Lepton Photon 2023

Precision measurements of W and Z production at ATLAS

Zhibo Wu

On behalf of the ATLAS Collaboration

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Introduction

- The Drell-Yan mechanism was proposed and observed in 1970, then led to the discovery of W and Z bosons in 1983, therefore confirming the electroweak unification.
- Standard candle for precision measurements and theory at LHC.
- Precision measurements help check the consistency of the Standard Model (SM) through the electroweak fit:

  m_W re-analysis at 7 TeV (ATLAS-CONF-2023-004)
- Differential measurements give information on perturbative and non-perturbative QCD, which in turn reduces the modeling uncertainties in the precision measurements:

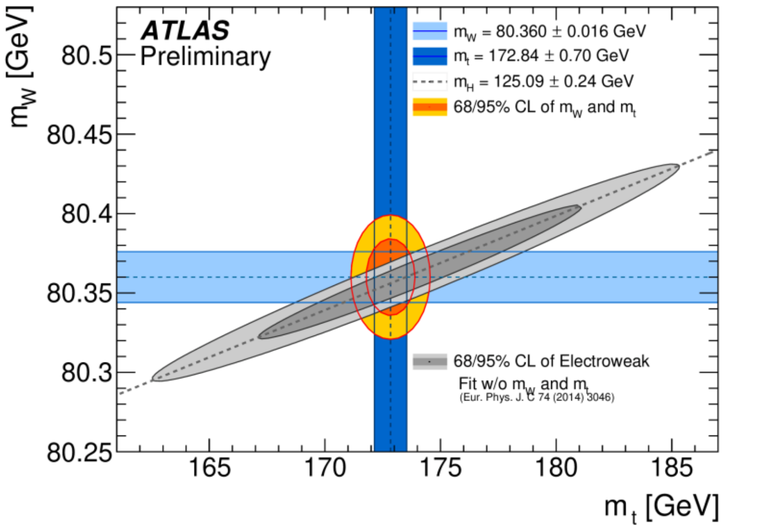
  Z p_T and y at 8 TeV (ATLAS-CONF-2023-013)

  Extraction of α_s from p_T^Z at 8 TeV (ATLAS-CONF-2023-015)

  p_T^W and p_T^Z with low pile-up data (ATLAS-CONF-2023-028)

m_W re-analysis at 7 TeV

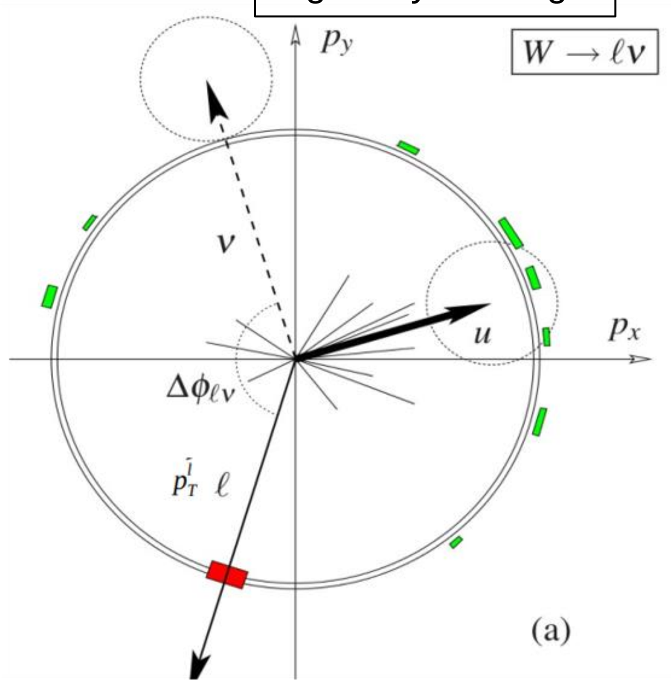
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



Importance of m_W measurement:

- Input to global EW fit.
- Indirect search of BSM physics.
- Independent check of the new CDF result.

Figure by T. Dorigo

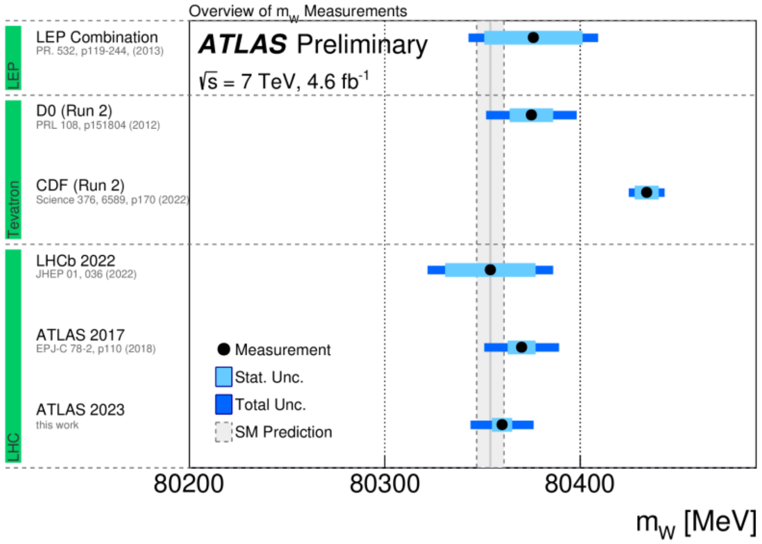


Measurement strategy:

- Leptonic decay of W-boson.
- Use the dependence of lepton transverse momentum (p_T^l) and W transverse mass (m_T) to determine m_W.

$$m_T=\sqrt{2p_T^l E_T^{miss}\left(1-\cos\left(\phi_l-\phi_{E_T^{miss}}\right)\right)}$$

$\vec{p}_T^{\,miss}=-(\vec{p}_T^{\,l}+\vec{u}_T)$ for the neutrino



m_W re-analysis at 7 TeV

New result:

$$m_W = 80360 \pm 5\ \text{(stat.)} \pm 15\ \text{(syst.)} = 80360 \pm 16\ \text{MeV}$$

- Detector calibration mostly reused from the previous measurement.
- Dominant uncertainties: lepton calibration and PDF.
- Update PDF set: CT10NNLO -> CT18NNLO

χ^2 offset method -> profile likelihood fit:

- Total uncertainty reduced by 15**%:** 19 MeV -> **16 MeV.**
- Central value closer to the SM prediction: **10 MeV** shift.

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

Improvements mainly brought by profiling.

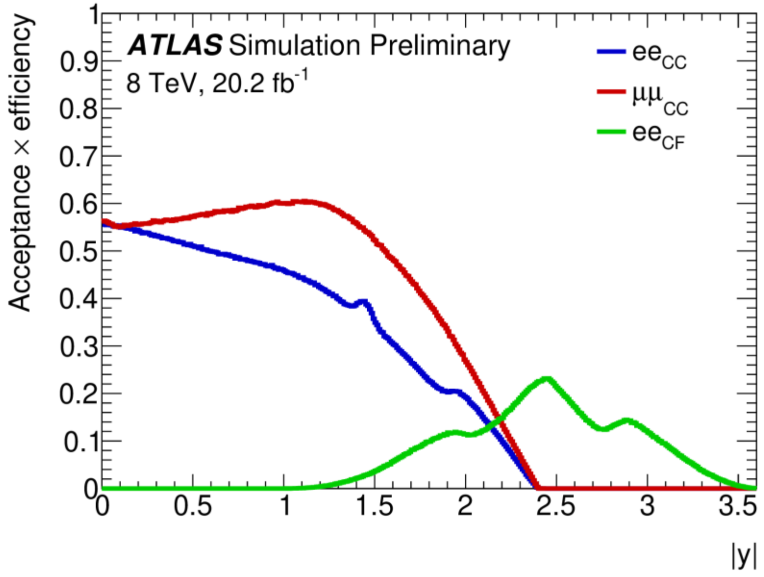
	PDF	PS & A_i
p_T^ℓ	~15%	~40%
m_T	~30%	~10%

Z p_T and rapidity at 8 TeV

- Simultaneous measurement of cross-sections and angular coefficients in full lepton phase space, double differential in p_T and y near the Z pole.

$$\frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

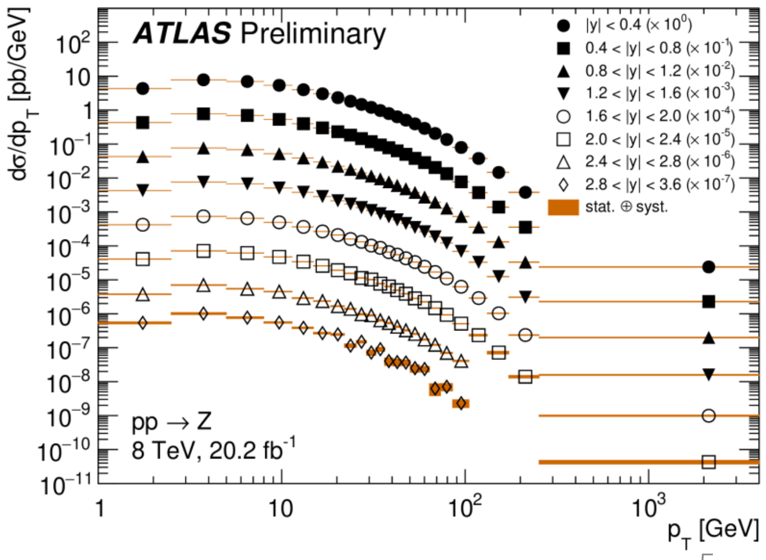
- Better probe of large rapidity/small parton momentum fraction thanks to the improved forward electrons calibration.



ee_{CC}: Two electrons with
p_T > 20 GeV and $|\eta|$ < 2.4

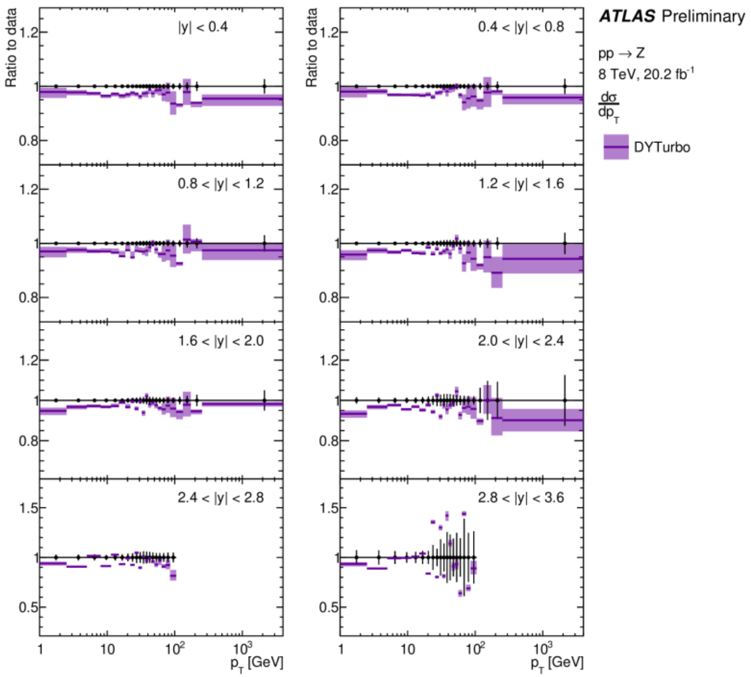
$\mu\mu_{CC}$: Two muons with
p_T > 20 GeV and $|\eta|$ < 2.4

ee_{CF}: central electron with
p_T > 20 GeV and $|\eta|$ < 2.4
forward electron with
p_T > 20 GeV and 2.5 < $|\eta|$ < 4.9

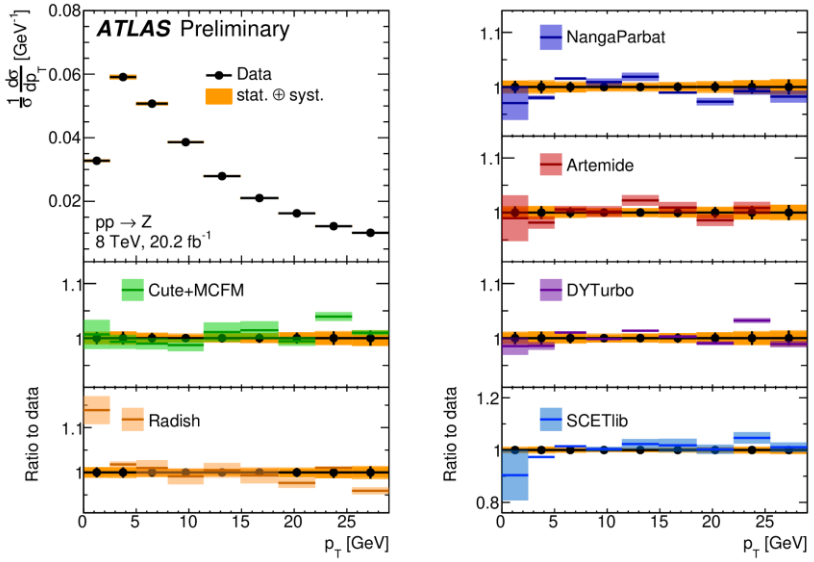


Z p_T and rapidity at 8 TeV

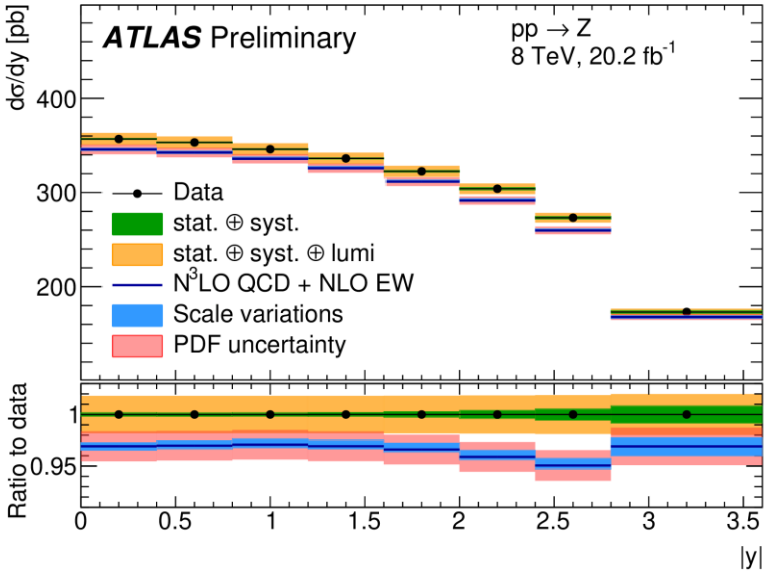
- Stringent test of the state-of-the-art QCD theories.



Double differential cross-section: Statistics dominated.
PDF uncertainty at $10^{-4}\sim 10^{-3}$.

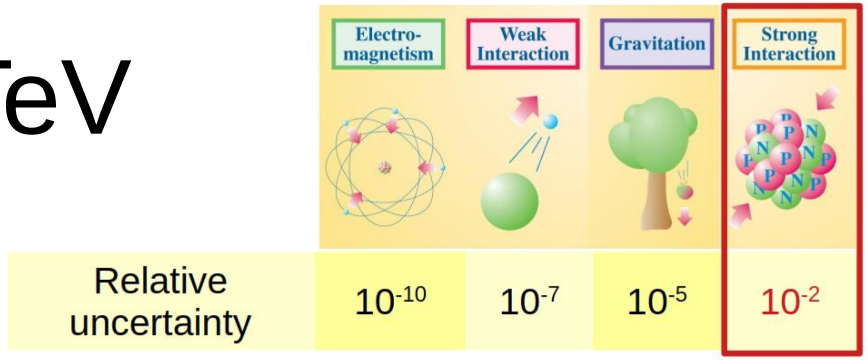


p_T^Z comparison with $\mathrm{aN^4LL}$ analytical resummation: good agreement.



Rapidity: Permille level precision in the central region and sub-percent precision up to $|y|$ <3.6.
➢ NLO EW corrections computed with ReneSANCe.

Extraction of α_s from p_T^Z at 8 TeV



- α_s is the least well know coupling constant.
- Non-zero p_T^Z given by the QCD ISR -> The Sudakov peak of p_T^Z is linearly sensitive to α_s.
- Profiled χ^2 template fit:

➢ Equivalent to including the new dataset in the PDF without refitting

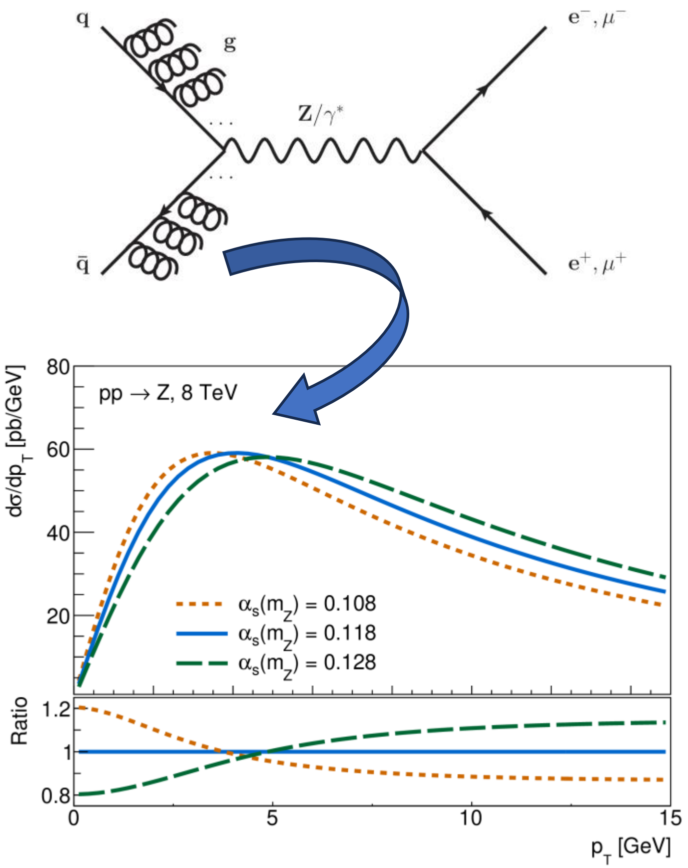
➢ The non-perturbative form factor is added with unconstrained nuisance parameters.

$$\chi^2(\beta_{\rm exp}, \beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,{\rm exp}} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,{\rm th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,{\rm exp}}^2 + \sum_k \beta_{k,{\rm th}}^2 .$$

β: NPs for experimental systematics and PDF variations.

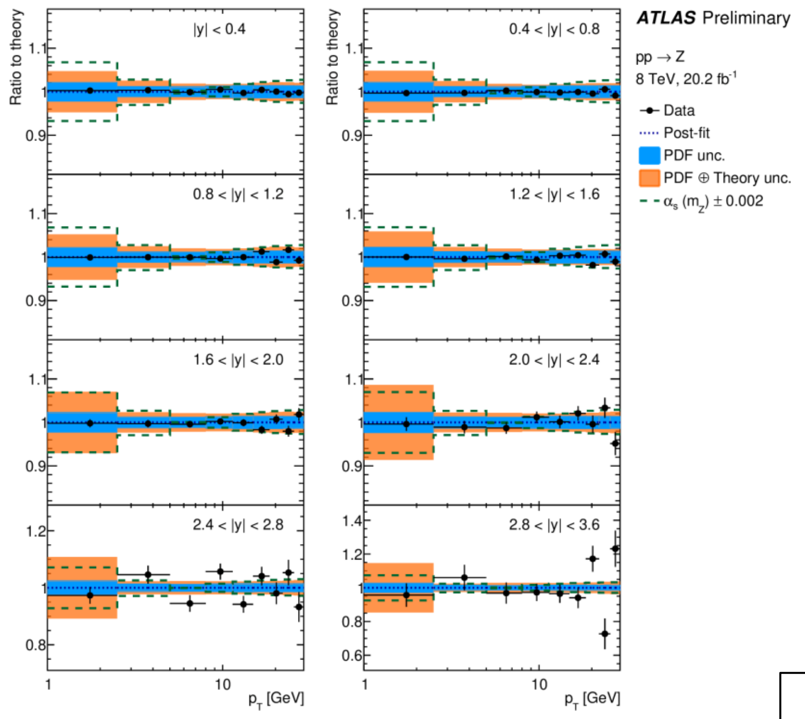
Γ: The influence of uncertainties on data and prediction.

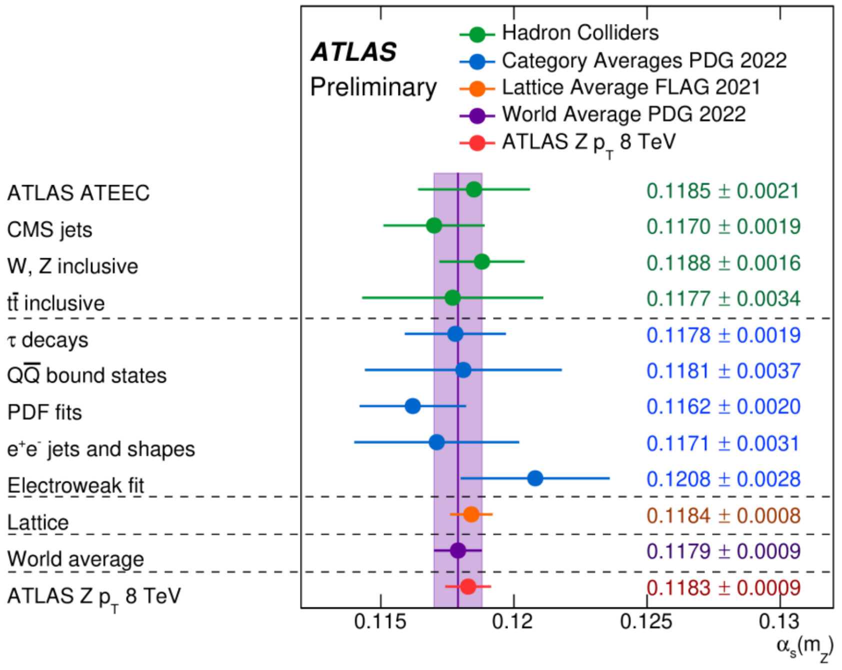
Δ: Uncorrelated experimental uncertainties.



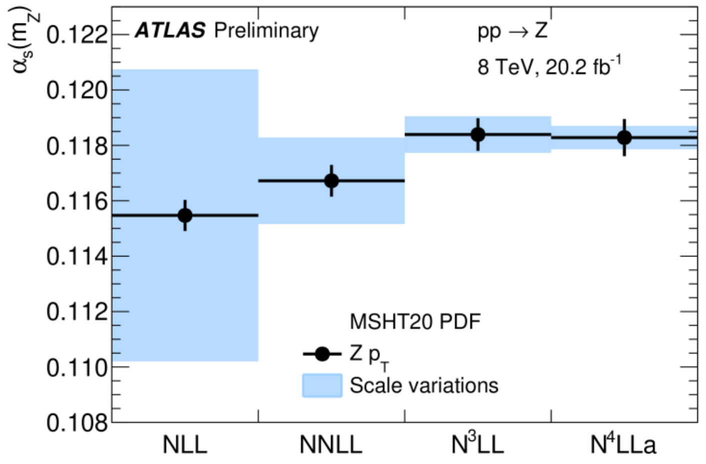
Extraction of α_s from p_T^Z at 8 TeV

- Fit range: p_T^Z < 29 GeV of the double differential Z p_T, y measurement.
- The most precise experimental measurement of α_s.
- The first α_s determination with N^3LO+aN^4LL prediction for p_T^Z.
  (Baseline PDF set: aN^3LO MSHT20)





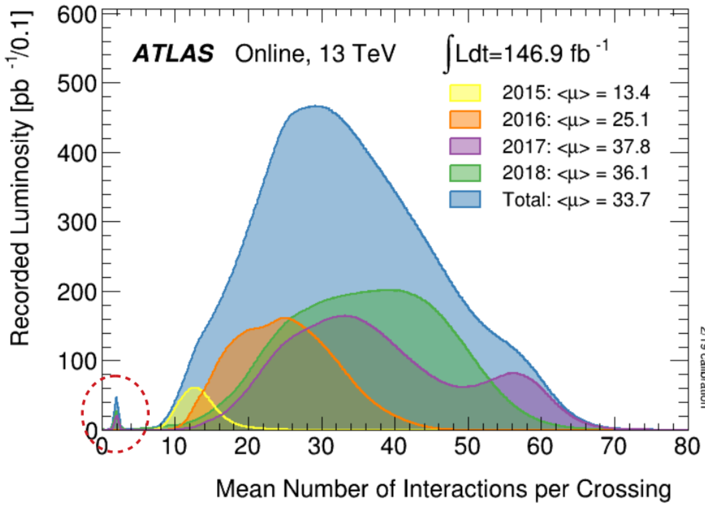
α_s = 0.11828 + 0.00084 - 0.00088

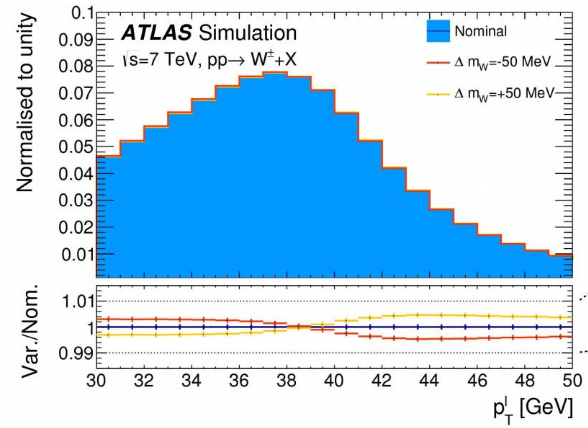


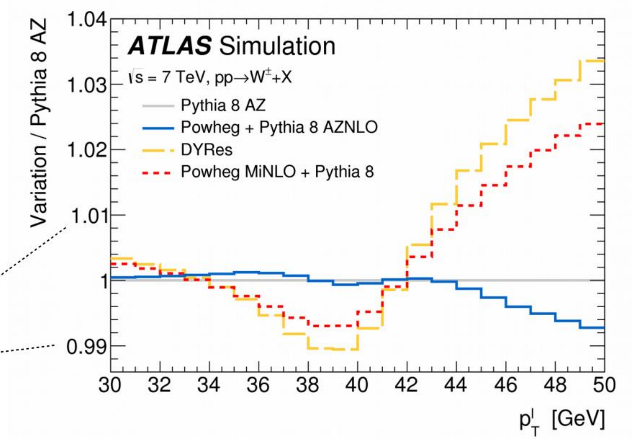
Good convergence of α_s determination using different orders of resummation series.

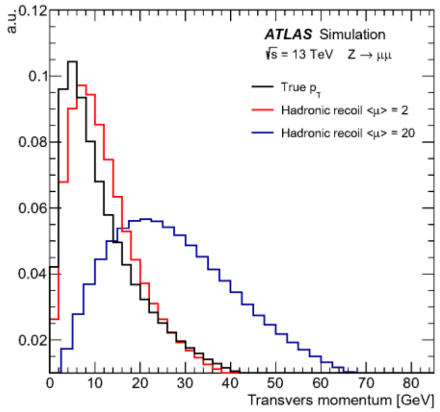
p_T^W and p_T^Z with low pile-up data

2017+2018 <μ>~2 data: 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13 TeV.









- Motivation: Reduce the p_T^W modelling uncertainty in m_W measurement by replacing the Z->W extrapolation with a direct measurement.
- Probe of perturbative and non-perturbative QCD in W events thanks to the improved missing E_T resolution, as well as in Z events at 5.02 TeV.
- Dedicated efforts for both theory modelling and detector calibration.

Detector calibration

Calibration of recoil (u_T) is carried out in-situ using Z events.

- Correction of mis-modelling of underlying event.
- Corrections of the azimuthal angle, response and resolution.

Lepton calibration uses high <μ> data extrapolated to low <μ> conditions wherever possible. Otherwise the in-situ calibrations are performed using standard ATLAS techniques.

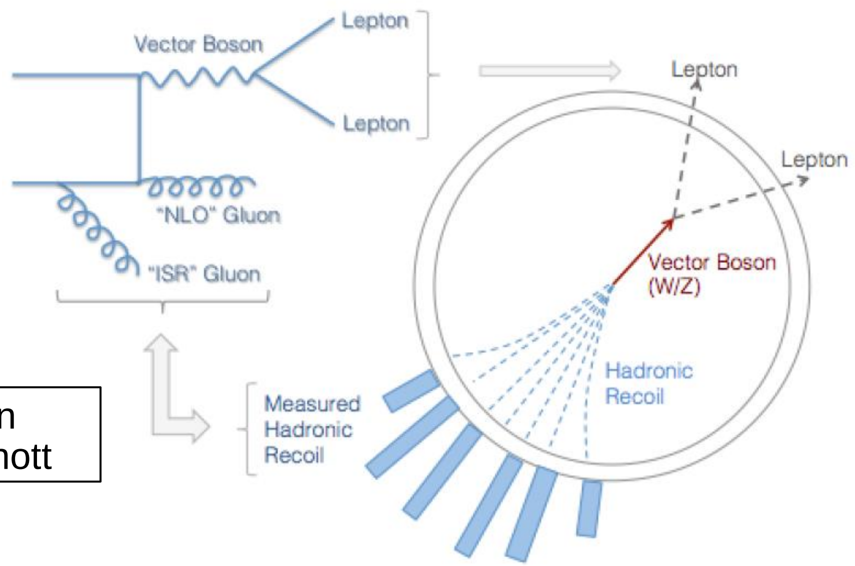
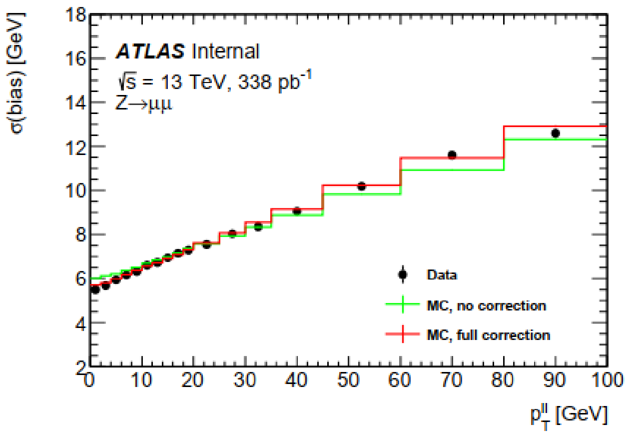
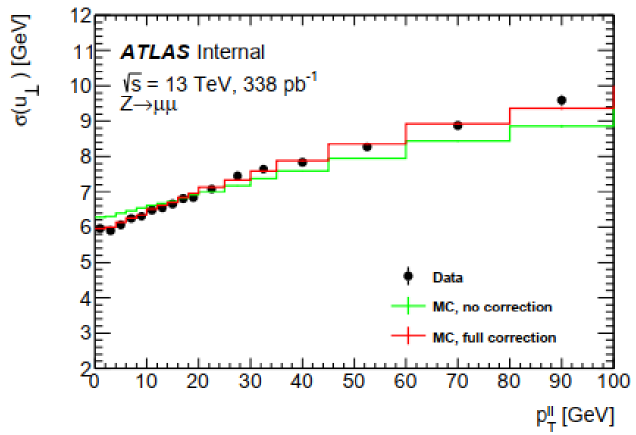


Figure taken from M. Schott

The hadronic system recoils against p_T^W.

- Input of recoil reconstruction: Particle Flow Objects.
- Inference of neutrino p_T: $\vec{p}_T^{miss} = -(\vec{u}_T + \vec{p}_T^{l})$





Analysis strategy

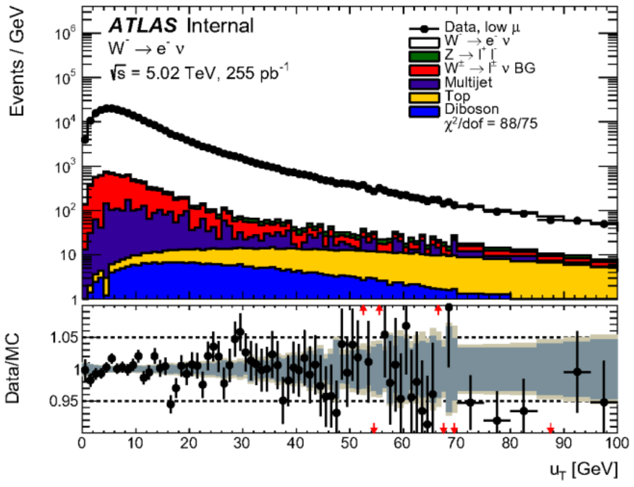
- Iterative Bayesian Unfolding:

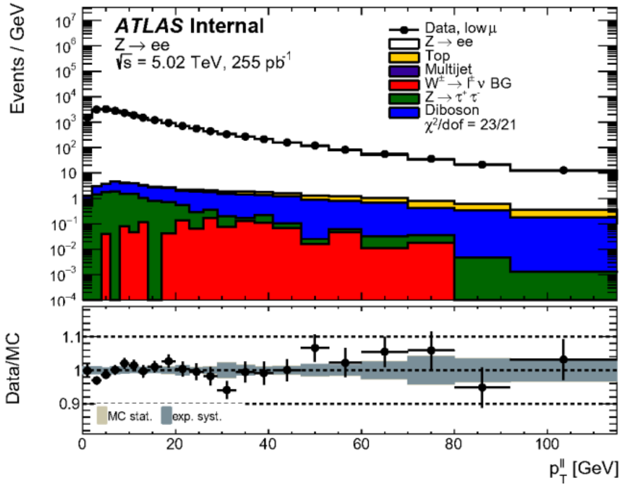
  u_T -> p_T^W and p_T^{ll} -> p_T^Z.

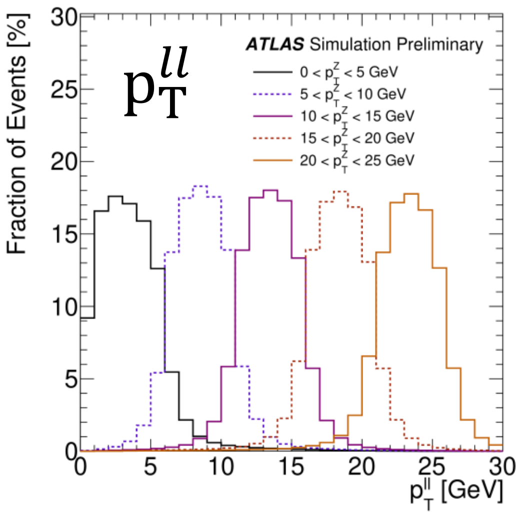
➢ 9 (25) iterations with 7 GeV bin width in the low p_T^W region for W channels at 5.02 (13) TeV.

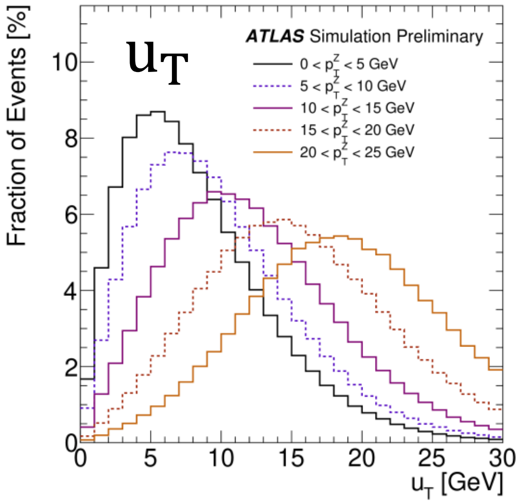
➢ 2 iterations with 7 GeV bin width at low p_T^Z for Z.

- Good compatibility in the combination of electron and muon channels.









Combination χ^2

Channel	χ^2/dof
5.02 TeV	
$W^- \to \ell^- \nu$	14.6/15
$W^+ \to \ell^+ \nu$	14.5/15
$W \to \ell \nu$	12.1/15
$Z \to \ell\ell$	13.7/26
$W^+ \to \ell^+ \nu$ / $W^- \to \ell^- \nu$	13.0/15
$W \to \ell \nu / Z \to \ell\ell$	16.3/15
13 TeV	
$W^- \to \ell^- \nu$	16.0/17
$W^+ \to \ell^+ \nu$	17.6/17
$W \to \ell \nu$	22.1/17
$Z \to \ell\ell$	21.4/27
$W^+ \to \ell^+ \nu$ / $W^- \to \ell^- \nu$	11.3/17
$W \to \ell \nu / Z \to \ell\ell$	17.1/17
Ratio 13 TeV/5.02 TeV	
$W^- \to \ell^- \nu$	11.5/15
$W^+ \to \ell^+ \nu$	9.3/15
$W \to \ell \nu$	7.3/15
$Z \to \ell\ell$	14.2/25

Fiducial volume:

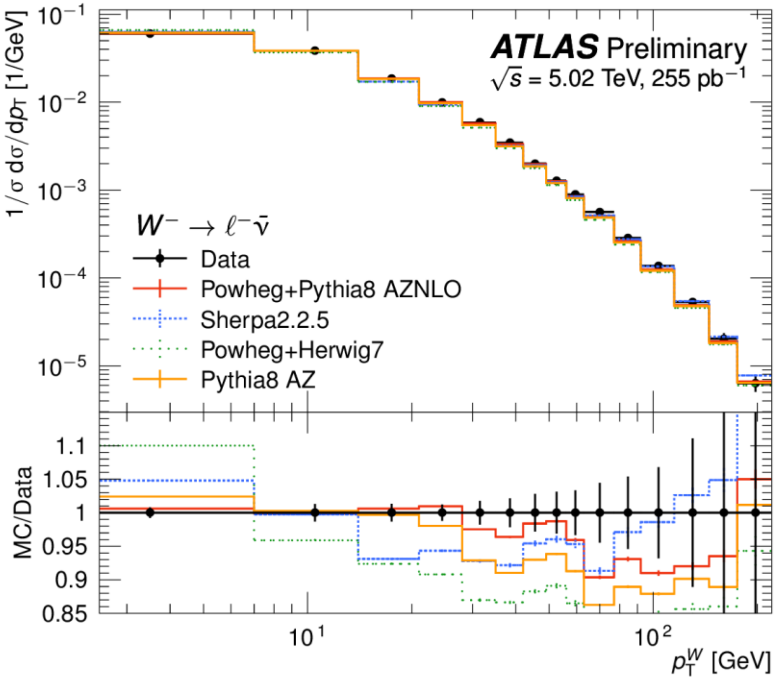
p_T^l > 25 GeV, $|\eta_l|$<2.5

W: p_T^ν > 25 GeV and m_T^W > 50 GeV

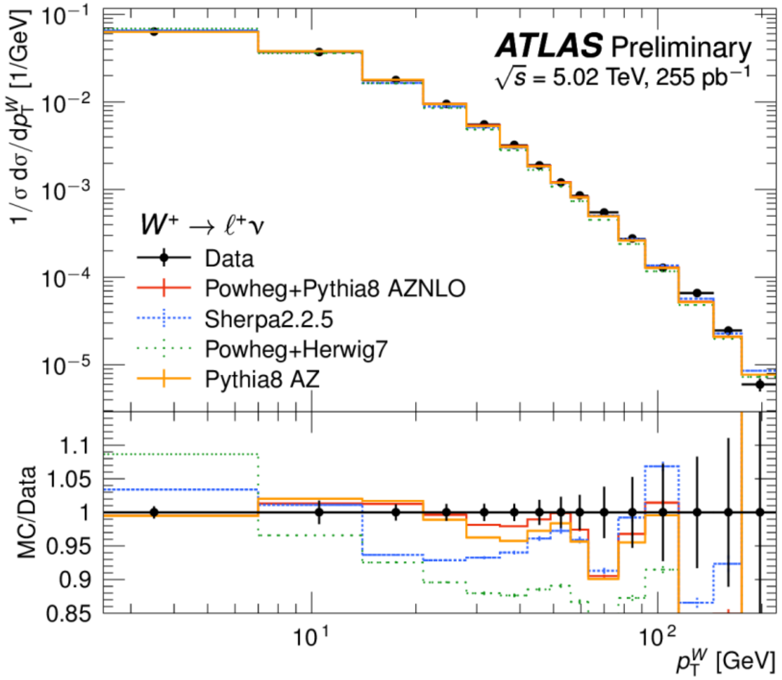
Z: 66 < m_{ll} < 116 GeV

Results at 5.02 TeV

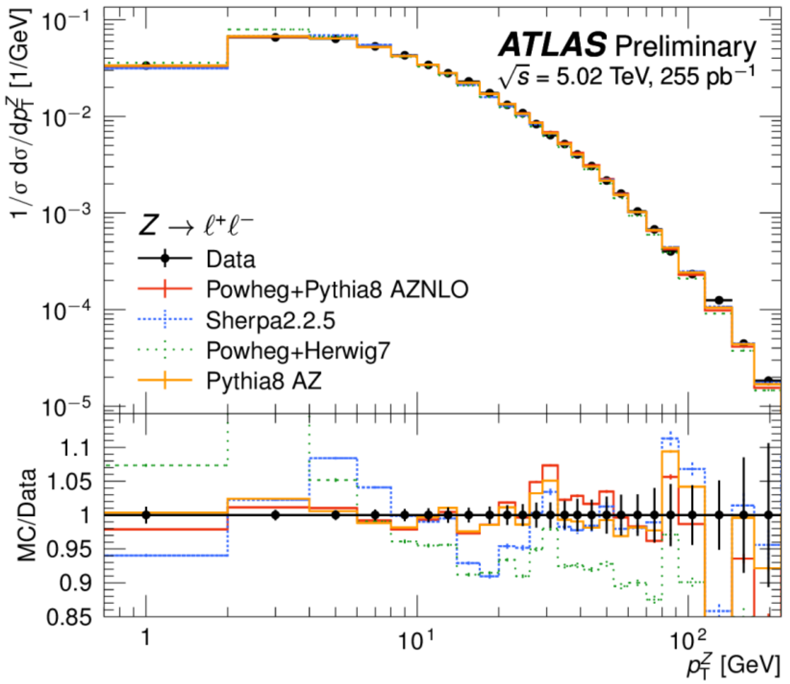
- Good agreement with ATLAS tunes on 7 TeV Z data at low p_T.



W^-



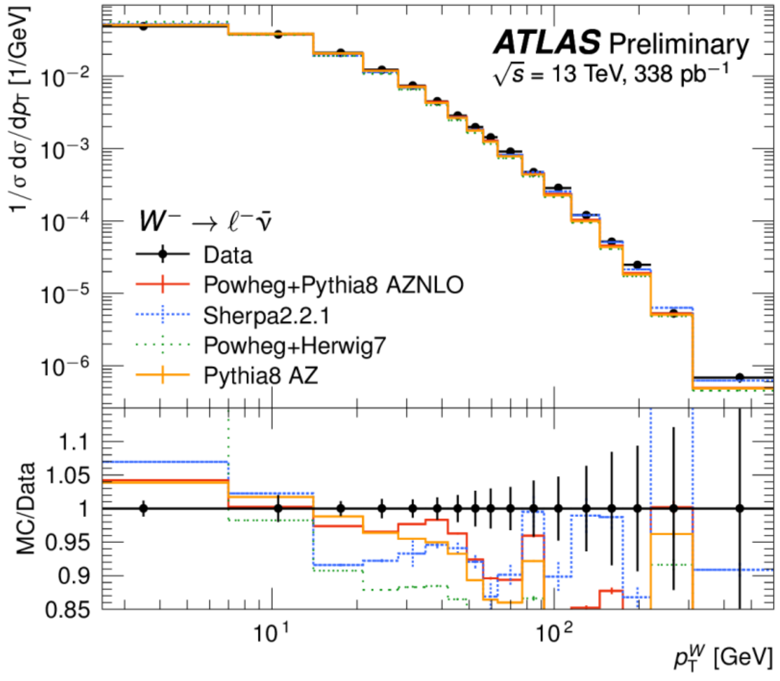
W^+



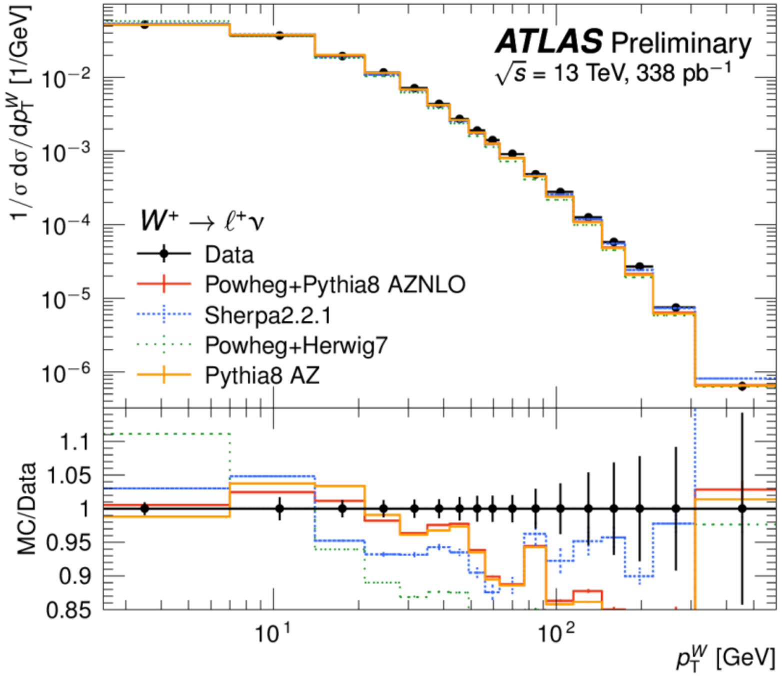
Z

Results at 13 TeV

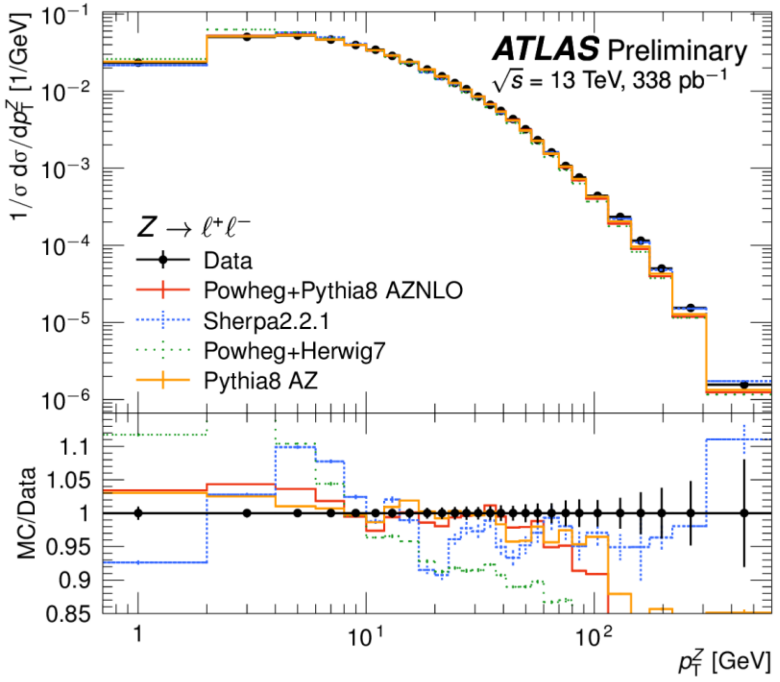
- Parton showers tuned with ATLAS 7 TeV Z data fail to describe the data at 13 TeV.



W^-



W^+



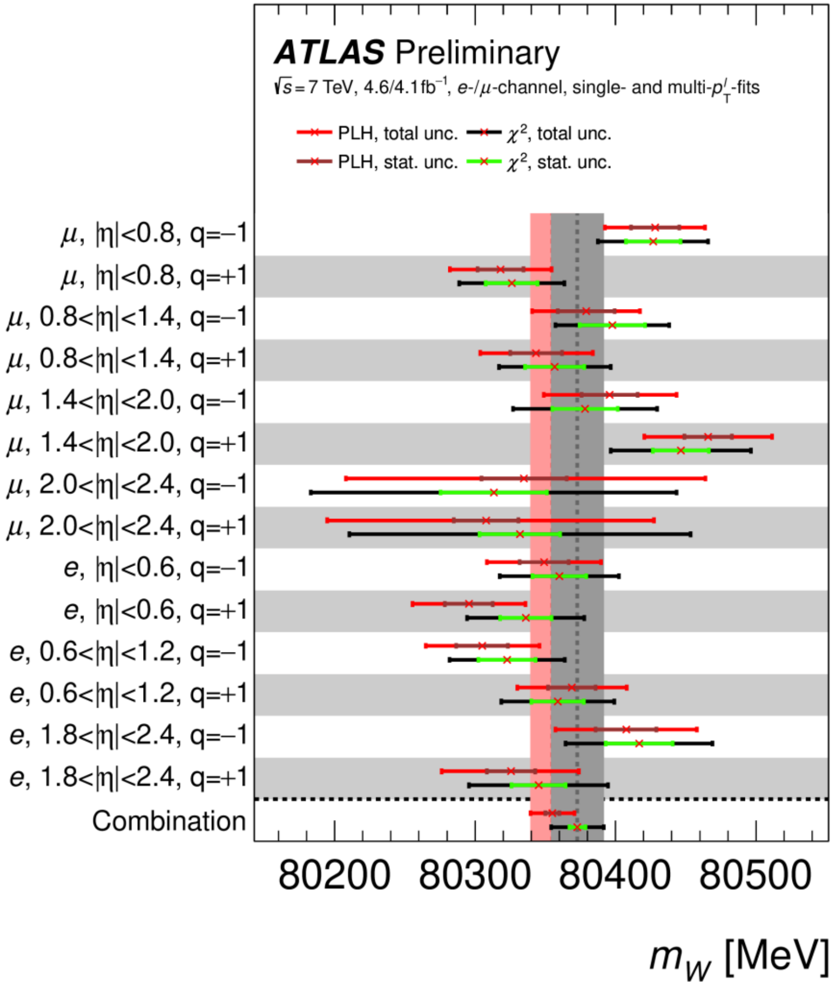
Z

Summary

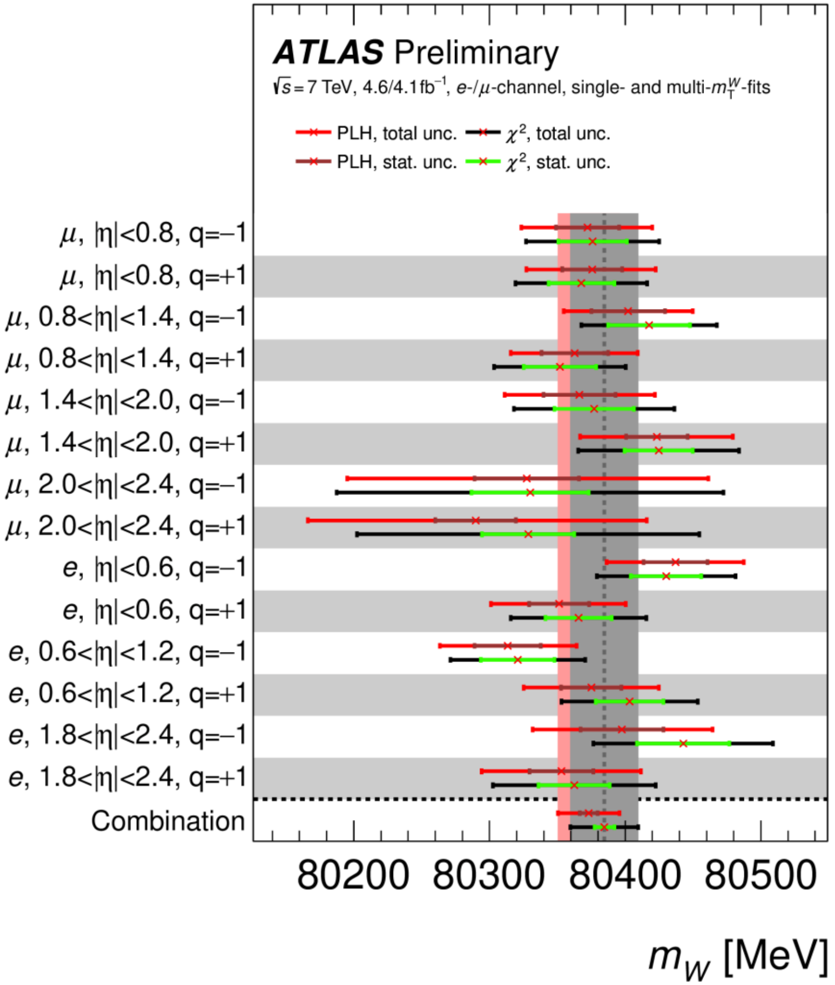
- New preliminary m_W measurement by ATLAS at 7 TeV has improved the precision by 15% thanks to the better fit method.
- The Z p_T and y double differential cross-section has been measured in the full lepton phase space for the first time and compared with theory predictions. No significant tension to the state-of-the-art predictions with QCD accuracy up to N^3LO+aN^4LL is observed.
- The most precise experimental determination of α_s has been achieved by ATLAS.
- New preliminary p_T^W and p_T^Z measurement using low pile-up dataset is reported. Its sensitivity to the Sudakov region will bring improvements in future m_W measurements.

Backup

PLH fit vs χ^2 offset method: stat. only

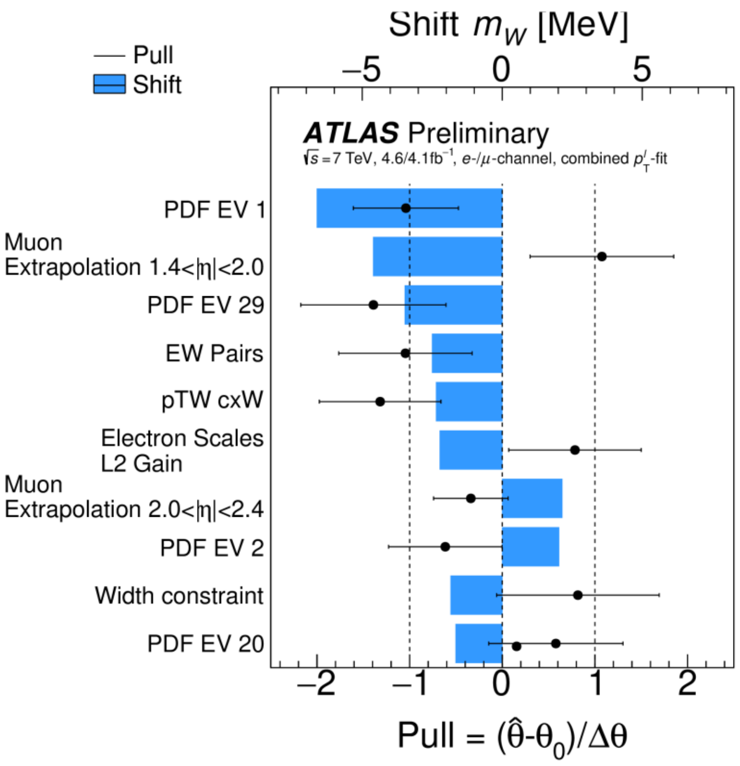


p_T^l fit

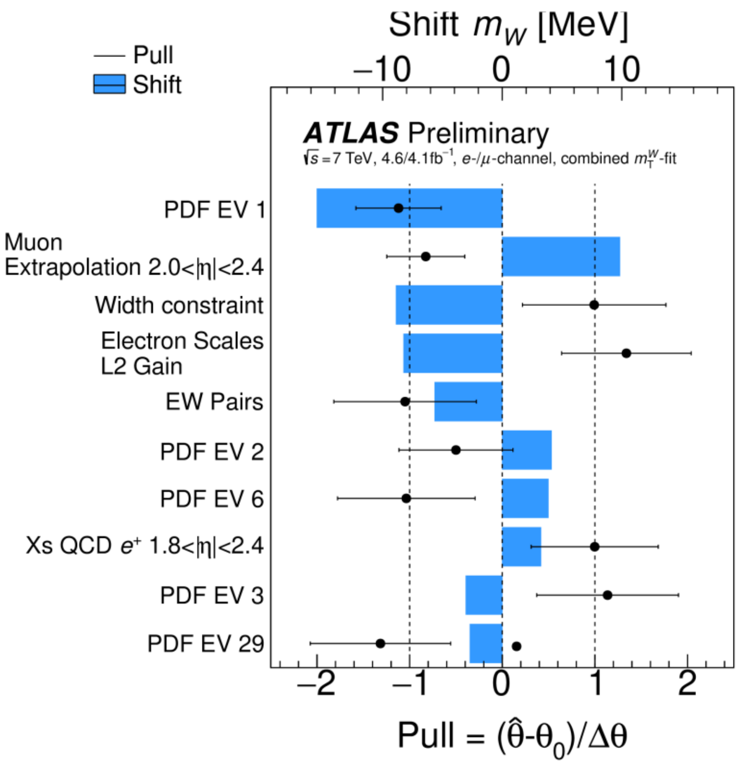


m_T fit

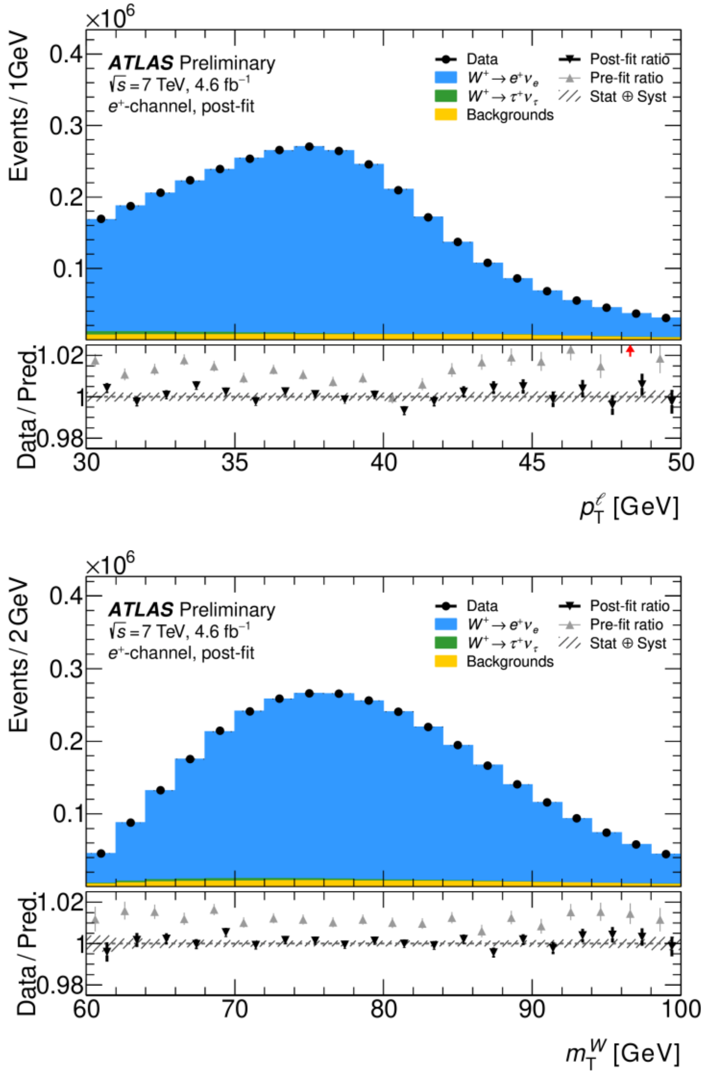
PLH fit: shift of the central value



p_T^l fit

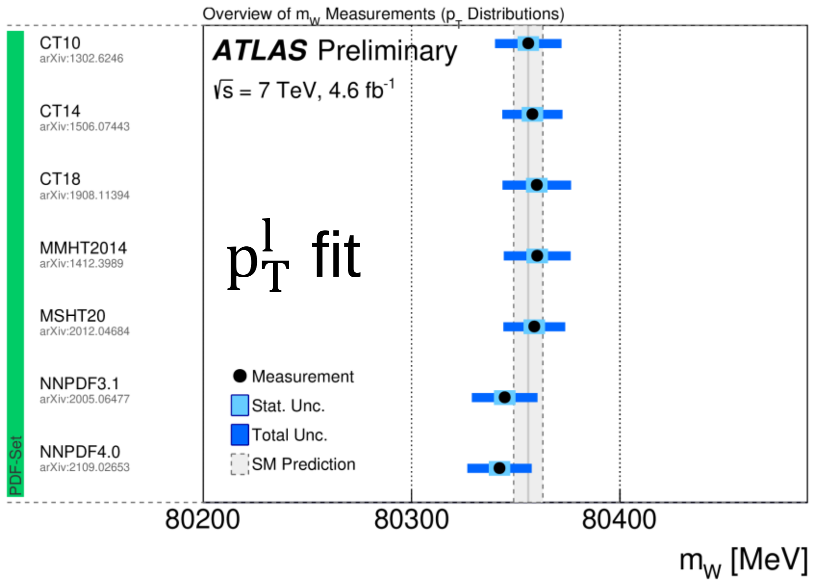


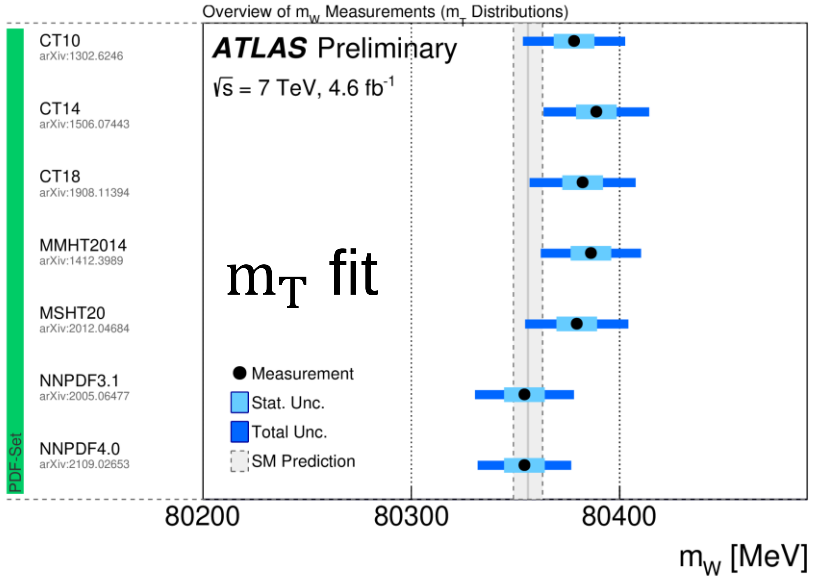
m_T fit



Comparison between PDF sets

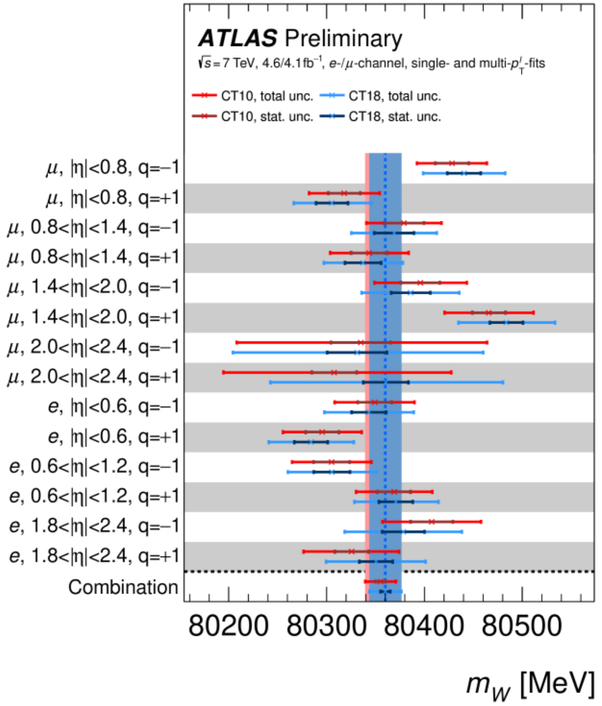
PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$



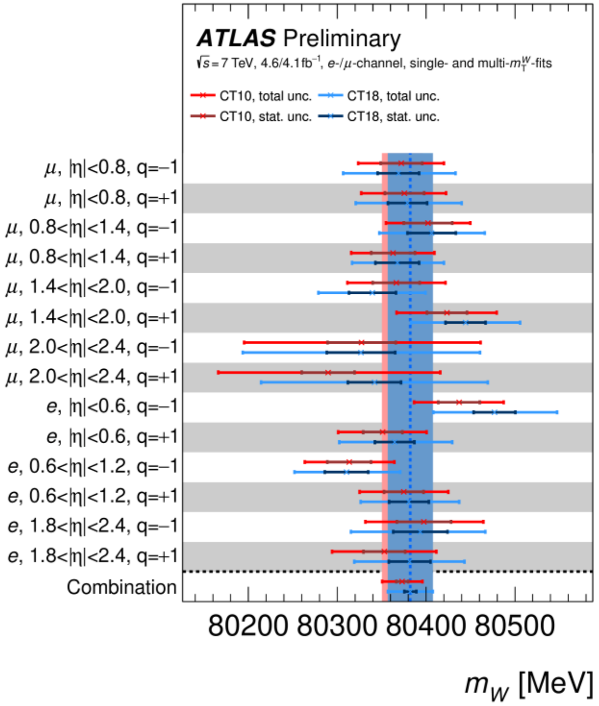


Comparison between PDF sets

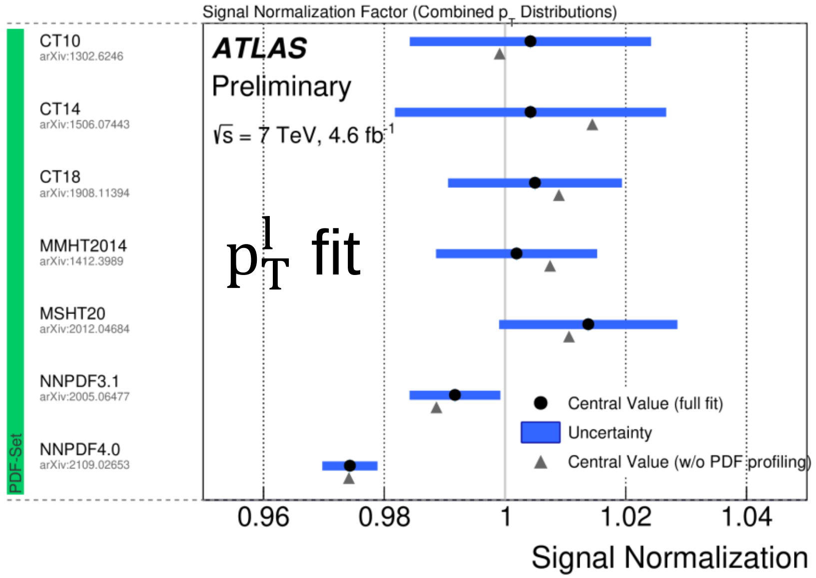
p_T^l fit

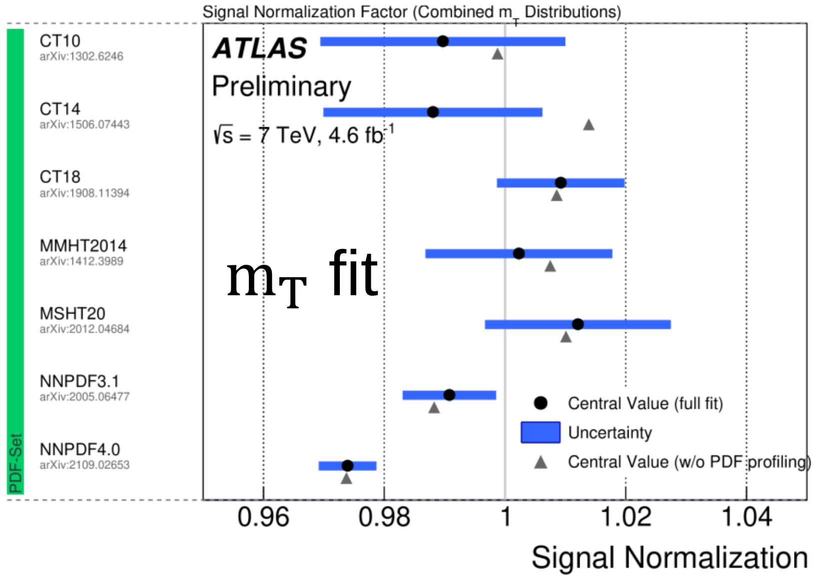


m_T fit

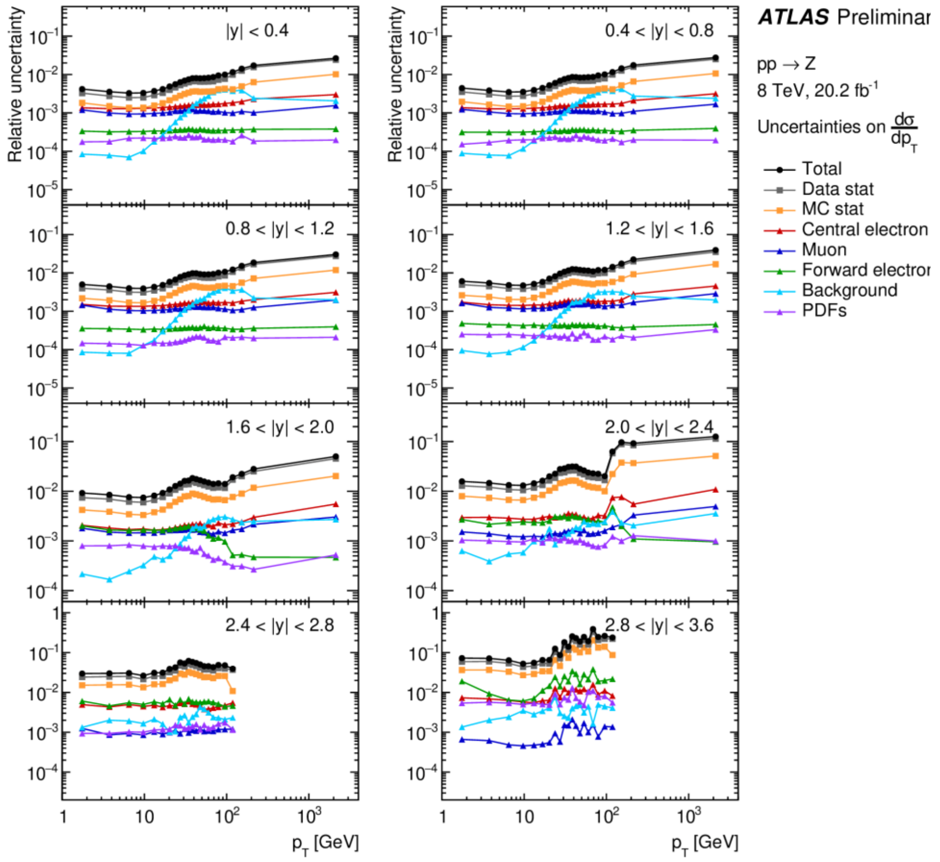


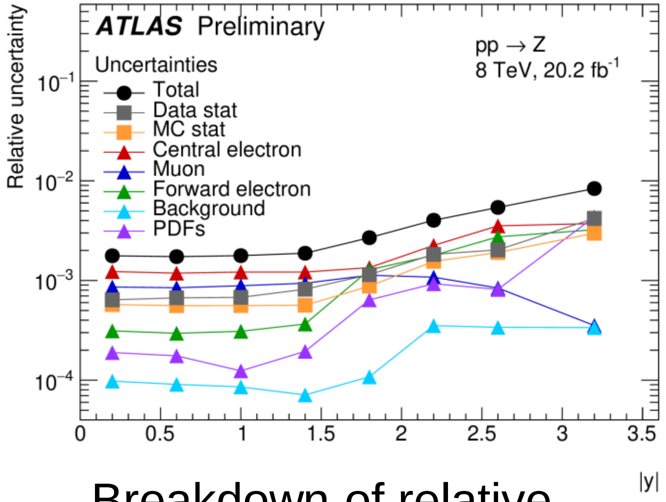
CT10NNLO vs CT18NNLO



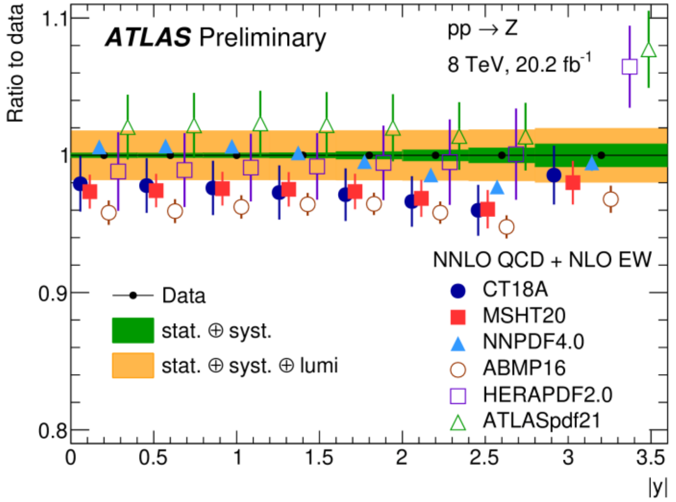


Z p_T and rapidity at 8 TeV





Breakdown of relative uncertainties in the measured absolute differential cross-section in y.



Comparison with NNLO PDF sets.

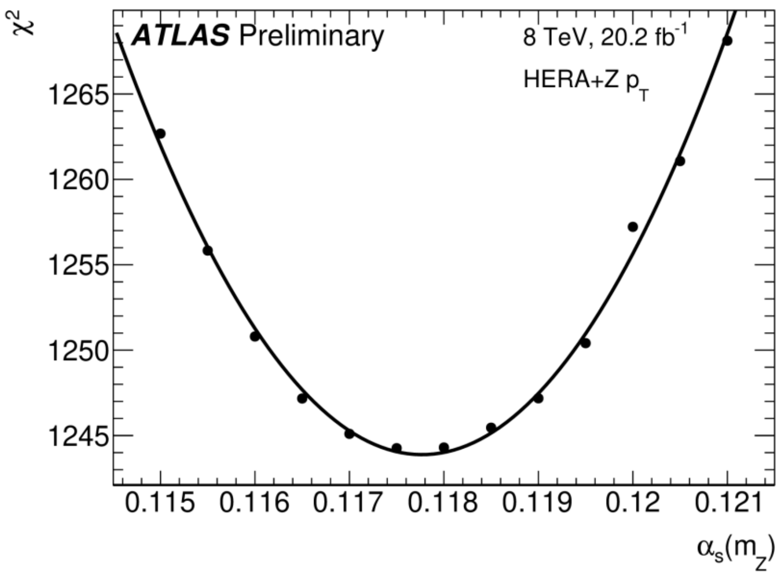
Breakdown of relative uncertainties in the measured absolute double differential cross-sections.

PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ± 0.8

Extraction of α_s from p_T^Z at 8 TeV

Uncertainties on the determination of $\alpha_s(m_Z)$

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088



Values of the χ^2 function for the determination of $\alpha_s(m_Z)$ from a combined fit of PDFs and non-perturbative parameters:

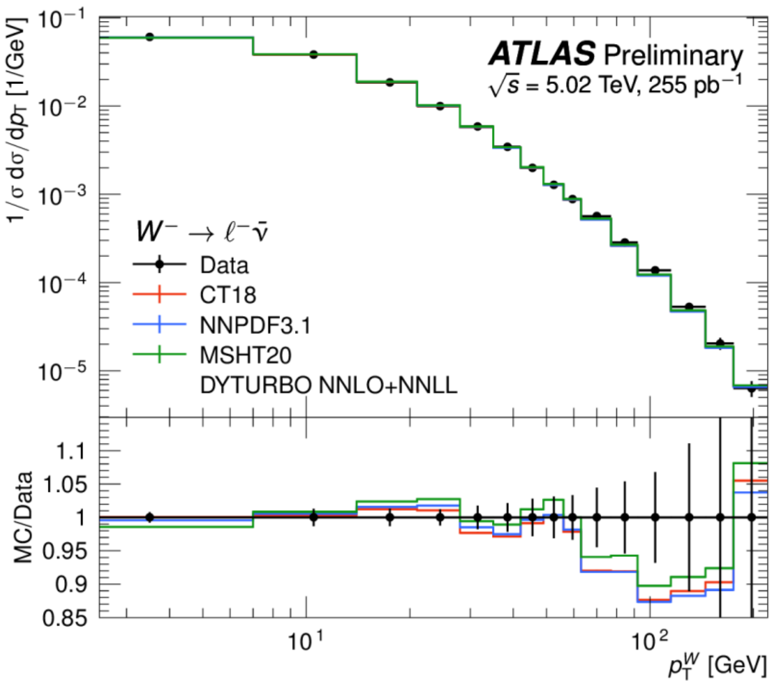
0.11777 ± 0.00065

Cross-check of N^3LL fits using NNLO PDF sets.

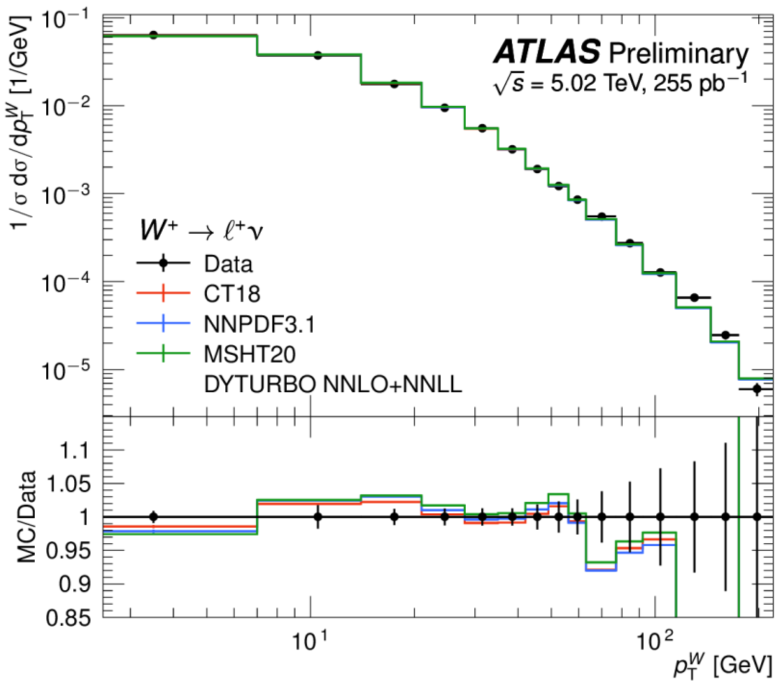
PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]	χ^2/dof
MSHT20 [32]	0.11839	0.00040	0.44	-0.07	96.0 /69
NNPDF40 [78]	0.11779	0.00024	0.50	-0.08	116.0/69
CT18A [79]	0.11982	0.00050	0.36	-0.03	97.7 /69
HERAPDF20 [63]	0.11890	0.00027	0.40	-0.04	132.3/69

Variations of the upper end of the p_T^Z fit range have performed to test the stability of the results with respect to missing higher order corrections in the matching to fixed order.

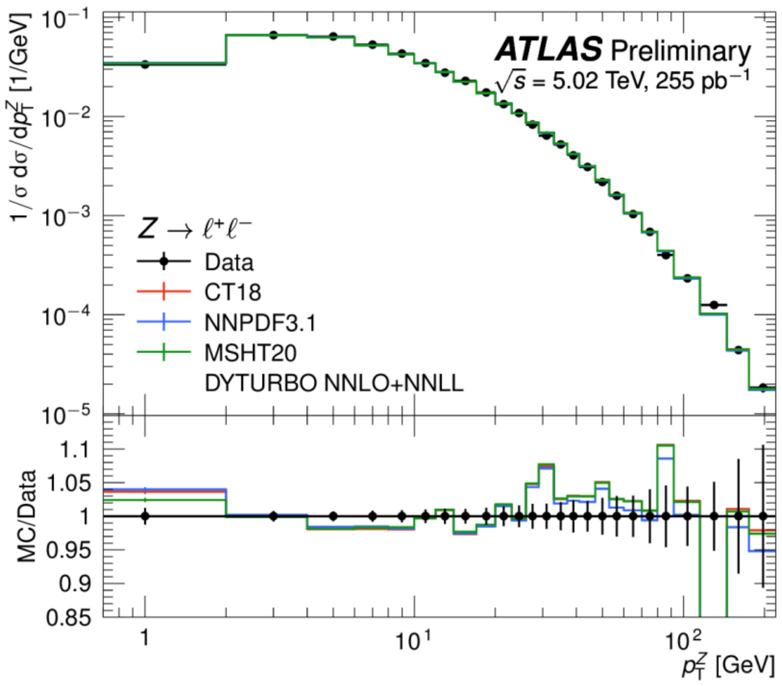
p_T^W and p_T^Z at 5.02 TeV



W⁻

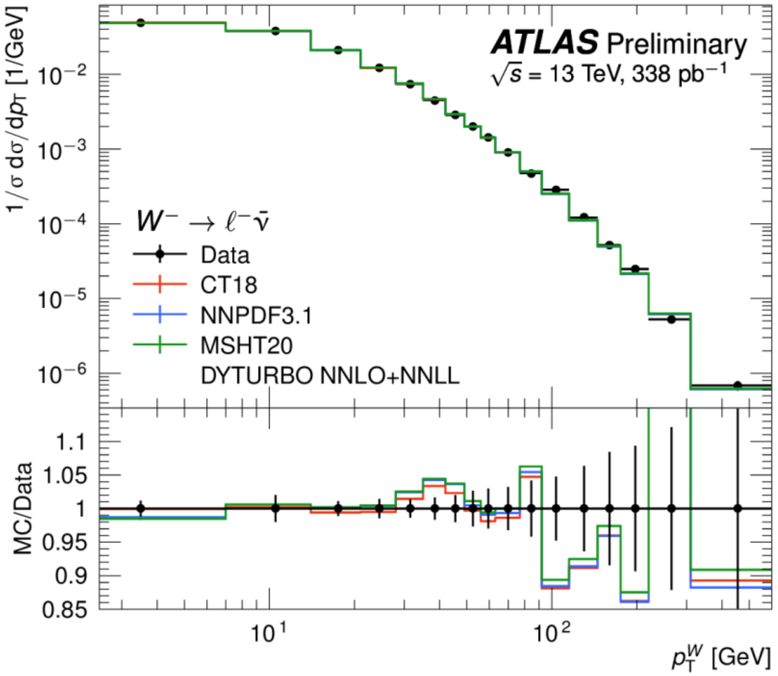


W⁺

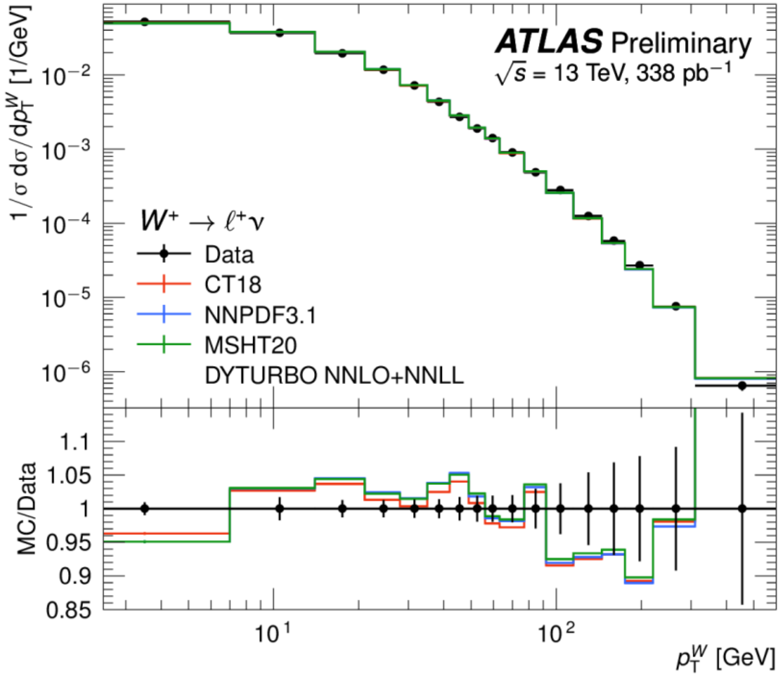


Z

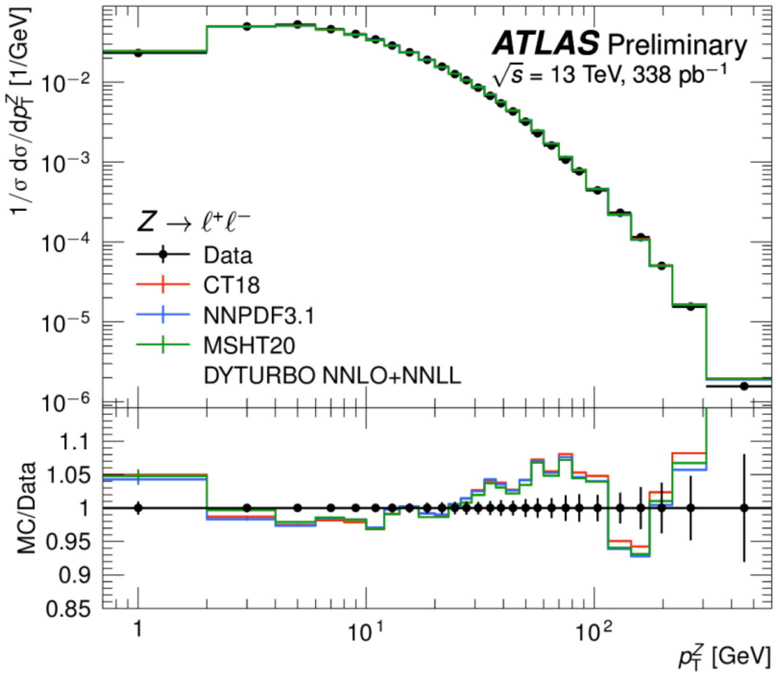
p_T^W and p_T^Z at 13 TeV



W^-

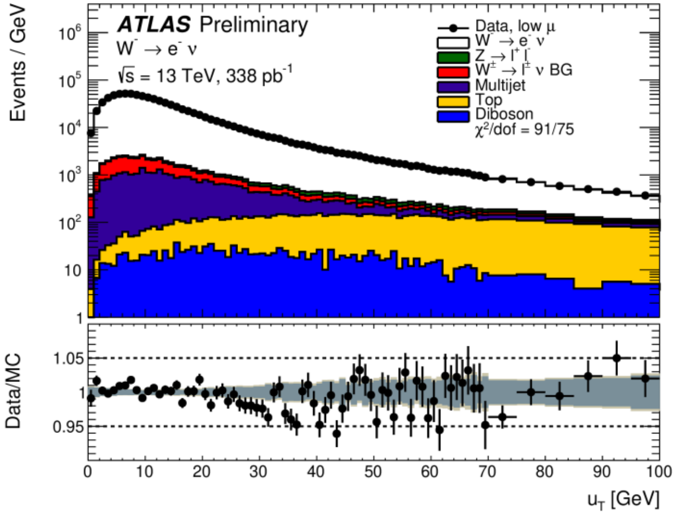


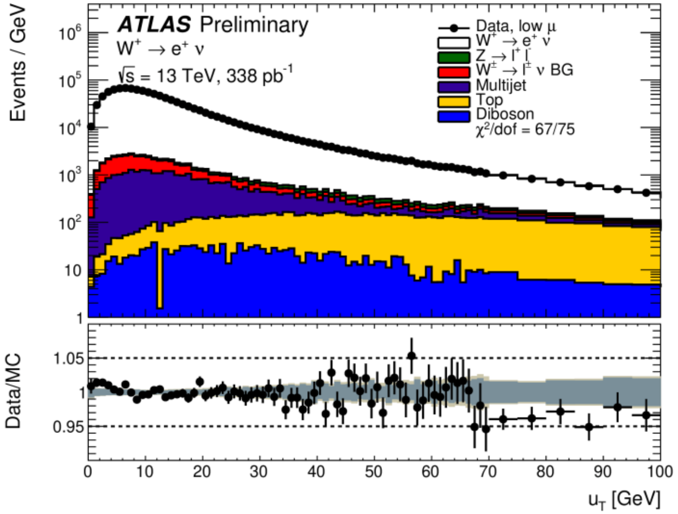
W^+

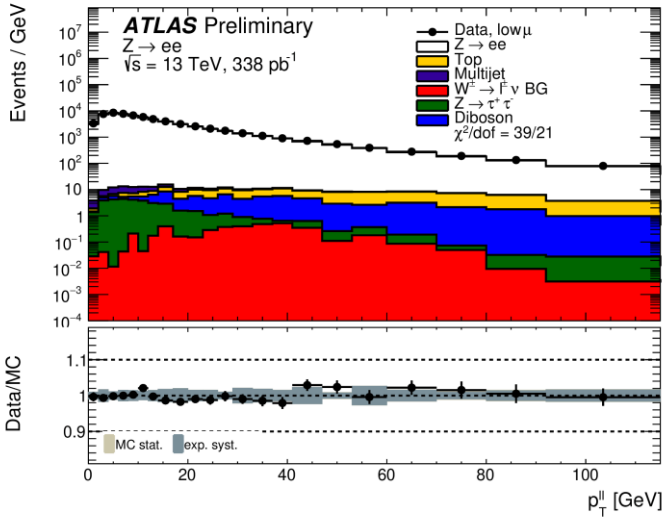


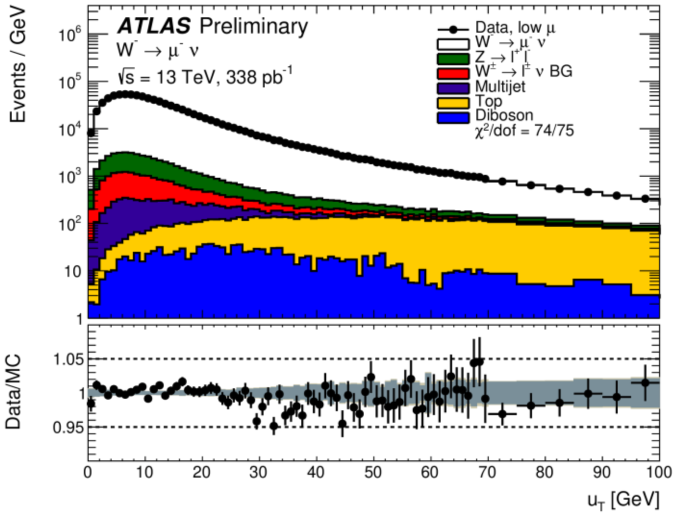
Z

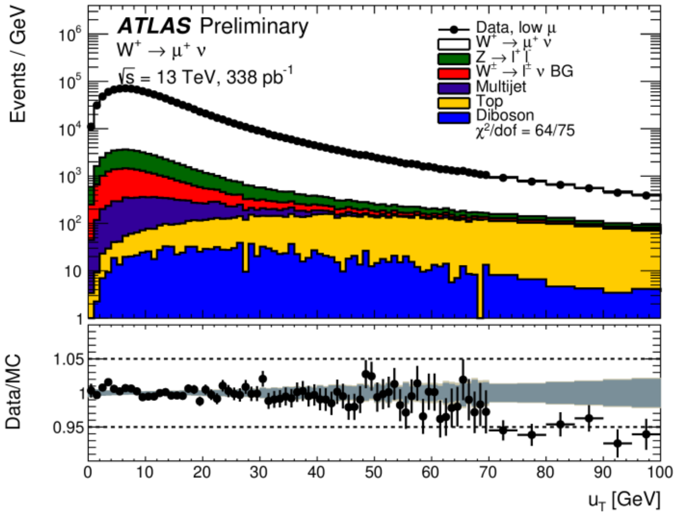
p_T^W and p_T^Z: reco-level control plots @ 13 TeV

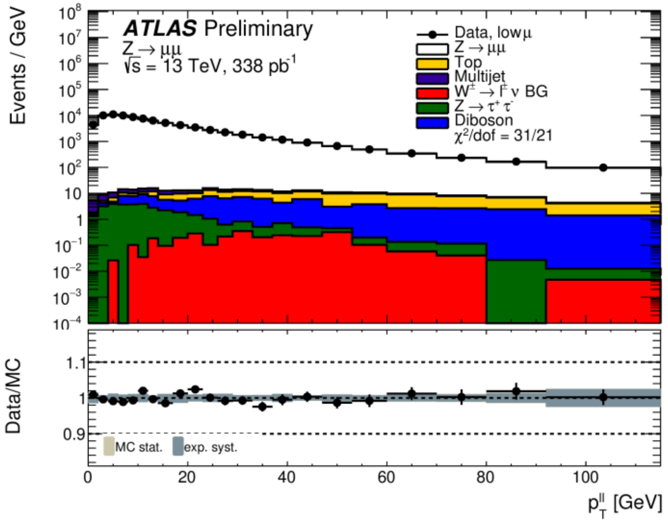






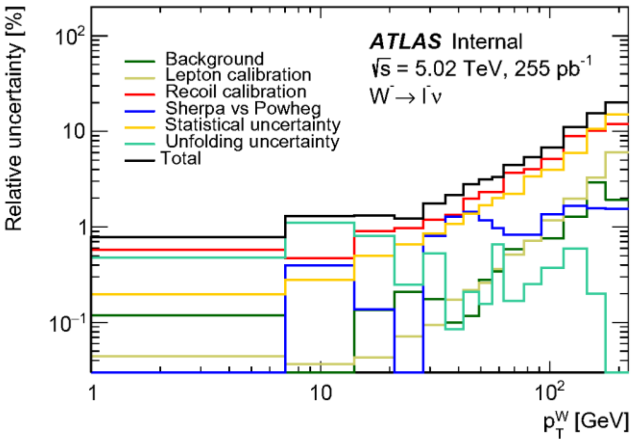


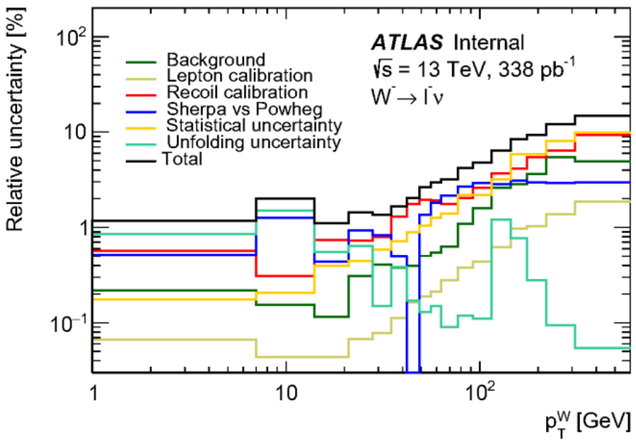




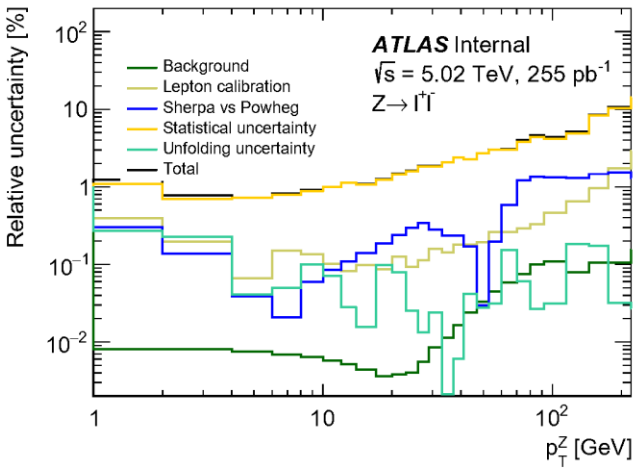
p_T^W and p_T^Z: combination and χ^2

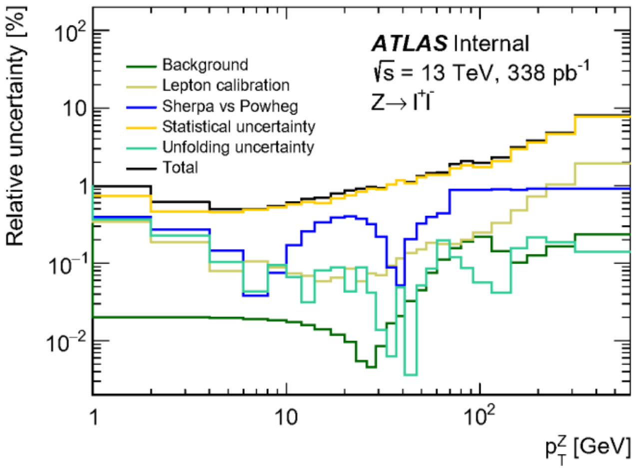
- Statistical procedure: BLUE prescription with 4 iterations





Break-down of uncertainty for the combined W⁻→lν measurements at 5.02 TeV (left) and at 13 TeV (right).





Break-down of uncertainty for the combined Z →ll measurements at 5.02 TeV (left) and at 13 TeV (right).