Heavy quark production at LHCb

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on behalf of the LHCb Collaboration

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Motivation
Why study heavy flavour production?

- Run 2 of the LHC probes a new energy, $\sqrt{s} = 13\,\text{TeV}$
- LHCb provides a unique kinematic region for testing QCD
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**$J/\psi$ cross-section**

- Probes perturbative QCD, at $c\bar{c}$ production, and non-perturbative QCD, at $J/\psi$ hadronisation
- Can help distinguish between non-relativistic QCD$^a$ and colour singlet model$^b$
- Previously measured by LHCb at $\sqrt{s} = 2.76\text{ TeV}^c$, 7 TeV$^d$ and 8 TeV$^e$

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$^a$ Hua-Sheng Shao et al. *JHEP*. 05. 2015.
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$c\bar{c}$ cross-section

- Constrain parton distributions at low $x^a$
- Estimate charm backgrounds in atmospheric neutrino experiments$^b$
  - $\sqrt{s} = 13$ TeV corresponds to 90 PeV neutrinos
- Previously measured by LHCb at $\sqrt{s} = 7$ TeV$^c$

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$^b$ Atri Bhattacharya et al. JHEP. 06. 2015 .
The LHCb detector
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- Acceptance between 2 and 5 in pseudorapidity
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- Excellent primary vertex and momentum resolution
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LHC Run 2 trigger changes

- Trigger/offline reconstruction unified
- Real time alignment and calibration
- Analysis quality reconstruction available in the trigger
LHC Run 2 trigger changes

- New Turbo Stream added\(^1\)
- Raw event can be discarded reducing event size (~14x)
- Total output rate can be increased
- Many analyses can now be done using the trigger reconstruction

Methodology
Differential production cross-section of $H_c$ given by

$$\frac{d^2\sigma_i (H_c)}{dp_T dy} \approx \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i (H_c \rightarrow f + c.c.)}{\epsilon_{i,tot} (H_c \rightarrow f) \cdot B (H_c \rightarrow f) \cdot L_{int}}$$

where:

- $i$ - a bin in $p_T$ and $y$
- $N (H_c \rightarrow f + c.c.)$ - signal yield
- $\epsilon_{tot} (H_c \rightarrow f)$ - total signal efficiency
  - Factorised into components
  - Evaluated using independent data samples if possible
  - Estimated from simulation where necessary
- $B (H_c \rightarrow f)$ - branching ratio to the decay products
- $L_{int}$ - total integrated luminosity calibrated using beam-gas imaging$^2$

$^2$ LHCb collaboration. JINST. 9. 2014.
Two main sources of charm at LHCb:

- Prompt
  - Direct production at the primary vertex
  - Decays of higher resonances
- Secondary
  - Decays of B hadrons
13 TeV $J/\psi$ cross-section
• Integrated luminosity of $3.05 \pm 0.12 \text{ pb}^{-1}$ (collected July 2015)
• Uses samples of $J/\psi \rightarrow \mu^+ \mu^-$
• Integrated luminosity of 3.05 ± 0.12 pb⁻¹ (collected July 2015)
• Uses samples of $J/\psi \rightarrow \mu^+ \mu^-$
• Two dimensional unbinned maximum likelihood fit
  • Mass fit to remove combinatorial background
J/ψ analysis

- Integrated luminosity of $3.05 \pm 0.12 \text{ pb}^{-1}$ (collected July 2015)
- Uses samples of $J/\psi \rightarrow \mu^+\mu^-$
- Two dimensional unbinned maximum likelihood fit
  - Mass fit to remove combinatorial background
  - Fit the pseudo proper time distribution of the $J/\psi$ vertex

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

Double differential cross-sections, $\frac{d^2\sigma_{J/\psi}(H_c)}{dp_T\ dy}$, of prompt $J/\psi$

Integrated over acceptance:

$$\sigma \left( \text{prompt } J/\psi, p_T < 14 \text{ GeV}, 2.0 < y < 4.5 \right) = 15.30 \pm 0.03 \pm 0.86 \mu \text{b}^{-1}$$
$J/\psi$ from $b$ cross-section

Double differential cross-sections, $\frac{d^2\sigma_i(H_c)}{dp_T dy}$, of $J/\psi$ from $b$

Integrated over acceptance:

$$\sigma \left( J/\psi \text{ from } b, p_T < 14 \text{ GeV}, 2.0 < y < 4.5 \right) = 2.34 \pm 0.01 \pm 0.13 \mu b^{-1}$$

$$\sigma \left( pp \to b\bar{b}X \right) = 515 \pm 2 \pm 53 \mu b^{-1}$$
Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV for $J/\psi$

Differential in $y$ cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV for $J/\psi$ from $b$
\( \sqrt{s} \) dependence of \( J/\psi \) cross-section

**LHCb Prompt**

\[ \sigma [\mu b] \]

\[ \sqrt{s} \text{ [TeV]} \]

**\( J/\psi \) from \( b \)**

\[ \sigma [\mu b] \]

\[ \sqrt{s} \text{ [TeV]} \]

\( \sqrt{s} \) dependence of \( \sigma (J/\psi) \)

\( \sqrt{s} \) dependence of \( \sigma (J/\psi \text{ from } b) \)
13 TeV $c\bar{c}$ and D meson cross-sections
• Integrated luminosity of $4.98 \pm 0.19 \text{ pb}^{-1}$ (collected July 2015)
• Uses samples of $D^0$, $D^+$, $D_s^+$ and $D^{*+}$:
  • $D^0 \rightarrow K^- \pi^+$
  • $D^+ \rightarrow K^- \pi^+ \pi^+$
  • $D_s^+ \rightarrow (\phi \rightarrow K^- K^+) \pi^+$
  • $D^{*+} \rightarrow (D^0 \rightarrow K^- \pi^+) \pi^+$
• Integrated luminosity of $4.98 \pm 0.19 \text{ pb}^{-1}$ (collected July 2015)
• Two one dimensional unbinned maximum likelihood fits
  • Mass fit to remove combinatorial background
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• Two one dimensional unbinned maximum likelihood fits
  • Mass fit to remove combinatorial background
  • Second fit to $\ln(\chi^2_{IP})$ to separate prompt and secondary charm
Double differential cross-sections, $\frac{d^2\sigma_{ij}(H_c)}{dp_T dy}$, of $D^+$

Integrated over acceptance:

$\sigma(D^0, p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 3370 \pm 4 \pm 200 \, \mu\text{b}^{-1}$

$\sigma(D^+, p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 1290 \pm 8 \pm 190 \, \mu\text{b}^{-1}$

$\sigma(D^+_s, 1 < p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 460 \pm 13 \pm 100 \, \mu\text{b}^{-1}$

$\sigma(D^{*+}, 1 < p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 880 \pm 5 \pm 140 \, \mu\text{b}^{-1}$
$\sigma(pp \to c\bar{c}X)$ from different sources

Integrated over acceptance:

$\sigma(pp \to c\bar{c}X, p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 2940 \pm 3 \pm 180 \pm 160 \mu\text{b}^{-1}$
$D$ meson cross-section ratios between species

$LHCb$ 
$\sqrt{s} = 13$ TeV

$LHCb$ 
$\sqrt{s} = 13$ TeV

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$\sqrt{s} = 13$ TeV

$LHCb$ 
$\sqrt{s} = 13$ TeV

Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV for $D^0$

Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV for $D^+$

Recent Run 1 result
Production of $\Upsilon$ and open charm hadrons via double parton scattering

- Observation of $\Upsilon (1S) D^0$, $\Upsilon (2S) D^0$, $\Upsilon (1S) D^+$, $\Upsilon (2S) D^+$ and $\Upsilon (1S) D^+_S$
- Cross-sections measured for $\Upsilon (1S) D^0$ and $\Upsilon (1S) D^+$
- Results in agreement with double parton scattering expectations
- Significantly exceed the expected yield in the single parton scattering approach
Summary

• Excellent start to LHC Run 2 for LHCb
• New Turbo Stream working well
• LHCb has already performed measurements at $\sqrt{s} = 13$ TeV for
  • $J/\psi$
  • $J/\psi$ from $b$
  • $b\bar{b}$
  • $D^0, D^+, D_s^+$ and $D^{*+}$
  • $c\bar{c}$
• More measurements coming soon
Questions?