Recent Electroweak Precision Measurements in ATLAS

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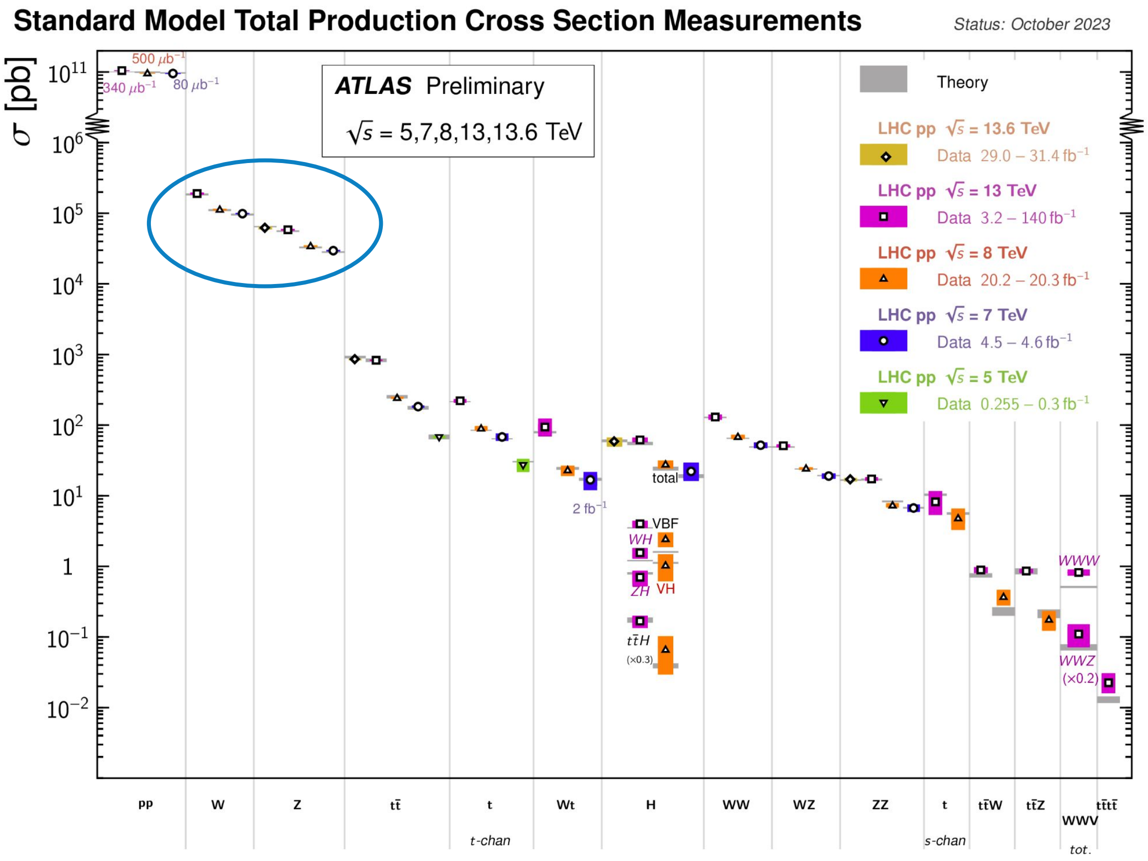
ATLAS EXPERIMENT

Overview

W and Z bosons are **produced in large amounts** allowing for precision measurements.

Measurements of W and Z boson at the LHC are an excellent **probe of QCD** and proton structure.

Precision measurements of the gauge boson properties allow for testing of higher order corrections to predictions and the consistency of the SM.



Overview

Papers Covered:

- *Measurement of **Vector Boson Production Cross Sections** and Their Ratios Using pp Collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS Detector.* *Phys.Lett.B 854 (2024) 138725*

- *Measurement of the **Z boson Invisible Width** at $\sqrt{s}$ = 13 TeV with the ATLAS Detector. Submitted to Phys. Lett. B, arXiv:2313.02789 (also see poster by Martin Klassen)*

- *Measurement of the **W-boson Mass and Width** with the ATLAS Detector Using proton-proton Collisions at $\sqrt{s}$ = 7 TeV. Submitted to EPJC, arXiv:2403.15085*

- *Precise Measurements of **W- and Z-boson Transverse Momentum Spectra** with the ATLAS Detector Using pp collisions at $\sqrt{s}$ = 5.02 TeV and 13 TeV. Submitted to EPJC, arXiv:2404.06204*

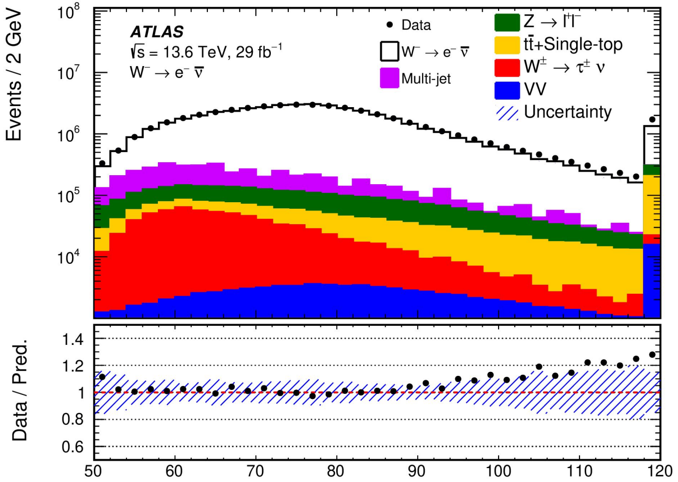
Vector Boson Production Cross Sections and Ratios at $\sqrt{s} = 13.6$ TeV

Measurement of fiducial and total $W^{\pm} \to \ell^{\pm}\nu(\bar{\nu})$ and $Z \to \ell^{+}\ell^{-}$ cross sections in pp collisions at $\sqrt{s}$ = 13.6 TeV with 29 fb^{-1} of data collected in 2022, the first year of Run 3 of the LHC.

Their ratios, and ratios of $t\bar{t}$ and W-boson fiducial cross sections are also measured.

Extracted using Profile Likelihood (PLH) fits to the inclusive data.

$W^{-} \to e^{-}\overline{\nu}$



$m_T\,[\mathrm{GeV}]$

EW and top-quark background processes estimated using MC and multijet (MJ) estimated using a data-driven technique.

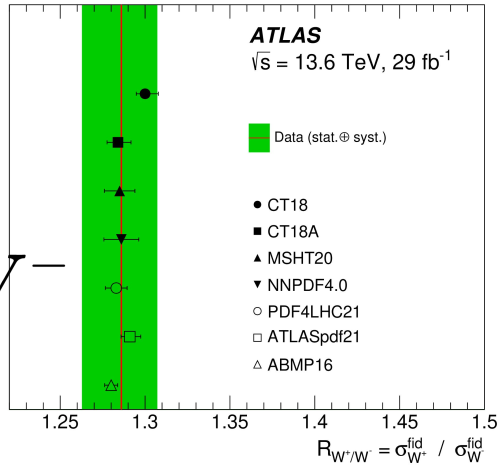
Compared to NNLO theory and NNLL q_T-resummation (QCD) + NLO (EW) accuracy with different PDF sets.

The W and Z-boson fiducial cross sections and their ratios are in overall good agreement to prediction.

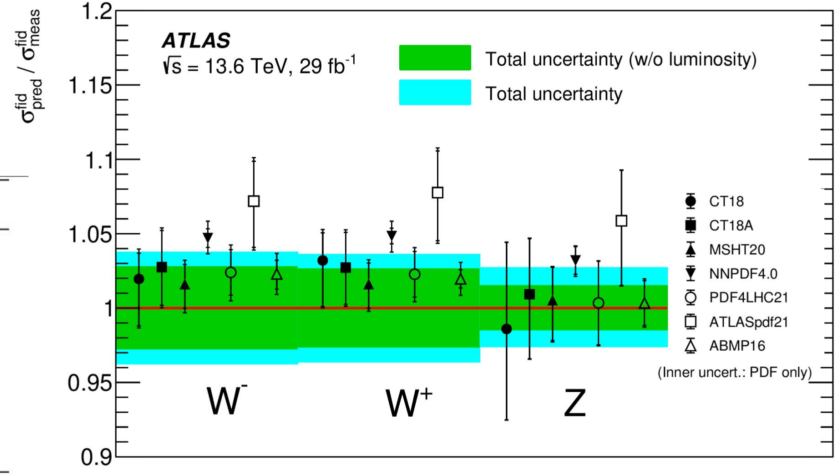
The $t\bar{t}/W$ ratios are slightly lower than predicted but consistent with Run 3 $t\bar{t}$ cross section measurement. First time measuring $t\bar{t}/W$ ratios.

Values are consistent across multiple PDF sets.

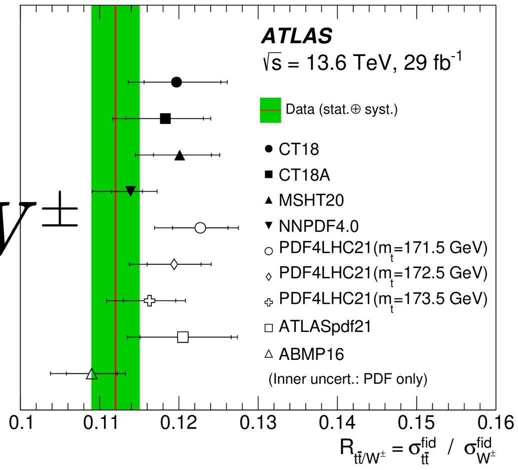
W^+/W^-

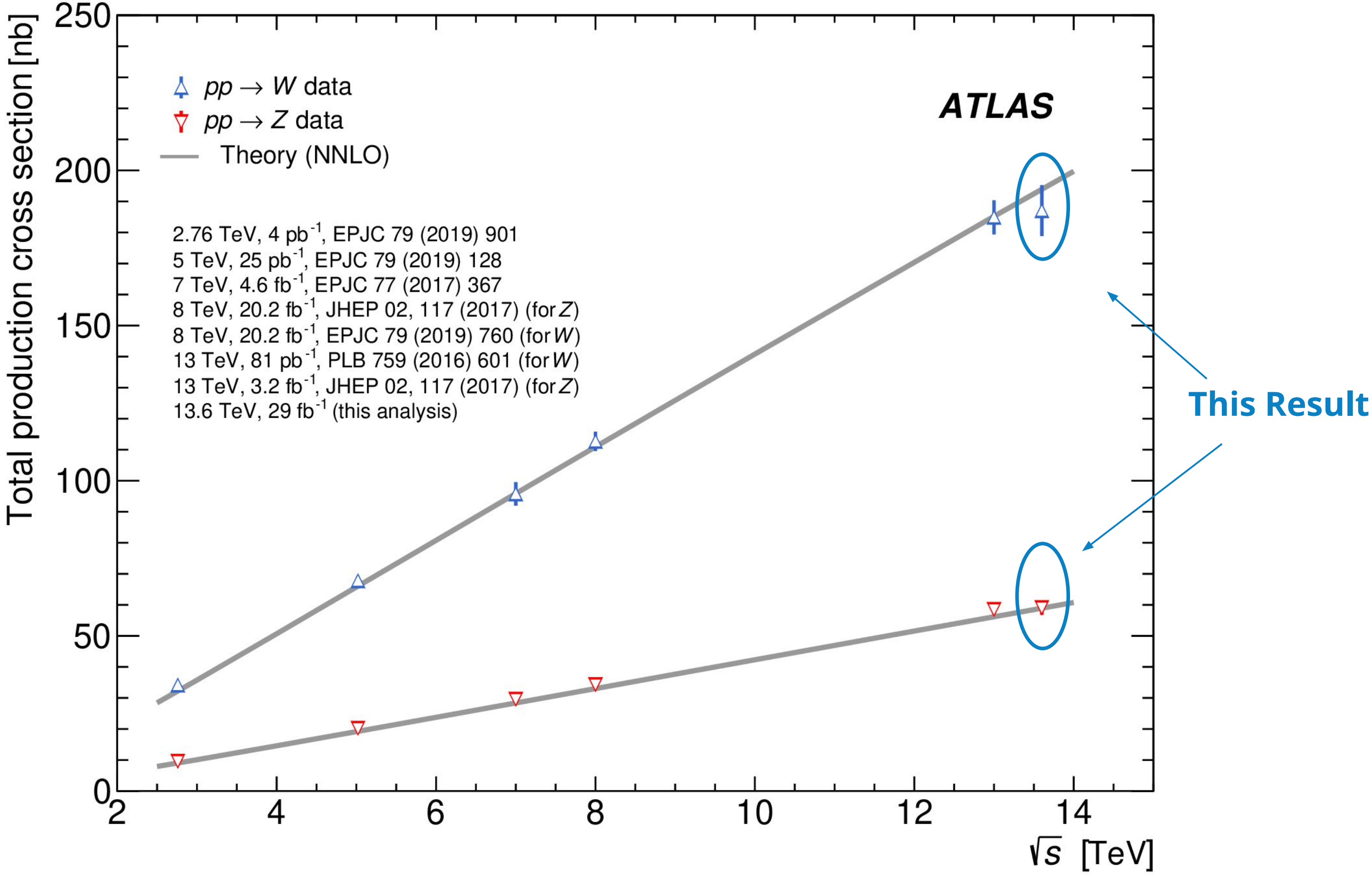


Ratio	$R \pm \delta R_{\text{stat} \oplus \text{syst}}$
W^+/W^-	1.286 ± 0.022
$W^\pm/Z$	10.17 ± 0.25
$t\bar{t}/W^-$	0.256 ± 0.008
$t\bar{t}/W^+$	0.199 ± 0.006
$t\bar{t}/W^\pm$	0.112 ± 0.003



$t\bar{t}/W^\pm$





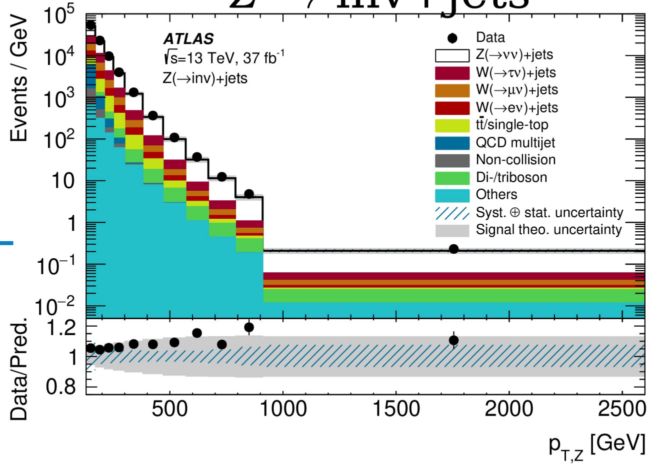
ATLAS
pp → W data
pp → Z data
Theory (NNLO)
2.76 TeV, 4 pb-1, EPJC 79 (2019) 901
5 TeV, 25 pb-1, EPJC 79 (2019) 128
7 TeV, 4.6 fb-1, EPJC 77 (2017) 367
8 TeV, 20.2 fb-1, JHEP 02, 117 (2017) (for Z)
8 TeV, 20.2 fb-1, EPJC 79 (2019) 760 (for W)
13 TeV, 81 pb-1, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb-1, JHEP 02, 117 (2017) (for Z)
13.6 TeV, 29 fb-1 (this analysis)
Total production cross section [nb]
√s [TeV]
This Result

Z boson Invisible Width at $\sqrt{s} = 13$ TeV

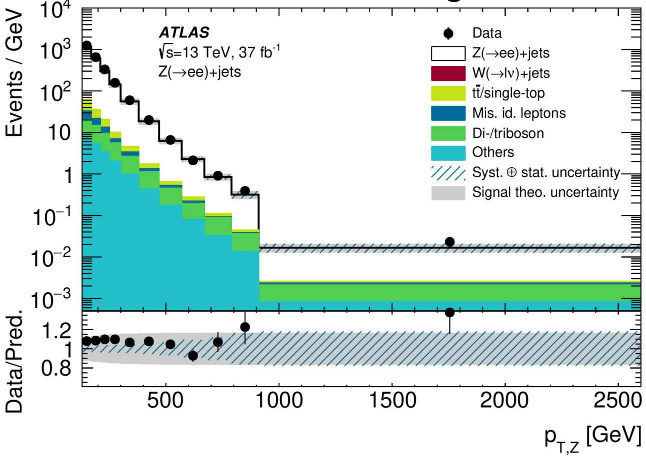
Z boson events with jets and missing transverse energy at √s = 13 TeV using 2015-16 data from Run 2 with 37 fb^{-1} the ratio of $Z \to$ invisible to $Z \to \ell^+\ell^-$ is measured.

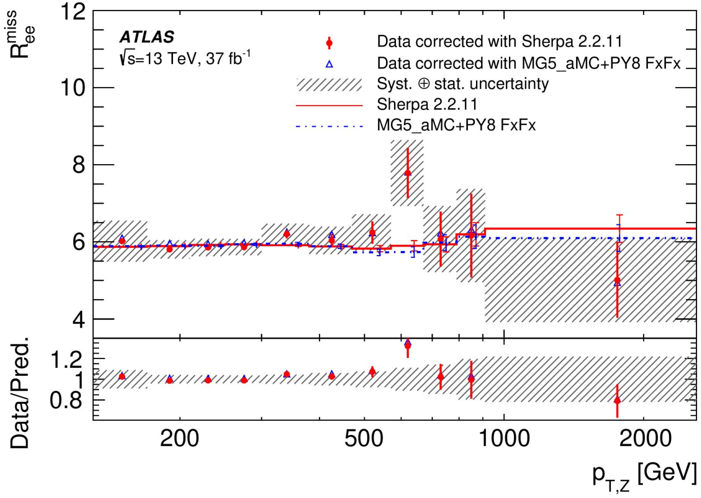
$$R^{\text{miss}} = \frac{d\sigma(Z\to\text{inv+jets})}{dp_T^Z} \Big/ \frac{d\sigma(Z\to\ell\ell\text{+jets})}{dp_T^Z}$$

$Z \to$ inv+jets



$Z \to e^+e^-$+jets





Using $\Gamma(Z \to \text{inv}) = \hat{R}^{\text{miss}} \cdot \Gamma(Z \to \ell\ell)$ to find the width, channels are in good agreement.

Channel	Value [MeV]
$Z \to ee$	$490 \pm 3\ (\text{stat.}) \pm 16\ (\text{syst.})$
$Z \to \mu\mu$	$511 \pm 2\ (\text{stat.}) \pm 13\ (\text{syst.})$
Combination	$506 \pm 2\ (\text{stat.}) \pm 13\ (\text{syst.})$

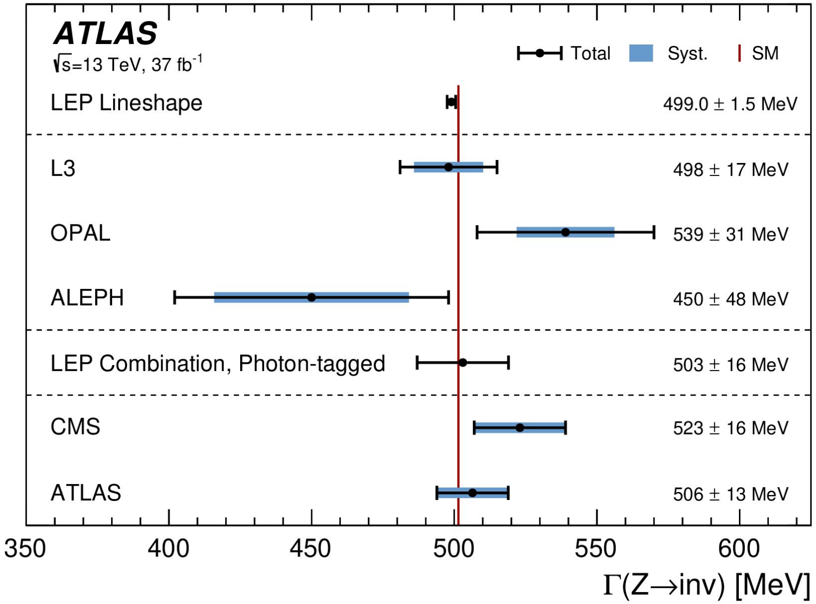
The **combined value of is in good agreement** with Z resonance lineshape from LEP 499.0 ± 1.5 MeV and SM prediction 501.445 ± 0.047 MeV.

Most precise measurement for recoil-based final states to date!

Sensitive to the number of light neutrinos that couple to the Z boson and potential non-SM contributions.

Uncertainty dominated by lepton systematics in denominator of ratio.

This result →



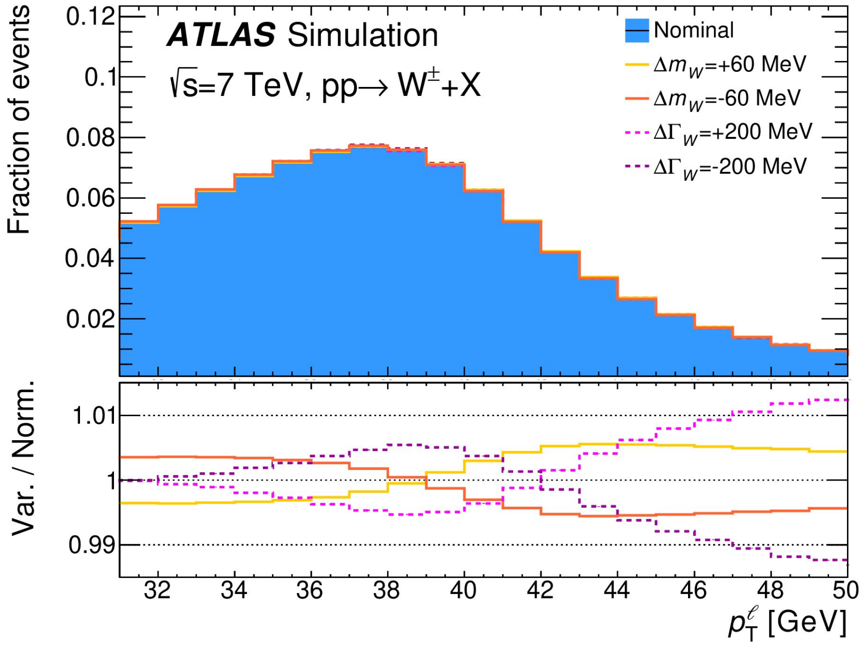
W Boson Mass and Width at $\sqrt{s} = 7$ TeV

Reanalysis of W boson mass and first W boson width measurement at LHC using 4.6 fb^{-1} of data taken at √s = 7 TeV during 2011.

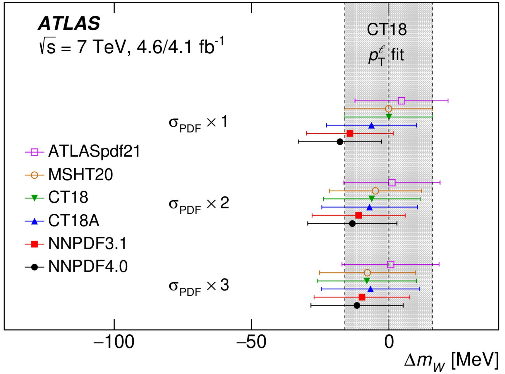
Things Updated:
Uses an improved method based on a PLH fit of p_T^ℓ and m_T using $W^\pm \to \ell^\pm \nu(\bar{\nu})$ events.

More recent PDFs used, now including of ATLASpdf21, CT18, CT18A, MHST20, NNPDF3.1, and NNPDF4.0 PDF sets.

The width is used as a constraining parameter in the fit $\Gamma_W^{SM} = 2088 \pm 1$ MeV



W Boson Mass



The p_T^ℓ and m_T results are combined using BLUE prescription.
Weight of p_T^ℓ ranges from 86-97% depending on the PDF set.

For CT18 the final result is $m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV}$
$= 80366.5 \pm 15.9\ \text{MeV}$

Compatible with:

- Previous measurement using same data
- Global EW fit
- SM expectation
- Recent combination with CDF measurement excluded

$m_W = 80369.2 \pm 13.3\ \text{MeV}$

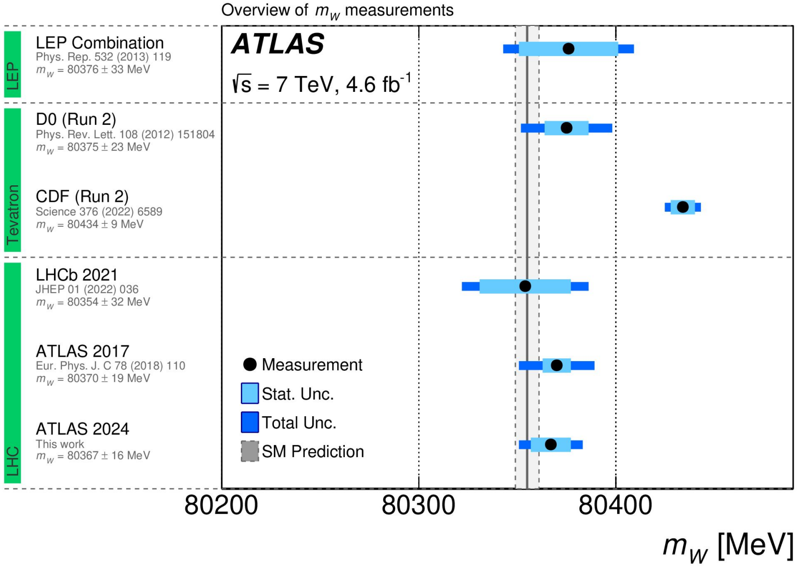
At slight tension with CDF measurement included

$m_W = 80394.6 \pm 11.5\ \text{MeV}$

Dominant Syst.

Unc. [MeV]	PDF	u_T
p_T^ℓ	4.9	0.9
m_T	11.7	11.4
Combined	5.7	2.3

This result

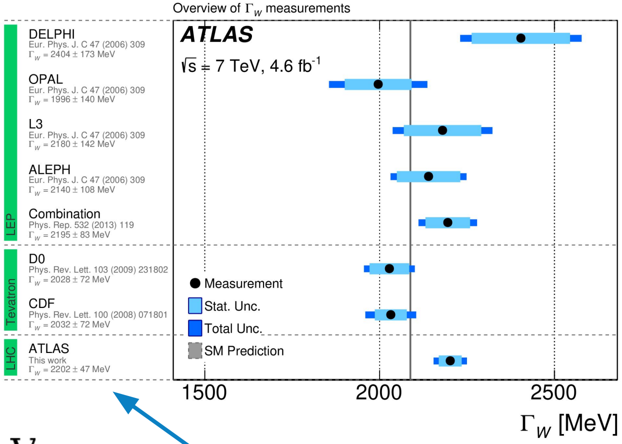


W Boson Width

The p_T^ℓ and m_T distributions are also sensitive the W boson width. Weight of m_T ranges from 84-89% depending on the PDF set.

W mass is treated as a constraining parameter using the SM expectation from EW fit $m_W^{\text{SM}} = 80355 \pm 6 \text{ MeV}$

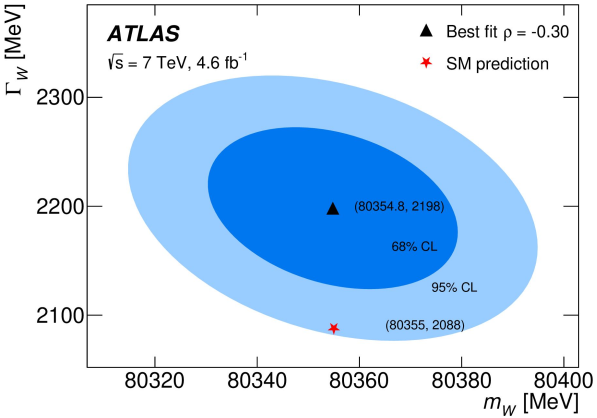
With CT18 the combined result is $\Gamma_W = 2202 \pm 32 \text{ (stat.)} \pm 34 \text{ (syst.) MeV}$
$= 2202 \pm 47 \text{ MeV}$



This result

First measurement of this at LHC and most precise to date!

A simultaneous PLH fit of both mass and width using the CT18 PDF set results in $m_W = 80354.8 \pm 16.1 \text{ MeV}$ and $\Gamma_W = 2198 \pm 49 \text{ MeV}$



Also Dominant Syst.

Unc. [MeV]	u_T
p_T^ℓ	12
m_T	18
Combined	17

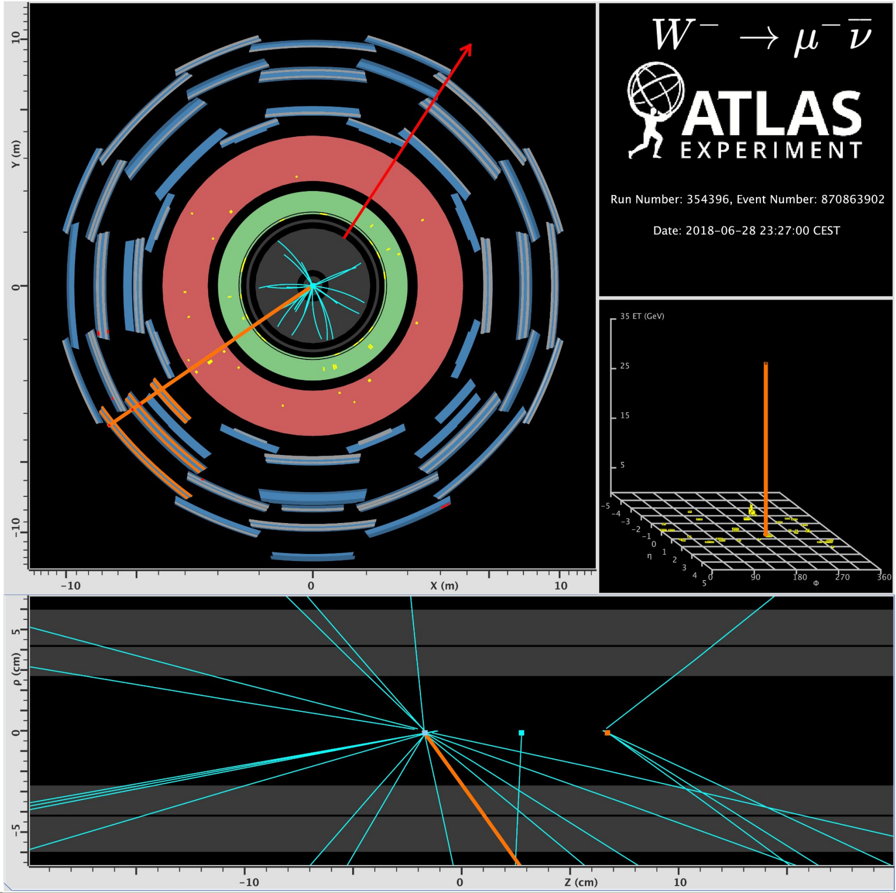
W and Z boson p_T Spectra at $\sqrt{s} = 5.02, 13$ TeV

Measurement of W and Z transverse momentum spectra using dedicated low pileup $(\langle\mu\rangle \sim 2)$ runs in 2017+2018 corresponding to 255 pb^{-1} and 338 pb^{-1} at √s = 5.02 and 13 TeV, respectively.

Special run conditions allow for **better hadronic recoil resolution** needed for the measurement of p_T^W.

Hadronic recoil resolution improved by 3% at low p_T^V and 15% at $p_T^V \approx 50$ GeV compared to √s = 7 TeV measurement.

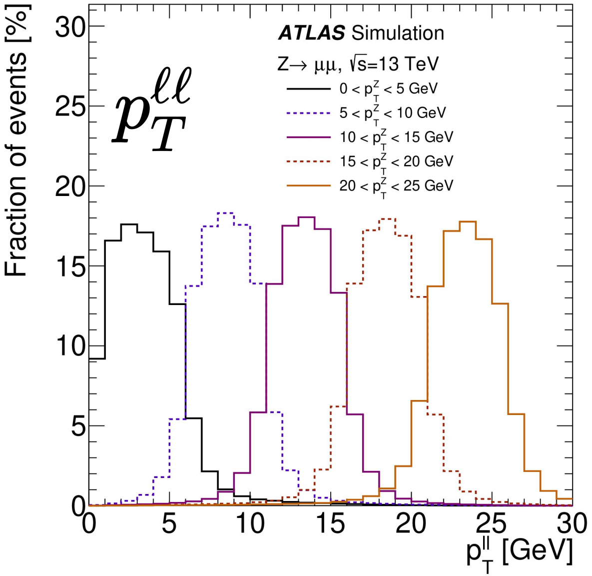
Hadronic recoil calibrated using $Z \rightarrow \ell^+\ell^-$ events since they are fully reconstructable.

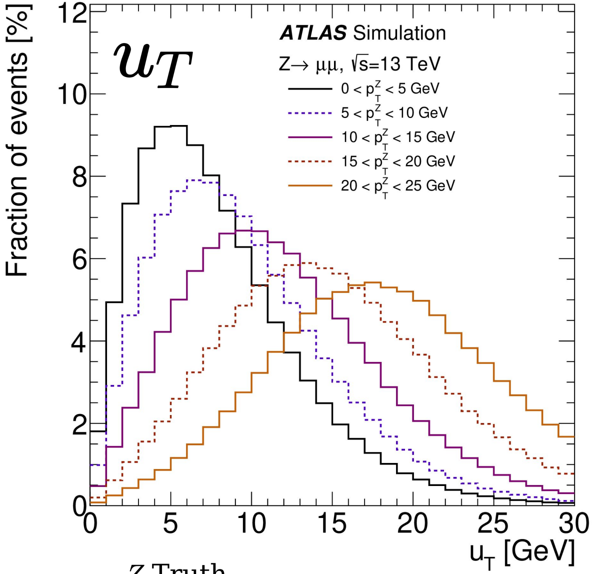


Hadronic recoil resolution allows for **minimum bin width of 7 GeV** at low p_T^V so unfolding systematics are ≤1%.

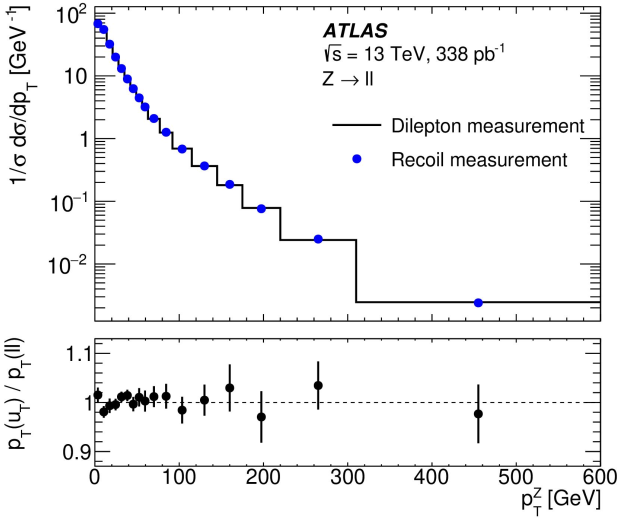
p_T^Z is measured separately using hadronic recoil and $p_T^{\ell\ell}$.

χ^2 minimization for data and simulation agreement optimized to the hadronic recoil distribution.





Reconstructed for fixed $p_T^{Z,\mathrm{Truth}}$

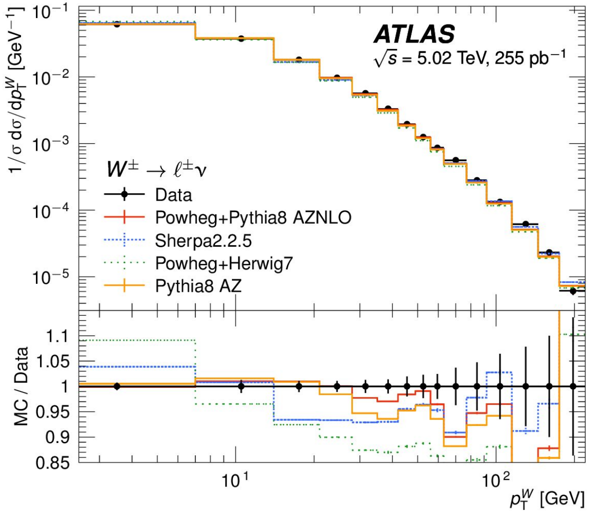


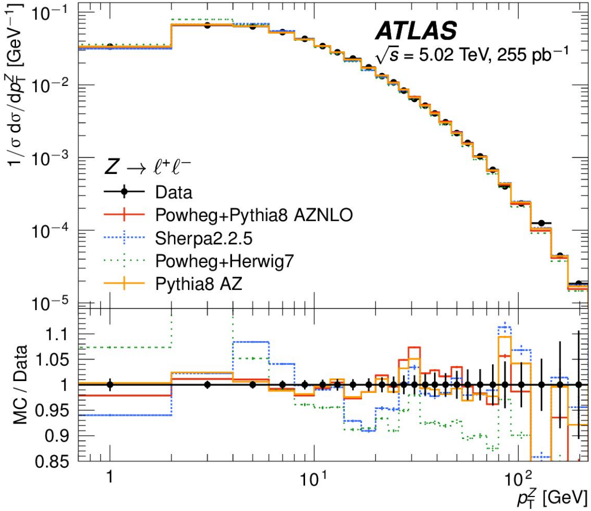
After analysis selection and background subtraction the distributions undergo iterative Bayesian unfolding to correct for detector effects.

Electron and muon channels are combined using [BLUE] prescription.

Final measurements are compared to extensive list of predictions.

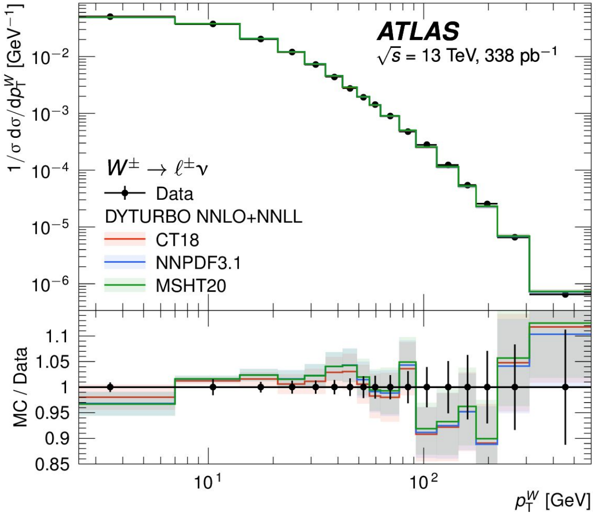
- ❖ DYTurbo v1.2.3 (NNLO+NNLL) using CT18, NNPDF3.1, and MSHT20
- ❖ Powheg+Pythia8 AZNLO tune
- ❖ Sherpa 2.2.1 / 2.2.5 / 2.2.11
- ❖ Powheg+Herwig7
- ❖ Pythia8 AZ
- ❖ MadGraph+Pythia8 FxFx
- ❖ RadISH

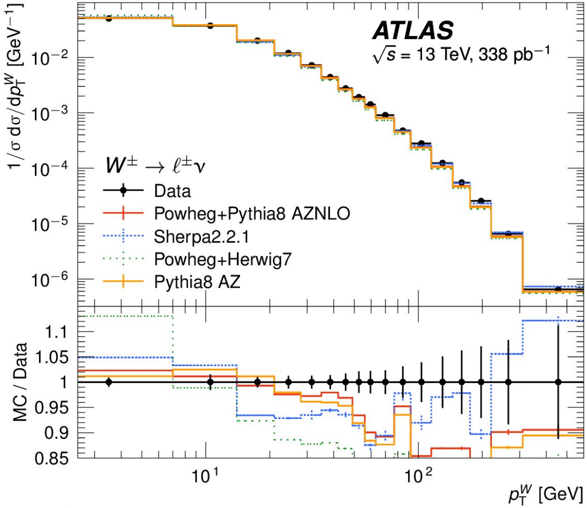




Comparisons of differential spectra show variety of discrepancies in the p_T^V distributions.

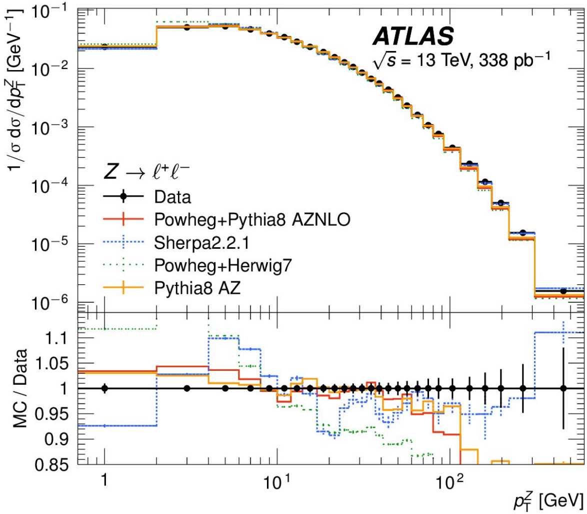
Dedicated data sets, reconstruction, and calibration techniques allow for granularity of 7 GeV in p_T^W and 1-2% level of precision.





Good modeling of the $\mathrm{p_T^W}$ spectrum important for future W boson mass measurements.

AZ Pythia8 tune (used for previous ATLAS m^W determination) validated against this data.



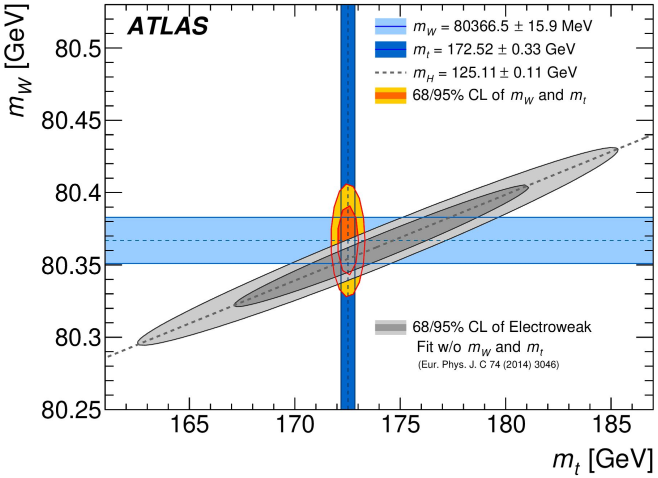
Conclusions

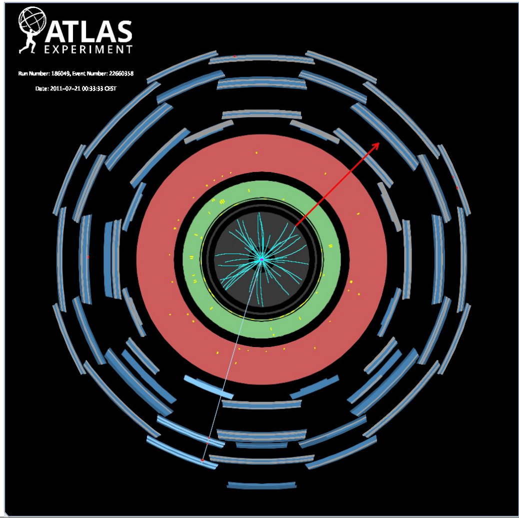
Measuring electroweak processes allows us to probe QCD and measure important electroweak parameters like the W boson mass.

Most precise hadronic recoil based measurement of Z invisible width to date.

First measurement of W width at LHC and most precise value to date.

Currently in second to last year of Run 3 so more measurements to come.





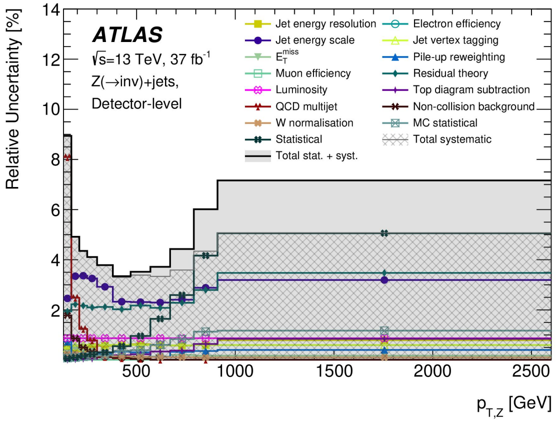
Questions?

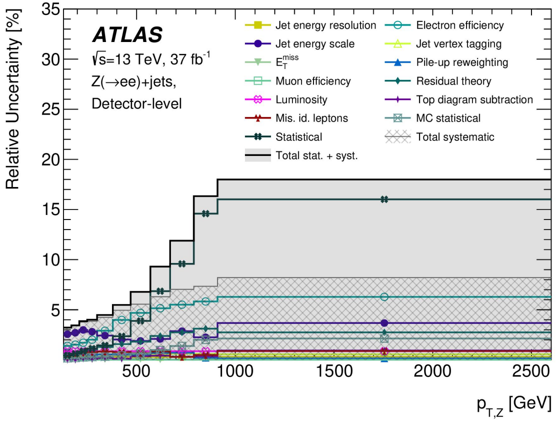
Cross-Section and Ratios Uncertainties

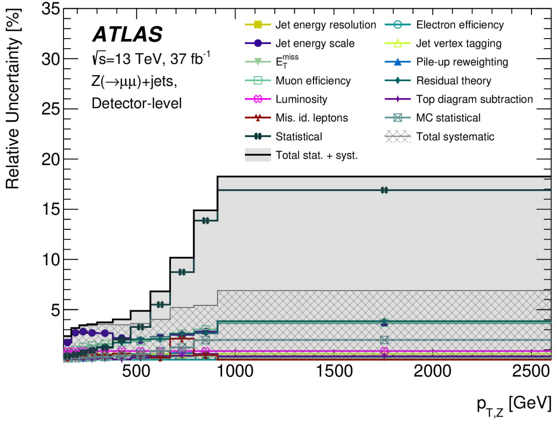
Category	$\sigma(Z \to ee)$	$\sigma(Z \to \mu\mu)$	$\sigma(Z \to \ell\ell)$	$\sigma(W^- \to e^-\bar{\nu})$	$\sigma(W^+ \to e^+\nu)$	$\sigma(W^- \to \mu^-\bar{\nu})$	$\sigma(W^+ \to \mu^+\nu)$
Luminosity	2.2	2.2	2.2	2.5	2.5	2.5	2.4
Pile-up	1.2	0.3	0.8	1.1	1.1	0.3	0.4
MC statistics	< 0.2	< 0.2	< 0.2	< 0.2	0.4	< 0.2	0.4
Lepton trigger	0.2	0.4	0.2	1.2	1.3	1.0	1.0
Electron reconstruction	1.4	–	0.9	0.7	0.8	–	–
Muon reconstruction	–	2.1	1.4	–	–	1.0	1.0
Multi-jet	–	–	–	2.9	2.4	1.3	1.1
Other background modelling	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.5	0.4
Jet energy scale	–	–	–	1.4	1.4	1.3	1.4
Jet energy resolution	–	–	–	< 0.2	0.3	0.2	0.2
NNJVT	–	–	–	1.6	1.5	1.3	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ track soft term	–	–	–	< 0.2	0.4	< 0.2	< 0.2
PDF	0.2	0.2	< 0.2	0.8	0.8	0.6	0.5
QCD scale (ME and PS)	0.6	< 0.2	0.3	1.3	1.2	0.6	0.6
Flavour tagging	–	–	–	–	–	–	–
$t\bar{t}$ modelling	–	–	–	–	–	–	–
Total systematic impact [%]	3.0	3.1	2.7	5.0	4.5	3.8	3.6
Statistical impact [%]	0.04	0.03	0.02	0.02	0.01	0.01	0.01

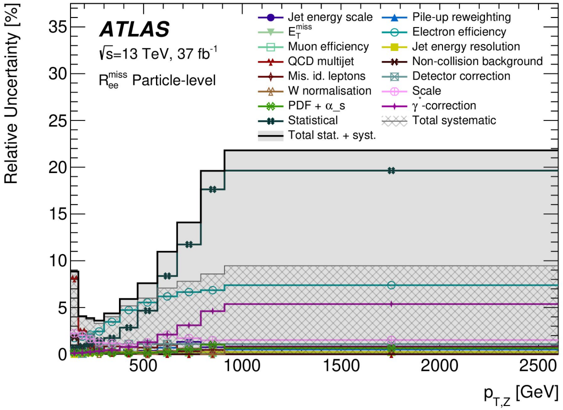
Category	$\sigma(W^- \to \ell^-\bar{\nu})$	$\sigma(W^+ \to \ell^+\nu)$	$\sigma(W^\pm \to \ell\nu)$	R_{W^+/W^-}	$R_{W^\pm/Z}$	$R_{t\bar{t}/W^\pm}$
Luminosity	2.5	2.4	2.4	< 0.2	0.3	< 0.2
Pile-up	0.5	0.7	0.6	< 0.2	< 0.2	< 0.2
MC statistics	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
Lepton trigger	1.0	0.9	0.9	< 0.2	0.7	0.8
Electron reconstruction	0.4	0.5	0.4	< 0.2	0.5	0.4
Muon reconstruction	0.6	0.6	0.6	0.2	0.8	0.6
Multi-jet	1.2	1.2	1.2	1.6	1.1	1.0
Other background modelling	0.4	0.4	0.4	< 0.2	0.3	0.9
Jet energy scale	1.3	1.3	1.3	< 0.2	1.3	1.3
Jet energy resolution	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
NNJVT	1.4	1.3	1.3	< 0.2	1.3	< 0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ track soft term	< 0.2	0.3	0.3	< 0.2	0.3	0.3
PDF	0.5	0.5	0.3	0.5	0.2	0.4
QCD scale (ME and PS)	0.8	0.7	0.6	< 0.2	0.7	0.7
Flavour tagging	–	–	–	–	–	< 0.2
$t\bar{t}$ modelling	–	–	–	–	–	1.1
Total systematic impact [%]	3.7	3.5	3.5	1.7	2.4	2.5
Statistical impact [%]	0.01	0.01	0.01	0.01	0.02	0.32

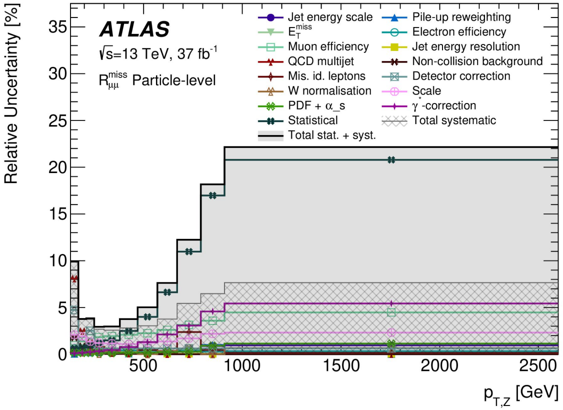
Z to Invisible Uncertainties



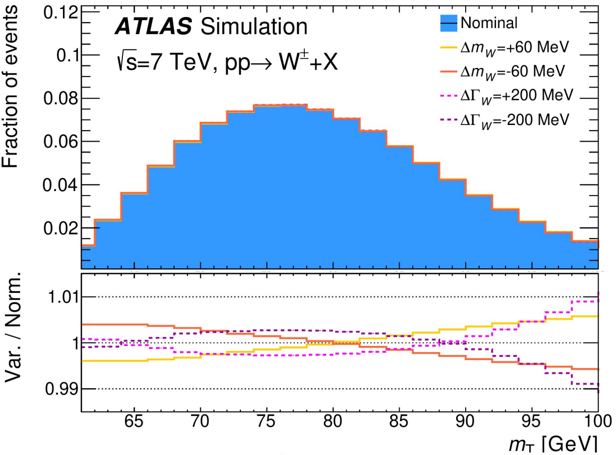


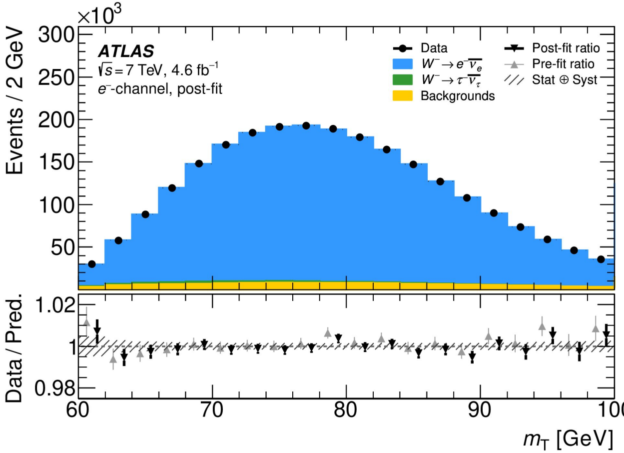


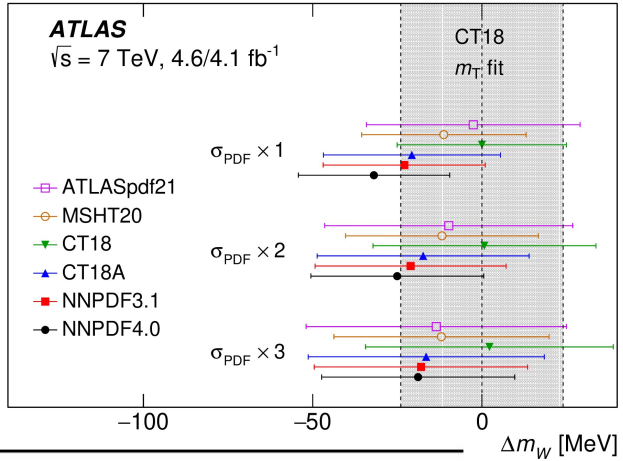




W Boson Mass







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

Γ_W

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

W and Z Transverse Momentum Spectra at $\sqrt{s} = 13$ TeV