b&c hadron spectroscopy at LHCb

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on behalf of the LHCb collaboration

Rencontres de Moriond
QCD and High Energy Interactions
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Outline

- LHCb detector + Selection
- Excited $D_J$ states
- Search for $\Xi^+_c c$  
- $X(3872)$ radiative decays  
- $b$-hadrons lifetime  
- $b$-baryons (covered by Conor Fitzpatrick) 
- $B_c^+$ physics

- Summary
LHCb detector

- High cross-section of heavy-quark production
- Good time resolution to select B and D candidates
- Good particle identification
- Good momentum resolution

- Cherenkov detectors
  \( \varepsilon(K \to K) \sim 95\% \)
  at 5% \( \pi \to K \) mis-identification

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

- Tracking system
  \( \Delta p/p = 0.4\% \) at 5 GeV/c
  to \( 0.6\% \) at 100 GeV/c

- Calorimeters
  \( \sigma_E/E \sim 1\% \oplus 10\%/\sqrt{E} \) [GeV]

- Muon system
  \( \varepsilon(\mu \to \mu) \sim 97\% \)
  at 1-3% \( \pi \to \mu \) mis-identification

- Interaction point

- See talk by Juan Jose Saborido
Selection

- Trigger on detached vertex and high-$p_T$ hadrons and muons
- Good quality tracks
- $\mu$, $K$, $\pi$, $\gamma$ identification (Muon, RICH, CALO)
- Vertex quality
- PV and SV separation
- Daughter particles not from PV
- B-candidate from the PV
- Decay structure consistent

Efficiencies:
- Efficiencies from simulation
- when possible from data – for PID, trigger

Rectangular cuts or Boosted Decision Trees (BDT)
Excited $D_J$ states

LHCb, 1 fb$^{-1}$, JHEP 09 (2013) 189
Excited $D_J$ states

- D spectroscopy provides a powerful tool to test the quark model predictions
- Only a few states are well established
- BaBar & Belle found new $D_J$ states that need to be confirmed

- Study the $D_J$ mesons produced in pp collisions in $D^+\pi^-, D^0\pi^+$ and $D^{*+}\pi^-$ final states with $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, $D^{*+} \to D^0\pi^+$

LHCb, 1 fb$^{-1}$, JHEP 09 (2013) 189

Godfrey and Isgur, PR D32 (1985) 189

BaBar & Belle found new $D_J$ states that need to be confirmed.
D*+π− final state

- Distinguish between *natural* parity (D*: 0+, 1−, 2+, ...) vs. *unnatural* parity (D: 0−, 1+, 2−, ...) using helicity angle $\theta_H$ in $D_J \rightarrow D^* (\rightarrow D^0 \pi^+) \pi^-$ decays

- 5 high-mass states seen with significance $> 5\sigma$

5 high-mass states seen with significance $> 5\sigma$
- Fit with the same approach
- Only natural parity resonances can contribute
- Model cross-feed from $D_J \rightarrow D^{*+0}(D^{+0}\pi^0/\gamma)\pi^-$ using fit to $D^{*+}\pi^-$ spectra (prev. slide)
- 2 more new states $D_{J}(3000)^{0/+}$ with natural parity are seen
Possible assignments

- Measured properties

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Final state</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yields $\times 10^3$</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{1}(2420)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2419.6 ± 0.1 ± 0.7</td>
<td>35.2 ± 0.4 ± 0.9</td>
<td>210.2 ± 1.9 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>$D_{2}^{*}(2460)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2460.4 ± 0.4 ± 1.2</td>
<td>43.2 ± 1.2 ± 3.0</td>
<td>81.9 ± 1.2 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>$D_{2}(2650)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2649.2 ± 3.5 ± 3.5</td>
<td>140.2 ± 17.1 ± 18.6</td>
<td>50.7 ± 2.2 ± 2.3</td>
<td>24.5</td>
</tr>
<tr>
<td>$D_{2}(2760)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2761.1 ± 5.1 ± 6.5</td>
<td>74.4 ± 3.4 ± 37.0</td>
<td>14.4 ± 1.7 ± 1.7</td>
<td>10.2</td>
</tr>
<tr>
<td>$D_{j}(2580)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2579.5 ± 3.4 ± 5.5</td>
<td>177.5 ± 17.8 ± 46.0</td>
<td>60.3 ± 3.1 ± 3.4</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_{j}(2740)$</td>
<td>$D^{*+}\pi^-$</td>
<td>2737.0 ± 3.5 ± 11.2</td>
<td>73.2 ± 13.4 ± 25.0</td>
<td>7.7 ± 1.1 ± 1.2</td>
<td>7.2</td>
</tr>
<tr>
<td>$D_{j}(3000)^{0}$</td>
<td>$D^{*+}\pi^-$</td>
<td>2971.8 ± 8.7</td>
<td>188.1 ± 44.8</td>
<td>9.5 ± 1.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$D_{2}^{*}(2460)^{0}$</td>
<td>$D^{+}\pi^-$</td>
<td>2460.4 ± 0.1 ± 0.1</td>
<td>45.6 ± 0.4 ± 1.1</td>
<td>675.0 ± 9.0 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>$D_{2}^{*}(2760)^{0}$</td>
<td>$D^{+}\pi^-$</td>
<td>2760.1 ± 1.1 ± 3.7</td>
<td>74.4 ± 3.4 ± 19.1</td>
<td>55.8 ± 1.3 ± 10.0</td>
<td>17.3</td>
</tr>
<tr>
<td>$D_{2}^{*}(3000)^{0}$</td>
<td>$D^{+}\pi^-$</td>
<td>3008.1 ± 4.0</td>
<td>110.5 ± 11.5</td>
<td>17.6 ± 1.1</td>
<td>21.2</td>
</tr>
<tr>
<td>$D_{2}^{*}(2460)^{+}$</td>
<td>$D^{0}\pi^+$</td>
<td>2463.1 ± 0.2 ± 0.6</td>
<td>48.6 ± 1.3 ± 1.9</td>
<td>341.6 ± 22.0 ± 2.0</td>
<td></td>
</tr>
<tr>
<td>$D_{2}^{*}(2760)^{+}$</td>
<td>$D^{0}\pi^+$</td>
<td>2771.7 ± 1.7 ± 3.8</td>
<td>66.7 ± 6.6 ± 10.5</td>
<td>20.1 ± 2.2 ± 1.0</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_{2}^{*}(3000)^{+}$</td>
<td>$D^{0}\pi^+$</td>
<td>3008.1 (fixed)</td>
<td>110.5 (fixed)</td>
<td>7.6 ± 1.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

- Possible assignments

$D_{1}(2420)$ – $1P$ state with $J^P = 1^+$ – well established
$D_{2}^{*}(2460)$ – $1P$ state with $J^P = 2^+$ – well established
$D_{j}(2580)$ – $2S$ state with $J^P = 0^-$ – consistent with D(2550) seen by BaBar
$D_{2}^{*}(2650)$ – $2S$ state with $J^P = 1^-$ – consistent with D*(2600) seen by BaBar
$D_{2}^{*}(2760)$ – $1D$ state with $J^P = 1^-$ – differs from D*(2760) seen by BaBar
$D_{j}(2740)$ – $1D$ state with $J^P = 2^-$
$D_{j}(3000)$ – $1F$ state
$D_{2}^{*}(3000)$ – $1F$ state

PR D82 (2010) 111101
Search for $\Xi^+_{cc}$

LHCb, 0.65 fb⁻¹, JHEP 12 (2013) 090
Search for $\Xi_{cc}^+$

- All of the ground baryon states with C=0,1 are discovered
  - 3 baryon states with C=2 are predicted: $\Xi_{cc}^{+0}$, $\Omega_{cc}^+$
- Predictions: $3500 < M(\Xi_{cc}^+) < 3700$ MeV/c$^2$, $100 < \tau(\Xi_{cc}^+) < 250$ fs
- The signals $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \rightarrow pD^+K^-$ were reported by SELEX
  - $M = 3519 \pm 2$ MeV/c$^2$, $\tau < 33$ fs
  - 20% of $\Lambda_c^+$ yield from $\Xi_{cc}^+$ decays
- Not confirmed by FOCUS, BaBar and Belle
- LHCb looks for $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
  - in range $3300 < M < 3800$ MeV/c$^2$, $100 < \tau < 400$ fs
- Upper limits are obtained for
  - $R \equiv \frac{\sigma(\Xi_{cc}^+) B(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$
- Doesn't exclude SELEX results
  - (different production environment and $\tau < 33$ fs)
X(3872) radiative decays

LHCb-PAPER-2014-008, 3 fb$^{-1}$, to appear in NPB
\(X(3872) \rightarrow \psi(2S)\gamma\) state was discovered in 2003 by Belle in \(B^+ \rightarrow X(3872)K^+\), \(X(3872) \rightarrow J/\psi\pi^+\pi^-\). Later was also observed by BaBar, CDF, D0, CMS, LHCb.

Possible interpretations are \(D^*\overline{D}\) molecule, \(c\bar{c} (2^3P_1)\), tetraquark, ... and their mixtures.

The ratio \(R = \frac{B(X(3872) \rightarrow \psi(2S)\gamma)}{B(X(3872) \rightarrow J/\psi\gamma)}\) is of special interest for theory:

- \(c\bar{c} (2^3P_1)\) interpretation: \(R \approx 1.2 - 15\)
- In molecular picture \(R \sim 3 \times 10^{-3}\)
- mixture of \(c\bar{c}\) and \(D\overline{D}^* \rightarrow R = 0.5 - 5\)

BaBar vs. Belle discrepancy

- BaBar: \(R = 3.4 \pm 1.4\) in \(B^+ \rightarrow X(3872)K^+\) decays
  
  \boxed{PRL 102 (2009) 132001}

- Belle: \(R < 2.1\) (at 90% C.L.) using B decays
  
  \boxed{PRL 107 (2011) 091803}

An additional measurement is needed.
The $X(3872)$ decays to $\psi(2S)\gamma$ and $J/\psi\gamma$ are reconstructed in $B^+ \rightarrow X(3872)K^+$

2D fits are used $(M(B), M(\psi\gamma))$ to determine signal yields

Peaking background from partially reconstructed B decays:

- $B^+ \rightarrow J/\psi K^+ (\rightarrow K^+\pi^0 (\rightarrow \gamma\gamma))$
- $B \rightarrow \psi(2S)K^+X + \text{random } \gamma$
determined with simulation

Dominant systematic uncertainty:

- signals yield determination
- photon reconstruction

LHCb-PAPER-2014-008, 3 fb$^{-1}$, to appear in NPB
\[ R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29 \pm 0.06 \] 

\text{(stat)} \quad \text{(syst)} \quad \text{(}\mathcal{B}(\psi \to \mu\mu)\text{)}

\text{BaBar 2009}

\text{Belle 2011}

\text{LHCb Preliminary}

predictions for pure \(c\bar{c}\) state

prediction for pure \(D\bar{D}^*\) model

predictions for admixture of \(c\bar{c}\) and \(D\bar{D}^*\)

LHCb-PAPER-2014-008, 3 fb\(^{-1}\), to appear in NPB

\text{PRL 102 (2009) 132001}

\text{PRL 107 (2011) 091803}
b-hadrons lifetime

LHCb, 1 fb$^{-1}$, arXiv:1402.2554v1

LHCb, 3 fb$^{-1}$, arXiv:1402.6242v1
In HQE, b-hadrons lifetime is mainly determined by $b \to cW^*$ transition, the differences in lifetimes depend on particular structures of the hadrons.

The lifetimes of b-hadrons are measured to be:

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Value [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{B^+ \to J/\psi K^+}$</td>
<td>$1.637 \pm 0.004 \pm 0.003$</td>
</tr>
<tr>
<td>$\tau_{B^0 \to J/\psi K^*0}$</td>
<td>$1.524 \pm 0.006 \pm 0.004$</td>
</tr>
<tr>
<td>$\tau_{B^0 \to J/\psi K_S}$</td>
<td>$1.499 \pm 0.013 \pm 0.005$</td>
</tr>
<tr>
<td>$\tau_{Λ_b^0 \to J/ψ \Lambda}$</td>
<td>$1.415 \pm 0.027 \pm 0.006$</td>
</tr>
<tr>
<td>$\tau_{Λ_b^0 \to J/ψ \phi}$</td>
<td>$1.480 \pm 0.011 \pm 0.005$</td>
</tr>
</tbody>
</table>

In addition, the precise measurement of $\tau(Λ_b^0)/\tau(B^0)$ is performed using kinematic similarity of $Λ_b^0 \to J/ψ p K^-$ and $B^0 \to J/ψ π^+ K^-$ decays:

$$\frac{\tau_{Λ_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004$$

Average of $Λ_b^0 \to J/ψ p K^-$ and $Λ_b^0 \to J/ψ Λ^0$ results:

$$\tau_{Λ_b^0} = 1.468 \pm 0.009 \pm 0.008 \text{ ps}$$

LHCb, 1 fb$^{-1}$, arXiv:1402.2554v1

more precise (single) measurements

compatible with theory predictions and world averages:

<table>
<thead>
<tr>
<th>Observable</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{B^+}$ [ps]</td>
<td>$1.641 \pm 0.008$</td>
</tr>
<tr>
<td>$\tau_{B^0}$ [ps]</td>
<td>$1.519 \pm 0.007$</td>
</tr>
<tr>
<td>$\tau_{B^0}$ [ps]</td>
<td>$1.516 \pm 0.011$</td>
</tr>
<tr>
<td>$\tau_{Λ_b^0}$ [ps]</td>
<td>$1.429 \pm 0.024$</td>
</tr>
</tbody>
</table>

LHCb, 3 fb$^{-1}$, arXiv:1402.6242v1

consistent with HQE predictions
$B_c^+ \text{ physics}$

LHCb, 2 fb$^{-1}$, arXiv:1401.6932

LHCB-PAPER-2014-009, 3 fb$^{-1}$, to appear in JHEP
The $B_c^+$ meson is a unique system, being double heavy-flavoured meson → good laboratory to test different models

Prior to LHCb only the $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu$ decays were observed, mass and lifetime measured by CDF and D0

LHCb has already observed many new decay modes:

- $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$
- $B_c^+ \rightarrow \psi(2S) \pi^+$
- $B_c^+ \rightarrow J/\psi K^+$
- $B_c^+ \rightarrow J/\psi D_s^{(*)+}$
- $B_c^+ \rightarrow B_s^0 \pi^+$
- $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$
- $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ new
**B_c^+ mass and lifetime**

**Most precise mass measurement**
- by studying $B_c^+ \rightarrow J/\psi D_s^{(*)^+}$ decays

- $m_{B_c^+} = 6276.28 \pm 1.44 \text{ (stat)} \pm 0.36 \text{ (syst)} \text{ MeV}/c^2$

  **In agreement with world average:**
  $m(B_c^+) = 6274.5 \pm 1.8 \text{ MeV}/c^2$

**Most precise lifetime measurement**
- by studying $B_c^+ \rightarrow J/\psi \mu^+\nu_{\mu}$ decays

- $\tau = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst)} \text{ fs}$

  **Consistent with world average:**
  $\tau(B_c^+) = 452 \pm 33 \text{ fs}$
New $B_c^+$ decay modes

$B_c^+ \rightarrow B_s^0 \pi^+:$

$B_c^+ \rightarrow J/\psi +$ multi hadrons:

$LHCb, 3 \text{ fb}^{-1}, PRL 111 (2013) 1818801$

$LHCb, 3 \text{ fb}^{-1}, JHEP 11 (2013) 94$

$LHCb-PAPER-2014-009, 3 \text{ fb}^{-1}, \text{to appear in JHEP}$
Summary

- LHCb has a rich program in b&c spectroscopy

- Many new most precise or first time measurements are performed
  - $X(3872) \rightarrow \psi(2S)\gamma$
  - $B^+, B^0, B_s^0$ and $\Lambda_b^0$ lifetime
  - $B_c^+$ lifetime and new decay modes
  - ...

- More new analysis are coming soon

Thank you!
Backup
X(3872) → ψ(2S)γ

References for the predictions

The predictions for the ratio $R = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)}$ are vary widely:

- $\bar{c}c$ $(2S_P)$ interpretation: $R \approx 1.2 \leftarrow 15$
  - [Barnes, Godfrey and Swanson, Phys. Rev. D72 (2005) 054026]
  - [Li and Chao, Phys. Rev. D79 (2009) 094004]

- In molecule picture $R \sim 3 \times 10^{-3}$
  - [Ferretti and Galata, arXiv:1401.4431]

- Mixture of $c\bar{c}$ and $DD^* \rightarrow R = 0.5 \leftarrow 5$
  - [Eichten, Lane and Quigg, Phys. Rev. D73 (2006) 014014]
B_c^+ lifetime

- Determine decay time with partially-reconstructed B_c^+ → J/ψμ^+ν_μ decays

- Use theoretical models for the B_c^+ → J/ψμ^+ν_μ decay and account for feed-down from ψ(2S) decay modes

- Determine background shape from data (B decays with misID, prompt, fake J/ψ and wrong PV) and simulation (combinatorial)

- Separate by 2D fit (M_{J/ψμ}, τ_{J/ψμ})

- Dominant uncertainty:
  - Prompt and combinatorial background
  - B_c^+ decay model

\[ \tau = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst)} \text{ fs} \]

- Consistent with world average (452 ± 33 fs), but more precise

LHCb, 2 fb^{-1}, arXiv:1401.6932