$b$ and $c$ hadron production and spectroscopy at LHCb

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On behalf of the LHCb collaboration
Outline

• Selected topics of LHCb
  – Determination of $X(3872)$ quantum numbers
  – Search for doubly charmed baryon $\Xi_{cc}^+$
  – First observation of $B_c^+ \rightarrow B_s^0 \pi^+$ decay
  – Measurement of $\Lambda_b^0$ lifetime

• Summary
Determination of $X(3872)$ quantum numbers

[PRL110 (2013) 222001]
$X(3872)$

- $X(3872)$ was discovered by Belle 10 years ago [PRL91 (2003) 262001], but its nature still remains unclear

- The quantum numbers are crucial for the understanding of $X(3872)$
  - $1^{++}$: $D^0\overline{D^0}$ molecule? tetra-quarks state? $c\overline{c}$ -molecule mixture?
    - $\chi_{c1}(2^3P_1)$?
  - $2^{-+}$: $\eta_{c2}(1^1D_2)$?

- Previous measurements
  - $X(3872) \rightarrow \gamma J/\psi$ observed $\Rightarrow C = +1$
  - CDF: Ruled out all possibilities but $1^{++}$ and $2^{-+}$ [PRL 98 (2007) 132002]
  - BaBar: Favours $2^{-+}$, but doesn't exclude $1^{++}$ (CL=7%) [PRD82 (2010) 011101]
  - Belle: Could not distinguish $1^{++}$ and $2^{-+}$ [PRD84 (2011) 052004]
**X(3872) quantum numbers at LHCb**

- Full 5D angular analysis of the decay chain $B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow (J/\psi \rightarrow \mu^+\mu^-)(\rho \rightarrow \pi^+\pi^-)$
  - The $X(3872)$ to $\pi\pi$ dominated by $\rho$ meson [JHEP 04 (2013) 154]
  - Decay angle $\Omega \equiv (\cos \theta_X, \cos \theta_{\pi\pi}, \Delta \phi_{X,\pi\pi}, \cos \theta_{J/\psi}, \Delta \phi_{J/\psi,\pi\pi})$
  - Dataset: 1 fb$^{-1}$ of 2011 data
$X(3872)$ quantum numbers at LHCb

- Likelihood ratio test used to distinguish $1^{++}$ and $2^{-+}$
  
  $$ t = -2 \ln \left[ \frac{\mathcal{L}(2^{-+})}{\mathcal{L}(1^{++})} \right] = -2 s_w \sum_i w_i \ln \left[ \frac{P(\Omega_i, 2^{-+})}{P(\Omega_i, 1^{++})} \right] $$

- $2^{-+}$ hypothesis is rejected with a significance of $8.4\sigma$
  - $\eta_{c2}(1^1D_2)$ state ruled out

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Search for doubly charmed baryon $\Xi_{cc}^+$

[arXiv:1310.2538]
Doubly charmed baryon $\Xi_{cc}^+$

- $\Xi_{cc}^+$ predicted by quark model and expected to decay weakly.

- Various theoretical predictions
  - $m(\Xi_{cc}^+) \sim [3500, 3700]\text{MeV}/c^2$
  - $\tau(\Xi_{cc}^+) \sim [100, 250] \text{fs}$
  - Expected cross-section at LHCb around $\mathcal{O}(10^2)\text{ nb}$

- SELEX claimed the observation of $\Xi_{cc}^+$ in $\Lambda_c^+K^-\pi^+$ and $pD^+K^-$ \cite{PRL 89 (2002) 112001, PLB 628 (2005) 18}
  - $m(\Xi_{cc}^+) = 3519 \text{ MeV}/c^2$
  - $\tau(\Xi_{cc}^+) < 30 \text{ fs} @ 90\%C.L.$

- Not confirmed by FOCUS, BaBar and Belle
Search for $\Xi_{cc}^{+}$ at LHCb

- Search for $\Xi_{cc}^{+}$ through $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}, \Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$
  - Dataset: 0.65 fb$^{-1}$ of 2011 data
- For signal yield construct $\delta m$ quantity
  - $\delta m = m(\Lambda_{c}^{+}K^{-}\pi^{+}) - m(\Lambda_{c}^{+}) - m(K^{-}) - m(\pi^{+})$
- No significant signal observed

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Upper limits for $R$

- Set upper limits for the production cross-section ratio $R$ relative to $\Lambda_c^+$
  \[
  R = \frac{\sigma(\Xi_{cc}^+) \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}
  \]

- Mass and lifetime unknown: upper limits given as a function of $\delta m$, for 5 different lifetime hypotheses

![Graph showing upper limits on $R$ at 95% CL as a function of $\delta m$ for different lifetime hypotheses.](graph.png)
First observation of $B_c^+ \rightarrow B_s^0 \pi^+$
[arXiv: 1308.4544, accepted by PRL]
$B_c^+$ measurement at LHCb

- $B_c^+$: unique double heavy-flavoured meson
  - Rich structure to test various models

- Many new decay modes of $B_c^+$ observed by LHCb
  - $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$ [PRL 108 (2012) 251802]
  - $B_c^+ \to J/\psi K^+$ [JHEP 09 (2013) 075]
  - $B_c^+ \to \psi(2S)\pi^+$ [PRD 87 (2013) 071103]
  - $B_c^+ \to J/\psi K^+ K^- \pi^+$ [arXiv: 1309.0587, JHEP]
  - $B_c^+ \to J/\psi D_s^{(*)^+}$ [PRD 87 (2013) 112012]
  - $B_c^+ \to B_s^0 \pi^+$ [arXiv: 1308.4544]

- New measurement of $B_c^+$ mass using $J/\psi D_s^+$

$$m(B_c^+) = 6278.28 \pm 1.44\,(stat.) \pm 0.36\,(syst.)\,\text{MeV}/c^2$$

- Most precise single measurement to date!
Observation of $B_c^+ \rightarrow B_s^0\pi^+$

- Dataset: 3 fb$^{-1}$ of 2011+2012 data
- The **first** weak $B$-to-$B$ decay
  - First $B_c^+$ decay through $c$ quark decay
- $B_s^0$ reconstructed using $D_s^-\pi^+$ and $J/\psi\phi$

\[
\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \rightarrow B_s^0\pi^+) = \left( 2.38 \pm 0.35 \text{(stat.)} \pm 0.11 \text{(syst.)}^{+0.17}_{-0.12}(\tau_{B_c^+}) \right) \times 10^{-3}
\]
Measurement of $\Lambda_b^0$ lifetime

[PRL 111 (2013) 102003]
The Heavy Quark Expansion (HQE) model predicts $\tau(\Lambda_b^0) \approx \tau(B^0)$ within several percent:

$$\tau_{\Lambda_b}/\tau_{B^0} = 0.98 + {\cal O}(1/m_b^3)$$

LEP results [arXiv/hep-ph:0304132] deviated from theoretical predictions:

$$\tau_{\Lambda_b}/\tau_{B^0} = 0.798 \pm 0.052$$

Recent measurements from CDF, ATLAS and CMS indicate a larger value but the uncertainties are large.
\( \Lambda^0_b \) lifetime measurement at LHCb

- Make the relative measurement to \( B^0 \)
  - \( \bar{B^0} \rightarrow J/\psi \pi^+ K^- \) and \( \Lambda^0_b \rightarrow J/\psi p K^- \)
  - Similar kinematics and topology
  - Dataset: 1 fb\(^{-1}\) of 2011 data

- Fit the yield ratio as a function of the decay time

\[
R(t) = R(0)[1 + \alpha t]e^{-t\Delta}, \Delta = \frac{1}{\tau_{\Lambda^0_b}} - \frac{1}{\tau_{B^0}}
\]

- Parameter \( \alpha \) determined from simulation: \( \alpha = 0.0033 \pm 0.0024 \text{ ps}^{-1} \)
\[ \Delta = 16.4 \pm 8.2 \pm 4.4 \text{ns}^{-1} \]

\[ \tau(\Lambda_b^0) / \tau(B^0) = 0.976 \pm 0.012 \pm 0.006 \]

- Using the world-average value of \( \tau_{B^0} \), gives:

\[ \tau_{\Lambda_b} = 1.482 \pm 0.018 \pm 0.012 \text{ ps} \]

- Consistent with recent measurements
- Consistent with HQE prediction
Because of time constraints, I didn’t touch

- First observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J\psi D_s^{*+}$ decays [PRD 87 (2013) 112012] (See Sebastian Neubert’s talk)
- First Observation of excited $\Lambda_b^0$ baryons [PRL 109 (2012) 172003]
- Study of $D_J$ meson decays to $D^+\pi^−, D^0\pi^+$ and $D^{*+}\pi^−$ final states in $pp$ collision [JHEP09 (2013) 145]
- Precise measurement of D meson masses [JHEP 1306(2013) 065]
- First observation of the decay $B_{s2}^*(5840)^0 \to B^{*+}K^−$ and studies of excited $B_s^0$ mesons [PRL 110 (2013) 151803]
- Observation of a resonance in $B^+ \to K^+\mu^+\mu^−$ [PRL 111 (2013) 112003]
Summary

• Determination of the $X(3872)$ quantum numbers
  – The measurement favours $J^{PC} = 1^{++}$
  – The $2^{-+}$ hypothesis is rejected with a significance of $8.4\sigma$
• No significant signal observed in $\Xi_{cc}^{+}$ search
• First observation of $B_c^+ \rightarrow B_s^0 \pi^+$
• Precise measurement of $\Lambda_b^0$ lifetime

• ...More results will come soon, stay tuned!
backup
The LHCb detector

Single-armed forward detector, optimized for heavy flavour physics

VELO
\( \sigma_{IP} \sim 20\mu m \) for high \( p_T \) tracks

RICH
\( \epsilon(K \to K) \sim 95\% \)
\( \pi \to K \) misID: \( \sim 5\% \)

HCAL
\( \frac{\sigma_E}{E} \sim \frac{70\%}{\sqrt{E} (GeV)} \oplus 9\% \)

ECAL
\( \sigma_E \) \( \epsilon \) \( E \sim 10\% \)
\( \oplus 1\% \)

Tracker
\( \delta p/p = 0.4\% \sim 0.6\% \)

Muon System
\( \epsilon(\mu \to \mu) \sim 97\% \)
\( \pi \to \mu \) misID: \( 1 \sim 3\% \)

Pseudorapidity coverage
\( 2 < \eta < 5 \)

JINST 3 S08005 (2008)
Motivation – nature of X(3872)

- $D^{*0} \bar{D}^0$ molecule, i.e. a $((u\bar{c})(c\bar{u}))$ system?
  - $1^{++}$

Tetraquark?
- $1^{++}$

Conventional charmonium states?
- $\chi_{c1}(2^3P_1)$ ($1^{++}$)
- $\eta_{c2}(1^1D_2)$ ($2^{-+}$)

$E_B = M(D^0D^{*0}) - M(X(3872))$
- $2M(D^0) + \Delta M(D^{*0} - D^0) - M(X(3872))$
- $0.16 \pm 0.26$ MeV/$c^2$.

LHCb arXiv:1304.6865

Measurement of X(3872) quantum numbers will help to better understand this intriguing narrow state.
D meson mass measurement

- Decay channel for mass measurement $D^0 \rightarrow K^- K^+ K^- \pi^+$
  - Small $Q = M(D^0) - \Sigma m_i$ : minimises the systematic error due to calibration of the momentum scale
- Select $D^0$ mesons from semi-leptonic $b$-hadron decays
- Data sample of 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

$$M(D^0) = 1864.75 \pm 0.15(\text{stat.)} \pm 0.11(\text{syst.}) \text{MeV/c}^2$$
  - Main systematic error due to momentum scale
$M(D^+) - M(D^0)$ and $M(D_s^+) - M(D^+)$ measured using $D^0 \rightarrow K^+K^-\pi^+\pi^-$ and $D_s^+ \rightarrow K^+K^-\pi^+$, since these modes have similar Q-values.

$M(D^+) - M(D^0) = 4.76 \pm 0.12\,(stat.) \pm 0.07\,(syst.)\,\text{MeV}/c^2$

$M(D_s^+) - M(D^+) = 98.68 \pm 0.03\,(stat.) \pm 0.04\,(syst.)\,\text{MeV}/c^2$

Main systematic error due to momentum scale

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Observation of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$

- Test for factorization at $q^2 = m^2(D_s^+)$
- Very clear signal of $B_c^+ \rightarrow J/\psi D_{s}^{(*)+}$ with $D_{s}^{(*)+} \rightarrow D_{s}^{+}\pi^{0}\gamma$, $D_{s}^{+} \rightarrow (K^{+}K^{-})\phi\pi^{+}$

The ratios of branching fractions are measured:

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_{s}^{+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 2.90 \pm 0.57 \text{(stat.)} \pm 0.24 \text{(syst.)}.$$ 

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_{s}^{(*)+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_{s}^{+})} = 2.37 \pm 0.56 \text{(stat.)} \pm 0.10 \text{(syst.)}.$$
Measurement of $B_c^+$ mass

- $B_c^+ \rightarrow J/\psi D_s^+$ is a good channel for precise $B_c^+$ mass measurement
  - Low Q value $\rightarrow$ Small systematic error

$$m(B_c^+) = 6278.28 \pm 1.44\,(\text{stat.}) \pm 0.36\,(\text{syst.}) \text{MeV}/c^2$$

- Most precise single measurement to date!
  - Main systematic uncertainties due to momentum scale
- Consistent with lattice QCD

PRD 87 (2013) 112012
Observation of $B_c^+ \to J/\psi K^+$

- Single Cabibbo Suppressed partner of $B_c^+ \to J/\psi \pi^+$
  - Fit $J/\psi K^+$ mass spectra in bins of PID
- Observe $B_c^+ \to J/\psi K^+$ decay at a significance of $5.0\sigma$
- The ratio of branching fraction is measured to be
  
  $$\frac{\mathcal{B}(B_c^+ \to J/\psi K^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 0.069 \pm 0.019(stat.) \pm 0.005(syst.)$$

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$B_c \rightarrow J/\psi D_s$ is it interesting?

- **Known modes:** $J/\psi l\nu$, $\psi' l\nu$, $J/\psi \pi$, $J/\psi 3\pi$, $\psi' \pi$, $J/\psi K$, $J/\psi KK\pi$ (by LHCb)

- **Interesting quark dynamic & structure:**
  - Nonleptonic mode without 1st generation quarks
    
    $B_s \rightarrow J/\psi \phi$, $\psi'\phi$, $\phi\phi [\phi\gamma]$  
    $B_s \rightarrow D_s(\ast)D_s(\ast)$ (?)

  - Four charm quarks are involved

- **Test for factorization at $q^2 = m^2(D_s)$**
  - Non-spectator annihilation graph is not suppressed
  - Good opportunity for precise mass-measurement: low $Q$-value, excellent mass resolution, no background; low sensitivity to reconstruction imperfectness: momentum scale, energy loss, alignment/z-scale,...
Fit

LHCb Preliminary

Signal
- Gauss
- CB2
- Bukin

Background
- expo
- expo ×
- Bernstein1-4

\[ A^{±±} A^{00} \]

\[ \text{Candidates/(25 MeV/c}^2) \]

\[ \text{Candidates/(10 MeV/c}^2) \]

\[ m(\psi D_s^+) \quad \text{[GeV/c}^2] \]

15 Feb 2k+13, Approval

V. Egorychev, M. Needham, V. Romanovsky & VB
\( \Lambda_b^0 \) lifetime measurement

- Make the relative measurement to \( B^0 \)
  - Reconstruct through \( \overline{B}^0 \rightarrow J/\psi \pi^+ K^- \) and \( \Lambda_b^0 \rightarrow J/\psi \rho K^- \)
  - Topological identical \( \Rightarrow \) Many systematic error cancel

- Fit the yield ratio as a function of the decay time

\[
R(t) = \frac{N_{\Lambda_b}^0(t)}{N_{B^0}(t)} = R(0) \left[ 1 + \alpha t \right] e^{-\Delta t}, \Delta = \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{B^0}}
\]

Acceptance correction. \( \alpha \) from MC: \( \alpha = 0.0024 \pm 0.0033 \text{ ps}^{-1} \)

Decay time resolution (~40 fs) negligible compared to decay time bin width (400 fs), and cancelled by the ratio.
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Item</th>
<th>$\Delta$ (ps$^{-1}$)</th>
<th>$\tau_{A_b^0}/\tau_{B^0}$</th>
<th>$\tau_{A_b^0}$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model</td>
<td>0.0014</td>
<td>0.0021</td>
<td>0.0032</td>
</tr>
<tr>
<td>Background</td>
<td>0.0012</td>
<td>0.0017</td>
<td>0.0026</td>
</tr>
<tr>
<td>Acceptance slope</td>
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<td>0.0033</td>
<td>0.0050</td>
</tr>
<tr>
<td>Acceptance function</td>
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<td>0.0001</td>
<td>0.0002</td>
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<tr>
<td>Fit range</td>
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<td>0.0045</td>
<td>0.0069</td>
</tr>
<tr>
<td>$pK$ helicity</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0002</td>
</tr>
<tr>
<td>$\bar{B}^0$ lifetime</td>
<td>-</td>
<td>0.0001</td>
<td>0.0068</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.0044</td>
<td>0.0062</td>
<td>0.0117</td>
</tr>
</tbody>
</table>

Other sources not included in total

| Linear background‡          | 0.0001                | 0.0002                      | 0.0002              |
| Alternate reflection model  | 0.00004               | 0.00008                     | 0.00008             |

‡ Accounted for in the “Background” row above.