PROCEEDINGS OF SCIENCE

Recent results on spectroscopy with LHCb

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The most recent LHCb results related to heavy hadron spectroscopy, encompassing both conventional and exotic states, have been reported. These results include the observation of new Ω_c^0 states, the first observation of a doubly charged tetraquark candidate and its neutral partner, the observation of a $c\bar{c}s\bar{s}$ candidate, $X(3960)$, evidence of a neutral hidden-charm tetraquark candidate with strangeness, and the first observation of a strange pentaquark candidate, $P_{\psi s}^{\Lambda}(4338)^0$.

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[*] Speaker

1. Introduction

Hadron spectroscopy is the study of meson and baryon spectra, as well as the search for exotic states. Similar to atomic spectra, where precise details led to the development of Quantum Electrodynamics (QED), hadron spectra beautifully encode the complex properties of Quantum Chromodynamics (QCD). Meson and baryon spectra provide an ideal platform for the study of quark-quark interactions and colour degrees of freedom. Exotic states, with quark configurations other than three quarks or quark-antiquark pairs, can reveal new or hidden aspects of the dynamics of strong interactions, which are described by QCD. While QCD is well-tested at high energies, where the strong coupling constant α_s is sufficiently small for perturbation theory to apply, it becomes a strongly coupled theory in the low-energy regime, where many aspects still await a better understanding. Because interactions within quark-formed hadrons occur in this regime, extensive and precise spectroscopy, particularly of exotic states, combined with a thorough theoretical analysis of the data, will significantly contribute to our knowledge. Here, I discuss the most recent studies on hadron spectroscopy performed by the LHCb collaboration.

2. Observation of new Ω_c^0 states

Back to 2017, LHCb experiment reported the observation of five new narrow Ω_c^0 states that decay into $\Xi_c^+ K^-$ final state [1] [1]. Four of them have been confirmed by the Belle experiment and also studied in the $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays at LHCb [2]. With additional 2016-2018 data, corresponding to about five times larger sample size compared to the previous publication, two new excited states, $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$, are observed. The previously observed five Ω_c^0 states are also confirmed [3]. The invariant-mass distribution of $\Xi_c^+ K^-$ is shown in Fig. 1. The quantum numbers of these states are remained to be determined. One interesting thing is that the two new states are very close to the mass thresholds of ΞD and ΞD^*.

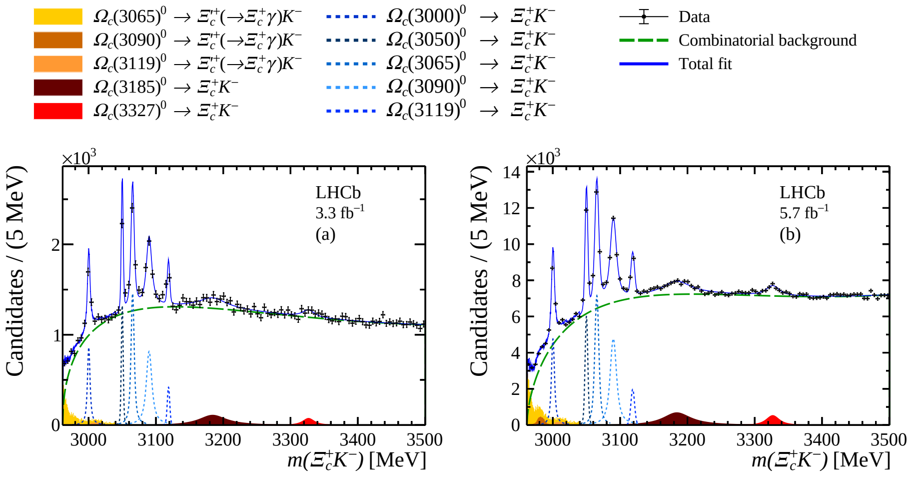

Figure 1: Invariant-mass distribution of the $\Omega_c(X)^0$ candidates in (a) 2011-2015 and (b) 2016-2018 datasets.

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[1] The inclusion of charge-conjugate processes is always implied and natural units with $\hbar = c = 1$ are used throughout the proceedings.

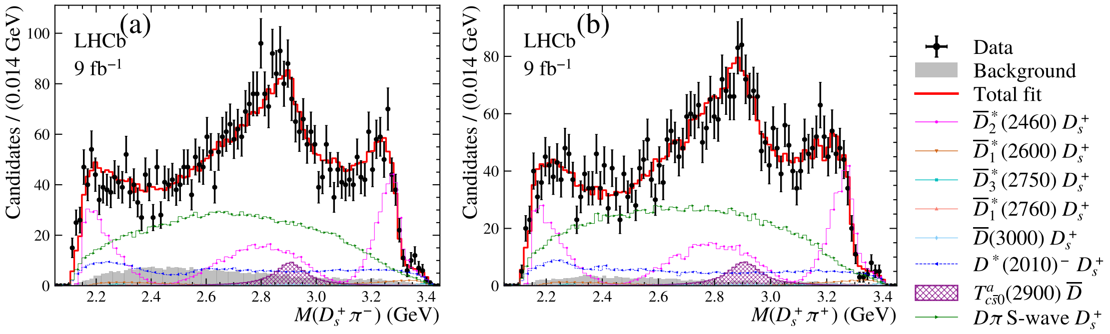

Figure 2: Distributions of (a) $M(D_s^+\pi^-)$ of $B^0 \to \bar{D}^0 D_s^+\pi^-$ decays; and (b) $M(D_s^+\pi^+)$ of $B^+ \to D^- D_s^+\pi^+$ decays, overlaid with the fit results with the inclusion of the new 0^+ $D_s^+\pi$ resonant states.

3. First observation of a doubly charged tetraquark candidate and its neutral partner

With an amplitude analysis of the $B^+ \to D^+D^-K^+$ decays, the LHCb collaboration discovered the first open-charm tetraquark candidates $X_{0,1}(2900)$ with four different flavours ($cs\bar{u}\bar{d}$) in the D^-K^+ system [4, 5]. This motivates the study of $B^0 \to \bar{D}^0 D_s^+\pi^-$ and $B^+ \to D^- D_s^+\pi^+$ decays, in which the two channels are related by isospin symmetry [6].

Using the full run-1 and run-2 LHCb data, 4420 $B^0 \to \bar{D}^0 D_s^+\pi^-$ and 3940 $B^+ \to D^- D_s^+\pi^+$ signal decays are reconstructed with purity more than 90%. The Dalitz-plot distributions for the two channels shows a faint horizontal band for the $D_s^+\pi^\pm$ invariant-mass squared at 8.5 GeV^2. The two decays are analyzed simultaneously with amplitude model assuming isospin symmetry. Fit with only excited charm resonances cannot described the data well. Then $D_s^+\pi^\pm$ resonances sharing their mass and width is tested, and the fit is significantly improved, with significance $> 9\,\sigma$. This gives the first observation of a doubly charged tetraquark candidate. The measured mass and width are $2.908 \pm 0.011 \pm 0.020$ GeV and $0.136 \pm 0.023 \pm 0.011$ GeV, respectively, thus named $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$. Throughout the proceedings, whenever uncertainties are shown, the first is the statistical and the second is the systematic. The fit projections are shown in Fig. 2. The spin-parity 0^+ is favored over than other hypothesis by more than $7.5\,\sigma$. Comparing with $X_0(2900)$ state, the observed $T^a_{c\bar{s}0}(2900)$ have similar mass, but larger width, and different flavour content $c\bar{s}\bar{u}d$ or $c\bar{s}u\bar{d}$. The amplitude analysis without isospin-symmetry assumption is detailed in Ref. [7].

4. First observation of $B^+ \to D_s^+D_s^-K^+$ decays and observation of $X(3960)$

The decay $B^+ \to D_s^+D_s^-K^+$ has never been explored, which can provide information for the charmonium(-like) spectroscopy from the $D_s^+D_s^-$ system, charm spectroscopy from the $D_s^-K^+$ system. With the full run-1 and run-2 LHCb data, the $B^+ \to D_s^+D_s^-K^+$ is observed for the first time [8]. The signal yield is 360 ± 22 and signal purity about 85%. The relative branching ratio with respect to the control channel $B^+ \to D^+D^-K^+$ is measured to be $0.525 \pm 0.033 \pm 0.027 \pm 0.034$, where the last uncertainty is due to the uncertainties on the branching fractions of the $D_s^\pm \to K^\mp K^\pm \pi^\pm$ and $D^\pm \to K^\mp \pi^\pm \pi^\pm$ decays.

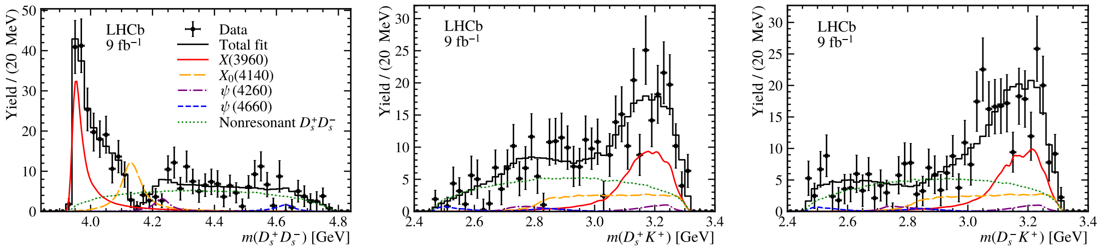

Figure 3: Invariant-mass distributions of the $B^+ \to D_s^+ D_s^- K^+$ decays, superimposed with fit projections.

The Dalitz-plot distribution shows a prominent near-threshold enhancement in the $D_s^+ D_s^-$ invariant mass, which is studied by an amplitude analysis [9]. The baseline model includes the threshold resonance structure $X(3960)$, resonance $X_0(4140)$, $\psi(4260)$, $\psi(4660)$ and a non-resonant contribution. The fit projections are shown in Fig. 3. The mass and width are determined to be $3956 \pm 5 \pm 10\,\text{MeV}$ and $43 \pm 13 \pm 8\,\text{MeV}$ for the $X(3960)$ structure respectively, with more than $12.6\,\sigma$ significance and $J^{PC} = 0^{++}$.

The measured mass and width of the $X(3960)$ state are consistent with those of the $\chi_{c0}(3930)$ meson [5] within $3\,\sigma$. Assuming the $X(3960)$ and $\chi_{c0}(3930)$ states are the same particle, the partial width ratio of such an X resonance is calculated as $\Gamma(X \to D^+D^-)/\Gamma(X \to D_s^+D_s^-) = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$, where the third error is systematic due to uncertainties on the measured branching fractions and fit fractions. Due to the facts that the creation of an $s\bar{s}$ quark pair from the vacuum is suppressed relative to $u\bar{u}$ or $d\bar{d}$ pairs, and $X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$, a conventional charmonium at this mass should have $\Gamma(X \to D^+D^-)$ considerably larger than $\Gamma(X \to D_s^+D_s^-)$. However, the value measured contradicts this expectation. This implies that the $X(3960)$ and $\chi_{c0}(3930)$ are the same non-conventional charmonium-like state, for instance, a candidate containing the dominant $c\bar{c}s\bar{s}$ constituents. If $X(3960)$ and $\chi_{c0}(3930)$ states are different particles, since they have similar mass, no obvious candidate within conventional charmonium multiplets can account for them; therefore at lease one of them is likely to be exotic.

5. Evidence of a $J/\psi K^0_S$ structure

Tetraquark candidates with new quark content ($c\bar{c}u\bar{s}$) have been observed since 2020. The state $Z_{cs}(3985)^+$ was observed by the BESIII experiment in the $D_s^+\bar{D}^{*0}$ and $D_s^{*+}\bar{D}^0$ mass spectra [10]. Two similar states, $Z_{cs}(4000)^+$, and $Z_{cs}(4220)^+$ were observed in $B^+ \to J/\psi\phi K^+$ decays by the LHCb experiment [11]. Interestingly, similar masses but very different widths are observed for the two states $Z_{cs}(3985)^+$ and $Z_{cs}(4000)^+$. Further studies may shed lights on the nature of those Z_{cs} states. One of such studies is to search for the isospin partners of those charged states.

Recently, the BESIII experiment reported evidence for the $Z_{cs}(3985)^0$ state ($c\bar{c}d\bar{s}$) in the $D_s^+D^{*-}$ and $D_s^{*+}D^-$ mass spectra [12]. The LHCb collaboration uses the $B^0 \to J/\psi\phi K^0_S$ decay, and found an evidence for the isospin partner of $Z_{cs}(4000)^+$ state [13]. Here we use LHCb new convention for exotic states, and denote Z_{cs} as $T_{\psi s}$ [14].

With LHCb full run1 and run2 data, about 2000 $B^0 \to J/\psi\phi K^0_S$ signal decays are reconstructed with a signal purity of more than 90%. Amplitude analysis is performed. Due to limited statistics, simultaneous fit is done to both the neutral and charged B decays, assuming isospin symmetry for

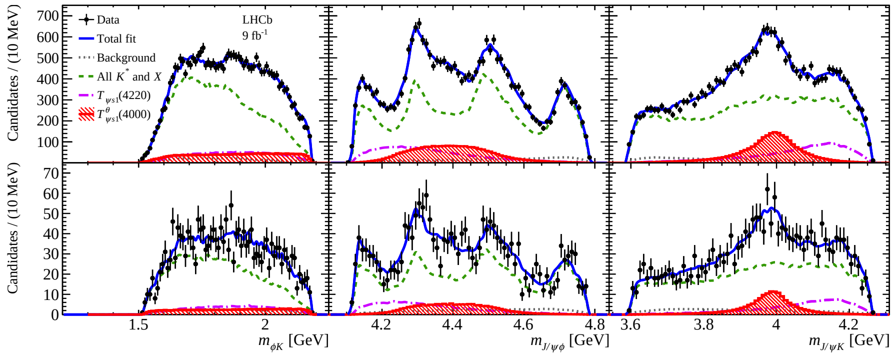

Figure 4: Distributions of (left) $m_{\phi K}$, (middle) $m_{J/\psi\phi}$, and (right) $m_{J/\psi K}$, overlaid with the corresponding projections of the default fit model. The upper and lower rows correspond to the $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K^0_S$ decays, respectively.

all the intermediate states, except for the charged and neutral $T^{\theta}_{\psi s1}(4000)$ states. Figure 4 shows the projections of invariant masses from the amplitude fit, which well reproduces the data for both decays. The mass different between the charged and neutral $T^{\theta}_{\psi s1}(4000)$ states is measured to be $-12.1^{+11.1+6.0}_{-10.2-4.2}$ MeV, consistent with being isospin partners. The significance for the neutral $T^{\theta}_{\psi s1}(4000)$ is determined to be $4.0\,\sigma$ without isospin symmetry requirement for $T^{\theta}_{\psi s1}(4000)$, while is increased to $5.4\,\sigma$ if with isospin symmetry constrain. This constructs the first evidence for the $T^{\theta}_{\psi s1}(4000)$ state.

6. First observation of a strange pentaquark candidate

The $B^- \to J/\psi\Lambda\overline{p}$ decay provides good opportunity to search for pentaquark states in both $J/\psi\overline{p}$ and $J/\psi\Lambda$. With LHCb full run1 and run2 data, about 4600 signal decays are reconstructed with very high purity. Its Dalitz-plot reveals a clear peak in the invariant mass of $J/\psi\Lambda$ at high mass threshold. An amplitude analysis is performed to the data sample, which can be modelled by a coherent sum of $J/\psi\overline{p}$ and $J/\psi\Lambda$ non-resonant contributions and a $J/\psi\Lambda$ resonance. The resonance contains at least five quarks $c\bar{c}sud$, consistent with strange pentaquark. The resonance, named as $P^{\Lambda}_{\psi s}(4338)^0$, has a Breit-Wigner mass $4338.2 \pm 0.7 \pm 0.4$ MeV, which is just at $\Xi_c^+ D^-$ threshold, and a narrow width $7.0 \pm 1.2 \pm 1.3$ MeV [15]. Figure 5 shows the mass fit projections. Similar properties that the mass is just below corresponding charm baryon and anti-charm meson threshold with a narrow width are found for all the previous observed pentaquark candidates $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ in $\Lambda^0_b \to J/\psi p K^-$ decays [16], and strange pentaquark candidate $P_{cs}(4459)^0$ in $\Xi^-_b \to J/\psi\Lambda K^-$ decays with $> 3.1\,\sigma$ significance [17].

7. Summary

In summary, many important results on heavy hadron spectroscopy for conventional and exotic states have been obtained by the LHCb experiments at high energy pp collisions. So far 64 new hadrons are observed by LHCb [18]. With the upgraded LHCb detector and an improved software-only trigger system in Run 3, more exciting results are to come!

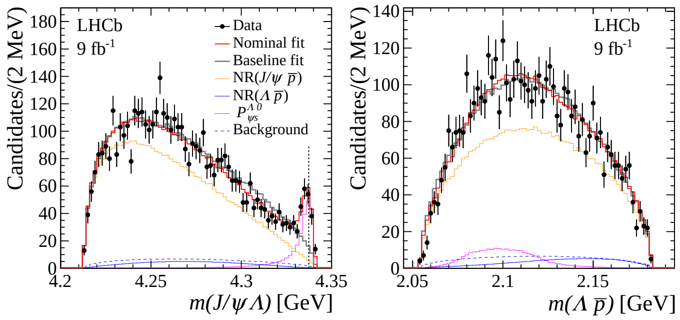

Figure 5: Distributions of (left) $m_{J/\psi\Lambda}$ and (right) $m_{\Lambda\overline{p}}$ from $B^- \to J/\psi\Lambda\overline{p}$ decays, overlaid with the corresponding projections of the nominal fit model.

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