Charmed meson production at LHCb

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Outline

1. Motivation
2. The LHCb detector
3. $J/\psi$ and $D$ meson production at 13 TeV
4. Associated production of $\Upsilon$ and open charm mesons at 7 and 8 TeV
Motivation
Why measure charm meson cross-sections (at $\sqrt{s} = 13$ TeV)?
Why measure charm meson cross-sections (at $\sqrt{s} = 13$ TeV)?

Perturbative QCD

Non-perturbative QCD

$\bar{q}$
$q$

$\psi$
$D^+$
Why measure charm meson cross-sections (at $\sqrt{s} = 13$ TeV)?

- Non-perturbative parameters must come from experiment
- Some predictions not matching new experimental results after 40 years of progress
Parton distribution functions

Production dominated by $gg$ fusion, measurements can constrain low $x$ gluon pdf.

1 PROSA collaboration, arXiv:1503.04581
Parton distribution functions

- Production dominated by $gg$ fusion, measurements can constrain low $x$ gluon pdf.\(^1\)

$c\bar{c}$ next-to-leading order predictions\(^2\)

\[ \begin{align*}
\text{NLO} & \quad \text{full uncertainty} \\
\text{scales} & \quad \text{mass} \\
\text{PDFs} & \quad \text{PDFs}
\end{align*} \]

- $13/7$ TeV cross-section ratio allows to further constrain the uncertainty.

\[ \begin{align*}
\text{NLO} & \quad \text{scales} \\
\text{PDFs} & \quad \text{PDFs}
\end{align*} \]

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\(^1\)PROSA collaboration, arXiv:1503.04581

Background in atmospheric neutrino experiments

Proton-proton $\sqrt{s} = 13$ TeV is equivalent to a $90$ PeV cosmic ray.

IceCube collaboration, Phys. Rev. Lett. 113 (2014) 101101
Production cross-sections can be used to estimate background contributions of neutrino experiments.¹

Proton-proton $\sqrt{s} = 13$ TeV is equivalent to a 90 PeV cosmic ray

¹IceCube collaboration, Phys. Rev. Lett. 113 (2014) 101101
Why measure charm production cross-sections at LHCb

LHCb MC = 7 TeV

LHCb MC = 14 TeV

Production peaks in the LHCb acceptance.

\[ \theta_1, \theta_2, \hat{b}, \hat{b}, z \]

\[ \text{Lhcb.web.cern.ch: } \bar{b}b \text{ production angle plots} \]

1Lhcb.web.cern.ch: \( \bar{b}b \) production angle plots
Why measure charm production cross-sections at LHCb

$\bar{b}b$ opening angles

Production peaks in the LHCb acceptance.

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1lhcb.web.cern.ch: $\bar{b}b$ production angle plots
The LHCb detector
The LHCb detector

<table>
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<td>Momentum of charged particles</td>
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<td>PID</td>
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<td>MUON Trigger on high $p_T \mu^\pm$, add PID</td>
<td>SPD/PS Separate $\gamma/e^\pm$ and $h^\pm/e^\pm$</td>
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The LHCb detector

VELO Primary and secondary vertex, impact parameter
TT, IT, OT Momentum of charged particles
The LHCb detector

VELO Primary and secondary vertex, impact parameter

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MUON Trigger on high $p_T$ $\mu^\pm$, add PID
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RICHs  \( K^\pm, \pi^\pm, \) and \( p/\bar{p} \) PID

MUON  Trigger on high \( p_T \), add PID

SPD/PS  Separate \( \gamma/e^\pm \) and \( h^\pm/e^\pm \)

ECAL/HCAL  EM/hadronic energy
The LHCb trigger system in LHC run 2

**Real time detector alignment and calibration**

At the beginning of every fill: buffer and use a small subset of data to do alignment and calibration.

**Turbo stream**

- Candidates out of trigger with offline-quality reconstruction.
- Analysis-ready candidates stored to disk with no need for additional offline reconstruction.
- Faster and smaller event size on disk.
- Candidate to become default procedure in Run3.

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1 G. Dujany et al., LHCb-PROC-2015-011
2 R. Aaij et al., arXiv:1604.05596
$J/\psi$ and $D$ meson production at $\sqrt{s} = 13$ TeV
Double differential cross-sections for different charm mesons $H_c$:

$$d^2\sigma_i(H_c) dp_T dy = \Delta p_T \Delta y \cdot N_i(H_c \rightarrow f) \varepsilon_i, \text{tot} (H_c \rightarrow f) \Gamma(H_c \rightarrow f) L_{\text{int}}$$

with $y = 1/2 \ln E + p_z c E - p_z c$

Prompt and from $b$-decays $J/\psi$ cross-sections, previously measured by LHCb at $\sqrt{s} = 2.76, 7, 8$ TeV.

1. LHCb collaboration, JHEP 1302 (2013) 041
4. LHCb collaboration, Nuclear Physics, Section B 871 (2013), pp. 1-20
Double differential cross-sections for different charm mesons $H_c$:

$$\frac{d^2\sigma_i(H_c)}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H_c \rightarrow f)}{\varepsilon_{i,tot}(H_c \rightarrow f) \Gamma(H_c \rightarrow f) L_{int}} \text{ with } y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}$$

- Prompt and from $b$ decays $J/\psi$ cross-sections, previously measured by LHCb at $\sqrt{s} = 2.76$, 7, and 8 TeV$^{1,2,3}$
- Prompt $D^0$, $D^+$, $D_s^+$ and $D^{*+}$ cross-sections, previously measured by LHCb at $\sqrt{s} = 7$ TeV$^4$

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$^1$LHCb collaboration, JHEP 1302 (2013) 041
$^3$LHCb collaboration, J. High Energy Phys. 06 (2013) 064
$^4$LHCb collaboration, Nuclear Physics, Section B 871 (2013), pp. 1-20
The dataset

All data collected during the 13 TeV ramp-up of the LHC in July 2015.

**J/ψ production measurement**

- Used 3 pb$^{-1}$ of luminosity.
- Final state: $J/ψ → μ^-μ^+$.

**Charm production measurement**

- Used 5 pb$^{-1}$ of luminosity.
- Final states: $D^0 → K^-π^+$, $D^+ → K^-π^+π^+$, $D_s^+ → φπ^+$ with $φ → K^-K^+$ and $D^{*+} → D^0π^+$ with $D^0 → K^-π^+$.

- Event selection relies on kinematic and quality cuts on the reconstructed tracks in the detector as well as requirements on the vertices.

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1. LHCb collaboration, JHEP10 (2015) 172
2. LHCb collaboration, JHEP03 (2016) 159
Number of signal events

Total number of signal events obtained by fitting the invariant mass of the combined final state particles

\[ J/\psi \rightarrow \mu^- \mu^+ \]

\[ D^0 \rightarrow K^- \pi^+ \]

This does not distinguish between prompt and secondary production.
Prompt and secondary discrimination

For the long-lived $D$ mesons, the reconstructed $D$ has to point back to the primary vertex of the $pp$ collision:

$B^{-} \mu^{-} \bar{\nu}_{\mu} / X$

$D^{0}$

$K^{-}$

$\pi^{+}$

$IP_{D^{0}}$

$p p$

$J/\psi$ decays instantaneously, life-time has to agree with zero:

$$t_{z} = \frac{(z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}}{p_{z}}$$

Both methods are smeared due to resolution effects.
For the $J/\psi$, both components are used to measure prompt and from $b$ production cross-sections.

Only the prompt signal is measured for the different $D$ mesons.
Results for $J/\psi$

LHCb collaboration, JHEP10 (2015) 172

- Double and single differential cross-sections in $p_T$ and/or $y$.
- Ratios between 13 and 8 TeV cross-sections.
- Integrated cross-sections.

**Dominant systematic uncertainties**

- Luminosity, tracking and Monte Carlo statistics.

- Compared to theoretical predictions:
  - NRQCD non-relativistic QCD\(^1\)
  - FONLL fixed order next-to-leading logarithms\(^2\)

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\(^1\)Shao et al., JHEP05 (2015) 103
\(^2\)Cacciari et al., JHEP10 (2012) 137
$J/\psi$ cross-sections at 13 TeV

LHCb collaboration, JHEP10 (2015) 172
In LHCb acceptance:

\[ \sigma_{\text{Prompt}} = 15.30 \pm 0.03 \text{ (stat)} \pm 0.86 \text{ (sys)} \mu b \]

\[ \sigma_{\text{from-}b} = 2.34 \pm 0.01 \text{ (stat)} \pm 0.13 \text{ (sys)} \mu b \]
$J/\psi$ cross-sections at 13 TeV- theory comparison

LHCb collaboration, JHEP10 (2015) 172

Compared to theoretical predictions:

1. NRQCD non-relativistic QCD
2. FONLL fixed order next-to-leading logarithms

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1. Shao et al., JHEP05 (2015) 103
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J/ψ cross-sections at 13 TeV - theory comparison

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Compared to theoretical predictions:

- NRQCD non-relativistic QCD
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\textsuperscript{1}Shao et al., JHEP05 (2015) 103
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$J/\psi$ cross-sections - 13 to 8 TeV ratio

LHCb collaboration, JHEP10 (2015) 172

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1 Shao et al., JHEP05 (2015) 103
2 Cacciari et al., JHEP10 (2012) 137
**J/ψ cross-sections - 13 to 8 TeV ratio**

LHCb collaboration, JHEP10 (2015) 172

**prompt J/ψ**

\[
R_{13/8}(d\sigma/dp_T) = \frac{\sigma_{13 TeV}}{\sigma_{8 TeV}}
\]

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

- LHCb
- NRQCD

**J/ψ from b**

\[
R_{13/8}(d\sigma/dp_T) = \frac{\sigma_{13 TeV}}{\sigma_{8 TeV}}
\]

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

- LHCb
- FONLL

\[\nabla\text{ Compared to theoretical predictions:}\]

- **NRQCD** non-relativistic QCD\(^1\)
- **FONLL** fixed order next-to-leading logarithms\(^2\)

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\(^1\)Shao et al., JHEP05 (2015) 103

\(^2\)Cacciari et al., JHEP10 (2012) 137
Results for $D$ mesons

LHCb collaboration, JHEP03 (2016) 159

- Double differential cross-sections in $p_T$ and $y$.
- Ratios between 13 and 7 TeV cross-sections.
- Ratios between different meson species.
- Integrated cross-sections per $D$ meson.
- Estimates for $c\bar{c}$ cross-sections using fragmentation fractions.\(^1\)

**Dominant systematic uncertainties**

- Luminosity, tracking, particle identification efficiencies and Monte Carlo statistics.

- Compared to theoretical predictions:
  - **FONLL** fixed order next-to-leading logarithms\(^2\)
  - **GMVFNS** general- mass variable-flavor-number scheme\(^3\)
  - **POWHEG** with a modified NNPDF3.0 using the 7 TeV LHCb results\(^4\)

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\(^1\)Particle Data Group collaboration et al., Phys. Lett. B 667 (2008) 1
\(^4\)Gauld et al., JHEP11 (2015) 9
$D^0$ meson cross-sections

LHCb collaboration, JHEP03 (2016) 159

\[ \frac{\sigma(D^0)}{d^2 \sigma / d y d p_T} \cdot 10^{-m} \mu b / ( \text{GeV}c^{-1}) \]

\[
LHCb \quad D^0 \\
\sqrt{s} = 13 \text{ TeV}
\]

POWHEG+NNPDF3.0L
FONLL
GMVFNS

0 2 4 6 8 10 12 14

\[ p_T \, [\text{GeV}/c] \]

\[
\sigma(D^0)_{1 < p_T < 8 \text{ GeV}} = 2460 \pm 3(\text{stat}) \pm 130(\text{syst}) \mu b
\]

**FONLL** fixed order next-to-leading logarithms\(^1\)

**GMVFNS** general- mass variable-flavor-number scheme\(^2\)

**POWHEG** with a modified NNPDF3.0 using the 7 TeV LHCb results\(^3\)

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\(^3\) Gauld et al., JHEP11 (2015) 9
0 < \pT < 8 \text{ GeV}

\begin{align*}
\sigma(pp \rightarrow c\bar{c}X) \text{ [\mu b]} \quad &\text{LHCb} \\
0 < \pT < 8 \text{ GeV}/c, \ 2 < y < 4.5 \quad &\text{LHCb} \quad \sqrt{s} = 13 \text{ TeV}
\end{align*}

LHCb $D^+$

LHCb $D^0$

LHCb average

FONLL \hspace{1cm} \text{arXiv:1507.06197}

POWHEG+NNPDF3.0L (scaled) \hspace{1cm} \text{arXiv:1506.08025}

POWHEG+NNPDF3.0L (absolute) \hspace{1cm} \text{arXiv:1506.08025}

1 < \pT < 8 \text{ GeV}

\begin{align*}
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1 < \pT < 8 \text{ GeV}/c, \ 2 < y < 4.5 \quad &\text{LHCb} \quad \sqrt{s} = 13 \text{ TeV}
\end{align*}

LHCb $D^0$

LHCb $D^+$

LHCb $D_s^+$

LHCb $D^{*+}$

LHCb average
$D$ meson 13 to 7 TeV ratios

LHCb collaboration, JHEP03 (2016) 159
Ratios between different mesons
LHCb collaboration, JHEP03 (2016) 159

- Ratios of $\sigma \cdot \Gamma$ for different $D$ mesons.
- Compared to ratios of measurements performed at $e^+e^-$ colliders.$^{1,2,3}$

$D^+/D^0$

$D^{*+}/D^0$

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Associated production of $\Upsilon$ and open charm mesons at 7 and 8 TeV
Motivation

LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

Single parton scattering (SPS)

1 A. Berezhnoy et al., IJMP A30 (2015) 1550125
2 LHCb collaboration, PLB 707 (2012) 52
3 JHEP 06 (2012) 141
Motivation

LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

\[ p \rightarrow p + b + b + \Upsilon(nS) + c + c + H + X \]

\[ \sigma_{\Upsilon c c} \sigma_{\Upsilon c c} = \sigma_{\Upsilon c c} \sigma_{\Upsilon c c} = \sigma_{\Upsilon c c} \sigma_{\Upsilon c c} \approx 10\% \]

Single parton scattering (SPS)

\[ p \rightarrow p + b + b + \Upsilon(nS) + c + c + H + X \]

\[ R_{\text{SPS}} = \sigma_{\Upsilon c c} \sigma_{\Upsilon c c} \approx 0.2 - 0.6\% \]

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1 A. Berezhnoy et al., IJMP A30 (2015) 1550125
2 LHCb collaboration, PLB 707 (2012) 52
3 JHEP 06 (2012) 141
Motivation
LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

\[ \sigma_{\Upsilon c} c H c + \mathcal{X} = \sigma_{\Upsilon c} \cdot \sigma_{c H c} \sigma_{\text{eff}}, \]

\[ R_{\text{DPS}} = \sigma_{\Upsilon c} c H c / \sigma_{\Upsilon c} \approx 10\%. \]

Single parton scattering (SPS)

\[ R_{\text{SPS}} = \sigma_{\Upsilon c} c H c / \sigma_{\Upsilon c} \approx 0.2 - 0.6\%. \]

LHCb previously measured \( J/\psi \) and open charm pair production.

1. A. Berezhnoy et al., IJMP A30 (2015) 1550125
2. LHCb collaboration, PLB 707 (2012) 52
3. JHEP 06 (2012) 141
Motivation

LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

\[
\sigma_{\Upsilon c} \sigma_{\Upsilon} = \sigma_{\Upsilon c} \sigma_{\Upsilon} \cdot \sigma_{\text{eff}} \\
\Rightarrow R_{\text{DPS}} = \sigma_{\Upsilon c} \sigma_{\Upsilon} = \sigma_{\Upsilon c} \sigma_{\text{eff}} \approx 10\%
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Single parton scattering (SPS)

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1. A. Berezhnoy et al., IJMP A30 (2015) 1550125
2. LHCb collaboration, PLB 707 (2012) 52
3. JHEP 06 (2012) 141
Motivation

LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

\[ p \rightarrow \bar{b}(nS) b, H_c + X \]

\[ \sigma^{\Upsilon c \bar{c}} = \frac{\sigma^{\Upsilon \cdot \sigma c \bar{c}}}{\sigma_{\text{eff}}} \]

\[ \Rightarrow R_{\text{DPS}} = \frac{\sigma^{\Upsilon c \bar{c}}}{\sigma^{\Upsilon}} = \frac{\sigma c \bar{c}}{\sigma_{\text{eff}}} \approx 10\% . \]

Single parton scattering (SPS)

\[ p \rightarrow \bar{c} \bar{c} \]

\[ \sigma_{\Upsilon c c} = \sigma_{\Upsilon} \cdot \sigma_{\text{eff}} \]

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1 A. Berezhnoy et al., IJMP A30 (2015) 1550125
2 LHCb collaboration, PLB 707 (2012) 52
3 JHEP 06 (2012) 141
Double parton scattering (DPS)

\[ \gamma(nS) \]

\[ H_c + X \]

\[ \sigma_{\gamma c\bar{c}} = \frac{\sigma_{\gamma \cdot \sigma_{c\bar{c}}}}{\sigma_{\text{eff}}} \]

\[ R_{\text{DPS}} = \frac{\sigma_{\gamma c\bar{c}}}{\sigma_{\gamma}} = \frac{\sigma_{c\bar{c}}}{\sigma_{\text{eff}}} \approx 10\% \]

Single parton scattering (SPS)

\[ H_c + X \]

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1 A. Berezhnoy et al., IJMP A30 (2015) 1550125
2 LHCb collaboration, PLB 707 (2012) 52
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**Motivation**

LHCb collaboration, arXiv:1510.05949

### Double parton scattering (DPS)

\[
\sigma \Upsilon \bar{c}c = \frac{\sigma \Upsilon \cdot \sigma \bar{c}c}{\sigma_{\text{eff}}},
\]

\[\Rightarrow \quad R_{\text{DPS}} = \frac{\sigma \Upsilon \bar{c}c}{\sigma \Upsilon} = \frac{\sigma \bar{c}c}{\sigma_{\text{eff}}} \approx 10\%.
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### Single parton scattering (SPS)

\[\Rightarrow \quad R_{\text{SPS}} = \frac{\sigma \Upsilon \bar{c}c}{\sigma \Upsilon} \approx 0.2\% - 0.6\%.
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1. A. Berezhnoy et al., IJMP A30 (2015) 1550125
2. LHCb collaboration, PLB 707 (2012) 52
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Double parton scattering (DPS)

\[
\begin{align*}
\sigma_{\Upsilon c\bar{c}} &= \sigma_{\Upsilon} \cdot \frac{\sigma_{c\bar{c}}}{\sigma_{\text{eff}}} \\
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Double parton scattering (DPS)

\[ \sigma^{\Upsilon c\bar{c}} = \frac{\sigma^{\Upsilon} \cdot \sigma^{c\bar{c}}}{\sigma_{\text{eff}}} \],

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LHCb collaboration, arXiv:1510.05949

Double parton scattering (DPS)

\[ \sigma^c \bar{c} = \frac{\sigma^c \cdot \sigma^{c\bar{c}}}{\sigma_{\text{eff}}} , \]

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\[ R_{\text{SPS}} = \frac{\sigma^c \bar{c}}{\sigma^c} \approx 0.2 - 0.6\% . \]

LHCb previously measured \( J/\psi \) and open charm pair production.\(^2,^3\)

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1. A. Berezhnoy et al., IJMP A30 (2015) 1550125
2. LHCb collaboration, PLB 707 (2012) 52
3. JHEP 06 (2012) 141
The measurement

LHCb collaboration, arXiv:1510.05949

Reconstruct and select events with \( \Upsilon(nS) \rightarrow \mu^+\mu^- \) and either \( D^0 \rightarrow K^-\pi^+ \), \( D^+ \rightarrow K^-\pi^+\pi^+ \) or \( D^+_{s} \rightarrow K^-K^+\pi^+ \). Both parts of the event are selected independently to allow independent correction for reconstruction and selection efficiencies.

\( \chi^2/\text{ndf} \) requirement on the common \( \Upsilon(nS) \) and \( D \) production vertex to reject decays from pile-up.
Reconstruct and select events with $\Upsilon(nS) \rightarrow \mu^+ \mu^-$ and either $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$ or $D_s^+ \rightarrow K^- K^+ \pi^+$.

Both parts of the event are selected independently to allow independent correction for reconstruction and selection efficiencies.

$\chi^2$/ndf requirement on the common $\Upsilon(nS)$ and $D$ production vertex to reject decays from pile-up.
Fit to $\Upsilon(nS)$ and $D$ invariant mass

LHCb collaboration, arXiv:1510.05949
Fit to $\Upsilon(nS)$ and $D$ invariant mass

LHCb collaboration, arXiv:1510.05949
Measurement limited by sample size.
Measurement limited by sample size.

First observation of associated production of $\Upsilon(1S)D^0$, $\Upsilon(2S)D^0$, $\Upsilon(1S)D^+$, $\Upsilon(2S)D^+$ and $\Upsilon(1S)D_s^+$!
Results

LHCb collaboration, arXiv:1510.05949

- Measurement limited by sample size.
- First observation of associated production of $\Upsilon(1S)D^0$, $\Upsilon(2S)D^0$, $\Upsilon(1S)D^+$, $\Upsilon(2S)D^+$ and $\Upsilon(1S)D_s^+$!
- Integrated cross-section measurements for $D^0$ and $D^+$ modes:

\[
\mathcal{B} (\Upsilon(1S) \rightarrow \mu^+ \mu^-) \cdot \sigma_{\Upsilon(1S)D^0}^{\sqrt{s=7\text{ TeV}}} = 155 \pm 21(\text{stat}) \pm 7(\text{syst}) \text{ pb}
\]
Results

LHCb collaboration, arXiv:1510.05949

- Measurement limited by sample size.
- First observation of associated production of $\Upsilon(1S)D^0$, $\Upsilon(2S)D^0$, $\Upsilon(1S)D^+$, $\Upsilon(2S)D^+$ and $\Upsilon(1S)D_{s}^+$!
- Integrated cross-section measurements for $D^0$ and $D^+$ modes:

$$
\mathcal{B}\left(\Upsilon(1S) \rightarrow \mu^+ \mu^-\right) \cdot \sigma_{\Upsilon(1S)D^0}^{\sqrt{s}=7\text{ TeV}} = 155 \pm 21(\text{stat}) \pm 7(\text{syst}) \text{ pb}
$$

- Differential kinematic distribution of the event indicate dominant production via DPS.
- Assuming 100% DPS:

$$
\sigma_{\text{eff}} = 18.0 \pm 1.3(\text{stat}) \pm 1.2(\text{syst}) \text{ mb}
$$
Summary
Summary

Presented 13 TeV production cross-sections for prompt and from-\(b\) \(J/\psi\).

Presented 13 TeV production cross-sections for prompt \(D\) mesons.

Both show tension with the QCD prediction in 13 TeV to 7 TeV and 8 TeV ratios respectively.

First observation of and production cross-sections for associated \(\Upsilon(nS)\) and \(D\) mesons.
Backup
$D^+$ meson cross-sections

LHCb collaboration, JHEP03 (2016) 159

$\sigma(D^+)_{1<p_T<8 \text{ GeV}} = 1000 \pm 3(\text{stat}) \pm 110(\text{syst}) \mu b$
\[ \sigma(D_s^+)_{1<p_T<8 \text{ GeV}} = 460 \pm 13(\text{stat}) \pm 100(\text{syst}) \mu b \]
$D^*$ cross-sections

LHCb collaboration, JHEP03 (2016) 159

\[
\sigma(D^{*+})_{1<p_T<8 \text{ GeV}} = 880 \pm 5(\text{stat}) \pm 140(\text{syst}) \mu b
\]
More $J/\psi$ ratios

LHCb collaboration, JHEP10 (2015) 172(supplementary material)
Fit to $\Upsilon(nS)$ and $D$ invariant mass

LHCb collaboration, arXiv:1510.05949

(a) LHCb $\Upsilon(1S)D^0$

(b) LHCb $\Upsilon(1S)D^+$

(c) LHCb $\Upsilon(1S)D^0$

(d) LHCb $\Upsilon(1S)D^+$