Hadron Spectroscopy and Exotic States at LHCb

M. Pappagallo

Dipartimento Interateneo di Fisica, Via G. Amendola 173, 70126 Bari, Italy

The latest years have seen a resurrection of interest in hadron spectroscopy where the LHCb experiment, using data collected at $pp$ collisions at 7, 8 and 13 TeV, is playing a leading role. After the discovery of two pentaquarks in 2015, five new narrow states observed in the $\Xi_c^+K^-$ spectrum are challenging our knowledge about QCD. Results and prospects for searches for exotic states in $b$-hadron decays are also presented.

1 Observation of five new narrow $\Omega_c^0$ states decaying to $\Xi_c^+K^-$

The spectroscopy of singly charmed baryons $cqq'$ ($q, q' = u, d, s$) is intricate. With three quarks and numerous degrees of freedom, many states are expected. At the same time, the large mass difference between the charm quark and the light quarks provides a natural way to understand the spectrum by using the symmetries provided by heavy quark effective theory. In recent years, considerable improvements have been made in the predictions of the properties of the singly charmed baryons. Among the expected charmed baryon states, the spectrum of $\Omega_c^0$ baryons is largely unknown: only the $\Omega_c^0$ and $\Omega_c^*(2770)^0$, presumed to be the $J^P = 1/2^+$ and $3/2^+$ ground states, have been observed. The above models predict seven states in the mass range 2.9–3.2 GeV, some of them narrow (Fig. 1).

![Figure 1](image_url)

Figure 1 – (Left) Mass predictions of the excited $\Omega_c^0$ states. The boxes cover the range of predictions for the masses of each state, and the red dots indicate the measured values. The x-axis reports the quantum numbers of the excited $\Omega_c^0$ states. The horizontal lines correspond to the hadronic thresholds of the possible final states. (Right) Distribution of the reconstructed invariant mass $m(\Xi_c^+K^-)$. The shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c(X)^0$ resonances.
A search for new $\Omega_c^0$ resonances that decay strongly to the final state $\Xi_c^+K^-$ has been carried out at the LHCb experiment by reconstructing the weak decays of the $\Xi_c^+$ baryons to the Cabibbo-suppressed $pK^-\pi^+$ final state. The measurement is based on samples of $pp$ collision data corresponding to integrated luminosities of 1.0, 2.0 and 0.3 fb$^{-1}$ at center-of-mass energies of 7, 8 and 13 TeV, respectively. One million of $\Xi_c^+$ candidates are reconstructed by a data-driven multivariate selection based on likelihood ratios. Each $\Xi_c^+$ candidate is then combined in turn with each $K^-$ candidate in the event, where the $K^-$ candidate must have a large kaon identification probability. The $\Xi_c^+K^-$ mass distribution for the combined data sets is shown in Fig. 1 where five narrow structures are observed. No structure is observed in the wrong-sign $\Xi_c^+K^-$ mass spectrum instead. The $\Xi_c^+K^-$ mass distribution is fitted by six Breit-Wigner functions for the peaking signals, an exponential function for the combinatorial background and three parametric functions to take in account possible feed-downs originating from the decay chain $\Omega_c(X)^0 \rightarrow \Xi_c^+K^-, \Xi_c^+ \rightarrow \Xi_c^+\gamma$, where photons are not included in the reconstruction. The latter structures might peak in the $m(\Xi_c^+K^-)$ mass distribution as well and appear shifted down in mass by $m(\Xi_c^+)-m(\Xi_c^+) = 110.5 \pm 0.4$ MeV$^2$.

Five new, narrow excited $\Omega_c^0$ states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$, and measurements of their masses and widths are shown in Table 1. The largest contribution on systematic uncertainties is found to be from possible interference originating when resonances are close in mass and have the same spin-parity.

Table 1: Results of the fit to $m(\Xi_c^+K^-)$ for the mass, width, yield and significance for each resonance. The asymmetric uncertainty on the $\Omega_c(X)^0$, arising from the $\Xi_c^+$ mass, is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yield</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>$1300 \pm 100 \pm 80$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>$970 \pm 60 \pm 20$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>$1740 \pm 100 \pm 50$</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>$2000 \pm 140 \pm 130$</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>$480 \pm 70 \pm 30$</td>
<td>10.4</td>
</tr>
</tbody>
</table>

2 Search for structure in $B_s^0\pi^\pm$ invariant mass spectrum

In 2016 the D0 collaboration claimed the observation with 5.1$\sigma$ significance of a narrow structure, which they dub the $X(5568)$, in the decay sequence $X(5568)^\pm \rightarrow B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$. The mass and width of the $X(5568)$ state are reported to be $m = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV/$c^2$ and $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.8}$ MeV/$c^2$. The fraction of $B_s^0$ mesons that come from $X(5568)^\pm \rightarrow B_s^0\pi^\pm$ decay is reported to be $\rho_{D_s} = (8.6 \pm 1.9 \pm 1.4)$%. Recently the significance of the signal has been revisited after loosening the selection of the $B_s^0\pi^\pm$ candidates.

The claimed $X(5568)$ state has been searched in a data sample corresponding to 3 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ and 8 TeV recorded by LHCb. The $B_s^0$ mesons are reconstructed in decays to $D_s^-\pi^+$ and $J/\psi\phi$ final states to obtain a $B_s^0$ yield approximately 20 times larger than that available to the D0 experiment (Fig. 2). The $B_s^0$ candidates are combined with each track that originates from the same primary vertex and that has a transverse momentum $p_T > 500$ MeV/$c$.

The $Q = m(B_s^0\pi) - M_{B^0} - M_\pi$ distributions are fitted with a function containing components for signal and background (Fig. 2). The signal shape is an S-wave Breit–Wigner function, with mass and width parameters fixed according to the central values obtained by the D0.
collaboration. The background is modelled with a polynomial function. No significant $X(5568)$ signal is observed. The results of the fits to the $B^0_s \pi^\pm Q$ value distributions are used to measure the ratio of cross-sections

$$\rho_{X}^{\text{LHCb}} = \frac{\sigma(pp \rightarrow X(5568) + \text{anything}) \times B(X(5568)^\pm \rightarrow B^0_s \pi^\pm)}{\sigma(pp \rightarrow B^0_s + \text{anything})} = \frac{N(X)}{N(B^0_s)} \times \frac{1}{\epsilon_{\text{rel}}(X)},$$

where the cross-sections $\sigma$ are for promptly produced particles within the LHCb acceptance. The relative efficiency $\epsilon_{\text{rel}}(X) = \frac{\epsilon(X)}{\epsilon(B^0_s)}$ is determined from simulation and accounts for the reconstruction and selection efficiency of the companion pion as well as the requirement that is within the LHCb acceptance. The dominant sources of systematic uncertainties are due to the variation of the signal width and the effect of the efficiency on the signal shape. Since the signal is not significant, upper limits on $\rho_{X}^{\text{LHCb}}$ are found to be

$$\rho_{X}^{\text{LHCb}}(p_T(B^0_s)) > 5 \text{ GeV}/c^2 < 0.011 (0.012) @ 90 (95) \% \text{ CL},$$

$$\rho_{X}^{\text{LHCb}}(p_T(B^0_s)) > 10 \text{ GeV}/c^2 < 0.021 (0.024) @ 90 (95) \% \text{ CL},$$

$$\rho_{X}^{\text{LHCb}}(p_T(B^0_s)) > 15 \text{ GeV}/c^2 < 0.018 (0.020) @ 90 (95) \% \text{ CL}.$$  

![Figure 2](image)

**Figure 2** – Selected candidates for (left) $B^0_s \rightarrow D^- \pi^+$ and (middle) $B^0_s \rightarrow J/\psi \phi$ decays. (Right) Results of the fit to the $B^0_s \pi^\pm$ mass distribution for candidates (both $B^0_s$ modes combined) with minimum $p_T(B^0_s)$ of 5 GeV.

3 **Observation of $\Lambda_b^0 \rightarrow \chi_{c1(2)} p K^-$ decays**

The LHCb collaboration observed the $P_c(4380)^+$ and $P_c(4450)^+$ states, which are consistent with $uudc\bar{c}$ hidden-charm pentaquarks decaying to $J/\psi p$. Many phenomenological models describe the dynamics of these states have been proposed, including meson-baryon molecules, compact pentaquarks and kinematic rescattering effects. In particular, the authors of Ref. 6 noted the closeness of the $P_c(4450)^+$ mass to the $\chi_{c1} p$ threshold and proposed that, if the $P_c(4450)^+$ state is a rescattering effect, then it would not appear as an enhancement near the $\chi_{c1} p$ threshold in the $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$ decay mode.

This decay mode, not observed so far, has been looked for by using a data sample corresponding to 1.0 fb$^{-1}$ of integrated luminosity collected by the LHCb experiment in $pp$ collisions at a centre-of-mass energy of 7 TeV in 2011, and 2.0 fb$^{-1}$ at 8 TeV in 2012.  

The $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates are reconstructed via the decays $\chi_{c1} \rightarrow J/\psi \gamma$ and $J/\psi \rightarrow \mu^+ \mu^-$. To separate signal from background, an offline selection is applied after the trigger, consisting of a loose preselection followed by a multivariate classifier based on a gradient-boosted decision tree. A kinematic fit is applied to the $\Lambda_b^0$ candidates, with the $J/\psi$ and $\chi_{c1}$ masses constrained to their known values. As a consequence, the $\Lambda_b^0 \rightarrow \chi_{c2} p K^-$ decay appears shifted down in mass by $m(\chi_{c2}) - m(\chi_{c1}) \simeq 45$ MeV (Fig. 3).

The following ratios of branching fractions are measured

$$\frac{B(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)}{B(\Lambda_b^0 \rightarrow J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009,$$
with open strangeness. The mass difference between $\Xi^{-}_b \rightarrow J/\psi K^- \Lambda$ and $\Lambda_b \rightarrow J/\psi K^-$ relative to that of $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decays is measured to be

$$\frac{f_{\Xi^{-}_b} B(\Xi^{-}_b \rightarrow J/\psi \Lambda K^-)}{f_{\Lambda_b^0} B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29 \text{ (stat)} \pm 0.14 \text{ (syst)}) \times 10^{-2},$$

where $f_{\Xi^{-}_b}/f_{\Lambda_b^0}$ is the ratio of the fragmentation fraction for $b \rightarrow \Xi^{-}_b$ and $b \rightarrow \Lambda_b^0$ transitions. The mass difference between $\Xi^{-}_b$ and $\Lambda_b$ baryons is also measured to be

$$M(\Xi^{-}_b) - M(\Lambda_b^0) = 177.08 \pm 0.47 \text{ (stat)} \pm 0.16 \text{ (syst)} \text{ MeV}. \quad (9)$$

With the full data sample accumulated before the long shutdown of the LHC in 2018, it should be possible to apply a full amplitude analysis to the $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$ decay to search for hidden-charm pentaquarks with open strangeness.

Figure 3 – Fits to the (a) $\Lambda_b^0 \rightarrow \chi_c p K^-$ and (b) $\Lambda_b^0 \rightarrow J/\psi p K^-$ invariant mass distributions. Data points are shown in black and the results of the fits are shown as solid blue lines.

4 Observation of the $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$ decays

A hidden-charm pentaquark with open strangeness ($udsc\bar{c}$) could be observed as a $J/\psi \Lambda$ state in the decay $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$. The decay is similar to $\Lambda_b^0 \rightarrow J/\psi p K^-$, where the two pentaquarks $P_u(4380)^+$ and $P_c(4450)^+$ were observed, and differs from the latter by exchanging one $u$ spectator quark with an $s$ spectator quark.

The $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates are reconstructed using the decays $J/\psi \rightarrow \mu^+ \mu^-$ and $\Lambda \rightarrow p \pi^-$. An offline selection is applied after the trigger, based on a loose preselection, followed by a multivariate classifier based on a Gradient Boosted Decision Tree. Given the long lifetime of the $\Lambda$ baryon, its decay vertex can be reconstructed either from a pair of tracks that include segments in the vertex detector (VELO) or from a pair of tracks reconstructed using only the tracking stations downstream of the VELO.

The first observation of the $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$ decay is reported with a data sample of $pp$ collisions corresponding to an integrated luminosity of 3 fb$^{-1}$. The observed signal yield is $308 \pm 21$. In the kinematic region of the $b$-baryon transverse momentum $p_T < 25$ GeV and rapidity in the range $2.0 < y < 4.5$, the production rate of $\Xi^{-}_b$ with $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$ decays relative to that of $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decays is measured to be

$$\frac{f_{\Xi^{-}_b} B(\Xi^{-}_b \rightarrow J/\psi \Lambda K^-)}{f_{\Lambda_b^0} B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29 \text{ (stat)} \pm 0.14 \text{ (syst)}) \times 10^{-2},$$

where $f_{\Xi^{-}_b}/f_{\Lambda_b^0}$ is the ratio of the fragmentation fraction for $b \rightarrow \Xi^{-}_b$ and $b \rightarrow \Lambda_b^0$ transitions. The mass difference between $\Xi^{-}_b$ and $\Lambda_b$ baryons is also measured to be

$$M(\Xi^{-}_b) - M(\Lambda_b^0) = 177.08 \pm 0.47 \text{ (stat)} \pm 0.16 \text{ (syst)} \text{ MeV}.$$
References
