Heavy-flavour production

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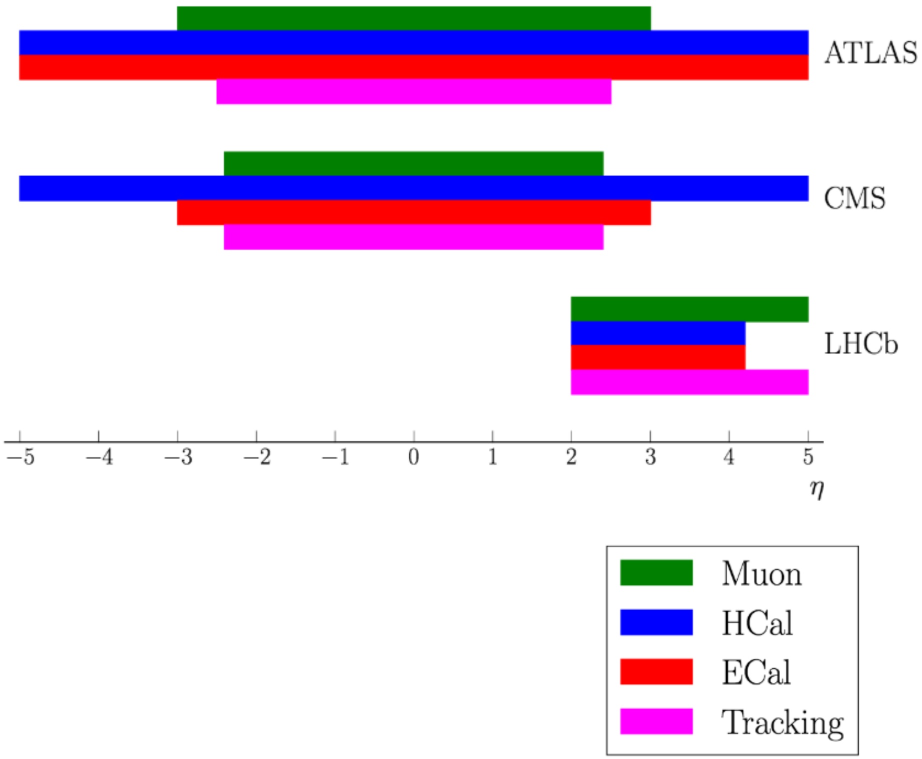
Introduction

- LHCb geometrical acceptance allows to perform **unique measurements** in the **forward region**
  - **Complementary** to ATLAS/CMS

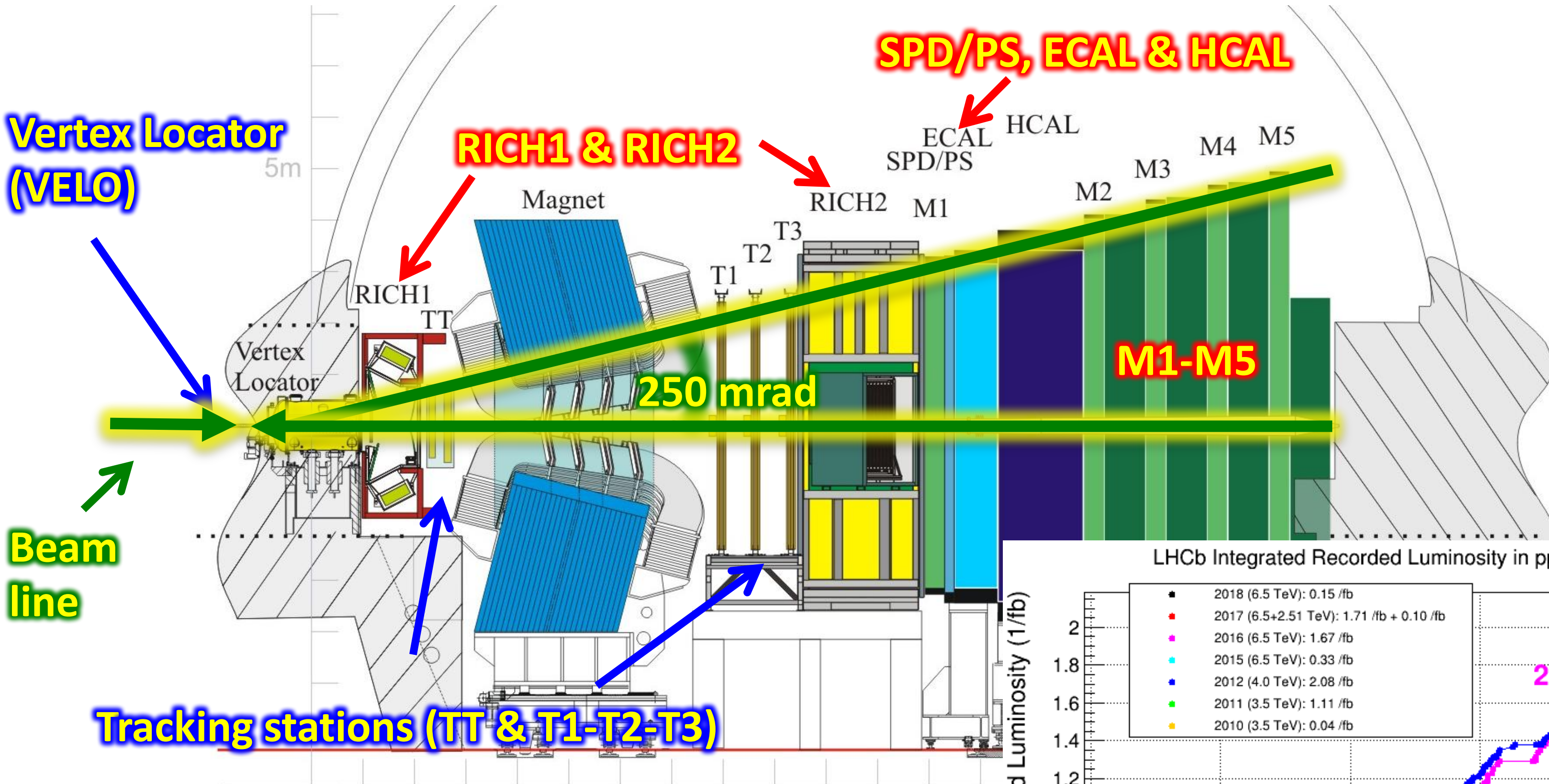
- Today results
  - Υ production in pp collisions at $\sqrt{s} = 13$ TeV
  - B^+ production cross-section in pp collision at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV
  - D_s^+ production asymmetry at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV

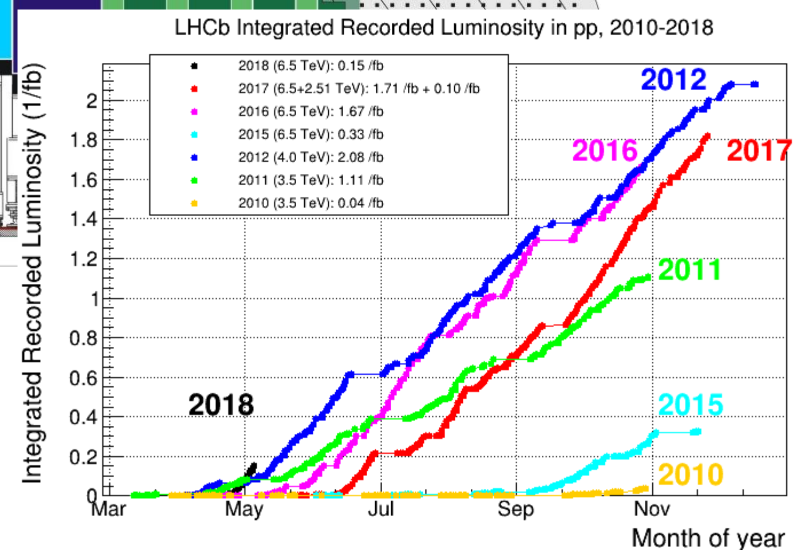


The LHCb detector

J. Instrum. 3 (2008) S08005

Single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$





LHCb integrated luminosity

1 fb^{-1} @ $\sqrt{s} = 7$ TeV

2 fb^{-1} @ $\sqrt{s} = 8$ TeV

2 fb^{-1} @ $\sqrt{s} = 13$ TeV (2015-2016)

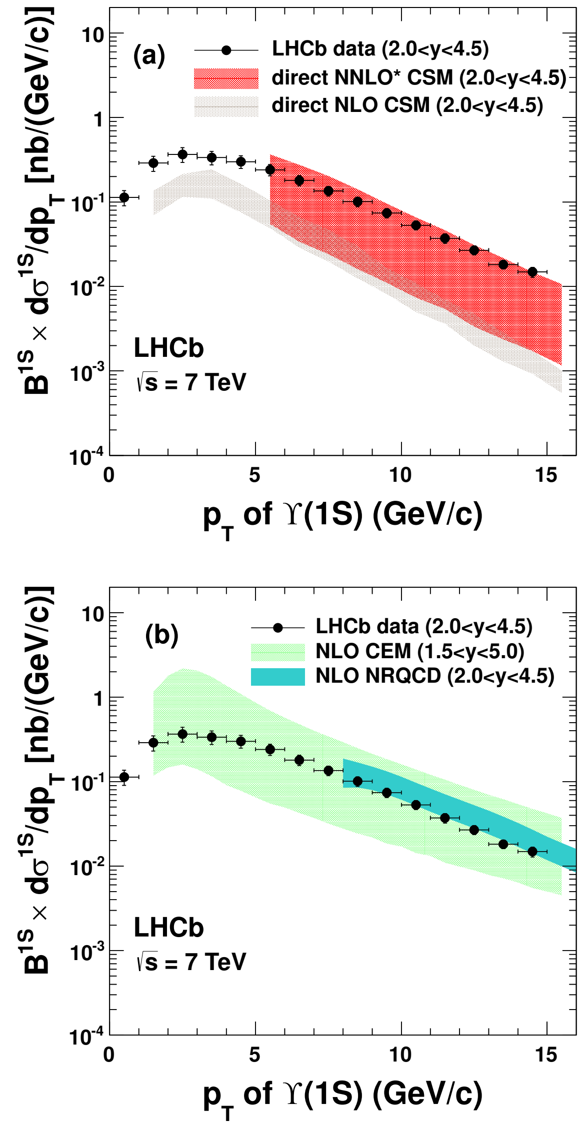
Magnet polarity **can be switched** when needed

Υ production in pp collisions at $\sqrt{s} = 13$ TeV

Motivations

LHCb-PAPER-2018-002

- Study of heavy quarkonium production in high-energy collisions provides information on QCD
- Several models proposed to describe underlying dynamics
  - Colour singlet model (CSM)
  - Non-relativistic QCD (NRQCD)
  - Colour Evaporation Model (CEM)
- Calculate ratio with respect to 7 and 8 TeV results → cancel majority of systematic uncertainties

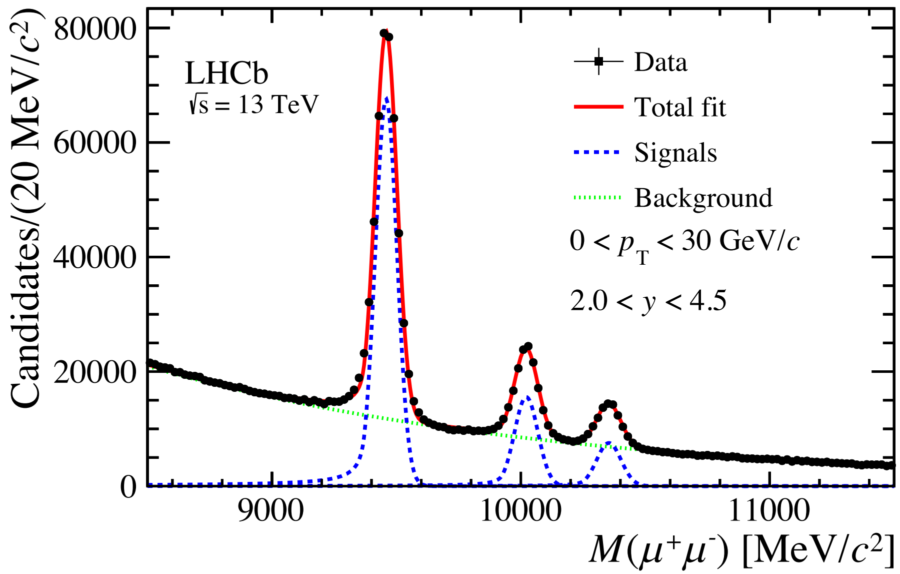


Eur. Phys. J. C72 (2012) 2025

Analysis strategy

LHCb-PAPER-2018-002

- Measure differential production cross-section as function of p_T and y multiplied by the $\Upsilon(nS) \to \mu^+\mu^-$ branching fractions
- Data sample
  - 277 pb^{-1} @ $\sqrt{s} = 13$ TeV



- Calculate

$$\frac{d^2\sigma}{dy\,dp_T} \times B(\Upsilon \to \mu^+\mu^-) = \frac{\boxed{N(p_T, y)}}{\boxed{L} \times \boxed{\varepsilon_{tot}(p_T, y)} \boxed{\times \Delta y \times \Delta p_T}}$$

Signal yields
$398 \cdot 10^3\ \Upsilon(1S)$
$100 \cdot 10^3\ \Upsilon(2S)$
$51 \cdot 10^3\ \Upsilon(3S)$

Total integrated luminosity

Total efficiency
- Detector acceptance, selection and trigger efficiencies from simulation
- Tracking efficiency from simulation and corrected with data-driven method
- Particle identification efficiency from calibration samples

Bin width

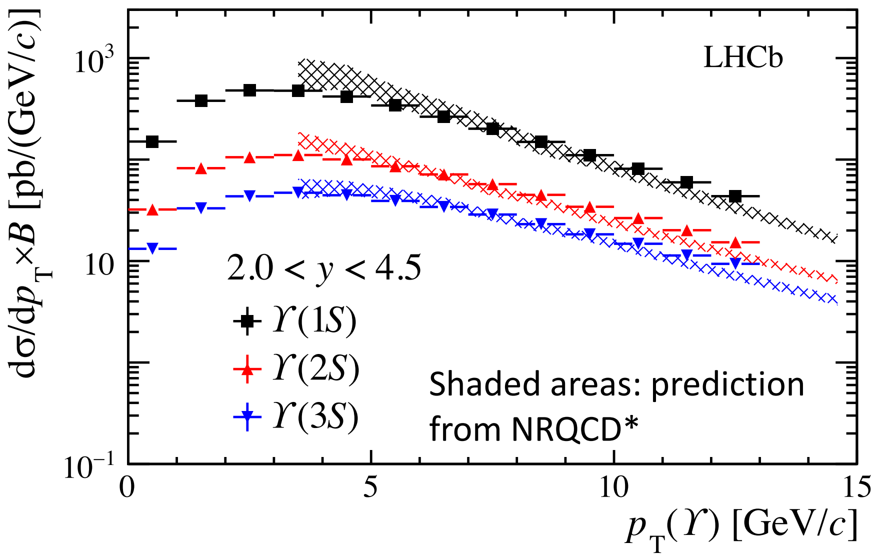
Results

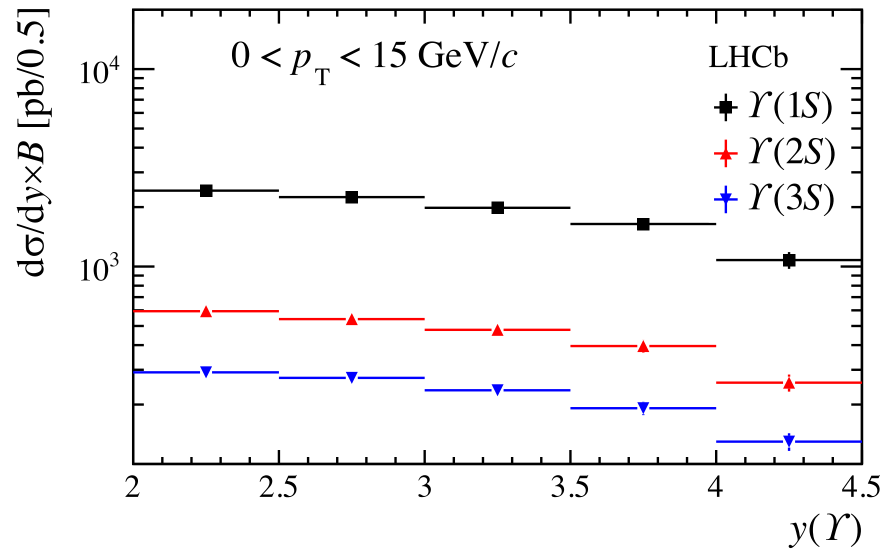
*Chinese Physics C 39 (2015) 12

LHCb-PAPER-2018-002

Integrated results

$$\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)\times\sigma(\Upsilon(1S),0<p_{\mathrm{T}}<15\,\mathrm{GeV}/c,2<y<4.5) = 4687\pm10\pm294\ \mathrm{pb}$$
$$\mathcal{B}(\Upsilon(2S)\to\mu^+\mu^-)\times\sigma(\Upsilon(2S),0<p_{\mathrm{T}}<15\,\mathrm{GeV}/c,2<y<4.5) = 1134\pm6\pm71\ \mathrm{pb}$$
$$\mathcal{B}(\Upsilon(3S)\to\mu^+\mu^-)\times\sigma(\Upsilon(3S),0<p_{\mathrm{T}}<15\,\mathrm{GeV}/c,2<y<4.5) = 561\pm4\pm36\ \mathrm{pb}$$





- Measurements are dominated by systematic uncertainty
  - Main contribution due to trigger efficiency and luminosity determination
- Prediction from NRQCD provides a reasonable description of data at high p_T

Ratios

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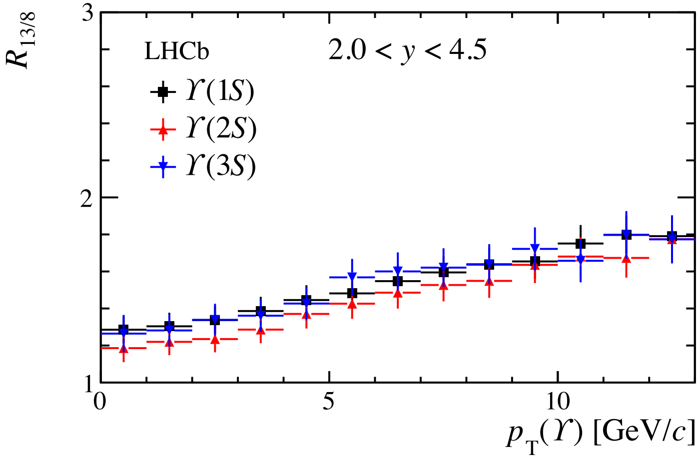
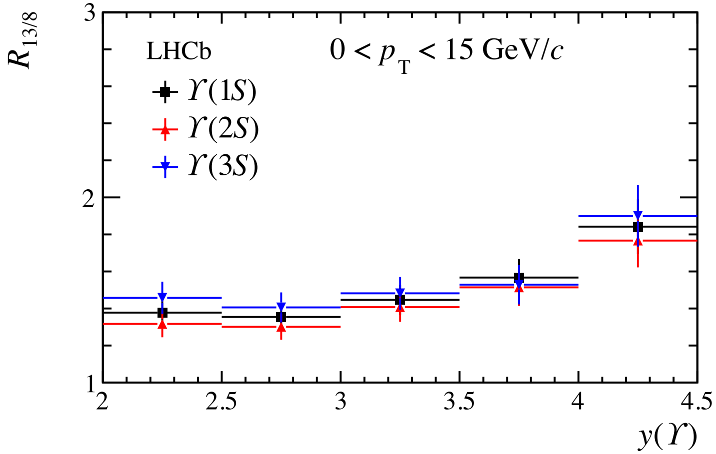
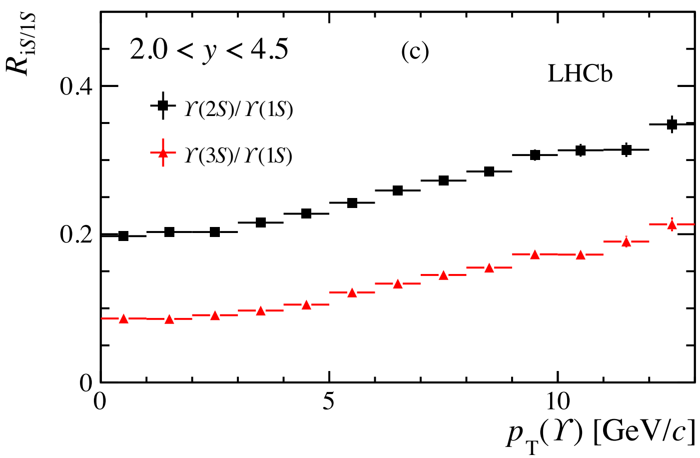
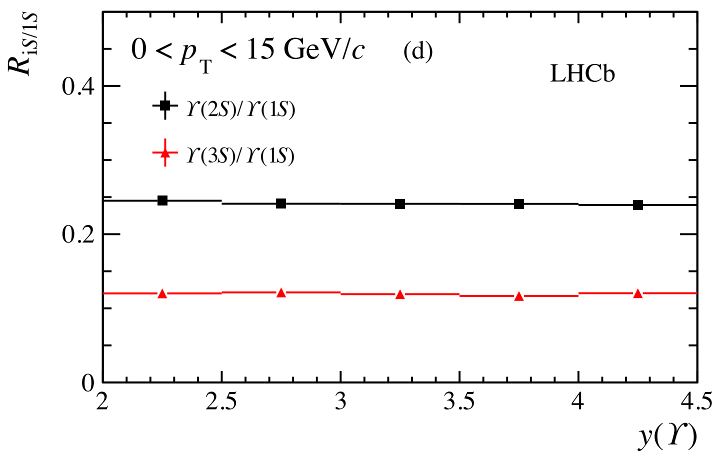
- 13/8 TeV ratio increasing as a function of p_T and y





- iS to 1S ratio increasing as function of p_T and flat as function of y





B^+ production cross-section in pp collision at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV

Motivations

JHEP 12 (2017) 026

- Precise measurement of production cross-section of B^+ mesons provides important test for QCD calculations
- Complementary phase-space with respect to ATLAS and CMS allow to test theory at low p_T/high y
- Possibility to measure ratios at different centre-of-mass energies to largely cancel theory and experimental uncertainties

Current experimental status

	Luminosity	$\sqrt{s}$ (TeV)	Range	Cross Section (μb)
CDF [2]	$739\,\mathrm{pb}^{-1}$	1.96	$p_T > 6\,\mathrm{GeV}/c$, $\|y\| < 1$	2.78 ± 0.24
CMS [3]	$5.8\,\mathrm{pb}^{-1}$	7	$p_T > 5\,\mathrm{GeV}/c$, $\|y\| < 2.4$	$28.1 \pm 2.4 \pm 2.0 \pm 3.1$
ATLAS [4]	$2.4\,\mathrm{fb}^{-1}$	7	$9 < p_T < 120\,\mathrm{GeV}/c$, $\|y\| < 2.25$	$10.6 \pm 0.3 \pm 0.7 \pm 0.2 \pm 0.4$
LHCb [5]	$35\,\mathrm{pb}^{-1}$	7	$0 < p_T < 40\,\mathrm{GeV}/c$, $2 < y < 4.5$	$41.5 \pm 1.5 \pm 3.1$
LHCb [6]	$362\,\mathrm{pb}^{-1}$	7	$0 < p_T < 40\,\mathrm{GeV}/c$, $2 < y < 4.5$	$38.9 \pm 0.3 \pm 2.8$

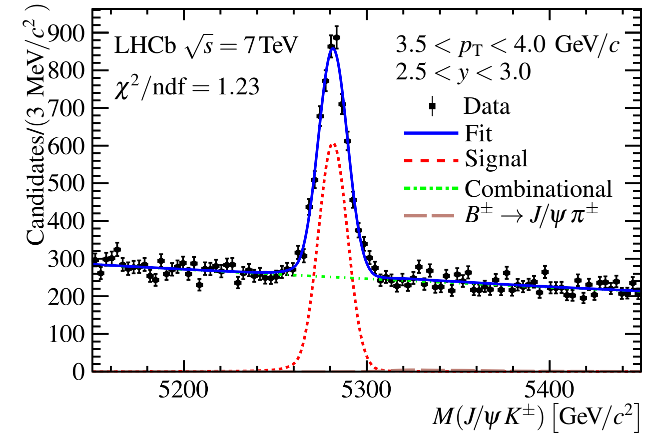
[2] Phys. Rev. D75 (2007) 012010
[3] Phys. Rev. Lett. 106 (2011) 112001
[4] JHEP 10 (2013) 042
[5] JHEP 04 (2012) 93
[6] JHEP 08 (2013) 117

Analysis

JHEP 12 (2017) 026

- Data sample
  - 1 fb^{-1} @ $\sqrt{s} = 7$ TeV
  - 0.3 fb^{-1} @ $\sqrt{s} = 13$ TeV

Signal yields in each bin obtained by means of extended unbinned maximum likelihood fits to $m(J/\psi K^{\pm})$ distribution



- Master formula

$$\frac{d^2\sigma}{dy\,dp_T} = \frac{N_{B^{\pm}}}{\mathcal{L} \times \varepsilon_{tot} \times \mathcal{B}(B^{\pm} \to J/\psi K^{\pm}) \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

Total integrated luminosity

Obtained combining Belle* and BaBar** measurements

Taken from PDG

Bin width

Total efficiency
- Detector acceptance, selection and trigger efficiencies from simulation
- Tracking efficiency from simulation and corrected with data-driven method
- Particle identification efficiency from calibration samples

*Phys. Rev. D67 (2003) 032003
**Phys. Rev. Lett. 94 (2005) 141801

Results

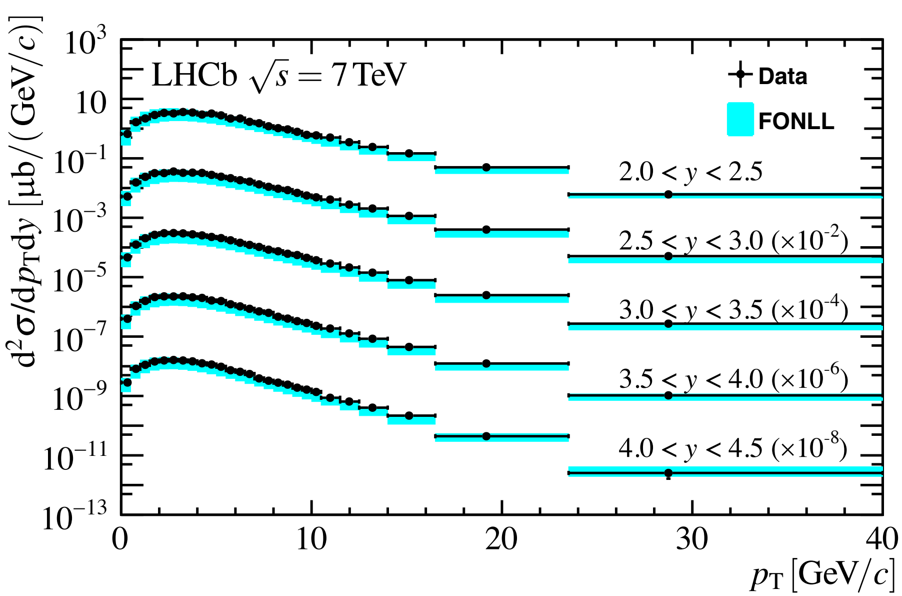
JHEP 12 (2017) 026

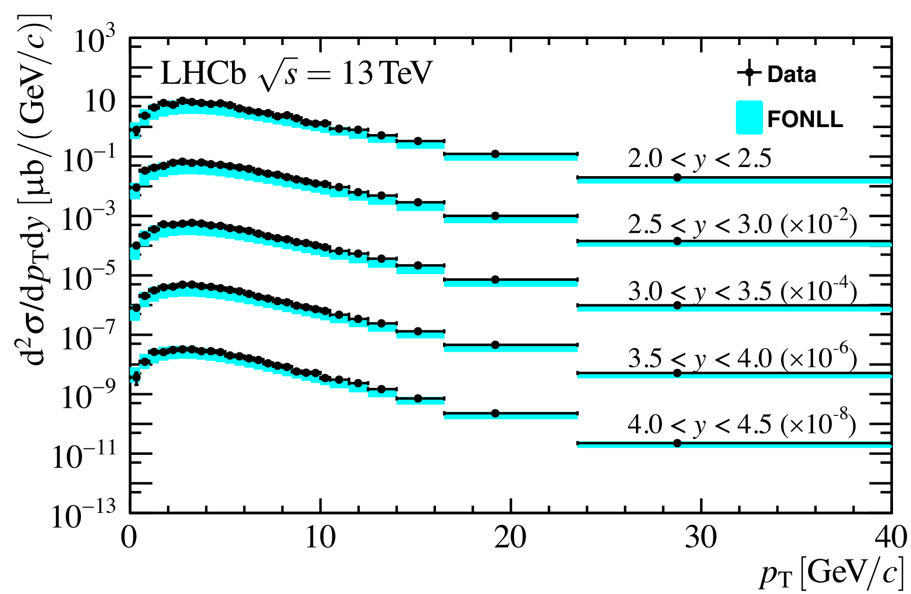
Integrated results

$$\sigma(pp \to B^{\pm}X, \sqrt{s} = 7\,\text{TeV}) = 43.0 \pm 0.2 \pm 2.5 \pm 1.7\,\mu\text{b}$$

$$\sigma(pp \to B^{\pm}X, \sqrt{s} = 13\,\text{TeV}) = 86.6 \pm 0.5 \pm 5.4 \pm 3.4\,\mu\text{b}$$

- The results are in good agreement with FONLL predictions



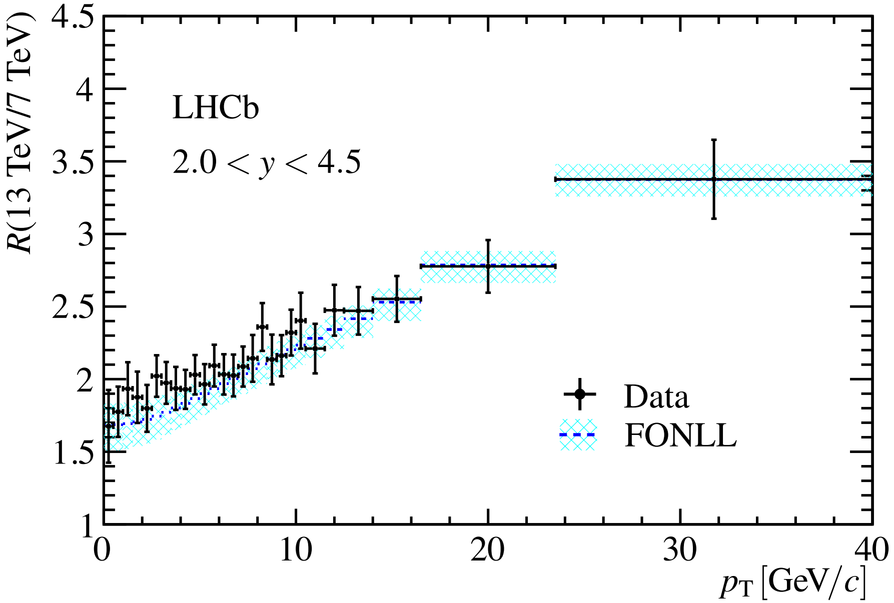


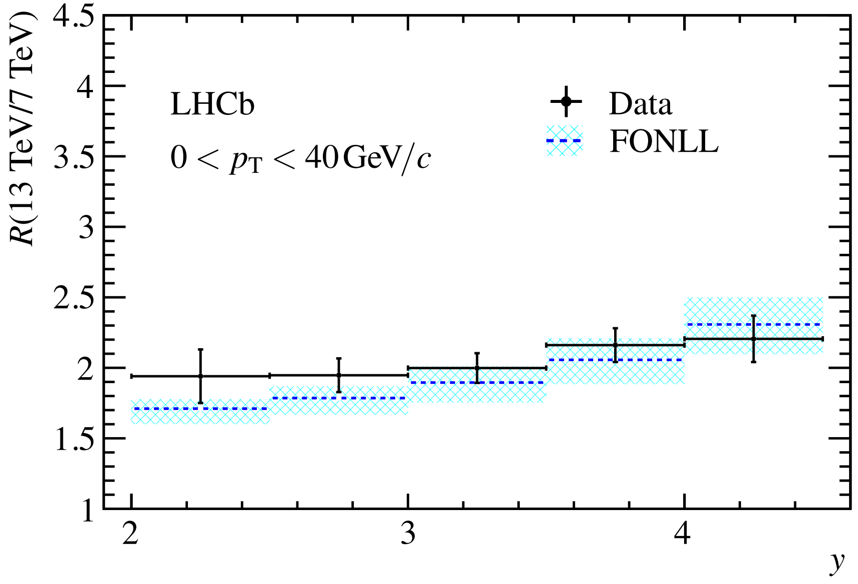
FONLL predictions: Eur. Phys. J C75 (2015) 610

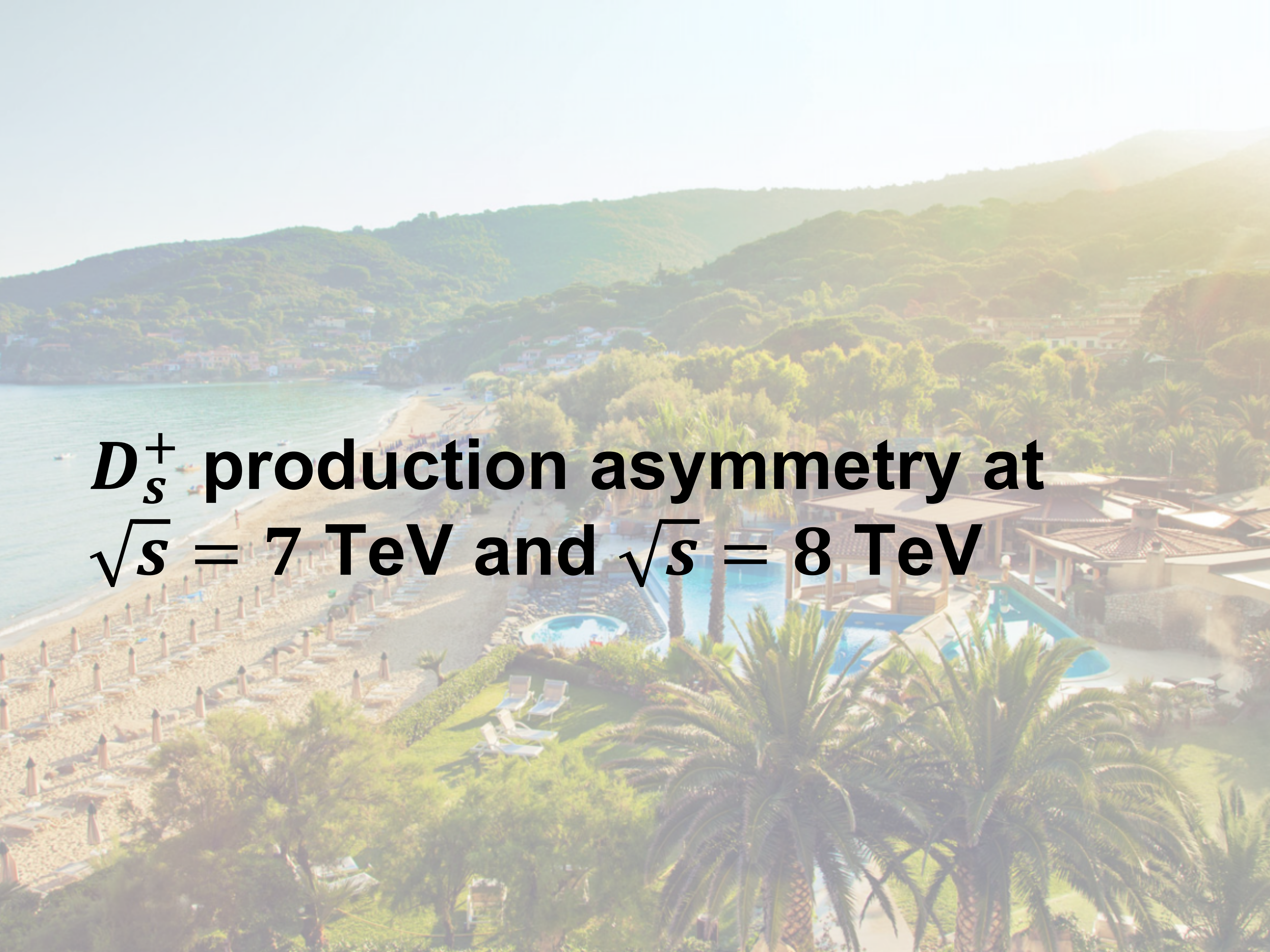
13/7 TeV ratio

JHEP 12 (2017) 026

- Also the ratio at the two different centre-of-mass energies (13 and 7 TeV) is compatible with FONLL predictions
  - FONLL predictions from Eur. Phys. J C75 (2015) 610





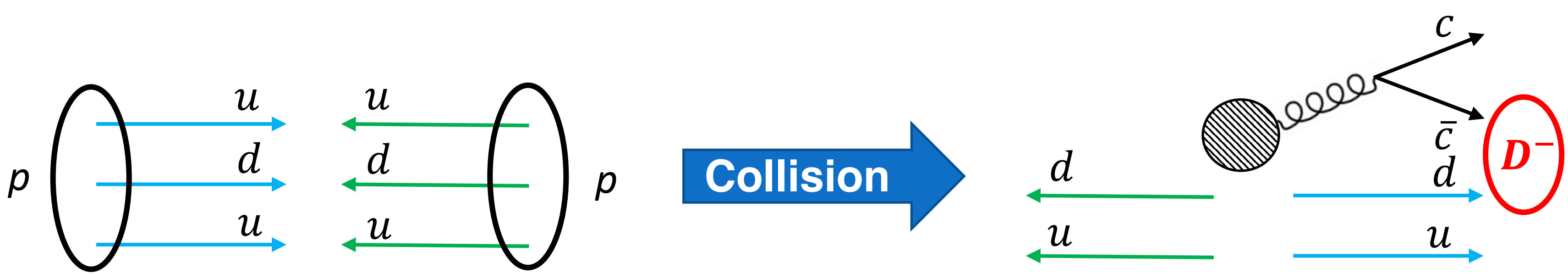


D_s^+ production asymmetry at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV

Motivation

LHCb-PAPER-2018-010

- b and c-hadrons are **not expected** to be produced at the **same rate** with respect to $\bar{b}$ and $\bar{c}$-hadrons in ***pp* collisions**
  - u and d quarks from the **remnants** of the colliding protons can combine with $\bar{b}$ and $\bar{c}$ quarks to form a **meson**, whereas the opposite **can't happen**
  - This has to be **compensated** by an opposite asymmetry in the other **species**



- Production asymmetry measurements are a **key ingredient** to perform **CP violation** measurements
  - One needs to disentangle the physical CP asymmetry from **other spurious effects**
- Production asymmetries are defined as:

$$A_P(D^+_{(s)}) = \frac{\sigma(D^+_{(s)}) - \sigma(D^-_{(s)})}{\sigma(D^+_{(s)}) + \sigma(D^-_{(s)})}$$

where σ is the inclusive prompt production cross-section

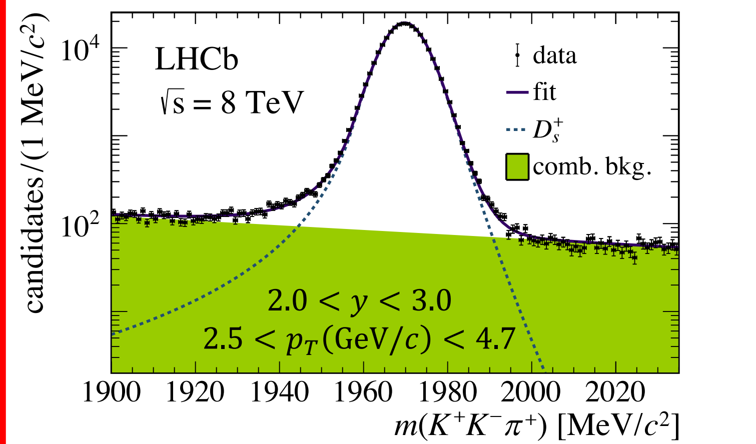
Analysis

*Phys. Rev. D95 (2017) 052005
Phys. Lett. B774 (2017) 139
Phys. Rev. Lett. 114 (2015) 041601

LHCb-PAPER-2018-010

- Data sample: $D_s^+ \to \phi(\to K^+K^-)\pi^+$
  - 1 fb^{-1} @ $\sqrt{s} = 7$ TeV
  - 2 fb^{-1} @ $\sqrt{s} = 8$ TeV
- Production asymmetry can be expressed as the sum of various components

Raw asymmetry measured by means of binned maximum-likelihood fits to invariant-mass spectra



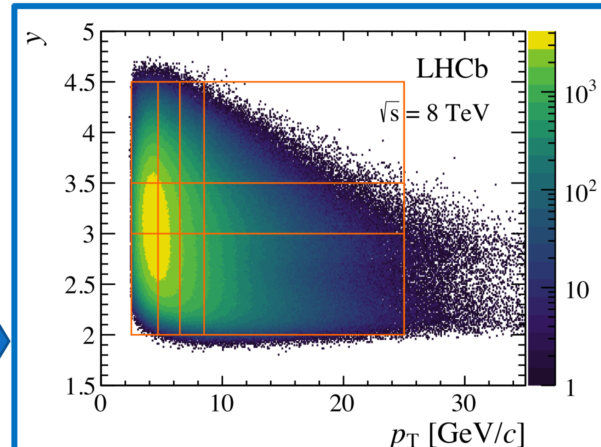
$$A_P(D_s^+) = \frac{1}{1 - \boxed{f_{bkg}}}\left(\boxed{A_{raw}} - \boxed{A_D} - f_{bkg}\boxed{A_P(B)}\right)$$

Fraction of secondary D_s^+ decays

Sum of various detection asymmetries

b-hadron production asymmetry*

Measurement performed as a function of p_T and y



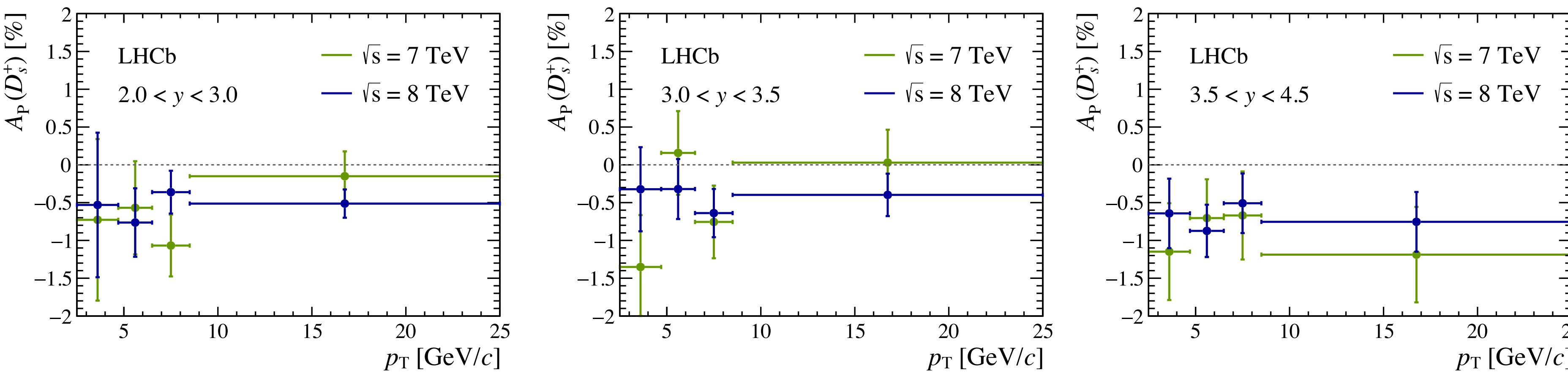
Results

LHCb-PAPER-2018-010

- Integrating in the range $2.5 < p_T(\mathrm{GeV}/c) < 25$ and $2.0 < y < 4.5$ the D_s^+ production asymmetry is found to be

$$A_P(D_s^+) = \big(-0.52 \pm 0.13\ (\mathrm{stat}) \pm 0.10(\mathrm{syst})\big)\%$$

- Evidence for nonzero asymmetry at 3.3σ level
- No dependence on kinematics observed



Comparison with Pythia 8.1

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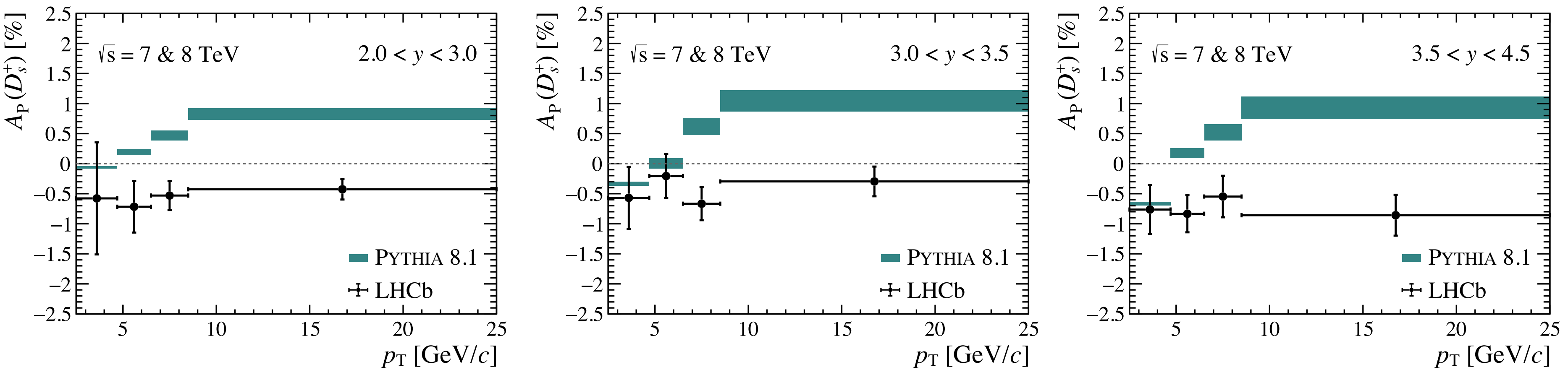
- The Pythia event generator includes models accounting for mechanisms that cause production asymmetries
- Pythia simulation shows a strong dependence on both p_T and y, that is not observed in data



- Results obtained in this analysis can be used to tune production models for various event generators

Conclusions

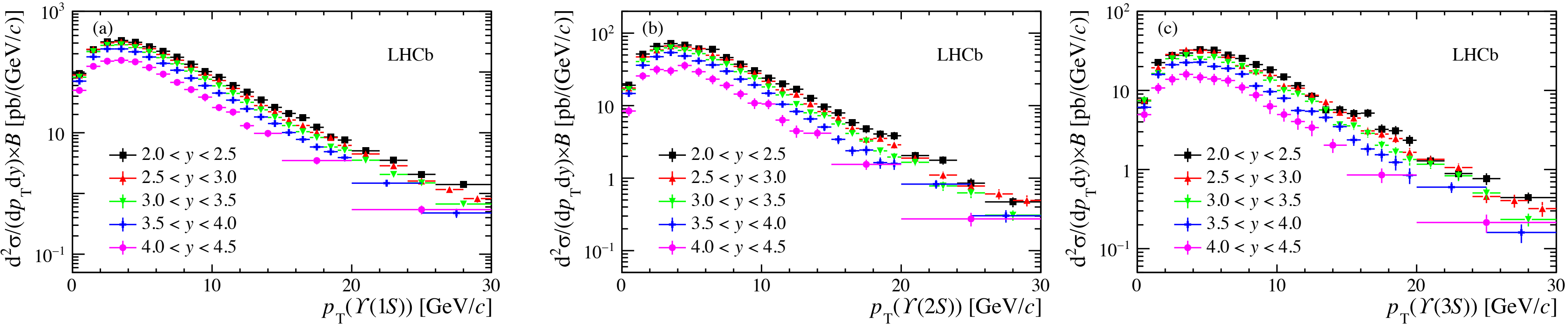
- Several results presented today, exploiting both Run 1 and Run 2 data samples collected by LHCb
- LHCb is testing theoretical model predictions in a unique kinematic region
  - Interplay with theory community very important
- Many more measurements are coming, using Run 2 and 5 TeV data sets
- Run 2 samples allow to perform analyses in final states that were limited by statistics in Run 1
- Several new results are coming this summer… stay tuned…!

Thanks for your attention!

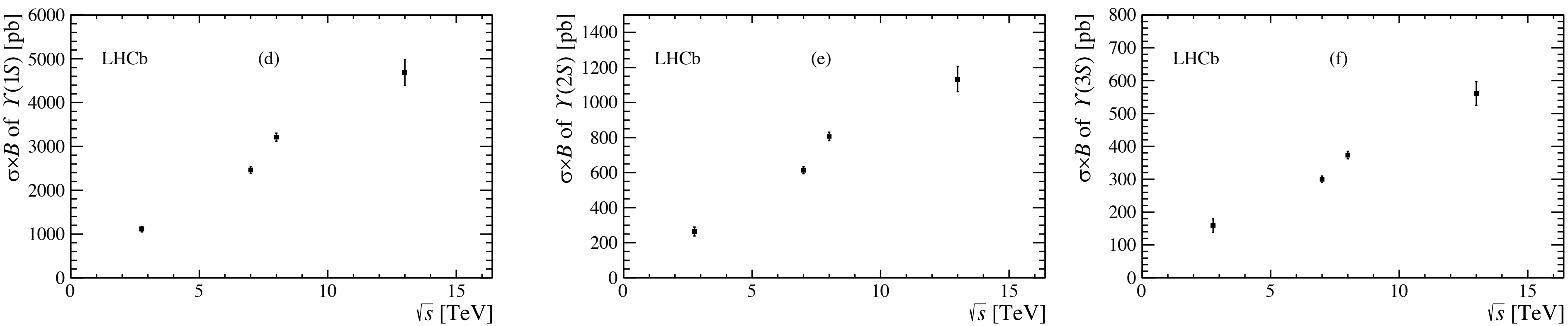
Backup

$\Upsilon(nS)$ production

- Double-differential cross-sections multiplied by dimuon branching fractions as a function of p_T



- Production cross-sections multiplied by dimuon branching fractions integrated over $0 < p_T(\mathrm{GeV}/c) < 15$ and $2.0 < y < 4.5$



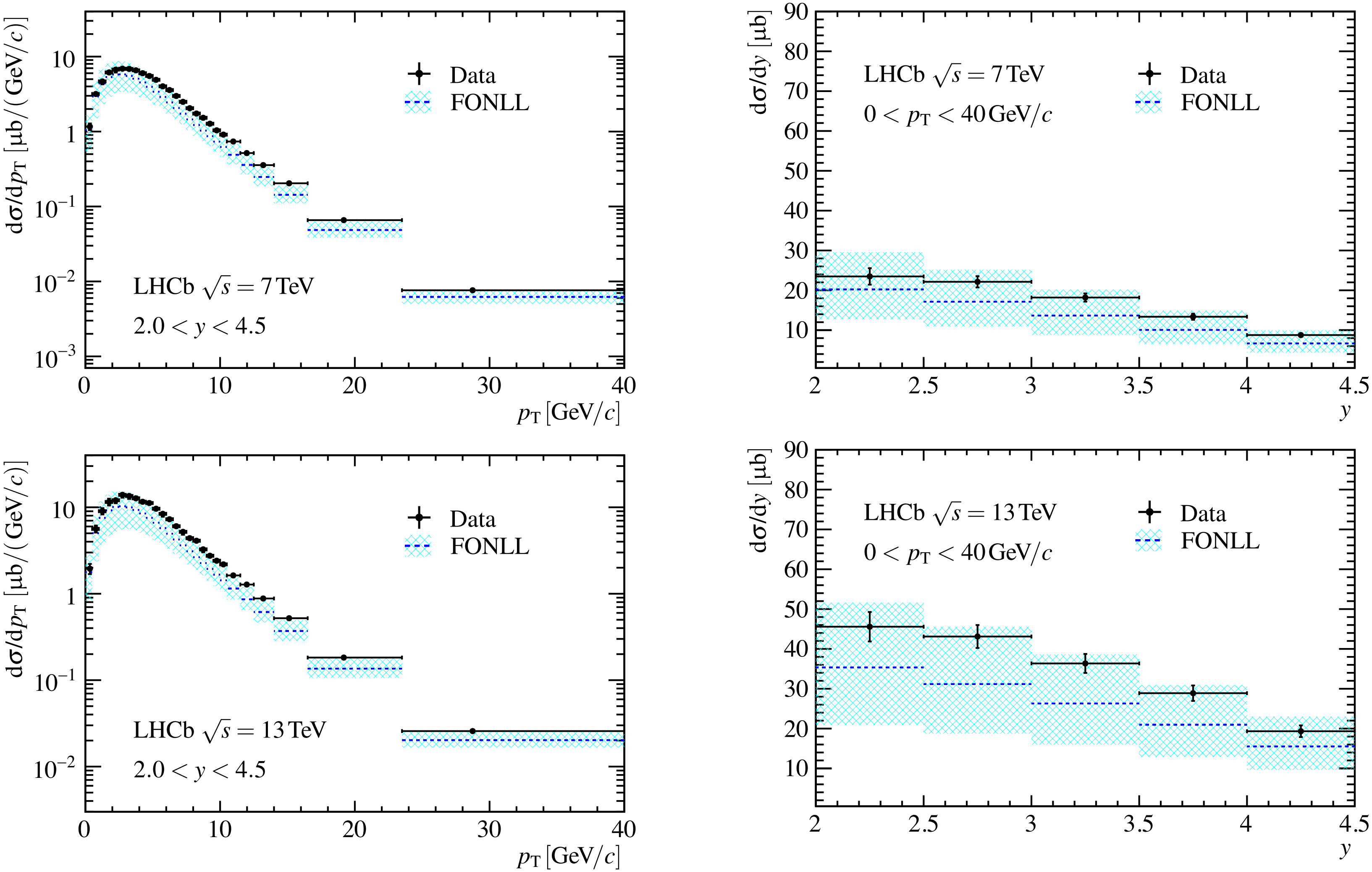
$\Upsilon(nS)$ production

- Summary of systematic uncertainties

Source	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Comment
Fit models	1.9	1.8	2.5	Correlated
Simulation statistics	$0.4-4.6$	$0.5-5.1$	$0.5-4.4$	Bin dependent
Global event requirements	0.6	0.6	0.6	Correlated
Trigger	$3.9-9.8$	$3.9-9.8$	$3.9-9.8$	Bin dependent
Tracking	$(0.1-6.6)$ $\oplus 2\times 0.8$	$(0.2-6.4)$ $\oplus 2\times 0.8$	$(0.2-6.5)$ $\oplus 2\times 0.8$	Correlated
Muon identification	$0.1-7.9$	$0.1-7.6$	$0.2-8.5$	Correlated
Vertexing	0.2	0.2	0.2	Correlated
Kinematic spectrum	$0.0-1.1$	$0.0-2.2$	$0.0-2.5$	Bin dependent
Radiative tail	1.0	1.0	1.0	Correlated
Luminosity	3.9	3.9	3.9	Correlated
Total	$6.2-14.3$	$6.2-14.6$	$6.4-14.9$	Correlated

B^+ production cross-section

- Measured differential cross-section as a function of p_T and y



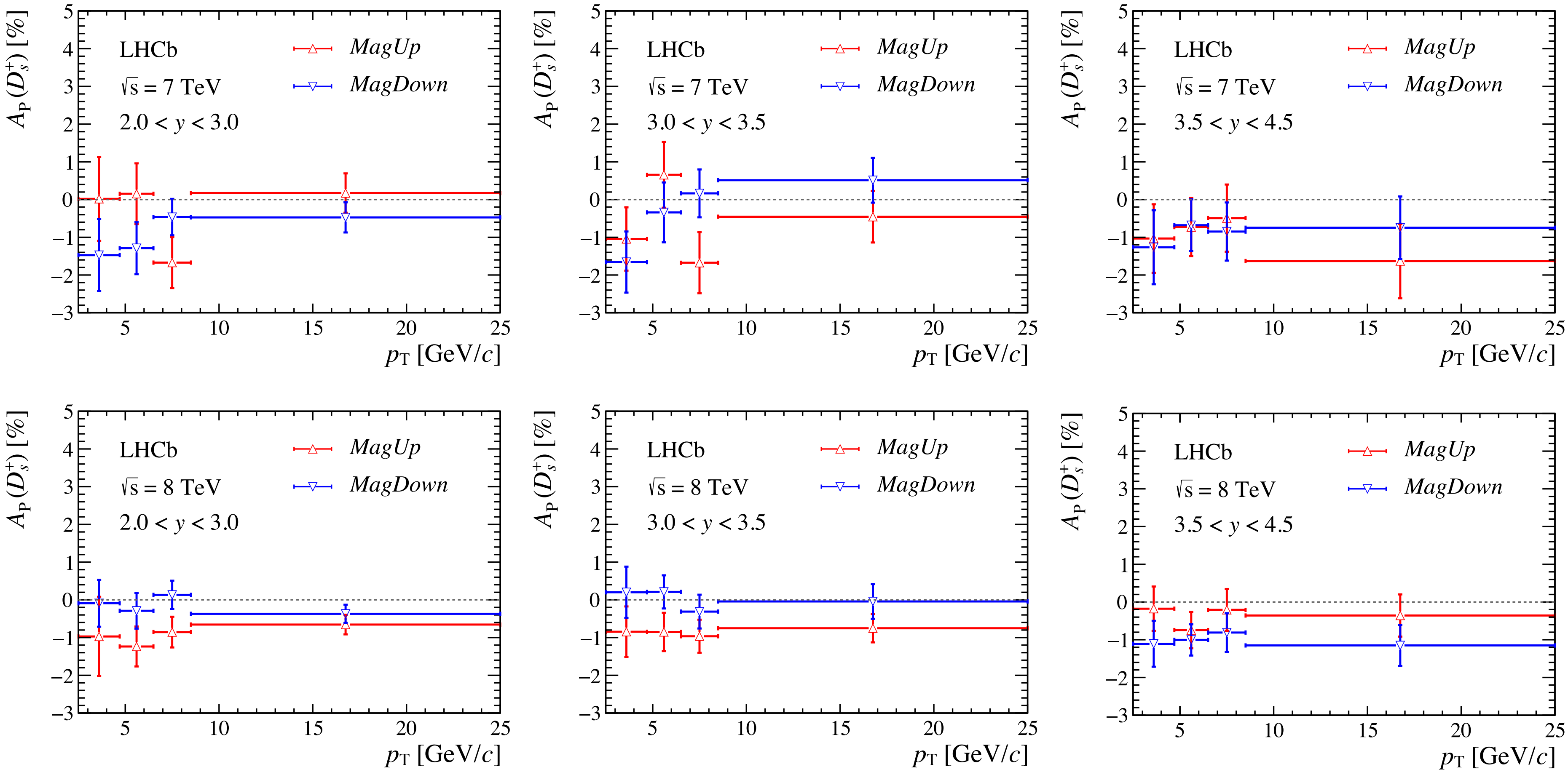
B^+ production cross-section

- Summary of systematic uncertainties

Sources	Uncertainty (%) 7 TeV	13 TeV	R(13 TeV/7 TeV)
Luminosity	1.7	3.9	3.4
Branching fractions	3.9	3.9	0.0
Binning	2.6	2.7	0.0
Mass fits	2.7	1.3	1.5
Acceptance	0.2	0.1	0.2
Reconstruction	0.1	0.1	0.2
Track	1.6	2.6	1.0
PID	0.4	0.1	0.4
Trigger	3.5	2.6	4.4
GEC	0.7	0.7	1.0
Selection	1.0	1.1	0.1
Weighting	0.2	0.2	0.3
Total	7.0	7.4	5.9

D_s^+ production asymmetry

- Production asymmetry as a function of p_T in bins of y, separated by magnet polarity



D_s^+ production asymmetry

- Numerical results

7 TeV

p_T [GeV/c]	y: 2.0 – 3.0	y: 3.0 – 3.5	y: 3.5 – 4.5
2.5 – 4.7	$-0.73 \pm 0.62 \pm 0.87$	$-1.35 \pm 0.55 \pm 0.41$	$-1.15 \pm 0.60 \pm 0.23$
4.7 – 6.5	$-0.57 \pm 0.51 \pm 0.35$	$0.16 \pm 0.49 \pm 0.25$	$-0.70 \pm 0.48 \pm 0.17$
6.5 – 8.5	$-1.07 \pm 0.40 \pm 0.08$	$-0.76 \pm 0.47 \pm 0.09$	$-0.67 \pm 0.56 \pm 0.16$
8.5 – 25.0	$-0.15 \pm 0.32 \pm 0.08$	$0.03 \pm 0.42 \pm 0.11$	$-1.19 \pm 0.63 \pm 0.09$

8 TeV

p_T [GeV/c]	y: 2.0 – 3.0	y: 3.0 – 3.5	y: 3.5 – 4.5
2.5 – 4.7	$-0.53 \pm 0.40 \pm 0.87$	$-0.32 \pm 0.37 \pm 0.41$	$-0.64 \pm 0.40 \pm 0.23$
4.7 – 6.5	$-0.76 \pm 0.29 \pm 0.35$	$-0.32 \pm 0.30 \pm 0.25$	$-0.87 \pm 0.30 \pm 0.17$
6.5 – 8.5	$-0.36 \pm 0.27 \pm 0.08$	$-0.64 \pm 0.31 \pm 0.09$	$-0.51 \pm 0.36 \pm 0.16$
8.5 – 25.0	$-0.51 \pm 0.17 \pm 0.08$	$-0.40 \pm 0.26 \pm 0.11$	$-0.75 \pm 0.39 \pm 0.09$

7+8 TeV

p_T [GeV/c]	y: 2.0 – 3.0	y: 3.0 – 3.5	y: 3.5 – 4.5
2.5 – 4.7	$-0.58 \pm 0.34 \pm 0.87$	$-0.57 \pm 0.31 \pm 0.41$	$-0.76 \pm 0.34 \pm 0.23$
4.7 – 6.5	$-0.72 \pm 0.25 \pm 0.35$	$-0.21 \pm 0.26 \pm 0.25$	$-0.83 \pm 0.26 \pm 0.17$
6.5 – 8.5	$-0.53 \pm 0.23 \pm 0.08$	$-0.67 \pm 0.26 \pm 0.09$	$-0.55 \pm 0.30 \pm 0.16$
8.5 – 25.0	$-0.43 \pm 0.15 \pm 0.08$	$-0.30 \pm 0.22 \pm 0.11$	$-0.86 \pm 0.33 \pm 0.09$