Hadron spectroscopy in LHCb

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On behalf of the LHCb Collaboration

Outline:

- The LHCb experiment.
- The observation of pentaquark candidates
- Observation of possible tetraquark states
- Observation of new Baryonic states

- High cross-section of heavy-quark production.
- Excellent decay time resolution.
- Excellent particle identification.
- Excellent momentum resolution.
- Flexible trigger.
Efficiency for $b\bar{b}$ production in LHCb is 27% of $b$ or $\bar{b}$ and 25% of $b\bar{b}$ pair.

Most of the analyses presented here made use of Run1 (7+8 TeV) (3 fb$^{-1}$) dataset only.

A few analyses make use also of the Run2 (13 TeV) (1.7 fb$^{-1}$) data.
Multiquark states

- In the original Gell-Mann paper (“A schematic model for baryons and mesons”, Phys. Lett. 8, (1964)).
- “Baryons can now be constructed from quarks by using combinations \((qqq), (qqqq\bar{q}),\) etc., while mesons are made out of \((q\bar{q}), (qq\bar{q}\bar{q}),\) etc.
- Today \(qqqq\bar{q}\) baryons are called pentaquarks, \(qq\bar{q}\bar{q}\) mesons are called tetraquarks.

**Pentaquarks**

**Quarkonium Tetraquarks**
- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium
- quarkonium adjoint meson
The rise and fall of pentaquarks

- Low statistics evidences for "pentaquarks" were provided by several experiments around 2005-2006 (see A. Dzierba, C. Mayer and A. Szczepaniak, hep-ex/04120).

- Evidences for Θ⁺ in the nK⁺ and pK⁰_S.


- Around 2007 pentaquarks were dead.
Observation of $J/\psi p$ resonances in $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays in LHCb

- Multivariate Analysis (MTVA) selection.
- $26,007 \pm 166 \Lambda_b^0$ events with 94.6% purity.
- The Dalitz plot shows rich $\Lambda$’s resonant structures along the $pK^-$ axis.
- Unexpected structure along the $J/\psi p$ axis.

(PRL 115, 072001 (2015)).
Amplitude analysis and mass projections

- Key point is a full amplitude analysis which also describes the complex resonant structure in the $pK^-$ final state.
- The analysis requires the presence of two new resonances (labelled $P_c$).

(PRL 115, 072001 (2015)).
### Resonances parameters and angular analysis

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Significance</th>
<th>Fit fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>4380 ± 8 ± 29</td>
<td>205 ± 18 ± 86</td>
<td>9σ</td>
<td>8.4 ± 0.7 ± 4.2</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>4449.8 ± 1.7 ± 2.5</td>
<td>39 ± 5 ± 19</td>
<td>12σ</td>
<td>4.1 ± 0.5 ± 1.1</td>
</tr>
</tbody>
</table>

- The best fit has $J^P = 3/2^-$ and $J^P = 5/2^+$.
- Good description of the angular distributions.
- Measure the real and imaginary parts of the $P_c$ amplitudes ([PRL 115, 072001 (2015)]).
- Argand Diagram consistent with expectations from a Breit-Wigner behaviour.

- Model independent analysis gives consistent results ([Phys. Rev. Lett. 117, 082002 (2016)]).
Search for other $P_c^+$ decay modes

- Finding the same $P_c^+$ in other channels is helpful to understand $P_c^+$ production mechanism and internal structure.
- Two $P_c^+$ production mechanisms predicted.

The two cases can be tested using the $R_{\pi/K}$ ratio which is expected to be very different.

$$R_{\pi/K} = \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08, \quad R_{\pi/K} = 0.58 \pm 0.05$$

Study of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ decays in LHCb

□ Branching fraction for the Cabibbo suppressed $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ is $\approx 8\%$ of the Cabibbo favoured $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay mode.

□ More complex because of the possible contribution of $Z_c(4200)^- \rightarrow J/\psi\pi^-$ (observed by Belle in $B^0 \rightarrow J/\psi K^+\pi^-$ (PRD 90 (2014) 112009)).

□ Full amplitude analysis. Accurate description of the rich resonant structure in the $p\pi^-$ final state.

$$\Lambda_b \rightarrow J/\psi N^* (\rightarrow p\pi^-), \quad \Lambda_b \rightarrow \pi^- P_c^+ (\rightarrow J/\psi p), \quad \Lambda_b \rightarrow pZ_c(4200)^- (\rightarrow J/\psi\pi^-)$$
Study of $\Lambda_b^0 \to J/\psi p\pi^-$ decays

- $Z_c(4200)^-$, $N^*$ and exotic states parameters fixed.
- Each $P_c$: 4 free parameters +6 fixed to that from $\Lambda_b^0 \to J/\psi pK^-$.  
- Significance of the two $P_c^+$ is 3.1$\sigma$.
- The $b \to c$ diagram strongly favoured.

Resonances decaying to $J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$

□ The X(4140) state is first claimed by the CDF collaboration in 2008. (PRL 102 242002).
□ Narrow width: $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV. Many experiments results.

□ Summary of the experimental evidences.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>CDF</th>
<th>Belle</th>
<th>CDF</th>
<th>LHCb</th>
<th>CMS</th>
<th>D0</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance ($N\sigma$)</td>
<td>3.8</td>
<td>1.9</td>
<td>5.0</td>
<td>1.4</td>
<td>5.0</td>
<td>3.1</td>
<td>1.6</td>
</tr>
</tbody>
</table>
New results on $B^+ \rightarrow J/\psi \phi K^+$ from LHCb

- Update of the analysis using Run1 data ($3 fb^{-1}$) ([PRL118, 022003 (2017), PRD95, 012002 (2017)]).
- Six dimensional amplitude analysis.
- The best fit requires the presence of four $X$ states and a non-resonant term.
New results on $B^+ \rightarrow J/\psi \phi K^+$ from LHCb

- Resonances parameters (PRL118, 022003 (2017)).

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$</th>
<th>$J^{PC}$</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4140)$</td>
<td>8.4</td>
<td>1$^{++}$</td>
<td>$4160 \pm 4^{+5}_{-3}$</td>
<td>$83 \pm 21^{+21}_{-14}$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>5.8</td>
<td>1$^{++}$</td>
<td>$4273 \pm 8^{+17}_{-4}$</td>
<td>$56 \pm 11^{+8}_{-11}$</td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>6.1</td>
<td>0$^{++}$</td>
<td>$4506 \pm 11^{+12}_{-4}$</td>
<td>$92 \pm 21^{+21}_{-20}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>5.6</td>
<td>0$^{++}$</td>
<td>$4704 \pm 10^{+14}_{-24}$</td>
<td>$120 \pm 31^{+42}_{-33}$</td>
</tr>
</tbody>
</table>

- The $X(4140)$ is not a narrow resonance.
- A possible diagram for producing a 4-quark state.

- Lot of discussions. Interpretation of these states still open.
Study of $\bar{B}^0 \to \psi'\pi^- K^+$ in LHCb

- First analysis from Belle: observation of a new $Z_c(4430)^+ \to \psi'\pi^-$ in $B \to K\pi^+\psi'$ (PRL 100, 142001 (2008)).
- Not confirmed by BaBar: data could be described without the presence of a $Z_c(4430)^+$ resonance (PRD 79, 112001 (2009)).
- Recent analysis from LHCb (PRL 112, 222002 (2014)).
- $B^0$ signal: 25,176 events (Belle: 2,010, BaBar: 2,021 events).
Study of $\bar{B}^0 \to \psi'\pi^- K^+$

- Amplitude analysis confirms the presence of the $Z_c$ resonance (PRL 112, 222002 (2014)).

- Argand diagram shows typical resonance behaviour. Resonance parameters:

\[
M(Z_c) = 4475 \pm 7^{+15}_{-25} \text{ MeV}, \quad \Gamma(Z_c) = 172 \pm 13^{+37}_{-34} \text{ MeV}.
\]

- In good agreement with Belle.
- Possible presence of an additional $Z_c$ at a mass of 4239 MeV.
- $Z_c$ is a charged charmonium state. Multiquark state?
Baryon spectroscopy

- Heavy quark effective theory (HQET) predictions for $\Omega_c$ states.

- $\Omega_c$ quark content: $ssc$.

- Only $1/2^+$ and $3/2^+$ ground states were known.
Observation of five new $\Omega_C$ states in LHCb

- Explore excited $\Omega_c$ states in their strong decay to $\Xi_c^+ K^-$ (PRL 118 (2017) 182001).
- Make use of data collected at 7, 8 and 13 TeV (3.3 $fb^{-1}$).
- $\Xi_c^+$ reconstructed in the Cabibbo suppressed mode $\Xi_c^+ \rightarrow pK^-\pi^+$.
- $\approx 10^6 \Xi_c^+$ reconstructed with a 83% purity.
- $\Xi_c^+$ combined with a prompt $K^-$: five narrow $\Omega_C$ observed.
- No structure in the $\Xi_c^+$ sidebands or in the wrong sign $\Xi_c^+ K^+$ mass spectrum.
Observation of five new $\Omega_c$ states

- Describe peaks with relativistic Breit-Wigner convoluted with Gaussian with $\sigma$ from 0.7 to 1.7 MeV.
- Account for feed-down from $\Omega_c \rightarrow K^-\Xi'_c(\rightarrow \Xi_c\gamma)$.
- Model enhancement at $\approx 3200$ MeV with one Breit-Wigner.
- Resonances parameters.

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<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</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>
</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>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$&lt; 1.2$ MeV, 95% CL</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188.1 \pm 4.8 \pm 12.7$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
</tr>
</tbody>
</table>

$\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ exceptionally narrow (PRL 118 (2017) 182001).
Observation of five new $\Omega_C$ states

- Comparison with theoretical expectations.

- $D$ and $P$-wave states may be narrow (G. Chiladze, A. Falk arXiv: 9707507).
- Need to measure the quantum numbers of these states.
- Many phenomenological interpretations, including the possible presence of pentaquarks.
The search for double charmed baryons $\Xi_{cc}$ states

- The first claim for observing the $\Xi_{cc}^+$ ($dcc$) state comes from SELEX experiment (PRL 89 (2002) 112001, PLB 628 (2005) 18)


- Different production mechanisms?
Observation of the double charmed baryon $\Xi_{cc}^{++}$ in LHCb

- Search for the $\Xi_{cc}^{++}$ ($ucc$) using the decay (Phys. Rev. Lett. 111 (2017) 180001).
  \[ \Xi_{cc}^{++} \rightarrow \Lambda_c K^- \pi^+ \pi^+, \quad \Lambda_c \rightarrow pK^- \pi^+ \quad (BR = 10\%) \]

- Analyze 1.7 $fb^{-1}$ of Run2 using a dedicated high efficiency trigger.

- First observation.
- No signal observed in the $\Lambda_c$ sidebands, no signal in the wrong sign $\Lambda_c K^- \pi^+ \pi^-$ combination.
- Consistent signal also observed in the Run1 data.
Observation of the double charmed baryon $\Xi^{++}_{cc}$

- Yield $313 \pm 33$ decays.

- The signal persists after a lifetime cut.
- $\Xi^{++}_{cc}$ parameters.

$$m(\Xi^{++}_{cc}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c) MeV$$

- Mass difference with respect to the possible SELEX isospin partner: $103 \pm 2$ MeV.
- Inconsistent with expected isospin splitting for $\Xi^{+}_{cc}$. 

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Amplitude analysis of $\Lambda_b \rightarrow D^0 p \pi^-$ in LHCb

- The $\Lambda_c$ spectrum needs to be completed.
- Explore the $\Lambda_c$ spectroscopy using the $D^0 p$ final state (JHEP 05 (2017) 30).
- The inclusive $D^0 p$ was studied by BaBar (PRL 98 (2007) 01).
- High statistics clean $\Lambda_b$ signal in LHCb (11,200 events, 86% purity).
Amplitude analysis of $\Lambda_b \to D^0 p\pi^-$

- Follow helicity formalism to describe 5D amplitude of $D^0 p$ and $p\pi^-$ masses (JHEP 05 (2017) 30).
- Dalitz plot and $D^0 p$ mass projection.

- $\Lambda_c(2860)^+$ parameters (first observation), $J^P = 3/2^+$:
  
  $m = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})$ MeV
  $\Gamma = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})$ MeV

- $\Lambda_c(2880)^+$ parameters, $J^P = 5/2^+$ preferred:
  
  $m = 2881.75 \pm 29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})$ MeV
  $\Gamma = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})$ MeV

- $\Lambda_c(2940)^+$ parameters, $J^P = 3/2^-$ preferred:
  
  $m = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})$ MeV
  $\Gamma = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})$ MeV
LHCb is a flavor factory, exploring a large set of physics topics.

In particular, in the spectroscopy field, many new unexplored regions are being studied.

These studies are producing unexpected results, such as the discovery of “exotic” states, or the observation of many unexpected resonances and particles.

Basic ingredients of these results are high statistics and purity of the final states and highly sophisticated and newly developed full amplitude analyses.

This field is in rapid development and much more experimental and theoretical work is needed to understand the full pattern.

Many more analyses are underway, making use of the large amount of data which are being collected at LHC.