those from previous analysis [2]. The $Z_c(3900)$ spin and parity are determined by studying the polar angle distribution of the $Z_c(3900)$ and the helicity angle distribution in the decay $Z_c(3900) \to \pi^\pm J/\psi$. They are determined to be 1^+ with a statistical significance larger than 7σ over other quantum numbers.

Since the $Z_c(3900)$ states are very close to the mass threshold of the open charm mesons, it was straightforward to study the decay mode $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ [7]. Using a data sample of 524 pb^{-1}, a clear structure is observed in the invariant mass distributions of D^0D^{*-} and D^-D^{*0}, and the mass and width determined to be $(3882.2 \pm 1.1 \pm 1.5)\,\mathrm{MeV}/c^2$ and $(26.5 \pm 1.7 \pm 2.1)$ MeV, respectively. This new resonance is labeled $Z_c(3885)^\pm$, the quantum numbers in agreement with the hypothesis $J^P = 1^+$, and its resonance parameters are consistent with those of $Z_c(3900)^\pm$ within the errors. Similarly, the neutral counterpart, dubbed as $Z_c(3885)^0$, is observed in the decay mode $e^+e^- \to \pi^0(D\bar{D}^*)^0$ [8] and its mass and width are reported in table I. Since the mass and width values are very close to those of the charged state, it favors the assumption that $Z_c(3885)$ forms an isospin triplet.

After the observation of the $Z_c(3900)$, similar structures are observed in the invariant mass distributions of a pion and the charmonium state h_c in the processes $e^+e^- \to \pi^+\pi^- h_c$ [9] and $e^+e^- \to \pi^0\pi^0 h_c$ [10], for which the masses and the widths are summarized in table I. These states are labeled as $Z_c(4020)^\pm$ and $Z_c(4020)^0$, respectively, and their resonance parameters are in agreement each other. Also in this case, since the mass of the $Z_c(4020)$ is very close to the mass threshold of $D^*\bar{D}^*$, the processes $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$ [11] and $e^+e^- \to \pi^0(D^*\bar{D}^*)^0$ [12] are studied. Structures of $Z_c(4025)^\pm$ and $Z_c(4025)^0$ are observed in the recoil mass of $\pi^\pm$ and π^0, respectively,

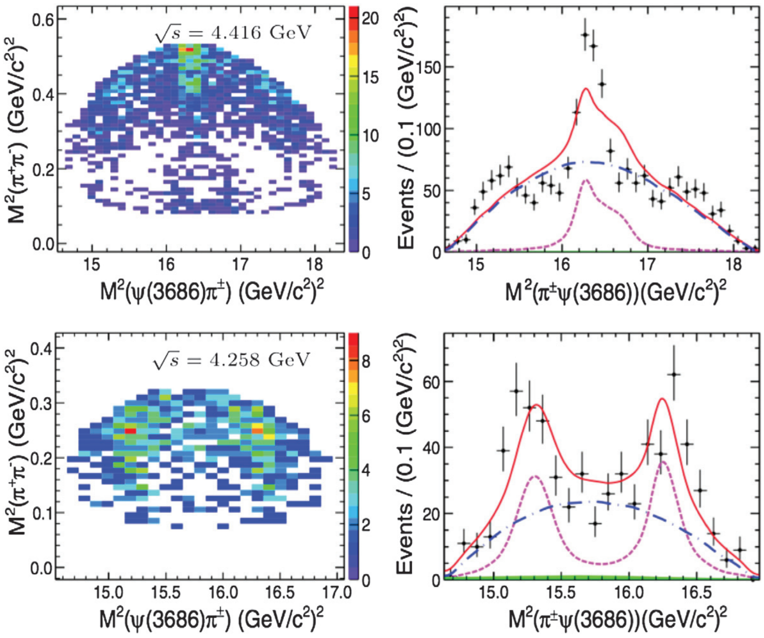

Fig. 2. – Dalitz plots of $M^2(\pi^+\pi^-)$ *vs.* $M^2(\pi^\pm\psi(3686))$ (left) and distributions of $M^2(\pi^\pm\psi(3686))$ (right) at $\sqrt{s} = 4.416$ GeV (up) and $\sqrt{s} = 4.258$ GeV (down). Dots with error bars are the data. The solid curves are the projections from the fit, the dashed curves show the intermediate states, while the dash-dotted curves refer to the direct process $e^+e^- \to \pi^+\pi^-\psi(3686)$. The small non-$\psi(3686)$ background contribution is also represented by histograms.

whose parameters are in good agreement each other. In addition, the parameters of $Z_c(4020)$ and $Z_c(4025)$ are consistent within 1.5σ.

A new structure, labeled $Z_c(4030)$ is recently observed by BESIII in the process $e^+e^- \to \pi^+\pi^-\psi(3686)$ [13]. Using $5.1\,\text{fb}^{-1}$ of data collected from $\sqrt{s} = 4.008$ and $4.600\,\text{GeV}$, the Born cross section of the $e^+e^- \to \pi^+\pi^-\psi(3686)$ process is measured, and the intermediate states are investigated in those data samples that have large integrated luminosity. Figure 2 shows the Dalitz plots of $\pi^+\pi^-$ invariant mass squared $(M^2(\pi^+\pi^-))$ *vs.* $\pi^\pm\psi(3686)$ invariant mass squared $(M^2(\pi^\pm\psi(3686)))$ for data samples at $\sqrt{s} = 4.416$ and $4.258\,\text{GeV}$. At $\sqrt{s} = 4.416\,\text{GeV}$, a prominent narrow structure is observed around $4030\,\text{MeV}/c^2$ in the $\pi^\pm\psi(3686)$ invariant mass, while at $\sqrt{s} = 4.258\,\text{GeV}$ two bumps around 3900 and $4030\,\text{MeV}/c^2$ are visible in the Dalitz plot and in the $M^2(\pi^\pm\psi(3686))$ spectrum. No clear structures are observed at other c.m. energies. An unbinned maximum likelihood fit is carried out on the Dalitz plot in order to characterize the observed structure at $\sqrt{s} = 4.416\,\text{GeV}$. Assuming the intermediate state with $J^P = 1^+$, the Dalitz plot is parametrized by the coherent sum of the process with an intermediate state and the direct process $e^+e^- \to \pi^+\pi^-\psi(3686)$. The fit yields a mass of $M = 4032.1 \pm 2.4\,\text{MeV}/c^2$ and a width of $\Gamma = 26.1 \pm 5.3\,\text{MeV}$, with a significance of 9.2σ. However, the overall fit result does not describe the data well, and the corresponding confidence level (C.L.) of the fit is only 8%. Alternative fits with different assumptions of spin parity, including the interference among charge conjugate modes, and including the contribution of $Z_c(3900)$ are also explored. However, in these fits, the parameters of

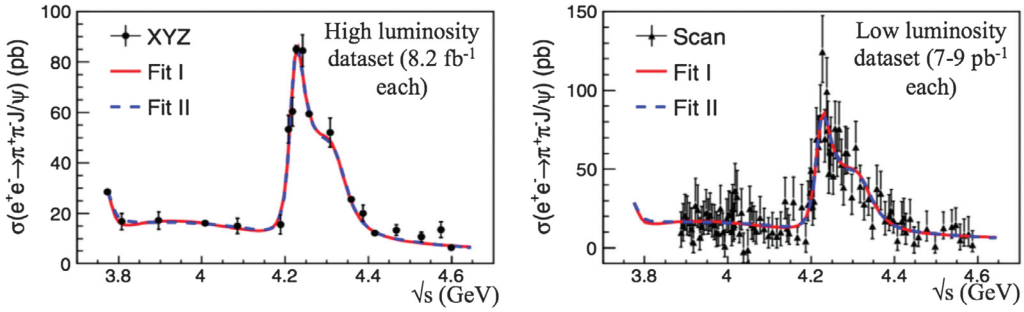

Fig. 3. – Measured cross section of the process $e^+e^- \to \pi^+\pi^- J/\psi$ and simultaneous fit to the XYZ and scan data sets. Dots with error bars refer to the data, while solid curves and dashed curves are the fit results using a coherent sum of three Breit-Wigner functions and a coherent sum of an exponential continuum with two Breit-Wigner functions, respectively.

the intermediate state are close to the nominal ones and the fit quality does not improve significantly.

Larger data sets, as well as more theoretical inputs, are necessary to further investigate the new structures observed in the $e^+e^- \to \pi^+\pi^-\psi(3686)$ process, as well as to understand the nature and the connections of the Z_c states.

2·2. *Y states at BESIII*. – The first Y state, called $Y(4260)$, was observed by BaBar in the process $e^+e^- \to \pi^+\pi^- J/\psi$ by means of the initial-state-radiation (ISR) technique [14], and confirmed by CLEO [15] and Belle [16] Collaborations in the same process. Being produced in e^+e^- annihilation, the Y states have quantum numbers $J^{PC} = 1^{--}$. However, despite the known 1^{--} charmonium-like states decay predominantly into open charm final states, the Y states show strong coupling to hidden-charm final states. Furthermore, the observation of other Y states, such as $Y(4360)$ and $Y(4660)$ in the $e^+e^- \to \pi^+\pi^-\psi(2S)$ decay mode [17, 18], together with the observation of new structures in the processes $e^+e^- \to \omega\chi_{c0}$ [19] and $e^+e^- \to \pi^+\pi^- J/\psi$ [20], overpopulates the charmonium spectrum predicted by the charmonium model.

BESIII performed several analyses of the line shape of a cross section with the aim to study the exotic Y states. A precise measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at c.m. energies from 3.77 GeV to 4.60 GeV [21] is obtained. The data samples used in this analysis include two different data sets: a high-luminosity data set (dubbed "XYZ" data) which contains more that $40\,\mathrm{pb}^{-1}$ at each c.m. energy point, and a low-luminosity data set (dubbed "scan" data), containing about 7–9 pb^{-1} at each c.m. energy point. The cross sections for the two data sets are shown in fig. 3. In order to study possible resonant structure, a binned maximum likelihood fit is performed simultaneously to the measured cross section of the "XYZ" and "scan" data. The fit result, also shown in fig. 3, indicates the presence of three resonances. The first one has mass and width consistent with that of $Y(4008)$ observed by Belle [3] within 1σ and 2.9σ, respectively. However, we cannot confirm its existence since a continuum term describes the cross section near 4 GeV equally well. The second resonance has a mass of $(4222.0 \pm 3.1 \pm 1.4)\,\mathrm{MeV}/c^2$, which agrees with the average $Y(4260)$ mass [22] within 3σ, but with a width much narrower than the average values [22]. Finally, a new resonance is observed for the first time in the $e^+e^- \to \pi^+\pi^- J/\psi$ process with a statistical significance of 7.9σ. The mass and the width are found to be $(4320.0 \pm 10.4 \pm 7.0)\,\mathrm{MeV}/c^2$ and $(101.4^{+25.3}_{-19.7} \pm 10.2)\,\mathrm{MeV}$,

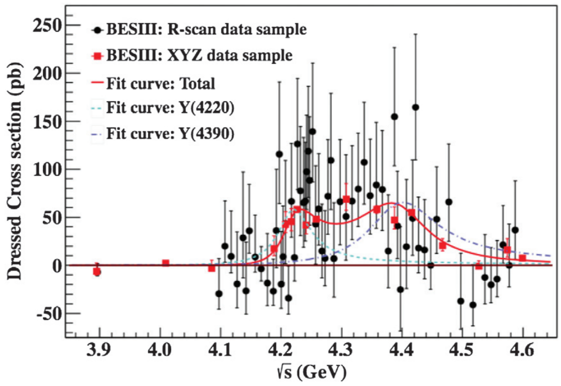

Fig. 4. – Fit to the dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ with a coherent sum of two Breit-Wigner functions (solid curve). The dash and dot-dashed curves show the contributions from the two resonances: $Y(4220)$ and $Y(4390)$, respectively. Dots are the cross section from the "scan" sample, while the squares are the cross section from the "XYZ" sample.

respectively, which are comparable with the mass and the width of the $Y(4360)$ state reported by Belle [18] and BaBar [17] in $e^+e^- \to \pi^+\pi^-\psi(2S)$.

In a similar study, the Born cross section for the process $e^+e^- \to \pi^+\pi^- h_c$ is calculated at c.m. energies from 3.896 to 4.600 GeV [20]. Also in this case, two different data samples are used: the "XYZ" sample constituted by 17 c.m. energy points with an integrated luminosity larger than $40\,\text{pb}^{-1}$, and the "scan" sample constituted by c.m. energy points with integrated luminosity smaller that $20\,\text{pb}^{-1}$. Figure 4 shows the dressed cross section (including vacuum polarization effect) with dots and squares for the "scan" and "XYZ" samples, respectively. The cross sections are of the same order of magnitude of $e^+e^- \to \pi^+\pi^- J/\psi$ [20], but follow a different shape. A maximum likelihood fit is used to fit the cross section and describes the two resonant structures observed in the spectra around 4.22 and $4.39\,\text{GeV}/c^2$. The masses and widths are found to be $M_1 = (4218.4^{+5.5}_{-4.5} \pm 0.9)\,\text{MeV}/c^2$, $\Gamma_1 = (66.0^{+12.3}_{-8.3} \pm 0.4)\,\text{MeV}$, and $M_2 = (4391.5^{+6.3}_{-6.8} \pm 1.0)\,\text{MeV}/c^2$, $\Gamma_1 = (139.5^{+16.2}_{-20.6} \pm 0.6)\,\text{MeV}$, and referred as $Y(4220)$ and $Y(4390)$, respectively. The significance of the assumption of two structures over one structure is greater than 10σ, and the parameters of $Y(4220)$ are consistent with those of the resonance observed in $e^+e^- \to \omega\chi_{c0}$ [19].

3. – Light hadron spectroscopy

BESIII collected the world largest J/ψ data sample, about 1.3×10^9, which are used to to study the structure of the hadrons and their interactions. On the light hadron sector, a lot of new states have been observed in the last years. The first observation of the $X(1835)$ state was done by the BESII experiment as a peak in the $\eta'\pi^+\pi^-$ invariant mass distribution in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ decay [23], and then confirmed by BESIII in the same process [24] with a statistical significance larger than 20σ, where also additional X states (*i.e.* $X(2120)$, $X(2370)$) are observed with significance larger than 6.4σ. The $X(1835)$ state is recently observed in the $\eta K^0_S K^0_S$ invariant mass spectra in the $J/\psi \to \gamma\eta K^0_S K^0_S$ process [25], and the spin-parity quantum numbers are determined to be $J^P = 0^-$ by performing a PWA.

Despite the strong efforts, the nature of the observed states is still unclear. However,

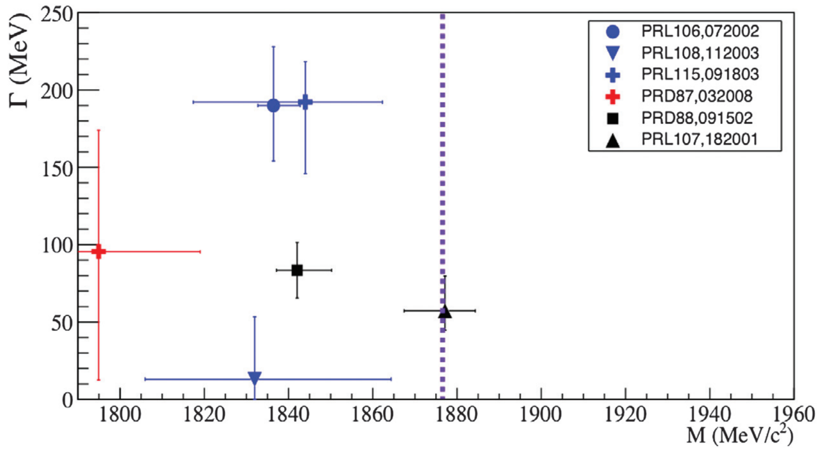

Fig. 5. – Comparison of masses and widths of some X states measured at BESIII. The error bars include statistical, systematic, and, where applicable, model uncertainties. The dotted line indicates the $p\bar{p}$ mass threshold.

due to the proximity of the $p\bar{p}$ threshold to the $X(1835)$ mass, one could assume the $X(1835)$ state as a $p\bar{p}$ bound state [26]. A strong enhancement was observed by BESIII at the $p\bar{p}$ mass threshold in the $J/\psi \to \gamma p\bar{p}$ decays [27] and the quantum number established to be $J^P = 0^-$ by a PWA. A summary of several BESIII measurements of masses and widths of different X states is reported in fig. 5.

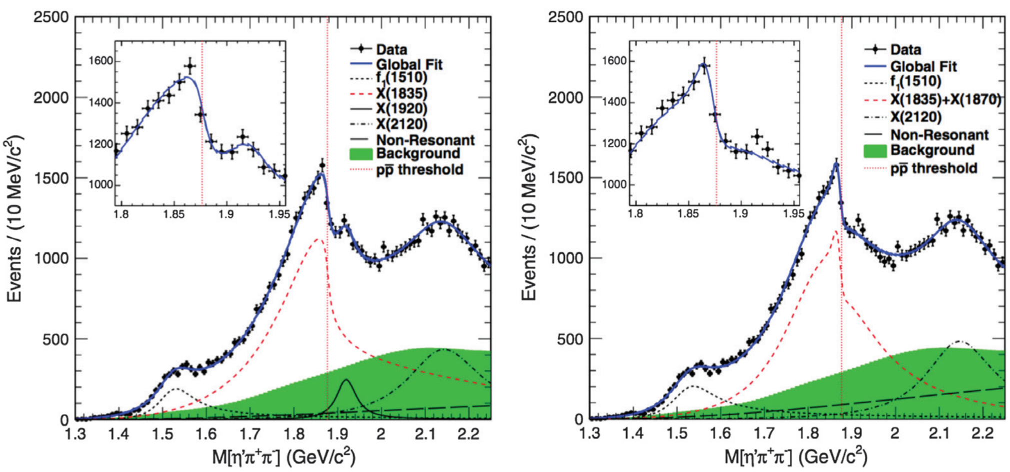

Fig. 6. – Fit results (solid curve) obtained by using the Flattè formula (left plot), and a coherent sum of two Breit-Wigner functions (right plot), while the insets show the global fit results between 1.8 and 1.95 GeV/c^2. The dotted vertical line shows the $p\bar{p}$ threshold, the dots with error bars refer to the data, the dashed red curve is the $X(1835)$ state, and the short-dashed and dash-dotted curves show the $f_1(1500)$ and $X(2120)$ contributions, respectively. The non-resonant $\eta'\pi^+\pi^-$ fit result is represented by the long-dashed curve, while the shaded histogram are background events from phase-space MC simulation. In the right plot, the additional $X(1920)$ resonance (dash–double-dotted curve) is considered to improve the fit result.

At BESIII we study the $\eta'\pi^+\pi^-$ line shape of $X(1835)$ in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ channel [28] using 1.09×10^9 J/ψ events collected in 2012. A significant change in the slope is observed in correspondence of the $p\bar{p}$ threshold, which cannot be described by a simple Breit-Wigner (BW) function. If the $X(1835)$ state is a $p\bar{p}$ bound state, it should have a strong coupling to the 0^- $p\bar{p}$ system, and the line shape of $X(1835)$ at the $p\bar{p}$ threshold would be affected by the opening of the $X(1835) \to p\bar{p}$ decay mode. This model is studied by means of the Flattè formula, and the result is shown in fig. 6 (left plot). In a second model, we assume that the line shape distortion is produced by the interference of the $X(1835)$ state with a narrow resonance near the $p\bar{p}$ threshold, denoted as $X(1870)$, and the fit result is shown in fig. 6 (right plot). Both models give a significance larger that 7σ. However, with the current statistics we cannot rule out any significant conclusion about the nature of the $X(1835)$ state.

4. – Charm physics and Λ_c physics results and plans

4˙1. *Charm.* – Precision measurements of charm decays provide important information to understand strong and weak effects: from decay rates of leptonic and semileptonic D decays one can extract the decay constant f_{D^+} and the Cabibbo-Kobayashi-Maskawa matrix elements, while from hadronic decays one can access to the CP asymmetry in the $D^0\bar{D}^0$ mixing and strong phase parameters which can be used to constrain the γ/ϕ_3 angle. At BESIII, charmed hadrons can be studied thanks to data samples of $2.81\,\mathrm{fb}^{-1}$ and $0.482\,\mathrm{fb}^{-1}$ collected at the c.m. energies of 3.770 (corresponding to the $\psi(3770)$ resonance) and 4.009 GeV, respectively. These two energy points correspond to the $D^0\overline{D}^0/D^+D^-$ and $D_s^+D_s^-$ thresholds, and then they decay into a $D\overline{D}$ pair without any additional hadrons. The measurements of hadronic branching fraction of D mesons and the accurate knowledge of the intermediate states are also important to reduce systematic uncertainties in those analyses that use a particular D decay for reference. In addition, these measurements also help to improve the background estimation in the precise measurements of B meson decays performed at LHCb or at B-factories. A new data set of about $3.1\,\mathrm{fb}^{-1}$ was collected at BESIII in 2016 at the c.m. energy of 4.18 GeV, which corresponds to the $D_s^*D_s$ threshold. A lot of new analyses are ongoing and interesting results will be ready soon.

4˙2. Λ_c. – An intense Λ_c physics program started is 2014, when BESIII collected a data sample of more than $500\,\mathrm{pb}^{-1}$ at the c.m. energy of $4.6\,\mathrm{GeV}/c^2$, which is just above the threshold of the Λ_c pair production. Despite the Λ_c is the lightest charmed baryon, its physics is quite limited, and roughly the 68% of the total branching ratio is known. A deep knowledge of the Λ_c decays may help to investigate the heavy quark-quark interaction dynamics, as well as heavier charmed baryon states decaying into Λ_c.

The first direct measurement of the Λ_c branching fractions into 12 different decay modes at threshold was published in ref. [29], which is followed by a series of studies of new decay modes and searches for rare decays [30]. However, the statistic available is still limited, and BESIII is planning to collect an integrated luminosity of about $3\,\mathrm{fb}^{-1}$ in order to improve the precision and to investigate further decay modes.

5. – Conclusions

Since 2009, BESIII collected a wide set of data sets that allow to cover several physics topics, such as hadron spectroscopy, search for exotic states, study of charm and charmonium decays, Λ_c physics, and others. In this paper we summarized only a brief selection of the latest BESIII results. New data sets will be collected and new analyses are ongoing. Interesting results will be expected in the near future.

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