Measurement of m_W and Γ_W with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV

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On behalf of the ATLAS Collaboration

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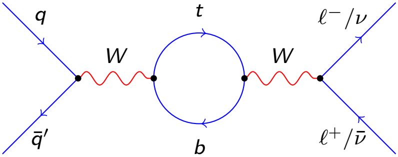
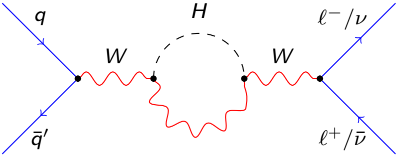
Motivation

- Precision test of the Standard Model





$$\sin^2\theta_W = (1 - \frac{m_W^2}{m_Z^2}) \quad (1)$$

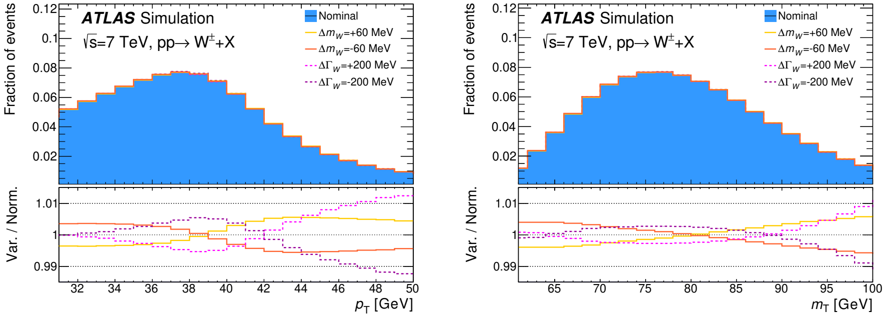
$$m_W^2(1 - \frac{m_W^2}{m_Z^2}) = \frac{\pi\alpha}{\sqrt{2}G_F}(1 + \Delta r) \quad (2)$$

- Reanalyse 7 TeV dataset with the profile likelihood (PLH) approach
  - Reductions of several systematic uncertainties of m_W, especially PDF uncertainty
  - First Γ_W measurement at the LHC

- Previous measurement: Eur. Phys. J. C 78, 110 (2018)
- Reanalysis Paper accepted by EPJC: arxiv:2403.15085

Fitting Setup

- Two separate fits with two observables: p_T^ℓ and m_T



- Two joint fits in 14 event categories:
  - Electron: 2 charges $\times$ 3 η regions + Muon: 2 charges $\times$ 4 η regions
  - 10 bins for each category: p_T^ℓ from 30 to 50 GeV, m_T from 60 to 100 GeV

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	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

Small Improvements

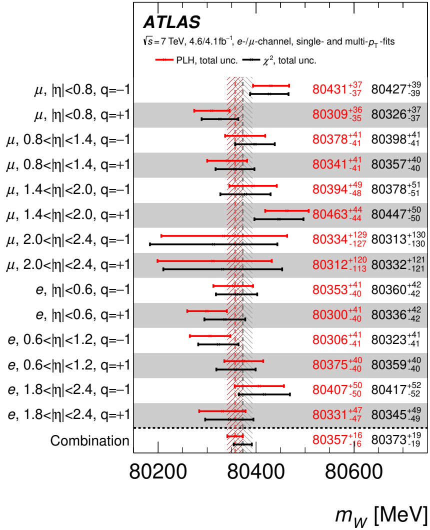
- MJ background
  - Re-evaluated with the final luminosity calibration (within the previous uncertainty) $\rightarrow$ a 20% increase of the MJ background in the electron channel
  - Update the shape extrapolation, Uncertainty reduced
- Electroweak modeling
  - Systematic estimated on reco-level instead of particle-level
  - Uncertainty higher than the previous result, the impact on m_W increased by 20%
- Impact due to these changes (Same procedure as the previous measurement)
  - Central value: shifted by 2.4 MeV (0.12σ of the published result)

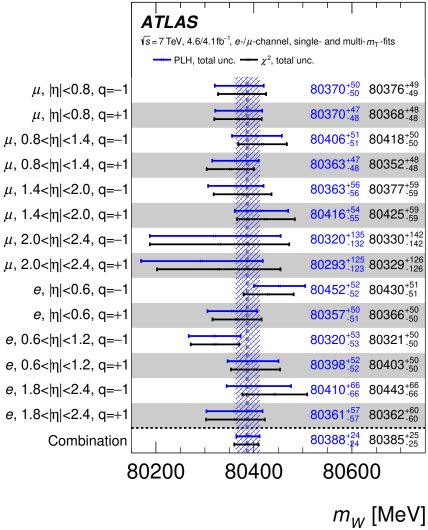
Validation Step	m_W [MeV]
Previously published	80369.5 ± 18.5
After all these updates	80371.9 ± 18.8

Profile Likelihood Method

- Impact of parameters introduced by variations and templates
- Normalization parameter: Φ, for signal sample only

$$
\begin{aligned}
\mathcal{L}(\vec{\mu},\vec{\theta}) &= \prod_{i=1}^{N} Poisson\left(n_i, \nu_i(\vec{\mu},\vec{\theta})\right) \times \prod_{i=1}^{M} Gaus(\theta_i) \\
\nu_i &= \Phi \times \left(S_i^{\text{norm}} + \sum_{j=1}^{K} (S_i(\mu_j) - S_i^{\text{norm}}) \right) + \sum_{j=1}^{M} \left(\theta_j \times (S_i^{\theta_j \text{ var}} - S_i^{\text{norm}})\right) + \\
& B_i^{\text{norm}} + \sum_{j=1}^{M} \left(\theta_j \times (B_i^{\theta_j \text{ var}} - B_i^{\text{norm}})\right) \qquad (3)
\end{aligned}
$$





- m_W PLH fitting result: 80357 ± 16 MeV and 80388 ± 24 MeV
  - m_W shifted by -16 MeV and +3 MeV respectively
  - Total uncertainty reduced by about 3 MeV as expected

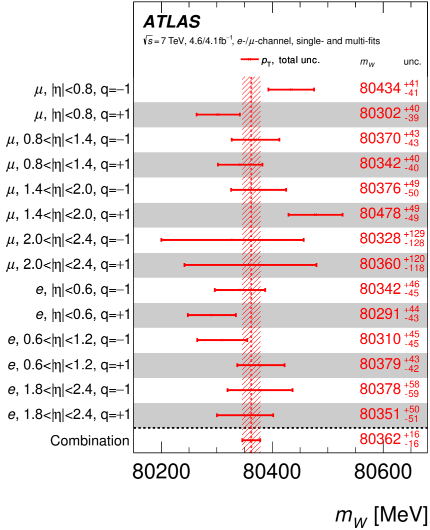
Impact due to the update of PDF

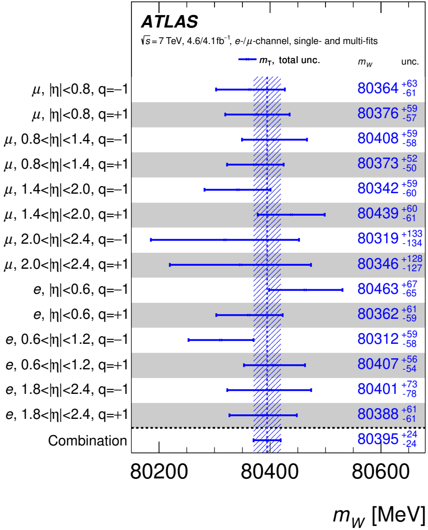
- Previous measurement: CT10nnlo
- PDF updated with p_T^Z constraint applied

PDF set	p_T^ℓ fit				m_T fit			
	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	80358.3	$^{+16.1}_{-16.2}$	4.6	543.3/558	80401.3	$^{+24.3}_{-24.5}$	11.6	557.4/558
CT18	80362.0	$^{+16.2}_{-16.2}$	4.9	529.7/558	80394.9	$^{+24.3}_{-24.5}$	11.7	549.2/558
CT18A	80353.2	$^{+15.9}_{-15.8}$	4.8	525.3/558	80384.8	$^{+23.5}_{-23.8}$	10.9	548.4/558
MMHT2014	80361.6	$^{+16.0}_{-16.0}$	4.5	539.8/558	80399.1	$^{+23.2}_{-23.5}$	10.0	561.5/558
MSHT20	80359.0	$^{+13.8}_{-15.4}$	4.3	550.2/558	80391.4	$^{+23.6}_{-24.1}$	10.0	557.3/558
ATLASpdf21	80362.1	$^{+16.9}_{-16.9}$	4.2	526.9/558	80405.5	$^{+28.2}_{-27.7}$	13.2	544.9/558
NNPDF3.1	80347.5	$^{+15.2}_{-15.7}$	4.8	523.1/558	80368.9	$^{+22.7}_{-22.9}$	9.7	556.6/558
NNPDF4.0	80343.7	$^{+15.0}_{-15.0}$	4.2	539.2/558	80363.1	$^{+21.4}_{-22.1}$	7.7	558.8/558

- Span a range of about 18 MeV for the p_T^ℓ fits and about 42 MeV for the m_T fits
  - Dominated by the NNPDF3.1 and NNPDF4.0 fits
  - The range spanned by the other sets: 9 MeV for p_T^ℓ and 21 MeV for m_T
- The new baseline result: CT18
  - the most conservative uncertainty
  - the ATLAS 7 TeV precision W/Z data not included

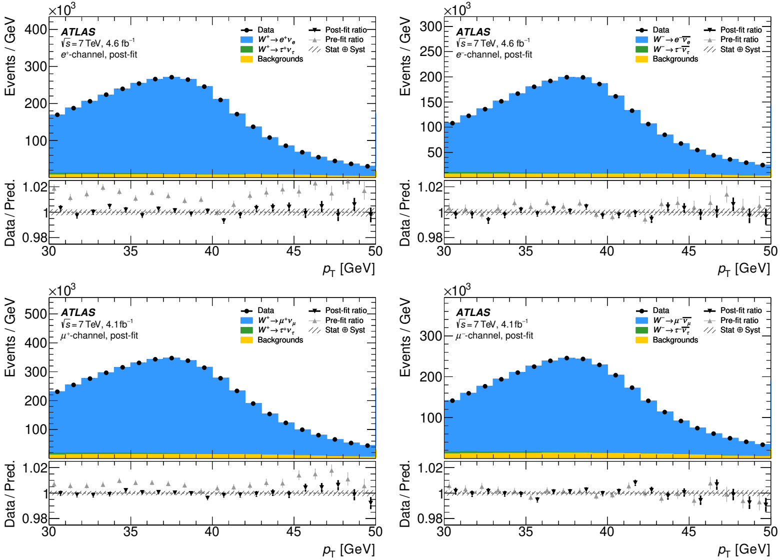
Full Fit Results with the New Baseline PDF set (CT18)





$$
\begin{aligned}
p_T^{\ell} : m_W &= 80362^{+16}_{-16} \text{ MeV} \\
m_T : m_W &= 80395^{+24}_{-24} \text{ MeV}
\end{aligned} \tag{4}
$$

Postfit p_T^ℓ Distributions



- Consistent with the data within uncertainties

Final Result and Uncertainty Decomposition

PDF set	Correlation	weight (p_T^ℓ)	weight (m_T)	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%	89%	11%	80349.6 ± 15.3
NNPDF4.0	59.5%	90%	10%	80345.6 ± 14.9

- The weight of the p_T^ℓ fit ranges from 86% to 97%, dominates the final result

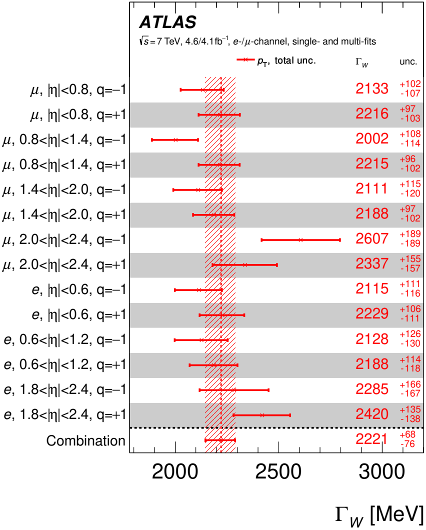
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

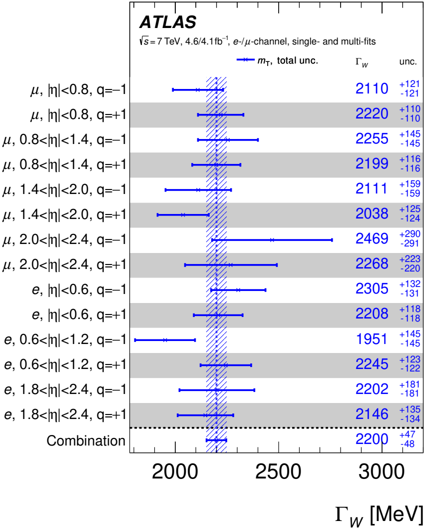
$$\begin{aligned} m_W &= 80366.5 \pm 9.8(\text{stat.}) \pm 12.5(\text{syst.})\ \text{MeV} \\ &= 80366.5 \pm 15.9\ \text{MeV} \end{aligned} \quad (5)$$

- Total uncertainty improved by 20% comparing to the previous measurement

Γ_W measurement (Baseline CT18 Fit)

- Similar strategy as m_W measurement
  - Background estimation, recoil and lepton calibration and physics modeling
  - PDF extrapolation, Fitting strategy, Combination strategy





Γ_W measurements with other PDF sets

PDF set	p_T^ℓ fit				m_T fit			
	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	2228	$^{+67}_{-83}$	24	550.0/558	2202	$^{+48}_{-48}$	5	556.8/558
CT18	2221	$^{+68}_{-76}$	21	534.5/558	2200	$^{+47}_{-48}$	5	548.8/558
CT18A	2207	$^{+68}_{-75}$	18	533.0/558	2181	$^{+47}_{-48}$	5	550.6/558
MMHT2014	2155	$^{+71}_{-78}$	19	546.0/558	2186	$^{+48}_{-48}$	5	562.2/558
MSHT20	2206	$^{+66}_{-79}$	15	556.5/558	2179	$^{+47}_{-48}$	4	559.4/558
ATLASpdf21	2213	$^{+67}_{-73}$	18	531.3/558	2190	$^{+47}_{-48}$	6	545.6/558
NNPDF31	2203	$^{+65}_{-78}$	20	531.7/558	2180	$^{+47}_{-47}$	6	560.4/558
NNPDF40	2182	$^{+69}_{-68}$	12	550.5/558	2184	$^{+47}_{-47}$	4	564.0/558

- All central values are well within the uncertainties of the baseline fit from CT18

Combination and Uncertainty Decomposition

- The same sgtrategy as the m_W measurement

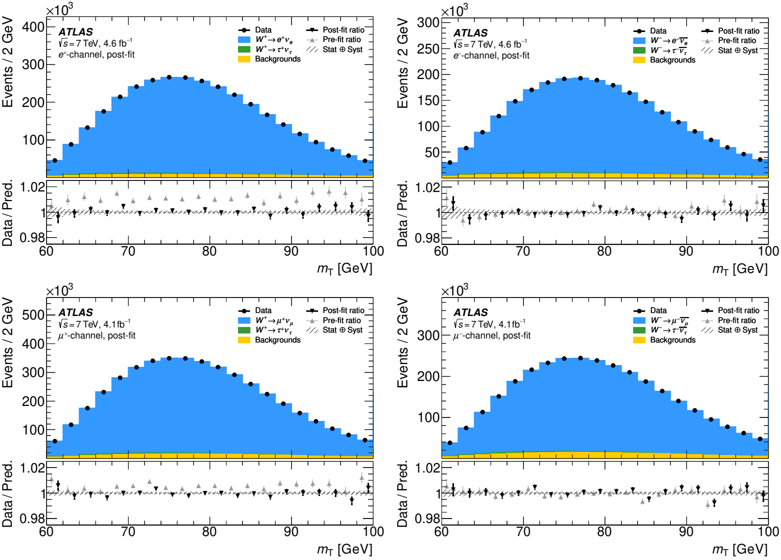
PDF set	Correlation	weight (m_T)	weight (p_T^ℓ)	Combined Γ_W [MeV]
CT14	50.3%	88%	12%	2204 ± 47
CT18	51.5%	87%	13%	2202 ± 47
CT18A	50.0%	86%	14%	2184 ± 47
MMHT2014	50.8%	88%	13%	2182 ± 47
MSHT20	53.6%	89%	11%	2181 ± 47
ATLASpdf21	49.5%	84%	16%	2193 ± 46
NNPDF31	49.9%	86%	14%	2182 ± 46
NNPDF40	51.4%	85%	15%	2184 ± 46

- The weight of the $m_T l$ fit ranges from 85% to 89%, dominates the final result

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

$$\begin{aligned} \Gamma_W &= 2202 \pm 32(\text{stat.}) \pm 34(\text{syst.})\ \text{MeV} \\ &= 2202 \pm 47\ \text{MeV} \end{aligned} \tag{6}$$

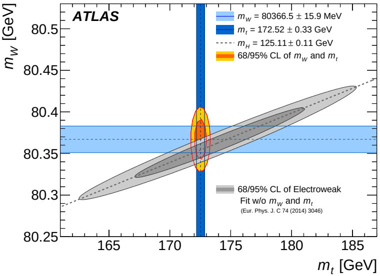
Postfit m_T Distributions

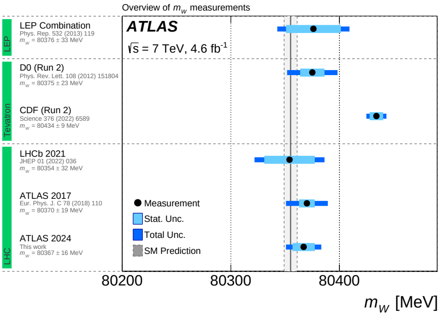


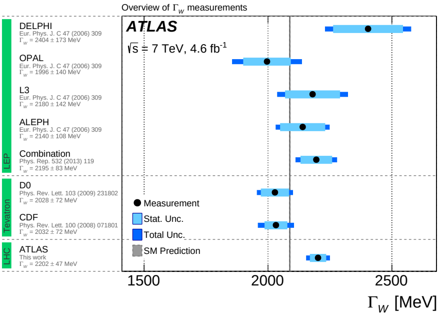
- Consistent with the data within uncertainties

Compare to other measurements and the Standard Model predictions

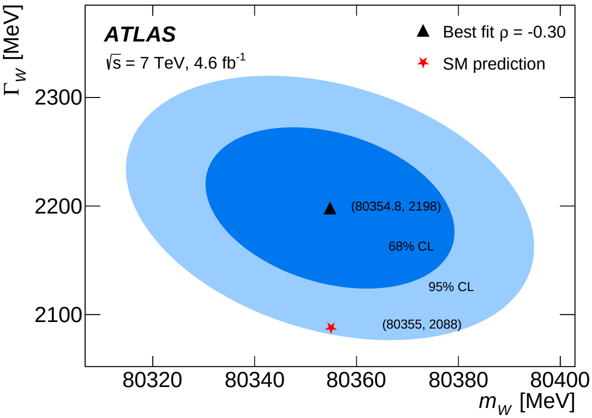
- Compare to the SM predictions
  - m_W: Consistent
  - Γ_W: Within two standard deviations
- Compare to GFitter results
  - Together with LHC m_t measurement







Additional Simutainous Determination



$$m_W = 80354.8 \pm 16.1 \text{ MeV}$$
$$\Gamma_W = 2198 \pm 49 \text{ MeV}$$

- Compare to the SM prediction: within 2σ
- Compare to the separate determinations: the uncertainties are a little larger (Since the relation between m_W and Γ_W is removed)

Summary

- The first m_W measurement with PLH method, which reduced the systematic uncertainties by data constrains, comparing to the previous measurement, the total uncertainty reduced by 20%
- The most precise measurement of Γ_W to date
- The result is based on CT18 PDF set

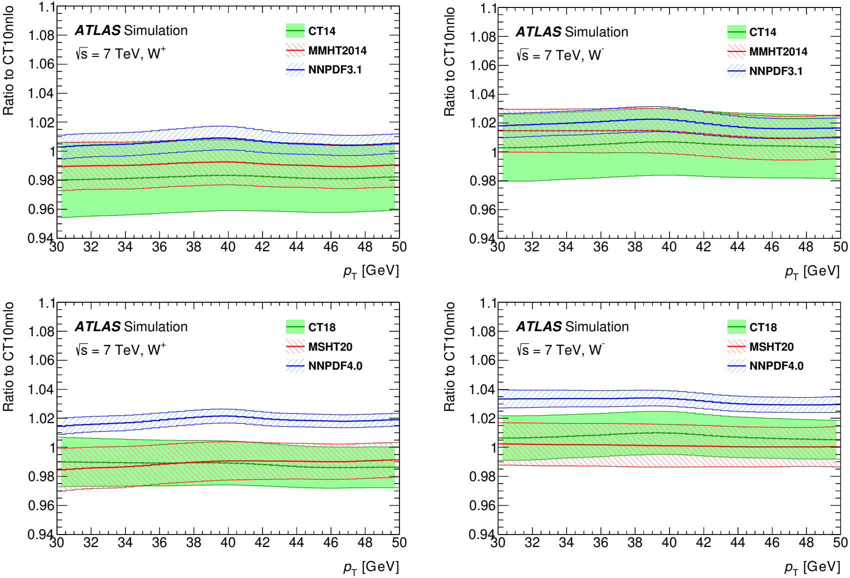
$$\begin{aligned} m_W &= 80366.5 \pm 9.8(\text{stat.}) \pm 12.5(\text{syst.})\ \text{MeV} \\ &= 80366.5 \pm 15.9\ \text{MeV} \end{aligned}$$

$$\begin{aligned} \Gamma_W &= 2202 \pm 32(\text{stat.}) \pm 34(\text{syst.})\ \text{MeV} \\ &= 2202 \pm 47\ \text{MeV} \end{aligned}$$

- Comparing to the SM predictions, our measured value of m_W is consistent, and that of Γ_W is within 2σ
- Future ATLAS m_W measurement
  - Improved p_T^W modeling with the latest ATLAS measurement
  - Joint fitting with the low-μ 5 and 13 TeV dataset

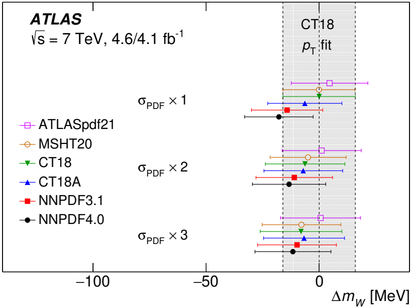
Impact of updated Parton Density Functions

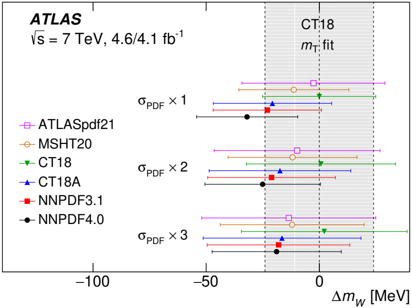
- PDF set in the previous measurment: CT10nnlo



PDF Uncertainty Scaling

- NNPDF sets stand out in terms of central value
  - Constrained by too aggressively defined PDF uncertainties
- Check if scaling up PDF uncertainty brings them closer to the others





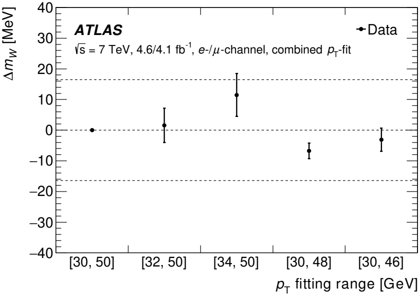
- The fitting results become closer to the baseline
  - Underestimated PDF uncertainty → Lack of flexibility → Significant PDF dependence

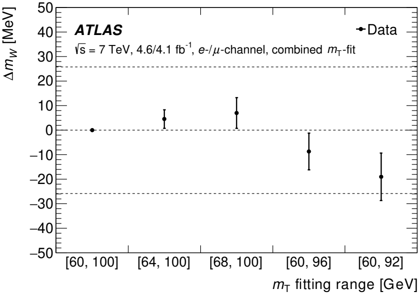
PDF dependence	p_T^ℓ fit	m_T fit
$\sigma_{PDF} \times 1$	18 MeV	42 MeV
$\sigma_{PDF} \times 2$	5 MeV	25 MeV

- Support the choice of the baseline PDF CT18
- No need to introduce an additional uncertainty due to the PDF choice

Consistency Check

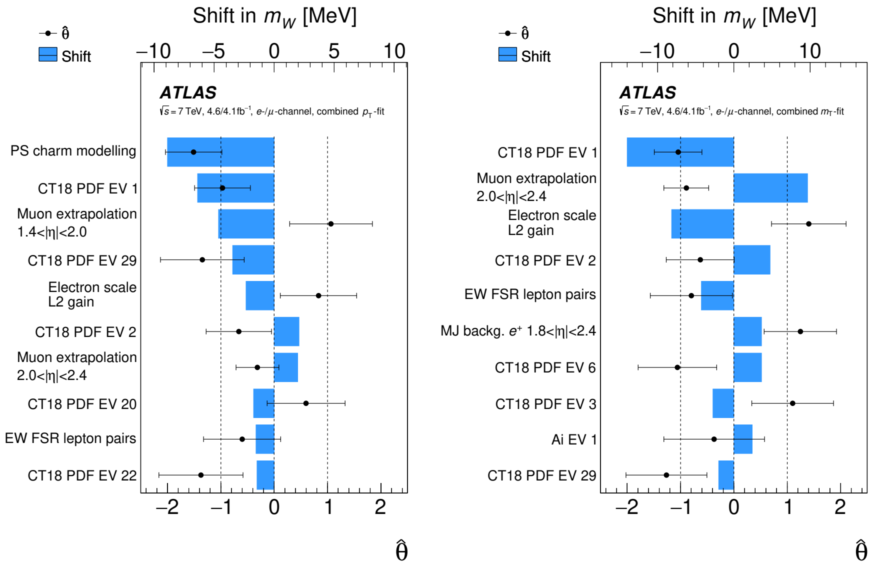
- Partical Fit Check: All consistent within 1σ
  - Separate the electron and muon channels
  - Separate W^+ and W^-
- Fitting Range Test:





- Show good stability of the PLH fit

The 10 Most Significant Pulls



- All observed pulls are within the expectations

$p_T^\ell - m_T$ Combination

- Correlation needed for the final combination with the BLUE method
  - Generate pseudo-data toys which include the impact from all uncertainty sources
  - Fit all these toys and calculate the correlation
- Statistical correlation between p_T^ℓ and m_T → Data 2D distribution
- Separate PCA procedures for p_T^ℓ and m_T → The original toys

- Analytical χ^2 method

$$\chi^2 = \Sigma_{ij}(y_i - \Sigma_k t_{ik}\theta_k - \Sigma_k \Gamma_{ik} a_k) V_{ij}^{-1} (y_j - \Sigma_k t_{jk}\theta_k - \Sigma_k \Gamma_{jk} a_k) + \Sigma_n (a_n - G_n)^2 \quad (7)$$

  - Impact of each parameter is assumed to be linear and symmetrical
  - Directly solve the equations $\frac{\partial \chi^2}{\partial \theta_i} = 0$, $\frac{\partial \chi^2}{\partial a_i} = 0$

PDF set	Correlation	weight (p_T^ℓ)	weight (m_T)	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%	89%	11%	80349.6 ± 15.3
NNPDF4.0	59.5%	90%	10%	80345.6 ± 14.9

- The weight of the p_T^ℓ fit ranges from 86% to 97%, dominates the final result

Uncertainty Decomposition

- Uncertainty Decomposition performed by ACS method[1]
  - Estimate the covariance between the nuisance parameters and m_W

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

$$\begin{aligned} m_W &= 80366.5 \pm 9.8(\text{stat.}) \pm 12.5(\text{syst.})\ \text{MeV} \\ &= 80366.5 \pm 15.9\ \text{MeV} \end{aligned} \quad (8)$$

- The dependence of the Γ_W input value:
  - Baseline: A nuisance parameter constrained by the world average $\Gamma_W = 2088 \pm 1$ MeV
  - Also tested with $\Gamma_W = 2091 \pm 1$ MeV: No significant impact

$$\delta m_W = -0.06 \times \delta\Gamma_W \quad (9)$$

[1] arXiv:2307.04007

Γ_W measurements with other PDF sets

PDF set	p_T^ℓ fit				m_T fit			
	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	2228	$^{+67}_{-83}$	24	550.0/558	2202	$^{+48}_{-48}$	5	556.8/558
CT18	2221	$^{+68}_{-76}$	21	534.5/558	2200	$^{+47}_{-48}$	5	548.8/558
CT18A	2207	$^{+68}_{-75}$	18	533.0/558	2181	$^{+47}_{-48}$	5	550.6/558
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MSHT20	2206	$^{+66}_{-79}$	15	556.5/558	2179	$^{+47}_{-48}$	4	559.4/558
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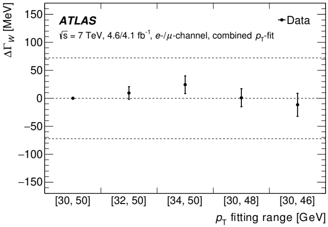
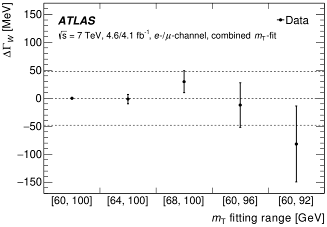
NNPDF40	2182	$^{+69}_{-68}$	12	550.5/558	2184	$^{+47}_{-47}$	4	564.0/558

- All central values are well within the uncertainties of the baseline fit
- Partical Fit Check: All Consistent within 1σ, Except:
  - W^+ and W^- consistency in the p_T^ℓ fit: within 2σ
- Fitting Range Test:





Combination and Uncertainty Decomposition

- The same sgtrategy as the m_W measurement

PDF set	Correlation	weight (m_T)	weight (p_T^ℓ)	Combined Γ_W [MeV]
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MMHT2014	50.8%	88%	13%	2182 ± 47
MSHT20	53.6%	89%	11%	2181 ± 47
ATLASpdf21	49.5%	84%	16%	2193 ± 46
NNPDF31	49.9%	86%	14%	2182 ± 46
NNPDF40	51.4%	85%	15%	2184 ± 46

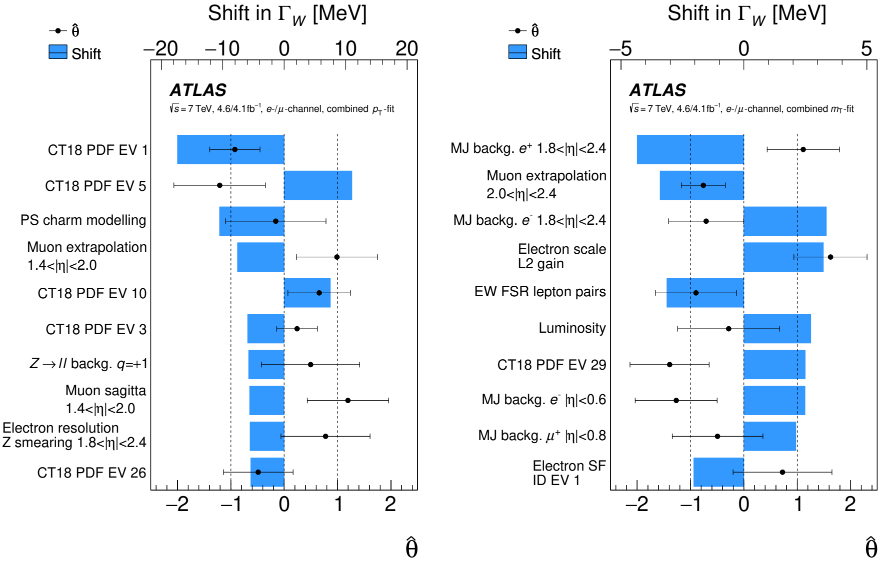
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

$$\begin{aligned}\Gamma_W &= 2202 \pm 32(\text{stat.}) \pm 34(\text{syst.})\ \text{MeV} \\ &= 2202 \pm 47\ \text{MeV} \qquad (10)\end{aligned}$$

- The dependence of the m_W input value:
  - Baseline: A nuisance parameter constrained by this analysis, $m_W = 80355 \pm 6$ MeV
  - Depends more strongly on the assumed value of m_W

$$\delta\Gamma_W = -1.25 \times \delta m_W \qquad (11)$$

The 10 Most Significant Pulls



- All observed pulls are within the expectations