Measurement of the *W*-boson mass with the ATLAS detector

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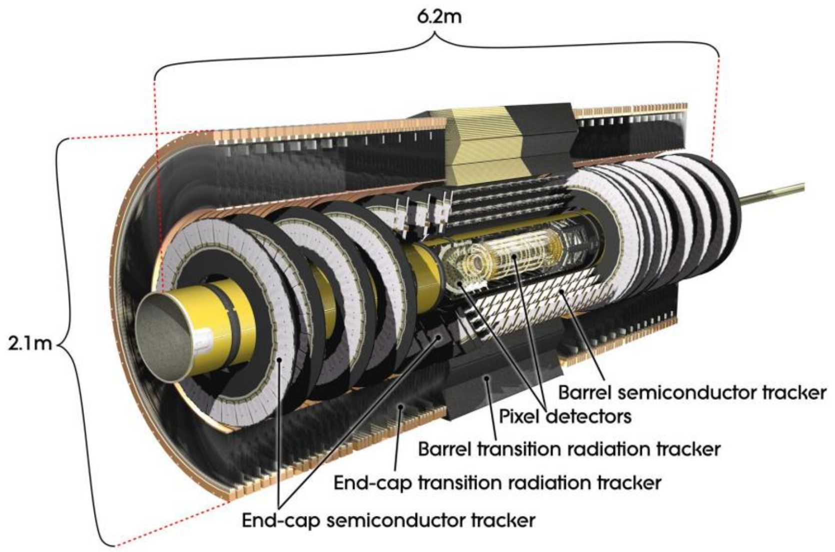
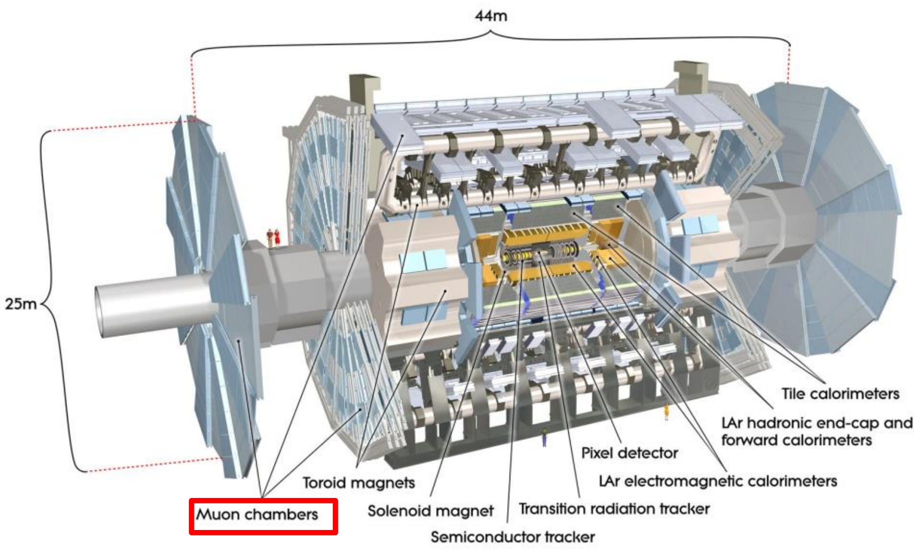
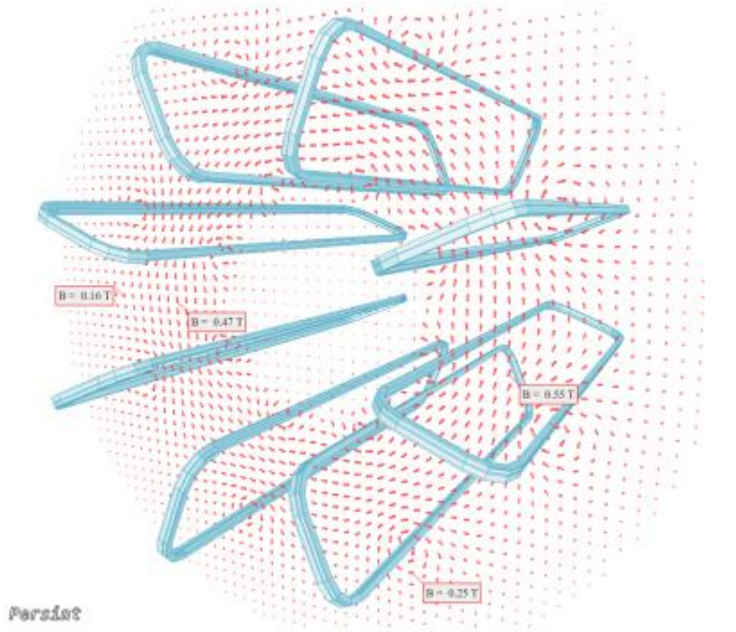
The ATLAS detector

- Multi-purpose particle detector designed to study fundamental physics.
- **Sub-detectors:** Inner Detector (ID), calorimeters, Muon Spectrometer (MS), and a complex magnetic field.







- Muon system is crucial for triggering and precise measurements, e.g. $pp \to W \to \mu\nu$.

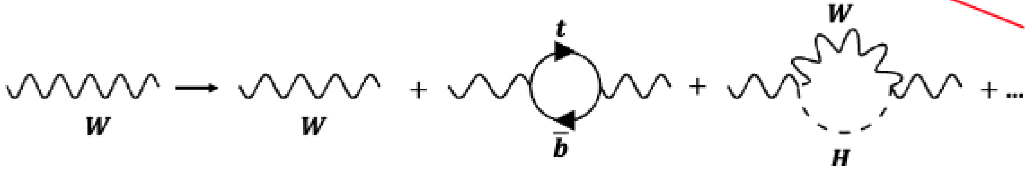
Why measuring the W boson mass?

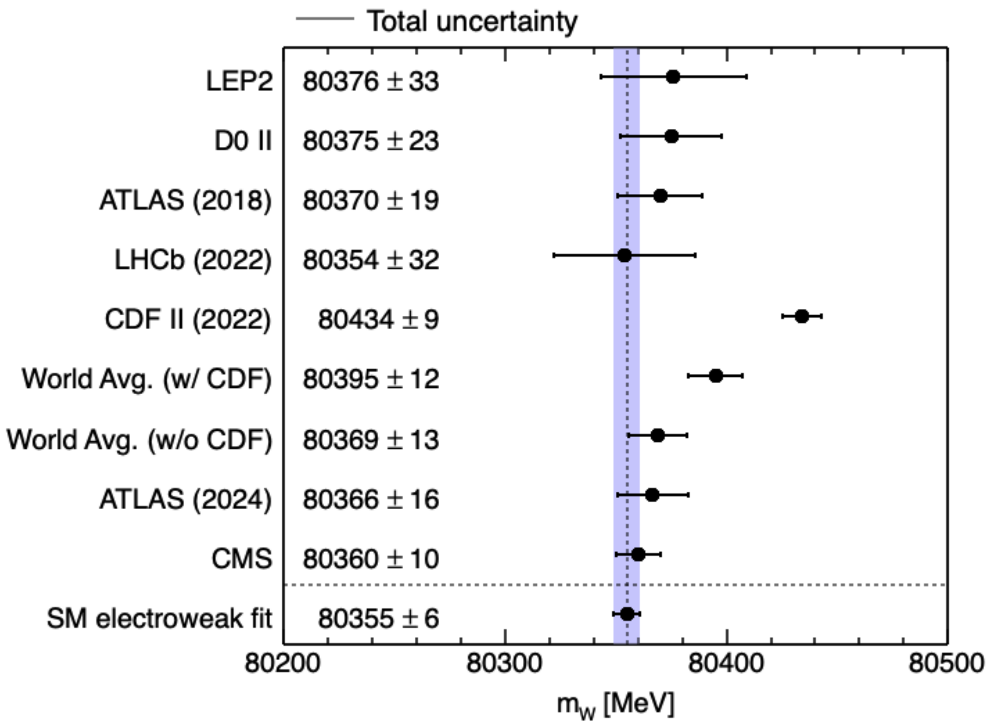
- The W boson mass (m_W) is important for testing the SM and BSM physics

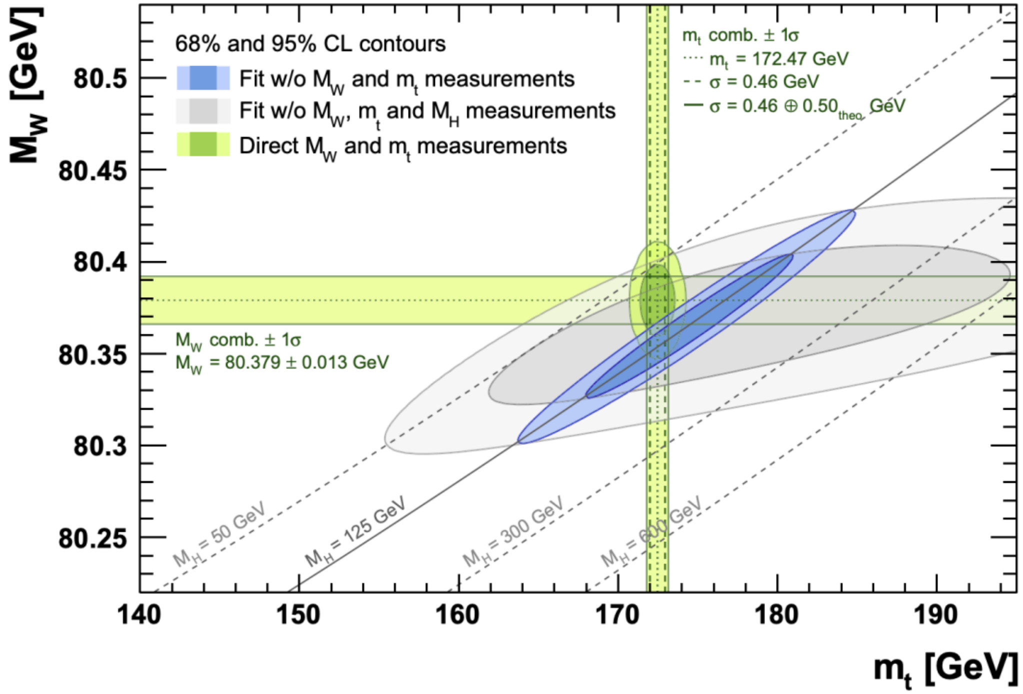
- BSM scenarios could modify m_W by radiative corrections Δr.

- In the SM, these corrections come mainly from the top-quark and Higgs boson

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}\,G_F}(1+\Delta r)$$

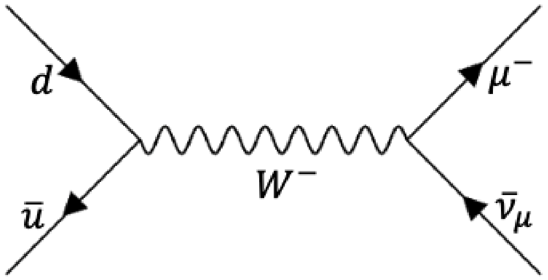


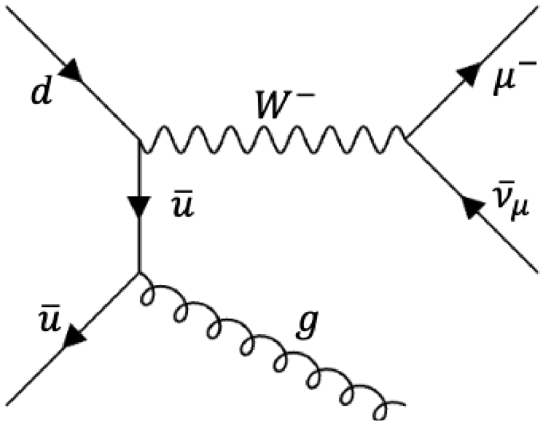


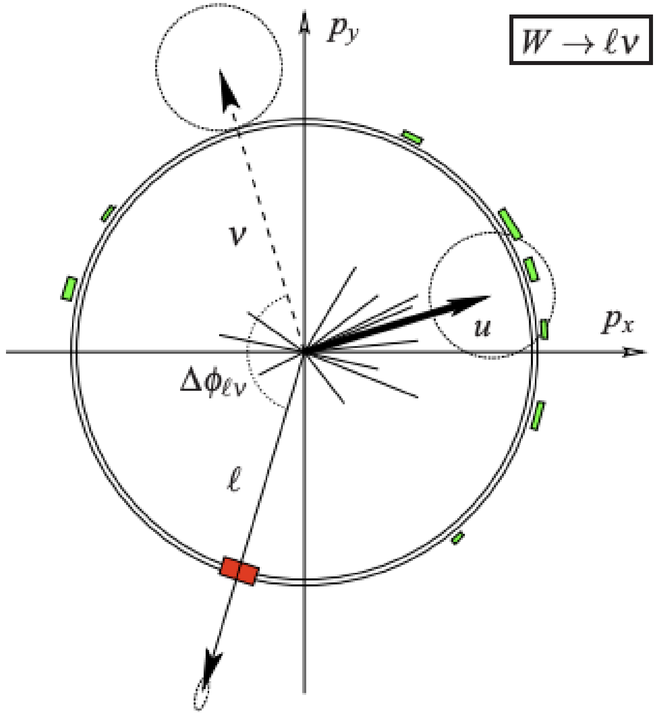


W boson production and leptonic decay

- In the SM, the W boson can decay in quarks and leptons, and its mass is measured via the lepton channels: $W \rightarrow \ell\nu$ ($\ell = e^{\pm}, \mu^{\pm}$).
- Higher-order corrections lead to a non-trivial p_T^W distribution that is crucial to control.
- This channel is challenging since the neutrino escapes the detection, and its momentum has to be inferred from other quantities.
- In the detector we measure:
  - The momentum of the charged lepton, p_T^{ℓ}.
  - The hadronic recoil, u_T.
- We can infer:
  - The energy of the neutrino: E_T^{miss}
  - The transverse mass: m_T





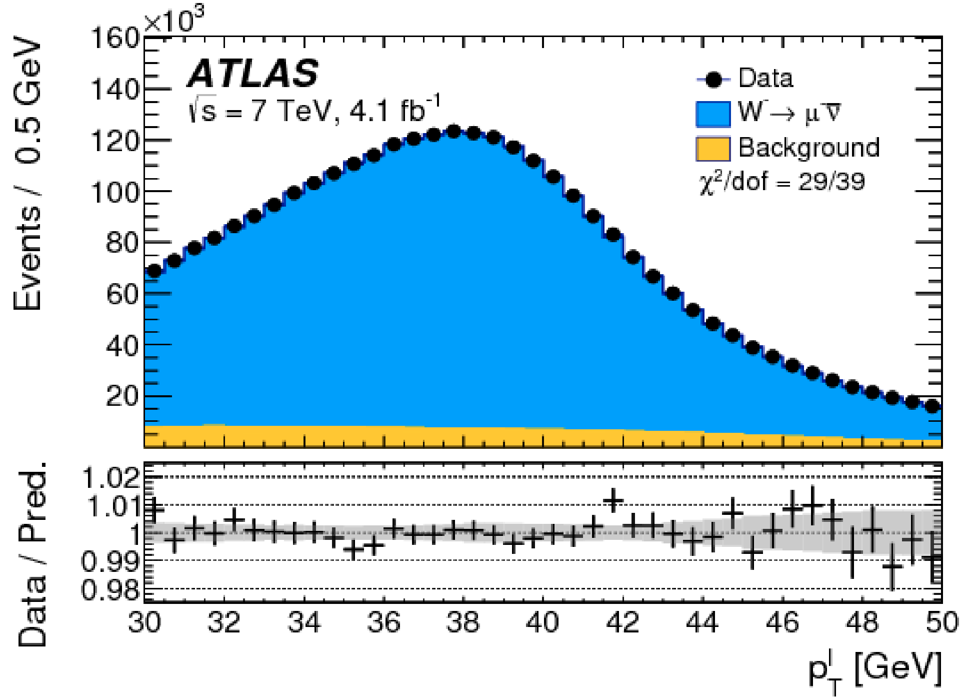


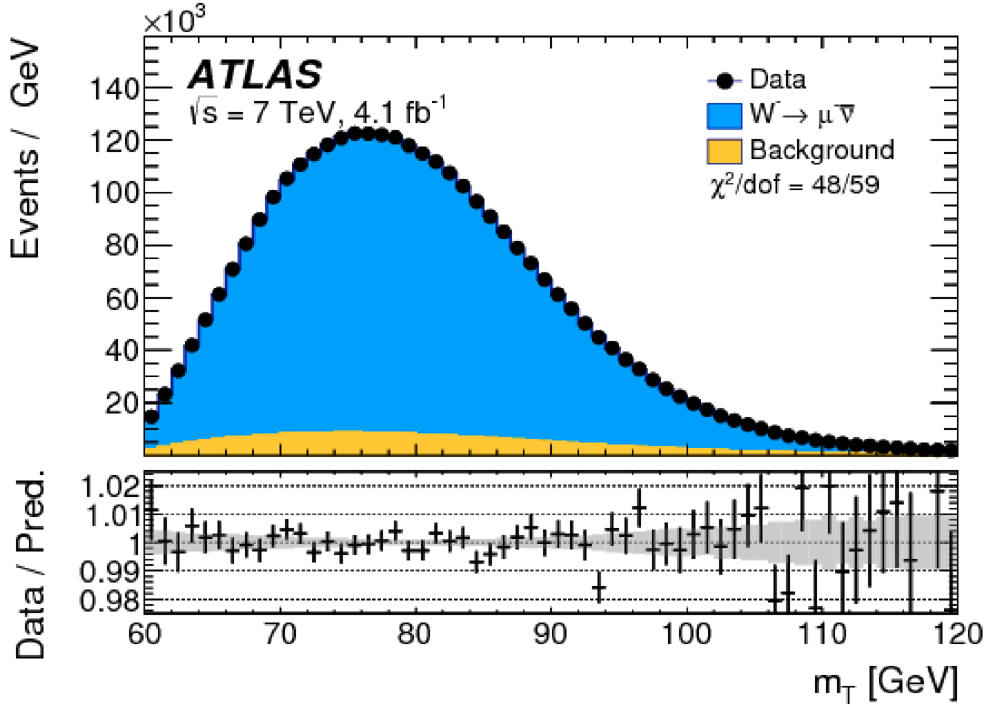
What do we measure?

- Observables sensitive to m_W
  - Lepton transverse momentum: p_T^ℓ
  - Transverse mass m_T

$$m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos\Delta\phi_{\ell\nu})}$$

- For p_T^ℓ, a good lepton calibration is required.
- For m_T, a precise calibration of u_T is required.



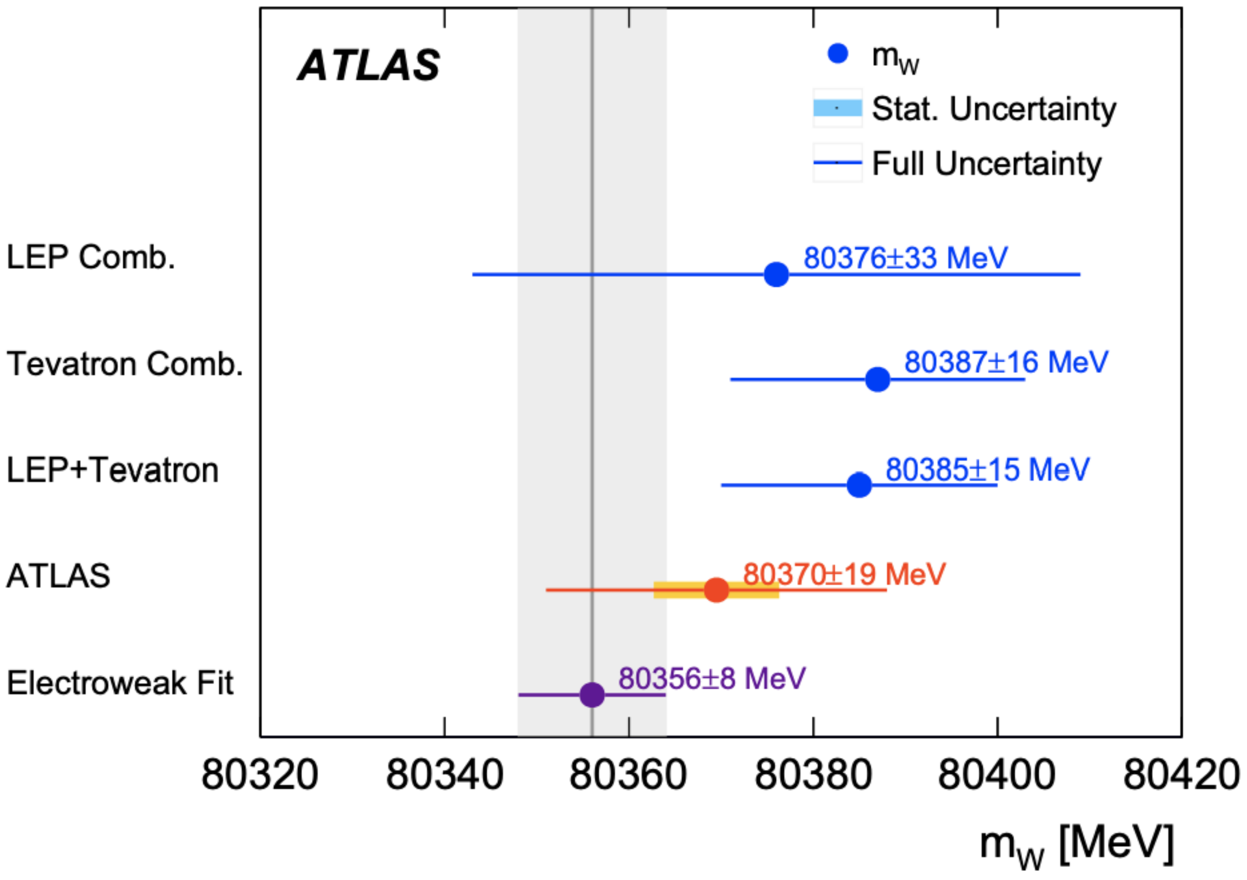


ATLAS and the W boson mass

- The ATLAS collaboration performed a first m_W measurement at 7TeV in 2018 (Eur.Phys.J.C 78 (2018) 2, 110)

$$m_W = 80370 \pm 19 \text{ MeV}$$

- Baseline PDF CT10
- This measurement was based on χ^2 minimization
- Systematics evaluated by offset method
- This talk is focused on the new ATLAS m_W measurement (Eur. Phys. J. C 84 (2024) 1309).



ATLAS m_W and Γ_W measurement at 7 TeV

- Motivation:
  - **Renalyse** 7 TeV dataset with an improve statistical approach, Profile Likelihood (PLH).
  - Reductions of several systematic uncertainties of m_W.
  - **First Γ_W measurement at the LHC**.

- Strategy:
  - Two channels, electrons and muons, and two observables m_T and p_T^ℓ.
  - Reproduce the results in the previous measurement.
  - Improvements and detailed study to the systematic uncertainties.
  - PLH fit for m_W and Γ_W.

Improvements

- New statistical treatment based of PLH with a dedicated uncertainty decomposition.
- **New PDF sets** are available.
- re-evaluated EW uncertainty defined on reco-level (2024) instead of particle-level (2018).
- Multi-jet background re-evaluated with the final luminosity calibration from Run 1.
- Principal Component Analysis (PCA) in certain systematics

MC samples and event selection

Data sample: $W \to e\nu$ and $W \to \mu\nu$ candidate events, collected in 2011 at 7 TeV with 4.6 fb^{-1}

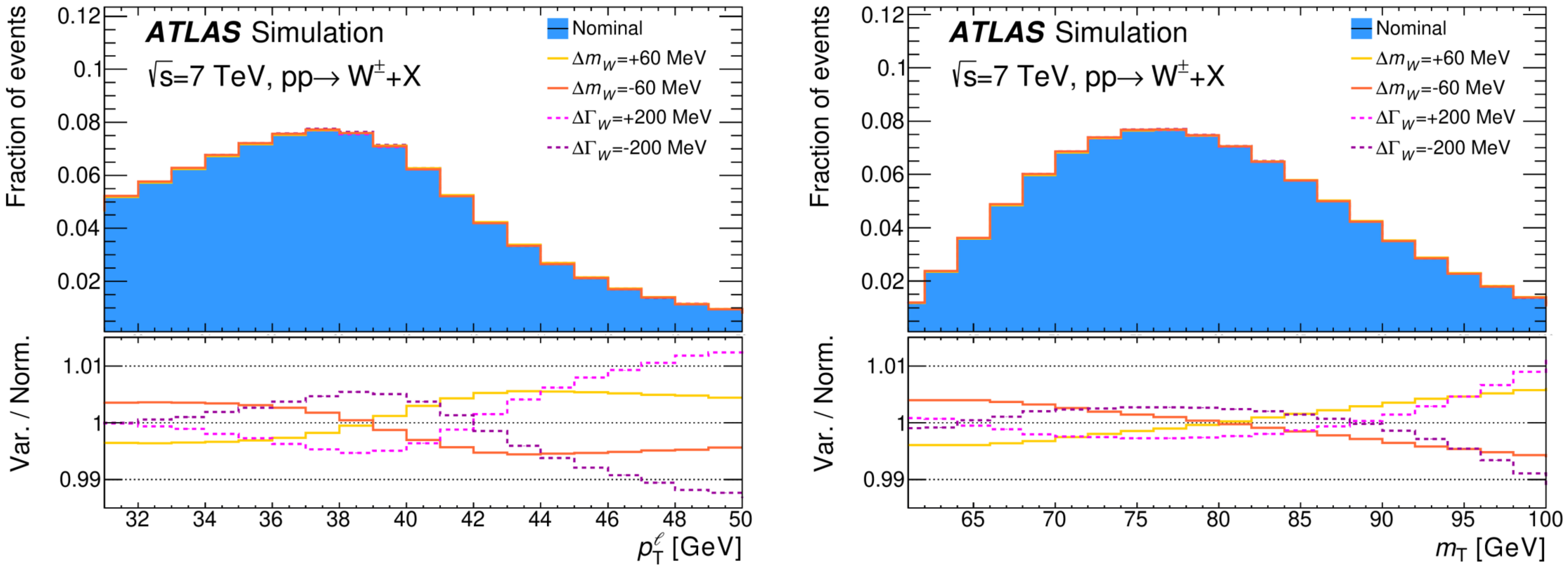
MC simulation: Powheg and Pythia8:
- W & Z production: Powheg +Pythia8 AZNLO with different PDF sets.
- Top-related background: Powheg +Pythia8.
- Di-boson background: Sherpa
- Multijet background: data-driven estimation

Selection (Gev)	
Charge	One electron or muon
Track	Combined (spectrometer + ID)
p_T^{ℓ}	>30
E_T^{miss}	>30
m_T	>60
u_T	<30
N° candidates	1.37×10^7

Fitting setup

- Template fits for m_W and Γ_W.
- Two joint fits in 14 event categories with 10 bins:

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]



Fitting strategy

- Two fitting method:
  - Numerical Profile Likelihood fit (baseline)
  - Analytical χ^2 method for uncertainty decomposition

- PLH model:

$$\mathcal{L}(\vec{m}|\vec{\theta},\vec{\alpha}) = \prod_{i\in\mathrm{bin}} \mathrm{Poisson}(m_i|\nu_i(\vec{\theta},\vec{\alpha})) \cdot \prod_{r\in\mathrm{syst.}} \mathrm{Gauss}(\alpha_r|a_r),$$

- m_i: Observed data per bin.
- ν_i : Total prediction per bin (signal modelling).
- $\vec{\theta}$: Parameter of interest (POI).
- $\vec{\alpha}$: Nuisance Parameter (NP) for systematics.
- $\vec{a}$: Global observable for NP.

Signal model

Nominal prediction for bin$-i$

Sensitivity of the prediction to the POI

Sensitivity of the prediction to the NP

$$\nu_{ji}(\theta,\vec{\alpha}) = \Phi \times \left[S_{ji}^{\mathrm{nom}} + \theta \times \left(S_{ji}^{\mu} - S_{ji}^{\mathrm{nom}}\right)\right] + \sum_{s} \alpha_s \times \left(S_{ji}^{s} - S_{ji}^{\mathrm{nom}}\right)$$

$$+ B_{ji}^{\mathrm{nom}} + \sum_{b} \alpha_b \times \left(B_{ji}^{b} - B_{ji}^{\mathrm{nom}}\right),$$

Nominal prediction for bin$-i$

Sensitivity of the prediction to the NP

- $\vec{\theta}$:POI
- $\vec{\alpha}$:NP
- Φ :Normalization factor
- S: signal
- B: background

Uncertainty components

In profile likelihood fits, commonly the uncertainty components are evaluated via the "impacts" method, as follows:

1. Total uncertainty (stat. + syst.) is computed: σ_{total}.
2. The fit is repeated removing a systematic source and the total uncertainty is computed: $\sigma'_{\text{total}} < \sigma_{\text{total}}$.
3. The impact of the systematic source is defined as: $\sigma_{\text{syst}} = \sqrt{\sigma^2_{\text{total}} - \left(\sigma'_{\text{total}}\right)^2}$

This method ignores the post-fit correlations between the NPs.

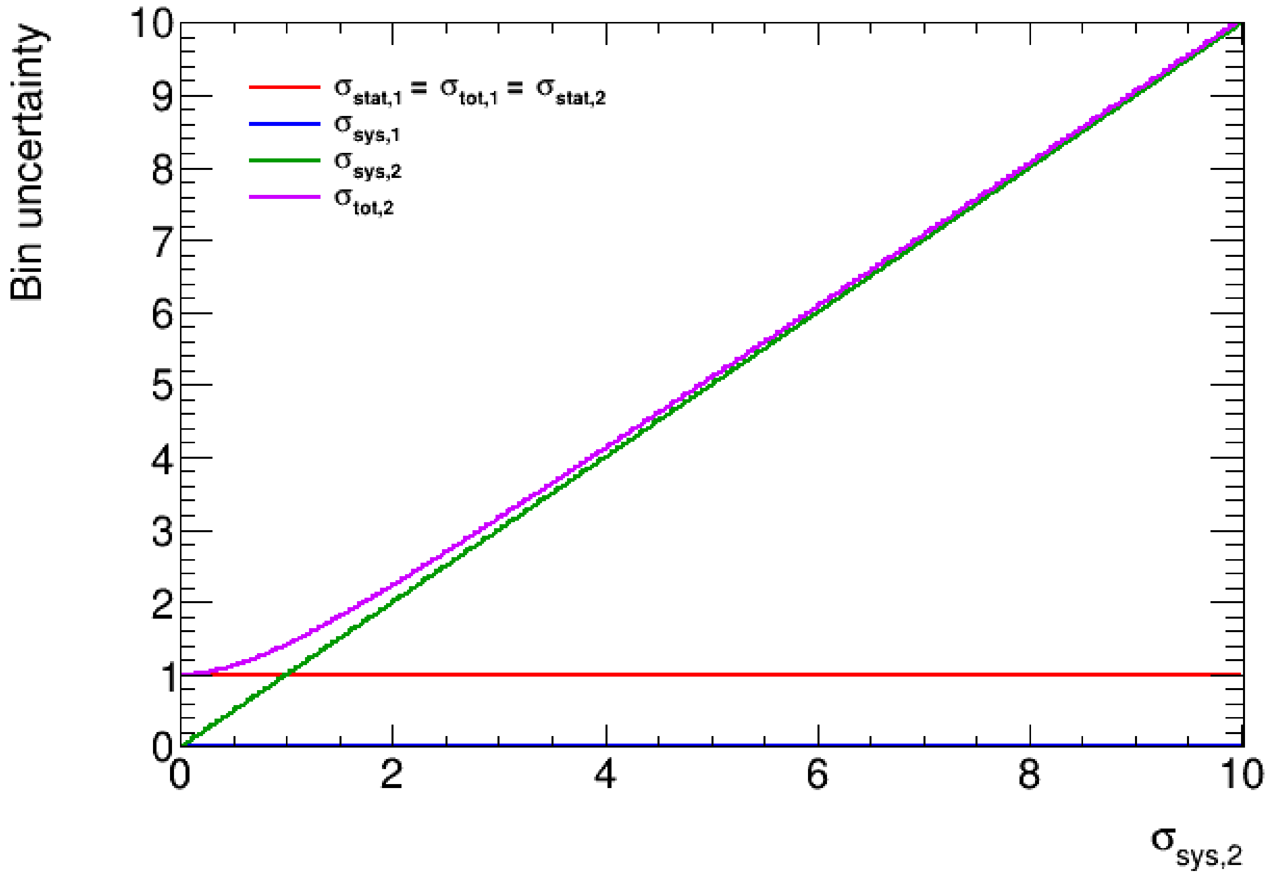
It is incorrect in the sense that the statistical component is underestimated, and the systematics are overestimated.

Impacts do not recover the total uncertainty.

Uncertainty components via "Impacts": Example

Consider two measurements:

- Measurement 1: $\sigma^1_{\text{total}} = 1, \sigma^1_{\text{stat}} = 1$ and $\sigma^1_{\text{syst}} = 0$.
- Measurement 2: $\sigma^2_{\text{total}} = 1 \oplus \sigma^2_{\text{syst}}, \sigma^2_{\text{stat}} = 1$ and $\sigma^2_{\text{syst}} \in [0, 10]$.



Uncertainty components via “Impacts”: Example

Combination unambiguous:

$$\sigma_{\text{total}} = [\,(\sigma_1^{\text{tot}})^{-2} + (\sigma_2^{\text{tot}})^{-2}]^{-1/2}$$

$$\sigma_{\text{total}} \in [1/\sqrt{2}, 1]$$

Uncertainty components:

- **Impacts:**

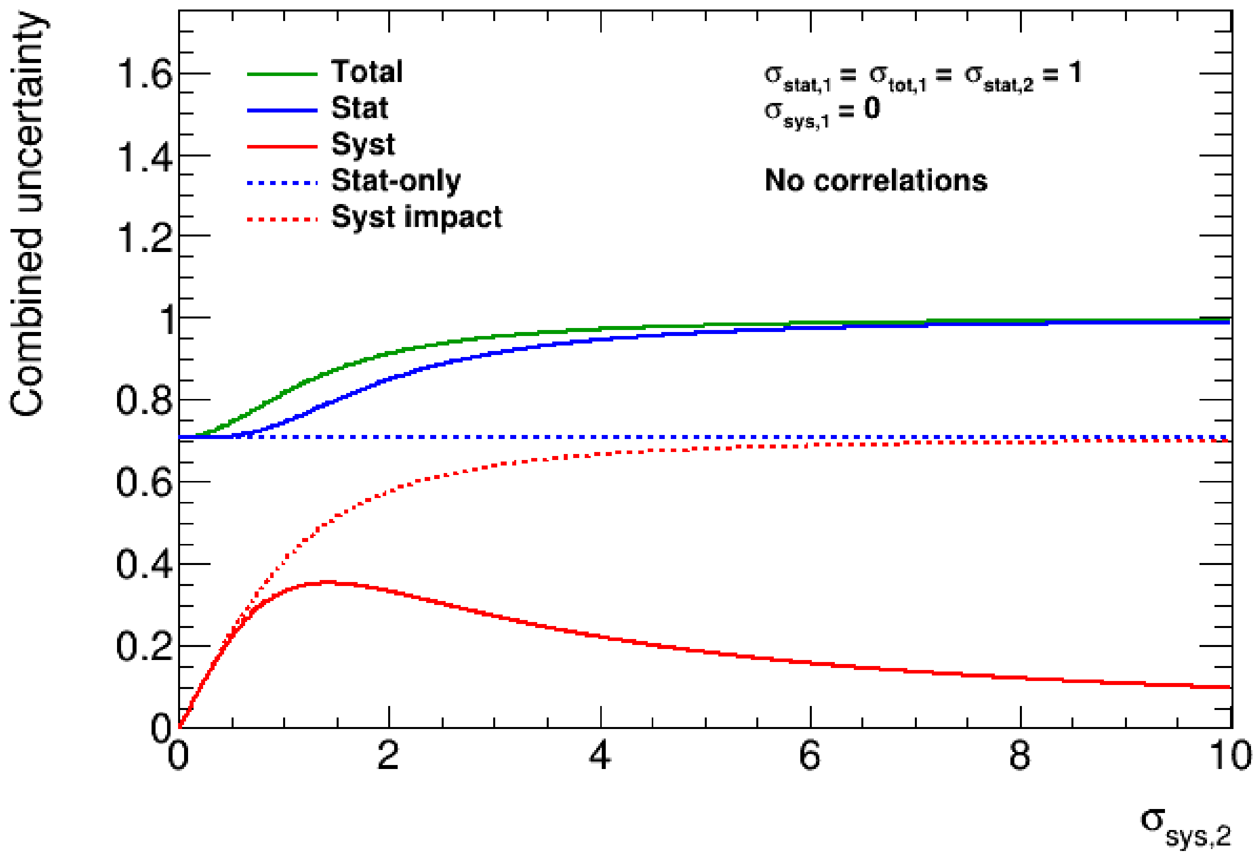
$$\sigma_{\text{stat}} = [\,(\sigma_1^{\text{stat}})^{-2} + (\sigma_2^{\text{stat}})^{-2}]^{-1/2} = 1/\sqrt{2}$$

$$\sigma_{\text{syst}} = \sqrt{\sigma_{\text{total}}^2 - \sigma_{\text{stat}}^2} \in [0, 1/\sqrt{2}]$$

- **Proper decomposition (BLUE):**

$$\sigma_{\text{stat}} \in [1/\sqrt{2}, 1]$$

$$\sigma_{\text{syst}} \to 0 \sim 0.35 \to 0$$



Analytical χ^2 method

- In the Gaussian limit, the likelihood has an analytical solution (Eur. Phys. J. C, vol. 84, 2024) that allows to simplify the calculations:

$$-2\ln\mathcal{L}(\vec{\theta},\vec{\alpha}) = \sum_{i,j}\left(m_i - t_i(\vec{\theta}) - \sum_r \Gamma_{ir}(\alpha_r - a_r)\right) V_{ij}^{-1}\left(m_j - t_j(\vec{\theta}) - \sum_s \Gamma_{js}(\alpha_s - a_s)\right) + \sum_r (\alpha_r - a_r)^2.$$

- This approach is particularly useful to study the uncertainty components.
- The systematic components can be properly evaluated.
- This can be generalized to non-Gaussian limits through the global shifted observable method.

Uncertainty components in PLH

In the Gaussian limit, the likelihood covariance can be divided in three block matrices:

Nuisance parameters covariance matrix

Systematic uncertainty components

$$\operatorname{cov}\left(-2\ln\mathcal{L}\right) = \left(\begin{array}{c|c} \operatorname{cov}\left(\hat{\alpha}_r, \hat{\alpha}_s\right) & \operatorname{cov}\left(\hat{\alpha}_r, \hat{\theta}_q\right) \\ \hline \operatorname{cov}\left(\hat{\theta}_p, \hat{\alpha}_s\right) & \operatorname{cov}(\hat{\theta}_p, \hat{\theta}_q) \end{array}\right)$$

Systematic uncertainty components

Parameter of interest covariance matrix

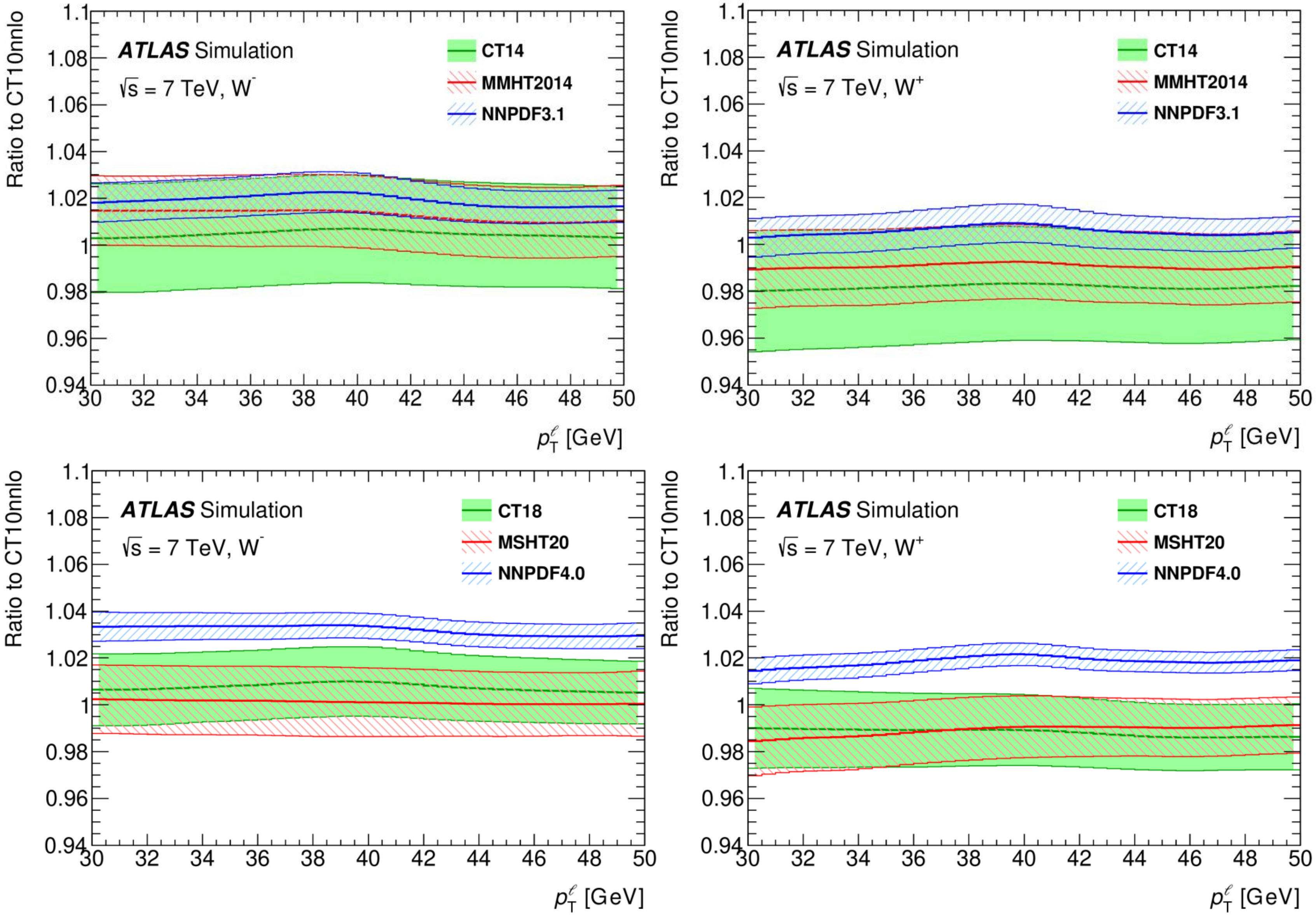
$$\sigma_{\text{total}} = \sqrt{\operatorname{cov}(\hat{\theta}_p, \hat{\theta}_p)},$$

$$\sigma_{\text{syst}} = \sqrt{\sum_r \operatorname{cov}(\hat{\theta}_p, \hat{\alpha}_r)\operatorname{cov}(\hat{\alpha}_r, \hat{\theta}_p)},$$

$$\sigma_{\text{stat}} = \sqrt{\sigma^2_{\text{total}} - \sigma^2_{\text{syst}}},$$

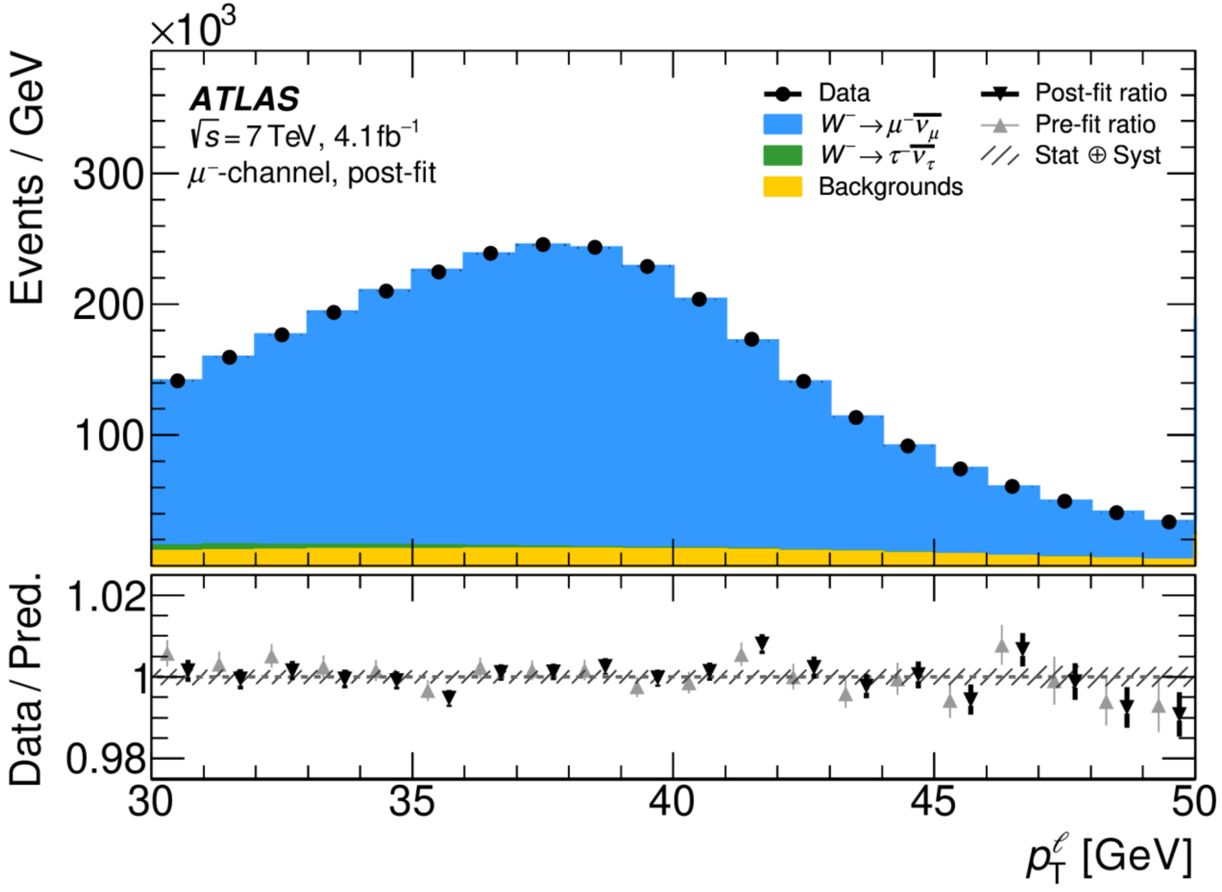
Impact of updated Parton Density Functions

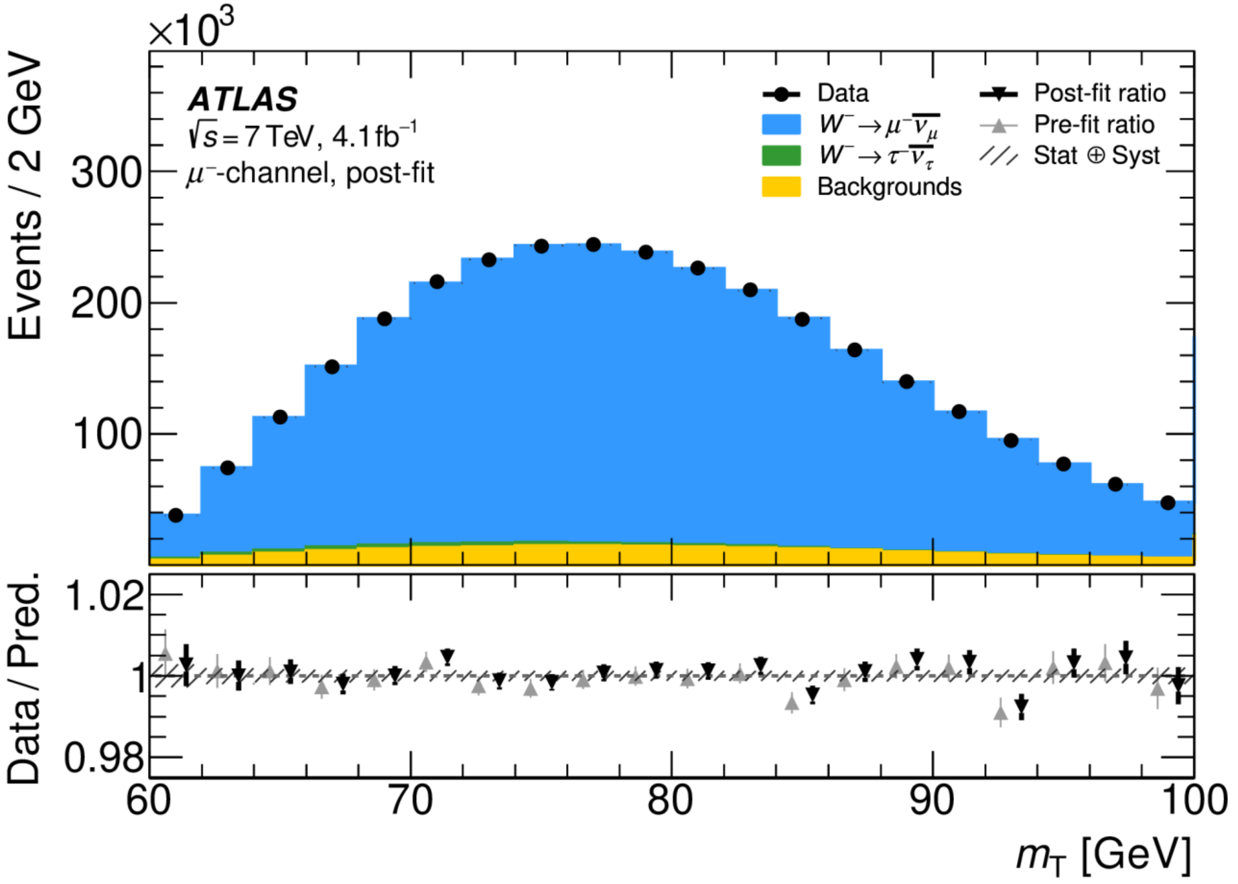
Evaluated with POWHEG on particle-level and transformed to reco-level with the migration matrix



Pre-fit and Post-fit plots

The post-fit, $|\eta|$ −inclusive p_T^ℓ, m_T distributions obtained with CT18 agree with the data within the uncertainties.

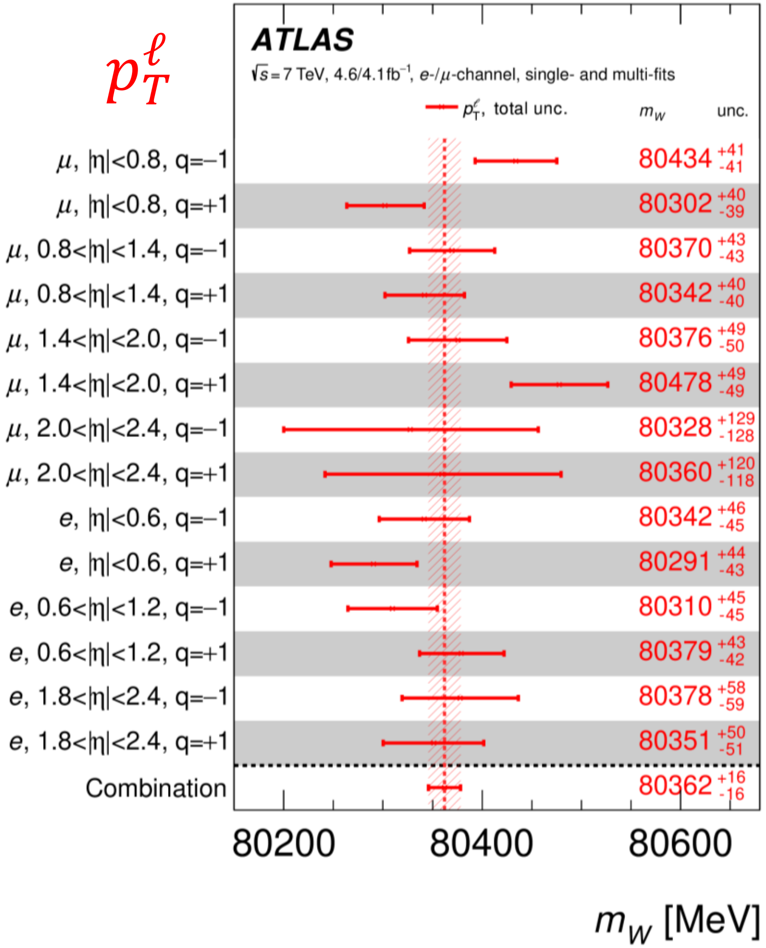




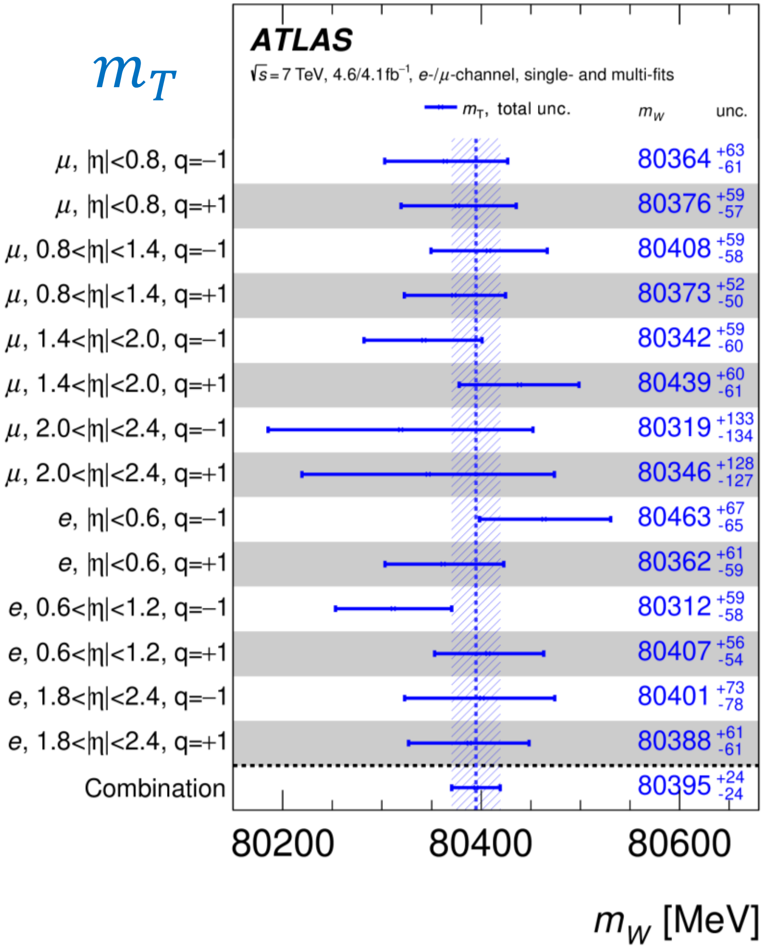
m_W measurement in categories

In each category, a separate fit for p_T^ℓ (left) and m_T (right) is performed, followed by a combined fit across all categories. Results show good compatibility.

p_T^ℓ

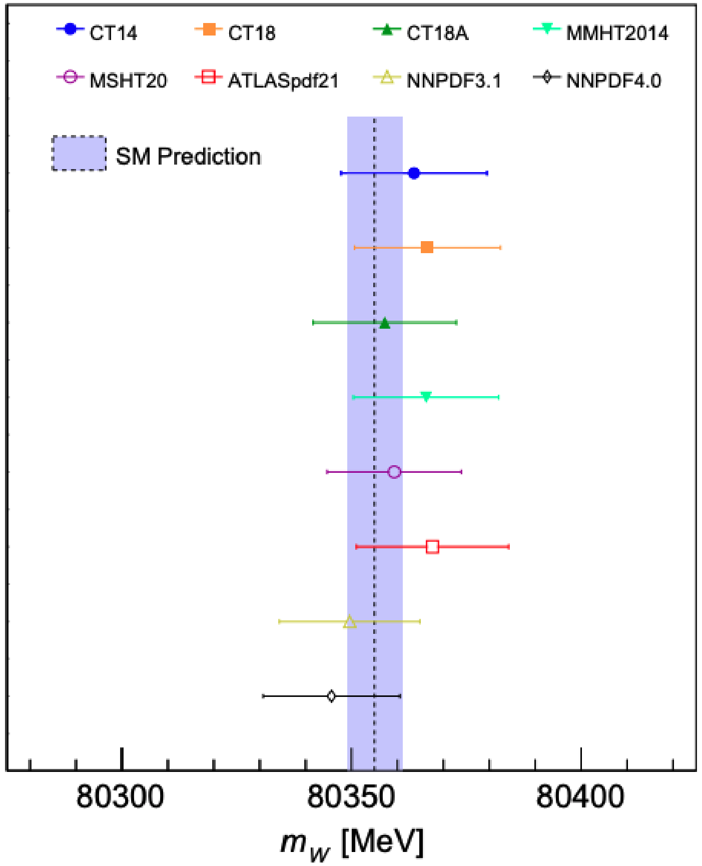


m_T

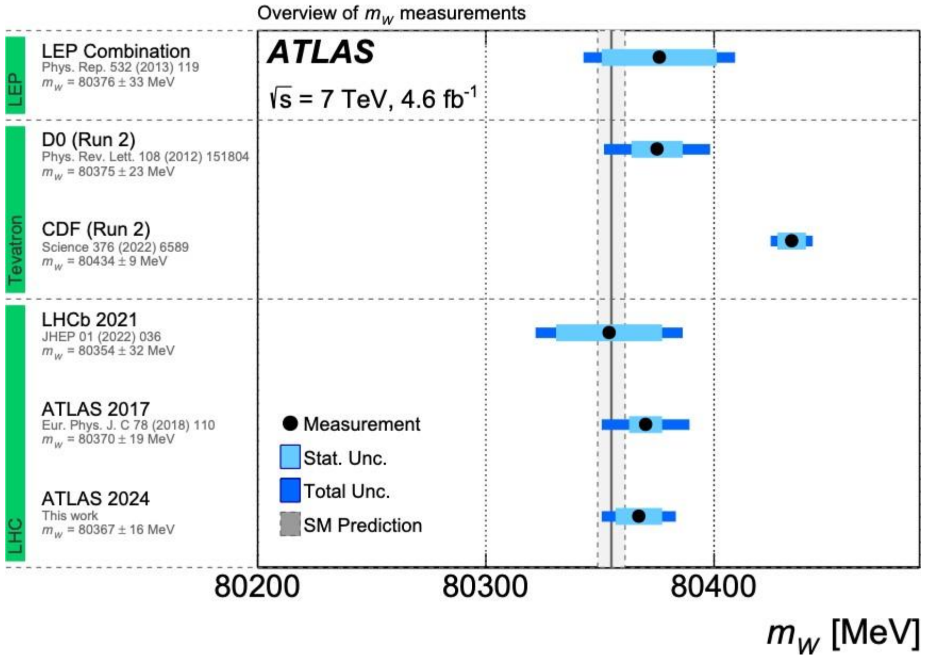


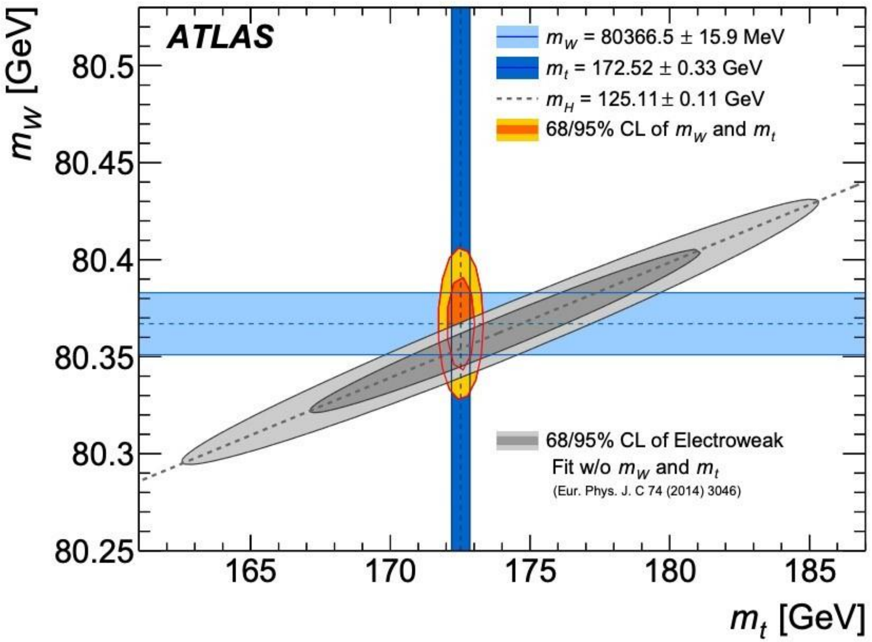
m_W combination

- The final $p_T^\ell - m_T$ combination is performed using the BLUE approach where the correlation is obtained by pseudo-experiments. CT18 PDF set is chosen as baseline.
- In agreement with the SM and improvement with respect to 2017 of about 15%.



(Eur. Phys. J. C 84 (2024) 1309).





m_W uncertainty components

- Final result corresponds to,

$$m_W = 80366.5 \pm 9.8\,(\text{stat.}) \pm 12.5\,(\text{syst.}) = 80366.5 \pm 15.9 \text{ MeV}$$

- With uncertainty decomposition,

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

- Using stat. only fit $\sigma_{\text{stat}} = 6$ MeV and **by impacts** $\sigma_{\text{syst}} = 15$ MeV which is **overestimating** the current result.

2018 vs 2024 comparison

- Comparison of the two m_W measurement performed by ATLAS

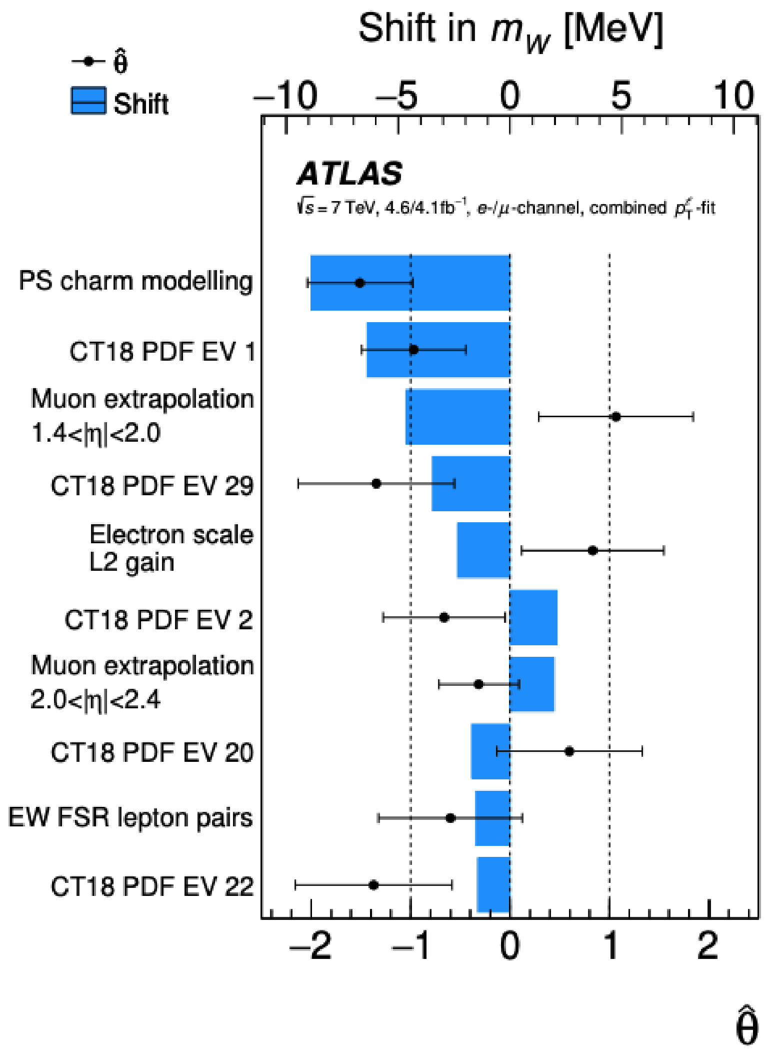
- PDF unc. Improved by 38%.
- QCD unc. $(A_i + p_T^W)$ improved by 47.5%
- Background reduced by 55.6%
- Among other reductions.

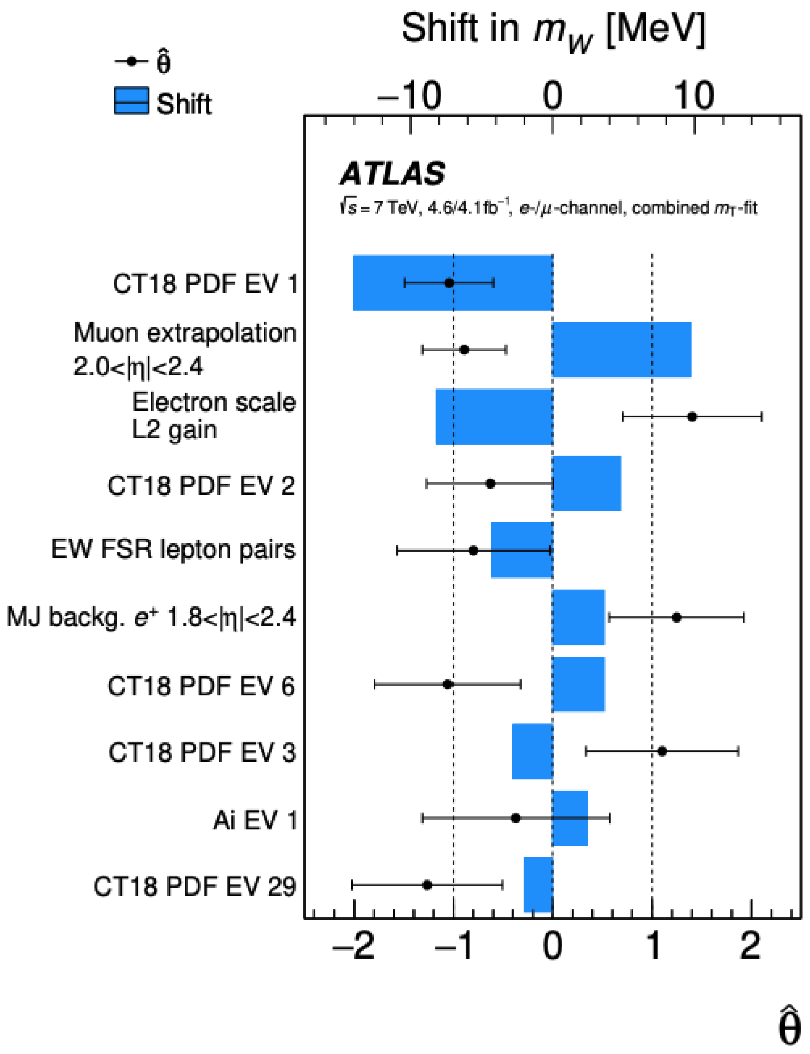
m_W [MeV]		Total	Stat.	Syst	Muon	Elec.	Recoil	Backg.	QCD	EW	PDF	Lumi	Γ_W
2018	80369.5	18.5	6.8	17.2	6.6	6.4	2.9	4.5	8.3	5.5	9.2	-	-
2024	80366.5	15.9	9.8	12.5	5.4	6.0	2.3	2.0	4.4	5.4	5.7	1.3	0.1
Reduction (%)		14.2	-	27.3	18.2	6.3	20.7	55.6	47.5	1.8	38.0	-	-

m_W nuisance parameters pulls

NPs inducing the largest shift in m_W:

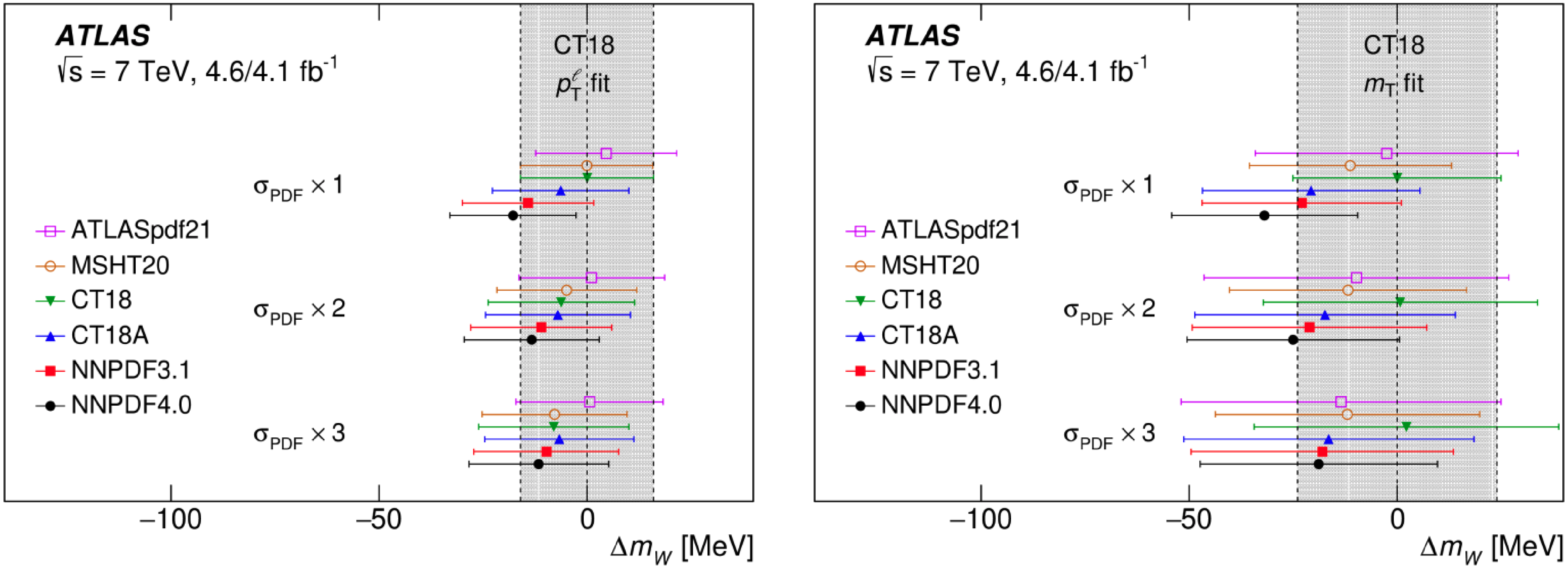
- Charm-induced production for the p_T^W
- Electron and muon calibration
- PDF eigen vectors
- Missing higher-order EW corrections





PDF dependency at $\sqrt{s} = 7$ TeV

Fits are performed for p_T^ℓ and m_T using different PDF sets to study the m_W dependency



Γ_W measurement in categories

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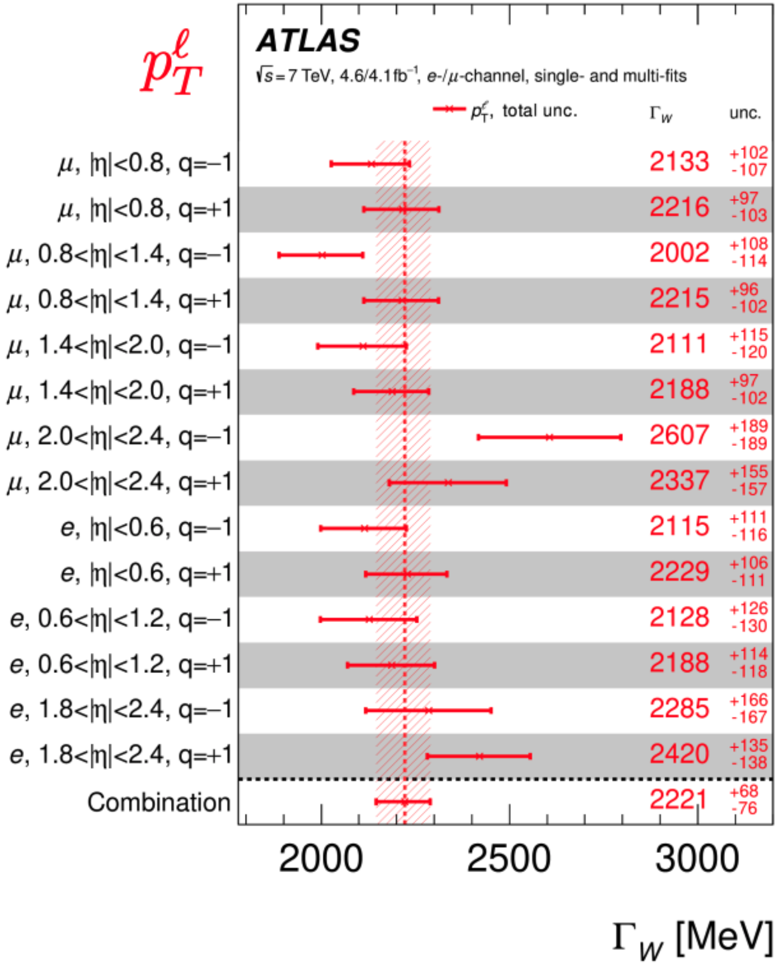
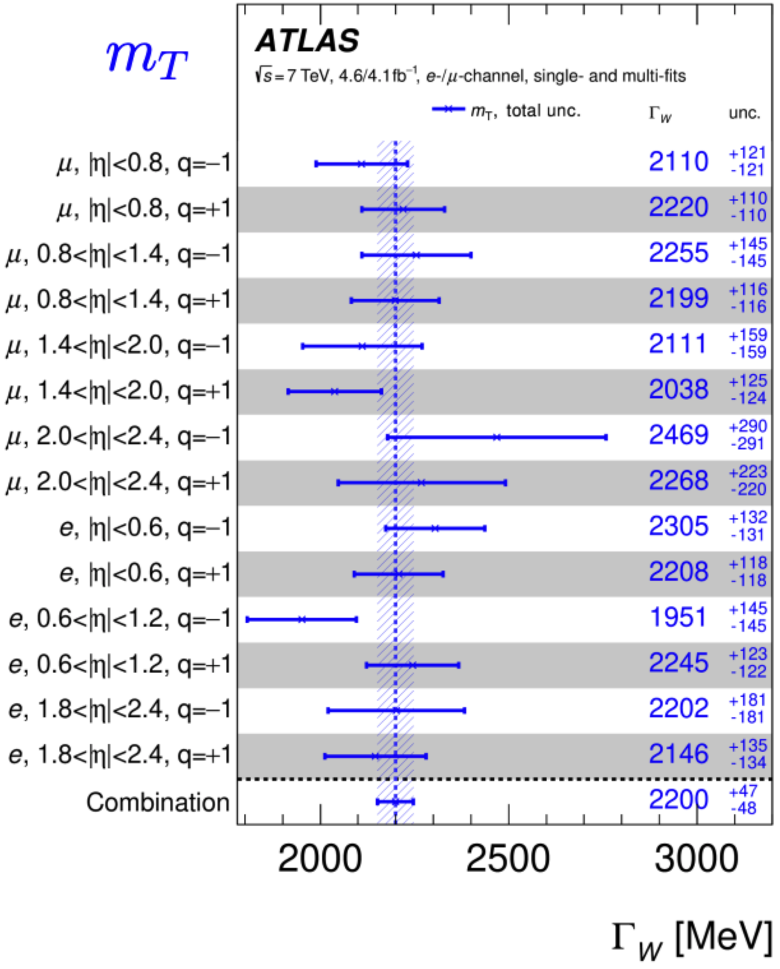
p_T^ℓ

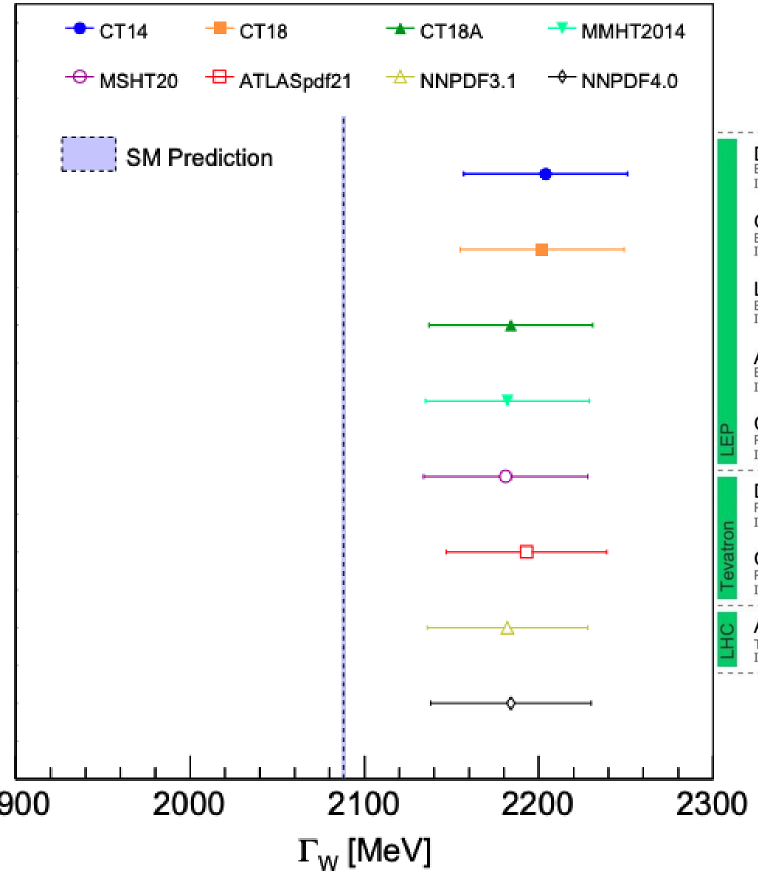


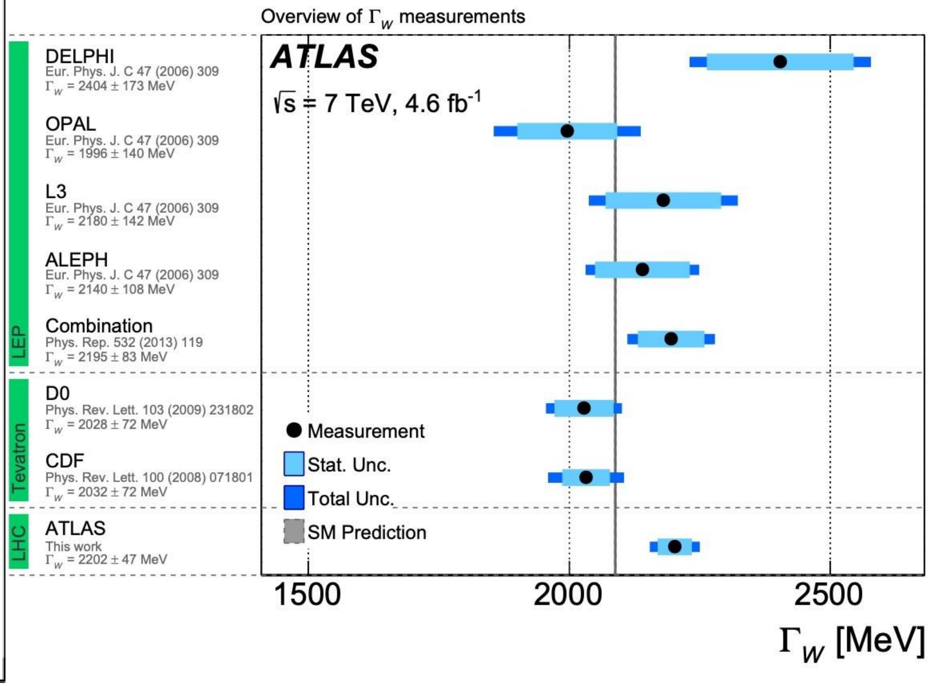
m_T

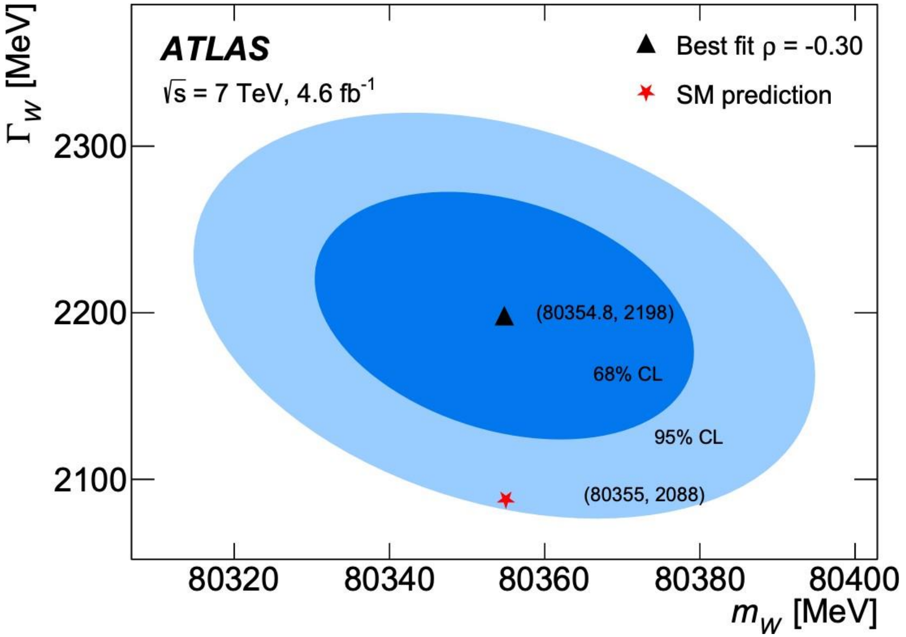


Γ_W combination

- The final $p_T^{\ell} - m_T$ combination is performed using the BLUE approach where the correlation is obtained by pseudo-experiments. CT18 PDF set is chosen as baseline.
- In agreement with the SM within 2σ and is the most precise single measurement.







Γ_W uncertainty components

- Final result corresponds to,

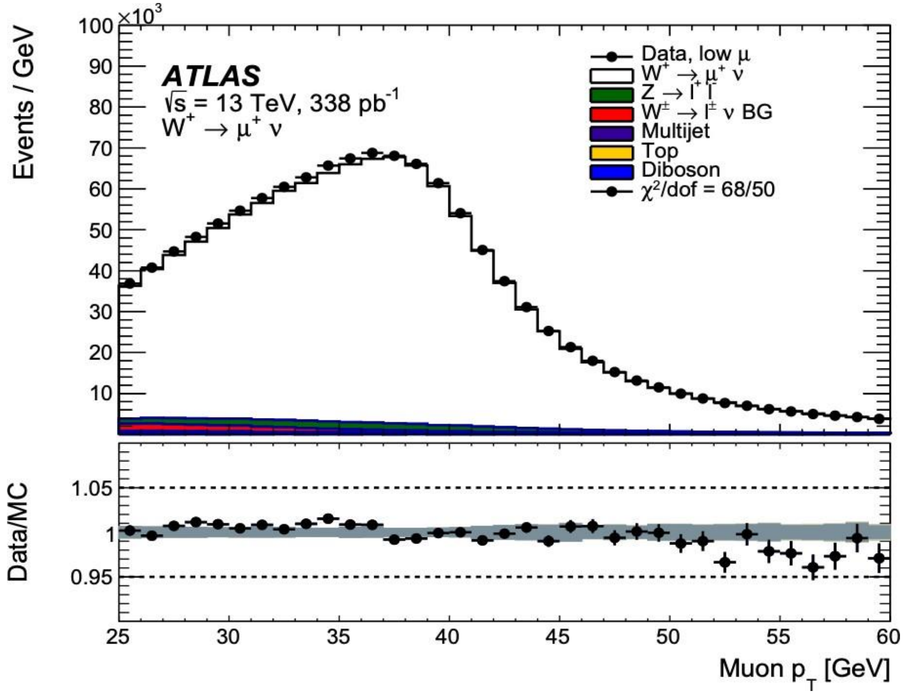
$$\Gamma_W = 2202 \pm 32\,(\text{stat.}) \pm 34\,(\text{syst.})\ \text{MeV} = 2202 \pm 47\ \text{MeV}$$

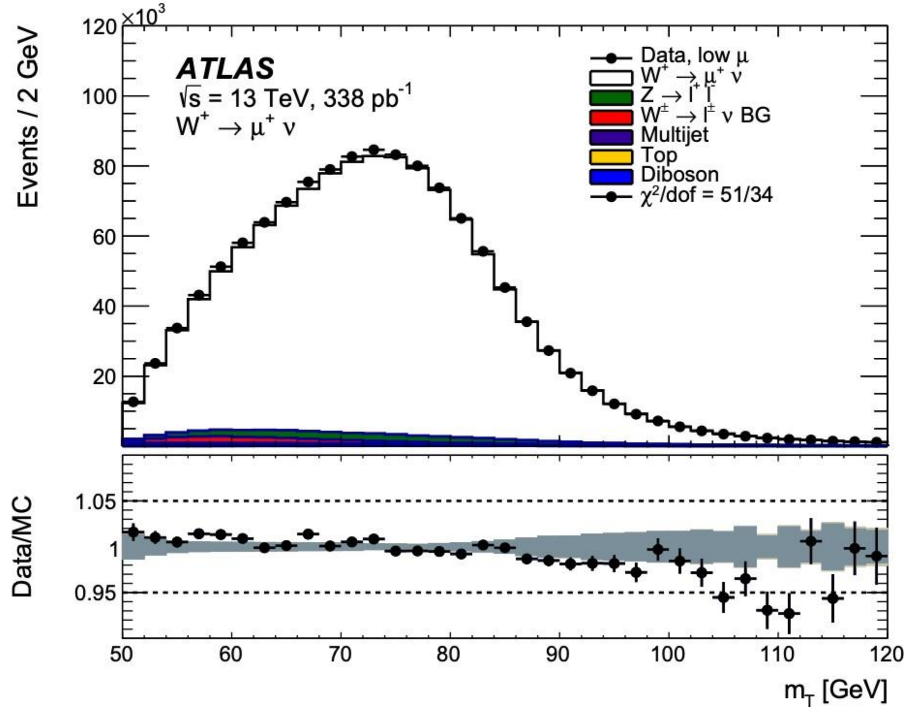
With uncertainty decomposition,

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

ATLAS current m_W status

- The ATLAS collaboration prepares a new measurement of m_W using low pile-up data set at 5.02 TeV and 13 TeV.
- This dataset provides a better resolution in the transverse mass, i.e. more sensitivity of m_T to m_W.
- Preliminary results show a competitive precision compared to other experiments.
- The precise measurement of p_T^W and p_T^Z was performed using this dataset [Eur. Phys. J. C 84 (2024) 1126]





Conclusions

- Profile likelihood fit improved the m_W precision with respect to 2017 measurement, leading to:

$$m_W = 80366.5 \pm 15.9\ (\pm 9.8 \pm 12.5)\ \mathrm{MeV}$$

- First single Γ_W measurement in agreement with SM within 2σ

$$\Gamma_W = 2202 \pm 47\ (\pm 32 \pm 34)\ \mathrm{MeV}$$

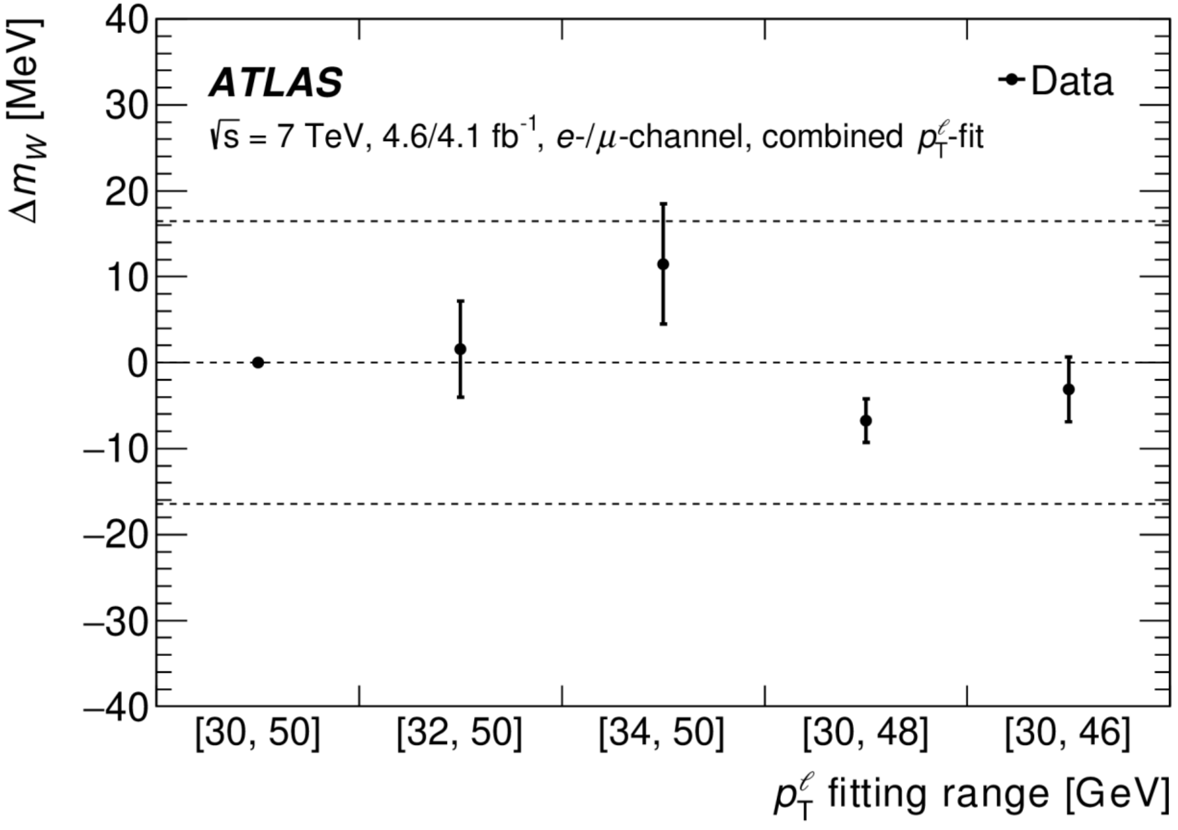
- New measurement of m_W using low pile-up dataset is in progress with preliminary results showing a competitive precision.

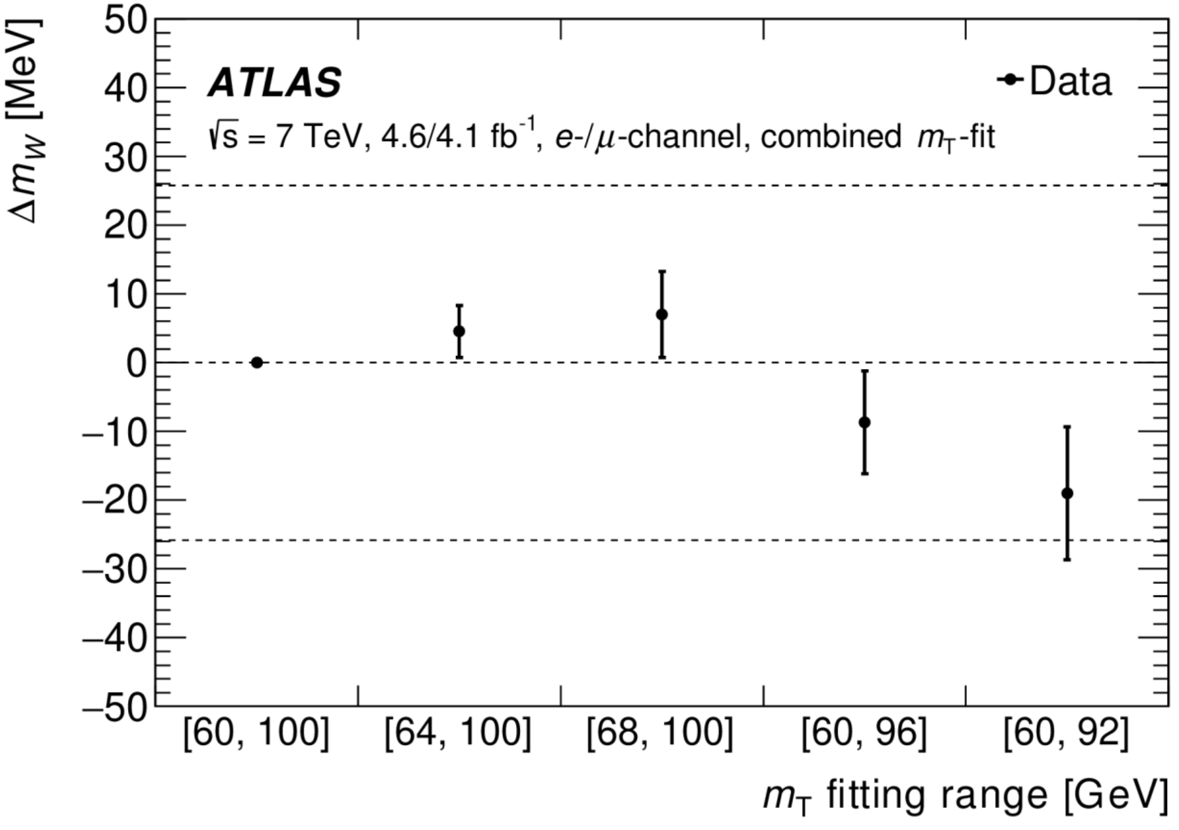
BACKUP

Nominal simulation

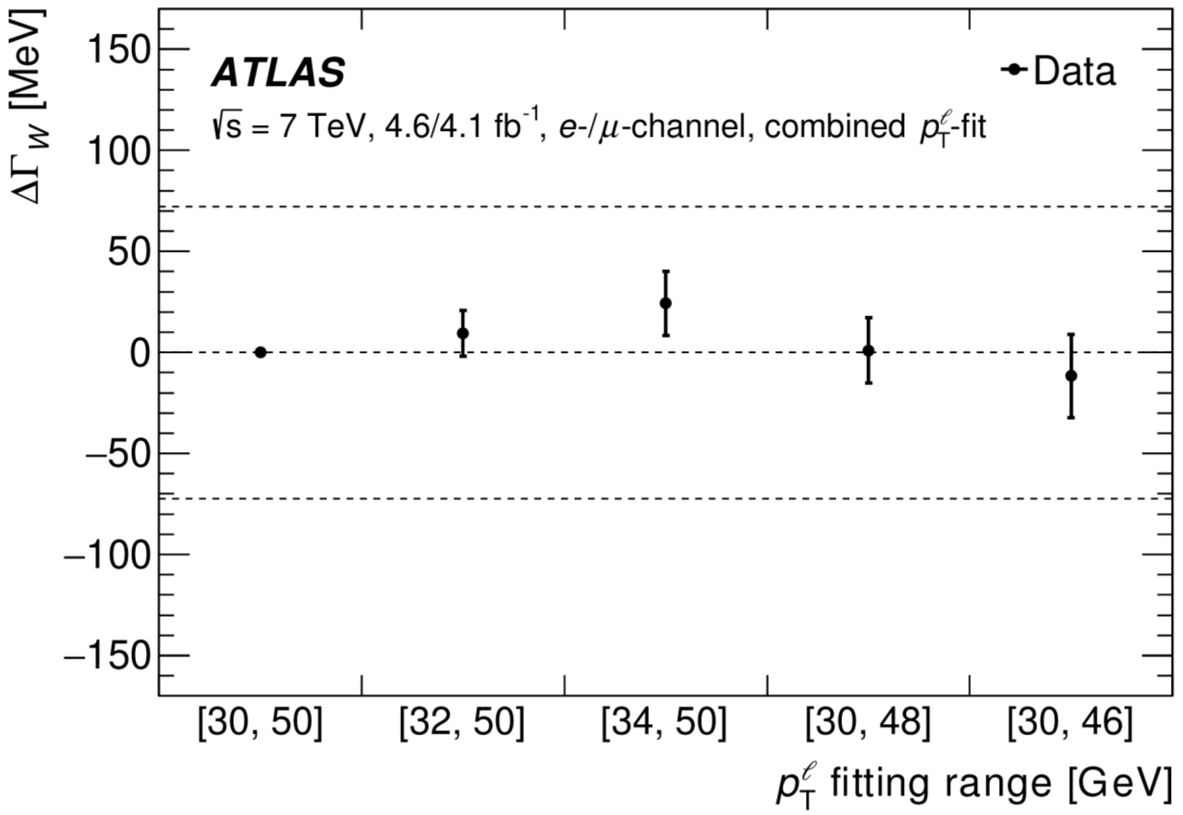
Component	Description
Generator	**Powheg** (v1/r1556)
Parton shower & hadronization	**Pythia 8** (v8.170), with **AZNLO tune**
Hard-process PDF	**CT10** (2018) or **CT18** (2024 baseline)
Parton-shower PDF	**CTEQ6L1**
FSR (final-state radiation)	**Photos** (v2.154)
Underlying event / pile-up	Simulated using **Pythia 8 (A2 tune)**
Tau decays	Simulated in Pythia with full polarization handling
W mass and width	Nominal values: $m_W = 80.399$ GeV, $\Gamma_W = 2085$ MeV
Detector simulation	Full Geant4 simulation with ATLAS geometry

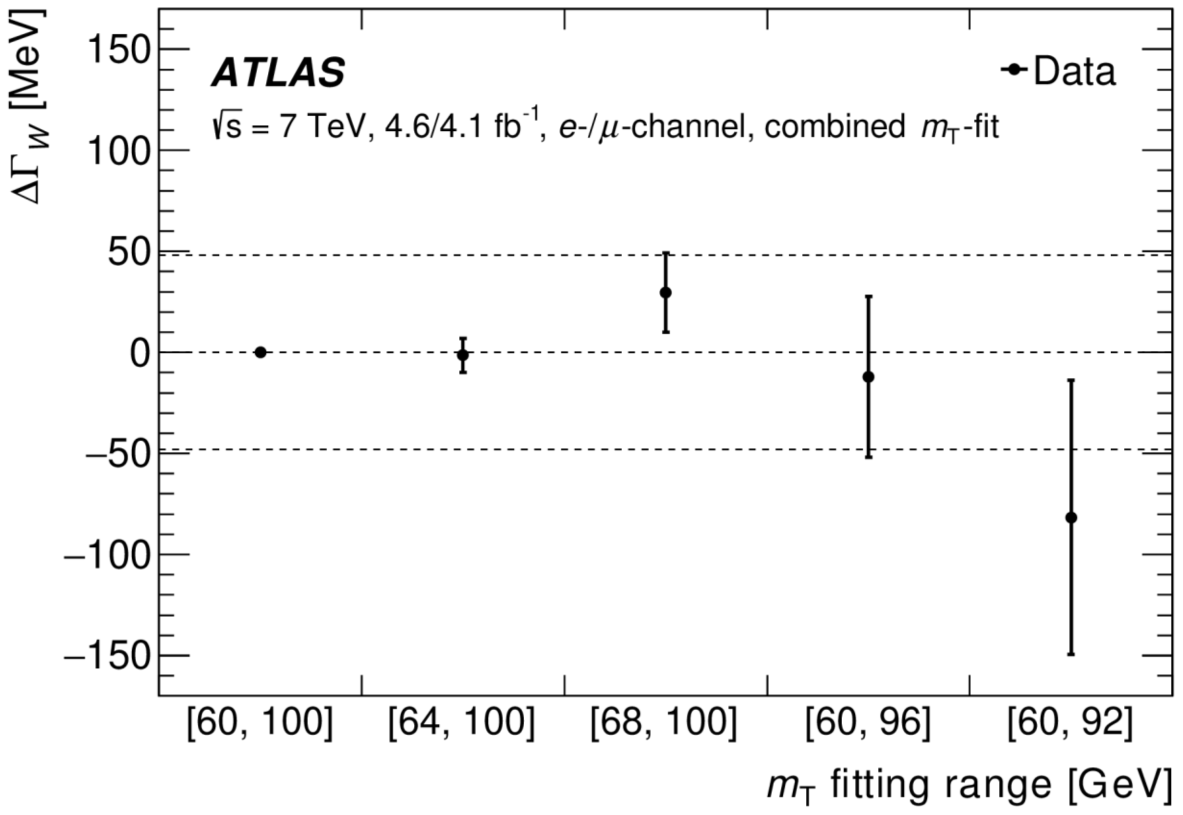
m_W fit stability



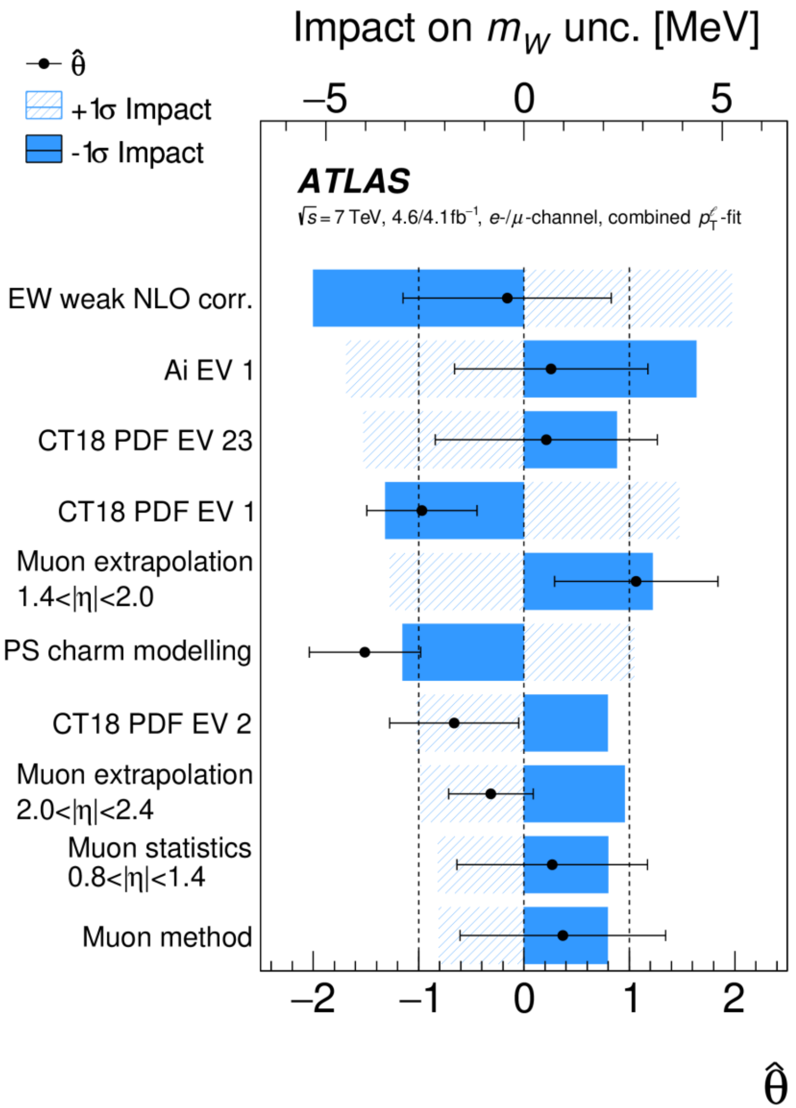


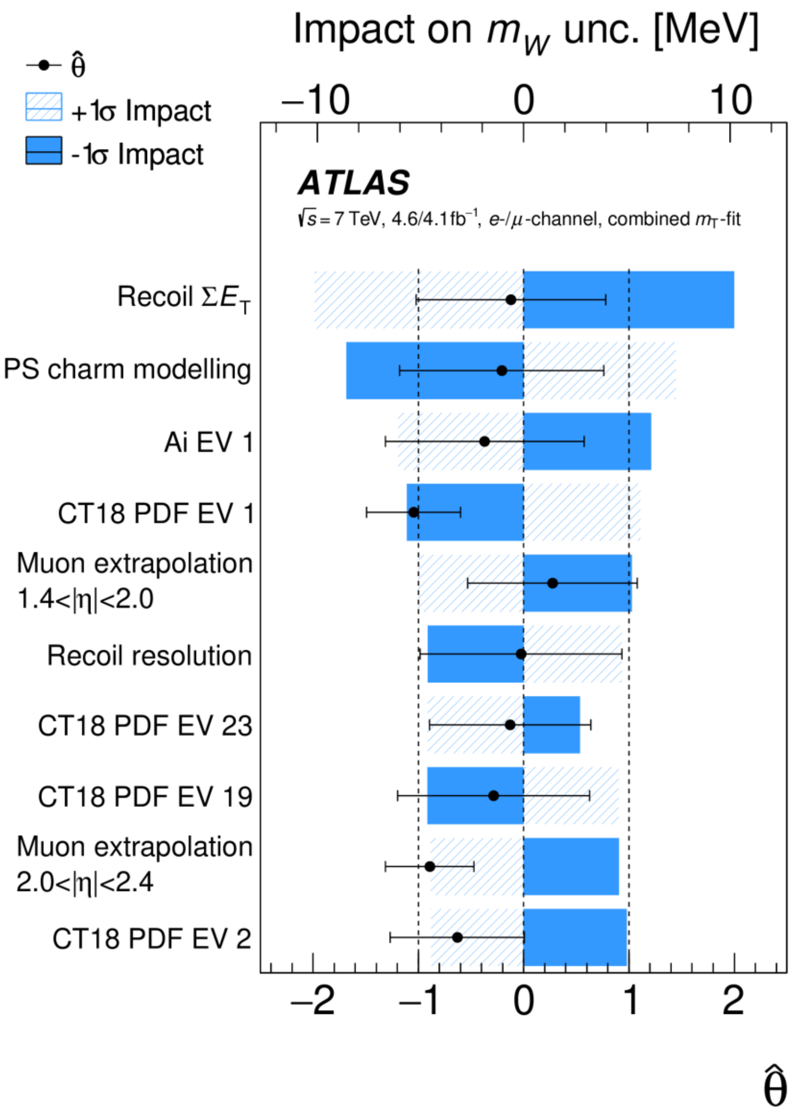
Γ_W fit stability





Impacts of systematic in m_W





Impacts of systematic in Γ_W