Search for excited $B_{c}^{**}$ at LHCb

Michele Veltri

On behalf of the LHCb Collaboration

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Introduction

- The $B_c$ is a unique system in the SM
  - Doubly heavy meson with different flavours ($\bar{b}c$)
  - The $B_c^+$ can decay only weakly
    → Longer lifetimes than quarkonia but smaller than other B–mesons
- Small production cross-section: $\mathcal{O}(\alpha_s^4)$
  - At hadron colliders the $B_c$ production is mainly due to $gg$ fusion
  - Requires the production of both $b\bar{b}$ and $c\bar{c}$
  - $\sigma_{B_c} \sim 10^{-3} \sigma_B$
- Scarce information before LHC
  - The $B_c^+$ was discovered in 1998 by CDF at Tevatron
  - Mass and lifetime by CDF and D0 at Tevatron (Run II)
- $\sigma(B_c)_{LHC}/\sigma(B_c)_{Tevatron} \sim \mathcal{O}(10)$
  - Many decay modes observed
  - High precision measurements of mass and lifetime
  - Relative production measurements
  - Starting the study of the excited states
The spectrum is predicted by many models and Lattice QCD.

Observation of these states can test the validity of the various approaches.

The states below the $BD$ threshold decay to the ground state only by radiative or hadronic transitions.

Only $B^+_c$ and $B^+_c(2S)$ observed so far.

Theory predicts also:

$$R_{B_c} = \sigma B^{*+}(2S)/\sigma B^+_c(2S) \sim 2.4 \div 2.6$$

$n^{2S+1}L_J$

$n$: Radial quantum number
$S$: Total spin of two quarks
$L$: Relative angular momentum
$J$: Total angular momentum
Theory predictions for the $B_c$ mass

- Incomplete list of theory prediction of the $(1S/2S)$ masses (in MeV)

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</table>

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Search for excited $B_{c}^{**}$ at LHCb
Theory predictions for the $B_c$ mass

- Average for $B_c^+$ mass is close to the PDG value
- Few predictions for LQCD but closer to the observed one
- Average ok also for the $B_c^+(2S)$

\[ \begin{align*}
\text{Bc Mass} & \quad \text{m1} \\
\text{Entries} & \quad 28 \\
\text{Mean} & \quad 6279 \\
\text{RMS} & \quad 27.76
\end{align*} \]

\[ \begin{align*}
\text{M(1S)} & \quad \Delta \text{dm1} \\
\text{Entries} & \quad 27 \\
\text{Mean} & \quad 58.85 \\
\text{RMS} & \quad 15.76
\end{align*} \]

\[ \begin{align*}
\text{Bc(2S) Mass} & \quad \text{m2} \\
\text{Entries} & \quad 21 \\
\text{Mean} & \quad 6868 \\
\text{RMS} & \quad 32.63
\end{align*} \]

\[ \begin{align*}
\text{M(2S)} & \quad \Delta \text{dm2} \\
\text{Entries} & \quad 21 \\
\text{Mean} & \quad 32.33 \\
\text{RMS} & \quad 11.11
\end{align*} \]
Excited $B_c$ states

- Theory predicts $\Delta M(1S) \sim \mathcal{O}(60)\text{MeV}$; $\Delta M(2S) \sim \mathcal{O}(35)\text{MeV}$
- 1S transition: experimentally very challenging to detect such a low energy $\gamma$
- 2S transition: can use the $\pi\pi$ emission to (1S) levels
- But:
  - $B_c^+(2S)$ goes to the ground state directly
  - $B_c^{*+}(2S) \rightarrow B_c^{*+}(1S) + \pi^+\pi^-$
  - Followed by $B_c^{*+}(1S) \rightarrow B_c^+ + \gamma$
- If the experimental resolution is good enough the $B_c^+\pi^+\pi^-$ invariant mass distribution will have a two peaks structure
- $M(B_c^{*+}(2S))_{\text{REC}} = M(B_c^+(2S)) - \Delta M(1S) + \Delta M(2S)$
- Since $\Delta M(1S) > \Delta M(2S)$ the $B_c^{*+}(2S)_{\text{REC}}$ will be the lower peak
Excited $B_c$ states – Experimental situation

- In 2014 ATLAS [PRL 113.212004] observed a state consistent with expectations for the (2S) state
  
  $m = 6842 \pm 4\text{(stat.)} \pm 5\text{(syst.)}\text{ MeV}/c^2$

- No discrimination between $B_c^{*+}(2S)$ and $B_c^+(2S)$

- In 2018 LHCb, using a data sample of only 2 fb$^{-1}$, did not find any structure in the invariant mass distribution [JHEP 01 (2018) 138]

- In a recent work CMS [PRL 122.132001], using the 2015–2018 data, reports two peaks in the invariant $B_c^+ \pi^+\pi^-$ separated by
  
  $m = 29 \pm 1.5\text{(stat.)} \pm 0.7\text{(syst.)}\text{ MeV}/c^2$

- And a $B_c^+(2S)$ mass of
  
  $m = 6871.0 \pm 1.2\text{(stat.)} \pm 0.8\text{(syst.)} \pm 0.8(B_c^+)\text{ MeV}/c^2$
The LHCb detector

- Originally designed to measure CP violation in the $b$ sector today is also developing a rich physics program in the forward region.

- **Acceptance**
  
  $10 \text{ mrad} < \theta < 300 \text{ mrad}$
  
  $2 < \eta < 5$ coverage

- **Vertex detector (VELO)**
  
  $\sigma_{IP} \sim 10 \mu m$, $\sigma_{\tau} \sim 45 \text{ fs}$

- **Tracking (TT and IT/OT)**
  
  $\Delta p/p = 0.5 - 1.0\%$
  
  (5 GeV/c–200 GeV/c)

- **RICH**
  
  $\epsilon(K \rightarrow K) \sim 95\%$
  
  mis-ID $(\pi \rightarrow K) \sim 5\%$

- **CALO (ECAL, HCAL)**
  
  $\Delta E/E = 1\% \oplus 10\%/\sqrt{E} \text{ GeV}$

- **Muon**
  
  $\epsilon(\mu \rightarrow \mu) \sim 97\%$
  
  misID $(\pi \rightarrow \mu) \sim 1 - 3\%$
Event selection

- Run I + Run II data sample: 8.5 fb$^{-1}$
- Common selection for $B_c^+(2S)$ or $B_c^{*(+)}(2S)$ candidates
- Use the decay: $B_c^+ \rightarrow J/\Psi\pi^+$
- Pre-selection cuts + BDT classifier
- To further improve S/B: $P_T(B_c^+) > 10$ GeV/c

$B_c^+$ signal yield: $3785 \pm 73$
Event Selection

- Combine the $B_c^+$ candidate with a pair of tracks from the PV
  - Opposite charge
  - Identified as $\pi$

- Check that selection does not produce artificial peaks in the $M(B_c^+\pi^+\pi^-)$ distribution
  - Apply the same cuts to same–sign sample: $B_c^+\pi^+\pi^+$, $B_c^+\pi^-\pi^-$

- One peak approximately at 6840 MeV/c$^2$
- Another structure at $\sim$6870 MeV/c$^2$

- No peaks in the same sign/sidebands sample

- Extract the masses and yields of $B_c^{(*)+}(2S)$ by fitting:
  \[ \Delta M = M(B_c^+\pi^+\pi^-) - M(B_c^+)_{REC} \]
  to eliminate the dependence on the reconstructed $B_c^+$ mass
Results

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<th></th>
<th>$B_c^*(2S)^+$</th>
<th>$B_c(2S)^+$</th>
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<tbody>
<tr>
<td>Signal yield</td>
<td>51 ± 10</td>
<td>24 ± 9</td>
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<td>Peak $\Delta M$ value (MeV/c²)</td>
<td>566.2 ± 0.6</td>
<td>597.2 ± 1.3</td>
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<td>Resolution (MeV/c²)</td>
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<td>Global significance</td>
<td>6.3 $\sigma$</td>
<td>2.2 $\sigma$</td>
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- The mass difference of the two peaks amounts to:
  $$\Delta M_{1-2} = 31.0 \pm 1.4(stat.) \text{ MeV/c}^2$$

- Adding the $B_c^+$ mass from PDG to the fitted peaks
  $$M(B_c^{*+}(2S))_{REC} = 6841.2 \pm 0.6(stat.) \pm 0.8(B_c^+) \text{ MeV/c}^2$$

  $$M(B_c^{+}(2S)) = 6872.1 \pm 1.3(stat.) \pm 0.8(B_c^+) \text{ MeV/c}^2$$

- Systematic studies
  - Momentum scale
  - Missing photon
  - Signal and background models

- Total systematic contribution: 0.1 MeV/c²
Summary

- Using the data collected from 2011 to 2018 corresponding to an integrated luminosity of 8.5 fb\(^{-1}\) LHCb has observed an excited \(B_c^+\) state
- It is consistent with being a \(B_c^{*+}(2S)\) state with the low energy photon of the decay to ground state missing

\[
M(B_c^{*+}(2S))_{REC} = 6841.2 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.}) \pm 0.8(B_c^+) \text{ MeV}/c^2
\]

- Hint also for a second structure consistent with \(B_c^+(2S)\)

\[
M(B_c^+(2S)) = 6872.1 \pm 1.3(\text{stat.}) \pm 0.1(\text{syst.}) \pm 0.8(B_c^+) \text{ MeV}/c^2
\]

- These findings are in agreement with the recent CMS results and within the range of theory predictions
BACKUP
LHCb previously searched for excited $B_c^+$ states using the 2012 data
- MLP (neural network) bin with worst S/B removed
- Invariant mass distribution in MLP response bins
- The $M(B_c^+\pi^+\pi^-)$ distribution was consistent with background only
Search for excited $B^+_c$ states

- Setting an upper limit on $R$

$$R = \frac{\sigma_{B^+_c(2S)}^{(*)}}{\sigma_{B^+_c}} \cdot \mathcal{B}(B^+_c(2S) \rightarrow B^+_c(\pi^+\pi^-)) = \frac{N_{B^+_c(2S)}^{(*)}}{N_{B^+_c}} \cdot \frac{\varepsilon_{B^+_c}}{\varepsilon_{B^+_c(2S)}}$$

- Evaluated for 4 values of $\Delta M = \Delta M(1S) - \Delta M(2S)$ (0, 15, 25, 35 MeV/c$^2$)

- $R \sim 0.09$ at $\sim 6840$ MeV/c$^2$ at 95%CL using 2012 data

- Using the full data sample of Run1 and Run2 (this analysis): $R = 0.08 \pm 0.03$

- Consistent with the upper limit previously obtained

![Reconstructed $M(B_c(2S)^*)$ [MeV/c$^2$]](image1.png)

![Reconstructed $M(B_c(2S)^*)$ [MeV/c$^2$]](image2.png)
### Theory predictions for the $B_c$ mass

- Additional theory prediction of the $(1S/2S)$ masses (in MeV)

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<tr>
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Trigger and data processing

- Upgrade of the trigger system during LS1
- Improved computing resources
- New HLT architecture
- Fast automated calibration
- More than double stored event rate


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