Measurement of the relative $B_c^\pm/B^\pm$ production cross section at ATLAS

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ATLAS EXPERIMENT

THE UNIVERSITY OF NEW MEXICO

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Subsystems essential for B-physics: Inner Detector and Muon Spectrometer.

- Inner Detector: tracking, momentum and vertexing, $|\eta|<2.5$, $d^0$ resolution $\sim10\ \mu m$.
- Muon Spectrometer: trigger ($|\eta|<2.4$) and muon identification ($|\eta|<2.7$).
- $J/\psi$ mass resolution: $\sim60\ \text{MeV}$, $\Upsilon(1S)$: $\sim119\ \text{MeV}$ (resolutions depend on $\eta$).
Relative $B_c/B^{\pm}$ production cross section

- 20.3 fb$^{-1}$ of 8 TeV $pp$ collision data.
- Submitted to Phys. Rev. D.
- Motivation:
  - Test of QCD predictions.
  - Important input for heavy quark production models.
  - Performed differentially in $p_T$ and $y$ in the central rapidity region.
  - Complements CMS and LHCb measurements.
Analysis overview (1/4)

- $B_c^\pm \rightarrow J/\psi (\mu^+ \mu^-) \pi^\pm$
- $B^\pm \rightarrow J/\psi (\mu^+ \mu^-) K^\pm$
- Dimuon trigger, $p_T(\mu_1, \mu_2) > 4$ GeV, $2.5 < m(\mu\mu) < 4.3$ GeV.
- $J/\psi$ candidates are formed from oppositely charged muons, $p_T(\mu) > 4$ GeV, $|\eta| < 2.3$, $2.6 < m(J/\psi) < 3.5$ GeV. Three invariant mass windows, defined by the ATLAS detector resolution.
- Hadronic tracks: $p_T > 2$ GeV.
- $B$ candidates are formed from the 3 tracks: two muonic and one hadronic.
- The $\chi^2(B$ vertex)/NDoF $< 1.8$.
- Instead of a cut on $B$ lifetime, a cut on $d_{xy}^0$ hadron impact parameter significance is introduced, $d_{xy}^0/\sigma(d_{xy}^0) > 1.2$.
- Selections are optimised with MC signal and background data sideband studies.
Extended unbinned maximum likelihood fits to the $B$ meson invariant mass distributions yield $\sim 400k$ events for the $B^{\pm}$ and $\sim 800$ events for the $B^{\pm}_{c}$.

$p_T(B) > 13$ GeV, $|y| < 2.3$. 

Relative $B^{\pm}_{c}/B^{\pm}$ production cross section
In addition to the full bin we define two bins in $p_T$: [13—22 GeV] and [>22 GeV] and two bins in rapidity: $|y|<0.75$ and $0.75<|y|<2.3$.

Bin sizes are selected to equalize the $B^\pm_c$ yields.

Example: fits for two bins in $p_T$ for the $B^\pm_c$. 

![Graphs showing fits for two bins in $p_T$ for the $B^\pm_c$.]
The relative cross section times branching fraction is given by:

\[
\frac{\sigma(B_c^{\pm}) \cdot \mathcal{B}(B_c^{\pm} \rightarrow J/\psi\pi^{\pm}) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\sigma(B^{\pm}) \cdot \mathcal{B}(B^{\pm} \rightarrow J/\psi K^{\pm}) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} = \frac{N^{\text{reco}}(B_c^{\pm})}{N^{\text{reco}}(B^{\pm})} \cdot \frac{\epsilon(B^{\pm})}{\epsilon(B_c^{\pm})}
\]

\(N^{\text{reco}}(B)\) are obtained from the fits. Overall analysis efficiencies \(\epsilon(B_c^{\pm})\) and \(\epsilon(B^{\pm})\) are obtained from the MC.

MC is corrected in several ways:

- sPlot reweighting of the \(p_T(B)\) and \(y(B)\) distributions;
- trigger acceptance;
- distributions of variables used for minimal selections.
The measurement of the relative cross section times branching fraction is performed in five bins:

<table>
<thead>
<tr>
<th>Analysis bin</th>
<th>$\sigma(B_c^\pm)/\sigma(B^\pm) \times \mathcal{B}(B_c^\pm \rightarrow J/\psi\pi^\pm)/\mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B) &gt; 13$, $</td>
<td>y(B)</td>
</tr>
<tr>
<td>$13 &lt; p_T(B) &lt; 22$, $</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 22$, $</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$, $0.75 &lt;</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$, $0.75 &lt;</td>
<td>y(B)</td>
</tr>
</tbody>
</table>
The measurement precision is limited by the statistical uncertainty on the number of $B_c^{\pm}$ candidates.

The following systematic uncertainties are considered:

- fitting procedure (including Cabibbo-suppressed decays contribution);
- trigger, reconstruction and tracking effects;
- $B_c^{\pm}$ lifetime uncertainty;
- MC-related uncertainties (sample size, minimal selection criteria).

The measurement suggest a dependence on the $p_T$: the production cross section of the $B_c^{\pm}$ meson decreases faster with $p_T$ than the production cross section of the $B$ meson. No significant dependence on rapidity has been observed.
The production mechanism of the $B_c^{\pm}$ differs from the one of the $B^{\pm}$: in the latter case heavy $b$-quark catches light $u$-quark from the sea.

For the $B_c^{\pm}$ case a collinear production of two distinct heavy quarks is required.

The complete perturbative calculation for $gg \to B^+ b\bar{c}$ was performed by several authors (e.g. hep-ph/9408242, hep-ph/9408284, hep-ph/94042346), with results in some disagreement with each other.

Results depend on different choices of the gluon distribution functions and on the scale of the $\alpha_s$. 
Naively, the higher the $p_T$ the higher the chance for the $c\bar{c}$-pair to be created.

The data show the opposite behaviour, and this is also consistent in fact with what seen for the $B_s^0/B^\pm$ ratio.

Michelangelo Mangano in private discussion suggests the following two possible explanations:

- at low $p_T$, the $B_c^\pm$ is mostly formed by the $b$-quark finding nearby a $\bar{c}$, created independently as part of the hard process ($gg \rightarrow bbcc$). When $p_T$ becomes larger, it is more rare to find the $b$ and $\bar{c}$ close enough in phase-space so that they bind together;
- at low $p_T$, the $c\bar{c}$ comes mostly from the first and only gluon emission of the produced $b$-quark: $b \rightarrow b + g [\rightarrow \bar{c}]$. The $b - \bar{c}$ pair is automatically in a color-singlet state and if they are close enough in phase space they bind. When we go to higher $p_T$, there is enough acceleration for more gluons being radiated, e.g. there could be a second gluon radiated after the primary $g \rightarrow \bar{c}$ splitting, and therefore the $b + \bar{c}$ system is not in a color singlet state. It is a bit like a Sudakov suppression effect, the larger the $p_T$, the less likely it is to have the $b$ and $\bar{c}$ nearby.
Conclusions

- ATLAS has studied the $B_c^\pm/B^\pm$ production cross section at 8 TeV.
- Differential ($p_T$, $y$) study in the central rapidity region.
- The measurement suggests some $p_T$ dependence.
B-physics starts with single or di-muon triggers with various thresholds:

- $p_T(\mu) > 6$ GeV
- $p_T(\mu) > 18$ GeV
- $p_T(\mu_1) > 4$ GeV and $p_T(\mu_2) > 4$ GeV
- $p_T(\mu_1) > 6$ GeV and $p_T(\mu_2) > 4$ GeV
- $p_T(\mu_1) > 6$ GeV and $p_T(\mu_2) > 6$ GeV

Di-muon mass range:

- $m(\mu\mu) \in [2.5; 4.3]$ GeV for final states containing $J/\psi$;
- $m(\mu\mu) \in [4.0; 8.5]$ GeV for $B \rightarrow \mu$ transitions.
Table 1: Summary of corrections due to the minimal selection criteria in the MC simulation. The first uncertainty is statistical, the second one is systematic.

<table>
<thead>
<tr>
<th>Analysis bin</th>
<th>Correction to the $B_{c}^{\pm}$</th>
<th>Correction to the $B^{\pm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B) &gt; 13$, $</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
</tr>
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<td>y(B)</td>
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</tr>
<tr>
<td>$p_T(B) &gt; 13$, $</td>
<td>y(B)</td>
<td>&lt; 0.75$</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13$, $0.75 &lt;</td>
<td>y(B)</td>
<td>&lt; 2.3$</td>
</tr>
</tbody>
</table>
The efficiency of the analysis selection criteria, $\epsilon^{\text{selection}}$, derived from MC simulation, is incorporated into the final efficiency ratios. The efficiency ratios $\epsilon(B^\pm)/\epsilon(B_c^\pm)$, excluding the Minimal Selection Criteria corrections, are found to be:

- $2.19 \pm 0.05$ for $13 < p_T < 22$,
- $1.22 \pm 0.03$ for $p_T > 22$,
- $1.75 \pm 0.03$ for $p_T > 13$,
- $1.74 \pm 0.05$ for $|y| < 0.75$,
- $1.76 \pm 0.04$ for $0.75 < |y| < 2.3$.  

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Relative $B_c^\pm/B^\pm$ production cross section
Table 2: Summary of the absolute values of systematic uncertainties for the analysis efficiency ratios.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Absolute value of the uncertainty in the efficiency ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_T &gt; 13$</td>
</tr>
<tr>
<td>Size of the MC samples and the event counting</td>
<td>0.03</td>
</tr>
<tr>
<td>sPlot-based MC reweighting procedure</td>
<td>0.04</td>
</tr>
<tr>
<td>Minimal selection criteria</td>
<td>0.04</td>
</tr>
<tr>
<td>Tracking uncertainty</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Table 3: Summary of all systematic uncertainties for the number of signal events in the combined bin ($p_T > 13$, $|y| < 2.3$).

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B_c^\pm$</td>
</tr>
<tr>
<td></td>
<td>$B^\pm$</td>
</tr>
<tr>
<td>Signal model of the fit</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Cabibbo-suppressed decay modeling</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>2.9%</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Trigger effects and reconstruction effects</td>
<td>0.9%</td>
</tr>
<tr>
<td></td>
<td>0.9%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>$&lt; 0.1%$</td>
</tr>
</tbody>
</table>