Baryonic and mesonic resonances at LHCb

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XIII Workshop on Particle Correlations and Femtoscopy
Krakow, Poland, 22-26 May 2018
Outline

- Introduction
- Study of $D_s$ family
- Search for $B_c^*(2S)$
- Muonic decays of $\chi_{c1}$ and $\chi_{c2}$
- Doubly charmed baryons $\Xi_{cc}^{++}$
- Study of $\Omega_{c}^{**}$ family
- Summary and future perspective
The simplest definition for resonances is that they are extremely short lived particles, with lifetime around $10^{-23}$ seconds or less. In more technical a way, resonances are poles in the unphysical sheets of the S-matrix, which manifest themselves as structures in experimental observables.

Well isolated, relatively narrow and far from the threshold resonances can be described by standard Breit-Wigner parametrization.

If there are overlapping resonances, it is generally incorrect to use a sum of Breit-Wigner functions. K-matrix formalism can be more appropriate.

Resonances at threshold can be better treated using the Flatté parametrization.
As with everything else resonances carry quantum numbers and are, of course, also subject to conservation laws. The study of the angular distributions and correlations is mandatory to determine the quantum numbers of the resonances. There are different spin formalisms:

- Non-relativistic tensor formalism (Zemach)
- Spin-projection formalisms:
  - **Helicity Formalism.** Quantization axis parallel to the direction of motion.
  - **Canonical Formalism.** The quantization axis is diagonal to the direction of motion.
  - **Tranversality Formalism.** Similar to helicity formalism, but the quantization axis is chosen to be normal to the direction of motion.
- Relativistic tensor Formalisms (Rarita-Schwinger)
How to measure quantum number of resonance?

- Be sure the bump you are observing is signal.
- Identify the possible quantum number assignments (respect the conservation laws).
- Write down an amplitude and a fit model corresponding to each possible resonance quantum number.
- Fit the models and perform hypothesis tests to identify which is the model preferred by data.
- Each model corresponds to a set of quantum numbers for the resonance.

- High precision tracking system: $\sigma(\text{IP}) = 20 \mu m$, $\delta p/p = 0.4 - 0.6\%$
- Excellent particle ID with two RICH detectors ($\epsilon_{\text{PID}}(K) \approx 95\%$, $\text{MisID}(K \rightarrow \pi) \approx 5\%$)

Despite the high background level inherent to hadronic collisions the detector allows to search for resonances produced in heavy flavour decays.
LHCb focuses on Heavy Flavour hadrons (hadrons with charm (c) or beauty (b) quarks).

Beyond ground-state hadrons:
- spin excitations
- angular momentum excitations
- radial excitations

**C=1**
- mesons: $D^+(c\bar{d}), D^0(c\bar{u}), D_s^+(c\bar{s})$
- baryons: $\Lambda_c^+(cdu), \Xi_c^+(cus), \Xi_c^0(cds), \Omega_c^0(css)$

**B=1**
- mesons: $B^+(\bar{b}u), B^0(\bar{b}d), B_s^0(\bar{b}s), B_c^+(\bar{b}c)$
- baryons: $\Lambda_b^0(bdu), \Xi_b^0(bus), \Xi_b^-(bds), \Omega_b^-(bss)$
Excited charmed $D_s$ mesons

Spectrum of charmed mesons ($c\bar{s}$) is predicted theoretically [S. Godfrey, N. Isgur, Phys. Rev. D32 (1985) 189]

- Besides two S-wave states ($D_s, D_s^*$) four P-wave states have been observed ($D_{s0}^*(2317)^+, D_{s1}(2460)^+, D_{s1}(2536)^+, D_{s2}^*(2573)^+$)
- Later at B-factories in $DK$ and $D^*K$ modes the $D_{s1}(2700)^+, D_{sJ}(2860)^+$ and $D_{sJ}(3040)^+$ have been observed with quantum number assignments not known.
Excited charmed $D_s$ mesons

LHCb performed two studies of $D_s$ spectra:

- in production analysing $D^+ K_s$ and $D^0 K^+$ final state [JHEP 1210(2012)151]
- in Dalitz plot analysis of $B^0_s \rightarrow \bar{D}^0 K^- \pi^+$ [PRL113 162001(2014)].

In the first measurement $D_{s1}(2700)^+$ and $D_{sJ}(2860)^+$ have been observed for the first time in hadronic interactions and their mass and width have been measured.

![Graph showing candidates](JHEP 1210(2012)151)

![Graph showing candidates](PRL113 162001(2014))
Excited charmed $D_s$ mesons

Second work performed full amplitude analysis (angular distributions are given in the Zemach tensor formalism). It shows with more than 10 $\sigma$ significance that structure at $m(\bar{D}^0 K^-) \approx 2.86$ MeV/$c^2$ contains both spin-1 and spin-3 components. Mass and width for both spin-1 and spin-3 components have been measured.
First excited $B_c(2S)^+$ state is observed by ATLAS [Phys. Rev. Lett. 113 (2014) 212004]:
$m = 6842 \pm 4(\text{stat}) \pm 5(\text{syst}) \text{ MeV}/c^2$

LHCb searched for this decay in the same final state:
$B_c(2S)^+ \rightarrow B_c^+ \pi^+ \pi^-$
$B_c(2S)^{*+} \rightarrow B_c^{*+}(\rightarrow B_c^+ \gamma)\pi^+ \pi^-$

LHCb has a large sample of $B_c$ mesons ($\sim 3k$); no signal is observed

The results from ATLAS and LHCb are compatible only if the (unpublished) relative efficiency of reconstructing $B_c(2S)^+$ w.r.t. the $B_c^+$ is much larger for ATLAS.
Muonic decay $\chi_{cJ} \rightarrow J/\Psi \mu^+ \mu^-$

- First observation of $\chi_{cJ} \rightarrow J/\Psi \mu^+ \mu^-$ [PRL 119 (2017) 221801].

- The very low Q-value of the decay and the absence of Bremsstrahlung of the soft muons allow extraordinary resolution.

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(\chi_{c1})$</td>
<td>4755 ± 81</td>
</tr>
<tr>
<td>$N(\chi_{c2})$</td>
<td>3969 ± 96</td>
</tr>
<tr>
<td>$m(\chi_{c1})$ [MeV]</td>
<td>3510.66 ± 0.04</td>
</tr>
<tr>
<td>$m(\chi_{c2})$ [MeV]</td>
<td>3556.07 ± 0.06</td>
</tr>
<tr>
<td>$\Gamma(\chi_{c2})$ [MeV]</td>
<td>2.10 ± 0.20</td>
</tr>
</tbody>
</table>
Doubly charmed baryons

- Baryons containing 2 or 3 charmed constituent quarks are predicted by the quark model: $\Xi^{+}_{cc}(ccd), \Xi^{++}_{cc}(ccu), \Omega^{+}_{cc}(ccs), \Omega^{++}_{ccc}(ccc)$
- Many theoretical calculations of their properties:
  - $M(\Xi^{++}_{cc}) \approx M(\Xi^{+}_{cc}) \approx 3600 \pm 100 \text{ MeV}/c^2$
  - Large ambiguity of lifetimes, but:
    - $\tau(\Xi^{++}_{cc}) \sim 400 - 700 \text{ fs} \gg \tau(\Xi^{+}_{cc}) \sim 100 - 250 \text{ fs}$
Observation of $\Xi_{cc}^+$ by SELEX

Claims by SELEX:

- Observation of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ in 2002 [PRL89(2002)112001]
- Confirmation with $\Xi_{cc}^+ \rightarrow D^+ pK^-$ in 2004 [PLB628(2005)18]
- Combined $m(\Xi_{cc}^+) = 3518.7 \pm 1.7\text{MeV}/c^2$
- $\tau < 33\text{ fs}$ is much shorter than expected
- Evidence of $\Xi_{cc}^+$ in more decays

No evidence observed at Babar, FOCUS, Belle and LHCb
LHCb searched for $\Xi_{cc}^{++}$ signal in $\Lambda_c^+ (\rightarrow pK^-\pi^+)K^-\pi^+\pi^-$ mass spectrum and found with $12\sigma$ significance in 13 TeV and $7\sigma$ in 8 TeV data set.

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.17\,(\Lambda_c^+) \,\text{MeV}/c^2$$

Mass difference with the SELEX measurement ($\Delta m = 103\,\text{MeV}/c^2$) is too large to be an isospin partner.

Signal persists when requiring a significant lifetime $\rightarrow$ weakly decaying.

Studies are ongoing on lifetime, production rate, other decay modes and the isospin partner.
\( \Omega^*_c \) states. Introduction.

- In \( \Omega_c (css) \) system the large difference in mass between the charm quark and the light quarks, provides a natural way to understand the spectrum by using the symmetries provided by the Heavy Quark Effective Theories (HQET).

- In this model, the heavy quark is essentially a spectator and interacts with the diquark which is treated as a single object.

- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET.
The SU(3) multiplets containing the ground state charmed baryons, grouped according to the spin $j$ of the light diquark and the spin-parity $J^P$ of the baryon.

$$j_{qq} = 1, J^P = \frac{1^+}{2}, \quad j_{qq} = 0, J^P = \frac{1^+}{2}, \quad j_{qq} = 1, J^P = \frac{3^+}{2}$$

All the grounds states have been observed even if the quantum numbers of many of them are not measured.

Excited states of $\Lambda_c^+, \Xi_c, \Sigma_c$ have been reported but no excited $\Omega_c$ states have been observed before LHCb measurements.
Spectrum of excited $\Omega_c^0$ states.

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.
Observation of $\Omega_c^*$ states [Phys. Rev. Lett. 118 (2017) 182001]

- Data sample: $1.0 \, fb^{-1}$ (7 TeV) + $2.0 \, fb^{-1}$ (8 TeV) + $0.3 \, fb^{-1}$ (13 TeV) = $3.3 \, fb^{-1}$
- Reconstruct $\Xi_c^+ \rightarrow pK^-\pi^+$
- Combine with tight PID $K^-$ and require $p_T > 4.5 \, GeV$
- Observation of 5 new excited $\Omega_c$ states. Two of them are very narrow.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>Yield</th>
<th>$N_\sigma$</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>(&lt; 1.2 , MeV, 95% , CL)</td>
<td></td>
<td></td>
<td></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>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
<td>$60 \pm 15 \pm 11$</td>
<td>$1670 \pm 450 \pm 360$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3066)^0_{ld}$</td>
<td></td>
<td></td>
<td>$700 \pm 40 \pm 140$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3090)^0_{ld}$</td>
<td></td>
<td></td>
<td>$220 \pm 60 \pm 90$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3119)^0_{ld}$</td>
<td></td>
<td></td>
<td>$190 \pm 70 \pm 20$</td>
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</tbody>
</table>
Interpretation of $\Omega_c^*$ states


- Either all five P-wave states but why two are so narrow?
- Or three P-wave states and two 2S-states but where are two 1/2 states?
- Chiral QCD approach by M. Praszalowicz, M. Polyakov and H.C. Kim interpret two narrowest states as pentaquarks [Phys. Rev. D96 (2017) no.1, 014009]. Easy to check at LHCb since $\Omega_c^{**}$ are predicted to be not "isospin singlet" but "isospin triplets".

### Table II: Spin-parity ($J^P$) numbers of the newly observed $\Omega_c$ states suggested in various works.

<table>
<thead>
<tr>
<th>State</th>
<th>[19]</th>
<th>[20]</th>
<th>[21]</th>
<th>[23]</th>
<th>[29]</th>
<th>[25]</th>
<th>[27]</th>
<th>[28]</th>
<th>[32]</th>
<th>[26]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)$</td>
<td>$1/2^-$</td>
<td>$1/2^- (3/2^-)$</td>
<td>$1/2^-$</td>
<td>$1/2^- 1/2^- 1/2^- 1/2^- 1/2^+ or 3/2^+ 1/2^-$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$1/2^-$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(3050)$</td>
<td>$1/2^-$</td>
<td>$1/2^- (3/2^-)$</td>
<td>$1/2^- 5/2^- 3/2^- 1/2^- 5/2^+ or 7/2^+ 3/2^- 3/2^-$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$3/2^-$</td>
</tr>
<tr>
<td>$\Omega_c(3066)$</td>
<td>$1/2^+$</td>
<td>$1/2^+ or 1/2^-$</td>
<td>$3/2^- (5/2^-)$</td>
<td>$3/2^- 3/2^- 5/2^- 3/2^- 1/2^+ 3/2^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$3/2^-$</td>
</tr>
<tr>
<td>$\Omega_c(3090)$</td>
<td>$3/2^- (1/2^+)$</td>
<td>$3/2^- 1/2^- 1/2^- 3/2^- 5/2^- 1/2^+ 5/2^-$</td>
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<tr>
<td>$\Omega_c(3119)$</td>
<td>$3/2^+$</td>
<td>$3/2^+$</td>
<td>$5/2^- (3/2^+)$</td>
<td>$5/2^- 3/2^- 3/2^- 3/2^- 5/2^- 5/2^+ or 7/2^+ 3/2^+ 1/2^- 1/2^+ or 3/2^+$</td>
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</table>
Summary and prospects for hadron spectroscopy

- 1 $fb^{-1}$ at 7 TeV and 2 $fb^{-1}$ at 8 TeV
- $\sim 6$ $fb^{-1}$ at 13 TeV is expected with $\sigma_{b\bar{b}}(13 \text{TeV})/\sigma_{b\bar{b}}(7 \text{TeV}) \approx 2$

Analyses expected with full RUNI +RUNII data:
- search for excited $B_c$ states
- properties of $\Xi_{cc}^{++}$: lifetime, production cross-sections, new decay modes
- searches for $\Xi_{cc}^+, \Omega_{cc}^+, \Xi_{bc}^+, \Xi_{bc}^0$

LHCb will be upgraded in 2019, software trigger with 40MHz, PID at the trigger level – great increase ($\sim 2\times$) of trigger efficiency on full hadronic final states.