News on the W boson mass from the ATLAS experiment

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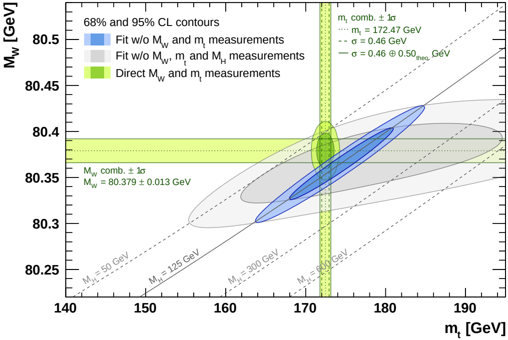
W boson mass

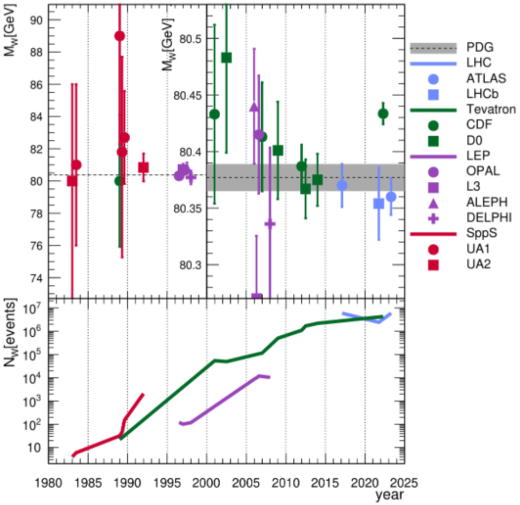
- *W* boson mass is a crucial parameter of the SM

$$m_W = \left(\frac{\pi\alpha_{\mathrm{EM}}}{\sqrt{2}G_{\mathrm{F}}}\right)^{1/2} \frac{\sqrt{1+\Delta r}}{\sin\theta_{\mathrm{W}}}$$

  - radiative corrections Δr introduce dependence on m_t, m_H
  - check self-consistency of SM in electroweak fit → or find new physics
  - global EW fits predict $m_W = 80354 \pm 7$ MeV



W boson mass experimentally



2017 ATLAS measurement: STDM-2014-18

2023 ATLAS measurement: ATLAS-CONF-2023-004

- 1983 CERN SPS – W discovery
- 1983 – UA1

  $m_W = 81 \pm 5$ GeV
- 1992 – UA2 (with m_Z from LEP)

  $m_W = 80.35 \pm 0.37$ GeV
- 2013 – LEP combined

  $m_W = 80.376 \pm 0.033$ GeV
- 2013 – Tevatron combined

  $m_W = 80.387 \pm 0.016$ GeV
- 2017 – ATLAS

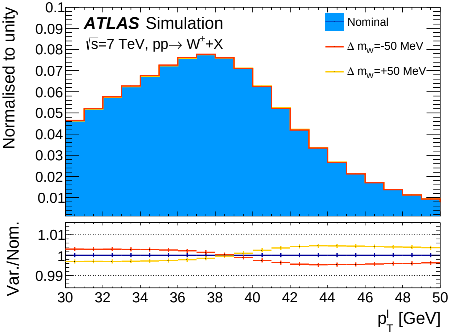
  $m_W = 80.370 \pm 0.019$ GeV
- 2021 – LHCb

  $m_W = 80.354 \pm 0.032$ GeV
- 2022 – CDF

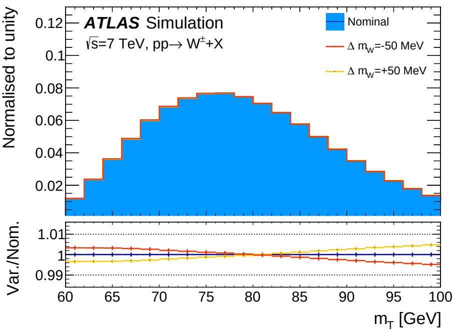
  $m_W = 80.434 \pm 0.009$ GeV
- 2023 – ATLAS

  $m_W = 80.360 \pm 0.016$ GeV

General measurement procedure



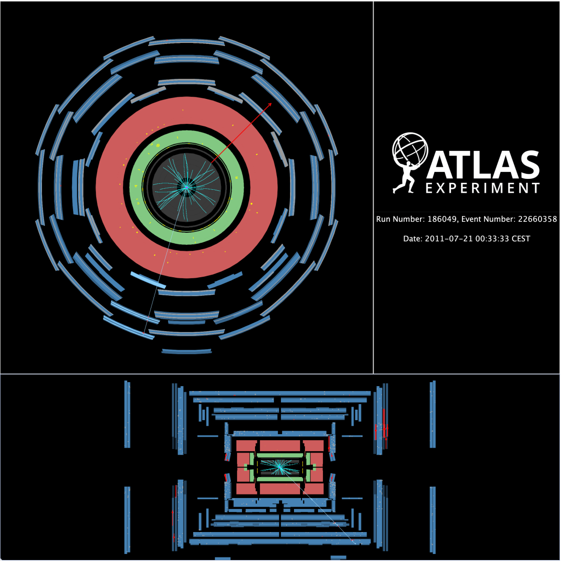
Lepton p_T: Jacobian edge at $m_W/2$



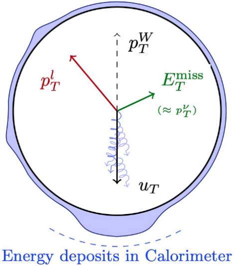
Transverse mass: Jacobian edge at m_W

- Use leptonic W boson decays: $W^{\pm} \to \ell^{\pm}\nu$ $(\ell = e,\ \mu)$
- Vary m_W in signal prediction to generate template distributions of p_T^{ℓ} and m_T
- Find m_W value that optimises agreement of generated templates with data

Event selection



- Lepton selections
  - muons: $|\eta| < 2.4$, isolated
  - electrons: $|\eta| < 1.2$ or $1.8 < |\eta| < 2.4$, isolated
- Kinematic requirements
  - use hadronic recoil to reconstruct neutrino kinematics
  - $p_{\mathrm{T}}^{\ell} > 30$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
  - $m_{\mathrm{T}} > 60$ GeV, $u_{\mathrm{T}} < 30$ GeV



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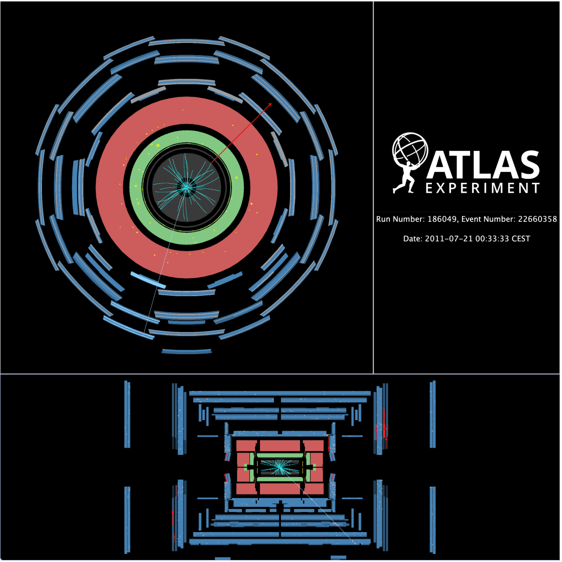

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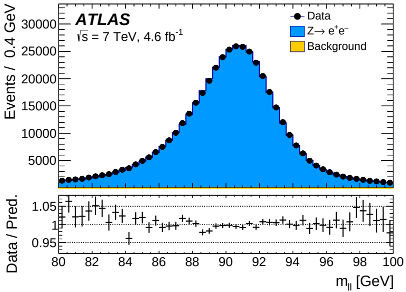
  - $m_T > 60$ GeV, $u_T < 30$ GeV
- Muon channel: 7.8M events
- Electron channel: 5.9M events

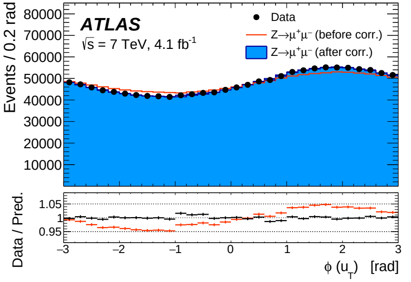
- Measurement categories
  - electron/muon
  - 3/4 rapidity regions
  - lepton charge

Reanalysis strategy

- Reproduce and validate results from original analysis
  - reproduce cutflows, distributions, background estimates, ...
  - re-test calibrations with Z boson events
  - re-evaluate systematic uncertainties
  - reproduce χ^2 fit results
- Improvements to systematic uncertainties
  - multi-jet background estimation
  - higher-order electroweak corrections
  - consider Γ_W uncertainty
- Further improvements to analysis
  - recover 1.5% data in electron channel
  - improve electron energy calibration setup
- Validate updates in χ^2 fit
- Implement profiled likelihood (PLH) fit for m_W
- Study m_W dependence on PDF sets

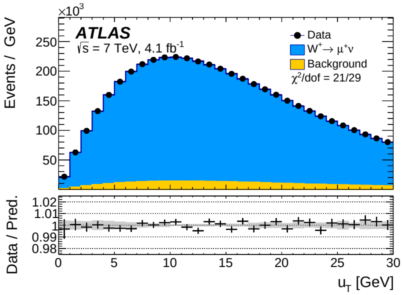
Detector calibrations

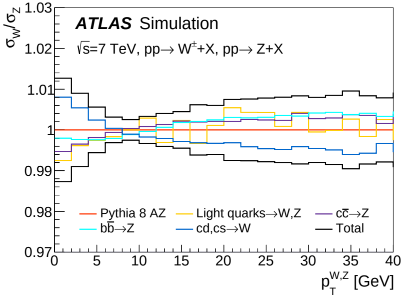




- Detector calibrations unchanged from original analysis
- Electron energy and muon momentum calibrated using $Z \to \ell\ell$ events
- Lepton efficiencies determined using tag-and-probe method
- Hadronic recoil calibrated using $Z \to \ell\ell$ events and transfer to $W \to \ell\nu$ events

Physics modelling





- Baseline model for p_T^W
    - Pythia8 with AZ tune (fit to ATLAS 7 TeV p_T^Z measurement)
    - p_T^Z data described within 2%
    - transfer from p_T^Z to p_T^W and evaluation of p_T^W/p_T^Z uncertainties using Pythia8
- New verifications
    - AZ tune describes p_T^W distribution in 5 TeV data within exp. uncertainties
    - resummed calculation from DYTurbo also in agreement with AZ tune
- Treatment of angular coefficients (A_i) unchanged → NNLO prediction + uncertainties from Z boson measurements
- Study several NNLO PDF sets: CT10, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0

PLH fit setup

- Comparison to χ^2 fit
  - advantage: reduce systematic uncertainties via profiling of nuisance parameters (NP)
  - disadvantage: computationally intensive, not straightforward to investigate systematic uncertainties
- Statistical framework: TRExFitter
  - use 12 templates around $m_W = 80399$ MeV
  - linear vertical interpolation between templates $\rightarrow$ tested to 0.1 MeV
- Technical details
  - 1000s of NP reduced to ~ 200 via pruning $\rightarrow < 1\%$ change in final result
  - Principal Component Analysis applied to toy-based uncertainties $\rightarrow$ further reduction in number of NP
- Normalisation scheme
  - normalisation of templates left free in the fit
  - global normalisation factor applied to all signal samples
  - model-independent approach $\rightarrow$ neglect dependence on W boson cross-section

PLH fit: normalisation scheme

Expected number of events

POI

$$\nu_{\text{cb}} = \Phi \times \left[S^{\text{nom}}_{\text{cb}} + \alpha_{m_W} \times \left(S^{\text{BW}}_{\text{cb}} - S^{\text{nom}}_{\text{cb}}\right)\right] + \sum_{p} \alpha_p \times \left(S^{p}_{\text{cb}} - S^{\text{nom}}_{\text{cb}}\right)$$

Free floating normalisation factor acting on signal samples

All templates normalised to event yields of template with nominal mass and width hypotheses

$$+B^{\text{nom}}_{\text{cb}} + \sum_{p'} \alpha_{p'} \times \left(B^{p'}_{\text{cb}} - B^{\text{nom}}_{\text{cb}}\right)$$

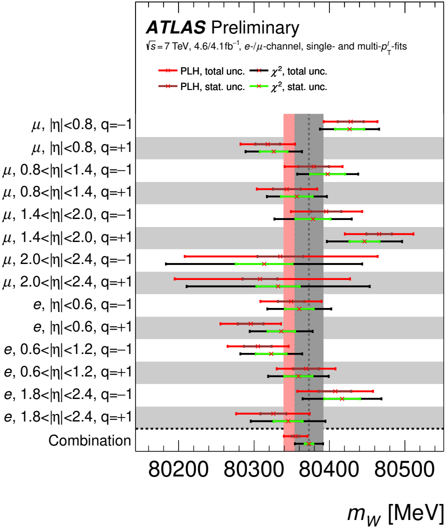
Normalisation is kept for NPs

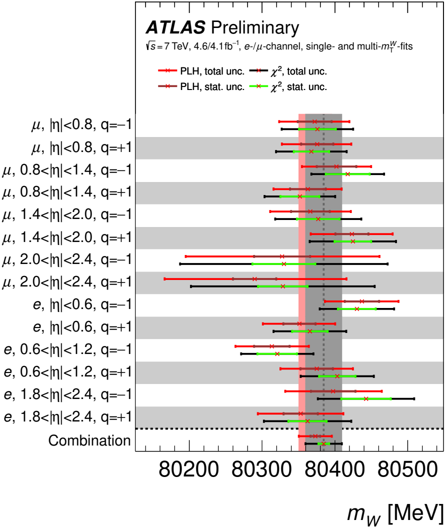
Lumi uncertainty on background samples

$$+MJ^{\text{nom}}_{\text{cb}} + \sum_{p''} \alpha_{p''} \times \left(MJ^{p''}_{\text{cb}} - MJ^{\text{nom}}_{\text{cb}}\right)$$

slide from Philipp König

Transition from χ^2 to PLH fits





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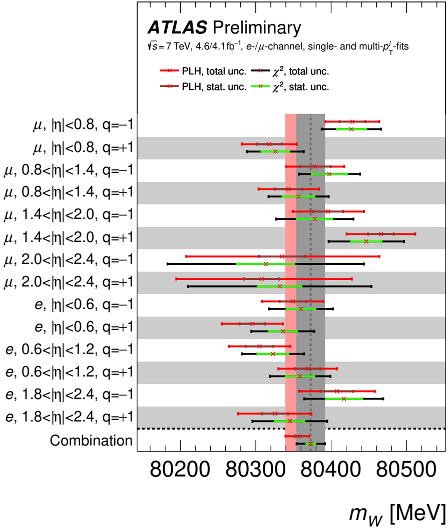
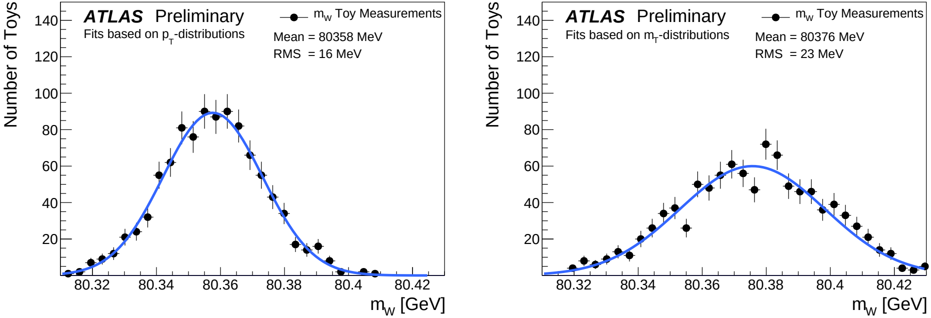


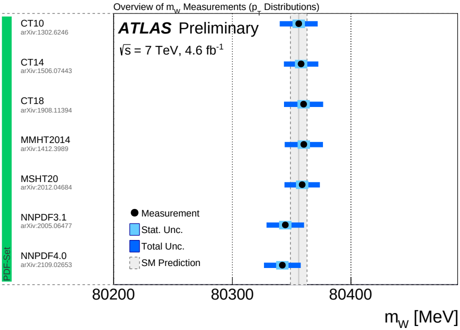
- Consistency between fit methods
  - with stat. uncertainties only → reproduce results from original analysis
  - including systematic uncertainties → lower central value, reduced total uncertainty
- PLH fit consistency
  - vary fitting ranges
  - lepton charge and flavour
  - separate η regions
  - compare p_T^ℓ and m_T fits → correlation from pseudodata using toy variations of all systematics
- Good closure in all checks

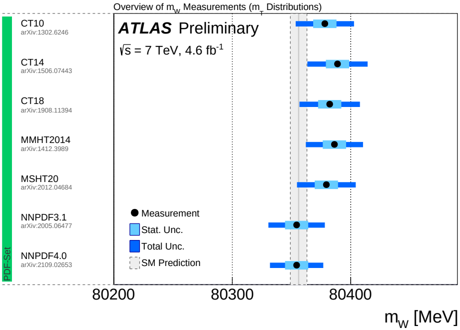
PLH fit: what is expected?



- PLH fit can move the m_W central value → how big a shift is ”allowed”?
- Study using pseudodata with toy variations of systematic uncertainties:
  - 1σ change in the p_T^ℓ fit corresponds to 16 MeV
  - 1σ change in the m_T fit corresponds to 23 MeV
- Central values of χ^2 and PLH fits differ by $\sim 1\sigma$ (p_T^ℓ) and $< 1\sigma$ (m_T)

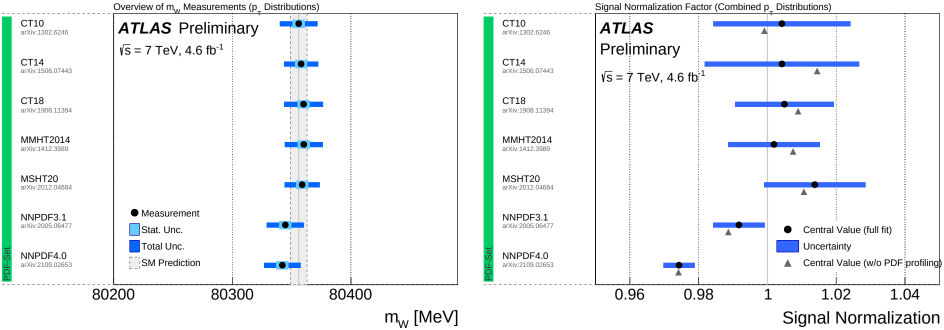
m_W dependence on PDF set





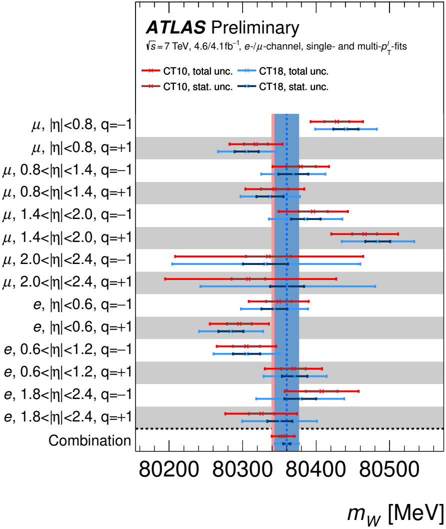
- Several modern PDF sets considered → spread of m_W values reduced by profiling of uncertainties
- CT18 PDF set chosen as new baseline
  - yields most conservative uncertainties
  - CT18 PDF uncertainties cover most other considered sets

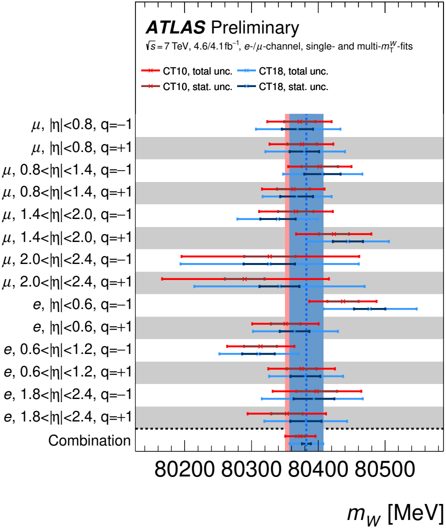
m_W dependence on PDF set



- NNPDF3.1 and NNPDF4.0 sets stand out in terms of central values
- Signal normalisation factor for these sets also deviates slightly from other sets
- In particular, NNPDF4.0 normalisation factor not consistent with 1

Transition from CT10 to CT18 PDF set



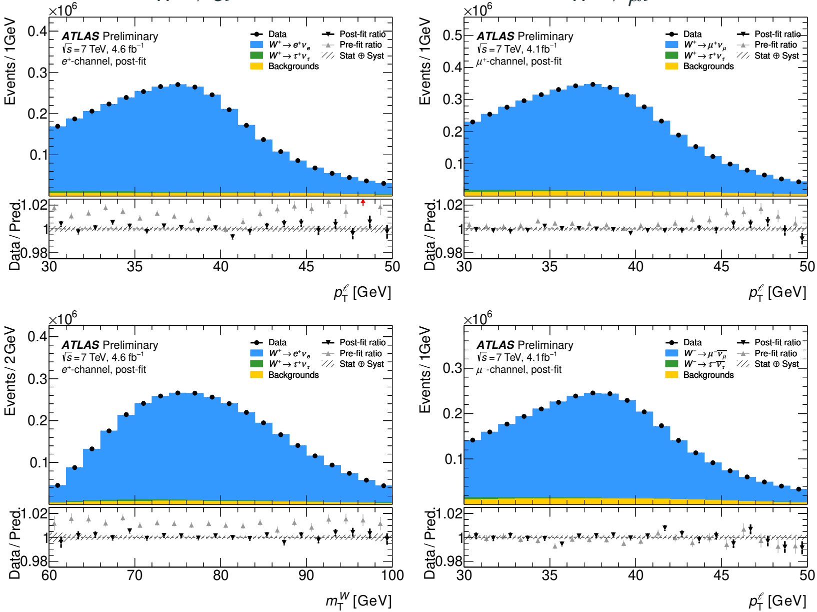


Good consistency across all categories

Post-fit distributions

$W \to e\nu$

$W \to \mu\nu$



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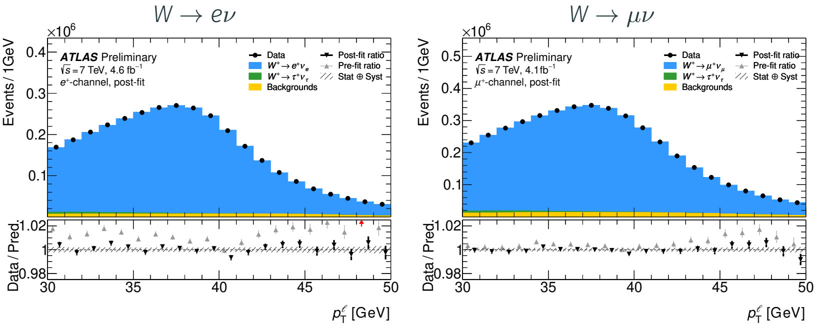
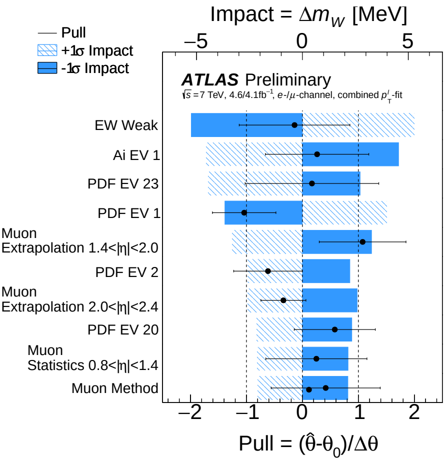
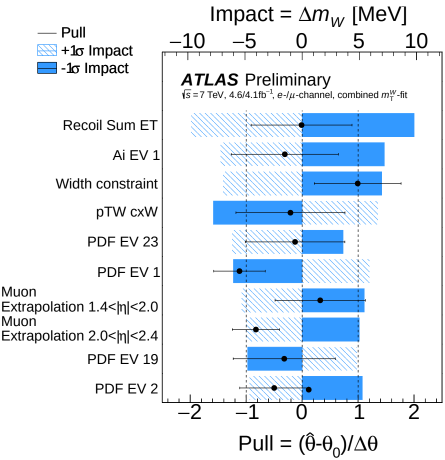


- Post-fit distributions show very good agreement with data
- Improvement compared to χ^2 fits using only statistical uncertainties

Systematic uncertainties

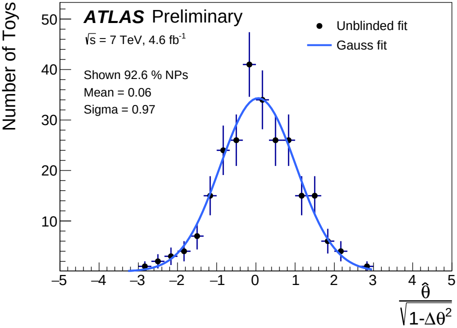




- Δm_W: difference between nominal fit and fit with NP fixed to $\pm 1\sigma$
- Largest contributions from physics modelling uncertainties (electroweak, A_i, PDF), muon calibration, hadronic recoil calibration

Systematic uncertainties

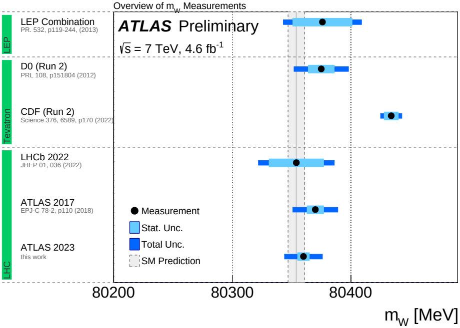
- Check of NP pull significances:
  - Distribution as expected (Gaussian with $\mu = 0,\ \sigma = 1$)
  - Suggests no significant over- or underestimations of uncertainties

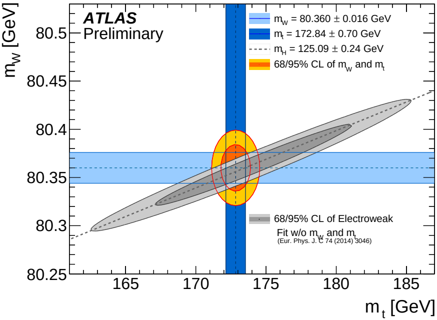


- Reduction of uncertainties compared to original analysis:
  - 15 — 30% for PDF
  - 10 — 40% for A_i and parton shower
  - $\sim$ 15% for total uncertainties

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_{T}^{ℓ}	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_{T}	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

Results



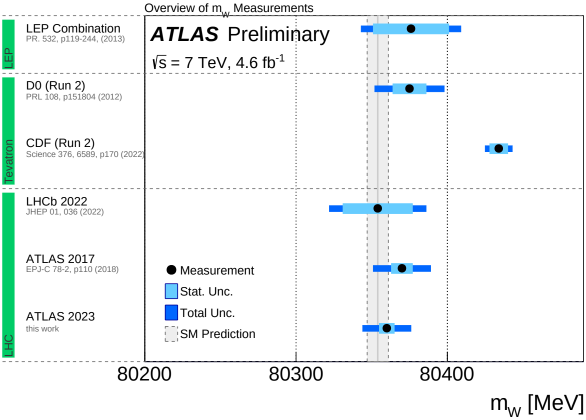


- New ATLAS measurement of *W* boson mass yields:

$$m_W = 80360 \pm 5\,(\text{stat}) \pm 15\,(\text{syst}) = 80360 \pm 16\ \text{MeV}$$

- Result even more consistent with prediction of global electroweak fits than original analysis ($m_W = 80370 \pm 19$ MeV)

Summary



- First measurement of m_W using PLH fit approach
- Result: $m_W = 80360 \pm 16$ MeV → precision improved by 15%
- Foresee improvements to physics modelling for future m_W measurements, see e.g. measurement of p_T^W and p_T^Z at 5 and 13 TeV (ATLAS-CONF-2023-028)