

XYZ STATES AT THE LHCb*

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The recent results obtained in the sector of heavy-flavour spectroscopy of exotic states are presented. The observation of hidden-charm pentaquarks is reviewed, followed by the presentation of new evidences for X and Z states.

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1. Introduction

Since 2003, around thirty new, heavy and potentially exotic states have been observed by various experiments. Most of them are charmonium ($c\bar{c}$) or bottomonium ($b\bar{b}$) like (see [1] for a recent review). As “standard” will be referred the states with the most economical content of valence quark combinations *i.e.* $q\bar{q}$ for mesons and qqq for baryons, all the other, which cannot be accommodated to this scheme, will be labelled “exotic”. This broad category encompasses in particular tetraquarks, pentaquarks, dibaryons, hybrid mesons, glueballs and molecules like *e.g.* meson–anti-meson bound states.

The LHCb spectrometer [2, 3] is the first hadron-collider experiment that is designed for heavy flavour physics and characterised by forward geometry. The results discussed in this article correspond to the data sample with the integrated luminosity of 3 fb^{-1} of pp collisions data at $\sqrt{s} = 7 \text{ TeV}$ and 8 TeV recorded in 2011–12 during Run 1. Even more abundant data sample (3.7 fb^{-1}) was collected in 2015–17, with higher cross sections for heavy-hadron production and substantial improvements in the LHCb trigger. Thus, the precision of all results presented below should be substantially improved in the near future.

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The paper is organized as follows. First, the status of pentaquark studies is presented (Sec. 2). This will be followed by the discussion of two families of X states (Sec. 3) and of the charged exotic state $Z(4430)^-$ (Sec. 4).

2. Pentaquarks studies

The pentaquarks *i.e.* bound states composed of four quarks and an anti-quark¹ have been considered from the onset of the quark model [4]. However, in spite of intense searches carried on mainly in the sector of light-quark states, no single indisputable pentaquark have been observed [5].

In 2015, the LHCb Collaboration has provided the first observation of the decay $\Lambda_b^0 \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+ \mu^-$ [6] with large sample of 26007 ± 166 signal candidates containing 5.4% background within ± 15 MeV ($\pm 2\sigma$) of the $J/\psi p K^-$ mass peak. As seen in the Dalitz plot of m_{Kp}^2 versus $m_{J/\psi p}^2$ (Fig. 1), the dynamics of the decay in question is characterised not only by the presence of the Λ^* resonances (dense region on the left part of the plot), but also exhibits an anomalous peaking structure in the $J/\psi p$ -invariant mass spectrum (horizontal band on the plot). The latter was interpreted as the presence of a resonance(s) strongly decaying into $J/\psi p$ pair. For such a state(s), the minimal content of valence quarks should be $uudc\bar{c}$. Thus, it would be classified as a hidden-charm (charmonium) pentaquark(s) decaying strongly to $J/\psi p$.

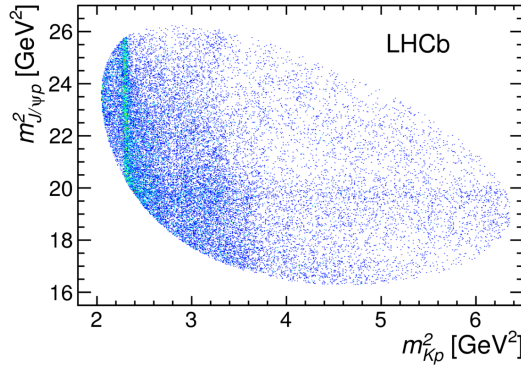


Fig. 1. The Dalitz plot of m_{Kp}^2 versus $m_{J/\psi p}^2$ for candidates within ± 15 MeV of the Λ_b^0 mass.

The full amplitude analysis (AA) using the helicity formalism has been applied in order to determine the resonances present. It was based on six observables: the invariant mass of the $J/\psi p$ system, three helicity angles

¹ The inclusion of charge conjugate modes is implied throughout this paper.

and two angles between the respective two-body decay planes. The study took into account 14 known Λ^* resonances, described by the Breit–Wigner (BW) amplitudes. To obtain a satisfactory description of the data, it was necessary to add two resonances, characterised by the two additional BW amplitudes and labelled P_c (the P referring to pentaquarks). The model allowed also for interference between the decays $\Lambda_b^0 \rightarrow J/\psi \Lambda^* (\rightarrow p K^-)$ and $\Lambda_b^0 \rightarrow P_c^+ (\rightarrow J/\psi p) K^-$. With the above-defined amplitude analysis, the masses and widths of the two P_c states were measured (*cf.* Table I). The spin-parity values have been measured as well with the assignment giving the best fit which is presented as first, and its alternative in parenthesis.

TABLE I

Selected parameters of the P_c states.

State	Signif. [σ]	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	9	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^- \left(\frac{3}{2}^+ \right)$
$P_c(4450)^+$	12	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+ \left(\frac{5}{2}^- \right)$

The amplitude analysis approach is very powerful, however, it requires a detailed knowledge about the Λ^* resonances. The uncertainties related to these states are the source of important systematic errors for pentaquark candidates. Due to this fact, the LHCb Collaboration has extended the studies of the $\Lambda_b \rightarrow J/\psi p K^-$ data sample by using a model-independent (MI) approach [6, 7]. The former does not require any detailed knowledge about the Λ^* resonances. This advantage comes at a price that MI method can only provide indication about the presence of exotic states. It was based on the expansion of the cosine of the helicity angle of the K^-p system into Legendre polynomials. The expansion is carried out in several bins of the K^-p -invariant mass and its coefficients, so-called Legendre moments (LM) containing all the information about the angular structure of the system. The K^-p components cannot contribute to LM of rank higher than $2J_{s_{\max}}$, where $J_{\max}$ is the highest spin of any known Λ^* resonance at the given m_{Kp} value. The model-independent approach demonstrated at more than nine standard deviations that $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays cannot be described with K^-p contributions alone. Moreover, it was shown that an inclusion of $J/\psi p$ contributions yields a good description of data.

The LHCb Collaboration has extended the search for pentaquarks by observing for the first time the decay $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ [8], which is Cabibbo suppressed as compared with $\Lambda_b^0 \rightarrow J/\psi p K^-$. With 1885 ± 50 signal candidates, both the AA and MI approaches were applied. The following contributions to the overall decay amplitude were taken into consideration: a standard

one from $\Lambda_b \rightarrow J/\psi N^*(\rightarrow p\psi^-)$ and three exotic $\Lambda_b \rightarrow P_c(\rightarrow J/\psi p)\pi^-$ (P_c denotes $P_c(4380)^+$ and $P_c(4450)^+$ states) and $\Lambda_b \rightarrow Z_c(4200)^-(\rightarrow J/\psi\pi^-)p$. The particle $Z(4200)^-$ was observed first by the Belle Collaboration [9]. The LHCb analysis confirmed the existence of exotic contributions in the decay in question with a significance of more than three standard deviations.

The decays $\Lambda_b \rightarrow \chi_{c1}pK^-$ and $\Lambda_b \rightarrow \chi_{c1}pK^-$ were observed for the first time by the LHCb Collaboration with high statistical significance exceeding 17 and with 453 ± 25 and 285 ± 23 signal events, respectively. Due to the closeness of the $P_c(4450)^+$ mass to the $\chi_{c1}p$ threshold, the observation of the decay $\Lambda_b \rightarrow \chi_{c1}pK^-$ provides a litmus test for the nature of the $P_c(4450)^+$ state: the lack of an enhancement near the $\chi_{c1}p$ would indicate that the $P_c(4450)^+$ is not a resonance but rather a kinematic rescattering effect [10]. This hypothesis can be tested in the near future when Run 2 data will be analysed.

The LHCb hunt for pentaquarks has been also extended in two additional directions: searches for hidden-charmonium strange states and for b -flavoured pentaquarks decaying weakly. The former was based on the observation of the decay $\Xi_b \rightarrow J/\psi \Lambda K^-$ [11] (320 signal events; statistical significance 21σ). Here, the decisive searches for pentaquarks will be performed with larger data samples of Run 2.

The b -flavoured pentaquarks are predicted in particular in the Skyrme model [12]. These states are expected to decay via the weak interaction, be tightly bound and narrow ($\Gamma \sim 4$ MeV). The LHCb has searched for such pentaquarks, labelled P_b and decaying into four specific final states: $J/\psi K^+\pi^-p$, $J/\psi K^-\pi^-p$, $J/\psi K^-\pi^+p$ and $J/\psi\phi(1020)p$ [13]. No signals have been observed and upper limits at the level 10^{-2} – 10^{-3} (90% C.L.) were set on the product of the production cross section times branching fraction, evaluated w.r.t. that of the Λ_b^0 .

3. X states

Since 2009, there have been several evidences [1] for the two states, denoted as $X(4140)$ and $X(4274)$, and decaying to $J/\psi\phi$. The LHCb collected large sample of 4289 ± 151 candidates of $B^+ \rightarrow J/\psi\phi K^+$ decay (with background fraction of 23%) which allowed to perform, for the first time, the amplitude analysis [14]. The latter was using the similar six kinematical variables as in Sec. 2. The AA approach aimed at resolving the $K^* \rightarrow K\phi$ contributions from the potential $X \rightarrow J/\psi\phi$ resonances. The data were not represented properly while assuming only amplitudes from excited kaon states. The good description was provided only upon the inclusion of four broad exotic resonances. Their parameters are collected in Table II.

TABLE II

Selected parameters of the X states decaying to $J/\psi\phi$.

State	Signif. [σ]	Mass [MeV]	Width [MeV]	J^{PC}
$X(4140)$	8.4	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
$X(4274)$	6.0	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++}
$X(4500)$	6.1	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
$X(4700)$	5.6	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

The LHCb Collaboration has also searched for the particle $X(5568)$ decaying into $B_s^0\pi^\pm$ [15]. This state was evidenced by the DØ experiment [16, 17]. However, the study of the LHCb Collaboration did not confirm the existence of $X(5568)$.

4. Z states

The charged charmonium-like state $Z(4430)^-$ was first evidenced by Belle in 2008 [18] in the $\psi'\pi$ mass distribution while studying the decay $B^0 \rightarrow \psi'\pi^- K^+$. Based on a large data sample of 25176 ± 174 candidates of the decay in question, the LHCb Collaboration was able to perform both the amplitude analysis (with four variables) [19] together with a model-independent approach [20]. These studies fully confirmed the existence of the exotic state $Z(4430)^-$, yielding the precise measurements of mass (width) of $4485 \pm 22^{+28}_{-11}$ MeV (200^{+41+26}_{-46-35} MeV). Moreover, the spin-parity of $Z(4430)^-$ was determined unambiguously for the first time to be 1^+ .

5. Summary

The status of recent LHCb studies of pentaquarks, X and Z states has been briefly reviewed.

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