PDF Correlations

ATLAS - Tevatron combination:

N. Andari, W. Ashmanskas, F. Balli, G. Belletini, M. Boonekamp, G. Chiarelli, C. Hays, A. Kotwal, J. Kretzschmar, J. McFayden, J. Stark, D. Toback, K. Vellidis

https://indico.cern.ch/category/3290/ discussion on LHC / Tevatron combinations of mW

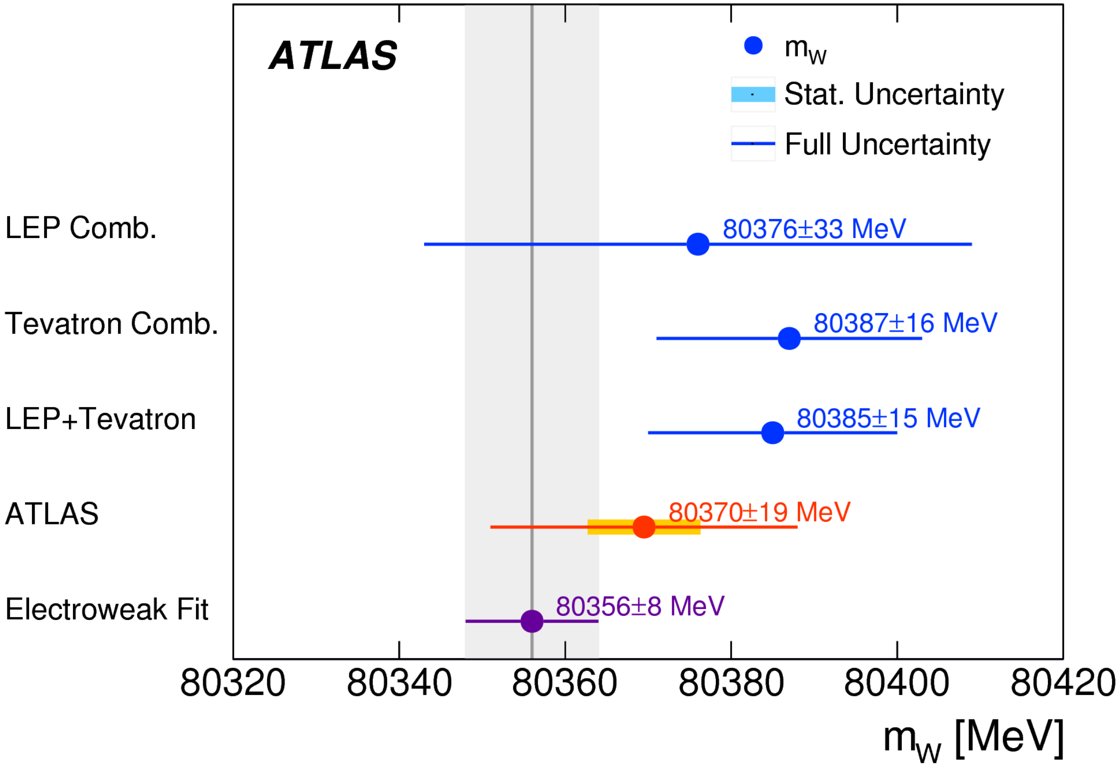
mW-sin2thetaW correlation:

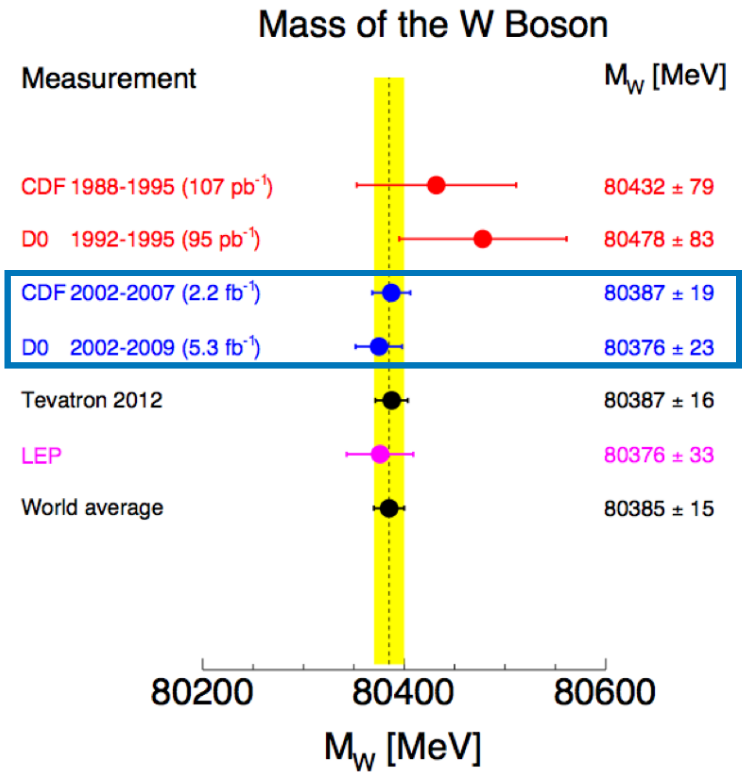
N. Andari, L. Aperio-Bella, A. Armbruster, M. Boonekamp, S. Camarda, M.Schott

Ultimate Precision at Hadron Colliders workshop
28/11/2019

ATLAS - Tevatron combination

Introduction





Aim: provide a new world average value combining the existing public results (no change or improvement in the individual results is foreseen)

Motivation

- at least 3 unofficial, handwaving combinations around (EW fitters, PDG)
- Quantitatively addressing the question of PDF correlations among hadron collider measurements. This will become a major issue in the future:
  - Combinations : m_W or $\sin^2\theta_{eff}$ measurements at different experiments / colliders
  - Interpretation : correlation between m_W and $\sin^2\theta_{eff}$ measurements, in an EW fit for example
  - Beyond this, correlations in measurements of Higgs properties, diboson rates, ... will ultimately become significant and need to be accounted for when interpreting results
- Enable porting existing measurements to other existing or future PDF set
- Put in place a methodology for future combinations including fellow LHC experiments

- Problem : dominance of modelling uncertainties. These are physically strongly correlated, but addressed in different ways in all measurements

Tevatron Results

CDF experiment:

Phys. Rev. Lett.108 (2012) 151803

electron/muon channels **1.1 M**

2.2 fb^{-1} integrated luminosity

m_W= 80387±12(stat)±15(syst) MeV

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

D0 experiment:

Phys. Rev. Lett. 108 (2012) 151804

electron channel **1.7 M**

~5.3 fb^{-1} integrated luminosity

m_W= 80375±11(stat)±20(syst) MeV

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

$$M_W = 80\,387 \pm 16 \text{ MeV}$$

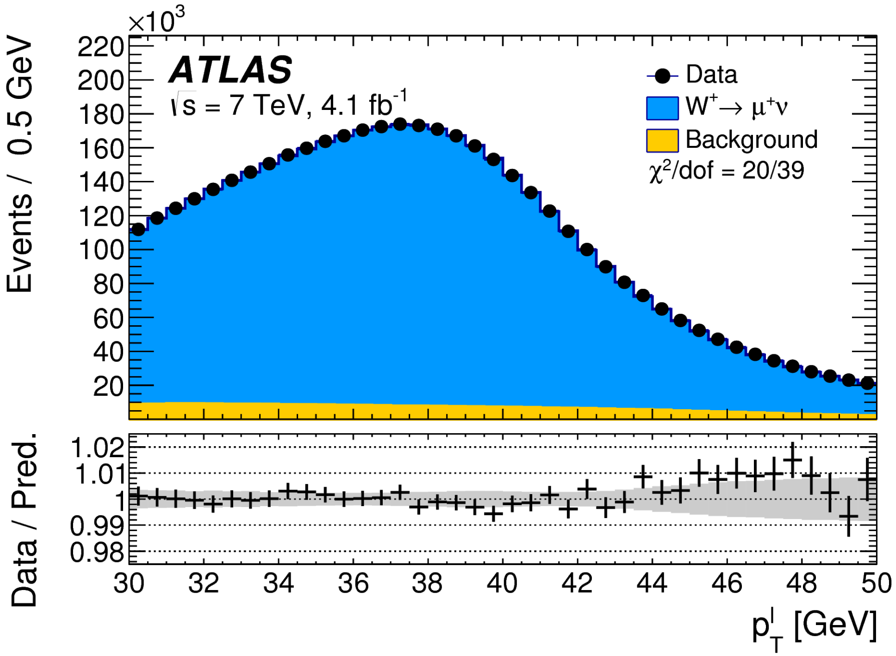
ATLAS Results

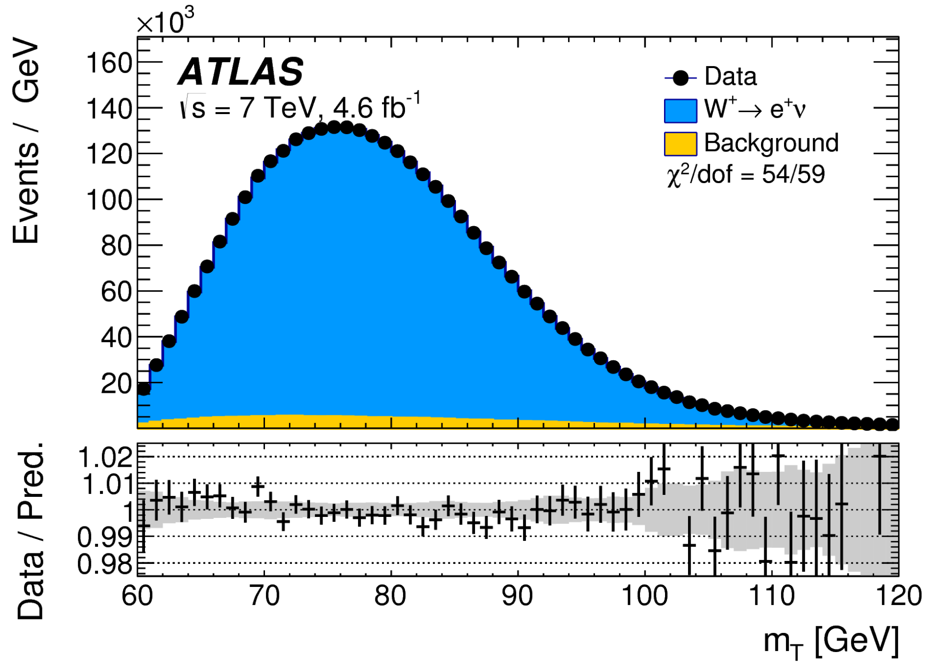
[Eur.Phys.J.C (2018) 78:110]

$$m_W = 80369.5 \pm 6.8\ \text{MeV}(\text{stat.}) \pm 10.6\ \text{MeV}(\text{exp. syst.}) \pm 13.6\ \text{MeV}(\text{mod. syst.})$$
$$= 80369.5 \pm 18.5\ \text{MeV},$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

~6M/8M observed in the electron/muon channel





Uncertainty correlation

Stat and Experimental uncertainties: decorrelated
Theory-related uncertainties: correlations to be evaluated

EW

ATLAS

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

CDF

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

QCD

ATLAS

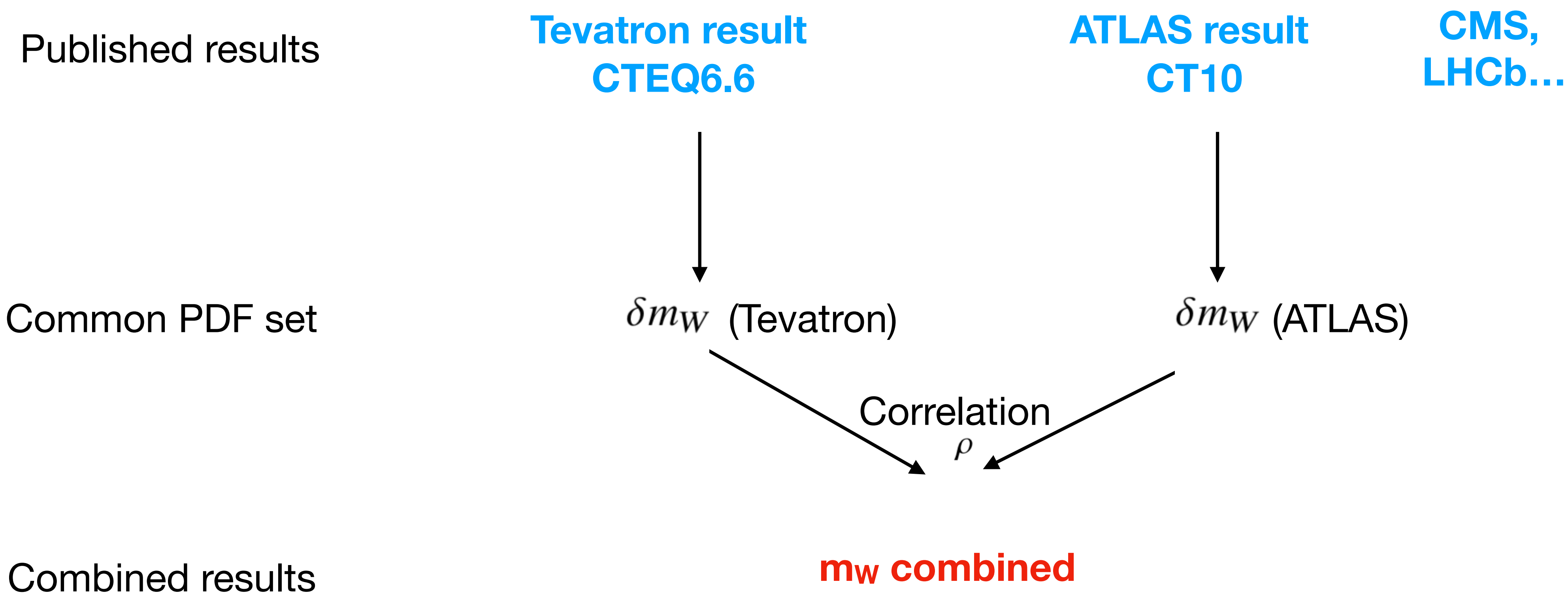
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty (PDF)	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass (pTW)	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients (Ai)	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

Uncertainty correlation

	ATLAS	Tevatron
pT	Pythia8	RESBOS
Ai, y	DYNNLO	RESBOS
PDF	CT10nnlo	CTEQ6.6
EW	Photos	Photos

- All experimental : uncorrelated
  - Small caveat : m Z, the primary reference for calibration in ATLAS and D0 (CDF uses J/psi)
- Physics modelling
  - Boson pT : can be assumed uncorrelated
    - Model purely based on Z data at the Tevatron
    - Combination of Z data and Z → W extrapolation at ATLAS
  - QED / EW corrections : under discussion
    - Photon radiation uncertainties
    - Radiation of pairs
    - Weak corrections
  - PDFs are the main source of correlations

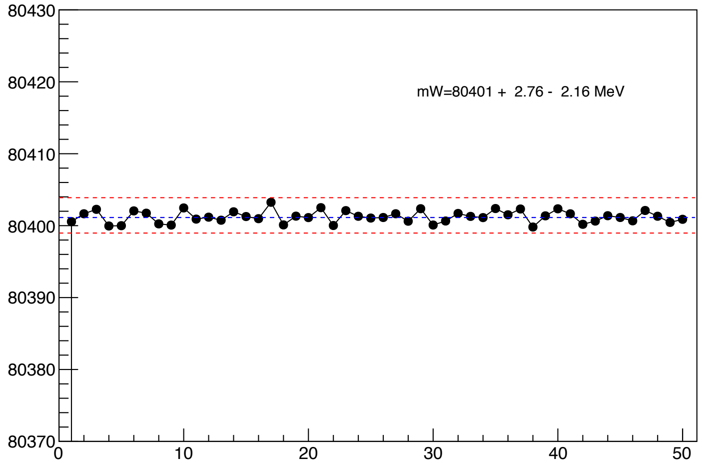
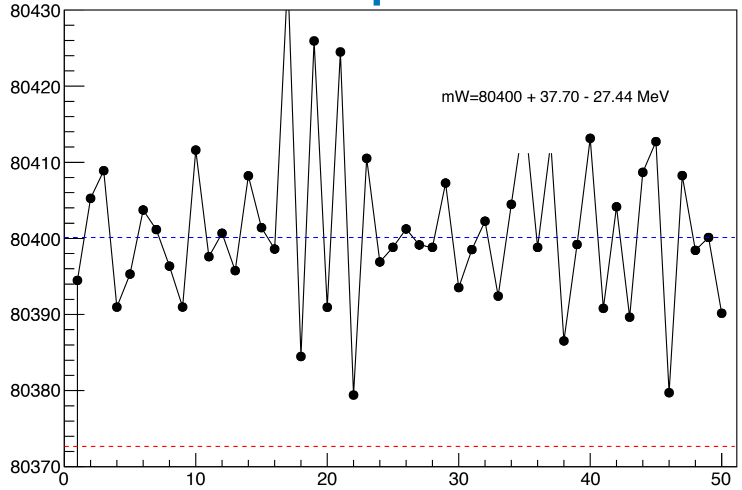
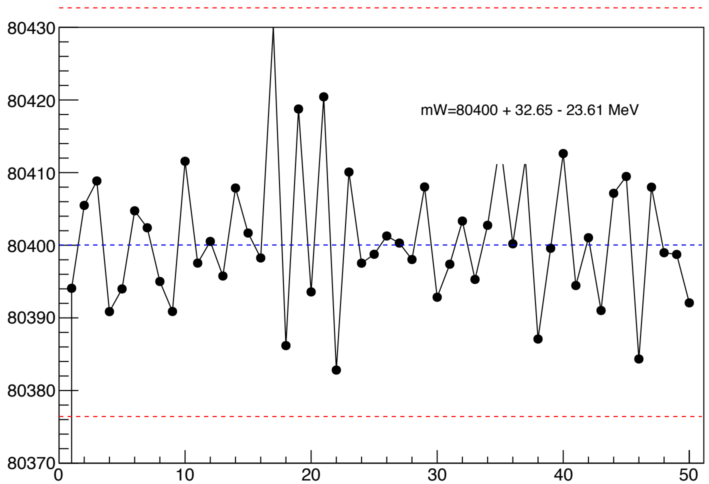
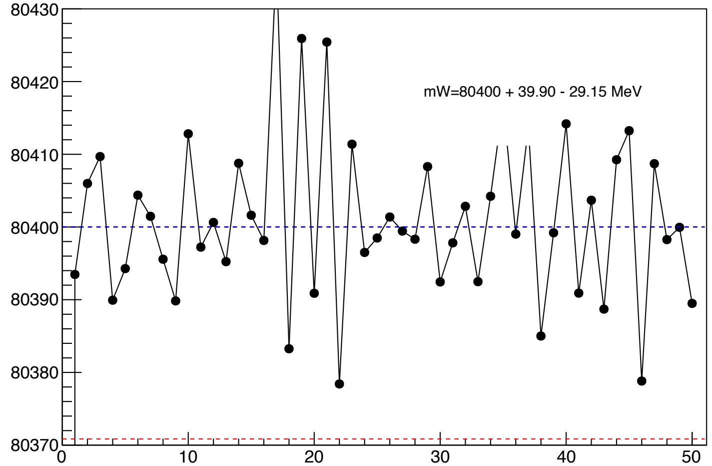
Correlation between PDF uncertainties to be evaluated



- PDFs are the main source of correlations:
  - Re-create analyses on "smeared" truth-level samples (Powheg) with variety of weights corresponding to different PDFs
  - Evaluate shifts in m_W from use of different PDF sets and PDF uncertainties from EV
  - Evaluate correlations and perform combinations

Emulation approach

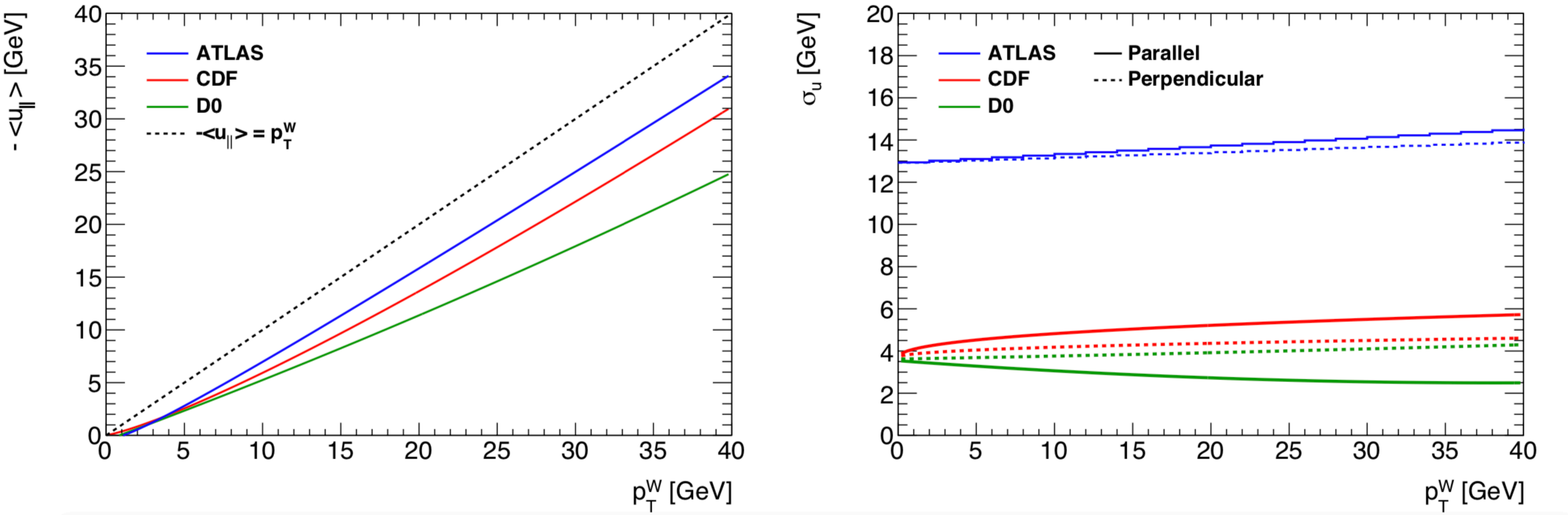
Mimic recoil and lepton resolution effects through a smearing approach of the truth level distributions to the one published in the measurements

	mT	pTl
Generator Level		
After detector effects		

Factor 10 between born and smeared for mT, small effect from smearing on pTl

Emulation approach

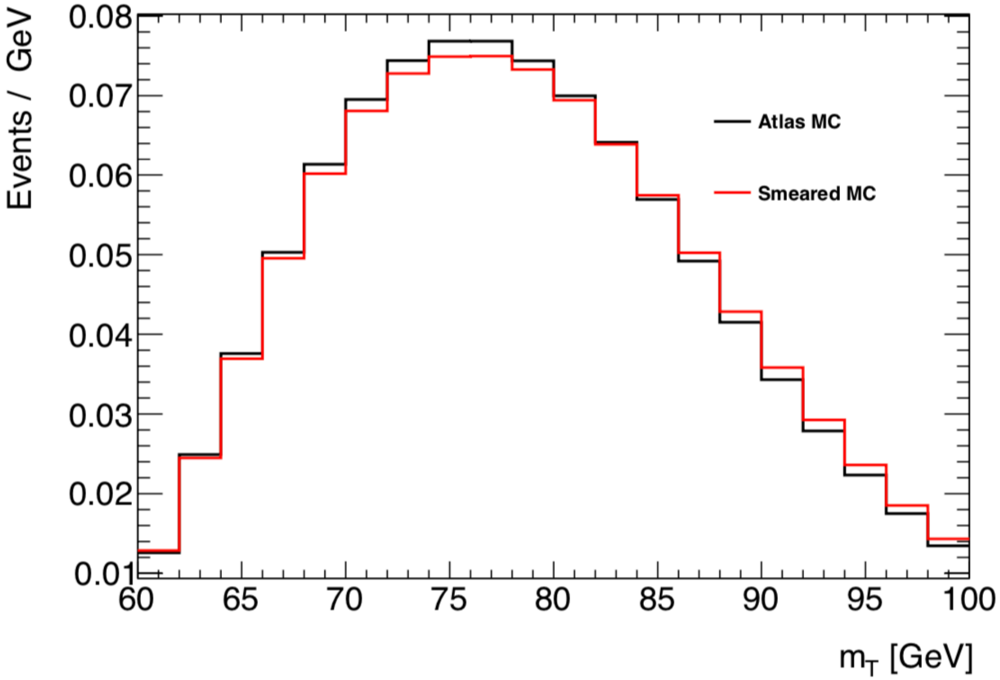
- Smearing is important effect for m_T fit: difference between truth and reco level large which increases PDF uncertainties significantly
- On the other hand effect for p_T^ℓ small

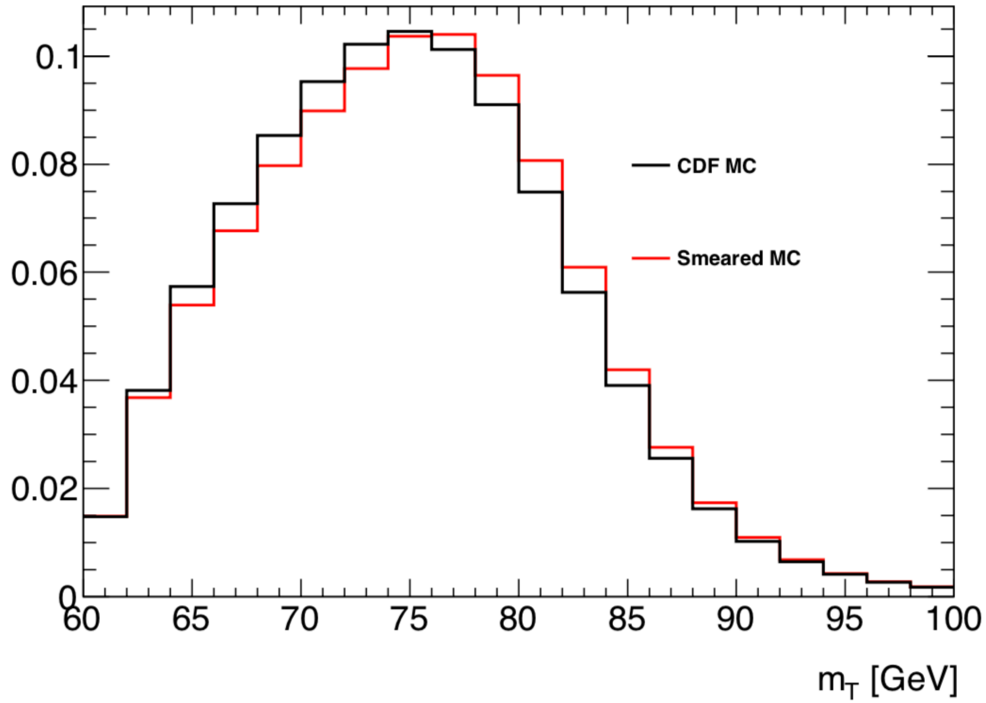


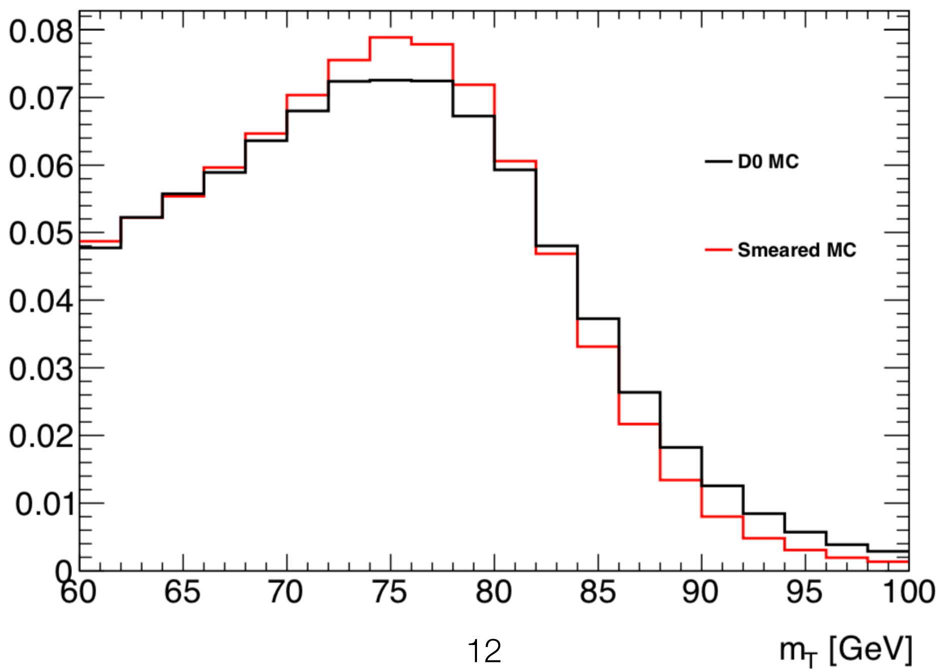
D0 experiment:

- Simple recoil parametrization, from private communication. Could be improved

Emulation approach validation







PDF uncertainties and correlations

PDF variations are applied as event weights on the generator level, calculated internally in Powheg as the ratio of the event cross sections predicted by CT10 and alternative PDF sets:

- CT10 nnlo, CTEQ6.6, CTEQ6.1, MSTW2008 used in publications
- *CT10*, *CT14, MMHT2014, NNPDF31, CT18:* other PDF sets

Different energies 2, 7 TeV (pp-bar for 2 TeV)

$$\delta m^{+}_{W\alpha} = \left[\sum_i \left(\delta m^i_{W\alpha} \right)^2 \right]^{1/2} \text{ if } \delta m^i_{W\alpha} > 0, \qquad \delta m^{-}_{W\alpha} = \left[\sum_i \left(\delta m^i_{W\alpha} \right)^2 \right]^{1/2} \text{ if } \delta m^i_{W\alpha} < 0,$$

Where i runs for the uncertainty sets

$$\rho_{\alpha\beta} = \frac{\sum_i \delta m^i_{W\alpha} \delta m^i_{W\beta}}{\delta m_{W\alpha} \delta m_{W\beta}}$$

Correlation of PDF uncertainties between different categories alpha and beta

PDF uncertainties

Reminder

- CDF:
  - Central value: CTEQ6.6 (ResBos)
  - Uncertainty: EV of MSTW2008 68%C.L.
- D0:
  - Central value: CTEQ6.6 (ResBos)
  - Uncertainty: EV of CTEQ6.1 / 1.645 (Pythia6)
- ATLAS:
  - Central value: CT10nnlo (DYTURBO y_W & A_i, Pythia8 p_{T}^{W})
  - Uncertainty: EV of CT10nnlo / 1.645 (DYTURBO), envelope of CT14nnlo and MMHT2014nnlo central values

Corresponds to a reduction factor of 2.15 wrt to MSTW2008 90%CL

- uses constraints from pTZ data : consider only PDF-induced variations on the pTW/pTZ ratio

$$w_{PDFi \to PDFj} \to w_{PDFi \to PDFj} \times \left(\frac{1}{\sigma_Z} \frac{d\sigma_Z}{dp_{\mathrm{T}}} \right)_{PDFi} \Big/ \left(\frac{1}{\sigma_Z} \frac{d\sigma_Z}{dp_{\mathrm{T}}} \right)_{PDFj}$$

Event Selections

- Event selection applied as for publication

Experiment	Event selections	Fit ranges
CDF	$30 < p_{\mathrm{T}}^{\ell} < 55$ GeV, $\lvert\eta_\ell\rvert < 1$ $30 < E_{\mathrm{T}}^{\mathrm{miss}} < 55$ GeV, $60 < m_{\mathrm{T}} < 100$ GeV $u_{\mathrm{T}} < 15$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV $32 < E_{\mathrm{T}}^{\mathrm{miss}} < 48$ GeV $65 < m_{\mathrm{T}} < 90$ GeV
D0	$p_{\mathrm{T}}^{\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 1.05$ $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 50$ GeV $u_{\mathrm{T}} < 15$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV $65 < m_{\mathrm{T}} < 90$ GeV
ATLAS	$p_{\mathrm{T}}^{\ell} > 30$ GeV, $\lvert\eta_\ell\rvert < 2.4$ $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, $m_{\mathrm{T}} > 60$ GeV $u_{\mathrm{T}} < 30$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 45$ GeV $66 < m_{\mathrm{T}} < 99$ GeV

- CDF: six categories $\{W \to e\nu, W \to \mu\nu\} \times \{p_{\mathrm{T}}^{\ell}, E_{T,miss}, m_{\mathrm{T}}\}$
- D0: two categories $\{W \to e\nu\} \times \{p_{\mathrm{T}}^{\ell}, m_{\mathrm{T}}\}$
- ATLAS: 28 categories $\{W^+ \to \ell\nu, W^- \to \mu\nu\} \times \{e, \mu\} \times \{p_{\mathrm{T}}^{\ell}, m_{\mathrm{T}}\} \times \{3(4)\eta\}$

Results CDF

- Published central value with CTEQ6.6 well reproduced in combination

Category		CTEQ6.6†
$W \to e\nu$	m_T fit	80 408
$W \to e\nu$	p_T^ℓ fit	80 393
$W \to e\nu$	E_T^{miss} fit	80 431
$W \to \mu\nu$	m_T fit	80 379
$W \to \mu\nu$	p_T^ℓ fit	80 348
$W \to \mu\nu$	E_T^{miss} fit	80 406
Combined (published)		80 387
Combined (emulated)		80 389

- Published uncertainty with MSTW2008 well reproduced in

	Published CTEQ6.6† MSTW2008§	MSTW2008§ *Emulated*
Central value	80 387	80 388
Stat.	12	12
Exp. syst.	10	
QCD, QED	6	
PDF	10	10
Total	19	19

Results D0

- Published central value with CTEQ6.6 reasonably reproduced in combination

Category		CTEQ6.6[†]
$W \to e\nu$	m_{T} fit	80 371
$W \to e\nu$	p_{T}^{ℓ} fit	80 343
Combined (published)		80 367
Combined (emulated)		80 370

- Some holes to fill here still... we managed to obtain CTEQ6.1 PDF in LHAPDF6 (thanks to help from Andy Buckley), cannot quite reproduce the published PDF uncertainty of $\delta m_W = 11$ MeV

Results ATLAS

- Central value with CT10nnlo well reproduced

Channel	$\|\eta\|$ range	CT10nnlo†
m_T fits		
$W^- \to e\nu$	0–0.6	80 416
$W^- \to e\nu$	0.6–1.2	80 298
$W^- \to e\nu$	1.8–2.4	80 424
$W^+ \to e\nu$	0–0.6	80 353
$W^+ \to e\nu$	0.6–1.2	80 382
$W^+ \to e\nu$	1.8–2.4	80 353
$W^- \to \mu\nu$	0–0.8	80 376
$W^- \to \mu\nu$	0.8–1.4	80 418
$W^- \to \mu\nu$	1.4–2.0	80 380
$W^- \to \mu\nu$	2.0–2.4	80 335
$W^+ \to \mu\nu$	0–0.8	80 372
$W^+ \to \mu\nu$	0.8–1.4	80 355
$W^+ \to \mu\nu$	1.4–2.0	80 427
$W^+ \to \mu\nu$	2.0–2.4	80 335

p_T^ℓ fits		
$W^- \to e\nu$	0–0.6	80 352
$W^- \to e\nu$	0.6–1.2	80 310
$W^- \to e\nu$	1.8–2.4	80 414
$W^+ \to e\nu$	0–0.6	80 337
$W^+ \to e\nu$	0.6–1.2	80 346
$W^+ \to e\nu$	1.8–2.4	80 345
$W^- \to \mu\nu$	0–0.8	80 428
$W^- \to \mu\nu$	0.8–1.4	80 396
$W^- \to \mu\nu$	1.4–2.0	80 381
$W^- \to \mu\nu$	2.0–2.4	80 316
$W^+ \to \mu\nu$	0–0.8	80 328
$W^+ \to \mu\nu$	0.8–1.4	80 358
$W^+ \to \mu\nu$	1.4–2.0	80 447
$W^+ \to \mu\nu$	2.0–2.4	80 335

Combined (published)	80 370
Combined (emulated)	80 369

- Uncertainty of 9 MeV also agrees well with ATLAS publication

PDF correlations (preliminary; to be redone with latest inputs...)

CT10	1.	2.	3.	4.
1. W^+ 2 TeV	1	0.99	0.26	0.51
2. W^- 2 TeV	0.99	1	0.31	0.52
3. W^+ 7 TeV	0.26	0.31	1	-0.23
4. W^- 7 TeV	0.51	0.52	-0.23	1

CTEQ6.6	1.	2.	3.	4.
1. W^+ 2 TeV	1	1	0.37	0.45
2. W^- 2 TeV	1	1	0.36	0.46
3. W^+ 7 TeV	0.37	0.36	1	-0.42
4. W^- 7 TeV	0.45	0.46	-0.42	1

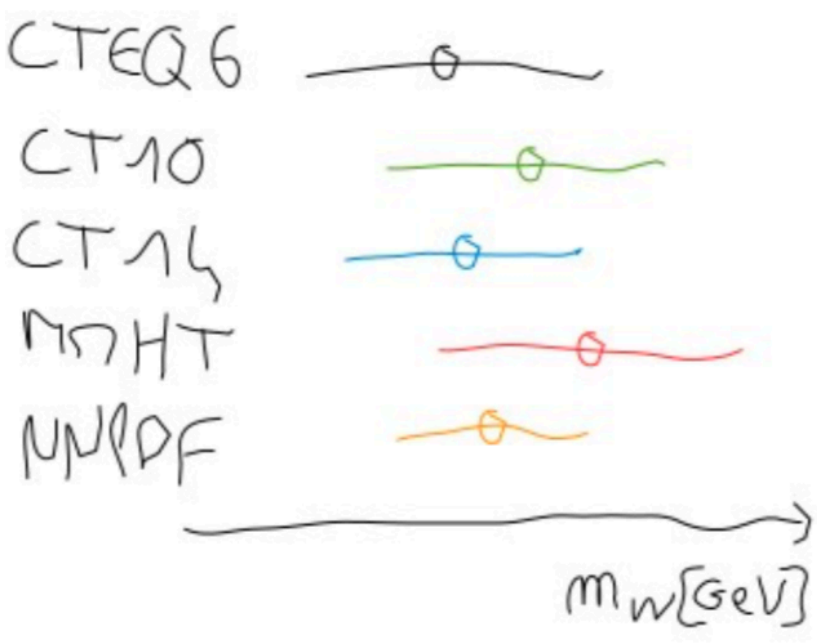
Few % stat uncertainties to be evaluated on the correlations

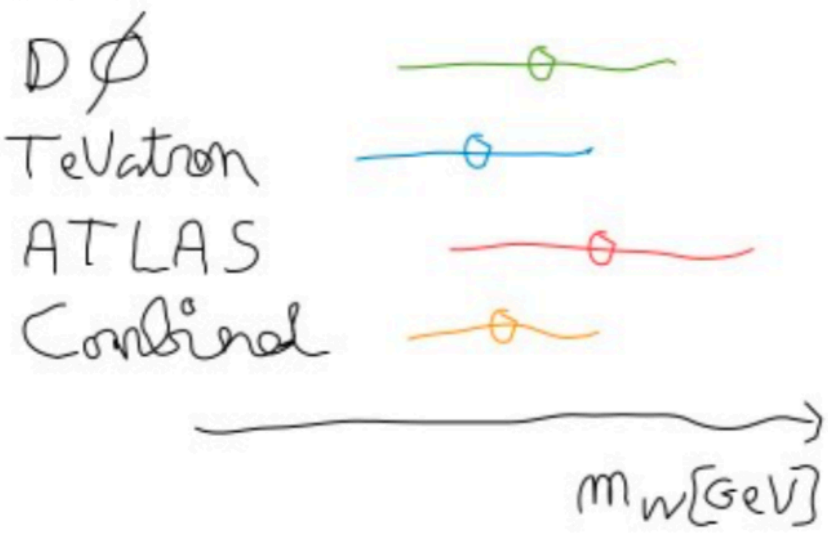
Conclusions

- Machinery in place for the combination and evaluation of PDF uncertainties
- Smearing procedure in place to estimate PDF uncertainties (important effect for mT, factor of 10 difference between Born-level and emulated reco-level)
- Different W+/- correlations between different PDF sets observed
- Published results reproduced with the emulation procedure
- Reupdate results with the improved parameterisation for D0

Strategy (under discussion)

- Use recent PDF sets for the final result
- Use only PDFs which provide explicit 68% set (MMHT, NNPDF, CT18 (soon?))
- Define an envelope uncertainty for the final quoted result

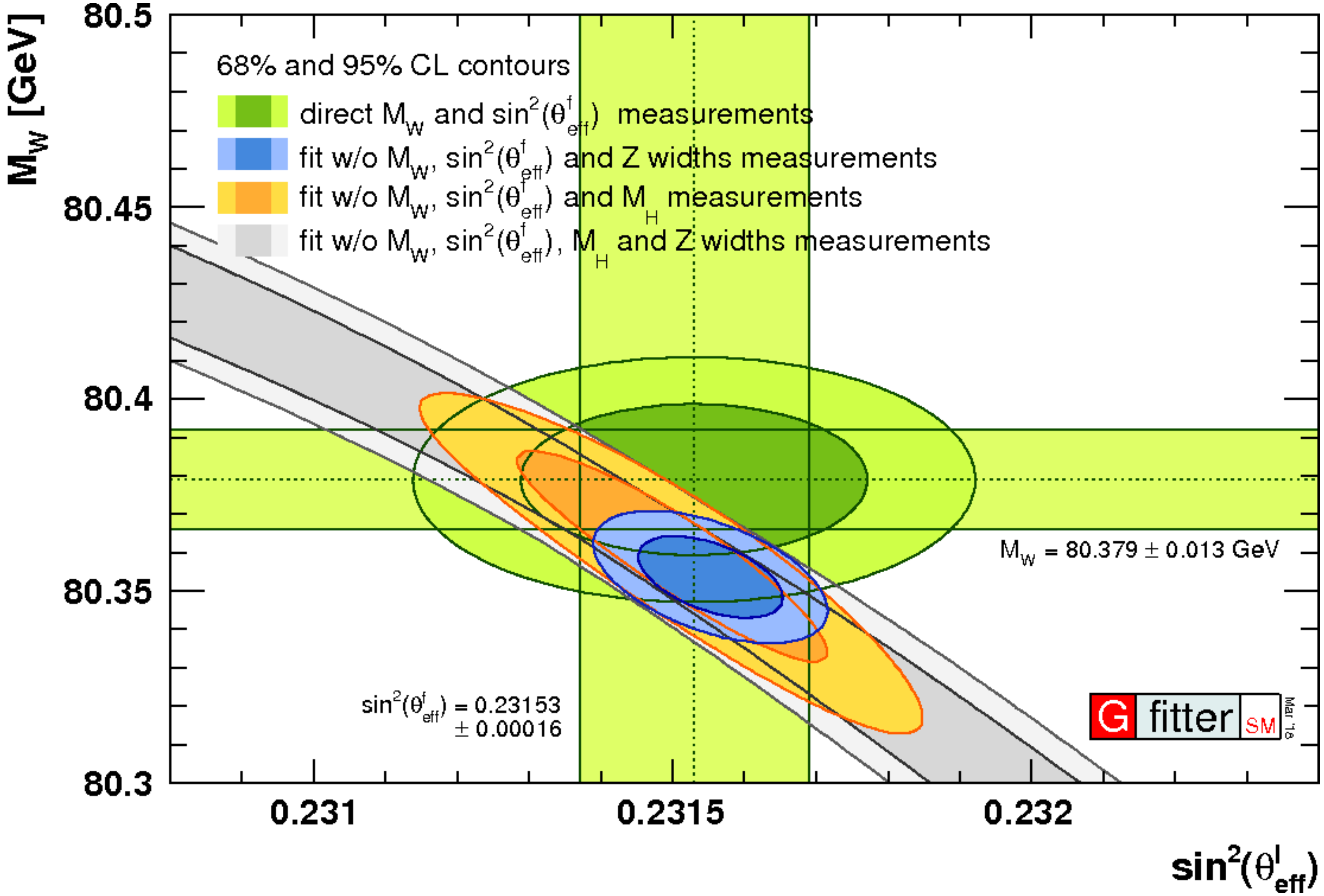




mW-sin2thetaW correlation

mW vs sin2thetaW

http://project-gfitter.web.cern.ch/project-gfitter/Figures/Standard_Model/2018_03_20_Scan2D_MWvsSinEffLep_logo_large.gif



So far no correlation between direct measurements of mW and sin2thetaW

In the future, when the LHC will dominate the measurements, such correlations need to be taken into account

Inputs

Inputs for mW:

7 TeV results 28 categories combined published

7 TeV results 28 categories combined emulated (smearing procedure applied)

13 TeV results used for the PUB note: ATL-PHYS-PUB-2018-026

PDF sets: CT10nnlo, CT14, MMHT and LHeC

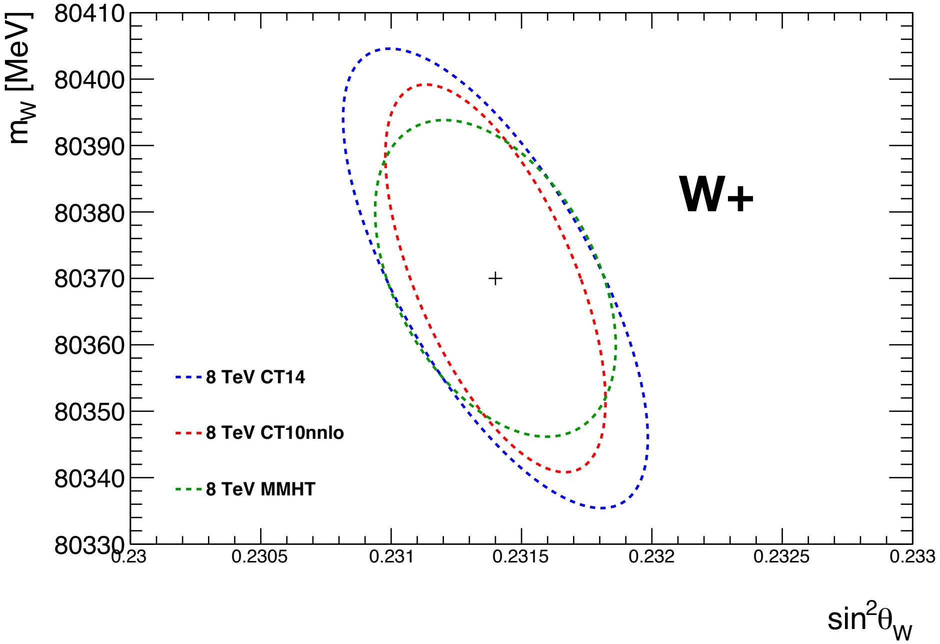
Inputs for sin2thetaW:

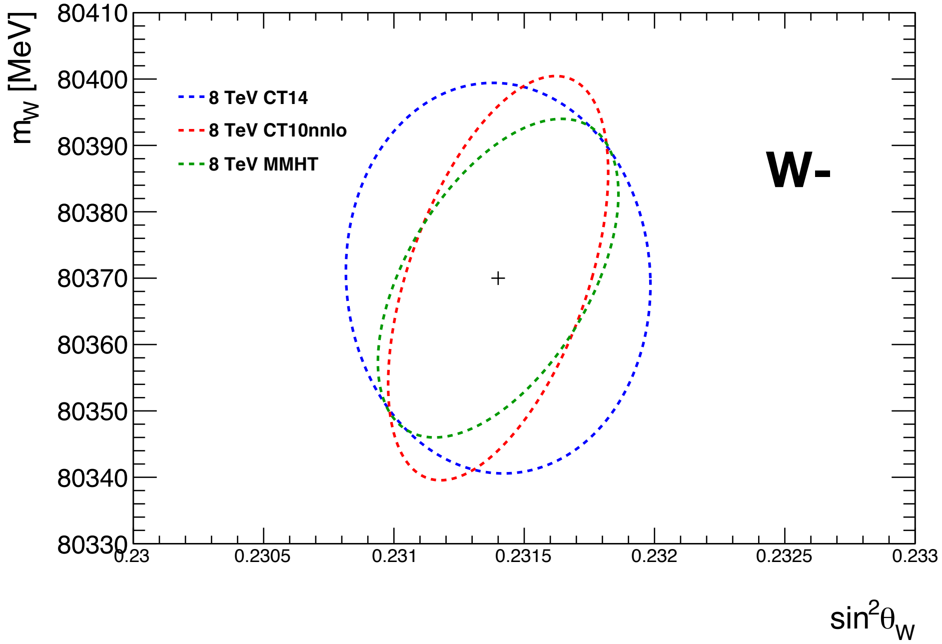
- 8 TeV (Ai conf note): CT10nnlo, CT14 and MMHT
- 13 TeV (CC-CF-FF HL-LHC prospects note ATL-PHYS-PUB-2018-037): CT14 and LHeC

7 TeV mW
8 TeV sin2theta

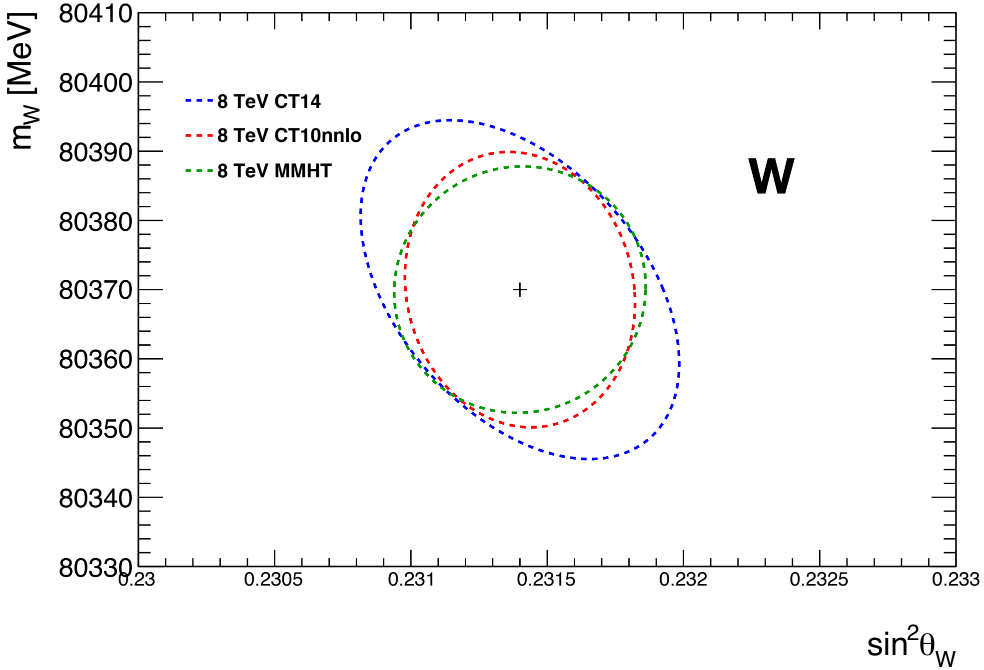
Correlation ellipses *(Preliminary)*

Eur. Phys. J. C (2018) 78:110
ATL-CONF-2018-037





Opposite correlation W+/-

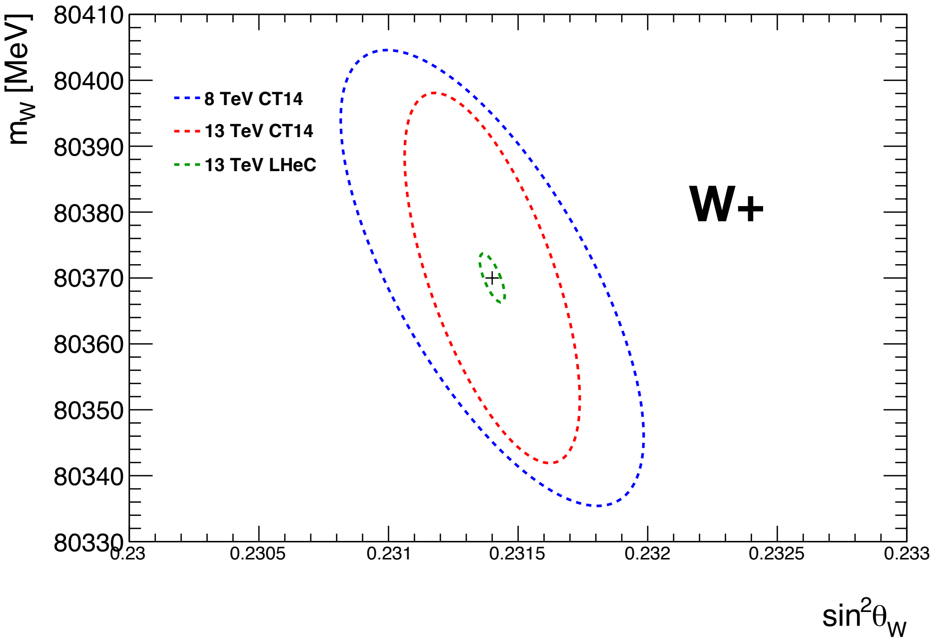


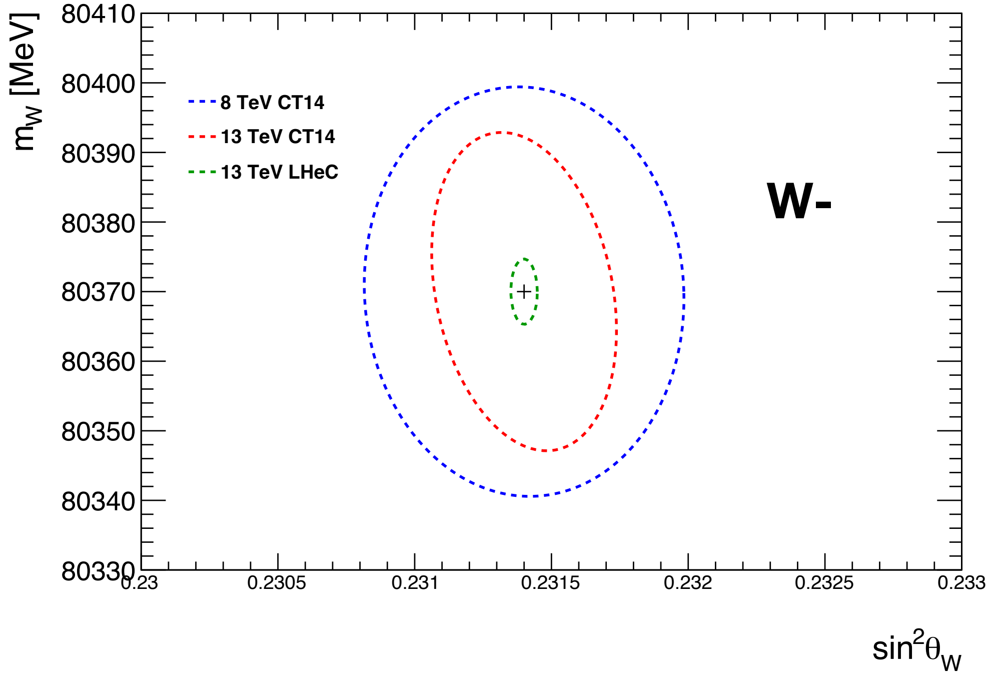
Only PDF uncertainties

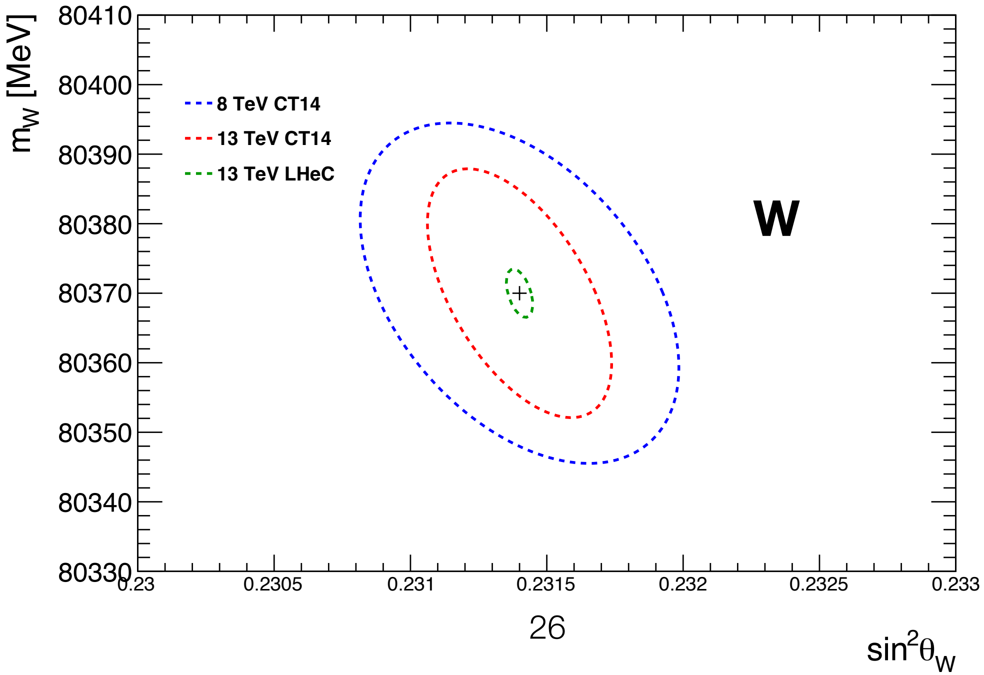
13 TeV mW
13 TeV sin2theta

Correlation ellipses
(Preliminary)

ATL-PHYS-PUB-2018-026
ATL-PHYS-PUB-2018-037





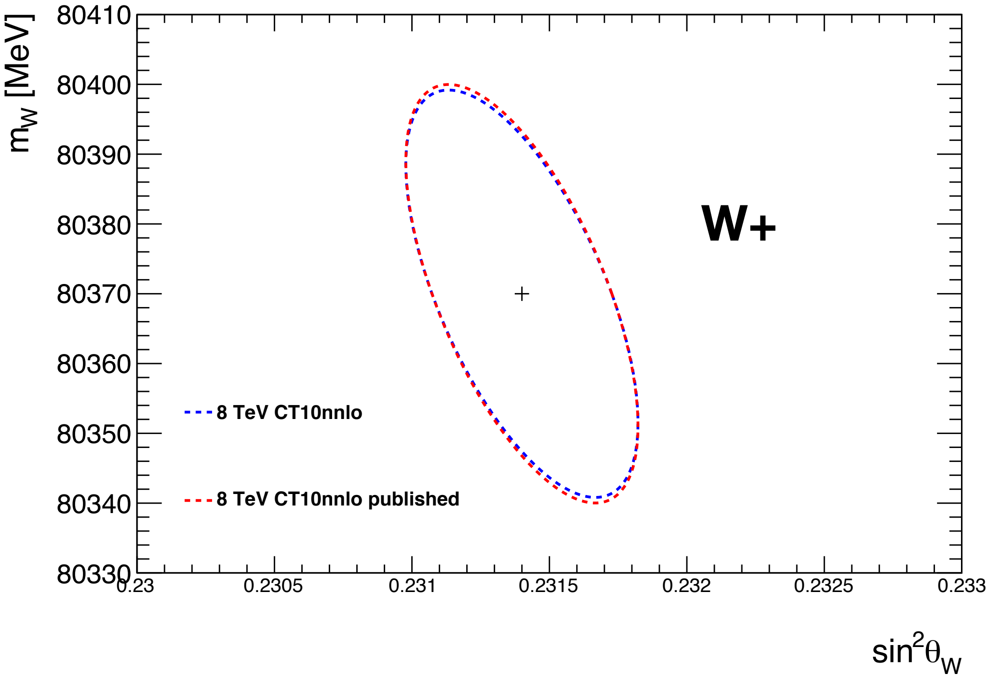


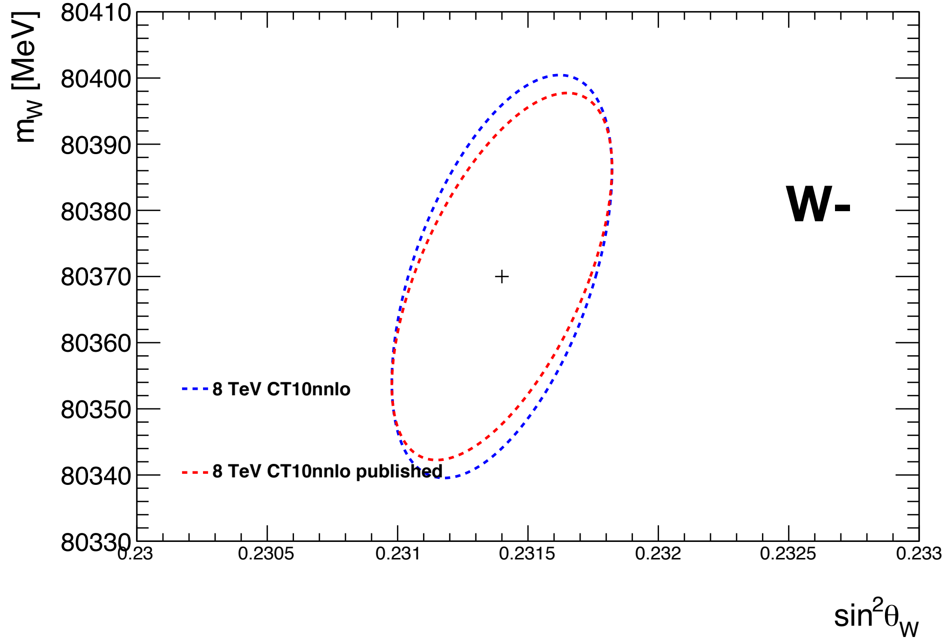
Only PDF uncertainties

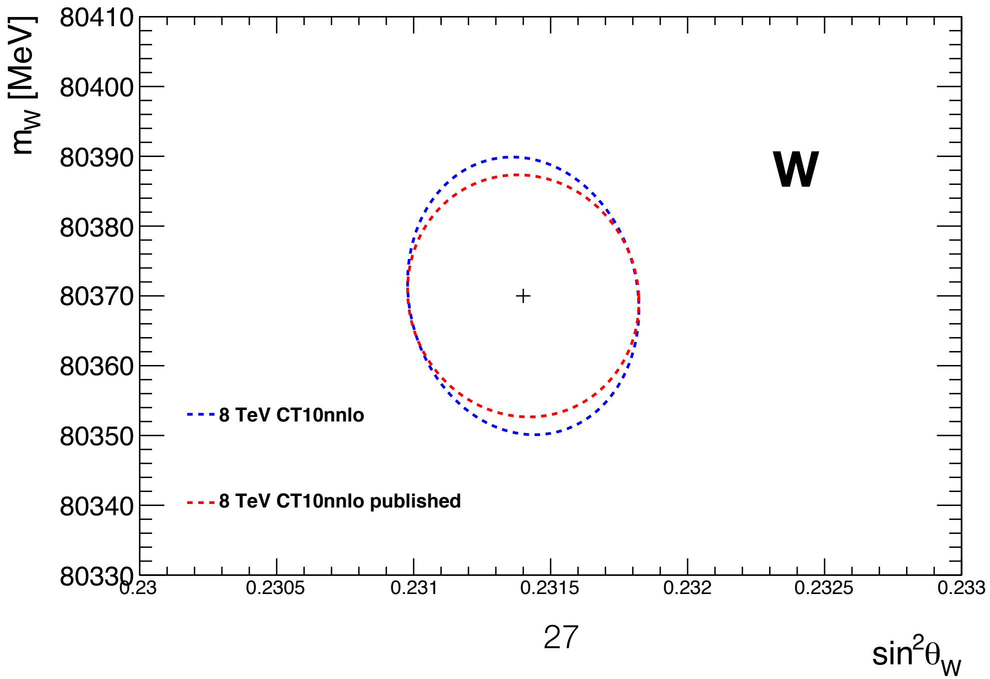
7 TeV published
7 TeV emulated

Correlation ellipses *(Preliminary)*

Eur. Phys. J. C (2018) 78:110
ATL-CONF-2018-037







Only PDF uncertainties

EW fit study with GFitter
(Preliminary)

Only PDF uncertainties correlation

	mW input	Sin2theta input	Correlation mW/sin2theta PDF	Delta mH (no corr) GeV	Delta mH (with corr) GeV	Corr effect
CT10nnlo W	80370+/-7 (stat) +/- 9 (PDF)	0.23140 +/- 0.00021 (stat) +/- 0.00024 (PDF)	-5 %	18.89	19.01	0.6 %
CT10nnlo W+	80352.7+/-9 (stat) +/- 14.6 (PDF)	0.23140 +/- 0.00021 (stat) +/- 0.00024 (PDF)	-63 %	25.24	26.8	6 %
CT10nnlo W-	80383.6+/-10 (stat) +/- 13.6 (PDF)	0.23140 +/- 0.00021 (stat) +/- 0.00024 (PDF)	+60%	20.3	16.4	-19 %
LHeC W	80370+/-0 (stat) +/- 2 (PDF)	0.23140 +/- 0.000 (stat) +/- 0.00008 (PDF)	-46 %	10.8	11.1	3 %

Preliminary Conclusions

Opposite sign observed for W+ and W- for 7/8 TeV

Implemented in GFitter with the assumption of PDF uncertainties only

Effect of PDF correlation between mW/sin2thetaW is small on mH uncertainty

Checks effects on other observables like S,T,U