

# Status of the $m_W$ combination

Tevatron-LHC W-boson mass Combination Working Group

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/MWCOMB>

LHC EW WG General Meeting

16/11/2022

Jan Kretzschmar (University of Liverpool)

# The $m_W$ landscape

DO ( $4.3+1.1 \text{ fb}^{-1}$ ) [*Phys. Rev.* **D89** (2014) 012005]

$$m_W = 80375 \pm 11 \text{ (stat.)} \pm 20 \text{ (sys.) MeV}$$

CDF ( $8.8 \text{ fb}^{-1}$ ) [*Science* **376** (2022) 170]

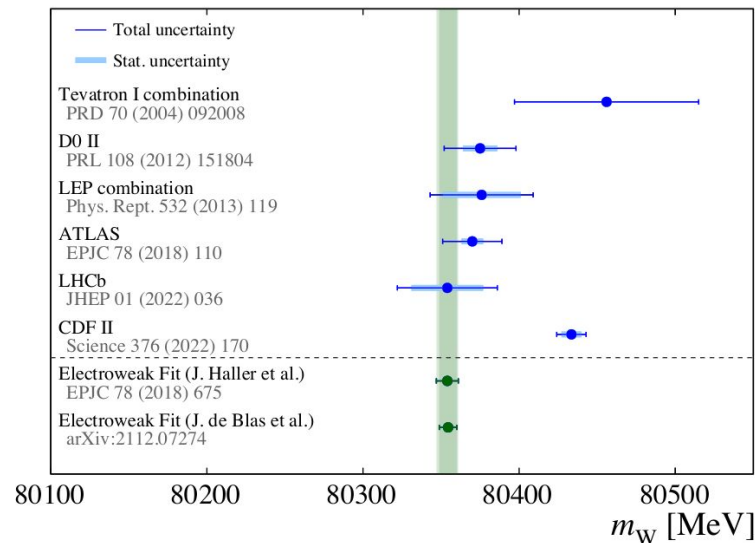
$$m_W = 80433.5 \pm 6.4 \text{ (stat.)} \pm 6.9 \text{ (sys.) MeV}$$

ATLAS ( $4.6 \text{ fb}^{-1}$ ) [*Eur. Phys. J.* **C78** (2018) 110]

$$m_W = 80370 \pm 7 \text{ (stat.)} \pm 18 \text{ (sys.) MeV}$$

LHCb ( $1.7 \text{ fb}^{-1}$ ) [*JHEP* **01** (2022) 036]

$$m_W = 80354 \pm 23 \text{ (stat.)} \pm 22 \text{ (sys.) MeV}$$



- Sensitive probe for BSM physics
- Dominated by hadron collider measurements: difficult measurement with significant theory input, non-trivial correlations e.g. from PDFs
- New CDF result significantly away from the SM and prior measurements

# The $m_W$ combination working group

- Created in 2020 with ATLAS, CMS, CDF, D0; LHCb added more recently
- Primary goals:
  - Official combinations of measurements with treatment of correlations of systematic uncertainties
  - Publication signed by corresponding collaborations
- Established a methodology to combine existing and future measurements; can also be used to enable physics modelling updates of past measurements (i.e. PDFs, pTW ) or e.g. correlate measurements of  $m_W$  and  $\sin^2\theta_W$
- Intermediate results presented at ICHEP2022 + public note released

CERN-LPCC-2022-06  
FERMILAB-TM-2779-V  
7th July 2022

## **Towards a combination of LHC and TeVatron W-boson mass measurements**

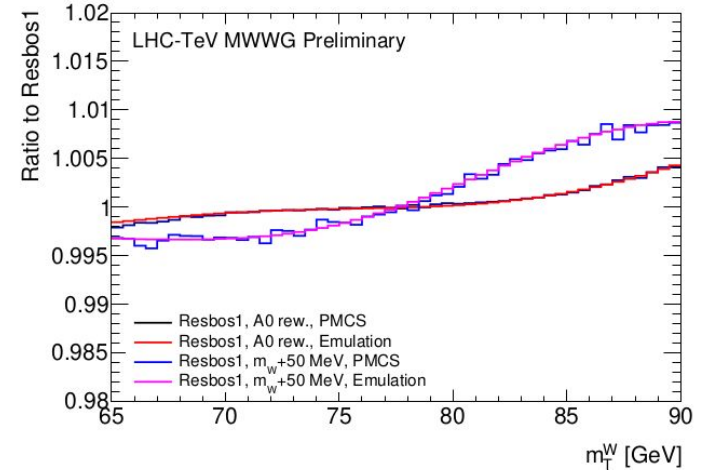
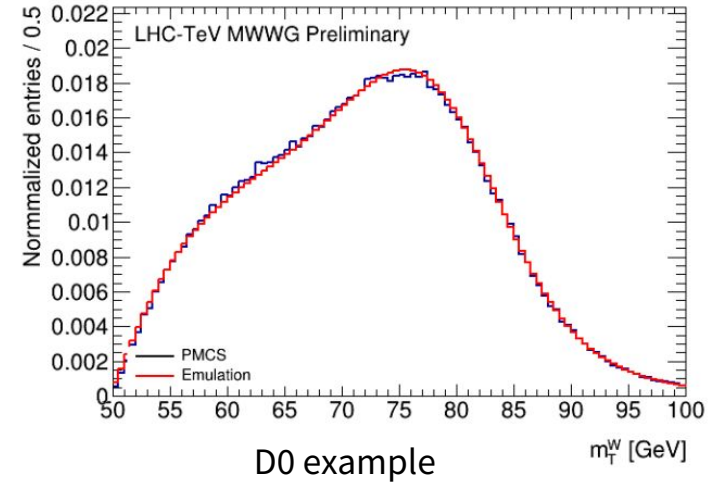
The LHC–TeVatron *W*-boson mass combination working group<sup>1</sup>

In this note methodological and modelling considerations towards a combination of the ATLAS, CDF and D0 measurements of the *W*-boson mass are discussed. As they were performed at different moments in time, each measurement employed different assumptions for the modelling of *W*-boson production and decay, as well as different fits of the parton distribution functions of the proton (PDFs). Methods are presented to accurately evaluate the effect of PDFs and other modelling variations on existing measurements, allowing to extrapolate them to any PDF set and to evaluate the corresponding uncertainties. Based on this approach, the measurements can be corrected to a common modelling reference and to the same PDFs, and subsequently combined accounting for PDF correlations in a quantitative way.

<https://cds.cern.ch/record/2815187>

# Detector Emulation

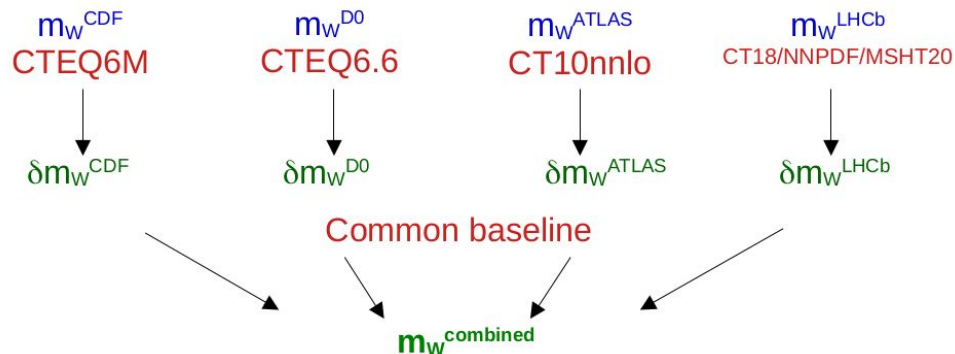
- Original analyses and detector simulations generally hard to reproduce
- Instead, use parametrized detector response on large generator-level sets (lepton energy/momentum scale & resolution, efficiencies; recoil response)
- After event selection published distributions reproduced at the % level
- Note emulation does not have to be perfect, as we are primarily after changes  $\delta m_W$  relative to a baseline
- Systematic uncertainty from emulation estimated to be at the level of 1-2 MeV



# Combination strategy

- Measurements performed at different times, using different baseline PDFs and QCD tools, two-step procedure :

- correct to common PDF & QCD accuracy
- combination including correlations



- Full procedure, decomposed into generator and PDF effects

$$m_W^{updated} = \boxed{m_W^{ref.}} - \boxed{\delta m_W^{QCD}} - \boxed{\delta m_W^{PDF}}$$

published     
 Improved predictions, PDF extrapolation for reference PDF     
 PDF extrapolation

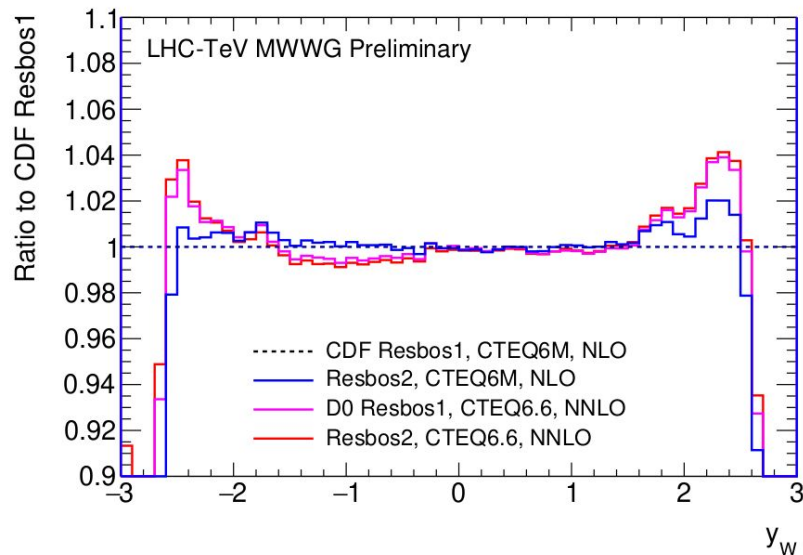
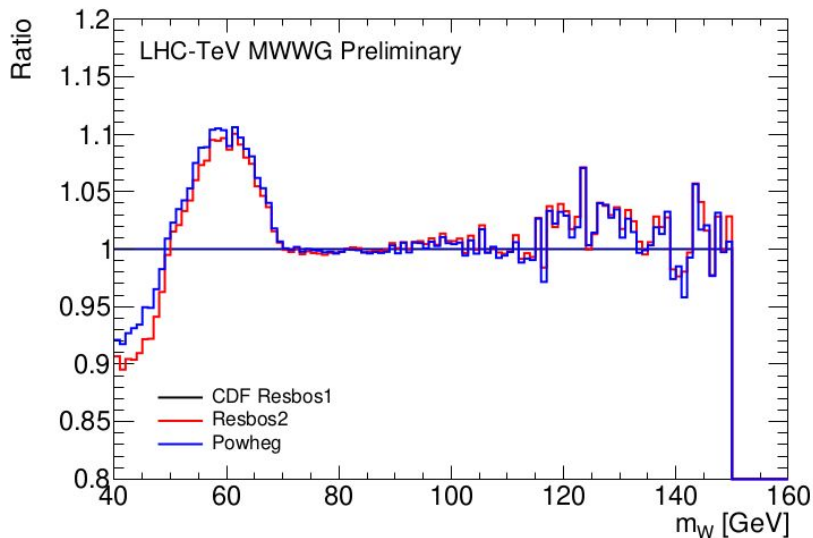
- Allows to improve existing experimental results for improved theory & PDFs

# QCD/generator corrections

- Need to know exact starting point to estimate  $\delta m_W$  correctly – fully reproduced the event generation chain from the original measurements:
  - D0: Resbos CP (NNLO+NNLL) generated with CTEQ66 (NLO)
  - CDF: Resbos C (NLO+NNLL) generated with CTEQ6M (NLO)
  - ATLAS: Powheg+Pythia8 (NLO+PS);  $\gamma W + A_i$  at NNLO with CT10 (NNLO)
  - LHCb: Powheg+Pythia8 (NLO+PS);  $A_i$  at NNLO, as PDF the average of NNPDF3.1, CT18, MSHT20 (NLO)
- Variety of predictions used to estimate shifts in  $m_W$  under PDF variations and estimate the possible need of QCD correction to published measurements
  - Powheg (NLO+PS), MiNNLOPS (NNLO+PS), DYNNLO (NLO/NNLO F.O.)
  - In addition, updated integration grids from the Resbos authors at NLO+NNLL and NNLO+NNLL with improved treatment of spin correlations [2205.02788]

# QCD/generator corrections

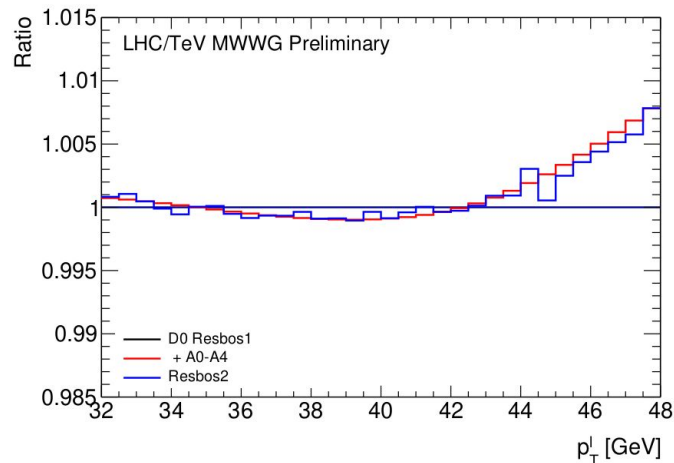
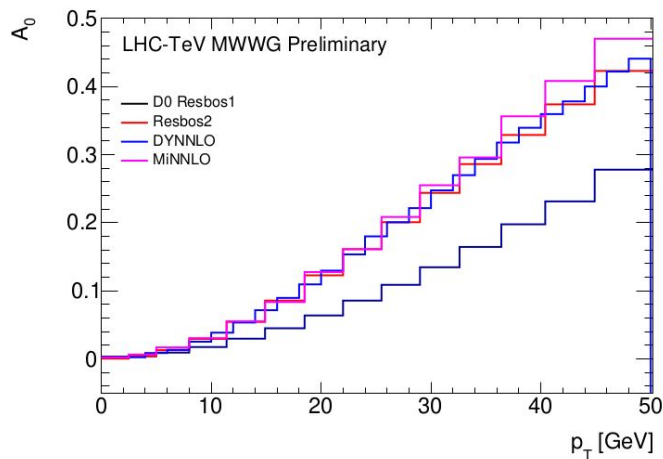
- Specifically  $\delta m_W^{\text{QCD}}$  used to improve Resbos predictions for TeVatron results
- Features and cuts in mass distribution 1.4 – 2.7 MeV effect for CDF
- Small distortions in rapidity have no significant impact



# QCD/generator corrections

- Angular coefficients have known deficits in Resbos1

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm dp_T dy} \left[ (1 + \cos^2 \theta) + \frac{1}{2} A_0 (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi + \dots \right]$$

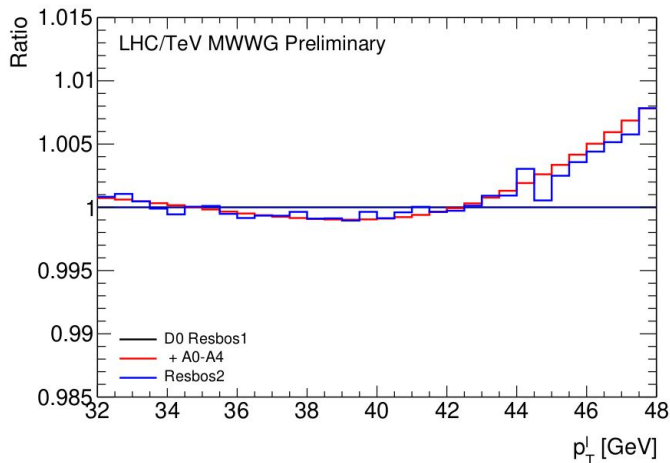
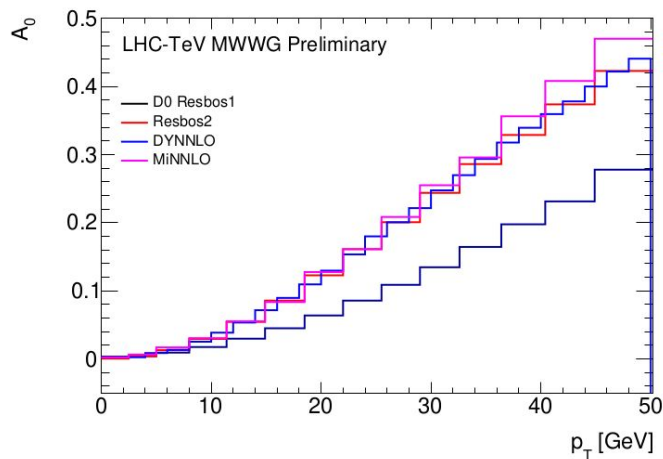


- Lepton distributions too “forward” in Resbos1,  $p_T$  distribution too soft,  $m_W$  (slightly) overestimated

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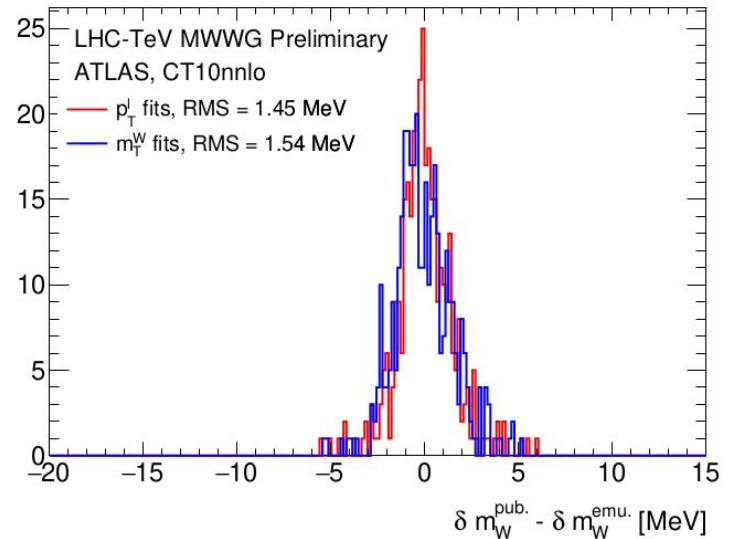
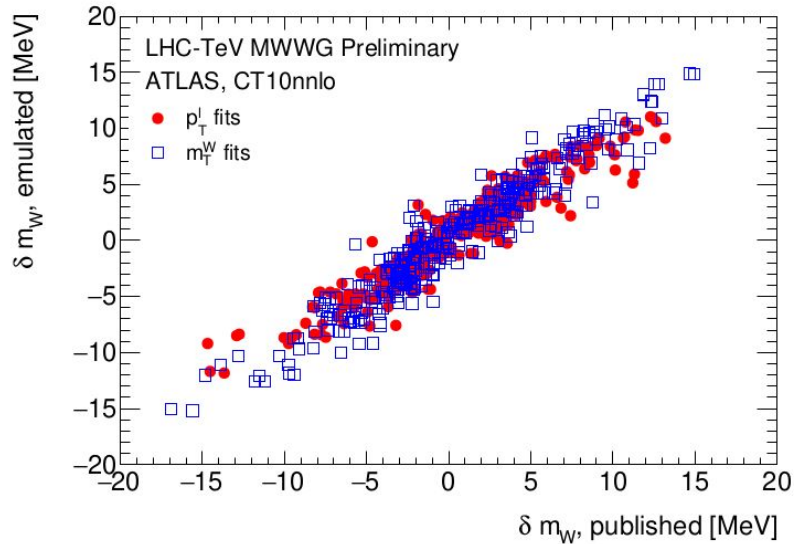
# QCD/generator corrections

- Example impact for D0: 7 – 14 MeV for relevant distributions

Correction	$\delta m_W^{\text{QCD}}$ [MeV]					
	$p_T^W$ -constrained			No constraint		
	$p_T^\ell$	$m_T$	$p_T^\nu$	$p_T^\ell$	$m_T$	$p_T^\nu$
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$A_0$	7.6	10.0	15.8	16.0	12.6	19.5
$A_1$	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
$A_2$	-3.0	-2.6	2.9	-4.2	-3.0	2.3
$A_3$	2.9	1.6	-0.5	3.5	1.8	-0.2
$A_4$	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
RESBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

# PDF extrapolations and uncertainties

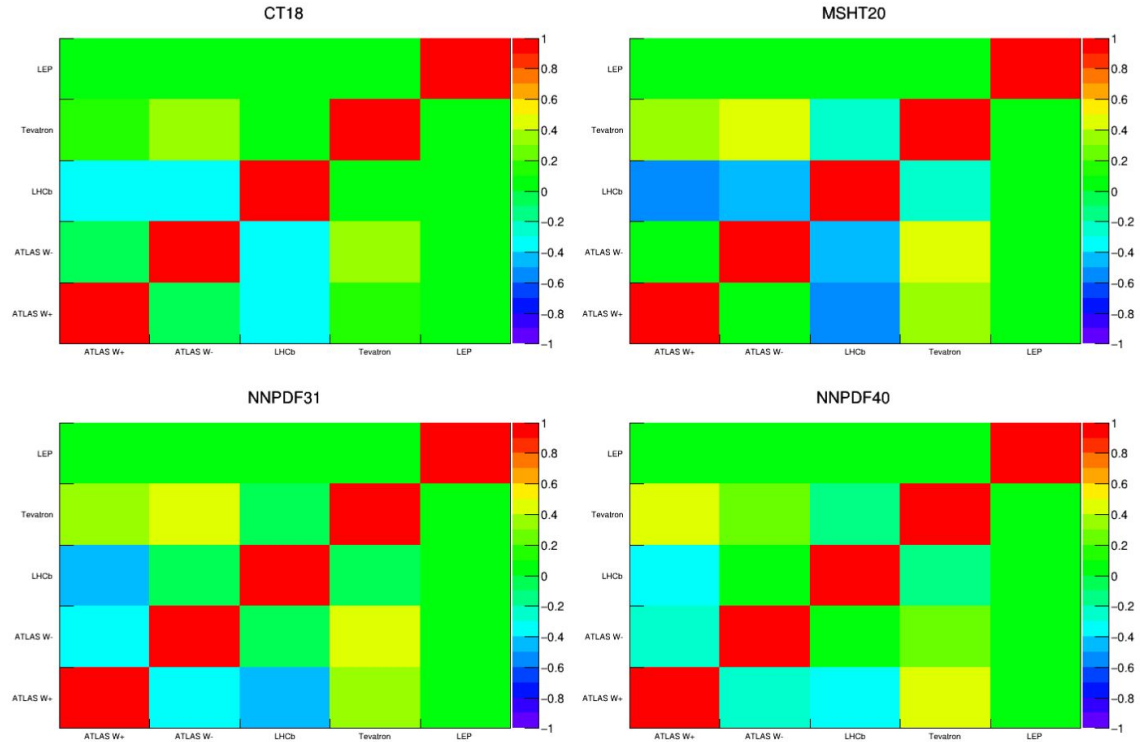
- Validation of PDF eigenvector variations for ATLAS case gives good closure of published vs. emulated variations – estimated 1.5 MeV uncertainty on shift(s)



- Allows to compute shifts from published to common (modern) PDF set and compute correlations

# PDF correlations

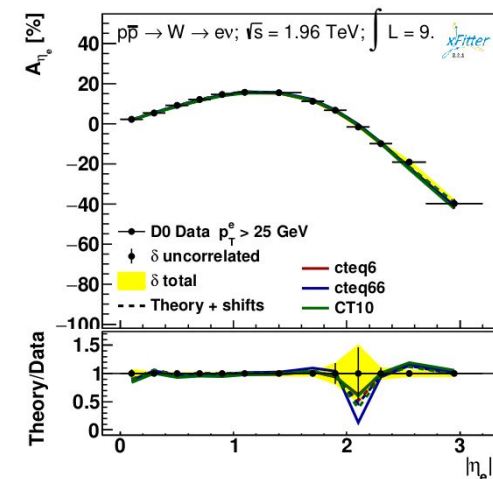
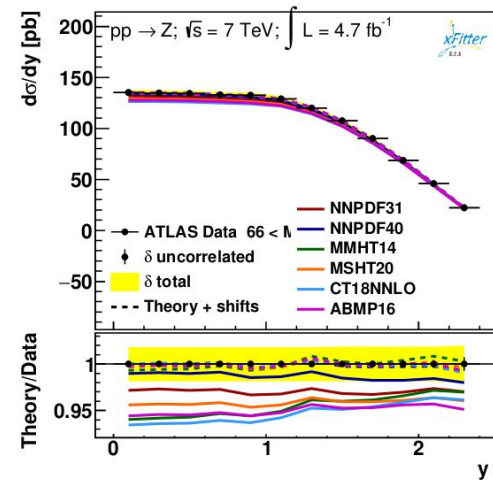
- Simplified picture of estimated PDF correlations across colliders and experiments
- As expected: not trivial ranging from -0.5 to +0.5
- Exact values found to depend significantly on PDF set
- Note: many of the other uncertainties will be largely uncorrelated between measurements



# Which PDF sets to use/choose?

- Benchmarking of PDF sets against Tevatron and LHC W and Z cross-section measurements with predictions at NNLO QCD x NLO EW
- Modern NNLO PDFs provide the best description, but no set gives a  $\chi^2/\text{ndf} \sim 1$
- Decision on the final PDF will consider this benchmarking and the compatibility of the  $m_W$  combination

PDF set	Chi2/ndf	PDF set	Chi2/ndf
Cteq66	231/126	CT18NNLO	163/126
CT10	179/126	CT18ANNLO	170/126
NNPDF31	200/126	MSHT20	270/126
NNPDF40	195/126	ABMP16	236/126



# Conclusions and Outlook

- Significant progress towards combination (and understanding) of existing  $m_W$  measurements
  - Detailed study of generator features such as decay angle/polarization effects
  - PDF archeology
- Close to having a fully final set of numbers for QCD corrections, PDF shifts and correlations and combinations
- In contrast to initial remit, the LHCb measurement will be fully incorporated
- Expecting a complete documentation with combinations using different PDFs sets and different subsets of experiments:
  - TeVatron, LHC, All (including LEP); N-1
  - PDFs: ABMP16, CT18, NNPDF3.1, NNPDF4.0, MSHT20
- Also expecting remaining incompatibilities between measurements even after applying relevant theory updates – iterating on how to present & discuss the results