Heavy quark production at LHCb

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on behalf of the LHCb Collaboration

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LHCb

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/ψ cross-section

- Probes perturbative QCD, at $c\bar{c}$ production, and non-perturbative QCD, at J/ψ 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], $7\,\text{TeV}$[d] and $8\,\text{TeV}$[e]

[a] Hua-Sheng Shao et al. *JHEP*. 05. 2015 .
[b] V. G. Kartvelishvili et al. *Sov. J. Nucl. Phys.* 28. 1978 .
[c] LHCb collaboration. *Eur. Phys. J.*. C74. 2014 .
[d] LHCb collaboration. *Eur. Phys. J.*. C71. 2011 .
[e] LHCb collaboration. *JHEP*. 11. 2015 .

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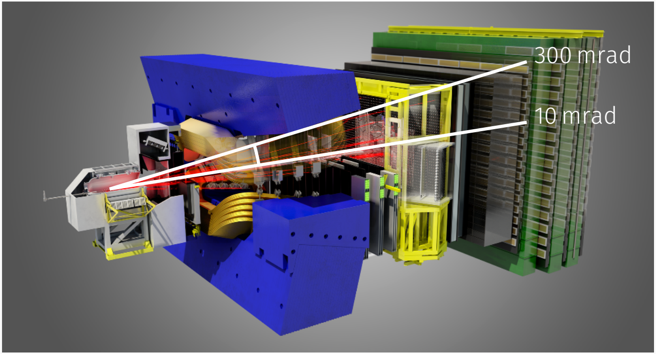
$c\bar{c}$ cross-section

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

[a] Oleksandr Zenaiev et al. *Eur. Phys. J.*. C75. 2015 .
[b] Atri Bhattacharya et al. *JHEP*. 06. 2015 .
[c] LHCb collaboration. *Nucl. Phys.* B871. 2013 .

The LHCb detector

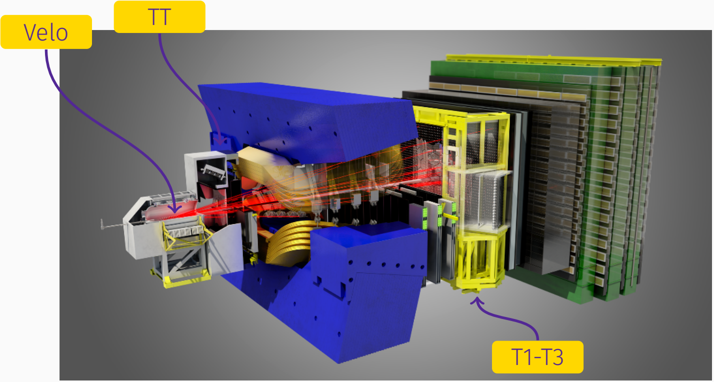
The LHCb detector



- Acceptance between 2 and 5 in pseudorapidity

LHCB-DP-2014-002 DOI:10.1142/S0217751X15300227

The LHCb detector



- Acceptance between 2 and 5 in pseudorapidity
- Excellent primary vertex and momentum resolution

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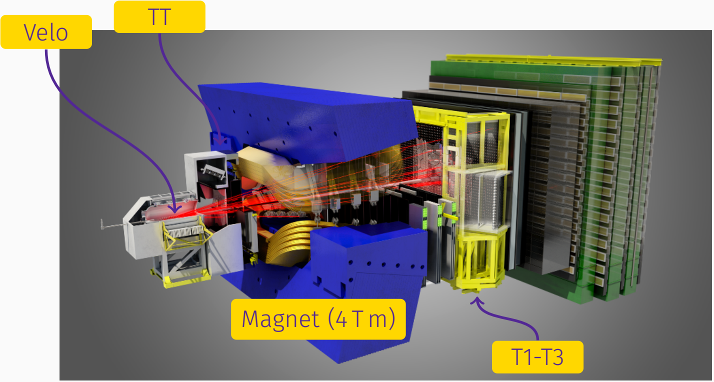

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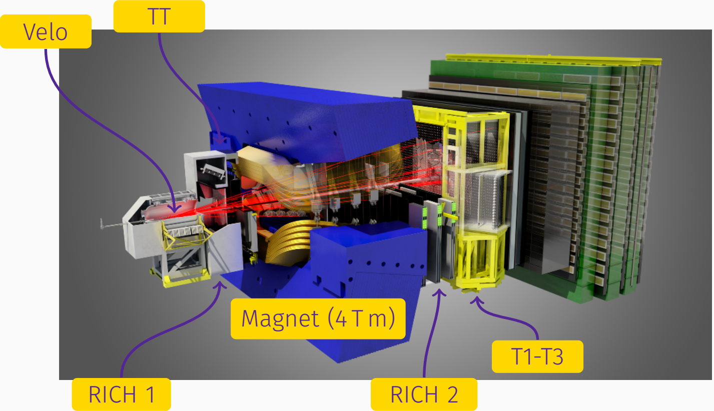

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- Excellent primary vertex and momentum resolution
- Particle identification with RICH detectors to separate $\pi^{\pm}$, $K^{\pm}$ and $p/\overline{p}$

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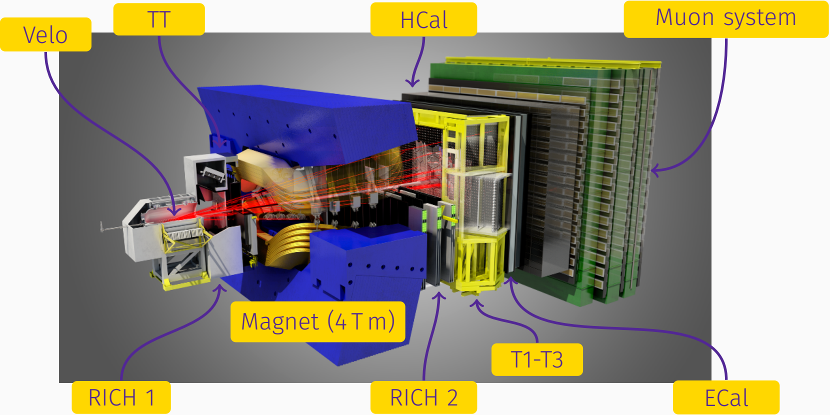

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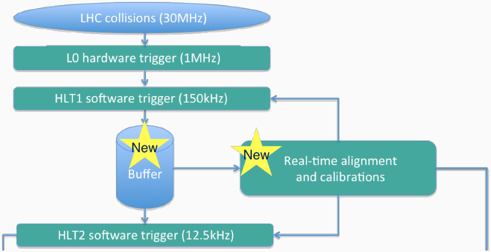
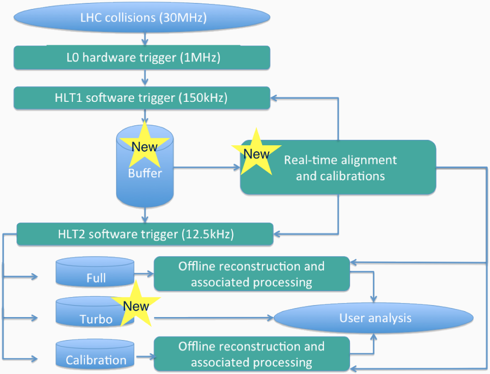
LHC Run 2 trigger changes



- 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

[1] Sean Benson et al. *J. Phys. Conf. Ser.* 664. 2015 .

Methodology

Methodology

Differential production cross-section of H_c given by

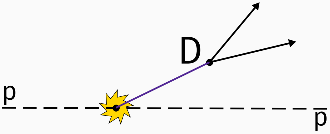
$$\frac{\mathrm{d}^2\sigma_i\left(H_c\right)}{\mathrm{d}p_T\,\mathrm{d}y} \approx \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i\left(H_c \to f + \text{c.c.}\right)}{\epsilon_{i,\text{tot}}\left(H_c \to f\right) \cdot \mathcal{B}\left(H_c \to f\right) \cdot \mathcal{L}_{\text{int}}}$$

where:

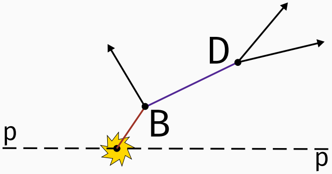
- i - a bin in p_T and y
- $N\left(H_c \to f + \text{c.c.}\right)$ - signal yield
- $\epsilon_{\text{tot}}\left(H_c \to f\right)$ - total signal efficiency
    - Factorised into components
    - Evaluated using independent data samples if possible
    - Estimated from simulation where necessary
- $\mathcal{B}\left(H_c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

[2] LHCb collaboration. *JINST*. 9. 2014 .

Sources of charm



Prompt



Decays involving *b* quarks

Two main sources of charm at LHCb:

- Prompt
  - Direct production at the primary vertex
  - Decays of higher resonances
- Secondary
  - Decays of B hadrons

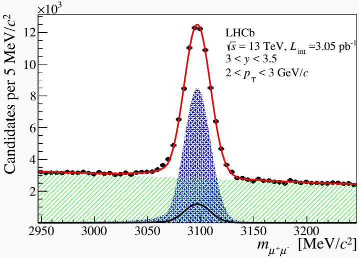
13 TeV J/ψ cross-section

J/ψ analysis

- Integrated luminosity of $3.05 \pm 0.12\,\text{pb}^{-1}$ (collected July 2015)
- Uses samples of J/$\psi \to \mu^+\mu^-$

LHCB-PAPER-2015-037 DOI:10.1007/JHEP10(2015)172

J/ψ analysis



- Integrated luminosity of $3.05 \pm 0.12\,\mathrm{pb}^{-1}$ (collected July 2015)
- Uses samples of J/$\psi \to \mu^+\mu^-$
- Two dimensional unbinned maximum likelihood fit
  - Mass fit to remove combinatorial background

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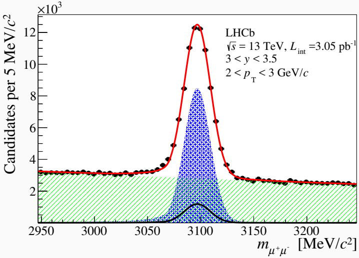
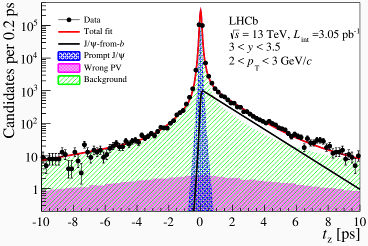
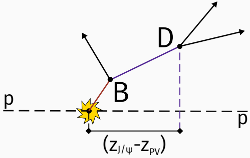




- Integrated luminosity of $3.05 \pm 0.12\,\mathrm{pb}^{-1}$ (collected July 2015)
- Uses samples of $\mathrm{J}/\psi \to \mu^+\mu^-$
- Two dimensional unbinned maximum likelihood fit
    - Mass fit to remove combinatorial background
    - Fit the pseudo proper time distribution of the J/ψ vertex

$$t_z = \frac{(z_{\mathrm{J}/\psi} - z_{\mathrm{PV}})\, M_{\mathrm{J}/\psi}}{p_z}$$



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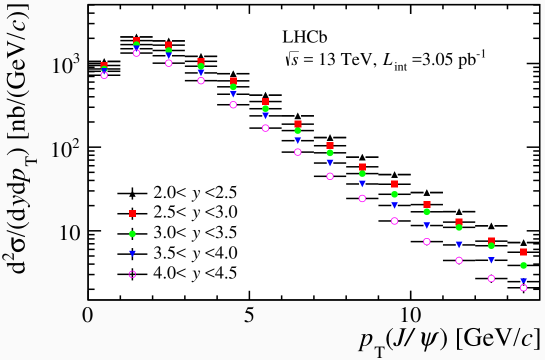
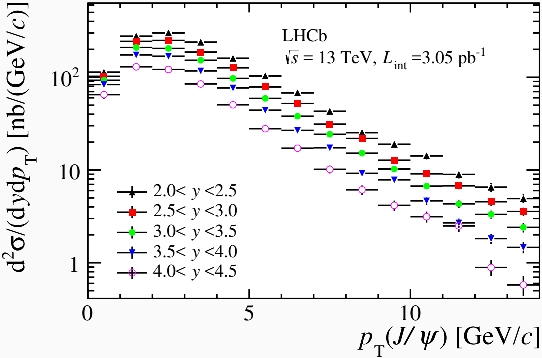


Double differential cross-sections, $\frac{d^2\sigma_i(H_c)}{dp_T\,dy}$, of prompt J/ψ

Integrated over acceptance:

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



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

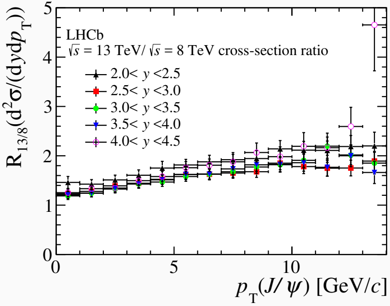
Integrated over acceptance:

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

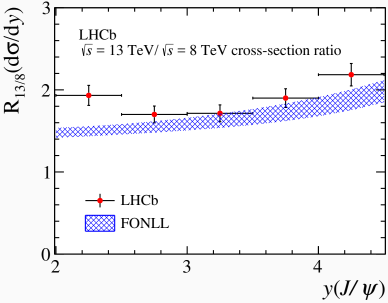
$$\sigma\left(pp \to b\bar{b}X\right) = 515 \pm 2 \pm 53\,\mu b^{-1}$$

LHCB-PAPER-2015-037 DOI:10.1007/JHEP10(2015)172

J/ψ cross-section ratios between energies



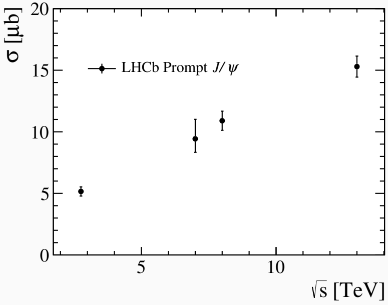
Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV for J/ψ



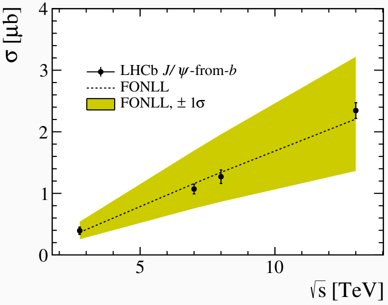
Differential in y cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 8$ TeV for J/ψ from b

LHCB-PAPER-2015-037 DOI:10.1007/JHEP10(2015)172

$\sqrt{s}$ dependence of J/ψ cross-section



$\sqrt{s}$ dependence of σ (J/ψ)



$\sqrt{s}$ dependence of σ (J/ψ from b)

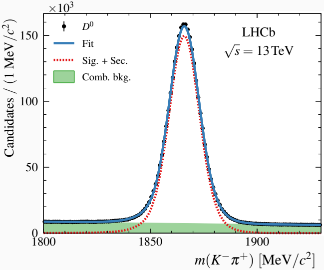
LHCB-PAPER-2015-037 DOI:10.1007/JHEP10(2015)172

13 TeV $c\overline{c}$ and D meson cross-sections

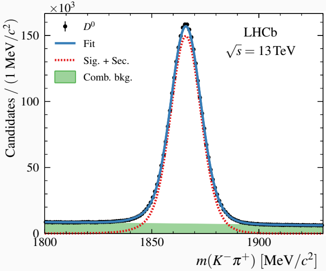
- Integrated luminosity of $4.98 \pm 0.19\,\mathrm{pb}^{-1}$ (collected July 2015)
- Uses samples of D^0, D^+, D_s^+ and D^{*+}:
    - $D^0 \to K^-\pi^+$
    - $D^+ \to K^-\pi^+\pi^+$
    - $D_s^+ \to \left(\phi \to K^-K^+\right)\pi^+$
    - $D^{*+} \to \left(D^0 \to K^-\pi^+\right)\pi^+$

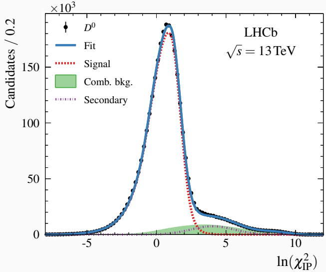
LHCb-PAPER-2015-041 arXiv:1510.01707

$c\bar{c}$ analysis

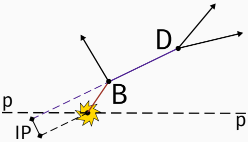


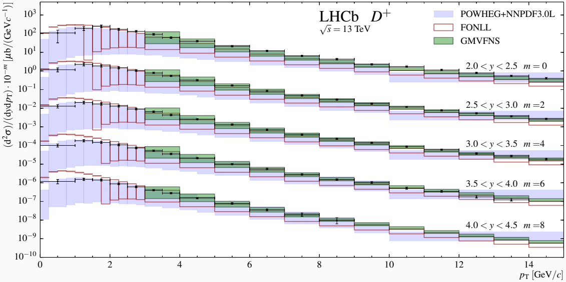
- Integrated luminosity of $4.98 \pm 0.19\,\text{pb}^{-1}$ (collected July 2015)
- Two one dimensional unbinned maximum likelihood fits
    - Mass fit to remove combinatorial background





- 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
  - Second fit to $\log\left(\text{IP}\chi^2\right)$ to separate prompt and secondary charm





Double differential cross-sections, $\frac{d^2\sigma_i(H_c)}{dp_T\, dy}$, of D^+

Integrated over acceptance:

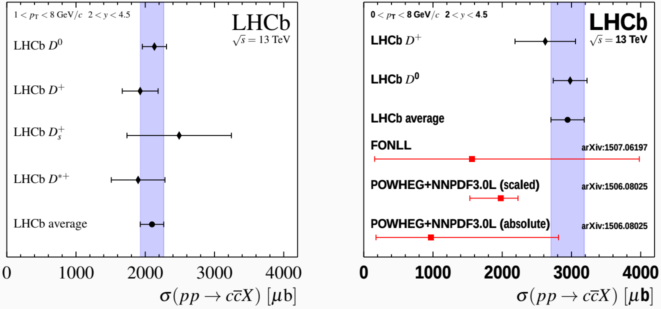
$$\sigma(D^0, p_T < 8\,\text{GeV}, 2.0 < y < 4.5) = 3370 \pm 4 \pm 200\,\mu\text{b}^{-1}$$

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

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

$$\sigma(D^{*+}, 1 < p_T < 8\,\text{GeV}, 2.0 < y < 4.5) = 880 \pm 5 \pm 140\,\mu\text{b}^{-1}$$

LHCb-PAPER-2015-041 arXiv:1510.01707



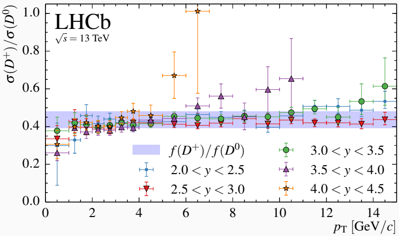
$\sigma\left(pp \to c\bar{c}X\right)$ from different sources

Integrated over acceptance:

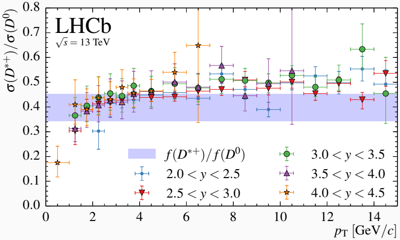
$$\sigma(pp \to c\bar{c}X, p_T < 8\,\mathrm{GeV}, 2.0 < y < 4.5) = 2940 \pm 3 \pm 180 \pm 160\,\mu\mathrm{b}^{-1}$$

LHCb-PAPER-2015-041 arXiv:1510.01707

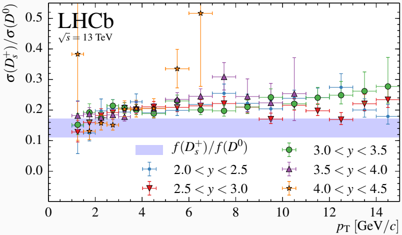
D meson cross-section ratios between species



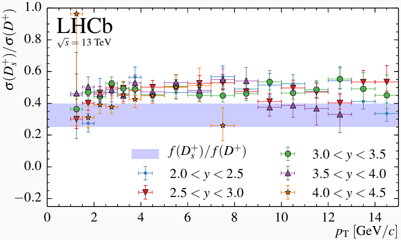
$\sigma(D^+)/\sigma(D^0)$



$\sigma(D^{*+})/\sigma(D^0)$



$\sigma(D_s^+)/\sigma(D^0)$



$\sigma(D_s^+)/\sigma(D^+)$

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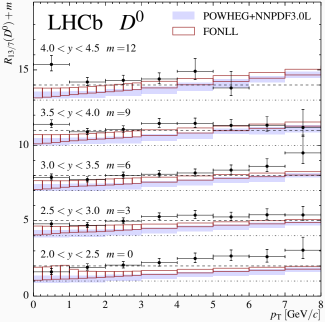
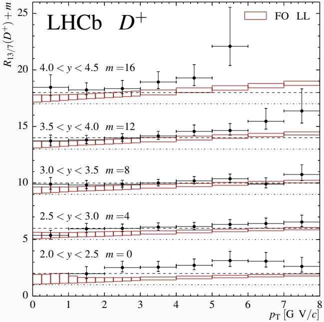
D meson cross-section ratios between energies



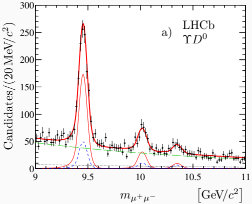
Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV for D^0



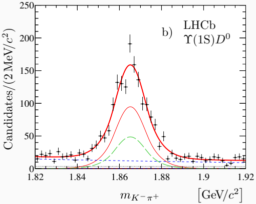
Double differential cross-section ratios between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV for D^+

Recent Run 1 result

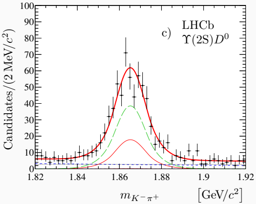
Production of ϒ and open charm hadrons via double parton scattering



ϒ (XS) mass



D^0 mass in the ϒ (1S) region



D^0 mass in the ϒ (2S) region

- 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

LHCb-PAPER-2015-046 arXiv:1510.05949

Summary

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

Questions?