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XYZ states: An experimental point-of-view

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ABSTRACT

Since 2003, a new family of states without a clear theoretical interpretation has been measured in the heavy quarkonium spectrum, the so-called XYZ states. While the nature of these states is so far unclear, the experimental search is one of the most active fields in the intensity frontier. In this review, the most important and representative results obtained in this field in recent years are going to be illustrated, providing insights into the nature of these exotic states. The focus will be on the experimental side, describing how it is possible to investigate their exotic nature with respect to the conventional quarkonium states.

1. Introduction

Quantum ChromoDynamics (QCD) is, at the present level of knowledge, the best model to describe the strong interaction, the force which bounds the nucleons inside the atomic nuclei and the partons inside the hadrons. Gluons and quarks can be described in terms of a color charge, as a representation of the SU(3) group; this degree of freedom can assume three different values, which are usually identified as the three additive colors of the RGB color model: red, green, blue. So far, no free particles have been observed experimentally with one of these colors as a charge; indeed, quarks with different colors mix in color-neutral (*white*) combinations to constitute color singlet states, which are the hadrons we observe. Based on their valence quarks, *i.e*, the constituents that influence their quantum numbers, the quark model classifies most of the known hadrons in two categories: three-quarks states called *baryons*, where each quark assumes a different color to finally form a colorless state, and quark–antiquark pair states called *mesons*, where one color and its anti-color mix together. However, the theory does not forbid the existence of additional combinations to form colorless states: pure glueballs (states with no quarks, made only of gluons), hybrids (regular mesons with at least a gluon inside), multiquark states (tetraquark, pentaquark, hexaquark...) are white states that have been predicted and could be observed.

The search of these states, called *exotics* due to their non-conventional structure, has begun in the light quark sector, where many states were predicted. However, the mass of the light quarks u d s is comparable to the QCD scale of hundreds of MeV, and the states are often broad and interfere with each other, making it difficult to disentangle the experimental signatures of exotic states from conventional ones. More details about the dynamics of the light quarks in mesons and the theoretical implications can be found in Ref. [1].

In contrast, the masses of the heavy quarks c and b are large and well separated from the QCD scale, and the hadron spectrum at these energies is much cleaner and almost free from interference patterns: it is possible to describe $c\bar{c}$ and $b\bar{b}$ pairs, namely

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[1] Both authors have contributed to the preparation of this paper in equal parts: conceptualization of the work, writing of the original draft, the review and the editing, data visualization, and funding acquisition. As a review of published works, the credit for the presented analyses has to be assigned to the authors of the original papers.

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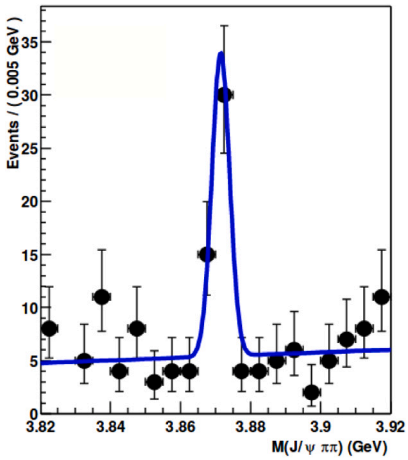

Fig. 1. The first observation of the $X(3872)$ state in $\pi\pi J/\psi$ invariant mass, as presented in Ref. [3].

charmonium and *bottomonium* states, respectively, in terms of non-relativistic potentials [2], and calculate the mass of these states. Indeed, the heavy sector has become of great interest since the discovery, in 2003, of an unexpected very narrow peak seen in the $\pi\pi J/\psi$ invariant mass by the Belle Collaboration [3]. This resonance, called $X(3872)$, showed an internal charmonium structure, demonstrated by its decay into a J/ψ, but its mass did not fit into the potential model, which was successfully used to describe all the other charmonium states discovered until then. This has been the first candidate of a new family of exotic states, appearing in the charmonium and bottomonium mass regions, that were observed experimentally but could not be predicted by the potential models. Since these states do not have a place in the conventional spectrum, the letters XYZ were adopted to name them, waiting to understand their true nature.

The field is very rich as will be clear in the following paragraphs; a detailed in-depth technical review can be found in Ref. [4]. To provide an introductory overall picture, a brief historical overview of the earlier studies and a description of the most used production techniques are presented below.

1.1. Brief historical review and today's nomenclature

In 1974, the discovery of the first charmonium state, the J/ψ, with the simultaneous observation of a very narrow resonance in experiments at BNL [5] and SLAC [6] colliders, led to significant refinement of the quark model. The fourth quark, the *charm*, predicted more than ten years prior to solve the problem of flavor-changing neutral currents, was finally discovered. After a few years, in 1977, also the *bottom* quark was discovered [7], in the observation of a dimuon resonance which was the first bottomonium state, the $\Upsilon(1S)$. Rapidly, several particles in these new families were discovered. The earlier potential model approach was integrated later by more advanced models, such as the NonRelativistic QCD (NRQCD) [8] and the coupled channel model [9,10], to better describe the experimental measurements. After roughly 20 years of the discovery period, in the 90s and in the beginning of the new millennium the research activities went towards the precision frontier, to search for the missing states, such as the $J^{PC} = 1^{+-}$, the $J^{PC} = 2^{-+}$, and the $J^{PC} = 2^{--}$ (where J is the spin, P is the parity and C is the charge-conjugation quantum number), which were expected to appear with the increasing luminosity and technology. Ref. [11] gives a more historical perspective on this topic.

In this context, the Belle Collaboration was searching for the 2^{--} state by looking at the $\pi\pi J/\psi$ invariant mass distribution, expecting a narrow peak just below to the $D\bar{D}^*$ threshold since, due to parity conservation, the decay into $D\bar{D}$ would be forbidden [12]. They observed a narrow state, but in practice sitting at the $D\bar{D}^*$ threshold, with mass $M = (3872 \pm 0.6\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst}))\,\mathrm{MeV}/c^2$ [3], where the first errors are statistical and the second ones are systematic, as it will be always implied in this review. The invariant mass distribution is shown in Fig. 1.

Already in the original article, the authors underlined how this state was not compatible with the (at that time) present predictions on charmonium states based on potential models. The particle was named $X(3872)$ since no information was available on its nature. This was indeed the first observation of a new family of states, nowadays known as XYZ states, that have changed our understanding of the charmonium (and bottomonium) spectrum. All these states appear above the open charm (bottom) threshold, i.e. the minimum energy so that the charmonium (bottomonium) breaks into a pair of mesons, each one containing a charm (bottom) quark and a light quark. Fig. 2 shows the charmonium spectrum before 2003 and recently in the left and the right panel, respectively. It is possible to see clearly on the right that the region above the DD^* threshold is overpopulated with these new states. In the bottomonium spectrum, fewer non-conventional states have been discovered than in the charmonium case, since the region above the open bottom threshold has been less explored so far.

Historically, the name of the XYZ family originates from the mystery that arose just after the discovery of the exotic states, whose nature was not clear. Nowadays, the Particle Data Group (PDG) [13] has proposed to classify the exotics with the conventional nomenclature of quarkonium states.

Throughout the paper, for these states the traditional nomenclature - XYZ - will be used, defined following this scheme:

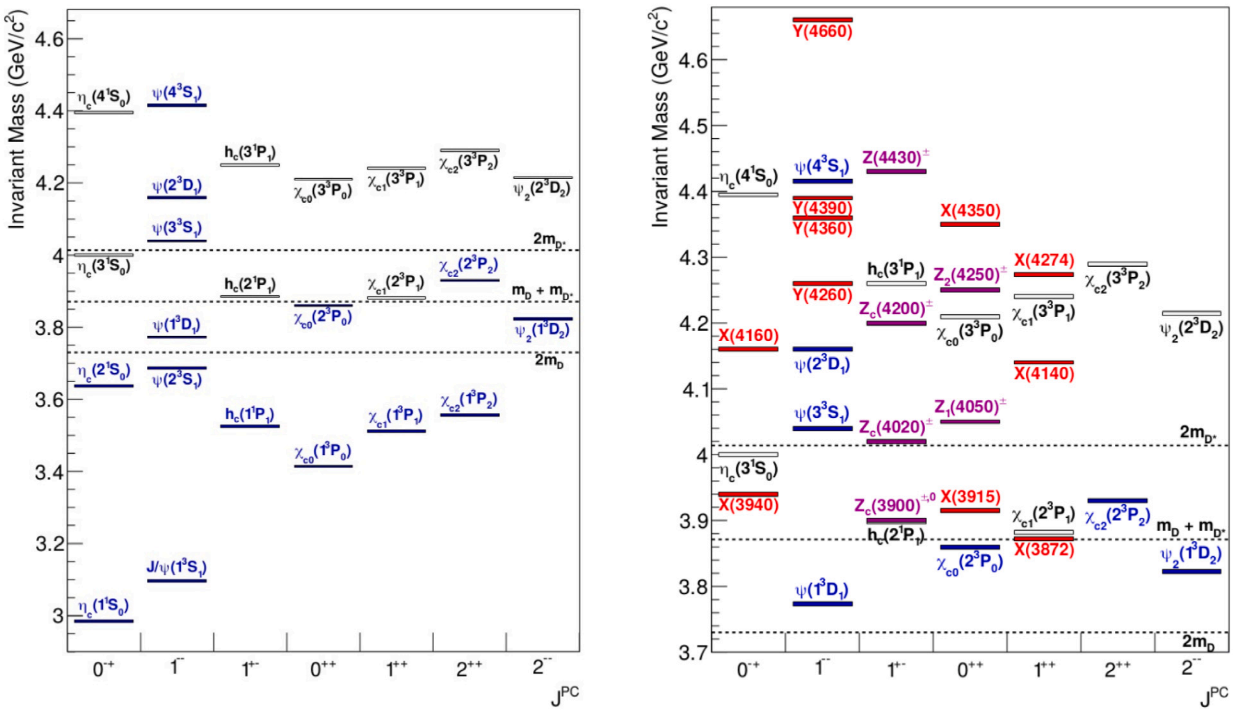

Fig. 2. States of the charmonium spectrum: (left) full charmonium spectrum before 2003; (right) charmonium spectrum above the open-charm threshold nowadays. The blue boxes show the predicted and discovered charmonium states; the gray boxes represent the predicted conventional charmonium states but not yet discovered; the red boxes represent the neutral non-conventional XYZ mesons, while the magenta boxes show the charged non-conventional states.

- Y states are all the exotic vectorial states, i.e. with quantum number $J^{PC} = 1^{--}$; they have the same quantum numbers of the photon and can be produced easily in e^+e^- collisions, in formation or through initial-state radiation;
- Z states are all the exotic charged states, which decay into a quarkonium state and a light charged meson; it seems they can be organized in isospin triplets;
- X states are all the other neutral states with quantum numbers different from $J^{PC} = 1^{--}$.

Recently, a new letter has been introduced in the exotic alphabet, the P, which stands for pentaquark, states with an inner content of four quarks and one anti-quark; the LHCb Collaboration has observed resonances compatible with this kind of states [14], but they are outside the scope of this review and will not be discussed.

1.2. Production techniques

Before introducing the current experimental picture on the exotic particles, the main techniques used to produce quarkonium states in high energy physics experiments are hereby described. There are two typical kinds of ways to produce these states: by direct production or by decay of heavier particles.

The direct production process (namely *formation*) has been extensively used at B-factories (BaBar [15,16], Belle [17], CLEO [18, 19]) and $\tau - \mathrm{charm}$ factories (CLEO-C, BES [20]) to investigate the properties of vector states at e^+e^- colliders. At these energies, the e^+e^- pair annihilates producing a virtual photon with quantum numbers $J^{PC} = 1^{--}$, which afterwards may decay into a quark–antiquark pair; if the total energy is close to the mass of a 1^{--} state, such as the J/ψ, the cross section increases drastically due to the formation of the resonance. The experimental advantage of direct production is that the interaction energy can be determined with extreme precision from the knowledge of beam parameters, without being limited by the detector resolution; moreover, it is possible to perform energy scans of narrow resonances to determine with high accuracy their line shape. In this way, only 1^{--} states sitting at the collision energy appear to be produced, but the two electrons have the possibility to emit one or more initial state photons, by the so-called Initial-State Radiation (ISR) process, granting access to an energy range up to the collision energy; the process is depicted in Fig. 3d. This technique has allowed, for example, the discovery of the $Y(4260)$ state by the BaBar [21] and the Belle [22] Collaborations. The direct production can also occur at $p\bar{p}$ colliders, as studied by the E835 [23] experiment at Fermilab and under planning for the $\bar{\mathrm{P}}$ANDA experiment at FAIR [24]; in this case, all the quarks can coherently annihilate emitting two or three gluons, which can couple to form a quarkonium state. In this case, it is possible to access states with different quantum numbers, and this would be the best way to produce exotic quantum numbers (if any); unfortunately, production cross sections in this energy regime are either poorly measured or even unknown.

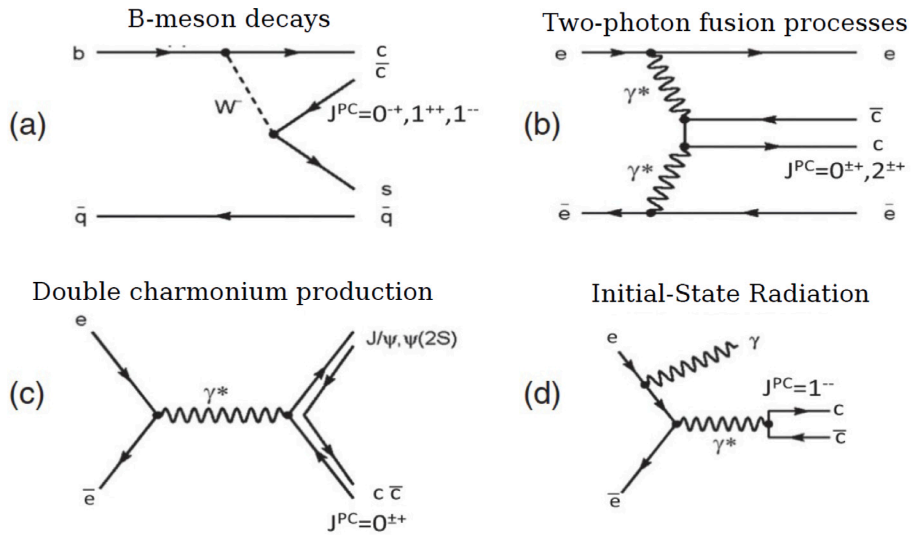

Fig. 3. Production techniques of charmonium states in e^+e^- colliders, from Ref. [1].

In order to study states with quantum numbers different from $J^{PC} = 1^{--}$, the main alternative technique consists in detecting the decay of heavy mesons, which could be other quarkonium states or open bottom mesons (i.e. made by a b quark and a lighter quark). It is possible to investigate the properties of the states so produced by reconstructing all the particles involved in the decay, thus depending on the detector performances. This has made clear the exotic nature of the $Z_c(4430)$ [25] and the $Z_c(3900)$ [26] immediately. In particular, the charmonium production in B meson decays is depicted in Fig. 3a. The dominant process is the weak decay of the b-quark into a c-quark: in the hadronization, the c-quark can combine with other sea-quarks to form a conventional or an exotic hadron. This process is very clean, all possible quantum numbers can be produced but with small production rates; nevertheless, this is one of the main production techniques, since in B-factories a huge amount of B mesons is produced in the collisions. This technique is used also by the LHCb experiment at CERN [27].

Other production techniques in e^+e^- collisions in B-factories are the two-photon fusion, depicted in Fig. 3b, where the two leptons irradiate photons which can form a J- and C-even state but with a low cross-section (it scales with α^2), and the double charmonium production, where, given enough energy, a charmonium pair is produced and so far with cross-sections higher than predicted (Fig. 3c). Moreover, in hadron collisions at high energy, such as at Tevatron, RHIC, and LHC, hadroproduction of quarkonium states can occur. These techniques will not be discussed extensively in this paper due to the reduced particle discovery potential. Nevertheless, they contribute considerably in understanding the nature of exotic states, combined with the other techniques.

2. The vectorial Y states

2.1. The $Y(4260)$ and the $Y(4230)$ states

Early measurements. From the historical point of view, the discovery of the vector exotic states has to be assigned to the BaBar Collaboration in the process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$ [21]. They were using the ISR process, shown in Fig. 3d, to access the charmonium spectrum to investigate the $\pi\pi J/\psi$ invariant mass. The interest was to assess the $X(3872)$ quantum numbers, or at least to prove that this state was not $J^{PC} = 1^{--}$. What they observed was instead an excess near 4.26 GeV, shown in Fig. 4. The peak was confirmed later by the CLEO [28] and the Belle Collaborations [22]. The production mechanism automatically suggested that the $Y(4260)$ could be a vector charmonium, but all the $c\bar{c}$ levels in that energy region had been already assigned to well-established resonances, which can be seen from the measurement of $R = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, as shown in Fig. 5: at the energy where we shall observe the $Y(4260)$ resonance, we observe a non-expected dip in the cross section, breaking the paradigm of the OZI rule. The OZI rule tells us that, in the strong interaction, in a description of a decay mode with a Feynman diagram with disconnected quark lines (i.e. the diagram can be separated in two parts, with the initial state particles on one side and the final state particles on the other, by just cutting the gluon lines), the process is suppressed compared to the one with connected lines. In the case of $Y(4260)$ state, if a simple charmonium content of $c\bar{c}$ pair is assumed, the decay into open-charm pairs should be the dominant decay since the charm lines are uncut, and the cross section into hadrons should have a peak as it appears for other conventional 1^{--} states; the dip around 4.26 GeV suggests that the inner structure of this state could be different, together with the fact that in $\pi^+\pi^-J/\psi$ decay we observe a peak in the cross section, in contradiction with OZI rule since this diagram has disconnected lines (the charm and anti-charm quarks do not appear in the final state since they annihilate). The same dip could also be explained in terms of destructive interference between the $Y(4260)$ and the continuum process $e^+e^- \rightarrow hadrons$.

In order to understand its nature, several hypotheses were proposed to describe its inner structure, based on exotic models such as a molecule, a hybrid, or a tetraquark; some of them can be found in Ref. [29–31].

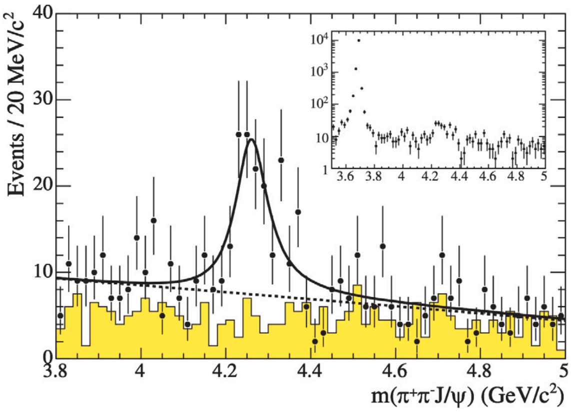

Fig. 4. Invariant mass distribution of $\pi^+\pi^- J/\psi$ measured by BaBar from Ref. [21]. The peak corresponds to the $Y(4260)$ state.

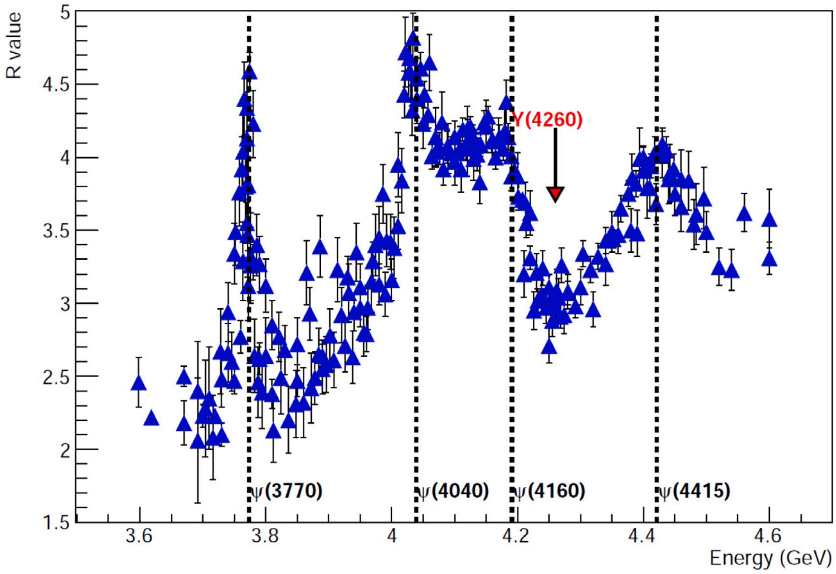

Fig. 5. $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$ scan data above open charm threshold from Ref. [13]. The black dashed lines are centered to the nominal masses of conventional 1^{--} states, while the arrow is pointing at the mass of the $Y(4260)$.

From the $Y(4260)$ *to the* $Y(4230)$. More insight about the nature of the vectorial states came from the BESIII experiment, which plays an important role in the search of exotic states, as the accelerator allows to tune the energy of the e^+e^- collisions and to perform a precise scan around the region of interest. Indeed, by scanning the energies above the open charm threshold up to 4.6 GeV, the BESIII experiment could achieve higher precision than the former ones, and the fit of the $e^+e^- \to \pi^+\pi^- J/\psi$ invariant mass distribution demonstrated that the peak at around 4.26 GeV was in reality made of two structures [32], one at lower energy, with mass $M_{Y(4230)} = (4222.0 \pm 3.1 \pm 1.4)\,\mathrm{MeV}/c^2$ and width $\Gamma_{Y(4230)} = (44.1 \pm 4.3 \pm 2.0)\,\mathrm{MeV}$, one at higher energy, with mass $M_{Y(4320)} = (4320.0 \pm 10.4 \pm 7.0)\,\mathrm{MeV}/c^2$ and width $\Gamma_{Y(4320)} = (101.4^{+25.3}_{-19.7} \pm 10.2)\,\mathrm{MeV}$. The line shape and the fit are presented in Fig. 6a.

In addition, the BESIII experiment has also reported the analysis of the process $e^+e^- \to \pi^0\pi^0 J/\psi$, using an extended dataset [33]. Fig. 6b shows the results, where a two-peak structure is visible, compatible with the one observed in the final state involving charged pions, and in agreement with the expectations from isospin conservation (as shown in the bottom part of Fig. 6b): the cross section ratios between the two processes $e^+e^- \to \pi^0\pi^0 J/\psi$ to $e^+e^- \to \pi^+\pi^- J/\psi$ was averaged over the whole range of c.m. energies, obtaining the value of 0.48 ± 0.02, consistent with the prediction of 0.5 based on isospin symmetry.

It is important to note that a state with mass at $4230\,\mathrm{MeV}/c^2$ had been already observed, again by BESIII, in $e^+e^- \to \omega\chi_{cJ}$, but originally it was not associated with the $Y(4260)$ since the obtained mass value was found inconsistent to the $Y(4260)$ measurements [34]; this is the historical reason why the Particle Data Group called originally this state $Y(4230)$, and the name persisted later even if the more precise measurements pointed to a mass value of $4220\,\mathrm{MeV}/c^2$. Indeed, several publications referred to $Y(4220)$.

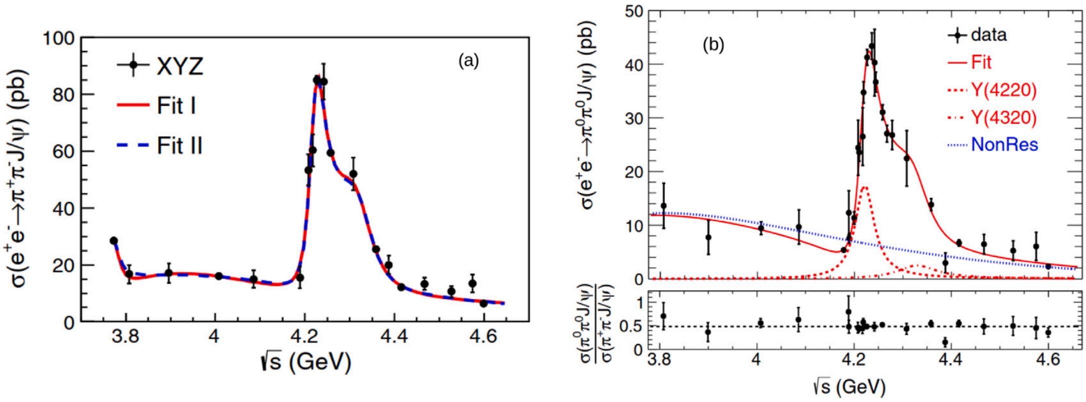

Fig. 6. Line shape of $e^+e^- \to \pi\pi J/\psi$ from BESIII. (a) The charged mode from Ref. [32]. (b) The neutral mode from Ref. [33]; in the bottom part the ratio with the results from Ref. [32] is also presented.

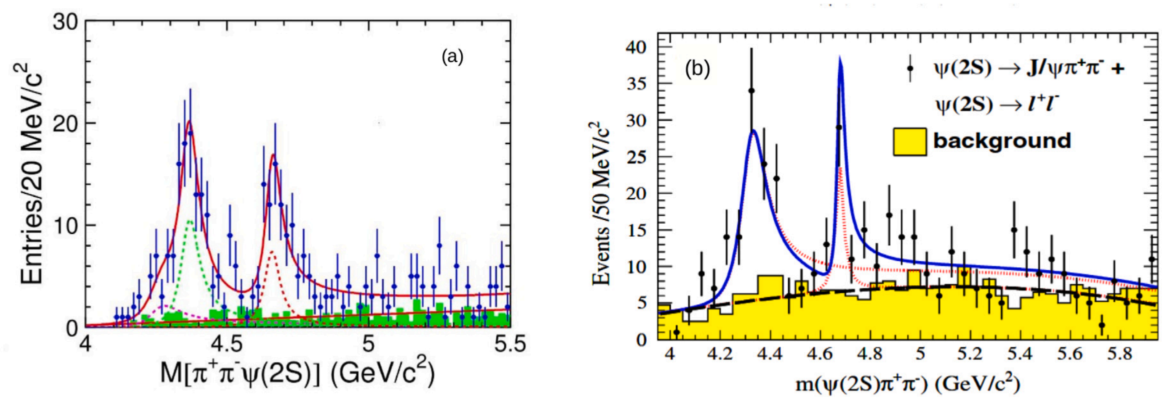

Fig. 7. Line shape of the $Y(4360)$ and $Y(4660)$ in $\pi\pi\psi(2S)$ final state in the Belle [35] and BaBar [36] data on the left and the right panels, respectively. In this plot, no $Y(4230)$ signal appears evidently.

The study of different decay processes can supply useful information on the properties of the charmonium-like states. In this sense, the search for the $Y(4260)$ has been extended by looking at the similar process $e^+e^- \to \pi\pi\psi(2S)$, where, instead of having the J/ψ in the final state, its first excited state was searched for. Two clear peaks were initially reported by both the Belle [35] and the BaBar [36] Collaborations, but none of them was compatible with the mass and the width of $Y(4260)$, as shown in Fig. 7a and Fig. 7b. In a more recent study, the higher precision of BESIII data showed that one of the formerly-reported peaks was, instead, formed by the sum of a signal compatible with the $Y(4230)$, together with a higher energy state called $Y(4390)$, as shown in Fig. 8 [37].

The $Y(4230)$ in non-vector charmonia and open charm final states. To understand the nature of this Y state, final states with other charmonia and charm mesons were searched for. A possible decay process involves the production of 1^{+-} state together with a pion pair; using the same dataset of Ref. [32], the BESIII Collaboration has reported the study of the $e^+e^- \to \pi^+\pi^- h_c$ [38], and the measured invariant mass distribution is shown in Fig. 9a. It is possible to see that, in order to fit the data, two resonant structures are needed: the lower mass structure has mass and width $M = (4218.4^{+5.5}_{-4.5} \pm 0.9)\,\mathrm{MeV}/c^2$ and $\Gamma = (66.0^{+12.3}_{-8.3} \pm 0.4)\,\mathrm{MeV}$, respectively, while the higher mass one has mass and width $M = (4391.5^{+6.3}_{-6.8} \pm 1.0)\,\mathrm{MeV}/c^2$ and $\Gamma = (139.5^{+16.2}_{-20.6} \pm 0.6)\,\mathrm{MeV}$. While the lower mass peak is compatible with the $Y(4230)$ observed in $\pi\pi J/\psi$ final state, the higher one differs from the $Y(4320)$, but is compatible with the higher mass $Y(4390)$ state required to fit the $\pi\pi\psi(2S)$ final state line shape, as shown before.

Despite the $Y(4230)$ state lies above the open charm threshold, no open charm decays were reported initially. The Belle Collaboration explored the process $e^+e^- \to DD^*\pi$, but they reported only evidence of the $\psi(4415) \to \pi DD^*$ process [39]. Recently, the BESIII Collaboration has published a new study of the same final state [40]; in this work, the $e^+e^- \to \pi^+D^0D^{*-}$ is fit with two resonances and a smooth three-body phase space continuum, as it can be seen in Fig. 9b. The fit parameters are compatible with the two signals observed also in $\pi\pi h_c$, but the higher mass state has a much broader width. This is the first observation of an open charm decay for the $Y(4230)$ state.

The $Y(4230)$ in hadronic transition to lower charmonia states. So far we presented mainly the processes involving a pion pair in the final state plus a vector ($J = 1$) charmonium states, and evidences of the $Y(4230)$ have been shown in all the cases, together with

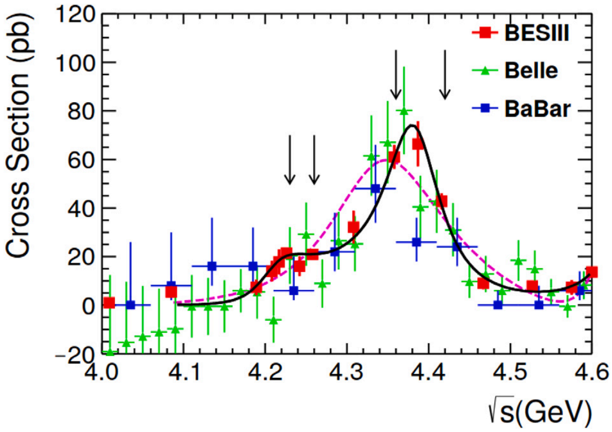

Fig. 8. The $e^+e^- \to \pi\pi\psi(2S)$ cross section line shape from Ref. [37]. In the plot, data from Ref. [35] and Ref. [36] are also shown as green triangles and blue squares, respectively. The black line shows the final fit with two resonances, the $Y(4230)$ plus the $Y(4390)$, while the dashed magenta line represents the single resonance fit in the single $Y(4360)$ hypothesis as shown in Fig. 7.

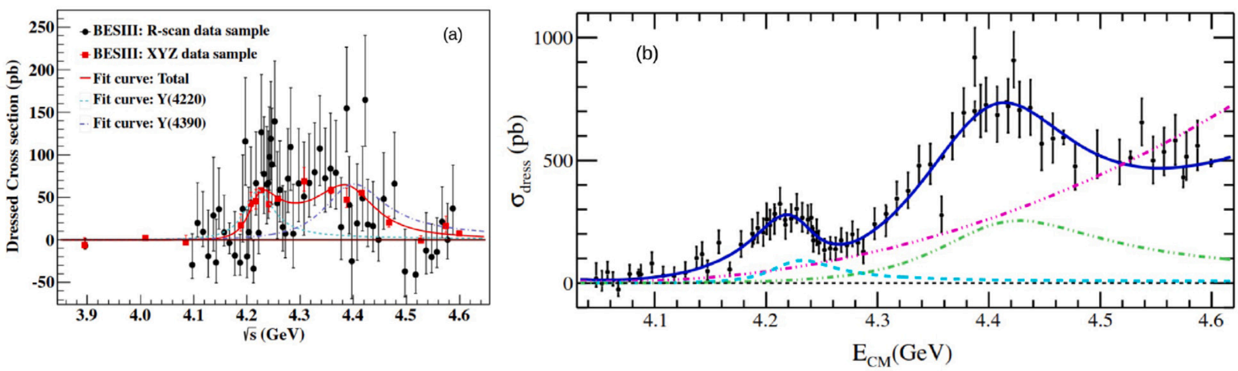

Fig. 9. The line shape of two processes where a $Y(4230)$ is present, associated with another state at higher mass different from the one observed in $\pi\pi J/\psi$. (a) The $e^+e^- \to \pi^+\pi^- h_c$ from Ref. [38]; the solid red line represents the final fit including the two resonances $Y(4230)$ and $Y(4390)$, whose contribution is presented separately as dashed lines. (b) The $e^+e^- \to \pi^+ D^0 D^{*-}$ from Ref. [40]; the solid blue line is the final fit including both the resonances, the cyan dashed line is the $Y(4230)$ state, the green dashed–dotted line represents the so-called $Y(4390)$ and the magenta line represents the three-body phase space.

other states at higher energies. The study of other possible hadronic transitions between $Y(4230)$ states and conventional charmonia can also be an important tool to investigate its nature. The BESIII Collaboration focused its efforts in this direction; in Ref. [41], they report the measurement of the process $e^+e^- \to \eta J/\psi$, as illustrated in Fig. 10a, which shows the measured cross section and the fit line shape. Assuming that the low mass resonance is the conventional $\psi(4040)$, two other resonances are observed, with mass and width values compatible with the states observed in $\pi\pi h_c$. Previous studies of the process were performed by the Belle [42], CLEO [43], and BES Collaborations [44], which indicated a contribution from the conventional $\psi(4160)$. In parallel to the aforementioned searches, and to understand whether the $\psi(4160)$ can be used to describe the full process, BESIII has studied also the $e^+e^- \to \eta' J/\psi$ process, as done in Ref. [45] but with a higher statistics. The cross section could not be fit by a single resonance, as shown by Fig. 10c, but as a coherent sum of $\psi(4160)$ and $Y(4260)$ with the parameters fixed to the PDG values of [46], and a statistical significance of 6.3σ and 4σ, respectively, has been estimated.

Using the same dataset, Fig. 10b shows a peak that is found in $\omega\chi_{cJ}$ cross section line shape, with the fit values $M_{Y\omega\chi_{cJ}} = (4215.5 \pm 1.6 \pm 4.0)\,\mathrm{MeV}/c^2$, $\Gamma_{Y\omega\chi_{cJ}} = (28.2 \pm 3.9 \pm 1.6)\,\mathrm{MeV}$, respectively [47].

An evidence of the $Y(4230)$ has also been found in the process $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ in Ref. [48], that extends the analysis performed in Ref. [49] with additional center of mass energies and final states. Fig. 10d shows the results of this search. The peak is compatible with the parameters of the $Y(4230)$.

Summary on the $Y(4260)$ state. So far, the presence of a state $J^{PC} = 1^{--}$ with a mass around 4.2 GeV/c^2 has been established in several decay channels and with different production mechanisms. This state has been originally called $Y(4260)$, from the position of the center of the Breit–Wigner function used to fit the $\pi\pi J/\psi$ data, but the recent studies pointed to a mass value around 4220 MeV/c^2. Nowadays, the Particle Data Group has decided to call it $\psi(4260)$, in agreement with the conventional $J^{PC} = 1^{--}$ state nomenclature even if the conventional $c\bar{c}$ content is excluded, but does not provide average mass or width values, since the peak has

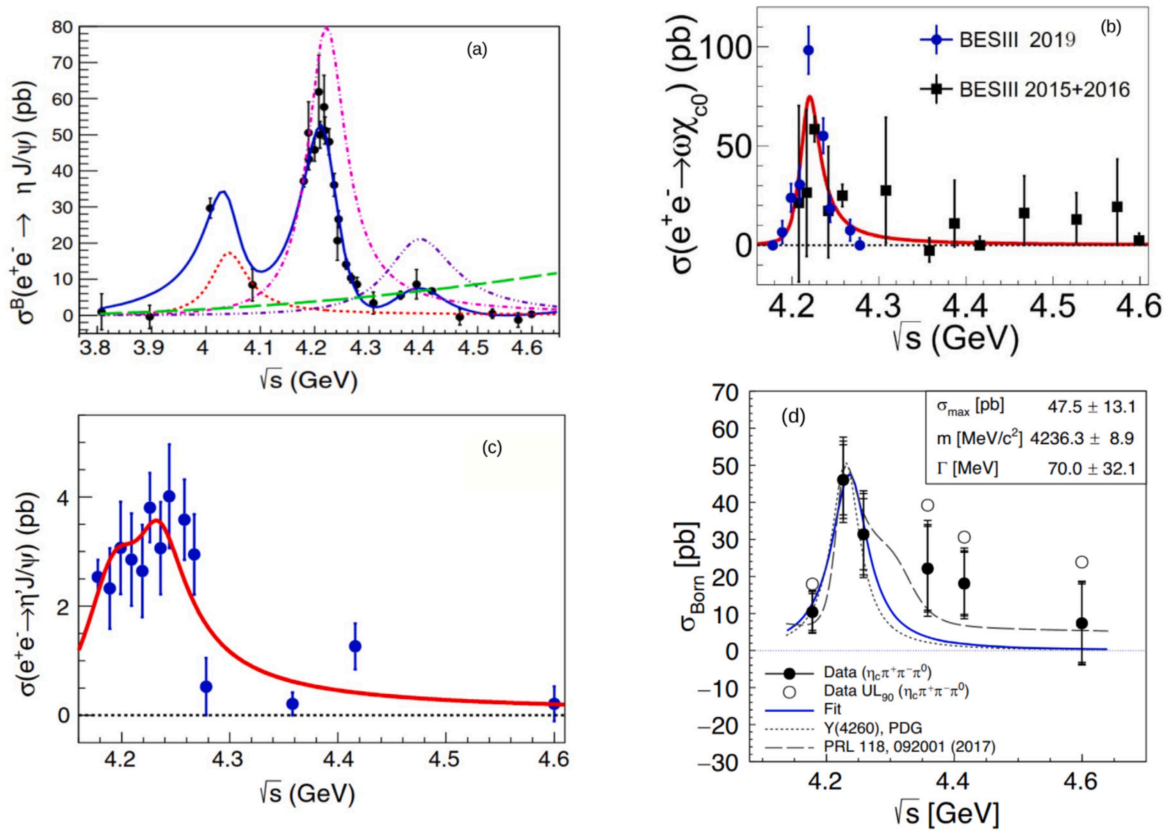

Fig. 10. Most recent results on the searches of hadronic transition between $Y(4230)$ and conventional charmonia. (a) The $e^+e^- \to \eta J/\psi$ cross section line shape from Ref. [41]. (b) The $e^+e^- \to \omega\chi_{c0}$ cross section line shape from Ref. [47]. (c) The $e^+e^- \to \eta' J/\psi$ cross section line shape from Ref. [50]. (d) The $e^+e^- \to \eta_c\pi\pi\pi$ cross section line shape from Ref. [48].

been proved being composed by the interference of different structures. Moreover, the PDG includes all the recent measurements from BESIII into a state called $\psi(4230)$, with an estimated mass of $(4220 \pm 15)\,\mathrm{MeV}/c^2$ and width from 20 to 200 MeV [13].

2.2. Other vector candidates: $Y(4360)$, $Y(4660)$

The $Y(4260)$ state has been extensively studied due to its easiness of being produced in e^+e^- collisions, but it is not the only exotic candidate which has been clearly observed in the vector charmonium-like spectrum.

The BaBar Collaboration was searching for the exotic state $Y(4260)$ in $e^+e^- \to \pi\pi\psi(2S)$ by ISR production, replacing the J/ψ in the final state by $\psi(2S)$; instead, a peak at around 4.3 GeV/c^2 was found [51], which was not predicted as a charmonium state. Afterwards, the Belle experiment confirmed the presence of a peak at 4.36 GeV/c^2 and measured a second one at 4.66 GeV/c^2 [52]. Later, both the experiments increased their luminosity and performed higher precision analyses to estimate the parameters of these two exotic states, which were named $Y(4360)$ and $Y(4660)$ [35,36], and the obtained values were compatible with the previous observations. The $Y(4360)$ has also been measured by BESIII, as already shown in Fig. 7 [37]. Nowadays, the Particle Data Group calls it $\psi(4360)$, with an average value of mass $M_{Y(4360)} = 4368 \pm 13\,\mathrm{MeV}/c^2$, and width $\Gamma_{Y(4360)} = (96 \pm 7)\,\mathrm{MeV}$ [13]. While there is quite a consensus about the existence of the $Y(4230)$ state, it is not clear whether the $Y(4360)$ state observed in $\pi\pi\psi(2S)$ invariant mass is the same state observed in other final states, such as the $Y(4390)$ seen in Fig. 8 [37]. Measurements from different decay channels could help to disentangle the scenario.

At higher energies, a near-threshold enhancement compatible with the $Y(4660)$ state has been observed in the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ by the Belle Collaboration [53], as shown in Fig. 11a, where the background-subtracted cross section is shown. Originally called $Y(4630)$, due to its vicinity to $Y(4660)$, several attempts were made to consider both as the same state. BESIII, whose data were limited up to 4.6 GeV as the maximum center-of-mass energy reachable by the accelerator, has studied the same process in a restricted energy range but with higher precision; the results do not hint at a possible clear resonance, as can be seen in Fig. 11b [54], and could suggest that the enhancement could be interpreted as a threshold effect.

The Belle Collaboration has searched for peaks of the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass in B-meson decays [55,56], but no evidence of a clear state was found. Indeed, our knowledge of this state is so far limited.

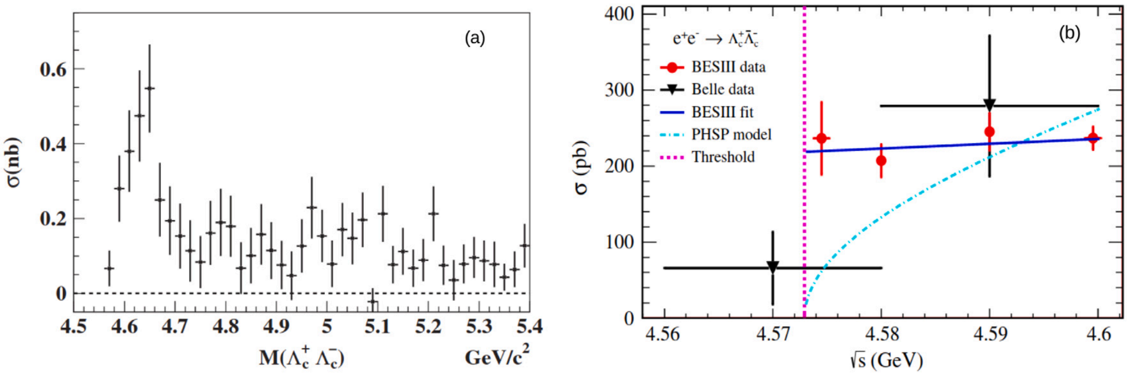

Fig. 11. The $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ cross section line shape from (a) Ref. [53] and (b) Ref. [54]. In (a), since the cross section is extracted after background subtraction, large statistical fluctuations can cause values lower than zero, as it happens around 5.1 GeV/c^2. In (b), the measurements from Belle data are shown as black triangles, the BESIII ones as red circles.

Currently, the PDG calls it $\psi(4660)$ and proposes as average mass $M = (4630 \pm 6)\,\mathrm{MeV}/c^2$, and width $\Gamma = (62^{+9}_{-7})\,\mathrm{MeV}$.

Recently, the BESIII experiment has increased the maximum achievable beam energy by the accelerator, and is going to collect more data in this energy region to unveil more features, and fix the number of additional charmonium-like resonances and their parameters [57].

2.3. $Y(10753)$: *a vector candidate in the bottomonium sector*

If compared to the ones observed in the charmonium spectrum, the number of exotic state candidates in the bottomonium family is limited. The reason is dual: on the one hand, the statistics available in e^+e^- collisions above the $\Upsilon(4S)$ energy, i.e. above the open-bottom threshold, is limited; on the other hand, the calculations above the $B\bar{B}$ threshold are more complicated than the ones above $D\bar{D}$, also for conventional states, so it is less straightforward to clearly identify overabundant states. Nevertheless, hints of exotic states are present also in the bottomonium spectrum, and one of them is a vector candidate.

The states $\Upsilon(10860)$ and $\Upsilon(11020)$ have been usually associated with the $\Upsilon(5S)$ and the $\Upsilon(6S)$ mesons, radial excitations of the $b\bar{b}$ bound state with $J^{PC} = 1^{--}$, even if several doubts on their nature were risen due to their mass values. The Belle Collaboration wanted to study their line shape with an energy scan in the range $\sqrt{s} = 10.63 - 11.05\,\mathrm{GeV}$; they measured the cross section of the process $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$, and when fitting the $R_{\Upsilon(nS)\pi\pi} = \sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)/\sigma(\mu^+\mu^-)$ distribution, by a sum of two S-wave Breit–Wigner functions for $\Upsilon(5S)$ and $\Upsilon(6S)$ and continuum terms, they noticed an excess at an energy value around 10.75 GeV [58]. In the same paper the $R_b = \sigma(e^+e^- \to b\bar{b})/\sigma(\mu^+\mu^-)$ distribution has been extracted, and it shows a dip in the same position, in a tight analogy with the $Y(4260)$ state. The distributions can be seen in the left panel of Fig. 12.

Later, Belle analyzed again the data with an improved reconstruction, and increased the statistics adding the ISR process in the $\Upsilon(10860)$ high-statistics resonance data [59]. The obtained cross section distributions are shown in the right panel of Fig. 12, together with the fit with three components. The parameters of this new vector candidate has been extracted as $M = (10752.7 \pm 5.9^{+0.7}_{-1.1})\,\mathrm{MeV}/c^2$, and width $\Gamma = (35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3})\,\mathrm{MeV}$, and it is called $Y(10753)$ by PDG.

So far no other experiment has observed this state, but Belle II has started to take data at these energies to verify the existence of this state and investigate its inner structure.

3. Z - the charged exotic states

While the Y states (and also the X states as described in the next section) could be interpreted as conventional quarkonia, the Z states are manifestly exotic states, and an inner structure based on a mere quark–antiquark pair is completely excluded by the experimental data; indeed, they have been observed decaying into conventional charmonium states, thus they must contain a c quark and a $\bar{c}$ quark inside, and they have a non-zero electric charge considering their decay products. The presence of an electric charge implies that these states must be constituted by (at least) four quarks.

The first state to be discovered was the $Z_c(4430)^\pm$, observed for the first time by the Belle Collaboration in B meson decays [25] and confirmed later by the LHCb Collaboration [60], but other charged states have also been observed in e^+e^- collisions at the charmonium energies. Besides charmonium-like charged states, also bottomonium-like states have been observed from $\Upsilon(5S)$ decays, hinting for an inner structure composed by a b quark, a $\bar{b}$ quark, and at least two lighter quarks. More recently, also charged charmonium-like states with a strange quark content have been reported [61,62].

All these states demonstrate the existence of a new class of hadrons, made of at least four quarks. They could be interpreted as compact tetraquark states, or as molecular states made of a bound open-charm(bottom) pair (such as $\bar{D}D^*$, $\bar{D}^*D$, ...), or as hadro-quarkonium states [63], i.e. a central heavy quarkonium core surrounded by a light quark cloud.

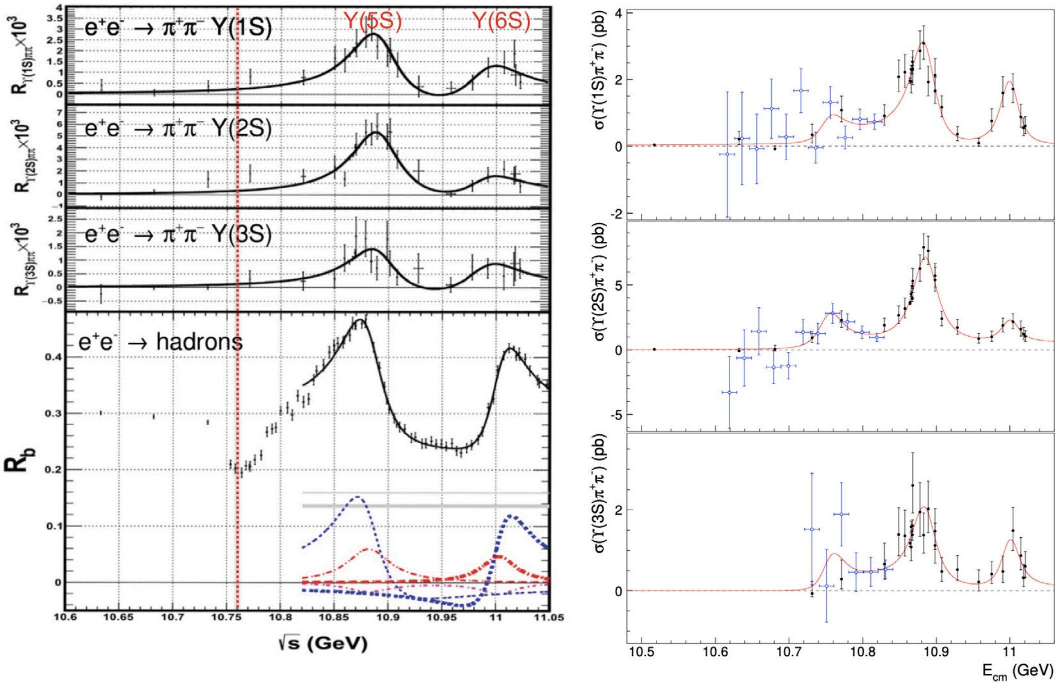

Fig. 12. Observation of the exotic candidate $\Upsilon(10753)$.)left) $R_{\Upsilon(nS)\pi\pi}$ distributions obtained for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ from the top, fit by two Breit–Wigner functions and continuum terms, and compared to R_b in the bottom; the red line indicates the energy value of 10.75 GeV [58]. (right) energy-dependent cross section distributions of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$), extracted by a more refined analysis (black dots) and adding ISR data from $\Upsilon(10860)$ on resonance data (blue dots); the fit includes an additional third resonance [59].

3.1. The $Z_c(4430)^\pm$ state

The $Z_c(4430)^\pm$ has been observed by the Belle Collaboration by studying the process $B \to K\pi^\pm\psi(2S)$, as a peak in the $\pi^+\psi(2S)$ invariant mass [25]. The Dalitz plot of $M^2(\pi\psi')$ versus $M^2(K\pi)$ showed intense bands in $K\pi$ invariant mass, connected to the known excited K states, *i.e.* $K^*(892)$ and $K_2^*(1430)$, which were vetoed in the analysis. The final fit was performed using a Breit–Wigner parametrization for the peak, over a smooth phase-space background function. They obtained a mass value of $M = (4433 \pm 4 \pm 2)\,\mathrm{MeV}/c^2$, and a width of $\Gamma = (45^{+18+30}_{-13-13})\,\mathrm{MeV}$, with a 6.5σ statistical significance, and the state was initially called $Z(4430)^\pm$. Due to its non-zero charge, its minimum quark content has to be exotic, i.e. $c\bar{c}u\bar{d}$ or $c\bar{c}d\bar{u}$ according to the charge. Analogously, the BaBar Collaboration searched for the same decay channel, but due to the limited statistics they could put only an upper limit [64], compatible with the Belle observation.

Later, the Belle Collaboration released a new analysis with slightly increased statistics, by performing a full amplitude analysis [65] of the decay $B^0 \to \psi' K^\pm\pi^\mp$, to take account of possible interference between the $Z_c(4430)^\pm$ state and the K^* resonances. Namely, in the full amplitude analysis the signal is not extracted just by fitting the invariant mass distribution, as done in the earlier mentioned analyses, but the amplitude of all the known (and unknown) processes which could lead at the same final states are summed up, taking into account different resonance parametrizations (such as energy-dependent widths), form factors, interference between intermediate states, spin and orbital quantum numbers, and finally used to fit the data. In this way it is possible to separate the contributions from different processes which overlap in the one dimensional distributions, thus to extract also the quantum numbers of unknown states.

In this new work, the mass and width values were found a bit larger (see Fig. 13), and the preferred spin-parity quantum numbers were assigned as $J^P = 1^+$, with a statistical significance over the other possible assignments by at least 3.4σ. However, since no other dataset was available at the time, the confirmation had to wait.

The LHCb Collaboration clarified the situation thanks to a larger data sample which was collected, corresponding to $3\,\mathrm{fb}^{-1}$ of pp collisions data. The available statistics has allowed to perform a four-dimensional model-dependent fit of the decay amplitude including all the known contributions from K^* resonances in order to better describe the data: the obtained values of mass $M_{Z_c(4430)} = (4475 \pm 7^{+15}_{-25})\,\mathrm{MeV}/c^2$ and width $\Gamma_{Z_c(4430)} = (172 \pm 13^{+37}_{-34})\,\mathrm{MeV}$ are compatible and improve the Belle results, and they confirm the existence of the $Z_c(4430)$ state with high (13.9σ) significance; moreover, the LHCb collaboration could also assign unambiguously the spin and parity of the state to $J^P = 1^+$, in agreement to the Belle result [66]. The results of the fit are shown in Fig. 14a.

For the first time in this field, the LHCb experiment studied also the behavior of the Argand diagram, i.e. the representation of the real and the imaginary part of amplitude in a Cartesian plane. In this case, the $M^2(\psi'\pi)$ distribution has been divided into

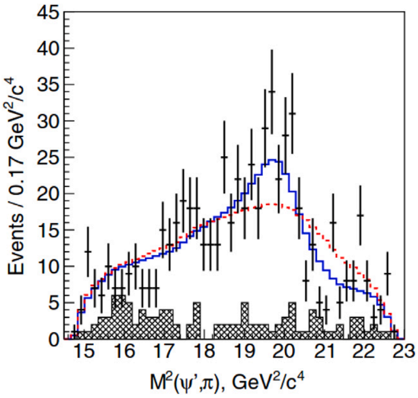

Fig. 13. Projection of the Dalitz plot on the $M^2(\psi'\pi)$ variable, from the full amplitude analysis of Belle experimental data [65]. The fit results are presented with (solid line) and without (dashed line) the $Z_c(4430)$ state with $J^P = 1^+$.

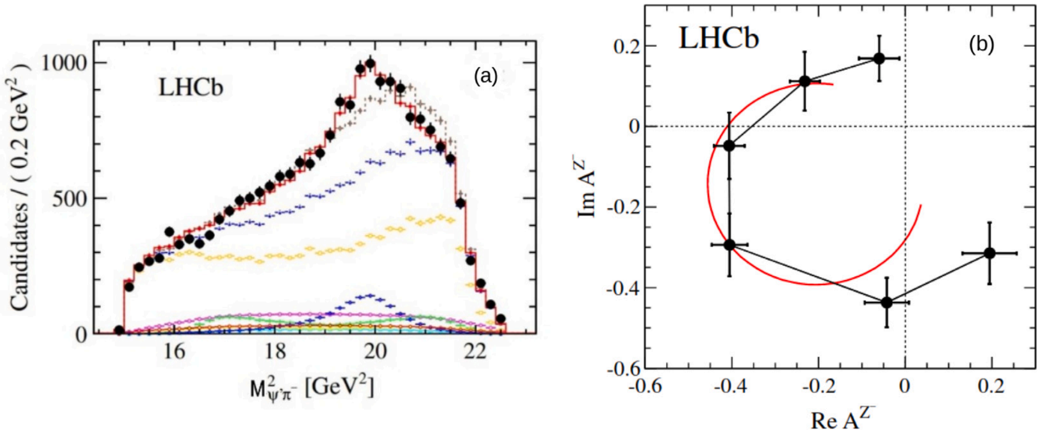

Fig. 14. Results of the 4D amplitude analysis from Ref. [66]. (a) Projection of the amplitude analysis, where the red full line is the sum of all the amplitudes. (b) Argand plot of the $Z_c(4430)$ amplitudes.

six equal intervals around the peak, and the complex amplitude is represented in the Argand diagram of Fig. 14b. All the obtained points travel the space by forming a circle, where the $M^2(\psi'\pi)$ value increases counter-clockwise; this is consistent with a rapid variation of the Z state phase when close to the maximum amplitude, which is a characteristic behavior of a *real* resonance, and excludes that the observed peak could be a kinematical effect [13]. The Argand plot of the $Z_c(4430)$ amplitude is then consistent with a resonant behavior, and it is also the first Argand plot of an exotic charmonium-like state. In the LHCb results, the authors tried also to include an additional Z resonance in the fit, at around 4.24 GeV/c^2 and obtaining a significance of 6σ, but the results from the Argand diagram were not conclusive.

Thanks to the start of the Belle II experiment, the planned upgrade of the LHCb detector, and the recent extension of the maximum center-of-mass energy of the accelerator of the BESIII experiment up to 4.95 GeV, more data will be available to search for the $Z_c(4430)$ in other final states, to help to understand fully its nature.

3.2. The $Z_c(3900)$ state

Before the confirmation of the aforementioned $Z_c(4430)$ by the LHCb Collaboration, another (at least) four-quarks candidate has been discovered, the $Z_c(3900)$ state, and this time confirmed by several experiments.

The BESIII and the Belle Collaborations wanted to understand better the properties of the $Y(4260)$, by studying the $e^+e^- \to \pi^+\pi^- J/\psi(\gamma_{ISR})$, in particular the distribution of the $\pi\pi$ invariant mass. Both discovered a peak in the $\pi^\pm J/\psi$ invariant mass [26,67]. Fig. 15 shows the BESIII and the Belle distributions of the $M(\pi^\pm J/\psi)$ invariant mass. The peak was fit with a Breit–Wigner convoluted with a Gaussian function to take into account the detector resolution. The measured mass and width values were in agreement with each other ($M_{BELLE} = (3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$ and $M_{BESIII} = (3894.5 \pm 6.6 \pm 4.5)\,\mathrm{MeV}/c^2$, $\Gamma_{BELLE} = (46{\pm}10{\pm}20)\,\mathrm{MeV}$ and $\Gamma_{BESIII} = (63{\pm}24{\pm}26)\,\mathrm{MeV}$), and it was assigned the name $Z_c(3900)^\pm$ to this new and charged charmonium-like state. The production rate of the $Z_c(3900)^\pm$ was estimated as $20 - 30\%$ of the total $e^+e^- \to \pi^+\pi^- J/\psi$ cross section.

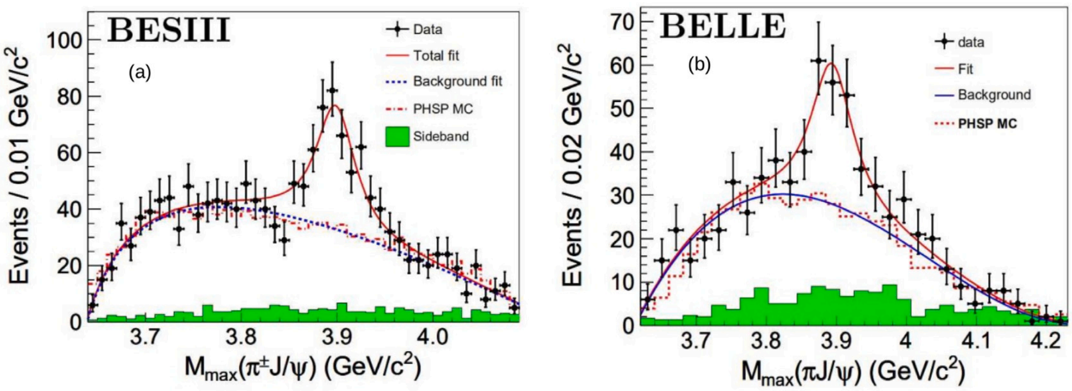

Fig. 15. Discovery plots of the $Z_c(3900)$ in $\pi^{\pm}J/\psi$ invariant mass from the BESIII [26] and the Belle [67] Collaborations on the left and on the right panel, respectively.

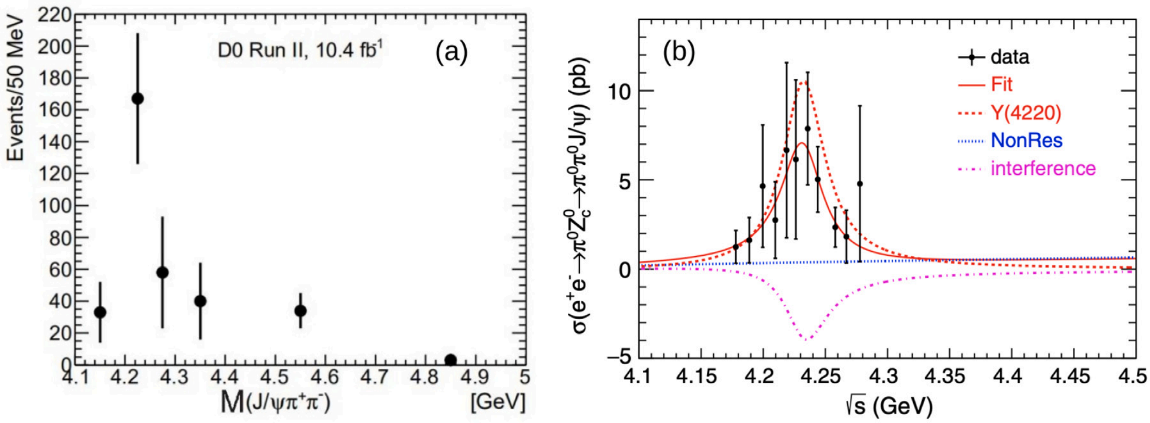

Fig. 16. Possible correlation between the $Z_c(3900)$ and the $Y(4230)$ states. (a) $Z_c(3900)$ signal yield as a function of $M(J/\psi\pi^+\pi^-)$ from D0 data [69]. (b) $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$ cross section as a function of $\sqrt{s}$ from BESIII [33].

The observation of the neutral partner of the $Z_c(3900)^{\pm}$ was reported by the BESIII Collaboration, in the similar decay process $e^+e^- \to \pi^0\pi^0 J/\psi$ [68]. The mass and width values obtained by the fit are $M = (3894.8\pm2.3\pm3.2)\,\mathrm{MeV}/c^2$ and $\Gamma = (29.9\pm8.2\pm8.2)\,\mathrm{MeV}$, respectively, in agreement with the values obtained for the $Z_c(3900)^{\pm}$ state. This leads to the conclusion that the $Z_c(3900)^0$ state is the neutral isospin partner of the $Z_c(3900)^{\pm}$, and this hypothesis is confirmed by the fact that the production rate of the neutral channel ($e^+e^- \to \pi^0 Z_c(3900)^0$) is half of the charged channel ($e^+e^- \to \pi^+ Z_c(3900)^- + c.c.$), as one would expect from isospin symmetry: the $Z_c(3900)$ is an isovector state.

The $Z_c(3900)$ has been observed not only by e^+e^- experiments but also in hadron collisions. Indeed, the D0 experiment has seen evidence of $Z_c(3900) \to \pi^{\pm}J/\psi$ in $p\bar{p}$ collisions at 1.96 TeV, in the analysis of semi-inclusive decays of b-flavored mesons. In this analysis, only part of the decay is reconstructed while the kinematics is used to identify the missing particles. The peak in the $\pi^{\pm}J/\psi$ invariant mass has been observed and fit in six energy bins of $M(J/\psi\pi^+\pi^-)$ [69], and the differential yield is shown in Fig. 16a. A clear enhancement can be observed in correspondence to the $Y(4230)$ invariant mass, while small to no signal can be seen elsewhere. In a similar way, an enhancement in correspondence of the $Y(4230)$ mass has also been found by BESIII, in a more recent analysis of $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$ [33] (Fig. 16b). This may be an indication of a possible correlation between the $Y(4230)$ and the $Z_c(3900)$ states, which could be tested in the future with the coming data from the BESIII, the Belle II and the upgraded LHCb experiments.

Since the mass of the $Z_c(3900)$ resonance lies a few MeV above the $D\bar{D}^*$ threshold, it was natural to search for the decay of this exotic state in open charm final states. The first observation was performed by the BESIII Collaboration, studying the $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp} + c.c.$ process, with single tag selection (only reconstructing the bachelor $\pi^{\pm}$ and one final state D, searching for the missing D^* by four-momentum conservation) [70], and with the double tag method (with full kinematic reconstruction of the events) [71]. In both the analyses the $(D\bar{D}^*)^{\pm}$ invariant mass distribution presented a peak that could be fit: the results have been averaged and the combined pole mass and width values are $(3882.2 \pm 1.1 \pm 1.5)\,\mathrm{MeV}/c^2$ and $(26.5 \pm 1.7 \pm 2.1)\,\mathrm{MeV}$, respectively.

To better understand the nature of the $Z_c(3900)$ state, the authors of Ref. [72] proposed to study the $Z_c \to \rho\eta_c$ decay channel. Indeed, by exploring different hypotheses on the spin–spin interaction between the inner quark pairs, the authors suggested that

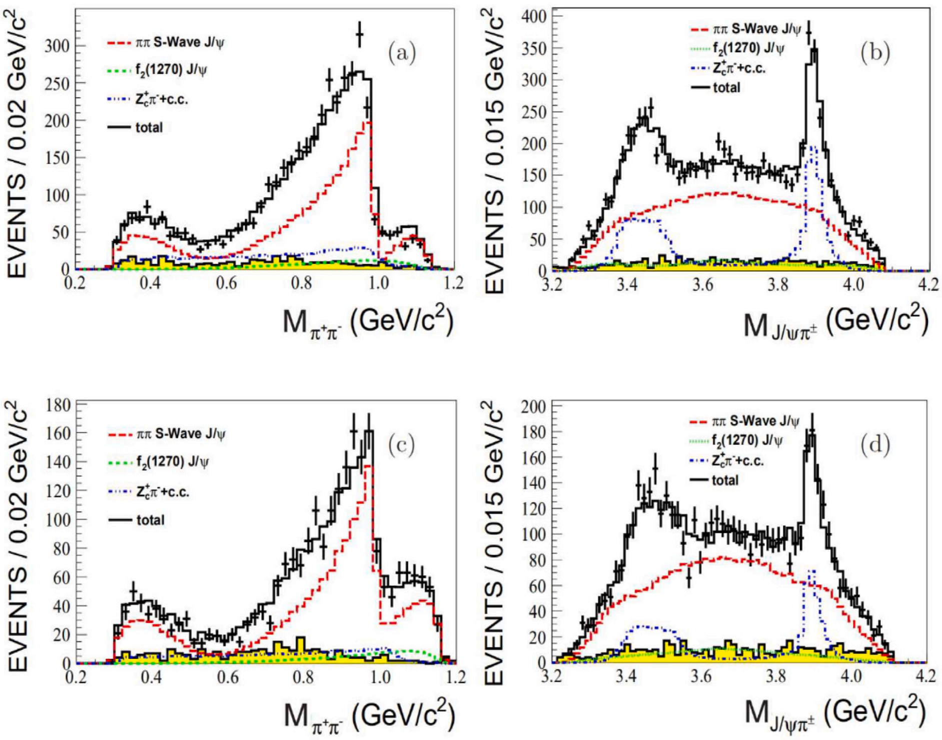

Fig. 17. Results of the partial wave analysis from Ref. [73]. (Top) Results from the 4.23 GeV dataset. (Bottom) Results from the 4.26 GeV dataset. (Left) Projection of the PWA on the $M_{\pi\pi}$ invariant mass. (Right) Projection of the PWA on the $M_{J/\psi\pi}$ invariant mass.

this process is sensitive to how the quarks couple: in a compact tetraquark model, the Z_c states would decay with high probability into $\rho\eta_c$, while in a loosely-bound molecular state this process should be suppressed. The authors estimated the most probable value of the branching fraction ratio between the $Z_c \to \rho\eta_c$ and the $Z_c \to \pi J/\psi$ processes under molecular and tetraquark hypotheses. The BESIII Collaboration has reported the evidence of this decay by studying the process $e^+e^- \to \pi^\mp Z_c(3900)^\pm \to \pi^\mp\rho^\pm\eta_c$ [49], and extracted the ratio $\mathcal{B}[Z_c(3900) \to \rho\eta_c]/\mathcal{B}[Z_c(3900) \to \pi J/\psi] = (2.2 \pm 0.9)$, which favors the compact tetraquark interpretation.

The spin and parity of the $Z_c(3900)$ have been initially measured by studying the angular distribution, pointing preferentially towards $J^P = 1^+$ as quantum numbers over 0^- and 1^- assumptions [70]. Later, the BESIII Collaboration has performed a dedicated partial wave analysis (PWA) [73] on the $e^+e^- \to \pi^+\pi^- J/\psi$ at 4.23 and 4.26 GeV, based on helicity covariant method [74–76]. The $e^+e^- \to \pi^+\pi^- J/\psi$ decay is described by processes involving the intermediate Z_c resonance ($e^+e^- \to Z_c^\pm\pi^\mp$), and without it ($e^+e^- \to RJ/\psi$, where $R = \sigma$, $f_0(980)$, $f_2(1270)$, and $f_0(1370)$). The two data samples were simultaneously fit and the results indicate that the $J^P = 1^+$ assignment is favored by more than 7σ over the other quantum numbers which were tested. The results are shown in Fig. 17. In the analysis, the process could only proceed via $Z_c \to \pi J/\psi$ and $Z_c \to D\bar{D}^*$ decays, but, in principle, other decays are admissible, *e.g.* πh_c, or $\pi\psi(2S)$, that have been already observed. As already mentioned, by the available increasing statistics, it will be possible to expand the knowledge of $Z_c(3900)$ decays and production mechanism and address deeply the structure of this exotic state.

3.3. The Z_{cs} state

Other charged exotic candidates have been observed but are waiting for confirmation from different experiments, which we are not discussing, but among them, it is relevant to note a recent result, which lead to the observation of the first charmonium-like four-quark state with non-zero strangeness, the so-called $Z_{cs}(3985)$.

The BESIII Collaboration has studied the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0) + c.c.$ in center-of-mass energies from 4.628 to 4.698 GeV [61], and an excess in the recoil mass of $K^\pm$ has been observed at $\sqrt{s} = 4.681$ GeV, as shown in Fig. 18, and explained it as a new charged state, the $Z_{cs}(3985)$, which decays into a charged strange-charmed meson plus a neutral charmed meson, i.e. $D_s^- D^{*0} + D_s^{*-} D^0$. The fit with a Breit–Wigner shape lead to the determination of a pole mass as $(3982.5^{+1.8}_{-2.6} \pm 2.1)\,\mathrm{MeV}/c^2$ and width as $(12.8^{+5.3}_{-4.4} \pm 3.0)\,\mathrm{MeV}$.

The existence of a candidate tetraquark with non-zero strangeness was predicted by many theoretical models, but no definitive experimental observations have been reported so far. It is interesting to note that the peak is more pronounced at the energy of $\sqrt{s} = 4.681\,\mathrm{GeV}$, and less at lower and higher energies; this could bring the idea that something "exotic" is happening around

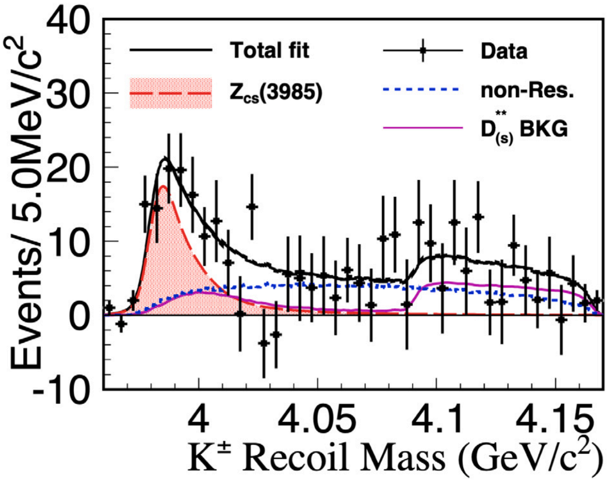

Fig. 18. The K^+ recoil-mass spectrum in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ data at $\sqrt{s} = 4.681$ GeV after subtraction of the combinatorial background [61].

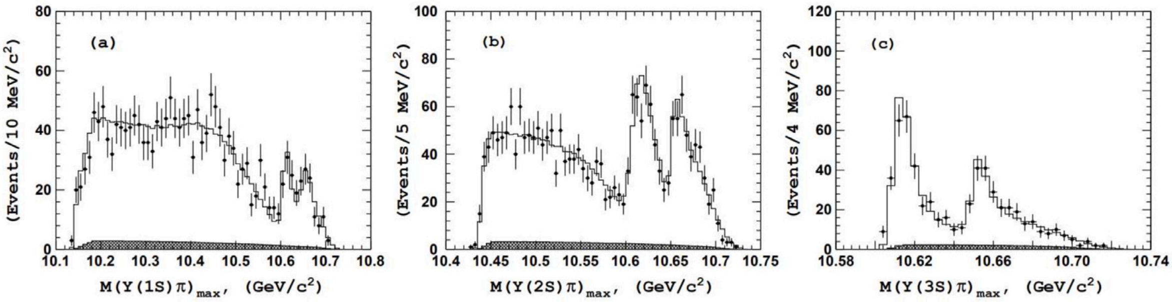

Fig. 19. Experimental invariant mass distributions (points with error bars) and fit results (open histogram) for (a) $\Upsilon(1S)\pi$, (b) $\Upsilon(2S)\pi$, (c) $\Upsilon(3S)\pi$ [77].

this energy value, but only more data will allow to fully characterize the Z_{cs}, understand the production mechanism, its quantum numbers, and maybe find a possible neutral counterpart.

Analogously, also LHCb reported a Z_{cs} candidate in the process $J/\psi K^+$ and $J/\psi\phi$ [62], and we believe this topic will be extensively studied in the near future.

3.4. The Z_b states in the bottomonium spectrum

The golden tool to search for non-conventional states in the charmonium region has been the study of the channels involving a charmonium state and a pion pair in the final state. The same was done by the Belle Collaboration, taking data at the $\Upsilon(5S)$ energy and studying the decays $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$, with $n = 1,2,3$ [77,78], and $\Upsilon(5S) \to \pi^+\pi^- h_b(mP)$, with $m = 1,2$ [78]. In both these processes, excesses at 10.61 and 10.65 GeV were observed in $\Upsilon(nS)\pi^\pm$ invariant mass distributions (see Fig. 19), and in the recoiling mass against a single charged pion in the h_b channel. These peaks were pointing to the existence of charged states with a $b\bar{b}$ content, which could be explained only by at least four constituent quarks, and they were named $Z_b(10610)$ and $Z_b(10650)$ following the naming scheme of the analogues in the charmonium spectrum.

Later, using the same dataset, the Belle experiment has also reported the observation of the neutral partner, the $Z_b(10610)^0$, in the processes $\Upsilon(5S) \to \pi^0\pi^0\Upsilon(nS)$ [79], while, due to the limited statistics, no evidence of $Z_b(10650)^0$ was found. This important result demonstrates that also the $Z_b(10610)$ state can be interpreted as an isospin triplet, as already seen for the $Z_c(3900)$.

Since the $Z_c(3900)$ state has been measured also in the $D\bar{D}^*$ decay channel, the open-bottom decay of the Z_b counterpart is expected: this measurement could give hints on a possible $B\bar{B}$ molecular structure. Using the full dataset taken at the $\Upsilon(5S)$ resonance, the Belle Collaboration reported the observation of the three-body $\Upsilon(5S) \to B\bar{B}^*\pi^\pm$ and $\Upsilon(5S) \to B^*\bar{B}^*\pi^\pm$ decays [80]. In Fig. 20 the missing mass distributions of the non-B pion is shown, for the $B\bar{B}^*\pi$ (a) and $B^*\bar{B}^*\pi$ (b) channels, together with the fits including the $Z_b(10610)$ and the $Z_b(10650)$ amplitudes. Interestingly, only the $Z_b(10610)$ is found as enhancement in $B\bar{B}^*$ signal, where substantially no evidence of $Z_b(10650)$ is found. The $Z_b(10650)$ signal is found instead in the $B^*\bar{B}^*$ invariant mass. Their present mass and width in the PDG are listed as the following: for the isospin triplet $Z_b(10610)$, the charged $Z_b(10610)^\pm$ as $M = (10607 \pm 2)\,\mathrm{MeV}/c^2$, $\Gamma = (18.4 \pm 2.4)\,\mathrm{MeV}$, and the neutral $Z_b(10610)^0$ as $M = (10609 \pm 4 \pm 4)\,\mathrm{MeV}/c^2$ (no width has been

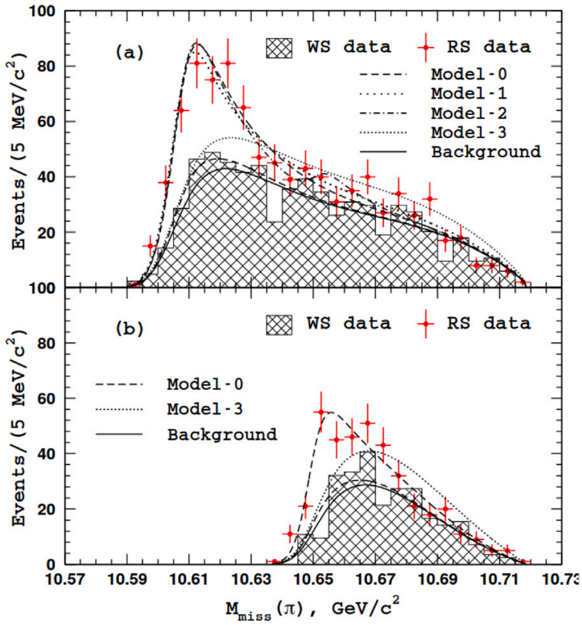

Fig. 20. Distributions of $M_{\text{miss}}(\pi)$ for the $B\bar{B}^{*}\pi$ (a) and $B^{*}\bar{B}^{*}\pi$ (b) candidates, showing the peaks associated to the two Z_b states [80].

estimated for the $Z_b(10610)^0$); for the $Z_b(10650)^{\pm}$, whose neutral partner has not yet been observed, $M = (10652.2 \pm 1.5)\,\text{MeV}/c^2$, $\Gamma = (11.5 \pm 2.2)\,\text{MeV}$.

These values are just above the open bottom threshold, but more accurate analyses [81,82] suggest that the real pole could be below BB^{*} threshold for the $Z_b(10610)$ (hinting at a molecular structure), and just above the $B^{*}B^{*}$ one for the $Z_b(10650)$. Moreover, both states have assigned $J^{PC} = 1^{+-}$ quantum numbers, but they require confirmation by further analyses. This will be possible within a few years with the incoming Belle II and LHCb data.

4. The $X(3872)$: a portal to understand the nature of exotics

Being the first discovered state, the $X(3872)$ is the most studied of the XYZ family. Due to a large number of final states and production techniques in which it has been observed, the $X(3872)$ is the perfect candidate to understand the approaches which were developed to study the nature (or the many natures) of the exotic states. In the following, we are trying to recall the most interesting results and the information which followed about its nature.

The $X(3872)$ has been established in e^+e^- collisions at the charmonium energies, in B-meson decays from the B-factories, in pp collisions at LHC but also in $p\bar{p}$ collisions at Tevatron. So far, the most precise channel to measure its mass has been the $X(3872) \to \pi^+\pi^- J/\psi$ decay, and the PDG [13] reports an average mass value of $M_{X(3872)} = (3871.65 \pm 0.06)\,\text{MeV}/c^2$, very close to DD^{*} threshold $(M_{D^0} + M_{D^{*0}}) = (3871.69 \pm 0.07)\,\text{MeV}/c^2$; indeed, the mass difference is so small that it is not yet established whether the mass is below or above the open charm threshold, opening to different interpretations about its nature.

There is consensus that the $X(3872)$ quantum numbers are $J^{PC} = 1^{++}$, as recently measured by the LHCb Collaboration [83]. Accordingly, the PDG has assigned the name $\chi_{c1}(3872)$, following the naming scheme derived by the quark model, but the $X(3872)$ cannot be identified as the predicted $\chi'_{c1}(2^3P_1)$ since its mass should be about 100 MeV/c^2 higher [84].

Despite the many measurements of the $X(3872)$ mass, its width is still not well determined and the PDG declared only an upper limit of $\Gamma < 1.2\,\text{MeV}$ until not long ago. Recently, the LHCb Collaboration reported a study of the line shape in order to better determine the width. At first, they parametrized the $X(3872)$ line shape as a pure Breit–Wigner, obtaining a value of $\Gamma_{BW} = (1.39 \pm 0.24 \pm 0.10)\,\text{MeV}$. Considering that $|M_{D^0} + M_{\bar{D}^{*0}} - M_{X(3872)}| < \Gamma_{BW}$, the proximity of the $X(3872)$ mass to the $D^0\bar{D}^{*0}$ threshold distorts its line shape and a simple Breit–Wigner cannot be a good description. Therefore, they used the Flatté parametrization [85] to take into account the coupling to the $D^0\bar{D}^{*0}$ channel. The obtained width is significantly smaller, $\text{FWHM} = (0.22^{+0.06+0.25}_{-0.08-0.17})\,\text{MeV}$, but by folding with the detector resolution leads to a line shape similar to the Breit–Wigner folded one.

Even if the PDG is now averaging the values from Breit–Wigner parametrizations, indicating a value of $\Gamma_{X(3872)} = (1.19 \pm 0.21)\,\text{MeV}$ [13], the debate is not yet finished. In the future, the $\bar{\text{P}}$ANDA experiment will profit from the $X(3872)$ formation allowed in $p\bar{p}$ collisions and will measure with higher precision the line shape performing an energy scan around the mass peak.

Due to its proximity to the $D^0\bar{D}^{*0}$ threshold, a natural explanation of this state could be a 1^{++} $D\bar{D}^{*}$ molecule, in analogy with the deuteron. Indeed, as a loosely bound meson pair, it should have a large spatial size, and the probability that the two D mesons

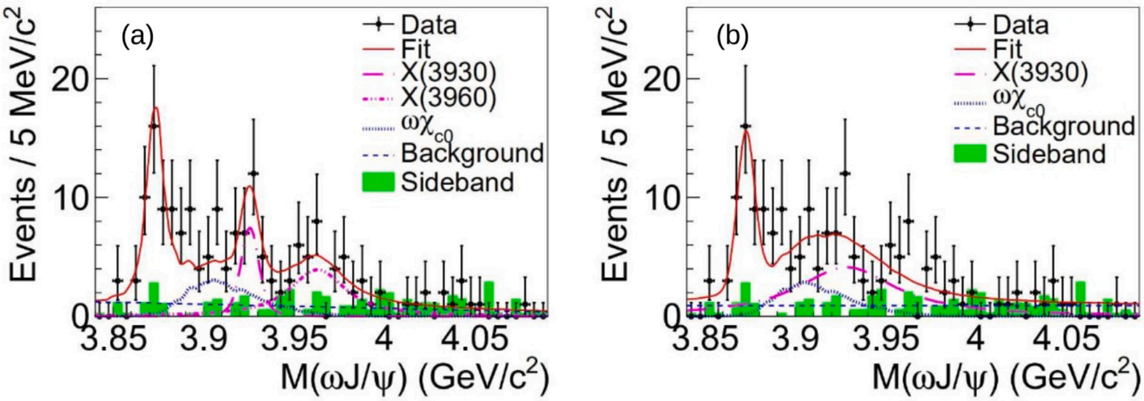

Fig. 21. The $\omega J/\psi$ invariant mass distribution from BESIII data [87]. (a) Results of the fit hypothesis with the $X(3872)$ state and two additional narrow states; (b) results of the fit with the $X(3872)$ and only one additional wide state.

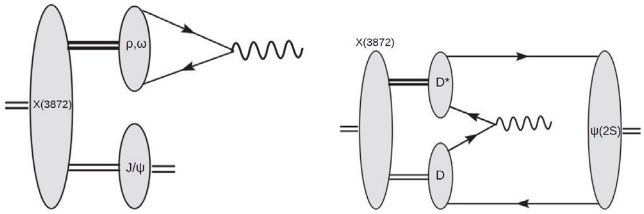

Fig. 22. Phenomenological models to explain $X(3872)$ radiative decays [91]. (a) Vector Meson Dominance: a light vector meson in the upper part of the diagram fluctuates into the radiative photon in the $X(3872) \rightarrow J/\psi\gamma$ decay. (b) Light Quark Annihilation: the light quarks of the $D^{(*)}$ mesons annihilate to form the radiative photon while the remaining $c\bar{c}$ pair forms the charmonium state, in the suppressed $X(3872) \rightarrow \psi(2S)\gamma$ decay.

annihilate to other hadrons is expected to be small: the decay into J/ψ would be preferable than into light hadrons, due to the OZI rule. This could explain the narrow width which has been measured. Moreover, the $X(3872)$ mass is close (within errors) to the $D^0\bar{D}^{*0}$ threshold, while the D^+D^{*-} threshold is 8.1 MeV higher, thus the latter is closed by phase-space; this should lead to potential isospin breaking in the wave functions [86].

The first hints of the isospin-violating nature of $X(3872)$ come from the observation of both the $\pi\pi J/\psi$ and also the $\pi\pi\pi J/\psi$ [87] final states, with the pions resonating in ρ and ω states respectively, with similar branching fractions. Fig. 21 shows the results of the latter measurement. A clear signal can be seen together with at least another resonance, whose existence is not confirmed yet. The $\omega J/\psi$ decay has been searched also by the Belle and the BaBar Collaborations in B decays, and claims of evidence of the transition have been reported in Ref. [88] and Ref. [89], respectively. Alternatively, a tetraquark hypothesis $cq\bar{c}\bar{q}'$ for the $X(3872)$ is not completely ruled out [90], but no charged partner of this state has been observed.

The study of radiative transitions can be a valid tool to understand the nature of the state. In a molecular model, the $X(3872)$ radiative transitions can proceed through Vector Meson Dominance (VMD) or through Light Quark Annihilation (LQA) models. Fig. 22 shows the diagrams of the two phenomenological models. VMD model was developed in the 60 s, before the success of QCD, to explain the interaction between photons and hadrons; in the model, the photon is a superposition of a pure electromagnetic component and of a vector meson components (*e.g.* the ρ, ω, ϕ), and a photon–hadron interaction can be described with the exchange of such mesons. Conversely, LQA model parametrizes an annihilation of two light quarks belonging to two different hadrons to form a photon. In the decay of $X(3872) \rightarrow \gamma J/\psi$ the VMD mainly contributes, while the decay $X(3872) \rightarrow \gamma\psi(2S)$ proceeds via the LQA and it should be suppressed [91].

The process $X(3872) \rightarrow \gamma J/\psi$ has been observed by Belle [92] and LHCb [93], while BaBar reported only an evidence [94]; instead, the measurements of the decay $X(3872) \rightarrow \gamma\psi(2S)$ have some tension. The BaBar Collaboration has reported evidence of the decay $X(3872) \rightarrow \gamma\psi(2S)$ with significance of 3.5σ [94], and measured a ratio $R = [\mathcal{B}[X(3872) \rightarrow \gamma\psi(2S)]/\mathcal{B}[X(3872) \rightarrow \gamma J/\psi] = 3.4 \pm 1.4$; this large value is generally inconsistent with a pure molecular interpretation of the $X(3872)$ state. The LHCb Collaboration has measured the same decay with significance 4.4σ, and obtained a ratio $R = (2.46 \pm 0.64 \pm 0.29)$ [93], substantially in agreement with BaBar measurement but with much higher precision; even in this study, the results disagree with the $D\bar{D}^*$ molecular interpretation, but they support a pure charmonium interpretation, or even a mixture of charmonium and molecule. Quite the opposite, Belle has not observed the transition [92], and set an upper limit for $R < 2.1$ (at 90% C.L.); in this case the $X(3872)$ may not have a large $c\bar{c}$ mixture with a $D^0\bar{D}^{*0}$ molecule. Authors of Ref. [4] calculated the expected ratio R combining all the available measurements $R = (2.31 \pm 0.57)$, without considering any correlation effect. More data will be useful to finalize the measurement of the radiative transitions and bring more insight.

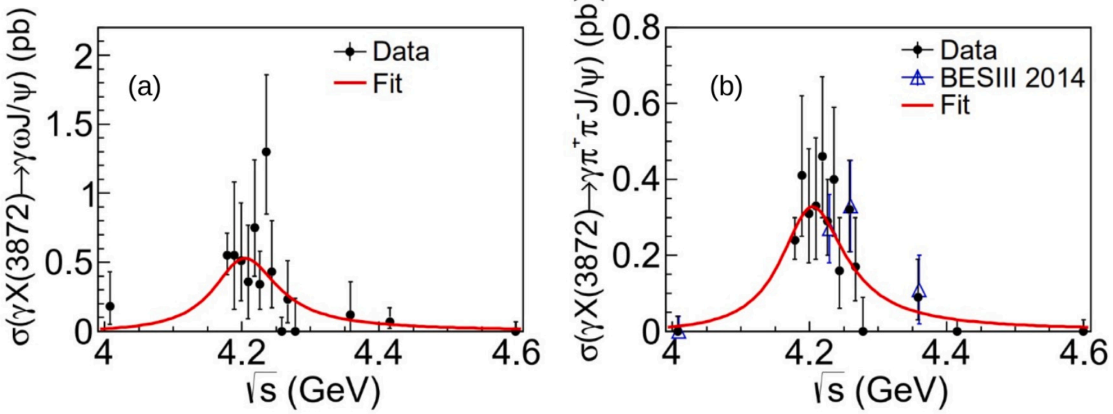

Fig. 23. The measured cross section of the processes $e^+e^- \to \gamma X(3872)$: (a) $X(3872) \to \gamma\omega J/\psi$ and (b) $X(3872) \to \gamma\pi\pi J/\psi$. The line shapes are fit simultaneously by a single Breit–Wigner resonance, hinting that the radiative transition $Y(4230) \to \gamma X(3872)$ could take place [87].

Different models suggested to study pionic transitions to the χ_{cJ} states to distinguish between different interpretations: in a conventional $c\bar{c}$ state the transitions to χ_{cJ} should be very small, while in a tetraquark or molecular state these transitions should be sizable [95–97]. The BESIII Collaboration has reported the observation of the process $X(3872) \to \pi^0\chi_{c1} \to \gamma J/\psi$ with 5.2σ significance by studying the process $e^+e^- \to \gamma X(3872)$ [98], measuring also the process $X(3872) \to \pi^+\pi^- J/\psi$ as normalization channel to reduce the systematical uncertainties. The measured value $R_{\chi_{cJ}} = \frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} = (0.88^{+0.33}_{-0.27} \pm 0.10)$ contradicts the interpretation of the $X(3872)$ as a conventional charmonium; in the same publication, upper limits for the transition to χ_{c0} and χ_{c2} were set.

More importantly, the BESIII Collaboration has reported that in e^+e^- collisions the $X(3872)$ can be produced only in the energy region between 4.15 and 4.30 GeV. This has led to the suggestion that there may be a direct connection between the $Y(4230)$ state, which peaks in the aforementioned region, and the $X(3872)$. This connection has been hinted also in the study of the process $e^+e^- \to \gamma\omega J/\psi$ [87], which has already been mentioned in the isospin-violation discussion. The measured cross section distributions are represented in Fig. 23a and Fig. 23b, with $\gamma\omega J/\psi$ and $\gamma\pi\pi J/\psi$ as final states, respectively. Both the distributions peak around 4.2 GeV: by simultaneously fitting the line shape, a mass value $\mathrm{M} = (4200.6^{+7.9}_{-13.3})\ \mathrm{MeV}/c^2$ and width $\Gamma = (115^{+38}_{-26}\pm 12)$ MeV were extracted, compatible with both $Y(4230)$ and $\psi(4160)$ resonances. If the contribution from $Y(4230)$ will be confirmed, this will demonstrate possible connections between the exotic states $X(3872)$, $Z_c(3900)$, and $Y(4230)$, hinting at a common underlying nature. At the moment, more data are needed to establish the connections.

More exclusive measurements were reported by BESIII to try to pin down theoretical models; the observation of the $X(3872) \to D^{*0}\bar{D}^0 + c.c.$ process has been reported with a statistical significance of 7.4σ, but no evidence for $X(3872) \to \gamma D^+ D^-$ has been found [99].

By combining all the known measurements, authors of Ref. [100] estimated for the first time the absolute branching fraction of the $X(3872)$ decays and found that, at present time, roughly the 31.9% of the total branching fraction remains unseen. Indeed, from the experimental point of view, there is still a lot to do. A large number of production mechanisms favor the studies by different experiments and with different approaches. Indeed, the $X(3872)$ state has been observed in B meson decays, possibly in radiative transitions from the $Y(4230)$ state, but also in the process $\Lambda_b^0 \to X(3872)pK^-$, $X(3872) \to J/\psi\pi^+\pi^-$ [101], as well as with prompt production at pp and $p\bar{p}$ colliders. The current generation of accelerators and experiments, combining high precision with continuously increasing luminosity, will shed new light on the nature of the $X(3872)$, as well as on the other exotic candidates.

5. Summary and outlook

The path for understanding the XYZ states has been drawn. Since the first observation in 2003 of the $X(3872)$, a large number of exotic XYZ states has been observed in the charmonium and the bottomonium sectors, and the discovery potential remains quite high. These states cannot be interpreted by a quark model based only on $c\bar{c}$ or $b\bar{b}$ systems, but they hint at the existence of new kinds of hadrons, which we call *exotics*, with a different underlying nature.

The effort is global, with several competitors and a huge interplay between them: the BESIII Collaboration is continuously acquiring data in the charmonium sector, and is planning several upgrades to increase luminosity and detector performances; the Belle II experiment has recently started taking data, and in a couple of years will overtake the statistics of the first generation B-factories; the LHCb Run-2 data are not yet fully analyzed, and soon there will be Run-3 data available; the P̄ANDA experiment will start in the next years to provide an alternative way to search for these states by $p\bar{p}$ formation, and different projects on super τ-charm factories are under planning for the upcoming future.

After almost twenty years of studies, our understanding of this sector has increased, but there are still many open questions. The $X(3872)$ is the most studied exotic candidate: its mass has been measured, but the width is not yet well set; its quantum numbers are known, several decay modes have been measured, and it has been seen in many different production mechanisms, but so far a unique interpretation of its nature has not emerged. The once believed $Y(4260)$ resonance is, in reality, a combination of two states, one at mass around 4.22 GeV/c^2 and one at higher mass values, tentatively identifiable at 4.39 GeV/c^2, and together with all the other (and less studied) vectorial exotic candidates its inner structure remains under debate. The discovery of Z_c states demonstrated the existence of at least four-quark states, which could be interpreted as a new tetraquark octet, compared to the conventional meson octet to extend the quark model. Moreover, from the available data, it is possible to identify connections between the $Y(4230)$ state and other two exotic states: a radiative transition to the $X(3872)$ and a hadronic transition to the $Z_c(3900)$. This may indicate that there is a common inner structure between these exotic states, and that could make the process $e^+e^- \to Y(4230)$ the golden tool to probe this world, as an exotic factory.

Finally, by understanding the nature of these states the knowledge of Quantum Chromodynamics will increase: the proposed models may be useful to get an insight on its non-perturbative regime, providing a key in understanding how the hadrons bind together. The new alphabet of particle physics will guide us towards an improved vision of the strong interaction and its confined properties.

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References

[1] S.L. Olsen, T. Skwarnicki, D. Zieminska, Nonstandard heavy mesons and baryons: Experimental evidence, Rev. Modern Phys. 90 (2018) 015003.
[2] T. Barnes, S. Godfrey, E.S. Swanson, Higher charmonia, Phys. Rev. D 72 (2005) 054026.
[3] S.-K. Choi, et al., The Belle Collaboration, Observation of a narrow charmoniumlike state in exclusive $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ Decays, Phys. Rev. Lett. 91 (2003) 262001.
[4] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C.E. Thomas, A. Vairo, C.-Z. Yuan, The XYZ states: Experimental and theoretical status and perspectives, Phys. Rep. 873 (2020) 1–154.
[5] J. Aubert, et al., Experimental observation of a heavy particle J, Phys. Rev. Lett. 33 (1974) 1404–1406.
[6] J. Augustin, et al., Discovery of a narrow resonance in e^+e^- annihilation, Phys. Rev. Lett. 33 (1974) 1406–1408.
[7] S. Herb, et al., Observation of a dimuon resonance at 9.5 GeV in 400-GeV proton-nucleus collisions, Phys. Rev. Lett. 39 (1977) 252.
[8] W. Caswell, G. Lepage, Effective lagrangians for bound state problems in QED, QCD, and other field theories, Phys. Lett. B 167 (4) (1986) 437–442.
[9] E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, T.M. Yan, Charmonium: The model, Phys. Rev. D 17 (1978) 3090–3117.
[10] E. Eichten, K. Gottfried, T. Kinoshita, K.D. Lane, T.M. Yan, Erratum: Charmonium: The model, Phys. Rev. D 21 (1980) 313.
[11] A. Vairo, Non-relativistic bound states: the long way back from the bethe-salpeter to the schroedinger equation, 2009, arXiv:hep-ex/0902.3346.
[12] E.J. Eichten, K. Lane, C. Quigg, B-Meson gateways to missing charmonium levels, Phys. Rev. Lett. 89 (2002) 162002.
[13] P. Zyla, et al., Particle Data Group Collaboration, Review of particle physics, Prog. Theor. Exp. Phys. 2020 (8) (2020) 083C01 and 2021 update.
[14] R. Aaij, et al., LHCb Collaboration, Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays, Phys. Rev. Lett. 115 (2015) 072001.
[15] B. Aubert, et al., The BaBar detector, Nucl. Instrum. Methods Phys. Res. A 479 (1) (2002) 1–116, Detectors for Asymmetric B-factories.
[16] B. Aubert, et al., The BaBar detector: Upgrades, operation and performance, Nucl. Instrum. Methods Phys. Res. A 729 (2013) 615–701.
[17] A. Abashian, et al., The Belle detector, Nucl. Instrum. Methods Phys. Res. A 479 (1) (2002) 117–232, Detectors for Asymmetric B-factories.
[18] Y. Kubota, et al., CLEO Collaboration, The CLEO II detector, Nucl. Instrum. Methods Phys. Res. A 320 (1) (1992) 66–113.
[19] D. Peterson, et al., The CLEO III drift chamber, Nucl. Instrum. Methods Phys. Res. A 478 (1) (2002) 142–146, Proceedings of the ninth Int.Conf. on Instrumentation.
[20] M. Ablikim, et al., Design and construction of the BESIII detector, Nucl. Instrum. Methods Phys. Res. A 614 (3) (2010) 345–399.
[21] B. Aubert, et al., Babar Collaboration, Observation of a broad structure in the $\pi^+\pi^- J/\psi$ Mass Spectrum around $4.26\mathrm{GeV}/c^2$, Phys. Rev. Lett. 95 (2005) 142001.
[22] C.-Z. Yuan, et al., Belle Collaboration, Measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section via initial-state radiation at belle, Phys. Rev. Lett. 99 (2007) 182004.
[23] G. Garzoglio, et al., E835 Collaboration, Experiment e835 at Fermilab, Nucl. Instrum. Methods Phys. Res. A 519 (3) (2004) 558–609.
[24] G. Barucca, et al., PANDA Collaboration, PANDA Phase one, 2021, arXiv:hep-ex/2101.11877.
[25] S.-K. Choi, et al., Belle Collaboration, Observation of a resonance-like structure in the $\pi^\pm\psi'$ mass distribution in $B \to K\pi^\pm\psi'$ decays, Phys. Rev. Lett. 100 (2008) 142001.
[26] M. Ablikim, et al., BESIII Collaboration, Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV, Phys. Rev. Lett. 110 (2013) 252001.
[27] The LHCb collaboration, et al., The LHCb detector at the LHC, J. Instrum. 3 (08) (2008) S08005.
[28] T.E. Coan, et al., CLEO Collaboration, Charmonium decays of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$, Phys. Rev. Lett. 96 (2006) 162003.
[29] N. Brambilla, et al., Heavy quarkonium: progress, puzzles, and opportunities, Eur. Phys. J. C 71 (2011) 1534.
[30] P. Guo, T. Yépez-Martínez, A.P. Szczepaniak, Charmonium meson and hybrid radiative transitions, Phys. Rev. D 89 (2014) 116005.
[31] L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, $Z(4430)$ and a new paradigm for spin interactions in tetraquarks, Phys. Rev. D 89 (2014) 114010.
[32] M. Ablikim, et al., BESIII Collaboration, Precise measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at center of mass energies from 3.77 to 4.60 GeV, Phys. Rev. Lett. 118 (2017) 092001.
[33] M. Ablikim, et al., BESIII Collaboration, Study of the process $e^+e^- \to \pi^0\pi^0 J/\psi$ and neutral charmoniumlike state $Z_c(3900)^0$, Phys. Rev. D 102 (2020) 012009.
[34] M. Ablikim, et al., BESIII Collaboration, Study of $e^+e^- \to \omega\chi_{cJ}$ at center of mass energies from 4.21 to 4.42 GeV, Phys. Rev. Lett. 114 (2015) 092003.
[35] X.L. Wang, et al., Belle Collaboration, Measurement of $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial state radiation at belle, Phys. Rev. D 91 (2015) 112007.
[36] J.P. Lees, et al., BaBar Collaboration, Study of the reaction $e^+e^- \to \psi(2S)\pi^+\pi^-$ via initial-state radiation at babar, Phys. Rev. D 89 (2014) 111103.

[37] M. Ablikim, et al., BESIII Collaboration, Measurement of $e^+e^-\to\pi^+\pi^-\psi(3686)$ from 4.008 to 4.600 GeV and observation of a charged structure in the $\pi^\pm\psi(3686)$ mass spectrum, Phys. Rev. D 96 (2017) 032004.
[38] M. Ablikim, et al., BESIII Collaboration, Evidence of two resonant structures in $e^+e^-\to\pi^+\pi^-h_c$, Phys. Rev. Lett. 118 (2017) 092002.
[39] G. Pakhlova, et al., Belle Collaboration, Measurement of the $e^+e^-\to D^0D^{*-}\pi^+$ cross section using initial-state radiation, Phys. Rev. D 80 (2009) 091101.
[40] M. Ablikim, et al., BESIII Collaboration, Evidence of a resonant structure in the $e^+e^-\to\pi^+D^0D^{*-}$ cross section between 4.05 and 4.60 gev, Phys. Rev. Lett. 122 (2019) 102002.
[41] M. Ablikim, et al., BESIII Collaboration, Observation of the $Y(4220)$ and $Y(4390)$ in the process $e^+e^-\to\eta J/\psi$, Phys. Rev. D 102 (2020) 031101.
[42] X.L. Wang, et al., Belle Collaboration, Observation of $\psi(4040)$ and $\psi(4160)$ decay into $\eta J/\psi$, Phys. Rev. D 87 (2013) 051101.
[43] T.E. Coan, et al., CLEO Collaboration, Charmonium decays of $Y(4260)$, $\psi(4160)$, and $\psi(4040)$, Phys. Rev. Lett. 96 (2006) 162003.
[44] M. Ablikim, et al., BESIII Collaboration, Observation of $e^+e^-\to\eta J/\psi$ at center-of-mass energy $\sqrt{s}=4.009\,\mathrm{GeV}$, Phys. Rev. D 86 (2012) 071101.
[45] M. Ablikim, et al., BESIII Collaboration, Observation of $e^+e^-\to\eta' J/\psi$ at center-of-mass energies between 4.189 and 4.600 GeV, Phys. Rev. D 94 (2016) 032009.
[46] M. Tanabashi, et al., Particle Data Group, Review of particle physics, Phys. Rev. D 98 (2018) 030001.
[47] M. Ablikim, et al., BESIII Collaboration, Cross section measurements of $e^+e^-\to\omega\chi_{c0}$ from $\sqrt{s}=4.178$ to 4.278 GeV, Phys. Rev. D 99 (2019) 091103.
[48] M. Ablikim, et al., BESIII Collaboration, Measurements of $e^+e^-\to\eta_c\pi^+\pi^-\pi^0$, $\eta_c\pi^+\pi^-$, and $\eta_c\pi^0\gamma$ at $\sqrt{s}$ from 4.18 to 4.60 GeV, and search for a Z_c state close to the $D\overline{D}$ threshold decaying to $\eta_c\pi$ at $\sqrt{s}=4.23\,\mathrm{GeV}$, Phys. Rev. D 103 (2021) 032006.
[49] M. Ablikim, et al., BESIII Collaboration, Study of $e^+e^-\to\pi^+\pi^-\pi^0\eta_c$ and evidence for $\mathrm{Z_c}(3900)^\pm$ decaying into $\rho^\pm\eta_c$, Phys. Rev. D 100 (2019) 111102.
[50] M. Ablikim, et al., BESIII Collaboration, Cross section measurement of $e^+e^-\to\eta' J/\psi$ from $\sqrt{s}=4.178$ to 4.600 GeV, Phys. Rev. D 101 (2020) 012008.
[51] B. Aubert, et al., BaBar Collaboration, Evidence of a broad structure at an invariant mass of 4.32 GeV/c^2 in the Reaction $e^+e^-\to\pi^+\pi^-\psi(2S)$ measured at BaBar, Phys. Rev. Lett. 98 (2007) 212001.
[52] X. Wang, et al., Belle Collaboration, Observation of two resonant structures in $e^+e^-\to\pi^+\pi^-\psi(2S)$ via Initial-State Radiation at Belle, Phys. Rev. Lett. 99 (2007) 142002.
[53] G. Pakhlova, et al., Belle Collaboration, Observation of a near-threshold enhancement in the $e^+e^-\to\Lambda_c^+\Lambda_c^-$ cross section using initial-state radiation, Phys. Rev. Lett. 101 (2008) 172001.
[54] M. Ablikim, et al., BESIII Collaboration, Precision measurement of the $e^+e^-\to\Lambda_c^+\overline{\Lambda_c^-}$ cross section near threshold, Phys. Rev. Lett. 120 (2018) 132001.
[55] Y.B. Li, et al., Belle Collaboration, Observation of $\Xi_c(2939)^0$ and updated measurement of $B^-\to K^-\Lambda_c^+\bar{\Lambda}_c^-$ at Belle, Eur. Phys. J. C 78 (3) (2018) 252.
[56] Y.B. Li, et al., Belle Collaboration, Evidence of a structure in $\bar{K}^0\Lambda_c^+$ consistent with a charged $\Xi_c(2930)^+$ and updated measurements of $\bar{B}^0\to K^0\Lambda_c^+\bar{\Lambda}_c^-$ at Belle, Eur. Phys. J. C 78 (11) (2018) 928.
[57] M. Ablikim, et al., BESIII Collaboration, Future physics programme of BESIII, Chin. Phys. C 44 (4) (2020) 040001.
[58] D. Santel, et al., Belle Collaboration, Measurements of the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances via $\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)$, Phys. Rev. D 93 (2016) 011101.
[59] R. Mizuk, et al., Belle Collaboration, Observation of a new structure near 10.75 GeV in the energy dependence of the $e^+e^-\to\Upsilon(nS)\pi^+\pi^-$ $n=1,2,3$ cross sections, J. High Energy Phys. 2019 (10) (2019) 220.
[60] R. Aaij, et al., LHCb Collaboration, Observation of the resonant character of the $mathrmZ(4430)^-$ State, Phys. Rev. Lett. 112 (2014) 222002.
[61] M. Ablikim, et al., BESIII Collaboration, Observation of a near-threshold structure in the K^+ recoil-mass spectra in $e^+e^-\to K^+(D_s^-D^{*0}+D_s^{*-}D^0)$, Phys. Rev. Lett. 126 (2021) 102001.
[62] R. Aaij, et al., LHCb Collaboration, Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$, 2021, arXiv:hep-ex/2103.01803.
[63] S. Dubynskiy, M. Voloshin, Hadro-charmonium, Phys. Lett. B 666 (4) (2008) 344–346.
[64] B. Aubert, et al., BaBar Collaboration, Search for the $Z(4430)^-$ at Babar, Phys. Rev. D 79 (2009) 112001.
[65] K. Chilikin, et al., Belle Collaboration, Experimental constraints on the spin and parity of the $\mathrm{Z}(4430)^+$, Phys. Rev. D 88 (2013) 074026.
[66] R. Aaij, et al., LHCb Collaboration, Observation of the resonant character of the $Z(4430)^-$ state, Phys. Rev. Lett. 112 (2014) 222002.
[67] Z.Q. Liu, et al., Belle Collaboration, Study of $e^+e^-\to\pi^+\pi^-J/\psi$ and observation of a charged charmoniumlike state at belle, Phys. Rev. Lett. 110 (2013) 252002.
[68] M. Ablikim, et al., BESIII Collaboration, Observation of $Z_c(3900)^0$ in $e^+e^-\to\pi^0\pi^0J/\psi$, Phys. Rev. Lett. 115 (2015) 112003.
[69] V.M. Abazov, et al., D0 Collaboration, Evidence for $\mathrm{Z_c}(3900)^\pm$ in semi-inclusive decays of b-flavored hadrons, Phys. Rev. D 98 (2018) 052010.
[70] M. Ablikim, et al., BESIII Collaboration, Observation of a charged $(D\overline{D}^*)^\pm$ Mass Peak in $e^+e^-\to\pi D\overline{D}^*$ at $\sqrt{s}=4.26\,\mathrm{GeV}$, Phys. Rev. Lett. 112 (2014) 022001.
[71] M. Ablikim, et al., BESIII Collaboration, Confirmation of a charged charmoniumlike state $Z_c(3885)^\mp$ in $e^+e^-\to\pi^\pm(\overline{DD^*})^\mp$ with double D tag, Phys. Rev. D 92 (2015) 092006.
[72] A. Esposito, A. Guerrieri, A. Pilloni, Probing the nature of Z_c' states via the $\eta_c\rho$ decay, Phys. Lett. B 746 (2015) 194–201.
[73] M. Ablikim, et al., BESIII Collaboration, Determination of the spin and parity of the $\mathrm{Z}_c(3900)$, Phys. Rev. Lett. 119 (2017) 072001.
[74] S.U. Chung, General formulation of covariant helicity-coupling amplitudes, Phys. Rev. D 57 (1998) 431–442.
[75] S.U. Chung, Erratum: Helicity-coupling amplitudes in tensor formalism [Phys. Rev. D 48, 1225 (1993)], Phys. Rev. D 56 (1997) 4419.
[76] S.-U. Chung, J.M. Friedrich, Covariant helicity-coupling amplitudes: A new formulation, Phys. Rev. D 78 (2008) 074027.
[77] K.-F. Chen, et al., Belle Collaboration, Observation of anomalous $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ Production near the $\Upsilon(5S)$ Resonance, Phys. Rev. Lett. 100 (2008) 112001.
[78] A. Bondar, et al., Belle Collaboration, Observation of two charged bottomoniumlike resonances in $\Upsilon(5S)$ decays, Phys. Rev. Lett. 108 (2012) 122001.
[79] P. Krokovny, et al., Belle Collaboration, First observation of the $Z_b^0(10610)$ in a Dalitz analysis of $\Upsilon(10860)\to\Upsilon(nS)\pi^0\pi^0$, Phys. Rev. D 88 (2013) 052016.
[80] A. Garmash, et al., Belle Collaboration, Observation of $\mathrm{Z}_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons, Phys. Rev. Lett. 116 (2016) 212001.
[81] F.-K. Guo, C. Hanhart, Y.S. Kalashnikova, P. Matuschek, R.V. Mizuk, A.V. Nefediev, Q. Wang, J.-L. Wynen, Interplay of quark and meson degrees of freedom in near-threshold states: A practical parametrization for line shapes, Phys. Rev. D 93 (2016) 074031.
[82] Q. Wang, V. Baru, A.A. Filin, C. Hanhart, A.V. Nefediev, J.-L. Wynen, Line shapes of the $Z_b(10610)$ and $Z_b(10650)$ in the elastic and inelastic channels revisited, Phys. Rev. D 98 (2018) 074023.
[83] R. Aaij, et al., LHCb Collaboration, Quantum numbers of the $X(3872)$ state and orbital angular momentum in its ρ^0J/ψ decay, Phys. Rev. D 92 (2015) 011102.
[84] T. Barnes, S. Godfrey, Charmonium options for the $X(3872)$, Phys. Rev. D 69 (2004) 054008.
[85] Y.S. Kalashnikova, A.V. Nefediev, Nature of $X(3872)$ from data, Phys. Rev. D 80 (2009) 074004.
[86] N.A. Törnqvist, Isospin breaking of the narrow charmonium state of belle at 3872 MeV as a deuson, Phys. Lett. B 590 (3) (2004) 209–215.
[87] M. Ablikim, et al., BESIII Collaboration, Study of $e^+e^-\to\gamma\omega J/\psi$ and Observation of $X(3872)\to\omega J/\psi$, Phys. Rev. Lett. 122 (2019) 232002.
[88] K. Abe, et al., Belle Collaboration, Evidence for $X(3872)\to\gamma J/\psi$ and the sub-threshold decay $X(3872)\to\omega J/\psi$, 2005, arXiv:hep-ex/0505037.
[89] P. del Amo Sanchez, et al., Babar Collaboration, Evidence for the decay $X(3872)\to J/\psi\omega$, Phys. Rev. D 82 (2010) 011101.
[90] L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, Diquark-antidiquark states with hidden or open charm and the nature of $X(3872)$, Phys. Rev. D 71 (2005) 014028.
[91] E.S. Swanson, The new heavy mesons: A status report, Phys. Rep. 429 (5) (2006) 243–305.
[92] V. Bhardwaj, et al., Belle Collaboration, Observation of $X(3872)\to J/\psi\gamma$ and Search for $X(3872)\to\psi'\gamma$ in B Decays, Phys. Rev. Lett. 107 (2011) 091803.
[93] R. Aaij, et al., LHCb Collaboration, Evidence for the decay $X(3872)\to\psi(2S)\gamma$, Nuclear Phys. B 886 (2014) 665–680.

[94] B. Aubert, et al., Babar Collaboration, Evidence for $X(3872)\to\psi(2S)\gamma$ in $B^{\pm}\to X(3872)K^{\pm}$ Decays and a Study of $B\to c\bar{c}\gamma K$, Phys. Rev. Lett. 102 (2009) 132001.
[95] S. Dubynskiy, M.B. Voloshin, Pionic transitions from $X(3872)$ to χ_{cJ}, Phys. Rev. D 77 (2008) 014013.
[96] S. Fleming, T. Mehen, Hadronic decays of the $X(3872)$ to χ_{cJ} in effective field theory, Phys. Rev. D 78 (2008) 094019.
[97] T. Mehen, Hadronic loops versus factorization in effective field theory calculations of $X(3872)\to\chi_{cJ}\pi^0$, Phys. Rev. D 92 (2015) 034019.
[98] M. Ablikim, et al., BESIII Collaboration, Observation of the decay $X(3872)\to\pi^0\chi_{c1}(1P)$, Phys. Rev. Lett. 122 (2019) 202001.
[99] M. Ablikim, et al., BESIII Collaboration, Study of open-charm decays and radiative transitions of the $X(3872)$, Phys. Rev. Lett. 124 (2020) 242001.
[100] C. Li, C.-Z. Yuan, Determination of the absolute branching fractions of X(3872) decays, Phys. Rev. D 100 (9) (2019) 094003.
[101] R. Aaji, et al., LHCb collaboration, Observation of the $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ decay, J. High Energ. Phys. 2019 (2019) 28.