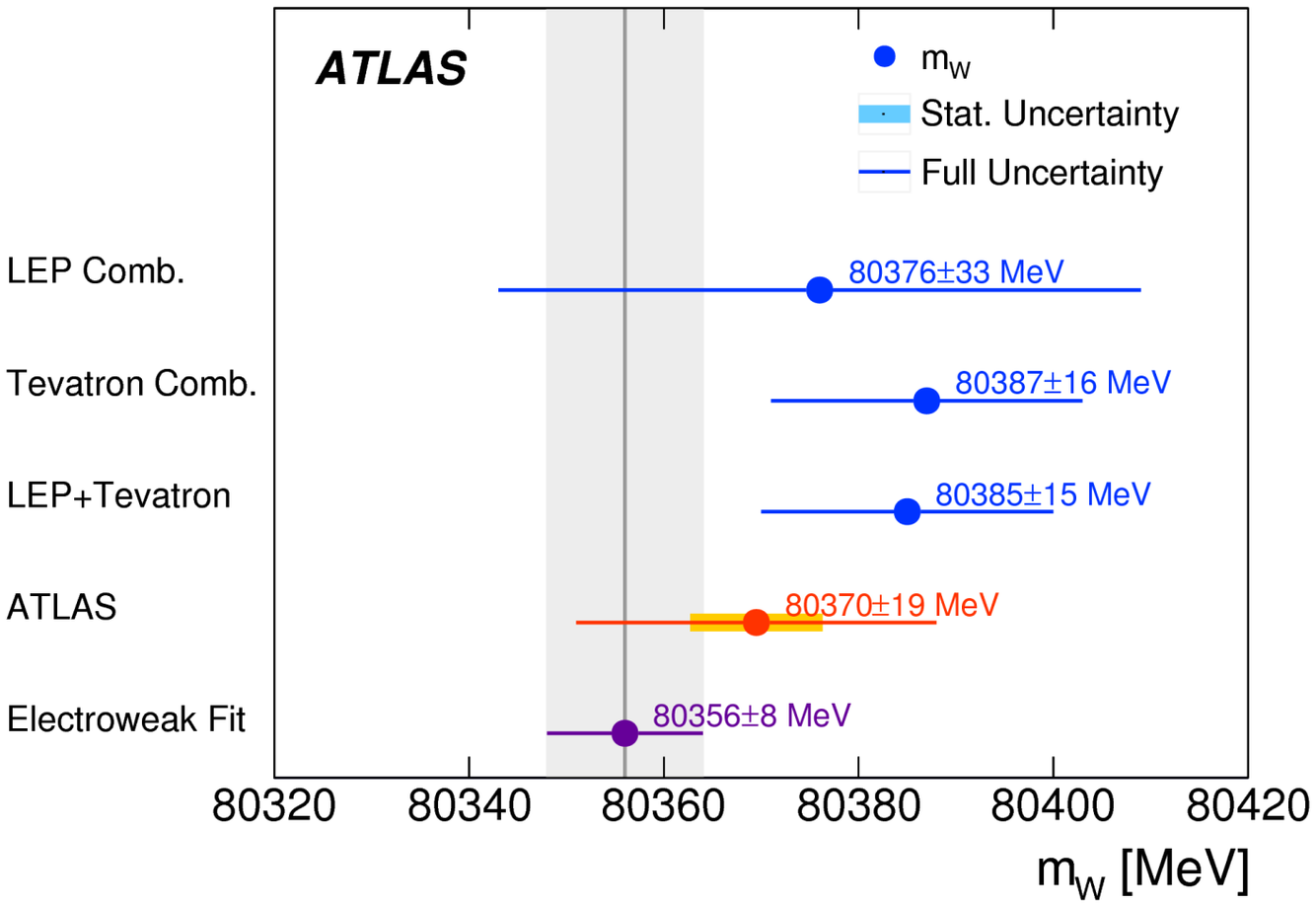
# LHC & Tevatron $m_W$ combination







Chris Hays, Oxford University

*for the Tevatron + LHC $m_W$ combination group*


LHC EW WG meeting

8 October 2020

# Motivation & Organization

**First LHC $m_W$ measurement motivates new evaluation of correlations between experiments**

Opportunity to update theoretical treatment

Provide more information to facilitate future global combinations

**A working group has been initiated with a contact from each experiment**

**D0**: Boris Tuchming, **CDF**: Chris Hays

**ATLAS**: Maarten Boonekamp, **CMS**: Josh Bendavid

**Determine correlations between each experiment's theoretical treatment**

*Harmonize central PDF and uncertainty*

*Combination will include ATLAS Run 1 and Tevatron Run 2 measurements*

Aim to update modelling to harmonize theory treatment in future combinations

# Strategy

**Subdominant theory uncertainties: estimate correlations**

Boson transverse momentum and decay angles uncorrelated

Some correlations in electroweak radiation, small overall uncertainty

**Dominant (PDF) uncertainty: evaluate correlations using detector emulations**

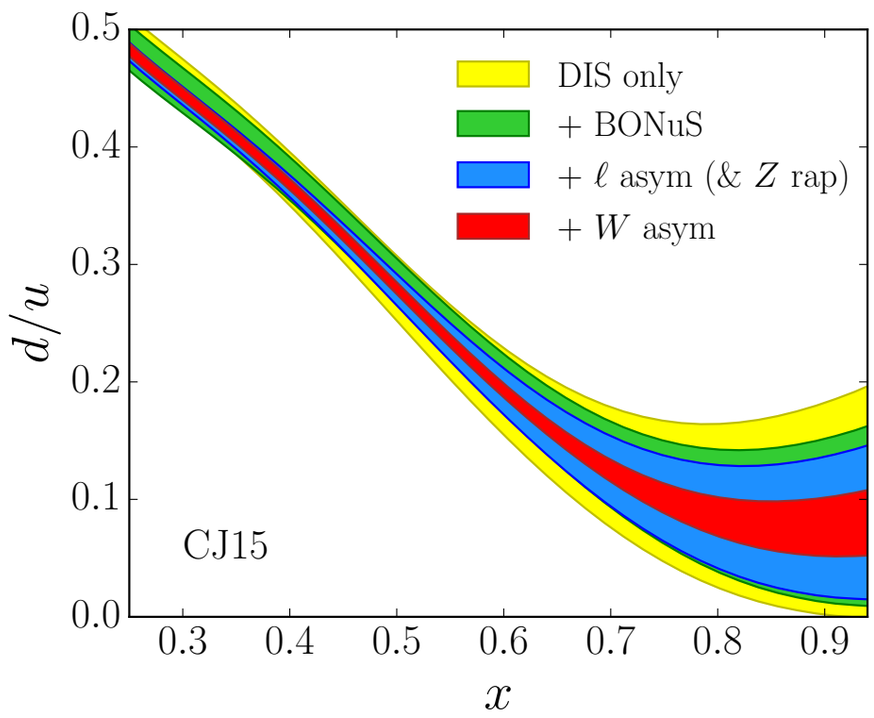
A combination setup has been validated by comparing to each of the experiment's full simulations

**Use best available NNLO PDF set for this measurement to obtain central value and uncertainty**

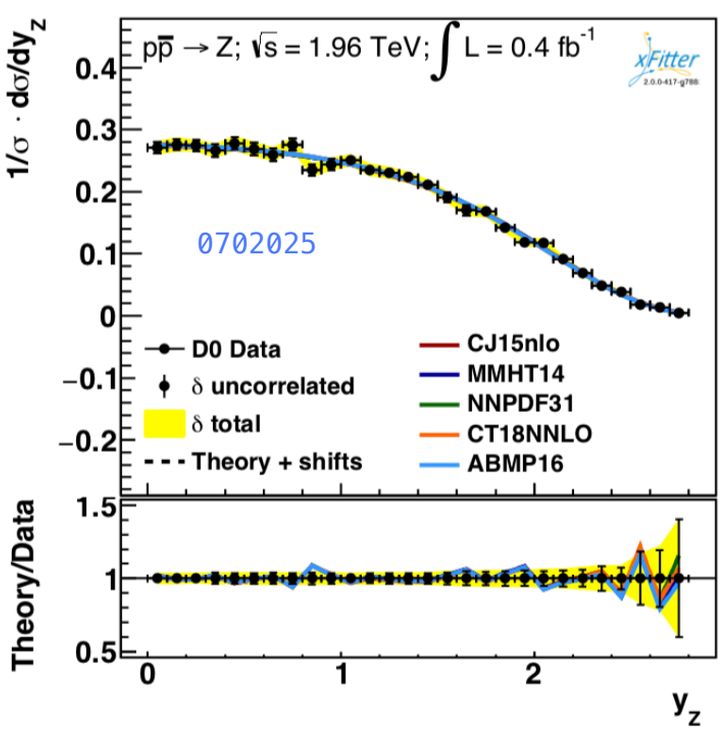
Also provide information from other state-of-the-art PDFs and from PDFs used in measurements

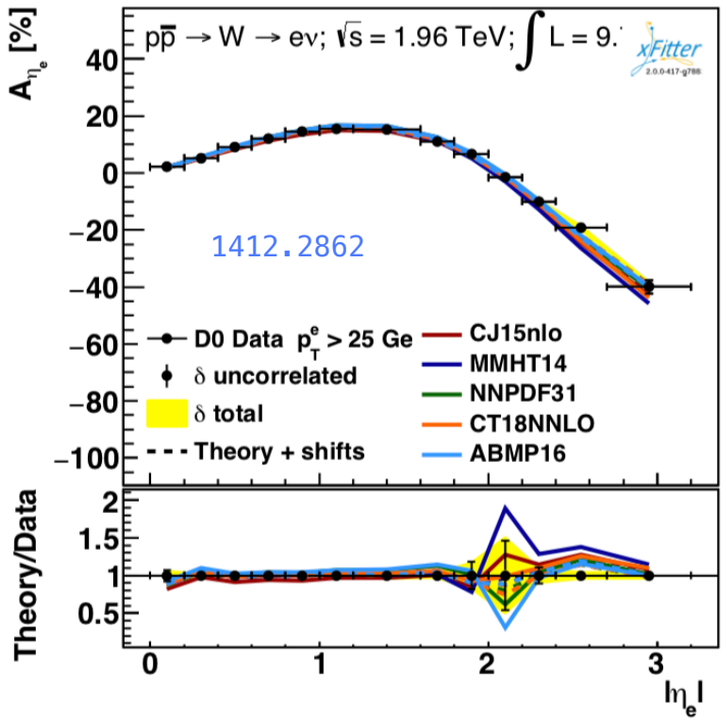
**Tevatron**

| Measurement | MMHT2014 | CJ15 | NNPDF3.1 | CT18 |
|---|---|---|---|---|
| CDF II $e$ asym. (0.2 fb$^{-1}$) [5] | × | ✓ | × | ✓ |
| CDF II $W$ asym. (1 fb$^{-1}$) [6] | ✓ | ✓ | × | × |
| D0 II $\mu$ asym. (0.3 fb$^{-1}$) [7] | × | × | × | ✓ |
| D0 II $\mu$ asym. (7.3 fb$^{-1}$) [8] | ✓ | ✓ | ✓ | × |
| D0 II $e$ asym. (0.75 fb$^{-1}$) [9] | ✓ | × | × | × |
| D0 II $e$ asym. (9.7 fb$^{-1}$) [10] | × | ✓ | ✓ | ✓ |
| D0 II $W$ asym. (9.7 fb$^{-1}$) [11] | × | ✓ | × | × |



# D0 measurements



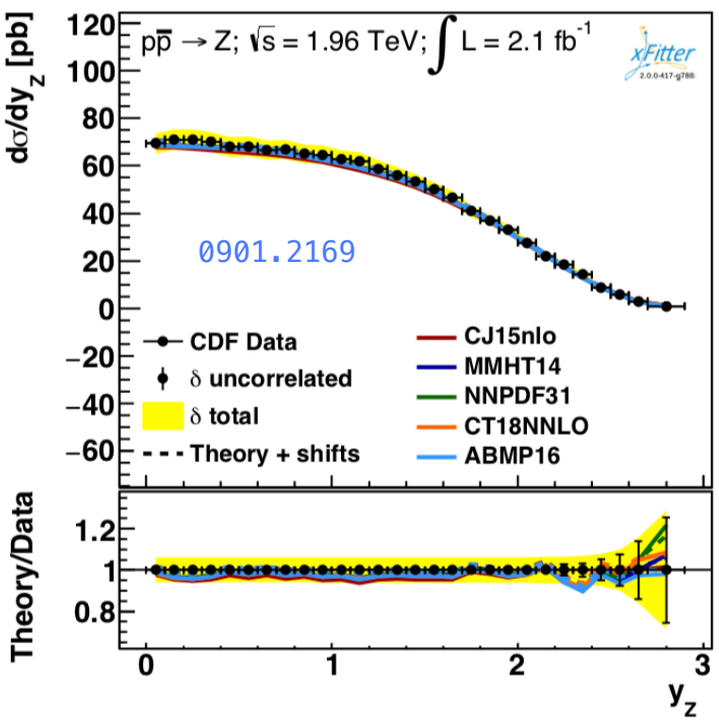



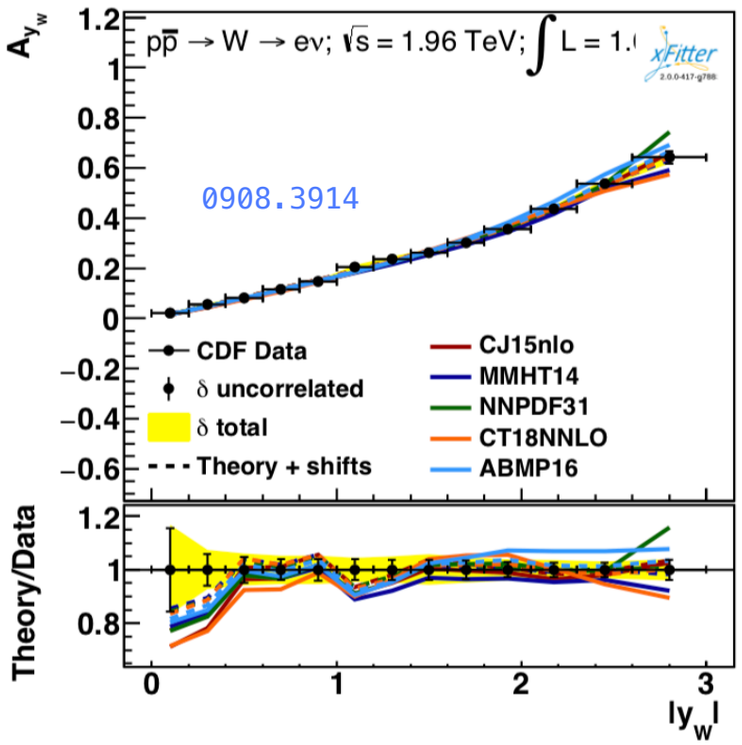

| Dataset | CJ15nlo | MMHT14 | NNPDF31 | CT18NNLO | ABMP16 |
|---|---|---|---|---|---|
| D0 W el nu lepton asymmetry ptl 25 GeV | 32 / 13 | 24 / 13 | 19 / 13 | 17 / 13 | 23 / 13 |
| Correlated $\chi^2$ | 8.7 | 11 | 7.4 | 4.6 | 4.1 |
| Log penalty $\chi^2$ | +0.00 | +0.00 | +0.00 | +0.00 | +0.00 |
| Total $\chi^2$ / dof | 41 / 13 | 35 / 13 | 27 / 13 | 22 / 13 | 27 / 13 |
| $\chi^2$ p-value | 0.00 | 0.00 | 0.01 | 0.05 | 0.01 |

| Dataset | CJ15nlo | MMHT14 | NNPDF31 | CT18NNLO | ABMP16 |
|---|---|---|---|---|---|
| D0 Z rapidity 2007 | 22 / 28 | 23 / 28 | 22 / 28 | 22 / 28 | 23 / 28 |
| Correlated $\chi^2$ | 0.0097 | 0.14 | 0.10 | 0.041 | 0.061 |
| Log penalty $\chi^2$ | +0.01 | -0.07 | +0.10 | +0.09 | -0.17 |
| Total $\chi^2$ / dof | 22 / 28 | 23 / 28 | 22 / 28 | 22 / 28 | 23 / 28 |
| $\chi^2$ p-value | 0.76 | 0.74 | 0.76 | 0.79 | 0.75 |

comparisons from Simone Amoroso

# CDF measurements

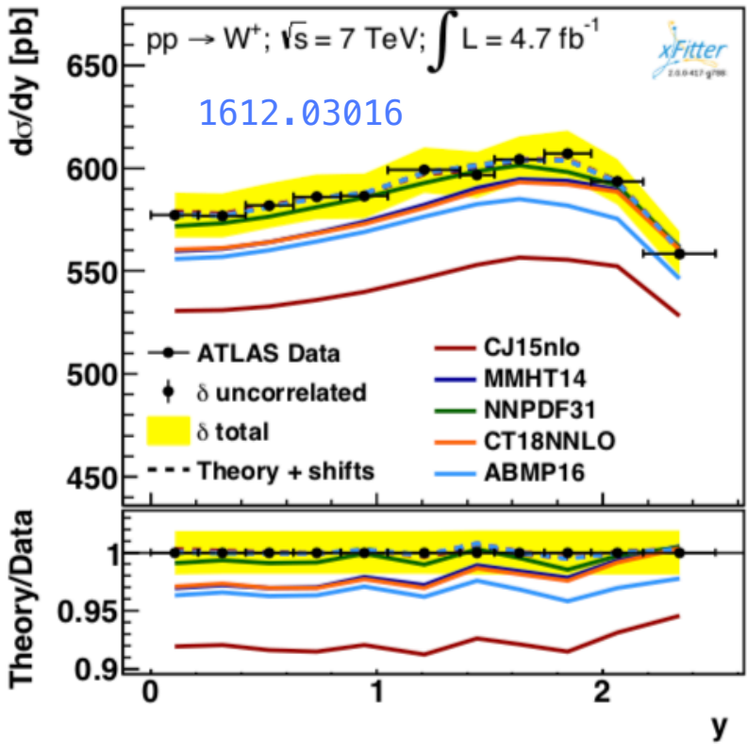



| Dataset | CJ15nlo | MMHT14 | NNPDF31 | CT18NNLO | ABMP16 |
|---|---|---|---|---|---|
| CDF W asymmetry 2009 | 18 / 13 | 12 / 13 | 11 / 13 | 13 / 13 | 17 / 13 |
| Correlated $\chi^2$ | 1.6 | 1.7 | 2.6 | 2.9 | 6.5 |
| Log penalty $\chi^2$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Total $\chi^2$ / dof | 19 / 13 | 14 / 13 | 13 / 13 | 16 / 13 | 23 / 13 |
| $\chi^2$ p-value | 0.11 | 0.37 | 0.43 | 0.25 | 0.04 |

| Dataset | CJ15nlo | MMHT14 | NNPDF31 | CT18NNLO | ABMP16 |
|---|---|---|---|---|---|
| CDF Z rapidity 2010 | 29 / 28 | 30 / 28 | 25 / 28 | 27 / 28 | 30 / 28 |
| Correlated $\chi^2$ | 1.5 | 0.99 | 1.7 | 0.49 | 0.69 |
| Log penalty $\chi^2$ | -1.16 | -0.63 | -0.44 | -0.60 | -0.90 |
| Total $\chi^2$ / dof | 30 / 28 | 30 / 28 | 26 / 28 | 27 / 28 | 30 / 28 |
| $\chi^2$ p-value | 0.37 | 0.36 | 0.55 | 0.53 | 0.36 |

# ATLAS measurements




| Dataset | CJ15nlo | MMHT14 | NNPDF31 | CT18NNLO | ABMP16 |
|---|---|---|---|---|---|
| ATLAS low mass Z rapidity 2011 | 26 / 6 | 18 / 6 | 14 / 6 | 12 / 6 | 21 / 6 |
| ATLAS peak CC Z rapidity 2011 | 52 / 12 | 21 / 12 | 12 / 12 | 16 / 12 | 24 / 12 |
| ATLAS peak CF Z rapidity 2011 | 16 / 9 | 11 / 9 | 11 / 9 | 10 / 9 | 9.2 / 9 |
| ATLAS high mass CC Z rapidity 2011 | 7.7 / 6 | 6.1 / 6 | 5.8 / 6 | 5.9 / 6 | 6.1 / 6 |
| ATLAS high mass CF Z rapidity 2011 | 4.6 / 6 | 5.5 / 6 | 4.7 / 6 | 4.8 / 6 | 4.5 / 6 |
| ATLAS W- lepton rapidity 2011 | 17 / 11 | 8.4 / 11 | 8.7 / 11 | 9.1 / 11 | 10 / 11 |
| ATLAS W+ lepton rapidity 2011 | 16 / 11 | 11 / 11 | 11 / 11 | 10 / 11 | 13 / 11 |
| Correlated $\chi^2$ | 118 | 50 | 31 | 40 | 50 |
| Log penalty $\chi^2$ | -9.09 | -3.32 | -2.45 | -3.66 | -4.22 |
| Total $\chi^2$ / dof | 247 / 61 | 127 / 61 | 95 / 61 | 104 / 61 | 134 / 61 |
| $\chi^2$ p-value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Best overall Tevatron + LHC W & Z description with NNPDF3.1 and CT18 (NNLO)**

# Event generation and simulation

**Uncertainties and correlations estimated using Powheg W_EW_BMNNP + Photos**

No EW corrections or QCD showering

$p_T^W$ distribution for central PDF smeared and weighted to match that of each experiment

Use internal reweighting to switch eigenvectors

**Validate uncertainties by comparing to Powheg + Pythia, Madgraph (N)LO + Pythia, and Pythia**

**Validate central shifts with RESBOS, Powheg + Pythia, Madgraph NLO + Pythia**

Also use DYTurbo to validate W boson rapidity

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**Detector response modelled with parameterized simulations**

e.g. for CDF recoil response:

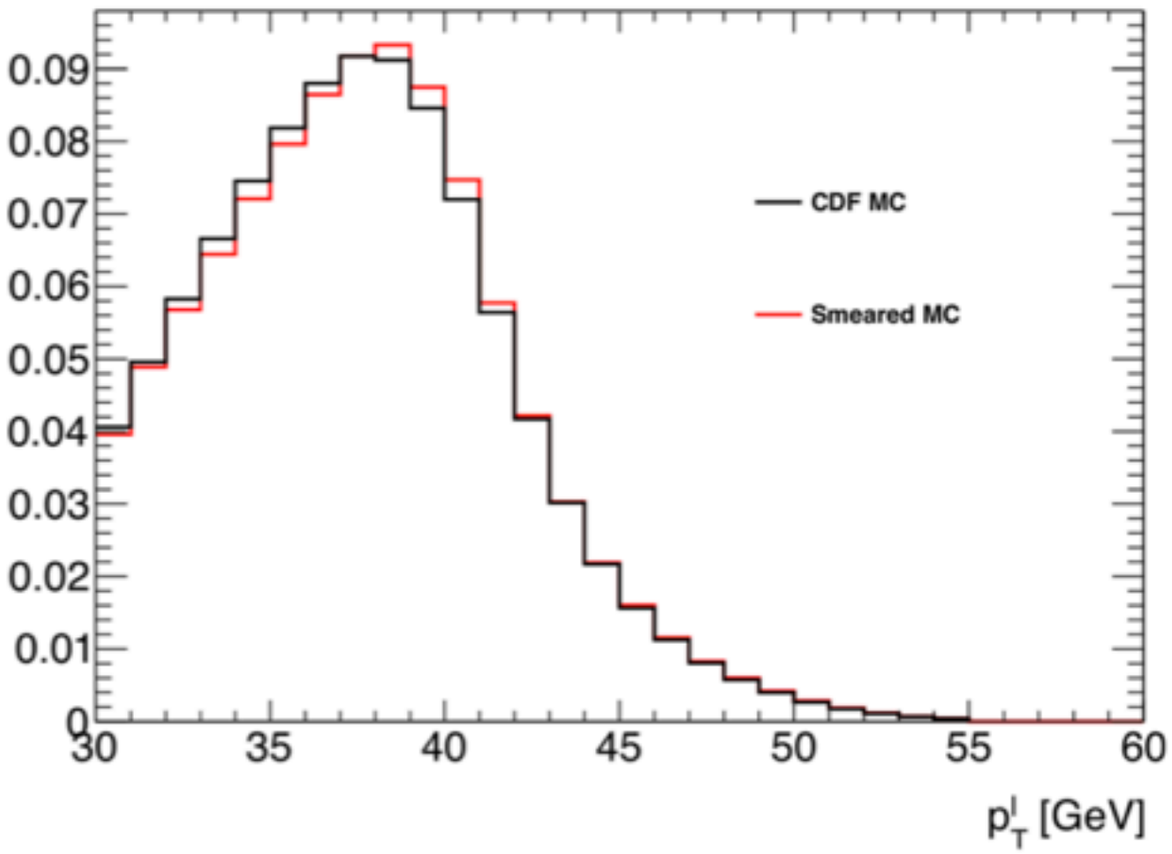
$$
\begin{aligned}
R(p_{\mathrm{T}}^W) &= 0.645 \times \log(5.1 \times p_{\mathrm{T}}^W + 8.2)/\log(5.1 \times p_T^{\max} + 8.2), \\
\sigma_{u_{\mathrm{T}}}(p_{\mathrm{T}}^W) &= 0.82 \times \sqrt{p_{\mathrm{T}}^W}\ \mathrm{GeV}, \\
\sigma_{u_\phi}(p_{\mathrm{T}}^W) &= 0.306 + 0.021 \times (9.4 - p_{\mathrm{T}}^W)\ \mathrm{rad};
\end{aligned}
\qquad
\sigma_{u_\phi}(p_{\mathrm{T}}^W) = 0.144 + 0.0048 \times (24.5 - p_{\mathrm{T}}^W)\ \mathrm{rad}.
$$

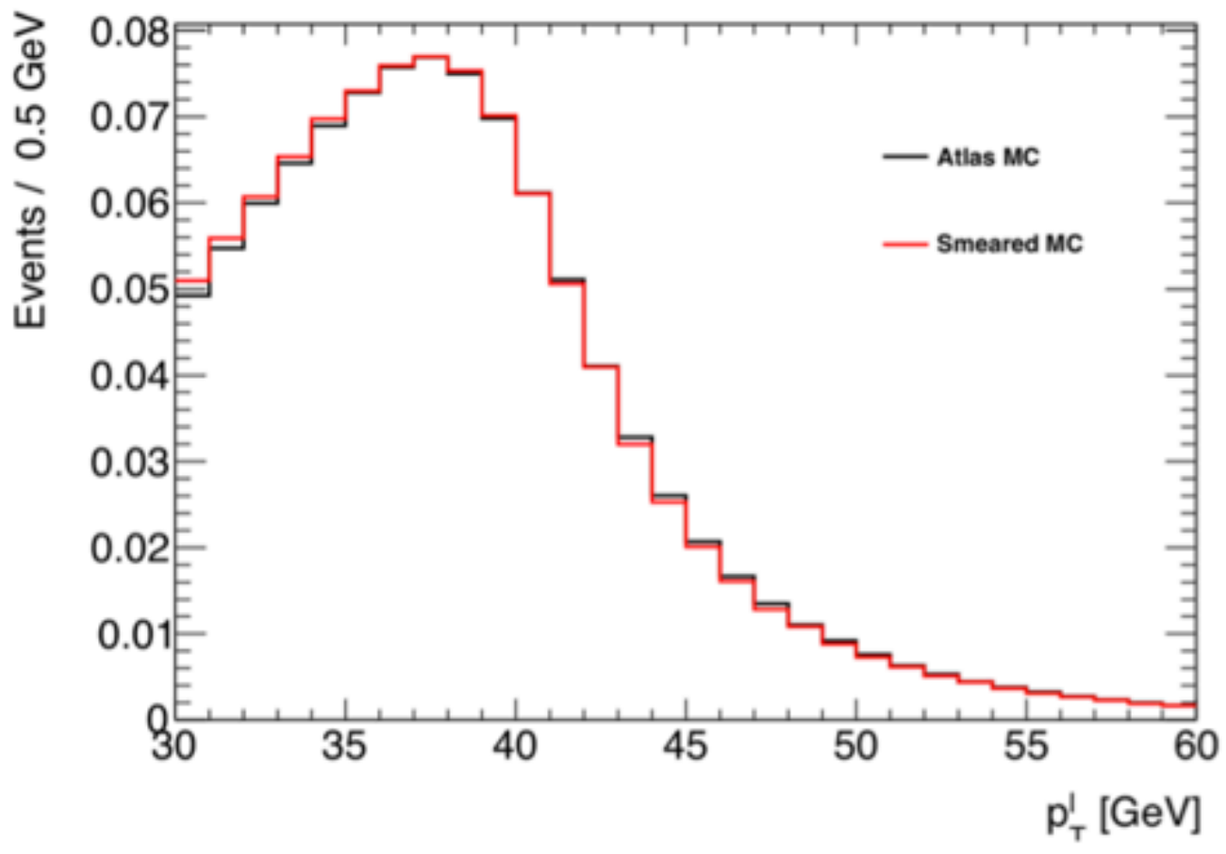
for $p_T^W$>15 GeV

**Validate by comparing to each experiment's simulation**

Also compare to independent parameterized CDF simulation

# Fit distributions




**Detector modelling sufficient for determining PDF corrections and uncertainties**

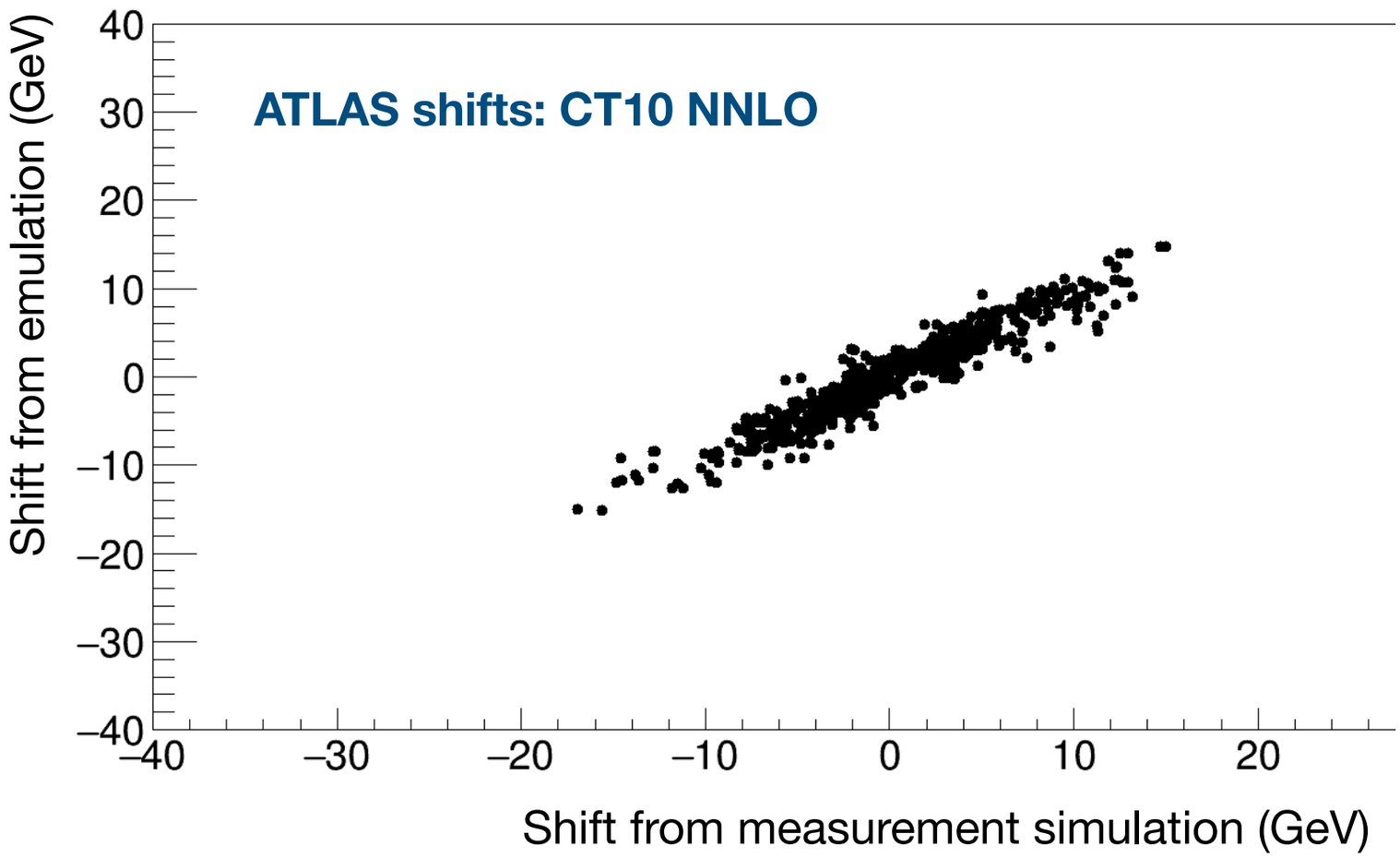
comparisons from
Nansi Andari

# Combination validation

**Performed BLUE combinations using published information**

| | Tevatron | Tevatron+LEP |
|---|---|---|
| Published | 80387 + 16 | 80385 + 15 |
| Validation | 80388 + 16 | 80385 + 15 (actually 14.47) |

# Validation



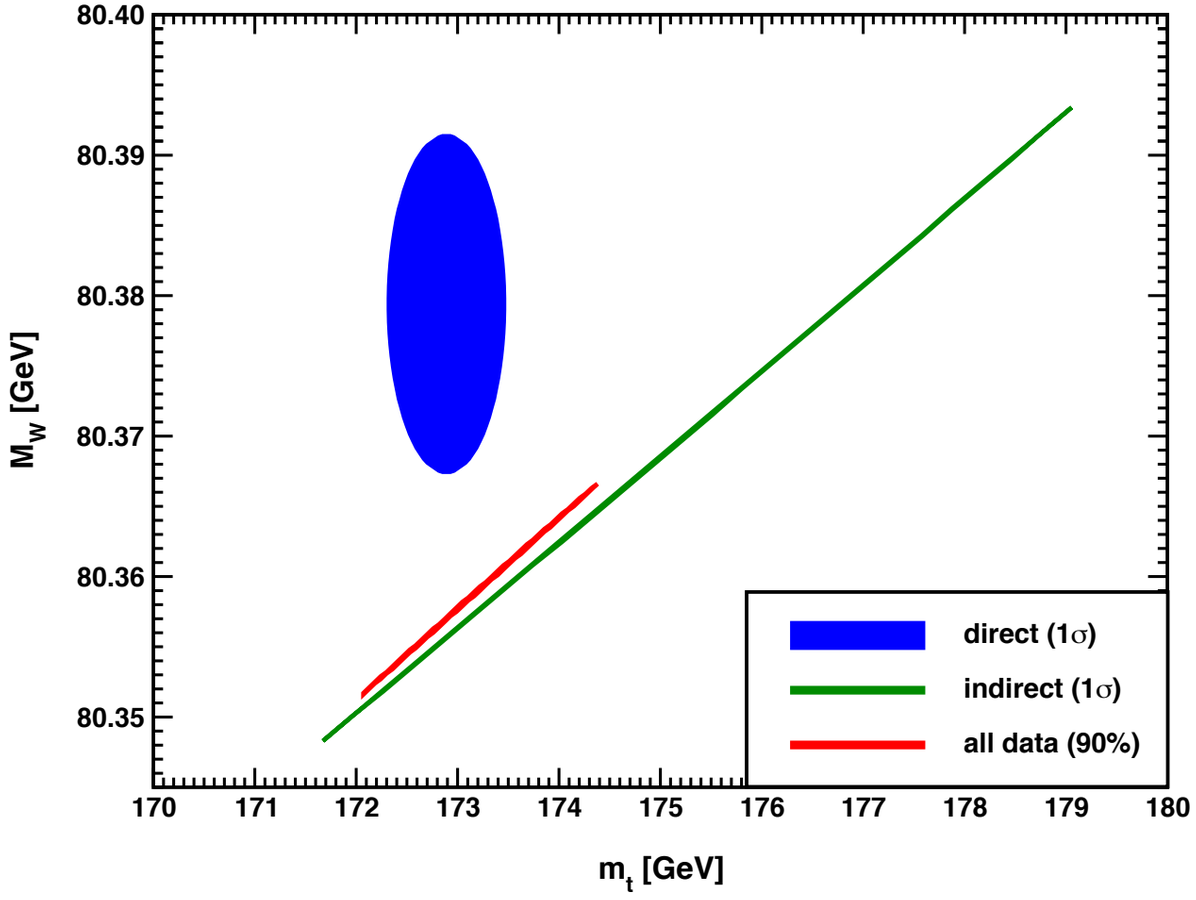

**Shift due to changing PDFs in each ATLAS measurement region**

# Summary

**Work ongoing to produce official Tevatron + LHC $m_W$ combination**

Procedures established and validated

Validating results (uncertainty correlations, shifts of central values)



# Backup

# Electroweak corrections

**NLO EW calculation**

Each experiment uses the PHOTOS generator to model final-state photon radiation

**CDF** applies a 4 ± 2 MeV correction from HORACE (matches single-photon emission to the NLO calculation)

*Additional uncertainty taken from HORACE vs PHOTOS validation*

**ATLAS & D0** have no correction

*ATLAS uses PHOTOS to calculate the effect, takes as an uncertainty*

*D0 takes an uncertainty based on a comparison to the NLO calculation*

**Harmonization**

Use PHOTOS with NLO correction for the measurement (residual uncertainty < 1 MeV)

| Uncertainty | CDF | D0 | ATLAS | CDF-ATLAS | CDF-D0 | D0-ATLAS |
|---|---|---|---|---|---|---|
| NLO calculation | 4 (4) | 5 (5) | 2.5 (3.3) | 0% | 0% | 100% |
| Photon $y$ cutoff | 2 (2) | 2 (1) | −− | −− | 100% | −− |
| FSR $e^+e^-$ | 1 (1) | −− | 0.8 (3.6) | 0% | −− | −− |
| Total | 4 (4) | 7 (7) | 2.6 (4.9) | | | |

**Electrons $m_T$ ($p_T$) fit**

| Uncertainty | CDF | ATLAS |
|---|---|---|
| NLO calculation | 4 (4) | 2.5 (3.5) |
| Photon $y$ cutoff | 2 (2) | −− |
| FSR $e^+e^-$ | 1 (1) | 0.8 (3.6) |
| Total | 4 (4) | 2.6 (5.6) |

**Muons $m_T$ ($p_T$) fit**

# Electroweak corrections

**Photon energy threshold in PHOTOS**

CDF changes threshold from 0.4 MeV to 4 MeV to estimate uncertainty
D0 changes threshold from from 10 MeV to 800 MeV to estimate uncertainty
ATLAS takes no uncertainty

**Harmonization**

Use a common threshold and variation

| Uncertainty | CDF | D0 | ATLAS | CDF-ATLAS | CDF-D0 | D0-ATLAS |
|---|---|---|---|---|---|---|
| NLO calculation | 4 (4) | 5 (5) | 2.5 (3.3) | 0% | 0% | 100% |
| Photon $y$ cutoff | 2 (2) | 2 (1) | −− | −− | 100% | −− |
| FSR $e^+e^-$ | 1 (1) | −− | 0.8 (3.6) | 0% | −− | −− |
| Total | 4 (4) | 7 (7) | 2.6 (4.9) | | | |

**Electrons $m_T$ ($p_T$) fit**

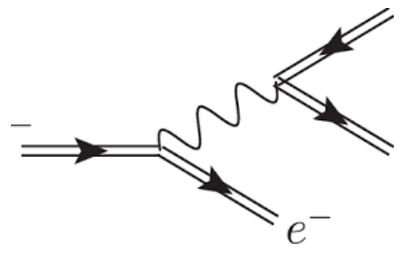
| Uncertainty | CDF | ATLAS |
|---|---|---|
| NLO calculation | 4 (4) | 2.5 (3.5) |
| Photon $y$ cutoff | 2 (2) | −− |
| FSR $e^+e^-$ | 1 (1) | 0.8 (3.6) |
| Total | 4 (4) | 2.6 (5.6) |

**Muons $m_T$ ($p_T$) fit**

# Electroweak corrections

**$e^+e^-$ radiation**

CDF applies a splitting function to PHOTOS radiation with residual uncertainty
ATLAS takes an uncertainty based on PHOTOS and WINHAC
D0 does not consider




**Harmonization**

Use PHOTOS to apply correction

| Uncertainty | CDF | D0 | ATLAS | CDF-ATLAS | CDF-D0 | D0-ATLAS |
|---|---|---|---|---|---|---|
| NLO calculation | 4 (4) | 5 (5) | 2.5 (3.3) | 0% | 0% | 100% |
| Photon $y$ cutoff | 2 (2) | 2 (1) | −− | −− | 100% | −− |
| FSR $e^+e^-$ | 1 (1) | −− | 0.8 (3.6) | 0% | −− | −− |
| Total | 4 (4) | 7 (7) | 2.6 (4.9) | | | |

**Electrons $m_T$ ($p_T$) fit**

| Uncertainty | CDF | ATLAS |
|---|---|---|
| NLO calculation | 4 (4) | 2.5 (3.5) |
| Photon $y$ cutoff | 2 (2) | −− |
| FSR $e^+e^-$ | 1 (1) | 0.8 (3.6) |
| Total | 4 (4) | 2.6 (5.6) |

**Muons $m_T$ ($p_T$) fit**

# W boson $p_T$ distribution

CDF & D0 use the RESBOS model (NNLO + NNLL inclusive accuracy)
*Currently no uncertainty on the model, only statistical uncertainty on the parameters from Z data*

ATLAS uses the PYTHIA parton shower model
- Statistical uncertainty from PS tune
- Additional uncertainty due to W production from heavy-flavour quarks

**Harmonization**
Check uncertainty for heavy-flavour production at the Tevatron

Fundamentally different approaches to describing data (PS vs fixed-order + resummed calculations)
- *Default models cannot be harmonized*

# W boson decay angles

CDF compares angular coefficients between RESBOS and a fixed-order NLO W+jet calculation
*Coefficients agree at a level corresponding to 3 MeV on the W boson mass*

ATLAS takes an uncertainty based on measurement in Z data

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^2\,\mathrm{d}y\,\mathrm{d}m\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^2\,\mathrm{d}y\,\mathrm{d}m} \times \Big[(1+\cos^2\theta) + A_0\,\frac{1}{2}(1-3\cos^2\theta) + A_1\,\sin 2\theta\cos\phi + A_2\,\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\,\sin\theta\cos\phi + A_4\,\cos\theta + A_5\,\sin^2\theta\sin 2\phi + A_6\,\sin 2\theta\sin\phi + A_7\,\sin\theta\sin\phi\Big]. \quad (3)$$

**Harmonization**
Use common model and take theoretical uncertainty

# PDF uncertainties

Experiments use different PDFs for central values and uncertainties

| | Published CTEQ6.6† MSTW2008§ |
|---|---|
| Central value | 80 387 |
| Stat. | 12 |
| Exp. syst. | 10 |
| QCD, QED | 6 |
| PDF | 10 |
| Total | 19 |

**CDF**

| | Published CTEQ6.6†, CTEQ6.1§ |
|---|---|
| Central value | 80 367 |
| Stat. | 13 |
| Exp. syst. | 18 |
| QCD, QED | 7 |
| PDF | 11 |
| Total | 26 |

**D0**

| | Published CT10nnlo†§ |
|---|---|
| Central value | 80 370 |
| Stat. | 7 |
| Exp. syst. | 11 |
| QCD, QED | 10 |
| PDF | 9 |
| Total | 19 |

**ATLAS**

Also differences in uncertainty calculations

$$\delta m_W^+ = \left[\sum_i \left(\delta m_W^i\right)^2\right]^{1/2} \quad \text{if } \delta m_W^i > 0,$$

$$\delta m_W^- = \left[\sum_i \left(\delta m_W^i\right)^2\right]^{1/2} \quad \text{if } \delta m_W^i < 0,$$

**ATLAS**

$$\delta m_W = (\delta m_W^+ + \delta m_W^-)/2,$$

$$\delta M_W^{\mathrm{PDF}} = \tfrac{1}{2}\sqrt{\textstyle\sum_i (M_W^{i+} - M_W^{i-})^2}$$

**CDF**

**Harmonization**

Use common PDF and uncertainty prescription