Electroweak and Charm Production Measurements at LHCb

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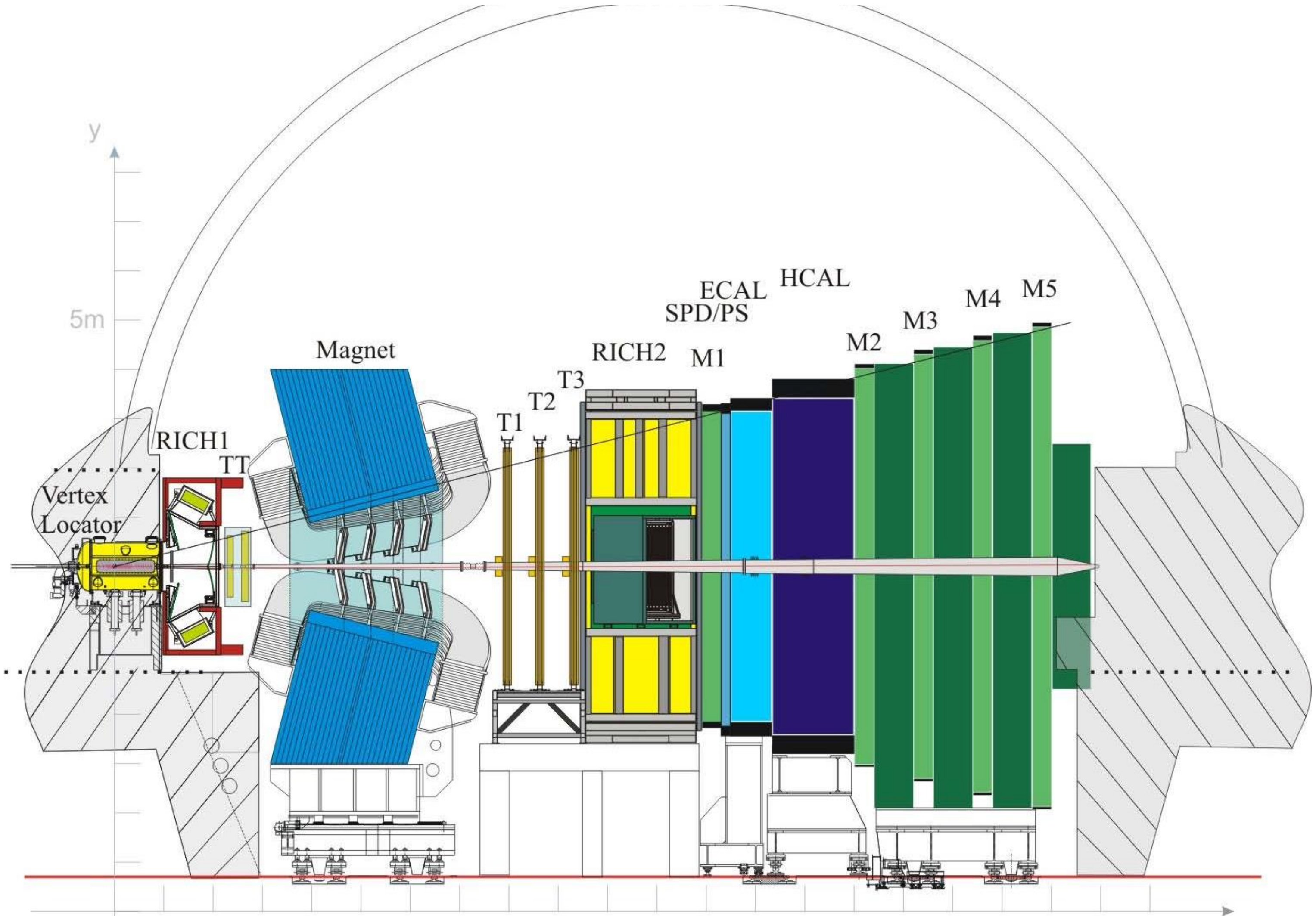
Outline

- LHCb detector
- Motivation for PDFs
- Kinematic coverage
- Recent EW results:
  - W and Z production
- Recent charm results:
  - Inclusive J/ψ and exclusive J/ψ and ψ(2s)
  - Prompt D production at 5 and 13 TeV
- Future outlook at LHCb
- Summary

LHCb Experiment

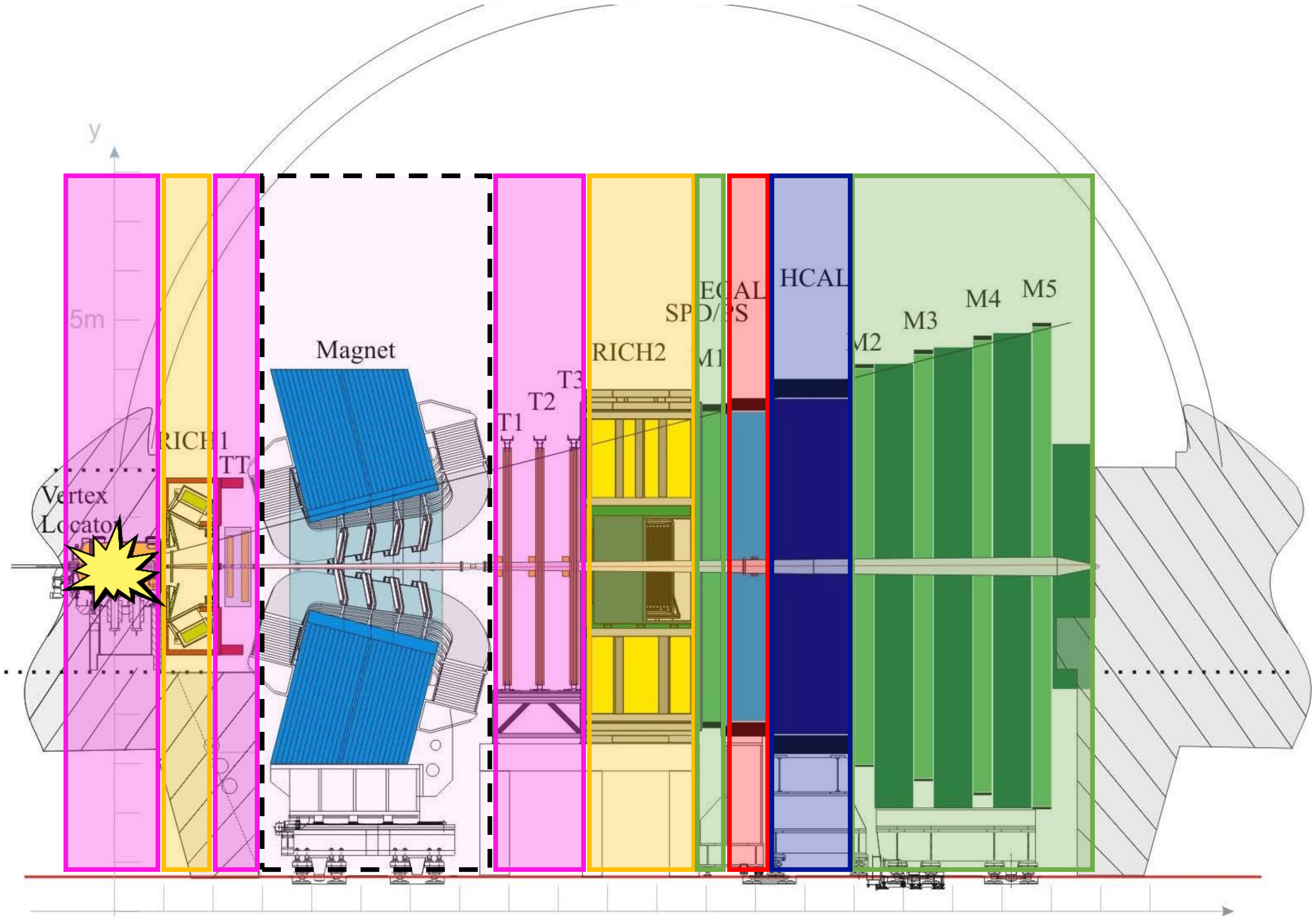
JINST 3 (2008) S08005



- Fully instrumented single-arm forward spectrometer

LHCb Experiment

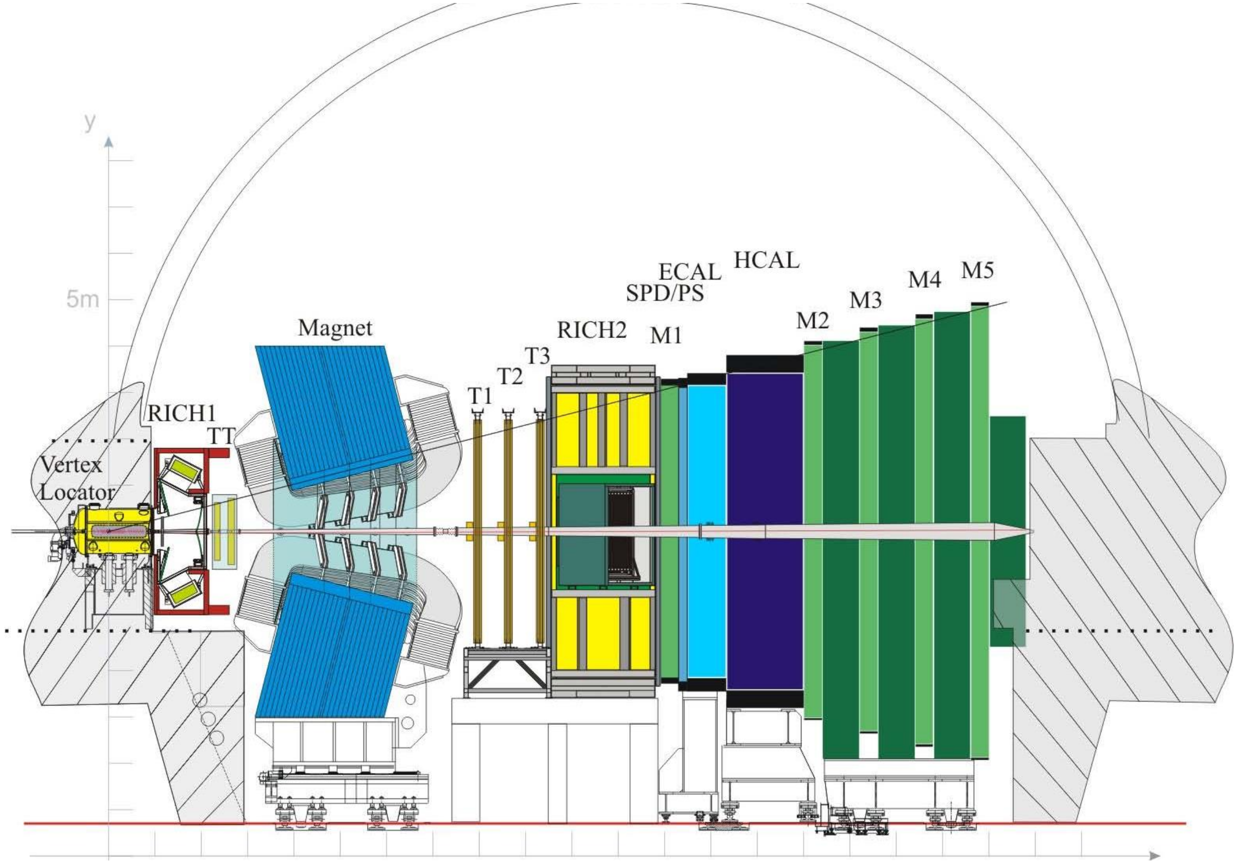
JINST 3 (2008) S08005



- interaction point
- Tracking system
- Hadron PID
- Electromagnetic calorimeter
- Hadronic calorimeter
- Muon stations
- Dipole magnet

LHCb Experiment

JINST 3 (2008) S08005



❖ Fully instrumented in **2 < η < 5**

- \+ Excellent vertex resolution
- \+ Good lepton and hadron ID
- \+ Low pile-up
- \+ Great lumi. determination
- +– Unique acceptance; not 4π
- \+ VELO backwards coverage -3.5 < η < -1.5
- – Cannot use E-miss or p_T-miss
- – Low instantaneous lumi.

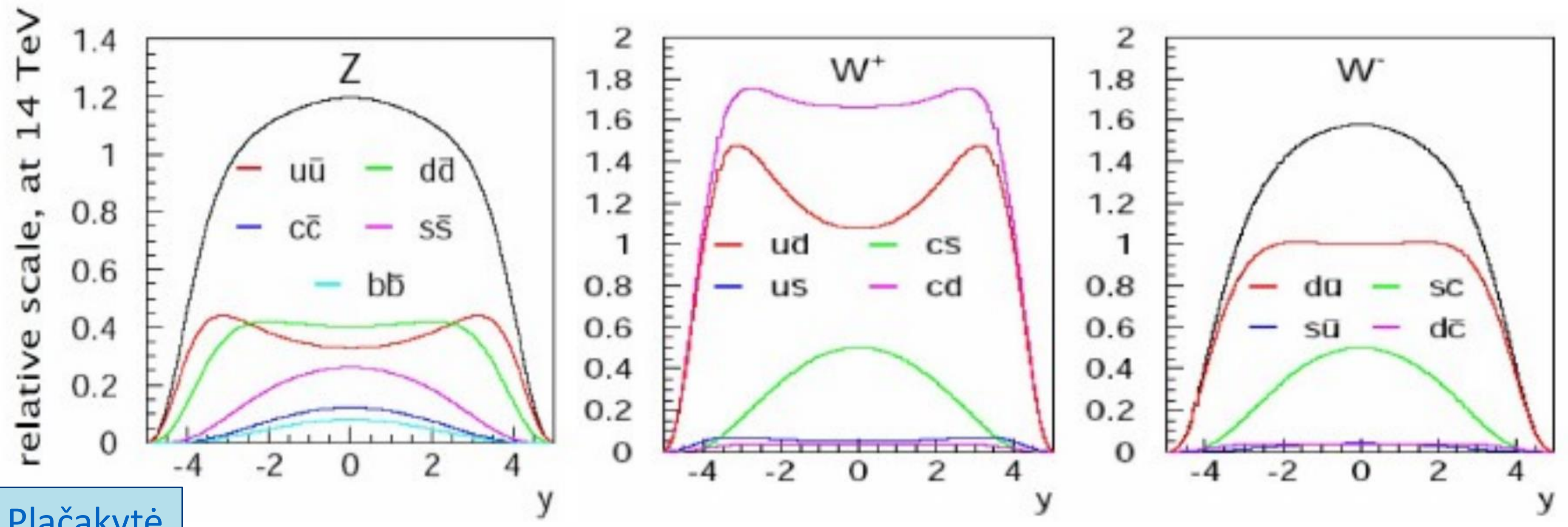
- Data Sets:
  - 7 TeV (2011): 1.0 fb^{-1} ± 1.7 %
  - 8 TeV (2012): 2.0 fb^{-1} ± 1.2 %
  - 13 TeV (2015+2016): ~2.0 fb^{-1} ± xx%

Motivation for PDFs

- Theoretical predictions for production of EW bosons are determined from parton-parton cross-sections convolved with parton distribution functions (PDFs)

$$\underbrace{\sigma(x,Q^2)}_{hadronic\ x-sec.} = \sum_{a,b} \int_0^1 dx_1\, dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs} \times \underbrace{\hat{\sigma}(x_1, x_2, Q^2)}_{partonic\ x-sec}$$

- Measurements of EW boson and other particle production cross-sections at LHCb can be invaluable tools for constraining PDFs

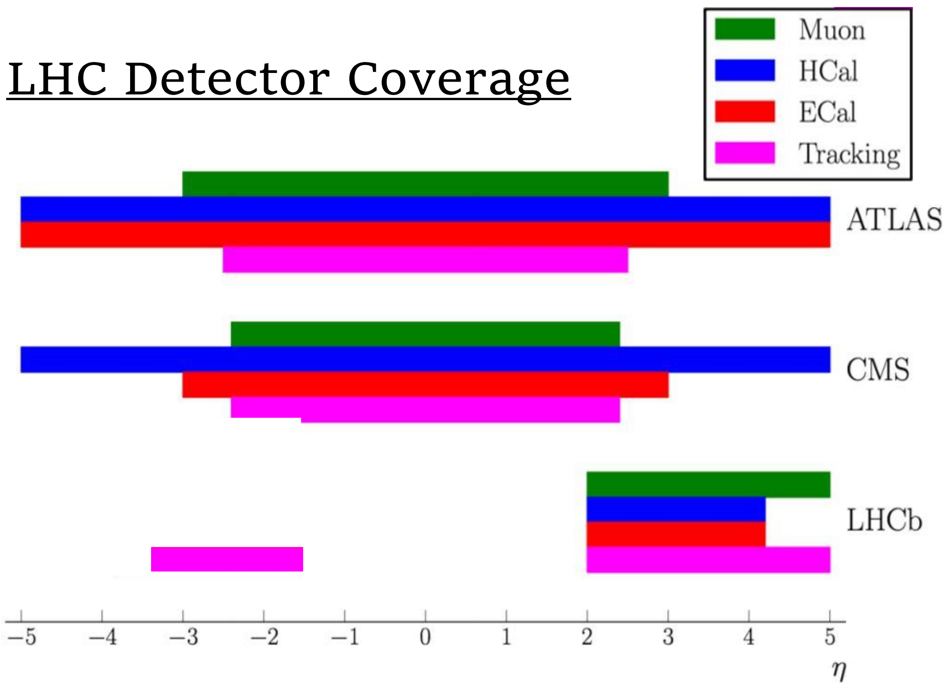


First generation quarks dominate W production; Z produced by all flavours

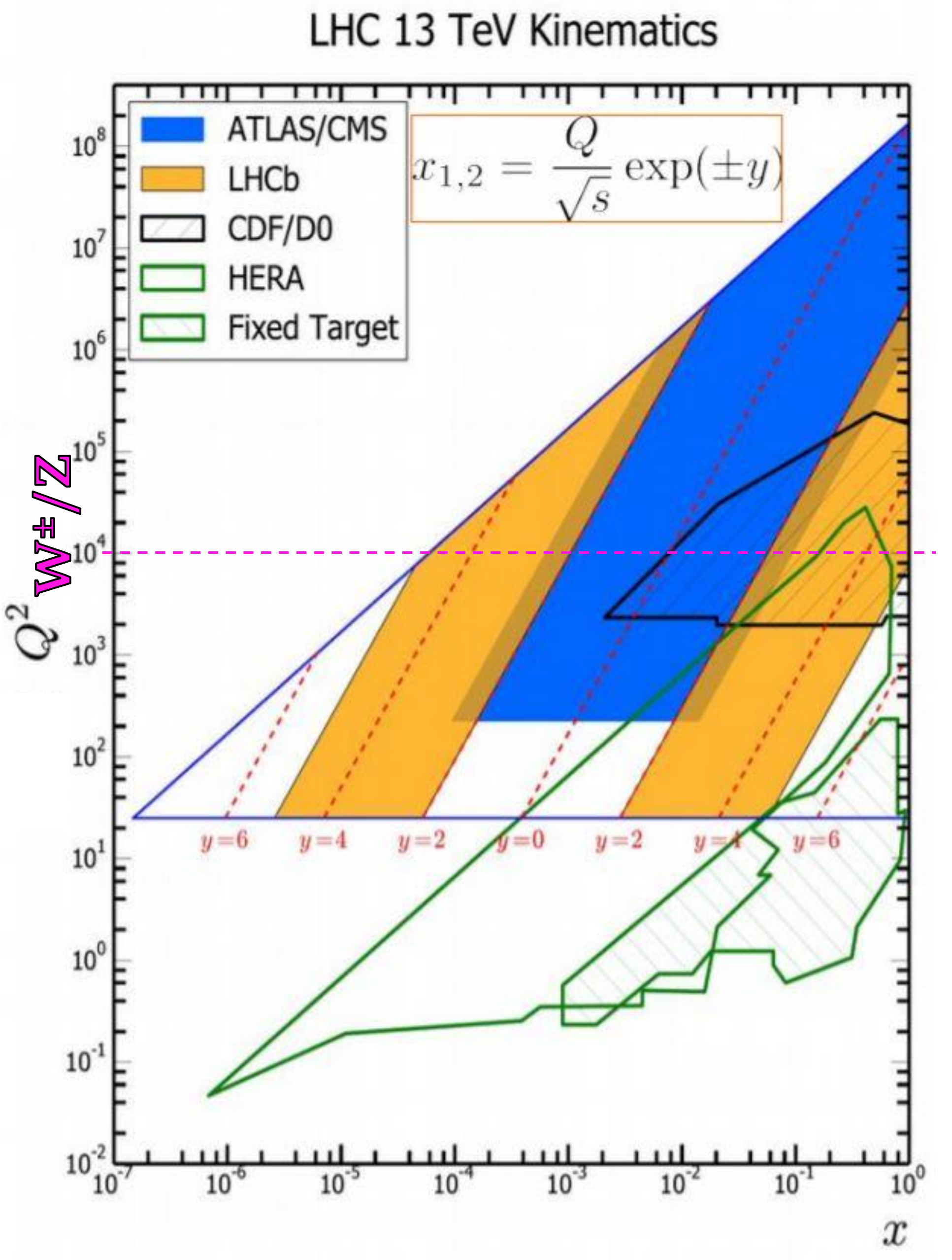
R.Plačakytė

Kinematic Coverage

LHC Detector Coverage



$$\eta = -ln\left(tan\frac{\theta}{2}\right)$$



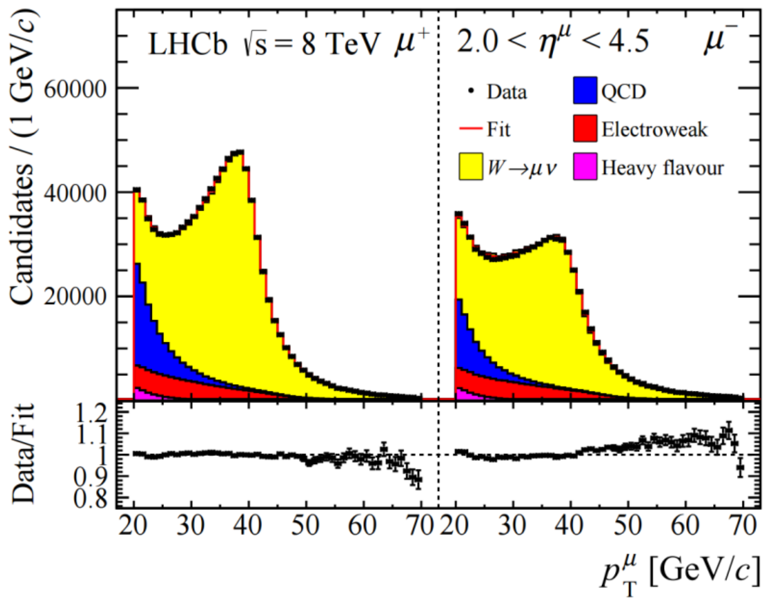
- **Unique kinematic coverage** in x-Q^2 plane at the LHC
- High Björken-x range covered by the fixed target experiments
- LHCb can probe the phase-space for **Björken-x down to x≈10^{-5}**!

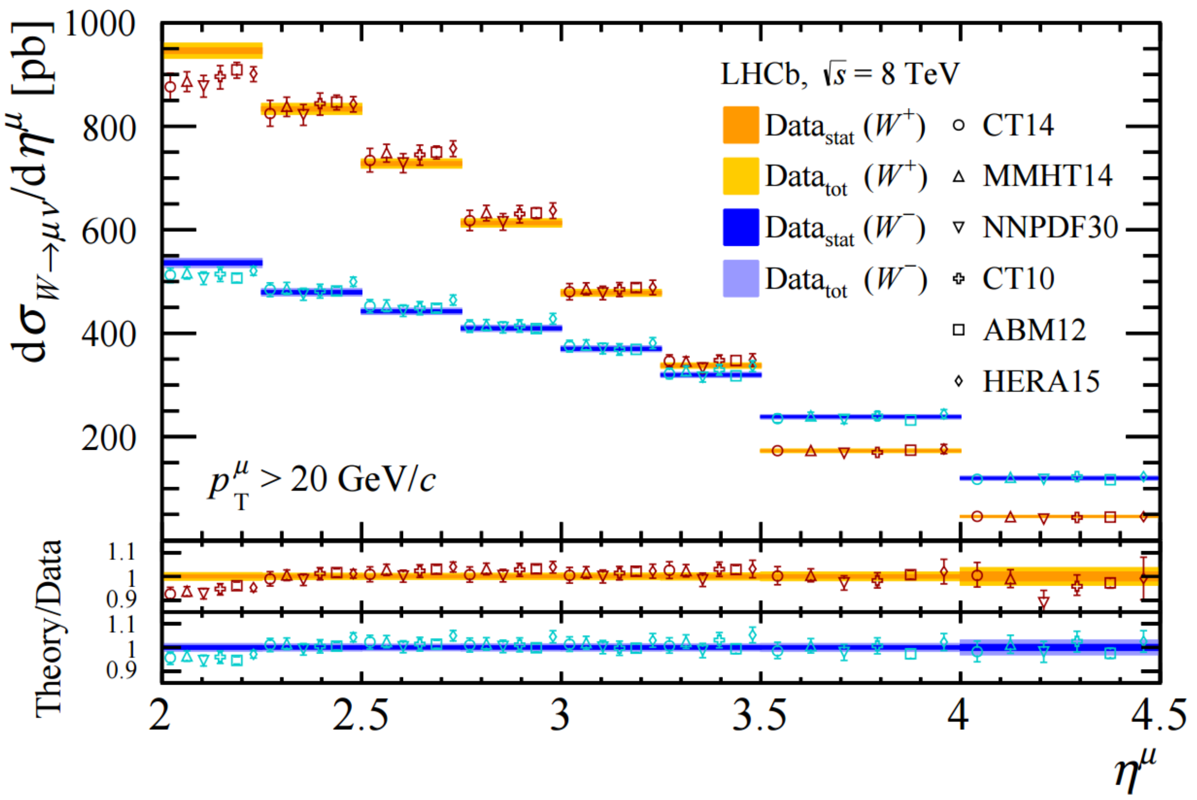
Electroweak Results

Electroweak: $W \rightarrow \mu\nu$ @ 8 TeV

JHEP 01 (2016) 155

- Trigger single muon with p_T > 10 GeV
- Select a μ with 2 < η < 4.5, p_T > 20 GeV
- Purity ~77-79%
- Backgrounds from heavy hadron decays, hadron mis-ID and EW
- Luminosity: 2.0 fb^{-1} ± 1.2 %



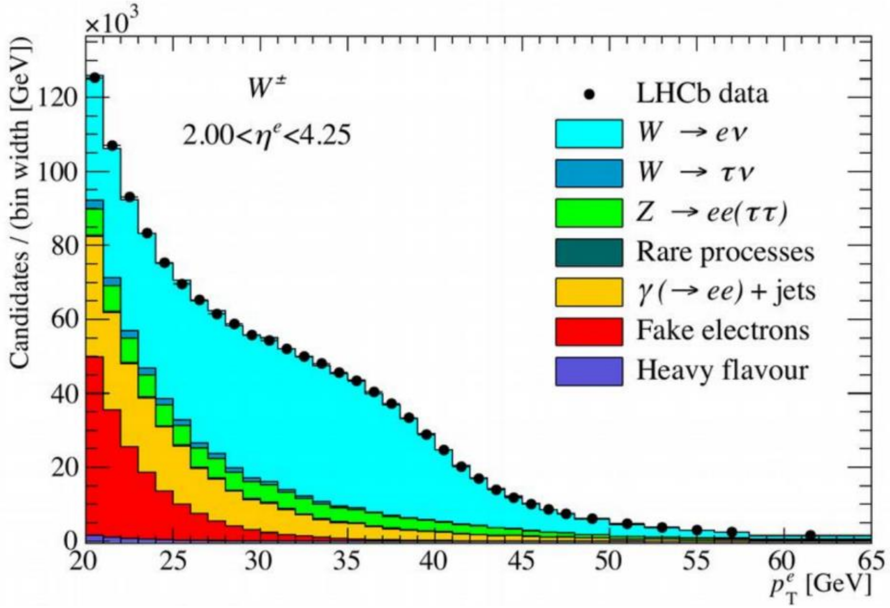


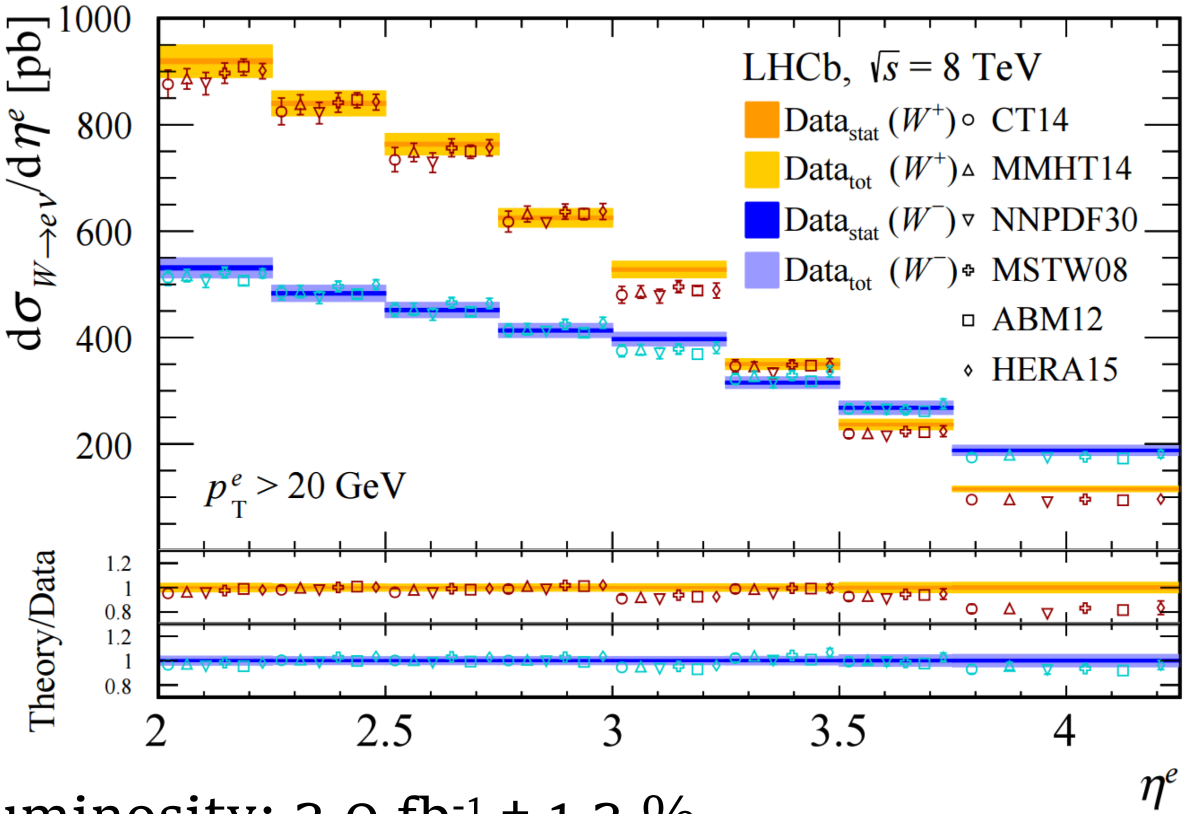
- Uncertainties ~2-4%
- Results for both W^+ and W^- agree with NNLO predictions calculated using FEWZ
- Good agreement with various PDF sets

Electroweak: $W \to e\nu$ @ 8 TeV

JHEP 10 (2016) 030

- Trigger single electron with $p_T > 15$ GeV
- Select an e with $2 < \eta < 4.25$, $p_T > 20$ GeV
- Purity ~60%
- Additional $\gamma \to ee$ background, mis-ID dominates
- Softer p_T spectrum compared to $W \to \mu\nu$
- ECAL saturation at $p_T > 10$ GeV

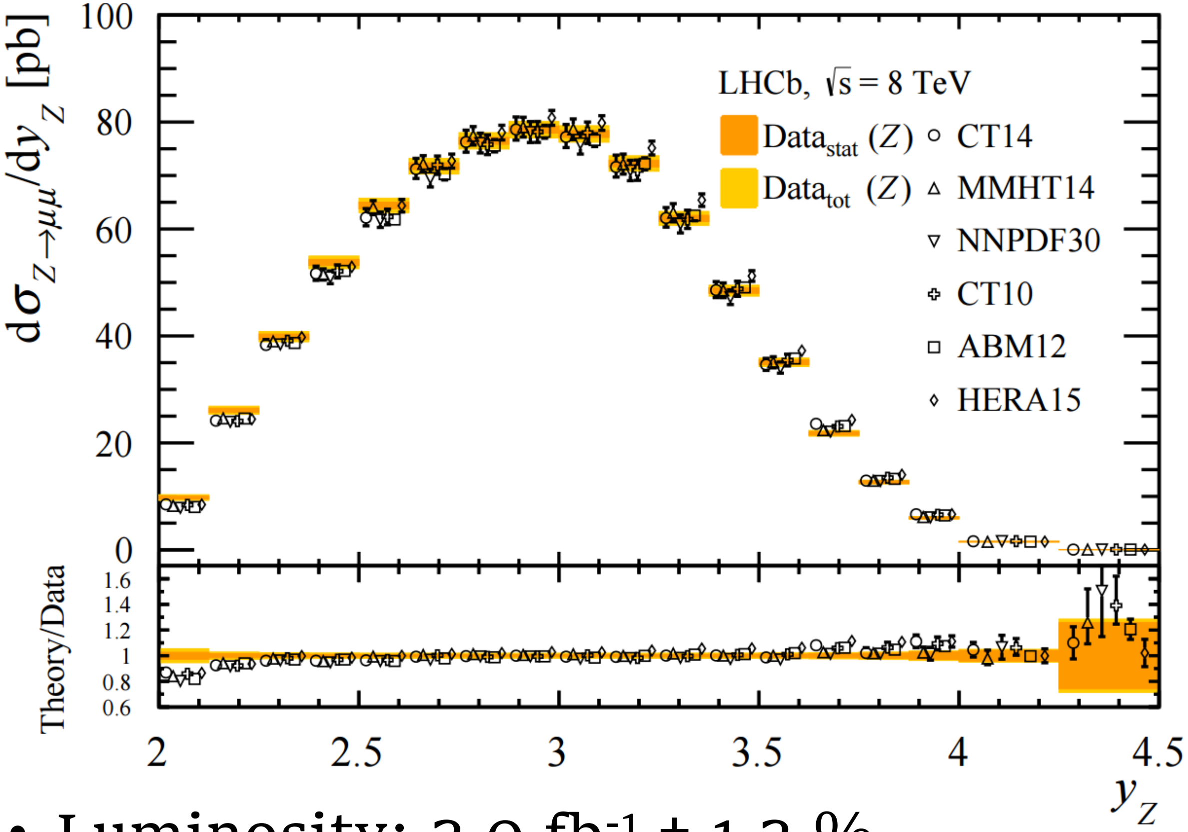




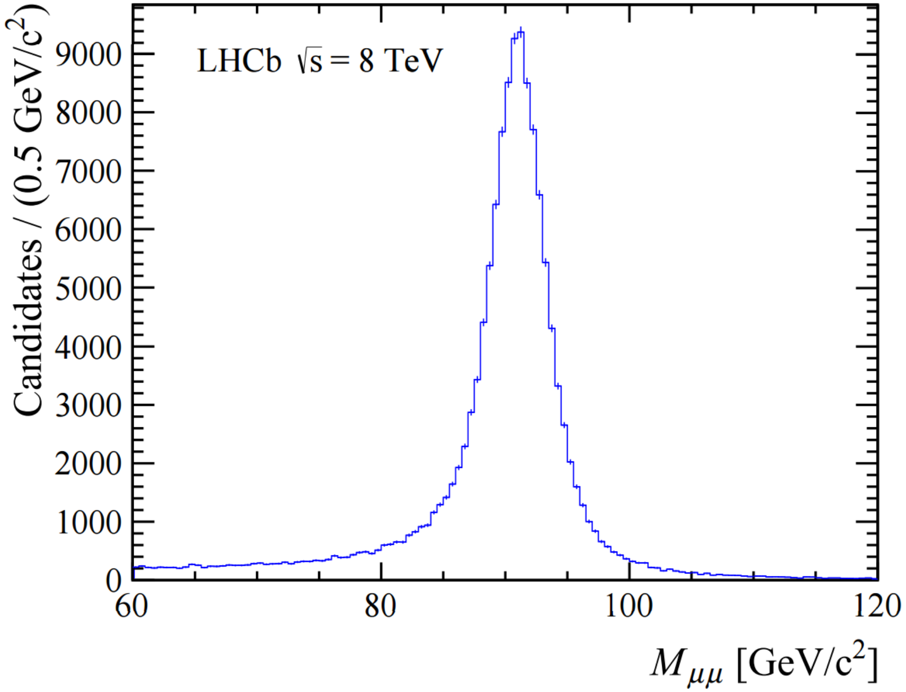
- Luminosity: 2.0 fb^{-1} ± 1.2 %
- Uncertainties ~2.5%, mainly systematic
- Good agreement between the measured cross-section and theoretical predictions with different PDF sets

Electroweak: $Z \to \mu^+\mu^-$ @ 8 TeV

JHEP 01 (2016) 155



- Trigger on 1 muon with $p_T > 10$ GeV
- Select 2 muons in $2 < \eta < 4.5$, $p_T > 20$ GeV
- Require di-muon mass $60 < M < 120$ GeV
- Purity ~99%

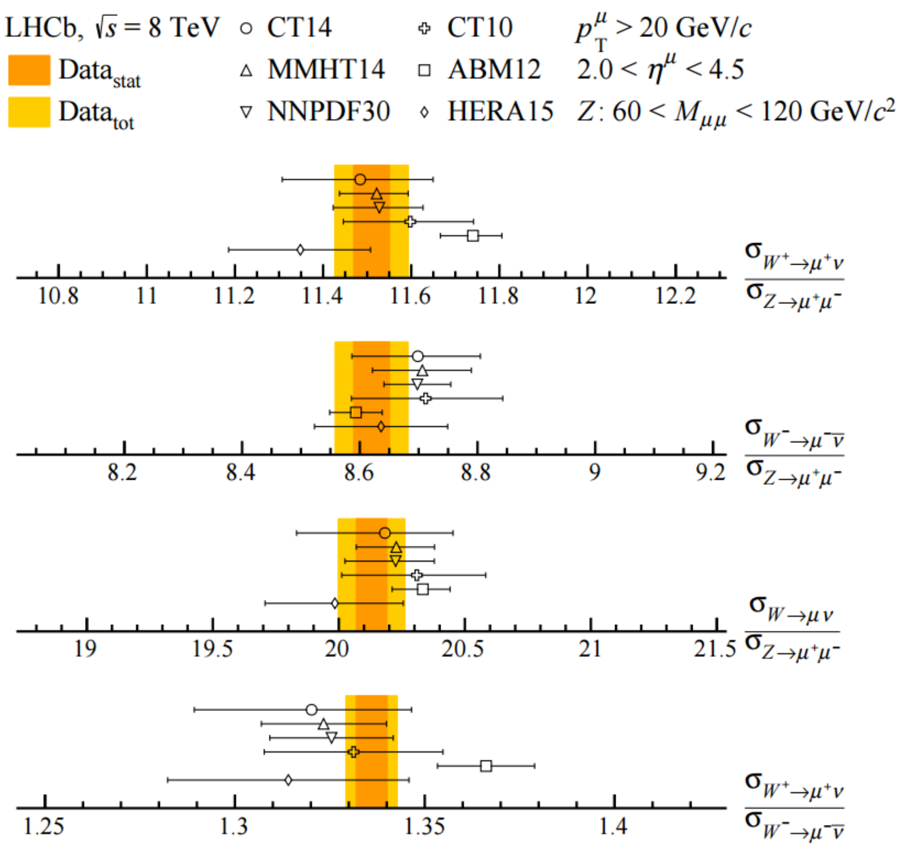


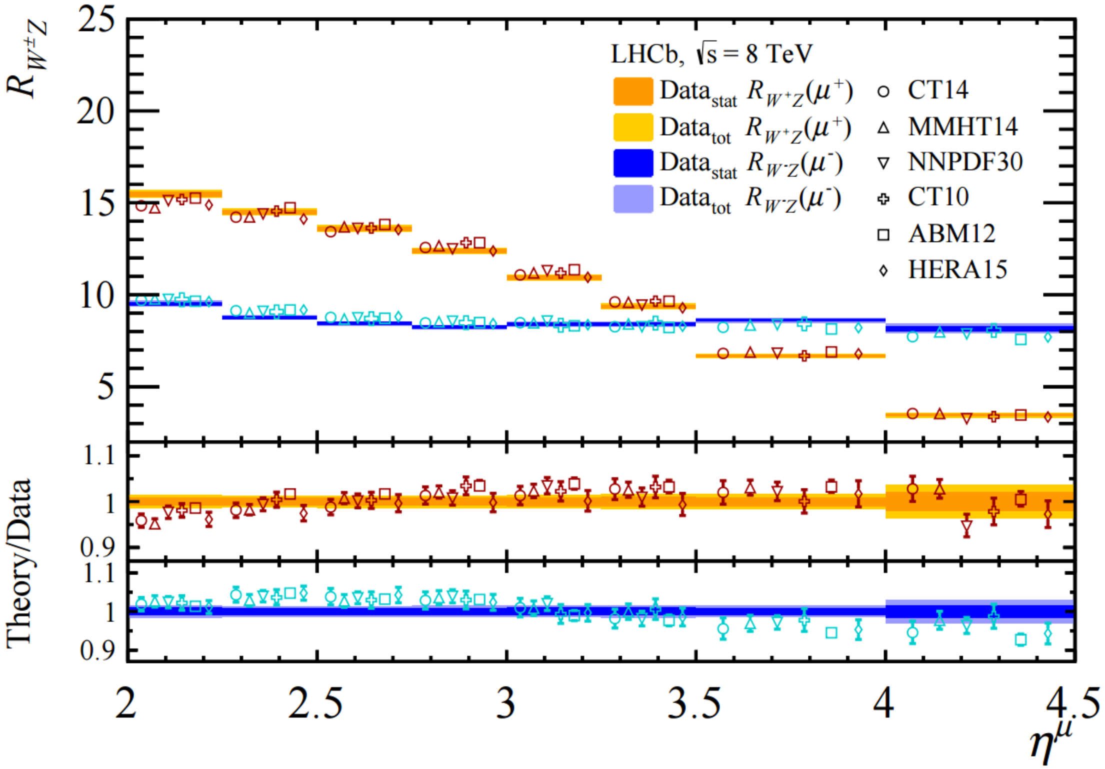
- Luminosity: 2.0 fb^{-1} ± 1.2 %
- Uncertainties ~1.8%; dominated by luminosity and beam energy determination
- Excellent agreement with all theoretical predictions calculated with different PDFs

Electroweak: W/Z ratios @ 8 TeV

JHEP 01 (2016) 155

- Extraction of ratios of vector boson production cross-sections eliminates some systematic uncertainties
- Exp. uncertainty < Theory uncertainty
- Even better probe for agreement with theory



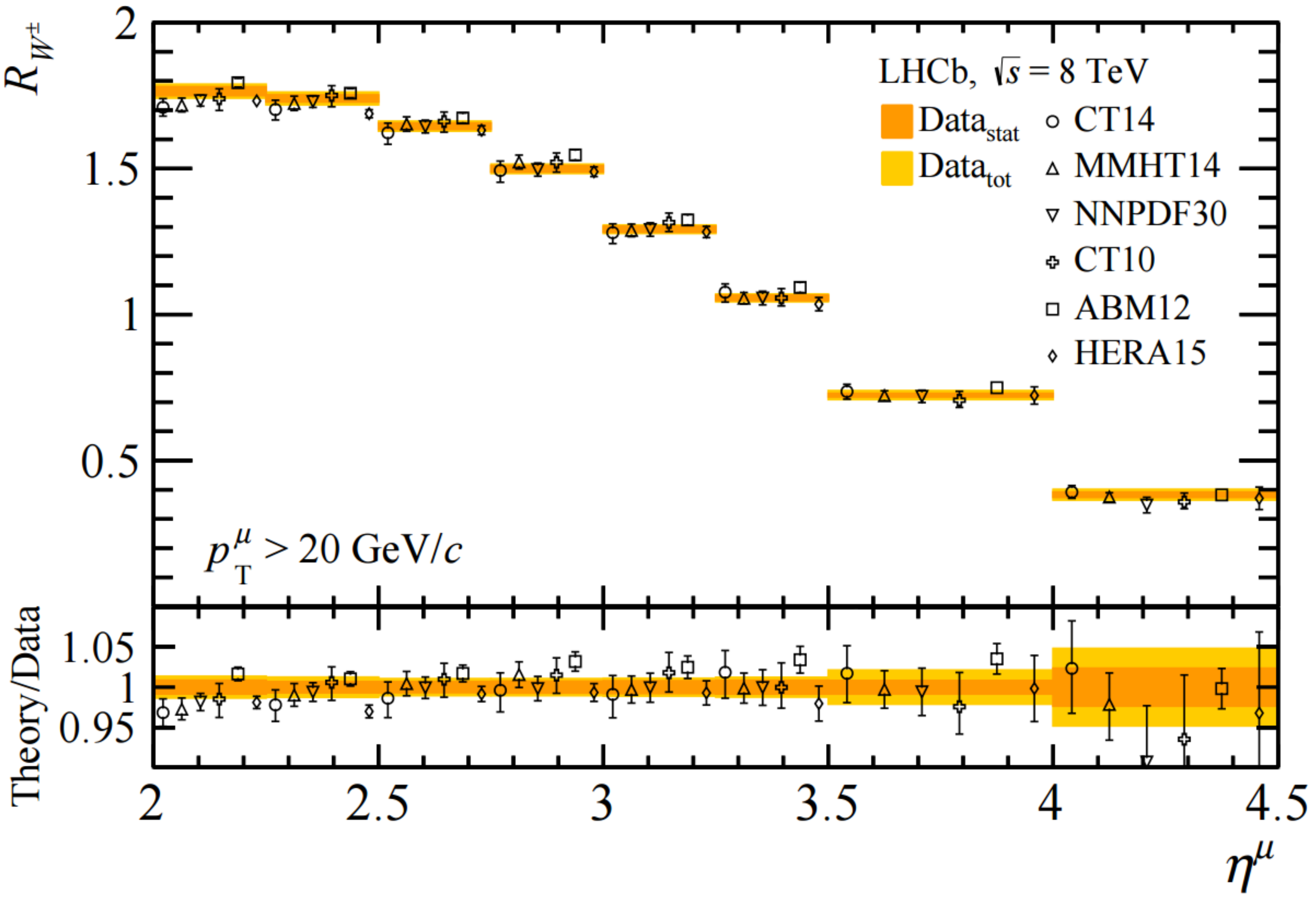


- Mostly good agreement between data and theory

Electroweak: W^+/W^- ratio

JHEP 01 (2016) 155

- The ratio between up and down type quarks in a proton can be probed by exploring the ratio between W^+ and W^- production cross-sections
- A good agreement between theory and data can be observed in the 8 TeV measurement



Electroweak: W/Z ratios @ 8 TeV

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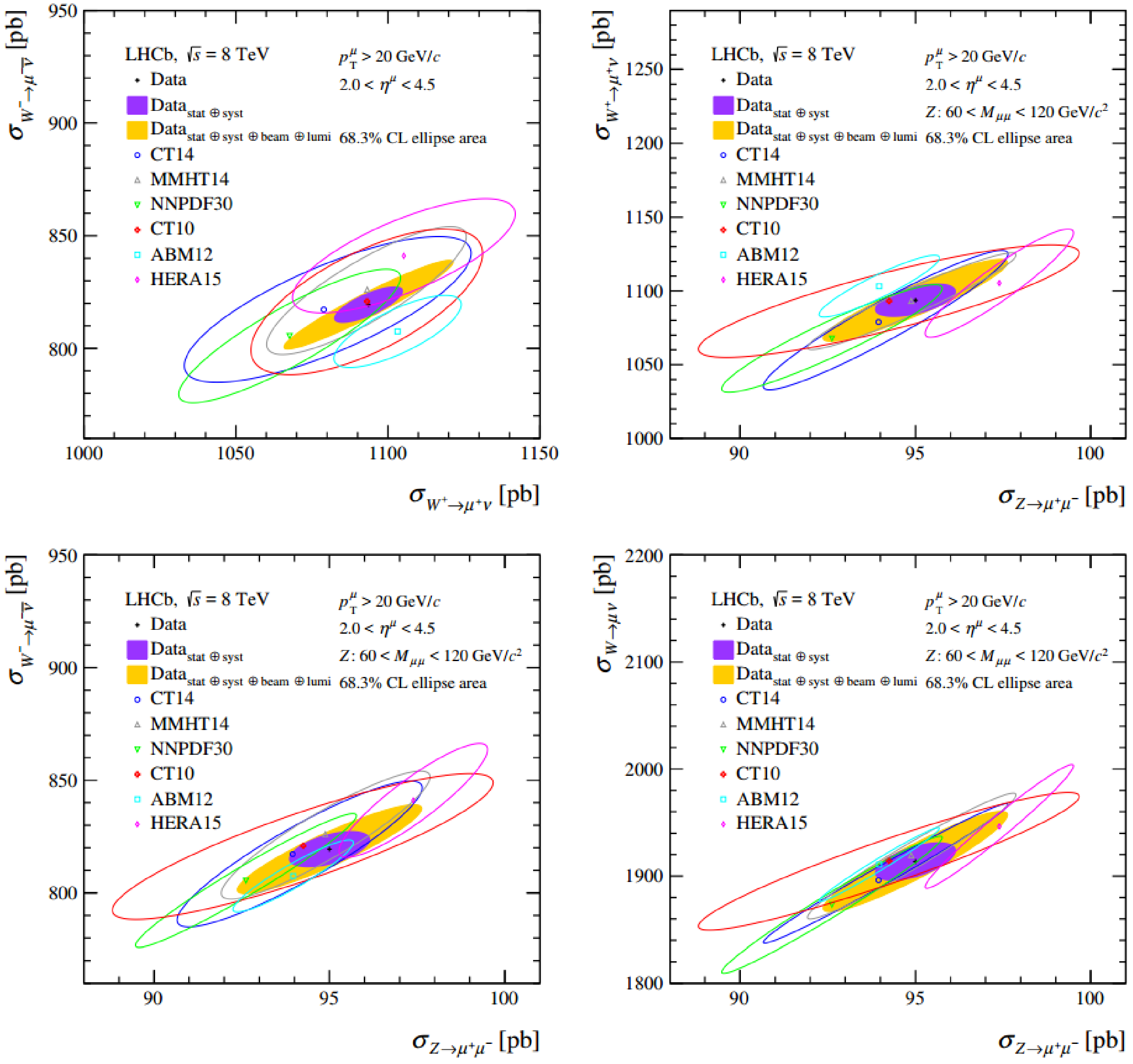

- 1σ elliptical representation of the data compared to the various theoretical models using different PDF sets
  - W⁻ vs W⁺ (top left)
    W⁺ vs Z (top right)
    W⁻ vs Z (bottom left)
    W vs Z (bottom right)
- Mostly good agreement between all ratios and theoretical predictions

Electroweak: 8 TeV vs 7 TeV ratios

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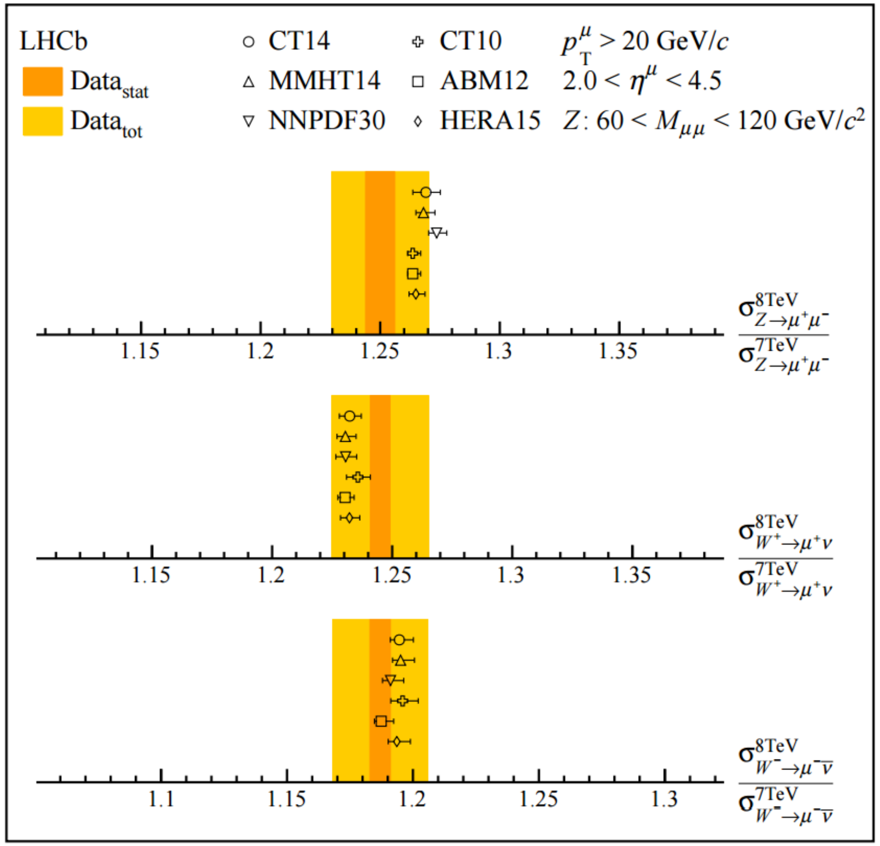
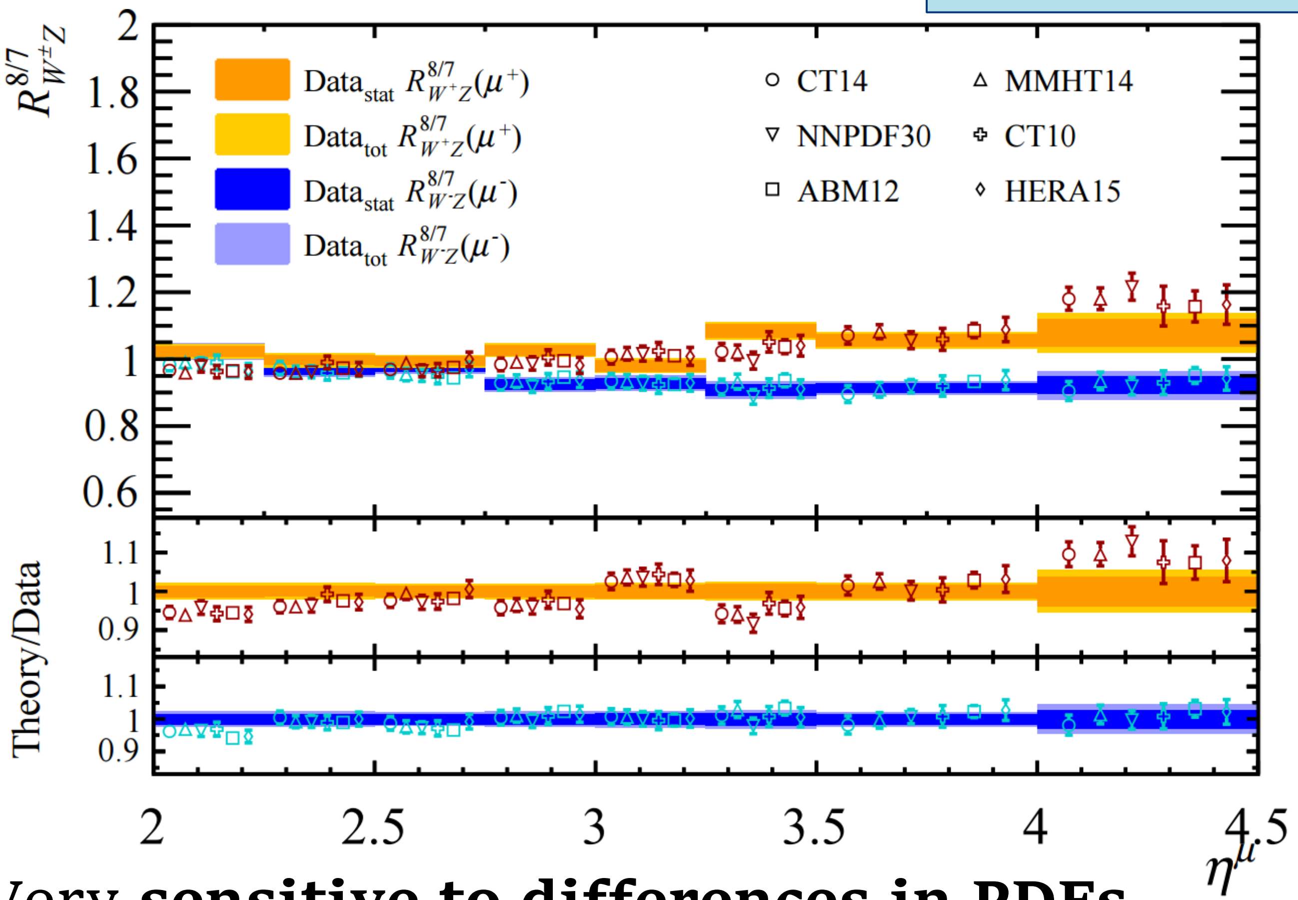
- Further precision achieved by taking a ratio of W/Z ratios at different centre-of-mass energies
- Lumi. uncertainties cancel!
- **Per-mille precision in theoretical predictions**



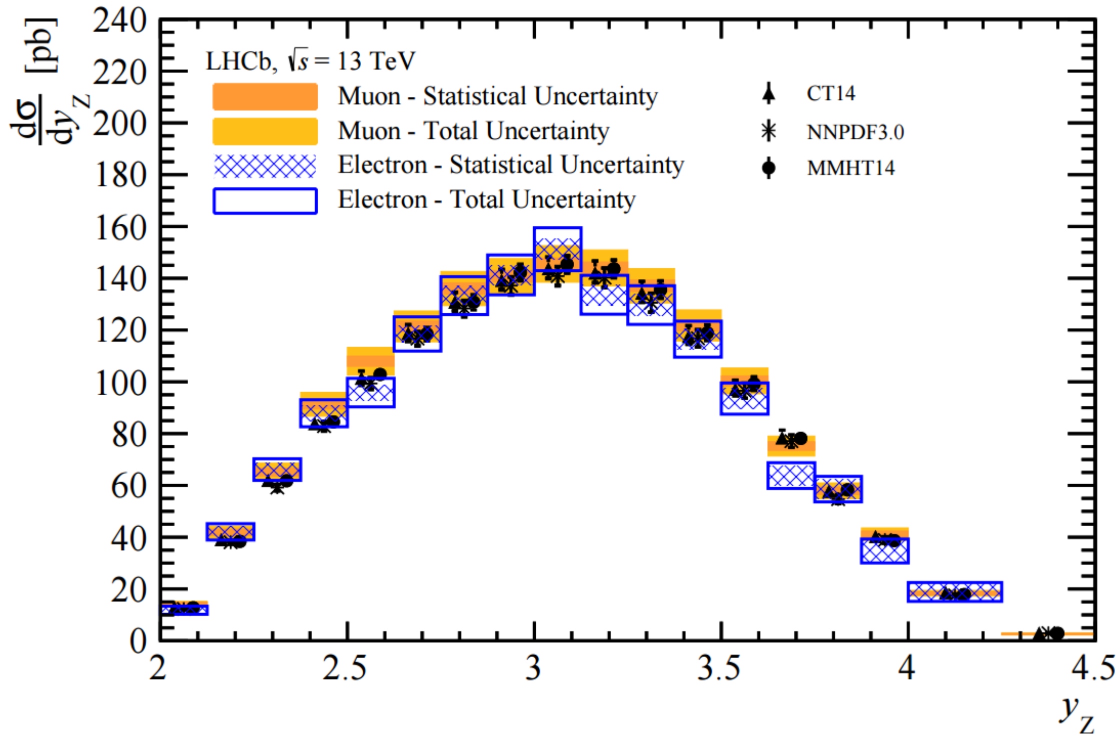


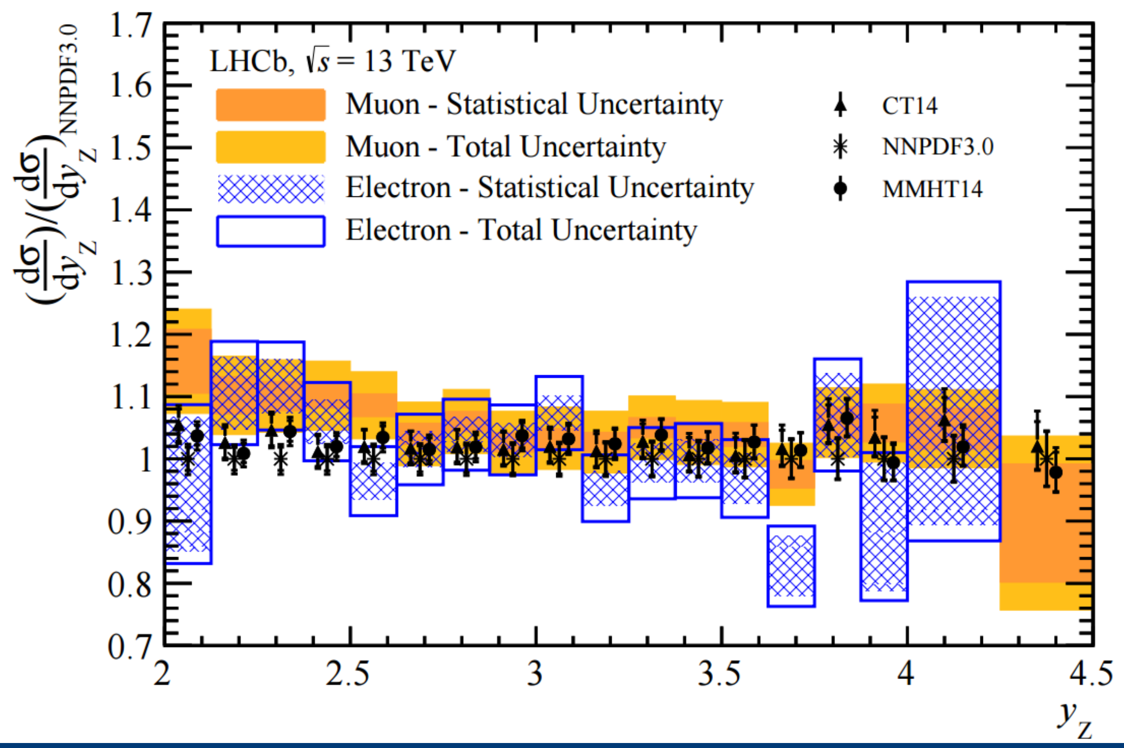
- Very **sensitive to differences in PDFs** (scale uncertainties cancel)
- Some discrepancies can be observed
- Other energy ratios to be produced (13/8, 13/7 TeV)

Electroweak: $Z \rightarrow l^+l^-$ @ 13 TeV

JHEP 09 (2016) 136

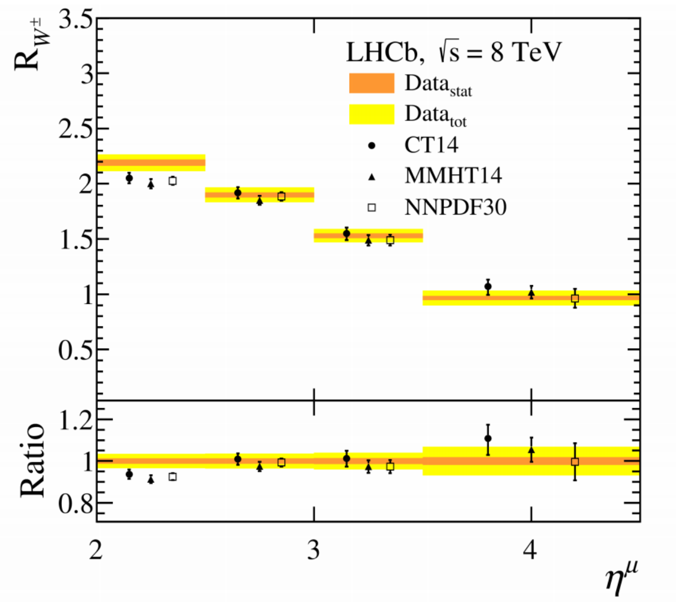
- Analysis strategy and selection similar to 7 and 8 TeV
- Smaller dataset (0.3 fb^{-1}); measurement dominated by lumi. uncertainty (3.9%)
- Cross-section of $Z \rightarrow ee$ (blue) and $Z \rightarrow \mu\mu$ (orange) measured
- No significant deviation between data and theory observed, no PDF set favoured
- Clear statistical limitation; awaiting more data in 2016 and beyond!

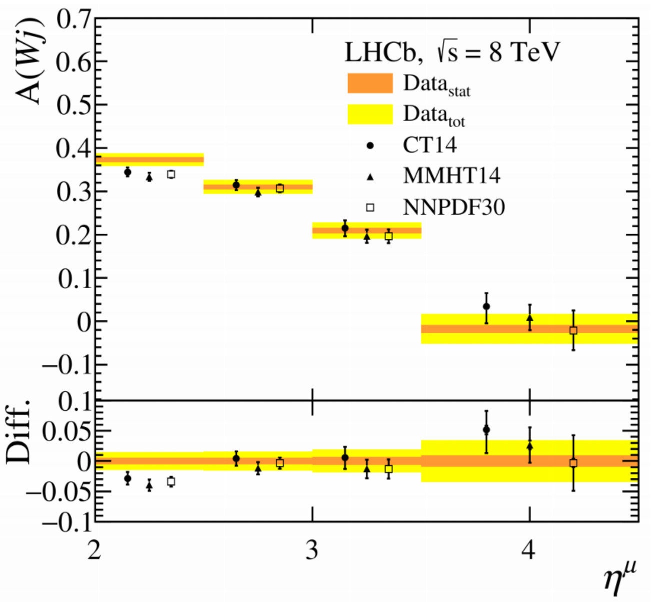




Electroweak: $W, Z + jet$ @ 8 TeV

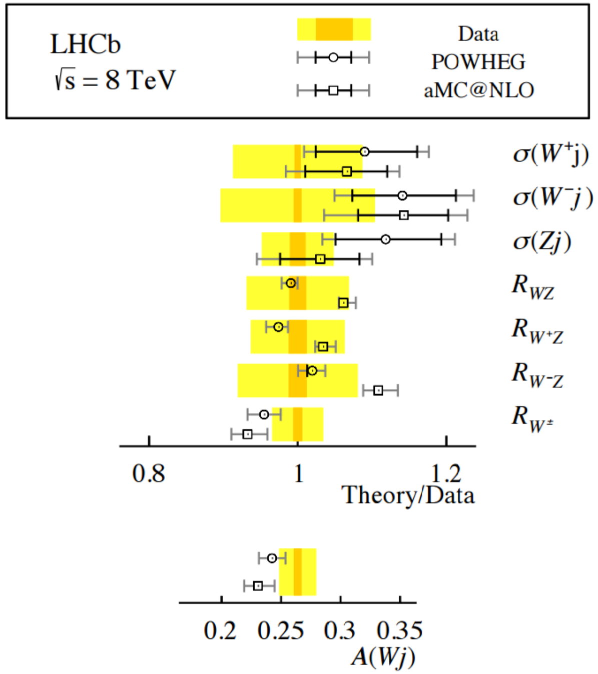
JHEP 05 (2016) 131





- Z and W selection same as before
- Select jets with:
  - $2.2 < \eta < 4.2$, $p_T > 20$ GeV
  - W+jet $p_T > 20$ GeV

- Uncertainties are 9% (W^++jet), 11% (W^-+jet) and 5% (Z+jet); dominated by jet energy scale and purity
- Theoretical predictions: FEWZ fixed order with various PDF sets
- Good agreement between data and theory
- Additional sensitivity to quark and gluon PDFs

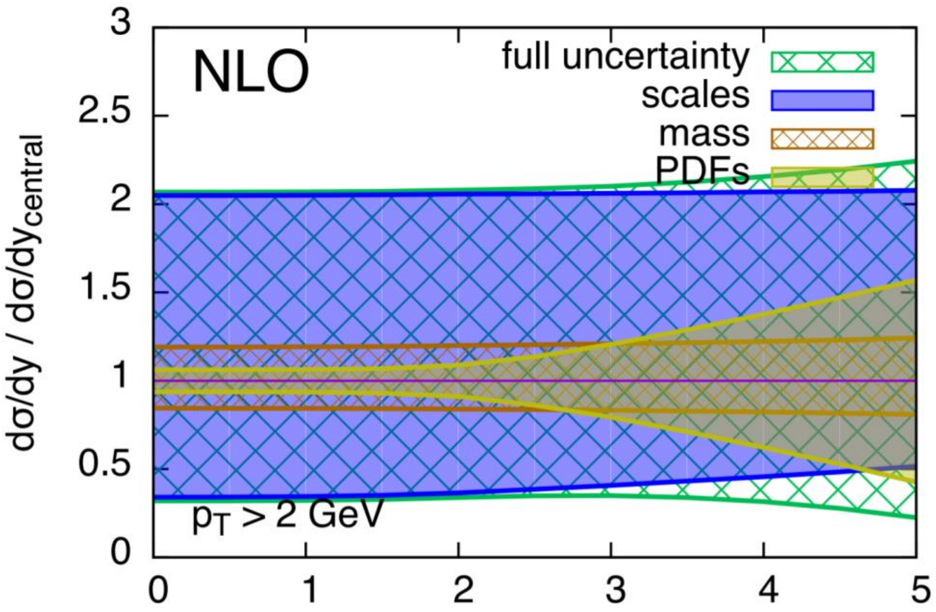


Charm Results

Charm: Inclusive J/ψ @ 13 TeV

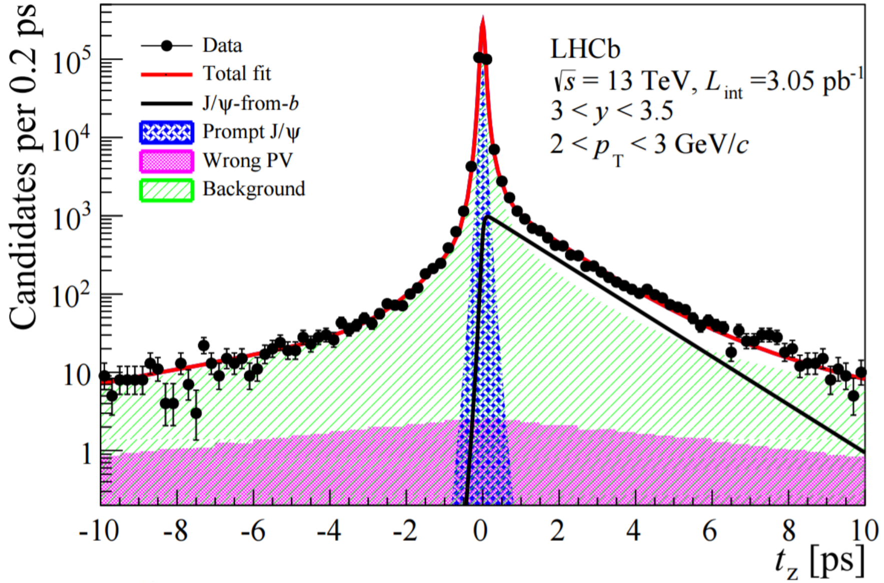
Phys. J. C (2015) 75: 610 | JHEP10(2015)172 | PROSA Coll. arXiv:1503.04581

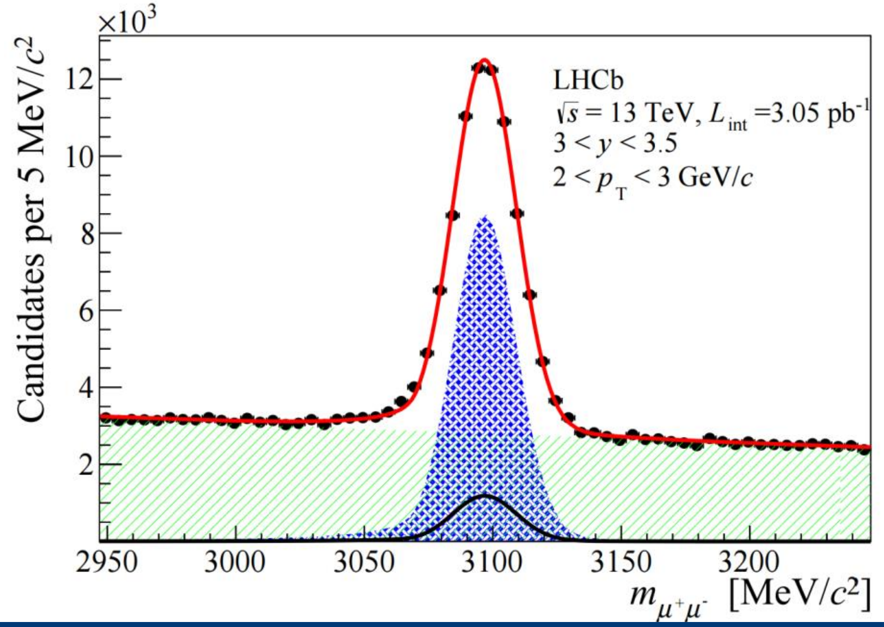
- Measuring the J/ψ cross-section can help constrain the gluon PDF



Pseudo-proper time variable, t_z:

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

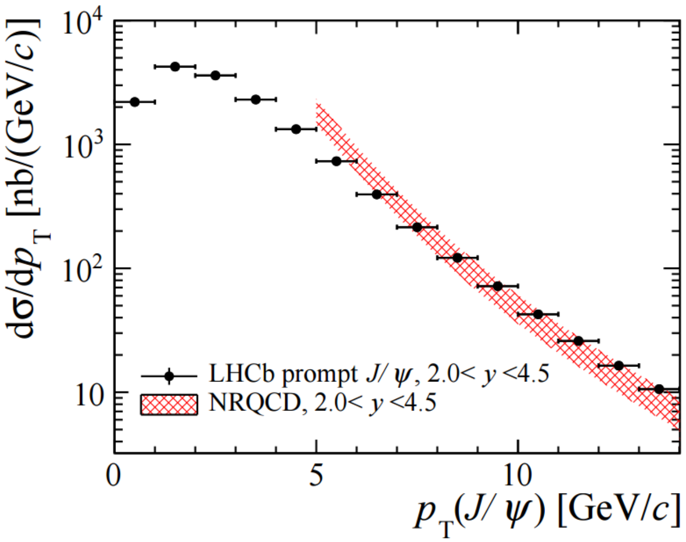


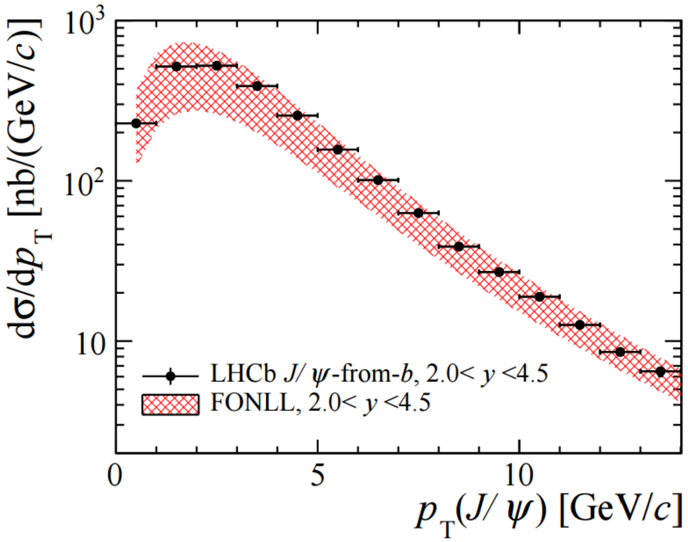


- Select muons with p_T > 0.7 GeV, p > 3 GeV
- On the right:
  - t_z used to select prompt J/ψ and J/ψ-from-b (top)
  - Invariant mass peak (bottom)

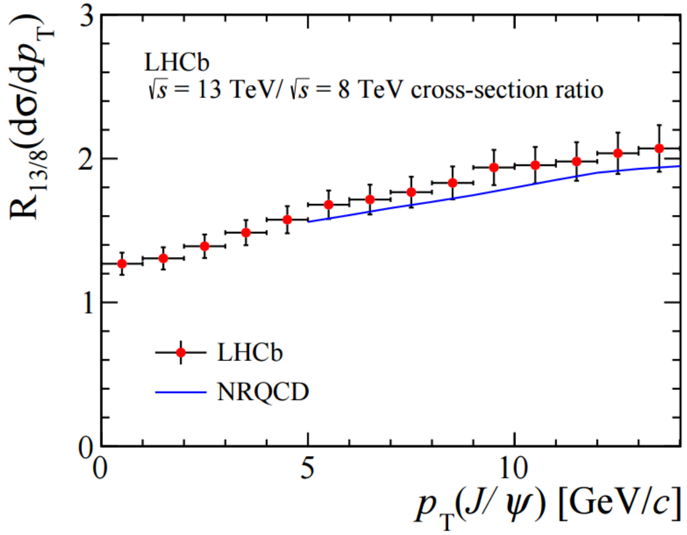
Charm: Inclusive J/ψ @ 13 TeV

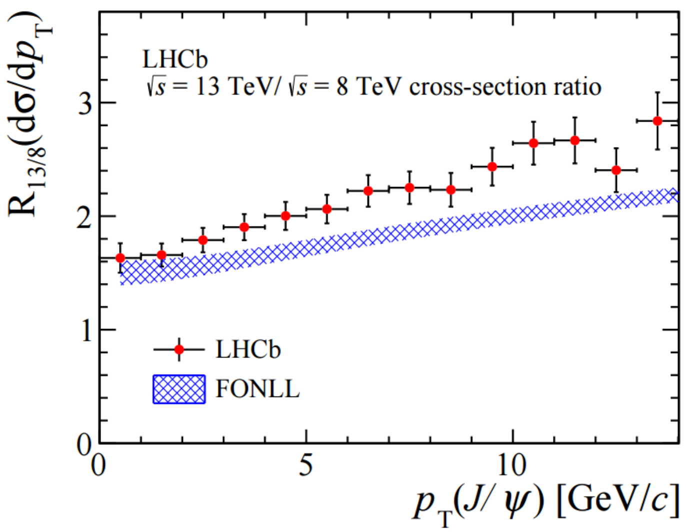
[Phys. J. C (2015) 75: 610](#) | [JHEP10(2015)172](#) | [PROSA Coll. arXiv:1503.04581](#)





- Top: J/ψ production cross-sections at 13 TeV compared to NRQCD and FONLL
- Uncertainties at ~5%; lumi. dominated



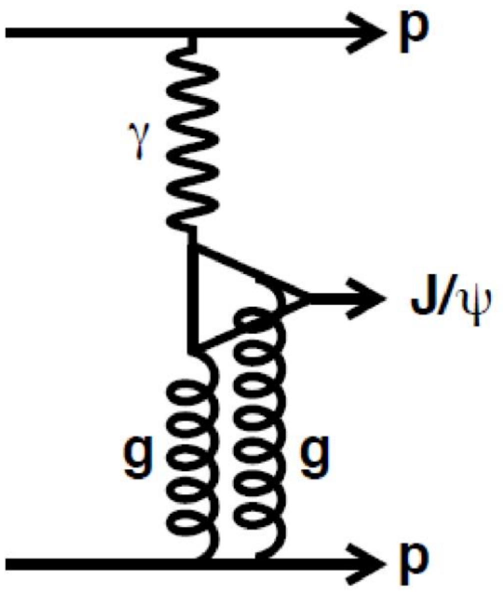


- Taking the 13/8 TeV measurement ratio eliminates some uncertainties
- Bottom: 13/8 TeV ratio for J/ψ and J/ψ –from-b compared to the NRQCD and FONLL predictions
- Mostly good agreement observed

Charm: Exclusive J/ψ and ψ(2s) @ 13 TeV

LHCb-CONF-2016-007

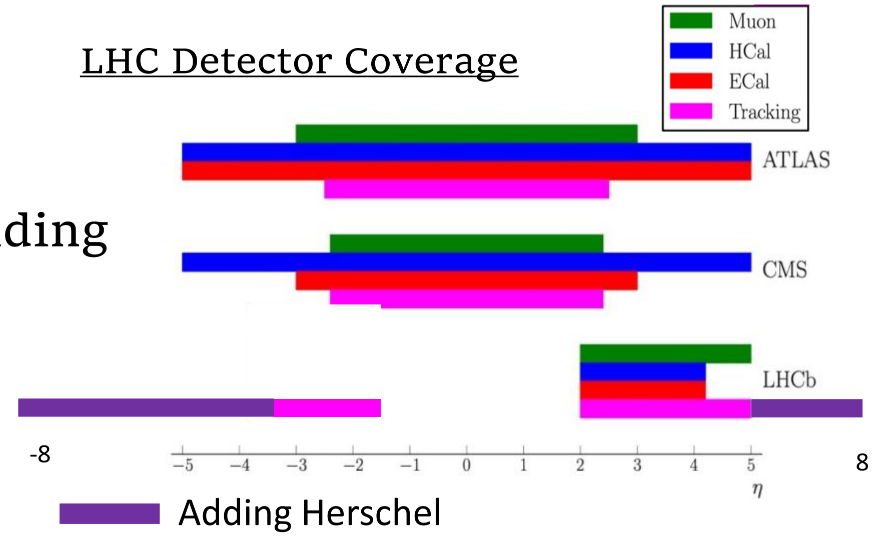
- Central Exclusive Production (CEP):
  - Colliding protons do not disassociate; rather an exchange of a colourless objects (photons, pomerons) occurs
  - Signature is observation of only the central event, no additional track in the acceptance, thus ‘exclusive’
- Exclusively produced J/ψ and ψ(2s) **can be additionally used to constrain the gluon PDF to $x \approx 5 \cdot 10^{-6}$**



New for Run-II

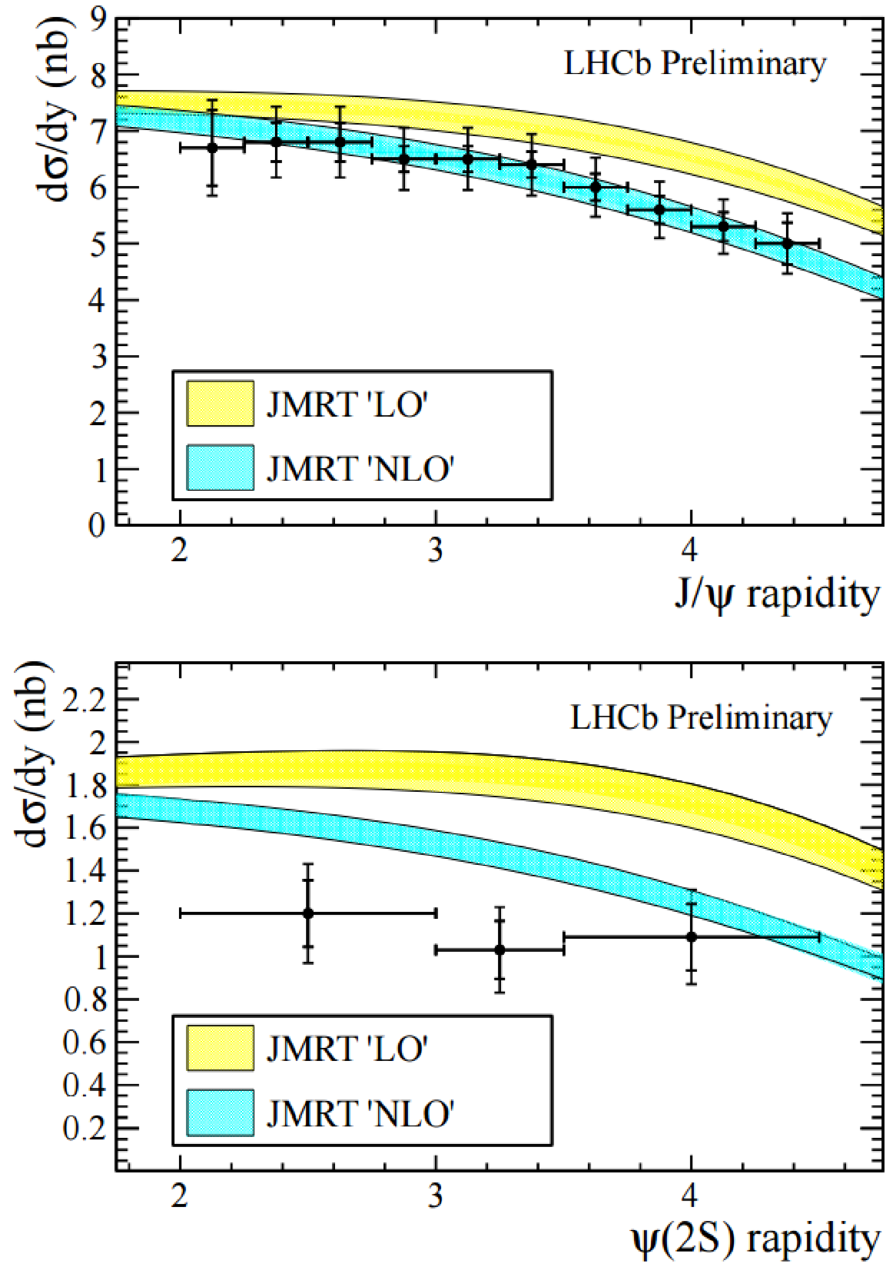
- **Herschel:**
  - Herschel is a set of scintillating pad stations surrounding the beam-pipe on both sides of the LHCb cavern
  - Increases the η coverage to (-8, 8)

LHC Detector Coverage



Charm: Exclusive J/ψ and ψ(2s) @ 13 TeV

LHCb-CONF-2016-007

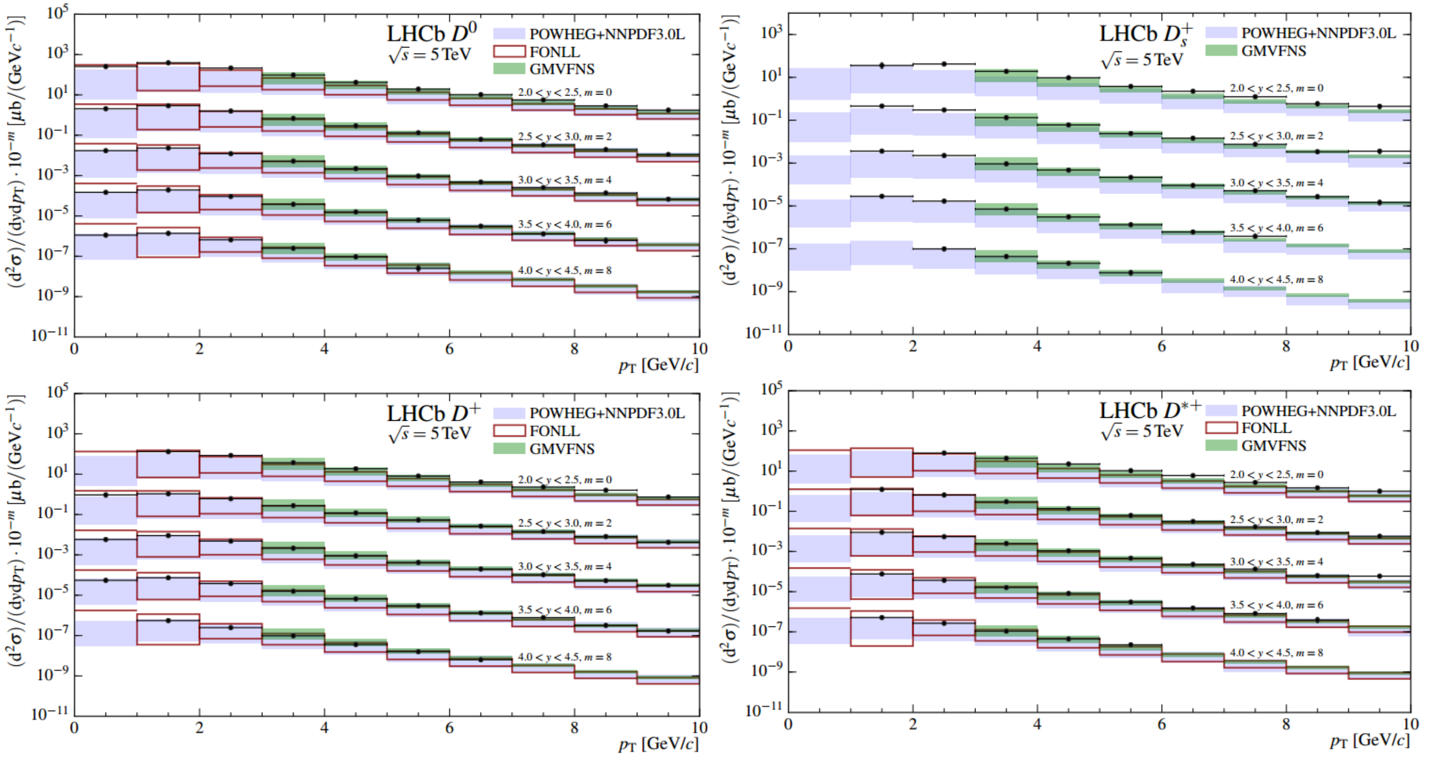


- Data sample: 200 pb^{-1}
- Select 2 muons in $2 < \eta < 4.5$
- **Herschel veto:** use Herschel to improve our ability to veto events with backwards tracks!
- Improves background suppression x2!
- Results for J/ψ (top) and ψ(2s) bottom compared to NLO and LO predictions
- Better agreement with NLO than LO
- First results encouraging, looking forward to more data and further integration of Herschel!

Charm: Inclusive D production

PROSA Coll. arXiv:1503.04581	LHCb-PAPER-2016-042
NNPDF3.0L, arXiv:1506.08025	JHEP09(2016)013

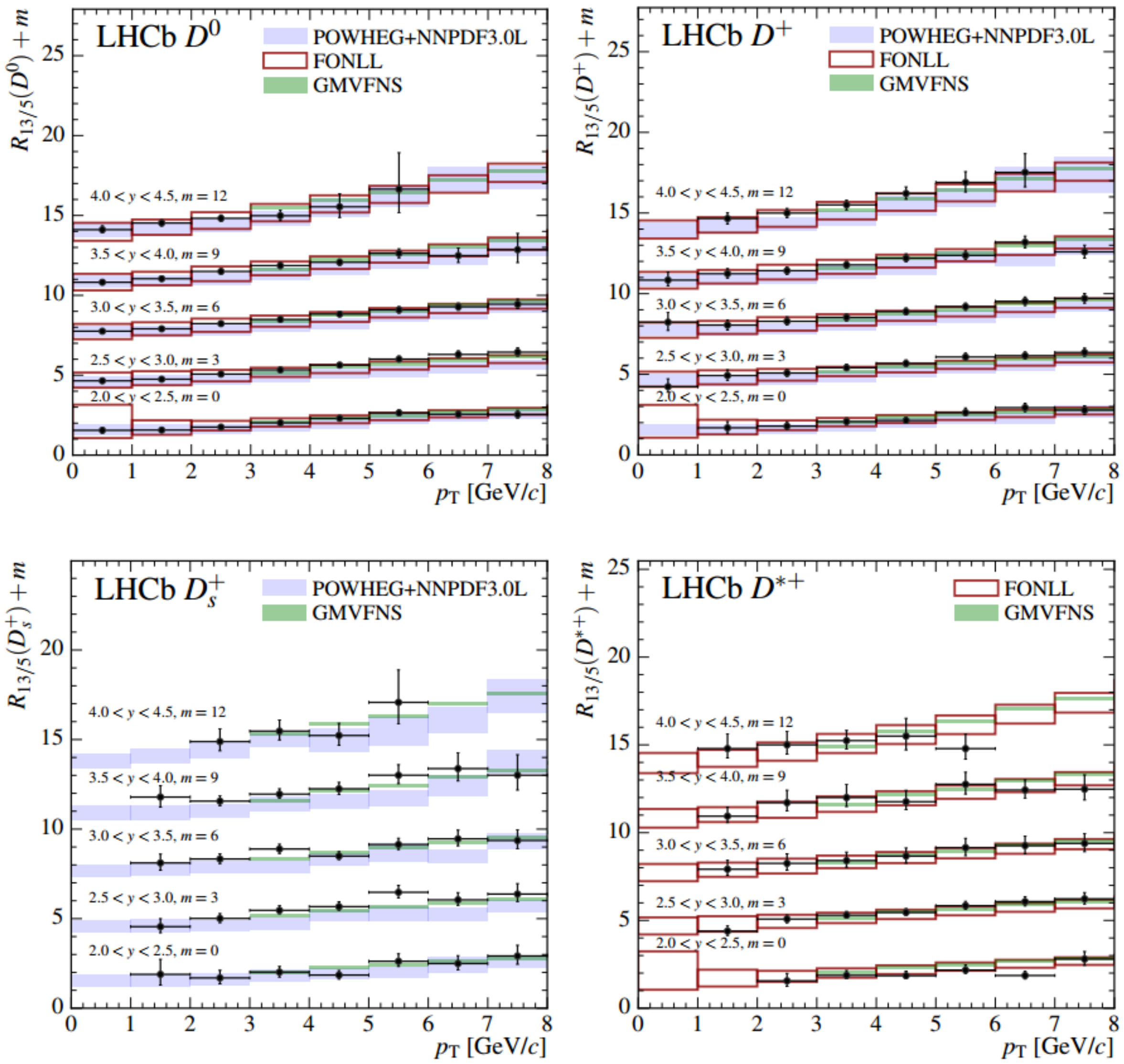
- Production of other inclusive prompt charm states can also put constraints on PDFs
- D^0, D^+, D_s^+, D^{*+} production is measured at 5 and 13 TeV
- Data sets:
  - 13 TeV (2016): 4.98 ± 0.19pb^{-1}
  - 5 TeV (2015): 8.60 ± 0.33 pb^{-1}
- Select mass range ±20 MeV of the known mass
- Good agreement between data and theory (POWHEG+NNPDF3.0L)
- Uncertainties increase at low pT



- Differential cross section at 5 TeV as a function of p_T (results similar for 13 TeV):
  - Top: D^0 [left], D_s^+ [right]
  - Bottom: D^+ [left], D^{*+} [right]

Charm: Inclusive D production

PROSA Coll. arXiv:1503.04581	LHCb-PAPER-2016-042
NNPDF3.0L, arXiv:1506.08025	JHEP09(2016)013



- Again ratios at different c.o.m. energies can be taken to eliminate some uncertainties
- 13/5 TeV ratio shown:
  - Top: D^0 [left], D^+ [right]
  - Bottom: D_s^+[left], D^{*+} [right]
- Good agreement between data and theory (POWHEG+NNPDF3.0L)
- More ratios to be measured!

Future Prospects

- PDFs have large uncertainties at low Björken-x values
- The higher the centre-of-mass energy, the lower x values that LHCb can probe
- Looking forward to analysing the full Run-II data set
- Also, anticipating further PDF constraints once LHC moves to 14 TeV
- Expecting interesting results in W and Z production and production ratios between 7, 8, 13 and 14 TeV in the future!
- Further reduction of the PDF uncertainties!
- Beyond Run-II, developments in LHCb trigger (fully software; full event reconstruction at the trigger level) expected to increase the quality and quantity of our data!

Conclusions

- LHCb has a **unique kinematic coverage** among the LHC experiments
- We have the ability to probe **high and low Björken-x** values
- Despite being designed as a heavy flavour experiment, **LHCb has a proven track record in EW vector boson measurements**
- Many vector boson and charm production measurements shown
- Along with other LHC experiments LHCb has had a great input in constraining various PDFs
- **Looking forward to many more measurements in both short and long term!**

Conclusions

- LHCb has a **unique kinematic coverage** among the LHC experiments
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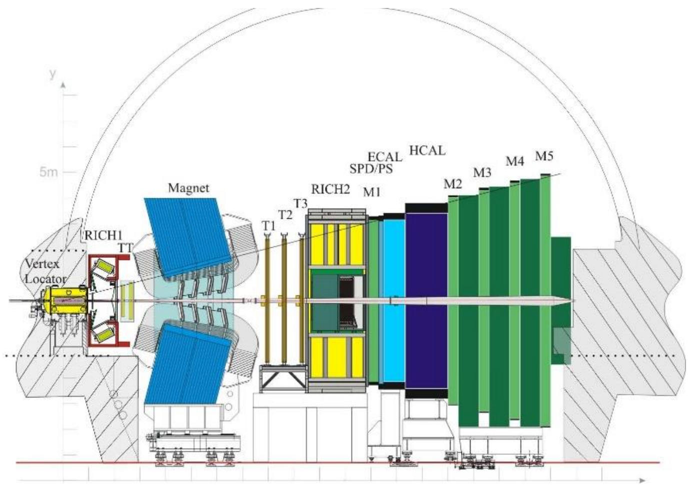
Thank You!

Backup

LHCb Experiment

JINST 3 (2008) S08005



- $\frac{\delta p}{p} \sim 0.5 - 1\%$ for 5 - 100 GeV
- IP resolution 20μm
- PID efficiency
  - e ~90%; e→ h mis-ID ~5%
  - M ~97%; π→ μ mis-ID 1-3%
- $\bar{\mu}$ = 2.2

❖ Fully instrumented in **2 < η < 5**

+ Excellent vertex resolution
+ Good lepton and hadron ID
+ Low pile-up
+ Great lumi. Determination

+− Unique acceptance; not 4π

+ VELO backwards coverage -3.5 < η < -1.5

− Cannot use E-miss or p_T-miss

− Low instantaneous lumi.

$Z \rightarrow ll$

- 7 TeV (JHEP 02 (2013) 106; JHEP 08 (2015) 039)
  - σ(Z→ee) = 76.0 ± 0.8 (stat) ± 2.0 (sys) ± 2.6 (lumi) ± 0.4 (FSR) pb
  - σ(Z→μμ) = 76.0 ± 0.3 (stat) ± 0.5 (sys) ± 1.0 (beam) ± 1.3 (lumi) pb
- 8 TeV (JHEP 05 (2015) 109)
  - σ(Z→μμ) = 95.0 ± 0.3 (stat) ± 0.7 (sys) ± 1.1 (beam) ± 1.1 (lumi) pb
  - σ(Z→ℓℓ) = 94.9 ± 0.2 (stat) ± 0.6 (sys) ± 1.1 (beam) ± 1.1 (lumi) pb
- 13 TeV (JHEP09 (2016) 136)
  - σ(Z→ee) = 190.2 ± 0.9 (stat) ± 4.7 (sys) ± 7.7 (lumi) pb
  - σ(Z→μμ) = 198.0 ± 1.7 (stat) ± 4.7 (sys) ± 7.4 (lumi) pb
  - σ(Z→ℓℓ) = 194.3 ± 0.9 (stat) ± 3.3 (sys) ± 7.6 (lumi) pb

$W \to l\nu$

- 7 TeV (JHEP 08 (2015) 039)
  - $\sigma(W^+ \to \mu^+ \nu)$ = 878.0 ± 2.1 (stat) ± 6.7 (sys) ± 9.3 (beam) ± 15.0 (lumi) pb
  - $\sigma(W^- \to \mu^- \nu)$ = 689.5 ± 2.0 (stat) ± 5.3 (sys) ± 6.3 (beam) ± 11.8 (lumi) pb

- 8 TeV (JHEP 01 (2016) 155)
  - $\sigma(W^+ \to \mu^+ \nu)$ = 1093.6 ± 2.1 (stat) ± 7.2 (sys) ± 10.9 (beam) ± 12.7 (lumi) pb
  - $\sigma(W^- \to \mu^- \nu)$ = 818.4 ± 1.9 (stat) ± 5.0 (sys) ± 7.0 (beam) ± 9.5 (lumi) pb
  - $\sigma(W^+ \to e^+ \nu e)$ = 1124.4 ± 2.1 (stat) ± 21.5 (sys) ± 11.2 (beam) ± 13.0 (lumi) pb
  - $\sigma(W^- \to e^- \nu e)$ = 809.0 ± 1.9 (stat) ± 18.1 (sys) ± 7.0 (beam) ± 9.4 (lumi) pb