b and c Spectroscopy at LHCb

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The LHCb Detector

Theory and motivation

Selected results
- $B_c$ and $B$ hadrons
- Exotic spectroscopy

Conclusions and outlook
Uncertainty on Luminosity in these analyses: 3.5-5% 

(JINST 7 (2012) P01010)
Motivations for heavy quark hadron spectroscopy

Different QCD models predict different masses, lifetimes, branching ratios, spin-parity etc. for many c- and b-hadrons.

Further confirmation and testing of models of the heavy quark interactions is provided by c- and b-hadron spectroscopy.

In some cases observation of new particles or new modes can help the theorists to build the big picture!

Why Spectroscopy?

Different QCD models predict different masses, lifetimes, branching ratios, spin-parity etc. for many c- and b-hadrons.

Further confirmation and testing of models of the heavy quark interactions is provided by c- and b-hadron spectroscopy.

In some cases observation of new particles or new modes can help the theorists to build the big picture!
**B_c Physics**

- B_c unique meson with two open heavy flavours, b\bar{c} or \bar{b}c
- Intermediate charmonium/bottomonium
- First observed CDF in 1998 in B_c^+ \rightarrow J/\psi l^+\nu, fully reconstructed in B_c^+ \rightarrow J/\psi\pi^+
- LHCb already measured the mass and production with 0.37 fb\(^{-1}\) in B_c^+ \rightarrow J/\psi\pi^+
- Two new B_c decay modes observed at LHCb!!
  - B_c^+ \rightarrow \psi(2S)\pi^+
  - B_c^+ \rightarrow J/\psi D_s^{(*)}

12.03.2013

G. Manca, Moriond QCD 2013
First observation of this mode!

First analysis to use full 2011+12 dataset 3 fb⁻¹, at √s = 7 and 8 TeV

We measure the ratio:

\[ \frac{B(B_c^+ \to J/\psi D_s^+)}{B(B_c^+ \to J/\psi \pi^+)} = \frac{1}{B_{D_s^+}} \times \frac{\varepsilon_{B_c^+ \to J/\psi \pi^+}^{tot}}{\varepsilon_{B_c^+ \to J/\psi D_s^+}^{tot}} \times \frac{N(B_c^+ \to J/\psi D_s^+)}{N(B_c^+ \to J/\psi \pi^+)} \]

Theory predictions disagree!

<table>
<thead>
<tr>
<th>References [see Pag.16]</th>
<th>( \mathcal{R}_{D_s^+/\pi^+} )</th>
<th>( \mathcal{R}_{D_s^{+*/D_s^+}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Simple approach” [B⁰]</td>
<td>2.90 ± 0.42</td>
<td>2.20 ± 0.35 ± 0.62</td>
</tr>
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<td>1.58 ± 0.34</td>
<td>2.07 ± 0.52 ± 0.52</td>
</tr>
<tr>
<td>[7]</td>
<td>1.3</td>
<td>3.9</td>
</tr>
<tr>
<td>[8]</td>
<td>2.6</td>
<td>1.7</td>
</tr>
<tr>
<td>[9]</td>
<td>2.2</td>
<td>—</td>
</tr>
<tr>
<td>[10]</td>
<td>1.2</td>
<td>—</td>
</tr>
</tbody>
</table>
**B_c^+ \rightarrow J/\psi D_s^*(\pm) : Results**

- Very clear signals of $B_c^+ \rightarrow J/\psi D_s^{(*)}$, with $D_s^{(*)} \rightarrow D_s^{+} \gamma/\pi^0$, $D_s \rightarrow (K K) \pi$

- Fits:
  - Background : exponential
  - Signal:
  - $B_c^+ \rightarrow J/\psi D_s^+$ : Gaussian
  - $B_c^+ \rightarrow J/\psi D_s^{*+}$ : Sum of two helicity amplitudes from MC $A_{00}$ and $A_{\pm\pm}$

\[
\begin{align*}
N(B_c^+ \rightarrow J/\psi D_s^+) &= 28.9 \pm 5.6 \\
N(B_c^+ \rightarrow J/\psi D_s^{*+}) &= 68.4 \pm 9.6
\end{align*}
\]

**Significance >7\sigma for each !**

- Using the $B_c^+ \rightarrow J/\psi \pi^+$ as normalisation channel we can measure the ratios:

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

$$\frac{B(B_c^+ \rightarrow J/\psi D_s^{*+})}{B(B_c^+ \rightarrow J/\psi D_s^+)} = 2.37 \pm 0.56\text{(stat)} \pm 0.10\text{(syst)}$$

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**12.03.2013**

G.Manca, Moriond QCD 2013
Theory predictions disagree!

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</tr>
</thead>
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<tr>
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<td>$2.90 \pm 0.42$</td>
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</tr>
<tr>
<td>“Simple approach” [B$^+$]</td>
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<td>-</td>
</tr>
<tr>
<td>[10]</td>
<td>1.2</td>
<td>-</td>
</tr>
</tbody>
</table>

In the “Simple approach” we assume that the spectator diagram dominates and that factorisation holds; then we can write the ratios as:

$$\mathcal{R}_{D_{s}^+/\pi^+} \equiv \frac{\Gamma (B_c^+ \rightarrow J/\psi D_{s}^+) \approx \Gamma (B \rightarrow D_{s}^+) \approx \Gamma (B \rightarrow D_{s}^{*+})}{\Gamma (B_c^+ \rightarrow J/\psi \pi^+) \approx \Gamma (B \rightarrow D_{s}^{*+}) \approx \Gamma (B \rightarrow D_{s}^{*+})}$$

$$\mathcal{R}_{D_{s}^{*+}/D_{s}^+} \equiv \frac{\Gamma (B_c^+ \rightarrow J/\psi D_{s}^{*+}) \approx \Gamma (B \rightarrow \bar{D}_{s}^+) \approx \Gamma (B \rightarrow \bar{D}_{s}^{*+})}{\Gamma (B_c^+ \rightarrow J/\psi \pi^+) \approx \Gamma (B \rightarrow D_{s}^{*+}) \approx \Gamma (B \rightarrow D_{s}^{*+})}$$

\[ B(B_c^+ \rightarrow J/\psi D_{s}^+) \] = 2.90±0.57(stat)±0.24(syst)

\[ B(B_c^+ \rightarrow J/\psi \pi^+) \] = 2.37±0.56(stat)±0.10(syst)
The low energy release (Q-value) in the $B_c^+ \rightarrow J/\psi D_s^+$ decay allows a precise measurement of the $B_c$ mass.

Main source of uncertainty: $D_s$ mass knowledge!

Writing: $m(D_{s^+}^+) = m(D^0) - [m(D^0) - m(D^+)] + [m(D_{s^+}) - m(D^+)] = 1968.31 \pm 0.20$ MeV/c$^2$ measured by LHCb [LHCb-PAPER-2013-011]

$B_c^+ - m(D_s^+) = 4307.97 \pm 1.44$(stat) $\pm 0.11$(syst) MeV/c$^2$.

$m(B_c^+) = 6276.28 \pm 1.44$(stat) $\pm 0.36$(syst) MeV/c$^2$.

**Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source</th>
<th>$m(B_c^+)$</th>
<th>$m(B_c^+) - m(D_s^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s$ mass</td>
<td>0.16</td>
<td>-</td>
</tr>
<tr>
<td>Energy Loss Corrections</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Momentum Scale Uncertainty</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Fit Model</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.36</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Averaged with PDG $m(D_{s^+}^+) = 1968.47 \pm 0.33$ MeV/c$^2$

Most precise single measurement to date!

LHCb Preliminary

LHCb-PAPER-2013-010

NEW

12.03.2013

G.Manca, Moriond QCD 2013
LHCb searched for this decay in 1 fb\(^{-1}\) \(\sqrt{s} = 7\) TeV data, observing it for the FIRST TIME 😊

- Events selected with Boost Decision Tree (BDT) trained on \(B_c^+ \to J/\psi\pi^+\)
- Fit: Crystal Ball + exponential

- Measured:
  
  \[
  \frac{B_c^+ \to \psi(2S)\pi^+}{B_c^+ \to J/\psi\pi^+} = \epsilon_{\text{rel}} \times \frac{N(B_c^+ \to \psi(2S)\pi^+)}{N(B_c^+ \to J/\psi\pi^+)} = 0.250 \pm 0.068 (\text{stat}) \pm 0.014 (\text{syst}) \pm 0.006 (B)
  \]

- Theory predicts:
  
  \[
  \frac{B(B_c^+ \to \psi(2S)\pi^+)}{B(B_c^+ \to J/\psi\pi^+)} \sim 0.13 - 0.42
  \]

Measurement of $\Lambda_b^0, \Xi_b^-, \Omega_b^-$ masses

- $b$-baryon status: 16 predicted ground states
- $\Lambda^0_b$, $\Xi^-_b$ and $\Omega^-_b$ baryons observed
- Their masses measured by simple cut based analysis on 1.0 fb$^{-1}$ data

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Yield</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5795.2 ± 0.9</td>
<td>5870</td>
<td>LHCb [1.0 fb$^{-1}$]</td>
</tr>
<tr>
<td>5619.4 ± 0.6</td>
<td>6870</td>
<td>CDF+LHCb average 6048.9</td>
</tr>
<tr>
<td>6046 ± 9</td>
<td>19</td>
<td>D0 [1.3 fb$^{-1}$]</td>
</tr>
</tbody>
</table>

Main systematic: momentum scale

[References on Pag.17]
X(3872) Quantum Numbers

- X(3872) discovered by Belle (2003) but nature still unclear
- LHCb measured the X mass and cross section in 2010 and now performed the J^PC measurement in 1 fb^{-1} @ \sqrt{s} = 7 TeV
- Measurement of quantum numbers (J^PC) crucial!!
  - If 1^{++}(D^0D^{*0} molecule, Tetra-quarks, \chi_{c1}(2^3P_J) or 2^+ (\eta_{c2}(1^1D_2))
- X reconstructed from B decays: \( B^+ \rightarrow X(3872) K^+ \)
  \( \rightarrow J/\psi \pi^+\pi^- \)
  \( \rightarrow \mu^+\mu^- \)

- Fit: Symmetric Crystal Ball Function + linear background
- \( N( B^+ \rightarrow \psi(2S)K^+) = 5642 \pm 76 \)
- \( N( B^+ \rightarrow X(3872)K^+) = 313 \pm 26 \) (68% purity)

B^+ \rightarrow \psi(2S)K^+ used as control channel
To discriminate between the two hypotheses we built a test statistic \( t = \text{ratio of the PDF} \) built as a product of the expected matrix element and the reconstruction efficiency.

- Helicity amplitudes can be expressed
  - Without free parameters: \( J^{PC} = 1^{++} \)
  - With a complex parameter (\( \alpha \)): \( J^{PC} = 2^{-+} \)

To discriminate between the two hypotheses we built a test statistic \( t = \text{ratio of the likelihoods of the two } J^{PC} \text{ values, such that} \)

- \( t > 0 \to 1^{++} \) favoured
- \( t < 0 \to 2^{-+} \) favoured

**RESULTS:**

- \( t_{\text{data}} \) prefers the \( 1^{++} \) hypothesis! 😊
  (tested with simulation)
- \( 2^{-+} \) hypothesis rejected with > 8\( \sigma \)

- PDF = Probability Density Function
RESULTS:
- $t_{\text{Data}}$ prefers the $1^{++}$ hypothesis! 😊

More tests/validations:
- Data prefer the value of $\alpha=(0.67,0.28)$ in agreement with Belle $(0.64,0.27)$ [Phys. Rev. D84 (2011) 052004]
- Checking the shape
- Going to one dimension

Figure 3: Distribution of $\ln\left[ P(\Delta^+ | 2^{++}), P(\Delta^+ | 1^{++}) \right]$ for the data (points with error bars) compared to the distributions for the simulated experiments with $J^{PC}=1^{++}$ (red solid histogram) and with $J^{PC}=2^{++}$ and $\hat{\alpha} = \tilde{\alpha}$ (blue dashed histogram) after the background subtraction using sWeights. The simulated distributions are normalized to the number of signal candidates observed in the data. Bin contents and uncertainties are divided by bin width because of unequal bin sizes.

In summary, we unambiguously establish that the values of total angular momentum, parity and charge-conjugation eigenvalues of the $X(3872)$ state are $1^{++}$. This is achieved through the first analysis of the full five-dimensional angular correlations between final state particles in $B^+ \to X(3872) K^+$, $X(3872) \to \pi^+ \pi^-$ $J/\psi$, $J/\psi \to \mu^+ \mu^-$ decays using the likelihood-ratio test. The $2^{++}$ hypothesis is excluded with a significance of more than eight Gaussian standard deviations. This result rules out the explanation of the $X(3872)$ meson as a conventional $\psi(3686)$ state. Among the remaining possibilities are the $\psi(3686)$ charmonium, disfavored by the value of the $X(3872)$ mass [32], and unconventional explanations such as a $D^{*0} \bar{D}^0$ molecule [7], tetraquark state [8] or charmonium-molecule mixture [9].

Figure 4: Background-subtracted distribution of $\cos\theta_X$ for (top) all candidates and for (bottom) candidates with $|\cos\theta_{\pi\pi}| > 0.6$ for the data (points with error bars) compared to the expected distributions for the $J^{PC}=1^{++}$ (red solid histogram) and $J^{PC}=2^{++}$ hypotheses (blue dashed histogram). The simulated distributions are normalized to the number of signal candidates observed in the data across the full phase space.
LHCb has a rich program in spectroscopy which is flourishing with the new data!!

Many important results already achieved (new decay modes observed, unique first measurements...)

Many more available but not shown today for time issues:

- Prompt charm cross section [arXiv:1302.2864]
- Study of $D_{sj}$ decays to $D^+K^0_S$ and $D^0K^+$ final states [J. High Energy Phys. 10 (2012) 151]

Still about 2 fb$^{-1}$ of data to be analysed!!
- There will be many more news...

As usual...
References $B_c^+ \rightarrow J/\psi \, D_s^{(*)+}$


References Baryon Masses


Uncertainties on the ratio of $\text{Br } B_c \rightarrow J/\psi D_s/\pi$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated efficiencies</td>
<td>1.0</td>
</tr>
<tr>
<td>Trigger systematic</td>
<td>1.1</td>
</tr>
<tr>
<td>Fit model</td>
<td>1.8</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>$2 \times 0.6$</td>
</tr>
<tr>
<td>Hadron interactions</td>
<td>$2 \times 2.0$</td>
</tr>
<tr>
<td>Track quality selection</td>
<td>$2 \times 0.4$</td>
</tr>
<tr>
<td>Kaon identification</td>
<td>3.0</td>
</tr>
<tr>
<td>$B_c^+$ lifetime</td>
<td>1.0</td>
</tr>
<tr>
<td>Stability for various data taking conditions</td>
<td>2.5</td>
</tr>
<tr>
<td>$\mathcal{B}\left(D_s^+ \rightarrow (K^- K^+)\phi \pi^+\right)$</td>
<td>5.6</td>
</tr>
<tr>
<td>Total</td>
<td>8.4</td>
</tr>
</tbody>
</table>
$B_c \rightarrow J/\psi \ D_s$

- Different binning scheme

Figure A.5: Mass distributions for $J/\psi \ D_s^+$ pairs. The overlaid curve represents the fit results described in text. This is a rebinne dversion of Fig. 4.2.
**X(3872) Quantum numbers**

- **X(3872)** discovered by Belle >10yrs ago but its nature still unclear
- Measurement of quantum numbers crucial in shedding light on this state
  - Possibilities: 1++(D^0D^{*0} molecule? Tetra-quarks? \(\chi_{c1}(2^3P_1)\) OR 2−+ (\(\eta_{c2}(1^{1}D_{2})\))
- LHCb performed the measurement in 1fb\(^{-1}\) of data \(\sqrt{s}=7\)TeV
- 5-dimensional analysis \(B^+ \rightarrow X(3872) K^+\)
  \[P(\Omega|J_X) = |\mathcal{M}(\Omega|J_X)|^2 \epsilon(\Omega)/I(J_X), \text{ where } I(J_X) = \int |\mathcal{M}(\Omega|J_X)|^2 \epsilon(\Omega) d\Omega.\]
  \[|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \left| \sum_{\lambda_{J/\psi},\lambda_{\pi\pi}} A_{\lambda_{J/\psi},\lambda_{\pi\pi}}^{\Delta\lambda_{\mu}} D_{0,\lambda_{J/\psi}}^{\Delta\lambda_{\mu}}(\phi_X, -\phi_X, \theta_X, -\phi_X) D_{1,\lambda_{\pi\pi}}^{\Delta\lambda_{\mu}}(\phi_{\pi\pi}, -\phi_{\pi\pi}) D_{1,\lambda_{J/\psi}}^{\Delta\lambda_{\mu}}(\phi_{J/\psi}, -\phi_{J/\psi}) \right|^2\]
  \[\Omega \equiv (\cos \theta_X, \cos \theta_{\pi\pi}, \Delta \phi_X, \Delta \phi_{J/\psi})\]
  Helicity coupling \(A_{\lambda_{J/\psi},\lambda_{\pi\pi}}^{\Delta\lambda_{\mu}}\): no free parameter if 1++
  one complex parameter (\(\alpha\)) if 2−+
- Likelihood ratio test to discriminate the two hypotheses
  \[t = -2 \ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{++})]\]
  2−+ favored \(t\) 1++ favored
Two narrow states are observed in $\Lambda_b^0\pi^+\pi^-$ spectrum in $L=1.0$ fb$^{-1}$ data.

Expected at $J^P = 1/2^-$ and $3/2^-$. 

$\Lambda_b^0$ peak
Two narrow states are observed in $\Lambda_b^0\pi^+\pi^-$ spectrum in $L=1.0\ fb^{-1}$ data. Expected at $J^P = 1/2^-$ and $3/2^-$. 

$\Lambda_b^0$ First Observation!!

arxiv:1205.3452
Two narrow states are observed in $\Lambda_b^0\pi^+\pi^-$ spectrum in L=1.0 fb$^{-1}$ data

Expected at $J^P = 1/2^-$ and $3/2^-$

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>width</th>
<th>Significance</th>
</tr>
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<tbody>
<tr>
<td>$\Lambda_b^0(5912)$</td>
<td>16.4±4.7</td>
<td>0.19 MeV/c$^2$</td>
<td>4.6 $\sigma$</td>
</tr>
<tr>
<td>$\Lambda_b^0(5920)$</td>
<td>49.5±7.9</td>
<td>0.27 MeV/c$^2$</td>
<td>10.1 $\sigma$</td>
</tr>
</tbody>
</table>

Main systematics:
- Signal/background modelling, momentum scale

Limits on natural widths (95% C.L.):
- $\Gamma_{\Lambda_b^0(5912)} < 0.82$ MeV
- $\Gamma_{\Lambda_b^0(5920)} < 0.71$ MeV