PROCEEDINGS OF SCIENCE

Advances in experimental hadron physics

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Hadron spectroscopy serves as an indispensable tool for exploring the nonperturbative aspects of Quantum Chromodynamics and the mechanism of confinement. There has been an exciting period of recent two years, during which a significant number of new hadrons, mainly exotic candidates, have been discovered, primarily in the BESIII and LHCb experiments. This talk review the progresses on the experimental studies of the light and heavy hadrons. High-statistics data become crucial for identifying the exotic features of known states and discovering new particles. In the future, the upgraded BEPCII-U, Belle II and LHC RUN 3 experiments would be promising in boosting the studies of hadron physics.

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1. Introduction

Hadron spectroscopy stands as an indispensable tool for exploring the nonperturbative aspects of Quantum Chromodynamics (QCD), the theory that describes the strong interaction between quarks and gluons. The quark model, a simplified theoretical framework within QCD, posits that mesons are composed of a quark and an antiquark pair, while baryons are made up of three quarks. However, this model is merely a starting point for understanding the richness of the hadron spectrum predicted by QCD. Beyond the basic quark model, QCD suggests a more complex scenario where gluons play a significant role in binding quarks together and contribute to the overall mass and properties of hadrons. In addition to the standard mesons and baryons, QCD predicts the existence of more exotic states, such as glueballs (particles made entirely of gluons), hybrids (hadrons with valence gluonic excitations), and multiquark states like tetraquarks and pentaquarks. These states provide unique insights into the dynamics of quark confinement, a phenomenon where quarks are always found in bound states and cannot be isolated. While the theoretical framework of QCD is well-established, the mechanism of confinement remains one of the most challenging unsolved problems in modern physics. There have been many progresses in hadron spectroscopy since the last version of the ICHEP conference, during which overall more than 20 new hadrons are observed.

2. Light hadron spectroscopy

Based on quark model expectations, the experimental light meson spectrum appears to be overpopulated, which has inspired speculation about states beyond the $q\bar{q}$ picture, whereas fewer states have been observed in the baryon spectrum, which has led to the problem of the so-called missing baryon resonances. Even for several well-established baryons, their spins and parities have never been decisively determined and are based merely on quark model assignments, particularly for resonances involving strange quarks. Whether pure glueballs made of multiple gluons and hybrids made of gluons and quarks, as predicted by QCD, truly exist is still an open question. These are some of the important issues limiting the current understanding of hadron physics. Another critical and poorly studied sector is the strangeonium states, which can provide critical information on the connection between the light quark and heavy quark sectors. Hadron production via e^+e^- collisions plays an important role. Current and future experiments present a real opportunity for a dramatic improvement in our knowledge of the light hadron spectrum. Among them, BESIII is making great achievements in light hadrons since the last ICHEP conference. Quite a few new hadrons have been observed, especially the light exotic states.

One striking result is the observation of $\eta_1(1855)$ with exotic quantum number 1^{-+} in PWA of $J/\psi \to \gamma\eta\eta'$ based on 10B J/ψ events [1]. The exotic quantum number of the hadron state can not be formed with quark-antiquark meson state and must be exotic states. Furthermore, two new states of $h_1(1900)(1^{+-})$ and $X(2900)(1^{--})$ are observed in decaying into $\phi\eta$ in PWA of an isospin violating process $J/\psi \to \phi\eta\pi^0$ [2]. The $h_1(1900)$ can be the $h_1(2P)$ strangeonium state, while the $X(2000)$ can be associated to the $\phi(3S)$ or $\phi(2D)$ strangeonium states.

Based on about 18 fb^{-1} e^+e^- collision data collected at the energies between 3.5 GeV and 4.7 GeV, an enhancement near the $\Lambda\bar{\Lambda}$ mass threshold, denoted as $X(2356)$, is observed [3]. So

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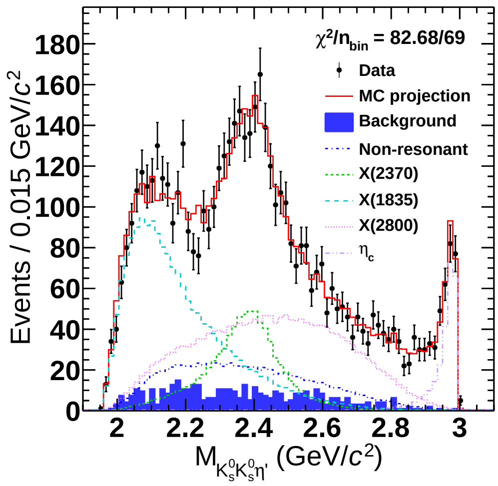

Figure 1: Fit projection to the invariant mass $M_{K_S^0 K_S^0 \eta'}$ spectrum with the requirement of $M_{K_S^0 K_S^0} < 1.1$ GeV$/c^2$, based on the PWA results of $J/\psi \to \gamma K_S^0 K_S^0 \eta'$. The component of the $X(2370)$ is plotted.

far there is no assignment of the $X(2356)$ to any known $q\bar{q}$ mesons and it could be candidate of hexaquark or baryonium states.

In addition, the light hadrons can be explored via charmed hadron weak decays. For example, the $a_0(1817)^+$ is firstly reported in charmed meson decay. A new decay channel of $a_0(1817)^+ \to K_S K^+$ is found in Dalitz analysis of $D_s^+ \to K_S K^+ \pi^0$ [4]. It is the isovector partner of the isosinglet state $f_0(1710)$, which has been considered to have large exotic components like glueball or $K^* \bar{K}^*$ molecule.

2.1 A glueball-like state $X(2370)$

The $X(2370)$ resonance was firstly observed in $J/\psi \to \gamma \pi^+ \pi^- \eta'$ in the mass spectrum of $\pi^+ \pi^- \eta'$ at BESIII [5], and later observed from the combined measurement of $J/\psi \to \gamma K^+ K^- \eta'$ and $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ at BESIII [6]. To understand the nature of the $X(2370)$, it is crucial to determine its quantum numbers J^{PC} and search for more decay modes. Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected at BESIII, a PWA of the decays $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is carried out [7], where the η' decays to the two most dominant channels $\eta' \to \gamma \pi^+ \pi^-$ and $\eta' \to \eta \pi^+ \pi^- (\eta \to \gamma\gamma)$ are used. The PWA fit indicates a contribution from $X(2370) \to K_S^0 K_S^0 \eta'$ with a statistical significance greater than 14σ. The spin-parity of the $X(2370)$ is determined to be 0^{-+} for the first time. Furthermore, according to preliminary studies at BESIII, the X(2370) along with the η_c are observed in decaying into other final states of $K_S^0 K_S^0 \pi^0$, $\pi^0 \pi^0 \eta$ and $a_0(980)^0 \pi^0$ via J/ψ radiative decays. The measured mass of the $X(2370)$ is in a good agreement with the mass prediction of the lightest pseudoscalar glueball, which is expected to be (2.395 ± 0.014) GeV$/c^2$ from latest LQCD calculations [8], although there exist other explanations on its nature.

2.2 Anomolous lineshape of the X(1840) in $J/\psi \to \gamma 3(\pi^+ \pi^-)$

In the BESII, CLEO-c and BESIII experiment, there have been observations of new resonance structures near the threshold of $p\bar{p}$, such as the X(1835) in $J/\psi \to \gamma \eta' \pi^+ \pi^-$ and $X(p\bar{p}$ in $J/\psi \to$

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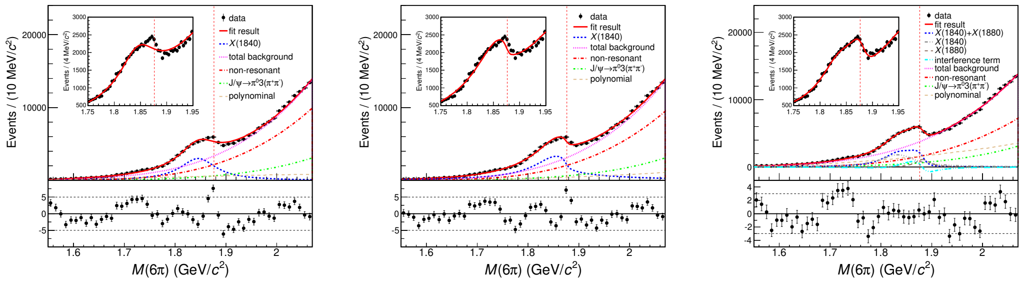

Figure 2: Fit to the $M(6\pi)$ distribution with a simple Breit-Wigner function (left), a Flatté model considering $p\bar{p}$ open channel (middle) and a model of two coherent resonance contributions (right). The dashed line in blue is the $X(1840)$ signal in the middle plot, and the sum of $X(1840)$ and $X(1880)$ in the right plot.

$\gamma p\bar{p}$ [9]. Among them, a prominent structure, $X(1840)$, was observed in decaying into $3(\pi^+\pi^-)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$ with a mass of $1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 and a width of $83 \pm 14 \pm 11$ MeV [10], which was interpreted as a new decay mode of $X(1835)$. Later on an updated analysis of the $X(1835)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$ with 1.1B J/ψ events observed a significantly abrupt lineshape change on the $X(1835)$ right at the position of the $p\bar{p}$ mass. This indicates that his lineshape change could be due to the opening of an additional $p\bar{p}$ decay channel (threshold effect) or the interference between two different resonance contributions [11]. To check whether a similar phenomenon for the $X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$, an improved study on the invariant mass $M(6\pi)$ spectrum with a sample of $(10087 \pm 44) \times 10^6$ J/ψ events, whose size is about 45 times greater than the previous work in Ref. [10], was conducted at BESIII.

As shown in Fig. 2, there is an obvious distortion of the lineshape at $M(p\bar{p})$ from the fit with a simple Breit-Wigner model of the $X(1840)$. To test the change on the lineshape at 1.84 GeV/c^2, two different models are tested: one is the opening channel for the $X(1840) \to p\bar{p}$ decay modeled with a Flatté function, and another is a coherent sum of two resonant structures. The observation of the common anomalous lineshape in the $M(6\pi)$ spectrum in $J/\psi \to \gamma 3(\pi^+\pi^-)$ and the $M(\pi^+\pi^-\eta')$ spectrum in $J/\psi \to \gamma\pi^+\pi^-\eta'$ reveal intriguing connections for the resonant structures near the $p\bar{p}$ mass threshold, which requires further investigation in experiment.

2.3 Opportunities of hyperon spectroscopy from charmed baryon decays

In the hyperon sector, during the last two years, there are several results on the hyperon spectroscopy using the charmed baryon decays. For example, 0.4M signals of $\Lambda_c^+ \to pK^-\pi^+$ are detected at LHCb, where a complicated PWA study is performed to extracted the involved Λ^* states decaying into pK^- [12]. By studying 1.5M yields of the same process, Belle reports a narrow peaking structure in the pK^- invariant mass spectrum near the $\Lambda\eta$ mass threshold [13]. By comparing different fit scenarios, the lineshape in data favors a cusp at the $\Lambda\eta$ threshold, and the obtained parameters are consistent with the known properties of $\Lambda(1670)$. Looking back to the LHCb analysis, the peak around $\Lambda\eta$ mass threshold in data presents a small deviation from the fit with the $\Lambda(1670)$ using a simple Breit-Wigner function, but it is not considered as significant in the LHCb PWA study.

Based on the threshold data of Λ_c^+ taken at BESIII, PWA studies are performed to explore the excited Λ^* and Σ^* states by using the open-source framework TF-PWA [16] in the decays of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ [14] and $\Lambda_c^+ \to \Lambda\pi^+\eta$ [15]. In both processes, $\Sigma(1385)$ are observed for the first

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time in the Λ_c^+ decays and the related decay rates, as well as decay asymmetries, are determined. In addition, Belle presents the observations of $\Lambda\pi^\pm$ invariant mass enhancements near the $N\bar{K}$ mass thresholds in the decay $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^-$ [17]. As the insufficient signal yields and the complexity of the backgrounds, the structure is indistinguishable between the $\Sigma(1430)$ resonances and $N\bar{K}$ threshold cusps.

3. Heavy hadron spectroscopy

3.1 The charmoniumlike states

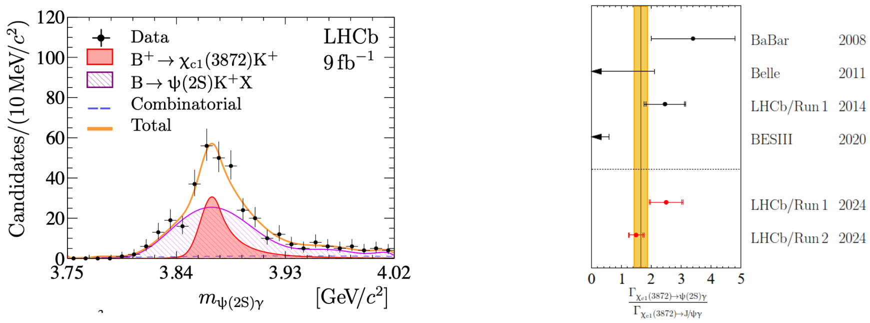

Figure 3: (left) Observation of the decay of $\chi_{c1}(3872) \to \psi(2S)\gamma$; (right) Comparison among different experimental results.

Charmoniumlike states, whose intrinsic constitution include the $c\bar{c}$ quark component, are difficult to be well fitted into any conventional charmonium states. The first such state, $\chi_{c1}(3872)$ (a.k.a $X(3872)$), was observed in 2003 at Belle in the $J/\psi\pi^+\pi^-$ mass spectrum via $B^+ \to J/\psi\pi^+\pi^-K^+$ decays [18]. There have been different hypotheses on its nature, such as a loosely-coupled $D^0\bar{D}^{*0} + \bar{D}^0D^{*0}$ molecular state, a $\chi_{c1}(3872)$ charmonium, a hadro-charmonium state, a hybrid meson or a compact tetraquark and their mixture. After many worldwide efforts during the past two decades, the properties of this state are still not clear. It is argued that the radiative decays of the $\chi_{c1}(3872)$ state into the $\psi(2S)\gamma$ and $J/\psi\gamma$ final states provides an independent way to probe its nature. The ratio of their branching fractions $\mathcal{R}_{\psi\gamma} = \mathcal{B}(\chi_{c1}(3872) \to \psi(2S)\gamma)/\mathcal{B}(\chi_{c1}(3872) \to J/\psi\gamma)$ cancel out many theoretical uncertainties on decay width and provides better discriminator on the nature of the $\chi_{c1}(3872)$. $\mathcal{R}_{\psi\gamma}$ has been studied at LHCb, Belle and BESIII. However the uncertainties are large due to the low statistics signal yields of the decay $\psi(2S)\gamma$. Recently, LHCb updated the analysis based on full RUN 1 and RUN 2 pp collision data via $B^+ \to \chi_{c1}(3872)K^+$. For the first time, as depicted in Fig. 3(left), LHCb establish the decay mode of $\chi_{c1}(3872) \to \psi(2S)\gamma$ with significance larger than 5σ, and the ratio is determined to be $\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$ [19]. As see in Fig. 3(right), the LHCb updated value is consistent with the previous measurements by the BaBar and LHCb collaborations. However, it is in tension with the upper limit set by BESIII. Overall, this large value of $\mathcal{R}_{\psi\gamma}$ disfavor the predictions based on the pure DD^* molecular hypothesis, hence, providing a strong argument in favor of a compact component in the $\chi_{c1}(3872)$ structure. However, some assumptions in molecular hypothesis could also enhance the ratio to the current experimental value [20, 21].

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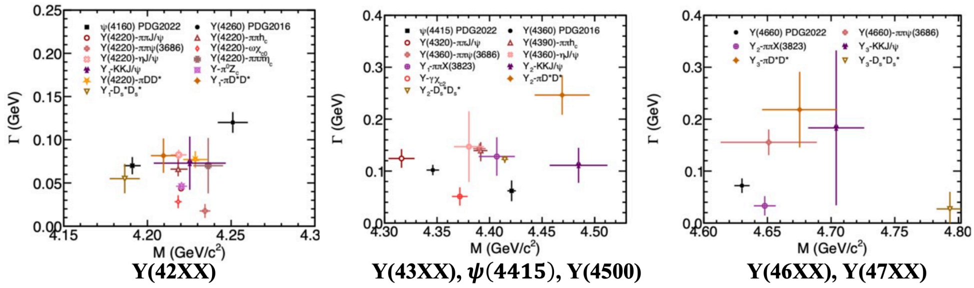

Figure 4: The vector charmoniumlike states, directly produced in e^+e^- annihilations, are divided into three energy groups.

For vector charmoniumlike states, denoted as Y states, BESIII has systematically studied many kinds of hidden and open charm final states from e^+e^- annihilations from $D\bar{D}$ threshold to 4.95 GeV, as listed in Fig. 4. BESIII has identified that the previous $Y(4260)$, observed at BaBar, is a coherent sum of the $Y(4220)$ and $Y(4320)$ states [22]. In the energy region between 4.3 GeV and 4.55 GeV, beside the $Y(4320)$, $Y(4360)$, $Y(4390)$ and $\psi(4415)$, which have been previously reported, there is a new $Y(4500)$ state observed in decaying into $K\bar{K}J/\psi$ [23, 24], $\omega\chi_{c1}$ [25] and $D^{*0}D^{*-}\pi^+$ [26]. In the energy region above 4.6 GeV, beside the $Y(4660)$, BESIII observes two new states of $Y(4710)$ and $Y(4790)$ in the final states of K^+K^-J/ψ [24], and $D_s^{*+}D_s^{*-}$ [26], respectively. As the newly established $Y(4500)$, $Y(4710)$ and $Y(4790)$ all have large rate of decaying into final state hadrons with $[s\bar{s}]$ components, the constitutions of these Y states could be exotic states consisting of the quark component of $[c\bar{c}s\bar{s}]$. Furthermore, BESIII have carried out a series of measurements of the cross sections of two-body open charm hadrons, such as $e^+e^- \to D_s^+D_s^-$ [27], $D^0\bar{D}^0$ and D^+D^- [28], which exhibit complicated distributions. Thus, couple channel analysis of the involved vector charmonium(like) states becomes necessary. BESIII also measures the cross sections of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ from threshold to 4.95 GeV with very high precisions [29]. As a result, it negates the existence of the $Y(4630)$, which is reported at Belle as a threshold enhancement in the $\Lambda_c^+\bar{\Lambda}_c^-$ mass spectrum in the initial-state-radiation (ISR) returned e^+e^- annihilations [30]. This indicates that there could be potentially overestimate the production cross sections near the threshold using the ISR technique. If we compare the cross sections of $e^+e^- \to D_s^+D_{s1}(2536)^-$ and $D_s^+D_{s2}^*(2573)^-$ between BESIII [31] and Belle [32, 33], we see the significant deviations on the cross section values near threshold.

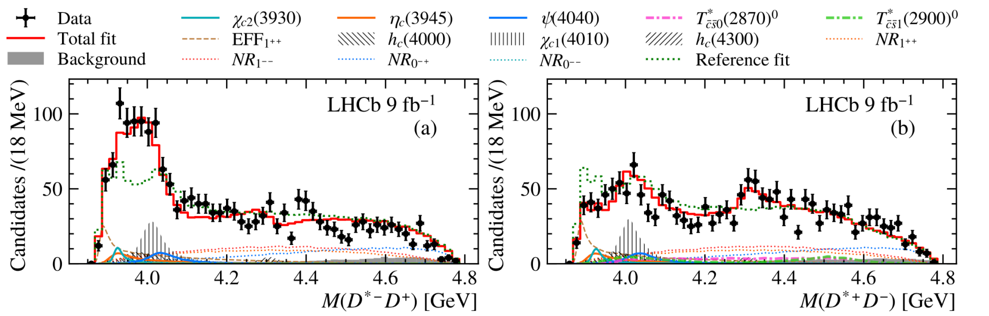

Figure 5: Projections of the simultaneous amplitude fits to the $B^+ \to D^{*-}D^+K^+$ (left) and $B^+ \to D^{*+}D^-K^+$ (right) samples.

At LHCb, amplitude analysis of $B^+ \to D_s^+D_s^-K+$ is conducted based on Run 1 and Run 2

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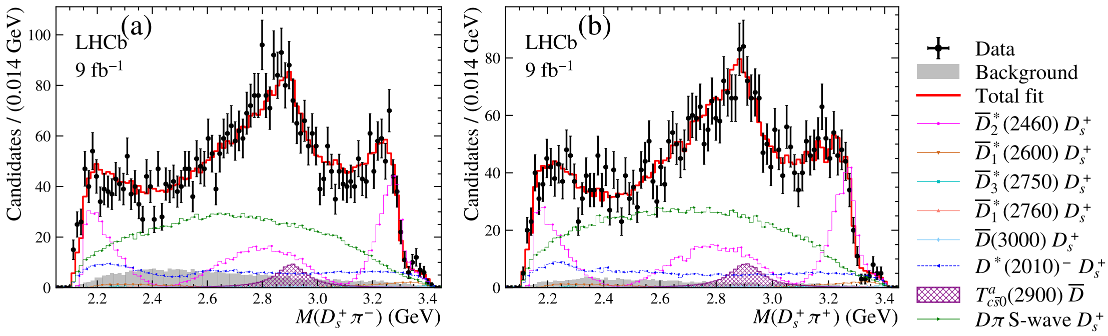

Figure 6: Fit projections to the distributions of (a) $M(D_s^+\pi^-)$ of $B^0 \to \bar{D}^0 D_s^+\pi^-$ decays; (b) $M(D_s^+\pi^+)$ for the $B^+ \to D^- D_s^+\pi^+$ sample.

data, in which a new charmoniumlike state $X(3960)$ is observed with $J^{PC} = 0^{++}$ in decaying into $D_s^+D_s^-$ [34]. This could be a candidate of exotic four-quark state with configuration of $[c\bar{c}s\bar{s}]$. Furthermore, for the first time a simultaneous amplitude analysis of the decay $B^+ \to D^{*\pm}D^{\mp}K^+$ decays is performed based on a pp collision data sample at Run 1 and Run 2 collected by LHCb, which exploits C-parity relations between contributions from charmonium(like) resonances in the two channels. As depicted in Fig. 5, four charmonium(like) resonances, $\eta_c(3945)$, $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$, decaying into $D^{*\pm}D^{\mp}$, are observed, with J^{PC} determined to be 0^{-+}, 1^{+-}, 1^{++} and 1^{+-}, respectively [35]. The $\eta_c(3945)$ is consistent with the previously observed $X(3940)$ state, while the other three are observed for the first time. In addition, the results confirm the existence of the $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}1}(2900)^0$ tetraquark states in a new production channel $B^+ \to D^{*+}T^*_{\bar{c}\bar{s}0,1}$. These results provide new insights into charmonium(like) spectroscopy.

The charged charmoniumlike states with strangeness of $Z_{cs}(3985)^+$ is observed in decaying into $D_s^{*+}\bar{D}^0 + D_s^+\bar{D}^{*0}$ at BESIII [36], while $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ are observed in decaying into K^+J/ψ at LHCb [37]. Later on, an evidence of the neutral partner of the $Z_{cs}(3985)^+$ is seen in the process $e^+e^- \to K_S^0(D_s^{*+}D^- + D_s^+D^{*-})$, which confirm the tetraquark state $Z_{cs}(3985)$ by identifying the isovector partners [38]. In addition, LHCb perform simultaneous fits to the processes $B^0 \to J/\psi\phi K_S^0$ and $B^+ \to J/\psi\phi K^+$ assuming isospin symmetry [39] and the neutral $Z_{cs}(4000)^0$ is seen. Moreover, three new neutral Z_{cs} states, $T_{c\bar{c}\bar{s}1}(4600)^0$, $T_{c\bar{c}\bar{s}1}(4900)^0$ and $T_{c\bar{c}\bar{s}1}(5200)^0$ are observed in a 7-dimensional amplitude analysis of high-statistics $B^+ \to \psi(2S)K^+\pi^+\pi^-$ [40].

3.2 Open charm tetraquarks

Based on RUN 1 and RUN 2 data at LHCb, a combined amplitude analysis of the $B^0 \to \bar{D}^0D_s^+\pi^-$ and $B^+ \to D^-D_s^+\pi^+$ decays is performed, under the assumption of isospin symmetry. Two new $D_s\pi$ exotic resonances are observed, as depicted in Fig. 6, and the common mass and width are determined to be $m = 2.908 \pm 0.011 \pm 0.020 \mathrm{GeV}/c^2$ and $\Gamma = 0.136 \pm 0.023 \pm 0.013 \mathrm{GeV}$, respectively, with spin-parities determined to be 0^+ [40, 41]. The $D_s^+\pi^+$ resonance state, $T^*_{c\bar{s}++}(2900)$, indicates the first observation of a doubly charged open-charm tetraquark state with minimal quark content $[c\bar{s}u\bar{d}]$, and the $D_s^+\pi^-$ state $T^*_{c\bar{s}0}(2900)$, is a neutral tetraquark composed of $[c\bar{s}\bar{u}d]$ quarks. They belong to a new type of open-charm tetraquark states with c and $\bar{s}$ quarks. The obtained mass of the $T^*_{c\bar{s}0}(2900)$ state is consistent with that of another 0^+ open-charm tetraquark, the $X_0(2900)^0([cs\bar{u}\bar{d}])$

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state discovered in the D^+K^- final state [42], but their widths and flavor contents are different.

3.3 Fully charmed tetraquarks

After the fully charmed tetraquark $X(6900)$ discovered at LHCb in the double J/ψ final states, CMS and ATLAS carries out search for near-threshold structures in the $J/\psi J/\psi$ invariant mass spectrum produced in pp collisions at 13 TeV [43, 44] and confirm the $X(6900)$ in the both experiments. Additionally, CMS observes a new structure $X(6600)$ and find an evidence of the $X(7100)$. ATLAS also conducts studies on the $J/\psi\psi(2S)$ final states and finds evidence of enhancement around 6.9 GeV [44]. Meanwhile, Belle looks for the fully charmed tetraquarks in the $\eta_c J/\psi$ final states and finds evidence of threshold enhancement in both inclusive and exclusive channels [45].

3.4 Pentaquark states with strangeness

In 2021, LHCb found first evidence for $[c\bar{c}uds]$ pentaquark candidate with strangeness $P_{c\bar{c}s}(4459)^0$ in $\Xi_b^- \to J/\psi\Lambda K^-$ [46]. This state is searched for in inclusive $\Upsilon(1S, 2s)$ decays and an evidence of $P_{c\bar{c}s}(4459)^0 \to J/\psi\Lambda$ with local significance of 4.0σ is reported.

Meanwhile, with full LHCb RUN 1 and RUN 2 data, an amplitude analysis of the process $B^- \to J/\psi\Lambda\bar{p}$ is implemented and a narrow structure $P_{c\bar{c}s}(4338)^0$ in the $J/\psi\Lambda$ mass spectrum is extracted with significance larger than 10σ. This is the first hidden-charm strange pentaquark. The spin-parity $\frac{1}{2}^-$ is preferred and its mass is close to $\Xi_c^+ D^-$ threshold [47].

4. Summary and Prospects

It has been an exciting period of recent two years during which a significant number of new hadrons, mainly exotic candidates, have been discovered, primarily through experiments at BESIII and LHCb. The discoveries are categorized into light and heavy hadrons, each with its unique findings and implications for the field of particle physics.

In the realm of light hadrons, high-statistics data is crucial for identifying the exotic features of known states and discovering new particles. A notable example is the $X(2370)$, which has properties consistent with a glueball state, a hypothetical particle composed entirely of gluons. Additionally, there is evidence of emerging strangenium-like states, characterized by distorted lineshapes at the thresholds of certain particle combinations, such as $p\bar{p}$, $N\bar{K}$ and $\Lambda\eta$ pairs. These distortions could indicate the nature of the decaying hadrons.

Regarding heavy hadrons, there have been advancements in understanding better the $X(3872)$ particle, particularly through studies of its radiative decays, which provide insights into its internal structure. Moreover, 8 neutral charmonium(like) states, 7 tetraquark states with strangeness, and 1 pentaquark state with strangeness have been identified.

Looking forward, more promising studies are foreseen based on even higher statistics data, thanks to the upcoming upgraded BEPCII-U, the ongoing LHC Run 3, and the ongoing Belle II experiment. These future endeavors would further enrich our knowledge of the hadron spectrum, potentially uncovering more exotic states and refining our understanding of QCD. This worldwide effort will ultimately constrain the standard model of particle physics.

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