Precision measurements of Standard Model parameters in ATLAS

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for the ATLAS Collaboration

ICHEP 2024, Prague, 18.07.2024

Outline

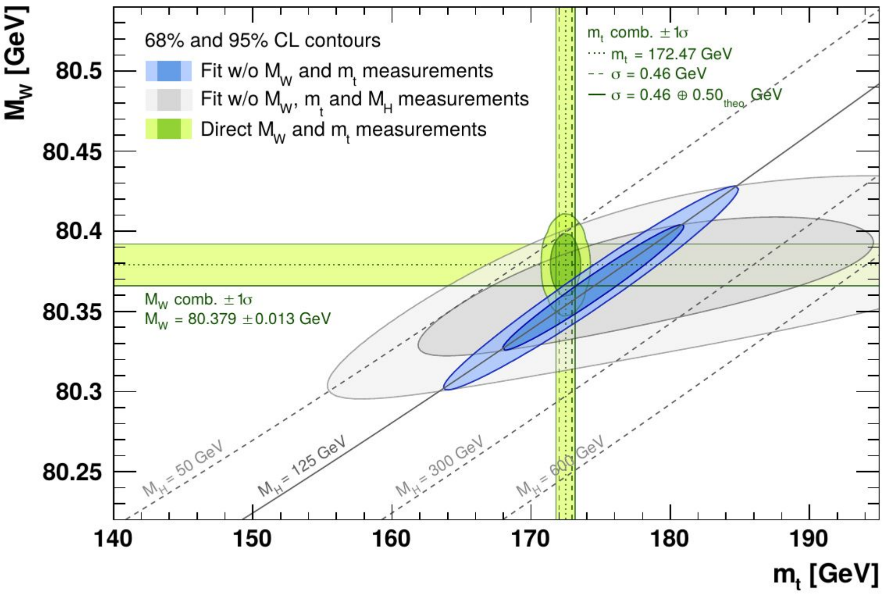
for more details see talk
by K. Schmieden at 14:30 today

1. **Strong coupling constant** from Z boson p_T distribution
   $\sqrt{s}$ = 8 TeV, LHC Run 1! arXiv:2309.12986

2. **Z boson invisible width**
   $\sqrt{s}$ = 13 TeV, partial LHC Run 2 dataset PLB 854 (2024) 138705

3. **Mass and width of W boson**
   $\sqrt{s}$ = 7 TeV, LHC Run 1! arXiv:2403.15085

Introduction



The Gfitter Group, Eur. Phys. J. C 78 (2018) 675

Parameters of Standard Model

interconnected with each other, e.g.:

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2} G_F}\right)^{1/2} \frac{\sqrt{1 + \Delta r}}{\sin \theta_W}$$

radiative corrections **Δr** with largest contributions from m_t^2, $\log(m_H)$

Precision measurements

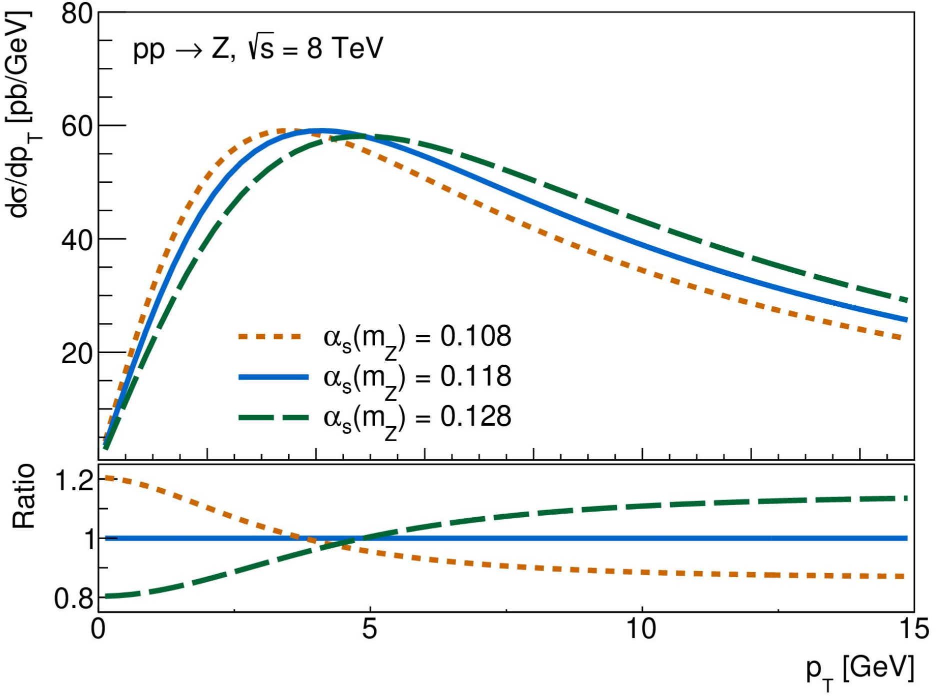
→ test self-consistency of SM theory in global EW fits

→ tensions could be signs of BSM effects

→ probe BSM beyond reach of searches

Strong coupling constant

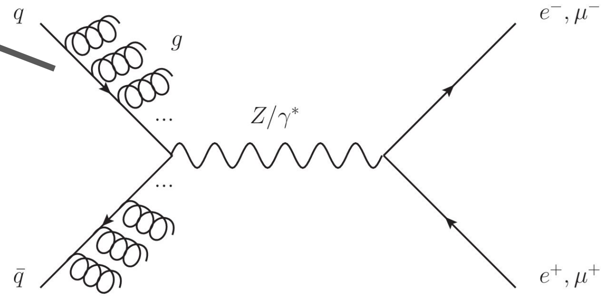
Predicted dependence of p_T^Z on $\alpha_s(m_Z)$



Coupling constant α_s → only free QCD parameter if quark masses neglected

Running: α_s decreases with interaction scale → $\alpha_s(m_Z)$ as conventional reference

Z boson p_T distribution in peak region directly sensitive to $\alpha_s(m_Z)$
↳driven by emissions of soft ISR gluons



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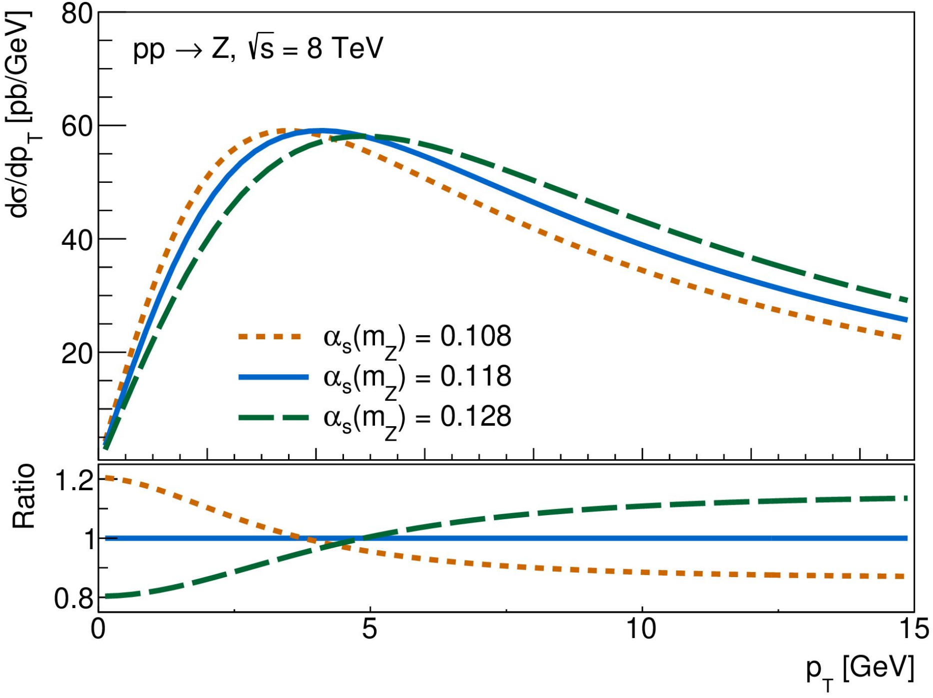


Coupling constant α_s → only free QCD parameter if quark masses neglected

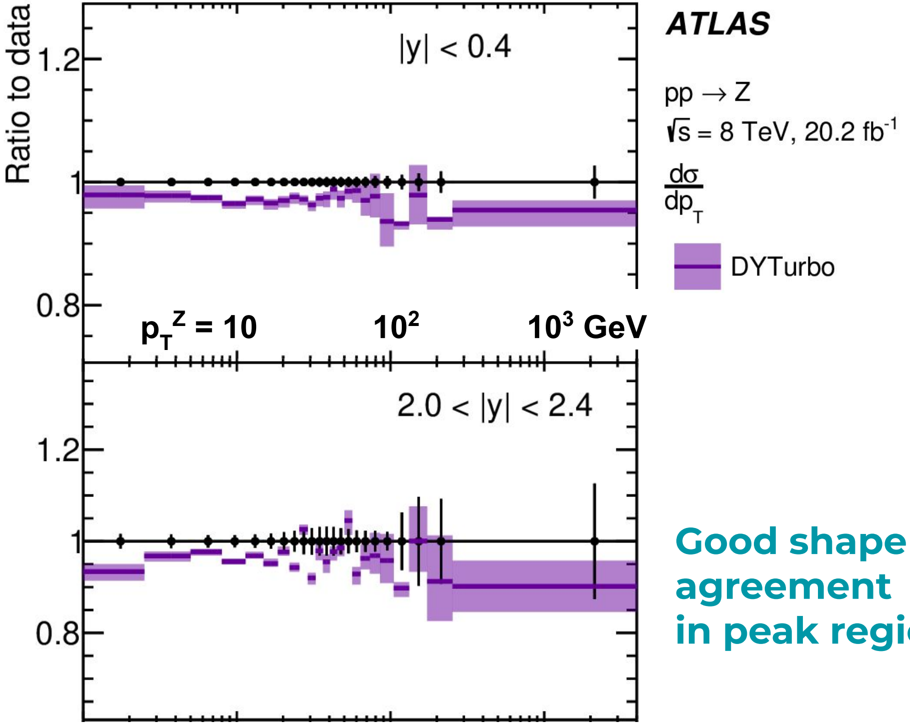
Running: α_s decreases with interaction scale → $\alpha_s(m_Z)$ as conventional reference

Z boson p_T distribution in peak region directly sensitive to $\alpha_s(m_Z)$
↳driven by emissions of soft ISR gluons
↳small non-perturbative QCD effects

Use very precise 8 TeV measurement of p_T-y cross-sections in full lepton phase-space: EPJ C 84 (2024) 315

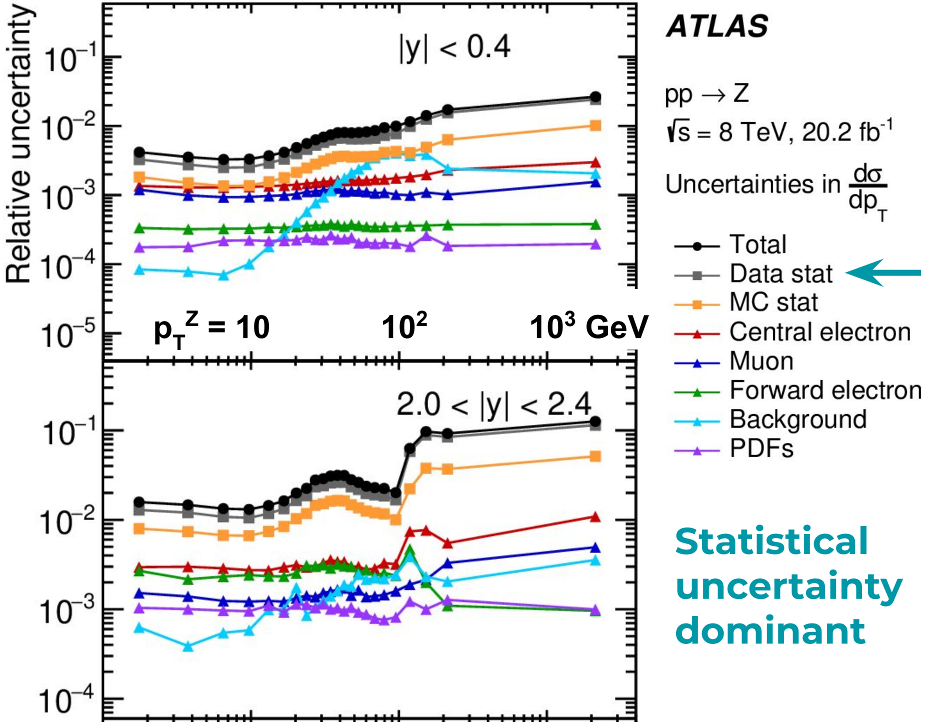
Z boson cross-sections

Comparison with DYTurbo predictions



Good shape agreement in peak region

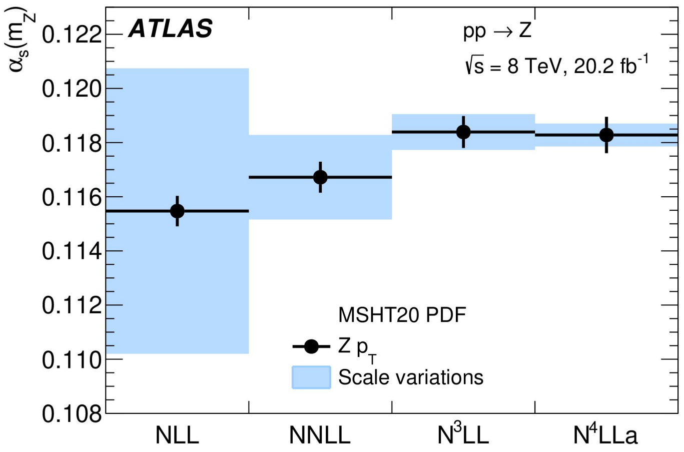
Breakdown of uncertainties



Statistical uncertainty dominant

Strong coupling constant

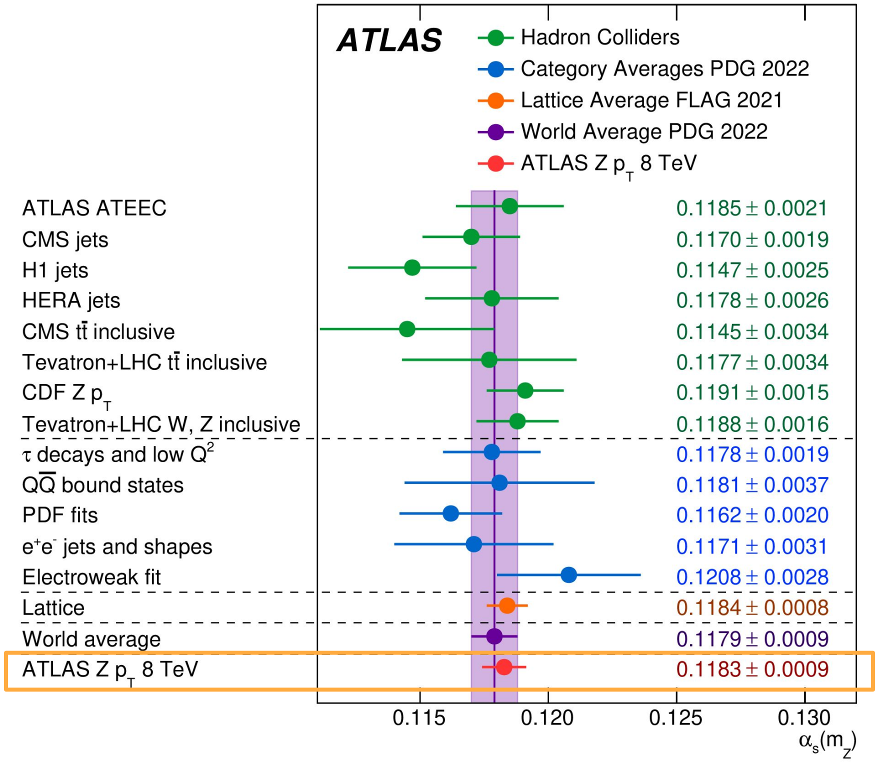
for more details see talk
by K. Schmieden at 14:30 today



Push theory predictions to **N^{3}LO+N^{4}LLa** in QCD
↳excellent convergence of perturbative series

Most precise experimental result

Uncertainty dominated by PDFs and experiment

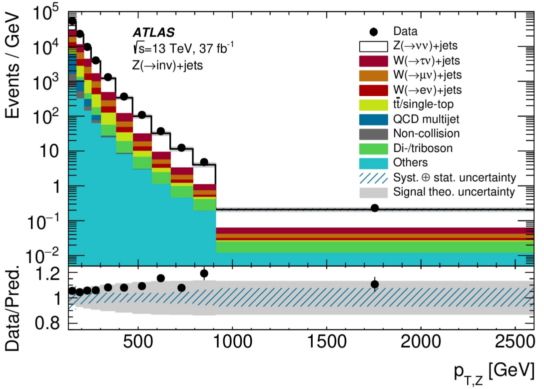


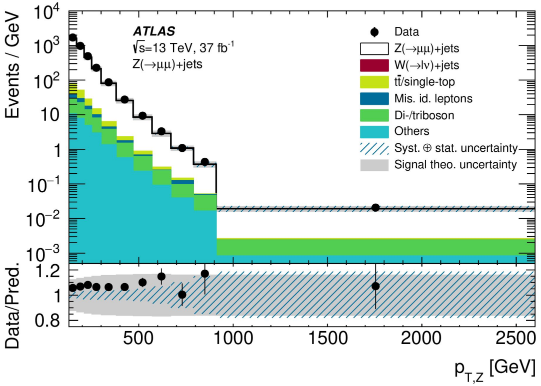
Z boson invisible width

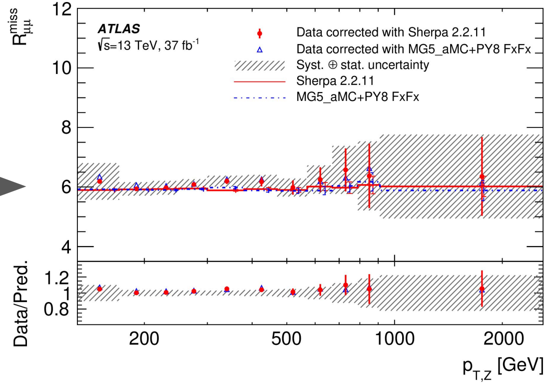
Width of **Z boson** for **decays into invisible states Γ(Z→inv)** sensitive to
↳ number of light neutrinos ($m_\nu < m_Z/2$)
↳ potential BSM contributions from new particles

$$R^{\text{miss}}(p_{\text{T,Z}}) \equiv \left(\frac{d\sigma(Z(\to \text{inv})+\text{jets})}{dp_{\text{T,Z}}}\right) \Big/ \left(\frac{d\sigma(Z(\to \ell\ell)+\text{jets})}{dp_{\text{T,Z}}}\right)$$

1. correct Z→inv and Z→ℓℓ to common phase-space
2. take ratio
3. fit constant $\hat{R}^{\text{miss}}$







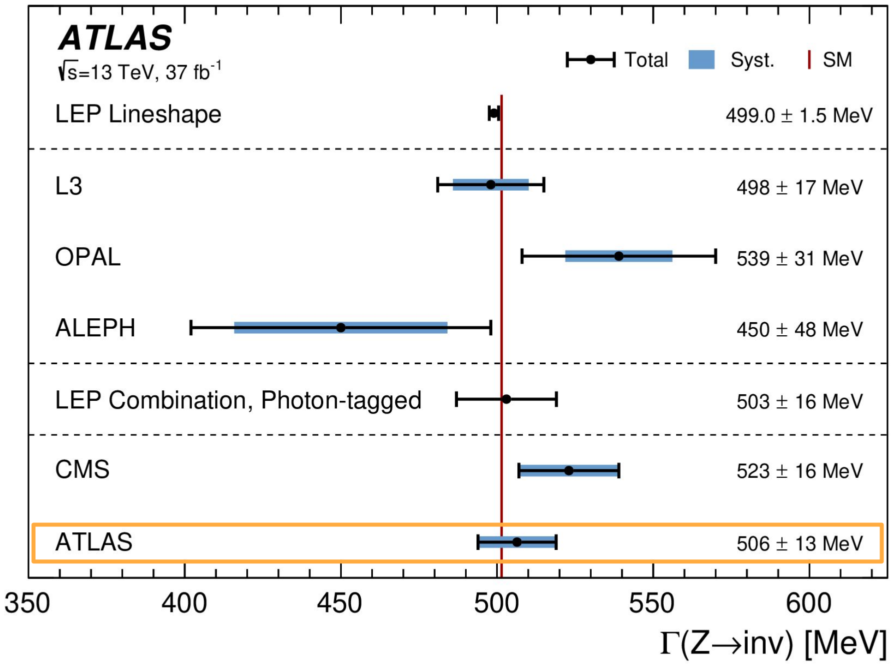
Z boson invisible width

Convert fitted constant to **Z boson invisible width** by combining with $Z \to \ell\ell$ width measurement from LEP

$$\Gamma(Z \to \text{inv}) = \hat{R}^{\text{miss}} \cdot \Gamma(Z \to \ell\ell)$$

Most precise recoil-based result

Precision limited by lepton systematic uncertainties in $Z \to \ell\ell$ events



W boson mass

First ATLAS measurement of m_W published in 2018 using 7 TeV data: $\mathbf{m_W = 80370 \pm 19}$ **MeV**
↳most precise result at the time

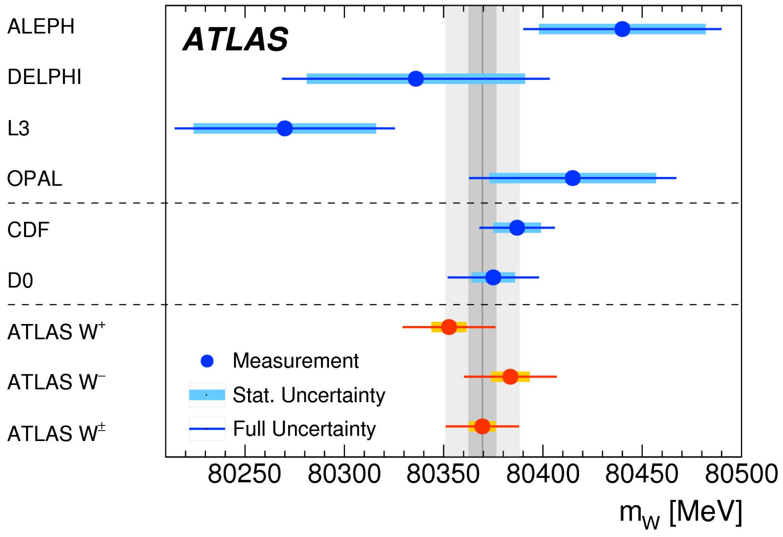
Since then new measurements
- CDF: $m_W = 80433 \pm 9$ MeV
- LHCb: $m_W = 80354 \pm 32$ MeV

and advances in theoretical modelling

↓

Can we get more out of the 7 TeV dataset?

Eur. Phys. J. C 78 (2018) 110



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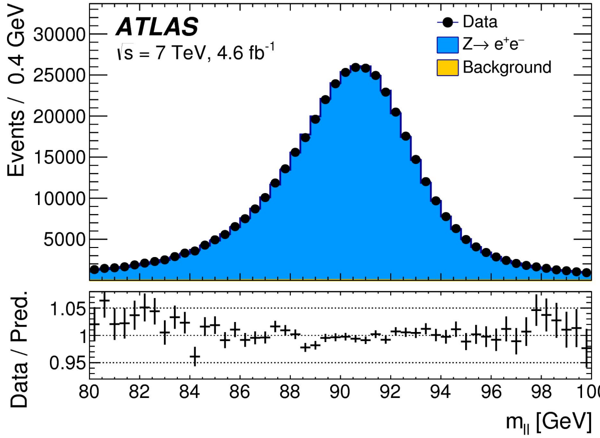
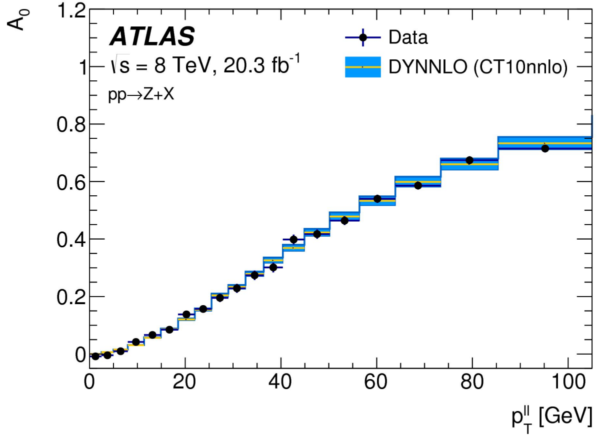
and advances in theoretical modelling

Yes! From previous measurement
↳excellent control over experimental corrections
↳good understanding of theory

Lepton calibration



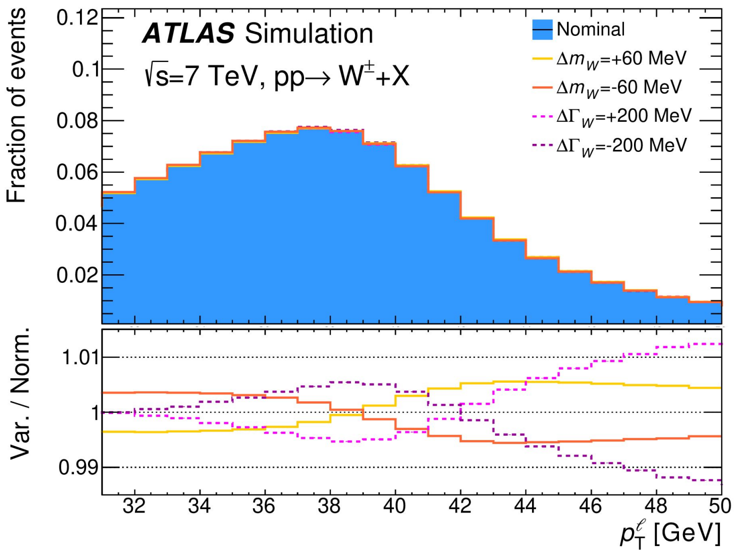
Angular coefficients A_i



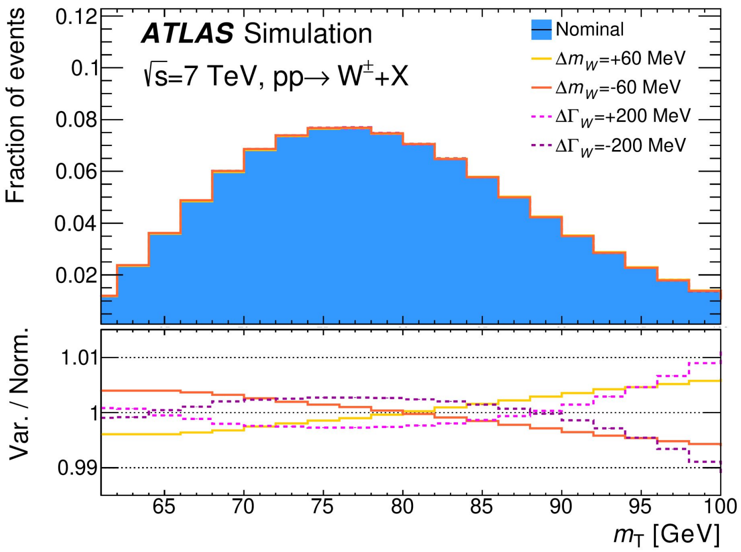
W boson mass and width

unchanged from previous analysis

Lepton p_T: Jacobian edge at $m_W/2$



Transverse mass: Jacobian edge at m_W, more sensitive to Γ_W in tails



- Use leptonic W boson decays: $W^{\pm} \rightarrow \ell^{\pm}\nu$ (ℓ = e, μ)
- Template fits using kinematic observables sensitive to m_W and Γ_W

W boson mass

Selections and measurement categories **unchanged from previous analysis**

NEW

↳ update to QCD background estimation
↳ more modern PDF sets → **see next slide**
↳ small update to uncertainties for higher-order electroweak corrections
↳ **key change: statistical analysis**

Previous measurement: χ^2 fit

↳ with statistical uncertainties only to find m_W central value

↳ systematic uncertainties determined a posteriori from offset method
↳ no handle on their correlations

New: profile likelihood fit

↳ constrain systematic uncertainties in situ
↳ directly determine their correlations

↳ challenge: m_W now also correlated with some systematic variations → **extensive validation of method to avoid biases**

W boson mass

- CT10nnlo used as baseline in previous measurement → **new baseline: CT18**
- Results for most PDF sets agree within ~10 MeV (lepton p_T) or ~20 MeV (m_T)
- NNPDF sets yield significantly lower values than other sets

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

W boson mass

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

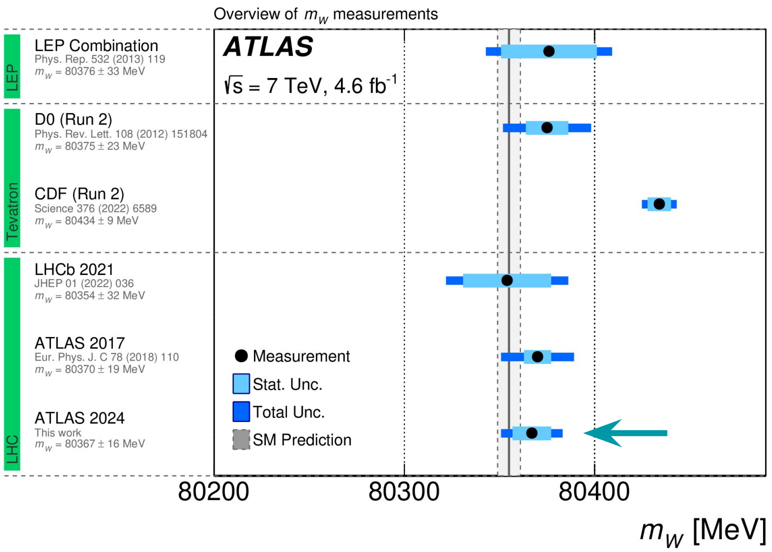
New result from combination of fits in lepton p_T and m_T: **m_W = 80366.5 ± 15.9 MeV**

Total uncertainty reduced by ~15%

↳precision driven by fits in lepton p_T

↳improvements in most unc. categories

↳notably PDF and A_i/PS uncertainties most constrained



W boson width

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

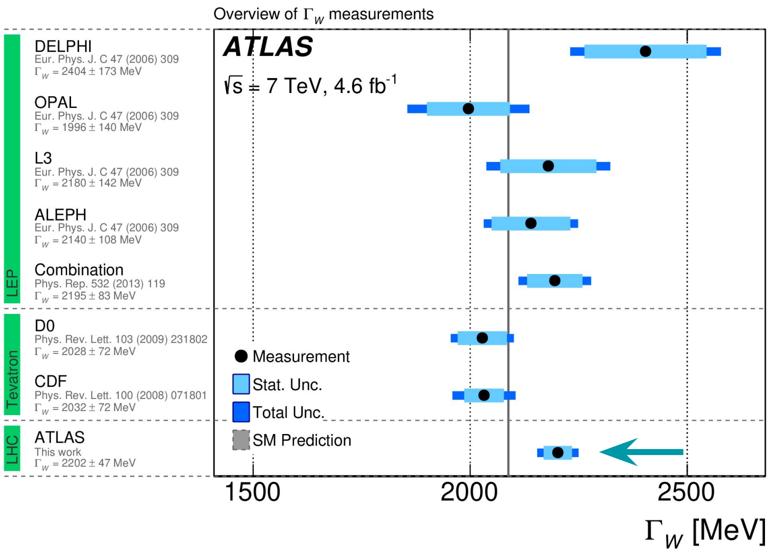
Same method used to measure **W boson width**: **Γ_W = 2202 ± 47 MeV**

First direct determination at the LHC!

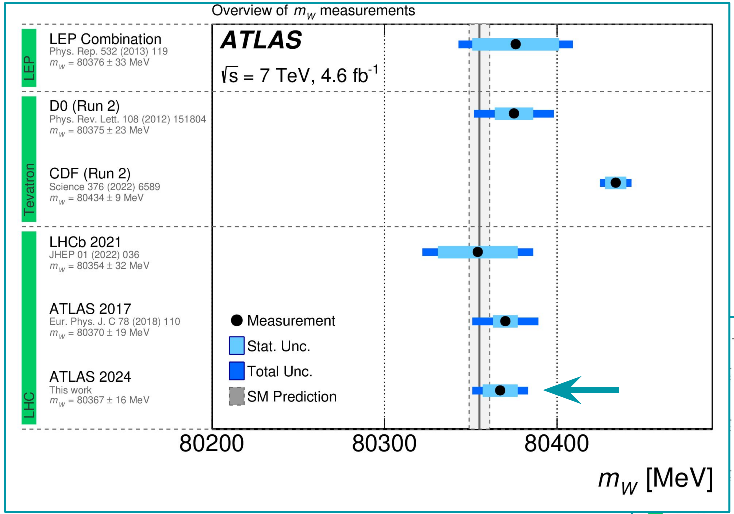
Most precise single-experiment result

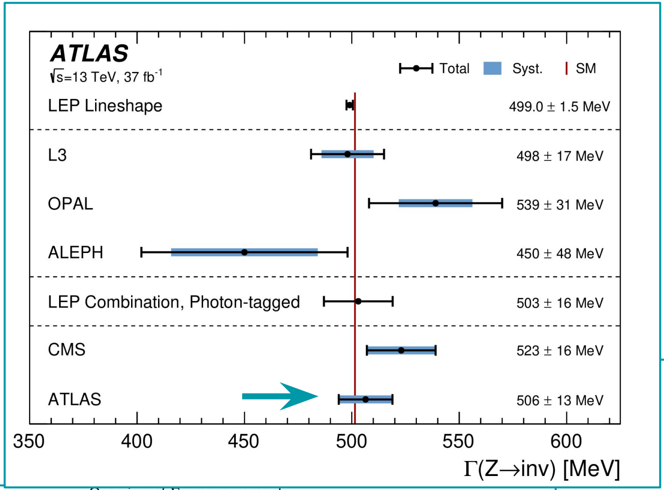
↳more sensitive to m_T distribution than m_W

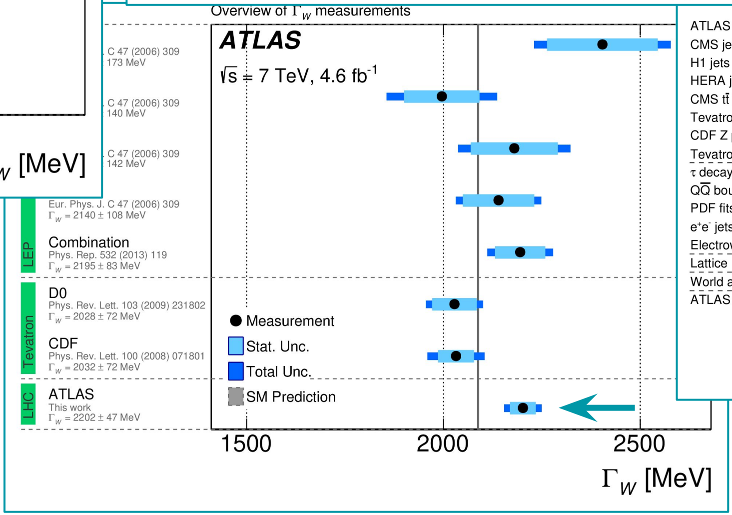
↳uncertainty driven by recoil calibration and PS modelling

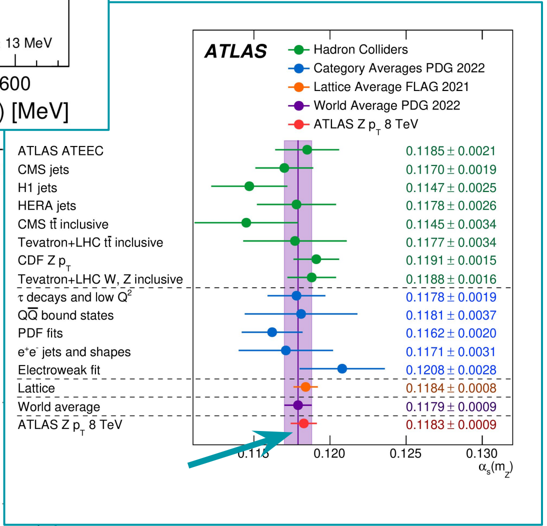


Summary







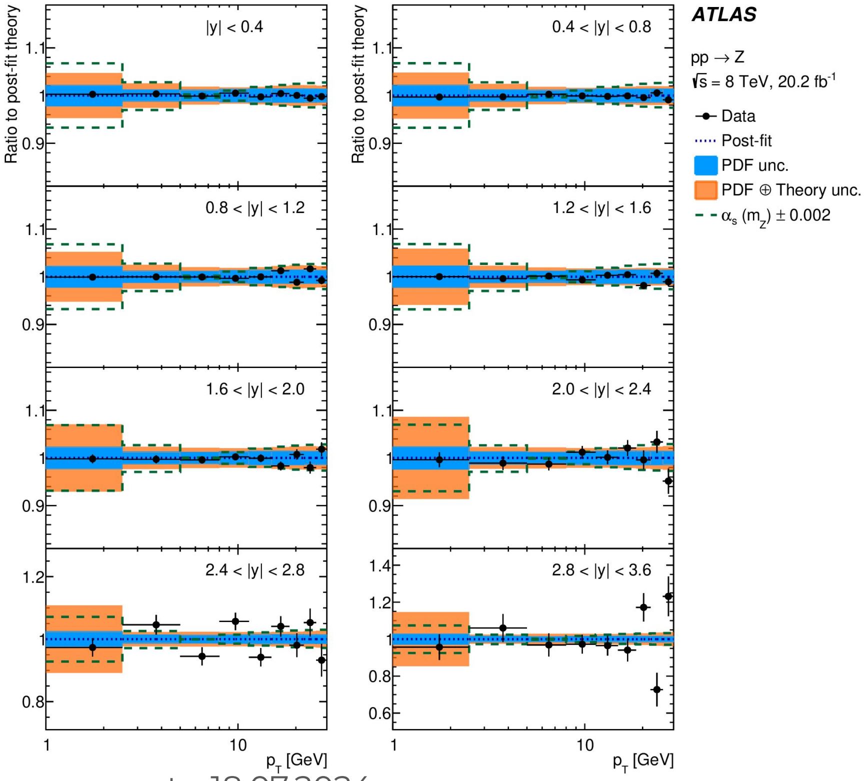


World-leading results for $\alpha_s(m_Z)$, $\Gamma(Z\to inv)$ and Γ_W!

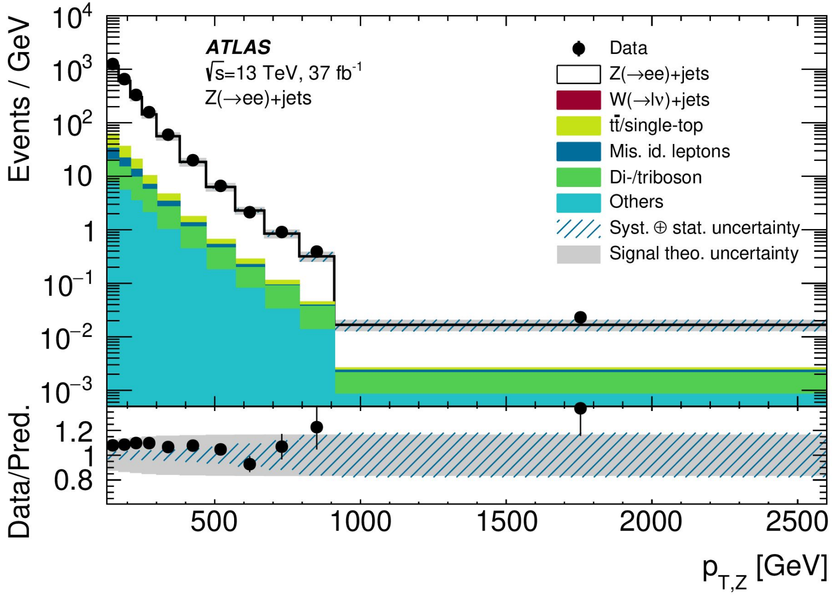
m_W precision improved by 15%!

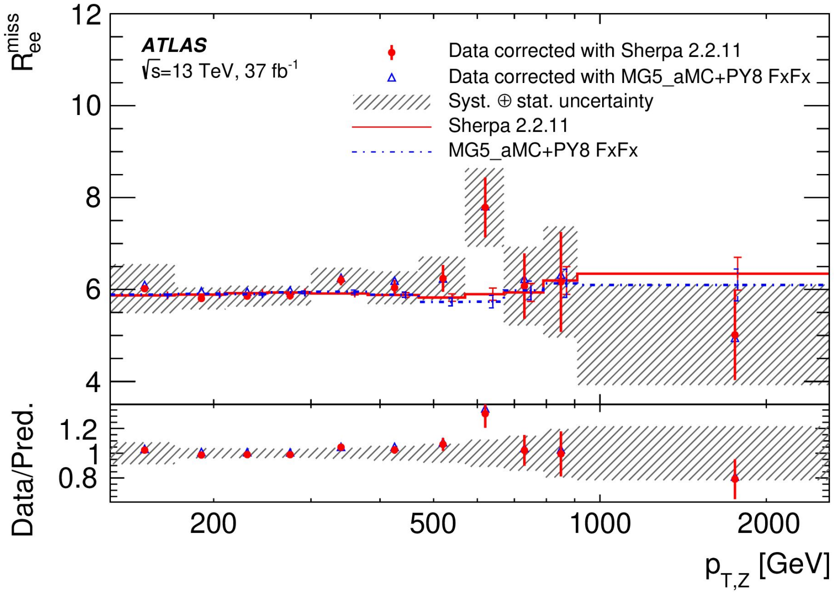
Additional slides

Strong coupling constant

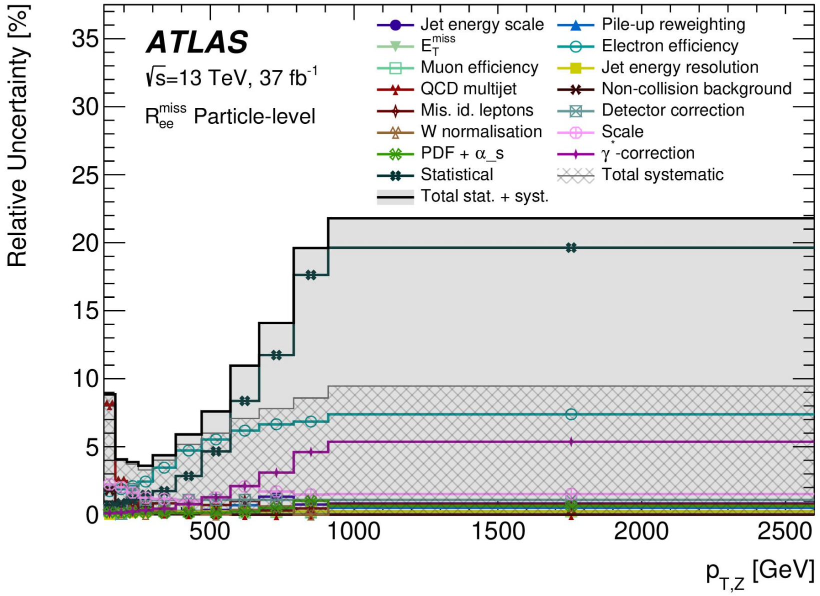


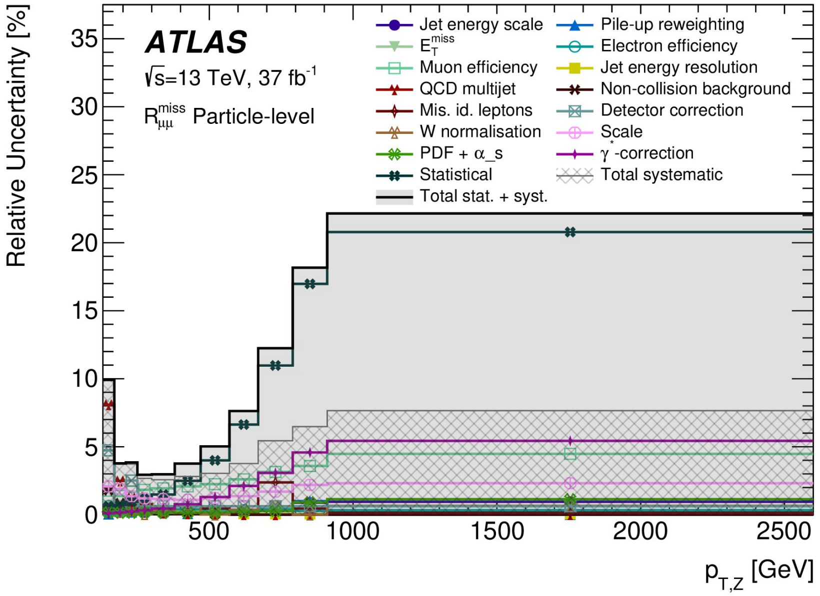
Z invisible width





Z invisible width: systematic uncertainties





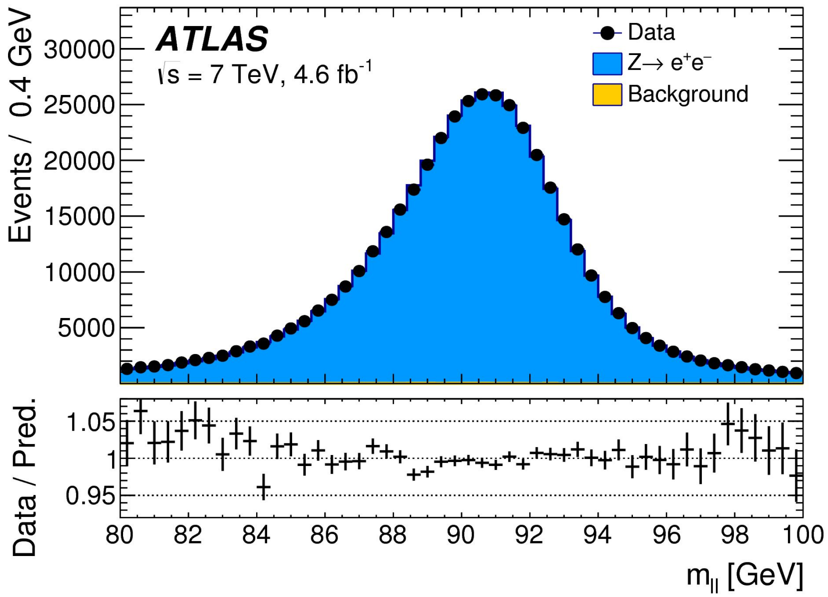
Z invisible width: systematic uncertainties

Systematic Uncertainty	Impact on $\Gamma(Z \to \text{inv})$	in [MeV]	in [%]
Muon efficiency		7.4	1.5
Renormalisation & factorisation scales		5.9	1.2
Electron efficiency		4.9	1.0
Detector correction		4.4	0.9
QCD multijet		3.2	0.6
$E_{\text{T}}^{\text{miss}}$		2.4	0.5
$Z(\to \mu\mu)$+jets misid. lepton estimate		1.9	0.4
Jet energy resolution		1.6	0.3
$W(\to \ell\nu)$+jets normalisation		1.5	0.3
Pile-up reweighting		1.5	0.3
Non-collision background estimate		1.3	0.3
Jet energy scale		1.3	0.3
γ^*-correction		1.0	0.2
$Z(\to ee)$+jets misid. lepton estimate		1.0	0.2
Luminosity		1.0	0.2
Parton distribution functions + α_s		0.7	0.1
$\Gamma(Z \to \ell\ell)$		0.5	0.1
Tau energy scale		0.4	0.1
Muon momentum scale		0.3	0.1
$W(\to \ell\nu)$+jets misid. lepton estimate		0.3	0.1
(Forward) jet vertex tagging		0.2	< 0.1
Top subtraction scheme		0.2	< 0.1
Electron energy scale		0.1	< 0.1
Systematic		12	2.4
Statistical		2	0.4
Total		13	2.5

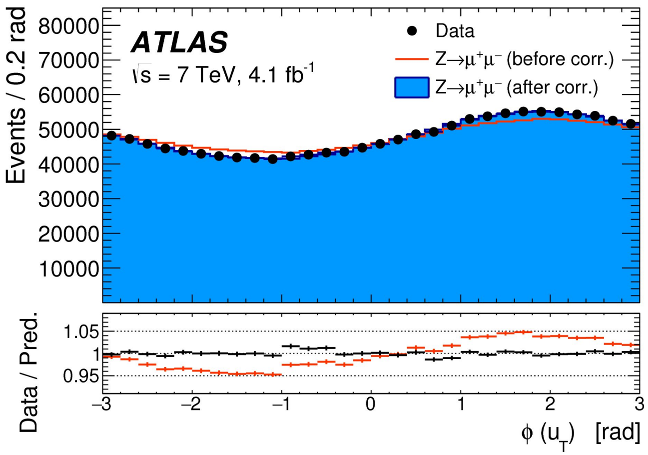
Experimental corrections

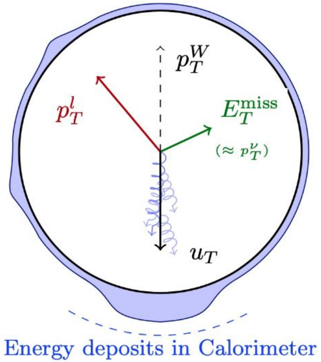
Benefit from excellent control of experimental corrections in previous ATLAS measurement → selections unchanged, update to QCD background estimation

Lepton momentum calibration (~10^{-4})



Hadronic recoil (u_T) calibration (~10^{-3})



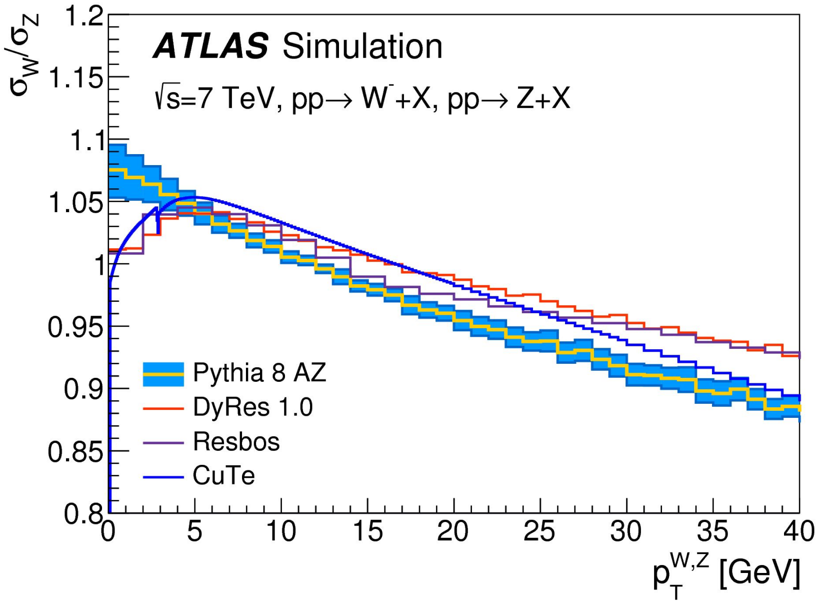


Also: lepton efficiencies, backgrounds (esp. data-driven QCD), ...

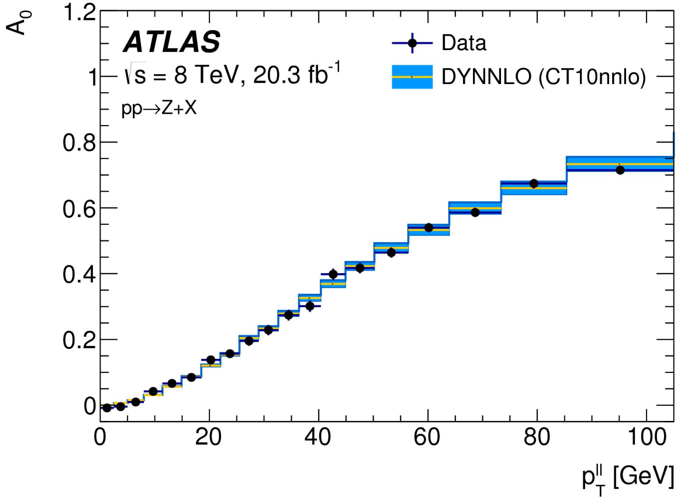
Theoretical modelling

Modelling largely unchanged from previous analysis → more modern PDF sets, small update to uncertainties for higher-order electroweak corrections

W/Z boson p_T modelling



Angular coefficients (A_i)



Also: parton distribution functions, higher-order electroweak corrections, …

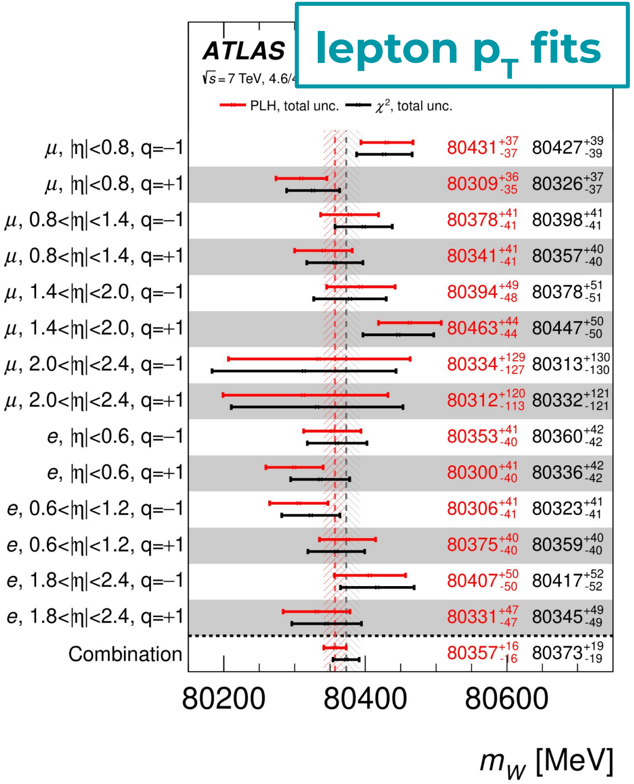
m_W: Comparison of statistical methods

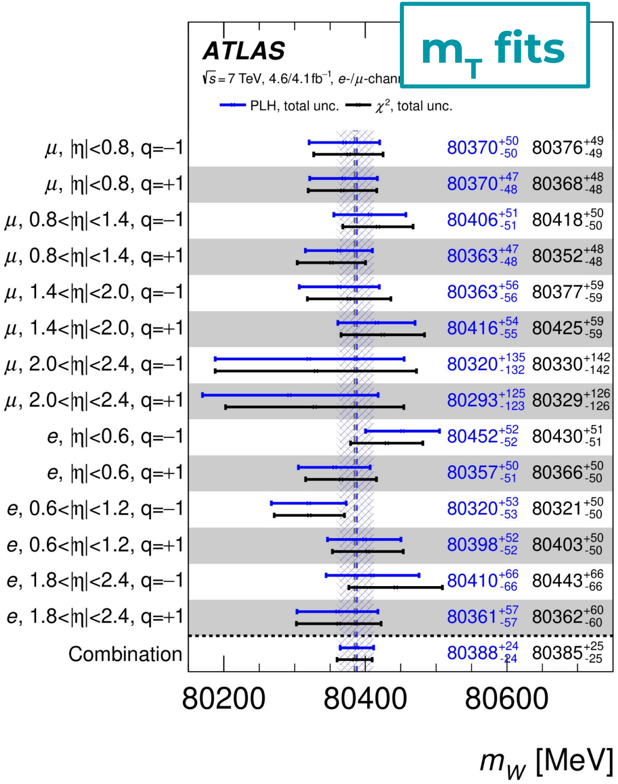
Compare fit results between χ^2+offset method and PLH fit

Use CT10nnlo PDF set (baseline in previous measurement)

Total uncertainties reduced with PLH fit

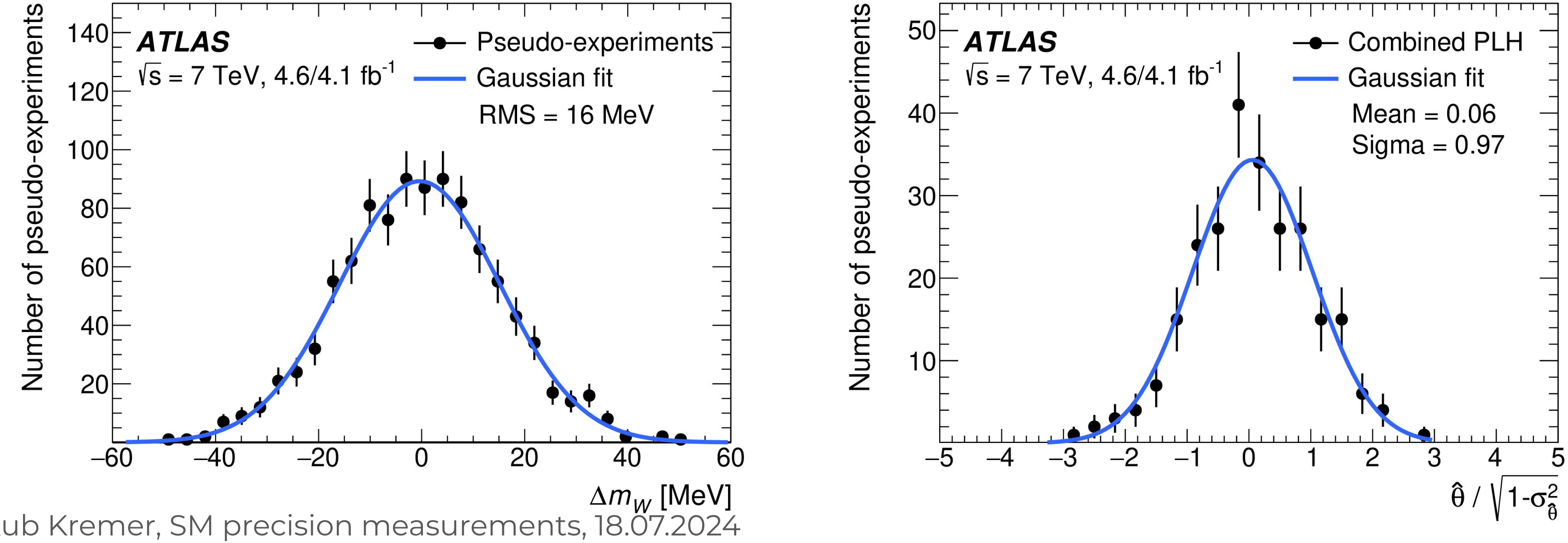
Combined lepton p_T fit: central value shifted by 16 MeV





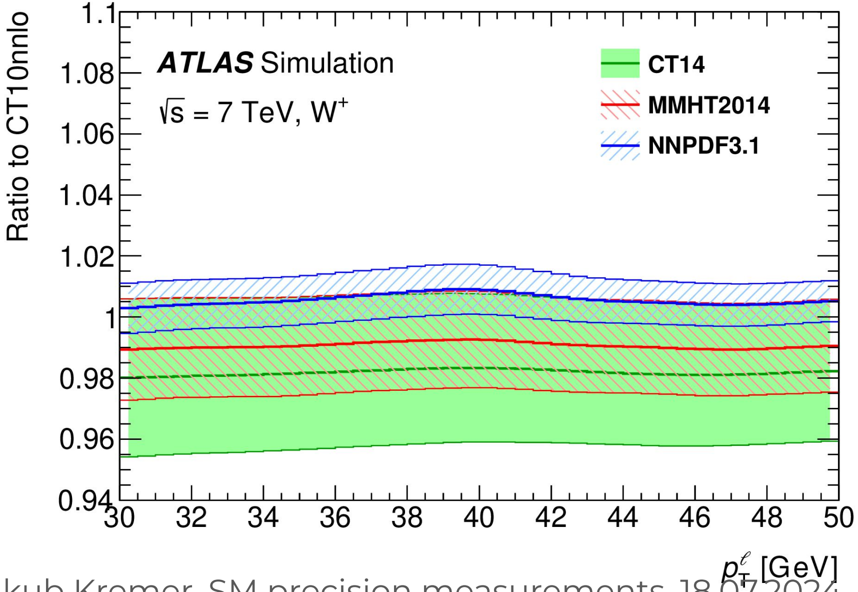
m_W: PLH fit checks

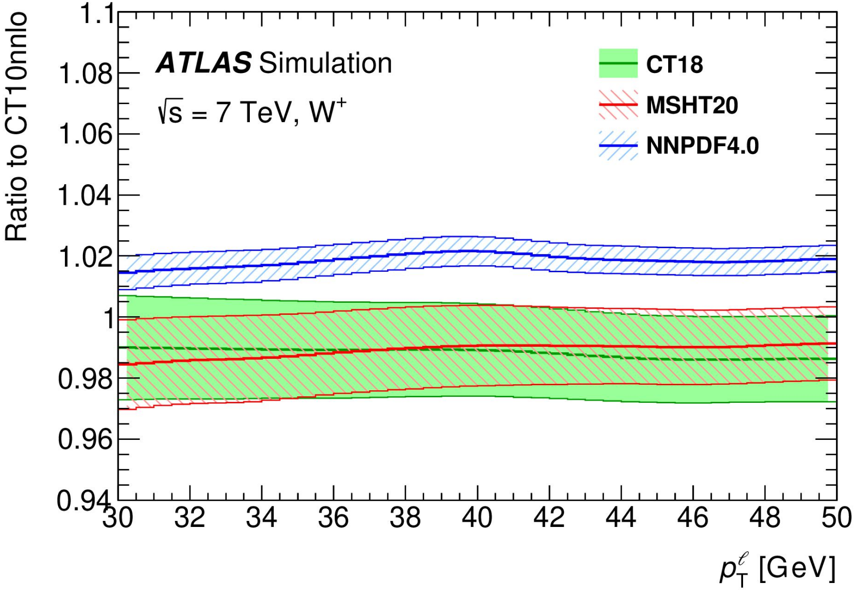
- Fit toys with random variations of nuisance parameters
- Central values for lepton p_T fit: 16 MeV spread → χ^2 and PLH results agree at 1σ
- Distribution of nuisance parameter pulls consistent with normal distribution



PDF set updates

- Kinematic distributions extrapolated from CT10nnlo to more modern PDF sets using reweighting derived with POWHEG
- Impact on both shape and normalisation of distributions (esp. NNPDF sets!)





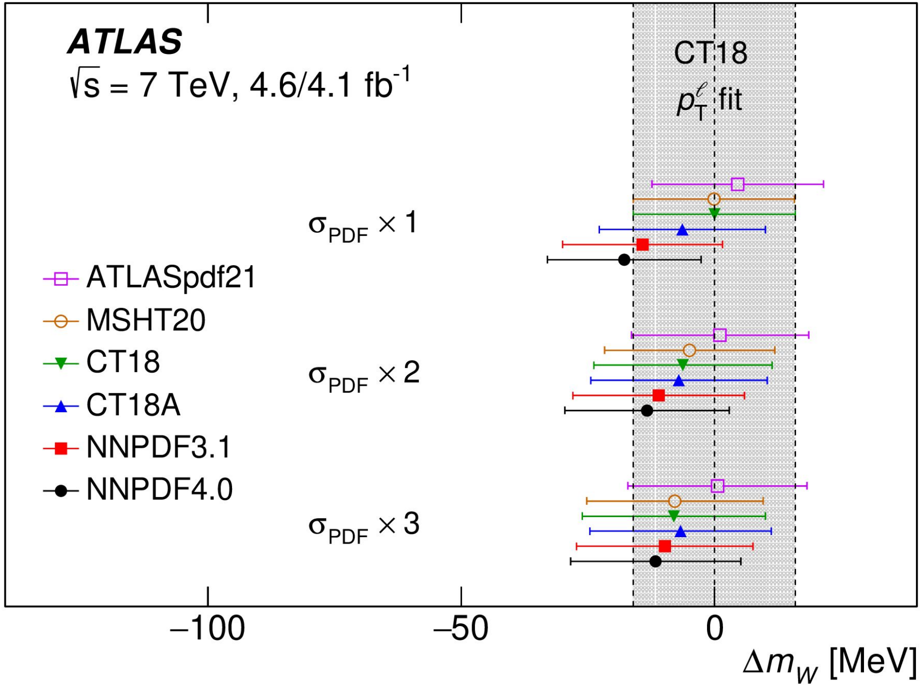
m_W: Scaling pre-fit PDF uncertainties

Cross-check: do enlarged PDF uncertainties improve agreement between different sets?

Yes: more freedom to adapt to data → reduced model dependence at cost of slightly increased total uncertainty

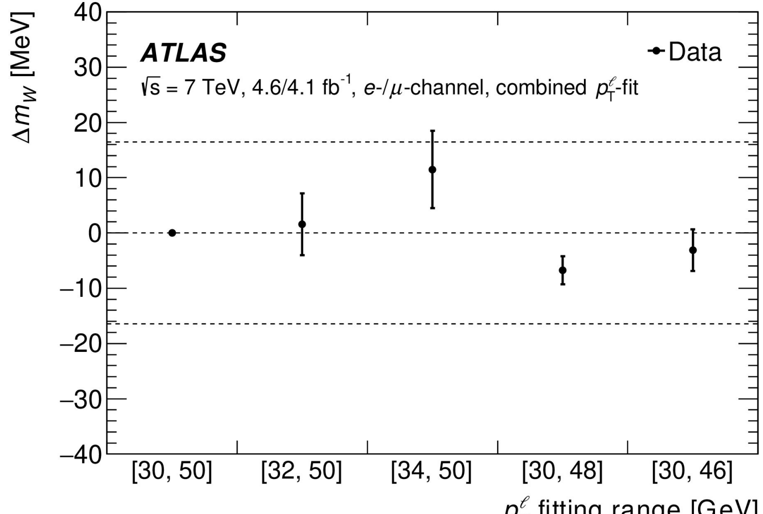
Baseline set for final results: **CT18**

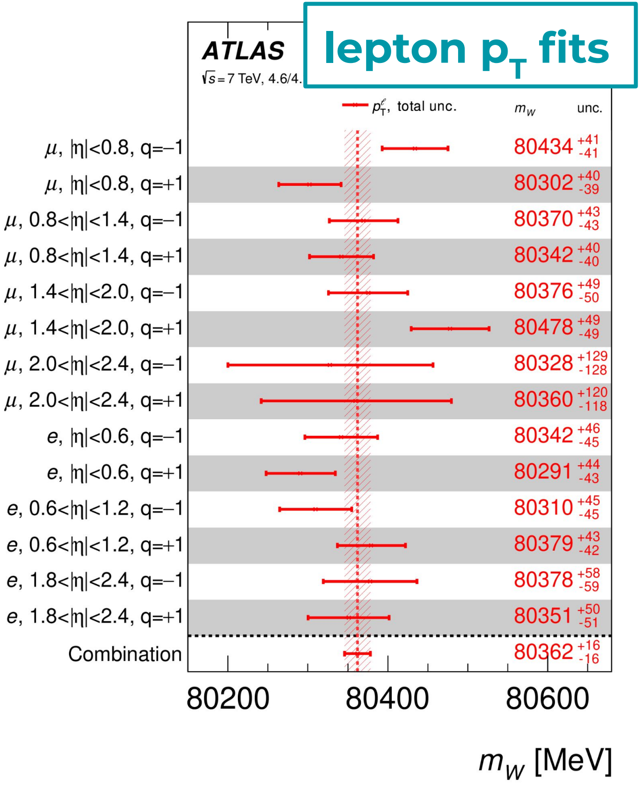
- does not include ATLAS W/Z boson cross-sections at 7 TeV
- most conservative uncertainty (except ATLASpdf21)



m_W: Fit results with CT18 PDF set

- Cross-checks done with separate combinations of e/μ or W^+/W^- channels
- All consistent within 1σ
- No significant dependence on fitting ranges





m_W: Lepton p_T-m_T combination

- Fits using lepton p_T and m_T not statistically independent → combine with BLUE
- Correlation determined using toy variations of data and NPs
- Lepton p_T fits dominate combined results

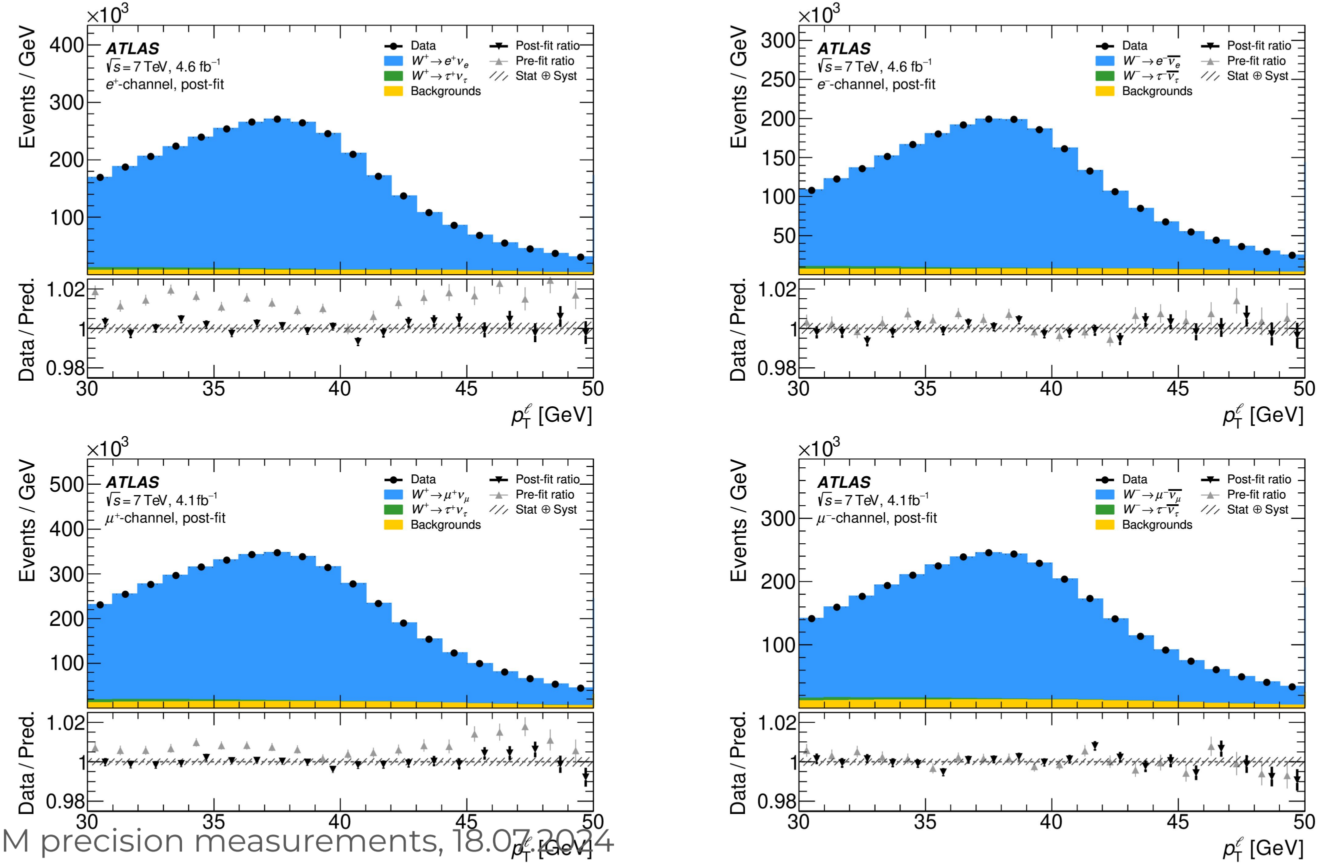
PDF set	Correlation	weight (p_T^ℓ)	weight (m_T)	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%	89%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

Γ_W: Results

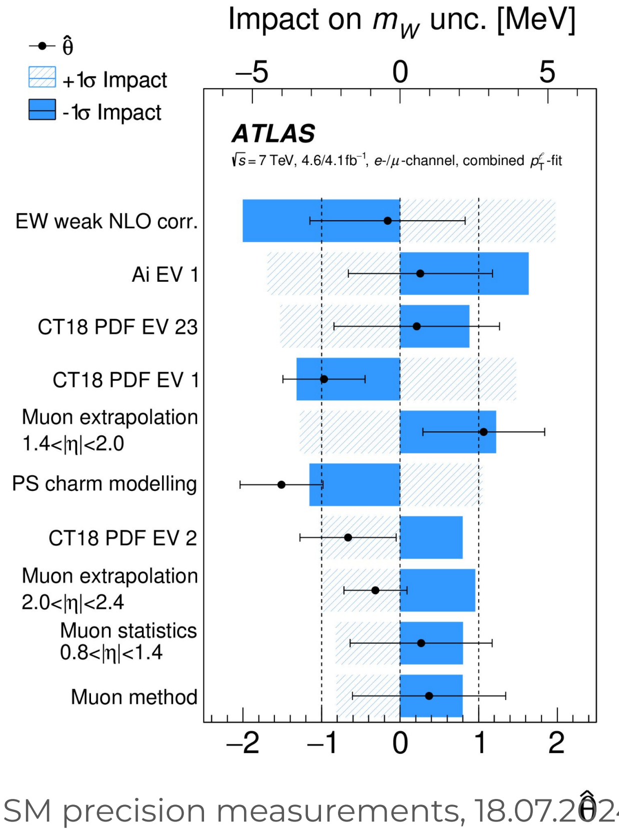
- Measurement procedure largely the same as for m_W fits
- Much less dependence on PDF set
- Combined results dominated by m_T fits

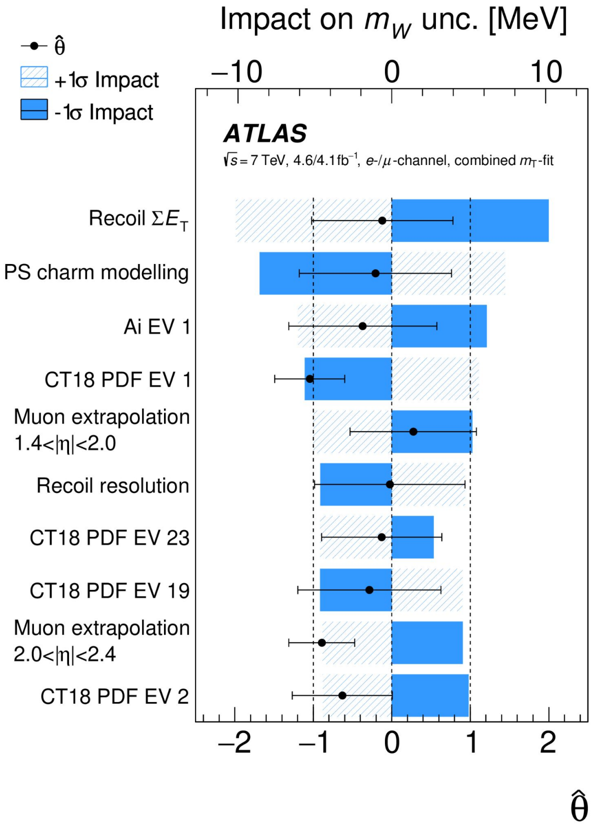
PDF set	Correlation	weight (m_T)	weight (p_T^ℓ)	Combined Γ_W [MeV]
CT14	50.3%	88%	12%	2204 ± 47
CT18	51.5%	87%	13%	2202 ± 47
CT18A	50.0%	86%	14%	2184 ± 47
MMHT2014	50.8%	88%	13%	2182 ± 47
MSHT20	53.6%	89%	11%	2181 ± 47
ATLASpdf21	49.5%	84%	16%	2193 ± 46
NNPDF31	49.9%	86%	14%	2182 ± 46
NNPDF40	51.4%	85%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

m_W: Post-fit lepton p_T distributions

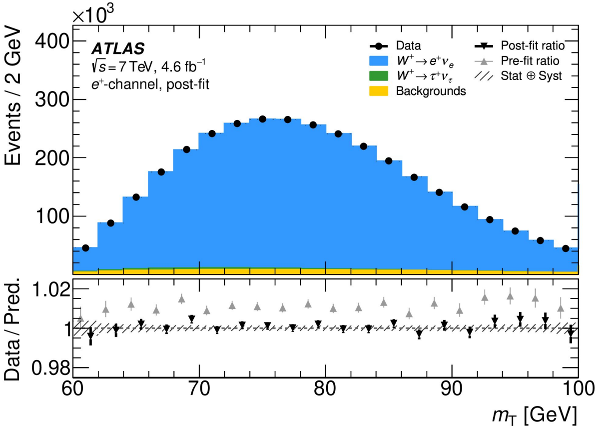


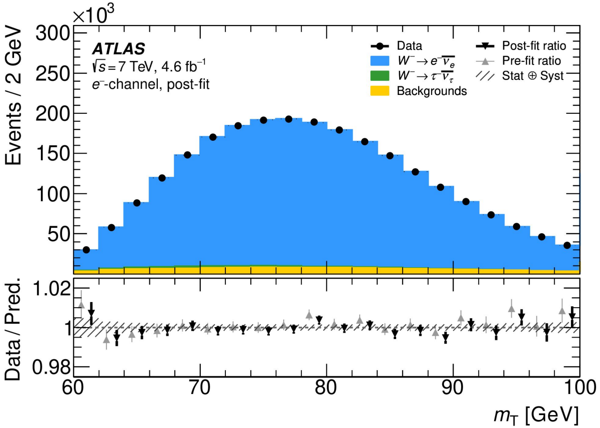
m_W: NP ranking

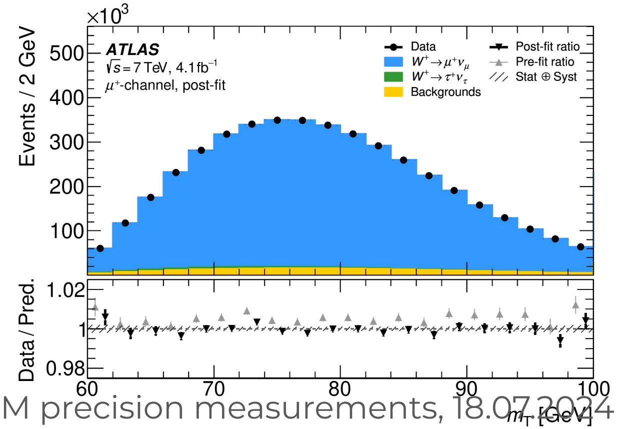


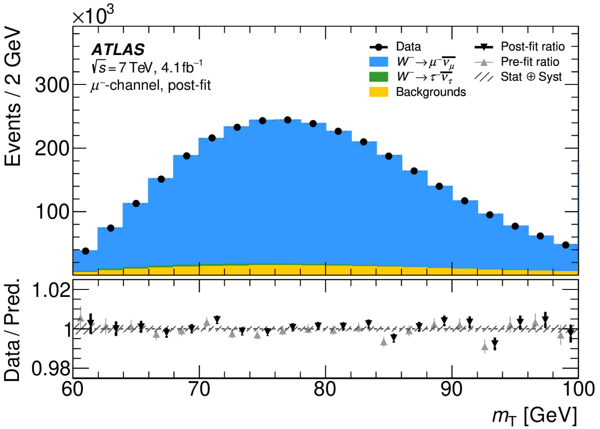


Γ_W: Post-fit m_T distributions

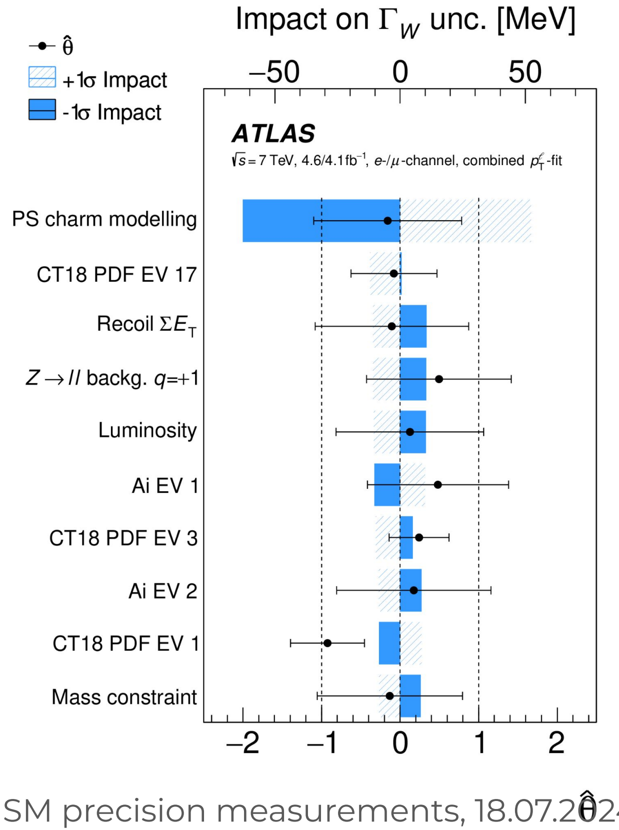


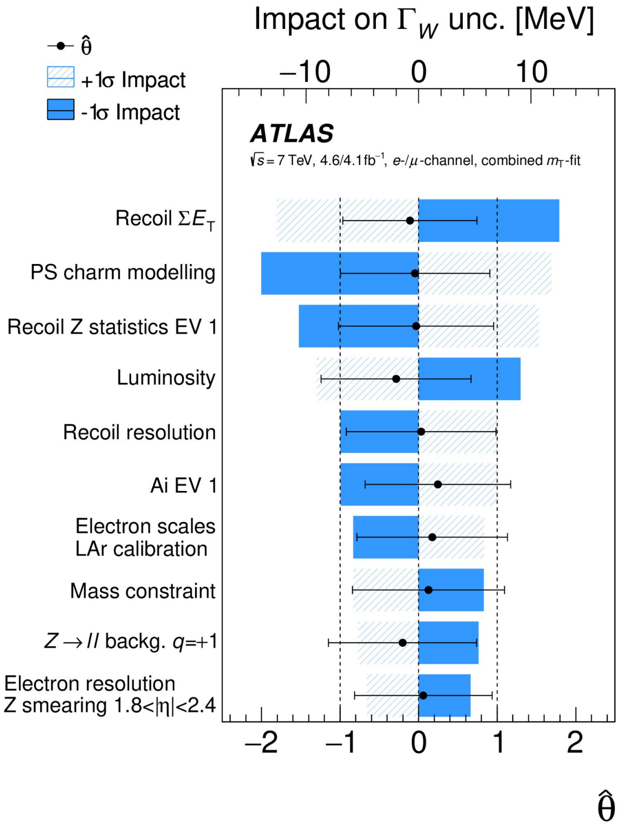




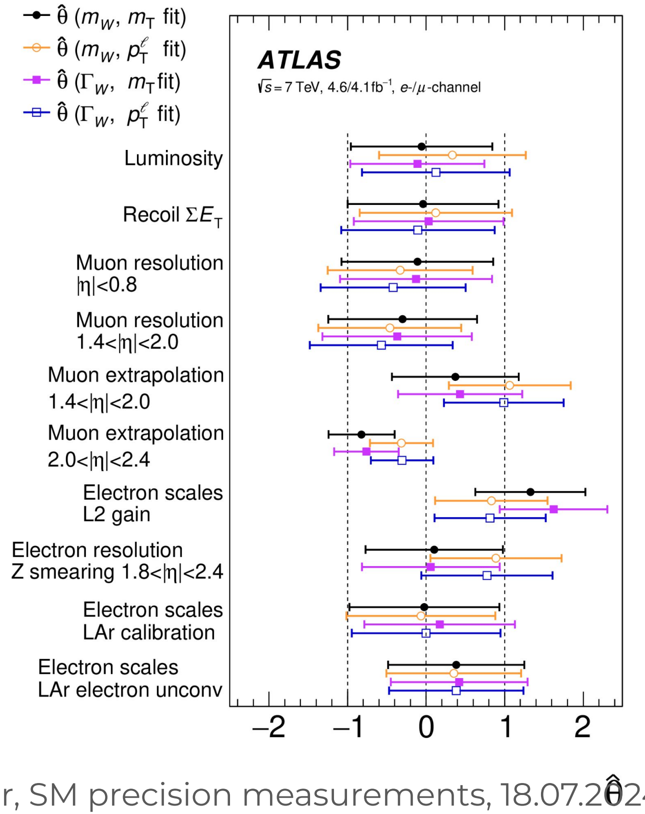


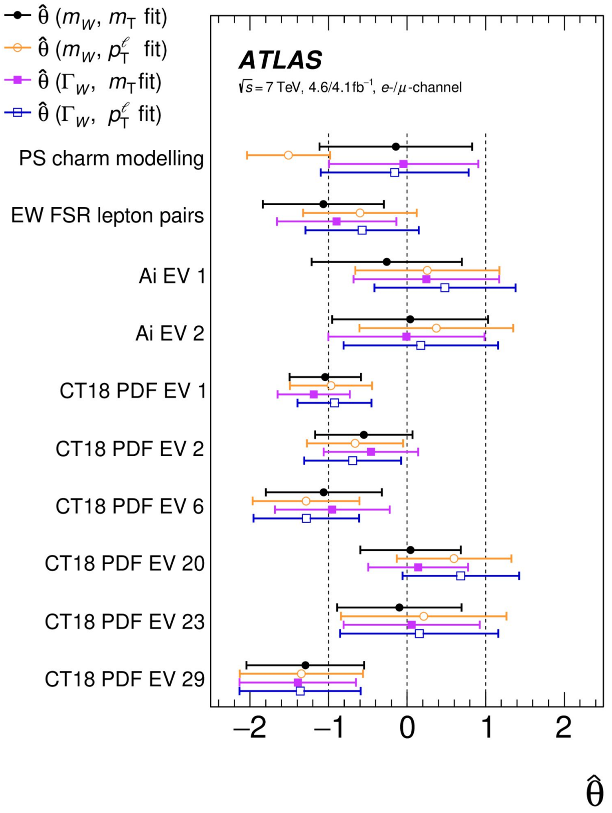
Γ_W: NP ranking



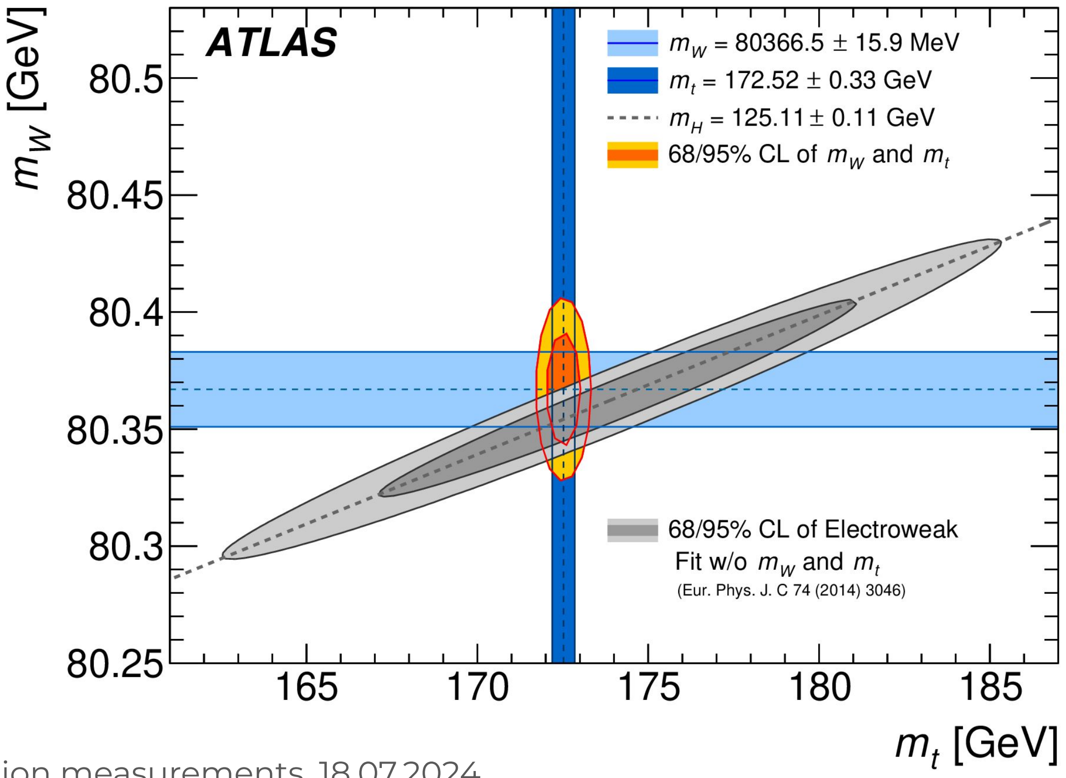


m_W/Γ_W: NP pull comparison





m_W: Comparison to global EW fit



Simultaneous m_W and Γ_W fit

Previously shown fits of m_W (Γ_W) use as input the Γ_W (m_W) value from EW global fit

Determined linear dependence of the two observables:

- $\Delta m_W = -0.06\ \Delta\Gamma_W$
- $\Delta\Gamma_W = -1.25\ \Delta m_W$

Further test interdependence with simultaneous fit of both observables:

- $m_W = 80354.8 \pm 16.1$ MeV
- $\Gamma_W = 2198 \pm 49$ MeV
- -30% correlation