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

Andrés Pinto

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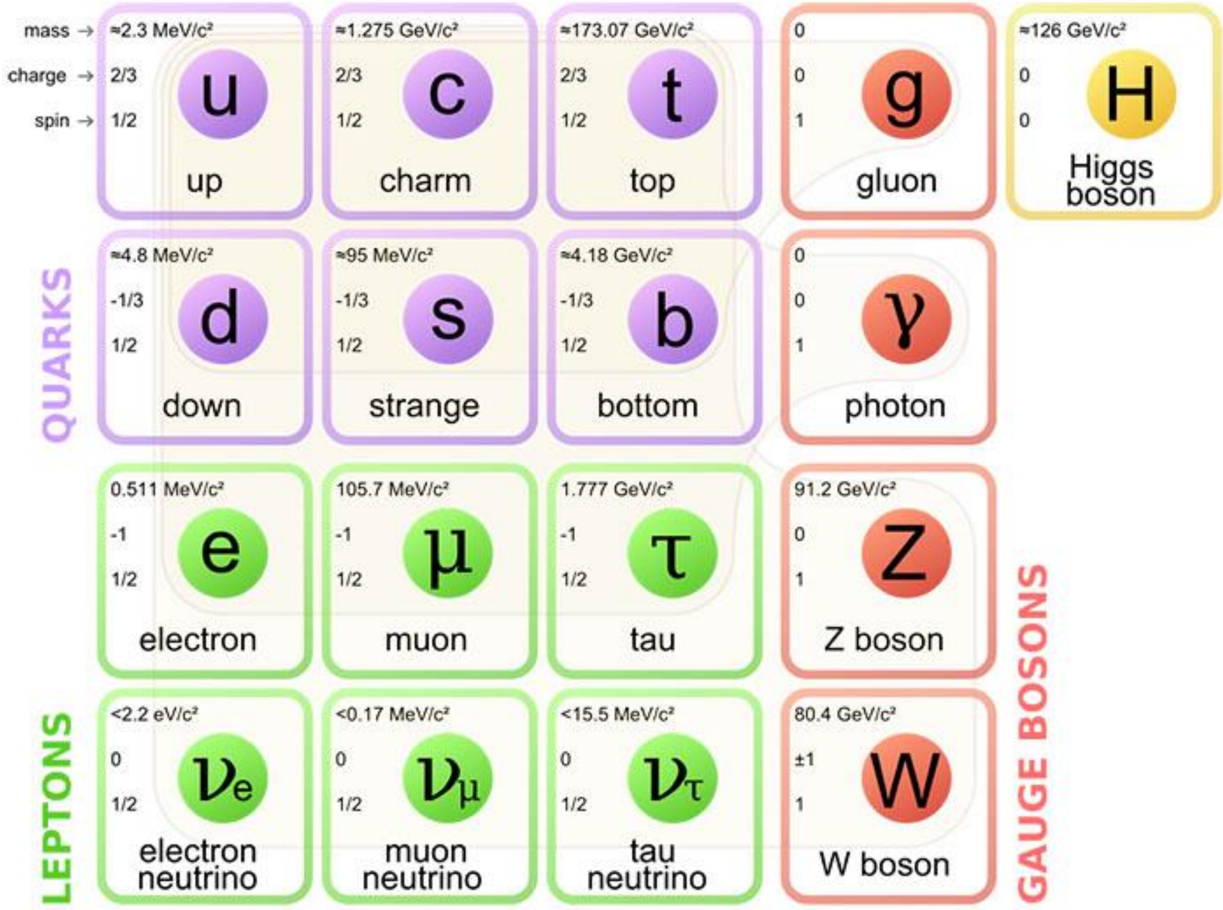
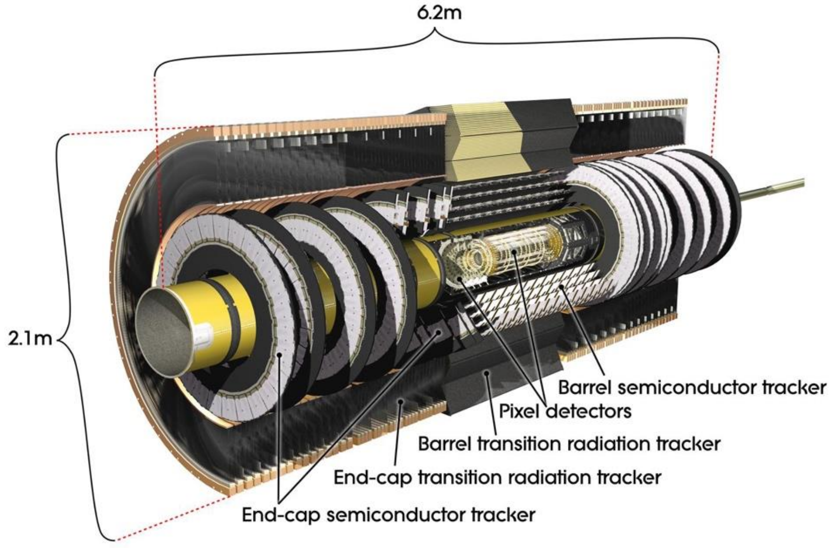
The Standard Model (SM) of particle physics

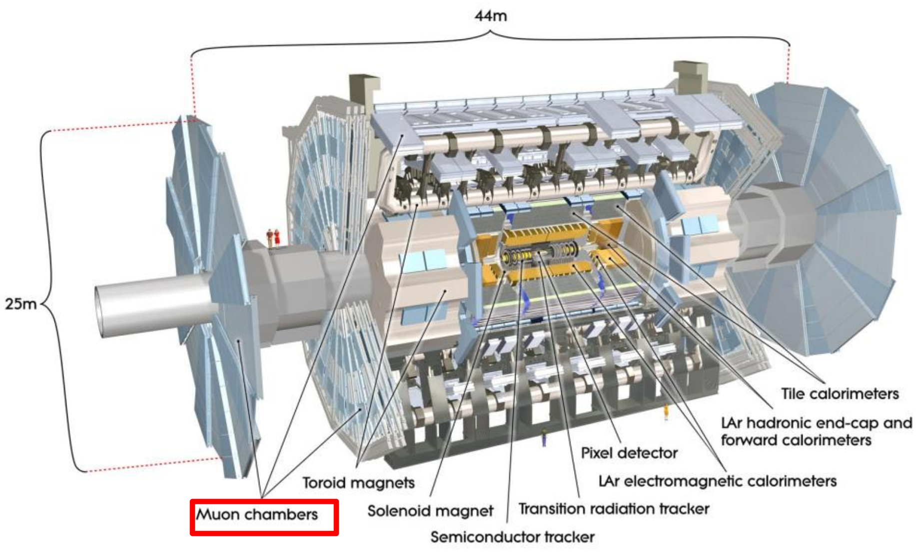


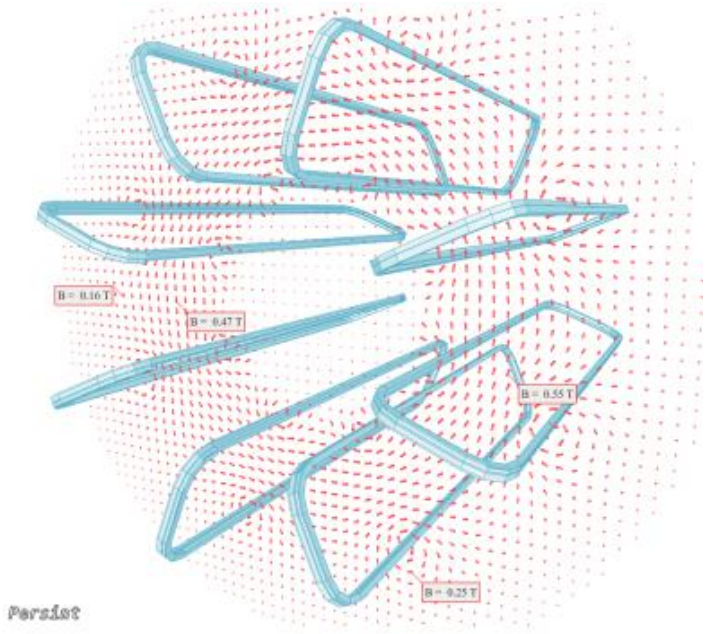
- Describes strong and Electroweak interactions.
- Explains the electroweak symmetry breaking via the Brout- Englert-Higgs mechanism.
- Particles:
  - Fermions: quarks and leptons.
  - Gauge bosons: gluon (g), photon (γ), $W^{\pm}$ and Z
  - Scalar boson: Higgs boson (H)

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. $pp \rightarrow W \rightarrow \mu\nu$.

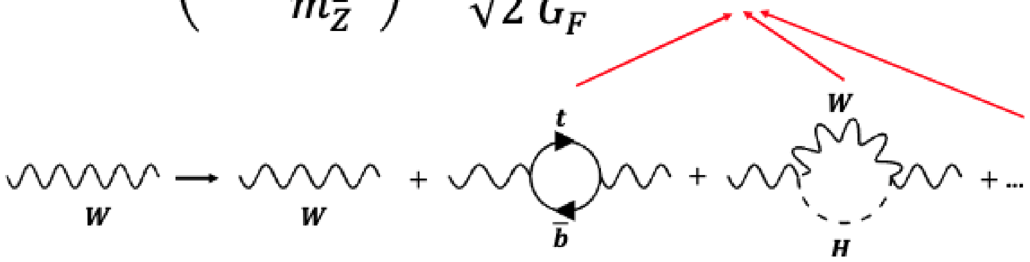
Why measuring the W boson mass?

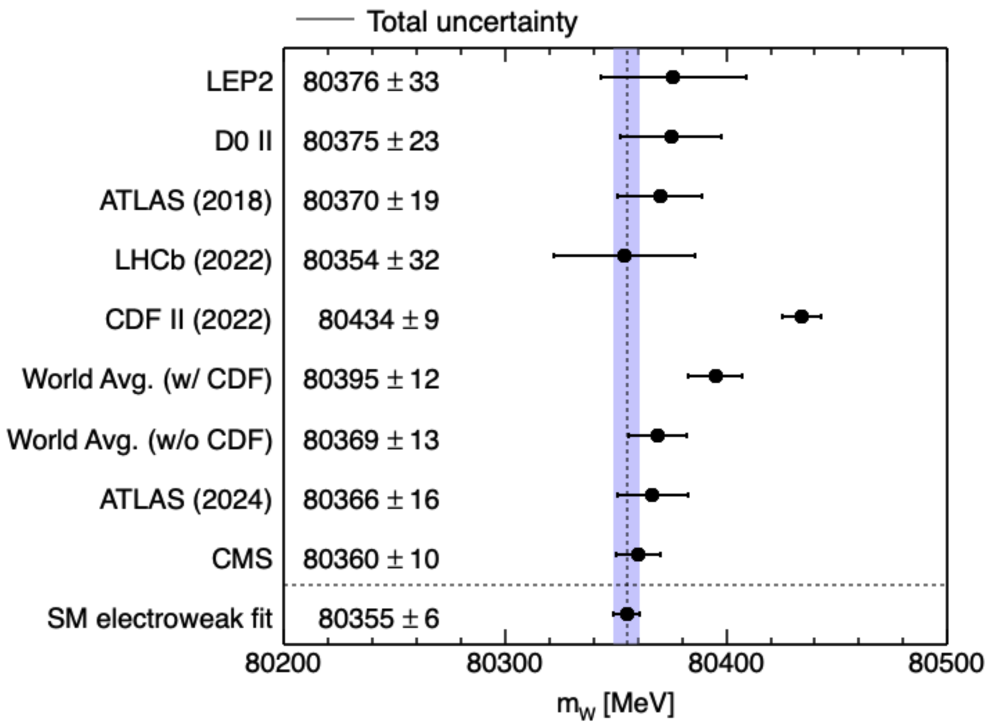
- The W boson mass (m_W) is important for testing the SM and BSM physics

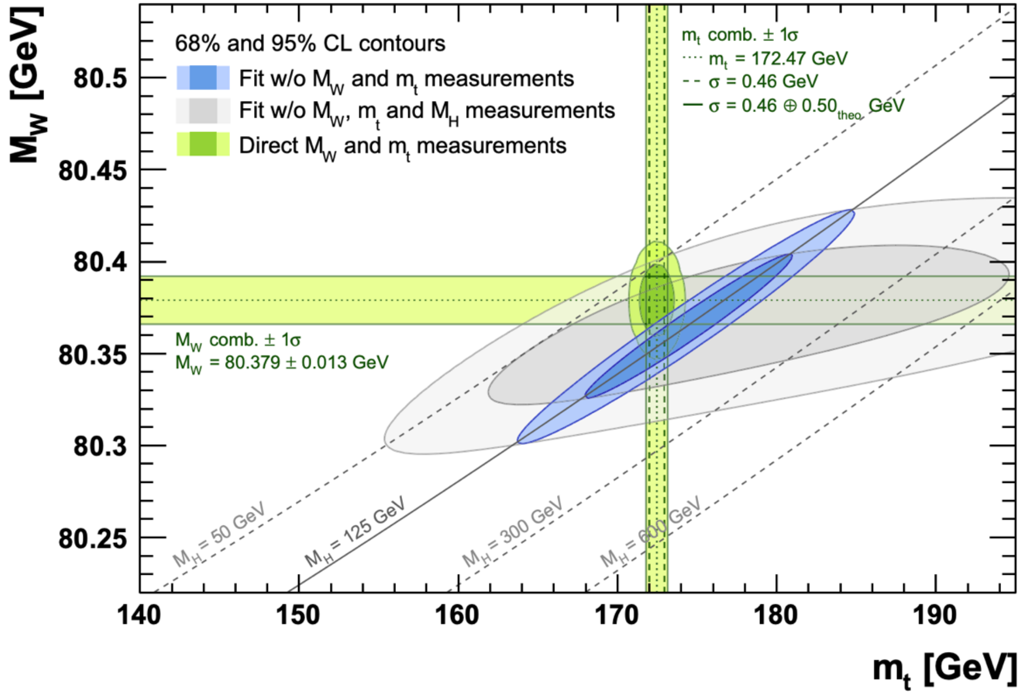
- BSM scenarios could modify m_W by radiative corrections Δr.

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

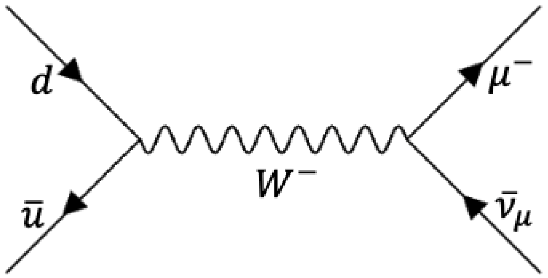
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}\,G_F}(1+\Delta r)$$

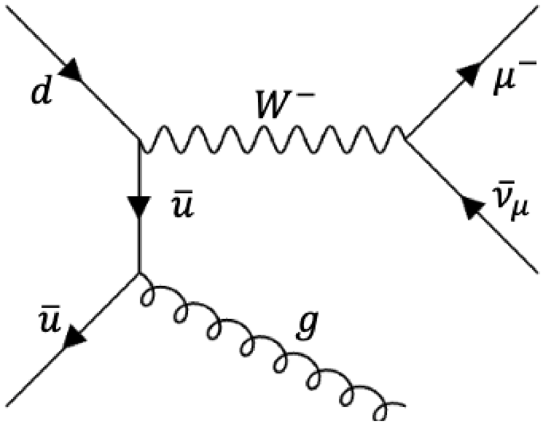


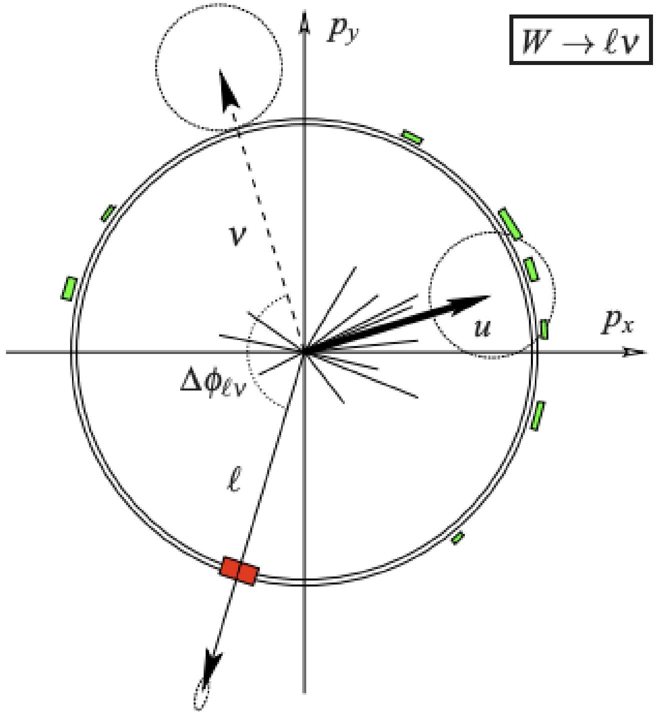




W boson production and leptonic decay







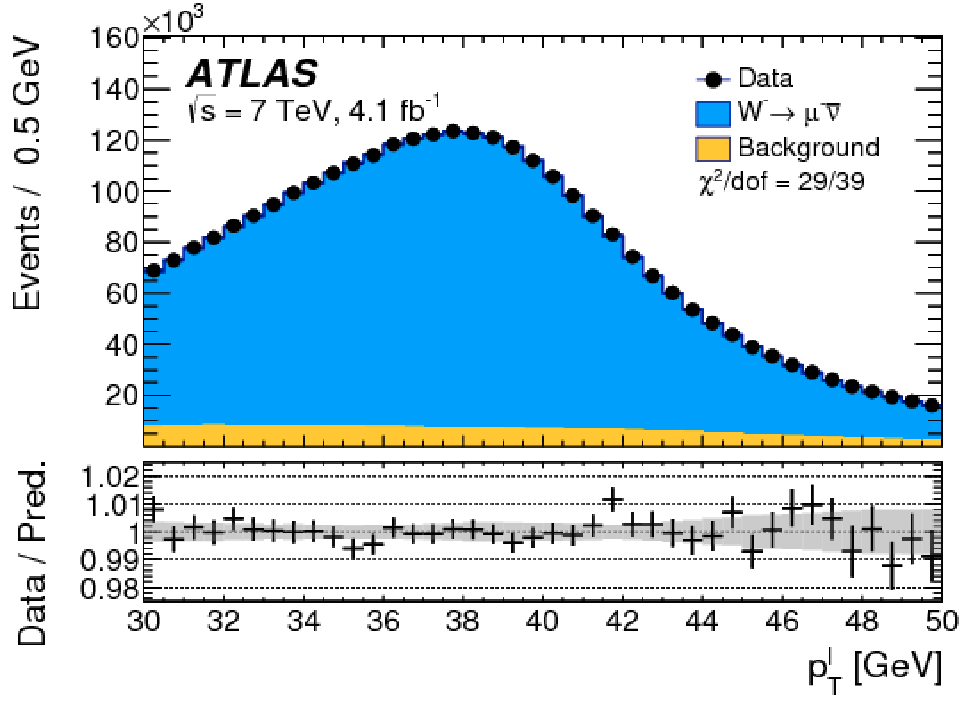
- In the SM, the W boson can decay in quarks and leptons and its mass is measured in the lepton channels: $W \to \ell\nu$ ($\ell = e^{\pm}, \mu^{\pm}$).
- Higher-order corrections lead to a non-trivial p_T^W distribution that is crucial to control.
- This channel is challenging since the neutrino escapes 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

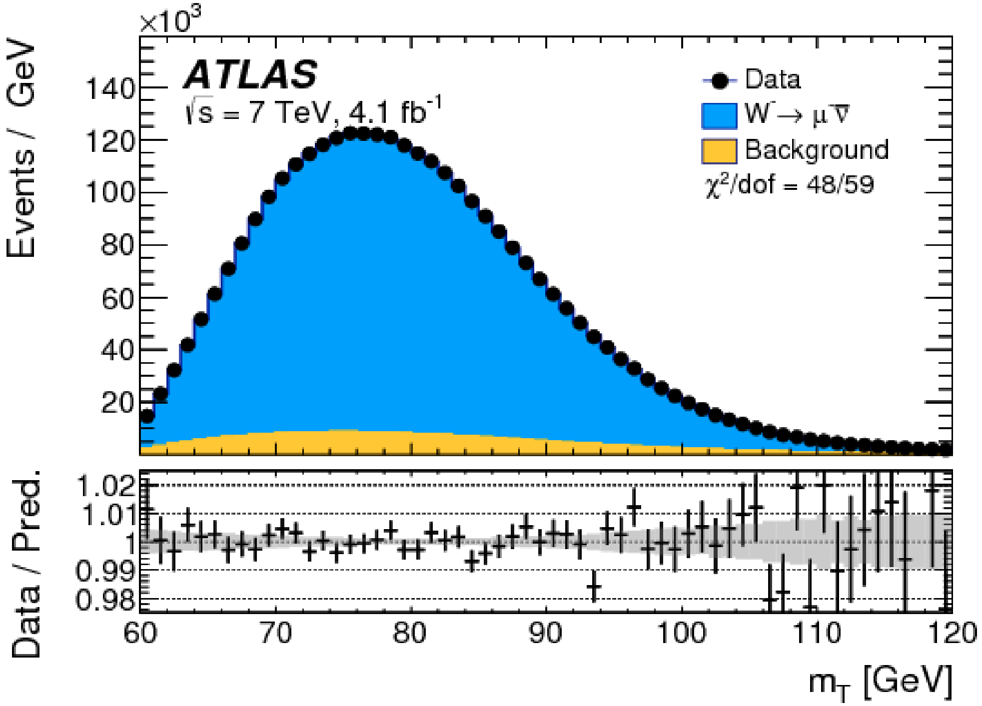
What do we measure?

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

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

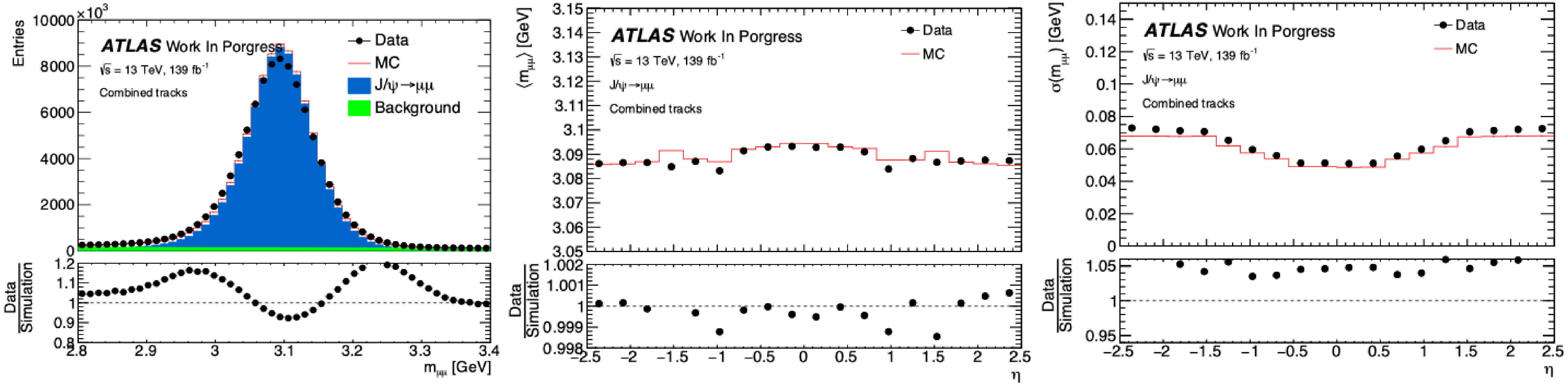
- For p_T^ℓ, a good lepton calibration is required.
- For m_T, a precise calibration of u_T is required.
- My work is focused on:
  - Muon momentum calibration
  - Parameter estimation and uncertainty components





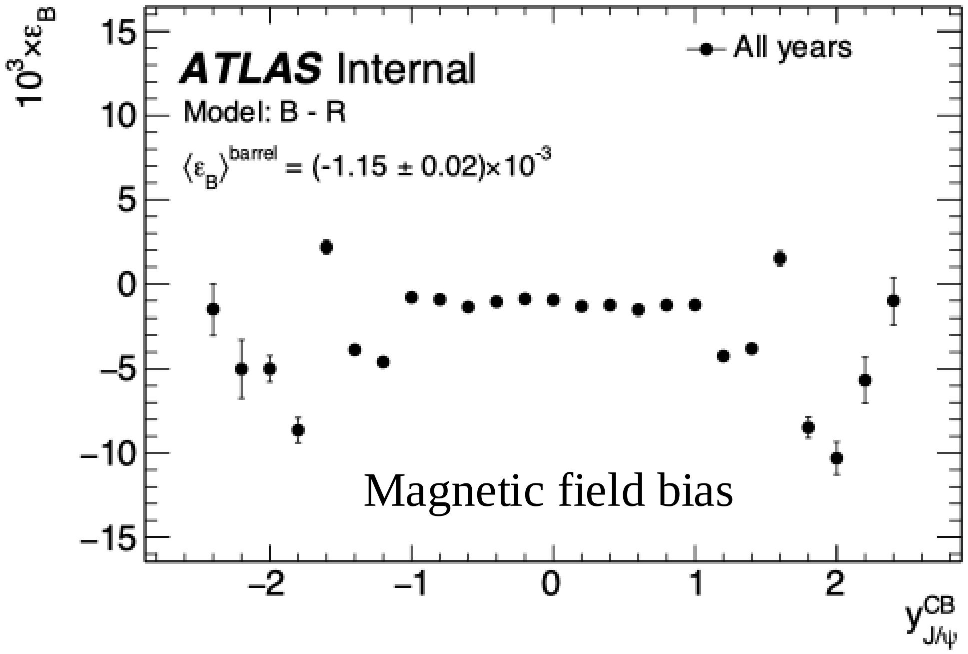
Detector calibration

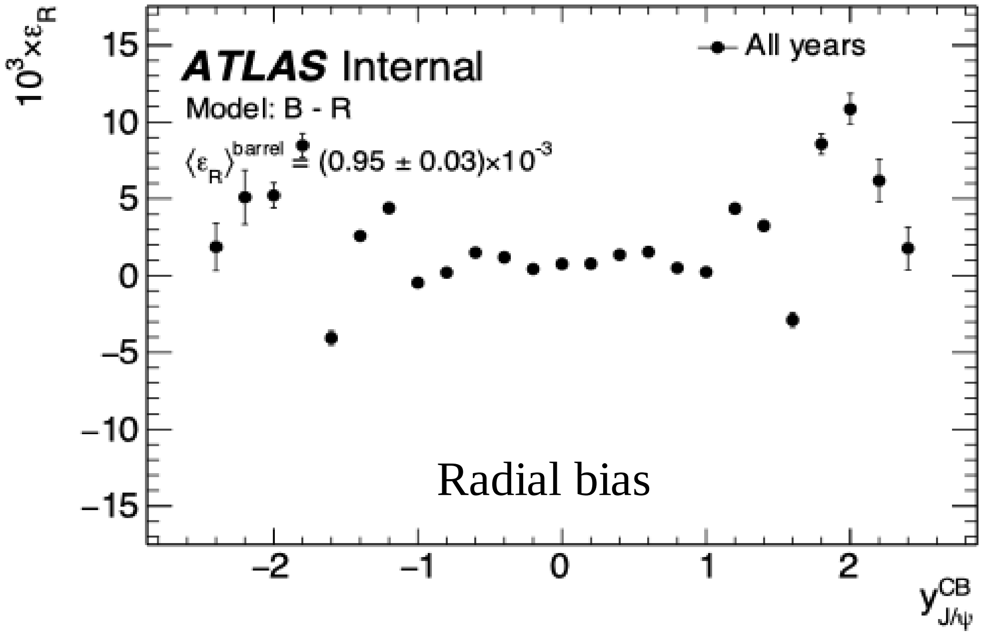
- Muons are reconstructed in the MS and ID. A combined (CB) candidate is formed using the MS + ID.
- Different sources can affect the momentum of the muons in the detector, known as:
  - Sagitta bias
  - Inner tracker detector deformations (length-scale bias)
  - Magnetic field and resolution mismodelling
- Before calibration, data and simulation are not in good agreement.



Length-scale bias

- To look for ID distortions, we can use the $J/\psi \rightarrow \mu\mu$ resonance in a frame defined in J/ψ direction of flight.
- The invariant mass versus the azimuthal angle scan can provide hints of possible ID deformations in rapidity
- These deformations are modelled using magnetic field distortions and radial distortions
- **Final fits show an average bias of about $\langle \boldsymbol{\varepsilon} \rangle \sim \mathbf{10^{-3}}$**
- These maps are used to correct the data





Magnetic field and resolution mismodelling

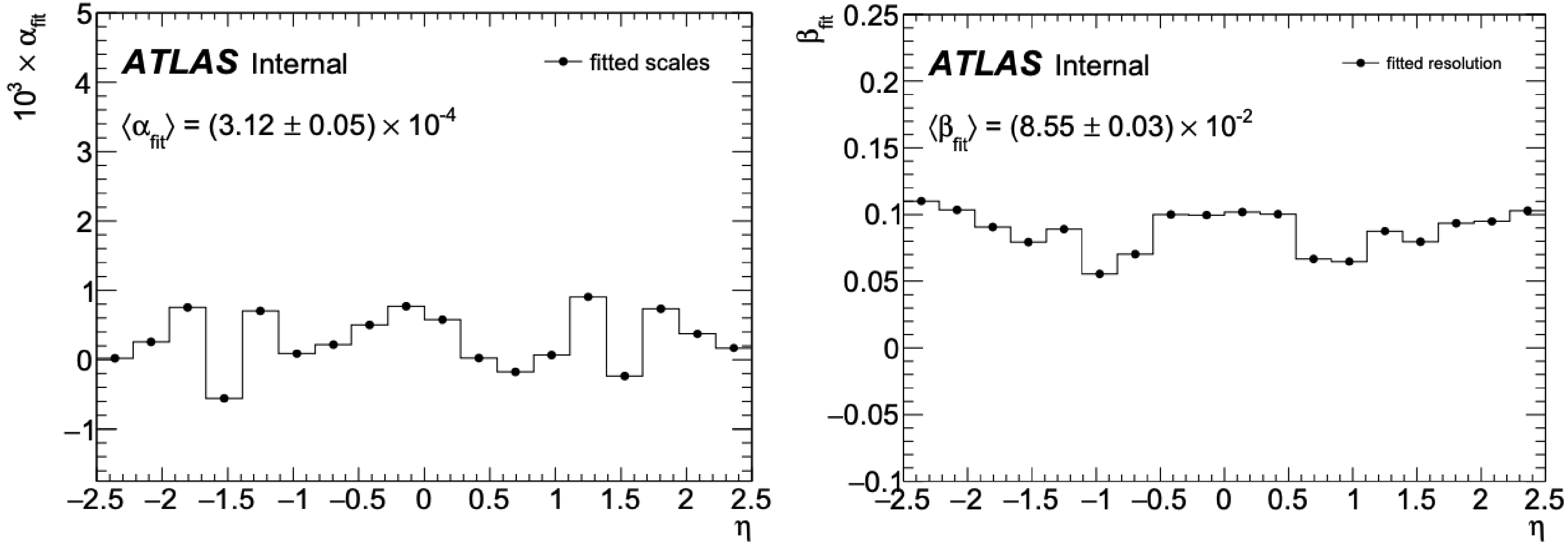
- After correcting for Sagitta and ID deformations, the next step is to correct for scale and resolution effects.
- The scale effect is modelled as a shift in the transverse momentum,

$$p_T^{scale} = (1+\alpha)\cdot p_T^{reco}$$

- The resolution is modelled by smearing the di-muon invariant mass

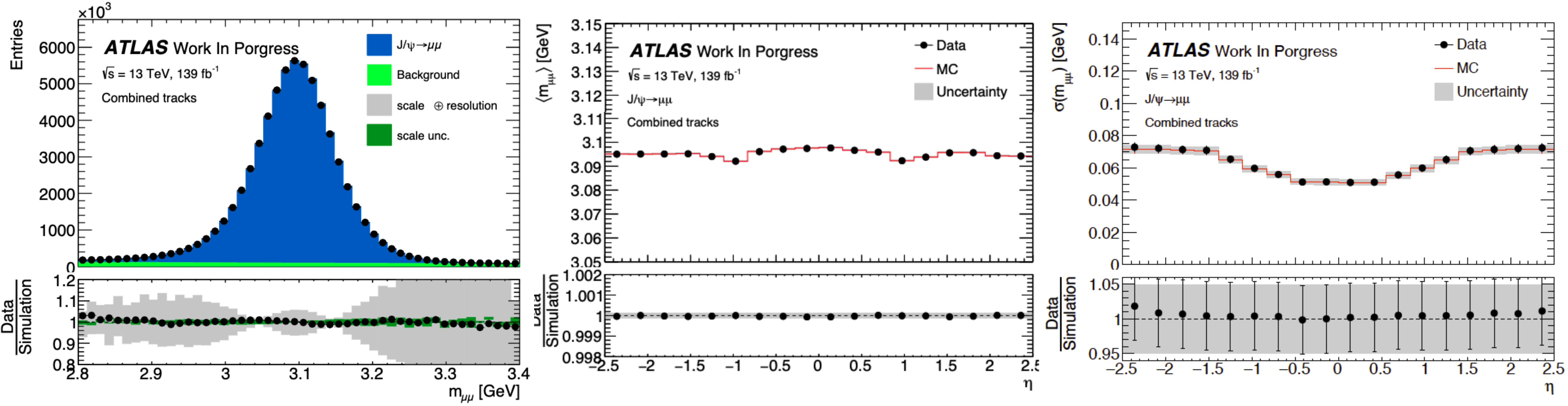
$$m_{\mu\mu}^{smear} = m_{\mu\mu}^{true} + (1+\beta)\cdot\left(m_{\mu\mu}^{reco} - m_{\mu\mu}^{true}\right)$$

- Templates are done to perform a fit of the invariant mass and to map the scale and resolution coefficients of the muons.



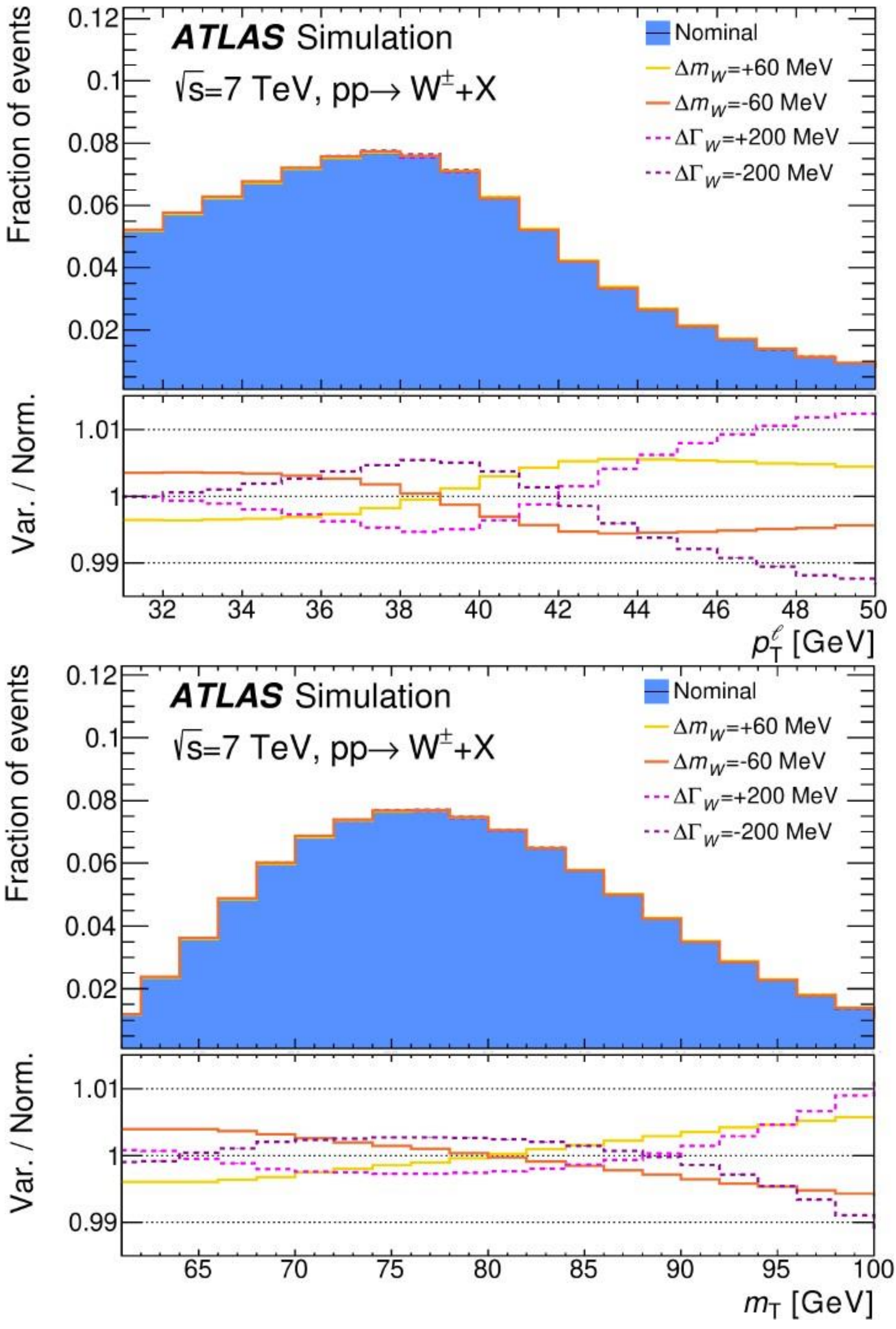
Final Muon Momentum Calibration

- After correction, a data-to-simulation agreement at the per mille level within the uncertainties is obtained. Systematics are evaluated by mass window variation.
- Relative systematic uncertainties of 8×10^{-5} in scale and 4×10^{-2} in resolution were found. **This is, a precision of about 6 MeV for m_W.**



How to measure the W boson mass?

- Once the calibration is done, we can use the corrected simulation to perform a fit data-to-simulation of W boson distributions.
- To extract m_W the template fit method is used.
- Different templates are done for different values of m_W.
- A likelihood function is maximized in order to find the template that best describes the data.
- At 7 TeV, two observables were used p_T^{ℓ} and m_T



Profile Likelihood fit for W mass

- The likelihood is giving by,

$$\mathcal{L}(\vec{m}|\vec{\theta},\vec{\alpha}) = \prod_i \text{Poisson}(m_i|\nu_i(\vec{\theta},\vec{\alpha})) \cdot \prod_r \text{Gauss}(\alpha_r|a_r)$$

Poisson likelihood for each bin

Constraint terms for the nuisance parameters: Systematics are assumed to be Gaussian distributed.

- m_i: Observed data per bin
- $\vec{\theta}$: POI (m_W)
- $\vec{\alpha}$: NP for systematics
- $\vec{a}$: Global observable for nuisance parameter.
- ν_i : Total prediction per bin ➡

$$\nu_{ji}\left(\vec{\theta},\vec{\alpha}\right) = \Phi \times \left[S_{ji}^{\text{nom}} + \sum_p \theta_p \times \left(S_{ji}^{\theta_p} - S_{ji}^{\text{nom}}\right)\right] + \sum_s \alpha_s \times \left(S_{ji}^{s} - S_{ji}^{\text{nom}}\right) + B_{ji}^{\text{nom}} + \sum_b \alpha_b \times \left(B_{ji}^{b} - B_{ji}^{\text{nom}}\right),$$

Φ : normalization factor.

S : signal

B : background

Profile Likelihood fit for W mass

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

Nuisance parameters covariance matrix

Systematic uncertainty components

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

Systematic uncertainty components

Parameter of interest covariance matrix

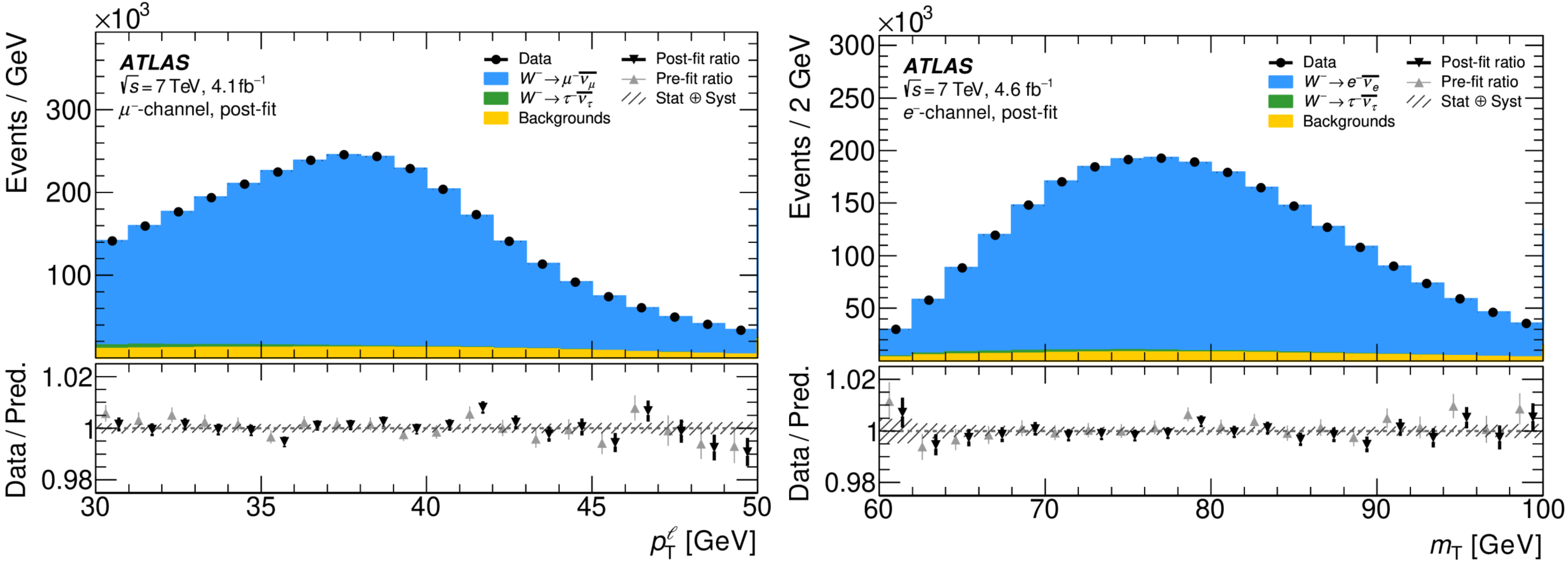
$$\sigma_{\text{total}} = \sqrt{\mathrm{cov}(\hat{\theta}_p, \hat{\theta}_p)},$$

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

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

Pre-fit and Post-fit plots

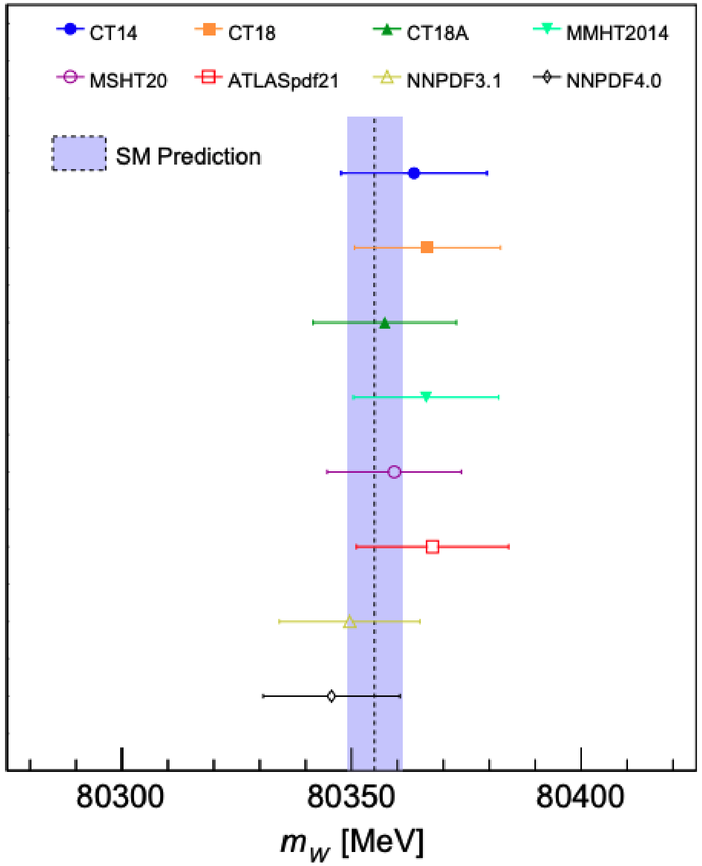
The post-fit, $|\eta|$ −inclusive p_T^ℓ, m_T distributions obtained with CT18 agree with the data within the uncertainties.

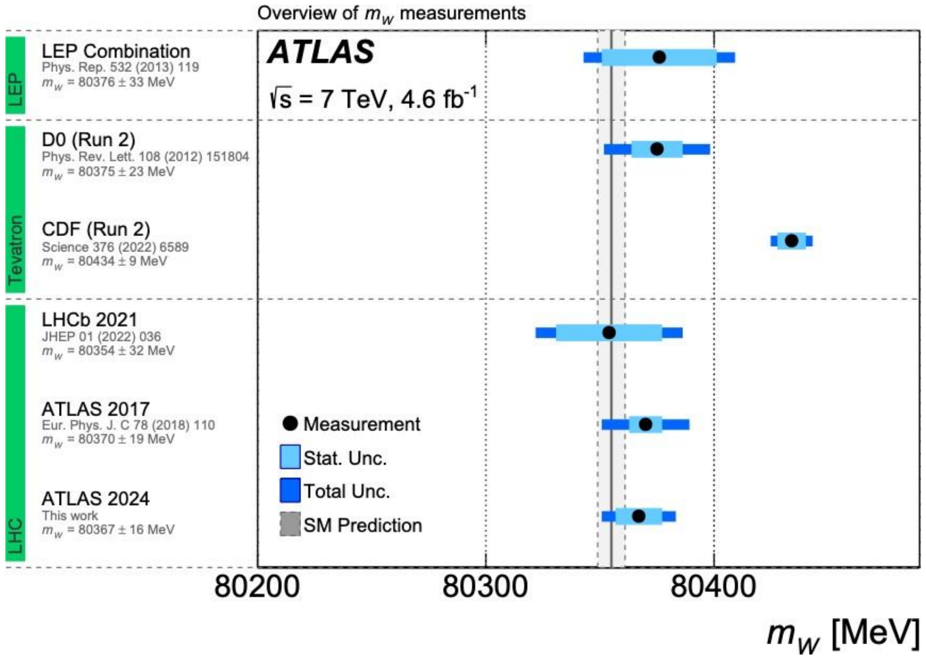


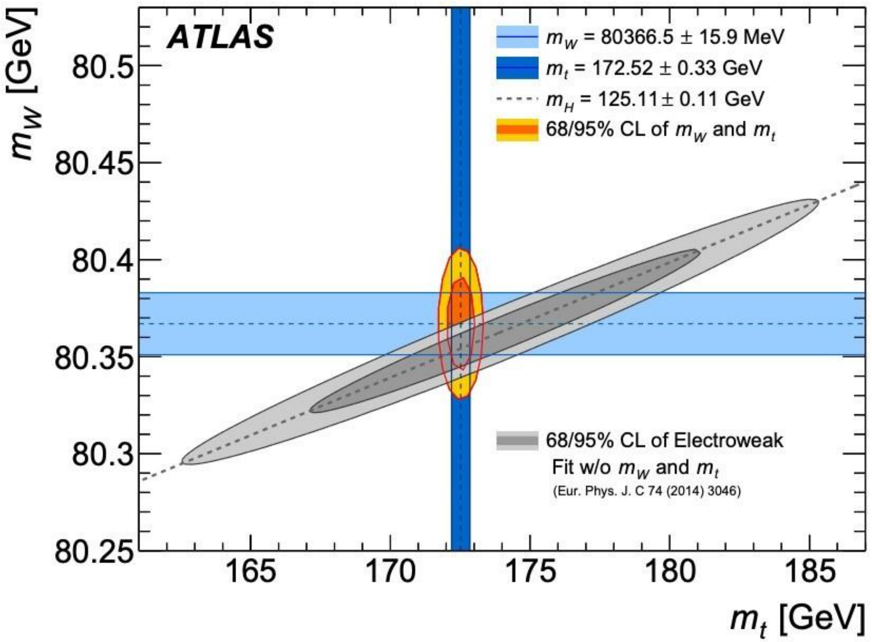
m_W measurement at $\sqrt{s} = 7$ TeV

- 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.
- Result agrees with the SM and improvement with respect to 2017 of about 15%.

(arXiv:2403.15085).







m_W measurement at $\sqrt{s} = 7$ TeV

- Final result corresponds to,

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

- 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

- In 2017, PDF unc. was ~ 9 MeV and $A_i + p_T^W$ unc. was ~ 8 MeV which means an improvement of about 37% and 45% respectively

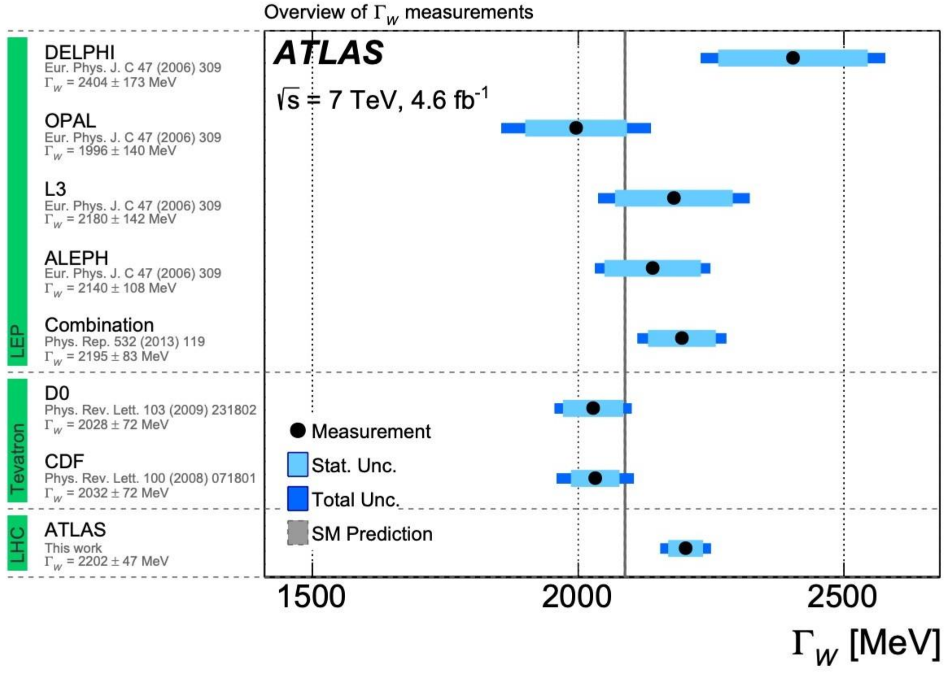
Measuring the W width at 7 TeV

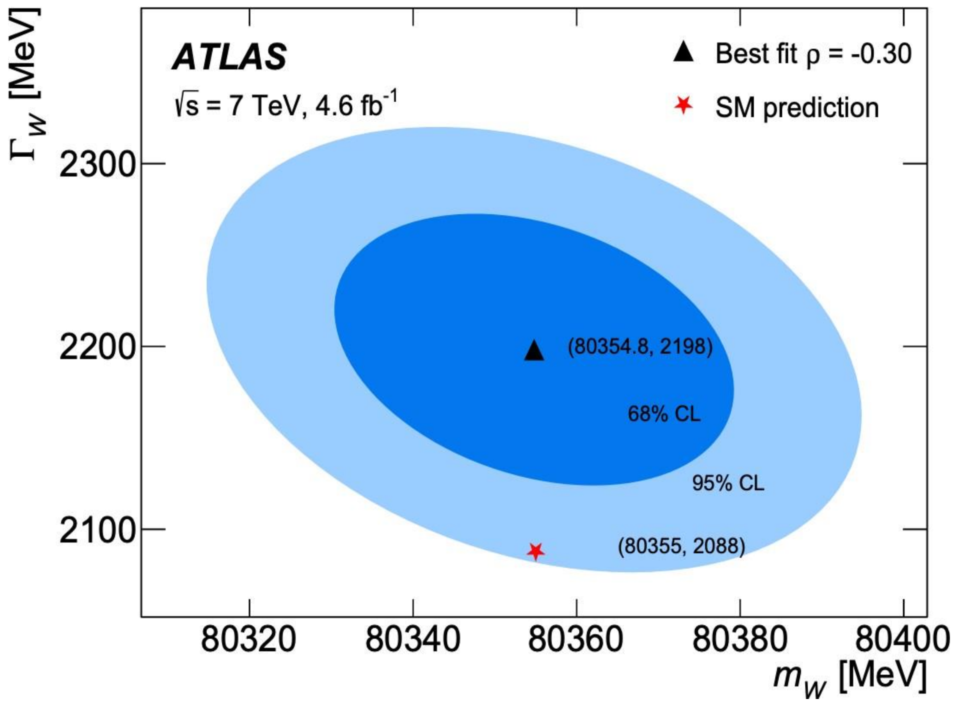
- The W-boson width was measured in a similar strategy. This is so far, the most precise measurement of Γ_W.
- Result is consistent with the SM within 2 standard deviations.

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

- With uncertainty decomposition:

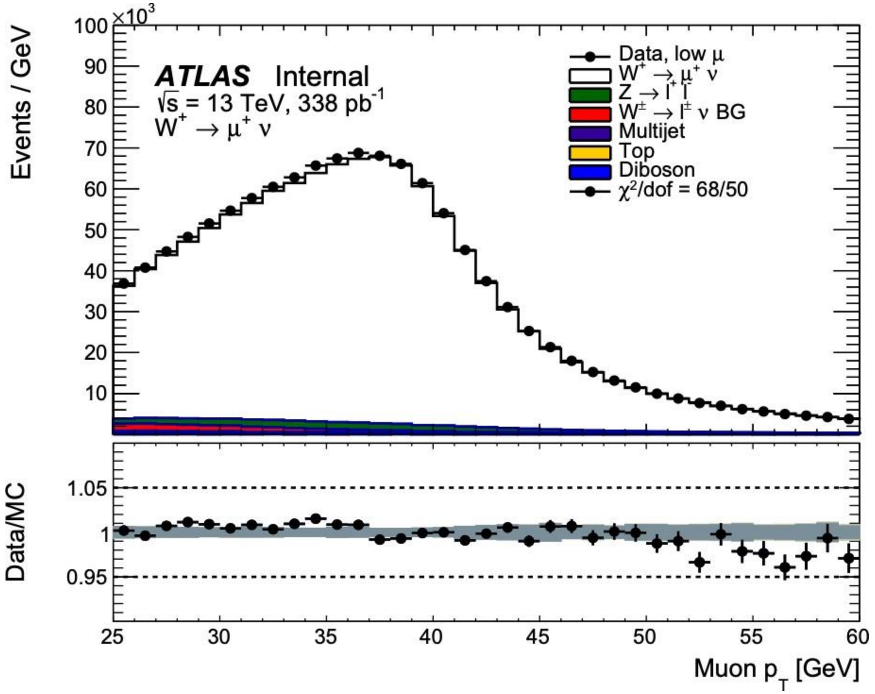
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

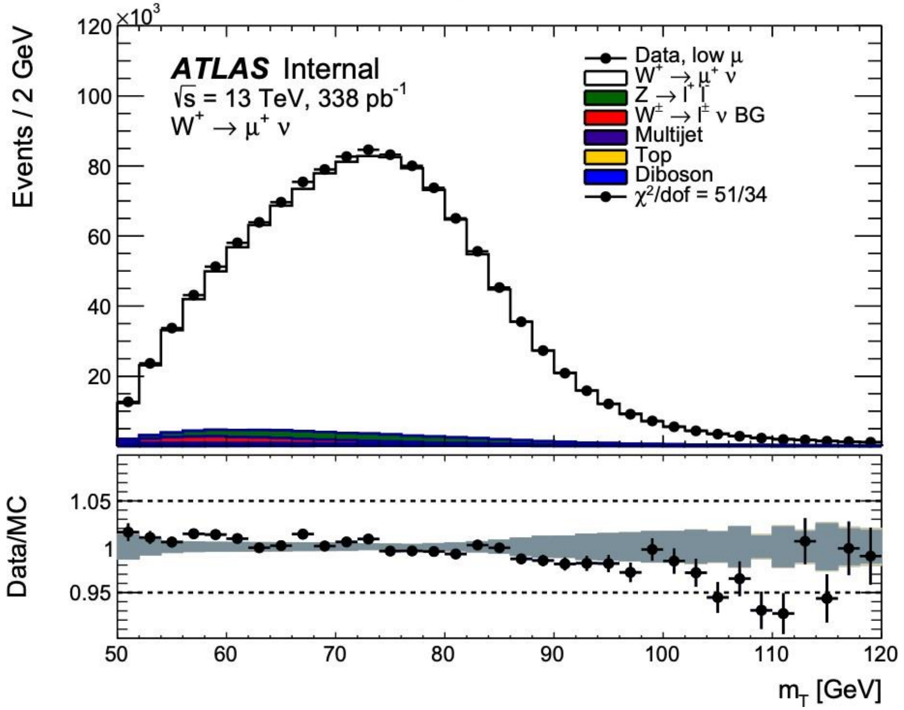




Current status in m_W

- Currently, 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 is of particular interest since it provides a better resolution in the transverse mass.
- This result in an increased sensitivity of m_T to m_W.
- These conditions provide a good modelling for the transverse momentum of the W boson, p_T^W, which is one of the large uncertainty sources in this measurement.
- Preliminary results show a competitive precision compared to other experiments.





Conclusions

- My work was focused on the W-boson mass measurement for which I developed the muon calibration and a fitting strategy for the uncertainty components.
- Muon calibration work chain shows a good performance with a data-to-simulation agreement at the per mille level.
- Profile likelihood fit improved the m_W and Γ_W precision with respect to 2017 measurement, leading to:

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

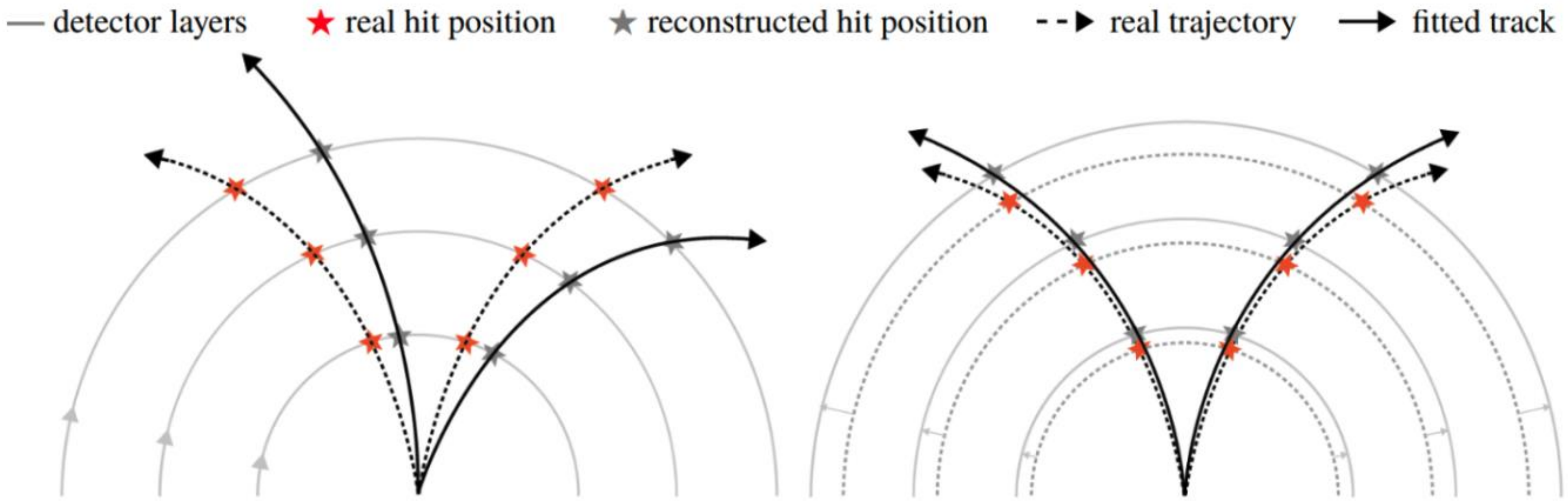
$$\Gamma_W = 2202 \pm 47\ (\pm 32 \pm 34)\ \text{MeV}$$

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

BACKUP

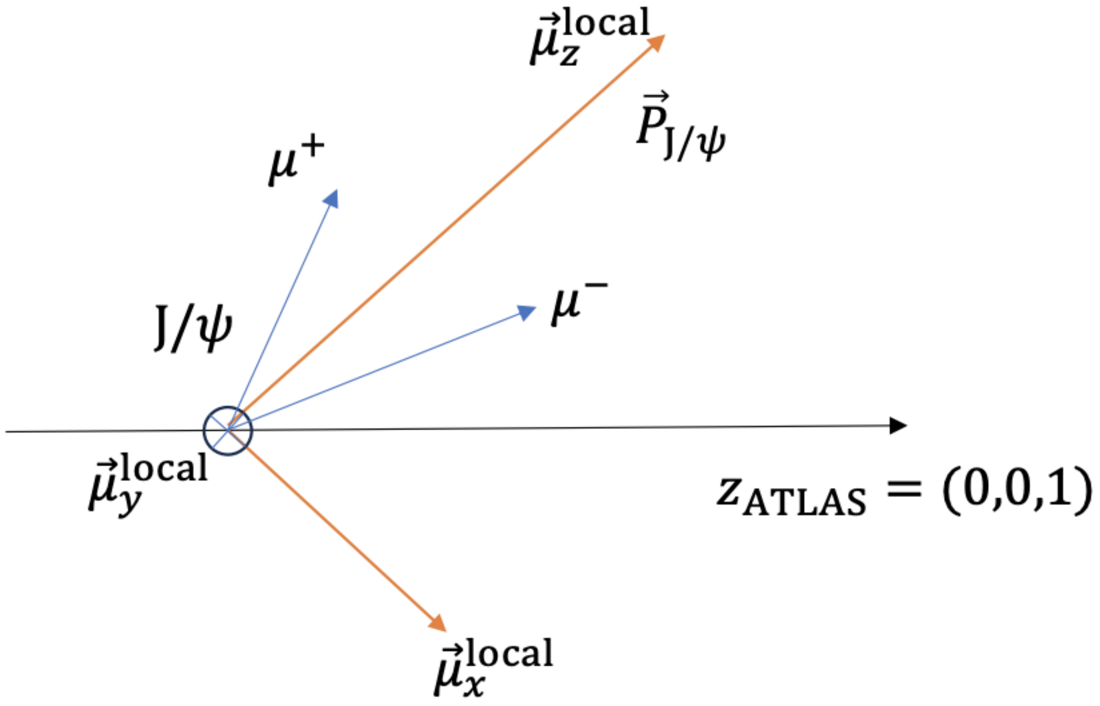
Tracking biases

- The two most common deformations that bias the curvature (momentum) are:
    - **Sagitta bias:** rotation of the detector layers (charge dependent).
    - **Length-scale bias:** radial expansion of the detector layers (charge independent).



Local frame

- Defined in the J/ψ momentum direction.
- This frame is not affected by a boost
- We defined only one angle: ϕ
- Templates are prepared to fit the data

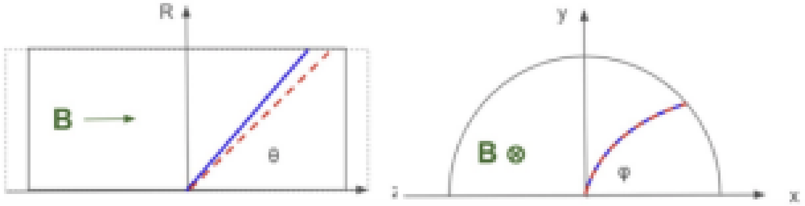


$$\vec{\mu}_z^{\text{local}} = \frac{\vec{P}_{J/\psi}}{|\vec{P}_{J/\psi}|} \qquad \vec{\mu}_x^{\text{local}} = \frac{\vec{\mu}_y^{\text{local}} \times \vec{\mu}_z^{\text{local}}}{|\vec{\mu}_y^{\text{local}} \times \vec{\mu}_z^{\text{local}}|}$$

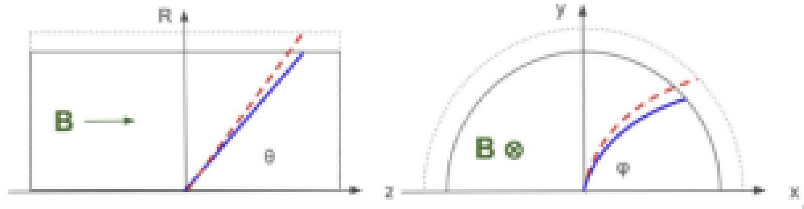
$$\vec{\mu}_y^{\text{local}} = \frac{\vec{\mu}_z^{\text{local}} \times z_{\text{ATLAS}}}{|\vec{\mu}_z^{\text{local}} \times z_{\text{ATLAS}}|} \qquad \phi^+_{\text{local}} = \text{atan}\left(\frac{\vec{p}^+ \cdot \mu_y^{\text{local}}}{\vec{p}^+ \cdot \mu_x^{\text{local}}}\right)$$

ID deformation models

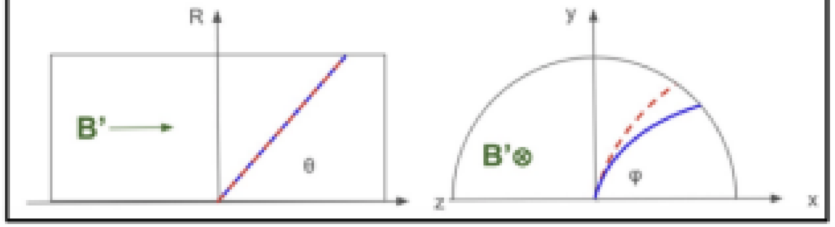
- **Longitudinal (Z) model:**
- Affects the **longitudinal** component of the momentum.
- $p'_T = p_T$
- $p'_z = (1 + \varepsilon_z) \cdot p_z$
- $\cot\theta' = (1 + \varepsilon_z) \cdot \cot\theta$



- **Radial (R) model:**
- Affects the **transverse** component of the momentum.
- $p'_T = (1 + \varepsilon_R) \cdot p_T$
- $p'_z = p_z$
- $\cot\theta' = \cot\theta / (1 + \varepsilon_R)$



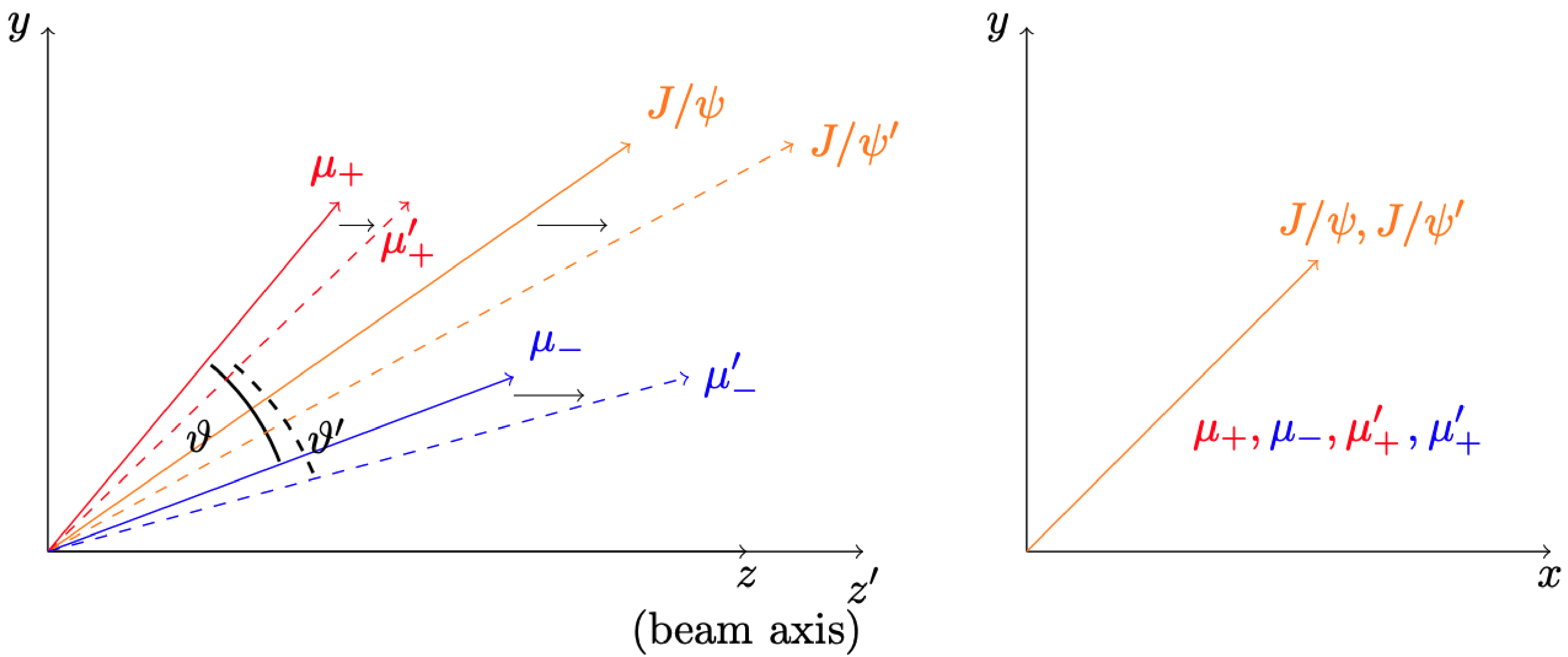
- **Magnetic field (B) model:**
- Affects both transverse and longitudinal component of the momentum.
- $p'_T = (1 + \varepsilon_B) \cdot p_T$
- $p'_z = (1 + \varepsilon_B) \cdot p_z$
- $\cot\theta' = \cot\theta$



Length-scale bias

Detector deformations can be studied using the invariant mass in $J/\psi \to \mu\mu$ decay.
Both muons at same φ and different pseudo-rapidity η.

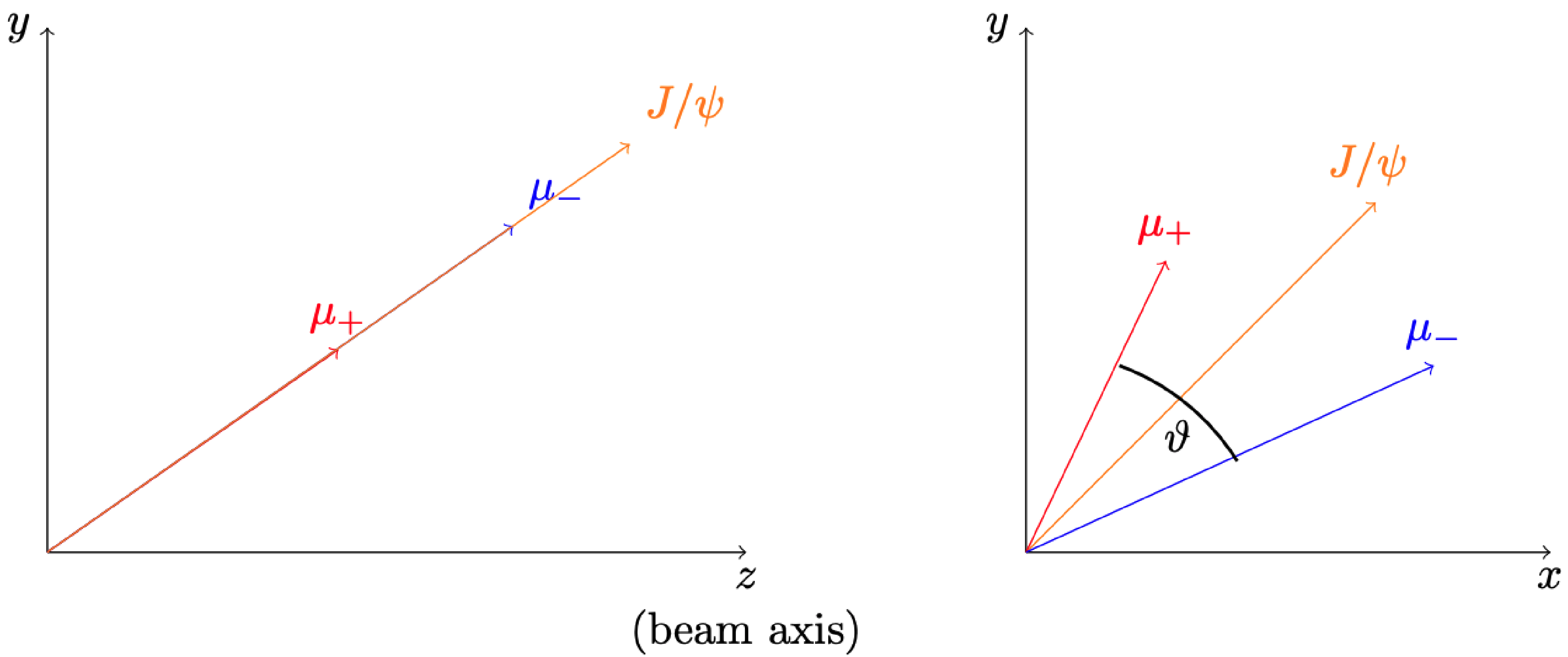
$$m_{\mu\mu}^2 \propto (1 - \cos\vartheta) \Longrightarrow m_{\mu\mu}^{2,\prime} \propto (1 - \cos\vartheta')$$



Length-scale bias

Both muons at different φ and same pseudo-rapidity η.

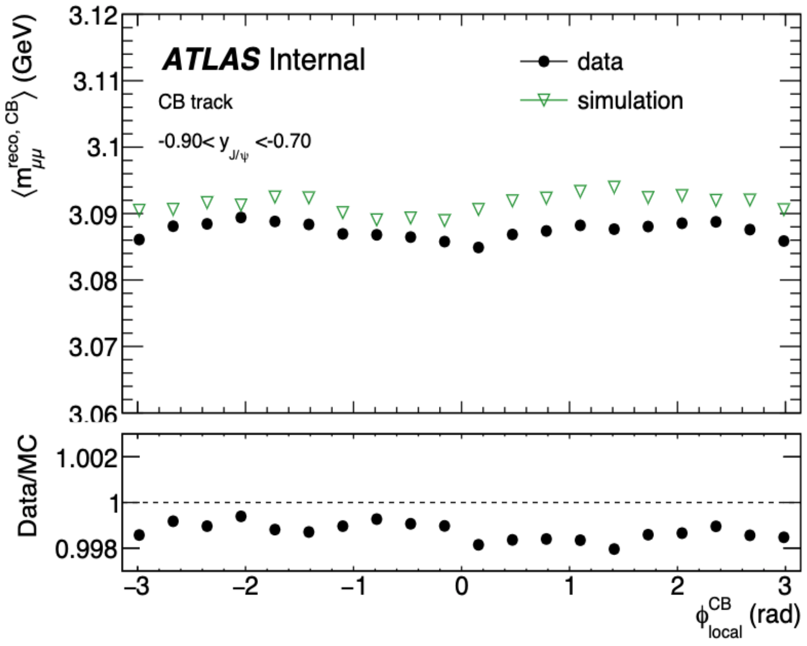
$$m_{\mu\mu}^2 \propto (1 - \cos\vartheta)$$



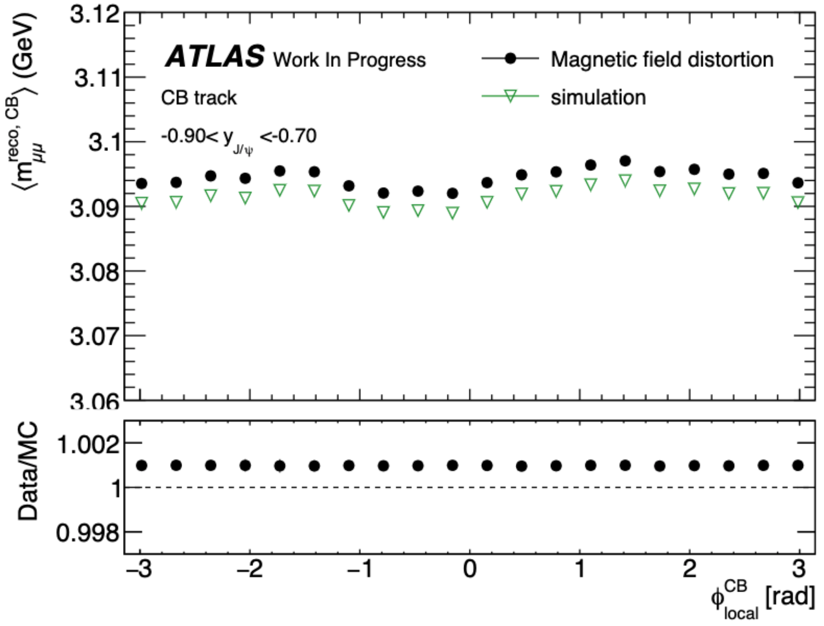
Similar behavior could appear if we expand the radial component ($x - y$ plane).

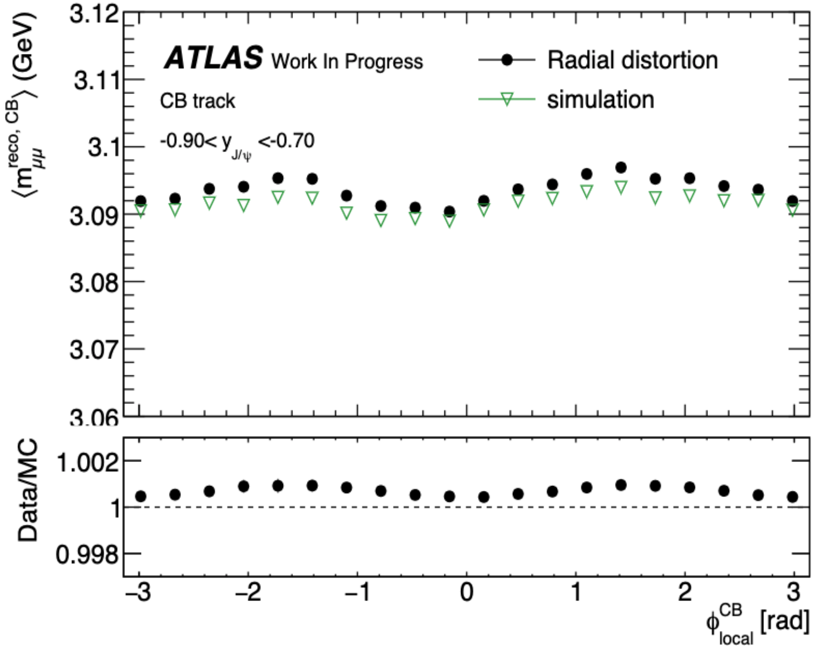
Data and simulation deformations

Data-to-simulation



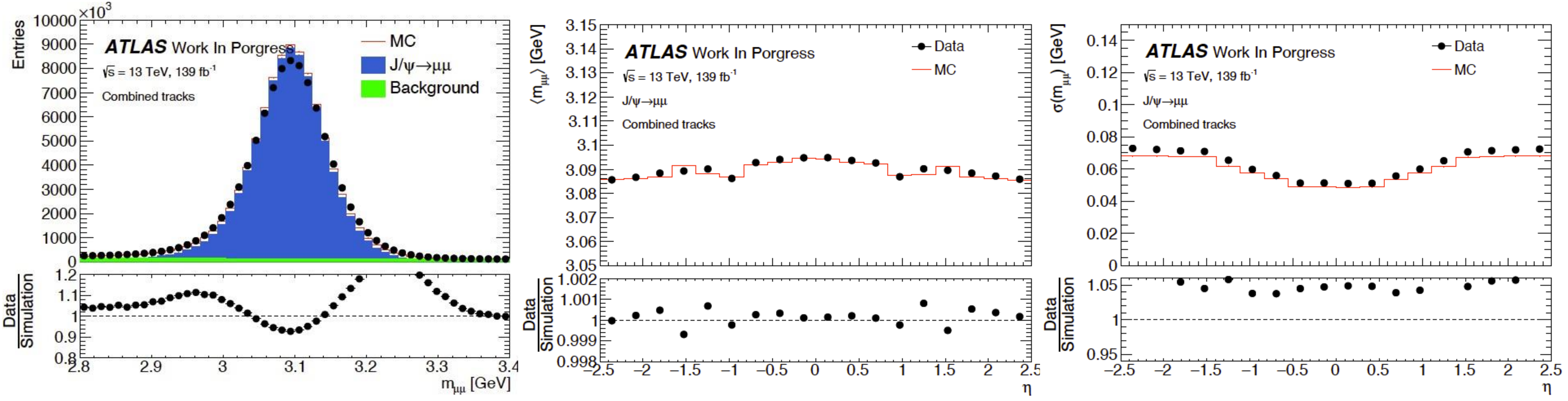
Model-to-simulation





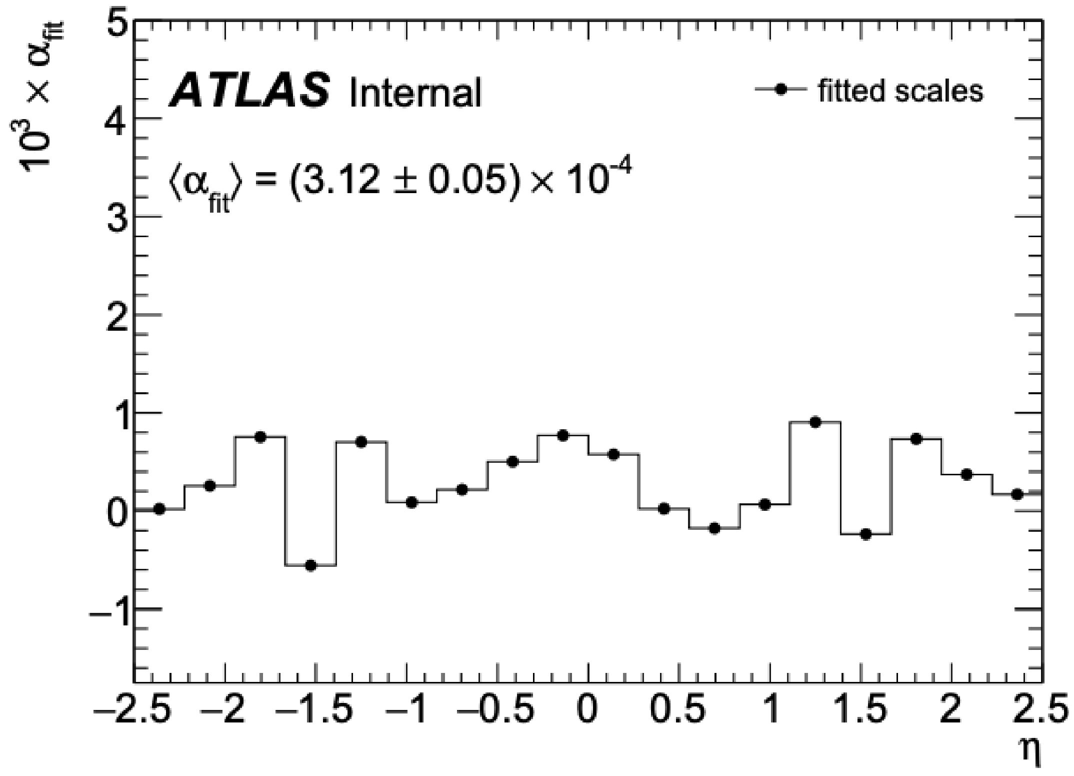
Correcting the ID deformations

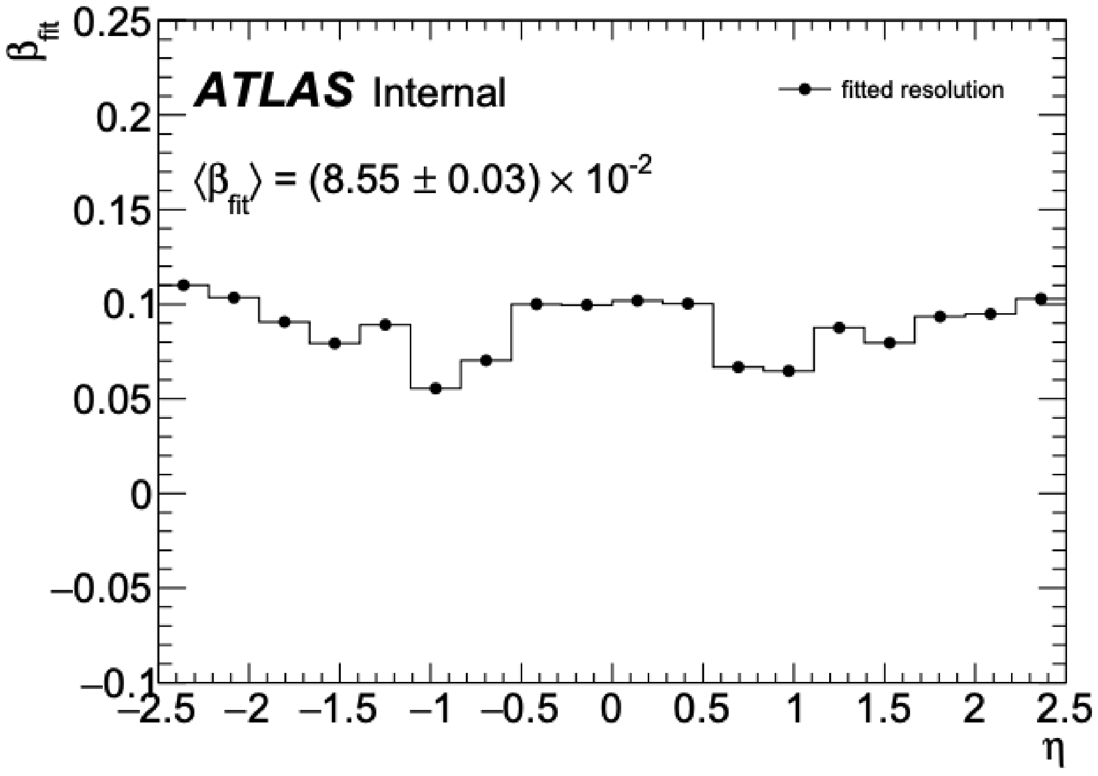
- After correction, an improvement in the scale is obtained (with a small residual).
- An additional step is needed to improve the resolution and remove the residual in scale.



Scale and resolution maps

Scales are found in average $\langle\alpha_{fit}\rangle = (3.12 \pm 0.05) \times 10^{-4}$ while the resolution is about $\langle\beta_{fit}\rangle = (8.55 \pm 0.03) \times 10^{-2}$.





Kinematic categories and uncertainties

The fits are is performed in 28 kinematic categories

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]

The following uncertainties are considered:

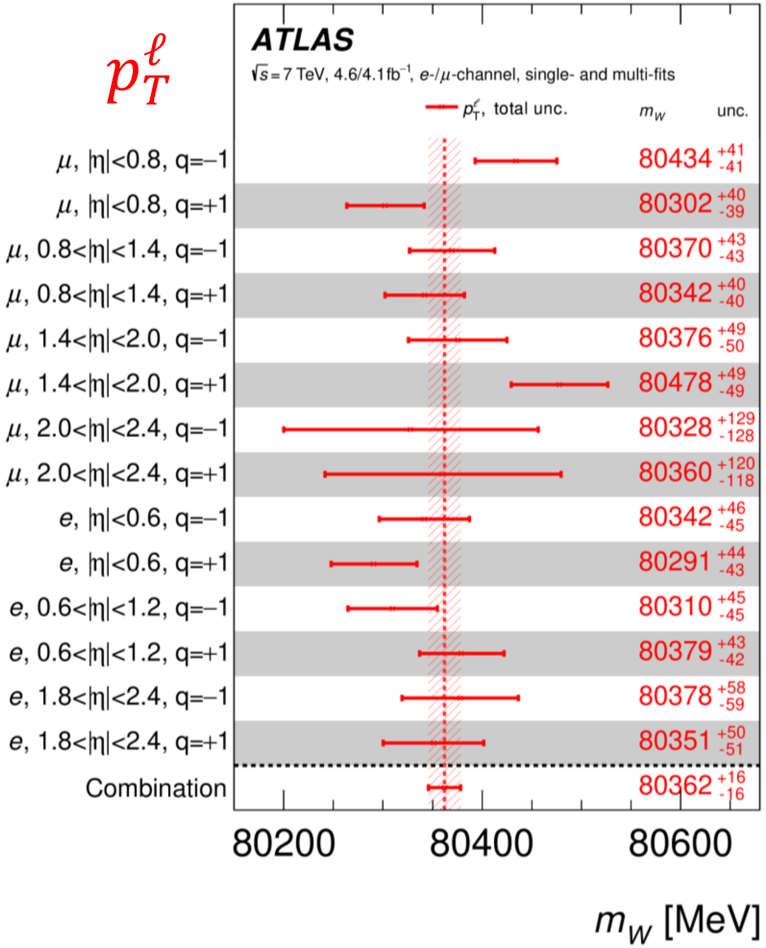
Experimental uncertainties:
- Lepton calibration, efficiency, recoil calibration
- Luminosity, Multijet (MJ) background

Theoretical uncertainties:
- p_T^W modelling
- Background cross-section uncertainties
- Parton distribution functions (PDFs)
- QCD predictions
- Electroweak corrections

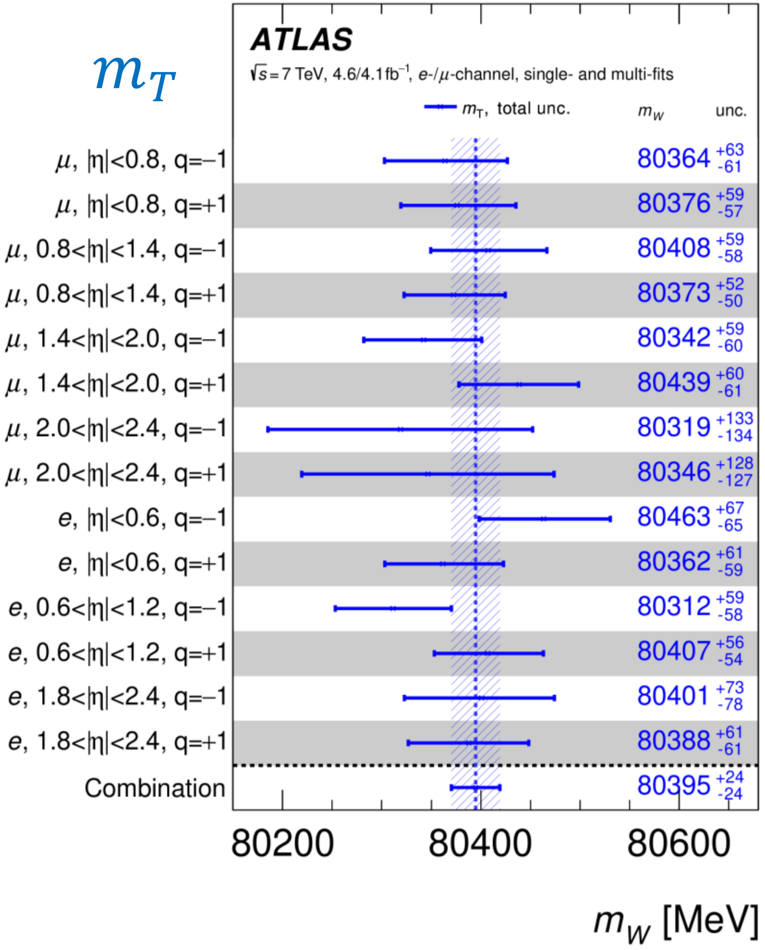
m_W measurement at $\sqrt{s} = 7$ TeV

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.

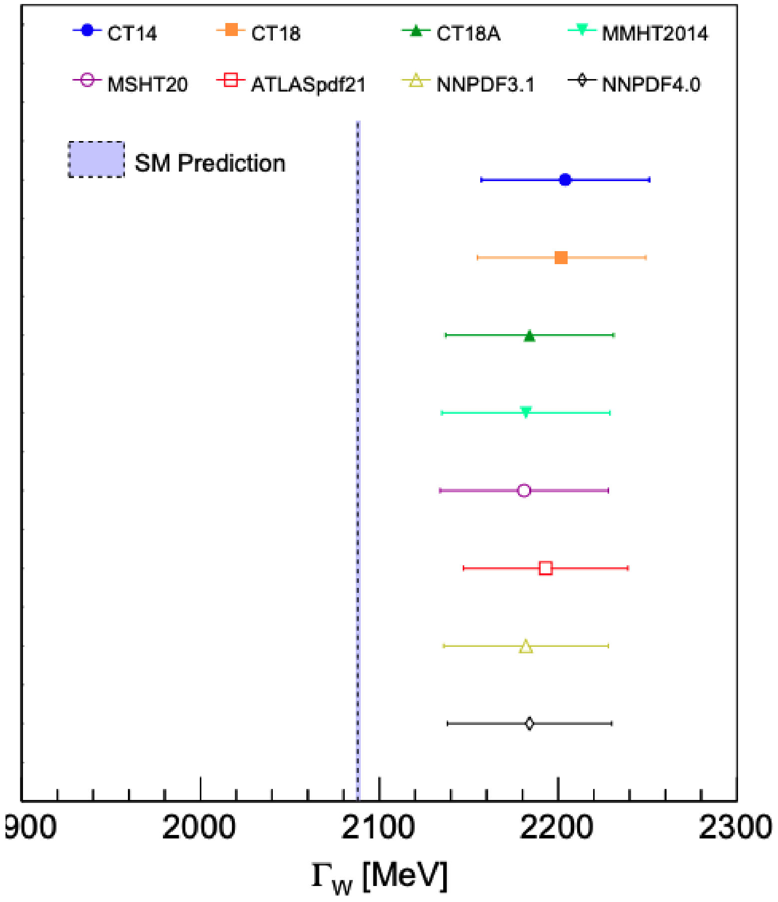
p_T^ℓ

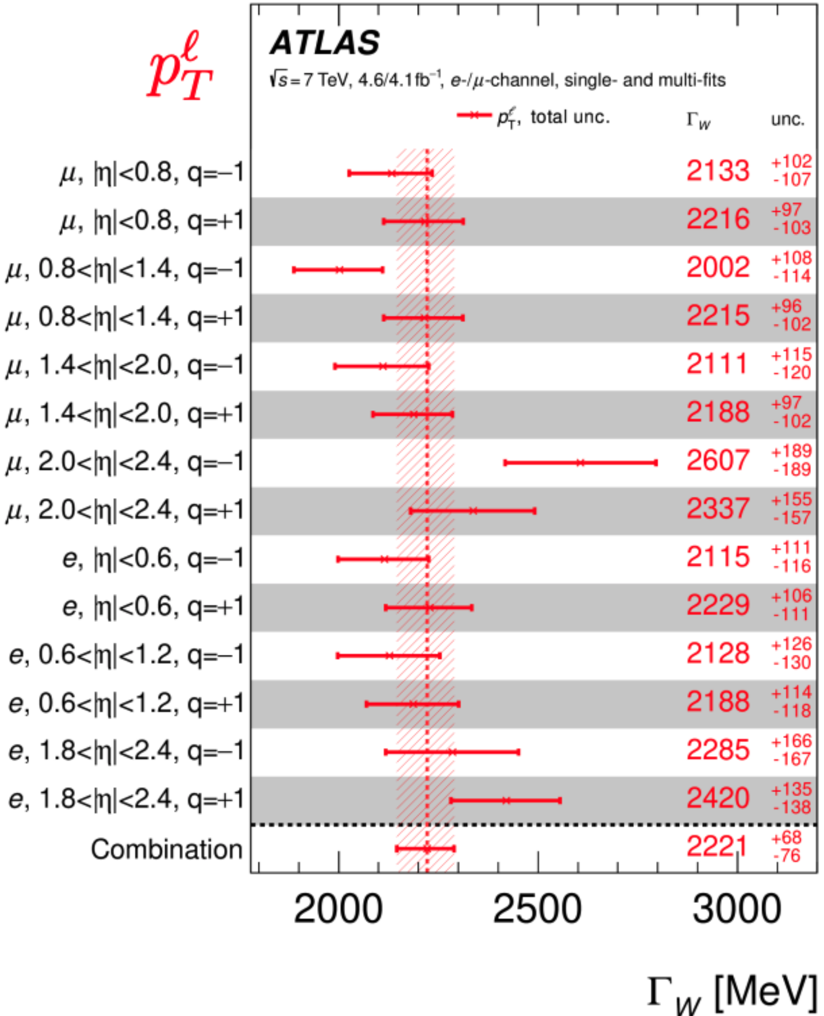


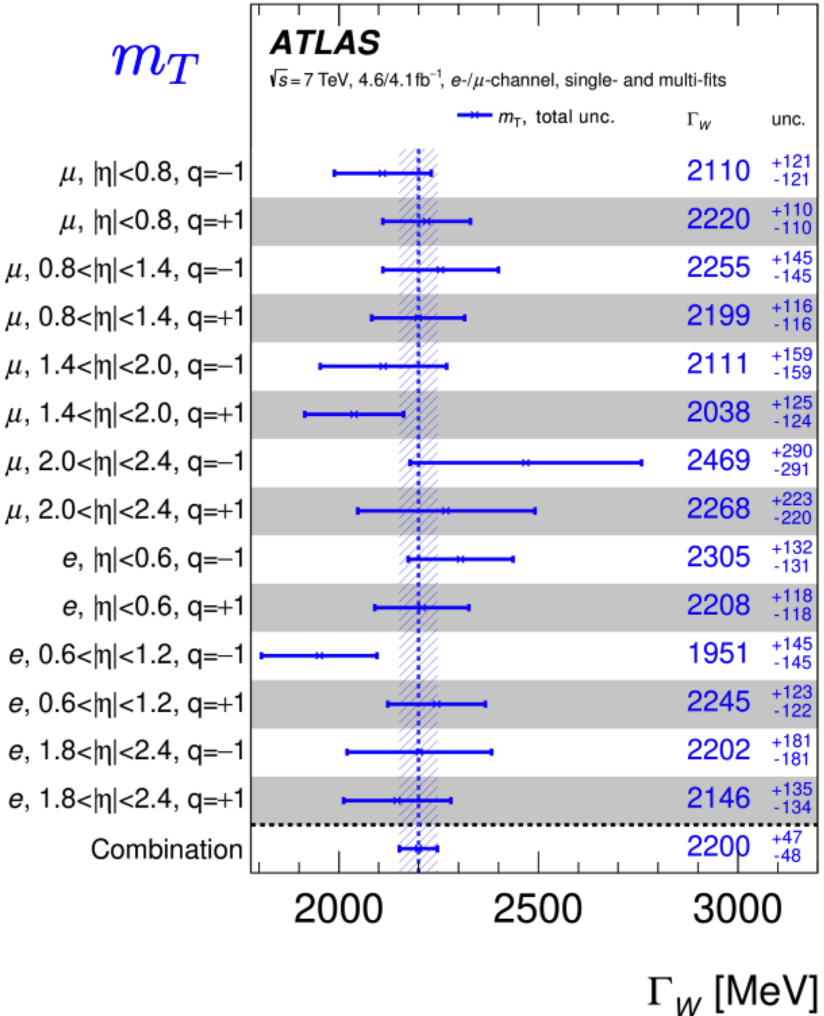
m_T



Γ_W category fits and PDF dependency

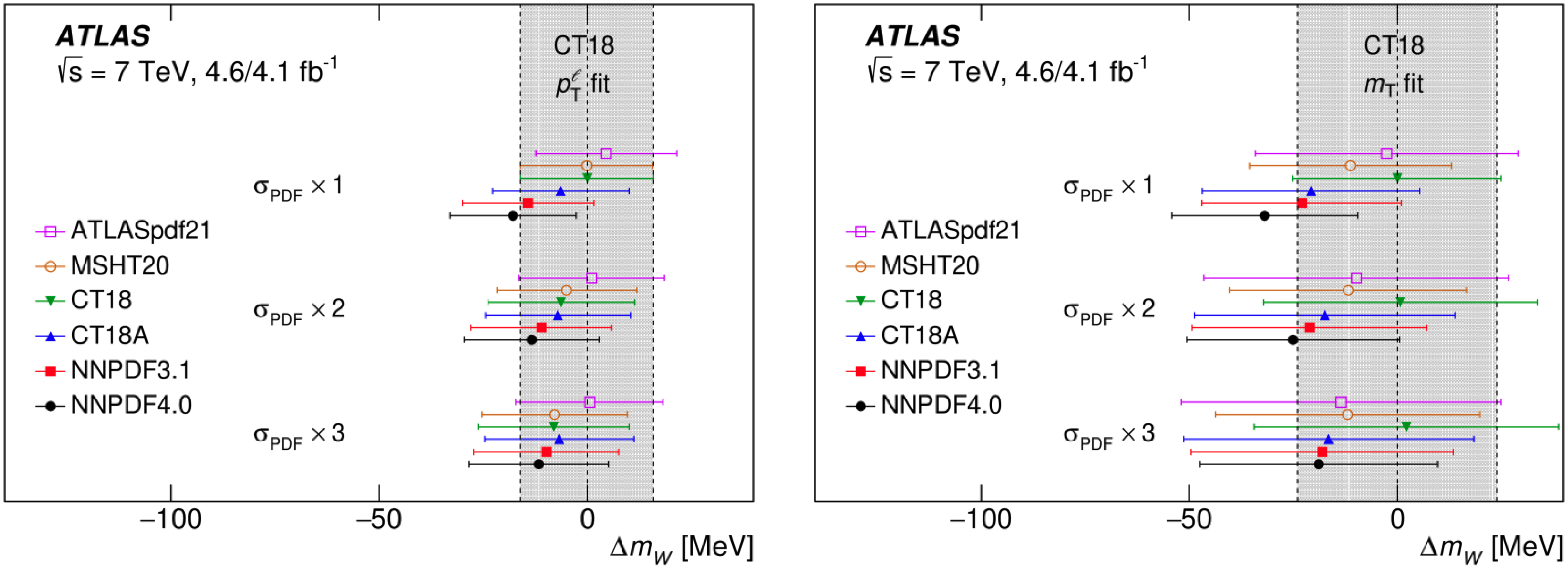






PDF dependency at $\sqrt{s} = 7$ TeV

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



m_W Nuisance parameters pulls