Precision Electroweak Physics at LHCb: Measurements and Prospects

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on behalf of the LHCb collaboration

Imperial College London
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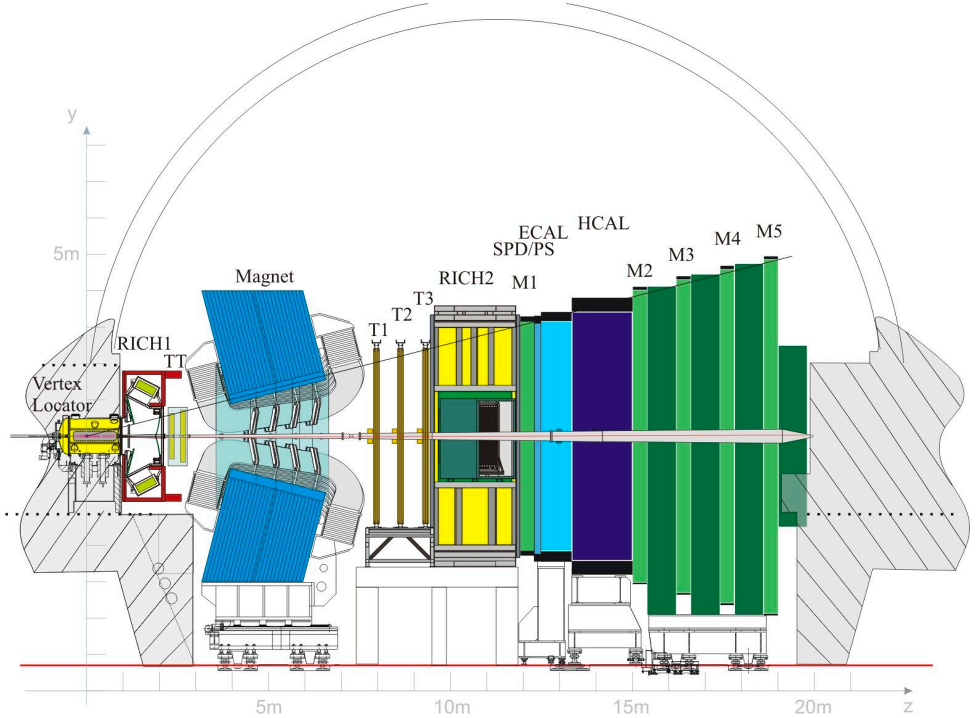
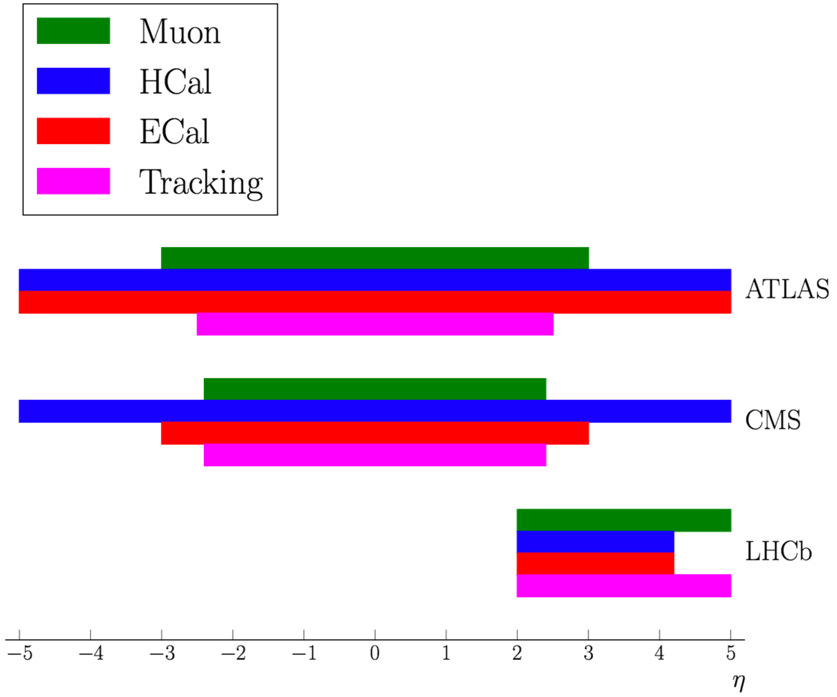
JINST 3 (2008) S08005
and Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb

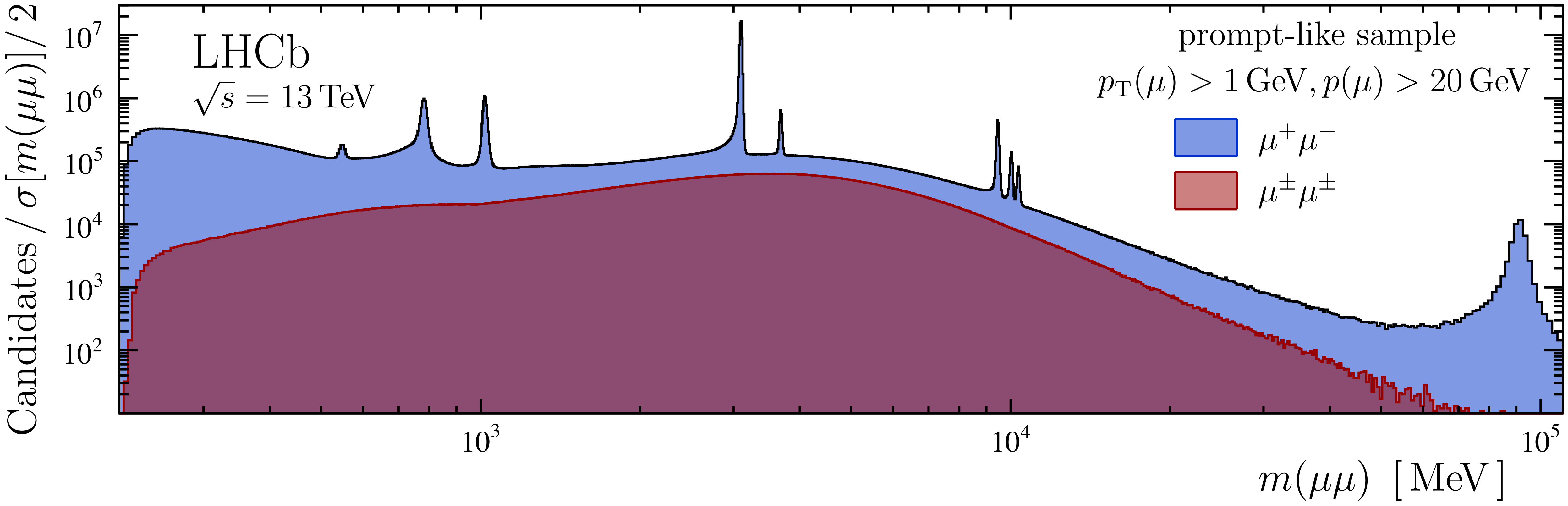
- Single arm spectrometer, fully instrumented in the forward region.





- Designed for flavour physics – but also able to act as general purpose forward detector.
- Overlap with ATLAS/CMS precision coverage in 2.0< η<2.5; unique precision coverage in 2.5<η<5.

LHCb

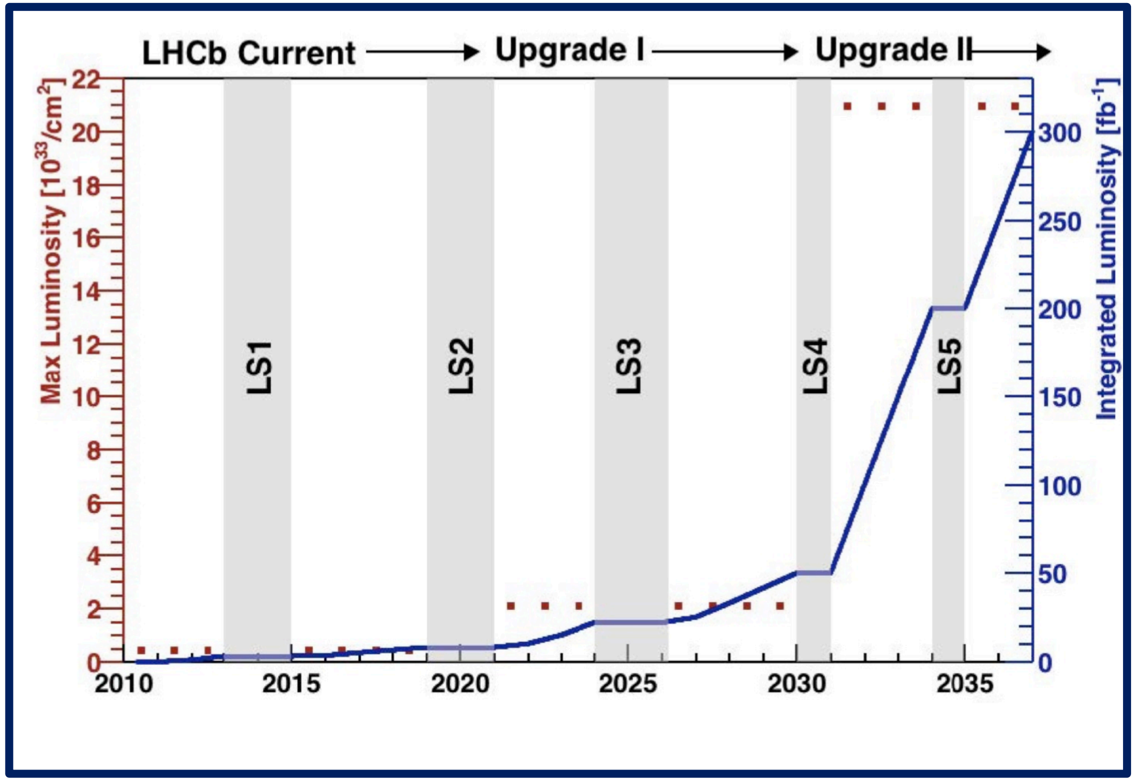

LHCb
$\sqrt{s} = 13\,\mathrm{TeV}$
prompt-like sample
$p_{\mathrm{T}}(\mu) > 1\,\mathrm{GeV}, p(\mu) > 20\,\mathrm{GeV}$
$\mu^+\mu^-$
$\mu^\pm\mu^\pm$
Candidates / $\sigma[m(\mu\mu)]/2$
$m(\mu\mu)$ [MeV]
10^2
10^3
10^4
10^5
10^6
10^7

LHCb – datasets

- LHCb runs at a reduced luminosity compared to ATLAS and CMS.
  - Provides very clean environment with reduced pileup.

- Integrated Luminosity recorded:
  - LHC Run 1:   3/fb @ 7, 8 TeV.
  - LHC Run 2:   6/fb @ 13 TeV.

- Proposal to record at least 300/fb of data at LHCb as part of the HL-LHC.



Cross-section Measurements

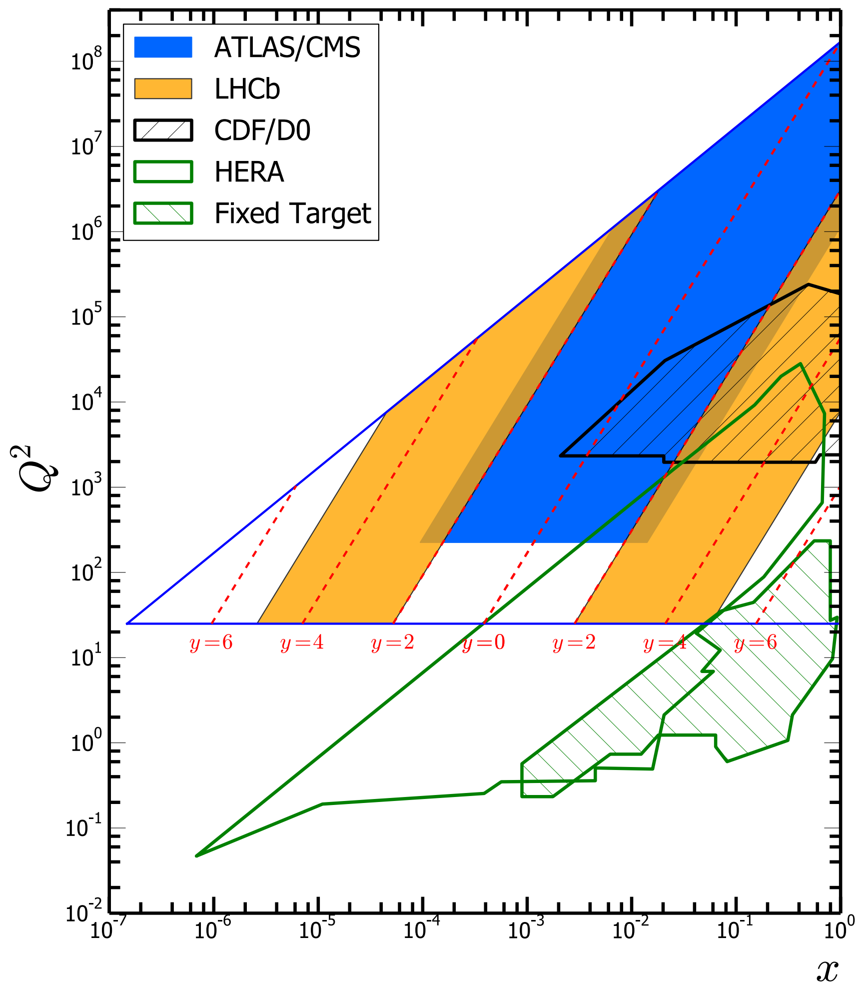
Electroweak Cross-section Measurements

- Factorisation theorem [schematic]:

$$\sigma_{AB\rightarrow X} = \sum_{a,\,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1, Q^2) f_b(x_2, Q^2) \cdot \sigma(ab \rightarrow X)$$

- Cross-section measurements and ratios are sensitive to PDFs.
  - Partonic level calculation give percent level accuracy; but PDF uncertainty usually larger.
  - Measurements used to constrain PDFs.
  - LHCb covers a unique region in x-Q^2 plane.
- But also probe pQCD in the hard interaction.

LHC 13 TeV Kinematics



More details at
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

Selected LHCb Measurements

- Wide selection of measurements at different $\sqrt{s}$ and for different final states – including:
  - $Z \rightarrow \mu\mu$ JHEP 09 (2016) 136, JHEP 01 (2016) 155, JHEP 08 (2015) 039, JHEP 06 (2012) 058
  - $Z \rightarrow ee$ JHEP 05 (2015) 109, JHEP 02 (2013) 106
  - $Z \rightarrow \tau\tau$ JHEP 09 (2018) 159, JHEP 01 (2013) 111
  - $W \rightarrow \mu\nu$ JHEP 01 (2016) 155, JHEP 12 (2014) 079
  - $W \rightarrow e\nu$ JHEP 10 (2016) 030
  - $Z +$ jets, W $+$ jets JHEP 05 (2016) 131, JHEP 01 (2014) 33
  - $Z +$ HF, W $+$ HF PLB 767 (2017) 110, PRD 92 (2015) 052001, JHEP 01 (2015) 064, JHEP 04 (2014) 091
  - $Z \rightarrow b\bar{b}$ PLB 776 (2018) 430

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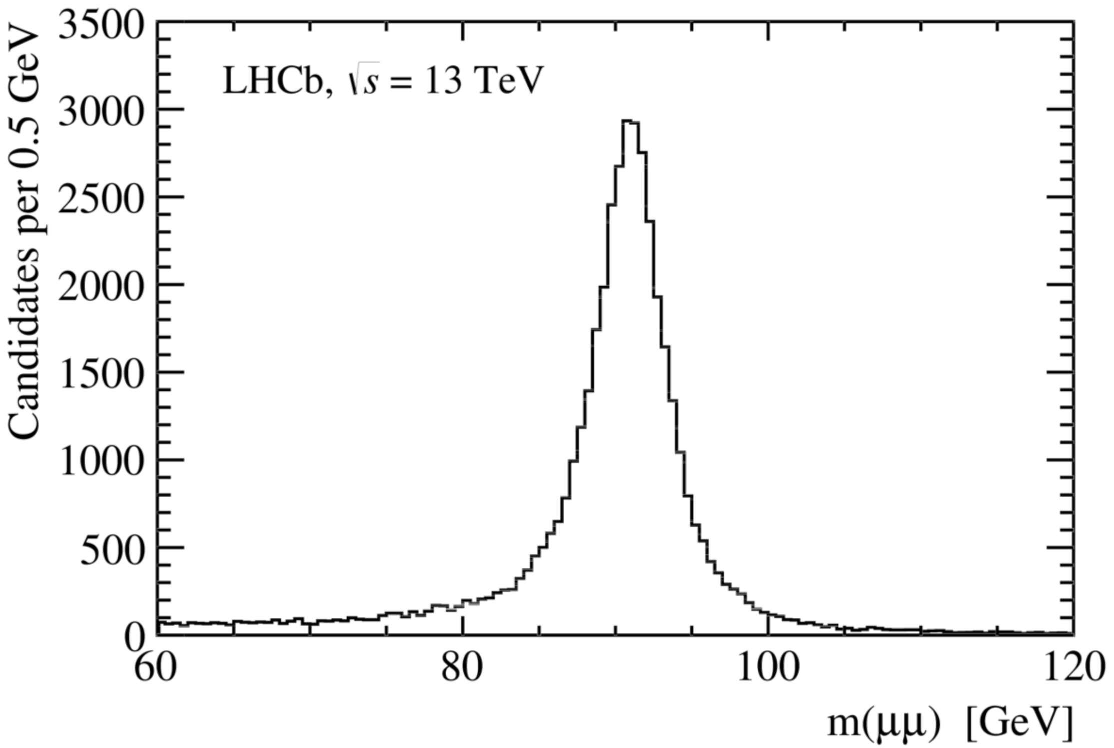
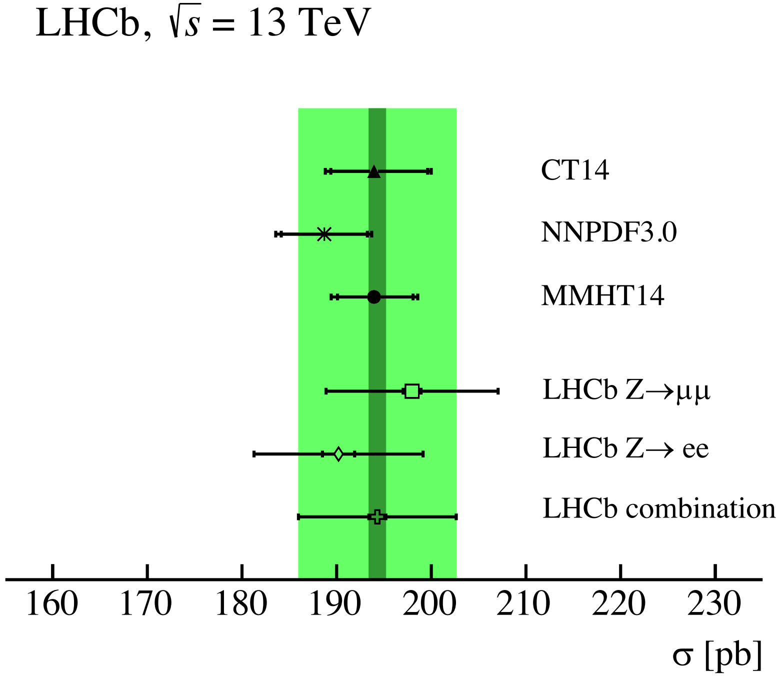
Precision Z production

- Require two forward leptons with $p_T > 20$ GeV, $2.0 < \eta < 4.5$, $60 < m_{ll} < 120$ GeV





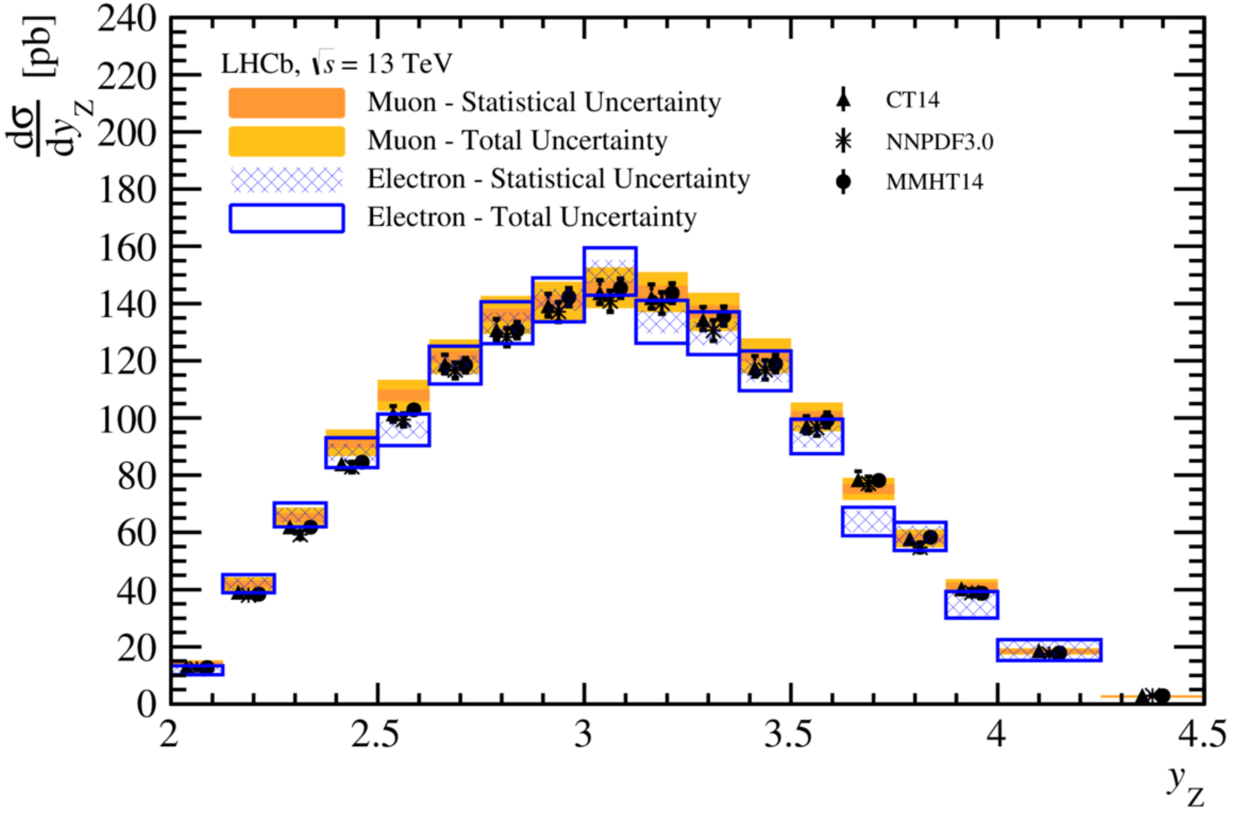
- Differences between PDF sets already show power of LHCb to provide constraints - but broad agreement between LHCb data and theory.

JHEP 09 (2016) 136
and A Banfi *et al.*, EPJC 71:1600 (2011)

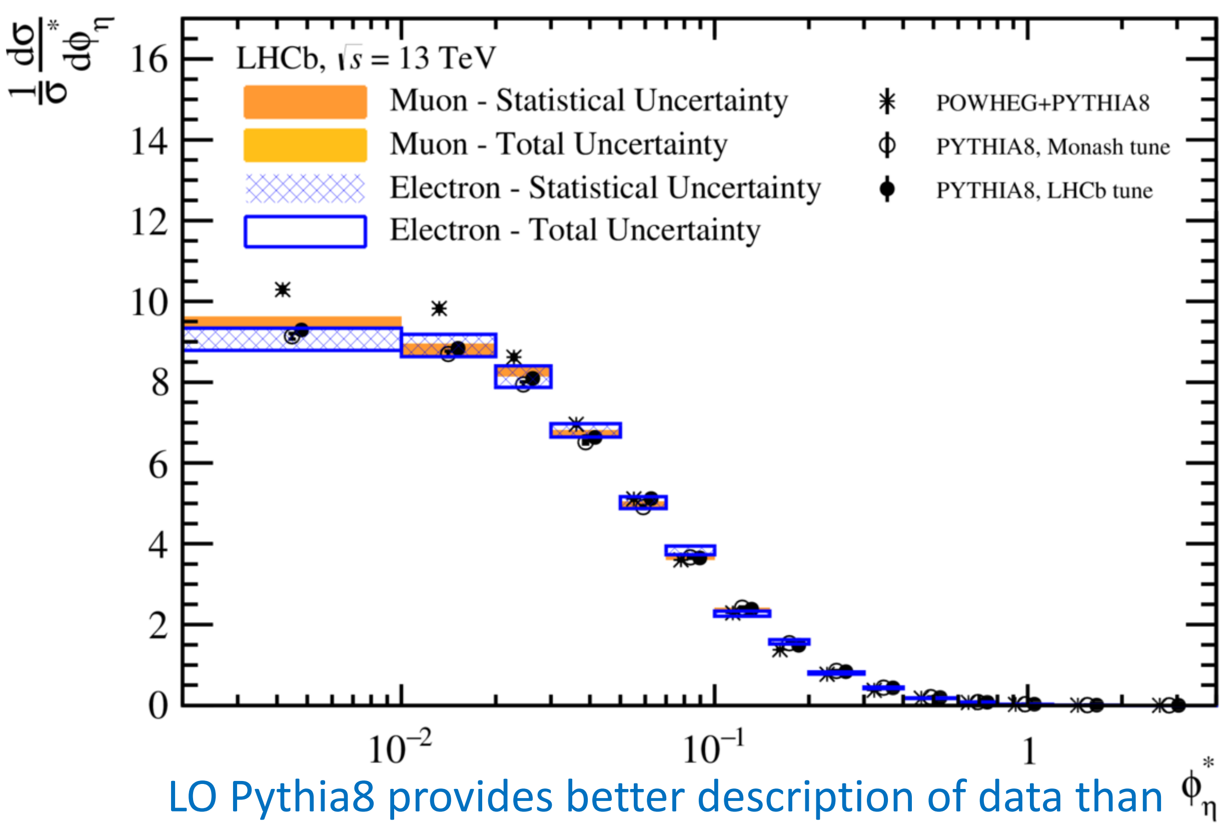
Precision Z production

Rapidity

$$\phi^*_\eta = \tan\left(\frac{\phi_{\rm acop}}{2}\right) / \cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{m_{ll}}$$



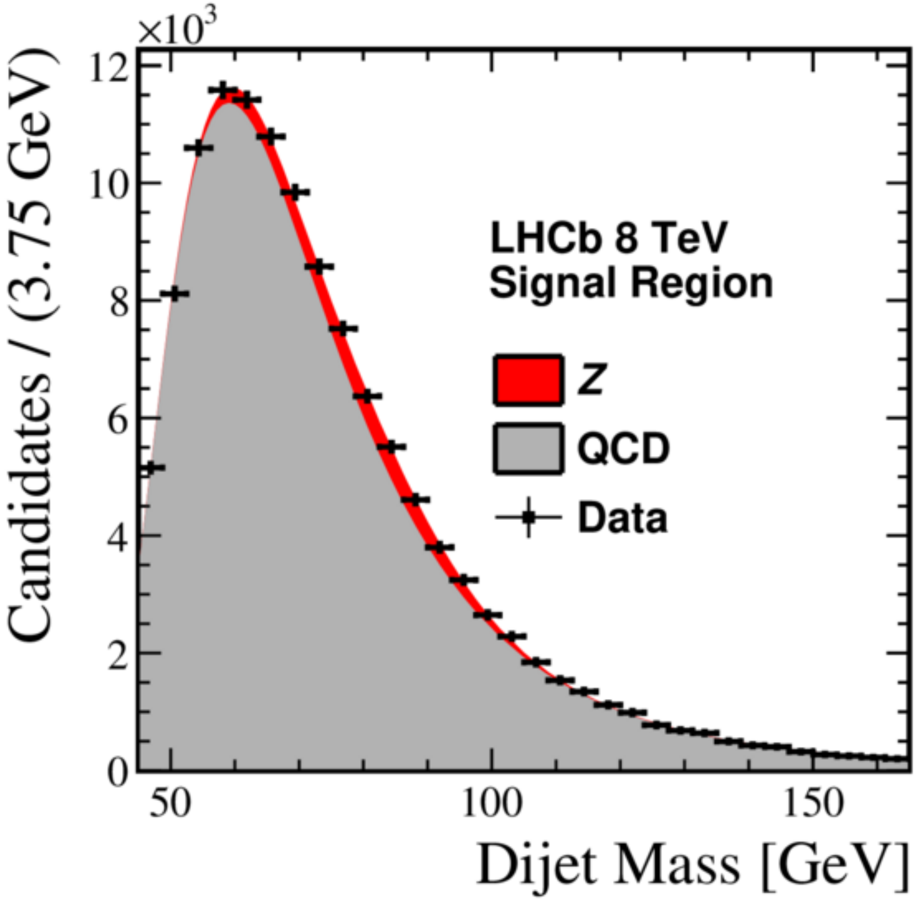
Broad Agreement between data and theory

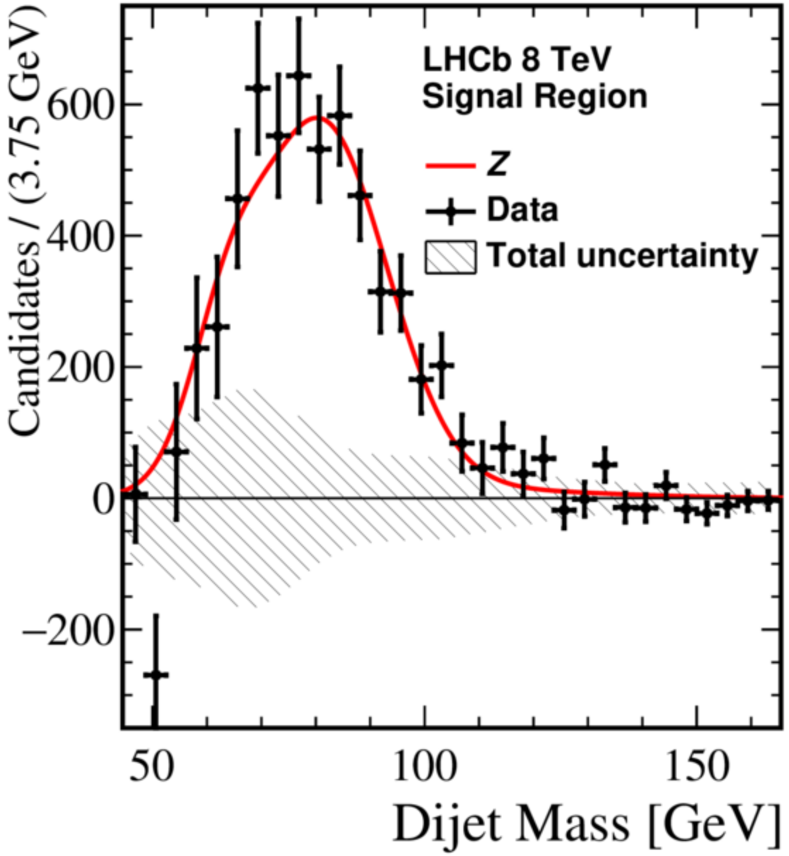


LO Pythia8 provides better description of data than NLO POWHEG + Pythia (when no dedicated POWHEG/Pythia tune used).

$Z \rightarrow b\bar{b}$ production

- Require two forward b-jets with p_T > 20 GeV, 2.2< η<4.2, $45 < m_{jj} < 165$ GeV





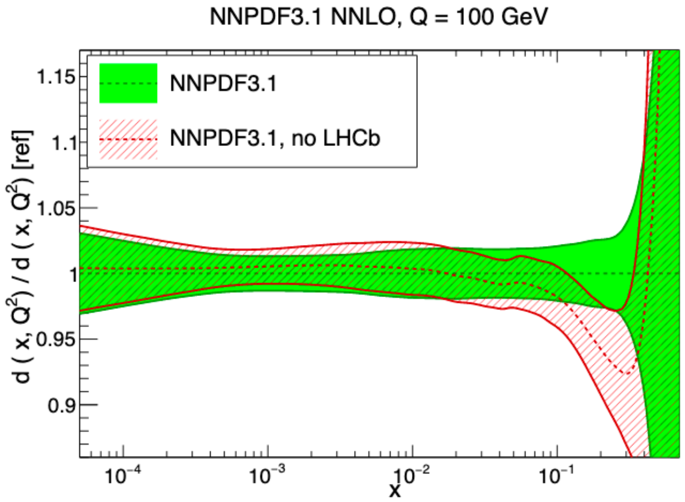
Measure:
$\sigma_{pp\rightarrow Z\rightarrow bb} = 332 \pm 46 \ \pm 59$ pb

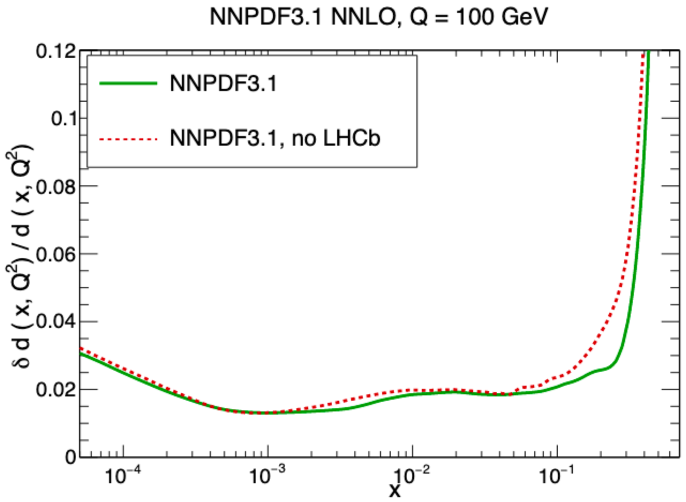
Predict with aMC@NLO:
$\sigma_{pp\rightarrow Z\rightarrow bb} = 272^{+9}_{-12} \ \pm 5$ pb

Good agreement between theory and data.

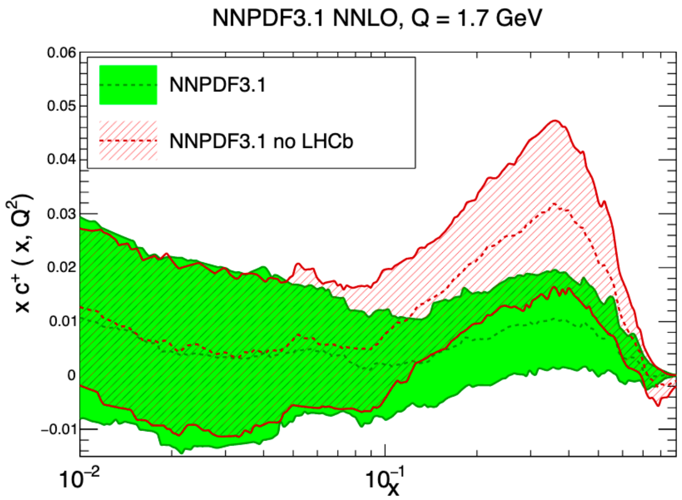
Impact of LHCb measurements

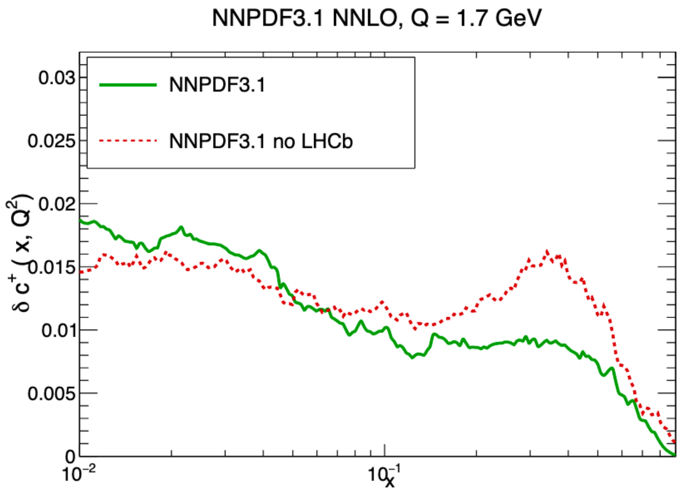
PDF uncertainties halved at high-x.





Key constraints on intrinsic charm.





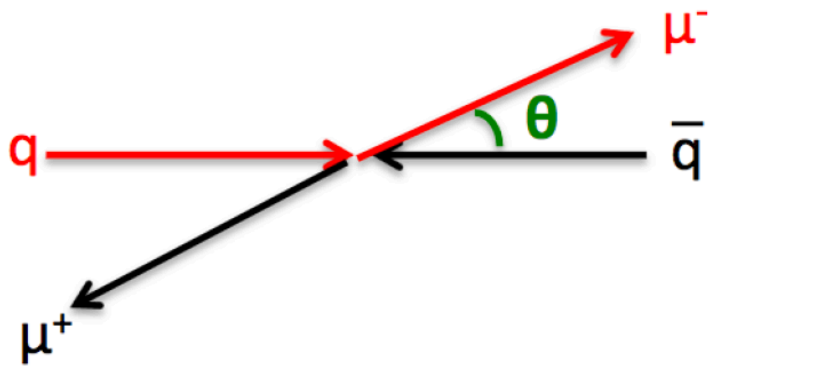
+ more!

Precision EW variables

Measuring the Weak Mixing Angle at the LHC

- Presence of vector and axial-vector couplings of Z boson (related to weak mixing angle) introduce parton level forward-backward asymmetry.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} \propto \frac{3}{8}A(1+\cos^2\theta^*) + \boldsymbol{B\cos\theta^*}$$



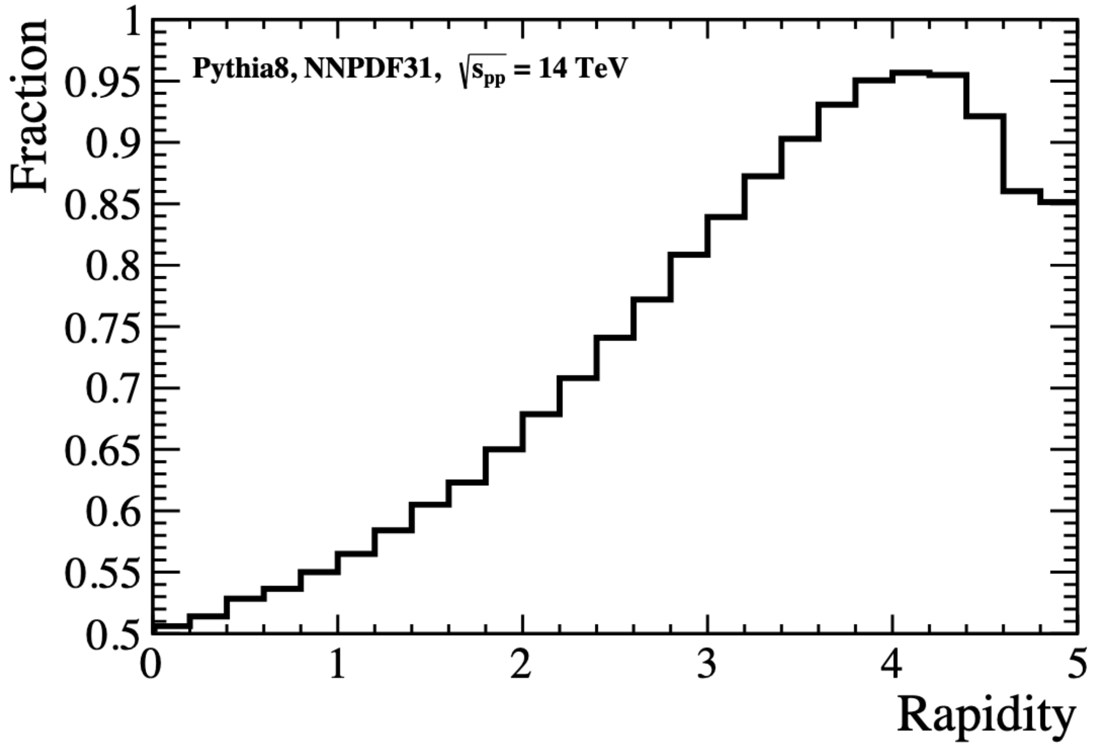
(*z*-axis defined by direction of initial state quark)

- Parton level A_{fb} diluted at proton level because of 180° ambiguity in direction of z-axis (which aligns with quark in collision). At rapidity = 0, A_{fb} = 0.
- However, when the Z is forward, it is produced by a high-x parton and low-x parton colliding. PDFs dictate that the high-x parton tends to be the quark – providing a well-defined axis and reduced dilution.

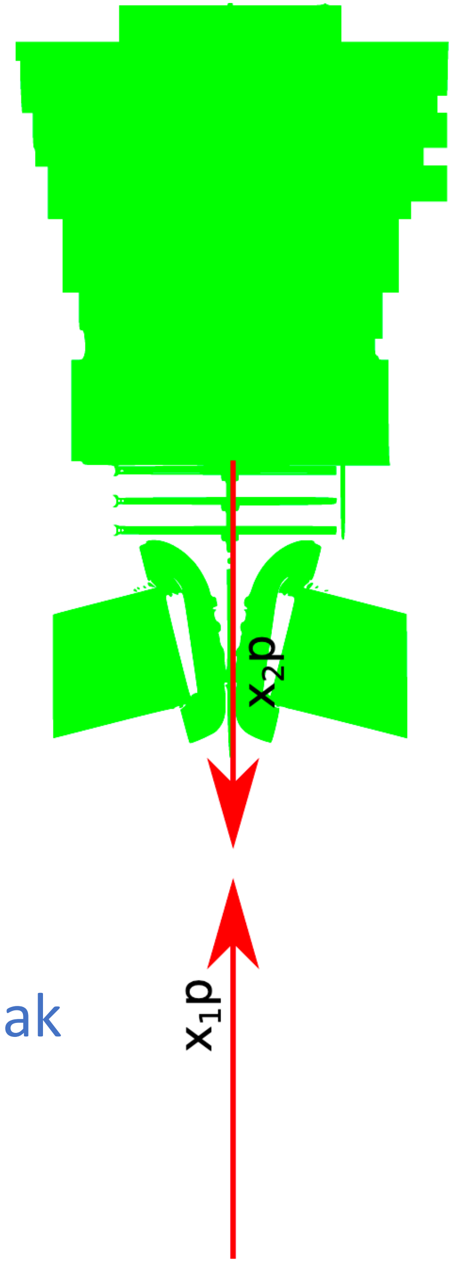
$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

Weak Mixing Angle – Why LHCb?

Collisions where Z boson follows quark direction

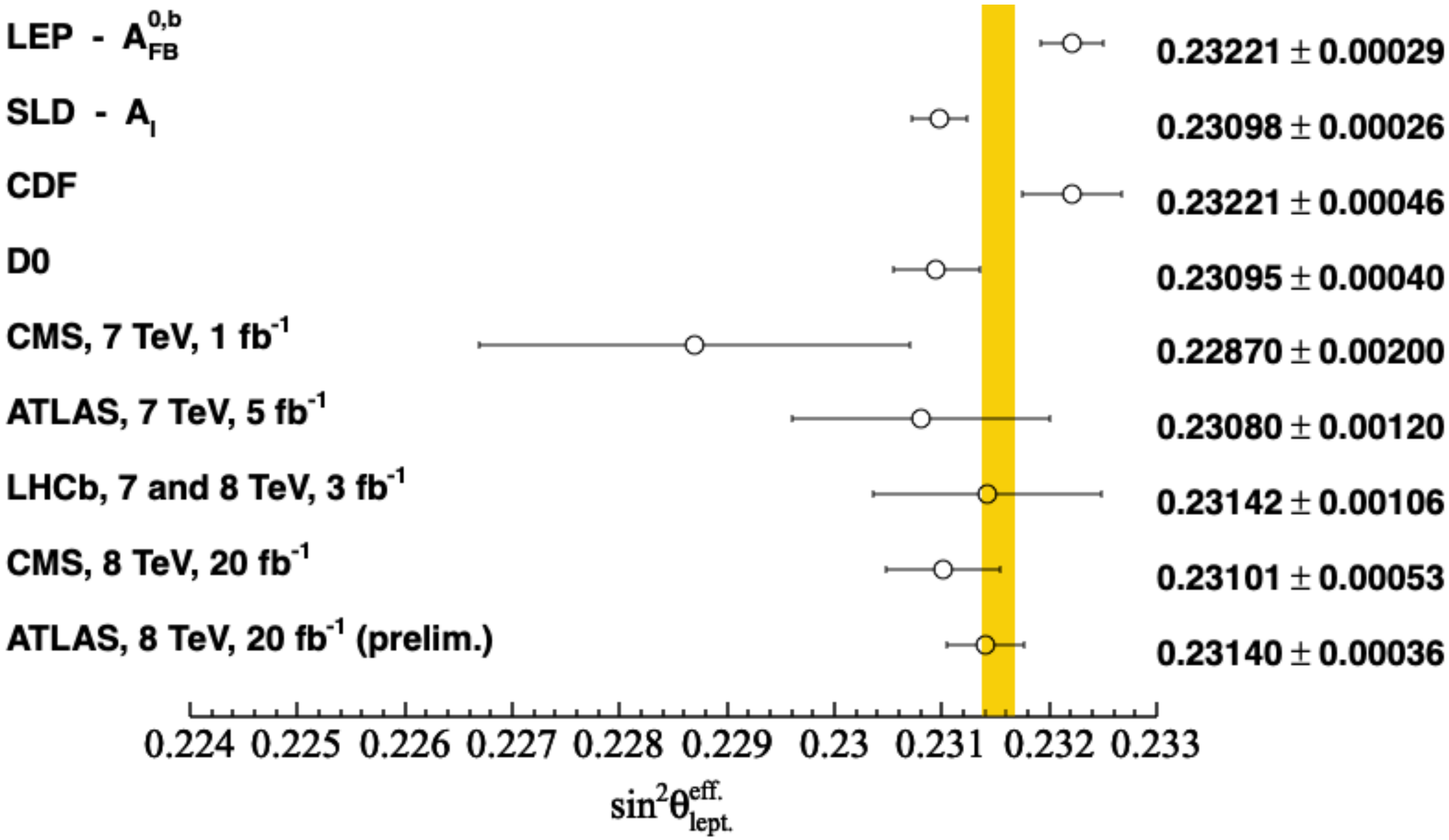


- Reduced dilution at larger rapidities improves statistical sensitivity of A_{fb} to weak mixing angle.
- Impact of how well we know dilution (PDFs) also reduced if correction for dilution is small $\Longrightarrow$ significantly reduces PDF uncertainty when extracting weak mixing angle from A_{fb} in high rapidity events.



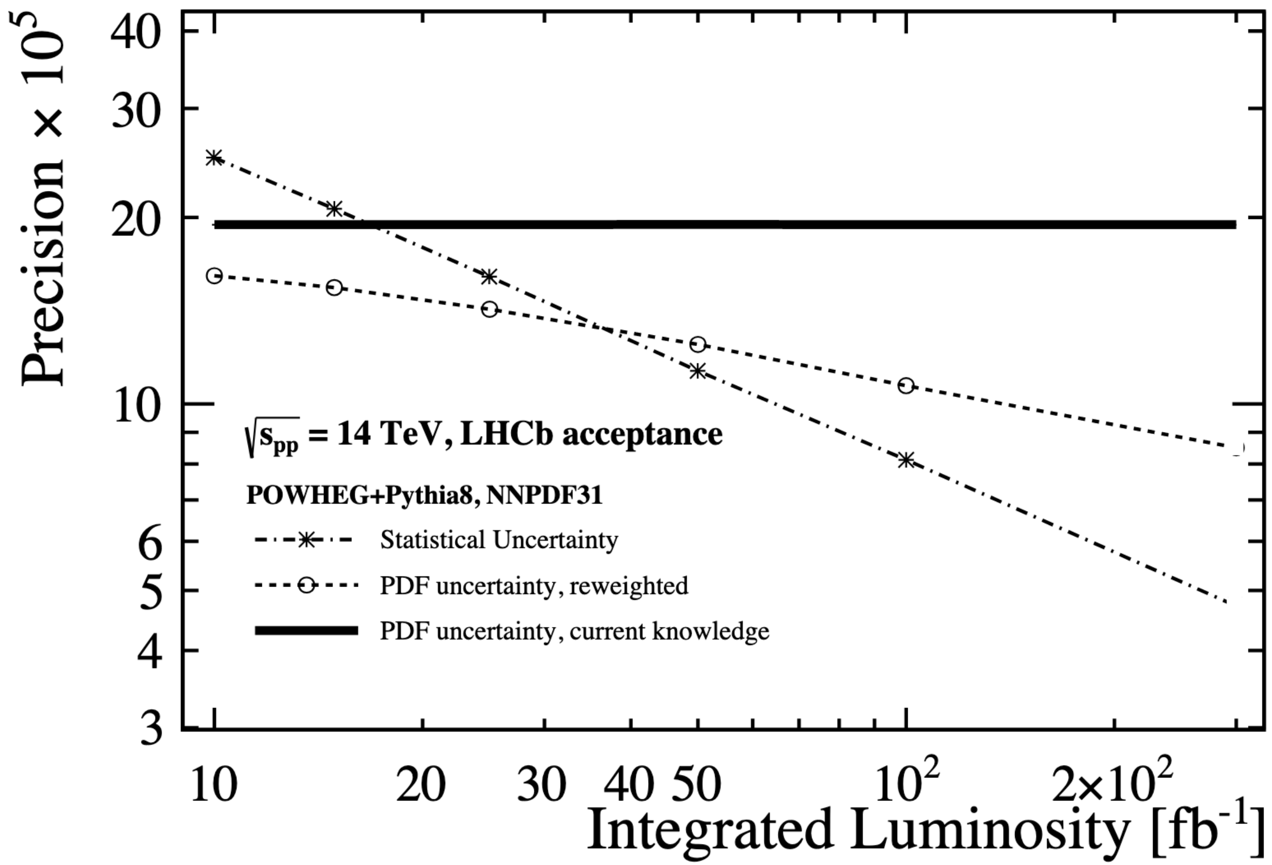
Weak Mixing Angle – Current Measurements

- LHCb result currently statistically limited.
- Other LHC experiments have large PDF uncertainties.
- However, forward acceptance leads to smaller theoretical uncertainties, so measurement at LHCb has significant potential with more data – which we will record following detector upgrades.



LHCb-PUB-2018-013, and P. Azzi *et al.*, arXiv:1902.04070
With method following A. Bodek *et al*, EPJC76:115 (2016)

Prospects for the Weak Mixing Angle at LHCb



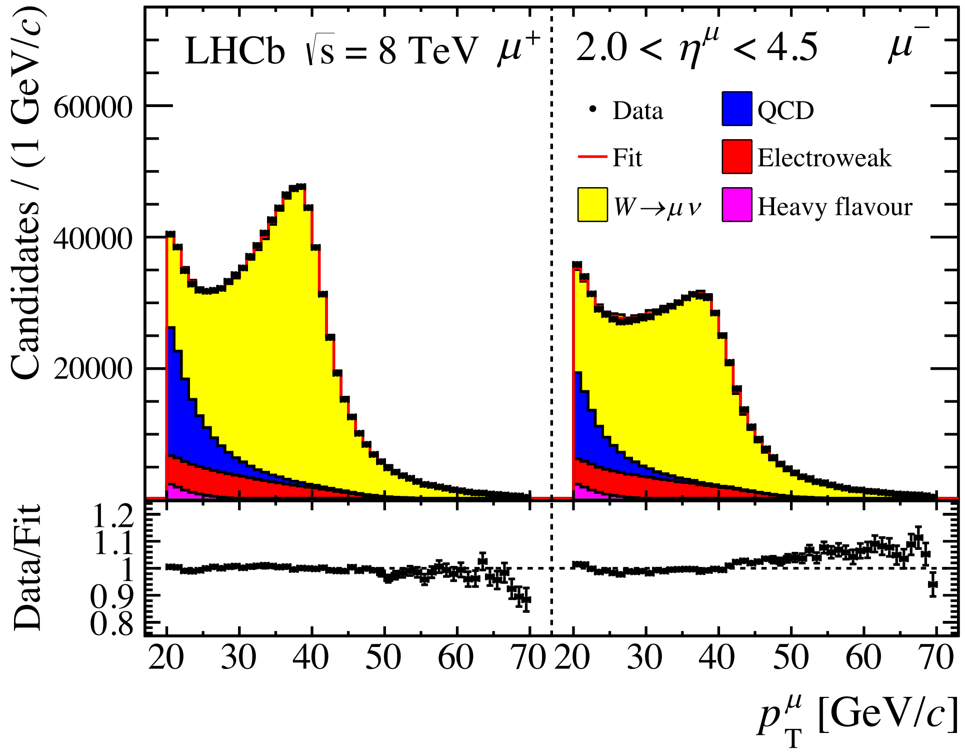
- Statistical uncertainty at LHCb negligible following upgrades.
- PDF uncertainty at LHCb from current knowledge is small: $\sim 20\times10^{-5}$ [cf CMS $\sim 57\times10^{-5}$].
- With Upgrade II dataset PDF unc at LHCb can be reduced below $\sim 10\times10^{-5}$ using PDF reweighting method [cf CMS@ 3000/fb, with reweighting $\sim 10\times10^{-5}$].

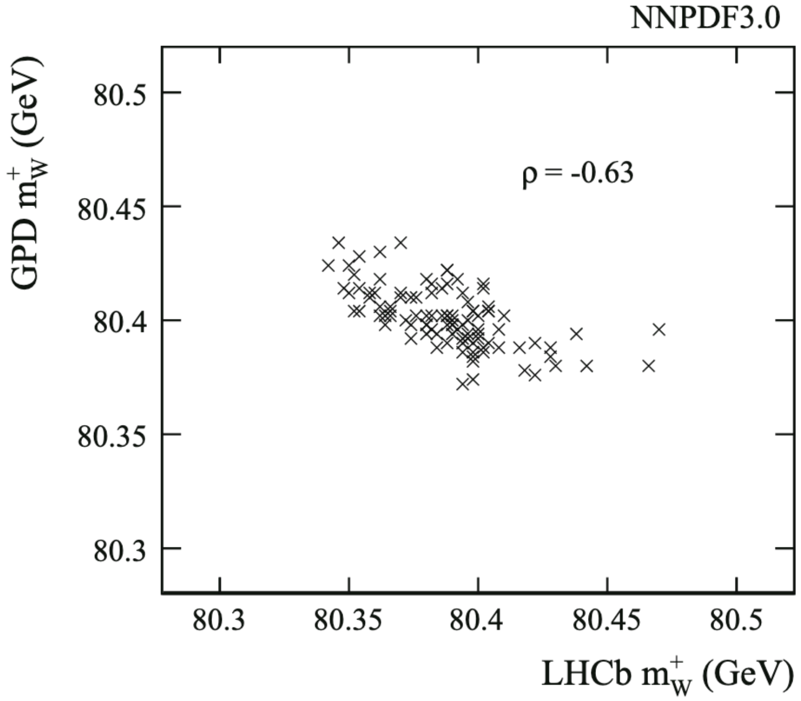
Note: ATLAS expected performance similar to CMS; CMS quoted as similar study performed to LHCb.

JHEP 01 (2016) 155, and G. Bozzi, L. Citelli, M. Vesterinen, A. Vicini, EPJC (2015) 75: 601 and S. Farry, O. Lupton, M. Pili, M. Vesterinen, EPJC (2019) 79: 497

Prospects for the W boson mass at LHCb

- $W \to \mu\nu$ production already (reasonably) well understood in LHCb data.





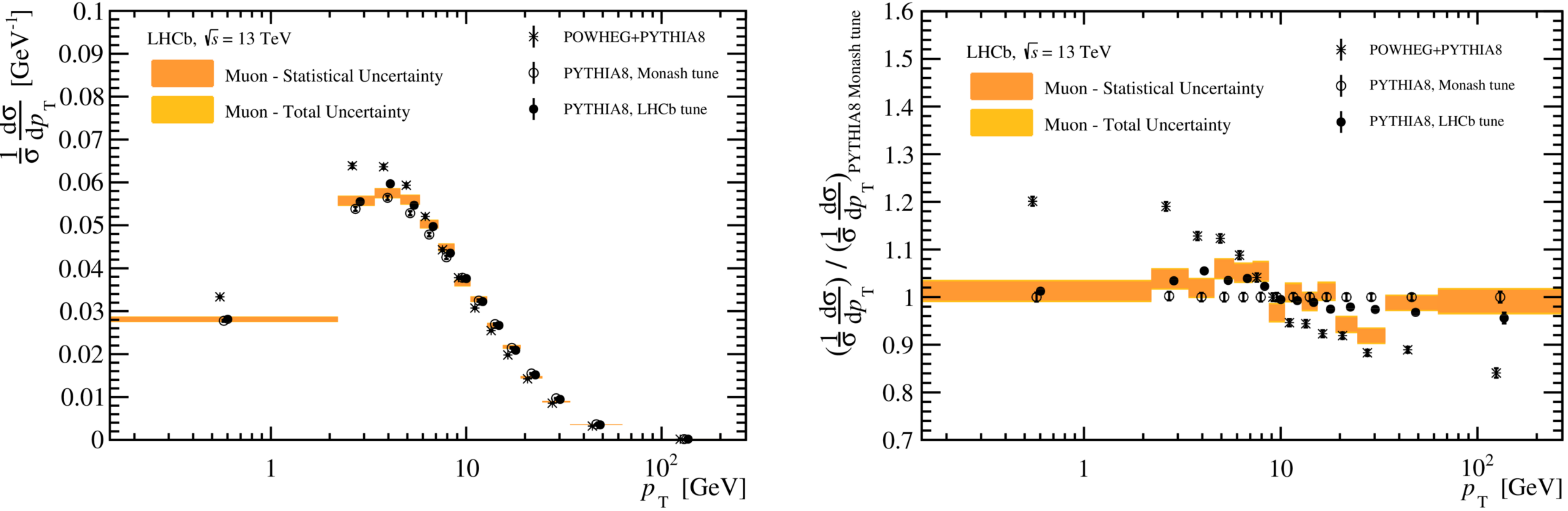
- Fit of the muon p_T spectrum will allow m_W measurement with statistical uncertainty $\mathcal{O}$(10MeV), and PDF uncertainty $\mathcal{O}$(10MeV) - enabling a high precision measurement.
- PDF uncertainty anti-correlated with ATLAS/CMS – LHCb will have major impact in LHC-wide combination.

Summary

Summary

- LHCb has a rich programme studying forward EW bosons.
- Measurements of cross-sections at LHCb are among the most precise at the LHC, and provide a unique environment to test QCD – probing PDFs and the hard interaction.
- The forward region provides unique opportunities to study precision EW variables.
- Theoretical uncertainties associated with measurement of the weak mixing angle are small at LHCb, and a future measurement should rival LEP+SLD precision - comparable precision in HL-LHC to ATLAS/CMS over same time-frame.
- Measurements of the W boson mass at LHCb have main theory uncertainty (PDF) anti-correlated with measurements at ATLAS/CMS (reaching similar precision to ATLAS/CMS), and will play a key role in any LHC-wide combination.

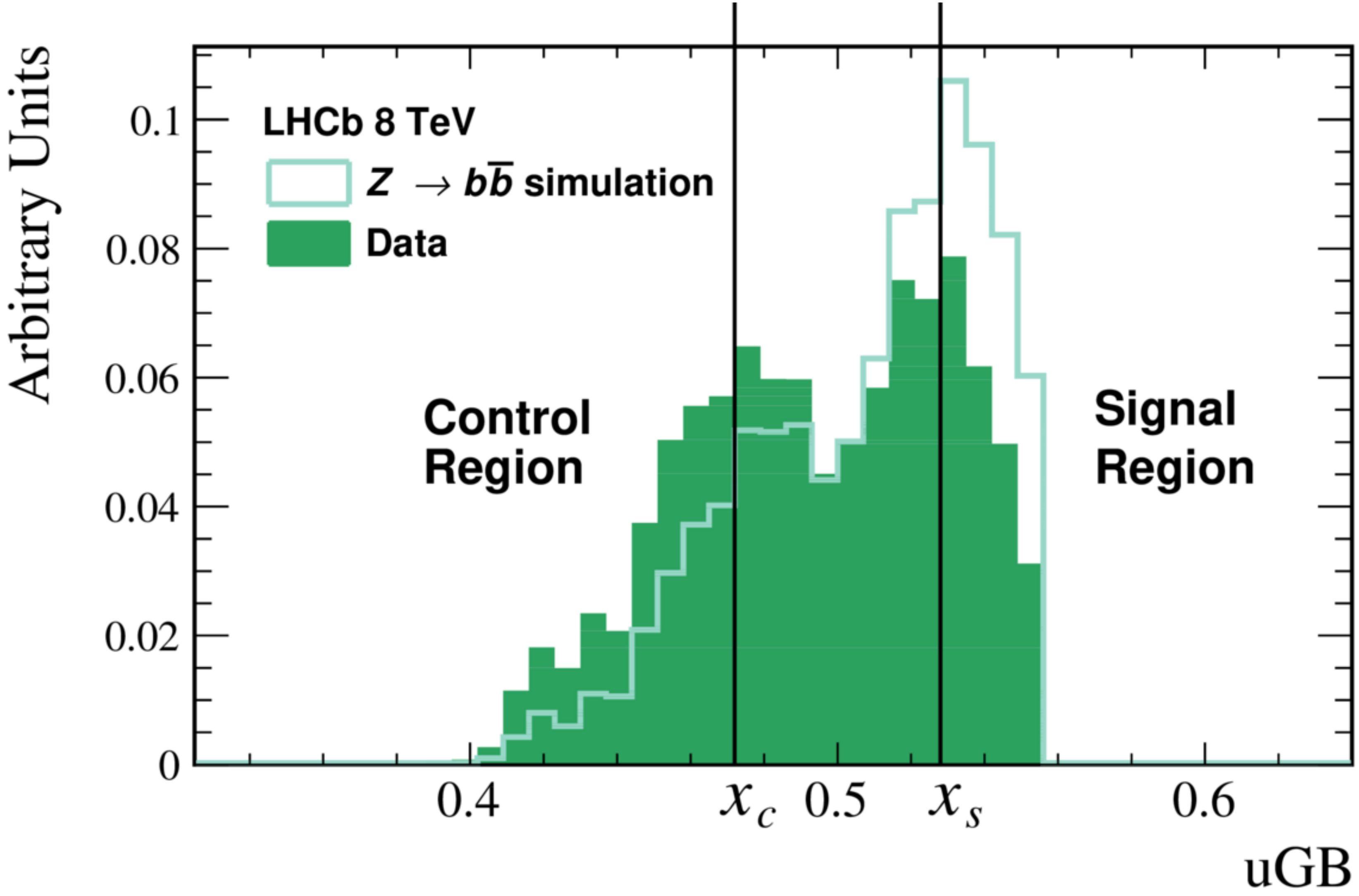
Backup slides



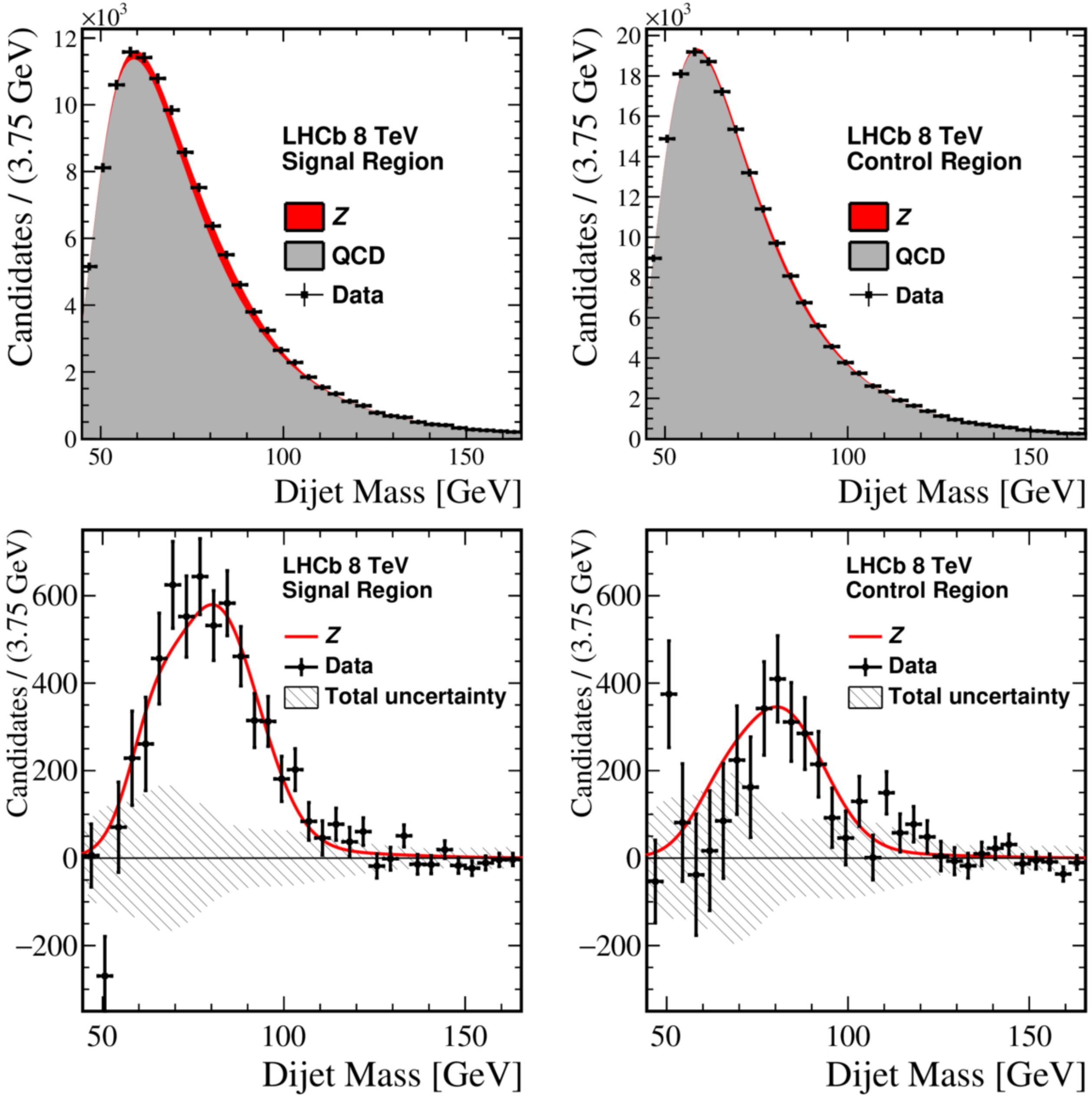
LHCb, $\sqrt{s}$ = 13 TeV
Muon - Statistical Uncertainty
Muon - Total Uncertainty
POWHEG+PYTHIA8
PYTHIA8, Monash tune
PYTHIA8, LHCb tune
$\frac{1}{\sigma}\frac{d\sigma}{dp_T}$ [GeV^{-1}]
$(\frac{1}{\sigma}\frac{d\sigma}{dp_T}) / (\frac{1}{\sigma}\frac{d\sigma}{dp_T})_{\text{PYTHIA8 Monash tune}}$
p_T [GeV]

Source	$\Delta\sigma_Z^{\mu\mu}$ [%]	$\Delta\sigma_Z^{ee}$ [%]
Statistical	0.5	0.9
Reconstruction efficiencies	2.4	2.4
Purity	0.2	0.5
FSR	0.1	0.2
Total systematic (excl. lumi.)	2.4	2.5
Luminosity	3.9	3.9

Phys. Lett. B776 (2018) 430

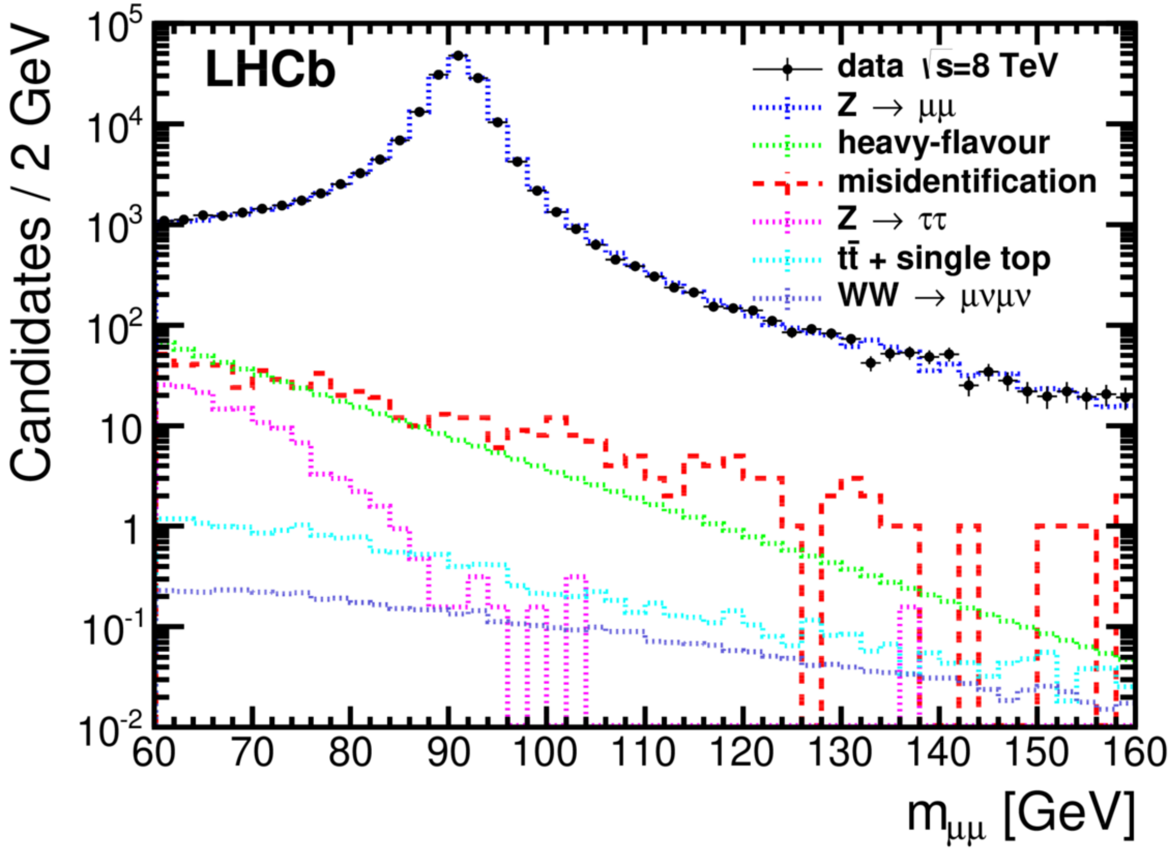


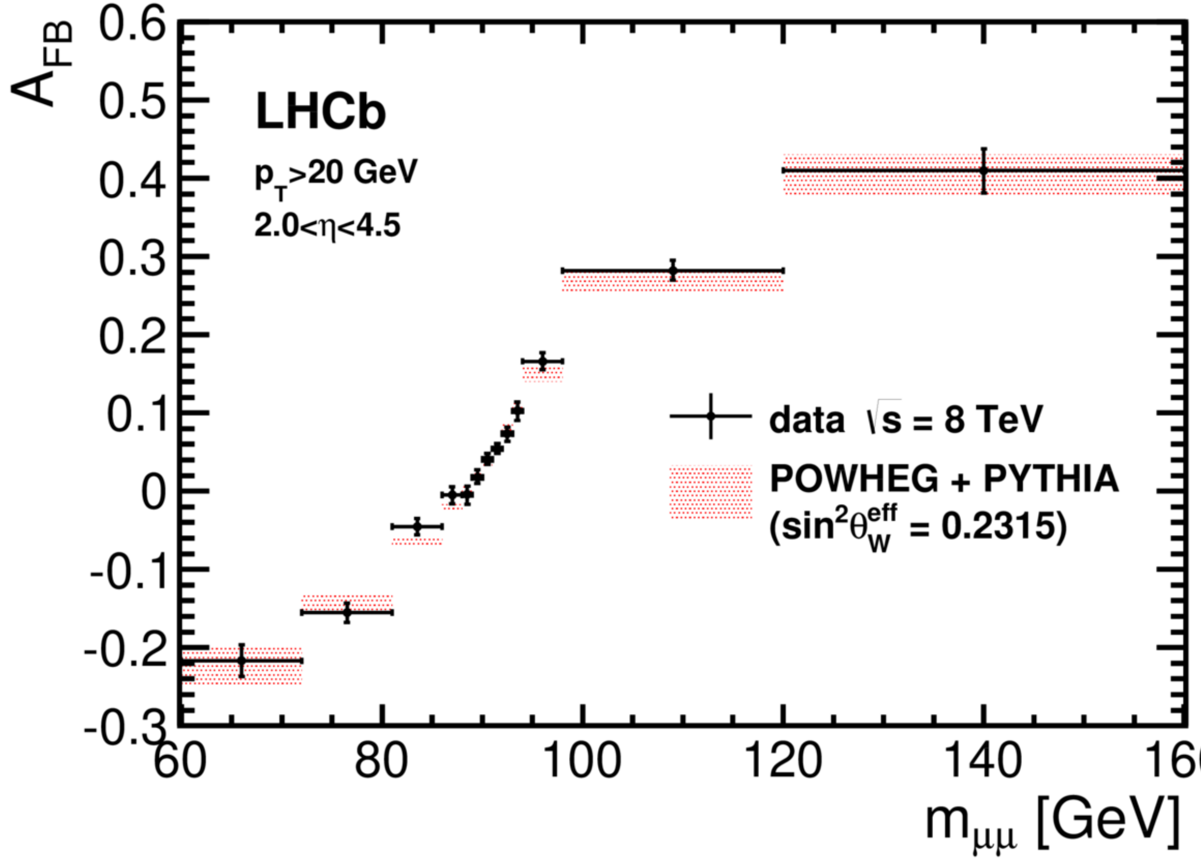
Phys. Lett. B776 (2018) 430



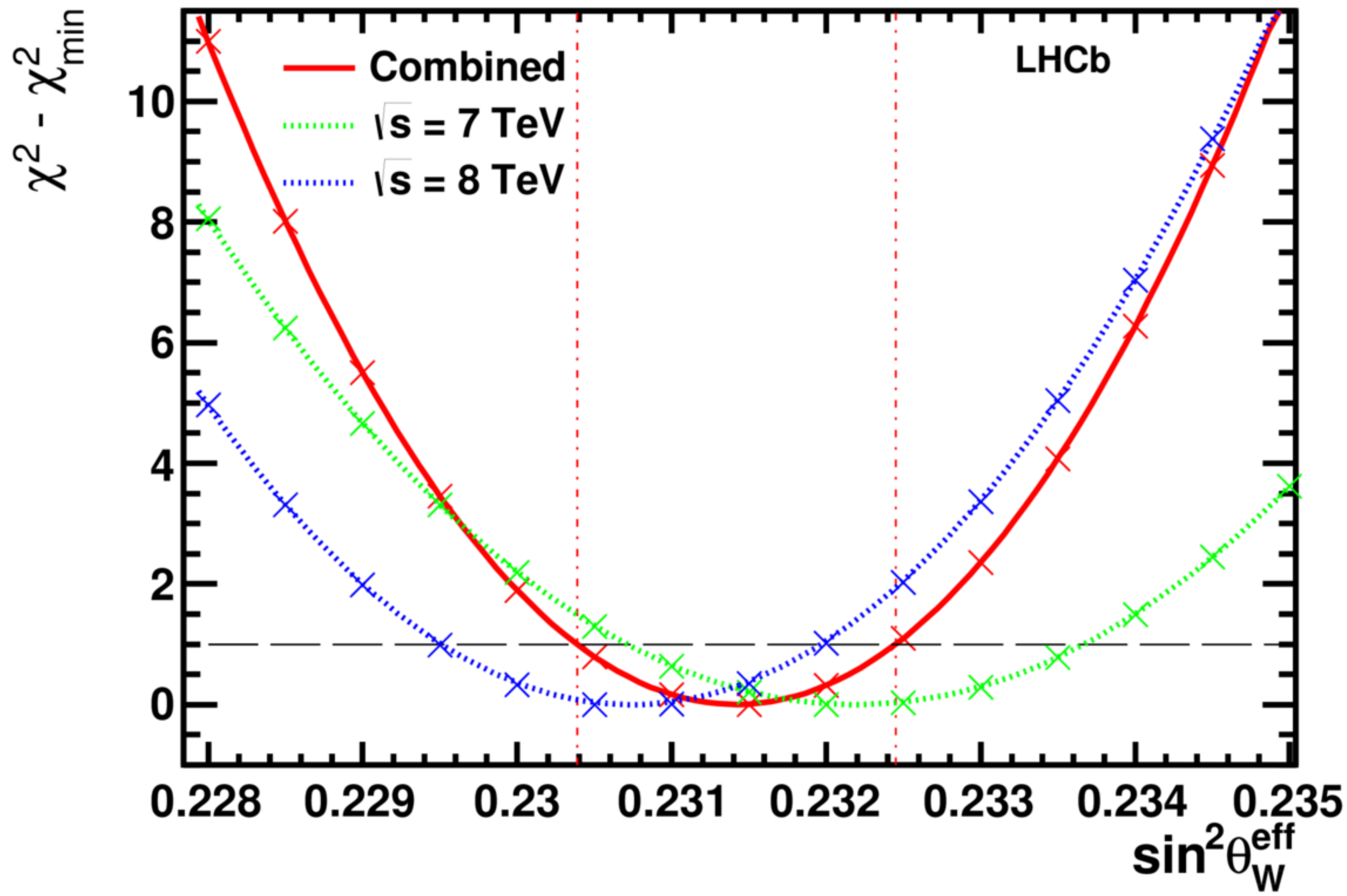
Phys. Lett. B776 (2018) 430

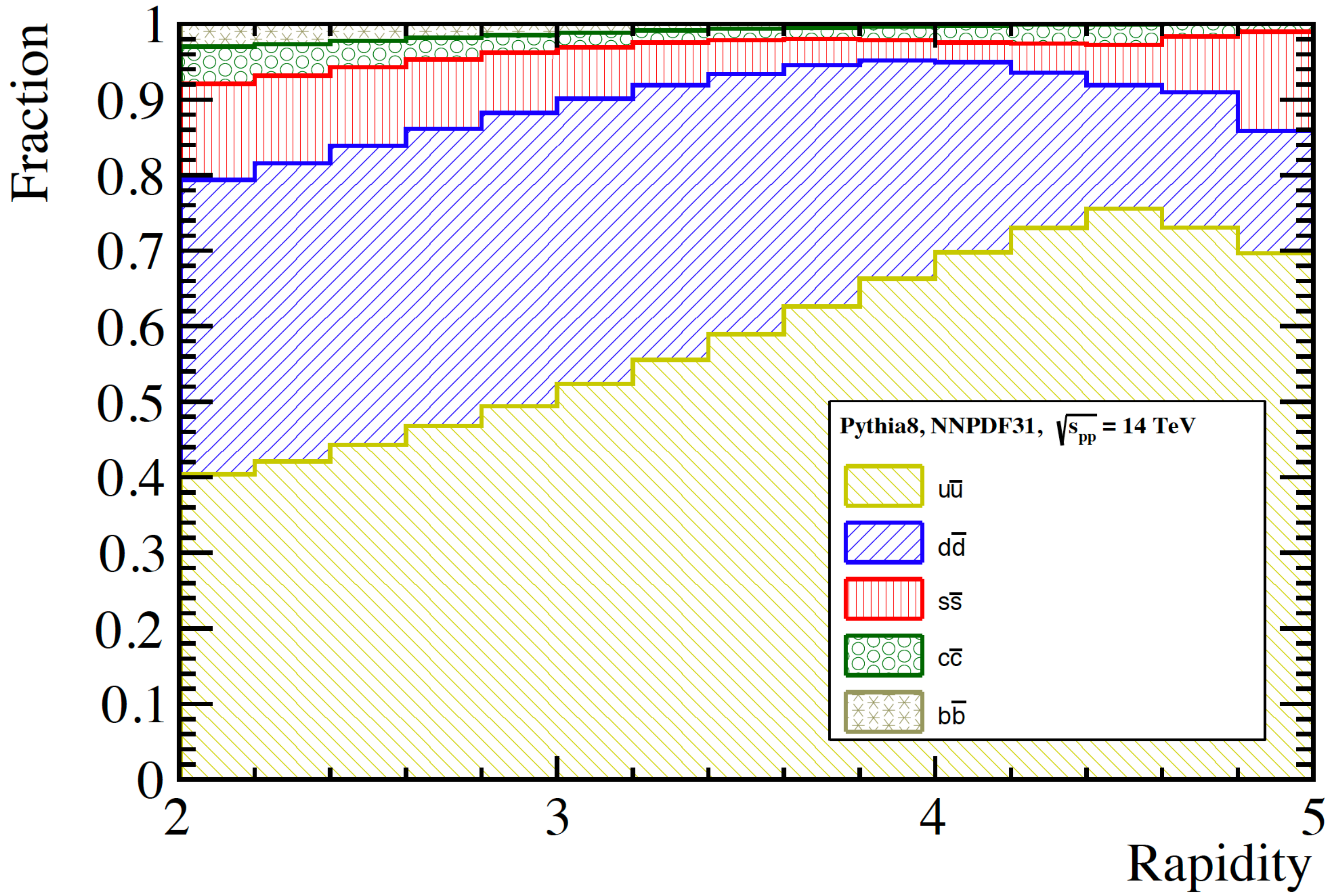
Systematic source	σ_Z [%]	k_{JES} [%]
Heavy-flavour tagging efficiency	16.6	0.5
Hardware trigger efficiency	1.9	–
GEC efficiency	1.7	–
Jet energy correction	2.7	0.3
Jet energy resolution	1.0	0.2
Jet identification efficiency	2.0	< 0.1
Balancing-jet selection efficiency	1.8	–
Signal model	2.0	0.3
QCD model	1.1	< 0.1
Transfer functions	1.5	0.8
R efficiencies ratio	0.3	< 0.1
Fit bias	2.1	–
Subdominant backgrounds ($t\bar{t}$, $W \to qq'$)	1.9	< 0.1
Final-state radiation	0.9	–
$f_{Z\to c\bar{c}}$ fraction	0.1	–
Luminosity	1.2	–
Total	17.7	1.1


LHCb
data $\sqrt{s}$=8 TeV
Z → μμ
heavy-flavour
misidentification
Z → ττ
$t\bar{t}$ + single top
WW → μνμν
Candidates / 2 GeV
$m_{\mu\mu}$ [GeV]

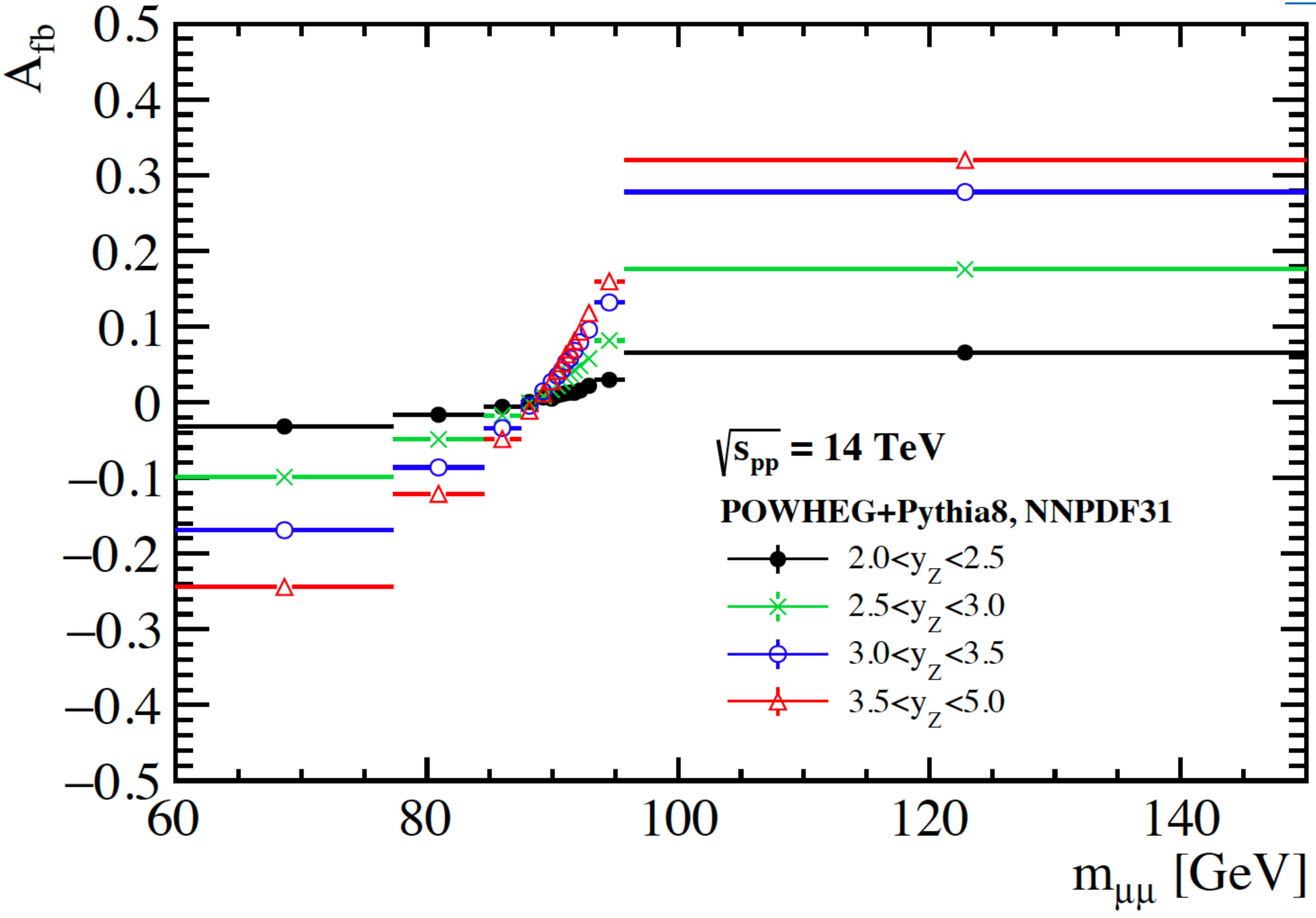

LHCb
p_T>20 GeV
2.0<η<4.5
data $\sqrt{s}$ = 8 TeV
POWHEG + PYTHIA
($\sin^2\theta_W^{eff}$ = 0.2315)
A_{FB}
$m_{\mu\mu}$ [GeV]

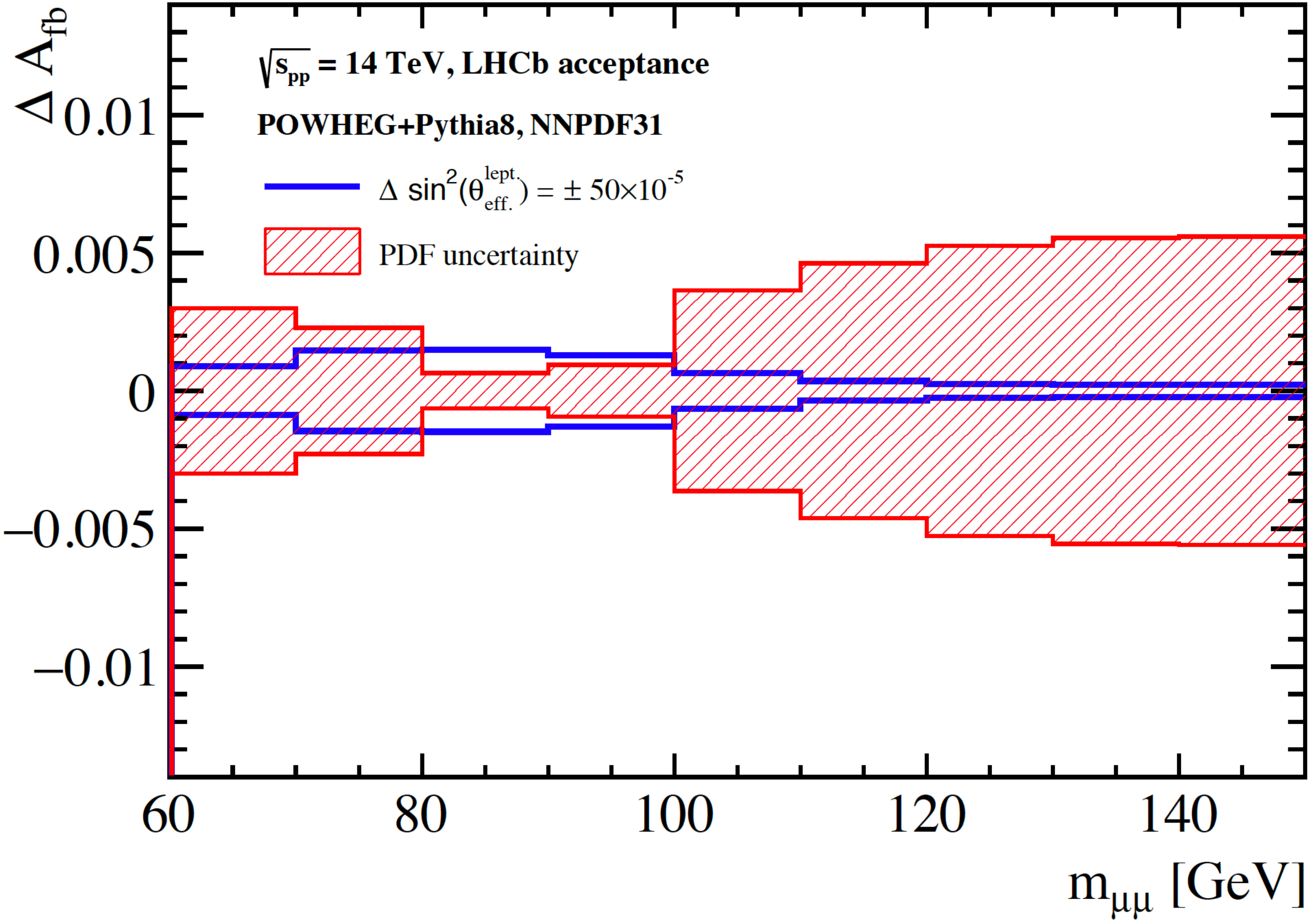
JHEP 11 (2015) 190



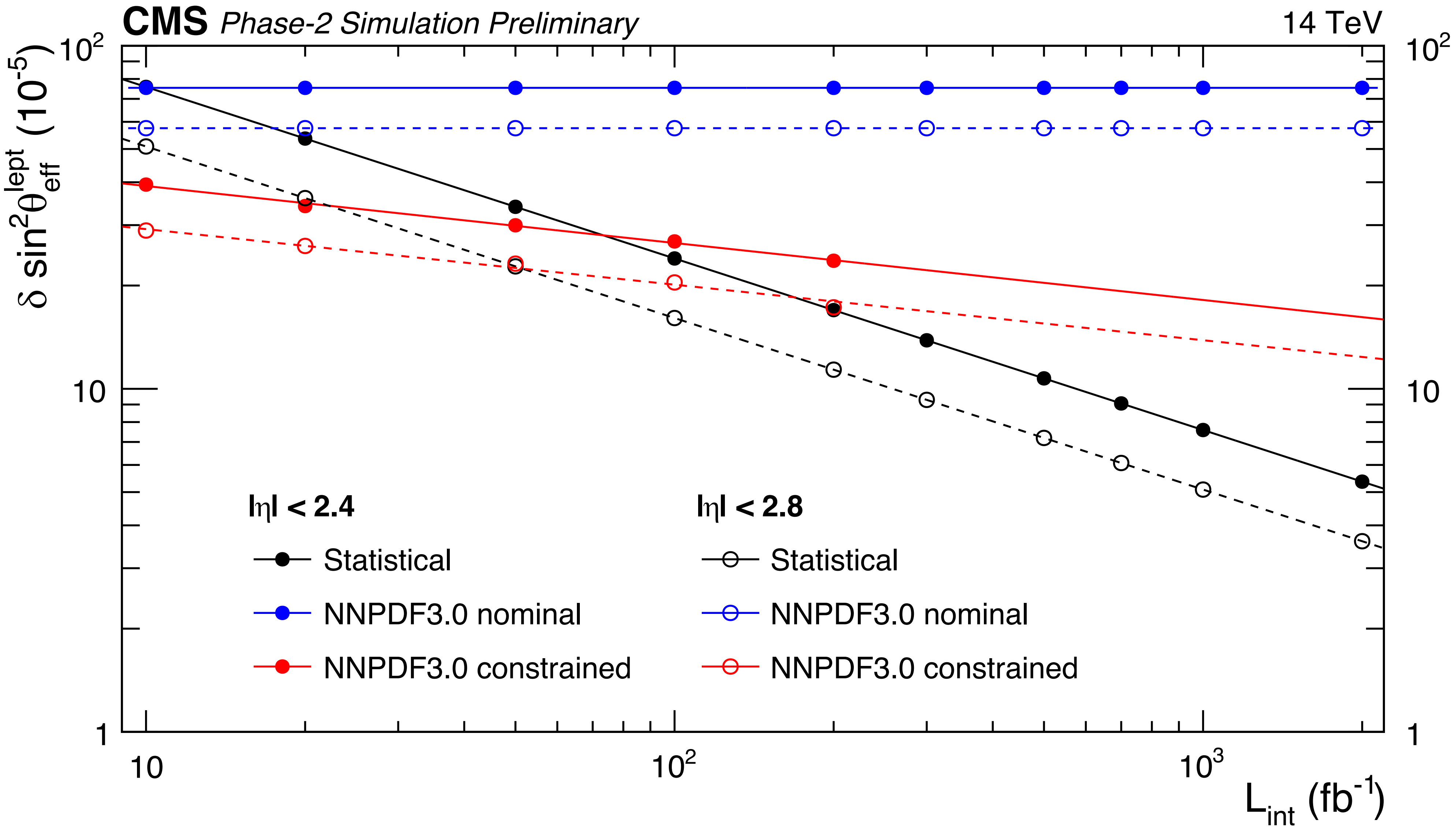

Fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
3
4
5
Rapidity
Pythia8, NNPDF31, $\sqrt{s_{pp}}$ = 14 TeV
$u\bar{u}$
$d\bar{d}$
$s\bar{s}$
$c\bar{c}$
$b\bar{b}$

LHCb-PUB-2018-013




$\sqrt{s_{pp}}$ = 14 TeV, LHCb acceptance
POWHEG+Pythia8, NNPDF31
$\Delta \sin^2(\theta^{lept.}_{eff.}) = \pm 50\times10^{-5}$
PDF uncertainty
ΔA_{fb}
0.01
0.005
0
−0.005
−0.01
60
80
100
120
140
$m_{\mu\mu}$ [GeV]

CMS collaboration, CMS-PAS-FTR-17-001



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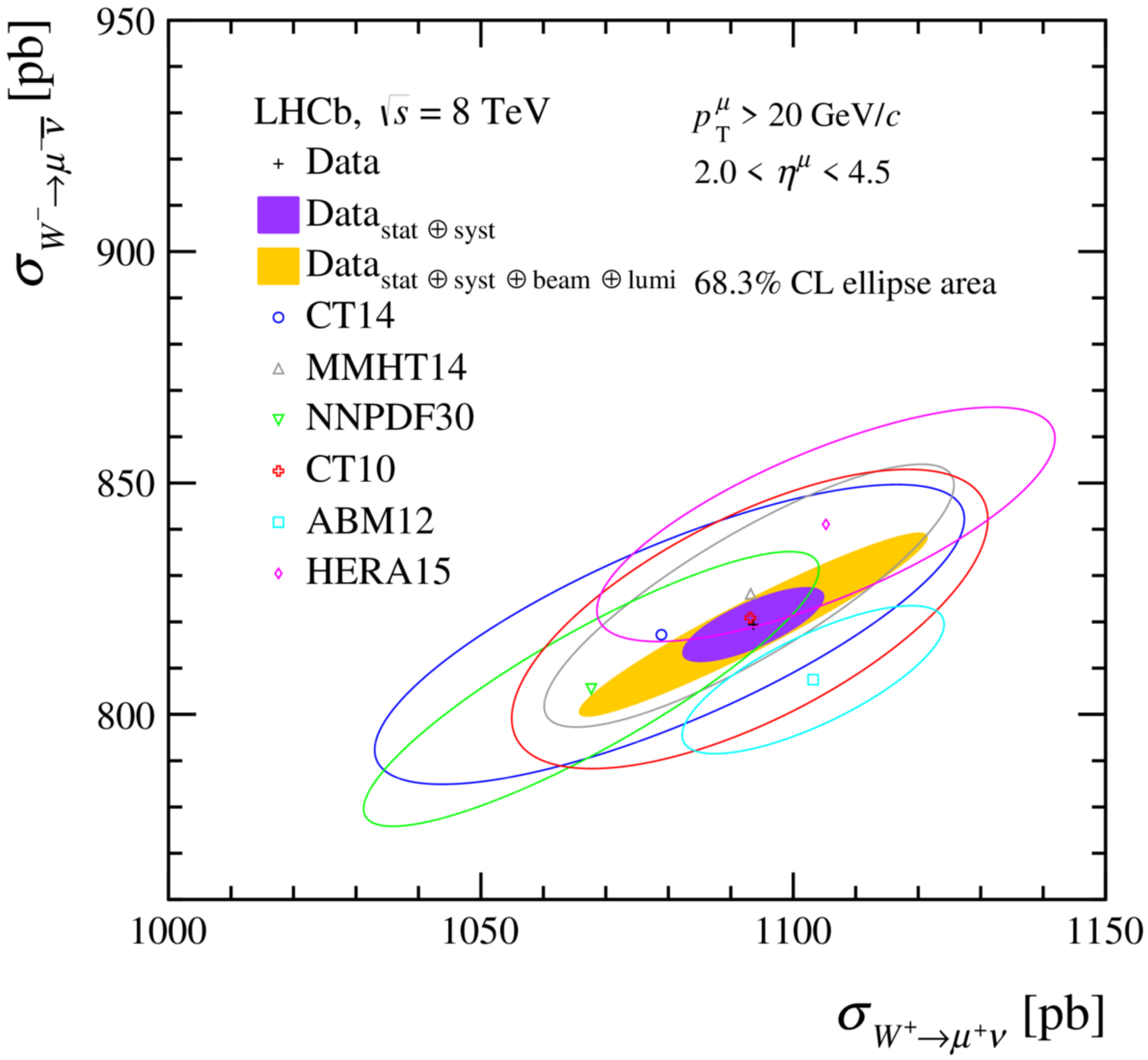
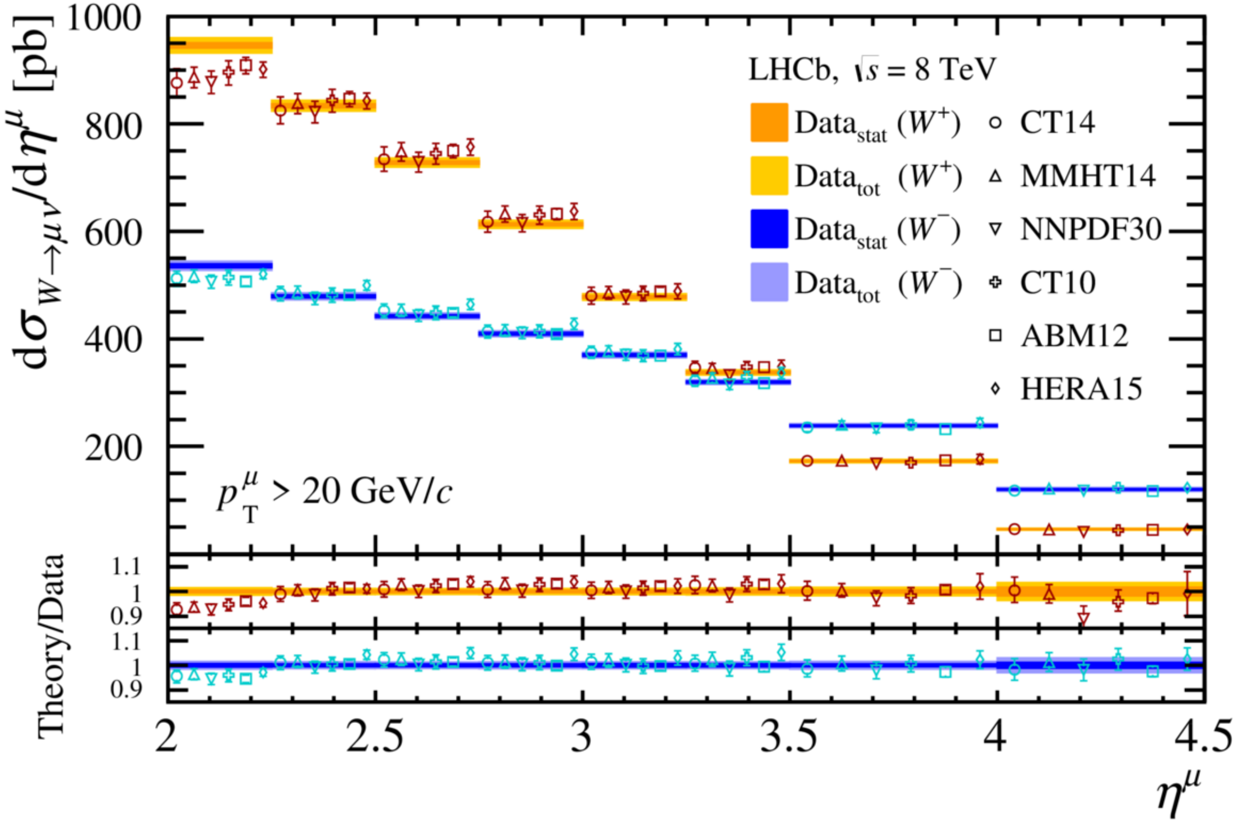
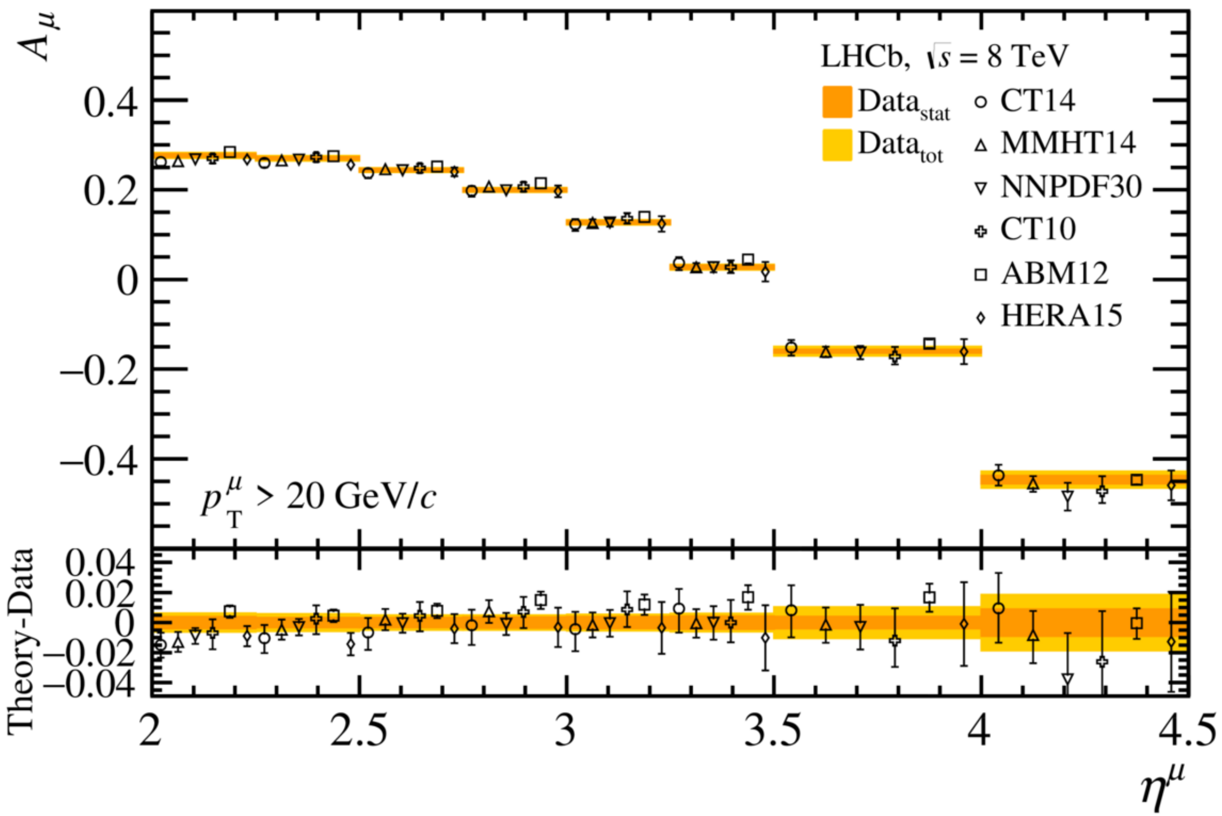
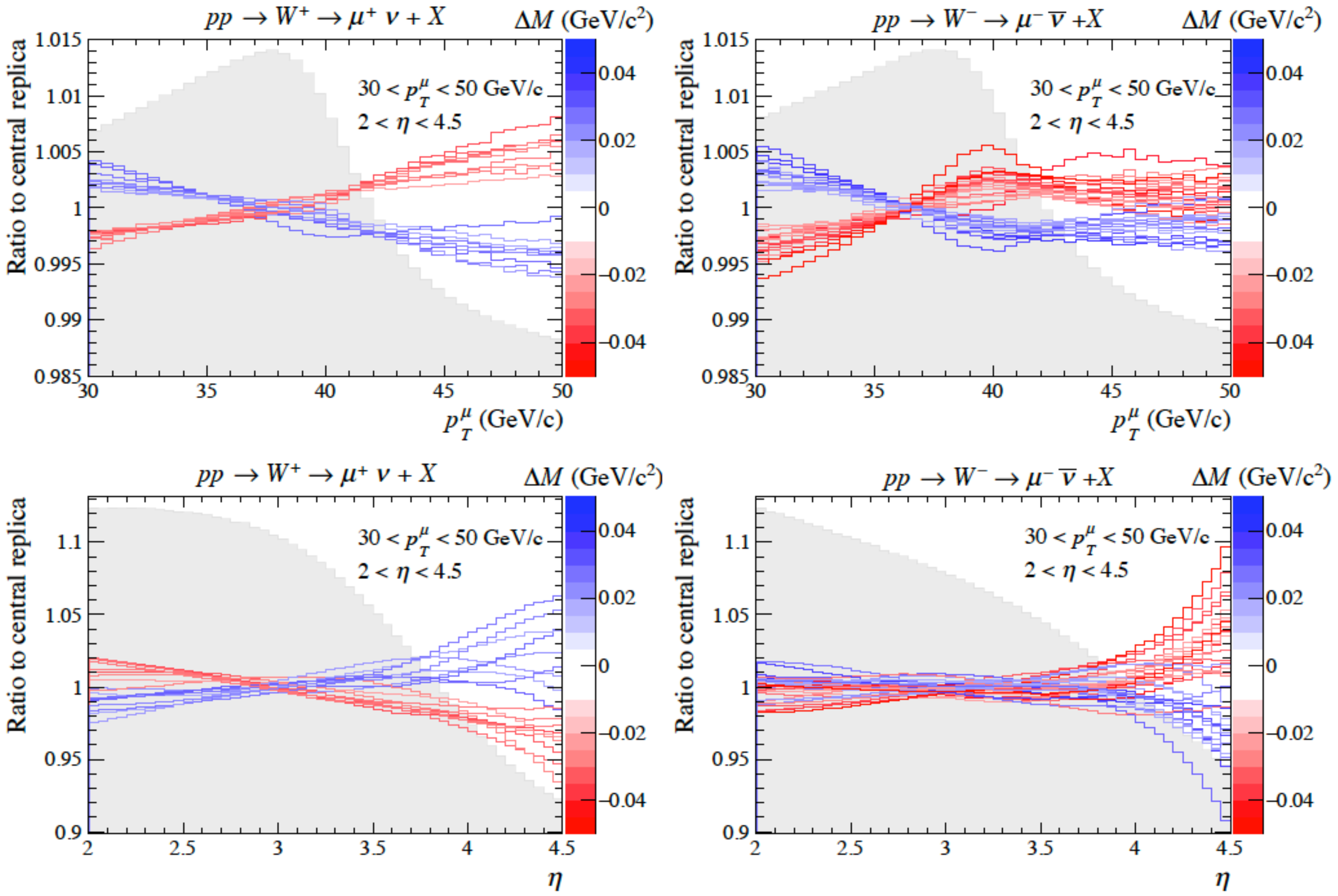


JHEP 01 (2016) 155





S. Farry, O. Lupton, M. Pili, M. Vesterinen, EPJC (2019) 79: 497



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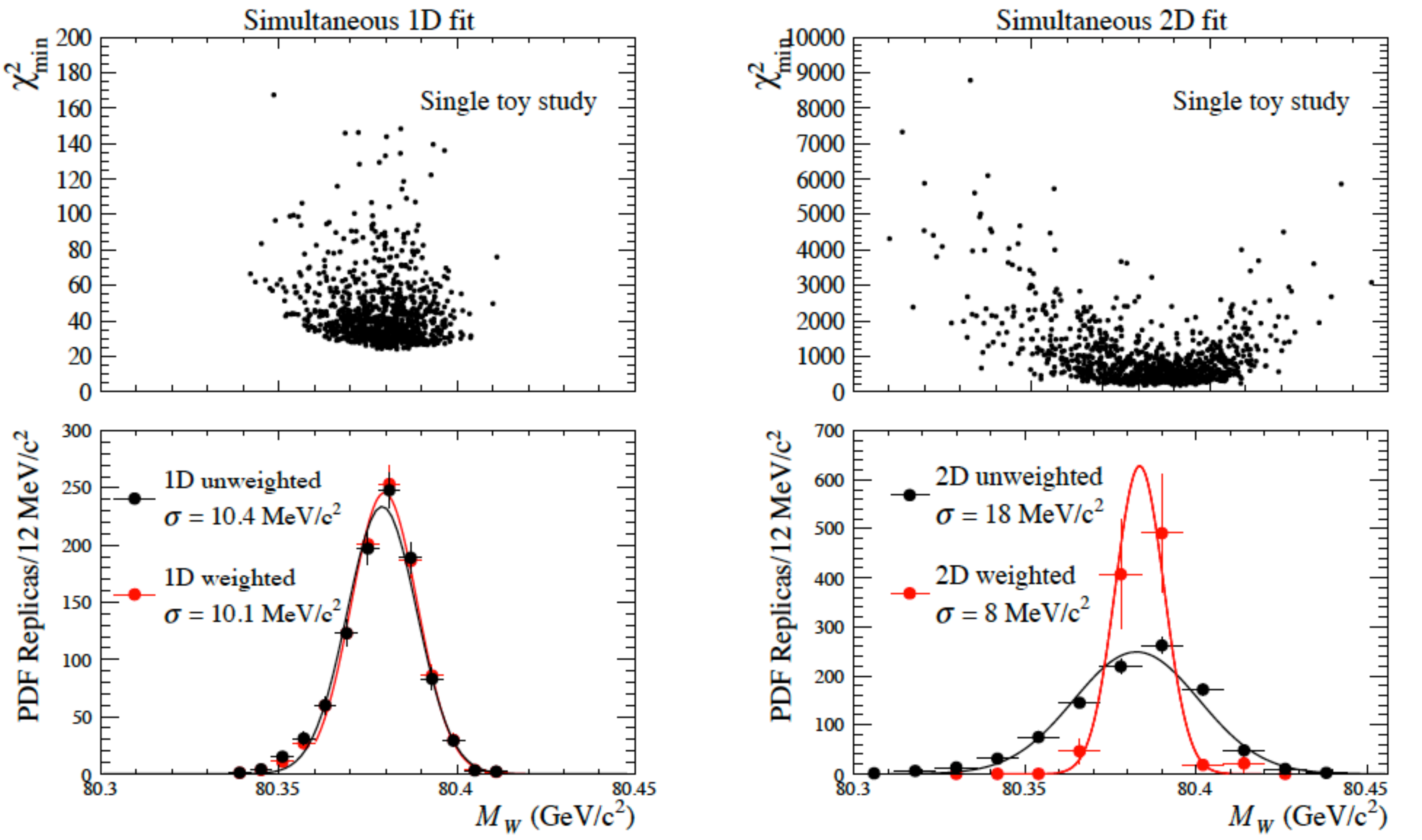

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