Compatibility and Combination of World W boson mass measurements

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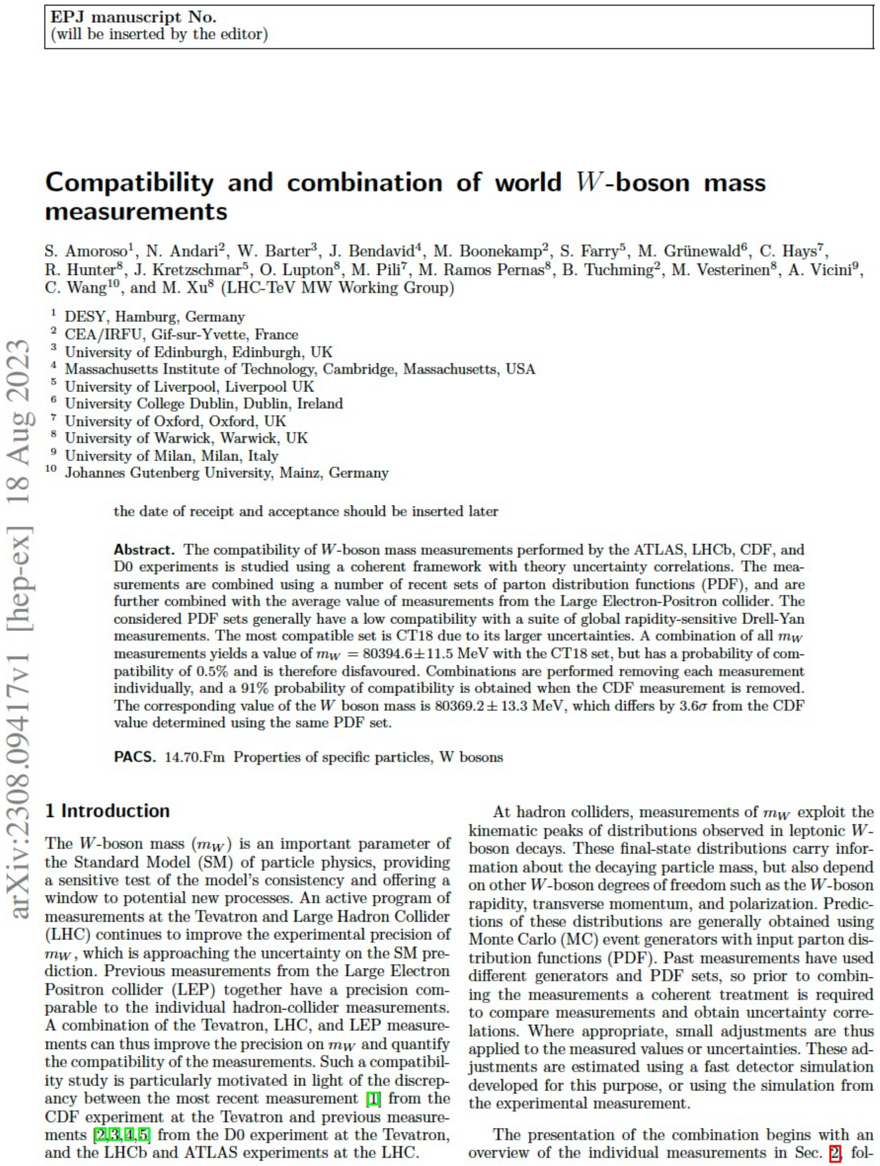
Introduction

- Will discuss the consistency and combination of W boson mass measurements.
- Based on paper submitted to arXiv [2308.09417] and to EPJC.
- Today: summary of key content of paper.



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Compatibility and combination of world W-boson mass measurements

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Abstract. The compatibility of W-boson mass measurements performed by the ATLAS, LHCb, CDF, and D0 experiments is studied using a coherent framework with theory uncertainty correlations. The measurements are combined using a number of recent sets of parton distribution functions (PDF), and are further combined with the average value of measurements from the Large Electron-Positron collider. The considered PDF sets generally have a low compatibility with a suite of global rapidity-sensitive Drell-Yan measurements. The most compatible set is CT18 due to its larger uncertainties. A combination of all m_W measurements yields a value of $m_W = 80394.6 \pm 11.5$ MeV with the CT18 set, but has a probability of compatibility of 0.5% and is therefore disfavoured. Combinations are performed removing each measurement individually, and a 91% probability of compatibility is obtained when the CDF measurement is removed. The corresponding value of the W boson mass is 80369.2 ± 13.3 MeV, which differs by 3.6σ from the CDF value determined using the same PDF set.

PACS. 14.70.Fm Properties of specific particles, W bosons

1 Introduction

The W-boson mass (m_W) is an important parameter of the Standard Model (SM) of particle physics, providing a sensitive test of the model's consistency and offering a window to potential new processes. An active program of measurements at the Tevatron and Large Hadron Collider (LHC) continues to improve the experimental precision of m_W, which is approaching the uncertainty on the SM prediction. Previous measurements from the Large Electron Positron collider (LEP) together have a precision comparable to the individual hadron-collider measurements. A combination of the Tevatron, LHC, and LEP measurements can thus improve the precision on m_W and quantify the compatibility of the measurements. Such a compatibility study is particularly motivated in light of the discrepancy between the most recent measurement [1] from the CDF experiment at the Tevatron and previous measurements [2,3,4,5] from the D0 experiment at the Tevatron, and the LHCb and ATLAS experiments at the LHC.

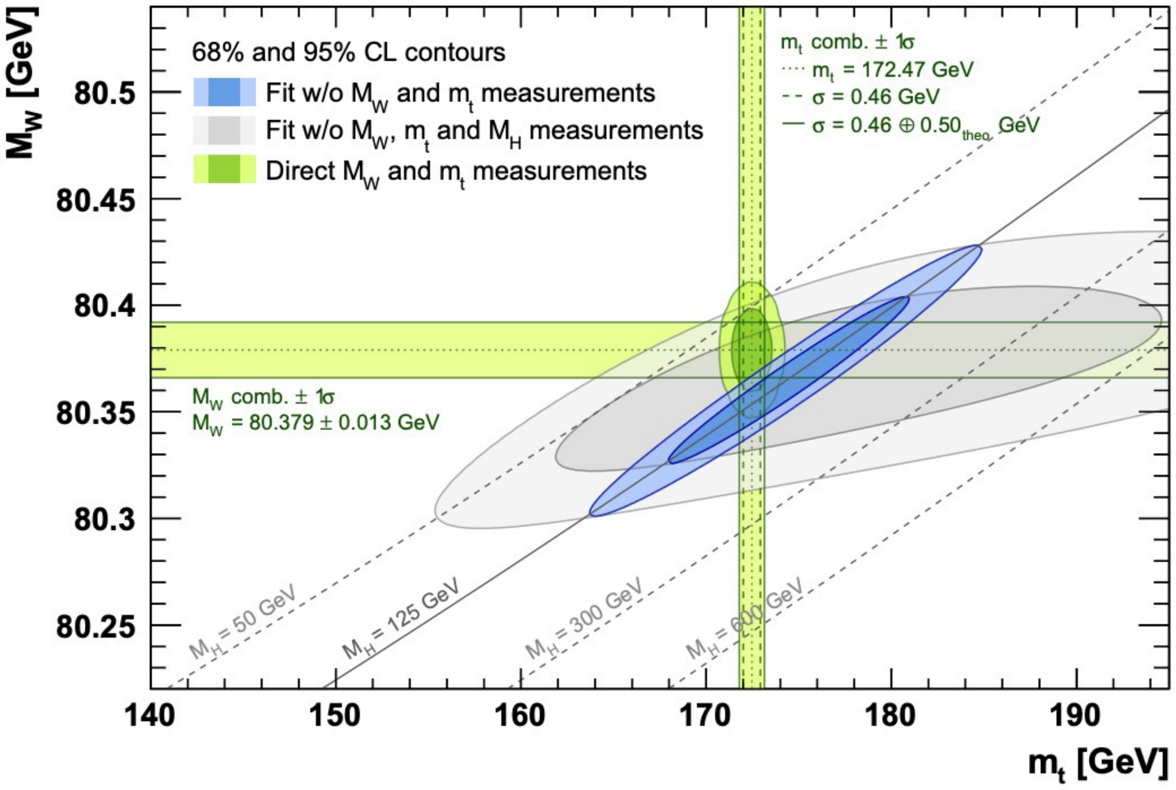
At hadron colliders, measurements of m_W exploit the kinematic peaks of distributions observed in leptonic W-boson decays. These final-state distributions carry information about the decaying particle mass, but also depend on other W-boson degrees of freedom such as the W-boson rapidity, transverse momentum, and polarization. Predictions of these distributions are generally obtained using Monte Carlo (MC) event generators with input parton distribution functions (PDF). Past measurements have used different generators and PDF sets, so prior to combining the measurements a coherent treatment is required to compare measurements and obtain uncertainty correlations. Where appropriate, small adjustments are thus applied to the measured values or uncertainties. These adjustments are estimated using a fast detector simulation developed for this purpose, or using the simulation from the experimental measurement.

The presentation of the combination begins with an overview of the individual measurements in Sec. 2, fol-

W boson mass

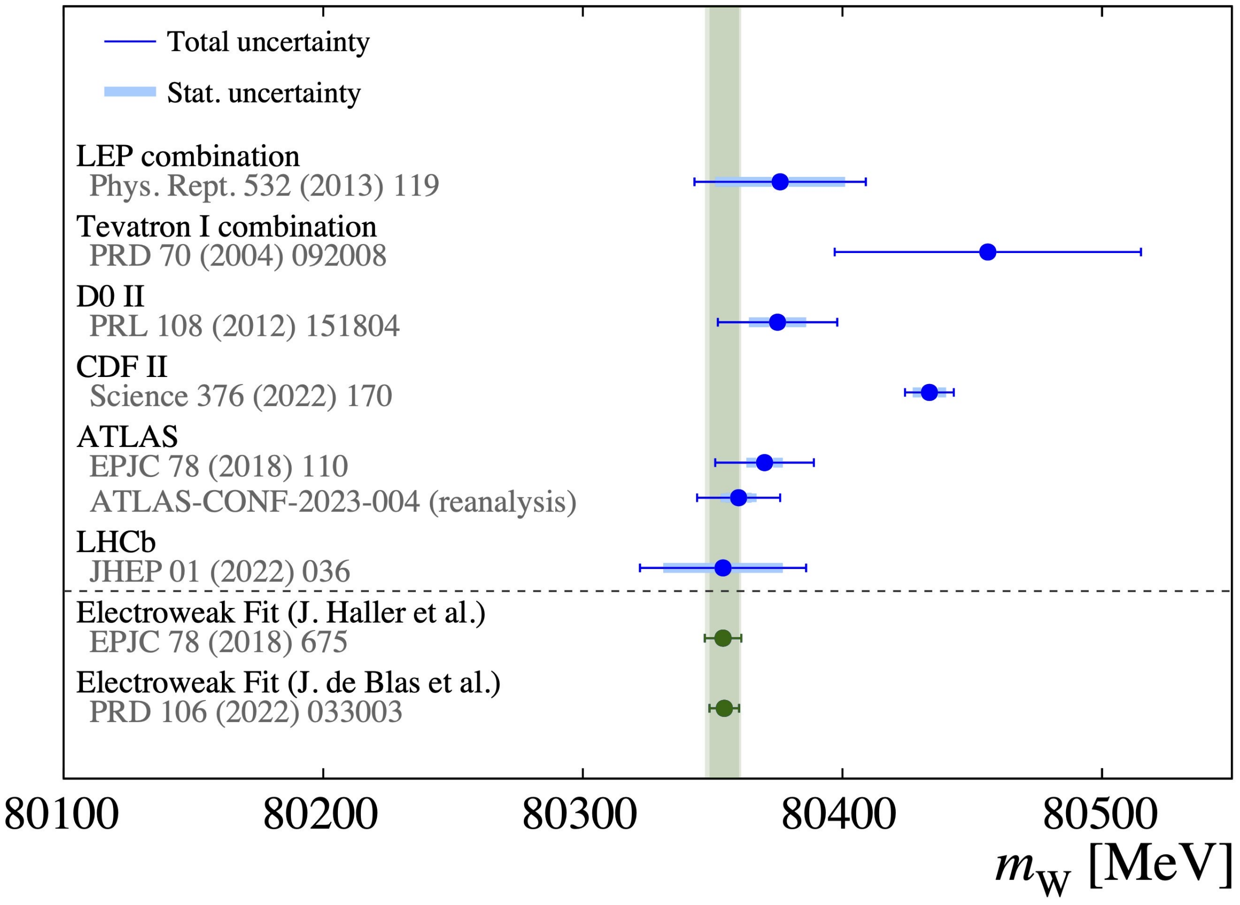
- Crucial parameter in Standard Model.
- Provides key test of Standard Model.
- Probes new physics at multi-TeV scales.

GFitter Group, EPJC 78 (2018) 675



Existing Measurements

- Challenging measurements – typically take multiple years to deliver.
- Three recent measurements:
  - LHCb (2021) – uses 2016 dataset.
  - CDF (2022) – uses Tevatron legacy dataset.
  - ATLAS (2023) – reanalysis of 2011 dataset [not used here].
- Clear tension between the existing measurements.



Input Measurements for combination

- CDF – $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV; fit variables are p_T^l, p_T^ν and m_T.
- D0 – two separate measurements using $p\bar{p}$ collisions @ $\sqrt{s}$ = 1.96 TeV; fit variables are p_T^e, m_T and p_T^ν.
- ATLAS – pp collisions @ $\sqrt{s}$ = 7 TeV; central region at LHC; fit variables are p_T^l and m_T.
  [Original analysis used following agreement to use published results]
- LHCb – pp collisions @ $\sqrt{s}$ = 13 TeV; forward region at LHC; fit variable is q/p_T^μ.

- LEP – legacy combination from LEP experiments.

Experiment	Event requirements	Fit ranges
CDF	$30 < p_T^\ell < 55$ GeV $\lvert\eta_\ell\rvert < 1$ $30 < E_T^{miss} < 55$ GeV $65 < m_T < 90$ GeV $u_T < 15$ GeV	$32 < p_T^\ell < 48$ GeV $32 < E_T^{miss} < 48$ GeV $60 < m_T < 100$ GeV
D0	$p_T^e > 25$ GeV $\lvert\eta_\ell\rvert < 1.05$ $E_T^{miss} > 25$ GeV $m_T > 50$ GeV $u_T < 15$ GeV	$32 < p_T^e < 48$ GeV $65 < m_T < 90$ GeV
ATLAS	$p_T^\ell > 30$ GeV $\lvert\eta_\ell\rvert < 2.4$ $E_T^{miss} > 30$ GeV $m_T > 60$ GeV $u_T < 30$ GeV	$32 < p_T^\ell < 45$ GeV $66 < m_T < 99$ GeV
LHCb	$p_T^\mu > 24$ GeV $2.2 < \eta_\mu < 4.4$	$28 < p_T^\mu < 52$ GeV

QCD Challenges

- Measurements made over a number of years
- QCD understanding has significantly improved over this time (modelling of PDFs, Matrix Element, Soft Radiation).
- Newer measurements typically use an improved QCD model than older measurements.

- Seek to ‘update’ measurements to a common QCD framework before compatibility assessed and combination.

$$m_W^{update} = m_W^{ref} + \delta m_W^{PDF} + \delta m_W^{pol} + \delta m_W^{other}$$

Update to common PDF

Additional (small) updates

Published value

Common W boson polarization update

QCD Challenges

- Starting point of fits to data therefore crucial.
  - D0: RESBOS CP (N2LO, N2LL) with CTEQ66 PDFs (NLO)
  - CDF: RESBOS C (NLO, N2LL) with CTEQ6M PDFs (NLO)
  - ATLAS: POWHEG + Pythia8 (NLO+PS) with DYTurbo for Angular Distribution (N2LO) with CT10 PDFs (NNLO)
  - LHCb: POWHEG + Pythia8 (NLO+PS) with DYTurbo for Angular Distribution (N2LO) with averaged result from MSHT20, NNPDF31 and CT18 PDFs (NLO)

[CDF publication applied a correction to reproduce Resbos2 + NNPDF3.1]

- Approach taken:
  - LHCb measurement "repeated" using same code framework but with PDF updates.
  - Effect of updates on other measurements using simulated samples from two models.

Fitting Pseudodata

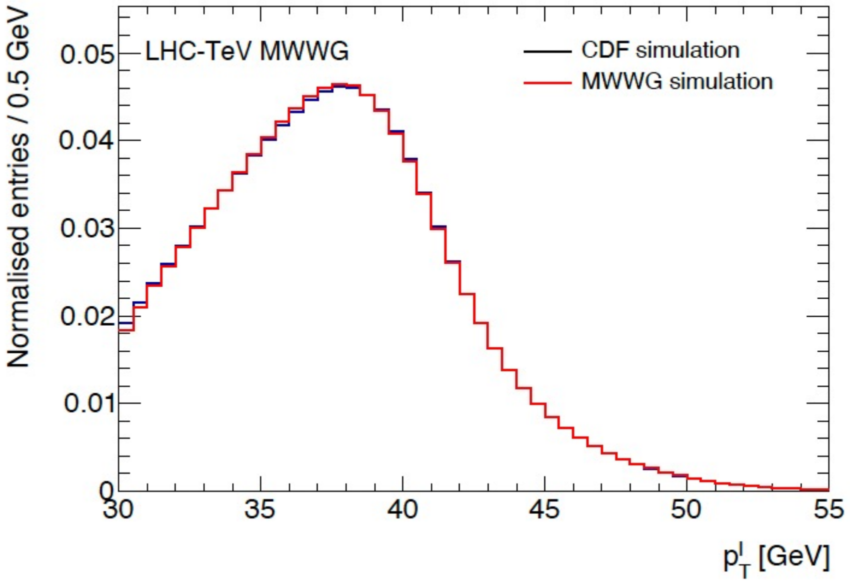
- Impact on mW studied by fitting reference and updated distributions using the same model.
- W boson mass varied by using weights drawn from a Breit-Wigner distribution.

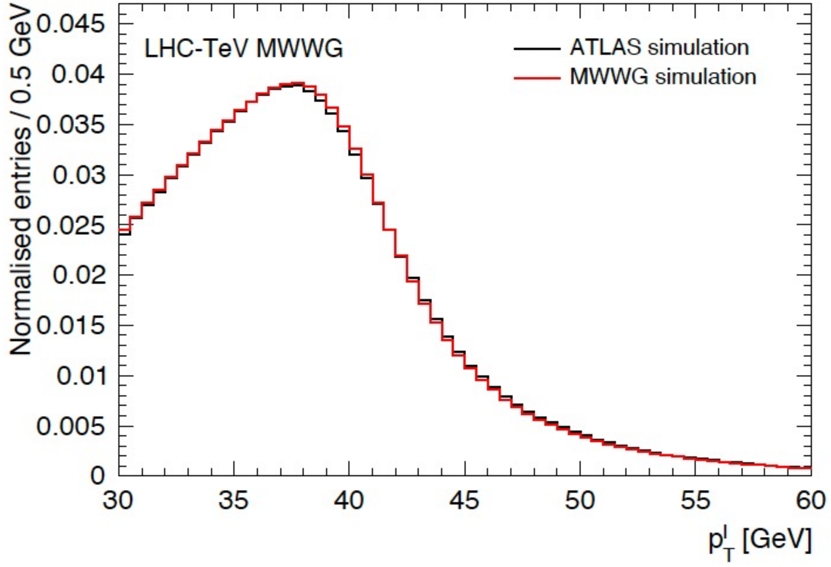
$$w(m, m_W, m_W^{\rm ref}) = \frac{(m^2 - m_W^2)^2 + m^4\Gamma_W^2/m_W^2}{(m^2 - m_W^{\rm ref 2})^2 + m^4\Gamma_W^2/m_W^{\rm ref 2}}$$

- Model (for PDF effects): POWHEG MiNNLOPS generator (NNLO).
- Models (for W boson polarisation effects): RESBOS-C (NLO+approximate NNLL); RESBOS-CP (NNLO+NNLL); RESBOS 2 (NLO+NNLL).

Detector Emulation

- ATLAS, CDF and D0 detectors emulated.
  - η- and p_T-dependent smearing of leptons.
  - Recoil modelling includes lepton removal and and event activity effects.
  - Agreement typically at the percent level between full simulation and LHC-TeV MWWG emulation.
  - Small imperfections in emulation lead to MeV-level uncertainties on δm_W.





PDF effects

Using the POWHEG MiNNLO generator to study impact of changes in the relevant distribution.

Analysis code rerun ↓

δm_W^{PDF}

PDF set	D0 p_T^ℓ	D0 E_T^{miss}	CDF p_T^ℓ	CDF E_T^{miss}	ATLAS W^+	ATLAS W^-	LHCb
CTEQ6	-17.0	-17.7	0.0	0.0	–	–	–
CTEQ6.6	0.0	0.0	15.0	17.0	–	–	–
CT10	0.4	-1.3	16.0	16.3	0.0	0.0	–
CT14	-9.7	-10.6	5.8	6.8	-1.2	-5.8	-1.1
CT18	-8.2	-9.3	7.2	7.7	12.1	-2.3	6.0
ABMP16	-19.6	-21.5	-1.4	-2.4	-22.5	-3.1	7.6
MMHT2014	-10.4	-12.7	6.1	5.5	-2.6	9.9	11.8
MSHT20	-13.7	-15.4	3.6	4.1	-20.9	4.5	2.0
NNPDF3.1	-1.0	-1.2	14.0	15.1	-14.1	1.8	-6.0
NNPDF4.0	6.7	8.1	20.8	24.1	-22.4	6.9	-8.3

$\sigma(m_W^{PDF})$

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ66	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1

Note Tevatron combination did not consider $\delta m_W^{PDF}(\text{CTEQ6, CTEQ6.6}) \sim 17$ MeV.

Uncertainties larger here than in some original publications, e.g. NNPDF3.1 ~6.6 MeV (CDF) here v 3.9 MeV in original publication (which used principal component analysis).

S. Carraza *et al.*, EPJC 75 (2015) 369

PDF effects

- Compatibility of PDF sets with Drell-Yan data studied.
  - No PDF set provides a good description of the full Tevatron+LHC dataset.
  - Best description given by CT18 (which has larger uncertainties).
  - CT18 therefore taken as the default PDF set.

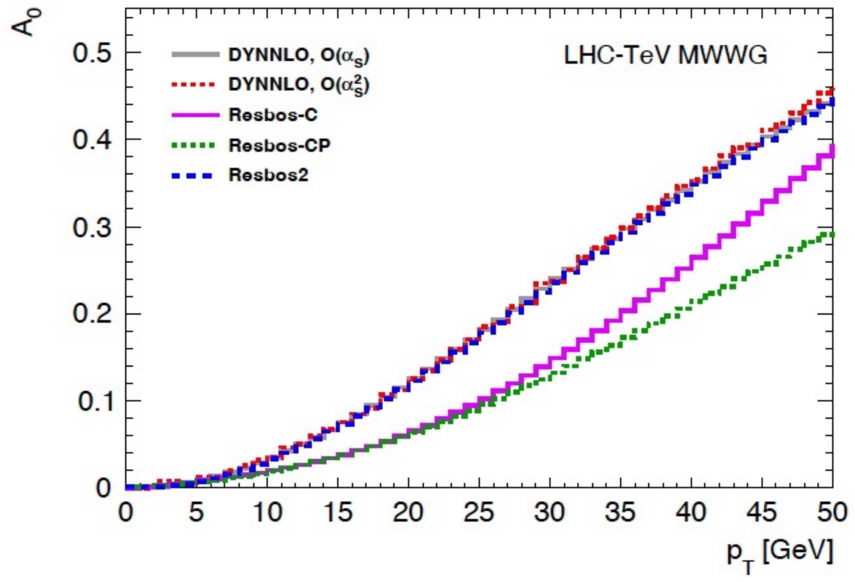
Measurement	NNPDF3.1	NNPDF4.0	MMHT14	MSHT20	CT14	CT18	ABMP16
CDF y_Z	24 / 28	28 / 28	30 / 28	32 / 28	29 / 28	27 / 28	31 / 28
CDF A_W	11 / 13	14 / 13	12 / 13	28 / 13	12 / 13	11 / 13	21 / 13
D0 y_Z	22 / 28	23 / 28	23 / 28	24 / 28	22 / 28	22 / 28	22 / 28
D0 $W \to e\nu$ A_ℓ	22 / 13	23 / 13	52 / 13	42 / 13	21 / 13	19 / 13	26 / 13
D0 $W \to \mu\nu$ A_ℓ	12 / 10	12 / 10	11 / 10	11 / 10	11 / 10	12 / 10	11 / 10
ATLAS peak CC y_Z	13 / 12	13 / 12	58 / 12	17 / 12	12 / 12	11 / 12	18 / 12
ATLAS W^- y_ℓ	12 / 11	12 / 11	33 / 11	16 / 11	13 / 11	10 / 11	14 / 11
ATLAS W^+ y_ℓ	9 / 11	9 / 11	15 / 11	12 / 11	9 / 11	9 / 11	10 / 11
Correlated χ^2	75	62	210	88	81	41	83
Total χ^2 / d.o.f.	200 / 126	196 / 126	444 / 126	270 / 126	210 / 126	162 / 126	236 / 126
$p(\chi^2, n)$	0.003%	0.007%	$< 10^{-10}$	$< 10^{-10}$	0.0004%	1.5%	10^{-8}

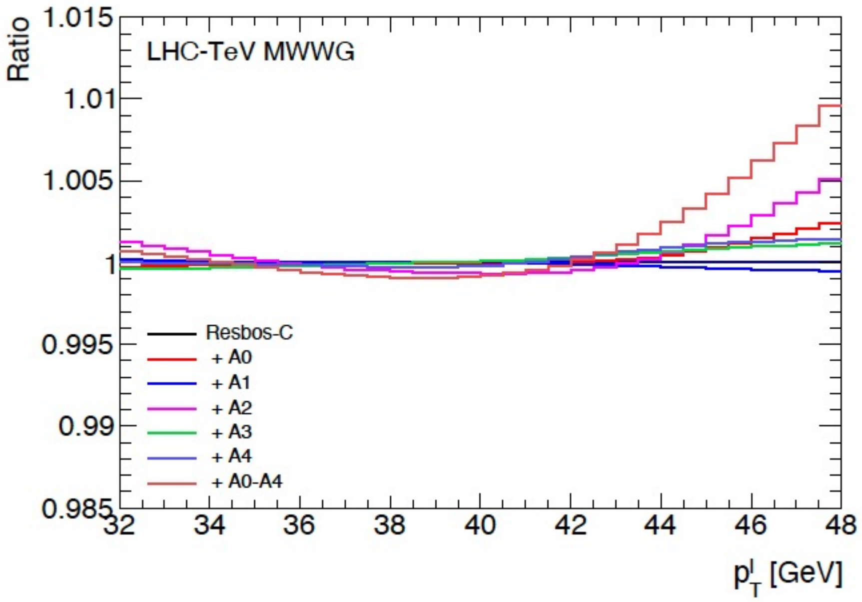
Note: CT coverage always rescaled to 68% level.

W boson polarisation

$$\frac{d\sigma}{dp_T^W\,dy\,dm\,d\Omega} = \frac{d\sigma}{dp_T^W\,dy\,dm}[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi]$$

- ATLAS and LHCb use DYTurbo treatment of polarisation – no update made.
- Fits to data using RESBOS-C (CDF) and RESBOS-CP (D0) ported so that $A_0 - A_4$ coefficients match O(α_s) predictions using RESBOS2.





W boson polarisation

$$\frac{d\sigma}{dp_T^W\, dy dm d\Omega} = \frac{d\sigma}{dp_T^W\, dy dm}[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi]$$

- ATLAS and LHCb use DYTurbo treatment of polarisation – no update made.
- Fits to data using RESBOS-C (CDF) and RESBOS-CP (D0) ported so that $A_0 - A_4$ coefficients match O(α_s) predictions using RESBOS2.

CDF δm_W^{pol}

Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-6.3	-2.6	-9.1
A_1	1.1	1.3	0.3
A_2	-0.7	0.4	-3.2
A_3	-2.1	-4.2	1.0
A_4	-1.4	-3.3	-1.6
$A_0 - A_4$	-9.5	-8.4	-12.5
ResBos2	-10.2±1.1	-7.6±1.2	-11.8±1.4
Difference	-0.7±1.1	0.8±1.2	0.7±1.4

D0 δm_W^{pol}

Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-9.8	-7.3	-15.6
A_1	1.9	2.4	1.8
A_2	3.0	3.3	-2.7
A_3	-1.6	-2.9	0.4
A_4	0.2	-2.3	0.5
$A_0 - A_4$	-6.4	-6.9	-15.8
ResBos2	-7.8±1.0	-6.6±1.1	-16.5±1.2
Difference	-1.4±1.0	0.3±1.1	-0.7±1.2

pT(W) modelling

- Keep each experiment's approach to pT(W) modelling – unified approach beyond scope of this study.
- Treat pT(W) uncertainties as uncorrelated between experiments since the different experiments use different generators to evaluate these uncertainties.

Experiment	Uncertainty
CDF	2.2 MeV
D0	2.4 MeV
ATLAS	6 MeV
LHCb	11 MeV

Other ‘updates’ and modelling effects

- Treatment of W boson width
  - Experiments use slightly different values for W boson width in fits.
  - Default value of 2089.5 MeV used.

- W boson resonance
  - Update to RESBOS 2 invariant mass modelling causes a 2 MeV shift in W boson mass for CDF.

- Higher-order electroweak effects
  - ATLAS and D0 use same shower models to study these effects, so uncertainties considered fully correlated in combination. CDF and LHCb are considered uncorrelated.

Combination

- Results combined using BLUE.

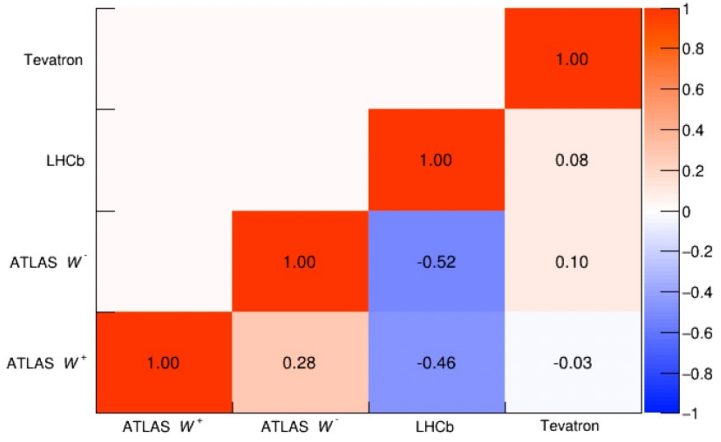
- Approach validated by reproducing internal experimental combinations.

- CDF measurement itself contains $\sim$3MeV δm_w effect (CTEQ6M → NNPDF31; mass modelling; polarisation) – this is removed as a first step before combination performed.

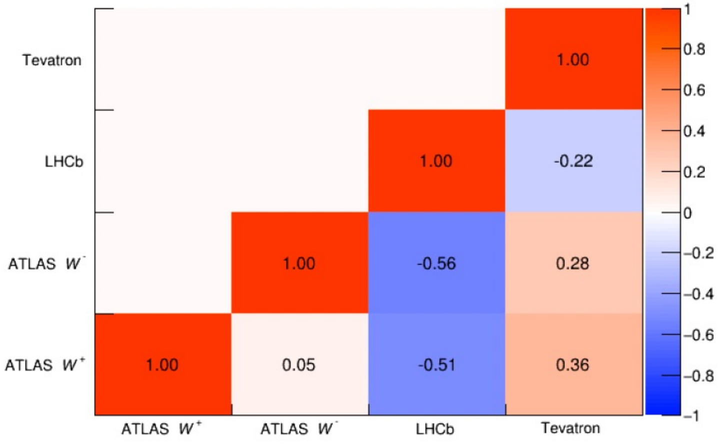
Combination: PDF Correlations

- PDF correlations determined in order to provide combination.
- Significantly different correlations reported by different PDF sets.
- Presence of anti-correlation provides stable results with reduced PDF dependence.

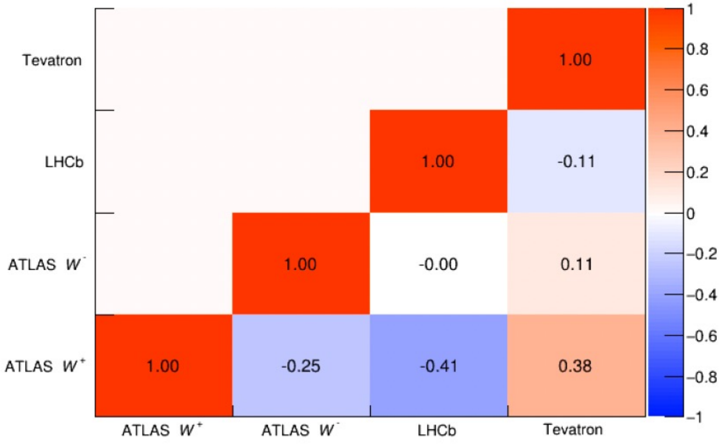
CT18



MSHT 20

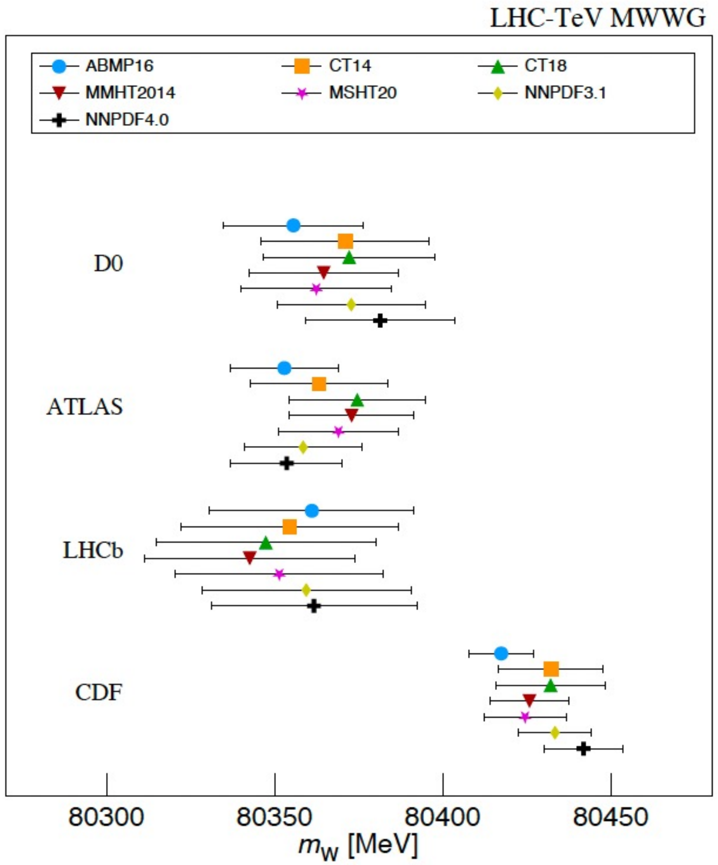


NNPF40



Combination

Input measurements with updates applied

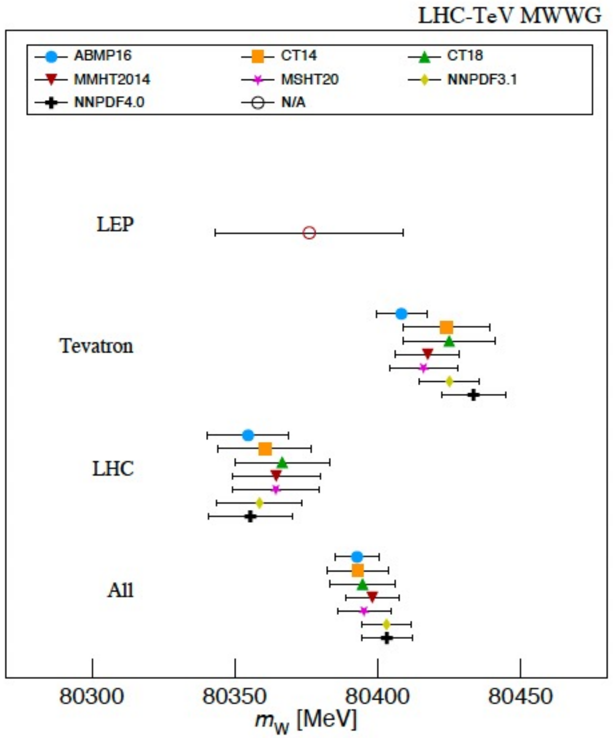


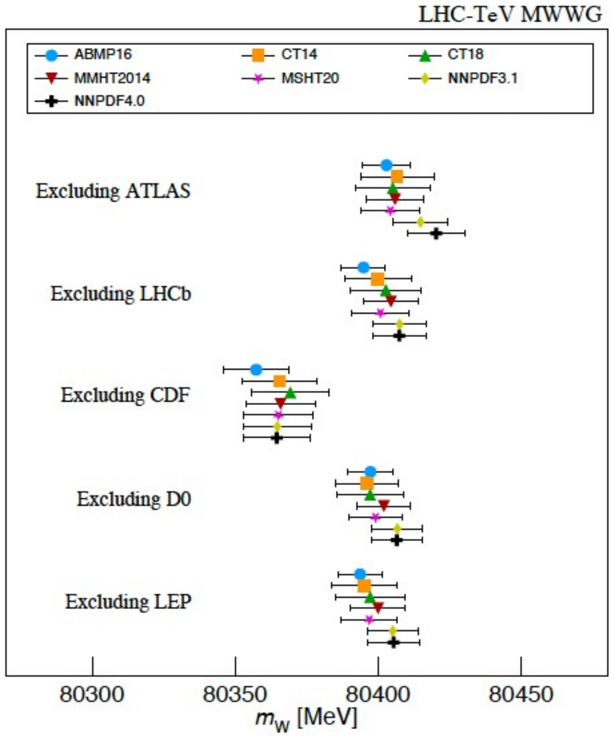
Combinations for different PDF sets

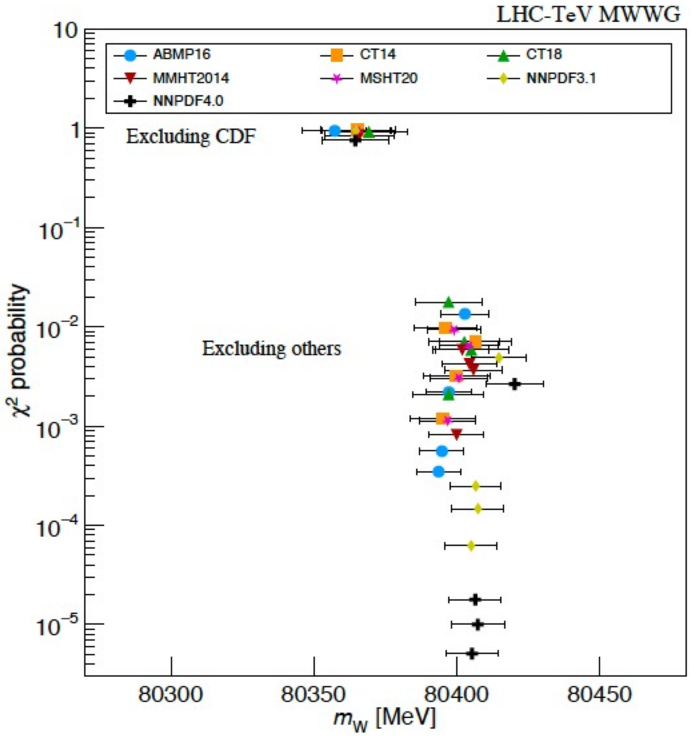
	All experiments			
PDF set	m_W	σ_{PDF}	χ^2	$p(\chi^2)$
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%
CT14	80393.0 ± 10.9	7.1	16	0.3%
CT18	80394.6 ± 11.5	7.7	15	0.5%
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%
MSHT20	80395.1 ± 9.3	5.8	16	0.3%
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%

Note: no combination of all measurements provides a good χ^2 probability, so the full combination is disfavoured.

Sub-combinations







PDF spread reduced compared to input measurements to roughly 5 MeV (without ABMP), 10 MeV (with ABMP)

Sub-combinations

- Combinations with CDF excluded have good compatibility.
  - **mW = 80369.2$\pm$13.3 MeV** (CT18)

    CDF, Science 376 (2022) 170

    [CDF measurement value (mW = 80433.5$\pm$9.4 MeV)].
  - Combination without CDF has a χ^2 probability of 91%.
  - Relative weights: 42% (ATLAS); 23% (D0); 18% (LHCb); 16% (LEP).

- Difference between “All-CDF” combination and the updated CDF value here is 3.6σ when the CT18 PDF set is used.

Conclusions

- W boson mass is a crucial parameter in the Standard Model.
- Extensive effort to provide common treatment of PDF and W boson polarization modelling for W boson mass measurements at hadron colliders.
- Updated treatments unable to solve tension between existing measurements.
- Full combination (**mW = 80394.6$\pm$11.5 MeV** [CT18]) but is disfavoured due to poor χ^2 probability (0.5%).
- Combination without CDF (**mW = 80369.2$\pm$13.3 MeV** [CT18]) has good χ^2 probability.
- Paper available on arXiv:2308.09417
- Further measurements essential.

References – PDFs

CTEQ6	JHEP 07 (2002) 012
CTEQ6.6	PRD 78 (2008) 013004
CT10	PRD 82 (2010) 074024
CT14	PRD 93 (2016) 033006
CT18	PRD 103 (2021) 014013
ABMP16	PRD 96 (2017) 014011
MMHT2014	EPJC 75 (1015) 204
MSHT20	EPJC 81 (2021) 341
NNPDF31	EPJC 77 (2017) 663
NNPDF40	EPJC 82 (2022) 428