Charmed meson production at LHCb

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Meson 2016, Kraków

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Outline

1. Motivation
2. The LHCb detector
3. J/ψ and D meson production at 13 TeV
4. Associated production of Υ and open charm mesons at 7 and 8 TeV

Motivation

Why measure charm meson cross-sections (at $\sqrt{s} = 13\,\text{TeV}$)?

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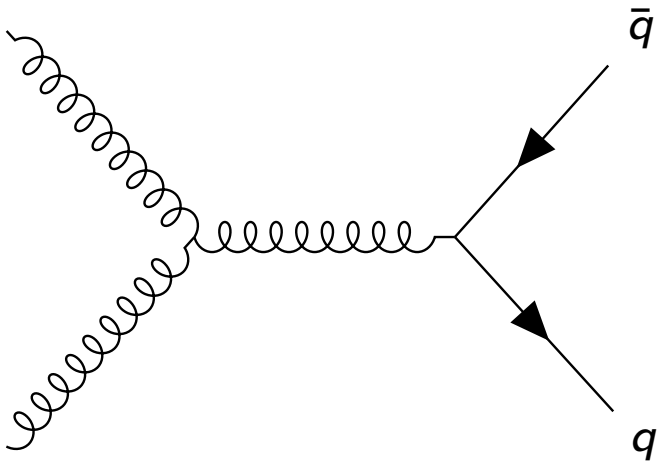
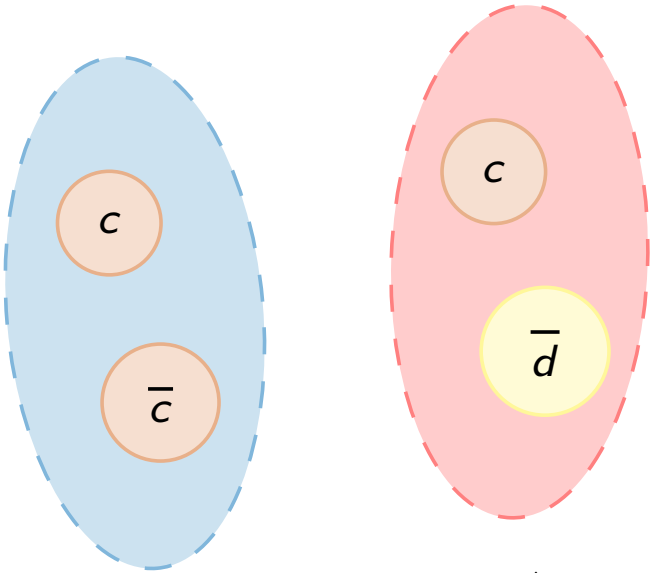
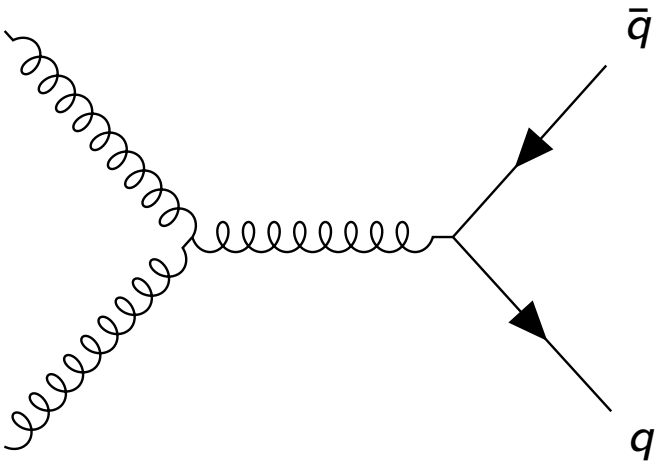


Perturbative QCD



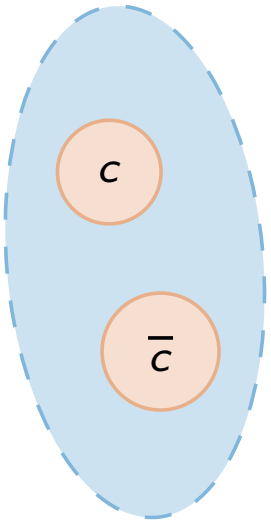
Non-perturbative QCD

Why measure charm meson cross-sections (at $\sqrt{s} = 13\,\text{TeV}$)?

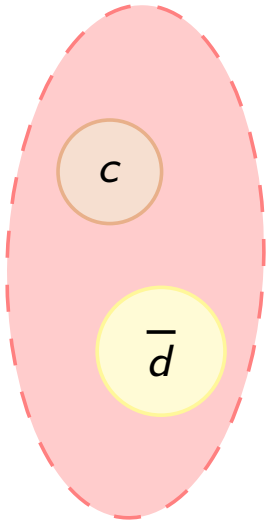


Perturbative QCD

magic



J/ψ



D^+

Non-perturbative QCD

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

Parton distribution functions

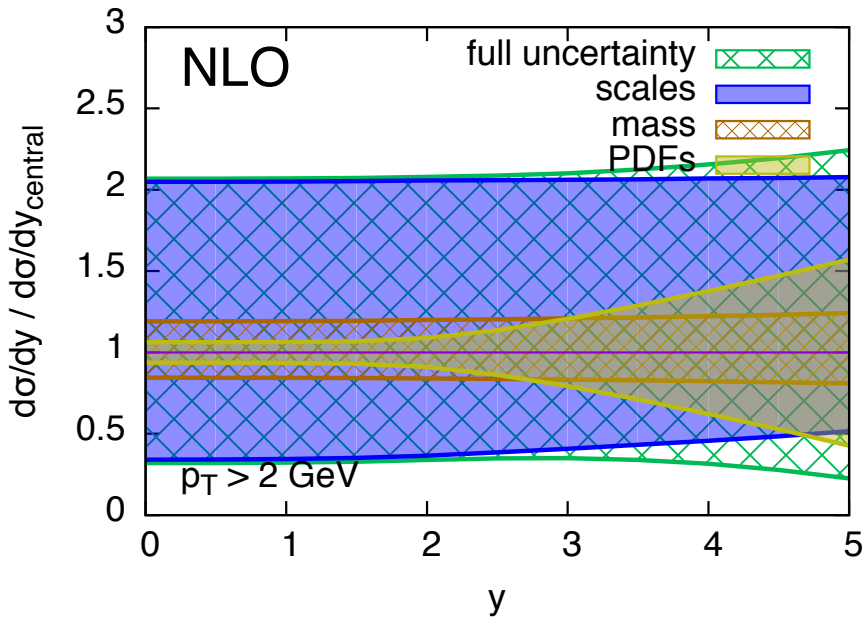
[1] PROSA collaboration, arXiv:1503.04581

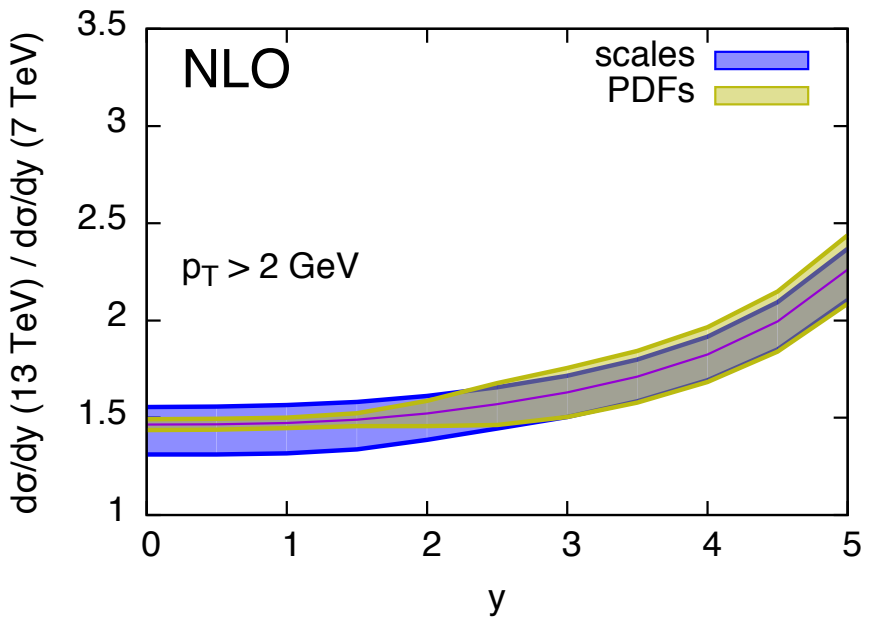
[2] Cacciari et al., Eur. Phys. J. C75 (2015) 610

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]





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

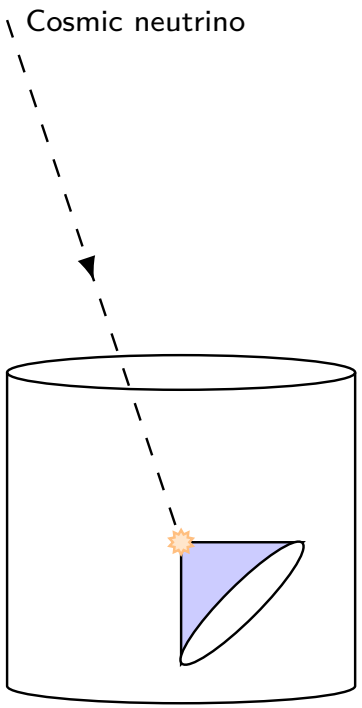
[1] PROSA collaboration, arXiv:1503.04581

[2] Cacciari et al., Eur. Phys. J. C75 (2015) 610

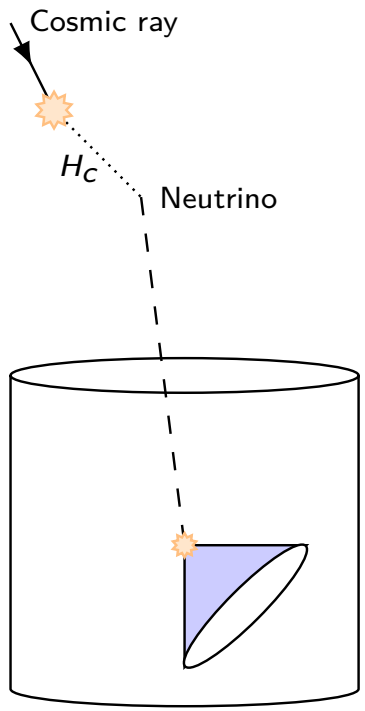
Background in atmospheric neutrino experiments

[1] IceCube collaboration, Phys. Rev. Lett. 113 (2014) 101101

Background in atmospheric neutrino experiments



Signal



Background

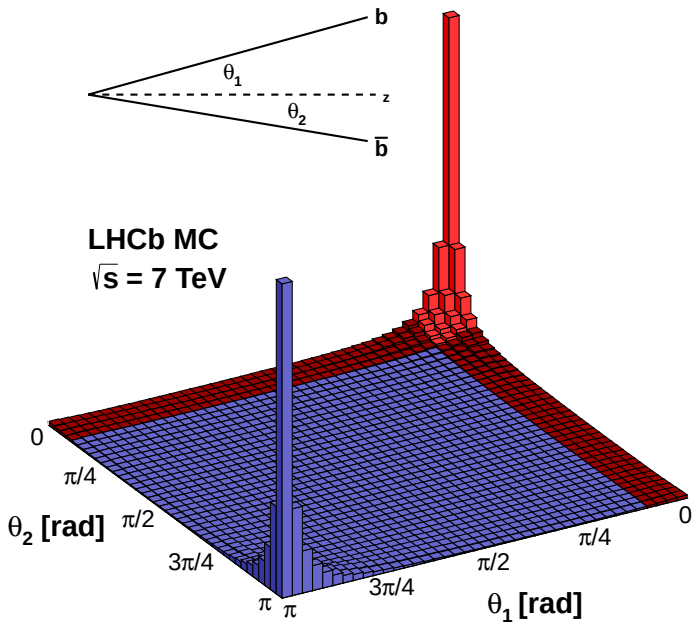
- Production cross-sections can be used to estimate background contributions of neutrino experiments.[1]
- Proton-proton $\sqrt{s} = 13\,\text{TeV}$ is equivalent to a 90 PeV cosmic ray

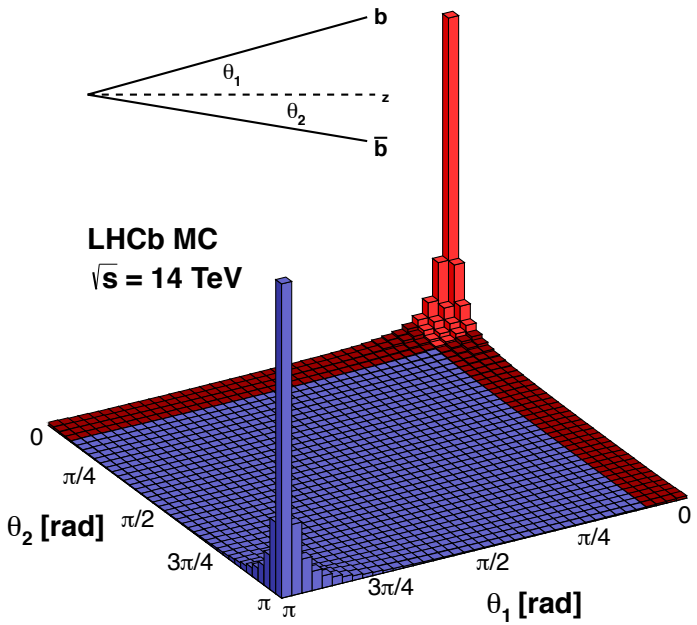
[1] IceCube collaboration, Phys. Rev. Lett. 113 (2014) 101101

Why measure charm production cross-sections at LHCb

[1] lhcb.web.cern.ch: $b\bar{b}$ production angle plots

$b\bar{b}$ opening angles[1]





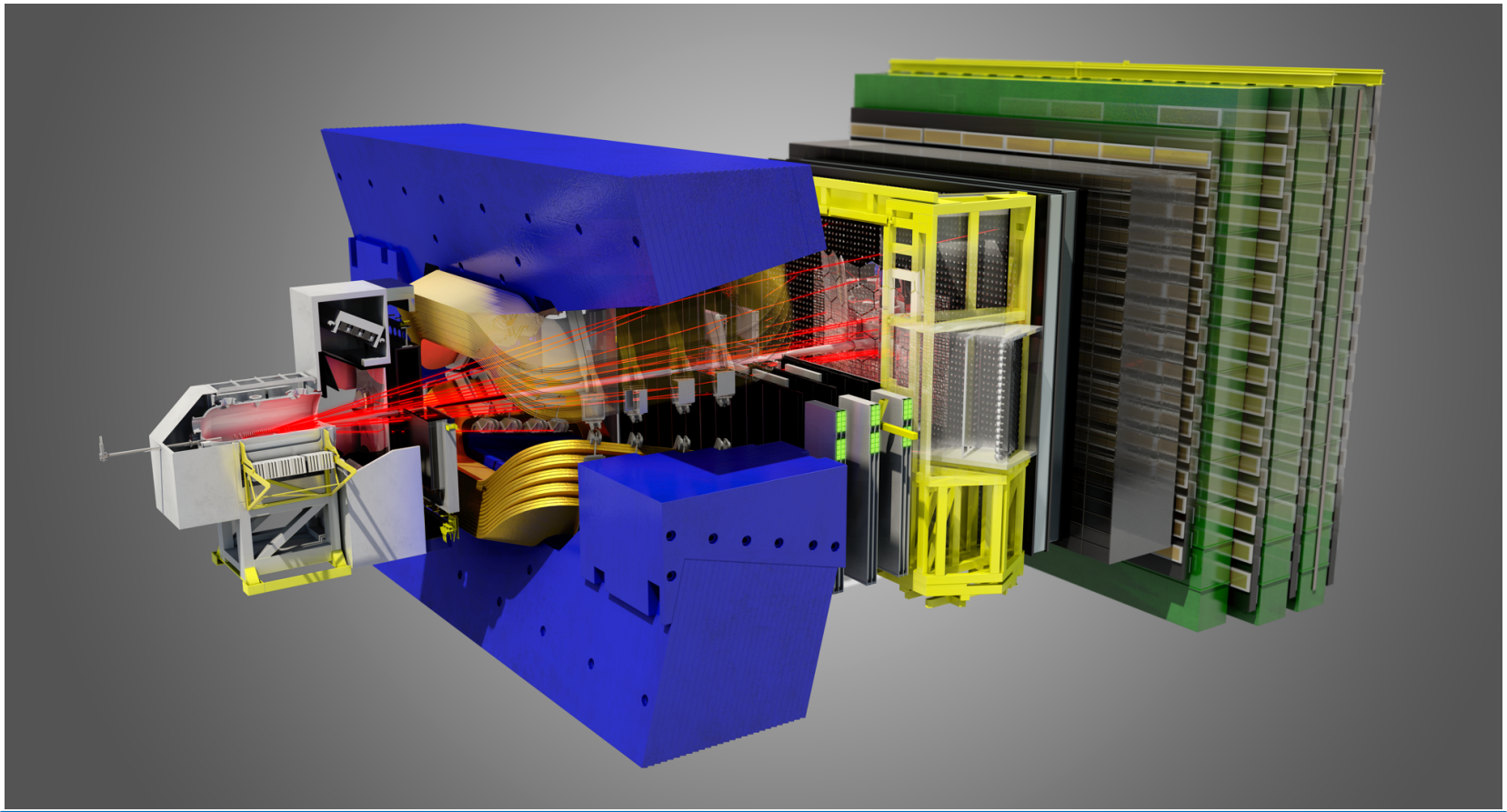
- Production peaks in the LHCb acceptance.

[1] lhcb.web.cern.ch: $b\bar{b}$ production angle plots

The LHCb detector

The LHCb detector

JINST 3 S08005 (2008)



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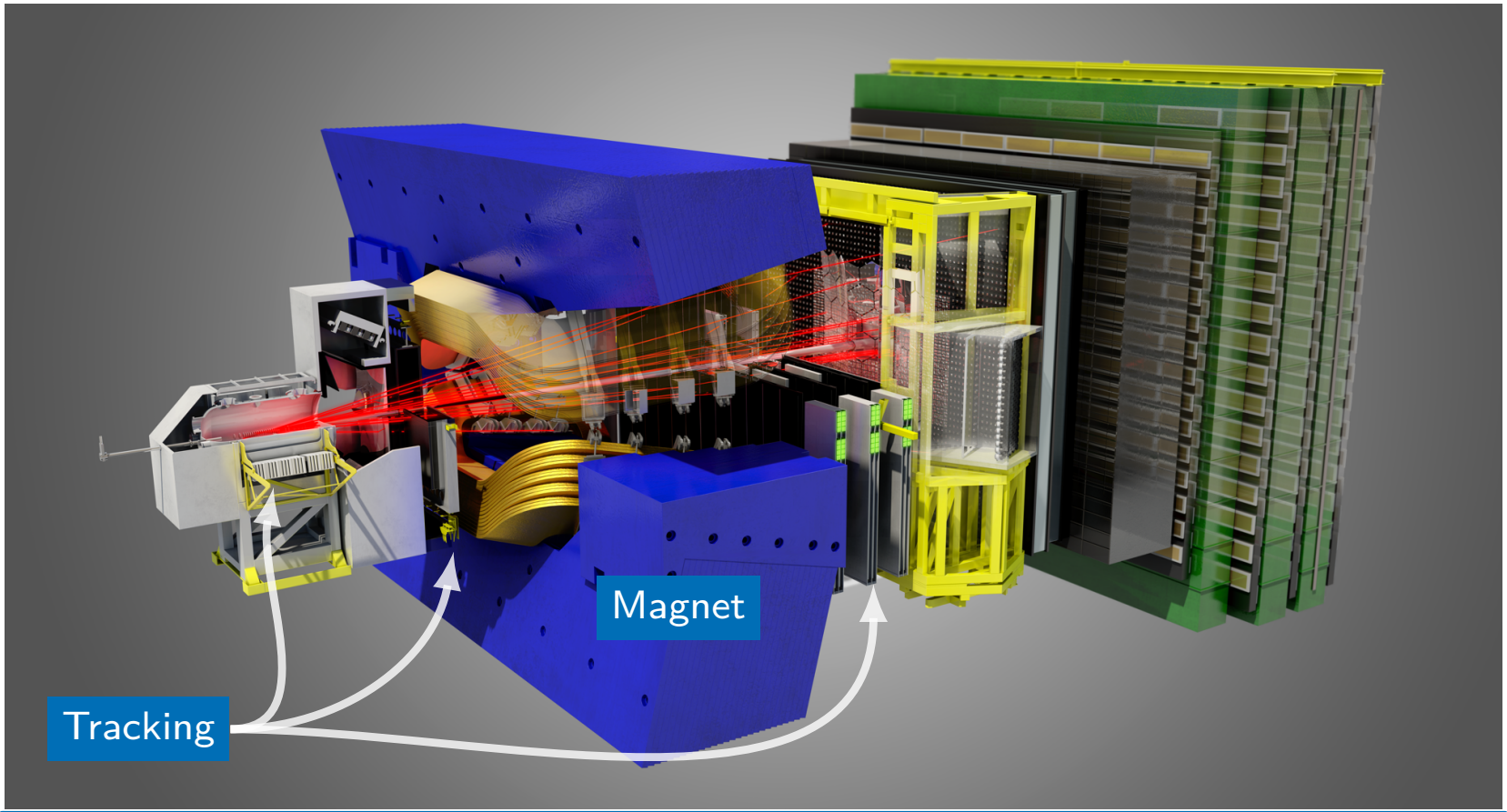

VELO Primary and secondary vertex, impact parameter

TT, IT, OT Momentum of charged particles

The LHCb detector

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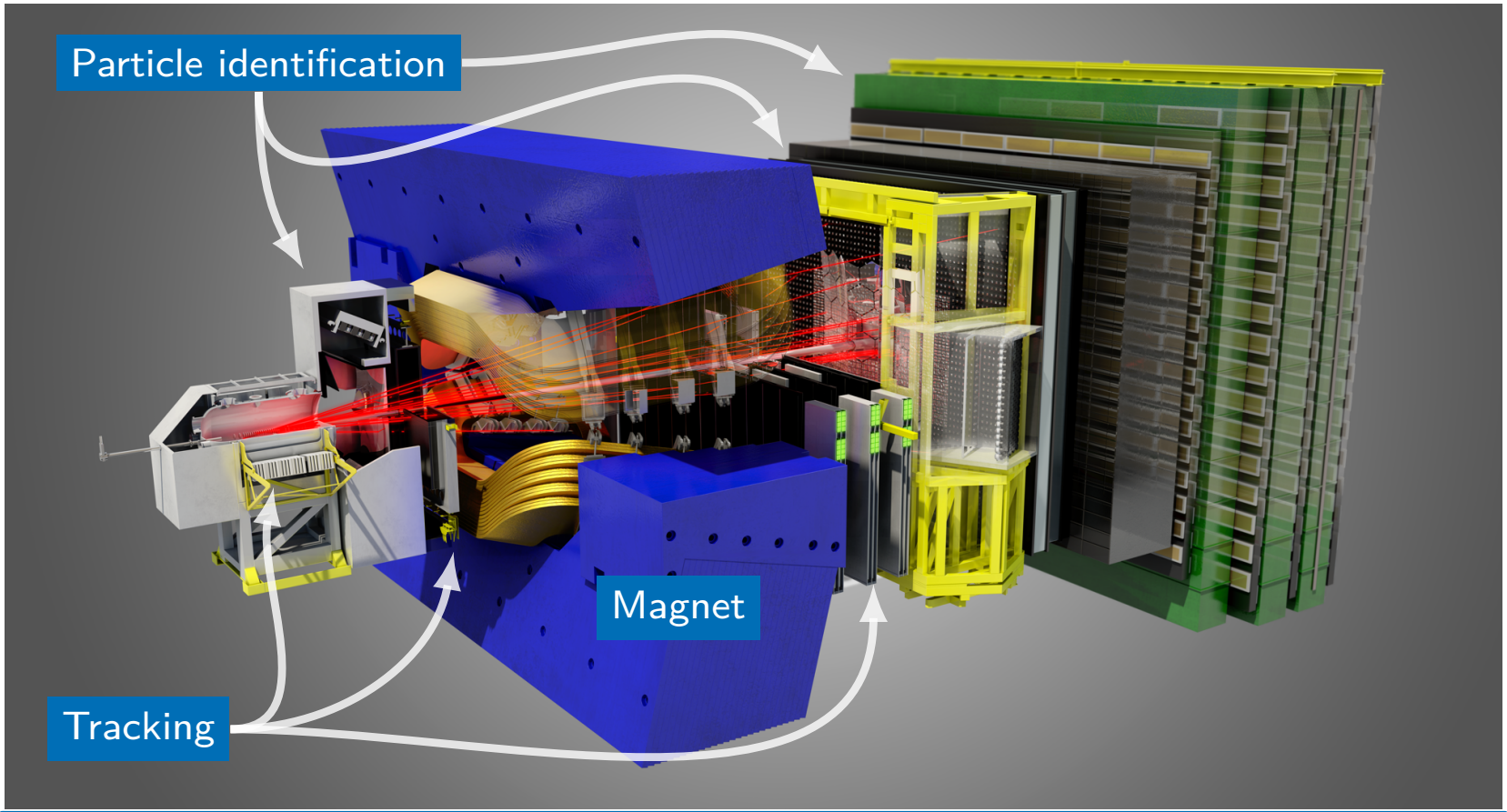

VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID
MUON	Trigger on high p_T $\mu^{\pm}$, add PID

The LHCb detector

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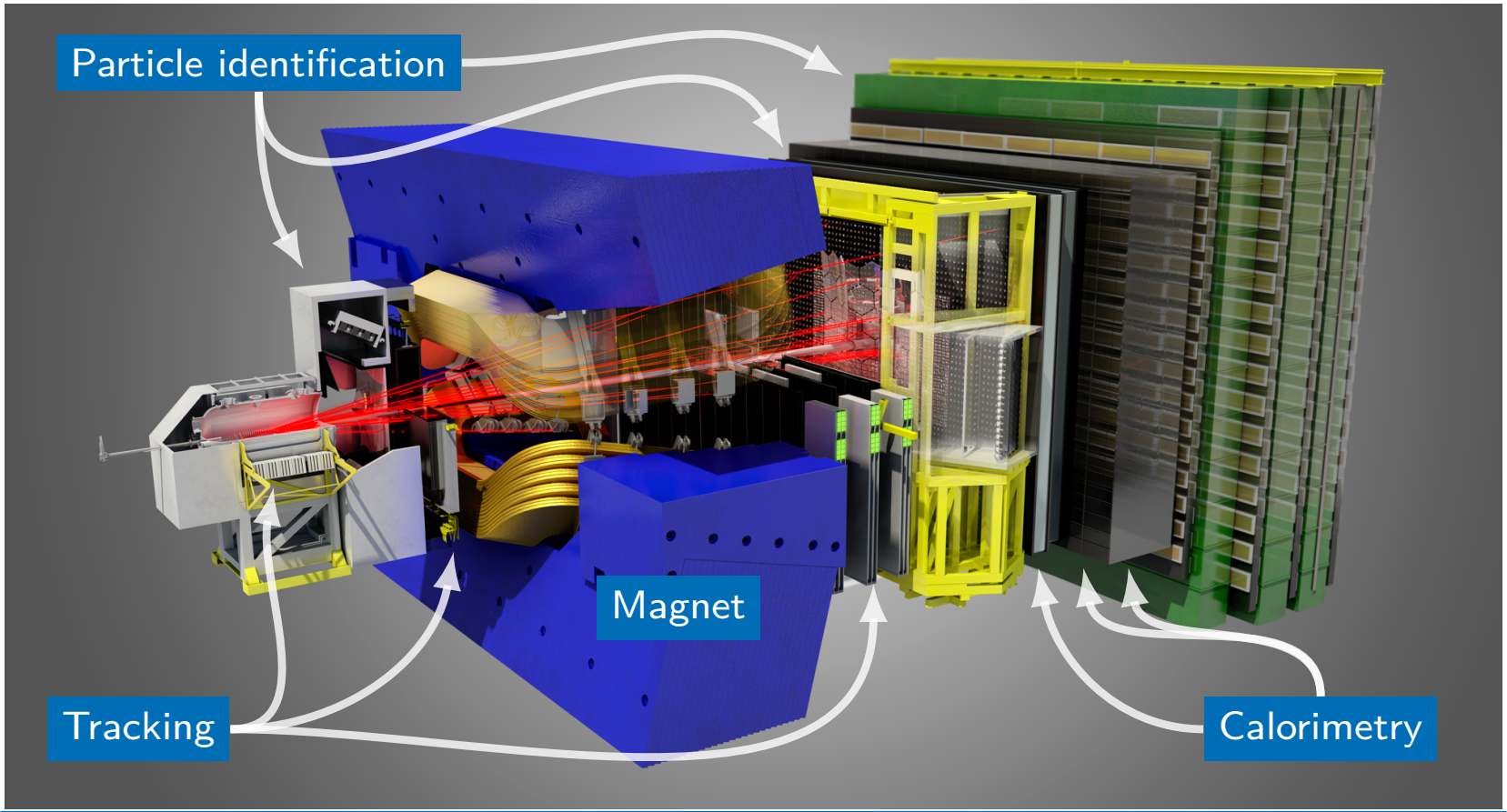


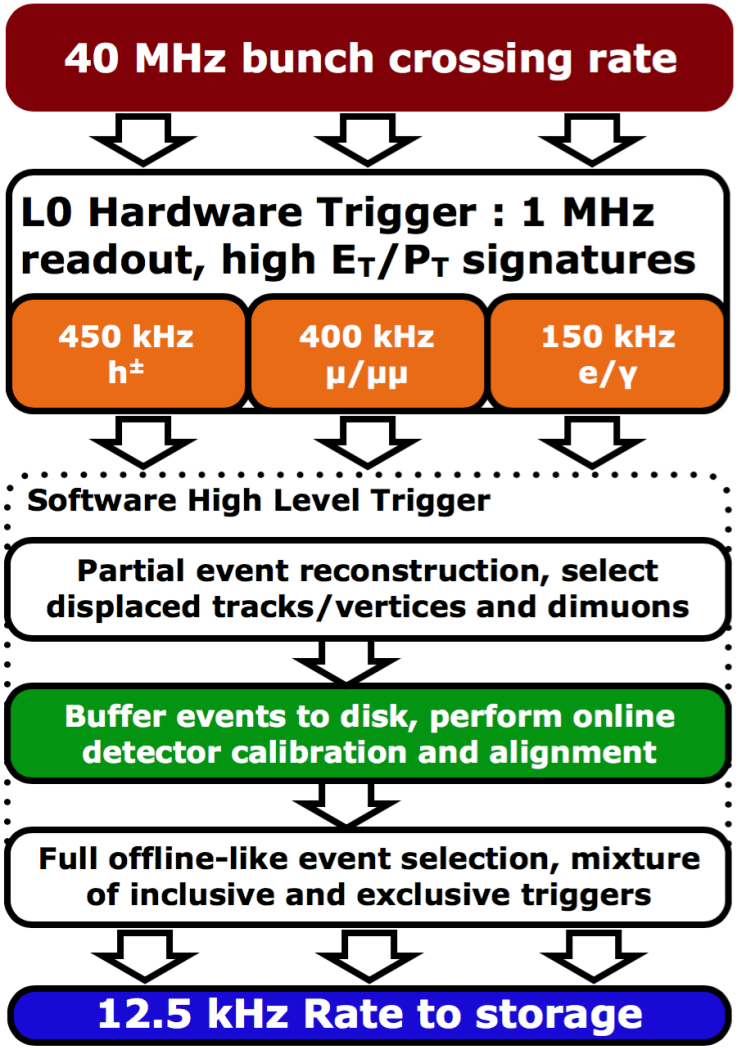
VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID
MUON	Trigger on high p_T $\mu^{\pm}$, add PID
SPD/PS	Separate $\gamma/e^{\pm}$ and $h^{\pm}/e^{\pm}$
ECAL/HCAL	EM/hadronic energy

Real time detector alignment and calibration[1]

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

Turbo stream[2]

- 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.



[1] G. Dujany et al., LHCb-PROC-2015-011

[2] R. Aaij et al., arXiv:1604.05596

J/ψ and D meson production at $\sqrt{s} = 13\,\mathrm{TeV}$

Measurement overview

[1] LHCb collaboration, JHEP 1302 (2013) 041
[2] LHCb collaboration, Eur.Phys.J.C71 (2011) 1645
[3] LHCb collaboration, J. High Energy Phys. 06 (2013) 064
[4] LHCb collaboration, Nuclear Physics, Section B 871 (2013), pp. 1-20

Measurement overview

Double differential cross-sections for different charm mesons H_c:

$$\frac{\mathrm{d}^2\sigma_i(H_c)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y} = \frac{1}{\Delta p_\mathrm{T}\Delta y}\cdot\frac{N_i(H_c\to f)}{\varepsilon_{i,\mathrm{tot}}(H_c\to f)\Gamma(H_c\to f)\mathcal{L}_\mathrm{int}} \text{ with } y = \frac{1}{2}\ln\frac{E+p_z c}{E-p_z c}$$

- Prompt and from b decays J/ψ 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]

[1] LHCb collaboration, JHEP 1302 (2013) 041
[2] LHCb collaboration, Eur.Phys.J.C71 (2011) 1645
[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[1]

- Used $3\,\text{pb}^{-1}$ of luminosity.
- Final state: $J/\psi \to \mu^-\mu^+$.

Charm production measurement[2]

- Used $5\,\text{pb}^{-1}$ of luminosity.
- Final states: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+$ with $\phi \to K^-K^+$ and $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$.

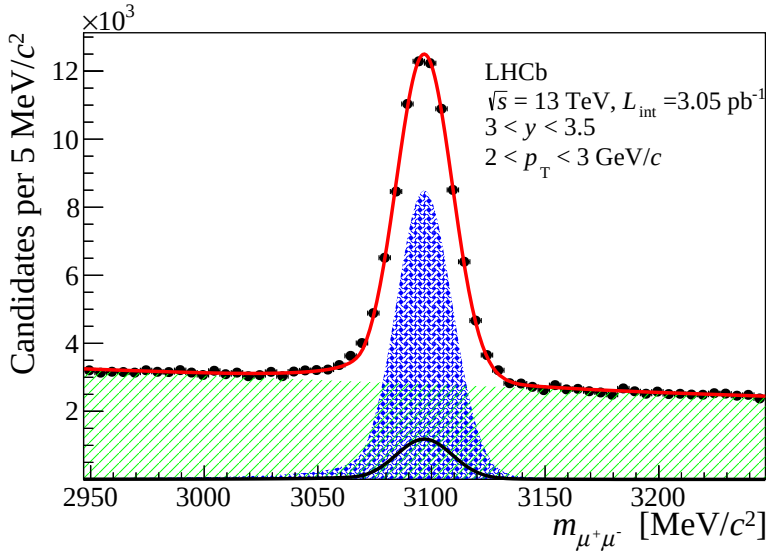
- Event selection relies on kinematic and quality cuts on the reconstructed tracks in the detector as well as requirements on the vertices.

[1] LHCb collaboration, JHEP10 (2015) 172
[2] LHCb collaboration, JHEP03 (2016) 159

Number of signal events

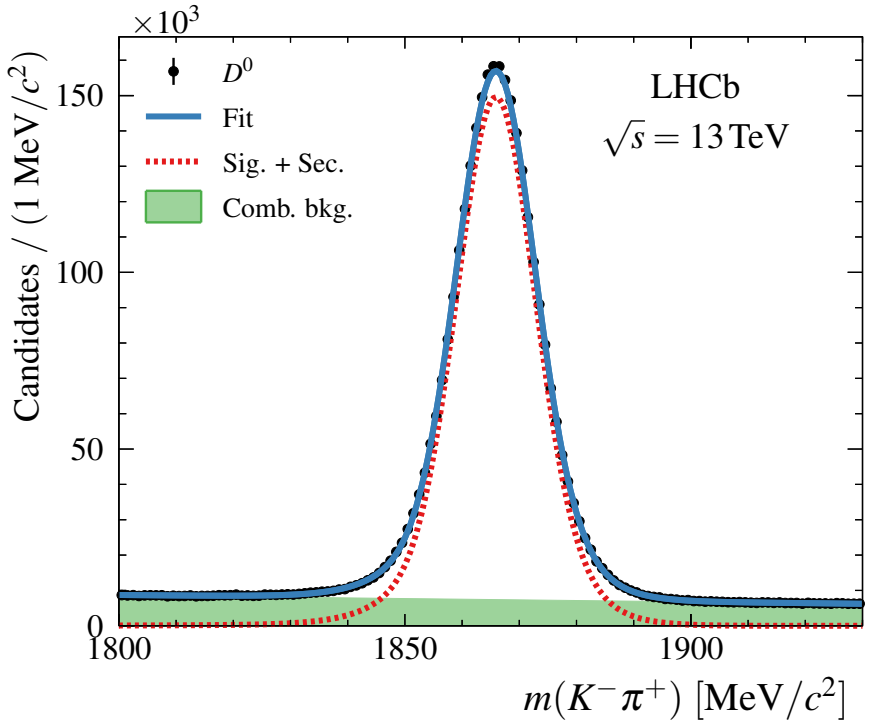
- Total number of signal events obtained by fitting the invariant mass of the combined final state particles

$J/\psi \to \mu^- \mu^+$



LHCb collaboration, JHEP10 (2015) 172

$D^0 \to K^- \pi^+$

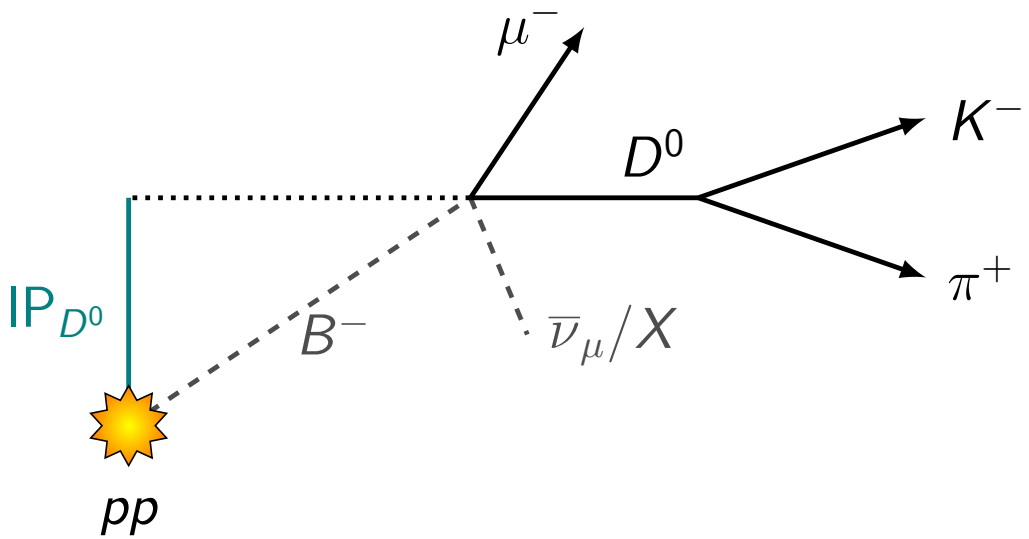


LHCb collaboration, JHEP03 (2016) 159

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:



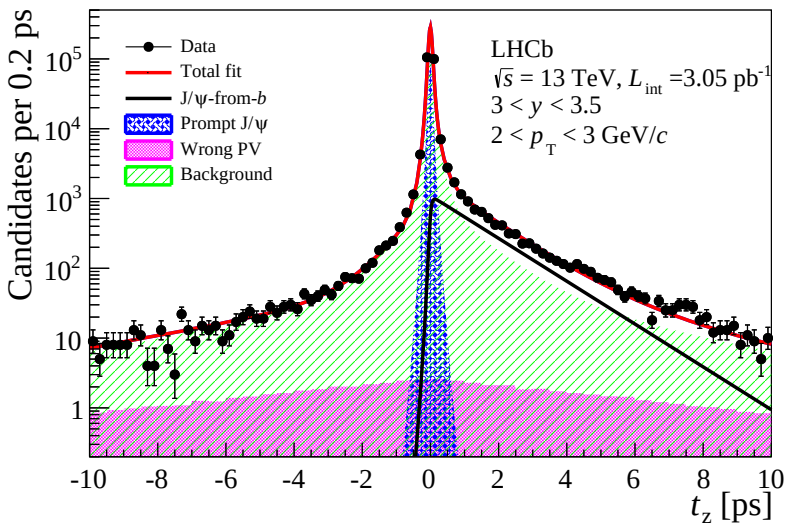
- J/ψ decays instantenously, life-time has to agree with zero:

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

- Both methods are smeared due to resolution effects.

Number of signal events

$J/\psi \to \mu^- \mu^+$



LHCb collaboration, JHEP10 (2015) 172

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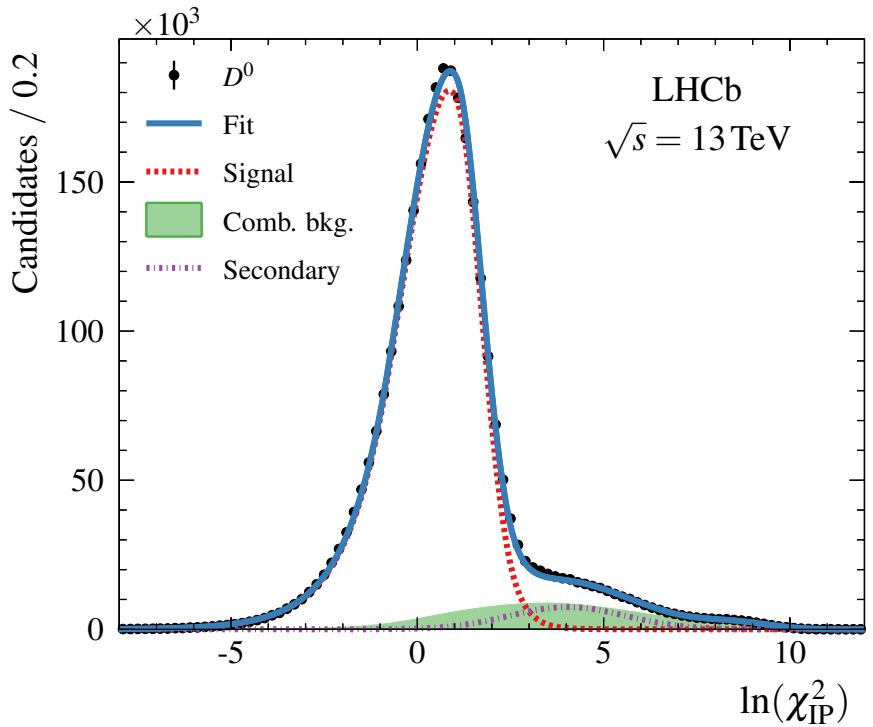


LHCb collaboration, JHEP03 (2016) 159

- For the J/ψ, 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/ψ

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]

[1] Shao et al., JHEP05 (2015) 103

[2] Cacciari et al., JHEP10 (2012) 137

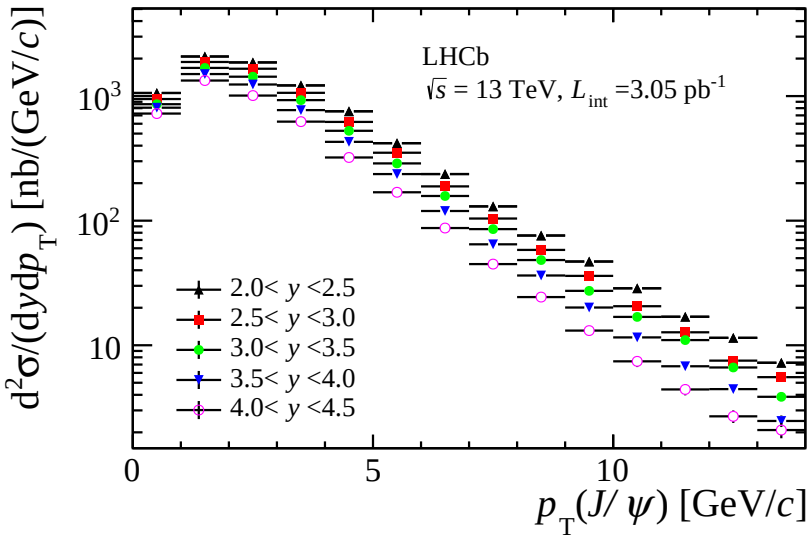
J/ψ cross-sections at 13 TeV

LHCb collaboration, JHEP10 (2015) 172

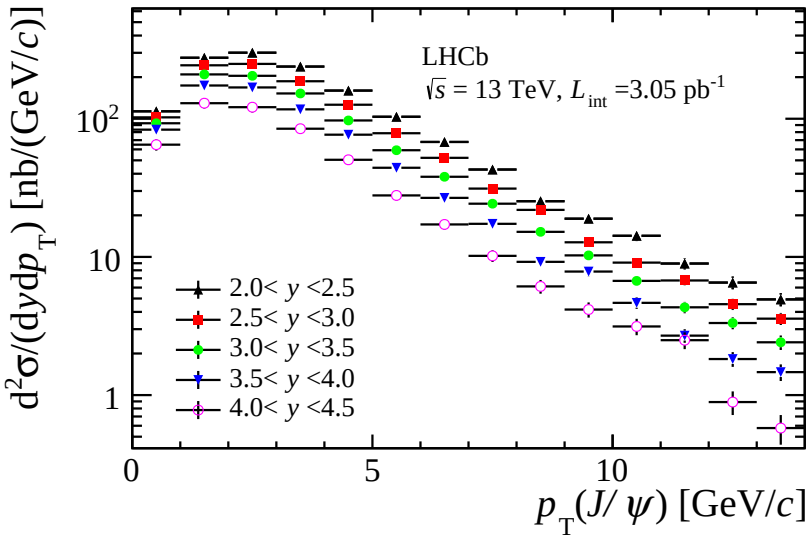
J/ψ cross-sections at 13 TeV

LHCb collaboration, JHEP10 (2015) 172

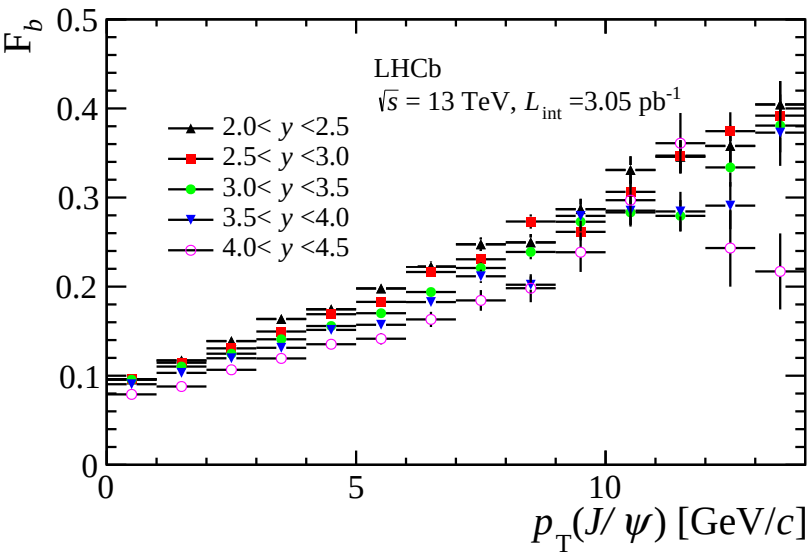
prompt J/ψ



J/ψ from b



J/ψ from b fraction



In LHCb acceptance:

$$\sigma_{\text{Prompt}} = 15.30 \pm 0.03\,(\text{stat}) \pm 0.86\,(\text{sys})\ \mu\text{b}$$
$$\sigma_{\text{from-}b} = 2.34 \pm 0.01\,(\text{stat}) \pm 0.13\,(\text{sys})\ \mu\text{b}$$

J/ψ cross-sections at 13 TeV- theory comparison

LHCb collaboration, JHEP10 (2015) 172

[1] Shao et al., JHEP05 (2015) 103

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J/ψ cross-sections at 13 TeV- theory comparison

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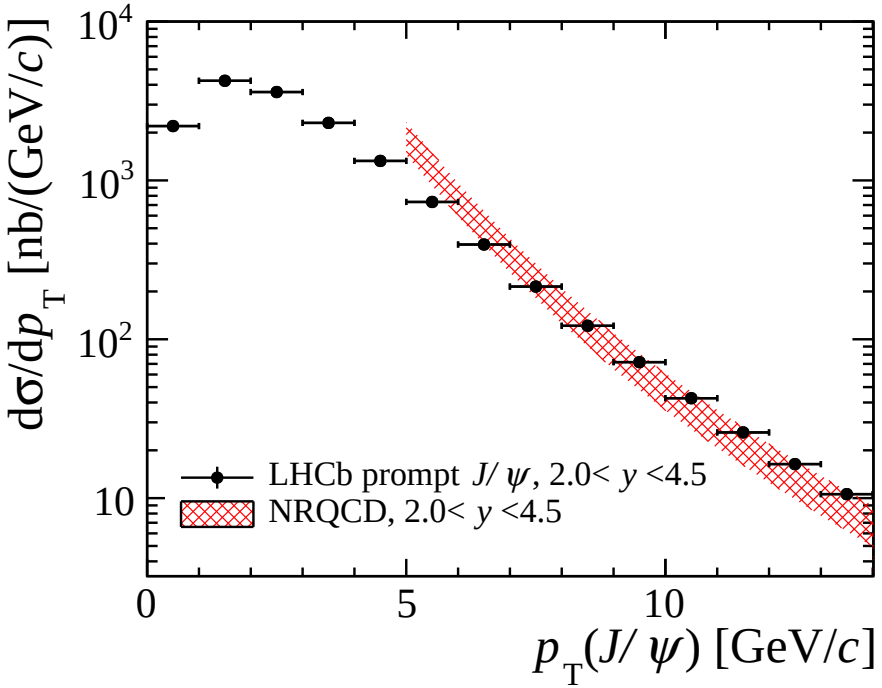
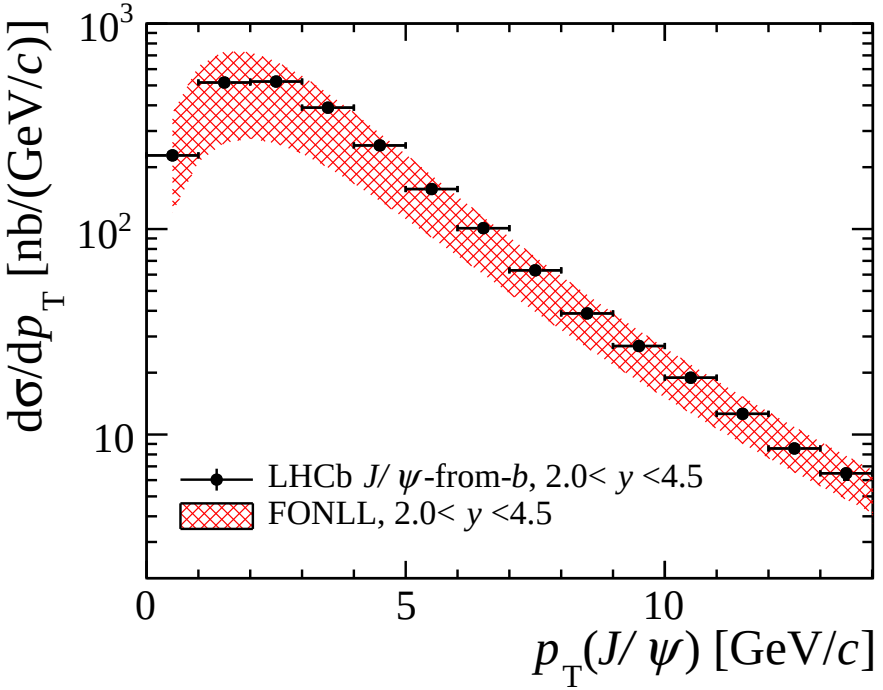
prompt J/ψ



J/ψ from b



- Compared to theoretical predictions:

  NRQCD non-relativistic QCD[1]

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J/ψ cross-sections - 13 to 8 TeV ratio

LHCb collaboration, JHEP10 (2015) 172

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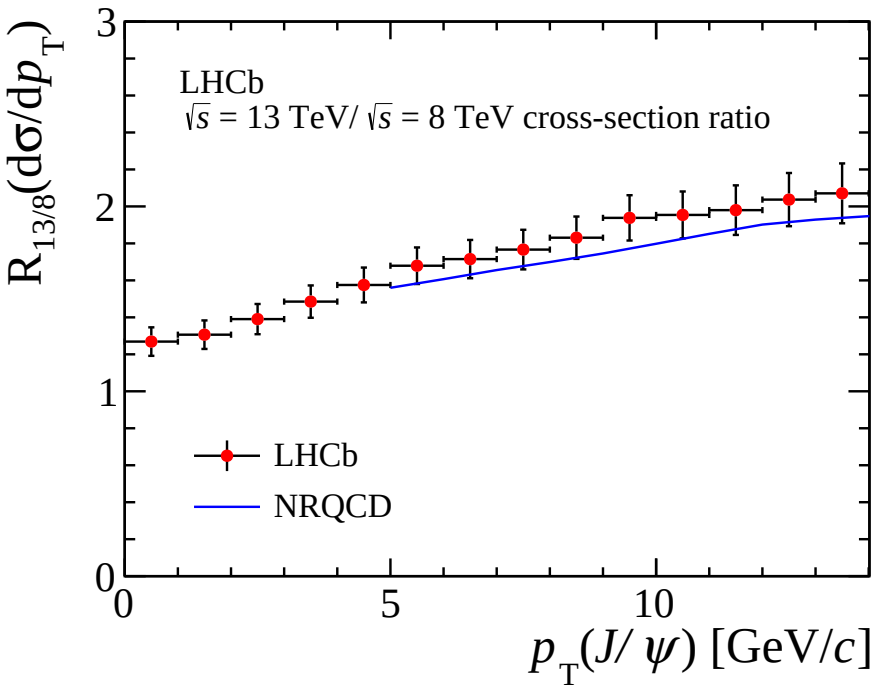

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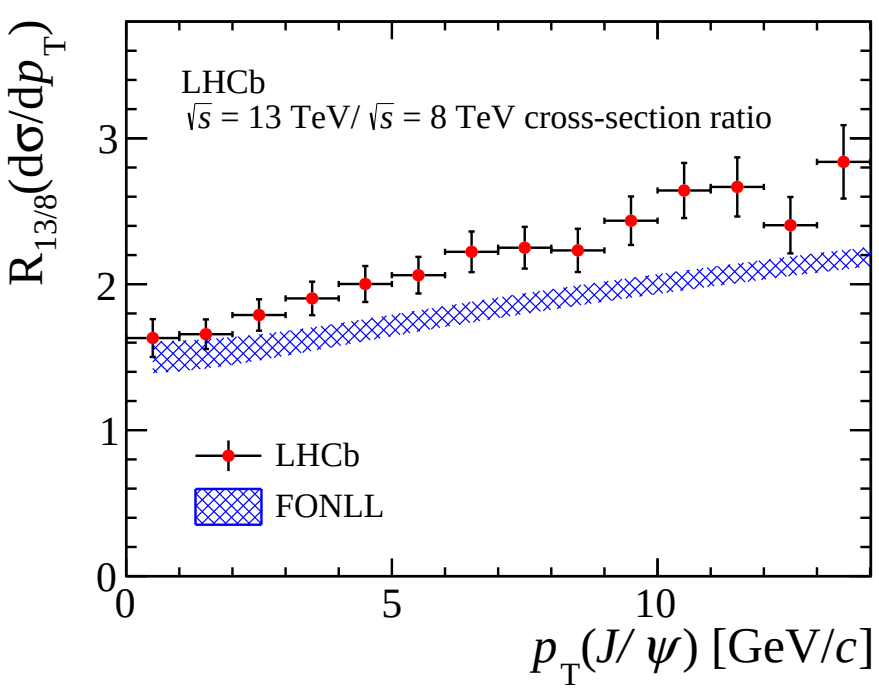

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[2] Cacciari et al., JHEP10 (2012) 137

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.
- Esimates for $c\bar{c}$ cross-sections using fragmentation fractions.[1]

Dominant systematic uncertainties

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

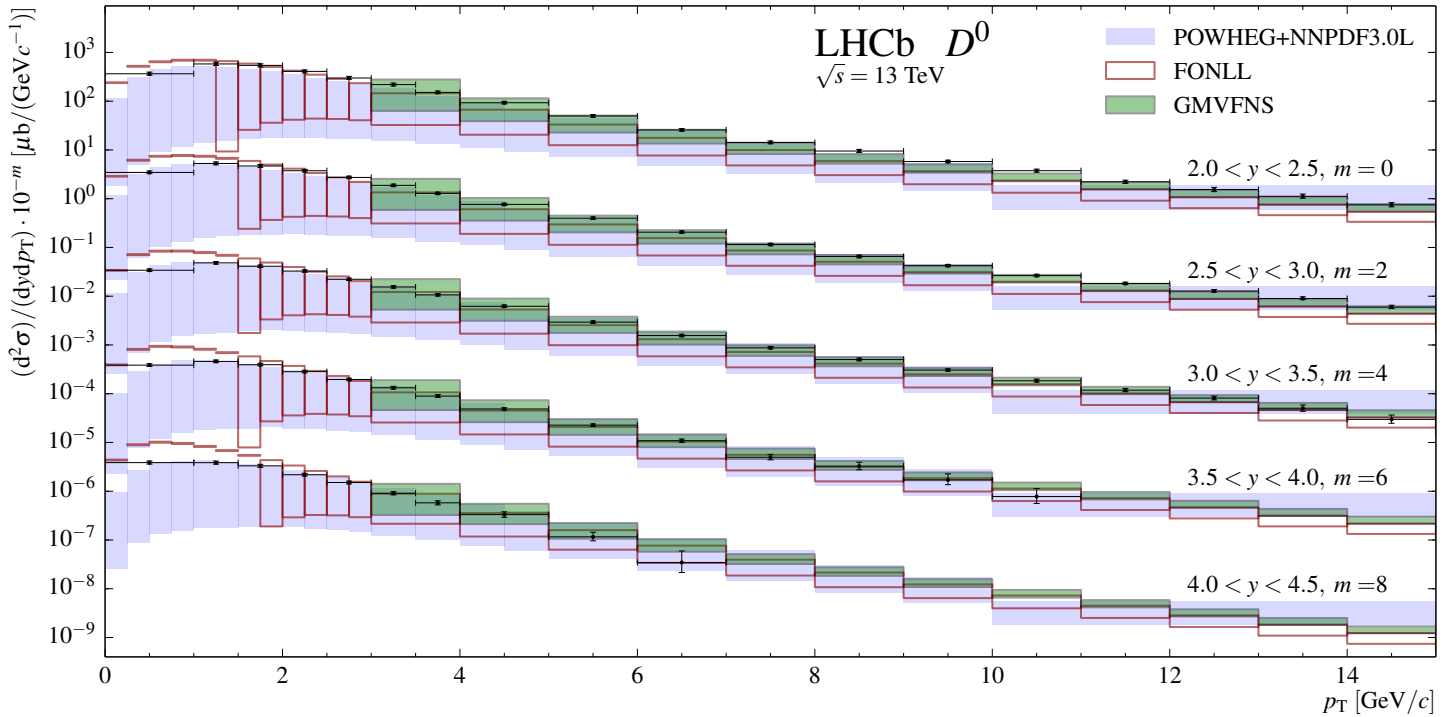
- Compared to theoretical predictions:

  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]

[1] Particle Data Group collaboration et al., Phys. Lett. B 667 (2008) 1
[2] Cacciari et al., Eur. Phys. J. C75 (2015) 610
[3] Spiesberger et al., Eur. Phys. J. C72 (2012) 2082
[4] Gauld et al., JHEP11 (2015) 9

D^0 meson cross-sections

LHCb collaboration, JHEP03 (2016) 159



$$\sigma(D^0)_{1<p_\mathrm{T}<8\,\mathrm{GeV}} = 2460 \pm 3(\mathrm{stat}) \pm 130(\mathrm{syst})\,\mu\mathrm{b}$$

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]

[1] Cacciari et al., Eur. Phys. J. C75 (2015) 610

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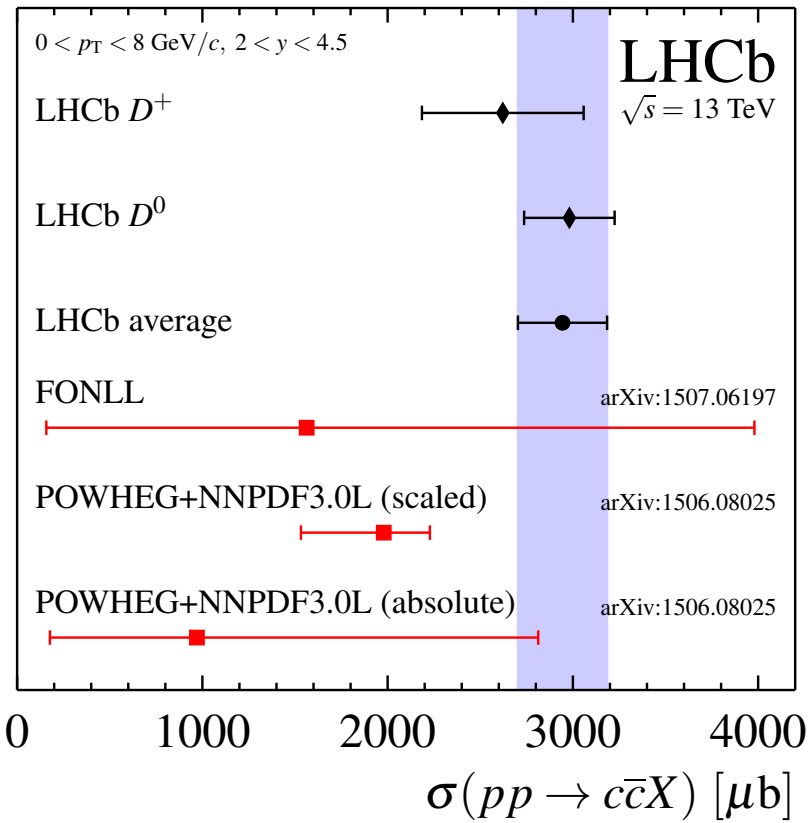
[3] Gauld et al., JHEP11 (2015) 9

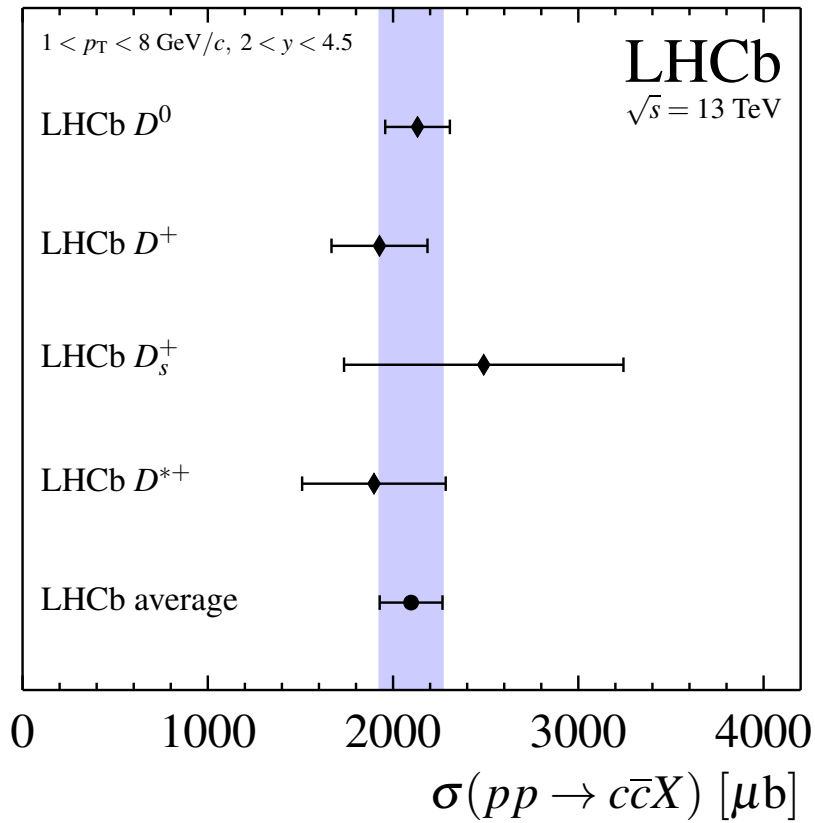
$c\bar{c}$ cross-section estimate

LHCb collaboration, JHEP03 (2016) 159

$0 < p_T < 8\,\text{GeV}$

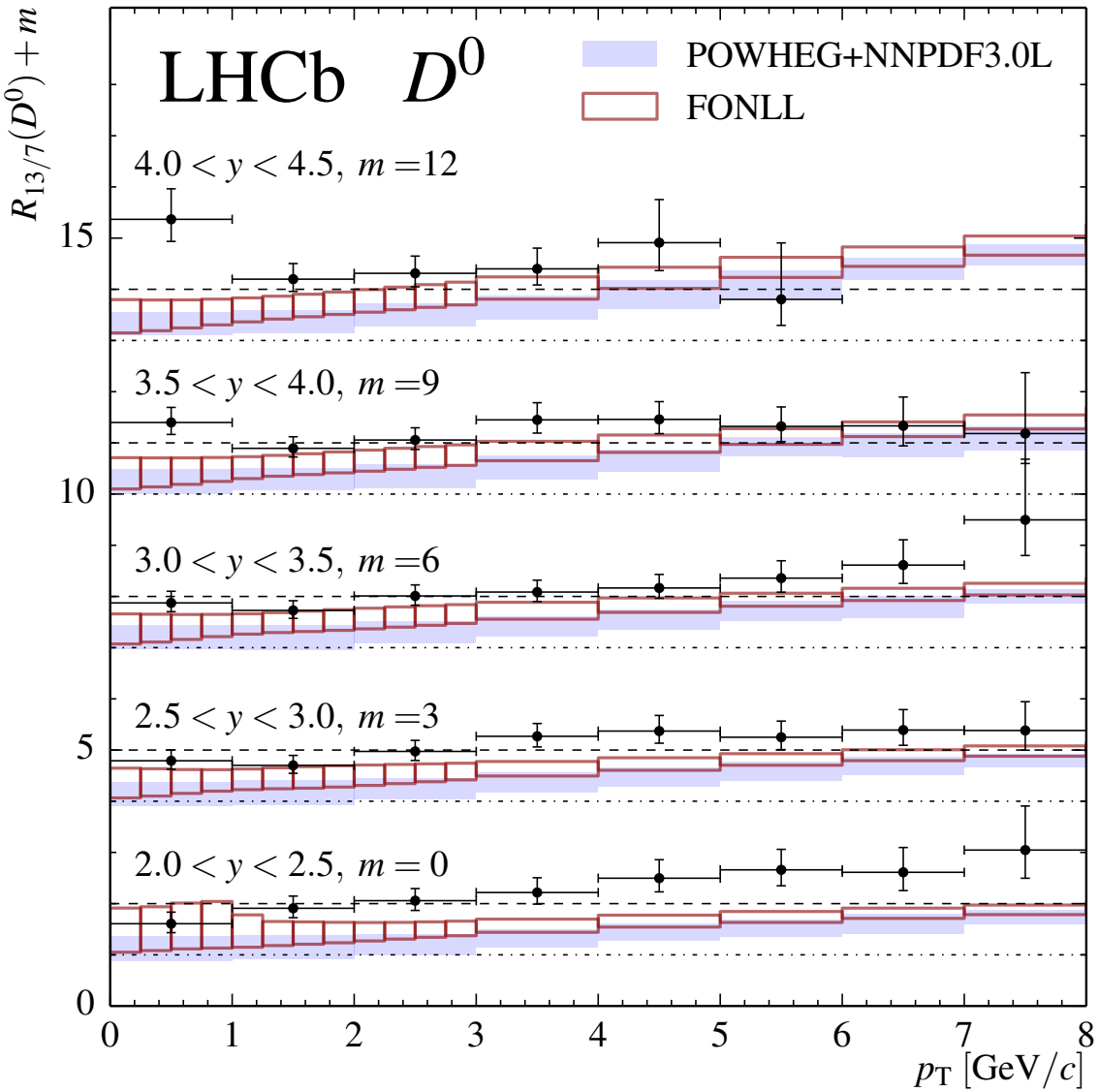


$1 < p_T < 8\,\text{GeV}$



D meson 13 to 7 TeV ratios

LHCb collaboration, JHEP03 (2016) 159

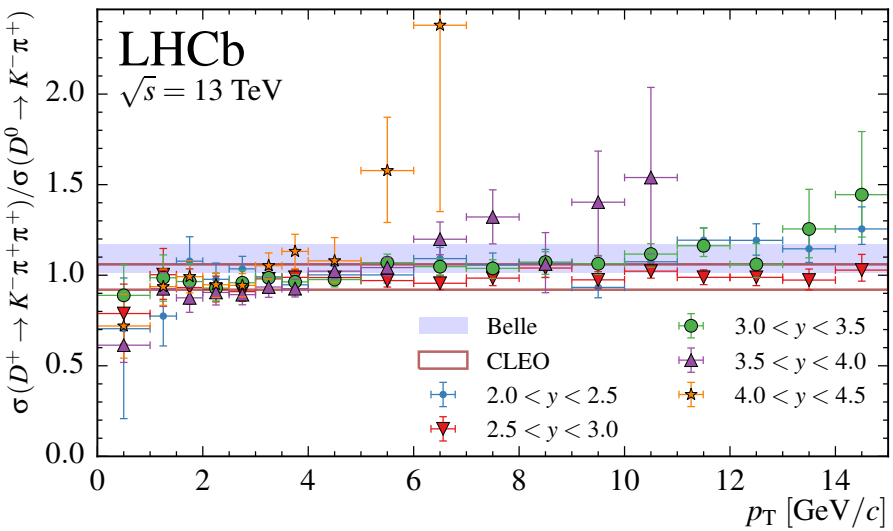


Ratios between different mesons

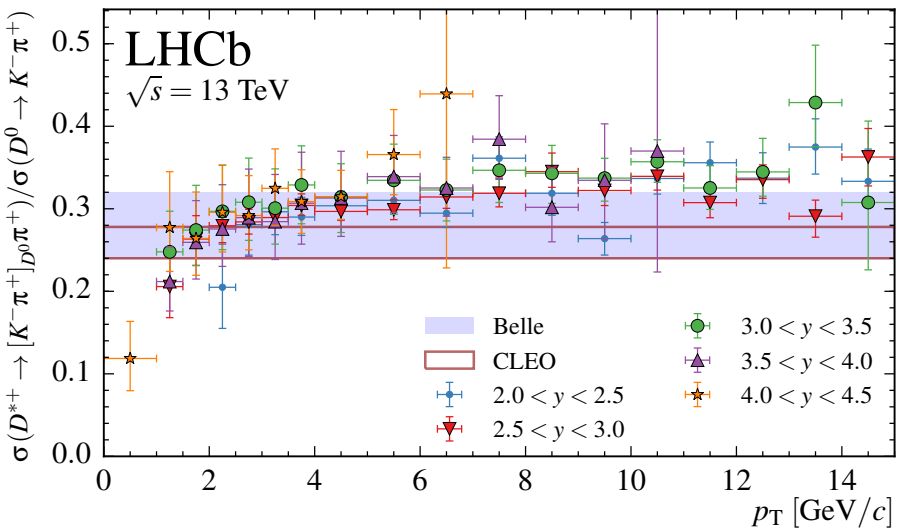
LHCb collaboration, JHEP03 (2016) 159

- 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



[1] Cleo collaboration, Phys. Rev. D 70 (2004) 112001
[2] Belle collaboration, Phys. Rev. D 73 (2006) 032002
[3] Babar collaboration, Phys. Rev. D 65 (2002) 091104

Associated production of Υ 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
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LHCb collaboration, arXiv:1510.05949

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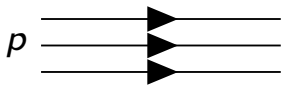

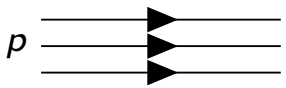

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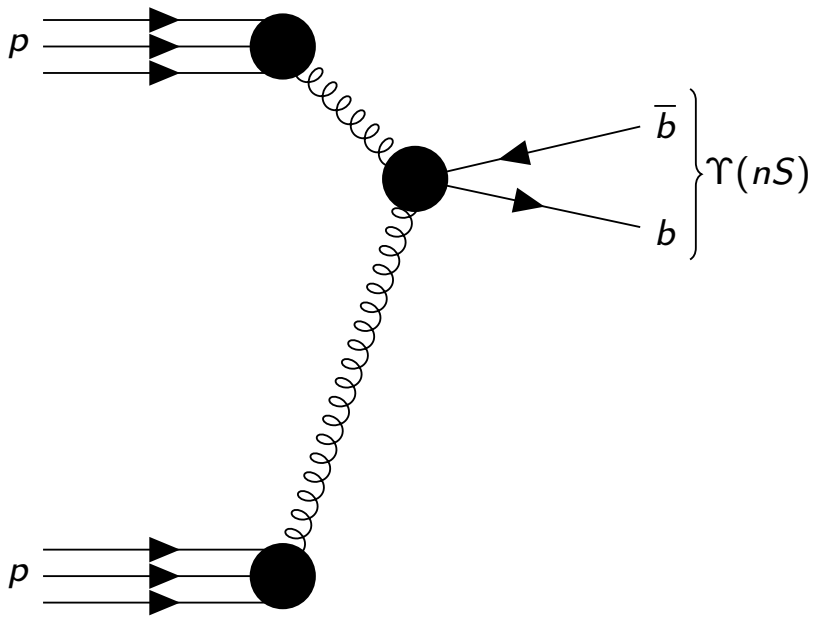

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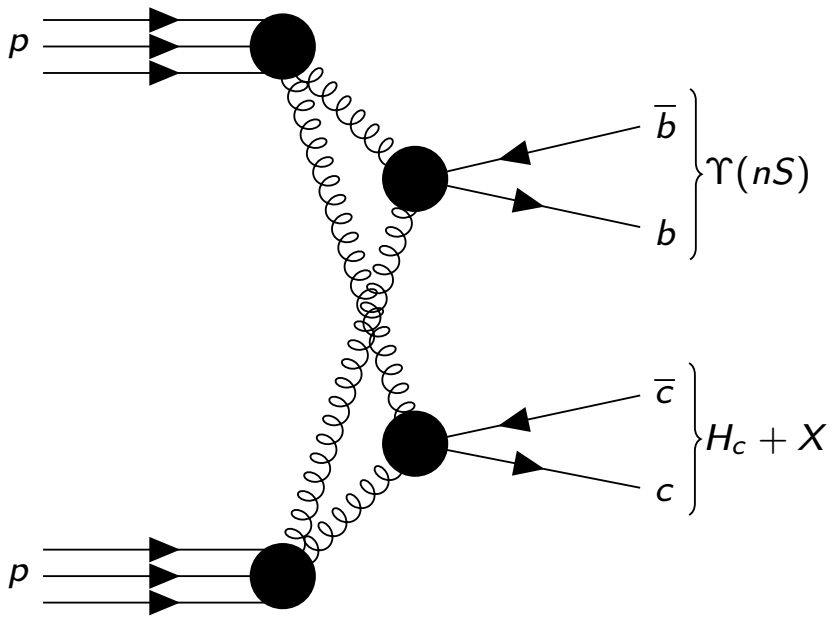

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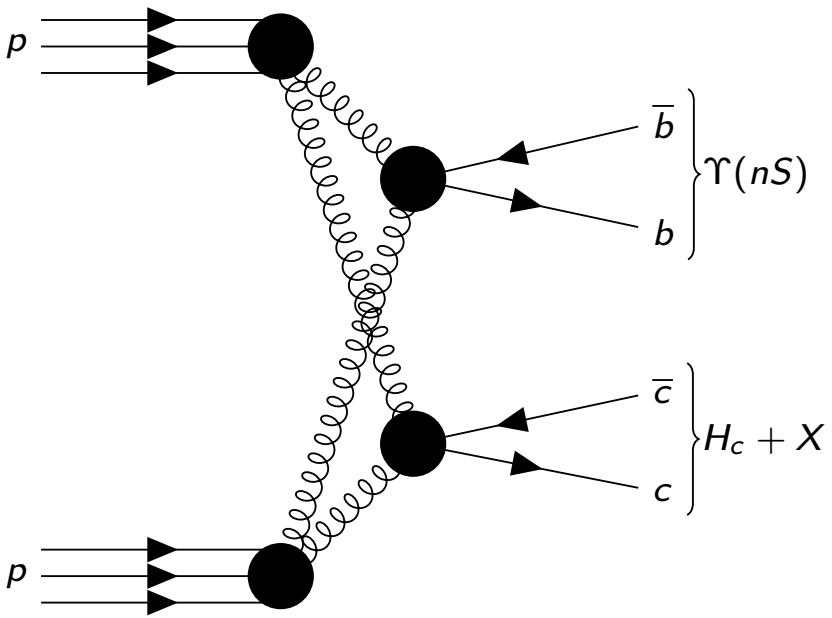

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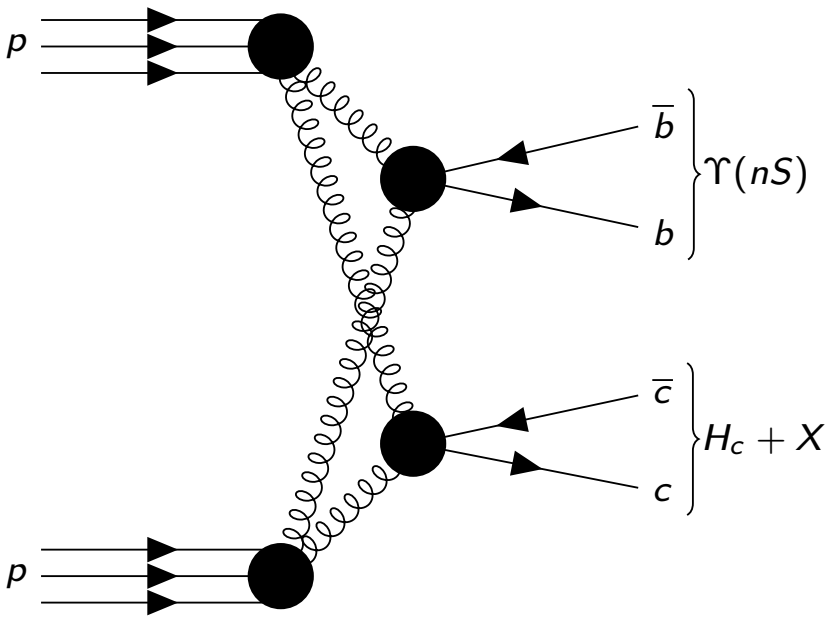

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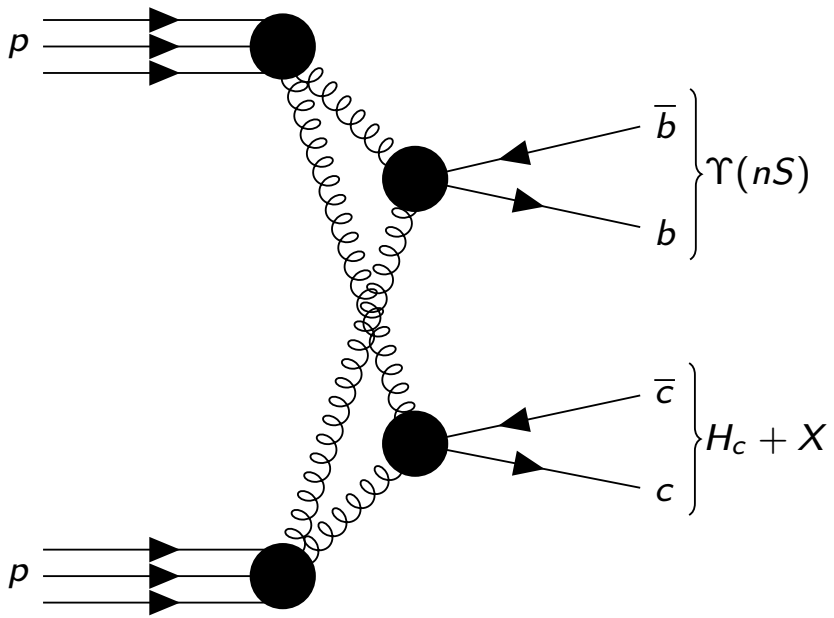

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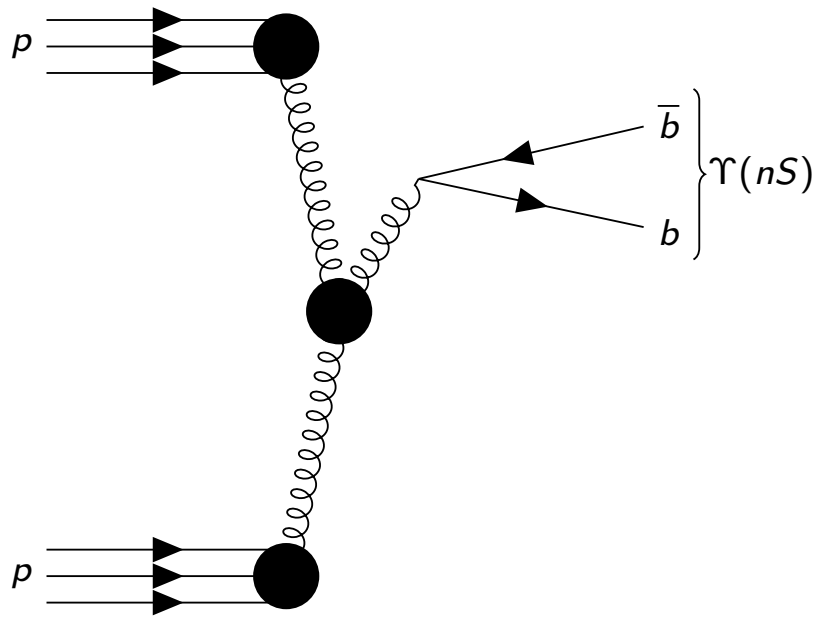

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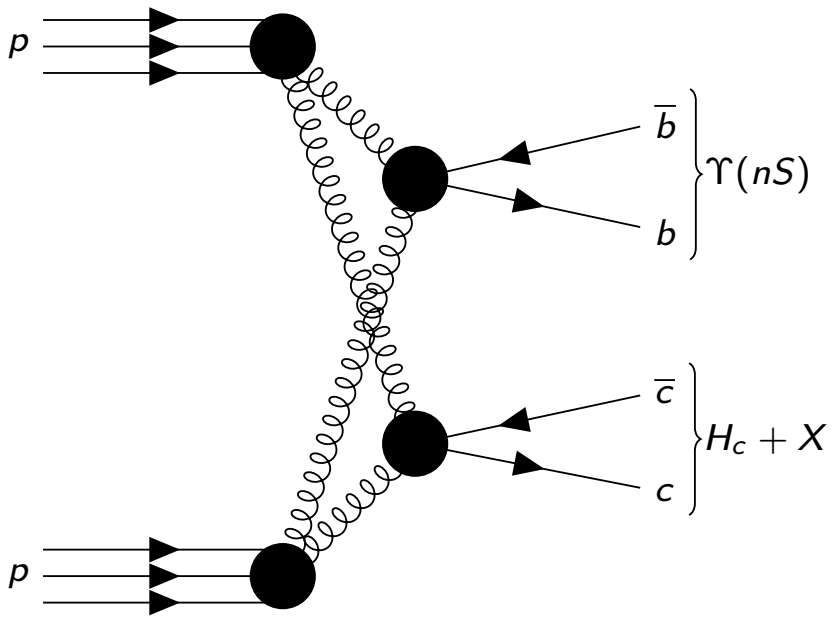

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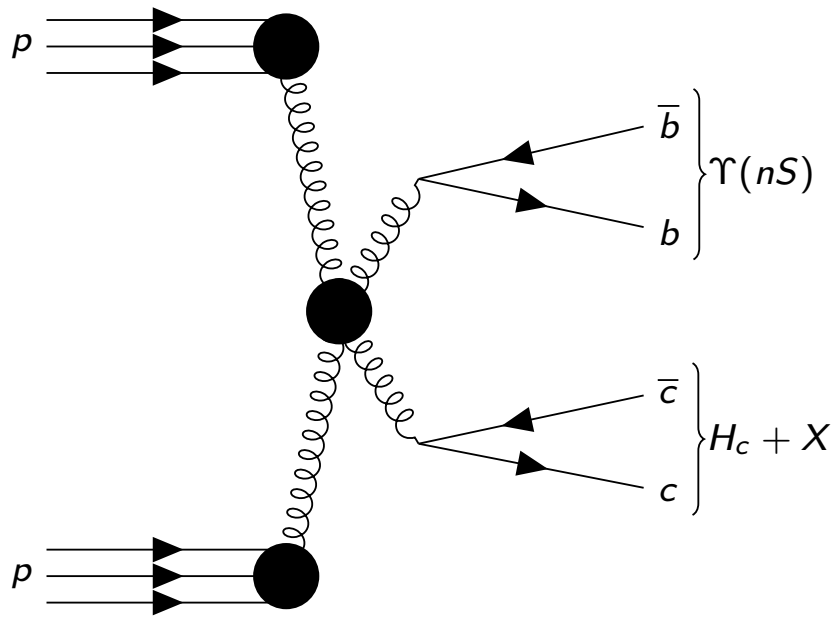

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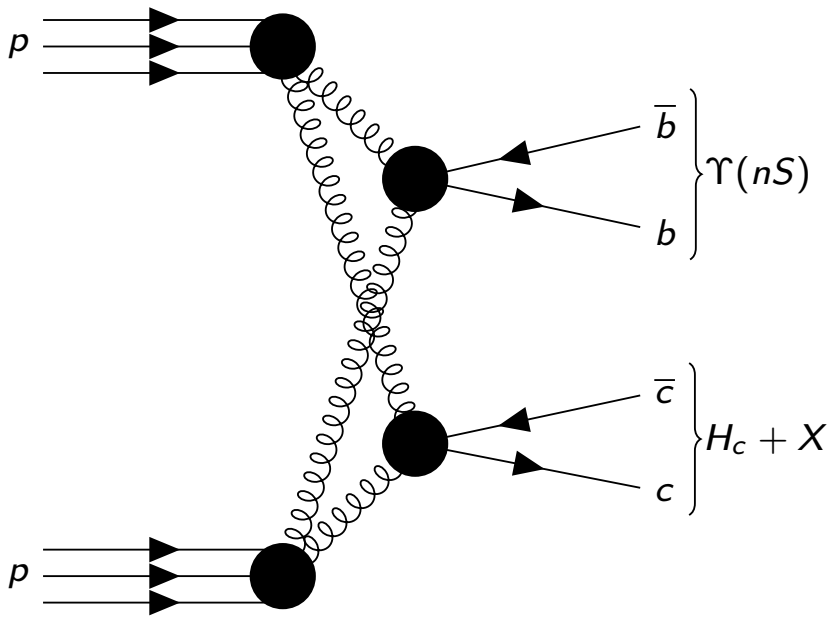

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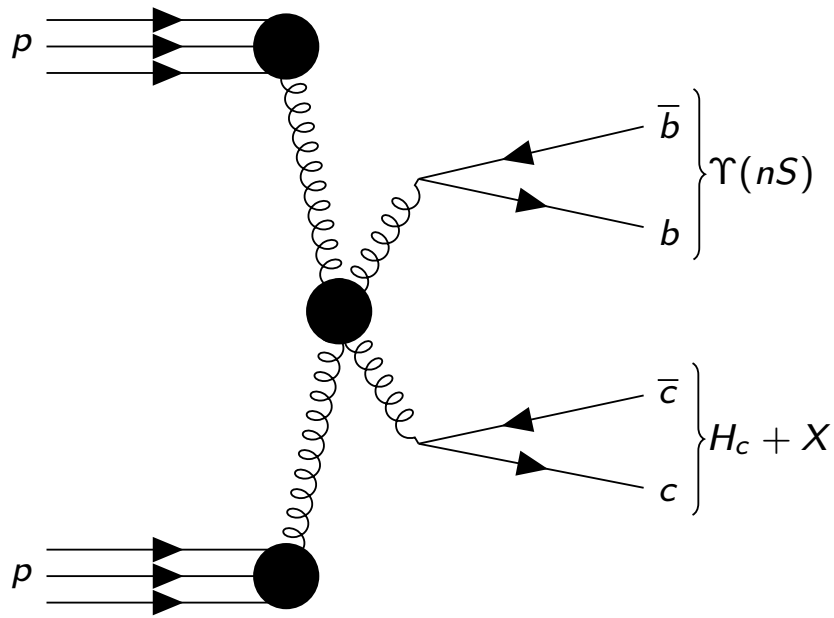

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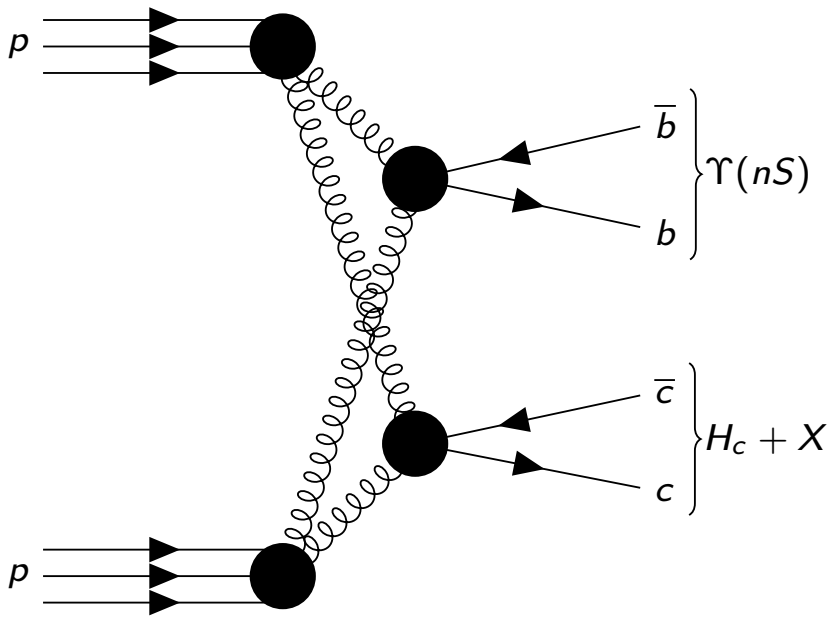

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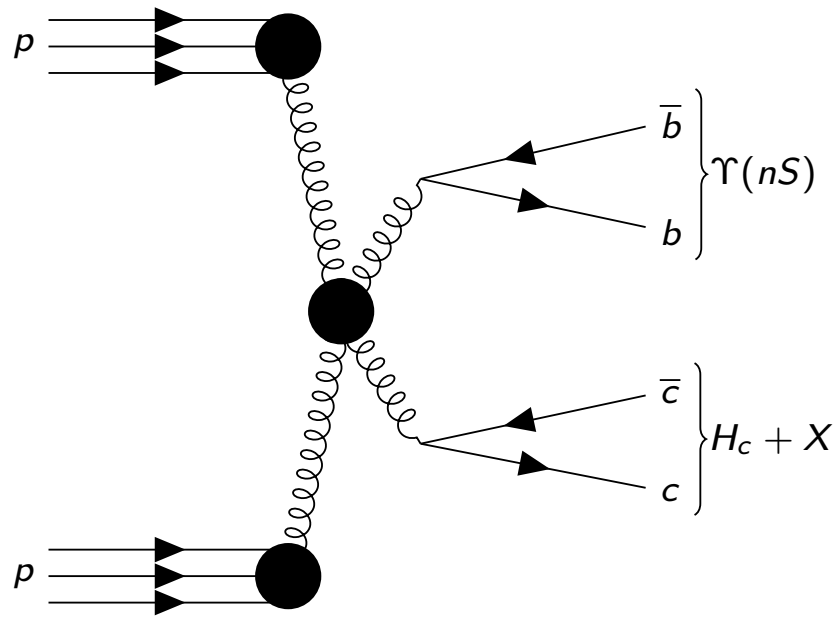

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- LHCb previously measured J/ψ and open charm pair production.[2,3]

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The measurement

LHCb collaboration, arXiv:1510.05949

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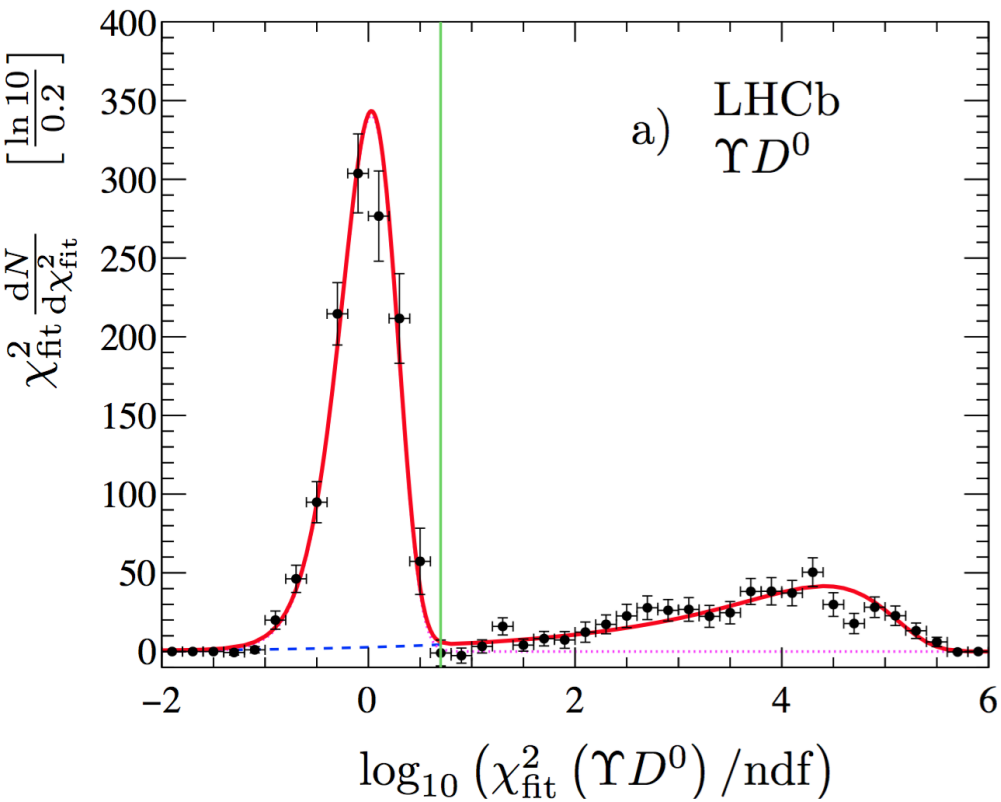
- Reconstruct and select events with $\Upsilon(nS) \to \mu^+\mu^-$ and either $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ or $D_s^+ \to K^-K^+\pi^+$.
- Both parts of the event are selected independently to allow independent correction for reconstruction and selection efficiencies.
- χ^2/ndf requirement on the common $\Upsilon(nS)$ and D production vertex to reject decays from pile-up.



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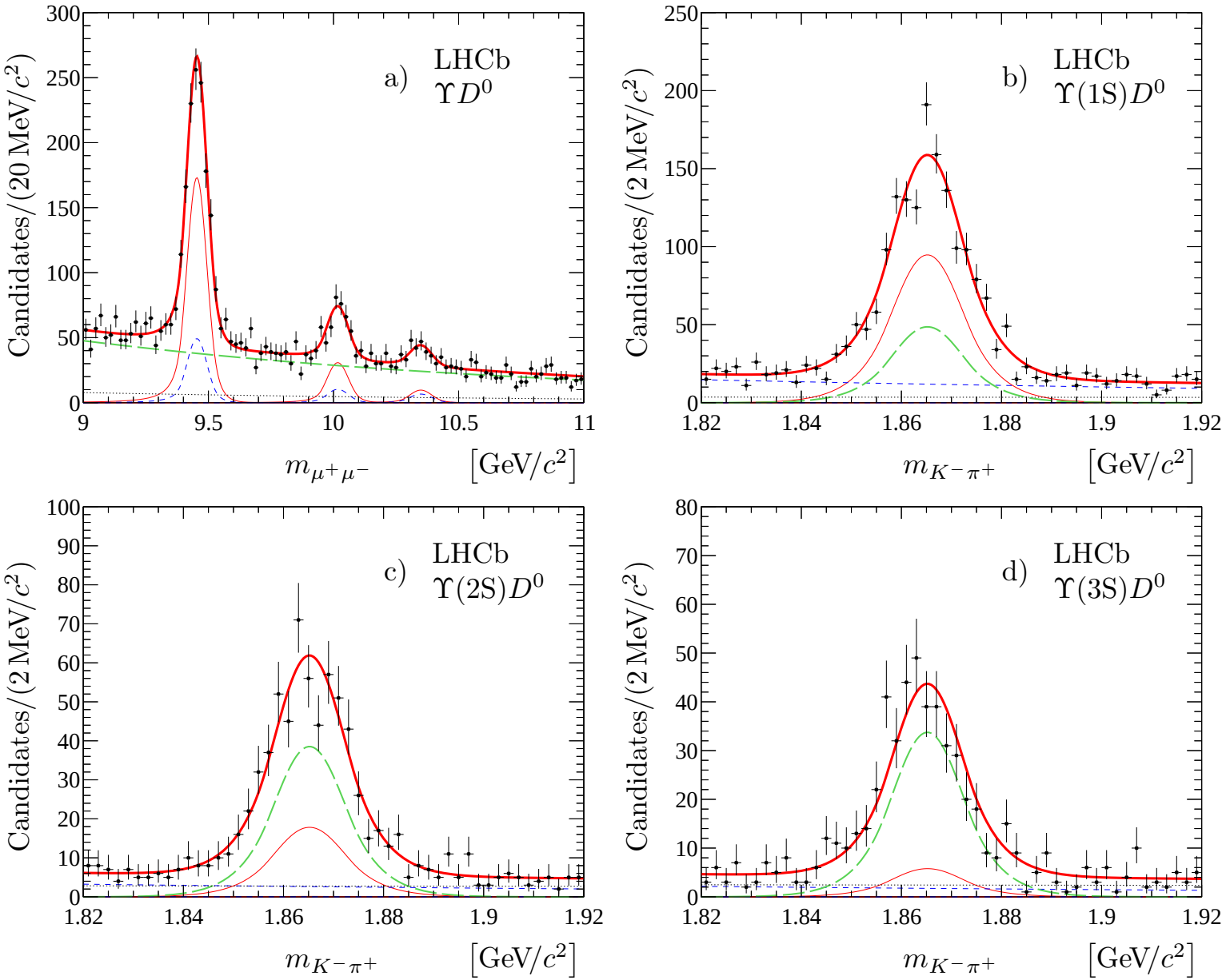

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- Integrated cross-section measurements for D^0 and D^+ modes:

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

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- 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

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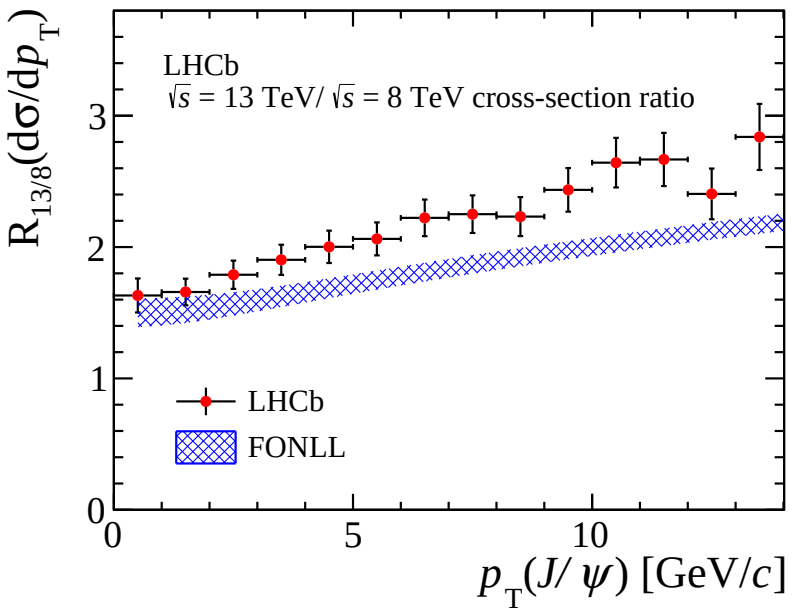
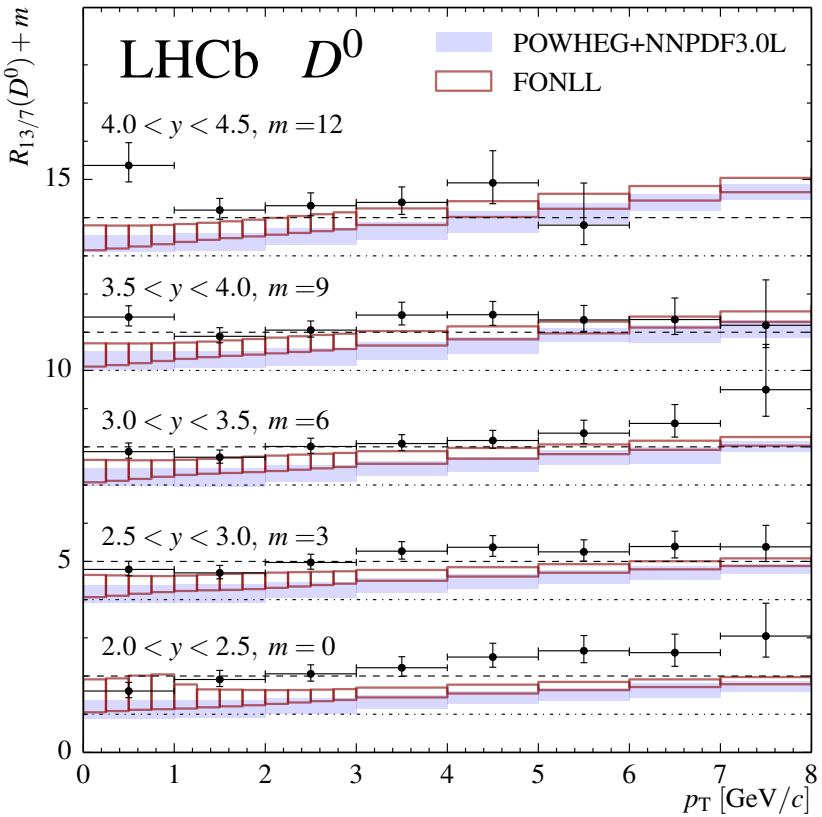
- Presented 13 TeV production cross-sections for prompt and from-b J/ψ.
- Presented 13 TeV production cross-sections for prompt D mesons.





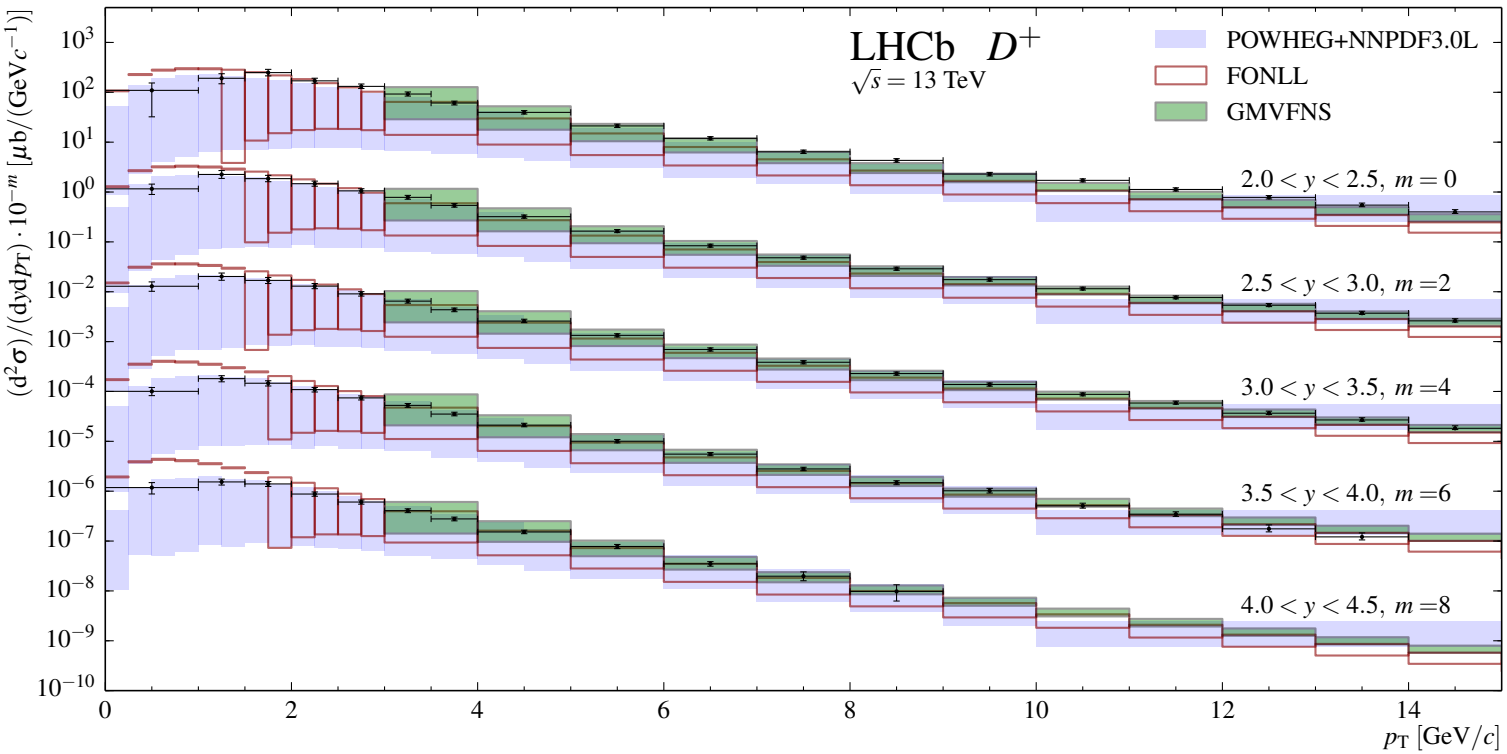
- Both show tension with the QCD prediction in 13 TeV to 7 TeV and 8 TeV ratios respectively.
- First observation of and production cross-sections for associated Υ(nS) and D mesons.

Backup

D meson cross-sections

LHCb collaboration, JHEP03 (2016) 159

D^+

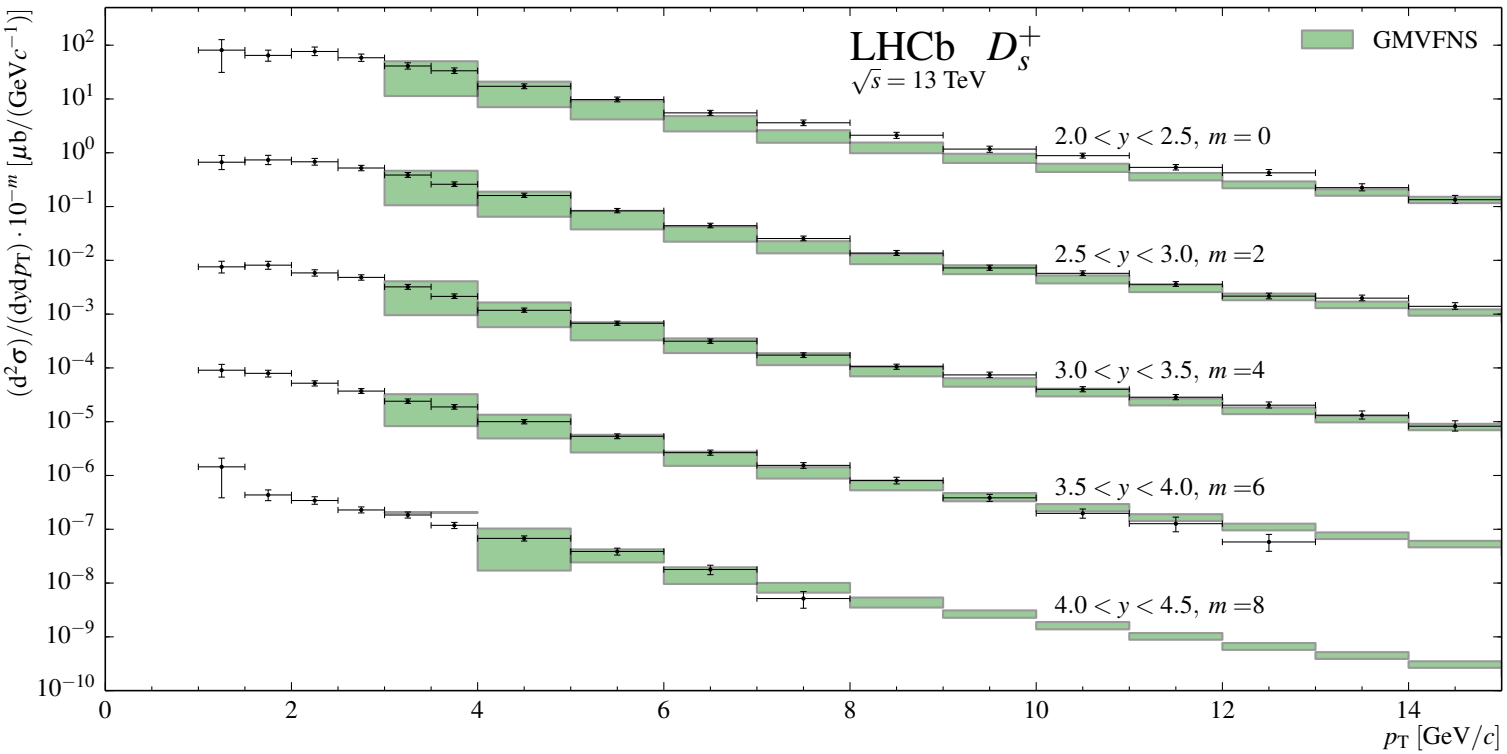


$$\sigma(D^+)_{1<p_\mathrm{T}<8\ \mathrm{GeV}} = 1000 \pm 3(\mathrm{stat}) \pm 110(\mathrm{syst})\ \mu\mathrm{b}$$

D meson cross-sections

LHCb collaboration, JHEP03 (2016) 159

D_s^+



$\sigma(D_s^+)_{1<p_T<8\ \mathrm{GeV}} = 460 \pm 13(\mathrm{stat}) \pm 100(\mathrm{syst})\ \mu\mathrm{b}$

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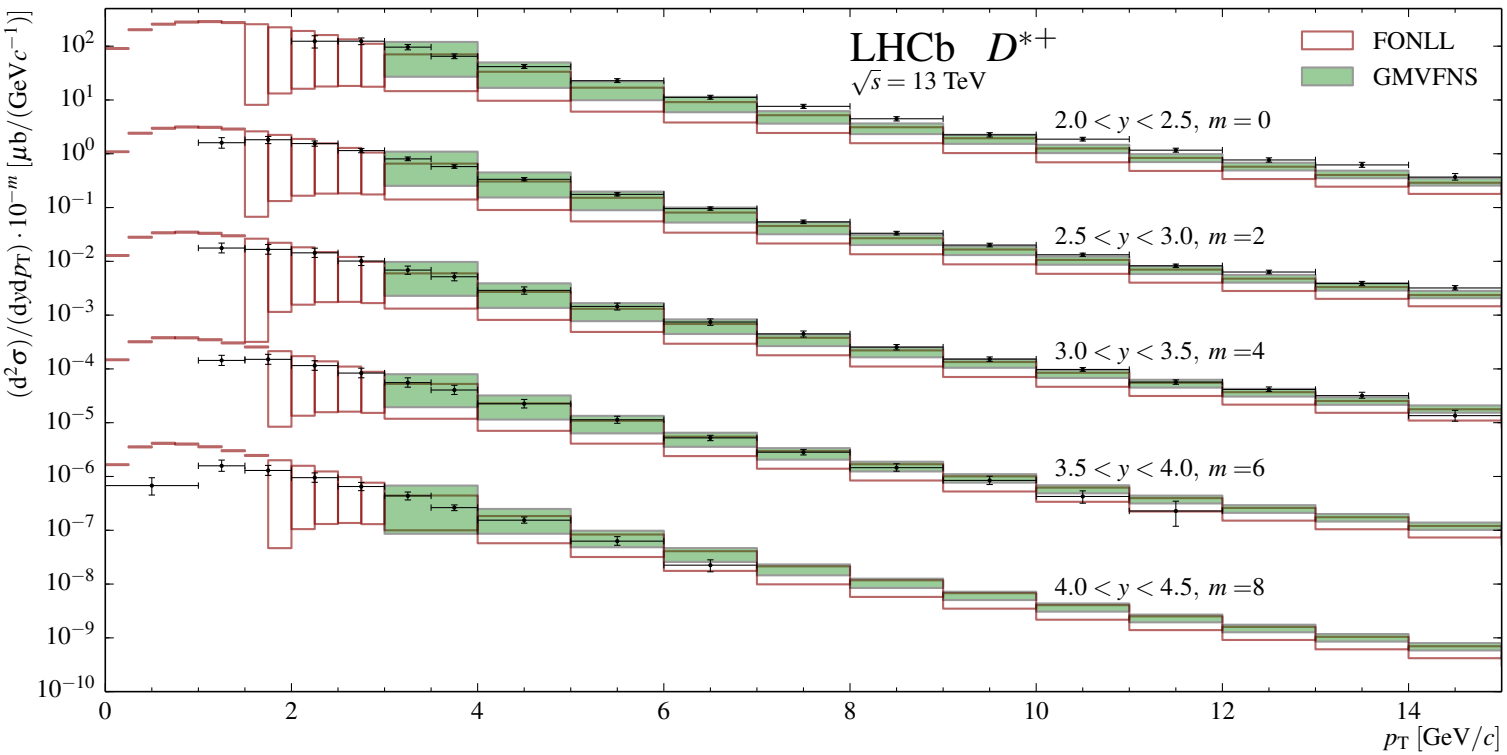
LHCb collaboration, JHEP03 (2016) 159

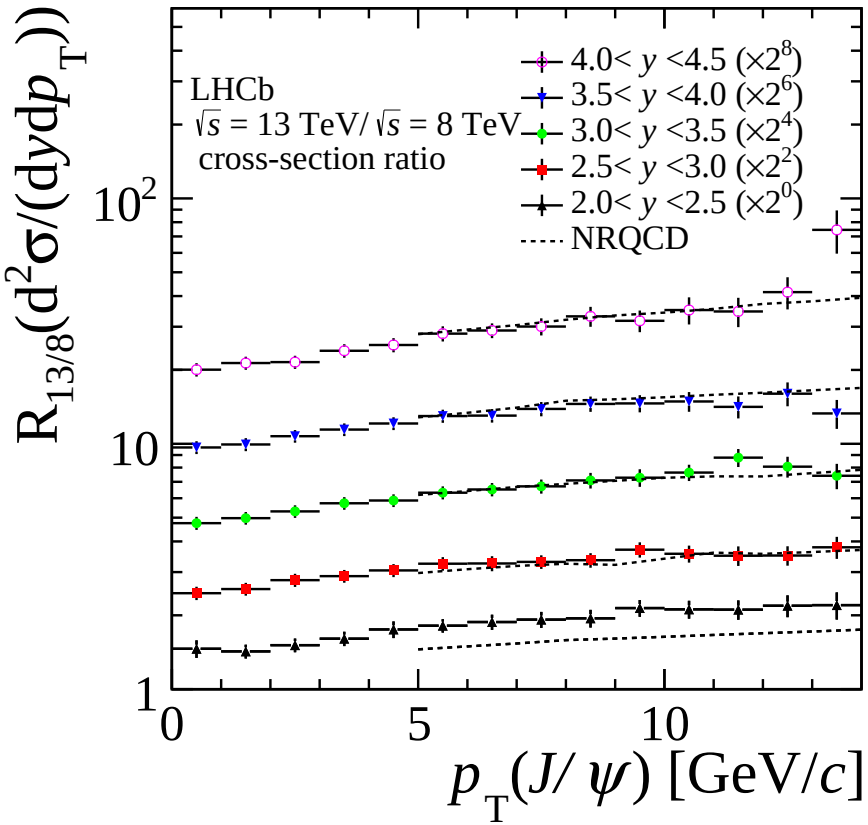
D^{*+}

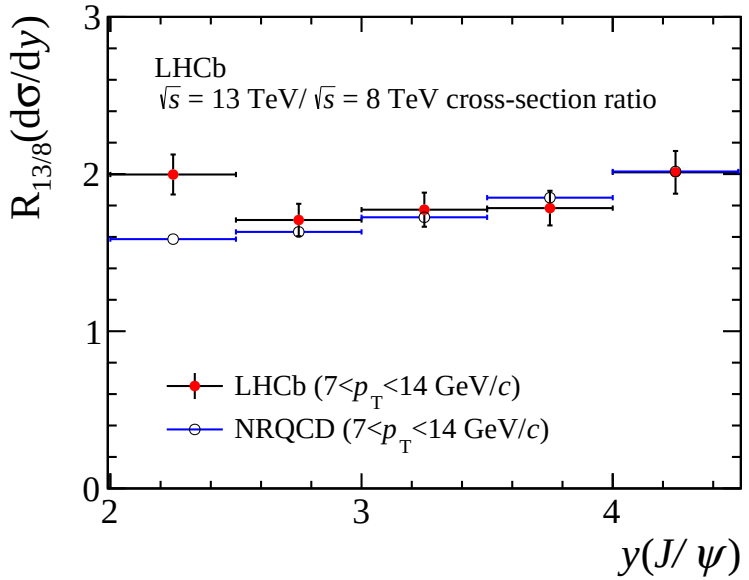


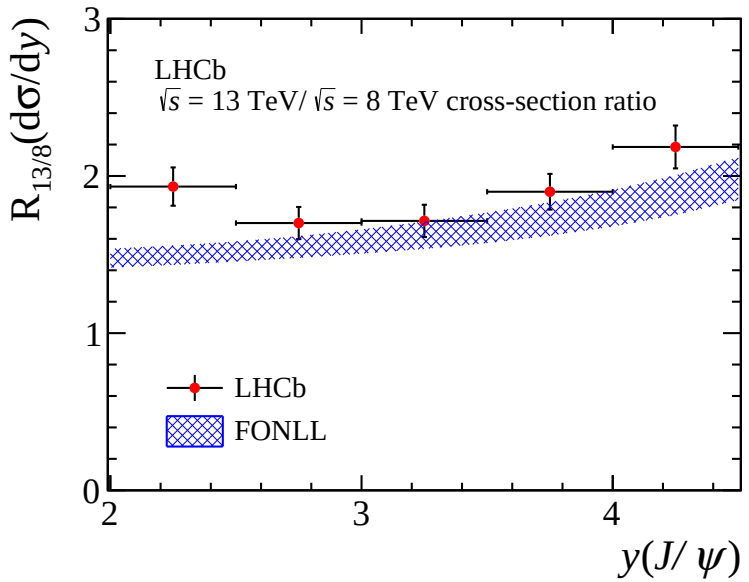
$$\sigma(D^{*+})_{1<p_T<8\ \mathrm{GeV}} = 880 \pm 5(\mathrm{stat}) \pm 140(\mathrm{syst})\ \mu\mathrm{b}$$

More J/ψ ratios

LHCb collaboration, JHEP10 (2015) 172(supplementary material)







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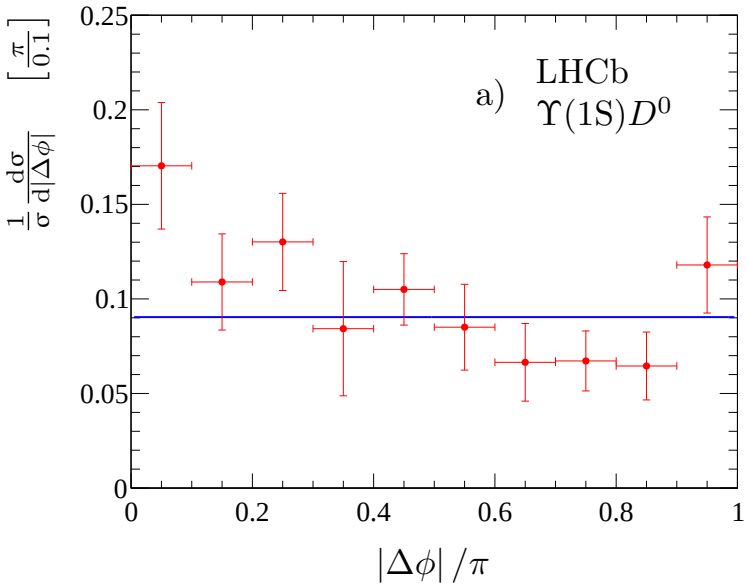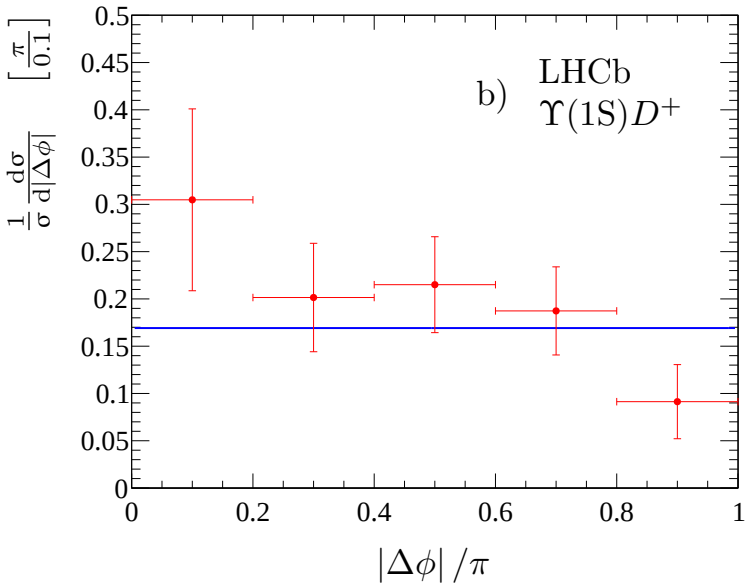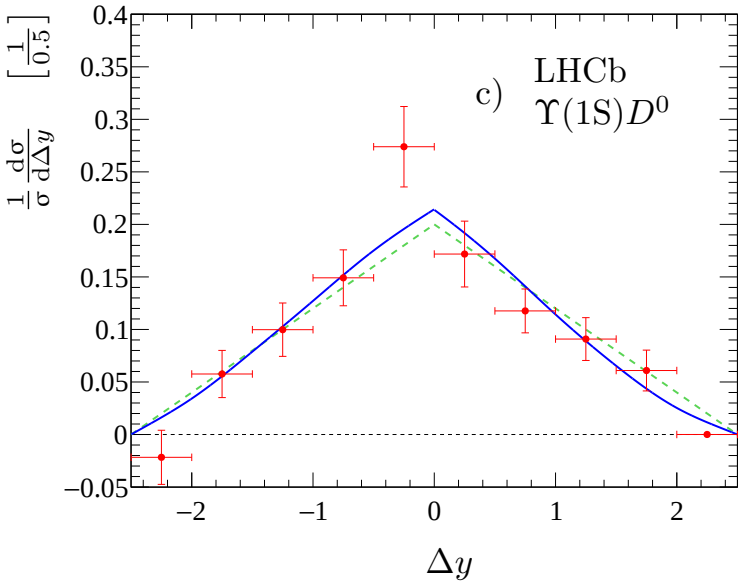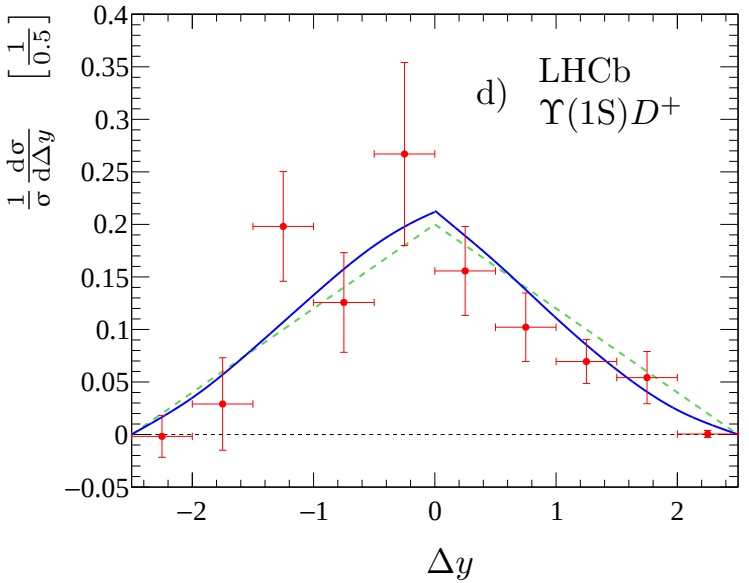
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