Spectroscopy at LHCb
Conventional states

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On behalf of the LHCb Collaboration
Beauty September 30th –October 4th 2019
Outline

LHC era: New golden years for spectroscopy. Concentrate on a selection of recent results

• Beautiful Baryons
• Double Charm baryons
• Hidden Charm

This talk focused on conventional states. See also LHCb talks:

Michel de Cian *Lifetime measurements* (Thursday afternoon)
Liming Zhang *Spectroscopy at LHCb: Exotic States* (Tuesday afternoon)
Marcello Rotondo *Heavy Flavour Production at LHCb* (Tuesday afternoon)
World largest heavy flavour dataset (9 fb\(^{-1}\)) collected during Run1+Run2

- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

Beautiful Baryons
Excited $\Lambda_b$ states

Large sample of $\Lambda_b$ baryons collected by LHCb has provided rich starting point to explore $b$-baryon spectroscopy

Observation of $\Lambda_b(5912)$ and $\Lambda_b(5920)$ via decays to $\Lambda_b \pi^+ \pi^-$ final state (PRL 109 (2012) 172003) [1 fb$^{-1}$]

Precise measurement of $\Sigma_b(\ast)^{\pm}$ states seen by CDF and observation of a new state $\Sigma_b(6097)^{\pm}$ (PRL 122 (2019) 012001) [3 fb$^{-1}$]
Excited $\Lambda_b$ states

Full Run 1+2 dataset: 9 fb$^{-1}$

Exploit large clean samples of $\Lambda_b$ decays to the $\Lambda_c^+ \pi^-$ and $J/\psi p K^-$ final states

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$N \ [10^3]$</th>
</tr>
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<tbody>
<tr>
<td>$\Lambda_b^0 \to \Lambda_c^+ \pi^-$</td>
<td>892.8 ± 1.2</td>
</tr>
<tr>
<td>$\Lambda_b^0 \to J/\psi p K^-$</td>
<td>217.5 ± 0.7</td>
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</tbody>
</table>
Excited $\Lambda_b$ states

Add two prompt pions

Suppress combinatorial background with BDT

Study $\Lambda_b \pi^+ \pi^-$ mass spectrum

New structure seen around 6.15 GeV above $\Sigma_b^{(*)\mp} \pi^\pm$ threshold

$\Lambda_b^0 \rightarrow \Lambda_b^+ \pi^-$

$\Lambda_b^0 \rightarrow J/\psi pK^-$

$\begin{align*}
m(\Lambda_b^0 \pi^+ \pi^-)[\text{GeV}] & \end{align*}$
Excited $\Lambda_b$ states

Split data into 3 regions of $\Lambda_b \pi^\pm$ invariant mass:

- $\Sigma_b$
- $\Sigma_b^*$
- Non-resonant

Simultaneous fit to data in 3 regions

Data favours hypothesis of 2 narrow near degenerate states at $7\sigma$ significance

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \text{ MeV}$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \text{ MeV}$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \text{ MeV}$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \text{ MeV}$$

arXiv: 1907.13598
Excited $\Lambda_b$ states

Fit $\Lambda_b \pi^+ \pi^-$ then sPlot $\Lambda_b \pi^\pm$ mass

$\Lambda_b(6512)^0$ couples to both $\Sigma_b^+$ and $\Sigma_b^{*+}$

$\Lambda_b(6546)^0$ couples primarily to $\Sigma_b^*$

Observed masses, width + decay patterns consistent $\Lambda_b (1D)^0$ doublet with $J^P = 3/2^+$ and $5/2^+$

arXiv: 1907.13598
Doubly Charmed Baryons
Doubly Charmed Baryons

Two SU(4) 20-plets containing SU(3) triplets

\[ \Xi_{cc}^+ = ccd, \quad \Xi_{cc}^{++} = ccu, \quad \Omega_{cc}^+ = ccs \]

\[ J^P = \frac{1^+}{2} \]

\[ J^P = \frac{3^+}{2} \]

\[ \Xi_{cc}^{++} \] first observed decaying to \( \Lambda_c^+ K^- \pi^+ \pi^+ \) by LHCb in 2017

\[ m(\Xi_{cc}^{++}) = (3621.40 \pm 0.72 \pm 0.27 \pm 0.14) \text{ MeV}/c^2 \]

\[ \tau(\Xi_{cc}^{++}) = (0.256^{+0.024}_{-0.022} \pm 0.014) \text{ ps} \]

See talk of Michel de Cian

PRL 119 (2017) 112001

PRL 121 (2018) 052002
Observation of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

State confirmed in $\Xi_c^+ \pi^+$ mode

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+; \Xi_c^+ \rightarrow pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+; \Lambda_c^+ \rightarrow pK^-\pi^+)}$$

$$\mathcal{R} = (3.5 \pm 0.9 \pm 0.3) \times 10^{-2}$$

Using recent Belle measurement:

$\mathcal{B}(\Xi_c^+ \rightarrow pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$

Phys.Rev. D100 031101

gives

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+)} \approx 0.5$$

Combining both modes

$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65 \pm 0.31 \text{ MeV/}c^2$$

PRL 121 (2018) 162002
Search for $\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+$

To further understand the dynamics of weak decays $\Xi_{cc}^{++}$ need to explore other modes

Good trigger efficiency for $D^+ \rightarrow K^+ K^- \pi^+$ 😊

Lower phase space 😞
Search for $\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+$

Study the $D^+ p K^- \pi^+$ spectrum with 1.7 fb$^{-1}$ of data collected in 2016

No significant signal seen

Limit set on:

$$\mathcal{R} \equiv \frac{B(\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+)}{B(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}$$

$$\mathcal{R} < 2.1 \times 10^{-2} \quad @ \ 95 \% \ CL$$

arXiv:1905.02421
Search for $\Xi_{cc}^+$

What about other doubly charmed baryons? e.g. $\Xi_{cc}^+$

Predicted to have similar mass to $\Xi_{cc}^{++}$ but shorter lifetime

Longstanding unconfirmed observation by the SELEX experiment


New
arXiv:1909.12273

LHCb search using $\Lambda_c^+ \pi^+ K^-$ mode and full Run 1+2 dataset
Search for $\Xi_{cc}^+$

No signal seen

$\sqrt{s} = 7, 8, 13$ TeV

LHCb

SELEX

LHCb $\Xi_{cc}^{++}$

arXiv:1909.12273
Search for $\Xi_{cc}^{++}$

No signal seen

arXiv:1909.12273
Search for $\Xi_{cc}^+$

Largest local significance 3.1\(\sigma\) (statistical) around 3620 MeV/c\(^2\)
Global significance 1.7\(\sigma\) no evidence, limits set
Search for $\Xi_{cc}^+$

Set upper limits on $R$ as a function of mass for different lifetime hypotheses.

New

- $R(\Lambda_c^+)$
  \[
  R(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times B(\Xi_{cc}^+ \to \Lambda_c^- \pi^+)}{\sigma(\Lambda_c^+)}
  \]

- $R(\Xi_{cc}^{++})$
  \[
  R(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}
  \]

• Improve LHCb limits by order of magnitude compared to Run 1 analysis,
• Limits significantly below expectations from SELEX (caveat different environment)
Missing Hidden Charm
Charmonium System

Since November revolution of 1974 hidden charm spectrum well mapped out over the last 45 years

Up to this year candidate for all but two of lowest states seen

Missing states $^{3}D_3$ and $^{1}D_2$

$^{3}D_3$ decays to open charm but expected to be narrow due to F-wave centrifugal barrier factor
- (−) C, cannot be produced in gluon fusion or $\gamma \gamma$ See PRD 72 (2005) 054026
Near Threshold $D\bar{D}$ spectroscopy

Exploit large samples of open charm collected in full Run 1+2 datasets

Select events with 2 reconstructed charm mesons from same PV
$X(3842)$

New narrow state
**X(3842)**

New narrow state

\[ m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV/c}^2 \]
\[ \Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 \text{ MeV} \]

Properties consistent with \(^3\)D\(_3\) state of charmonium system

Also measure:

\[ m_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6 \text{ MeV/c}^2 \]
\[ m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2 \text{ MeV/c}^2 \]
\[ \Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9 \text{ MeV} \]
Summary

- Golden Era for spectroscopy
- Many results have already come out of LHCb
- Today focused on recent results on $b$-baryons, doubly charmed baryons and hidden charm
- Several analyses already exploit fully Run 1+2 dataset
  - A lot more to come in next years
- Future: LHCb upgrade will increase dataset by factor 5-10 depending on mode
Backup
The LHCb Detector

- Muon System
- RICH Detectors
- Vertex Locator VELO
- Calorimeters
- Tracking System

pp collision Point

~ 1 cm

B