PROCEEDINGS OF SCIENCE

Experimental review of exotic states discoveries in the last 20 years

Chengping Shen[a,*]

[a] *Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University*
220 Handan Road, Shanghai, China

E-mail: shencp@fudan.edu.cn

The traditional quark model posits that hadrons are primarily composed of two quarks (mesons) or three quarks (baryons). However, the existence of exotic hadrons, such as tetraquarks, pentaquarks, and hybrid states, extends beyond this framework. Studying these exotic states helps refine the classification of hadrons and unveils the diversity of hadronic structures. Furthermore, the study of exotic hadron states provides crucial insights into the non-perturbative properties of Quantum Chromodynamics in the low-energy regime. By investigating the composition, mass, and decay properties of these states, we can delve deeper into the complex interactions between quarks and gluons. Since the discovery of the $X(3872)$, the study of exotic hadron states has seen tremendous progress both experimentally and theoretically. In this report, I will present some of the significant experimental advancements in the field of exotic hadron states over the past two decades.

The XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC24)
19-24 August, 2024
Cairns Convention Centre, Cairns, Queensland, Australia

*Speaker

https://pos.sissa.it/

PoS(QCHSC24)015

The study of hadron spectroscopy is a crucial frontier in particle physics, not only deepening our understanding of the fundamental structure of matter and interactions but also providing an essential foundation for exploring new physical phenomena. Exotic hadrons and hadron spectroscopy are deeply interconnected, as the study of exotic hadrons enriches our understanding of the hadron spectrum. While traditional hadrons are classified within the quark model as mesons (quark-antiquark pairs) and baryons (three quarks), exotic hadrons extend beyond this framework, encompassing states like tetraquarks, pentaquarks, hybrid states, and glueballs. These exotic states introduce new complexities to the hadron spectrum, revealing the diverse ways quarks and gluons can bind under the strong interaction described by Quantum Chromodynamics (QCD). By investigating the masses, decay modes, and internal structures of exotic hadrons, researchers can refine the hadron spectrum, test QCD predictions, and uncover non-perturbative aspects of strong interactions. Thus, exotic hadrons play a pivotal role in expanding and deepening our knowledge of the hadronic world.

Exotic states that do not seem to fit with expectations of ordinary quarkonia are dubbed either X(mass), or Y(mass), or Z(mass), and are usually referred to collectively as XYZ states. Y(mass) is usually used for exotics with vector quantum numbers, i.e., $J^{PC} = 1^{--}$ where J is the spin, P is the parity, and C is the charge-conjugation quantum number. Z(mass) is usually used for exotics with non-zero charge. Due to the significance of exotic hadron research, many high-energy physics experiments have dedicated substantial efforts to this field. Facilities like the Large Hadron Collider (LHC), Belle(II), BaBar, and BESIII have played crucial roles in identifying these states by analyzing their production, decay properties, and interactions. With more and more data collected by these experiments, they have led to the discovery of many exotic states (see Fig. 1 [1]) and to the collection of an impressive amount of measurements in production and decay channels.

The first X state, $X(3872)$, which triggered studies of the exotic states, was observed by the Belle experiment in 2003 [2]. The first vector charmonium-like state $Y(4260)$ was observed by BaBar in initial state radiation process $e^+e^- \to \pi^+\pi^- J/\psi$ [3]. Besides the $X(3872)$ and $Y(4260)$, the $Z_c(4430)$ and $Z_b(10610/10650)$, which are the first charged charmonium-like and bottomonium-like states with obvious exotic characteristics, were also observed by Belle [4, 5]. In the following sections, I will review a few significant experimental achievements from the perspectives of X, Y, and Z states.

1. *X* states

The $X(3872)$ was first observed by Belle in $B \to K\pi^+\pi^- J/\psi$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi$ final state [2]. Ten years after its discovery, LHCb performed a full five-dimensional amplitude analysis of the angular correlations between the decay products in $B^+ \to X(3872)K^+$ decays with $X(3872) \to \pi^+\pi^- J/\psi$ and $J/\psi \to \mu^+\mu^-$, which unambiguously gives the $J^{PC} = 1^{++}$ assignment under the assumption that the $\pi^+\pi^-$ and J/ψ are in an $S-$wave [6]. The most salient feature of the $X(3872)$ is that its mass coincides almost exactly with the threshold of $D^0\bar{D}^{*0}$. The mass and width of the $X(3872)$ as given in the latest version of the Review of Particle Physics [7] are (3871.64 ± 0.06) MeV and (1.19 ± 0.21) MeV, respectively.

Although the $X(3872)$ has been discovered for more than 20 years, there is still no solid conclusion on what its internal structure is. The measurement of the absolute branching fraction $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ brings useful information regarding its complex nature. Based on the

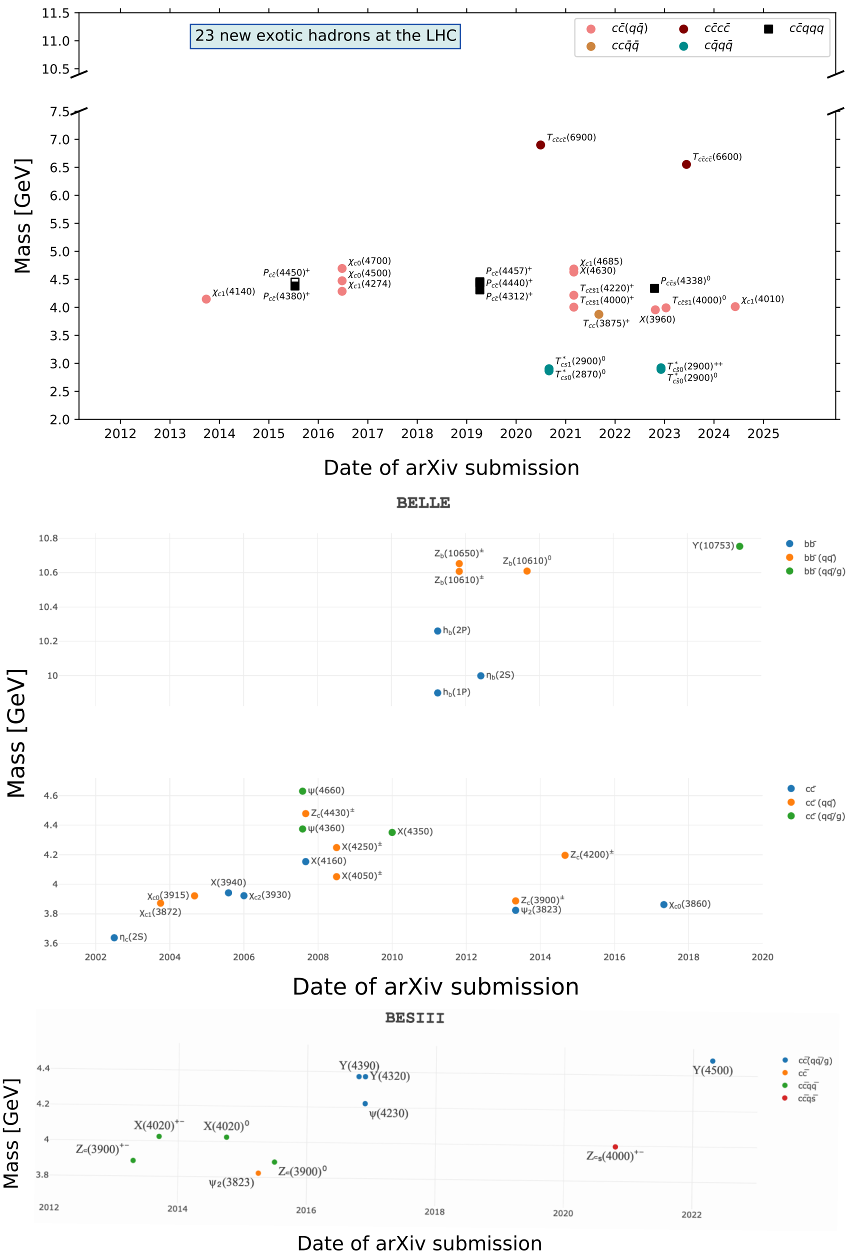

Figure 1: Exotic states discovered by LHC, Belle, and BESIII experiments over the past two decades [1].

measurement of the kaon momentum spectrum in the B rest frame, BaBar studied the two body decays $B^{\pm} \to X_{c\bar{c}} K^{\pm}$, where $X_{c\bar{c}}$ refers to one charmonium state, using a data sample of 424 fb^{-1} at $\Upsilon(4S)$ resonance [8]. The kaon momentum spectrum between 1 and 2.05 GeV/c with the fitted background subtracted is shown in Fig. 2, where the fit function shown by the red line includes signal peaks for nine particles indicated by the arrows. The fit function with the $X(3872)$ signal removed is drawn in blue. The significance of the $X(3872)$ is 3σ. The absolute branching fraction $\mathcal{B}(B^{+} \to X(3872)K^{+}) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$ was measured for the first time. Using the measured

$\mathcal{B}(B^+ \to X(3872)K^+)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.6 \pm 0.8) \times 10^{-6}$ [9], the absolute branching fraction $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$ was measured, supporting the hypothesis of a molecular component for the $X(3872)$.

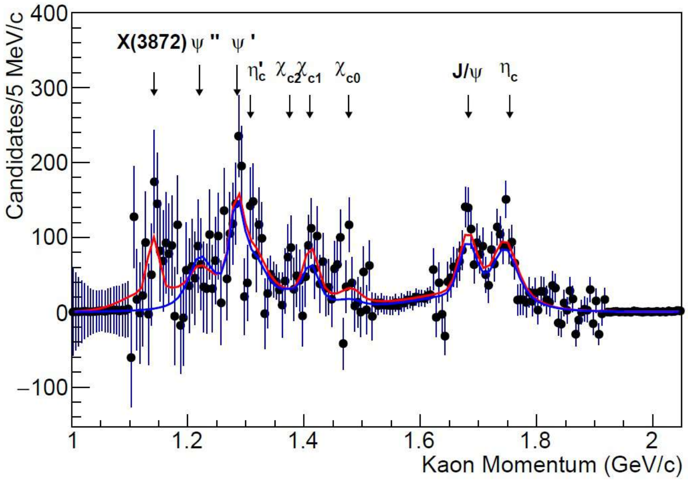

Figure 2: Kaon momentum spectrum in the B rest frame from BaBar measurement [8], where evidence of the $X(3872)$ signal can be seen.

The authors in Ref. [10] obtained the absolute branching fractions of the six $X(3872)$ decay modes by globally analyzing the measurements from available experiments, where the $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ was determined to be $(4.1^{+1.9}_{-1.1})\%$ and the branching fraction of the dominant decay mode $X(3872) \to D^0\bar{D}^{*0} + c.c.$ was $(52.4^{+25.3}_{-14.3})\%$. In addition, the fraction of the unknown decays of the $X(3872)$ was reported as $(31.9^{+18.1}_{-31.5})\%$, thus it is desirable to search for more $X(3872)$ decays in the future. From the above, we see that the dominant uncertainty in determining the $X(3872)$ decay branching fraction is statistical due to the large error in $\mathcal{B}(B^+ \to X(3872)K^+)$ [8]. The precision in $\mathcal{B}(B^+ \to X(3872)K^+)$ is expected to be improved largely at Belle II due to the two improvements: (1) an upgraded Full Event Interpretation (an exclusive reconstruction algorithm) is used to reconstruct thousands of final states for the tagging B candidates to increase the efficiency; (2) a unique multiple variable analysis of DeepSets based on the neural network is applied to suppress continuum backgrounds and reject the secondary kaons produced in B-daughter D meson decays. About 600 $X(3872)$ candidates from the $B \to X(3872)K$ decays per 1 ab^{-1} are expected be observed at Belle II [11].

Another crucial physical quantity for distinguishing different interpretations of the $X(3872)$ is the ratio of the partial radiative decay widths into $\psi(2S)\gamma$ and $J/\psi\gamma$ final states denoted as $\mathcal{R}_{\psi\gamma} = \Gamma_{X(3872)\to\psi(2S)\gamma}/\Gamma_{X(3872)\to J/\psi\gamma}$. A recent measurement of $\mathcal{R}_{\psi\gamma}$ from LHCb gives $1.67 \pm 0.21 \pm 0.12 \pm 0.04$ [12]. This ratio is quite different from the BESIII result, where an upper limit on the ratio $\mathcal{R}_{\psi\gamma} < 0.59$ is set at 90% confidence level [13]. This discrepancy needs to be understood in other experiments, especially at Belle II.

It is natural to search for a similar state with $J^{PC} = 1^{++}$ in the bottomonium system, called X_b. Searching for X_b supplies important information about the discrimination of a compact multiquark configuration and a loosely bound hadronic molecule configuration for the $X(3872)$. Unlike in $X(3872)$ decays, due to its negligible isospin-breaking effects, the X_b may decay preferentially into $\pi^+\pi^-\pi^0\Upsilon(1S)$ instead of $\pi^+\pi^-\Upsilon(1S)$. Searches for an X_b state in $\pi^+\pi^-\Upsilon(1S)$ by CMS and ATLAS [14], and in $\pi^+\pi^-\pi^0\Upsilon(1S)$ near the $\Upsilon(10860/10753)$ by Belle and Belle II [15], yielded negative results.

In 2009, CDF reported an evidence of a narrow structure near the $J/\psi\phi$ threshold in $B^+ \to J/\psi\phi K^+$, using a data sample of $p\bar{p}$ collisions corresponding to an integrated luminosity of 2.7 fb^{-1} at $\sqrt{s}$ = 1.96 TeV. This narrow structure is called $X(4140)$ and has a mass of $(4143.0 \pm 2.9 \pm 1.2)$ MeV and a width of $11.7^{+8.3}_{-5.0} \pm 3.7$ MeV with a statistical significance greater than 3.8σ [16]. This is the first unexpected particle discovered by Tevatron. Then Belle searched for it in two-photon process $\gamma\gamma \to \phi J/\psi$ using a data sample of 825 fb^{-1} at near $\Upsilon(4S)$ resonance, but no signal for the $X(4140)$ was observed in $\phi J/\psi$ mass spectrum [17]. Instead of the $X(4140)$, Belle reported another narrow peak with a significance of 3.2σ (named $X(4350)$). Its mass and width are $(4350^{+4.6}_{-5.1} \pm 0.7)$ MeV and $(13^{+18}_{-9} \pm 4)$ MeV, respectively. This state needs to be confirmed at Belle II in the near future. A search for the $X(4140)$ state in the same B decays was performed by LHCb with 0.37 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 TeV, but no evidence was found with a 2.4σ disagreement with the measurement by CDF [18]. Such result puts the $X(4140)$ on the very shaky ground at that moment. Later CMS and D0 serached for the $X(4140)$ in the same B decays or inclusive production, and the results showed that the evidence of $X(4140)$ could be seen [19].

With more and more data accumulated by LHCb, the first full amplitude analysis of $B^+ \to J/\psi\phi K^+ \to \mu^+\mu^-K^+K^-K^+$ decays was performed with a data sample of 3 fb^{-1} at $\sqrt{s}$ =7 and 8 TeV [20]. In this analysis, a few new states were observed, as shown in Fig. 3 (left plot), in which the lightest state has a mass consistent with, but width much larger than, previous measurements of the claimed $X(4140)$ state. The values of J^{PC} for the $X(4140)$ were determined to be 1^{++}. An updated amplitude analysis of the $B^+ \to J/\psi\phi K^+$ was also carried out by LHCb using proton-proton collision data corresponding to a total integrated luminosity of 9 fb^{-1} at centre-of-mass energies of 7, 8, and 13 TeV [21]. The obtained $J/\psi\phi$ mass spectrum is shown in Fig. 3 (right plot), where the red solid line shows the fitted results from the amplitude analysis. The obtained mass and width for the $X(4140)$ are $(4118 \pm 11^{+19}_{-36})$ MeV and $(162 \pm 21^{+24}_{-49})$ MeV, i.e., the width is even much wider. Besides the four previously reported $J/\psi\phi$ states were confirmed, a new 1^+ $X(4685)$ state decaying to the $J/\psi\phi$ final state was also observed with a high significance. In the future, when Belle II has large data samples, the similar amplitude analysis can be done to check LHCb's results.

An evidence of a narrow structure $X(5568)$ with a signal significance greater than 3.9σ was reported by D0 Collaboration in the hadronic decay $X(5568) \to B^0_s\pi^\pm \to J/\psi\phi\pi^\pm$ in proton–antiproton collisions at $\sqrt{s}$ =1.96 TeV [22]. The measured mass and width are $M = (5567.8 \pm 2.9^{+0.9}_{-1.9})$ MeV and $\Gamma = (21.9 \pm 6.4^{+5.0}_{-2.5})$ MeV. Based on its decay final states, we can easily infer that it contains at least four different flavors of quark components, thus it has received extensive attention from theoretical and experimental physicists. Later the $X(5568)$ was confirmed by D0 in the B^0_s semileptonic decay $B^0_s \to \mu^\mp D^\pm X$ with a statistical significance greater than 4.3σ [23]. While the D0 Collaboration reported the $X(5568)$ in both hadronic and semileptonic decays, negative results were reported in the CDF [24], CMS [25], ATLAS [26], and LHCb [27] experiments. Figure 4 shows the measured $M(B^0_s\pi^\pm)$ distributions from the above experiments. The $X(5568)$ state, if confirmed, would differ from any previously observed state, as it must have

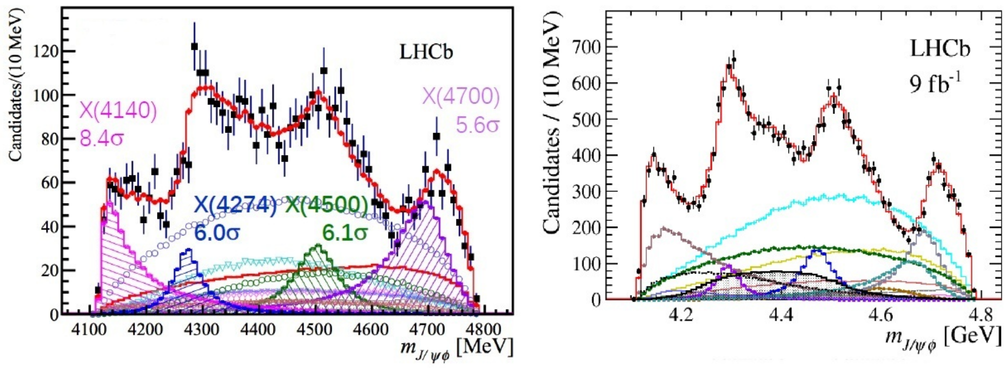

Figure 3: The $J/\psi\phi$ mass spectra from the amplitude analysis of $B^+ \to J/\psi\phi K^+$ process performed by LHCb, using data samples of 3 fb^{-1} of pp collision data at $\sqrt{s}$ =7 and 8 TeV (left) [20] and 9 fb^{-1} of pp collision data at $\sqrt{s}$ =7, 8, and 13 TeV (right) [21].

constituent quarks with four different flavors (b, s, u, d). Therefore, the urgent task in the future is to confirm or definitely exclude the existence of the $X(5568)$ with larger data samples and to look for possible similar exotic states in the $B_s^*\pi$, $D_s\pi$, and $D_s^*\pi$ systems.

In 2020, LHCb reported a narrow structure $X(6900)$ in the di-J/ψ channel [28]. The structure could be interpreted as a tetraquark with four charm quarks. Later ATLAS performed a search in the 4μ final state produced through the di-J/ψ and $J/\psi + \psi(2S)$ channels using 140 fb^{-1} of pp data at $\sqrt{s}$ = 13 TeV [29]. The di-J/ψ mass distribution from ATLAS is shown in Fig. 5 (left), where a significant excess of events in data is observed. Analogous to LHCb observations, a broad structure at lower mass and a resonance around 6.9 GeV are observed. A three-resonance model with interferences, or a model with the lower broad structure interfering with the background, can describe the data well. In the $J/\psi + \psi(2S)$ channel, a 4.7σ excess of events is observed when considering a model involving two resonances to fit the data, one of which is near the 6.9 GeV threshold. CMS also did a search for near-threshold structures in the $J/\psi J/\psi$ invariant mass spectrum produced in pp collisions at $\sqrt{s}$ = 13 TeV with an integrated luminosity of 135 fb^{-1} [30]. The corresponding $J/\psi J/\psi$ invariant mass spectrum from CMS is shown in Fig. 5 (right). Three structures are found. They are the $X(6900)$ observed by LHCb and ATLAS before, and two new structures at a mass of (6638^{+43+16}_{-38-31}) MeV and (7134^{+48+41}_{-25-15}) MeV with signal significances of 5σ and 4.7σ, respectively, from a fit with full interference.

2. Y states

The first Y state, $Y(4260)$, was observed by BaBar as a peak in the energy dependence of the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section [3] and was confirmed by Belle [31, 32] and CLEO [33] in the same process. A higher-statistics analysis by BESIII revealed an asymmetry in the cross section and resulted in a shift of the peak position to a lower mass, i.e., the $Y(4260)$ actually was composed of two resonances, the $Y(4230)$ and $Y(4320)$ [34]. The energy-dependent cross sections for e^+e^- to other channels also exhibit peaks in the same mass region, for examples, $e^+e^- \to \gamma X(3872)$ [35], $e^+e^- \to D^{*0}D^{*-}\pi^+$ [36]. The Belle and BESIII experiments have searched for and observed a

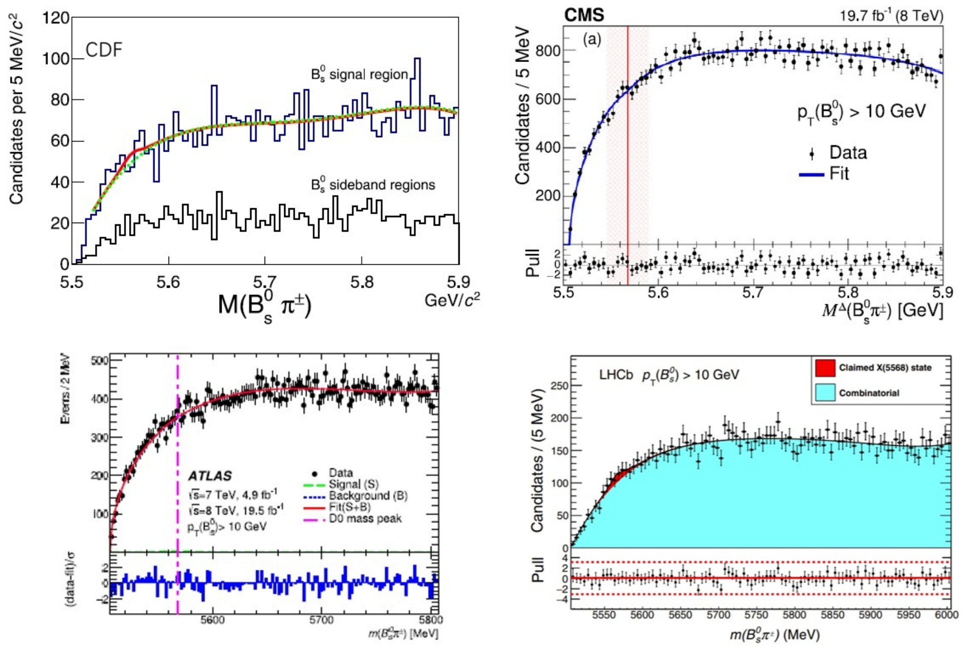

Figure 4: The $M(B_s^0\pi^\pm)$ distributions from the CDF [24], CMS [25], ATLAS [26], and LHCb [27] measurements for $B_s^0\pi^\pm \to J/\psi\phi\pi^\pm$ candidates. The solid lines are the best fits. In all the mass distributions, no clear $X(5568)$ signal could be seen.

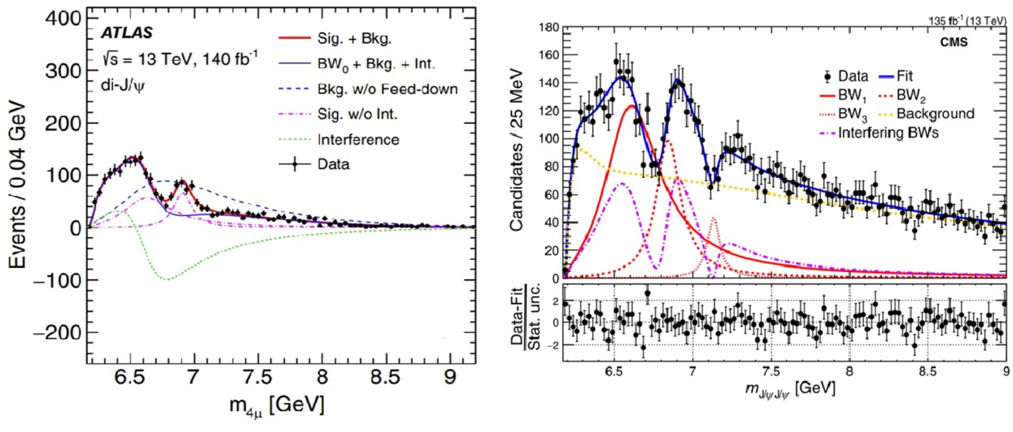

Figure 5: Di-J/ψ mass spectra from the ATLAS [29] (left) and CMS [30] (right) measurements, where a few new tetraquarks with $cc\bar{c}\bar{c}$ quark components decaying into a pair of J/ψ charmonium states can be seen clearly.

broad resonance in the $\pi^+\pi^- J/\psi$ system, referred to as the $Y(4008)$ [31, 32, 37]. However, the BaBar Collaboration disputed the existence of this state [38].

The pair production process of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ was firstly studied by Belle via the initial-state radiation technique [39]. A resonant structure around 4.63 GeV, denoted as the $Y(4630)$, was discerned in the cross-section line shape, as shown in Fig. 6 by the green open squares. However, flat cross sections around 4.63 GeV were obtained by BESIII [40] and no indication of the resonant structure $Y(4630)$ was found, as shown in Fig. 6 by the red dots and opens. In BESIII data, the near threshold cross-section plateau is confirmed up to 4.66 GeV and no resonance structure is observed around 4.63 GeV. The confusion regarding the $Y(4630)$ needs to be further examined in future experiments.

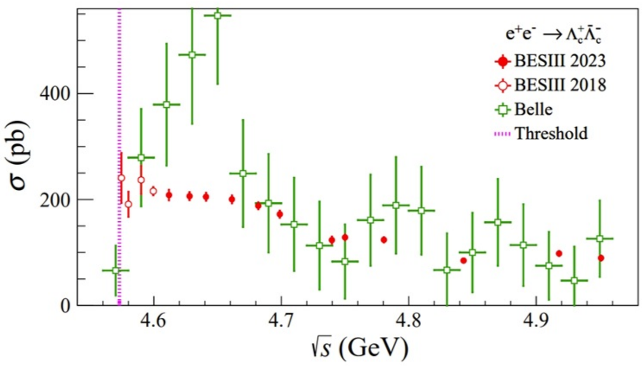

Figure 6: The distributions of the cross sections of the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process, where the red dots and opens are from BESIII measurements [40], and the green open squares indicate those of Belle [39].

Two resonant structures are observed in the line shape of the cross sections of $e^+e^- \to K^+K^- J/\psi$ from 4.127 to 4.600 GeV measured by BESIII, one for the $Y(4230)$ and the other for the new structure called the $Y(4510)$ [41]. Its statistical significance is greater than 8σ, and the measured mass and width are $(4484.7\pm13.3\pm24.1)$ MeV and $(111.1\pm30.1\pm15.2)$ MeV, respectively. Using data samples with an integrated luminosity of 5.85 fb^{-1} collected at center-of-mass energies from 4.61 to 4.95 GeV, BESIII measured the updated cross sections of $e^+e^- \to K^+K^- J/\psi$, as shown in Fig. 7 (left). A new resonance, called the $Y(4710)$, with a mass of $M = (4708^{+17}_{-15} \pm 21)$ MeV and a width of $\Gamma = (126^{+27}_{-23} \pm 30)$ MeV is observed in the energy-dependent line shape of the cross section distribution with a significance over 5σ [42]. Isospin process of $e^+e^- \to K_S^0 K_S^0 J/\psi$ was also studied by BESIII. Using data samples with a total integrated luminosity of 21.2 fb^{-1}, the measured cross sections are shown in Fig. 7 (right) at center-of-mass energies from 4.128 to 4.950 GeV, where the $Y(4230)$ is observed clearly. In addition, the $Y(4710)$ is seen with a statistical significance of 4.2σ [43] .

Recently, BESIII measured the cross sections of a few open-charm channels with high precision, including $e^+e^- \to D_s^{*+}D_s^{*-}$ [44], D^+D^-, $D^0\bar{D}^0$ [45], $D_s^+D_s^-$ [46], and $D^{*+}D^{*-}$, $D^{*+}D^-$ [47], as shown in Fig. 8. From these distributions, there is a rich presence of charmonium and charmonium-like states. However, the structures appear to be complex. We need better theoretical models to provide a unified description of them.

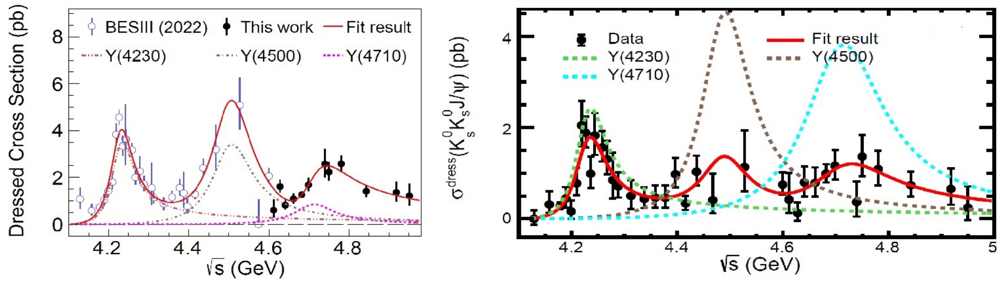

Figure 7: The distributions of measured cross sections of $e^+e^- \to K^+K^-J/\psi$ (left) and $K^0_SK^0_SJ/\psi$ (right) from BESIII [42, 43]. The red solid curves show the fitted results using the $Y(4230)$, $Y(4500)$, and $Y(4710)$ with interference.

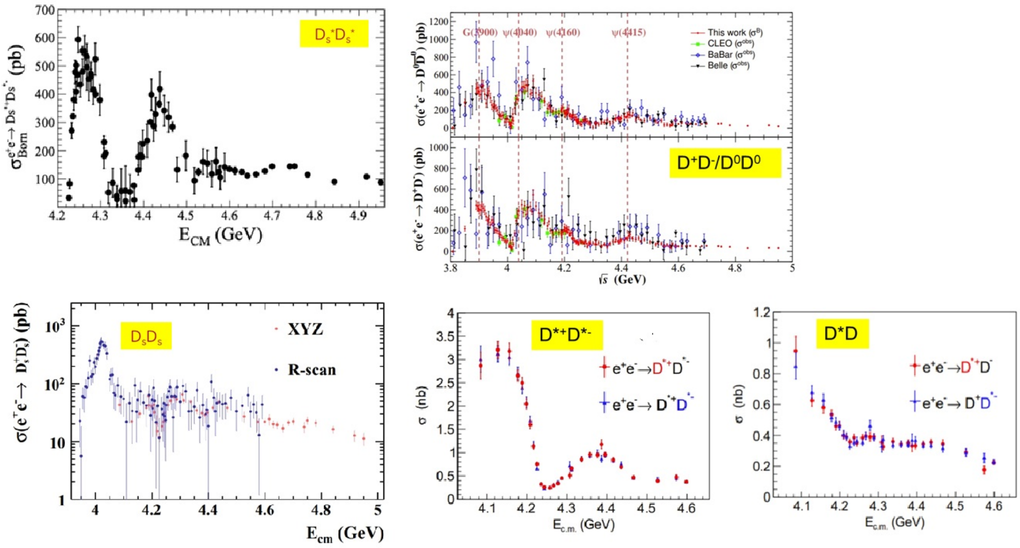

Figure 8: The measured cross sections of $e^+e^- \to D_s^{*+}D_s^{*-}$ [44], D^+D^-, $D^0\bar{D}^0$ [45], $D_s^+D_s^-$ [46], and $D^{*+}D^{*-}$, $D^{*+}D^-$ [47] by BESIII.

3. *Z* states

The first charged charmonium-like state, $Z_c(4430)^-$ was observed in the $B \to K\pi^-\psi(2S)$ decays with a measured mass and width of $(4430 \pm 4 \pm 1)$ MeV and (44^{+17+30}_{-13-11}) MeV by Belle using 657×10^6 $B\bar{B}$ pairs in 2008 [4]. The statistical significance of the observed peak is 6.5σ. A characteristic that clearly distinguishes multiquark states from hybrids or charmonia is the possibility to have charmonium-like mesons with non-zero charge. Without any doubt, if the $Z_c(4430)^-$ is true, it meets above characteristic. Thus, BaBar quickly analyzed the same process using an integrated luminosity of 413 fb^{-1} $\Upsilon(4S)$ data [48]. BaBar found that the $\pi^-\psi(2S)$ mass distribution can be well described by the reflection of the known $K\pi$ resonances. Although BaBar did not confirm the existence of the $Z_c(4430)$, its results did not contradict the Belle observation due to low statistics. To take into account the interference effect between the $Z_c(4430)^-$ and the K^* intermediate states in

$B \to K\pi^-\psi(2S)$ decays, Belle updated their $Z_c(4430)^-$ results with a four-dimensional amplitude analysis [49]. The $Z_c(4430)^-$ with a large width of (200^{+41+26}_{-46-35}) MeV was confirmed with a significance of 5.2σ and spin-parity $J^P = 1^+$ is favored over the other assignments by more than 3.4σ. The $\pi^-\psi(2S)$ mass spectra from Belle and BaBar are shown in Fig. 9 (left).

The inconsistent results on the $Z_c(4430)^-$ between BaBar and Belle measurements have been an open question for a very long time until LHCb has large B-samples to perform a four-dimensional fit of the decay amplitude [50]. In the amplitude fit, all known K^* resonances, a nonresonant term, and a Z_c^- amplitude represented by a BW function are included. The fit yields a mass of $(4475 \pm 7^{+15}_{-25})$ MeV and a width of $(172 \pm 13^{+37}_{-34})$ MeV, which are consistent with, but more precise than, the updated Belle results. The lowest significance for the $Z_c(4430)^-$ signal is 13.9σ. The projection of the four-dimensional amplitude fit on the $M(\pi^-\psi(2S))$ is shown in Fig. 9 (right), where the red solid (brown dashed) histogram represents the total amplitude with (without) the $Z_c(4430)^-$ component. Relative to $J^P = 1^+$, the 0^-, 1^-, 2^+, and 2^- hypotheses are ruled out by at least 9.7σ, thus the spin-parity of the $Z_c(4430)$ is established to be 1^+ unambiguously.

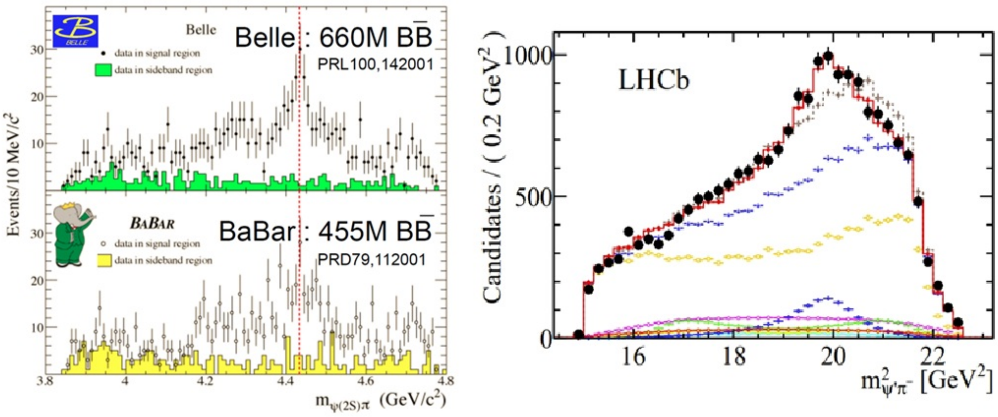

Figure 9: The distributions of $\pi^-\psi(2S)$ mass spectra from Belle [4], BaBar [48], and LHCb [50].

Replacing the $\psi(2S)$, Belle subsequently checked the $\pi^-\chi_{c1}$ system in exclusive $B^0 \to K^+\pi^-\chi_{c1}$ using 657×10^6 $B\bar{B}$ pairs [51]. A six-dimensional Dalitz plot analysis was performed to the selected signal candidates, where two Z_c^- resonances are needed to describe the data well with masses and widths of $M_1 = (4051 \pm 14^{+20}_{-41})$ MeV, $\Gamma_1 = (82^{+21+47}_{-17-22})$ MeV, $M_2 = (4248^{+44+180}_{-29-35})$ MeV, and $\Gamma_2 = (177^{+54+316}_{-39-61})$ MeV. They are denoted as $Z_{c1}(4050)$ and $Z_{c2}(4250)$ with signal significances greater than 5σ for both. These two charged resonances represent additional candidate states of similar characteristics to the $Z_c(4430)^-$. After Belle claimed the observation of the $Z_{c1}(4050)$ and $Z_{c2}(4250)$ states, the BaBar experiment analyzed the same process using an integrated luminosity of 429 fb^{-1} [52]. In this analysis, BaBar found that the fit to the efficiency-corrected $\pi^-\chi_{c1}$ mass distribution can describe the data well without the need of any charged Z_c resonance. Thus, further confirmation of the existence of the $Z_{c1}(4050)$ and $Z_{c2}(4250)$ states at LHCb and Belle II is needed in the future.

To study the $Y(4260)$, BESIII collected a 525 pb^{-1} data sample in 2013 at $\sqrt{s}$ =4.26 GeV [53]. Using the selected $e^+e^- \to \pi^+\pi^-J/\psi$ events, the Dalitz plot was checked for possible intermediate states by BESIII. At the same time, Belle updated the measurement of the cross section of $e^+e^- \to$

$\pi^+\pi^- J/\psi$ from 3.8 to 5.5 GeV with a 967 fb^{-1} data sample [32]. The Dalitz plot for events in the $Y(4230)$ signal region was also investigated,

Figure 10 shows the projections of the $M_{\max}(\pi^\pm J/\psi)$ [the maximum value out of $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$] distributions for the signal events from BESIII [53] (left) and Belle [32] (middle). Unbinned maximum-likelihood fits are applied to the distributions of $M_{\max}(\pi^\pm J/\psi)$ from Belle and BESIII measurements. The measured masses are $(3899.0 \pm 3.6 \pm 4.9)$ MeV and $(3894.5 \pm 6.6 \pm 4.5)$ MeV and the measured widths are $(46 \pm 10 \pm 20)$ MeV and $(63 \pm 24 \pm 26)$ MeV from the Belle and BESIII experiments, respectively. They are consistent with each other within the uncertainties. The signal significance is greater than 5σ in both measurements. This structure is now referred to as the $Z_c(3900)$. The $Z_c(3900)$ state was confirmed shortly after by Seth's group with CLEO-c data at $\sqrt{s}$ =4.17 GeV [54], and the mass and width agreed very well with the BESIII and Belle measurements, as shown in Fig. 10 (right). In addition, a 3.5σ evidence for the $Z_c(3900)^0$ in the CLEO-c data was also reported in the $e^+e^- \to \pi^0\pi^0 J/\psi$ process.

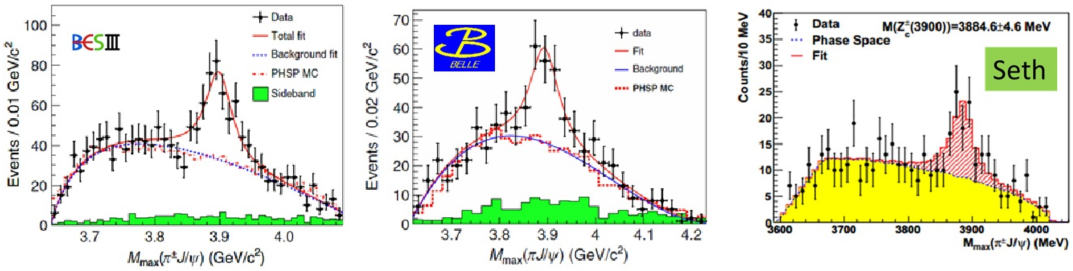

Figure 10: The distributions of $M_{\max}(\pi^\pm J/\psi)$ from BESIII [53], Belle [32], and Seth's group with CLEO-c data at $\sqrt{s}$ =4.17 GeV [54].

A neutral state $Z_c(3900)^0$ with a significance of 10.4σ was also observed by BESIII in $e^+e^- \to \pi^0\pi^0 J/\psi$ process, and the measured mass and width are close to those of $Z_c(3900)^-$ [55]. Thus, it is interpreted as the neutral partner of the $Z_c(3900)^-$, which confirms that the $Z_c(3900)$ is an isovector state. To determine the J^P values of the $Z_c(3900)$, BESIII performed a partial wave analysis to the selected $e^+e^- \to \pi^+\pi^- J/\psi$ candidates at $\sqrt{s} = 4.23$ and 4.26 GeV and found that the spin-parity $J^P = 1^+$ of the $Z_c(3900)$ are favored by more than 7σ over other quantum numbers [56].

Later more searches to the charged charmonium-like states were performed in the combination of one charged pion/kaon/proton and a charmonium state, like η_c, J/ψ, $\psi(2S)$, and h_c. Exactly more Z_c states were found in experiments. For details, please see some review papers, like Ref. [57].

The first charged bottomonium-like states, $Z_b(10610)$ and $Z_b(10650)$, were discovered by Belle in the $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ ($n = 1,\ 2,\ 3$) and $\Upsilon(5S) \to \pi^+\pi^- h_b(mP)$ ($m = 1,\ 2$) processes with 121.4 fb^{-1} data collected in the vicinity of the $\Upsilon(5S)$ resonance [58]. Amplitude analyses of the three-body $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$ decays with $\Upsilon(nS) \to \mu^+\mu^-$ were performed by means of unbinned maximum likelihood fits to the Dalitz distributions. One-dimensional invariant mass projections for events in the $\Upsilon(nS)$ signal regions are shown in Fig. 11, where two peaks are observed in the $\pi\Upsilon(nS)$ system near 10.61 GeV and 10.65 GeV [named as $Z_b(10610)$ and $Z_b(10650)$]. The combined statistical significance of the two peaks exceeds 10σ for all $\pi^+\pi^-\Upsilon(nS)$ channels. The $Z_b(10610)$ and $Z_b(10650)$ signals are also clear in $\pi h_b(mS)$ mass spectra although the available

PoS(QCHSC24)015

phase-space is smaller for $\pi h_b(2P)$. Analyses of charged pion angular distributions favor the $J^P = 1^+$ spin-parity assignment for both the $Z_b(10610)$ and $Z_b(10650)$. Their π^0 transition modes were measured to confirm their isospin [59], and the open bottom decay modes were studied to understand the couplings to various final states [60].

Up to now, in comparison with the number of charmonium-like states from PDG [7], the number of bottomonium-like states is smaller due to lower production rates and limited experimental conditions. The relevant measurements with data collected in bottomonium energy region at Belle II will provide additional information.

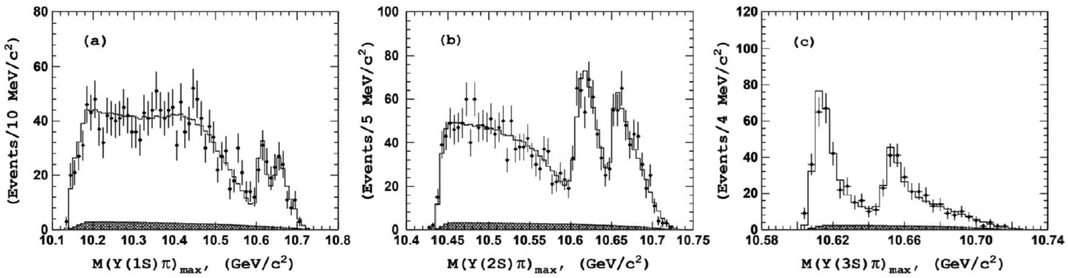

Figure 11: The distributions of $M_{\max}(\pi^\pm\Upsilon(1S, 2S, 3S))$ from Belle [58]. The open histograms are the fit results, and the points with error bars are the data for events in the (a) $\Upsilon(1S)$, (b) $\Upsilon(2S)$, and (c) $\Upsilon(3S)$ signal regions.

4. Summary

With the continuous accumulation of experimental data and the constant improvement of experimental analysis techniques, an increasing number of exotic hadrons have been discovered in experiments. These exotic hadrons exhibit properties that are distinctly different from those of ordinary hadrons. Regarding the exotic hadrons discovered experimentally, there remains significant theoretical uncertainty in their interpretation, particularly in how to comprehensively and self-consistently describe the majority of the observed exotic states within a unified theoretical framework. A particular challenge for theoretical studies is to properly account for the mixing of exotics with ordinary quarkonia, which may play an important role for some states.

To understand the existing XYZ states and finally understand the exotic hadrons, more efforts in both experiment and theory are needed. In experiment, we need to obtain more accurate information on the XYZs, including lineshapes and the resonance parameters for various the J^{PC} quantum numbers, the production and decay modes and so on. Whereas, on the theoretical side, we need improved calculations to more cleanly discriminate exotic hadrons from conventional hadronic states.

ACKNOWLEDGMENTS

This work is supported in part by National Key Research and Development Program of China under Grant No. 2024YFA1610503, National Natural Science Foundation of China under Grant No. 12161141008, and No. 12135005.

References

[1] For details, please see: https://qwg.ph.nat.tum.de/exoticshub/

[2] S. K. Choi *et al*. (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).

[3] B. Aubert *et al*. (BaBar Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).

[4] S. K. Choi *et al*. (Belle Collaboration), Phys. Rev. Lett. **100**, 142001 (2008).

[5] A. Bondar *et al*. (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2012).

[6] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. Lett. **110**, 222001 (2013).

[7] S. Navas *et al*. (Particle Data Group), Phys. Rev. D **110**, 030001 (2024).

[8] J. P. Lees *et al*. (BaBar Collaboration), Phys. Rev. Lett. **124**, 152001 (2020).

[9] M. Tanabashi *et al*. (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

[10] C. H. Li and C. Z. Yuan, Phys. Rev. D **100**, 094003 (2019).

[11] Sen Jia, Weitao Xiong, and Chengping Shen, Chin. Phys. Lett. **40**, 121301 (2023).

[12] R. Aaij *et al*. (LHCb Collaboration), Journal of High Energy Phys. **11**, 121 (2024).

[13] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **124**, 242001 (2020).

[14] S. Chatrchyan *et al*. (CMS Collaboration), Phys. Lett. B **727**, 57 (2013); G. Aad *et al*. (ATLAS Collaboration), Phys. Lett. B **740**, 199 (2015).

[15] X. H. He *et al*. (Belle Collaboration), Phys. Rev. Lett. **113**, 142001 (2014); I. Adachi *et al*. (Belle II Collaboration), Phys. Rev. Lett. **130**, 091902 (2023).

[16] T. Aaltonen *et al*. (CDF Collaboration), Phys. Rev. Lett. **102**, 242002 (2009).

[17] C. P. Shen *et al*. (Belle Collaboration), Phys. Rev. Lett. **104**, 112004 (2010).

[18] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. D **85**, 091103 (2012).

[19] S. Chatrchyan *et al*. (CMS Collaboration), Phys. Lett. B **734**, 261 (2014); V. M. Abazov *et al*. (D0 Collaboration), Phys. Rev. D **89**, 012004 (2014); V. M. Abazov *et al*. (D0 Collaboration), Phys. Rev. Lett. **115**, 232001 (2015).

[20] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. Lett. **118**, 022003 (2017); R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. D **95**, 012002 (2017).

[21] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. Lett. **127**, 082001 (2021).

[22] V. M. Abazov *et al*. (D0 Collaboration), Phys. Rev. Lett. **117**, 022003 (2016).

[23] V. M. Abazov *et al*. (D0 Collaboration), Phys. Rev. D **97**, 092004 (2018).

[24] T. Aaltonen *et al*. (CDF Collaboration), Phys. Rev. Lett. **120**, 202006 (2018).

[25] A. M. Sirunyan *et al*. (CMS Collaboration), Phys. Rev. Lett. **120**, 202005 (2018).

[26] M. Aaboud *et al*. (ATLAS Collaboration), Phys. Rev. Lett. **120**, 202007 (2018).

[27] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. Lett. **117**, 152003 (2016).

[28] R. Aaij *et al*. (LHCb Collaboration), Sci. Bull. **65**, 1983 (2020).

[29] G. Aad *et al*. (ATLAS Collaboration), Phys. Rev. Lett. **131**, 151902 (2023).

[30] A. Hayrapetyan *et al*. (CMS Collaboration), Phys. Rev. Lett. **132**, 111901 (2024).

[31] C. Z. Yuan *et al*. (Belle Collaboration), Phys. Rev. Lett. **99**, 182004 (2007).

[32] Z. Q. Liu *et al*. (Belle Collaboration), Phys. Rev. Lett. **110**, 252002 (2013).

[33] Q. He *et al*. (CLEO Collaboration), Phys. Rev. D **74**, 091104 (2006).

[34] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **118**, 092001 (2017).

[35] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **122**, 232002 (2019).

[36] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **130**, 121901 (2023).

[37] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. D **106**, 072001 (2022).

[38] J. P. Lees *et al*. (BaBar Collaboration), Phys. Rev. D **86**, 051102 (2012).

[39] G. Pakhlova *et al*. (Belle Collaboration), Phys. Rev. Lett. **101**, 172001 (2008).

[40] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **120**, 132001 (2018); M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **131**, 191901 (2023).

[41] M. Ablikim *et al*. (BESIII Collaboration), Chin. Phys. C **46**, 111002 (2022).

[42] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **131**, 211902 (2023).

[43] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. D **107**, 092005 (2023).

[44] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **131**, 151903 (2023).

[45] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **133**, 081901 (2024).

[46] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **133**, 261902 (2024).

[47] M. Ablikim *et al*. (BESIII Collaboration), Journal of High Energy Phys. **05**, 155 (2022).

[48] B. Aubert *et al*. (BaBar Collaboration), Phys. Rev. D **79**, 112001 (2009).

[49] K. Chilikin *et al*. (Belle Collaboration), Phys. Rev. D **88**, 074026 (2013).

[50] R. Aaij *et al*. (LHCb Collaboration), Phys. Rev. Lett. **112**, 222002 (2014).

[51] R. Mizuk *et al*. (Belle Collaboration), Phys. Rev. D **78**, 072004 (2008).

[52] J. P. Lees *et al*. (BaBar Collaboration), Phys. Rev. D **85**, 052003 (2012).

[53] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013).

[54] T. Xiao, S. Dobbs, A. Tomaradze, and Kamal K. Seth, Phys. Lett. B **727**, 366 (2013).

[55] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **113**, 212002 (2014).

[56] M. Ablikim *et al*. (BESIII Collaboration), Phys. Rev. Lett. **119**, 072001 (2014).

[57] Nora Brambilla, Simon Eidelman, Christoph Hanhart, Alexey Nefediev, Cheng-Ping Shen, Christopher E. Thomas, Antonio Vairo, and Chang-Zheng Yuan, Phys. Rept. **873**, 1 (2020).

[58] A. Bondar *et al*. (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2012).

[59] P. Krokovny *et al*. (Belle Collaboration), Phys. Rev. D **88**, 052016 (2013).

[60] A. Garmash *et al*. (Belle Collaboration), Phys. Rev. Lett. **116**, 212001 (2016).