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# Hadron spectroscopy at LHCb

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**Summary.** — The latest results on spectroscopy of conventional and exotic hadrons at the LHCb experiment are reviewed, such as the discovery of the first charmonium pentaquark states in the $J/\psi p$ invariant mass or the observation of five new narrow $\Omega_c^0$ states.

## 1. – Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b \to J/\psi K^- p$ decays

From the birth of the quark model by Gell-Mann and Zweig in the 1960s, it has been proposed that hadrons could be constructed also from multi-quark states. A large sample of $\Lambda_b^0 \to J/\psi K^- p$ decays with a high signal-to-noise ratio is available at LHCb [1]. An anomalous peaking structure in the $J/\psi p$ invariant mass spectrum, whose minimum quark content would be $c\bar{c}uud$, is observed in the Dalitz plot near $19.5\,\mathrm{GeV}/c^2$ shown in fig. 1 (left). A six-dimensional fit, has been performed on the data in order to understand if the observed structures are not due to reflections of the $\Lambda^*$ states. In order to have a good quality fit, two exotic states with opposite parities are required (see fig. 1 (right)). The measured masses for the two $P_c^+$ states are $4380 \pm 8(\mathrm{stat}) \pm 29(\mathrm{syst})\,\mathrm{MeV}$ and $4449.8 \pm 1.7(\mathrm{stat}) \pm 2.5(\mathrm{syst})\,\mathrm{MeV}$ and widths of $205 \pm 18(\mathrm{stat}) \pm 86(\mathrm{syst})\,\mathrm{MeV}$ and $39 \pm 5(\mathrm{stat}) \pm 19(\mathrm{syst})\,\mathrm{MeV}$, respectively. The best fit solution has spin-parity $J^P$ values of $(3/2^-, 5/2^+)$. Acceptable solutions are either $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$. The evolution of the complex amplitude in the Argand diagram is consistent with the characteristic behavior, for the $P_c(4450)^+$ state, for a resonance. A similar study for the $P_c(4380)$ leads to a non-conclusive result.

## 2. – Model-independent evidence for $J/\psi p$ contributions in $\Lambda_b^0 \to J/\psi p K^-$ decays

One of the main limitations of the amplitude analysis approach is due to the poor knowledge of the spectrum of the $\Lambda^* \to K^- p$ resonances. For this reason, a model-independent approach is investigated [2]. The method is based on the Legendre

 

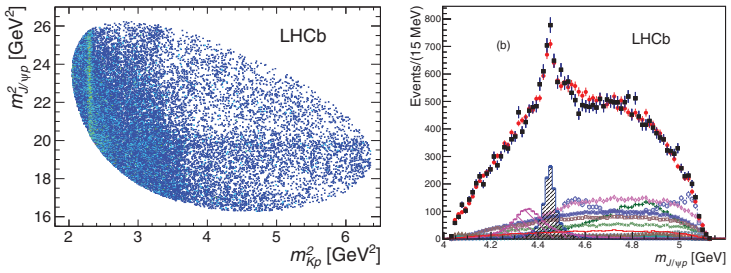


Fig. 1. – Left: invariant mass squared of $K^-p$ *vs.* $J/\psi p$ for $\Lambda_b \to J/\psi K^- p$ candidates. Right: fit projections for $m_{J/\psi p}$ with two $P_c^+$ states. Data are shown as solid (black) squares while the solid (red) points show the results of the fit. Each $\Lambda^*$ component is also shown. The (blue) open squares and (purple) solid squares show the two $P_c^+$ states.

polynomial moments extracted from the $Kp$ system with no assumptions on the $\Lambda^*$ resonances. The analysis allows to exclude that data can be described by the $pK$ contributions alone by more than $9\sigma$ and supports the amplitude model-dependent result.

## 3. – Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ decays

Observations of the same two pentaquark states in another decay would strengthen their interpretation as genuine exotic baryon states. An amplitude analysis of the Cabibbo-suppressed $\Lambda_b^0 \to J/\psi\pi^-$ decay is performed [3]. The available signal sample is about 15 times less than that of the Cabibbo-favored channel and with relatively high background level. The following possible contributions to the decay amplitude are taken into account in the analysis: $\Lambda_b^0 \to J/\psi N^*$ with $N^* \to p\pi^-$, $\Lambda_b^0 \to P_c^+\pi^-$ with $P_c^+ \to J/\psi p$ and $\Lambda_b^0 \to Z_c(4200)^- p$ with $Z_c(4200)^- \to J/\psi\pi^-$ [4]. The statistical significance of the both types of exotic resonances taken together is $3.1\sigma$. Data are found to be consistent with the presence of the $P_c(4380)^+$ and $P_c(4450)^+$ states at the level expected from the $\Lambda_b^0 \to J/\psi p K^-$ measurement and the Cabibbo suppression.

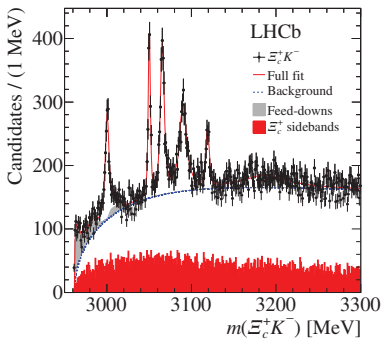


Fig. 2. – Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$. The solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the $\Xi_c^+$ sidebands and the shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c^0$ resonances.

## 4. – Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays and measurement of the $\Lambda_b^0$ mass

The $P_c(4450)^+$ state is close to the $\chi_{c1}p$ threshold. In order to investigate if this state could be due to a rescattering effect [5], $\Lambda_b^0 \to \chi_{c1} p K^-$ decays with $\chi_{c1} \to J/\psi\gamma$ are studied [6]. Both $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ channels are observed with a large significance and their branching fractions are measured with respect to the $\Lambda_b^0 \to J/\psi p K^-$ control channel. Using both channels a measurement of the $\Lambda_b^0$ mass is also performed.

## 5. – Observation of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay

With the observation of two hidden charm pentaquark states, the search of other similar states is of great interest. It has been suggested to search for a strangeness hidden charm pentaquark state ($udsc\bar{c}$) in the $J/\psi\Lambda$ system [7]. With about 300 reconstructed candidates in Run-1 data, a measurement of the branching fraction of the $\Xi_b^- \to J/\psi\Lambda K^-$ decay is performed normalized to the $\Lambda_b^0 \to J/\psi\Lambda$ control channel [8]. With the complete sample of data from Run-1 and Run-2, before the upgrade phase in 2019, it will be possible to perform an amplitude analysis of this decay.

## 6. – Observation of five new narrow $\Omega_c^0$ states decaying to $\Xi_c^+ K^-$

Spectroscopy of baryons with a charm quark is intricate and mostly unexplored. Strong $\Omega_c^0 \to \Xi_c^+ K^-$ with $\Xi_c^+ \to p K^- \pi^+$ decays are studied using the full Run-1 dataset and the 13 TeV dataset where a dedicated trigger has increased the available statistics [9]. Five new narrow excited $\Omega_c$ states are observed and their mass and width parameters are measured (see fig. 2). The fit model includes also feed-down contributions due to $\Omega_c^0 \to \Xi_c^{'} K^-$ with $\Xi_c^{'+} \to \Xi_c^+ \gamma$ decays. An indication of a broad state at high mass, which could be the superposition of several states, is also reported.

REFERENCES


[1] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 072001, arXiv:1507.03414 [hep-ex].
[2] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **117** (2016) 082002, arXiv:1604.05708 [hep-ex].
[3] LHCb Collaboration (Aaij R. *et al.*), *Phys. Rev. Lett.*, **117** (2016) 082003; **117** (2016) 109902(Addendum); **118** (2017) 119901(Addendum), arXiv:1606.06999 [hep-ex].
[4] Belle Collaboration (Chilikin K. *et al.*), *Phys. Rev. D*, **90** (2014) 112009, arXiv:1408.6457 [hep-ex].
[5] Guo F. K., Meiner U. G., Wang W. and Yang Z., *Phys. Rev. D*, **92** (2015) 071502, arXiv:1507.04950 [hep-ph].
[6] LHCb Collaboration (Aaij R. *et al.*), arXiv:1704.07900 [hep-ex].
[7] Chen H. X., Geng L. S., Liang W. H., Oset E., Wang E. and Xie J. J., *Phys. Rev. C*, **93** (2016) 065203, arXiv:1510.01803 [hep-ph].
[8] LHCb Collaboration (Aaij R. *et al.*), *Phys. Lett. B*, **772** (2017) 265, arXiv:1701.05274 [hep-ex].
[9] LHCb Collaboration (Aaij R. *et al.*), , *Phys. Rev. Lett.*, **118** (2017) 182001, arXiv:1703.04639 [hep-ex].