Heavy Flavour Production results at 13 TeV with LHCb

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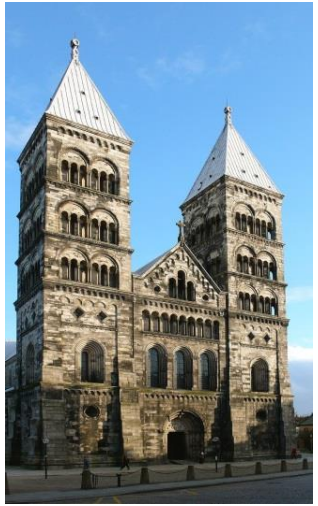
on behalf of the LHCb collaboration

Heidelberg University, Physikalisches Institut

LHCP 2016, Lund

June 13 – 18

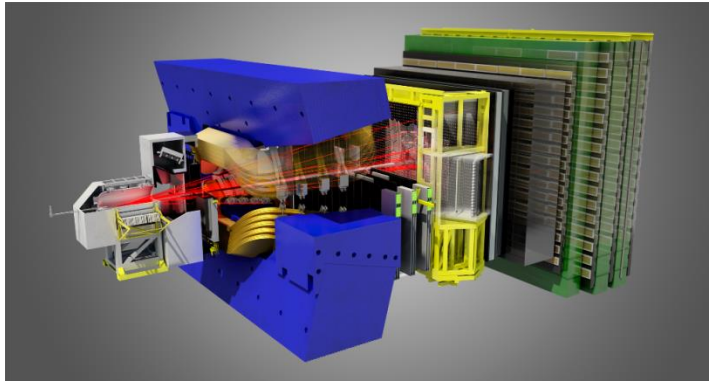


BMBF-Forschungsschwerpunkt FSP-105
LHCb-Experiment
Quark-Flavor-Physik am LHC

pictures from Wikipedia

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/ψ production using 3.05 pb^{-1} : JHEP10(2015)172
  - prompt charm production using 4.98 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

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

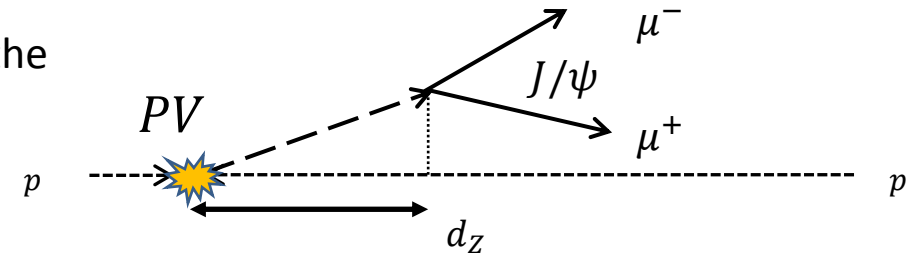
- compute σ in bins of p_T and y
- N(X) signal yield
- $\mathcal{L}$ integrated luminosity
- $\mathcal{B}(X \to f)$ branching fraction

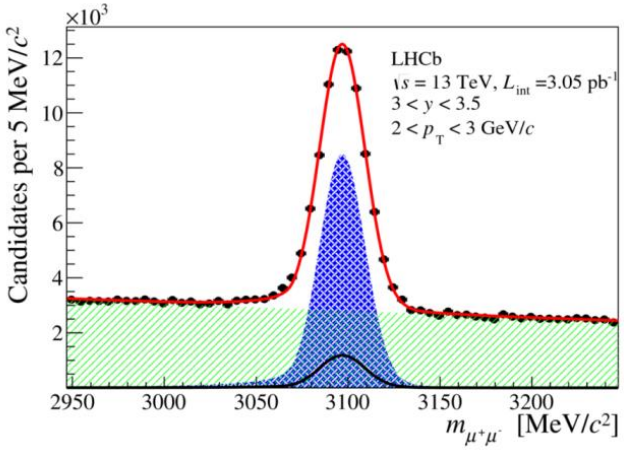
- ϵ efficiencies
  - selection from simulation
  - data-driven methods:
    - PID
    - trigger
    - tracking

J/ψ production cross-sections at $\sqrt{s}$ = 13 TeV

- separate prompt J/ψ and J/ψ-from-b using the pseudo-decay-time

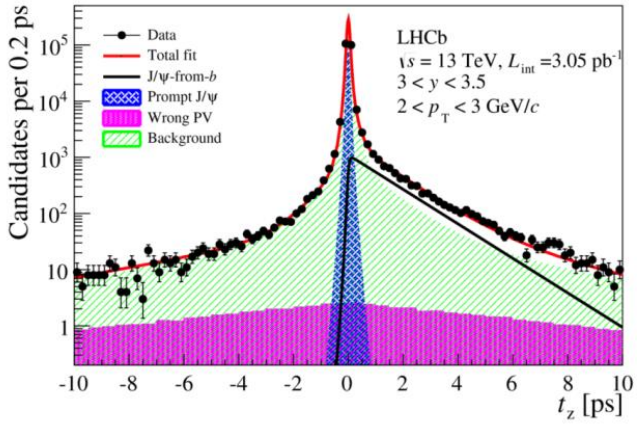
$$t_Z = \frac{d_Z \cdot M_{J/\psi}}{p_Z}$$





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

JHEP10(2015)172

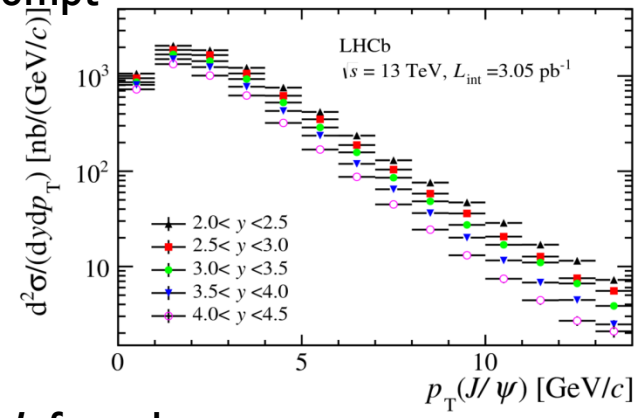


signal: Crystal Ball
bkg: exponential

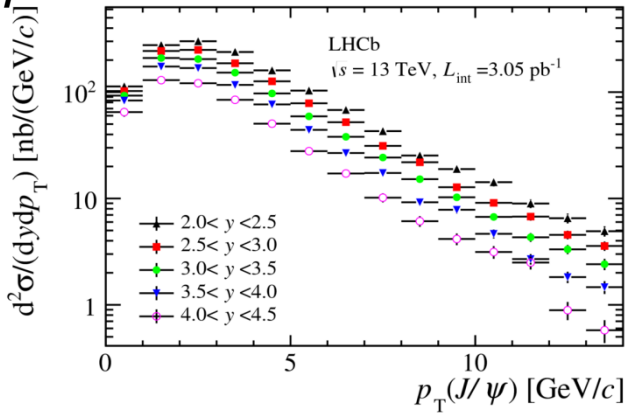
prompt signal: double Gaussian
from-b signal: exponential ∗ double Gaussian

Results: J/ψ cross-sections at $\sqrt{s}$ = 13 TeV

prompt



J/ψ-from-b



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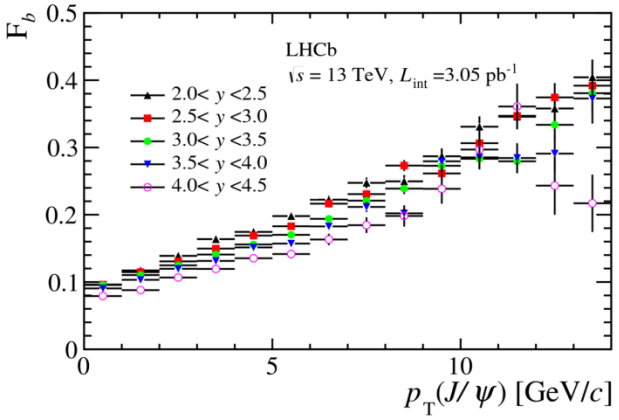


integrated cross-section p_T< 14 GeV/c and 2 < y < 4.5:

σ(prompt) = 15.30 ± 0.03 ± 0.86 μb
σ(from-b) = 2.34 ± 0.01 ± 0.13 μb

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

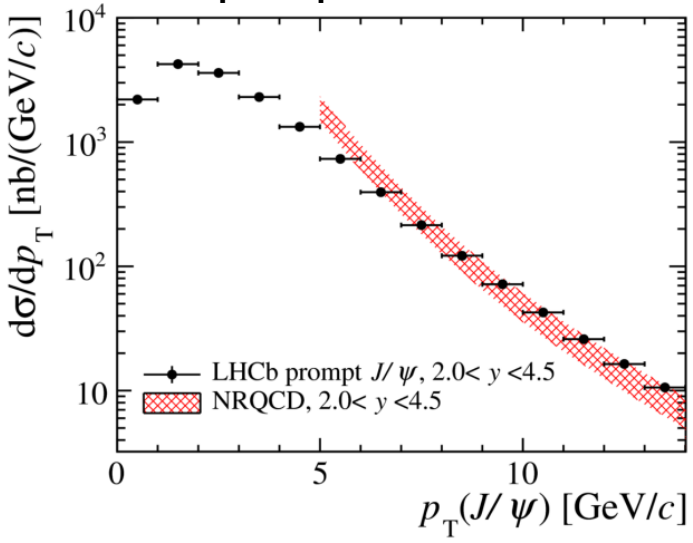
$\sigma(pp \rightarrow b\bar{b}\, X)$ = 515 ± 2 ± 53 μb

* $\mathcal{B}(b \rightarrow J/\psi\, X)$ = 1.16 ± 0.10 %; naïve PYTHIA 6 extrapolation

J/ψ production at 13 TeV: comparison with theory

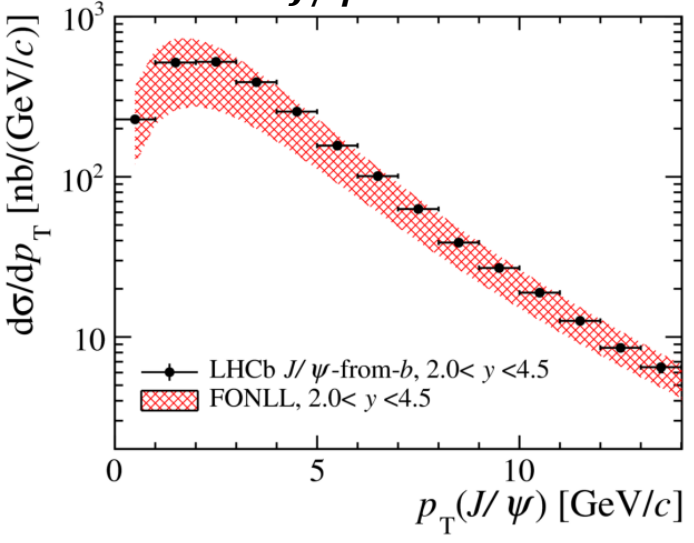
prompt

[JHEP10(2015)172]



- 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

J/ψ-from-b



- 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

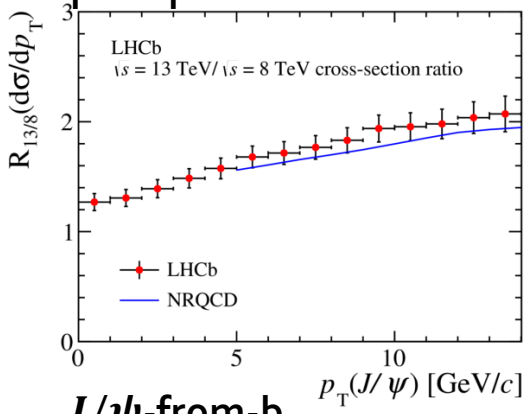
Systematic uncertainties

- luminosity dominant systematic uncertainty
- muon: tag-and-probe method
- large only for few bins at acceptance boundary

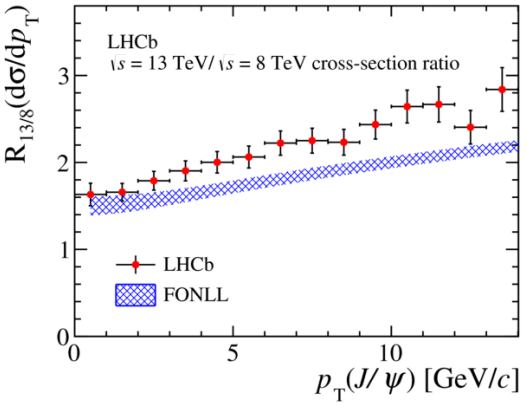
Source	Systematic uncertainty (%)
Luminosity	3.9
Hardware trigger	0.1 – 5.9
Software trigger	1.5
Muon ID	1.8
Tracking	1.1 – 3.4
Radiative tail	1.0
J/ψ vertex fit	0.4
Signal mass shape	1.0
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.6
p_{T}, y spectrum	0.1 – 5.0
Simulation statistics	0.3 – 5.0
t_z fit (J/ψ-from-b only)	0.1

J/ψ production ratio 13/8 TeV: comparison with theory

prompt



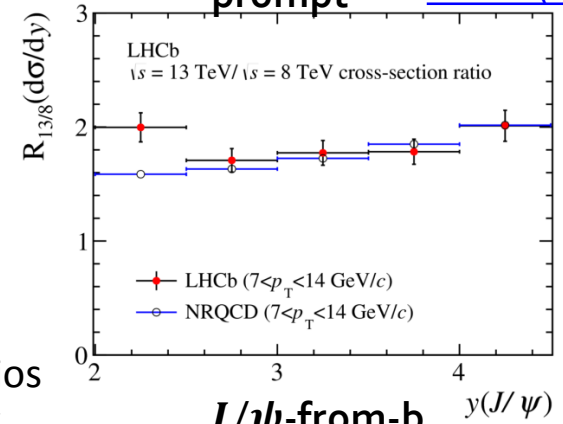
J/ψ-from-b



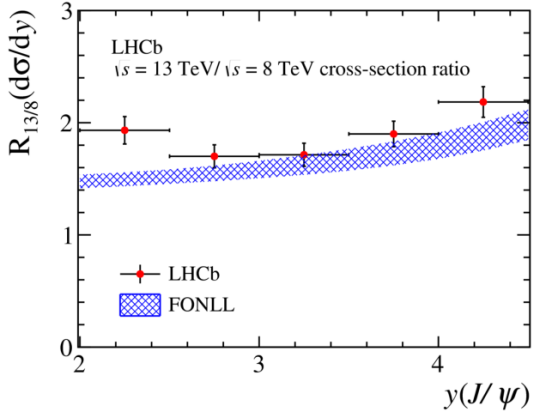
- NRQCD: not all uncertainties included
- measurements of ratios not well described by models for low y

JHEP10(2015)172

prompt

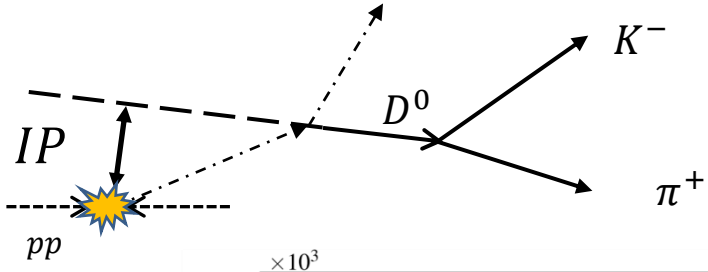


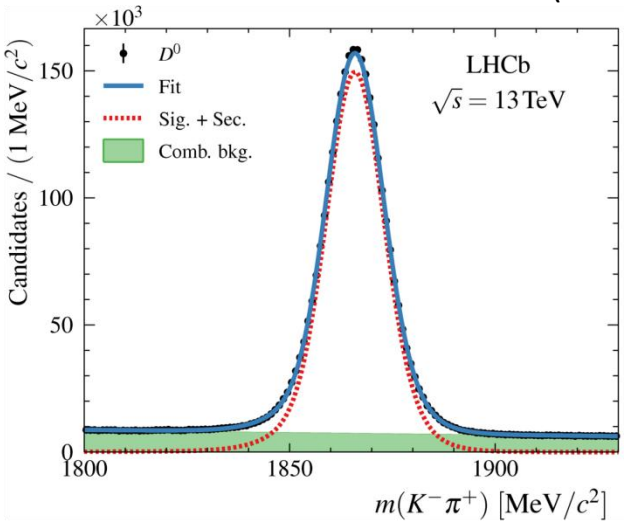
J/ψ-from-b



Prompt charm production at $\sqrt{s}$ = 13 TeV

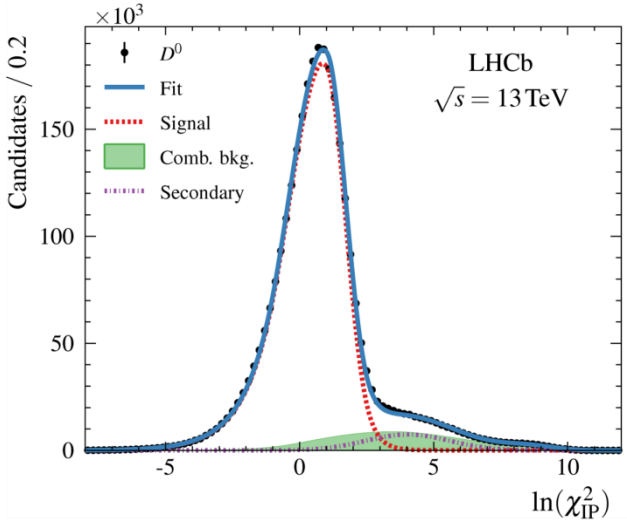
- reconstruct D^0, D^+, ${D_s}^+$ and $D^{*+} \to D^0\pi^+$
- separate prompt charm from secondary charm by using impact parameter (IP) significance (D^0 has lifetime itself)





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

JHEP03(2016)159



signal: Crystal Ball + Gaussian
bkg: linear

signal: asymmetric Gaussian + exp tail
secondary: Gaussian

Systematic uncertainties and models

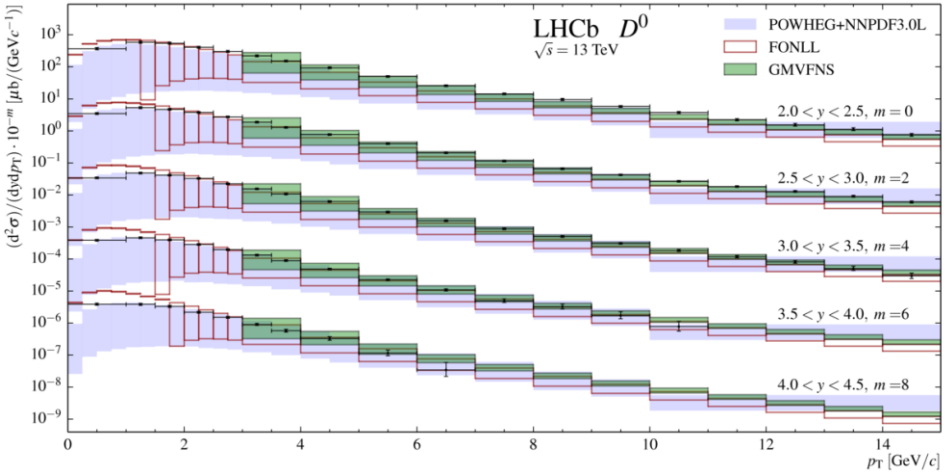
- luminosity dominant systematic uncertainty
- only few bins above 10 %

	Uncertainties (%)			
	D^0	D^+	D_s^+	D^{*+}
Luminosity	3.9			
Tracking	3–5	5–17	4–18	5–20
Branching fractions	1.2	2.1	5.8	1.5
Simulation sample size	2–24	4–55	3–55	2–21
Simulation modelling	2	1	1	1
PID sample size	0–2	0–1	0–2	0–1
PID binning	0–44	0–10	0–20	0-15
PDF shapes	1–6	1–5	1–2	1–2

Results: prompt charm production cross-sections at 13 TeV

double-differential D^0 cross-section

JHEP03(2016)159

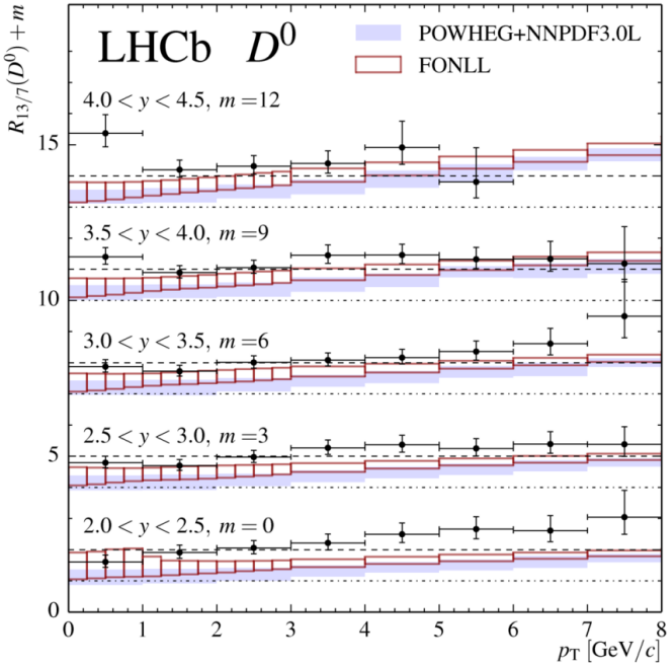


- measurements agree with models within uncertainties

Theory models:

- **POWHEG+NNPDF3.0L**
  (Gauld et al., JHEP06(2013)064)
  - POWHEG matched to Pythia 8 parton showers
- **FONLL** (Cacciari et al., Eur.Phys.J.C75(2015)no.12,610)
  - match NLO QCD with NLL in the limit $p_T >> m(q)$
  - tuned to c-fractions from e^+e^- colliders
- General-mass variable-flavor-number scheme (**GMVFNS**) (Spiesberger et al., Eur. Phys. J. C (2012) 72:2082)
  - NLO predictions are convolved with frag functions fitted to data from e^+e^- colliders

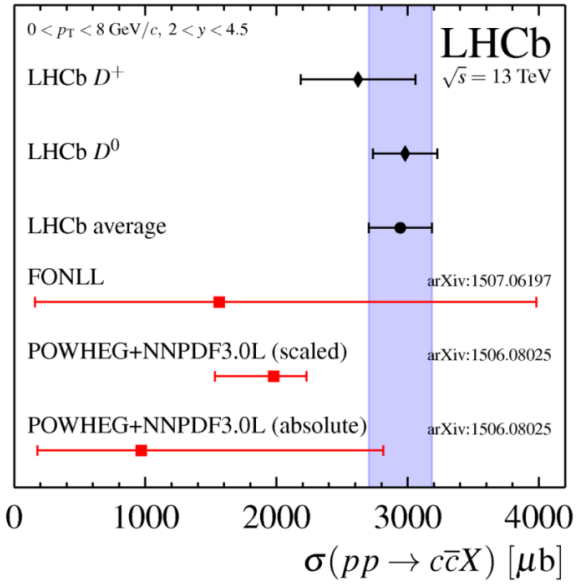
Results: ratio of 13/7 TeV and integrated cross-setions



- measurement of ratios not well described by models

combine D^0 and D^+ measurement:

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



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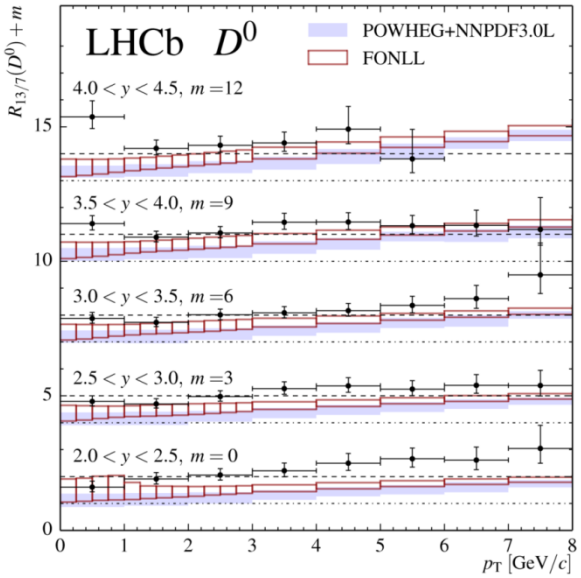

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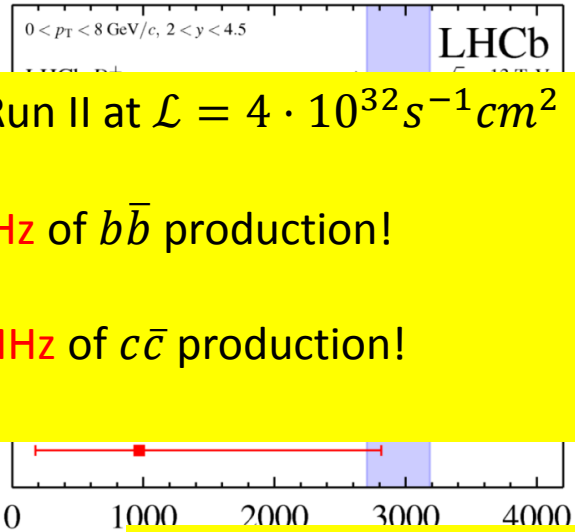


For Run II at $\mathcal{L} = 4 \cdot 10^{32} s^{-1} cm^2$:

40 kHz of $b\bar{b}$ production!

1.2MHz of $c\bar{c}$ production!

numbers: thanks to Patrick Spradlin

Conclusions

- heavy flavour production cross-section at $\sqrt{s}$ = 13 TeV with LHCb
  - in the range of p_T < 14 (8) GeV/c and 2.0 < y < 4.5
  - as a function of p_T and y for
- prompt J/ψ and J/ψ-from-b
  JHEP10(2015)172
- prompt charm JHEP03(2016)159

σ(prompt J/ψ) = 15.30 ± 0.03 ± 0.86 µb
$\sigma(J/\psi$ from-b) = 2.34 ± 0.01± 0.13 µb

σ(pp→ $b\bar{b}\ X$) = 515 ± 2 ± 53 µb *

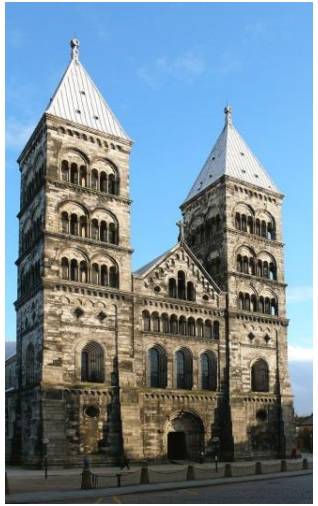
$\sigma(\text{pp} \rightarrow c\bar{c}\ X)_{(p_T < 8\ GeV/c,\ 2.0 < y < 4.5)}$
= 2940 ± 3 ± 180 ± 160 µb

- 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

*naïve PYTHIA 6 extrapolation

BACKUP

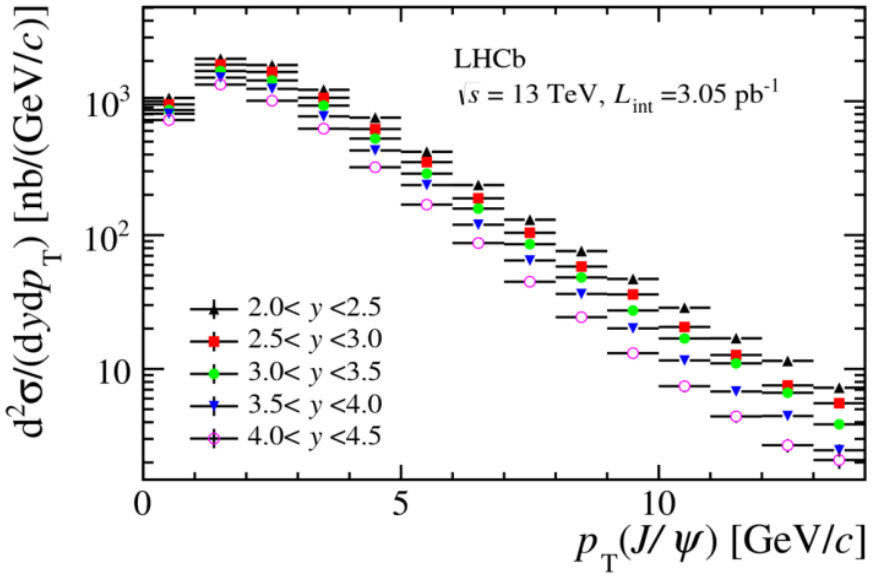


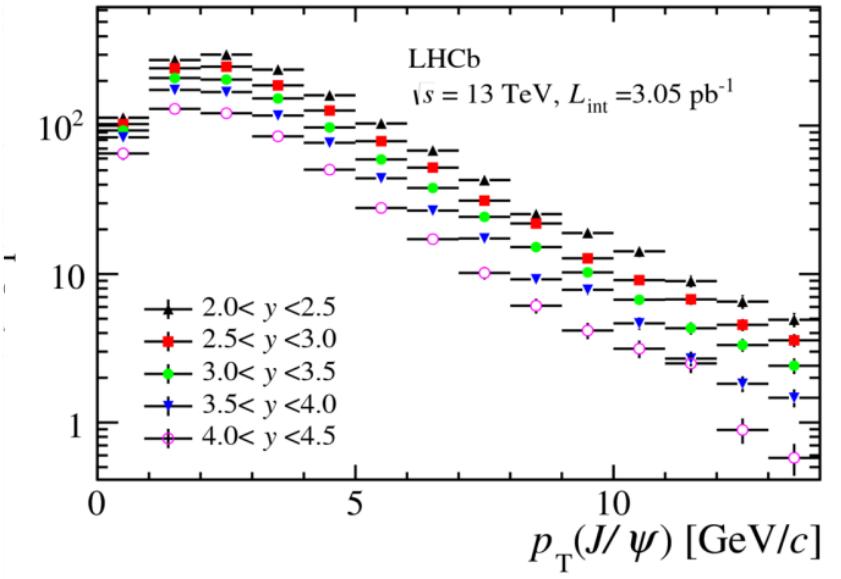
Results: J/ψ cross-sections at $\sqrt{s}$ = 13 TeV

prompt

JHEP10(2015)172

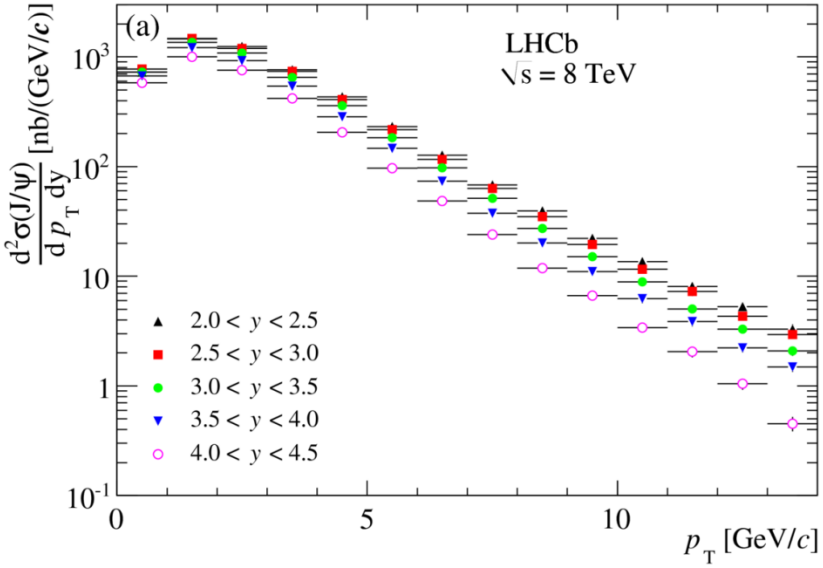
J/ψ-from-b

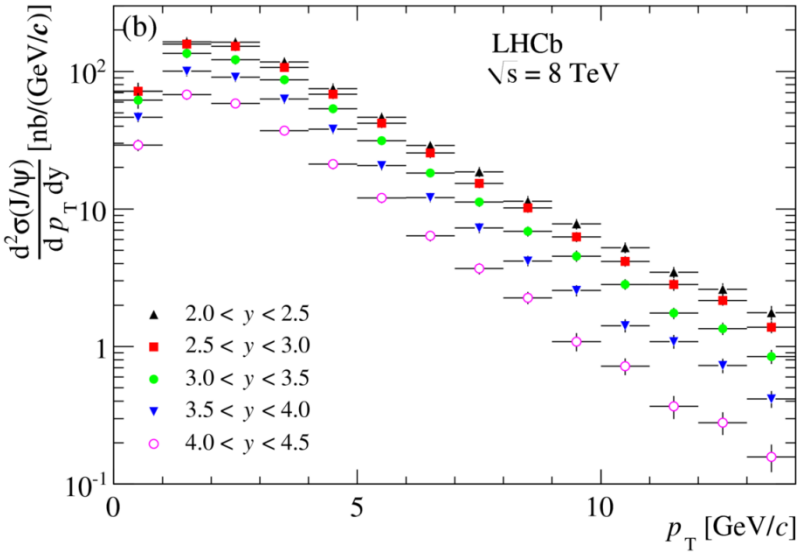




8TeV Results: J/ψ cross-sections at $\sqrt{s}$ = 8 TeV

JHEP06(2013)064





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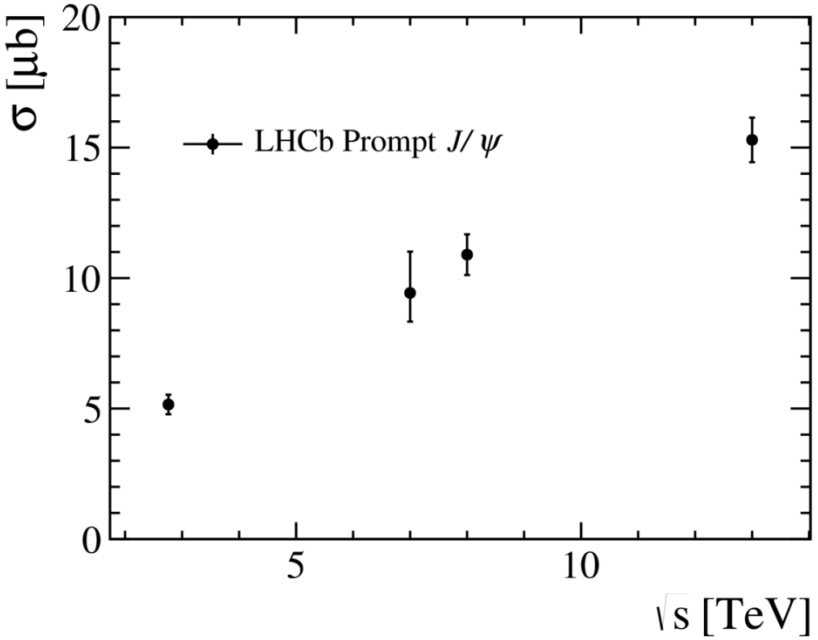
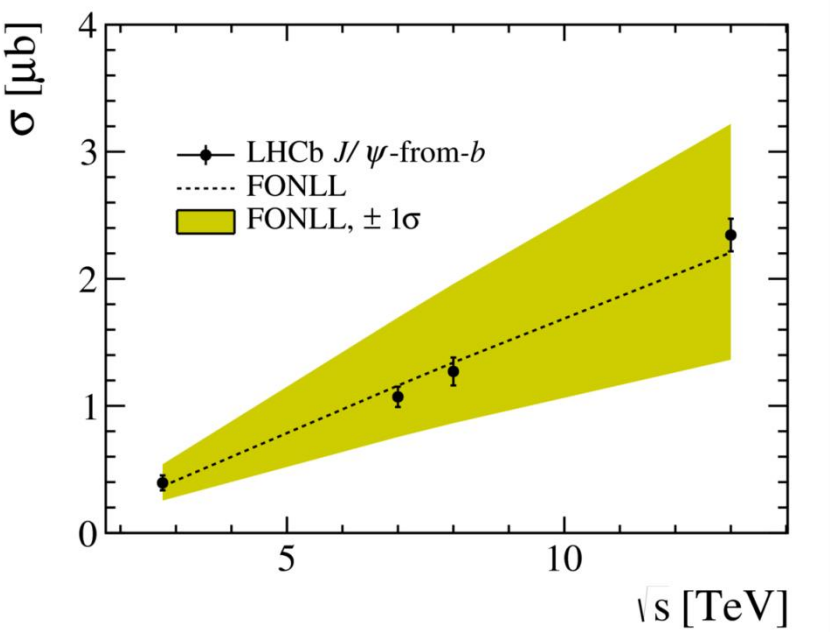
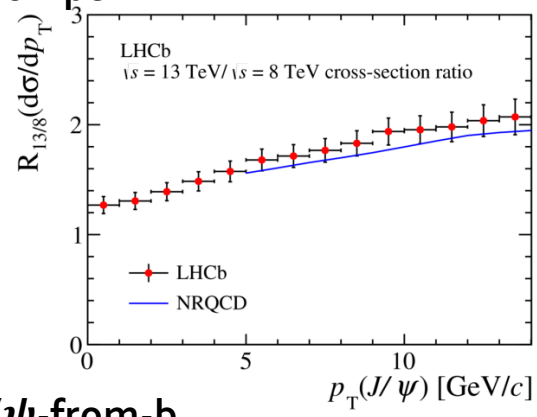


J/ψ-from-b



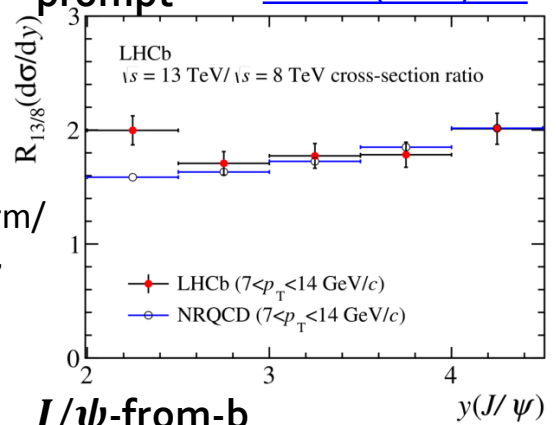
J/ψ production at 13 TeV: comparison with theory

prompt

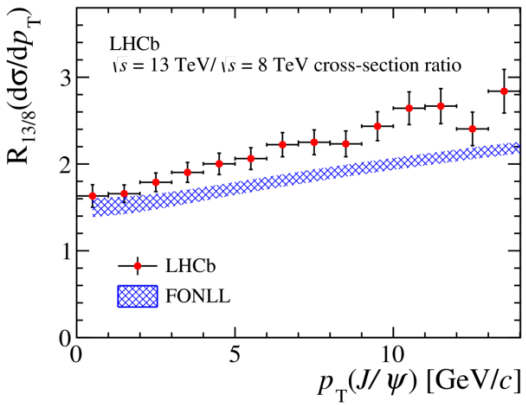


- NRQCD (Shao et al., JHEP 05 (2015) 103)
- includes LDME uncertainties which are dominant for absolute measurement
- not included are contributions from renorm/ factorization scale, relativistic corrections, charm mass and PDF uncertainties

prompt JHEP10(2015)172

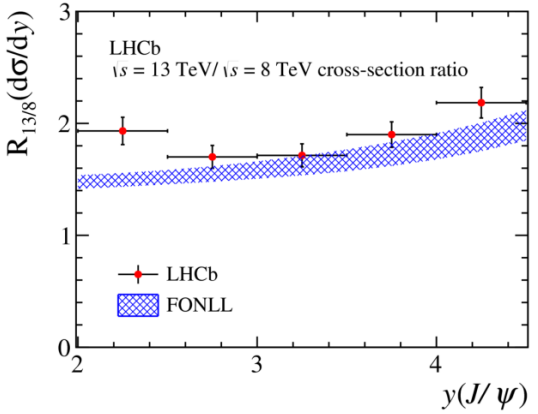


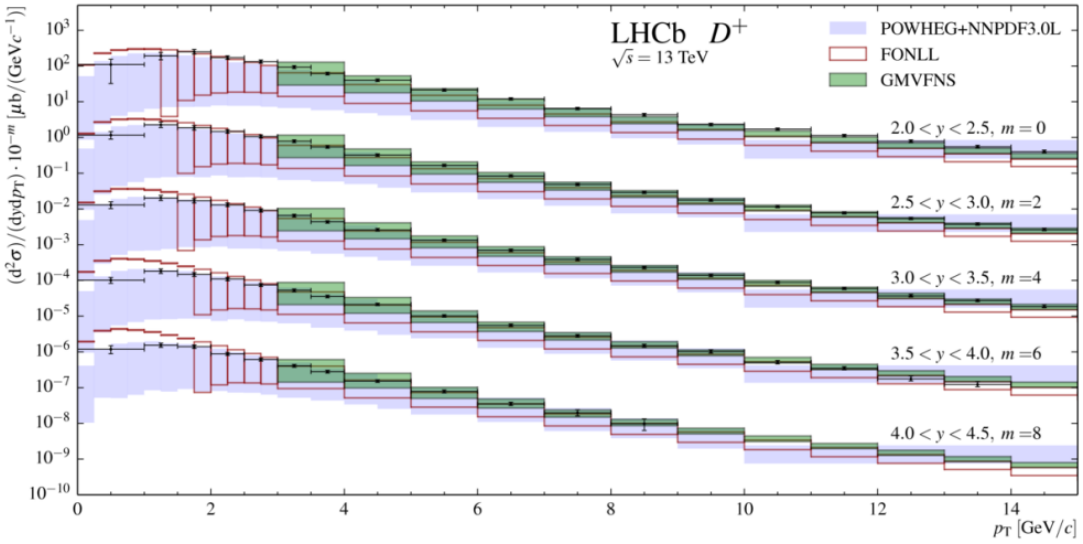
J/ψ-from-b

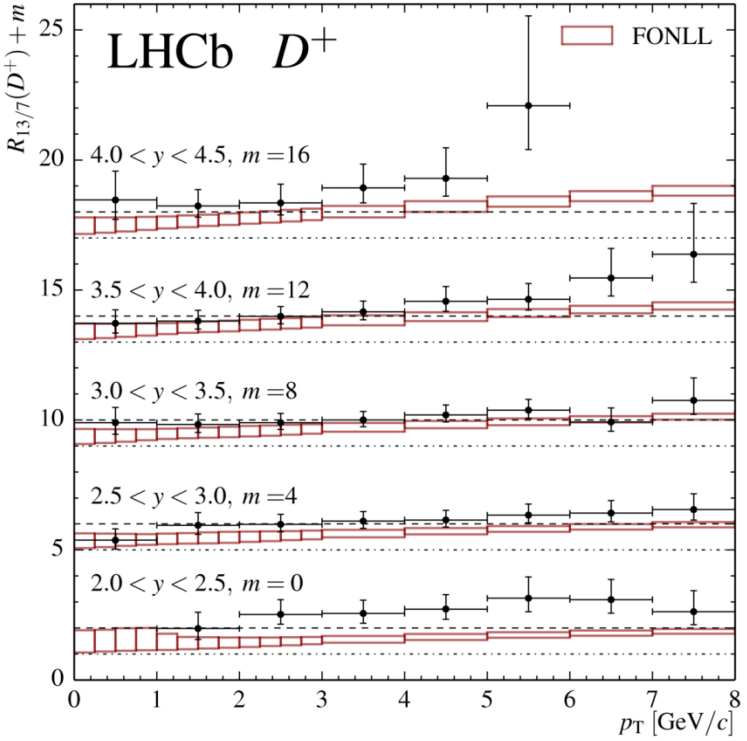


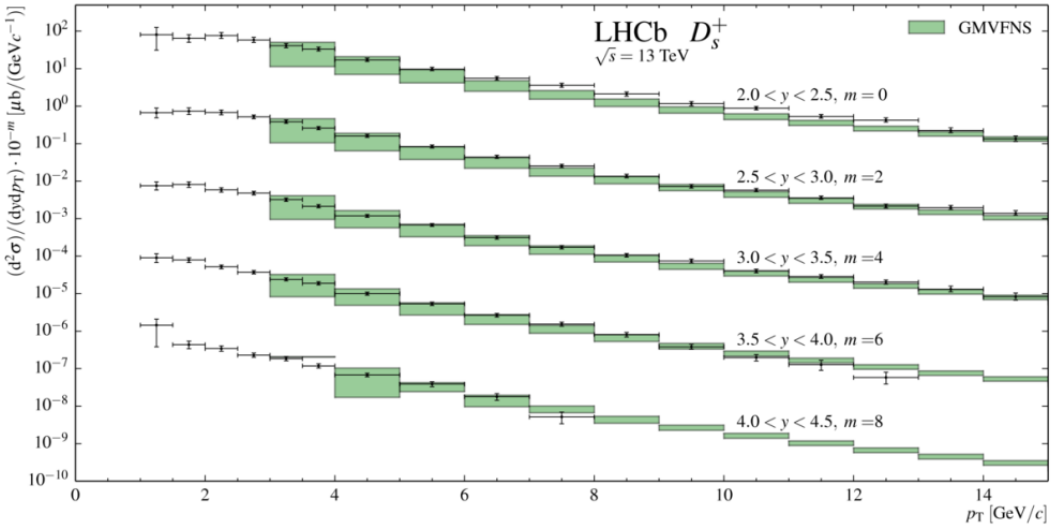
- FONLL (Cacciari et al., JHEP 05 (1998) 007, arXiv:1507.06197)
- theoretical uncertainties of b-quark mass, renorm/factorization scale, gluon PDF uncertainty

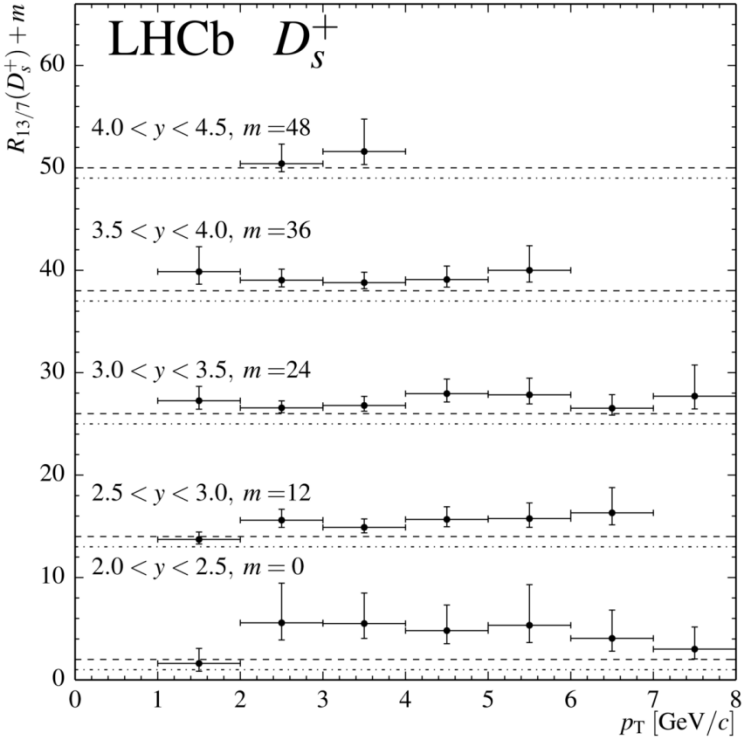
J/ψ-from-b

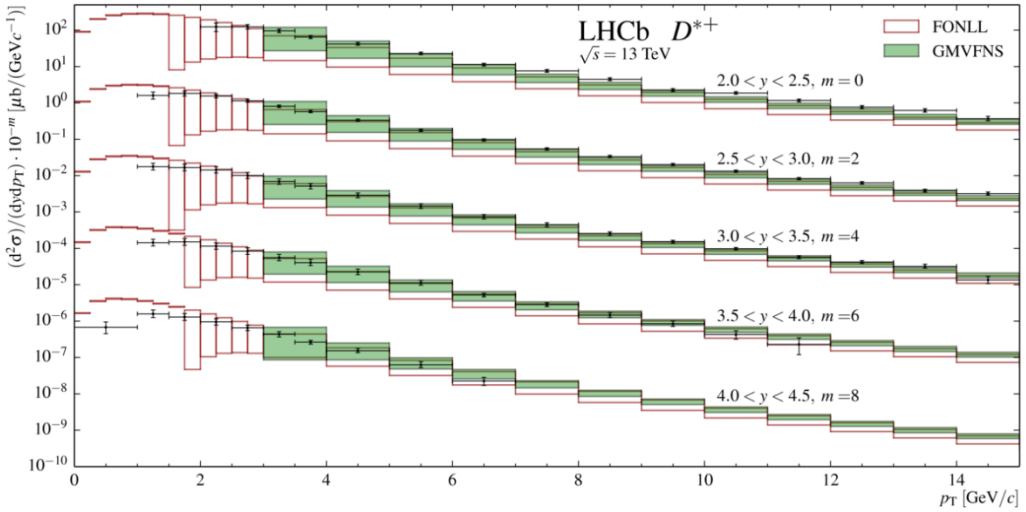


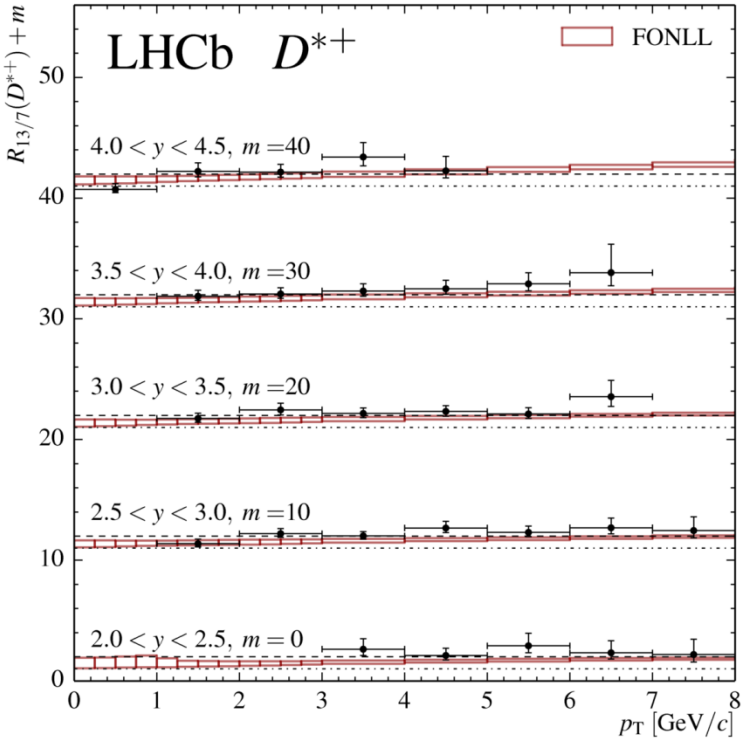

LHCb D^+
$\sqrt{s} = 13$ TeV
POWHEG+NNPDF3.0L
FONLL
GMVFNS
$2.0 < y < 2.5,\ m = 0$
$2.5 < y < 3.0,\ m = 2$
$3.0 < y < 3.5,\ m = 4$
$3.5 < y < 4.0,\ m = 6$
$4.0 < y < 4.5,\ m = 8$
$(d^2\sigma)/(dydp_T) \cdot 10^{-m}$ [μb/(GeVc^{-1})]
p_T [GeV/c]


LHCb D^+
FONLL
$4.0 < y < 4.5,\ m = 16$
$3.5 < y < 4.0,\ m = 12$
$3.0 < y < 3.5,\ m = 8$
$2.5 < y < 3.0,\ m = 4$
$2.0 < y < 2.5,\ m = 0$
$R_{13/7}(D^+) + m$
p_T [GeV/c]


LHCb D_s^+
$\sqrt{s} = 13$ TeV
GMVFNS
$2.0 < y < 2.5,\ m = 0$
$2.5 < y < 3.0,\ m = 2$
$3.0 < y < 3.5,\ m = 4$
$3.5 < y < 4.0,\ m = 6$
$4.0 < y < 4.5,\ m = 8$
$(d^2\sigma)/(dydp_T) \cdot 10^{-m}$ [μb/(GeVc^{-1})]
p_T [GeV/c]


LHCb D_s^+
$4.0 < y < 4.5,\ m = 48$
$3.5 < y < 4.0,\ m = 36$
$3.0 < y < 3.5,\ m = 24$
$2.5 < y < 3.0,\ m = 12$
$2.0 < y < 2.5,\ m = 0$
$R_{13/7}(D_s^+) + m$
p_T [GeV/c]


LHCb D^{*+}
$\sqrt{s} = 13$ TeV
FONLL
GMVFNS
$2.0 < y < 2.5,\ m = 0$
$2.5 < y < 3.0,\ m = 2$
$3.0 < y < 3.5,\ m = 4$
$3.5 < y < 4.0,\ m = 6$
$4.0 < y < 4.5,\ m = 8$
$(d^2\sigma)/(dydp_T) \cdot 10^{-m}$ [μb/(GeVc^{-1})]
p_T [GeV/c]


LHCb D^{*+}
FONLL
$4.0 < y < 4.5,\ m = 40$
$3.5 < y < 4.0,\ m = 30$
$3.0 < y < 3.5,\ m = 20$
$2.5 < y < 3.0,\ m = 10$
$2.0 < y < 2.5,\ m = 0$
$R_{13/7}(D^{*+}) + m$
p_T [GeV/c]

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 distrubution 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 $p_T > 3\ GeV/c$ due to scale uncertainties; take NLO predictins od charm production and convolute with fragmentation functions describing the $c \to H_c$ 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

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combine D^0 and D^+ measurement:

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