Recent results on heavy flavour production at LHCb

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on behalf of the LHCb Collaboration
LHCb provides a unique coverage for production studies
Complementary to other experiments
Results cover top, beauty and charm production
Only covering analyses of pp datasets
See Matt’s talk tomorrow for heavy ion results

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The LHCb Detector

- Instrumentation in the forward region $(2 < \eta < 5)$
- Excellent secondary vertex reconstruction
- Precise tracking before and after magnet
## LHCb $pp$ datasets

<table>
<thead>
<tr>
<th>Run</th>
<th>Year</th>
<th>$\sqrt{s}$</th>
<th>$\mathcal{L}$</th>
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<td>Run 1</td>
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<td>7 TeV</td>
<td>0.04 fb$^{-1}$</td>
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<tr>
<td></td>
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<td></td>
<td>2012</td>
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<td>2.08 fb$^{-1}$</td>
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<td>Run 2</td>
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<td></td>
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<td>13 TeV</td>
<td>1.67 fb$^{-1}$</td>
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<td></td>
<td>2017</td>
<td>13 TeV</td>
<td>1.71 fb$^{-1}$</td>
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<tr>
<td></td>
<td>2015</td>
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<tr>
<td></td>
<td>2017</td>
<td>5 TeV</td>
<td>0.10 fb$^{-1}$</td>
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Heavy flavour production @ LHCb  
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Wide range of heavy flavour production results
- Table not exhaustive
Impossible to cover everything
Will focus on **some new results** from the last year

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\sqrt{s}$ (TeV)</th>
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<td>$D^+$ prod. asym.</td>
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<tr>
<td>$D_s^+$ prod. asym.</td>
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<td>$J/\psi$ production</td>
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<tr>
<td>$J/\psi + J/\psi$ prod.</td>
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<tr>
<td>$J/\psi + D$ prod.</td>
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<tr>
<td>$J/\psi$ in jets</td>
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<tr>
<td>$W + c$</td>
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<tr>
<td>$W + c\bar{c}$</td>
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<tr>
<td>$B$ production</td>
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<tr>
<td>$\Upsilon$ produc</td>
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<tr>
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<td>$Z + b$</td>
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<td>$W + b\bar{b}$</td>
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<tr>
<td>$t$ production</td>
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<tr>
<td>$t\bar{t}$ prod.</td>
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Jet flavour tagging @ LHCb

- BDTs developed to tag jets in Run 1 data
- Efficiency determined on flavour-enriched samples
  - e.g. tagged by fully reconstructed (middle) $B$ or (bottom) $D$ decays on “other” jet
- 2D fit to corrected mass and track multiplicity of reconstructed secondary vertices also gives good separation of jet flavours

![Graphs showing jet tagging efficiency and mass distribution](image)
Jet studies @ LHCb

LHCb, $\sqrt{s} = 8$ TeV

- MCFM CT10

$\sigma(W^+b\bar{b})$

$\sigma(W^+c\bar{c})$

$\sigma(W^+b\bar{b})$

$\sigma(W^+c\bar{c})$

$\sigma(t\bar{t})$

$\sigma(W^+b\bar{b})$

$\sigma(W^+c\bar{c})$

- $\sigma(t\bar{t})$

- Too many jet production studies to cover everything
- Run 1 studies of heavy jet and dijet production in association with $W/Z$ bosons
- Cross sections in good agreement with calculations
Run 2 study of prompt and displaced $J/\psi$ candidates in jets

- Good mass and pseudo-decay-time resolution
- $p_T$ fraction carried by the $J/\psi$ meson consistent with expectations for $b$ jets
- $p_T$ fraction of prompt $J/\psi$ mesons do not agree with expectations
- First experimental measurement of $p_T$ fraction for prompt $J/\psi$ mesons in jets
Kinematic correlations between a heavy quark–antiquark pair can improve understanding of production mechanisms.

CDF, D0 and LHCb studies of $c \bar{c}$ correlations have identified gluon splitting, flavour-creation and flavour-excitation contributions.

$b\bar{b}$ correlations studied in $p\bar{p}$ by UA1, D0 and CDF and $pp$ by CMS and Atlas.

Plots reproduced from
JHEP 03 (2011) 136 and
JHEP 11 (2017) 062

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• $b$ candidates reconstructed in $J/\psi (\rightarrow \mu^+ \mu^-)X$ final state

• $J/\psi$ candidates from both $b$ candidates required to be associated with the same primary vertex have significantly displaced decay vertices

• 2D fit performed to the two dimuon invariant masses

• $sPlot$ technique used to isolate signal component

• Normalised differential cross section determined as a function kinematic variables using efficiency-corrected yields
Cross section as a function of:

- relative azimuthal angle and pseudorapidity of beauty hadrons
- $p_T$ asymmetry between $J/\psi$
- mass, $p_T$ and rapidity of $J/\psi$ pair

Good agreement with calculations

- NLO effects are small in this region cf. experimental precision
- no significant gluon splitting at small $|\Delta \phi^*|$
Previous LHCb studies of $B^{\pm}$ production at 7 TeV performed in 2010 and 2011.

Recent analysis updates these results and adds measurements for 13 TeV.

Based on 1.0 fb$^{-1}$ of data at 7 TeV and 362 pb$^{-1}$ at 13 TeV.

$B^{\pm}$ reconstructed from the $J/\psi K^{\pm}$ final state.

cross sections measured in range $0 < p_T < 40$ GeV/c and $2.0 < y < 4.5$. 

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Double differential cross sections determined as a function of $p_T$ and rapidity at both energies.

Results are in good agreement with FONLL predictions.

Integrated cross sections in $p_T < 40 \, \text{GeV}/c$, $2.0 < y < 4.5$

\[
\sigma(pp \rightarrow B^\pm X) = 43.0 \pm 0.2 \, \text{(stat)} \pm 2.5 \, \text{(syst)} \pm 1.7 \, (B^+) \, \mu b \, @ 7 \, \text{TeV}
\]

\[
\sigma(pp \rightarrow B^\pm X) = 86.6 \pm 0.5 \, \text{(stat)} \pm 5.4 \, \text{(syst)} \pm 3.4 \, (B^+) \, \mu b \, @ 13 \, \text{TeV}
\]
Ratio of differential cross sections between 13 and 7 TeV also in good agreement with FONLL predictions

Integrated ratio: $2.02 \pm 0.02 \text{ (stat)} \pm 0.12 \text{ (syst)}$
Study of $\Upsilon(nS)$ polarisations in 7 and 8 TeV data

Dimuon mass spectrum fitted in bins of $p_T^{\mu^+\mu^-}$

Angular distributions of $\Upsilon$ candidates extracted using sPlot technique

All can be converted into frame-invariant polarisation $\bar{\lambda}$ to cross-check systematics.

No large polarisation is observed

- Consistent with CMS results
Observation of $\Omega_c$ states

- Pure sample of $\Xi^+_c \rightarrow pK^-\pi^+$ candidates combined with charged kaons
- Five narrow peaks observed
  - correspond to excited $\Omega_c$ states
- Masses consistent with predicted masses for 1P and 2S states
- Further studies required to assign quantum numbers
Searches for $\Xi_{cc}^+(\pm)$ states

- Quark model gives three weakly-decaying doubly-charmed $J^P = \frac{1}{2}^+$ Baryons: $\Xi_{cc}^+(c\, c\, d)$, $\Xi_{cc}^{+\pm}(c\, c\, u)$ and $\Omega_{cc}^+(c\, c\, s)$
- SELEX reported observations of the singly-charged $\Xi_{cc}^+$ state in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$
  - Unexpected short lifetime and high production rate

- Subsequent searches by FOCUS, BaBar and Belle found no evidence of doubly-charmed baryons
- Initial search by LHCb set upper limit on long-lived states but not inconsistent with SELEX claim

SU(4) flavour multiplets of baryons containing $d$, $u$, $s$ and $c$ quarks, reproduced from Chin. Phys. C40 (2016) 100001.

JHEP 12 (2013) 090
New LHCb search for the doubly-charged state in $\Xi^{++}_{cc} \rightarrow \Lambda^{+}_c K^- \pi^+ \pi^+$ performed using data collected at $\sqrt{s} = 13$ TeV

Highly significant state found at $m = 3621.40 \pm 0.72$ (stat) $\pm 0.27$ (syst) $\pm 0.14 (\Lambda^{+}_c)$ MeV/$c^2$

- Local statistical significance in excess of 12$\sigma$

Verified in 8 TeV dataset

Large mass difference from SELEX claim (103 MeV/$c^2$)

- Inconsistent with being isospin partners
Summary and outlook

- LHCb tests cross section calculations in unique kinematic region
- Many new production results
  - but plenty more still to come
  - including results from the new larger 5 TeV dataset
- Jet tagging efficiency studies underway on 13 TeV dataset
  - Unlike in Run 1, these benefit from dedicated calibration samples
  - New 13 TeV jet studies to follow
$b \bar{b}$ correlations

\begin{align*}
\text{a)} & \quad p_T^{J/\psi} > 2 \text{ GeV}/c \\
\text{b)} & \quad p_T^{J/\psi} > 3 \text{ GeV}/c, \quad \sqrt{s} = 7, 8 \text{ TeV} \\
\text{c)} & \quad p_T^{J/\psi} > 5 \text{ GeV}/c \\
\text{d)} & \quad p_T^{J/\psi} > 7 \text{ GeV}/c
\end{align*}

These criteria ensure a good reconstruction and trigger efficiency. Only events triggered by the PV, is visible.

... with the function

$$F(m_1, m_2) = NSS S(m_1) S(m_2) + NSB^2 (S(m_1) B'(m_2) + B'(m_1) S(m_2)) + NBB B''(m_1, m_2).$$

These candidates are required to have a good-quality vertex, a reconstructed $J/\psi$ from that PV.

... produced $J$ mesons, both dimuon vertices are required to be significantly displaced at least by one of the $J$ masses, for the selected pairs of $J$ in the range $0.00 < m < 0.18$ GeV.

$T$ regions. $J$ candidates are required to have a good-quality vertex, a reconstructed $J/\psi$ candidates are retained. The two $\mu$ candidates is presented in Fig. 1 for several requirements on $p_T$.
The smearing of the transverse momenta of the initial gluons could result in significant correlations in contrast, the leading-order collinear approximation, where the transverse momentum to the measured (Powheg shown by the dashed magenta line. The uncertainties in the Pythia predictions. The expectations for uncorrelated $b\bar{b}$...
Heavy flavour production @ LHCb

Figure 5: Normalized differential production cross-sections (points with error bars) for a) $b\bar{b}$

Figure 6: Normalized differential production cross-sections (points with error bars) for a) $b\bar{b}$

This observation is in agreement with expectations, since the contribution from gluon splitting is suppressed due to the large mass of the beauty quark. For $b\bar{b}$ mesons, indicating that NLO effects in $b\bar{b}$ production are small compared with the experimental precision.

Unlike the measurements with open-charm correlations, suggesting that NLO effects in $b\bar{b}$ production are small compared with the experimental precision.
Heavy flavour production at LHCb

$p_T^{J/\psi} > 2\text{ GeV}/c$

$p_T^{J/\psi} > 3\text{ GeV}/c$

$p_T^{J/\psi} > 5\text{ GeV}/c$

$p_T^{J/\psi} > 7\text{ GeV}/c$

\(\bar{b}b\) correlations

\(\Delta\eta^{J/\psi}\)

\(\Delta\phi^{J/\psi}/\pi\)

\(\Delta y^{J/\psi}\)
$B^+$ production @ 7 and 13 TeV

<table>
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<tr>
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<th>7 TeV</th>
<th>13 TeV</th>
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<tr>
<td>Total</td>
<td>7.0</td>
<td>7.4</td>
<td>5.9</td>
</tr>
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</table>
Figure 3: The polarization parameters (top) and (right).
θφ measured in the CS frame.
Υ(1S) frame.
Υ(1S) frame.
Υ(1S) frame.
The horizontal error bars indicate the bin width. Some data points are displaced from the bin centers to improve visibility. The vertical inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical and systematic uncertainties added in quadrature. The horizontal error bars indicate the bin width. Some data points are displaced from the bin centers to improve visibility. The results for the rapidity ranges $y < 2$, $2 < y < 5$, and $5 < y < 2$ are shown with red circles, blue squares and green triangles, respectively. The results for the rapidity ranges $y < 3$, $3 < y < 4$, and $4 < y < 5$ are shown with red circles, blue squares and green triangles, respectively. The horizontal error bars indicate the bin width. Some data points are displaced from the bin centers to improve visibility. The results for the rapidity ranges $y < 3$, $3 < y < 4$, and $4 < y < 5$ are shown with red circles, blue squares and green triangles, respectively.
The polarization parameters for the Υ(3S) state in different bins of $p_T$ are shown in Figure 9 (top). In Figure 10, the polarization parameters are displayed in quadrature. The horizontal error bars indicate the bin width. Some data points are displaced from the bin centers to improve visibility.

The results for the rapidity ranges $0 < y < 5$, $3 < y < 8$, and $5 < y < 10$ are shown with red circles, blue squares, and green triangles, respectively. The HX frame for the Υ(3S) state in different bins of $p_T$ is compared with the GJ frame, measured in $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.
Figure 12: The polarization parameters (top) as a function of $\lambda$, (middle) $\phi$, and (bottom) $\theta$. The inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical and systematic uncertainties added in quadrature. Some data points are displaced from the bin centers to improve visibility.

Figure 13: The polarization parameters (top) as a function of $\lambda$, (middle) $\phi$, and (bottom) $\theta$. The inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical and systematic uncertainties added in quadrature. Some data points are displaced from the bin centers to improve visibility.

Figure 14: The polarization parameters (top) as a function of $\lambda$, (middle) $\phi$, and (bottom) $\theta$. The inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical and systematic uncertainties added in quadrature. Some data points are displaced from the bin centers to improve visibility.

LHCb, for data collected at $s = 8$ TeV. The results for the HX, CS and GJ frames are shown with red circles, blue squares and green diamonds, respectively. The inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical and systematic uncertainties added in quadrature. Some data points are displaced from the bin centers to improve visibility.
Observation of $\Omega_c$ states

TABLE I. Results of the fit to $m(\Xi_c^+K^-)$ for the mass, width, yield, and significance for each resonance. The subscript $fd$ indicates the feed-down contributions described in the text. For each fitted parameter, the first uncertainty is statistical and the second systematic. The asymmetric uncertainty on the $\Omega_c(X)^0$ arising from the $\Xi_c^+$ mass is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>Yield</th>
<th>$N_\sigma$</th>
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<tbody>
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<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>$1300 \pm 100 \pm 80$</td>
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<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>$970 \pm 60 \pm 20$</td>
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<td>$&lt;1.2$ MeV, 95% C.L.</td>
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<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>$1740 \pm 100 \pm 50$</td>
<td>23.9</td>
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<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>$2000 \pm 140 \pm 130$</td>
<td>21.1</td>
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<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>$480 \pm 70 \pm 30$</td>
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<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
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<tr>
<td>$\Omega_c(3066)^0_{fd}$</td>
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<td>$700 \pm 40 \pm 140$</td>
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<td>$220 \pm 60 \pm 90$</td>
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<td>$190 \pm 70 \pm 20$</td>
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Observation of $\Xi_{cc}^{++}$

Table 1: Systematic uncertainties on the $\Xi_{cc}^{++}$ mass measurement.

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<th>Source</th>
<th>Value [MeV/c^2]</th>
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<td>$\Lambda_c^+$ mass uncertainty</td>
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