# First steps towards $m_W$ at LHCb

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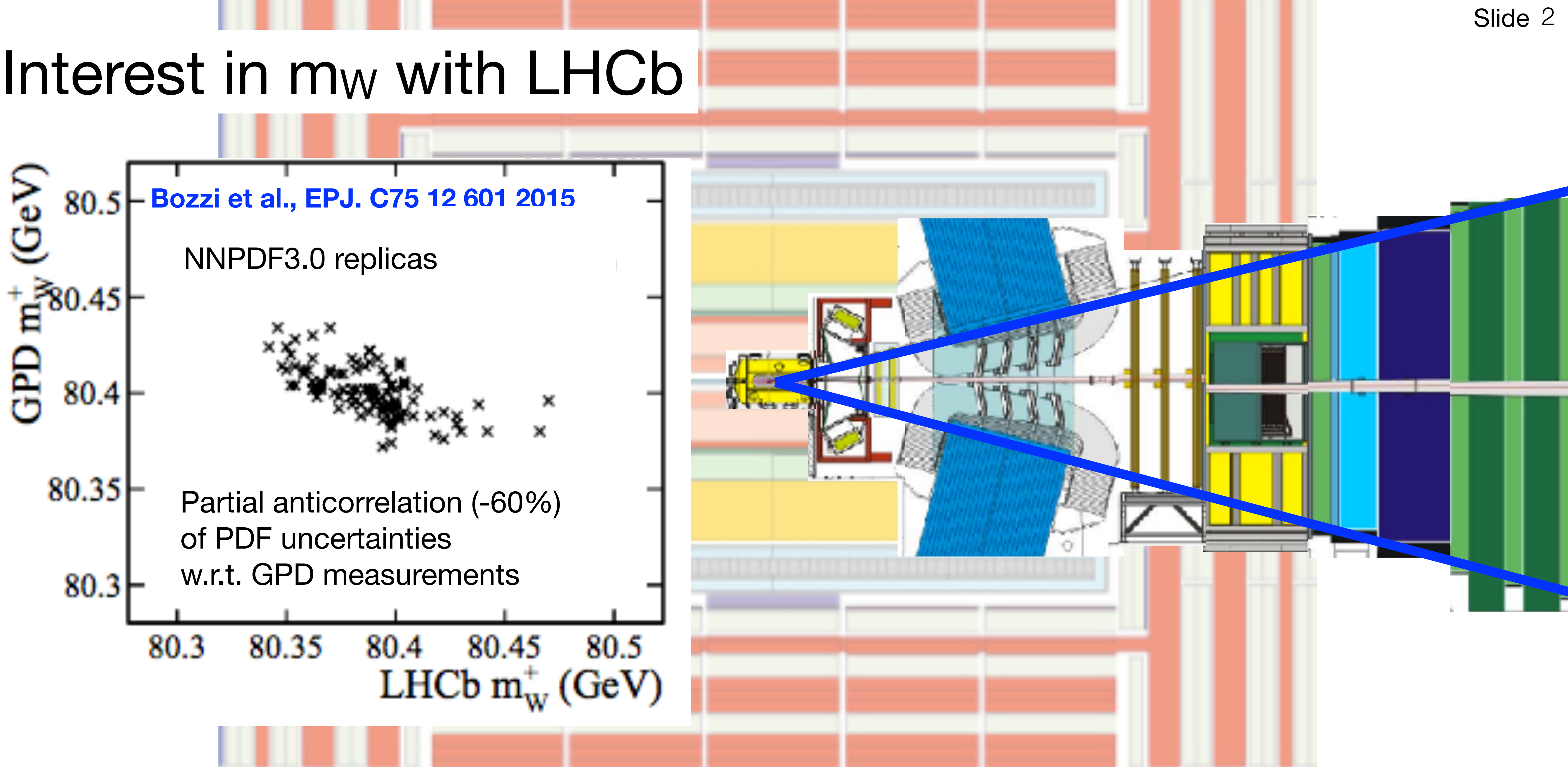
University of Oxford

Precision electroweak meeting,
LAL, 22-25 May 2018

# Interest in $m_W$ with LHCb



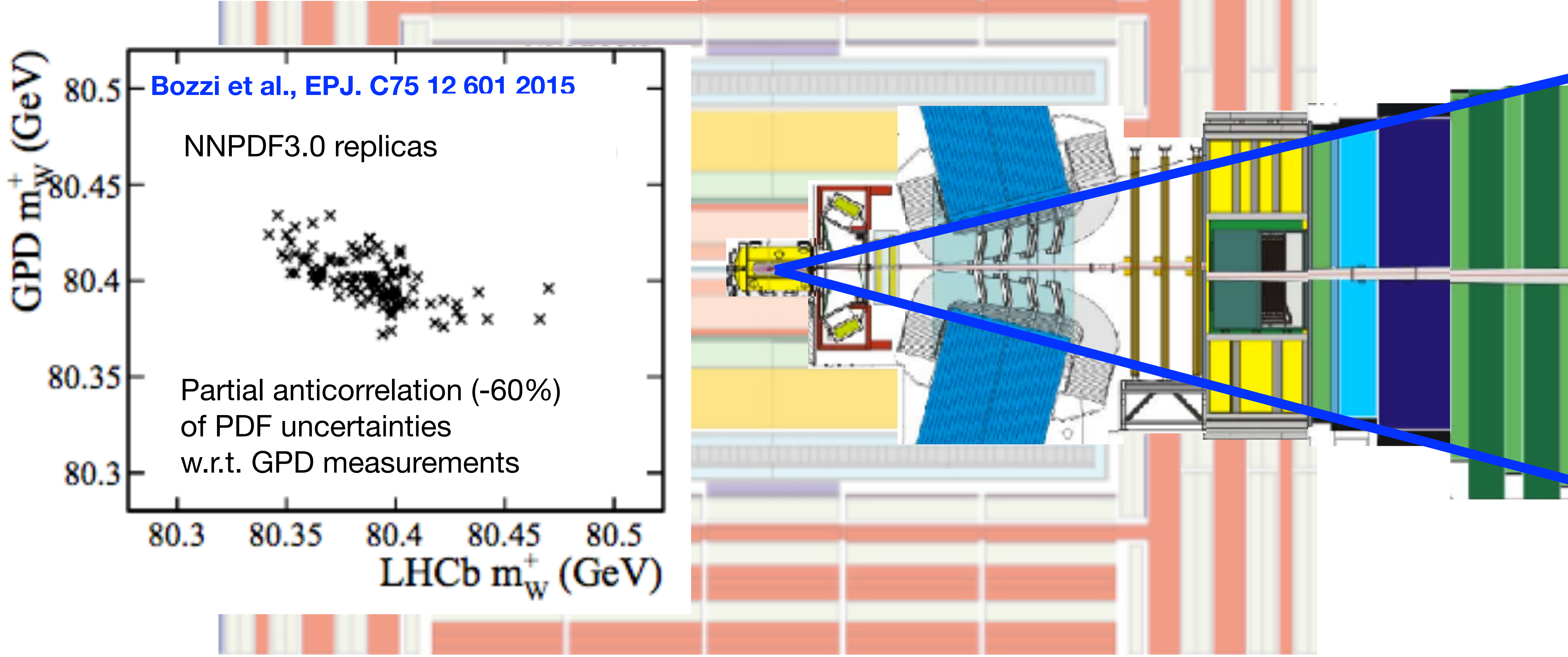

LHCb can measure $m_W$ from the muon $p_T$ spectrum in $W \to \mu\nu$ with better than 10 MeV statistical precision using Run-II data.

Complementary acceptance potentially beneficial in a LHC average.

Smaller contribution from 2nd generation quarks, softer $p_T(W)$ spectrum, … , …

Prospects with the extended trackers of the Phase II ATLAS and CMS detectors, especially with electrons. Encouraging to see Maarten's report at a recent HL-LHC WG1 meeting https://indico.cern.ch/event/721951/

# Interest in $m_W$ with LHCb




Outline of the rest of the talk

- Z $p_T$ modelling and published LHCb data
- PDF uncertainties

*!All work in progress!*

# LHCb data, including d$\sigma$($Z \to \mu\mu$)/d$p_T$

CERN-EP-2016-170
LHCb-PAPER-2016-021
September 7, 2016

## Measurement of the forward Z boson production cross-section in pp collisions at $\sqrt{s} = 13$ TeV

The LHCb collaboration†

**Abstract**

A measurement of the production cross-section of Z bosons in pp collisions at $\sqrt{s}$ = 13 TeV is presented using dimuon and dielectron final states in LHCb data. The cross-section is measured for leptons with pseudorapidities in the range $2.0 < \eta < 4.5$, transverse momenta $p_T > 20$ GeV and dilepton invariant mass in the range $60 < m(\ell\ell) < 120$ GeV. The integrated cross-section from averaging the two final states is

$$\sigma_Z^{\ell\ell} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6 \,\text{pb},$$

where the first uncertainty is statistical, the second is due to systematic effects, and the third is due to the luminosity determination. In addition, differential cross-sections are measured as functions of the Z boson rapidity, transverse momentum and the angular variable $\phi^*_\eta$.

Published in JHEP 09 (2016) 136

CERN-PH-EP-2015-301
LHCb-PAPER-2015-049
February 3, 2016

## Measurement of forward $W$ and $Z$ boson production in $pp$ collisions at $\sqrt{s} = 8$ TeV

The LHCb collaboration†

**Abstract**

Measurements are presented of electroweak boson production using data from $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The analysis is based on an integrated luminosity of 2.0 fb$^{-1}$ recorded with the LHCb detector. The bosons are identified in the $W \to \mu\nu$ and $Z \to \mu^+\mu^-$ decay channels. The cross-sections are measured for muons in the pseudorapidity range $2.0 < \eta < 4.5$, with transverse momenta $p_T > 20$ GeV/$c$ and, in the case of the $Z$ boson, a dimuon mass within $60 < M_{\mu^+\mu^-} < 120$ GeV/$c^2$. The results are

$$\sigma_{W^+\to\mu^+\nu} = 1093.6 \pm 2.1 \pm 7.2 \pm 10.9 \pm 12.7 \,\text{pb},$$
$$\sigma_{W^-\to\mu^-\bar{\nu}} = 818.4 \pm 1.9 \pm 5.0 \pm 7.0 \pm 9.5 \,\text{pb},$$
$$\sigma_{Z\to\mu^+\mu^-} = 95.0 \pm 0.3 \pm 0.7 \pm 1.1 \pm 1.1 \,\text{pb},$$

where the first uncertainties are statistical, the second are systematic, the third are due to the knowledge of the LHC beam energy and the fourth are due to the luminosity determination. The evolution of the $W$ and $Z$ boson cross-sections with centre-of-mass energy is studied using previously reported measurements with 1.0 fb$^{-1}$ of data at 7 TeV. Differential distributions are also presented. Results are in good agreement with theoretical predictions at next-to-next-to-leading order in perturbative quantum chromodynamics.

Published in JHEP 01 (2016) 155

CERN-PH-EP-2015-102
LHCb-PAPER-2015-001
Aug 20, 2015

## Measurement of the forward $Z$ boson production cross-section in $pp$ collisions at $\sqrt{s} = 7$ TeV

The LHCb collaboration†

**Abstract**

A measurement of the production cross-section for $Z$ bosons that decay to muons is presented. The data were recorded by the LHCb detector during $pp$ collisions at a centre-of-mass energy of 7 TeV, and correspond to an integrated luminosity of 1.0 fb$^{-1}$. The cross-section is measured for muons in the pseudorapidity range $2.0 < \eta < 4.5$ with transverse momenta $p_T > 20$ GeV/$c$. The dimuon mass is restricted to $60 < M_{\mu^+\mu^-} < 120$ GeV/$c^2$. The measured cross-section is

$$\sigma_{Z\to\mu^+\mu^-} = (76.0 \pm 0.3 \pm 0.5 \pm 1.0 \pm 1.3) \,\text{pb}$$

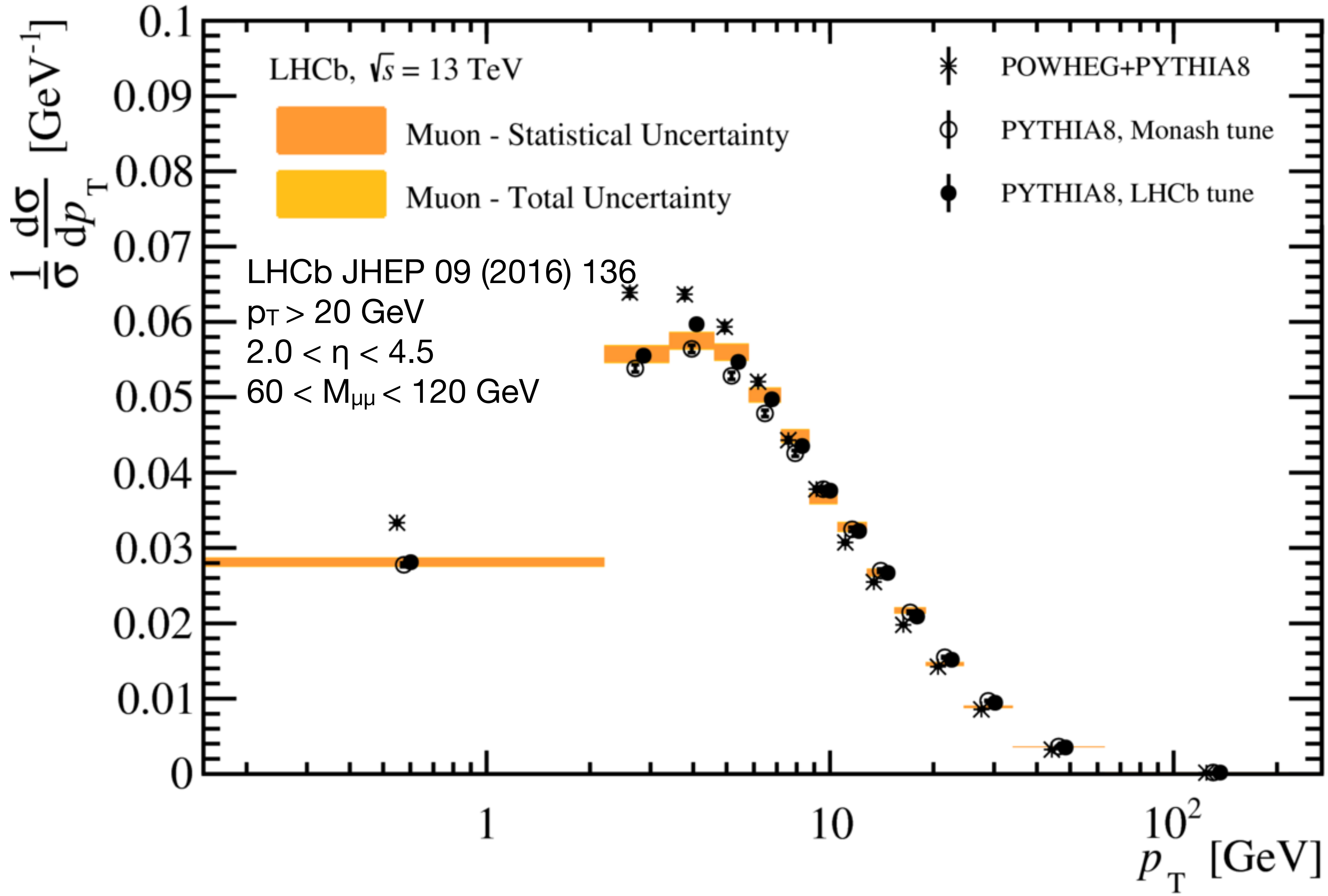
where the uncertainties are due to the sample size, systematic effects, the beam energy and the luminosity. This result is in good agreement with theoretical predictions at next-to-next-to-leading order in perturbative quantum chromodynamics. The cross-section is also measured differentially as a function of kinematic variables of the $Z$ boson. Ratios of the production cross-sections of electroweak bosons are presented using updated LHCb measurements of $W$ boson production. A precise test of the Standard Model is provided by the measurement of the ratio

$$\frac{\sigma_{W^+\to\mu^+\nu_\mu} + \sigma_{W^-\to\mu^-\bar{\nu}_\mu}}{\sigma_{Z\to\mu^+\mu^-}} = 20.63 \pm 0.09 \pm 0.12 \pm 0.05,$$

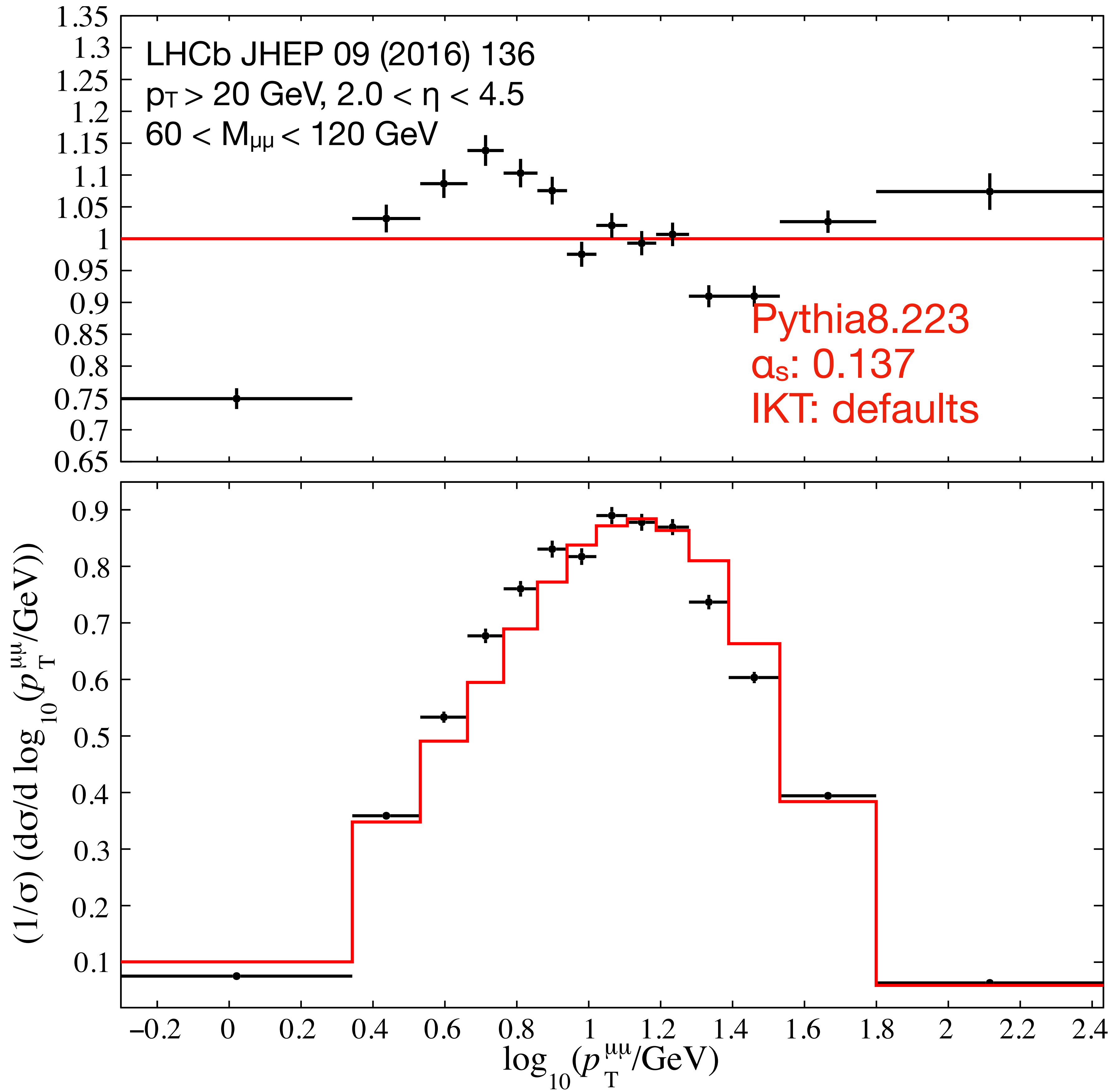
where the uncertainty due to luminosity cancels.

Published in JHEP 08 (2015) 039

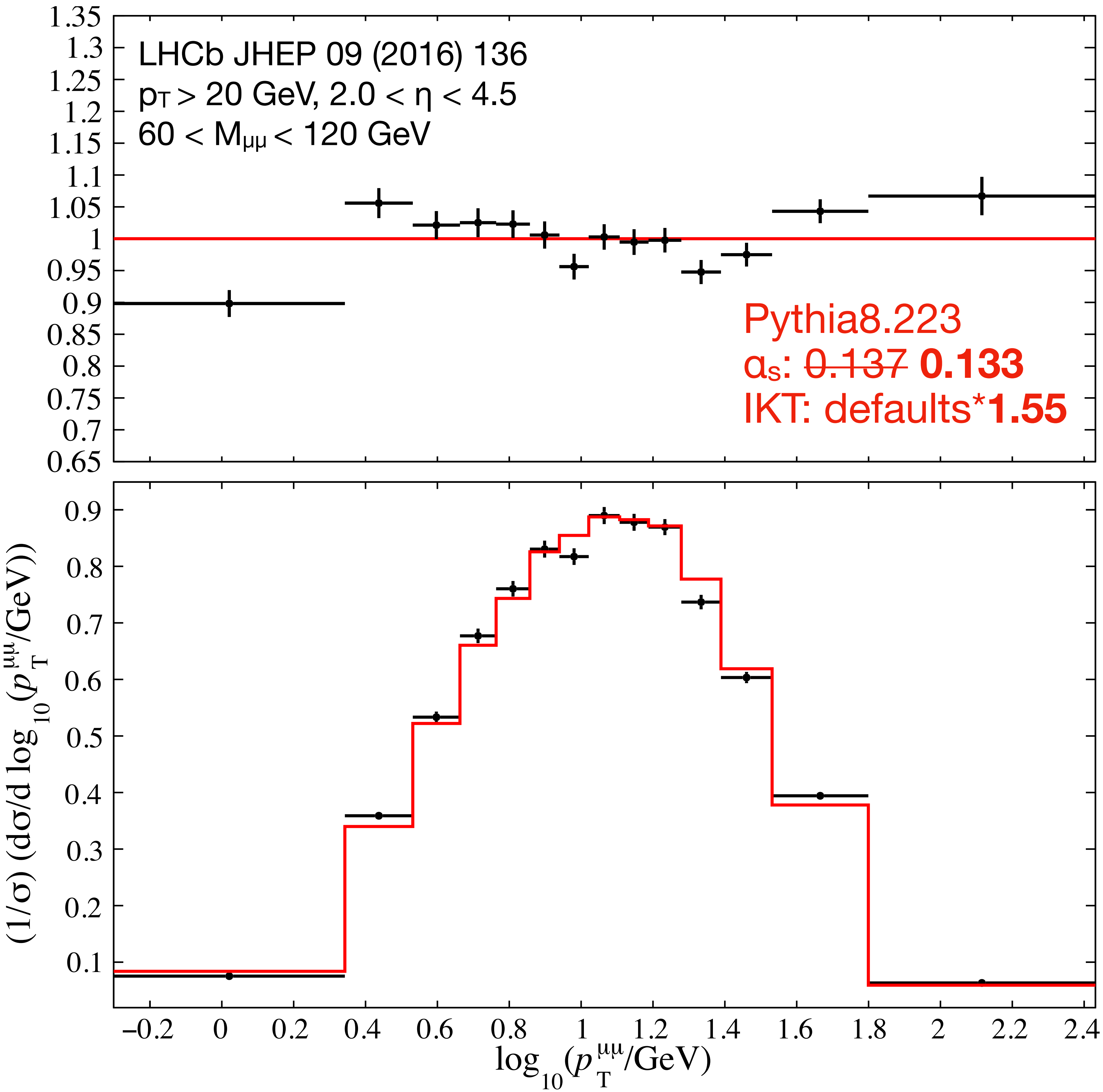
# Example data from 13 TeV paper



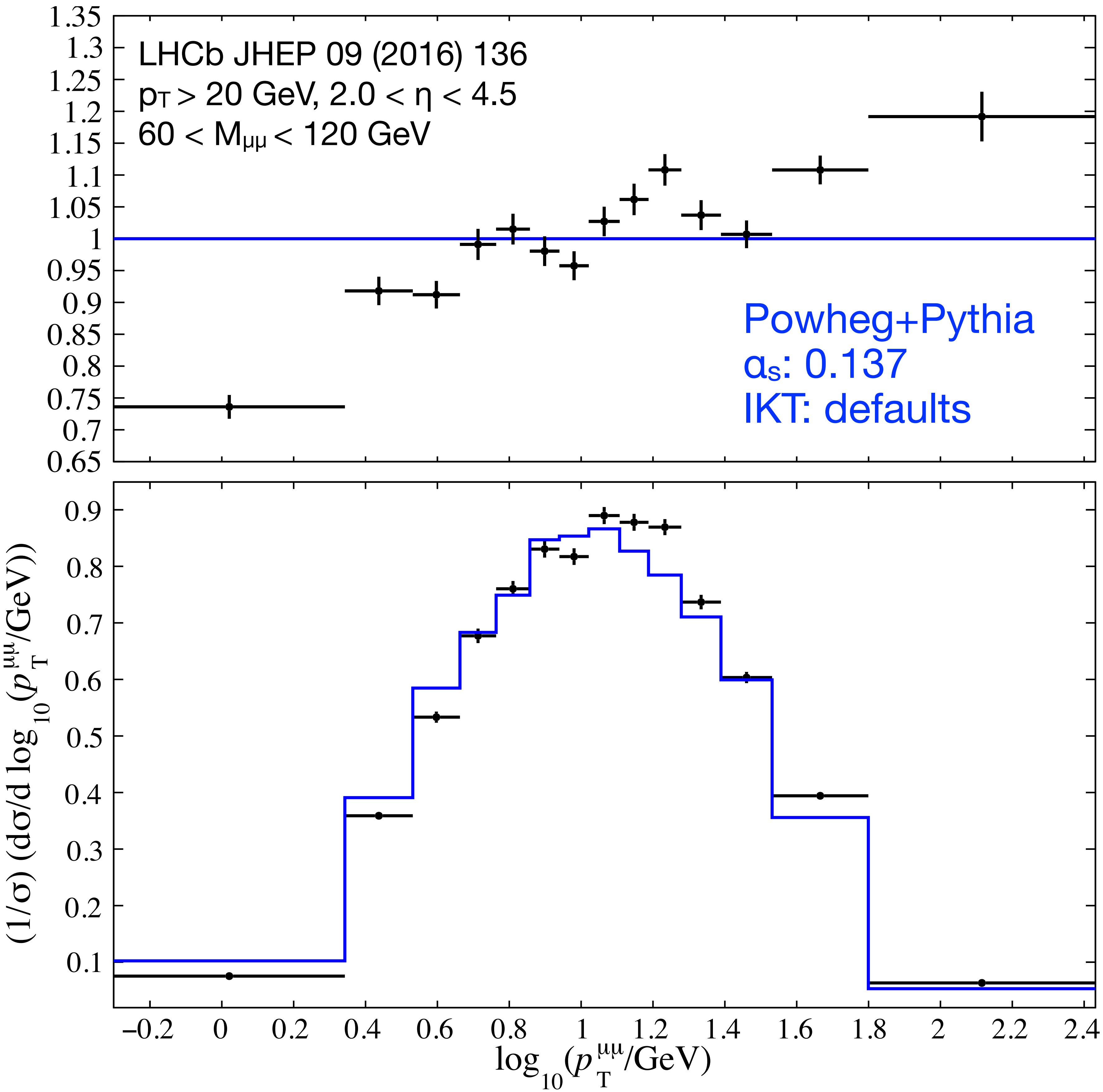
# Tuning to these data: *Pythia*



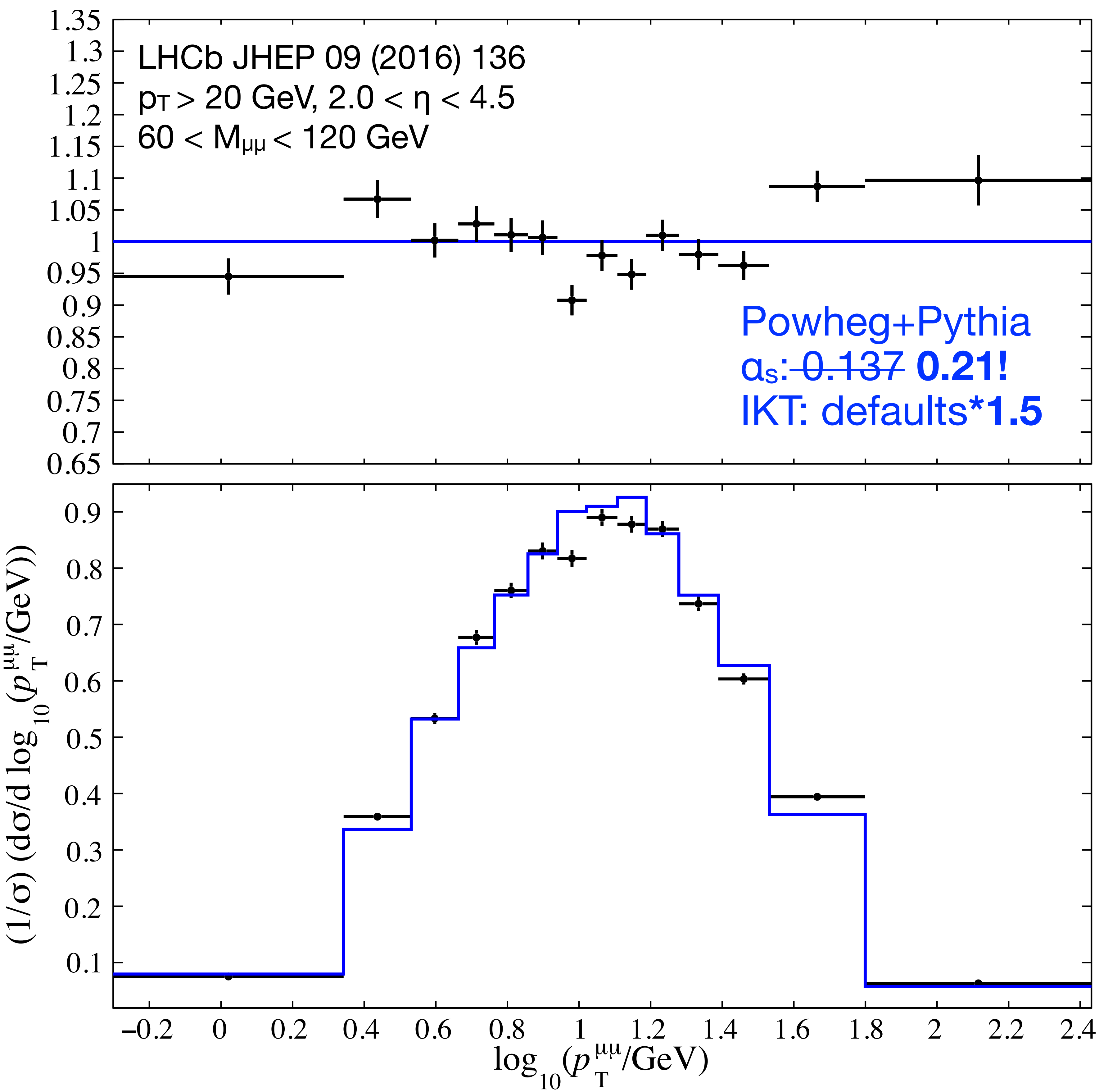
# Tuning to these data: *Pythia*



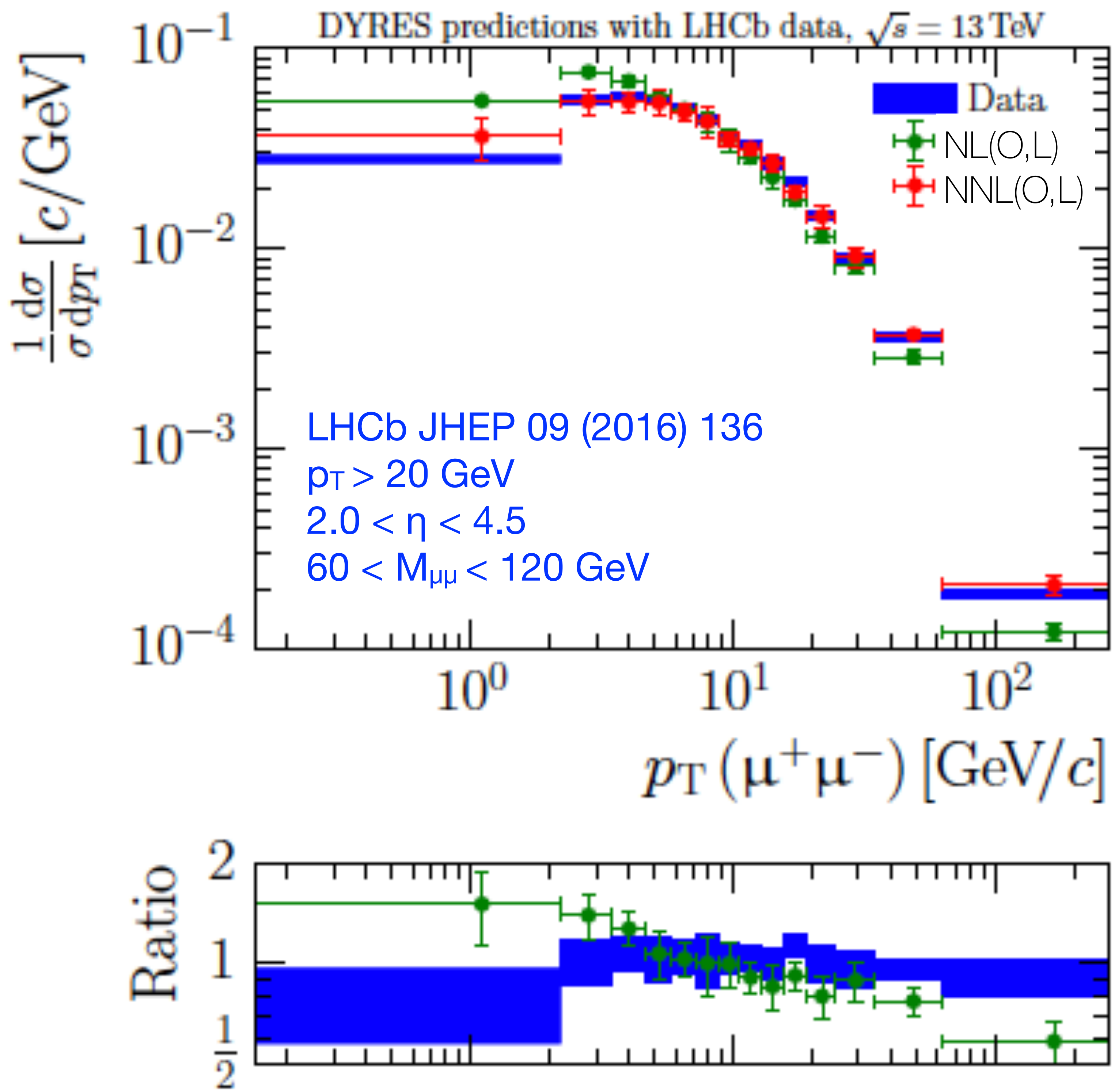
# Tuning to these data: *Powheg+Pythia*



# Tuning to these data: *Powheg+Pythia*



# Comparing with these data: *DYRES*

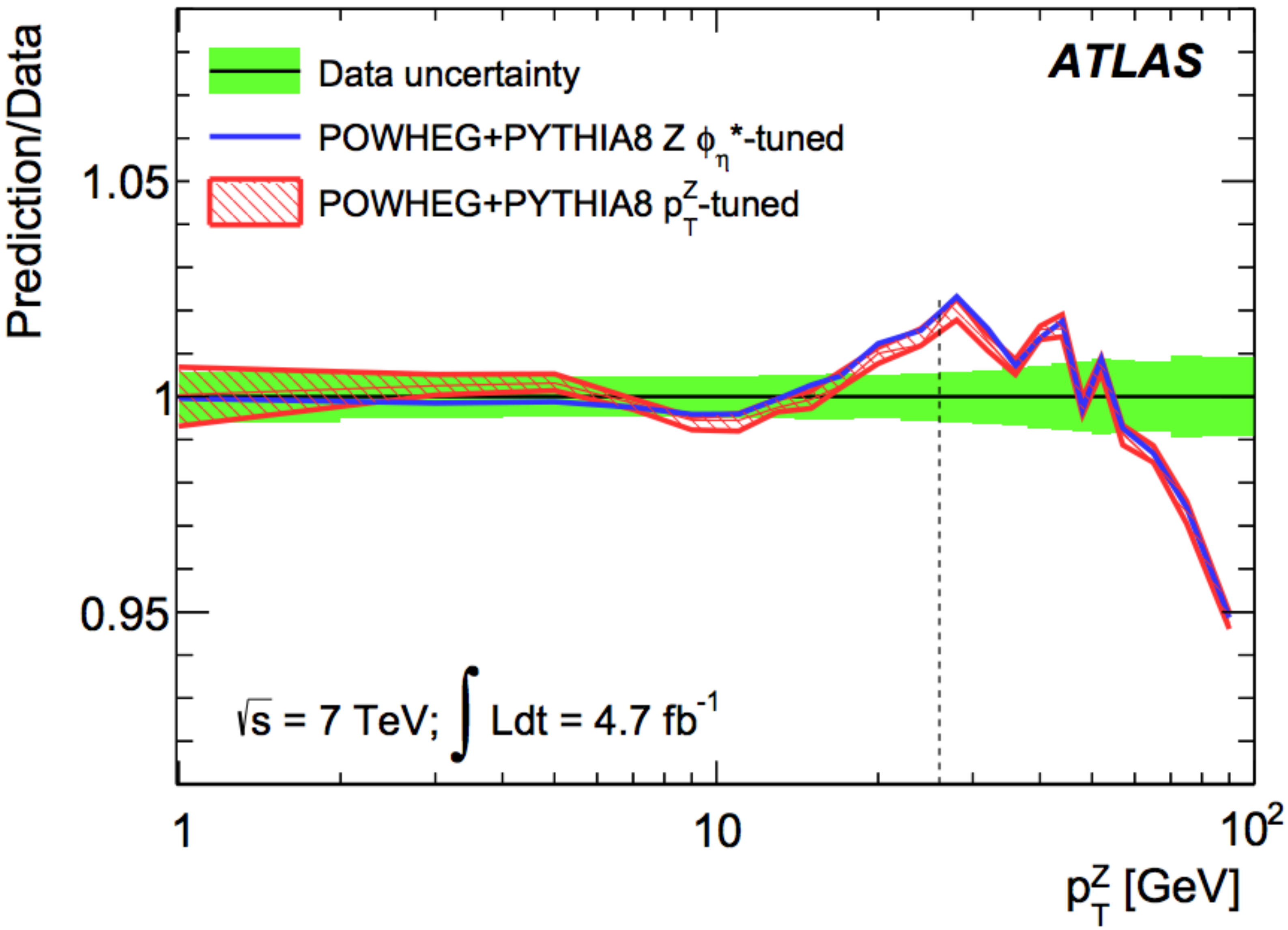



1)G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini, Phys. Lett. B696 207-213 (2011) 1008.2351
2)S. Catani, G. Ferrera, D. de Florian, M. Grazzini, JHEP 12, 047 (2015) 1507.06937

Table 7: The measured differential cross-sections as a function of $p_T$. The first uncertainty is due to the size of the dataset, the second is due to experimental systematic uncertainties, and the third is due to the luminosity.

| Bin index | $d\sigma_Z^{\mu\mu}/dp_{T,Z}$ [pb / GeV] | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 5.55 | ± | 0.11 | ± | 0.15 | ± | 0.22 |
| 2 | 11.01 | ± | 0.21 | ± | 0.29 | ± | 0.43 |
| 3 | 11.36 | ± | 0.21 | ± | 0.30 | ± | 0.44 |
| 4 | 11.06 | ± | 0.21 | ± | 0.29 | ± | 0.43 |
| 5 | 9.93 | ± | 0.18 | ± | 0.26 | ± | 0.39 |
| 6 | 8.86 | ± | 0.16 | ± | 0.23 | ± | 0.35 |
| 7 | 7.22 | ± | 0.13 | ± | 0.19 | ± | 0.28 |
| 8 | 6.48 | ± | 0.11 | ± | 0.18 | ± | 0.25 |
| 9 | 5.28 | ± | 0.09 | ± | 0.14 | ± | 0.21 |
| 10 | 4.29 | ± | 0.07 | ± | 0.12 | ± | 0.17 |
| 11 | 2.88 | ± | 0.05 | ± | 0.08 | ± | 0.11 |
| 12 | 1.760 | ± | 0.029 | ± | 0.046 | ± | 0.069 |
| 13 | 0.709 | ± | 0.011 | ± | 0.018 | ± | 0.028 |
| 14 | 0.0376 | ± | 0.0009 | ± | 0.0010 | ± | 0.0015 |

See paper for full error matrix, plus $d\sigma/d\Phi^*$ and $d\sigma/dy$ data




| | PYTHIA8 | POWHEG+PYTHIA8 | Base tune |
|---|---|---|---|
| Tune Name | AZ | AZNLO | 4C |
| Primordial $k_T$ [GeV] | $1.71 \pm 0.03$ | $1.75 \pm 0.03$ | 2.0 |
| ISR $\alpha_S^{ISR}(m_Z)$ | $0.1237 \pm 0.0002$ | 0.118 (fixed) | 0.137 |
| ISR cut-off [GeV] | $0.59 \pm 0.08$ | $1.92 \pm 0.12$ | 2.0 |
| $\chi^2_{min}$/dof | 45.4/32 | 46.0/33 | - |

# PDF uncertainties

Bozzi et al., EPJ. C75 12 601 2015

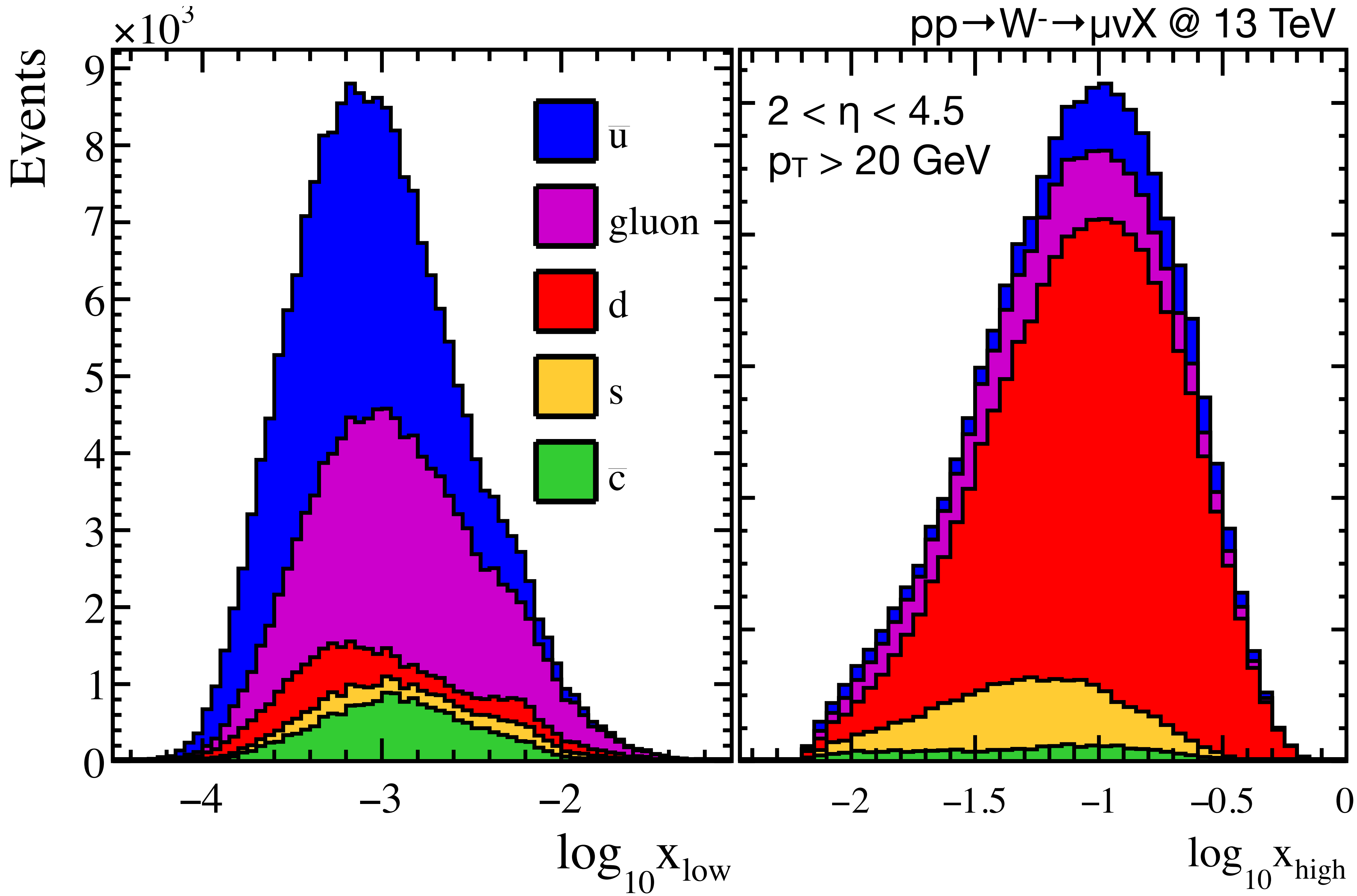
$$\delta_{\text{PDF}} = \begin{pmatrix} \mathbf{G}^+ & 24.8 \\ \mathbf{G}^- & 13.2 \\ \mathbf{L}^+ & 27.0 \\ \mathbf{L}^- & 49.3 \end{pmatrix} \rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}$$

Numbers correspond to $25 < p_T < 50$ GeV fit range, NNPDF2.3. Also assumed that the GPDs can perfectly reject events with W $p_T > 15$ GeV.

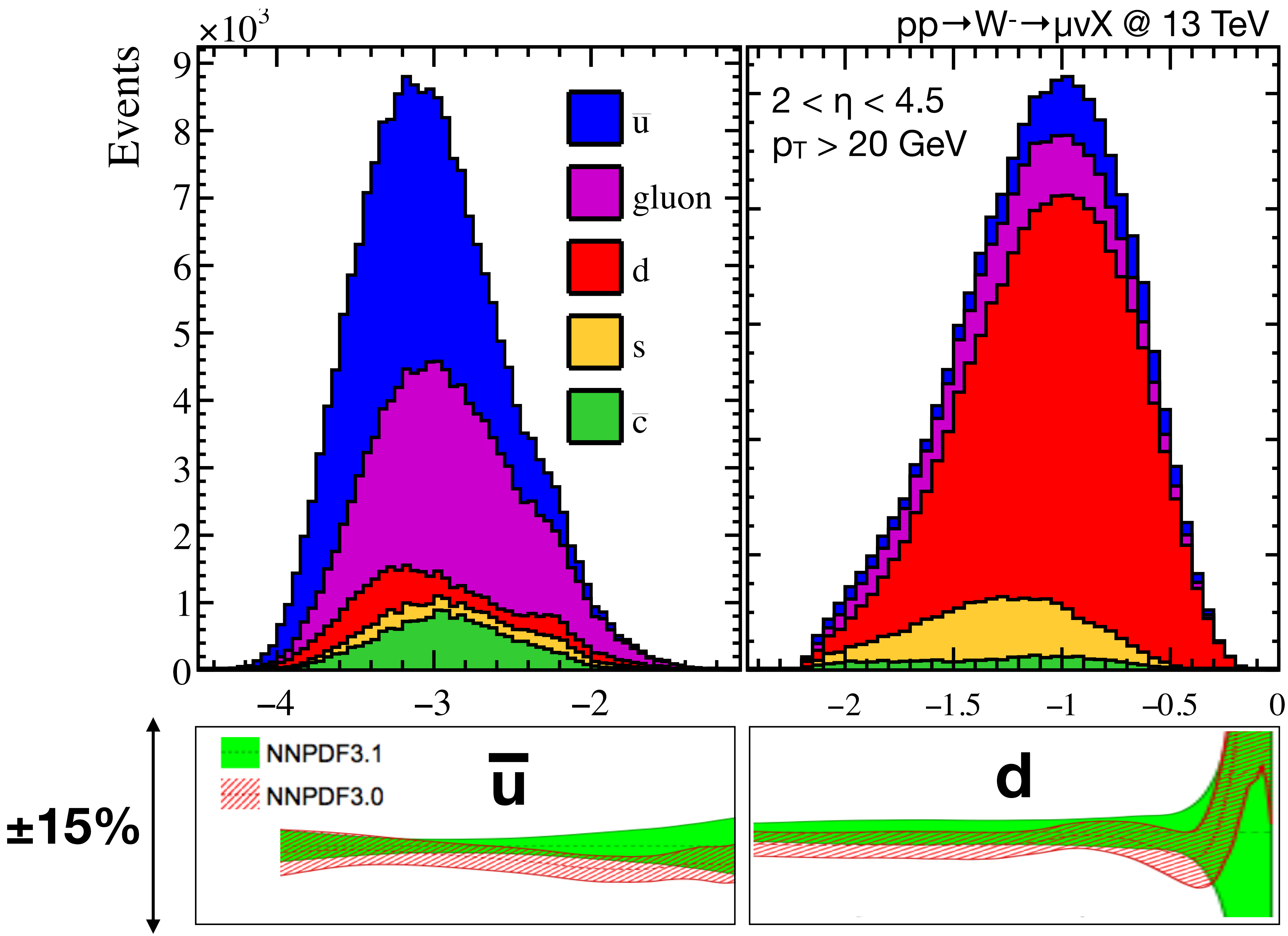
Negative correlation coefficients, between LHCb and GPD, are clearly beneficial in a LHC average. However, the standalone LHCb uncertainties are relatively large. Let's try to gain a deeper understanding of this…

Following slides present preliminary findings of a study by Martina Pili (1st year DPhil student in Oxford). I'll just show the results with $W^-$ and NNPDF3.1 for brevity.

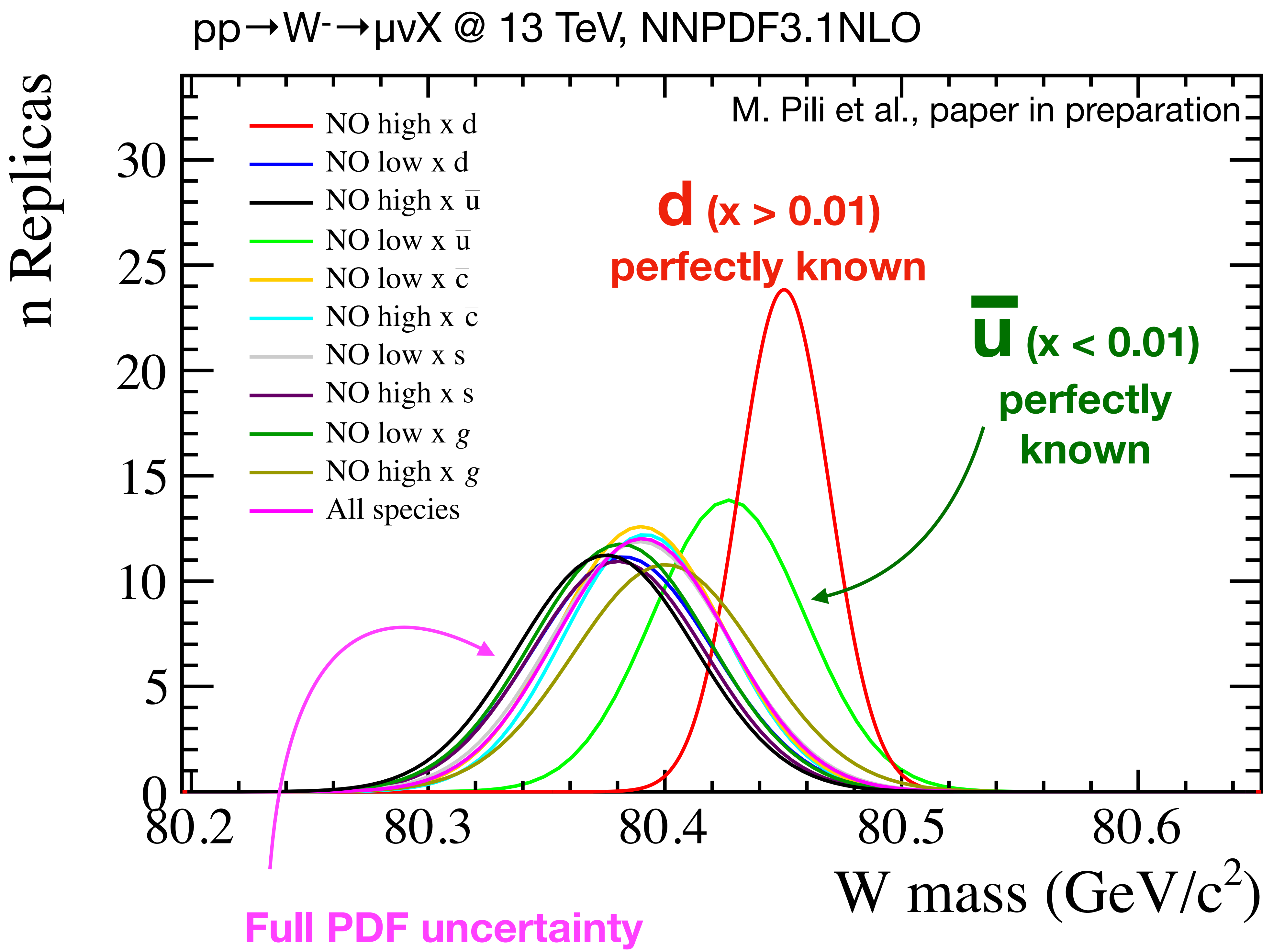
# Subprocess breakdown



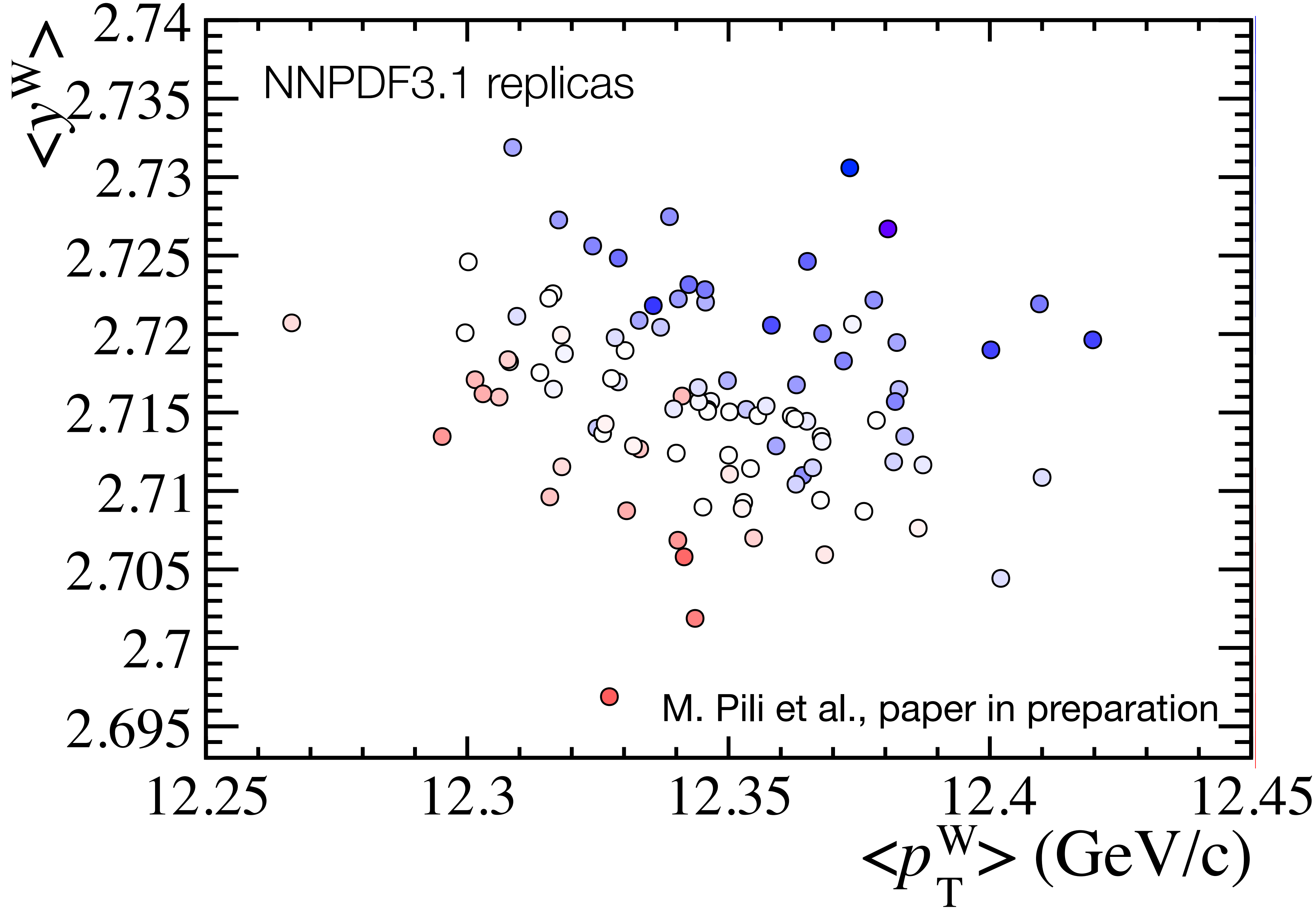
# Subprocess breakdown



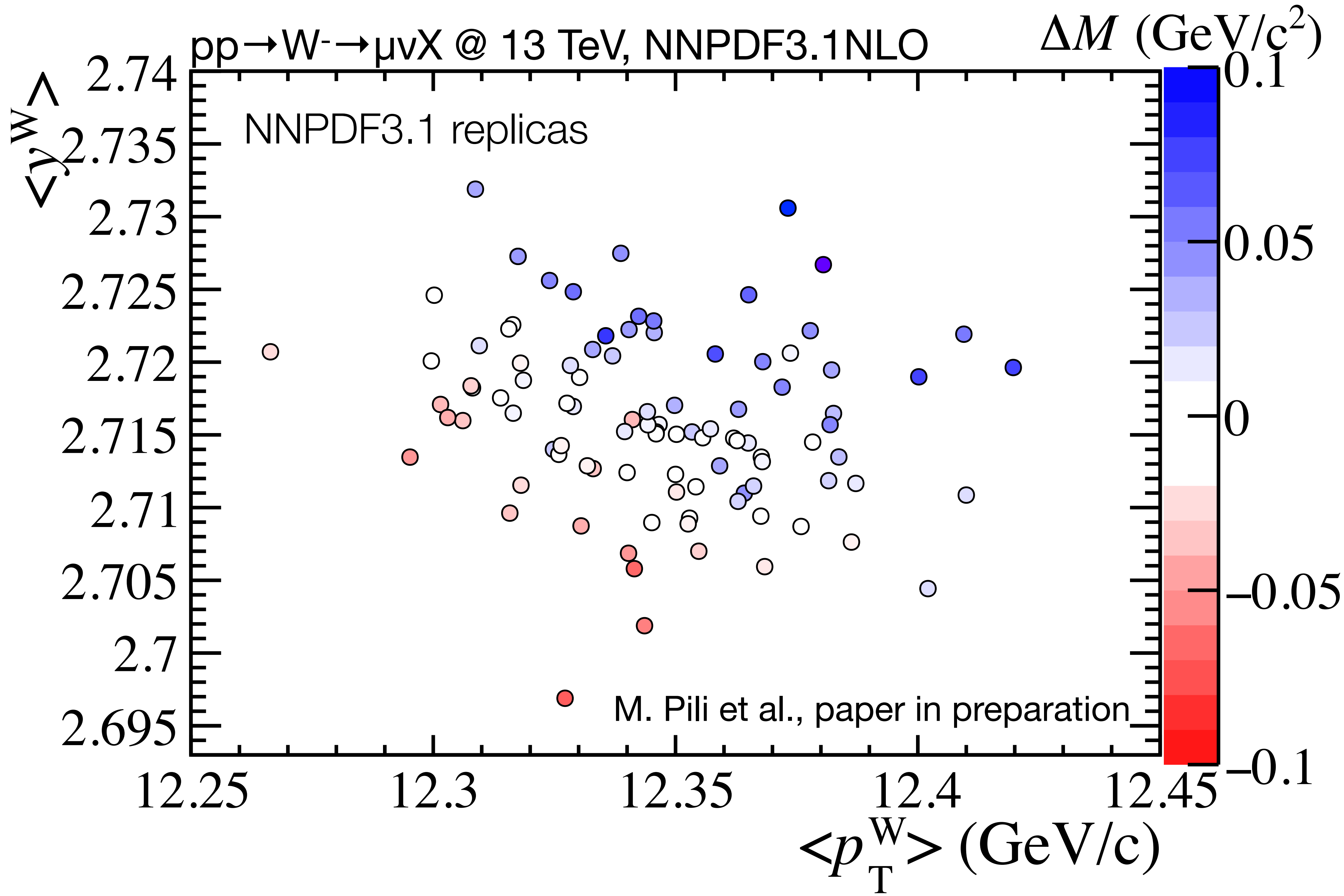
# "Importance" study



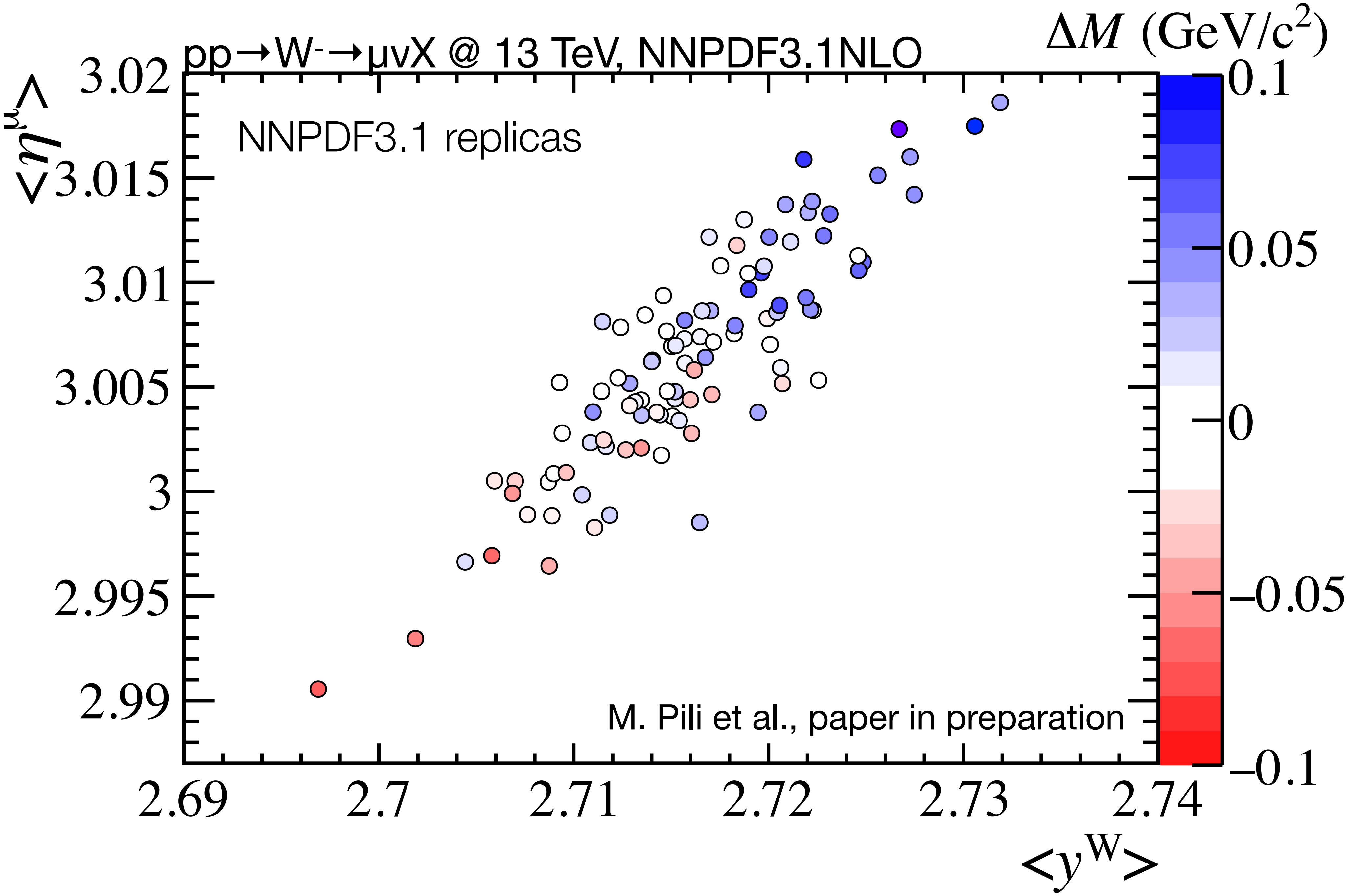
# PDF uncertainty mechanism study



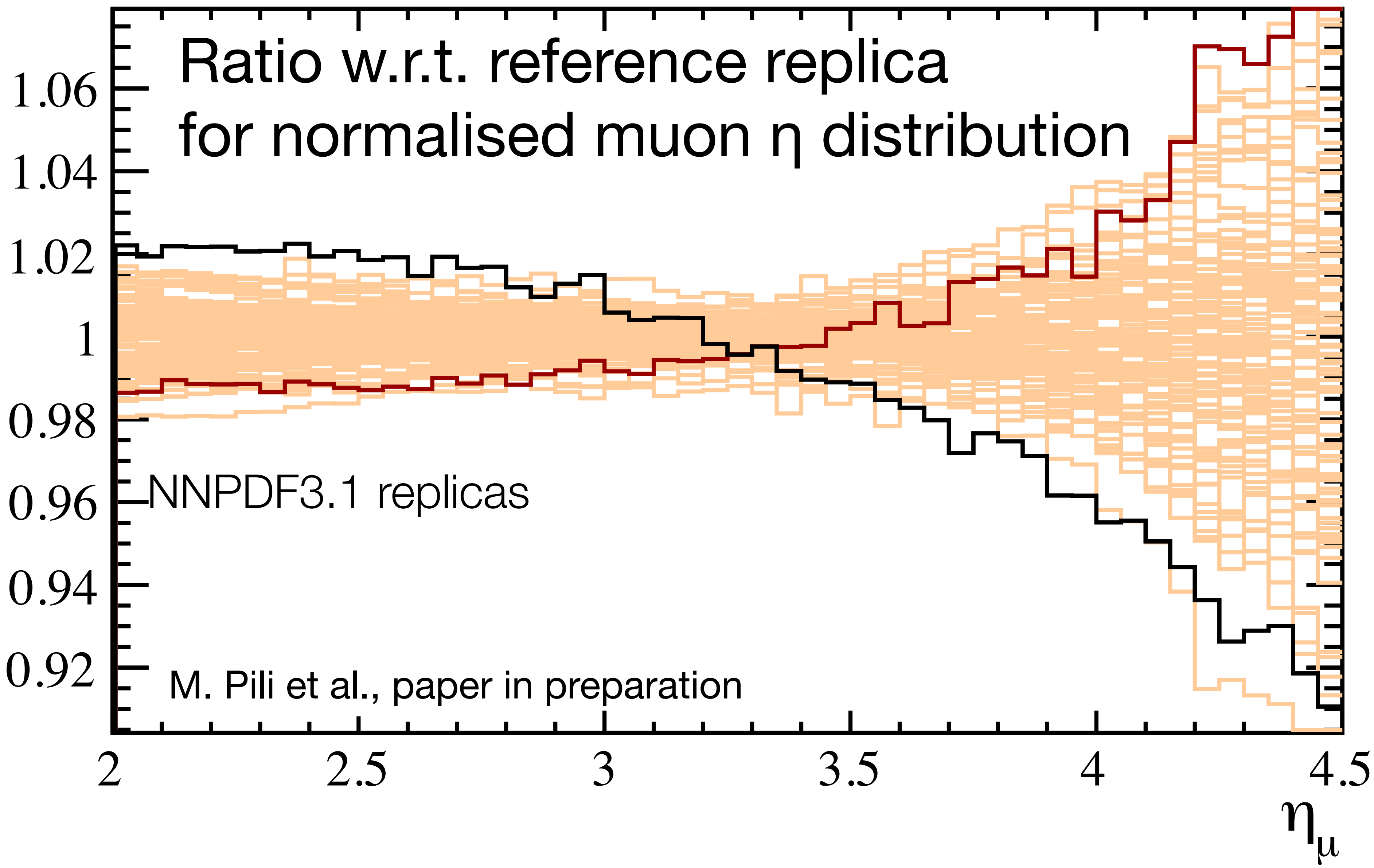
# PDF uncertainty mechanism study



# PDF uncertainty mechanism study



# Can this be exploited?



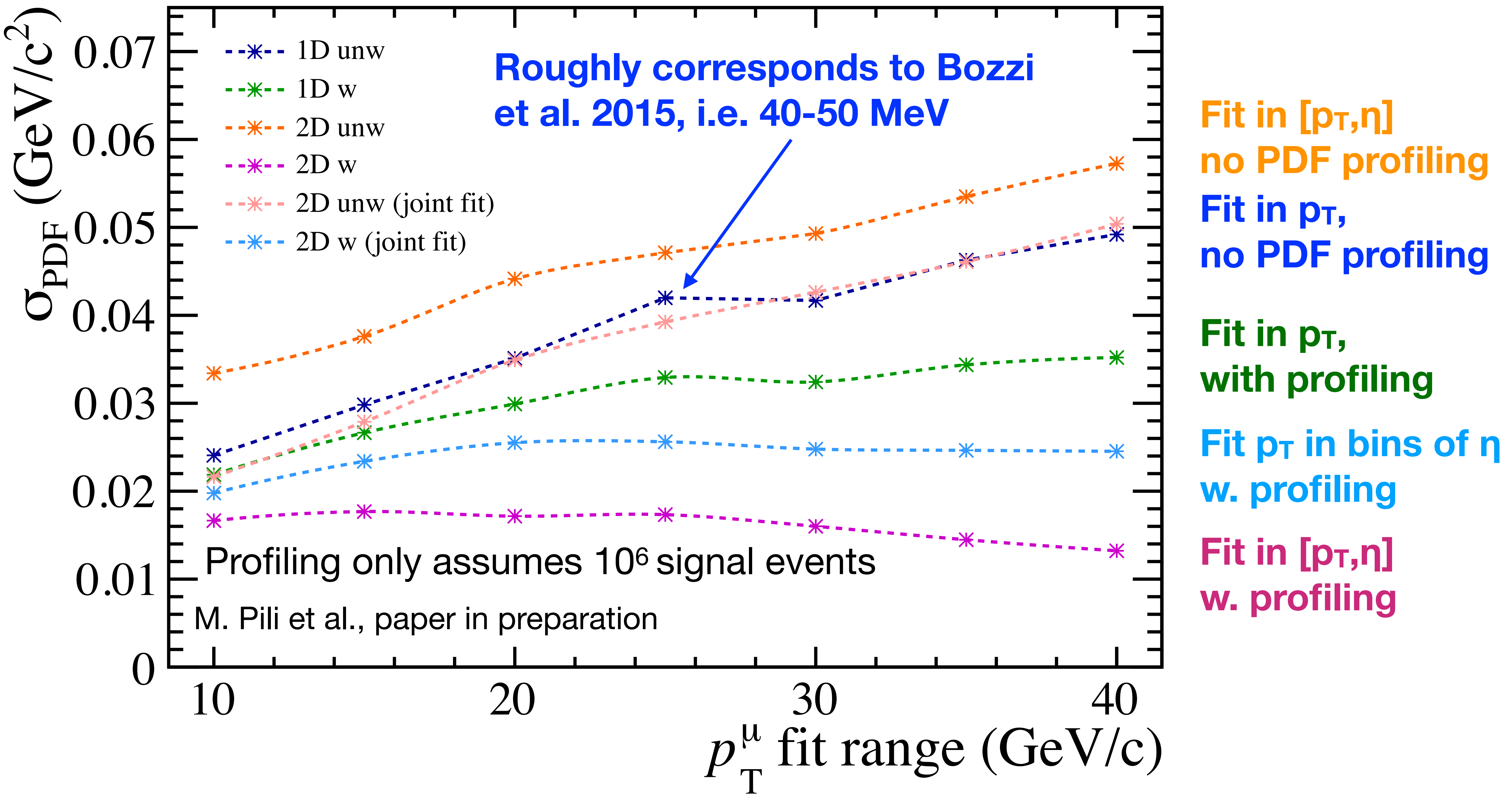

- Replica giving **lowest** $m_W$

- All replicas

- Replica giving **largest** $m_W$

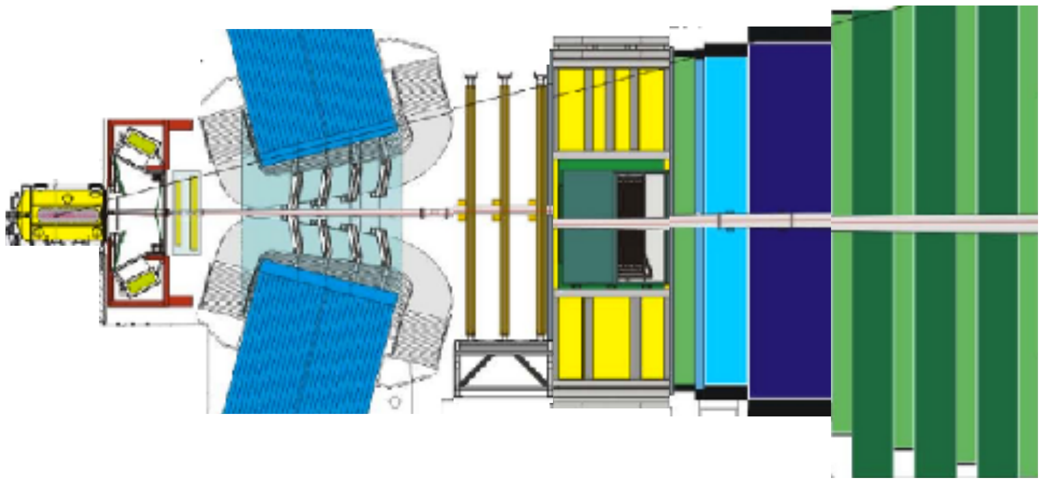
The replicas which contribute most to our PDF uncertainty could be discriminated against by our own data! Requires ~1% control over the η shape. Simply fit $m_W$ (and PDFs) against the 2D $p_{T}-\eta$ distribution.

# Potential




Note that there is no double counting of the same data in the PDF fits (no 13 TeV LHCb W data). In general we probably want some special PDF sets, without any LHCb W/Z data, and many replicas!

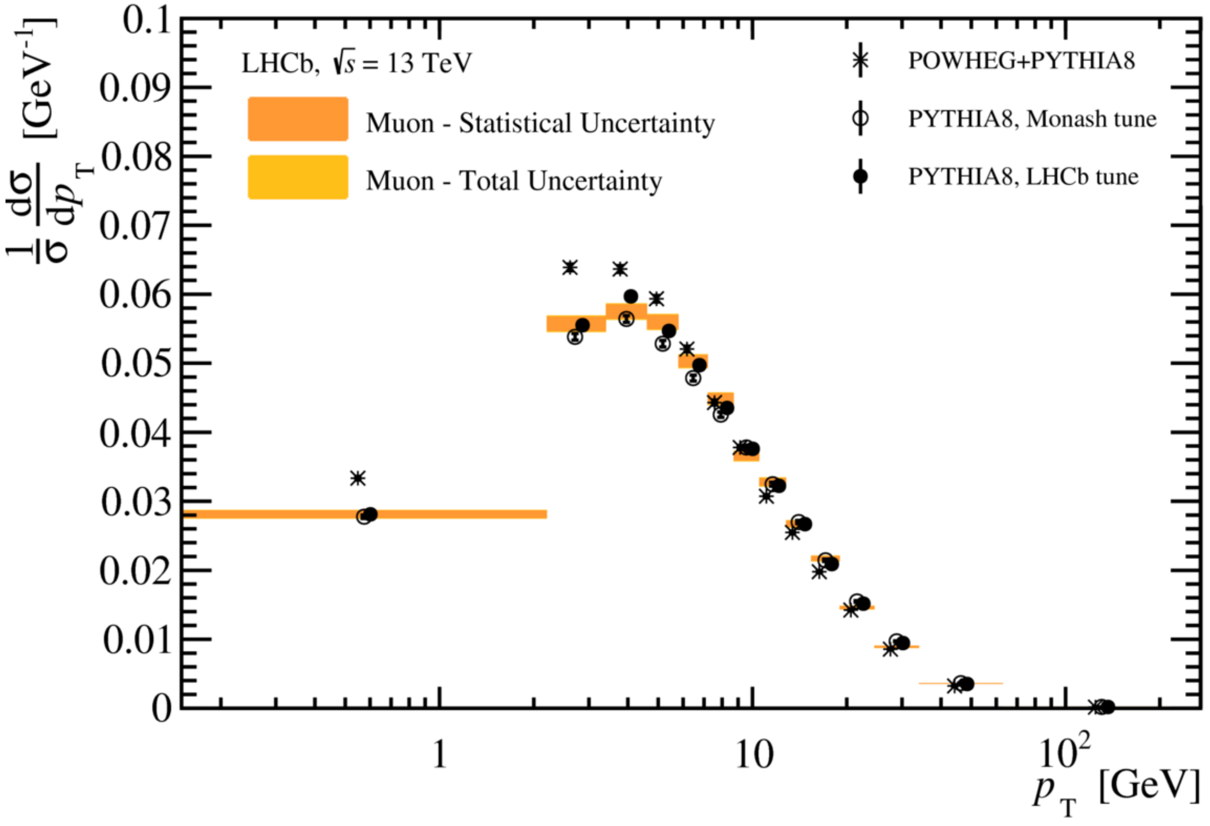
# Conclusions

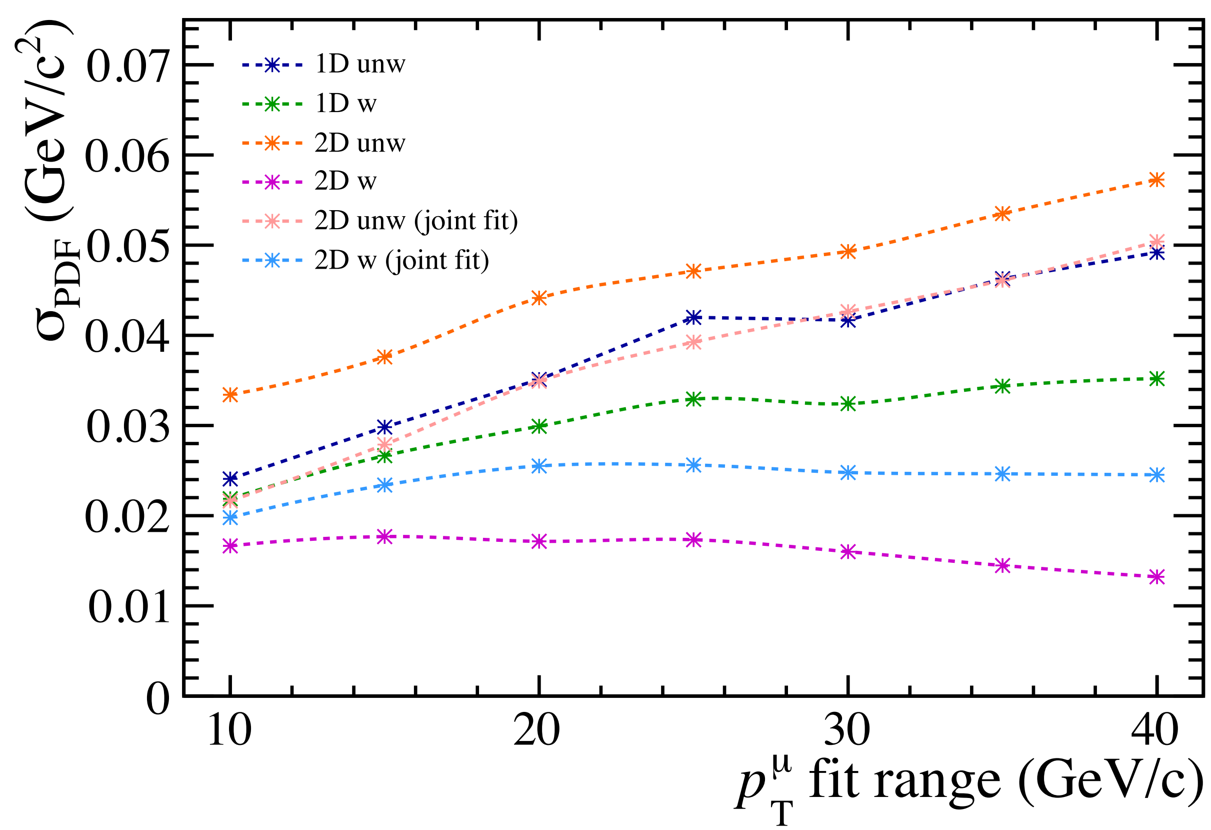


Current LHCb data capable of $m_W$ with $\delta_{stat}$ ~ 10 MeV with simple muon based analysis.

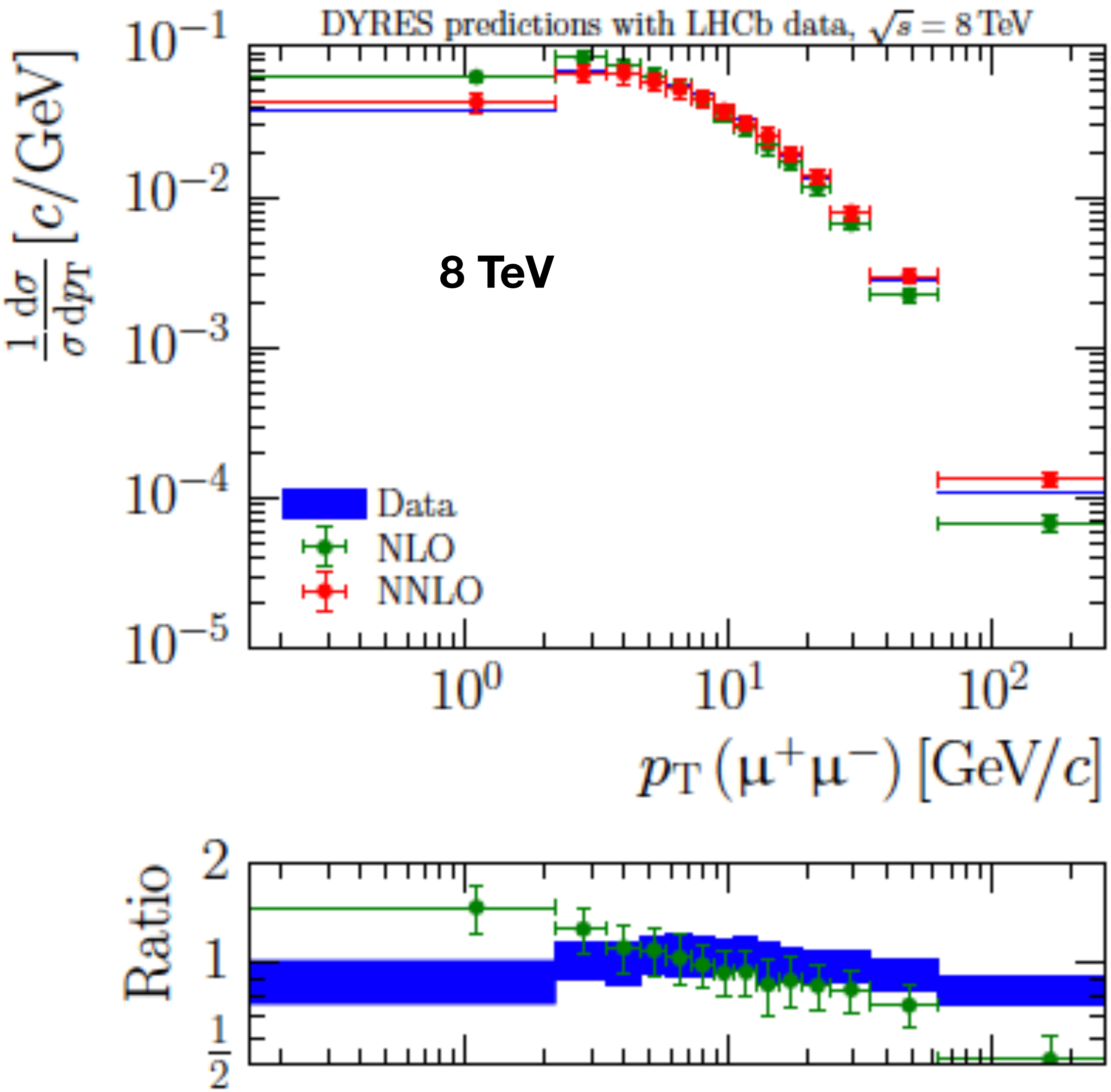
Complementary to ATLAS/CMS, but the clear challenge is to control the $p_T(W)$ without full recoil coverage.

First steps with $p_T(Z)$ and PDF uncertainties shown today.



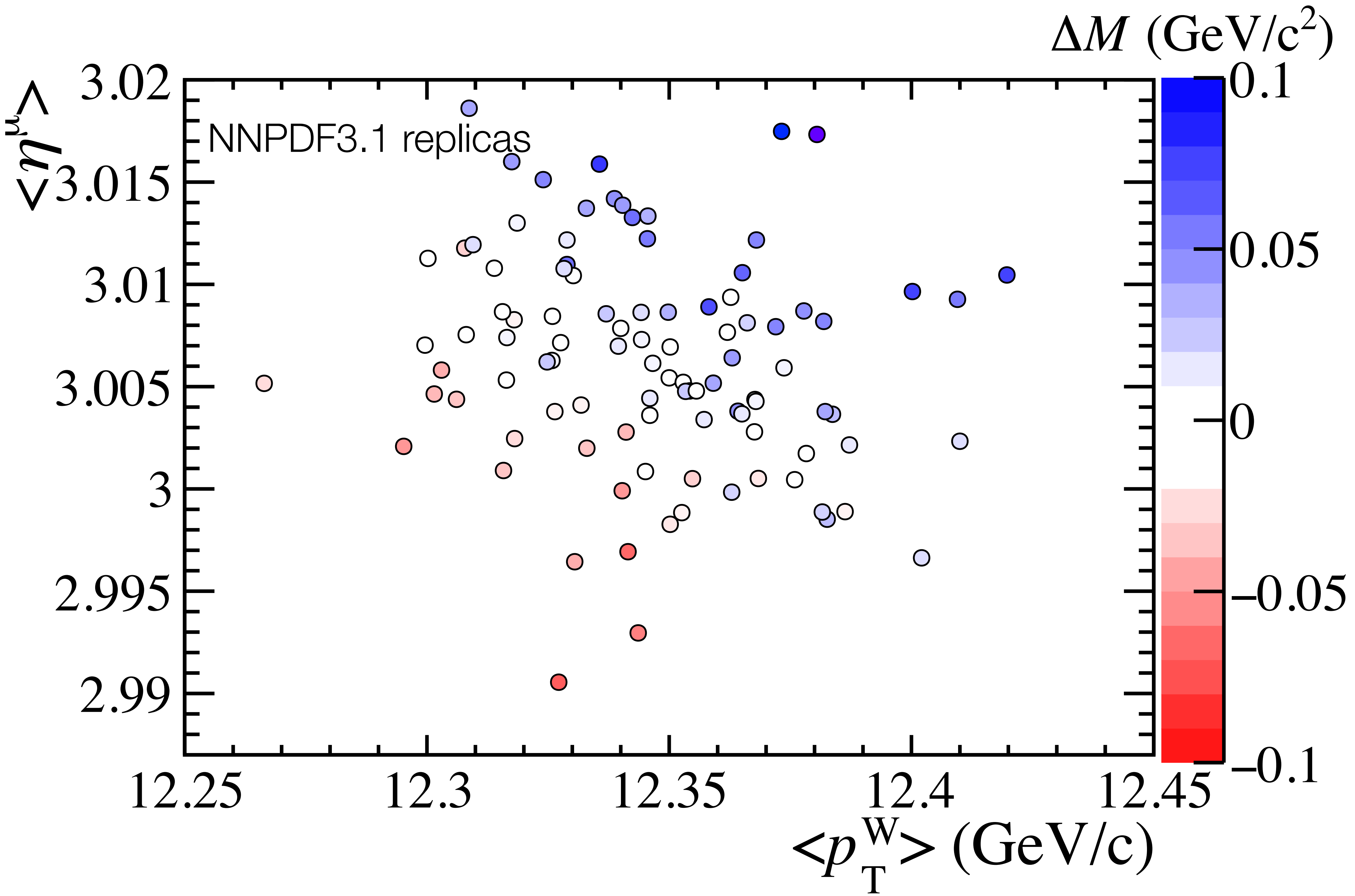



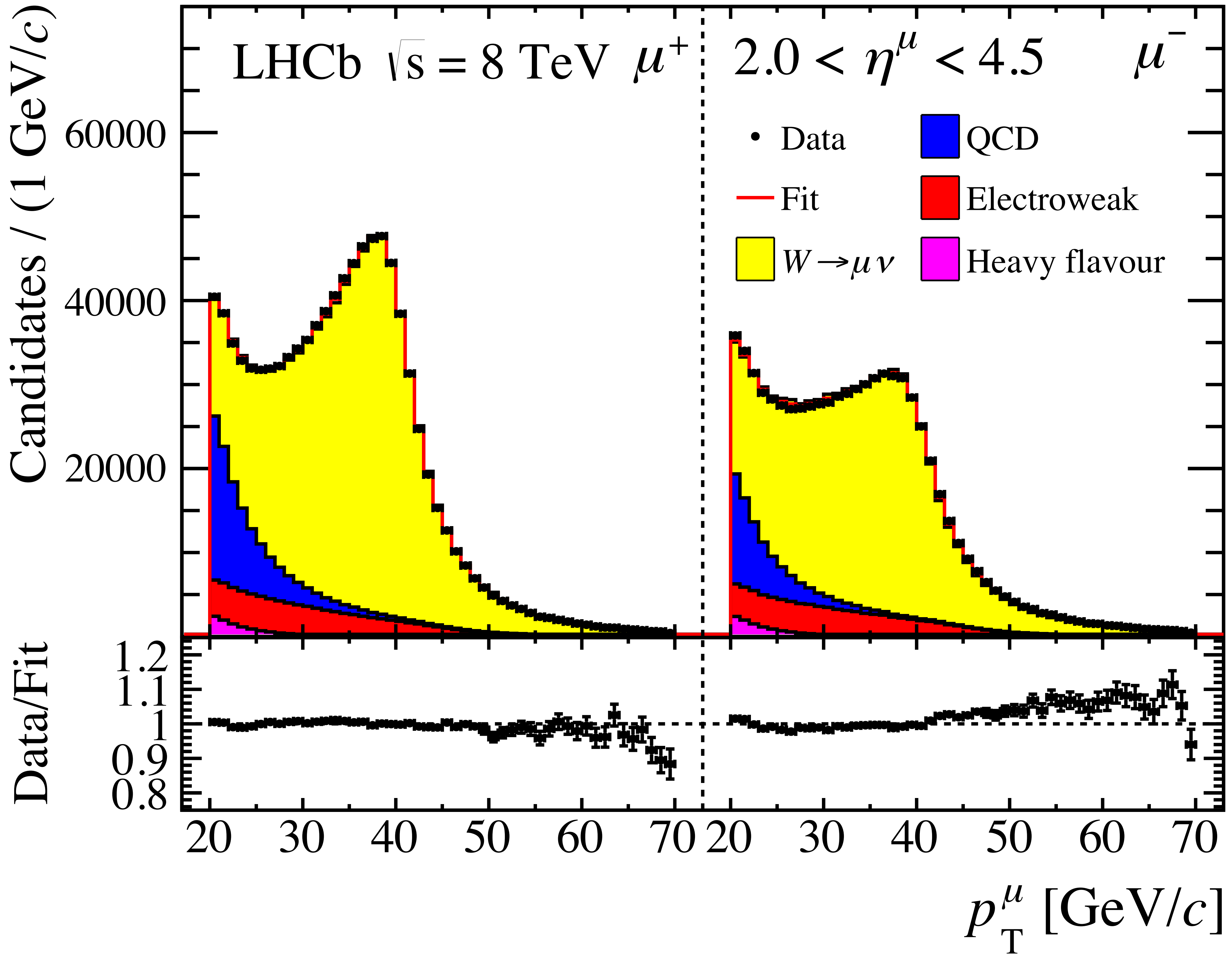
# Backup slides start here…




[1] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, and M. Grazzini, "Production of Drell-Yan lepton pairs in hadron collisions: Transverse-momentum resummation at next-to-next-to-leading logarithmic accuracy", Phys. Lett. **B696**, 207–213 (2011), arXiv:1007.2351; S. Catani, D. de Florian, G. Ferrera, and M. Grazzini, "Vector boson production at hadron colliders: transverse-momentum resummation and leptonic decay", JHEP **12**, 047 (2015), arXiv:1507.06937.

# PDF uncertainty mechanism study

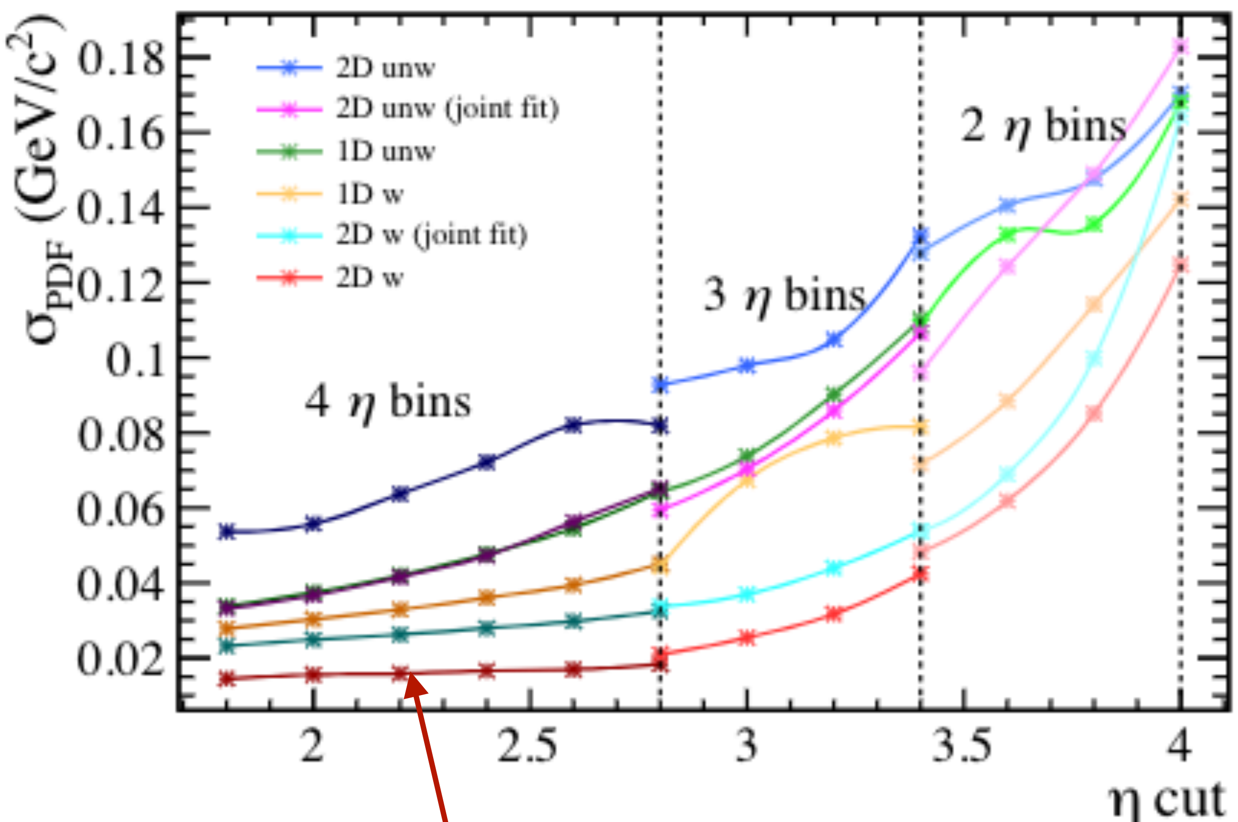


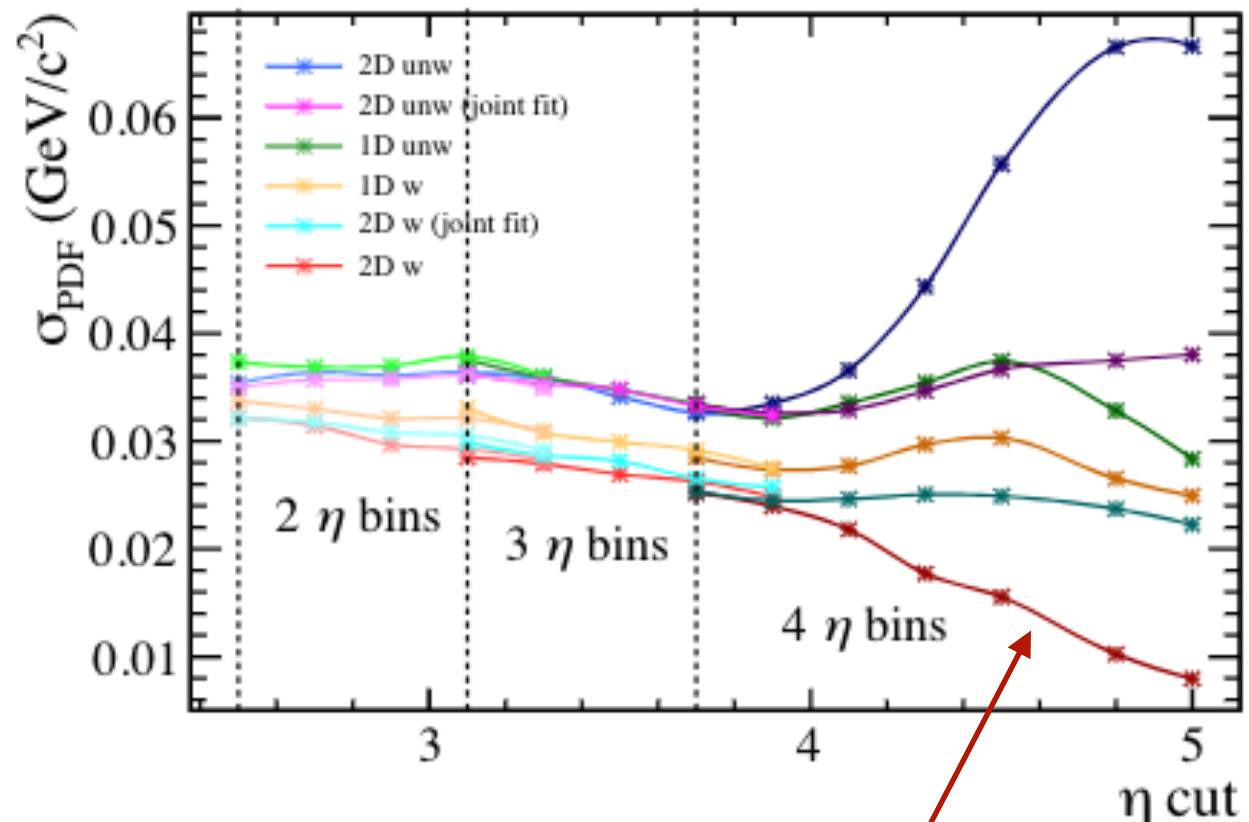


LHCb √s = 8 TeV μ+
2.0 < η^μ < 4.5
μ−
Data
Fit
W → μν
QCD
Electroweak
Heavy flavour
Candidates / (1 GeV/c)
60000
40000
20000
Data/Fit
1.2
1.1
1
0.9
0.8
20 30 40 50 60 70 20 30 40 50 60 70
p_T^μ [GeV/c]

# Further optimisations

W.r.t. fixed fit range of 30 < $p_T$ < 50 and 2 < η < 4.5, what happens if we separately vary the lower and upper η limit?




This is good, because the background is harder to control at low η, where part of our isolation cone goes out of acceptance

This tells us that we should invest some effort to understand how high we can go in η.