Precision measurements of *W* and *Z* boson production in ATLAS

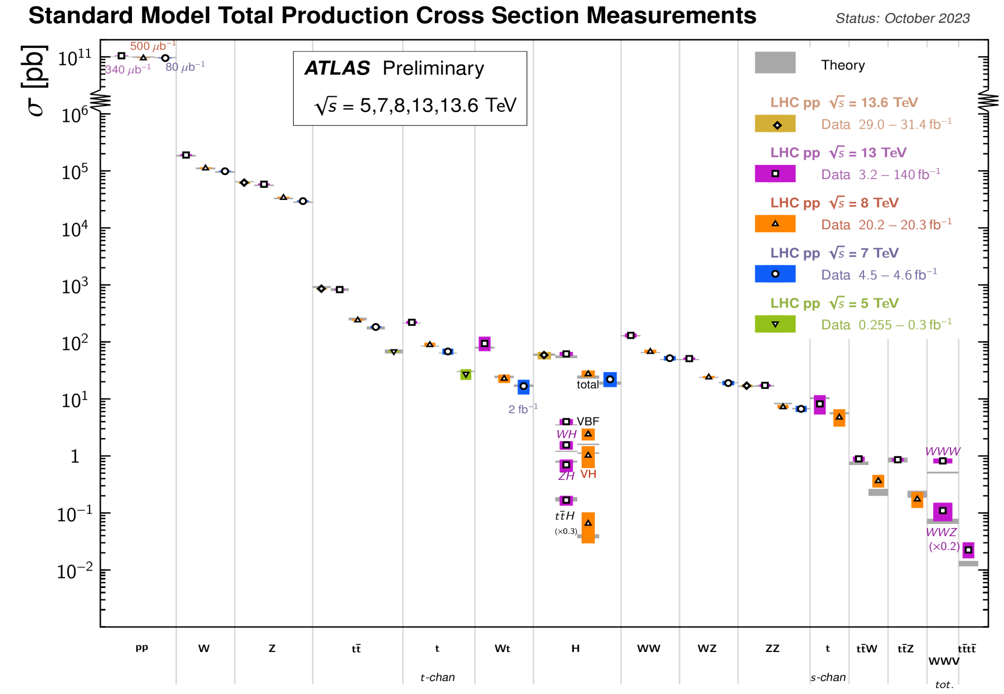
Andres Pinto
on behalf of the ATLAS Collaboration

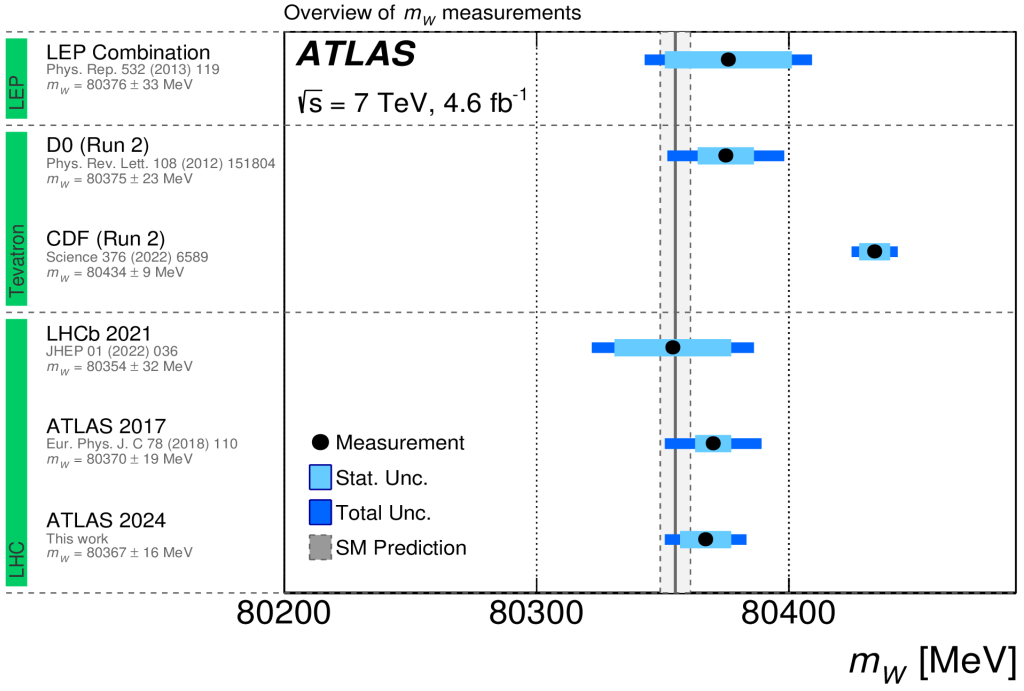
DIS2024

April 9th, 2024

W and Z boson physics at LHC

- W and Z boson production is extremely important to probe the SM Electroweak sector and to check the consistency of the Standard Model (SM).
  - W/Z mass, weak mixing angle, lepton universality, etc.
- It allows to probe (non) perturbative QCD predictions.
- These measurements provide inputs and sensitivity to Parton Distribution Functions (PDFs).
- It allows to set precise limits in physics Beyond the Standard Model (BSM).





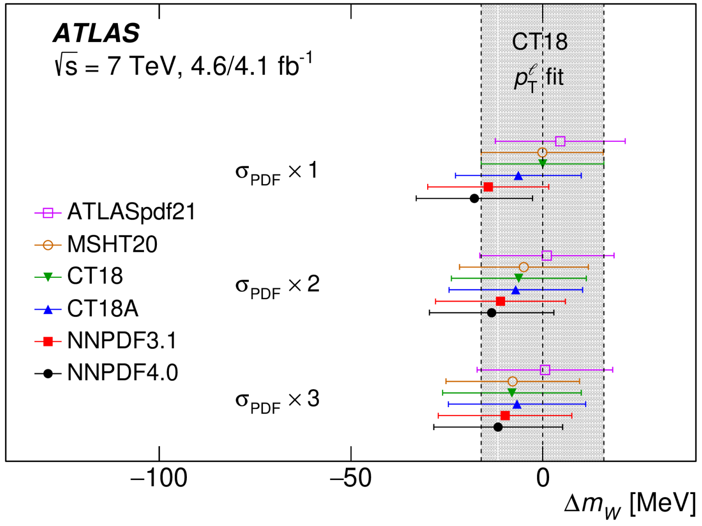
Topics for this talk

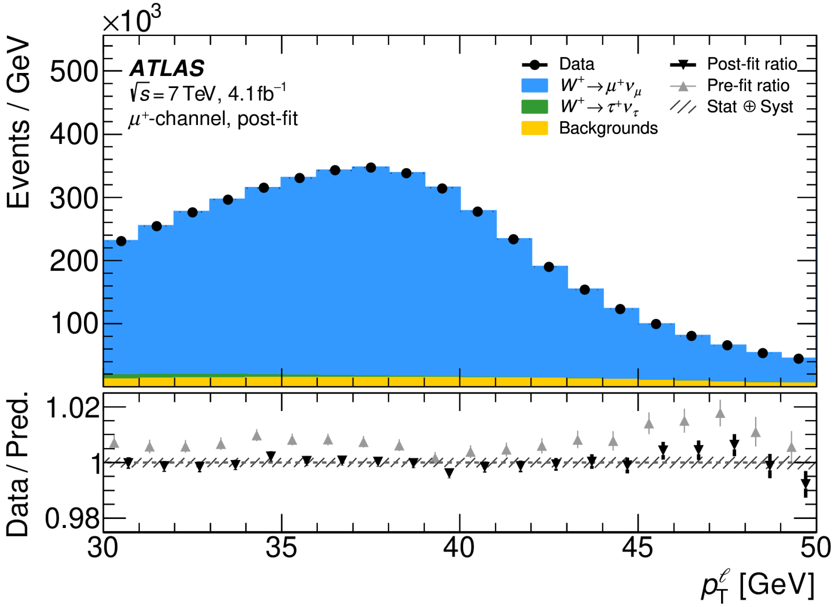
1. **Measurement of m_W and Γ_W at 7TeV arXiv:2403.15085**
2. Z Invisible Width Measurement: arXiv:2312.02789
3. Search for the exclusive hadronic W boson decays: arXiv:2309.15887
4. p_T^W and p_T^Z at 5 and 13 TeV with low pile-up data: ANA-STDM-2018-17
5. **W/Z cross section at 13.6 TeV with Run3 data arXiv:2403.12902**

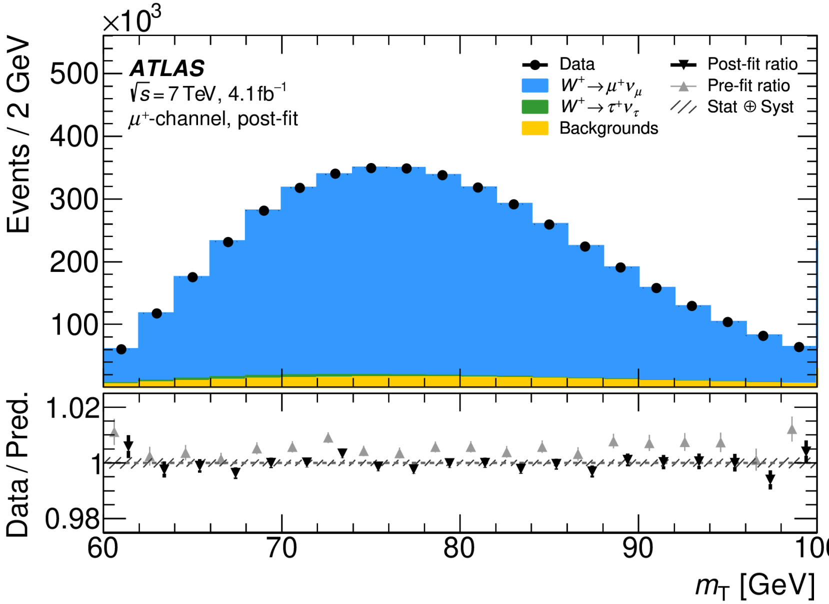
Measurement of m_W and Γ_W at 7TeV

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

- Precise m_W measurement allows to probe SM consistency and BSM through **loop corrections.**
- Measurement performed with two observables p_T^ℓ and m_T in $W\to e\nu,\mu\nu$ channels
- Fitting strategy by profile likelihood fit!
- Several tests with different PDFs → baseline CT18
- **Results improved respect to previous result EPJC 78 (2018) 10**







PDF set	Combined m_W [MeV]
CT14	80363.6 ± 15.9
CT18	80366.5 ± 15.9
CT18A	80357.2 ± 15.6
MMHT2014	80366.2 ± 15.8
MSHT20	80359.3 ± 14.6
ATLASpdf21	80367.6 ± 16.6
NNPDF31	80349.6 ± 15.3
NNPDF40	80345.6 ± 14.9

Measurement of m_W and Γ_W at 7TeV

- Uncertainty decomposition largely study and improvement in **PDFs** and **QCD**.
- m_W central value shifted by ~4 MeV, close to SM prediction

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

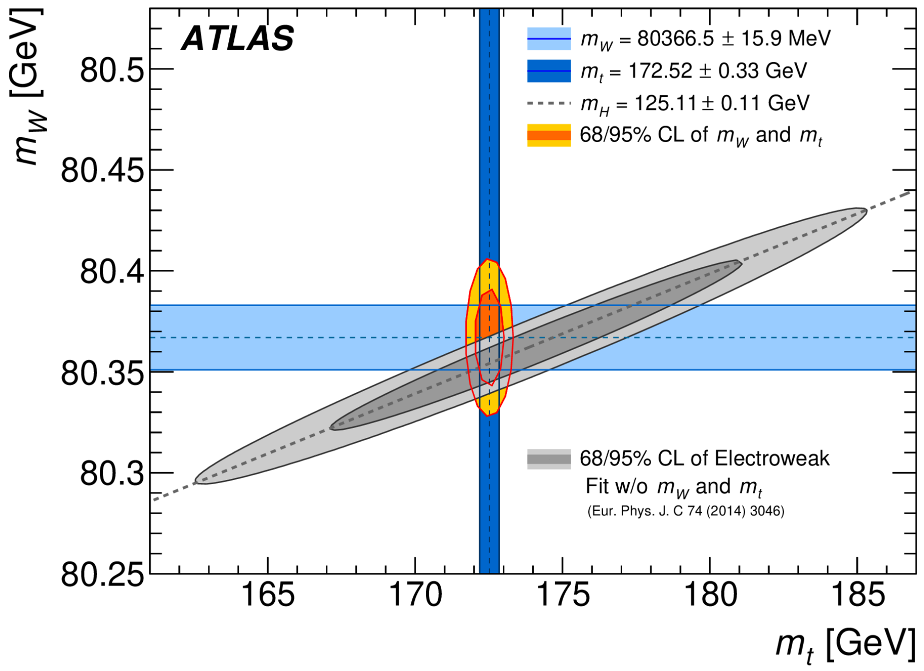
$$\boldsymbol{m_W = 80366.5 \pm 15.9\text{MeV}}$$

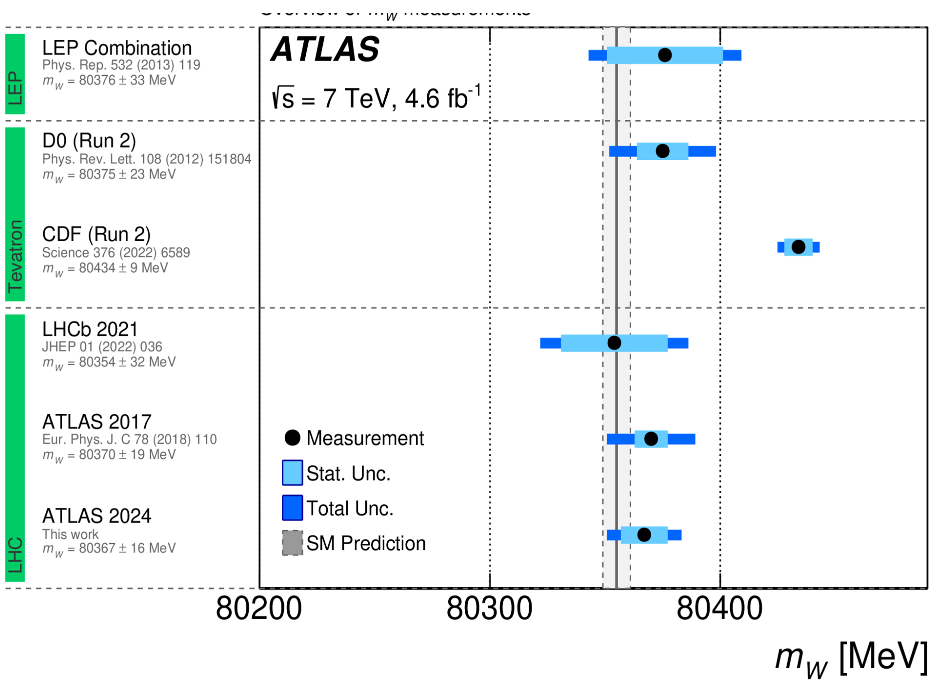
- Result is consistent with the expectation from fits to electroweak precision data.

PDF unc. reduced from 9.2 to 5.7!

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

PS + A_i unc. reduced from 8.3 to ~4.4!



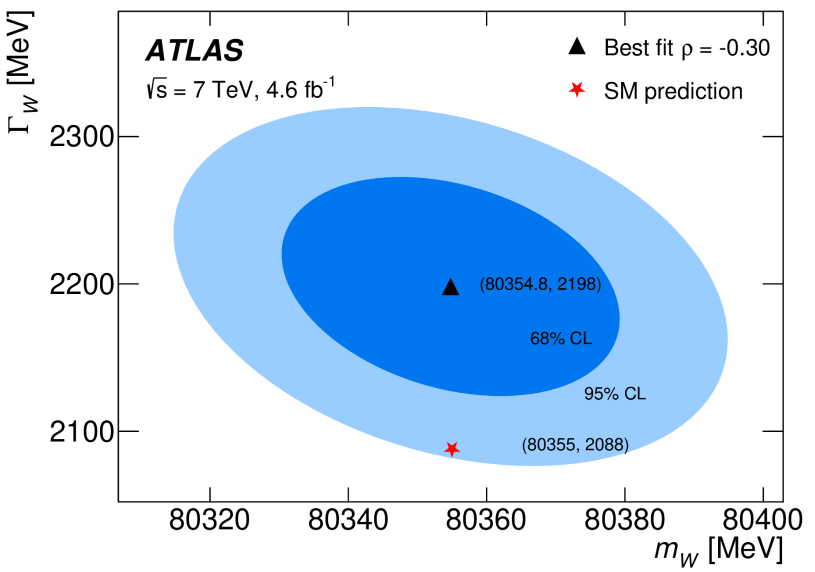


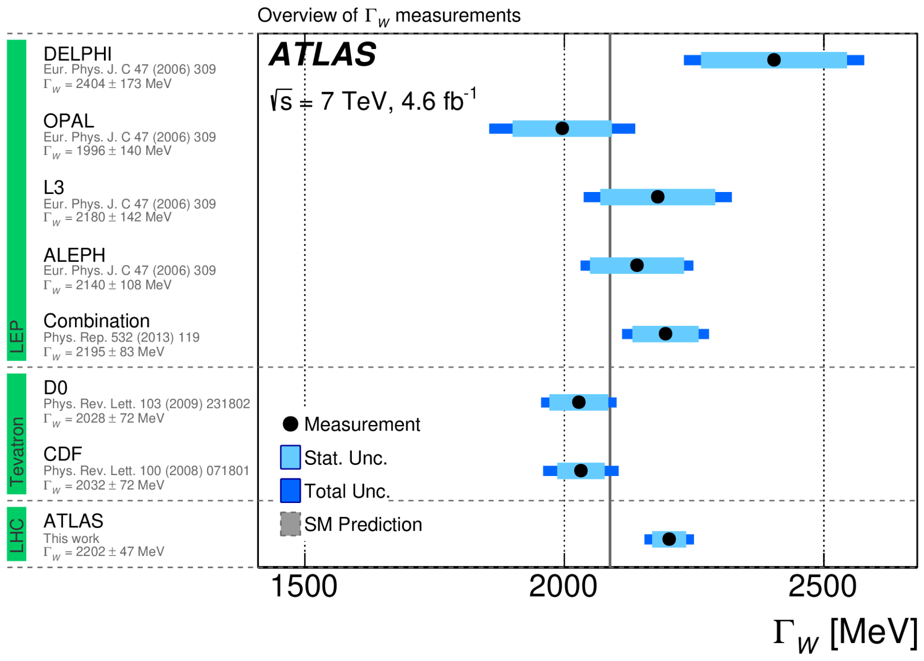
Measurement of Γ_W at 7TeV

- First Γ_W measurement in ATLAS!
- Same strategy as m_W → Profile likelihood fit with an extensive study in uncertainty decomposition
- Several tests with different PDFs → baseline CT18

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

- <u>Result is consistent with the expectation from fits to electroweak precision data.</u>

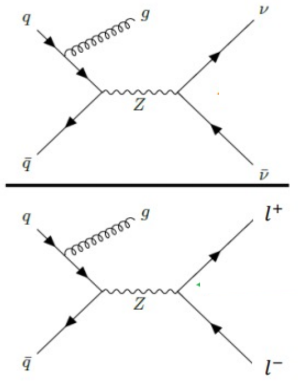




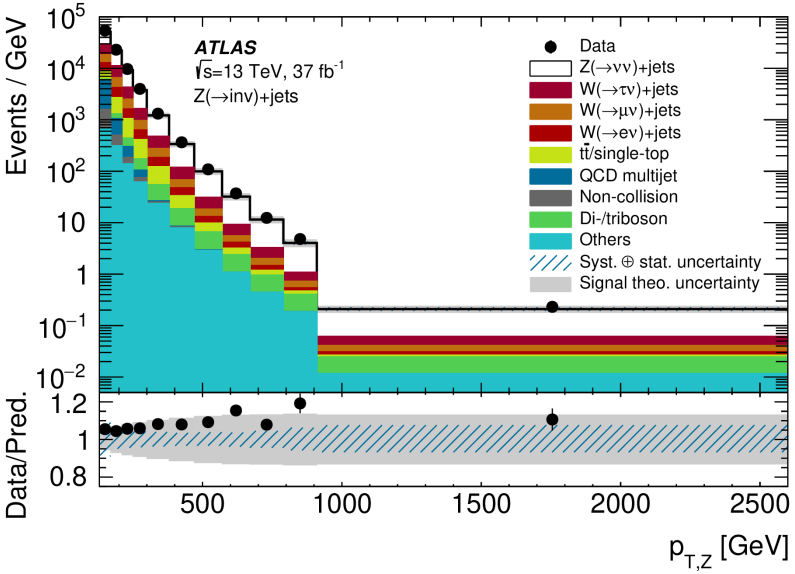
PDF set	Combined Γ_W [MeV]
CT14	2204 ± 47
CT18	2202 ± 47
CT18A	2184 ± 47
MMHT2014	2182 ± 47
MSHT20	2181 ± 47
ATLASpdf21	2193 ± 46
NNPDF31	2182 ± 46
NNPDF40	2184 ± 46

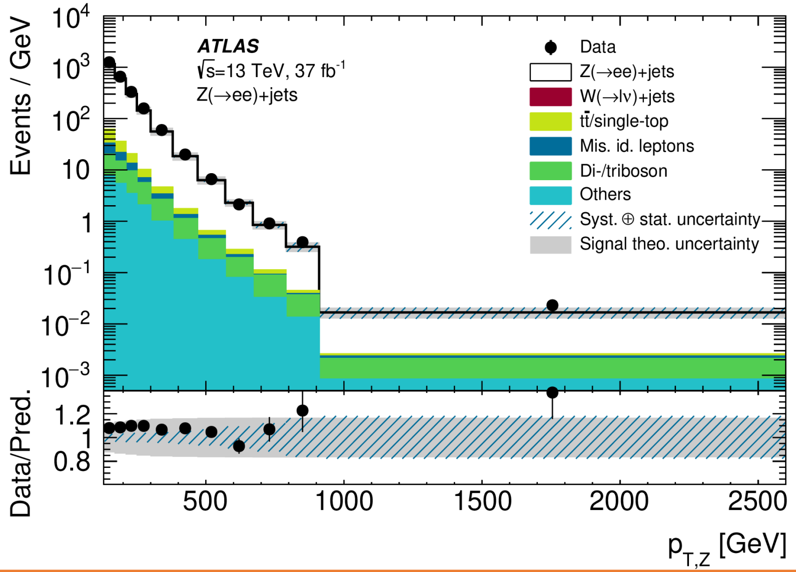
Z Invisible Width Measurement

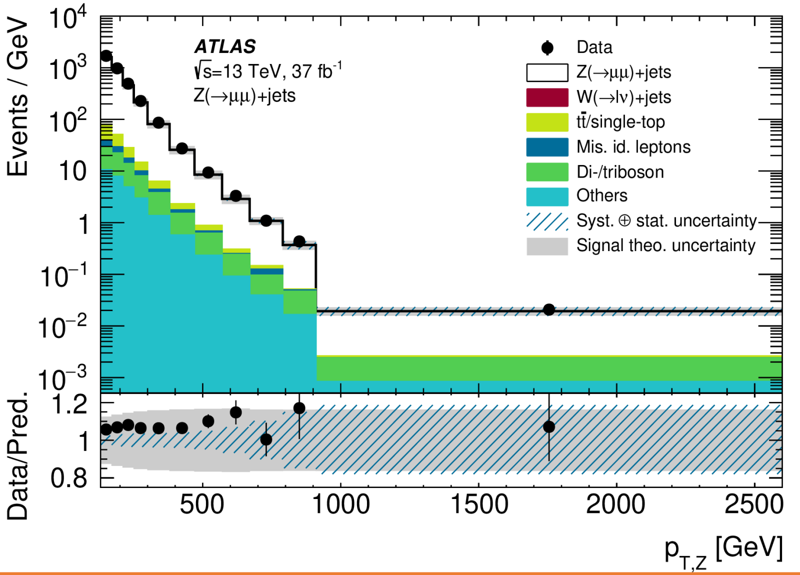
$$\frac{\Gamma(Z\to \text{inv})}{\Gamma(Z\to \ell\ell)} = \hat{R}^{\text{miss}} =$$



- The invisible width of the Z boson, $\Gamma(Z \to \text{inv})$ reflects the number of light neutrinos and potential SM contributions.
- Measured by using missing transverse energy E_T^{miss}+jets & $Z \to \ell\ell +$ jets to construct R^{miss} with data 2015/2016 → Measure $R_{\ell\ell}$ for leptons →Good data to MC agreement
- $\Gamma(Z \to \text{inv}), \Gamma(Z \to \ell\ell)$ are corrected for detector effects by bin-wise correction factors to adjust for the detector's efficiency, acceptance, and the impact of systematic uncertainties.
- Background estimated by data-driven: $W(\to l\nu)$ + JETS Background , Non-collision (Beam-induced-background) , QCD multijet , Lepton fakes.

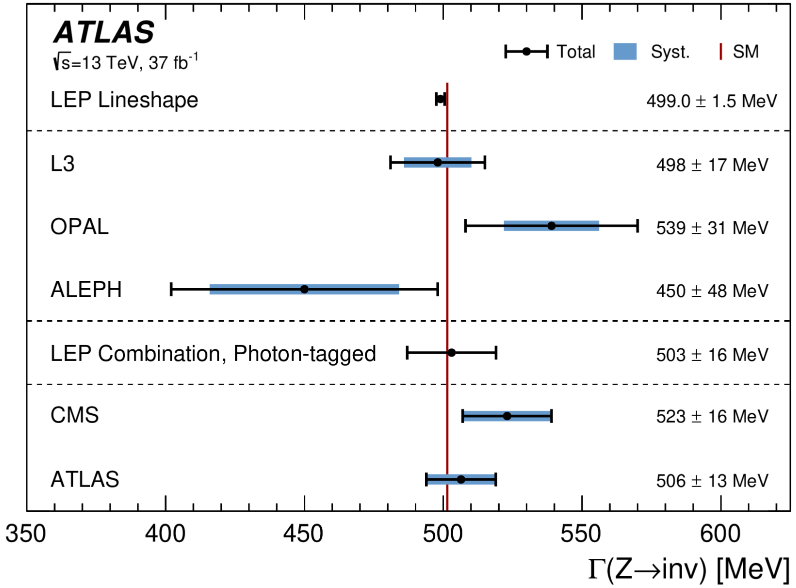




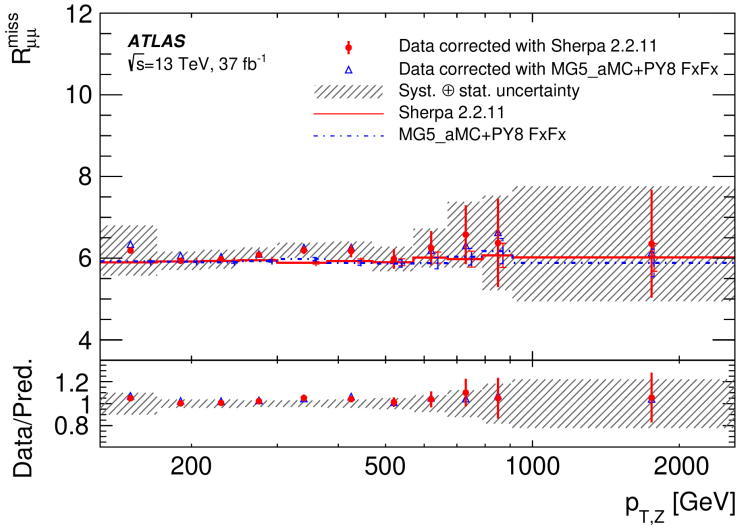


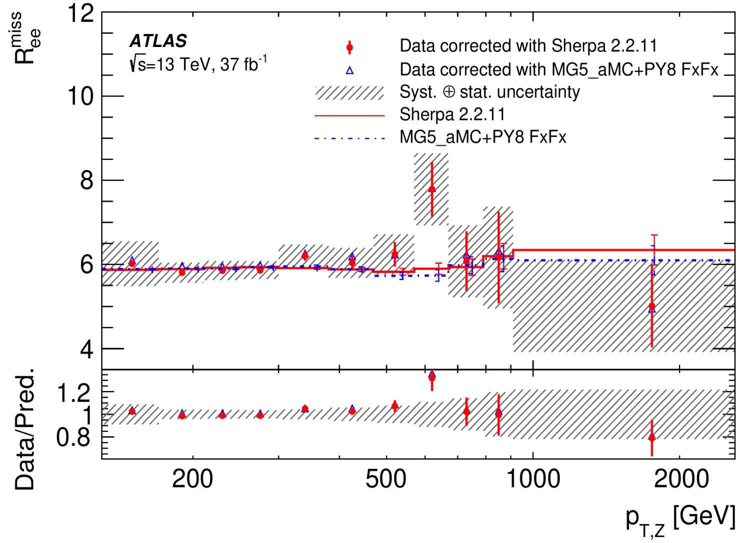
Z Invisible Width Measurement

- $R_{\ell\ell}^{miss}$ obtained using $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$
- Theoretical uncertainties (QCD scales, PDFs, strong coupling constant α_s)
- R^{miss} obtained by χ^2- minimization with correlated systematics.
- ATLAS combined result more precise than LEP combination:
- $\Gamma(Z \rightarrow \text{inv}) = 506 \pm 2\ (\text{stat.}) \pm 12\ (\text{syst.})$ MeV



Systematic Uncertainty	Impact on $\Gamma(Z \rightarrow \text{inv})$ 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_T^{miss}	2.4	0.5
$Z(\rightarrow \mu\mu)$+jets misid. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\rightarrow \ell\nu)$+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
$Z(\rightarrow ee)$+jets misid. lepton estimate	1.0	0.2
Luminosity	1.0	0.2
Parton distribution functions + α_s	0.7	0.1
$\Gamma(Z \rightarrow \ell\ell)$ [5, 9]	0.5	0.1
Tau energy scale	0.4	0.1
Muon momentum scale	0.3	0.1
$W(\rightarrow \ell\nu)$+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

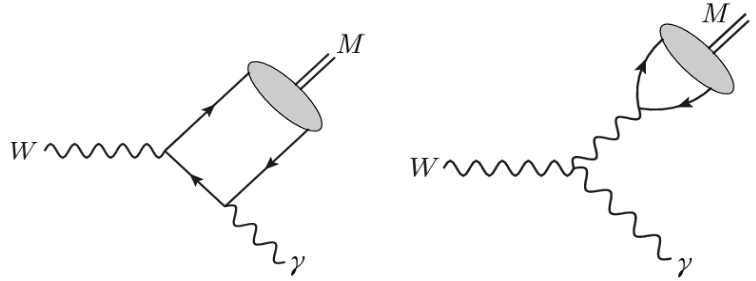




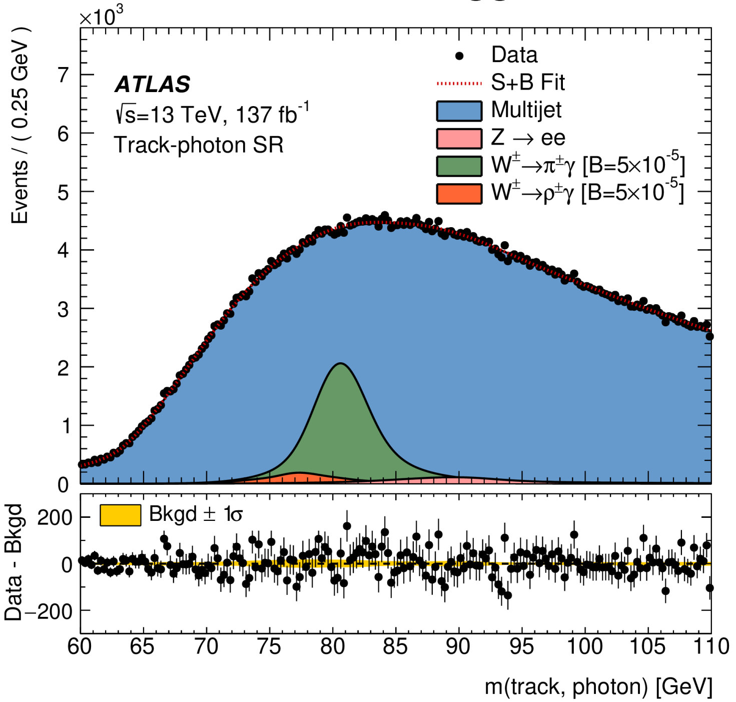
The result is dominated by systematic uncertainties, lepton efficiencies with the largest values.

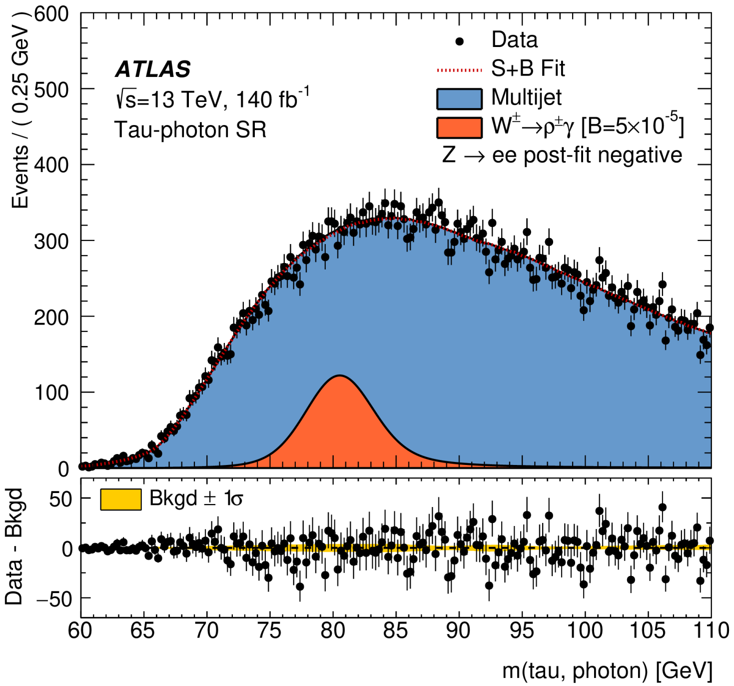
Search for the exclusive hadronic W boson decays

- First search at ATLAS for $W^{\pm} \rightarrow \pi^{\pm}\gamma$
- First search ever for $W^{\pm} \rightarrow \rho^{\pm}\gamma$ and $W^{\pm} \rightarrow K^{\pm}\gamma$
- Two final states of interest:
  - track + photon: Sensitive to $W^{\pm} \rightarrow \pi^{\pm}/K^{\pm}/\rho^{\pm} + \gamma$ decays
  - tau + photon: Sensitive to $W^{\pm} \rightarrow \rho^{\pm} (\rightarrow \pi^{\pm}\pi^{0})\gamma$ decay
- Dedicated triggers for each final state.



- This can offer novel precision studies of QCD factorization JHEP 1504 (2015) 101, possible BSM windows.
- Backgrounds (B): Multijet (data-driven) and Z→ee (MC)
- signal (S) modeled by Voigt functions
- Each channel is fitted by a S+B Maximum binned likelihood in the invariant mass distribution
- Final result by a combined fit! (no significant excess found)

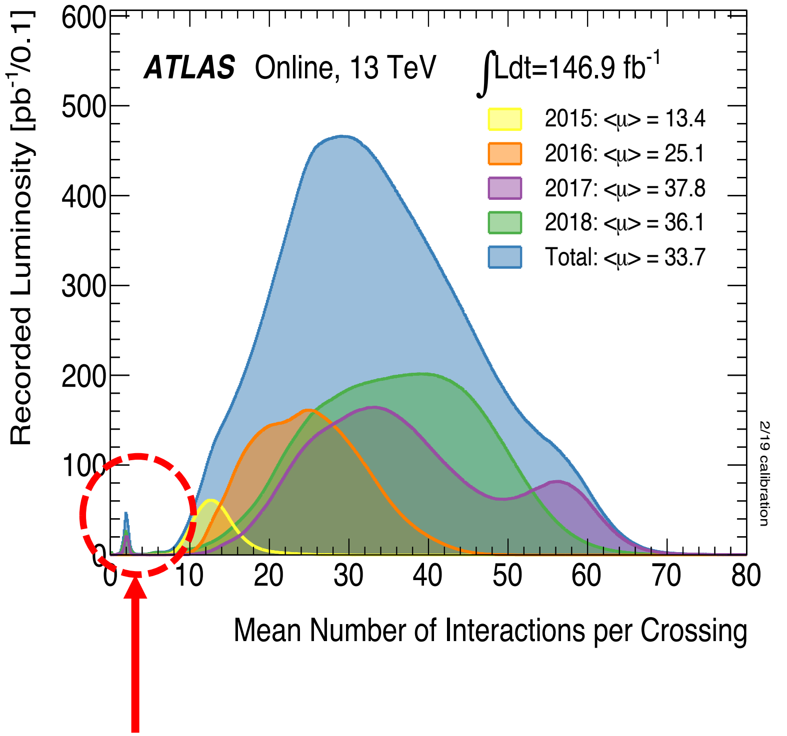


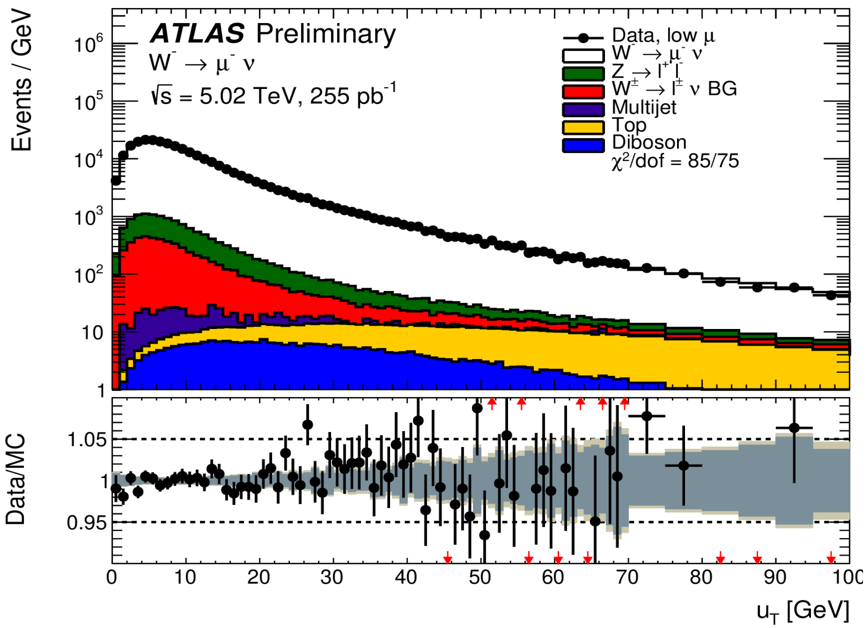


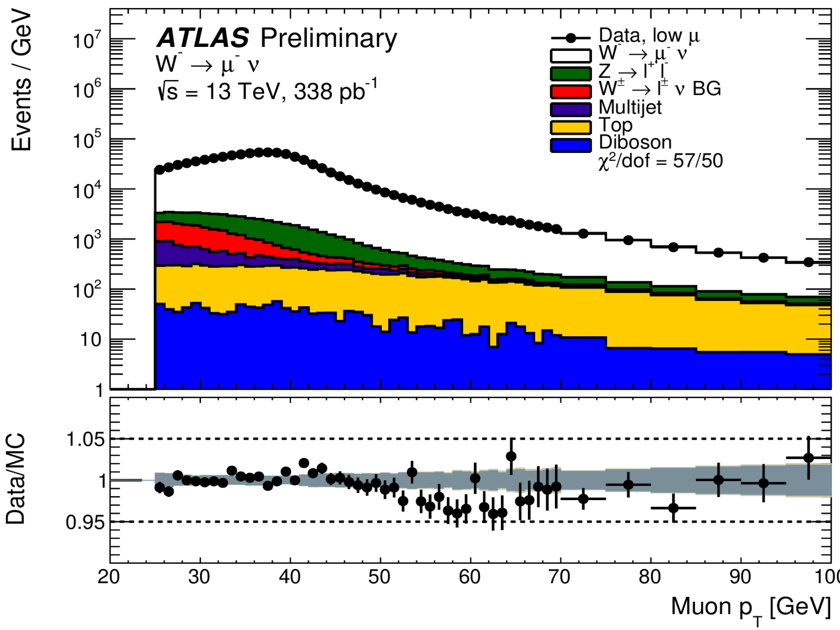
Branching fraction	95% CL upper limits	
	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^{\pm} \rightarrow K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^{\pm} \rightarrow \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

p_T^W and p_T^Z at 5 and 13 TeV with low pile-up data

- W and Z p_T spectra sensitive to pQCD and non-perturbative effects → Important for m_W
- In the m_W measurement, the lepton p_T spectrum requires a modelling of p_T^W < ~1% in the low p_T^W values where the fixed-order perturbative prediction fails.
- Direct measurement of p_T^W, instead of modelling p_T^W based on measured p_T^Z, avoids the uncertainty due to the extrapolation.



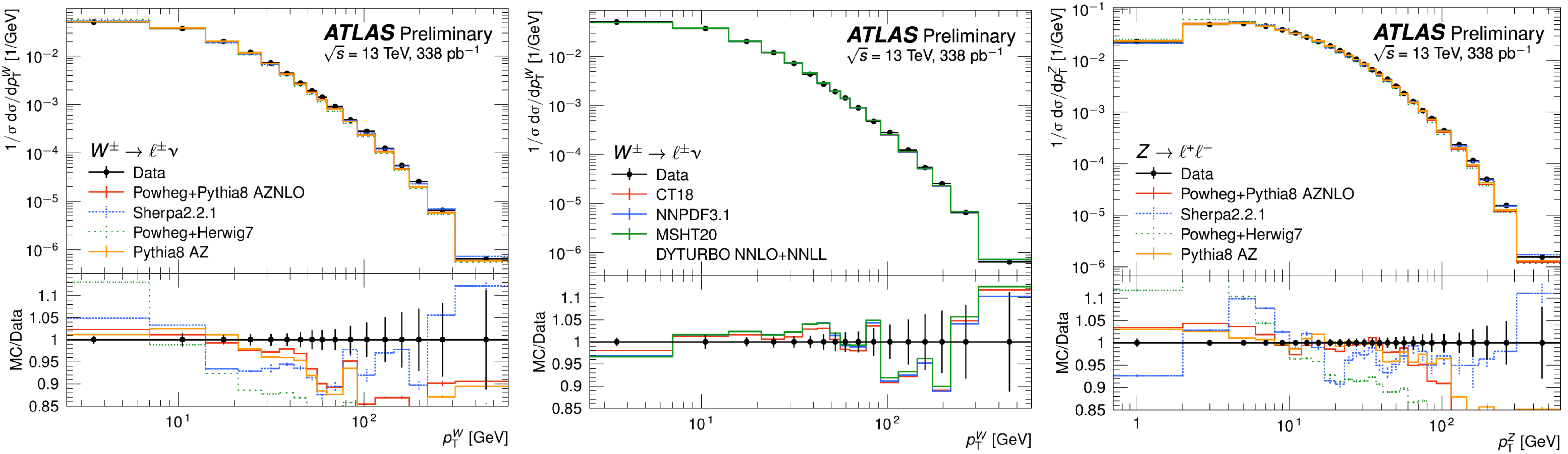




- Work done with low pile-up data for good hadronic recoil resolution
- Backgrounds:
  - EW (MC): Single/Diboson, top
  - QCD multijet by data-driven

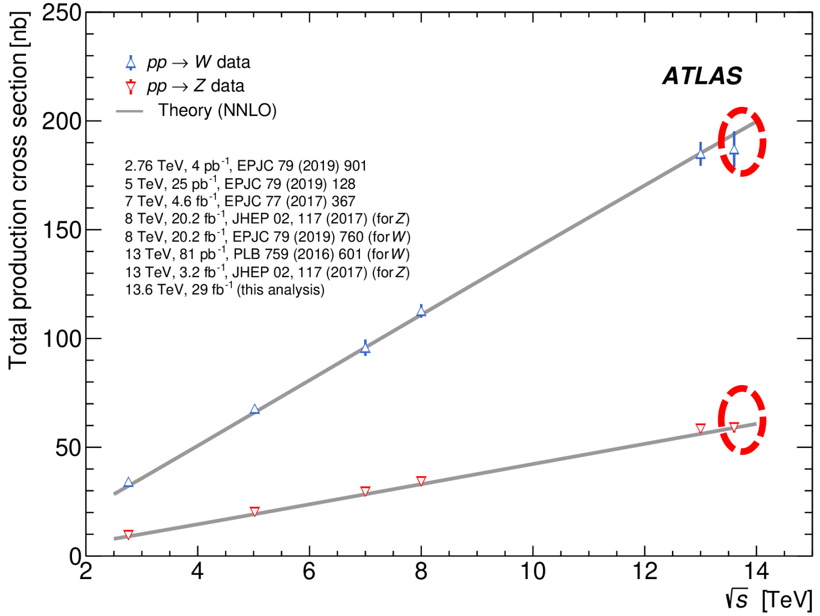
p_T^W and p_T^Z at 5 and 13 TeV with low pile-up data

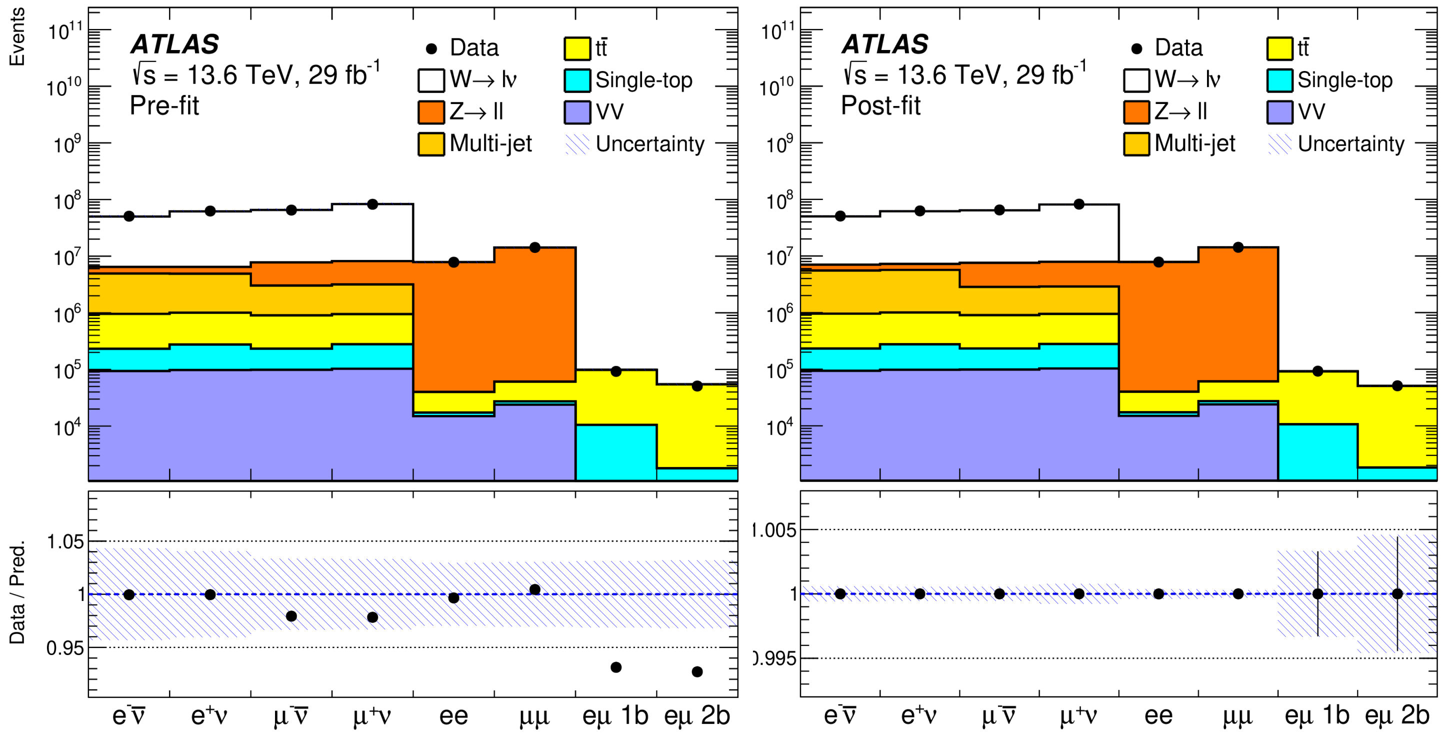
- Detector effects are corrected by Iterative Bayesian Unfolding.
- p_T distributions are measured for $W^\pm, W^+, W^-, Z$ and ratios $W^+/W^-, W/Z$.
- Differential cross section and ratios results are compared to MC and pQCD predictions
- Large differences between MCs, good description from resummed predictions (NNLO+NNLL)
- This measurement is a further validation of AZ tune, developed in the m_W 7 TeV determination.



W/Z cross section at 13.6 TeV with 2022 Run 3 data

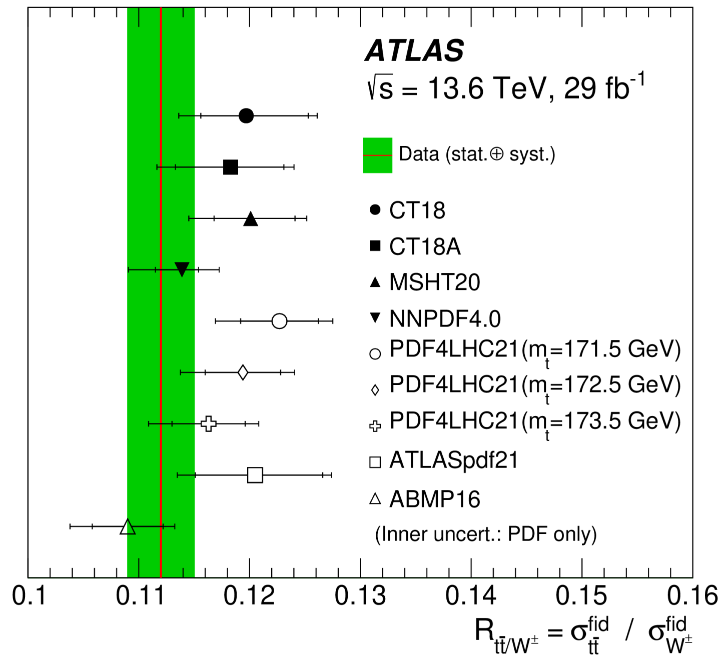
- Motivation:
  - First $t\bar{t}$/W ratio measurement
  - Test SM prediction at √s = 13.6 TeV (unprecedent)
  - Validation of detector performance and software
- Measurements:
  - Inclusive fiducial/total σ^W, σ^Z
  - Ratios: $\sigma^{W^+}/\sigma^{W^-}, \sigma^{W^\pm}/\sigma^Z$ and $\sigma^{t\bar{t}}/\sigma^{W^\pm}$
- Leptonic final states used for reconstruction and signal identification
- Background:
  - Electroweak and top (MC), Multijet (Data-driven)
- Cross section obtained from Profile likelihood fit



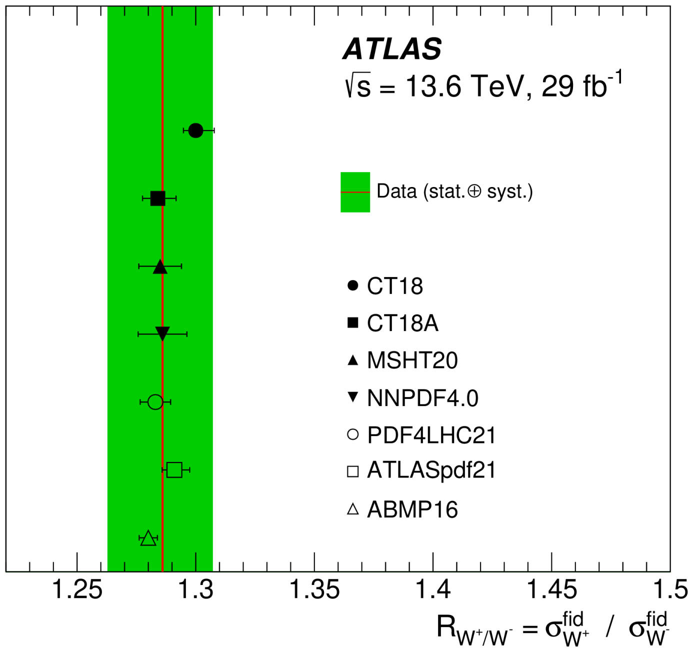


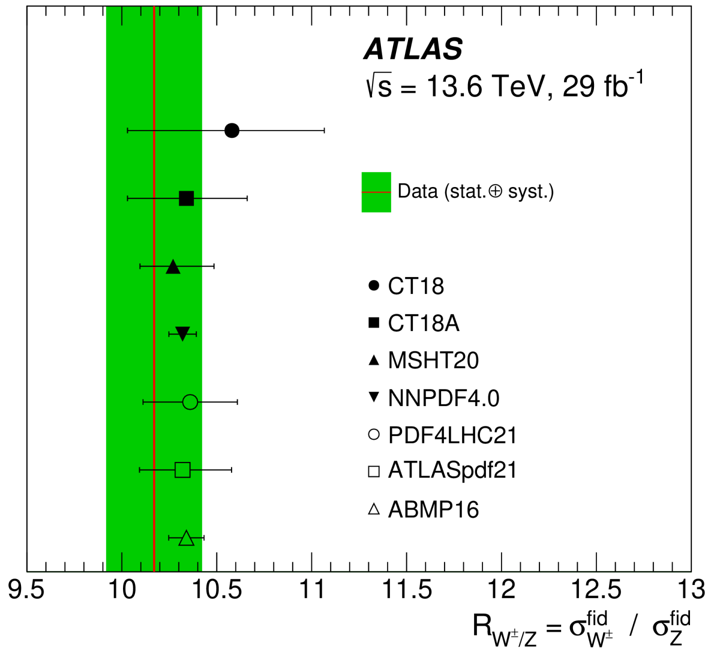
W/Z cross section at 13.6 TeV with 2022 Run 3 data

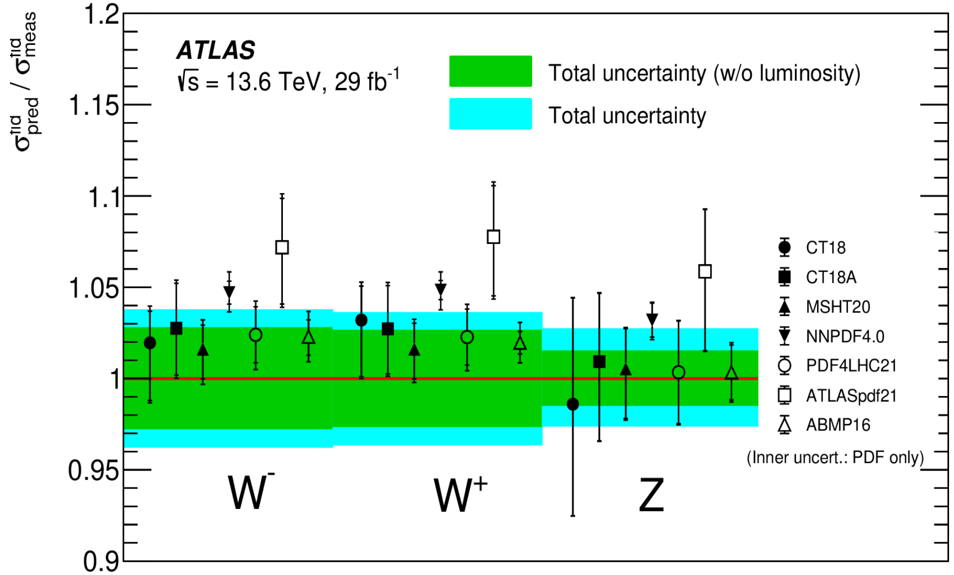
- $t\bar{t}/W$ cross section ratio is slightly lower than PDF4LHC21 prediction, but consistent with Run 3 $t\bar{t}/Z$ results PLB 848 (2024) 138376



- Good agreement is observed between measured results and theoretical predictions for W/Z results







Conclusions and prospects

- The current large statistics and excellent detector performance of LHC allowed to ATLAS to made significant contributions in the precision measurements of *W/Z* boson production.
- New statistical and numerical techniques are improving the current measurements such as m_W, W/Z cross-section, etc. and they will allow to test extensively the SM and physics BSM.
- All the presented results are improving and extending the knowledge we have in modeling for the simulations.

Thanks for your attention!

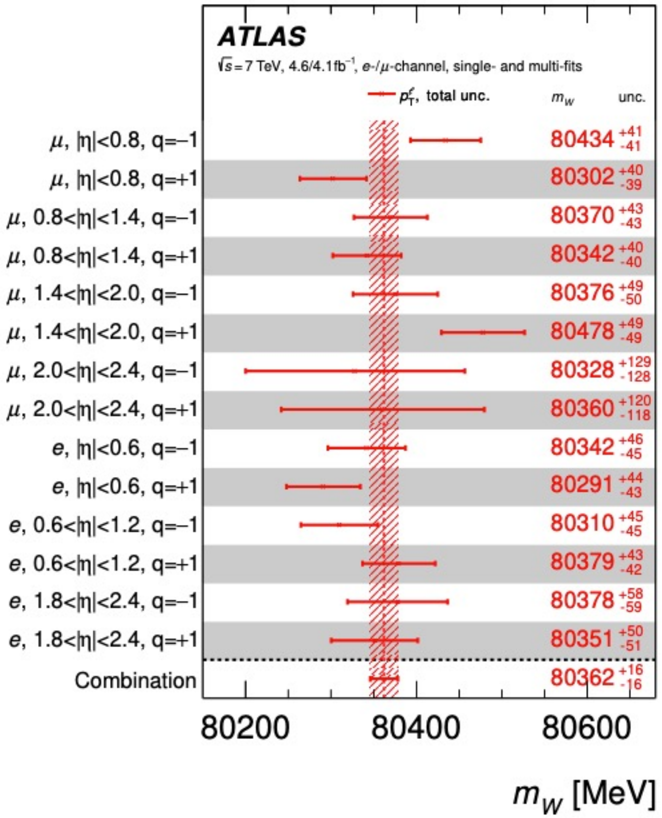
Backup and extra material

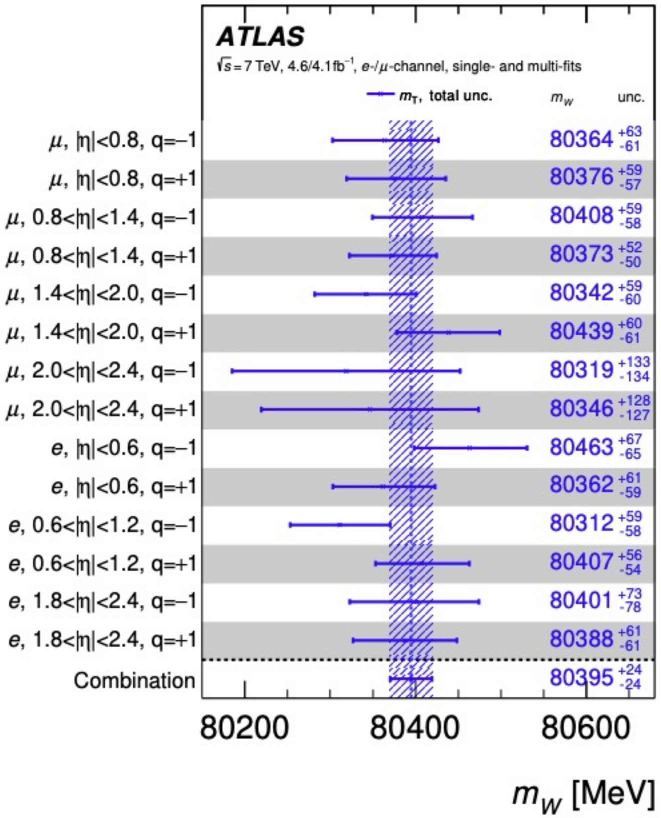
Measurement of m_W and Γ_W at 7TeV

- PLH fit results for m_W and combination

$$\mathcal{L}\left(\vec{n}|\,\mu,\vec{\theta}\right) = \prod_j \prod_i \mathrm{Poisson}\left(n_{ji}|\nu_{ji}(\mu,\vec{\theta})\right) \cdot \mathrm{Gauss}\left(\vec{\theta}\right)$$

$$\nu_{ji}(\mu,\vec{\theta}) = \Phi \times \left[S_{ji}^{\mathrm{nom}} + \mu \times \left(S_{ji}^{\mu} - S_{ji}^{\mathrm{nom}}\right)\right] + \sum_s \theta_s \times \left(S_{ji}^{s} - S_{ji}^{\mathrm{nom}}\right) + B_{ji}^{\mathrm{nom}} + \sum_b \theta_b \times \left(B_{ji}^{b} - B_{ji}^{\mathrm{nom}}\right),$$

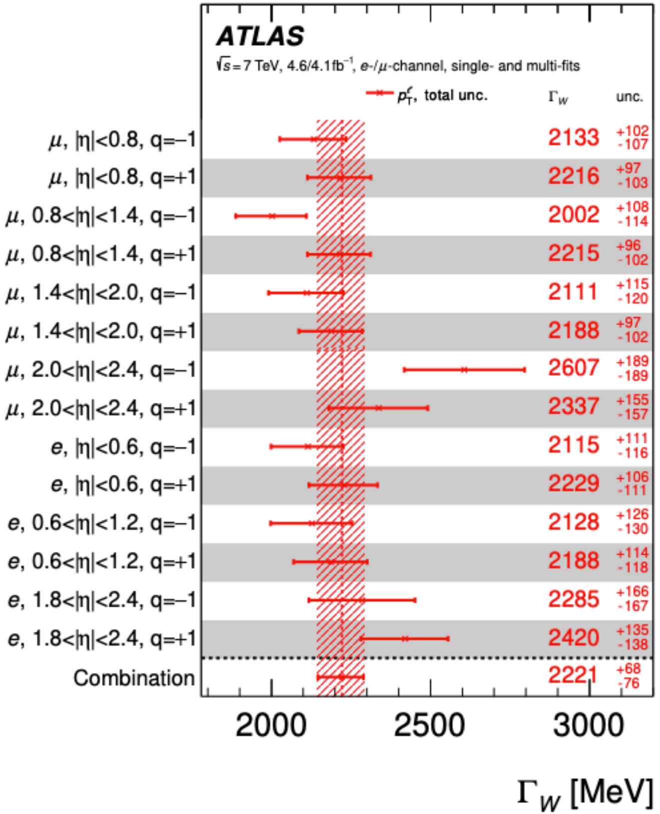


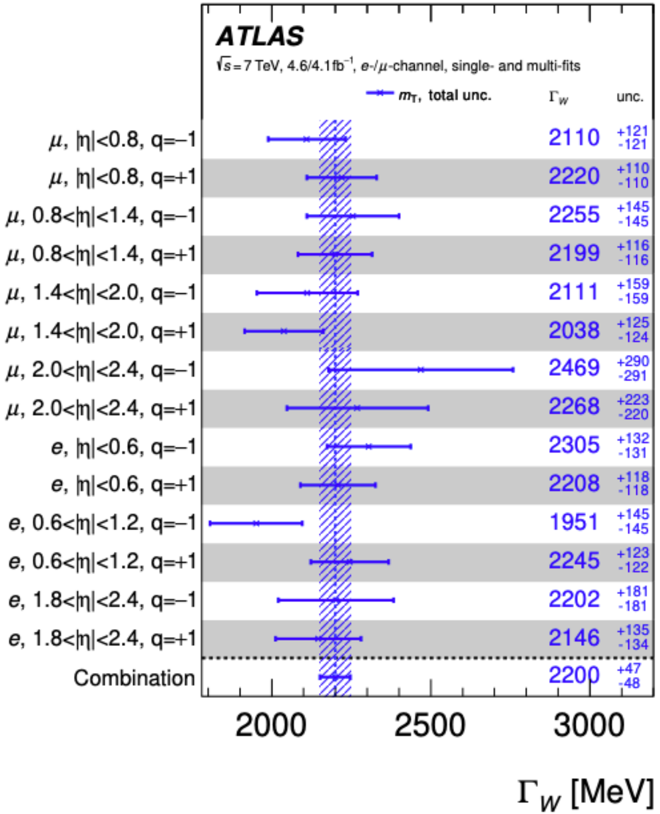


PDF set	Correlation	weight (p_{T}^{ℓ})	weight (m_{T})	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%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

Measurement of m_W and Γ_W at 7TeV

- Uncertainty decomposition, combination for the Width and PLH fit results in different channels



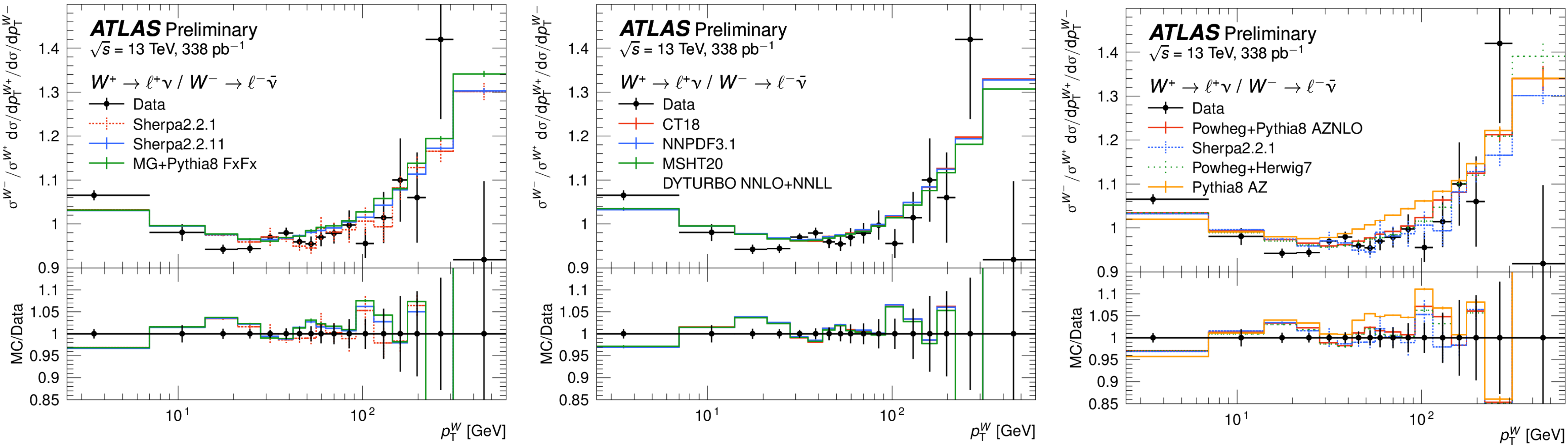


Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

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

p_T^W and p_T^Z at 5 and 13 TeV with low-μ data

- Ratio of cross sections benefit from uncertainties cancellation and data to model agreement within the errors.



W/Z cross section at 13.6 TeV with 2022 Run 3 data

- Fitting strategy: Profile likelihood fit
- For Z cross sections ($Z \rightarrow ee/\mu\mu$ and $Z \rightarrow \ell\ell$): ee and $\mu\mu$ regions are used for fit
- For W cross sections, W+ /W- and W± /Z ratios: ee, $\mu\mu$ and 4 single lepton regions are used as input (combined fit with Z regions)
- For $t\bar{t}$/W cross section ratios: 2 $e\mu$ regions (from $t\bar{t}$ analysis), 4 single lepton regions, ee and $\mu\mu$ regions are used

$$L(\vec{n};\mu_s,\vec{\theta}) = \prod_{c\in\text{channels}} \text{Pois}(n_{\text{data}}|\mu_{s,c}S_c(\vec{\theta}) + B_c(\vec{\theta})) \prod_{i\in\text{NPs}} G(\theta_i)$$

Ratio of measured over predicted cross-section

W/Z cross section at 13.6 TeV with 2022 Run 3 data

- Impact of uncertainties:
- Dominant uncertainty sources in each channel:
- Z cross sections: luminosity and lepton
- W cross sections: luminosity, jet and multi-jet background
- W+ /W- : multi-jet, W± /Z: jet and multi-jet background
- ttbar/W: ttbar modelling, background modelling, jet, multi-jet background

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