Charm and beauty production in $pp$ collisions at $\sqrt{s} = 13$ TeV at LHCb

Alex Pearce

on behalf of the LHCb collaboration

Wednesday 6th September 2017
PDF4LHC meeting
1. Prompt and secondary $J/\psi$ production at $\sqrt{s} = 13$ TeV;
2. Open charm production for $D^0$, $D^+$, $D_s^+$, and $D^{*+}$ at 13 and 5 TeV;
3. Open beauty production for $B^{0}_{(s)}$, $B^+$, and $\Lambda^0_b$, with $H_b \to H_c\mu X$ at 13 and 7 TeV;

\[^1\text{Erratum published for 1, 2; submitted for 3. All arXiv and HepData records now updated.}\]
Why LHCb?

Reach in $x$ is a function of quark mass and kinematics:

$$e^{-\frac{y \sqrt{p_T^2 + m_q^2}}{\sqrt{s}}} < x < e^{\frac{y \sqrt{p_T^2 + m_q^2}}{\sqrt{s}}}$$

LHCb *uniquely* can reach $x \sim 10^{-6}$ at LHC$^2$

\[\text{PROSA collaboration: epjc/s10052-015-3618-z}\]
Cross-section measurements

\[
\frac{d^2 \sigma_i(pp \rightarrow H_q X)}{d p_T dy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H_q \rightarrow f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(H_q \rightarrow f) \mathcal{B}(H_q \rightarrow f) \mathcal{L}_{\text{int.}}}
\]
Cross-section measurements

\[
\frac{d^2\sigma_i(pp \to HqX)}{dp_T \, dy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H_q \to f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(H_q \to f) B(H_q \to f) \mathcal{L}_{\text{int}}}.
\]

1. \(J/\psi\) directly from \(pp\) interaction;
2. \(J/\psi\) from \(b\) decays;

\[
\sigma(pp \to b\bar{b}) = \alpha_4 \pi \frac{\sigma(J/\psi\text{ from } b)}{2B(b \to J/\psi X)};
\]

3. \(D^0, D^+, D_s^+, \text{ and } D^*\) directly from \(pp\) interaction;
4. \(B_{(s)}^0, B^+, \text{ and } \Lambda_b^0, \text{ with } H_b \to H_c \mu X;\)
Related measurements

- Ratios between open charm hadrons, e.g. $\sigma(D^0)/\sigma(D^+)$
- Ratios between measurements at different $\sqrt{s}$
- Integrated over $p_T$, $y$, or both
- Total $c\bar{c}$ cross-section using $f(c \rightarrow H_c)$
- Total $b\bar{b}$ cross-section using semileptonic decays
**$J/\psi$ production**

- Data collected in July 2015, around $3 \text{ pb}^{-1}$

- Count signal by fitting the final state invariant mass distribution
- Separate $J/\psi$ from $pp$ and $J/\psi$ from $b$ using pseudo-proper time

\[ t_z = \frac{(z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}}{p_z} \]
$J/\psi$ production

Theory comparison for prompt

Theory comparison for $J/\psi$-from-$b$

$J/\psi$ cross-section in LHCb acceptance

$\sigma_{\text{Prompt}} = 15.30 \pm 0.03(\text{stat}) \pm 0.86(\text{syst}) \mu b$

$\sigma_{\text{from-}b} = 2.34 \pm 0.01(\text{stat}) \pm 0.13(\text{syst}) \mu b$

$b\bar{b}$ cross-section with $4\pi$ extrapolation

$\sigma = 515 \pm 2(\text{stat}) \pm 53(\text{syst}) \mu b$
Theory comparison for prompt

\[ R_{13/8}(d\sigma/dp_T) \]

- LHCb
- \( \sqrt{s} = 13 \text{ TeV/}\sqrt{s} = 8 \text{ TeV cross-section ratio} \)

- NRQCD

\[ p_T(J/\psi) \text{ [GeV/c]} \]

Theory comparison for \( J/\psi \)-from-\( b \)

\[ R_{13/8}(d\sigma/dp_T) \]

- LHCb
- \( \sqrt{s} = 13 \text{ TeV/}\sqrt{s} = 8 \text{ TeV cross-section ratio} \)

- FONLL

\[ p_T(J/\psi) \text{ [GeV/c]} \]

\[ R_{13/8}(d\sigma/dy) \]

- LHCb
- \( \sqrt{s} = 13 \text{ TeV/}\sqrt{s} = 8 \text{ TeV cross-section ratio} \)

- FONLL
$J/\psi$ production in jets

- New data processing for Run 2, Turbo, allowed us to save $J/\psi +$ reconstructed event directly out of HLT2
- With 2016 data, use special trigger line to reconstruct dimuons down to $p_T = 1$ GeV with no PV separation requirement
- Build anti-$k_T$ jets, measure fraction $z$ of jet momentum carried by $J/\psi$
Open charm production

- Data at $\sqrt{s} = 13$ TeV collected July 2015, around $3 \text{ pb}^{-1}$
- At $\sqrt{s} = 5$ TeV, collected November 2015, around $9 \text{ pb}^{-1}$ (shown here)

- Count signal by fitting the final state invariant mass distribution
- Separate $H_c$ from $pp$ and $H_c$ from $b$ using impact parameter significance $\chi_{\text{IP}}^2$
Open charm production

\[ \frac{d^2 \sigma}{dy dp_T} \cdot 10^{-m} [\mu b/(GeV c^{-1})] \]

\[ 2.0 < y < 2.5, \ m = 0 \]
\[ 2.5 < y < 3.0, \ m = 2 \]
\[ 3.0 < y < 3.5, \ m = 4 \]
\[ 3.5 < y < 4.0, \ m = 6 \]
\[ 4.0 < y < 4.5, \ m = 8 \]

LHCb D^0
\[ \sqrt{s} = 5 TeV \]

POWHEG+NNPDF3.0L
FONLL
GMVFNS

LHCb D^+}
\[ \sqrt{s} = 5 TeV \]

POWHEG+NNPDF3.0L
GMVFNS
Open charm production

$\sqrt{s} = 5\text{ TeV}$

$0 < p_T < 8 \text{ GeV/c}, 2 < y < 4.5$

LHCb D$^0$

LHCb $D^+$

LHCb average

FONLL

POWHEG+NNPDF3.0L
Open charm production

$\frac{R_{13/5}(D^0)}{R_{13/5}(D_s^+)} + m$

$0.0 < y < 2.5, m = 0$
$2.5 < y < 3.0, m = 3$
$3.0 < y < 3.5, m = 6$
$3.5 < y < 4.0, m = 9$
$4.0 < y < 4.5, m = 12$

LHCb $D^0$

POWHEG+NNPDF3.0L
FONLL
GMVFNS

LHCb $D_s^+$

POWHEG+NNPDF3.0L
GMVFNS
Open charm production

1 < $p_T$ < 8 GeV/c, 2 < $y$ < 4.5

LHCb
$\sqrt{s} = 5$ TeV

$D^0$

$D^+$

$D_s^+$

$D^{*+}$

POWHEG+NNPDF3.0L
Test fragmentation fraction invariance to production mechanism and kinematics
Using open charm results

- Constrains gluon PDFs at low $x$
- PDFs used as inputs to atmospheric neutrino experiments
• Idea: measure $b$-quark production ‘inclusively’ using semileptonic decays.

\[
\sigma(pp \to H_b) = \frac{1}{2}[\sigma(B^0) + \sigma(B^0)] + \frac{1}{2}[\sigma(B^+) + \sigma(B^-)] + \\
\frac{1}{2}[\sigma(B_s^0) + \sigma(B_s^0)] + \frac{1 + \delta}{2}[\sigma(\Lambda_b^0) + \sigma(\Lambda_b^0)]
\]

\(1\)

\(2\)

• Correct with missing $\Xi_b$ and $\Omega_b$ components using $\delta$, estimated to be $0.25 \pm 0.10$

• Neglect $B_c^+$ as predicted to be 0.1% of $b$-hadron production

• Exploit the equality and large magnitude $H_b \to H_c \mu \nu$ branching fractions
Open beauty production


$$\sigma(pp \rightarrow H_b) = \frac{1}{2\mathcal{L}} \left\{ \left[ \frac{N(D^0_\mu)}{\epsilon_{D^0_B} B_{D^0}} + \frac{N(D^+_\mu)}{\epsilon_{D^+ B_{D^+}}} \right] \frac{1}{\mathcal{B}(B \rightarrow DX_{\mu\nu})} + \left[ \frac{N(D^+_\mu)}{\epsilon_{D^+ B_{D^+}}} \right] \frac{1}{\mathcal{B}(B_s \rightarrow D_s X_{\mu\nu})} + \left[ \frac{N(\Lambda_c^+_\mu)}{\epsilon_{\Lambda_c^+ B_{\Lambda_c^+}}} \right] \frac{1 + \delta}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ X_{\mu\nu})} \right\}$$

- Reconstruct fully hadronic $H_c$ decays with branching fractions $\mathcal{B}_{H_c}$
- Measure $H_c + \mu$ event efficiency as $\epsilon_{H_c}$
- Neglect cross-feed, such as $\Lambda_b^0 \rightarrow D N_\mu^- X$, due to lack of sensitivity to these backgrounds
Open beauty production

- Use $300 \text{ pb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ and $4.6 \text{ pb}^{-1}$ at $13 \text{ TeV}$

- Count signal by fitting the $H_c$ final state invariant mass distribution
- Separate $H_c$ from $b$ from $H_c$ directly from $pp$ using impact parameter
- Measure pseudorapidity $\eta$ using difference between $H_c\mu$ vertex and PV
Open beauty production

<table>
<thead>
<tr>
<th>$p_T$ (charm+µ) [GeV]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.07</td>
</tr>
<tr>
<td>10</td>
<td>0.07</td>
</tr>
<tr>
<td>20</td>
<td>0.28</td>
</tr>
</tbody>
</table>

LHCb 13 TeV  (a)

**Most efficiencies derived using data:**

- Trigger and muon ID using calibration samples of $b \rightarrow J/\psi X$ decays
- Hadronic PID using $\Lambda \rightarrow p\pi^-$ and $D^{*+}$-tagged $D^0 \rightarrow K^-\pi^+$ decays
- Data-MC differences in tracking efficiencies evaluated using $J/\psi \rightarrow \mu^-\mu^+$
- Correct for missing low-$p_T$ regions, due to very small efficiencies, using MC
<table>
<thead>
<tr>
<th>Source</th>
<th>7 TeV</th>
<th>13 TeV</th>
<th>Ratio 13/7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tracking efficiency</strong></td>
<td>3.8%</td>
<td>4.3%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7%</td>
<td>3.9%</td>
<td>3.8%</td>
</tr>
<tr>
<td>$b$ semileptonic $B$</td>
<td>2.1%</td>
<td>2.1%</td>
<td>0</td>
</tr>
<tr>
<td>Charm hadron $B$</td>
<td>2.6%</td>
<td>2.6%</td>
<td>0</td>
</tr>
<tr>
<td>$b$ decay cocktail</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0</td>
</tr>
<tr>
<td>Ignoring $b$ cross-feeds</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0</td>
</tr>
<tr>
<td>Background</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0</td>
</tr>
<tr>
<td>$b \rightarrow u$ decays</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0</td>
</tr>
<tr>
<td>$\delta$</td>
<td>2.0%</td>
<td>2.0%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5.9%</td>
<td>7.1%</td>
<td>4.6%</td>
</tr>
</tbody>
</table>
Open beauty production

PhysRevLett.118.052002, erratum submitted

(a) \( \sigma(pp \to H_b X)/d\eta \) [\( \mu b \)]
- FONLL
- Data

(b) \( R_{13/7}(pp \to H_b X)/d\eta \)
- FONLL
- Data

LHCb 13 TeV

LHCb 7 TeV
Summary

- LHCb has measured $J/\psi$, $H_c$, and $H_b$ production cross-sections at $\sqrt{s} = 13$ TeV.
- Latest results are published, with $H_b$ measurement pending.
- Always looking to help improve understanding of parton distribution functions through our results.
Detector

Magnet (4 Tm)

Particle identification

Tracking

Calorimetry

VELO  Primary and secondary vertex, impact parameter
TT, IT, OT  Momentum of charged particles
RICHs  $K^\pm, \pi^\pm, \text{and } p/\bar{p}$ PID

MUON  Trigger on high $p_T \mu^\pm$, add PID
SPD/PS  Separate $\gamma/e^\pm$ and $h^\pm/e^\pm$
ECAL/HCAL  EM/hadronic energy
Trigger

- Minimum bias at L0 for charm, MUON trigger for $J/\psi$ and $B \rightarrow D \mu X$
- Fully reconstruct $J/\psi$ and $D$ in HLT2
- Thanks to offline-quality full event reconstruction...
- ...and an increase in HLT farm resources
- Buffer HLT1 output to a 10 PB disk array, large effective increase in HLT2 processing time
- Allows for publication-level analysis in near-real time
The charge collected in the LHCb VELO sensors is affected by radiation damage. One such effect, which is more pronounced in the outer regions of downstream sensors, arises from charge induction on second metal layer routing lines\(^3\). Prior to the start of Run 2, modifications were made to the digitization step in the LHCb simulation framework to model this effect. An error was made in the parametric implementation resulting in a reduction of the track reconstruction efficiency in simulation compared to data for tracks with low pseudorapidity. The tracking efficiency calibration procedure that was applied to the data and simulation\(^4\) was unable to correct the mismodelling.

\(^3\) LHCb-DP-2012-005
\(^4\) LHCb-DP-2013-002
$J/\psi$ production

$J/\psi$ from $b$-decays

$J/\psi$-from-$b$ production fraction
Open charm production

LHCb $D^0$

- $4.0 < y < 4.5$, $m = 12$
- $3.5 < y < 4.0$, $m = 9$
- $3.0 < y < 3.5$, $m = 6$
- $2.5 < y < 3.0$, $m = 3$
- $2.0 < y < 2.5$, $m = 0$

$LHCb D_s^+$

- $4.0 < y < 4.5$, $m = 48$
- $3.5 < y < 4.0$, $m = 36$
- $3.0 < y < 3.5$, $m = 24$
- $2.5 < y < 3.0$, $m = 12$
- $2.0 < y < 2.5$, $m = 0$

$p_T$ [GeV/c]

$R_{13/7}(D^0) + m$

$R_{13/7}(D_s^+) + m$