Heavy Flavour Production results at 13 TeV with LHCb

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Motivation for production measurements

- cross-section in unique forward region with 13 TeV pp collisions
- constrain gluon pdf in low x
- test production and fragmentation models
- input to tune simulation

heavy flavour production results at 13 TeV:
- $J/\psi$ production using $3.05\ \text{pb}^{-1}$ : JHEP10(2015)172
- prompt charm production using $4.98\ \text{pb}^{-1}$ : JHEP03(2016)159
- data collected with Turbo stream: saw talk by Lucia Grillo, June 13th 17:35:
  “Novel concepts for trigger, calibration & alignment, and data processing with LHCb”
Analysis strategy

\[ \frac{d^2 \sigma(pp \to X)}{dy \, dp_T} = \left[ \frac{N(X \to f)}{\mathcal{L} \cdot \epsilon \cdot \mathcal{B}(X \to f) \cdot \Delta p_T \cdot \Delta y} \right] \]

- compute \( \sigma \) in bins of \( p_T \) and \( y \)
- \( N(X) \) signal yield
- \( \mathcal{L} \) integrated luminosity
- \( \mathcal{B}(X \to f) \) branching fraction

- \( \epsilon \) efficiencies
  - selection from simulation
  - data-driven methods:
    - PID
    - trigger
    - tracking
$J/\psi$ production cross-sections at $\sqrt{s} = 13$ TeV

- separate prompt $J/\psi$ and $J/\psi$-from-$b$ using the pseudo-decay-time

$$t_Z = \frac{d_Z \cdot M_{J/\psi}}{p_Z}$$

- kinematic range:
  - $p_T < 14$ GeV/c; $2 < y < 4.5$
  - 2D fit to mass and $t_Z$

**signal**: Crystal Ball
**bkg**: exponential

**prompt signal**: double Gaussian
**from-b signal**: exponential * double Gaussian

JHEP10(2015)172
Results: $J/\psi$ cross-sections at $\sqrt{s} = 13$ TeV

prompt

$J/\psi$-from-b

integrated cross-section $p_T < 14$ GeV/c and $2 < y < 4.5$:

$$\sigma(\text{prompt}) = 15.30 \pm 0.03 \pm 0.86 \, \mu\text{b}$$
$$\sigma(\text{from-b}) = 2.34 \pm 0.01 \pm 0.13 \, \mu\text{b}$$

$b\bar{b}$ cross-section $4\pi$-extrapolated*:

$$\sigma(pp \rightarrow b\bar{b} X) = 515 \pm 2 \pm 53 \, \mu\text{b}$$

* $\mathcal{B}(b \rightarrow J/\psi X) = 1.16 \pm 0.10 \%$; naïve PYTHIA 6 extrapolation
**J/ψ production at 13 TeV: comparison with theory**

- **NRQCD** (Shao et al., JHEP 05 (2015) 103):
  - hadronisation of $c\bar{c}$ state described by long-distance matrix elements (LDME) according to spin configuration
  - LDME determined from CDF data

- **FONLL** (Cacciari et al., JHEP 05 (1998) 007, arXiv:1507.06197)
  - fixed-order next-to-leading logarithms
  - match NLO QCD with NLL in the limit $p_T >> m(q)$

- measurements agree with models within uncertainties

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**Graphs**

- **Prompt J/ψ**
  - $d\sigma/dp_T$ vs. $p_T$ (GeV/c)
  - LHCb prompt $J/\psi$, $2.0 < y < 4.5$
  - NRQCD, $2.0 < y < 4.5$

- **J/ψ from b**
  - $d\sigma/dp_T$ vs. $p_T$ (GeV/c)
  - LHCb J/ψ from b, $2.0 < y < 4.5$
  - FONLL, $2.0 < y < 4.5$
Systematic uncertainties

- Luminosity dominant systematic uncertainty
- Muon: tag-and-probe method
- Large only for few bins at acceptance boundary

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty (%)</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>3.9</td>
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<tr>
<td>Hardware trigger</td>
<td>0.1 – 5.9</td>
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<tr>
<td>Software trigger</td>
<td>1.5</td>
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<tr>
<td>Muon ID</td>
<td>1.8</td>
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<tr>
<td>Tracking</td>
<td>1.1 – 3.4</td>
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<tr>
<td>Radiative tail</td>
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<td>$J/\psi$ vertex fit</td>
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<tr>
<td>Signal mass shape</td>
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<tr>
<td>$\mathcal{B}(J/\psi \to \mu^+ \mu^-)$</td>
<td>0.6</td>
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<tr>
<td>$p_T$, $y$ spectrum</td>
<td>0.1 – 5.0</td>
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<tr>
<td>Simulation statistics</td>
<td>0.3 – 5.0</td>
</tr>
<tr>
<td>$t_z$ fit ($J/\psi$-from-$b$ only)</td>
<td>0.1</td>
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</tbody>
</table>
$J/\psi$ production ratio 13/8 TeV: comparison with theory

**prompt**

- NRQCD: not all uncertainties included

- measurements of ratios not well described by models for low $y$

![Graphs](JHEP10(2015)172)
Prompt charm production at $\sqrt{s} = 13$ TeV

• reconstruct $D^0, D^+, D_s^+$ and $D^{*+} \rightarrow D^0\pi^+$

• separate prompt charm from secondary charm by using impact parameter (IP) significance ($D^0$ has lifetime itself)

• kinematic range:
  • $p_T < 15$ GeV/c; $2 < y < 4.5$
  • sequent fits to mass and $\ln \chi_{IP}^2$

signal: Crystal Ball + Gaussian
bkg: linear

JHEP03(2016)159

signal: asymmetric Gaussian + exp tail
secondary: Gaussian
Systematic uncertainties and models

- Luminosity dominant systematic uncertainty
- Only few bins above 10%
Results: prompt charm production cross-sections at 13 TeV

double-differential $D^0$ cross-section

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Theory models:

- **POWHEG+NNPDF3.0L**
  (Gauld et al., JHEP06(2013)064)
  - POWHEG matched to Pythia 8 parton showers

  - match NLO QCD with NLL in the limit $p_T >> m(q)$
  - tuned to c-fractions from $e^+e^-$ colliders

  - NLO predictions are convolved with frag functions fitted to data from $e^+e^-$ colliders

- measurements agree with models within uncertainties
Results: ratio of 13/7 TeV and integrated cross-sections

- measurement of ratios not well described by models

\[
\sigma(pp \rightarrow c\bar{c}X)_{(p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5)} = 2940 \pm 3 \pm 180 \pm 160 \text{ \(\mu\)b}
\]
Results: ratio of 13/7 TeV and integrated cross-sections

- combination of $D^0$ and $D^+$ measurements:

\[
\sigma(pp \rightarrow c\bar{c} X)_{(p_T < 8 \text{ GeV}/c, \ 2.0 < y < 4.5)} = 2940 \pm 3 \pm 180 \pm 160 \mu b
\]

For Run II at $\mathcal{L} = 4 \cdot 10^{32} \text{s}^{-1} \text{cm}^2$:

- 40 kHz of $b\bar{b}$ production!
- 1.2 MHz of $c\bar{c}$ production!

numbers: thanks to Patrick Spradlin

- measurement of ratios not well described by models
Conclusions

- heavy flavour production cross-section at $\sqrt{s} = 13$ TeV with LHCb
  - in the range of $p_T < 14 \text{ (8) GeV/c}$ and $2.0 < y < 4.5$
  - as a function of $p_T$ and $y$ for
- prompt $J/\psi$ and $J/\psi$-from-b
  
  \[
  \sigma(\text{prompt } J/\psi) = 15.30 \pm 0.03 \pm 0.86 \text{ \(\mu b)}
  \]
  \[
  \sigma(J/\psi \text{ from-b)} = 2.34 \pm 0.01 \pm 0.13 \text{ \(\mu b)}
  \]

- prompt charm \[J\text{HEP03(2016)159}\]

- absolute cross-section measurement agree with models within uncertainties
- cross-section ratio 13/8(7) TeV not well described

- analysis of $b\bar{b}$ cross-section using semi-leptonic decays in the pipeline

\[
\sigma(pp \rightarrow b\bar{b} X) = 515 \pm 2 \pm 53 \text{ \(\mu b)}
\]
\[
\sigma(pp \rightarrow c\bar{c} X)(p_T < 8 \text{ GeV/c, } 2.0 < y < 4.5) = 2940 \pm 3 \pm 180 \pm 160 \text{ \(\mu b)}
\]

*naïve PYTHIA 6 extrapolation
Results: $J/\psi$ cross-sections at $\sqrt{s} = 13$ TeV

**prompt**

$J/\psi$ cross-sections at $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 3.05$ pb$^{-1}$

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

$J/\psi$ cross-sections at $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 3.05$ pb$^{-1}$

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JHEP10(2015)172
8TeV Results: $J/\psi$ cross-sections at $\sqrt{s} = 8$ TeV

JHEP06(2013)064
Max Neuner (Heidelberg University): Heavy Flavour Production results at 13 TeV with LHCb

**prompt**

![Graph of prompt J/ψ](image)

- **LHCb Prompt J/ψ**

**J/ψ-from-b**

![Graph of J/ψ-from-b](image)

- **LHCb J/ψ-from-b**
- **FONLL**
- **FONLL, ± 1σ**
promp$\text{t}$

$J/\psi$ production at 13 TeV: comparison with theory

- NRQCD (Shao et al., JHEP 05 (2015) 103)
  - includes LDME uncertainties which are dominant for absolute measurement
  - not included are contributions from renorm/factorization scale, relativistic corrections, charm mass and PDF uncertainties

$J/\psi$-from-b

- FONLL (Cacciari et al., JHEP 05 (1998) 007, arXiv:1507.06197)
  - theoretical uncertainties of b-quark mass, renorm/factorization scale, gluon PDF uncertainty
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details of charm models

• POWHEG+NPDF3.0L: obtained with POWHEG matched to Pythia8 parton showers; can be improved by re-weighting the NNPDF3.0L set such that FONLL calculations match LHCb’s 7TeV charm cross-section; this improves uncertainties for the gluon distribution at small x

• FONLL: match NNPDF3.0 NLO PDF with all-order resummation to next-to-leading log (NLL) accuracy in the limit $p_T < m(q)$; take hadronisation probabilities from $e^+e^-$ colliders

• general-mass variable-flavor-number (GMVFNS): provided only for $p_T > 3\text{ GeV}/c$ due to scale uncertainties; take NLO predictions of charm production and convolute with fragmentation functions describing the $c \rightarrow H_c$ transitions that are normalised to the respective total probabilities; the fragmentation functions are results of fits to the production measurement at $e^+e^-$ colliders
Integrated charm cross-sections at 13 TeV

combine $D^0$ and $D^+$ measurement:

$$\sigma(pp \to c\bar{c}X)(p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5) = 2940 \pm 3 \pm 180 \pm 160 \mu b$$

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