W mass measurement

N. Andari

On behalf of the ATLAS & CMS Collaborations

University of Birmingham

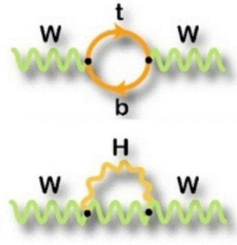
Les Rencontres de Moriond - EW

March, 18-25, 2017

Status of the measurement

In the electroweak sector of the SM, the W mass at the loop level: $m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$

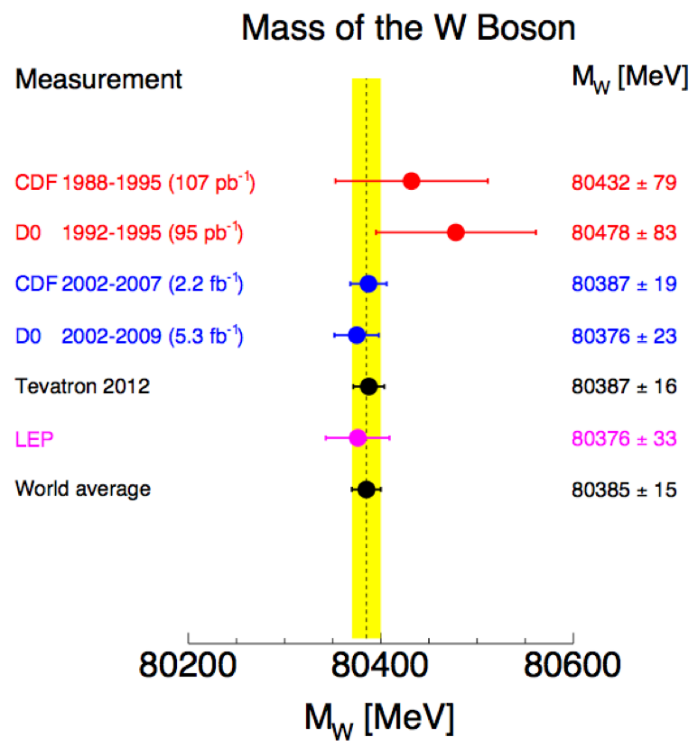
In SM, Δr reflects loop corrections and depends on m_t^2 and $\ln m_H$

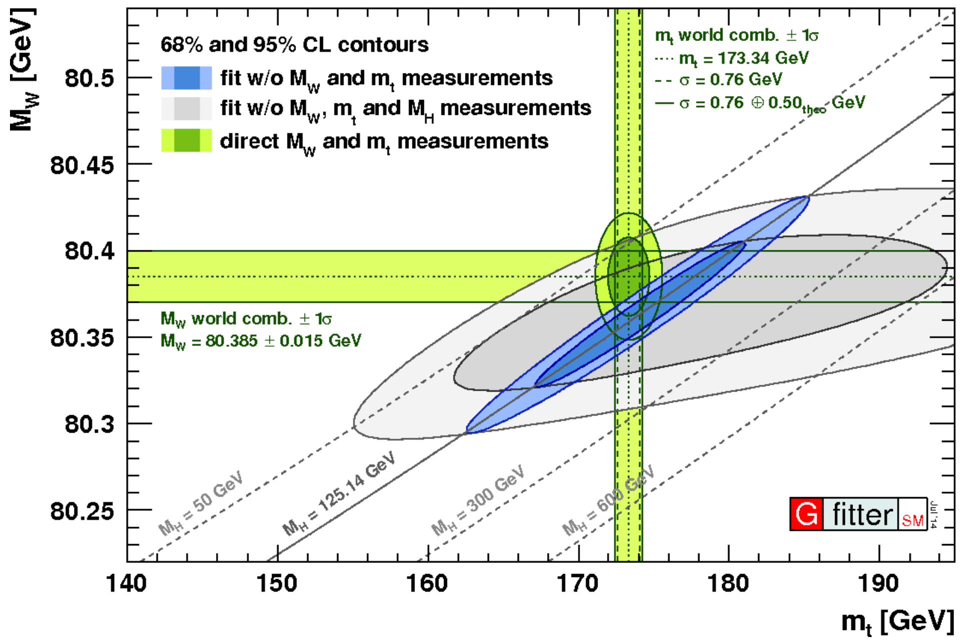


m_H=125.09±0.24 GeV (ATLAS+CMS) Phys. Rev. Lett. 114, 191803

m_t=172.84±0.70 GeV (ATLAS) m_t = 172.44±0.49 GeV (CMS)

Phys. Lett. B 761 (2016) 350-371 Phys. Rev. D 93 (2016), 072004





LEP+Tevatron: M_W uncertainty~ 15 MeV
Best individual measurement:
CDF M_W uncertainty 19 MeV

The relation between M_W, m_t, and M_H provides stringent test of the SM and is sensitive to new Physics

Tevatron results

CDF experiment:

Phys. Rev. Lett.108 (2012) 151803

electron/muon channels
2.2 fb^{-1} integrated luminosity

m_W= 80387±12(stat)±15(syst) MeV

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

D0 experiment:

Phys. Rev. Lett. 108 (2012) 151804

electron channel
~5.3 fb^{-1} integrated luminosity

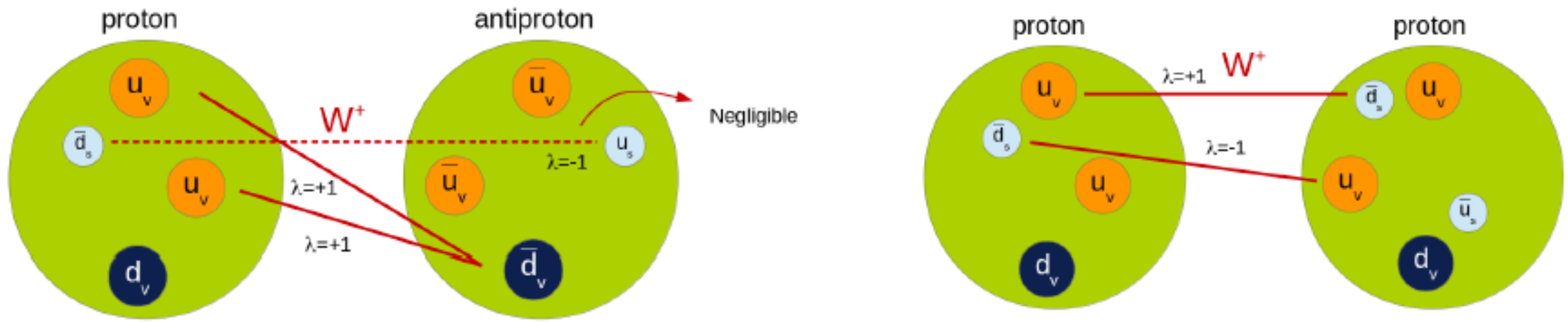
m_W= 80375±11(stat)±20(syst) MeV

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

$$M_W = 80\,387 \pm 16 \text{ MeV}$$

W mass @ LHC

Challenging environment @LHC: pileup, need a high experimental precision and an accurate theoretical modelling



- W^+/W^- production is asymmetric —> charge-dependent analysis

- Second generation quark PDFs play a larger role at the LHC *(25% of the W-boson production is induced by at least one second generation quark s or c).*

- The W polarisation is determined by the difference between the u,d valence and sea densities

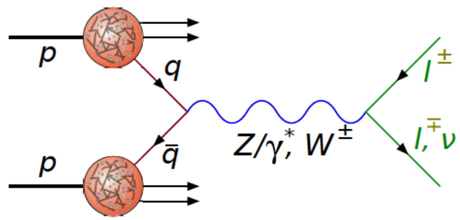
W-like Z mass measurement by CMS released for Moriond 2016 CMS PAS SMP-14-007

First measurement of the W-boson mass in pp collisions at the LHC by ATLAS New

arXiv:1701.07240 [hep-ex] submitted to EPJC

Strategy of the measurement (I)

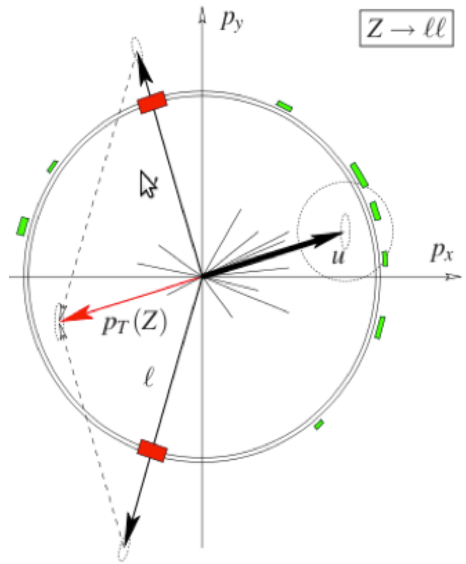
Not possible to fully reconstruct W mass



Sensitive final state distributions: **p_T^l, m_T,** p_T^{miss*}

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right), \quad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

u_T being the recoil



Benefit from the fully reconstructed mass in Z-boson sample to validate the analysis and to provide significant experimental *(lepton and recoil calibration using resp. m_Z measured at LEP and expected momentum balance with p_T^{ll})* and theoretical constraints *(ancilliary measurements).*

The whole analysis is checked by performing a measurement of the Z-boson mass and comparing to the LEP value, also a cross-check Z mass measurement in “W-like” i.e removing the 2nd lepton and treating it like a neutrino

Need to consider additional systematics for W mass measurement (*theory uncertainties, Z—>W extrapolation and background)*

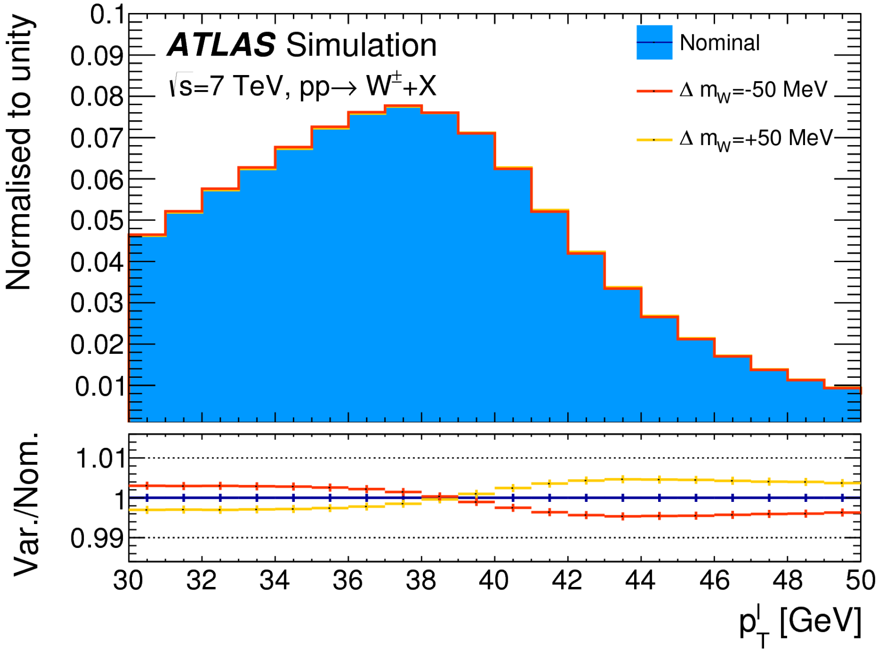
**used as cross-check only*

Strategy of the measurement (II)

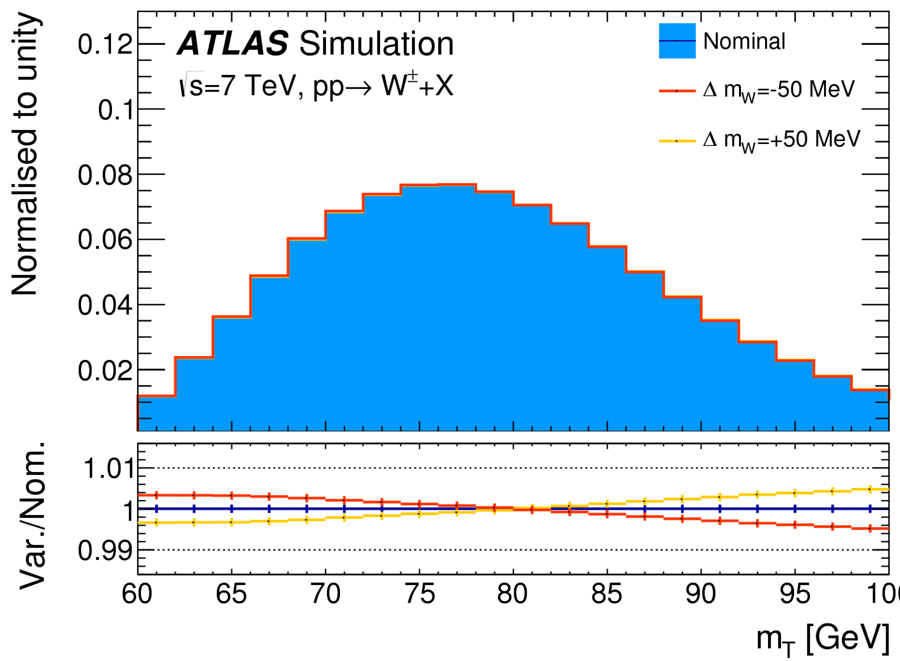
2011 7 TeV ~4.6-4.7 fb^{-1}

CMS: Z mass measurement in "W-like" considers central "tag" muon $|\eta|<0.9$
ATLAS: W mass measurement* muon and electron channels $|\eta|<2.4$

Template fit approach: compute the p_T^l and m_T distributions for different assumed values of m_W —> χ^2 minimisation gives the best fit template



p_T^l has a Jacobian edge at $m_W/2$



m_T has a Jacobian edge at m_W

**A blinding offset was applied throughout the measurement and removed when consistent results were found.*

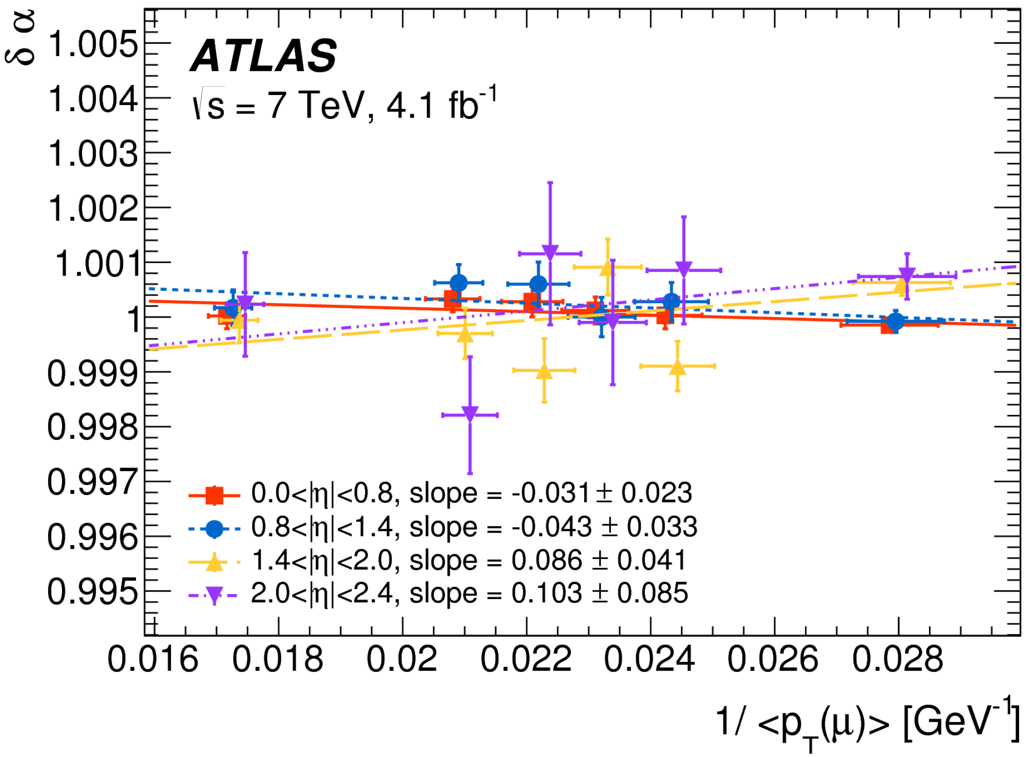
Muon Calibration (I)

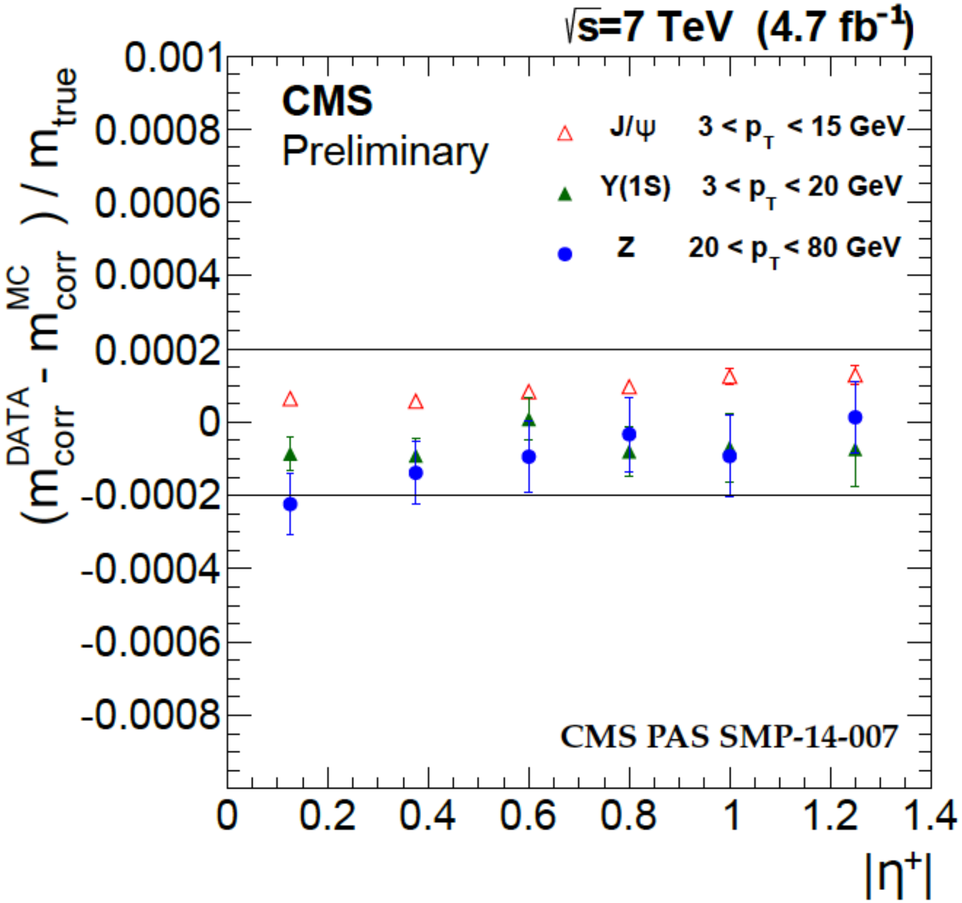
CMS: calibrate muon curvature ($k=1/p_T$) using J/ψ *(dominates the precision)* & Υ

ATLAS: calibration of ID muons using Z Eur.Phys.J.C 74 (2014) 3130

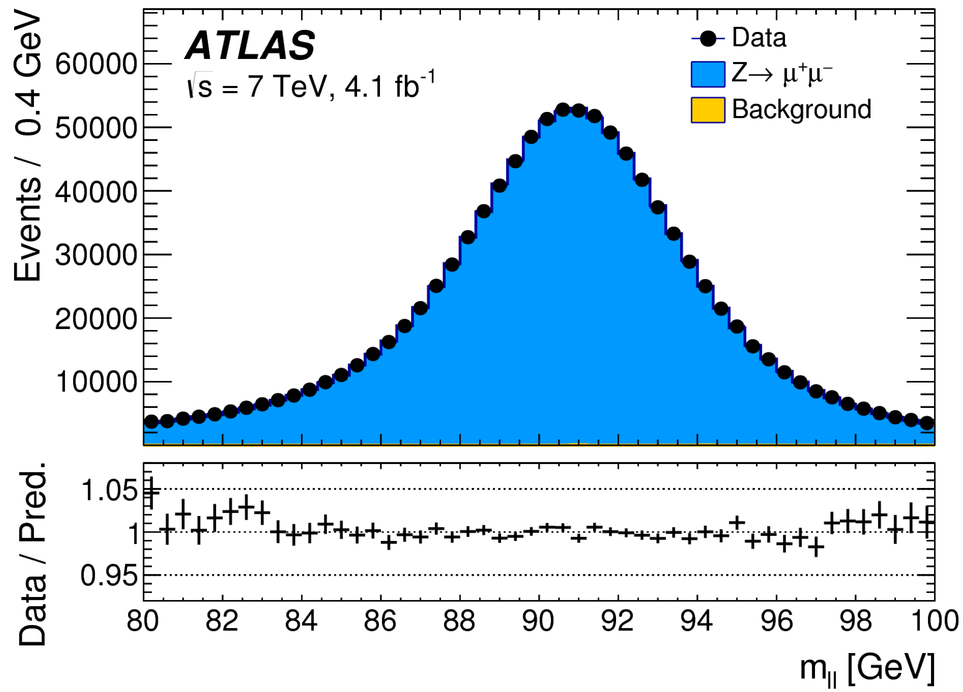
$$k^c = (A - 1)k + qM + \frac{k}{1 + k\epsilon \sin\theta}$$

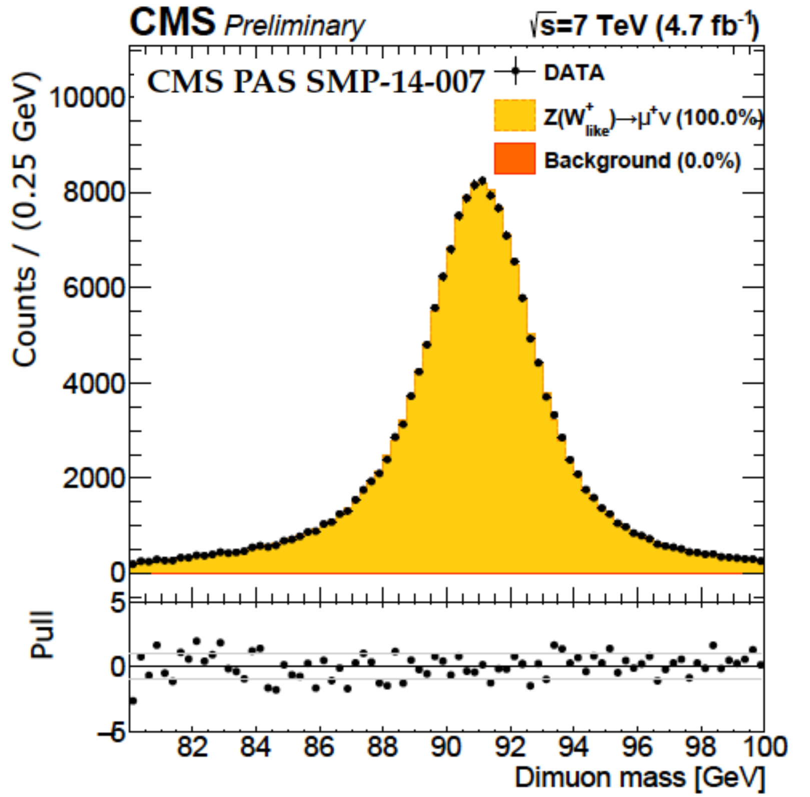
magnetic field — mis-alignement — material





Muon Calibration (II)



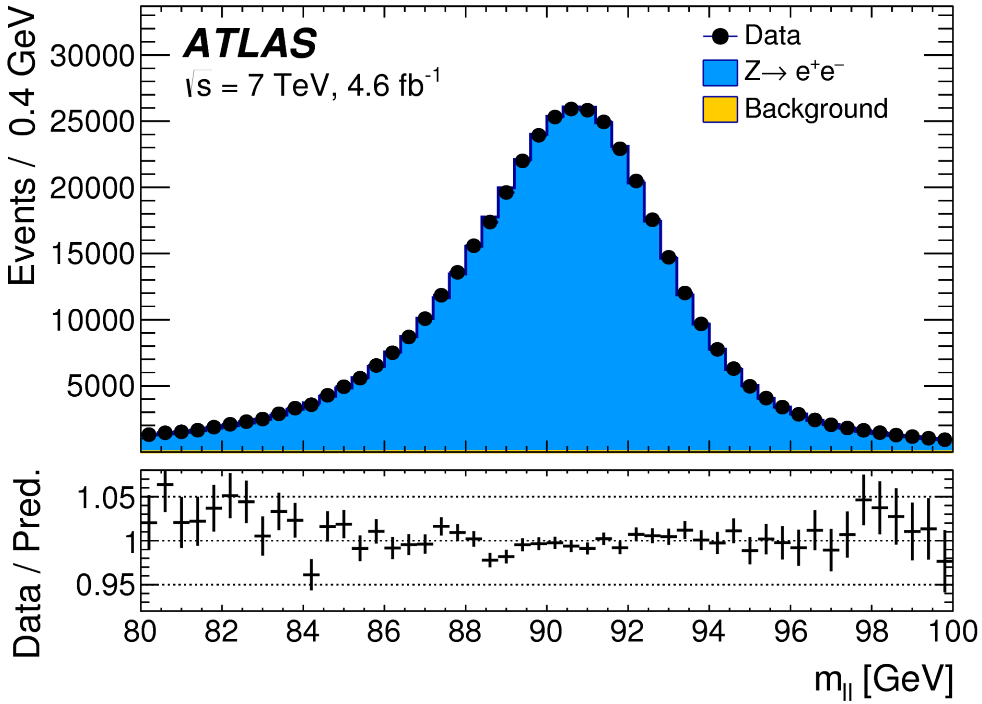


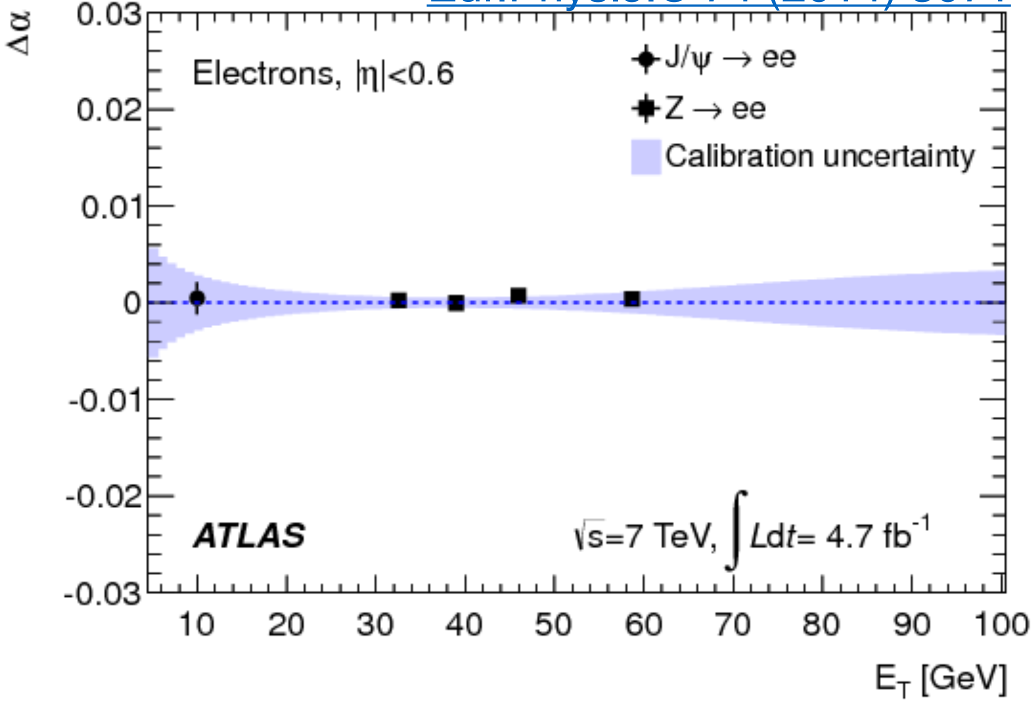
ATLAS

$\|\eta_\ell\|$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

Electron Calibration

[Eur.Phys.J.C 74 (2014) 3071]





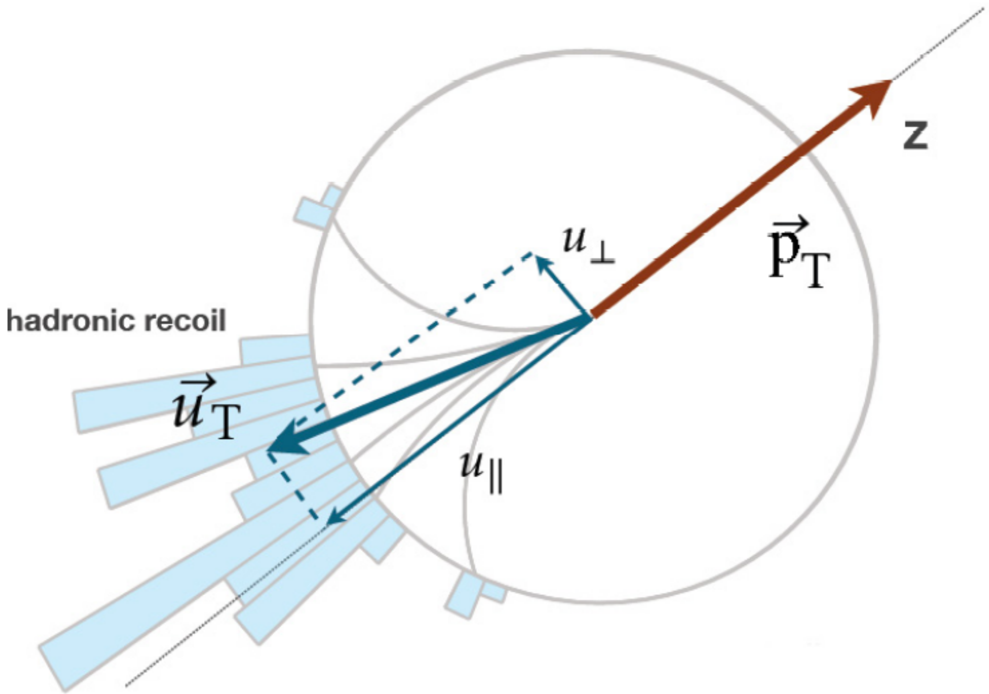
Exclude bin 1.2<|eta|<1.82 as the amount of passive material and its uncertainty are largest

$\vert\eta_\ell\vert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

Recoil Reconstruction

ATLAS: vector sum of the momenta of all clusters measured in the calorimeters

CMS: vector sum of the particle flow charged hadrons, loss in recoil response but more robust against pile-up

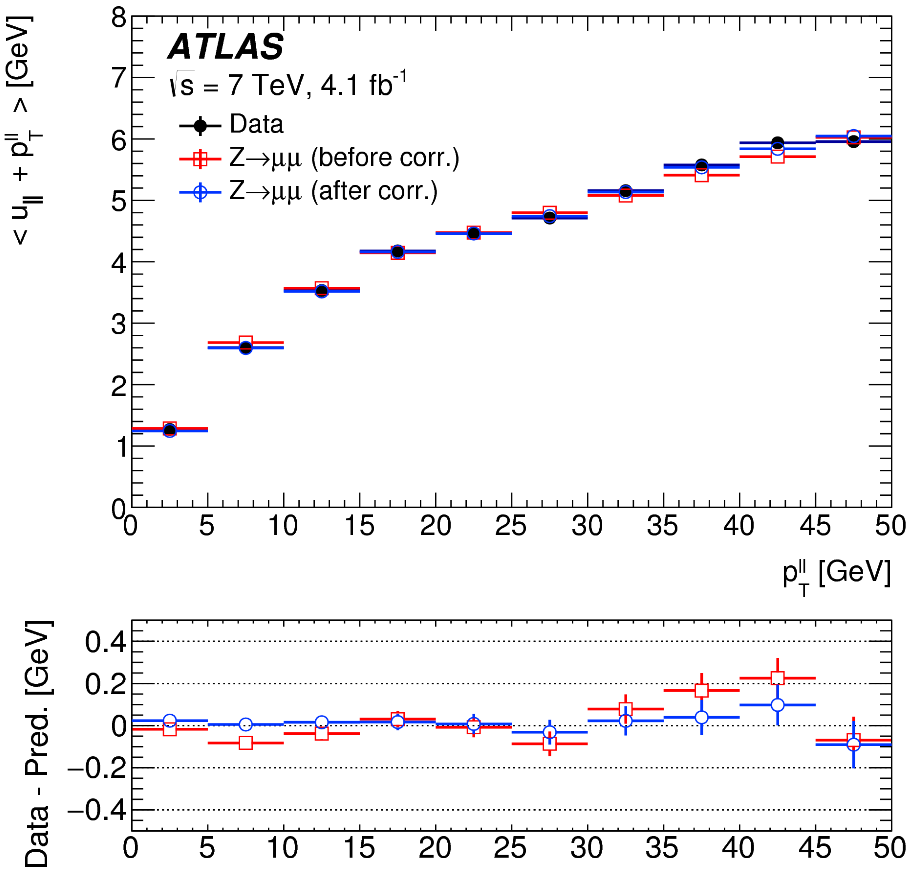


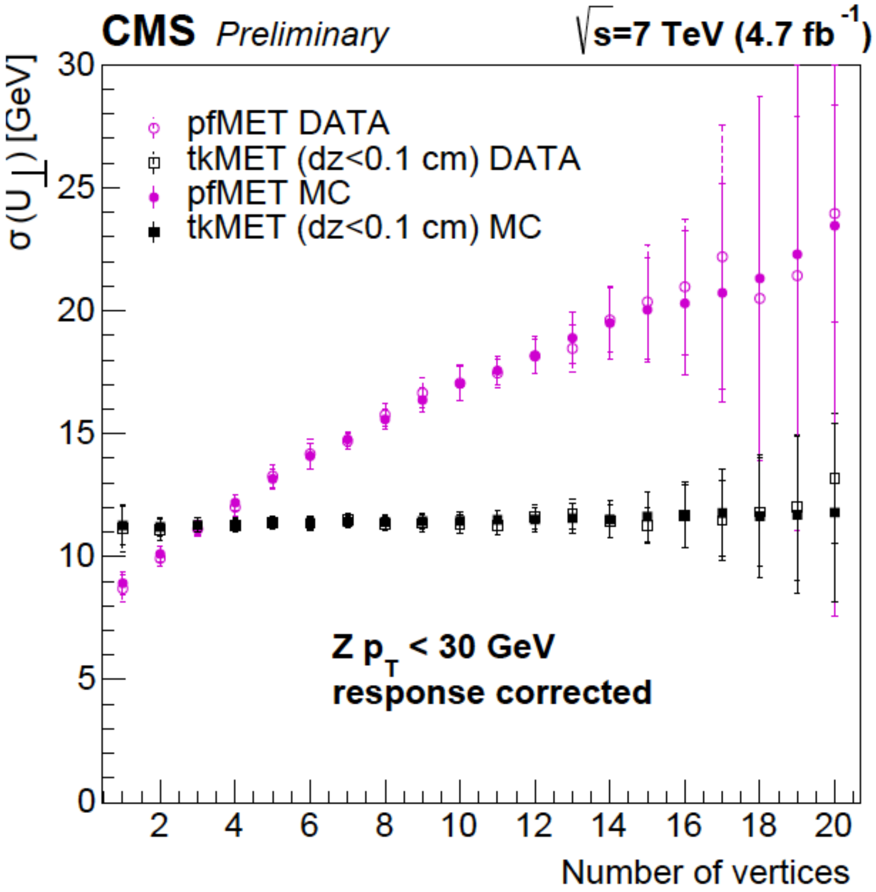
Also : $u_{||}^l$ is the projection of the recoil along the W decay lepton direction

Recoil Calibration

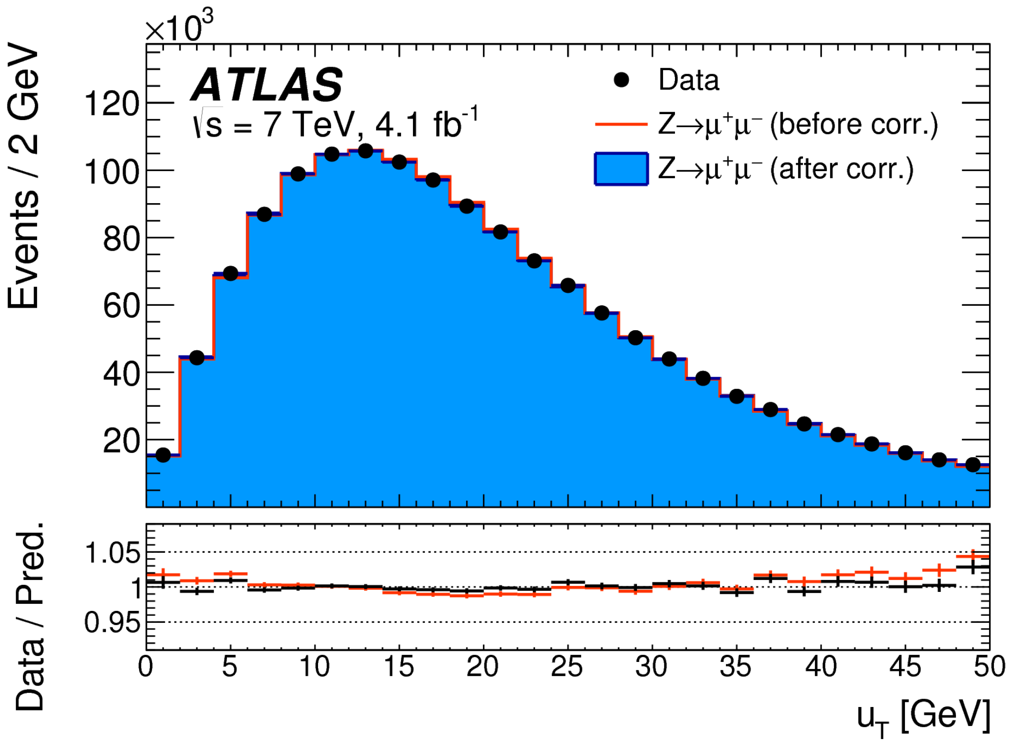
Calibrate the scale (resolution) of the recoil using $u_{||}$ ($u_{\perp}$) from Z events

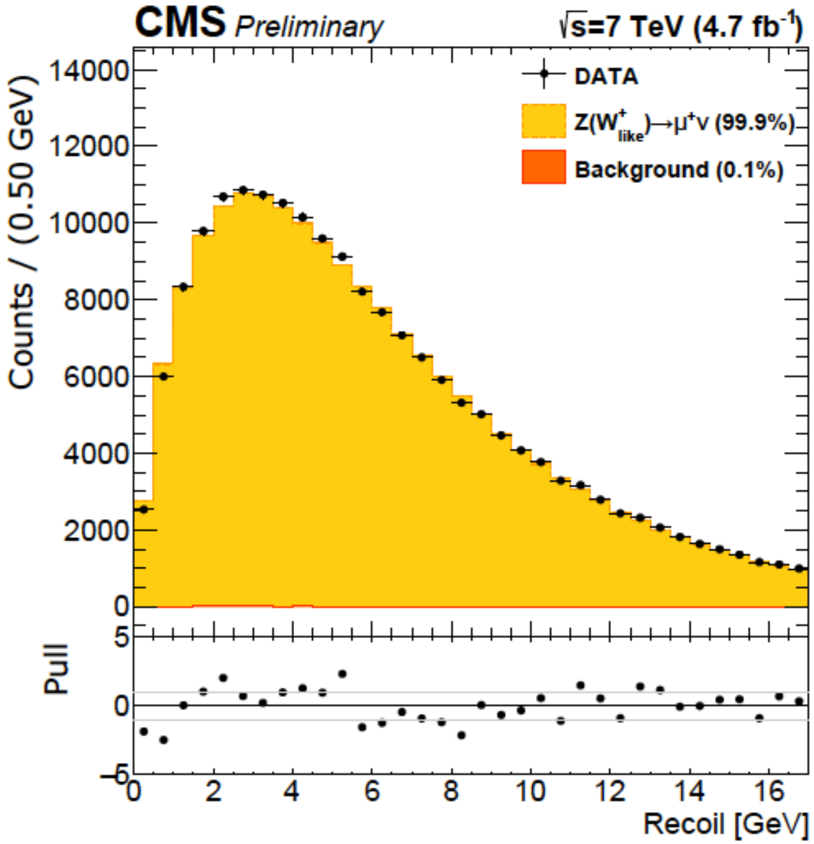
The pileup dependence of the recoil resolution in CMS (track-based) is better than ATLAS (cluster-based) but the use of the charged-only particles in the reconstruction leads to a loss in the response *(~40% in CMS vs 70-80% in ATLAS)*





Recoil Calibration



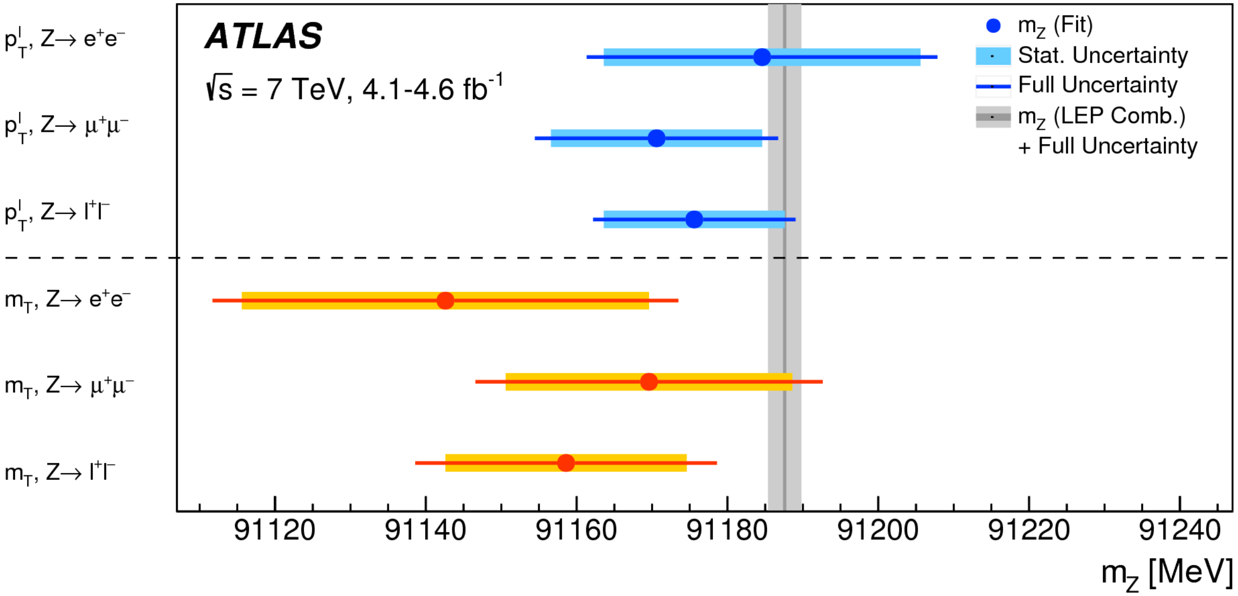


ATLAS

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

Cross check with Z events

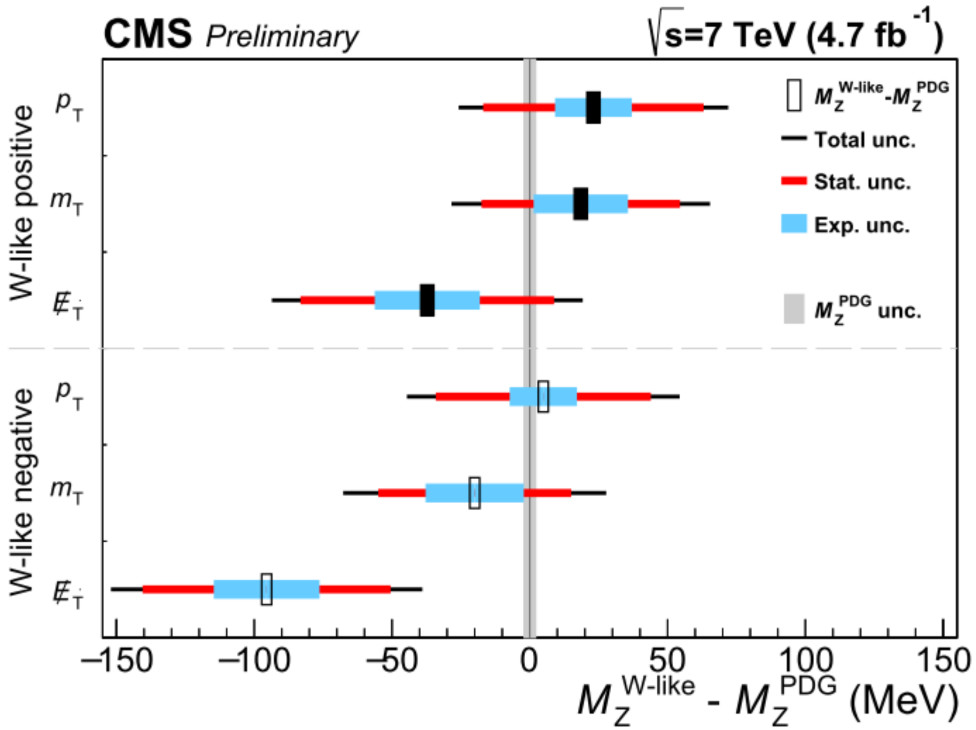
Results are consistent with the combined LEP value of m_Z within experimental uncertainties



Lepton charge Distribution	Combined p_T^ℓ	Combined m_T
Δm_Z [MeV]		
$Z \to ee$	$-3 \pm 21 \pm 10$	$-45 \pm 27 \pm 15$
$Z \to \mu\mu$	$-17 \pm 14 \pm 8$	$-18 \pm 19 \pm 13$
Combined	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

CMS PAS SMP-14-007

Sources of uncertainty	$M_Z^{\mathrm{Wlike}+}$ p_T	$M_Z^{\mathrm{Wlike}+}$ m_T	$M_Z^{\mathrm{Wlike}+}$ $\not{E}_T$	$M_Z^{\mathrm{Wlike}-}$ p_T	$M_Z^{\mathrm{Wlike}-}$ m_T	$M_Z^{\mathrm{Wlike}-}$ $\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Statistics of the data sample	40	36	46	39	35	45



Physics Modelling

No single generator able to describe all observed distributions.

Start from the Powheg+Pythia8 and apply corrections. Use ancillary measurements of Drell-Yan processes to validate (and tune) the model and assess systematic uncertainties.

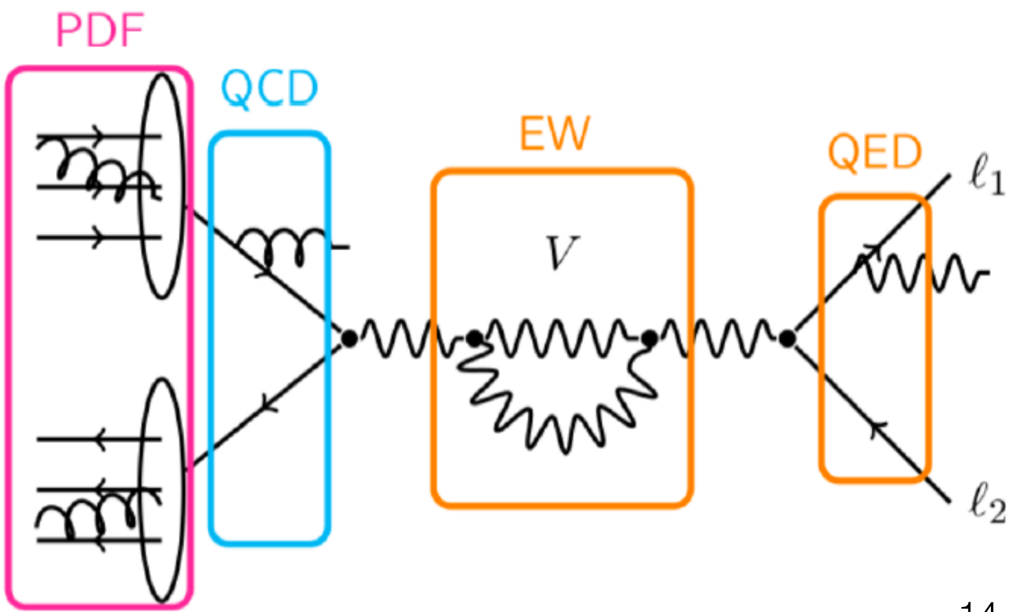
Physics modelling corrections

Electroweak corrections

- *QED FSR and ISR (included)*
- *missing higher order effects and FSR pair production (uncertainties)*

QCD corrections

- *pT distribution*
- *polarisation*
- *rapidity*



QCD corrections

The Drell-Yan cross-section can be decomposed by factorising the dynamic of the boson production and the kinematic of the boson decay. An approximate decomposition is given by:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

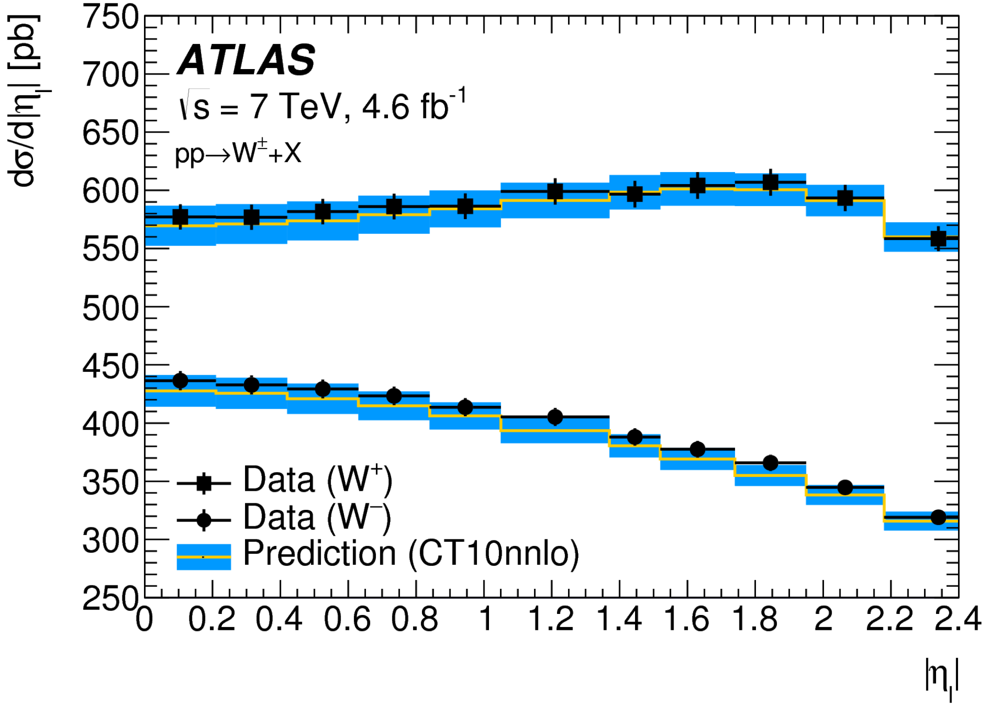
NNLO pQCD

Parton Shower

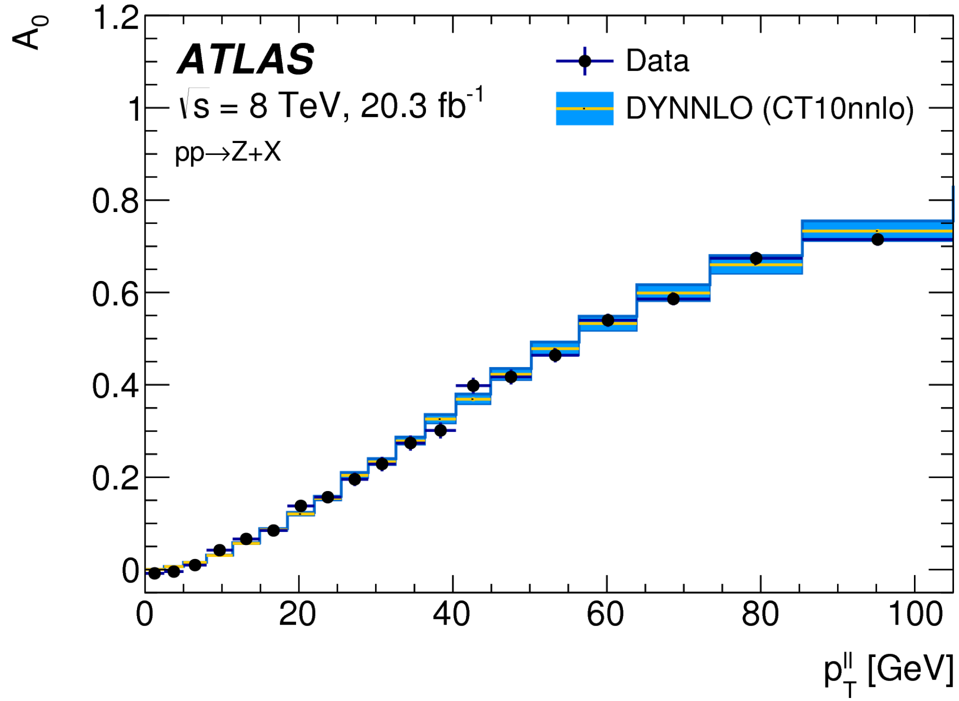
dσ/dm is modelled with a BW parameterisation (+ EW corrections)
dσ/dy and the Ai coefficients are modelled with fixed order pQCD at NNLO
$d\sigma/dp_T$ is modelled with parton shower (tried analytic resummation)

Rapidity and angular coefficients

The rapidity distribution and Ai coefficients are modelled with NNLO predictions and the CT10nnlo PDF set. PDF choice validated on the observed weaker suppression of the strange quark in the W,Z cross-section data as published in arXiv:1612.03016



Satisfactory agreement between the theoretical prediction and the measurements is observed: $\chi^2/\text{dof} = 45/34$



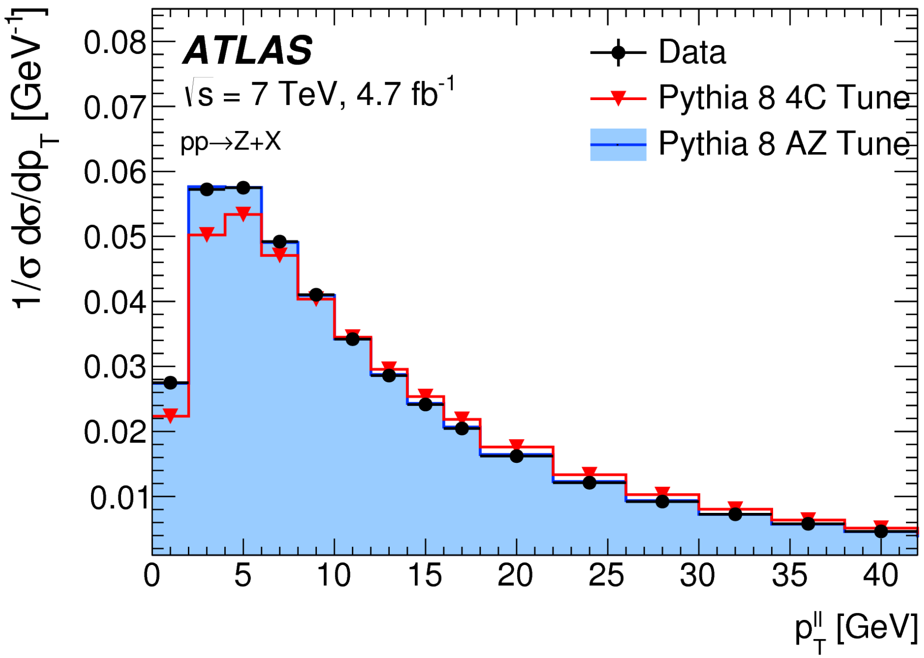
The predictions (DYNNLO) are validated by comparison to the Ai measurements in 8 TeV Z-boson data JHEP08(2016)159

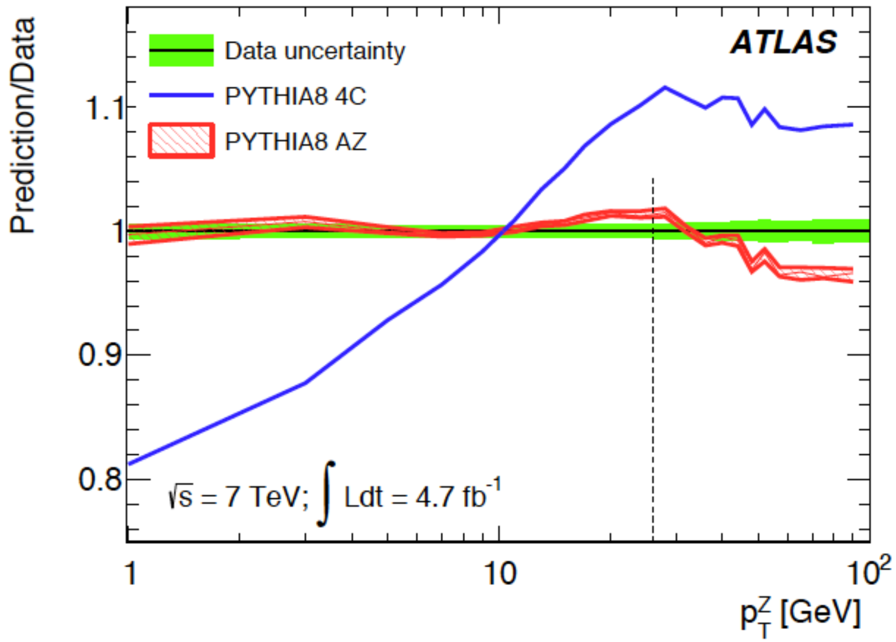
Z transverse momentum

Parton shower MC Pythia 8 tuned to the 7 TeV data AZ tune (better description in rapidity bins than the AZNLO tune of Powheg+Pythia) JHEP09(2014)145

	PYTHIA8
Tune Name	AZ
Primordial k_T [GeV]	1.71 ± 0.03
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002
ISR cut-off [GeV]	0.59 ± 0.08
χ^2_{min}/dof	45.4/32

The agreement between data and Pythia AZ is better than 1% for p_T<40 GeV



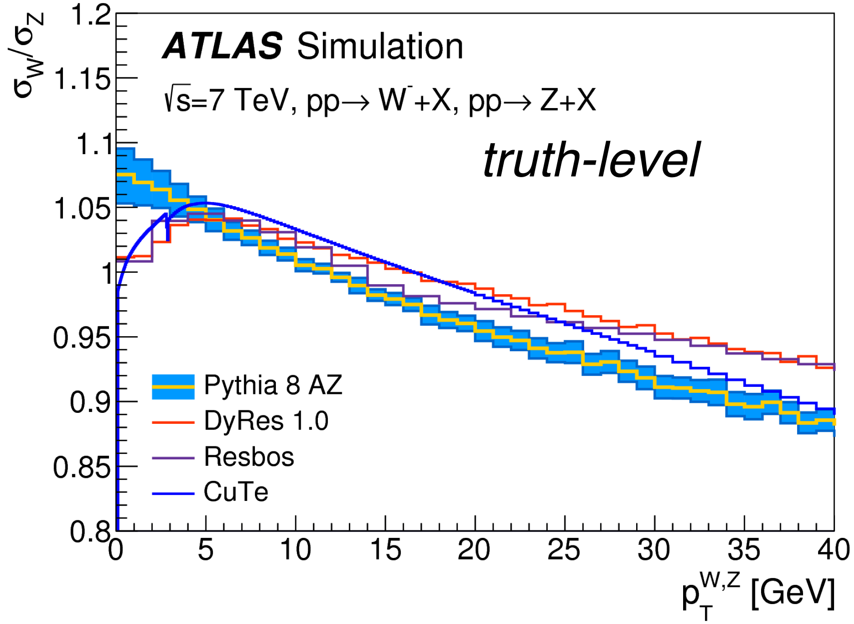


The accuracy of Z data is propagated and considered as an uncertainty

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4

W transverse momentum

The Pythia8 AZ tune is fixed by the p_T^Z data; extrapolate to W considering relative variations of the W and Z p_T distributions under uncertainty variations.

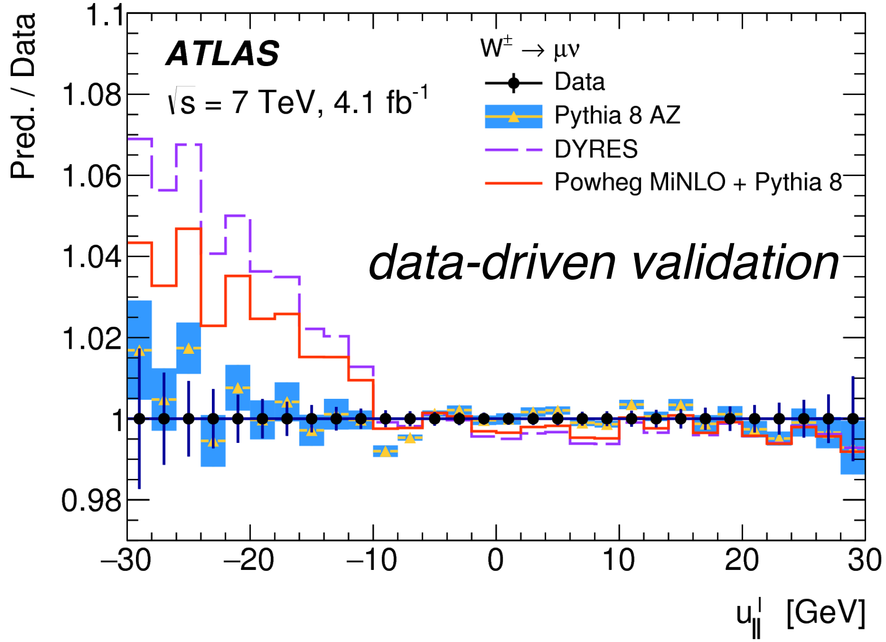


Resummed predictions (DYRES, ResBos, CuTe) and Powheg MiNLO+Pythia8 were tried but they predict a harder W p_T spectrum for a given p_T^Z spectrum

Phys.Rev.D 50 (1994) R4239, Phys.Rev.D 56 (1997) 5558-5583, JHEP12 (2015) 047, JHEP03 (2011) 032, JHEP10 (2012) 155, JHEP05 (2013) 082…

To validate the choice of Pythia8 AZ for the baseline, use $u_{||}^l$ distribution which is very sensitive to the underlying p_T^W distribution

NNLL resummed predictions and Powheg+MiNLO strongly disfavoured by the data however PS MC are in a good agreement; tested using Pythia8 , Herwig7 and Powheg+Pythia8



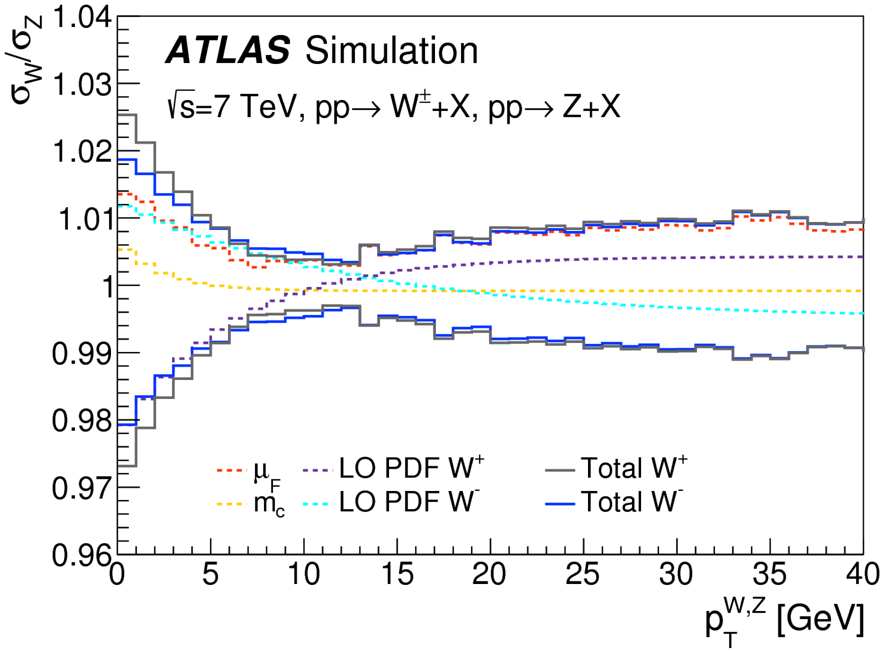
p_T^W uncertainties

Heavy flavour initiated production (HFI) introduces differences between Z and W and determines a harder pT spectrum, expect certain degree of decorrelation.

However higher-order QCD expected to be largely correlated between W and Z produced by light quarks

Uncertainty: heavy quark mass variations *(varying m_c by ±0.5 GeV),* factorisation scale variations in the QCD ISR *(separately for light and heavy-quark induced production)*

Largest deviation of $p_T(W)/p_T(Z)$ for the parton shower PDF variation: CTEQ6L1 LO (nominal) to CT14lo, MMHT2014lo and NNPDF2.3lo



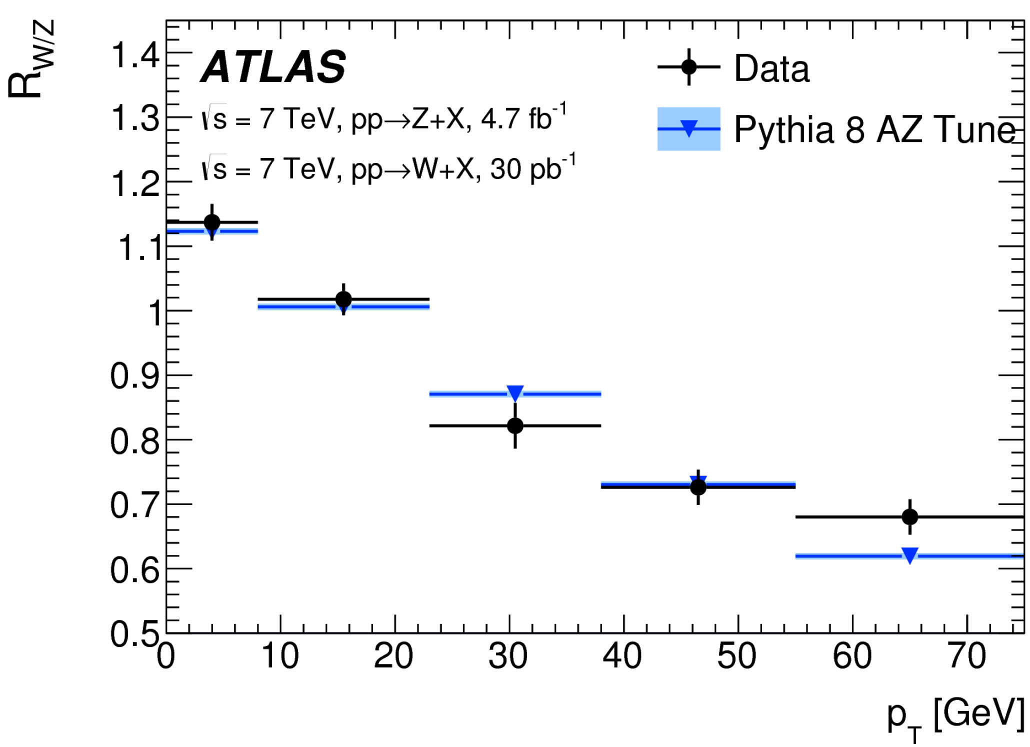
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6

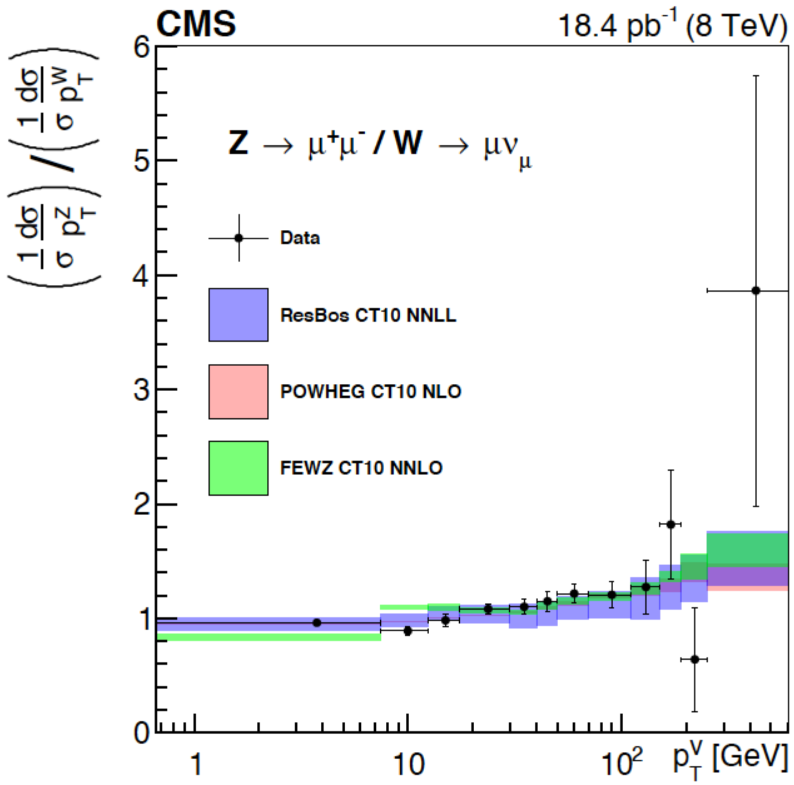
Reducing p_T^W uncertainties

The ratio of the W and Z pT distributions has been measured by ATLAS and CMS

JHEP 02 (2017) 096

Phys. Rev. D 85, 012005 arXiv:1701.07240





Limited precision of the data (~3%), and broad bin width (~8 GeV) limit the impact of these measurements on the systematic uncertainty.

Further measurements would be useful, ideally with low pile-up, targeting bin width <5 GeV and a precision about ~1%.

Summary of physics modelling uncertainties

QCD

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

EW

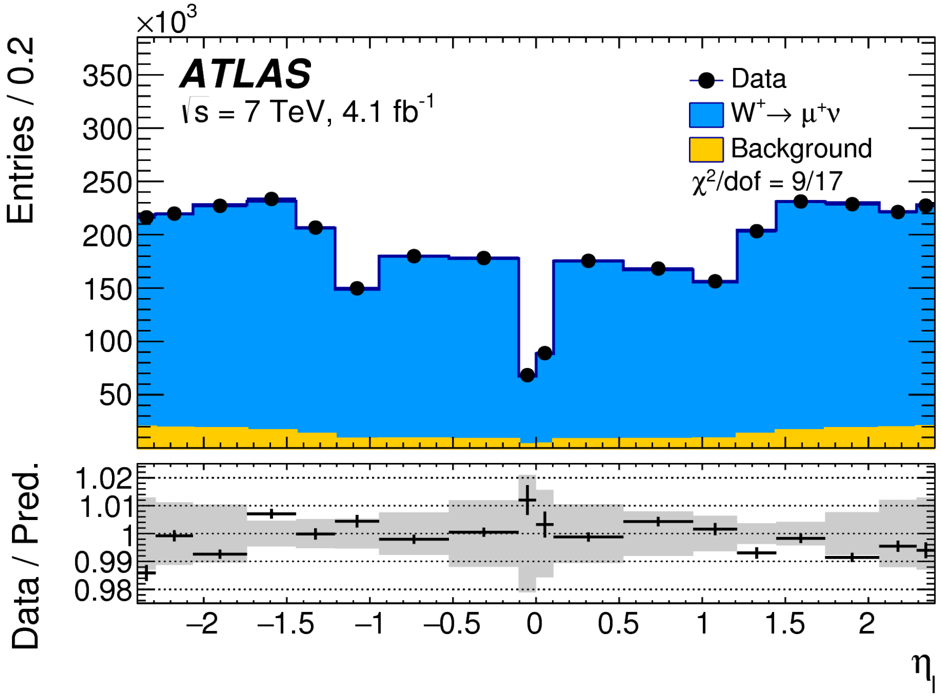
Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

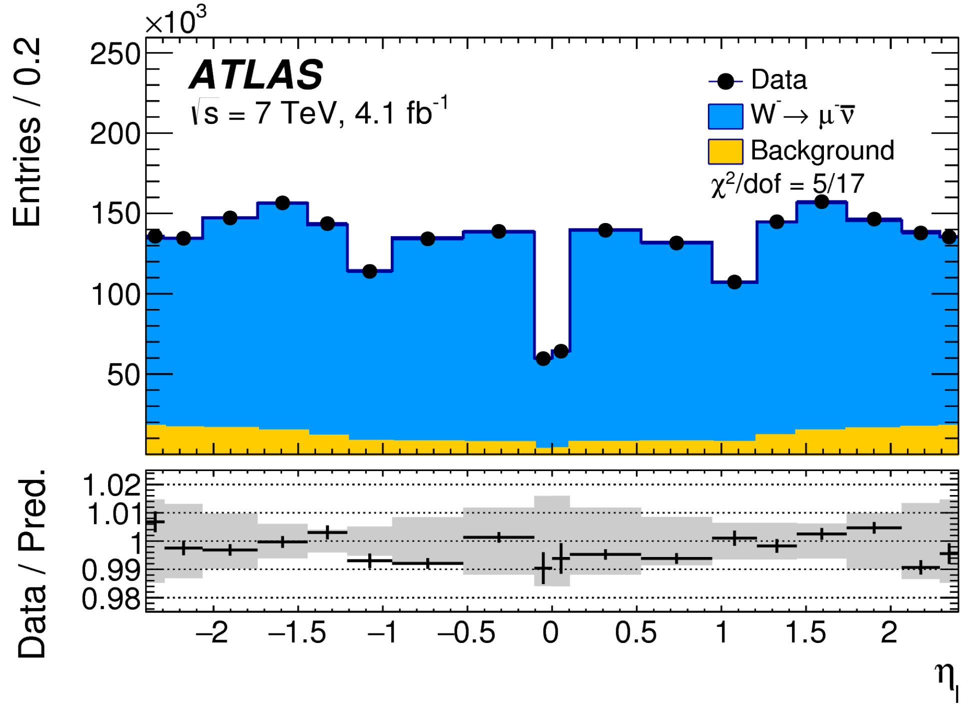
Fixed-order PDF uncertainties are dominant:

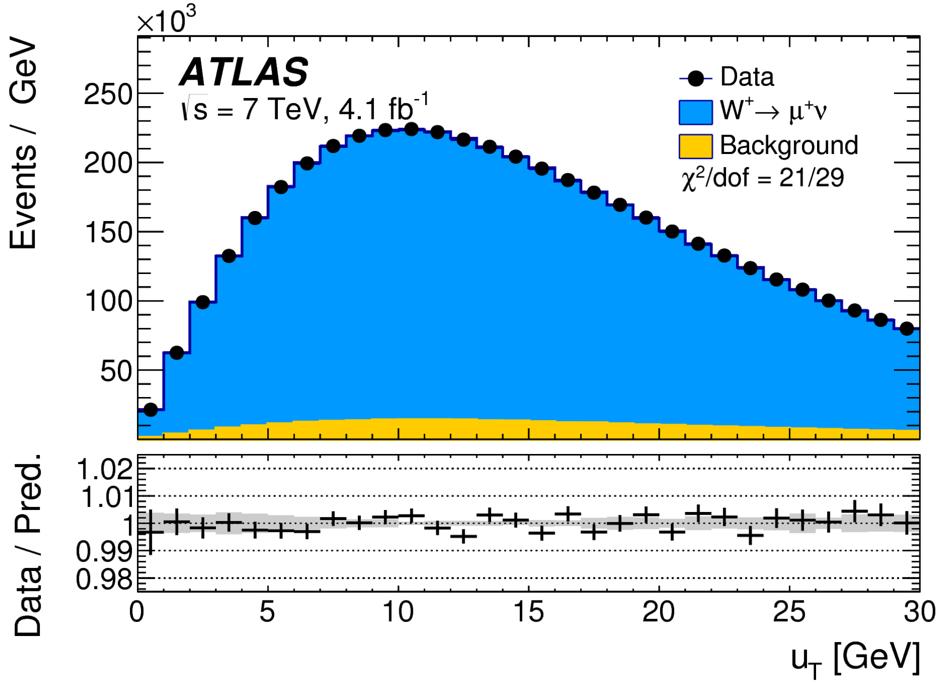
- PDF variations *(25 error eigenvectors)* of CT10nnlo applied simultaneously to the boson rapidity, Ai, and p_T distributions.
- Envelope taken from CT14 and MMHT2014~3.8 MeV

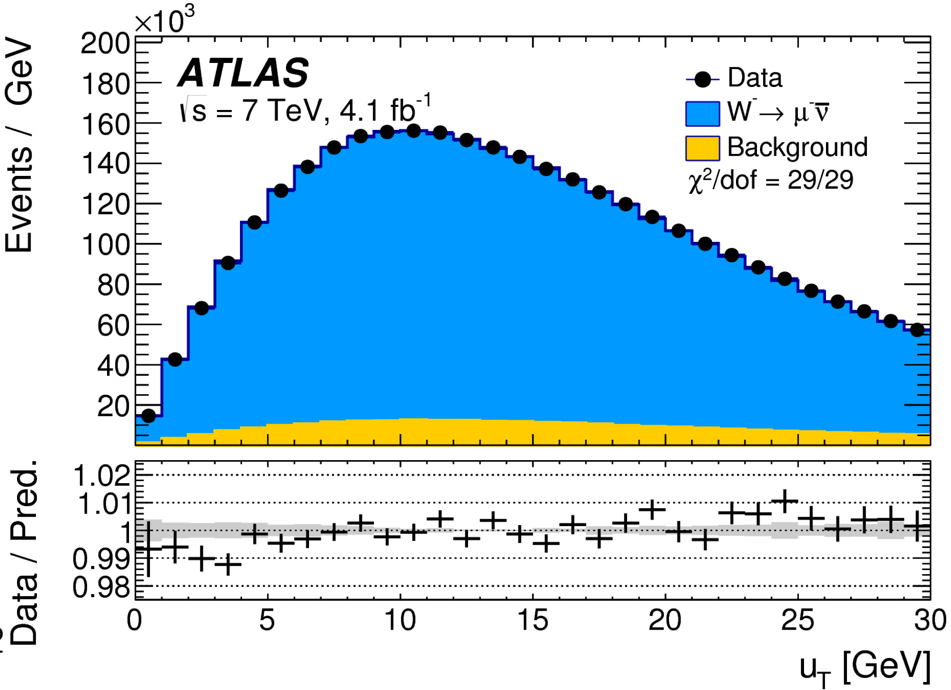
The PDF uncertainties very similar between p_T^l and m_T but strongly anti-correlated between W^+ and W^-

W control distributions: η, p_T

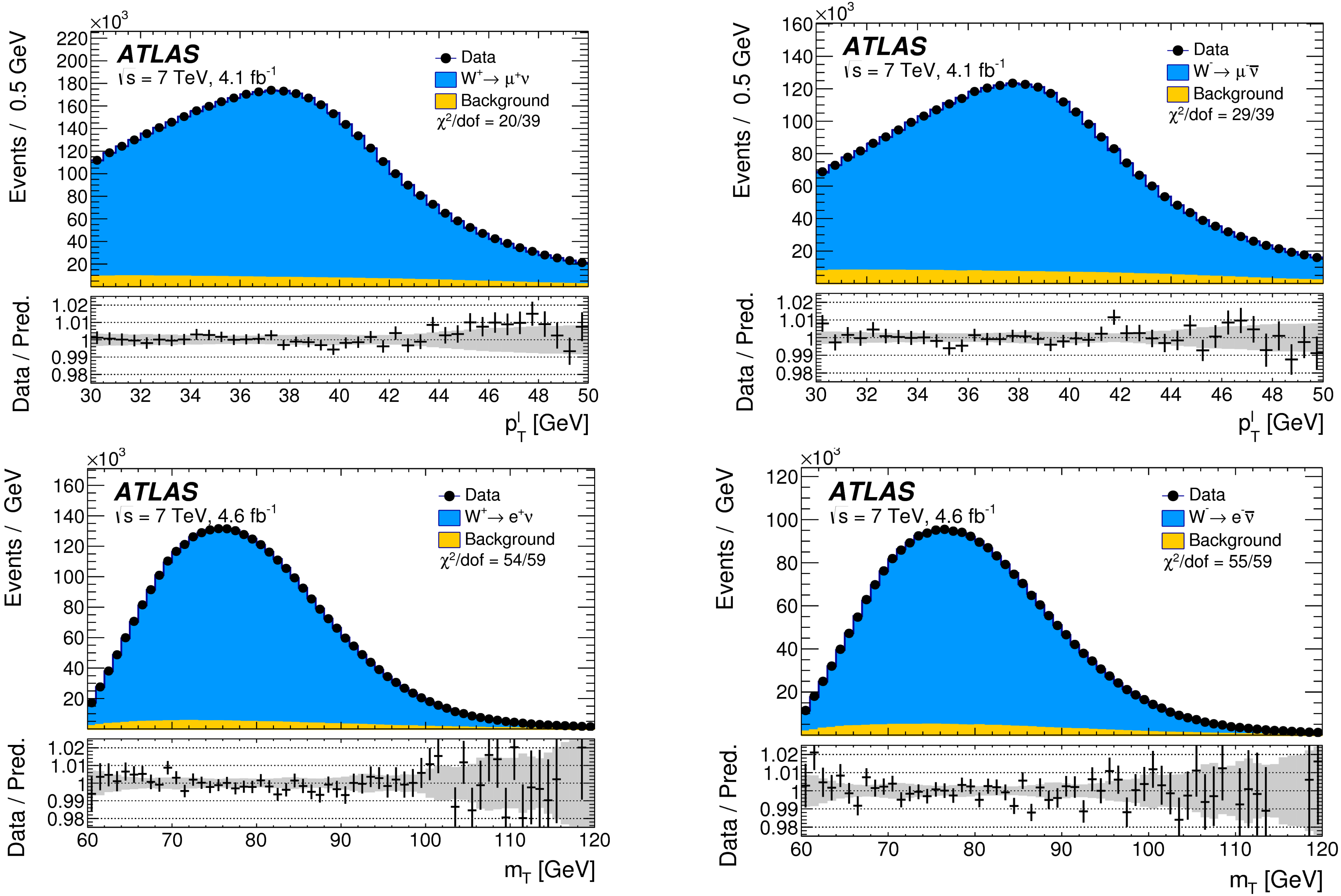






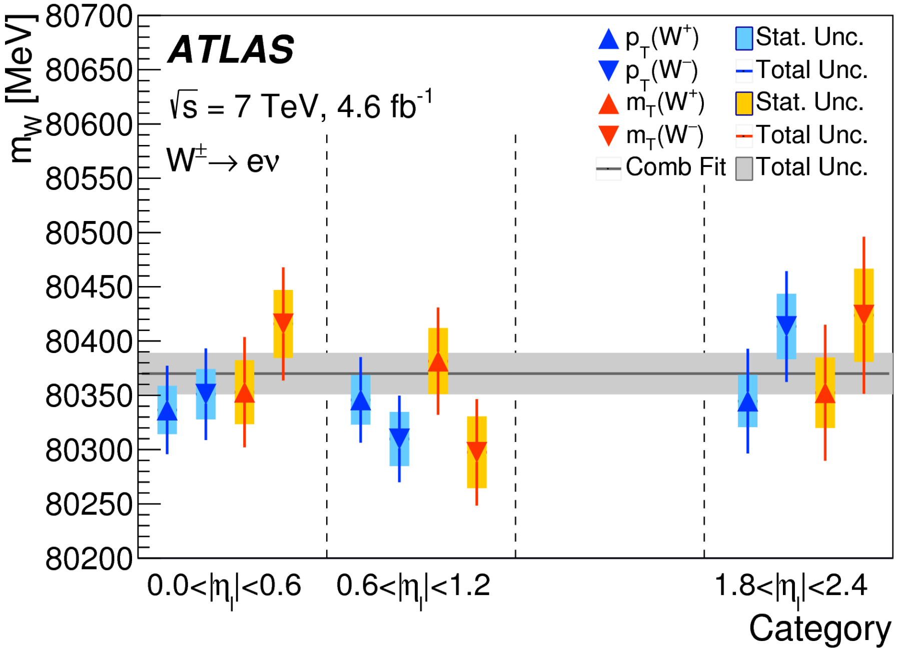


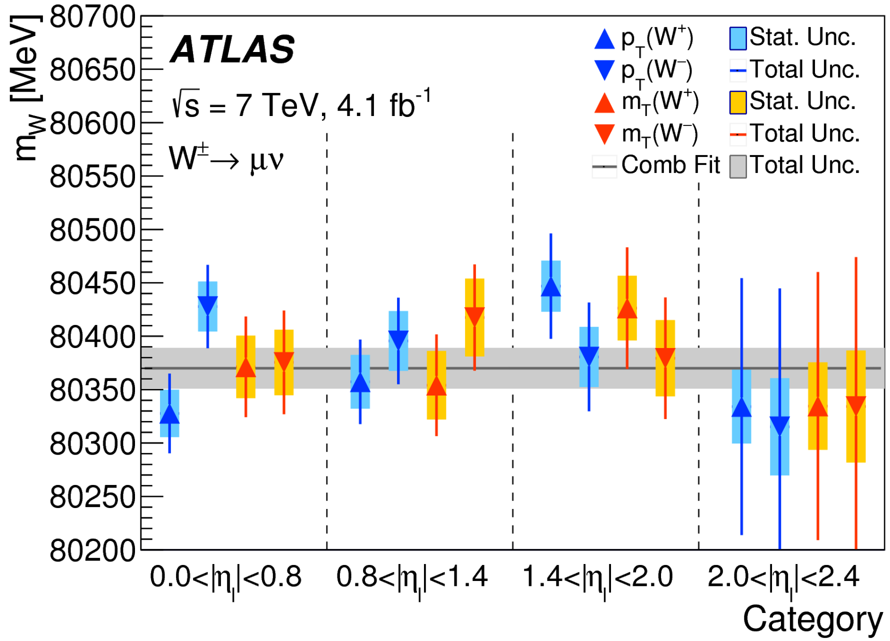
W mass-sensitive distributions: p_T^l and m_T

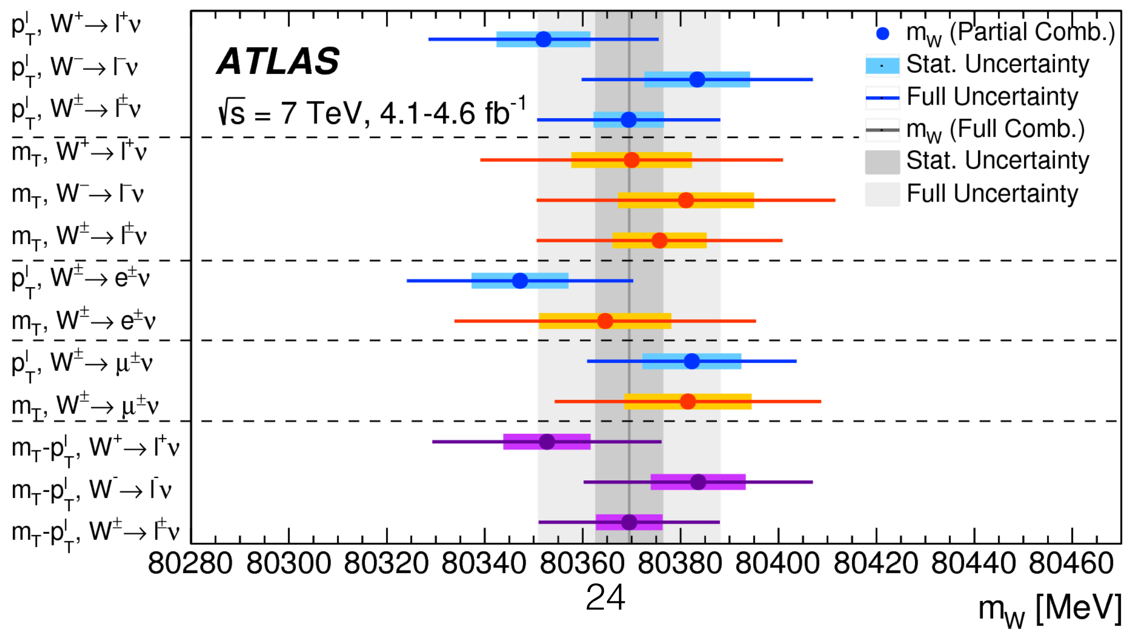


Consistency of the results

The consistency of the results was checked in the different categories but also in different pileup, u_T and $u_{//}$ bins





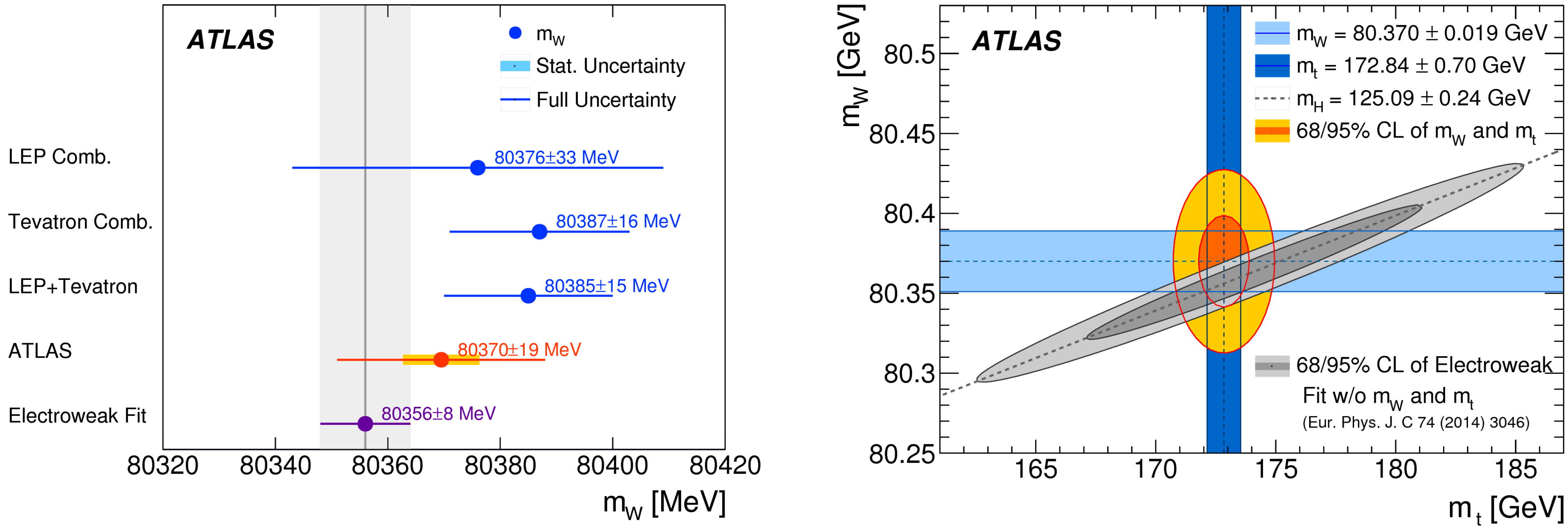


Fitting ranges:
$32<p_T^l<45$ GeV,
$66<m_T<99$ GeV

Results

$$m_W = 80369.5 \pm 6.8\,\text{MeV}(\text{stat.}) \pm 10.6\,\text{MeV}(\text{exp. syst.}) \pm 13.6\,\text{MeV}(\text{mod. syst.})$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27



The result is consistent with the SM expectation, compatible with the world average and competitive in precision to the currently leading measurements by CDF and D0

Conclusions and Perspectives

The first LHC measurement of mW = 80370+/-19 MeV is public now arXiv: 1701.07240v1 after many years of effort in the ATLAS collaboration.

The central value is consistent with the SM prediction and with the current world average value.

The uncertainty is dominated by theoretical modelling uncertainties, therefore more work in this direction is required and *a fully consistent model within one simulation tool* is needed.

The W mass measurement in CMS is ongoing. A first W-like measurement of the Z mass was shown.

More data are available with the 8 and 13 TeV datasets which can be used to improve the analysis and to further constrain the PDFs.

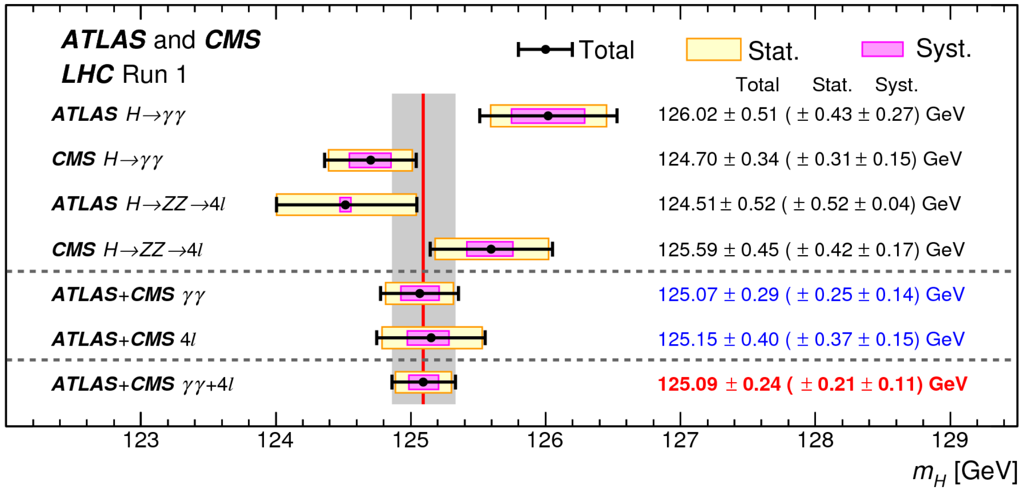
Experimentally, with the increase of the statistics in Z sample, most of the calibration uncertainties can be reduced. While more work is needed on the recoil with the increasing pileup.

Backup Sides

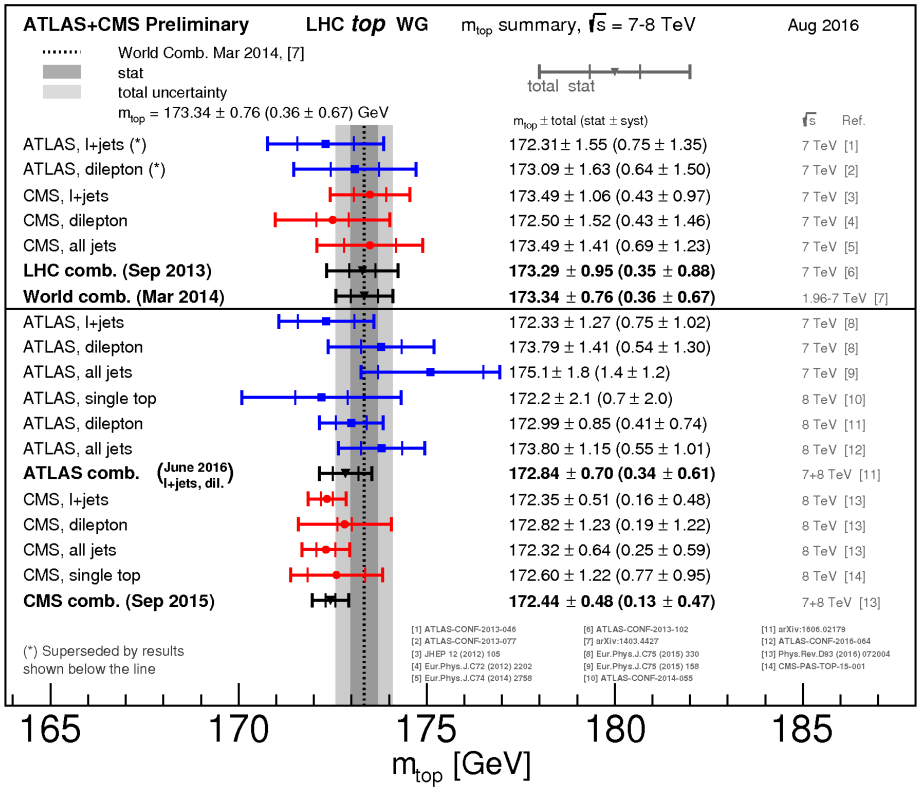
Status of the measurements

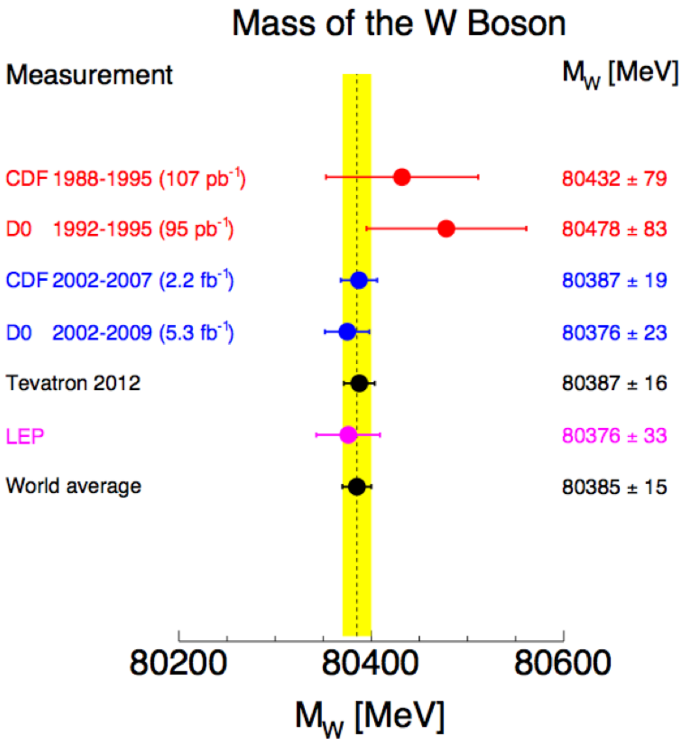
Higgs mass

[Phys. Rev. Lett. 114, 191803](#)



Top mass



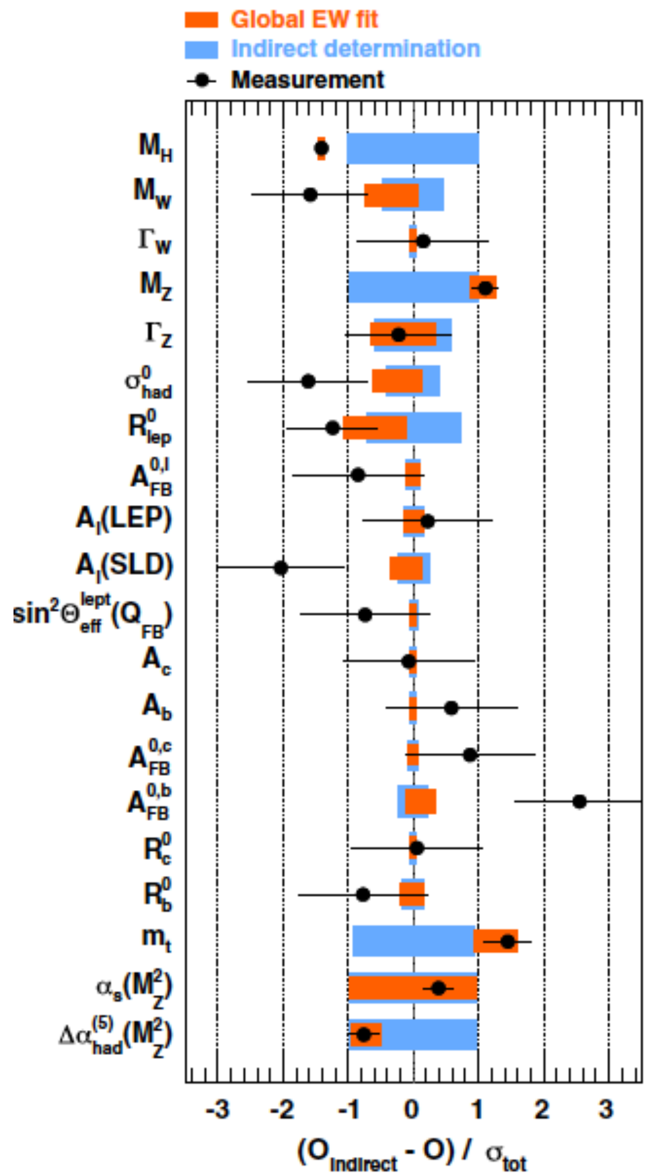


W mass uncertainty

LEP+Tevatron ~15 MeV

Best individual measurement:
CDF 19 MeV

Electroweak fit

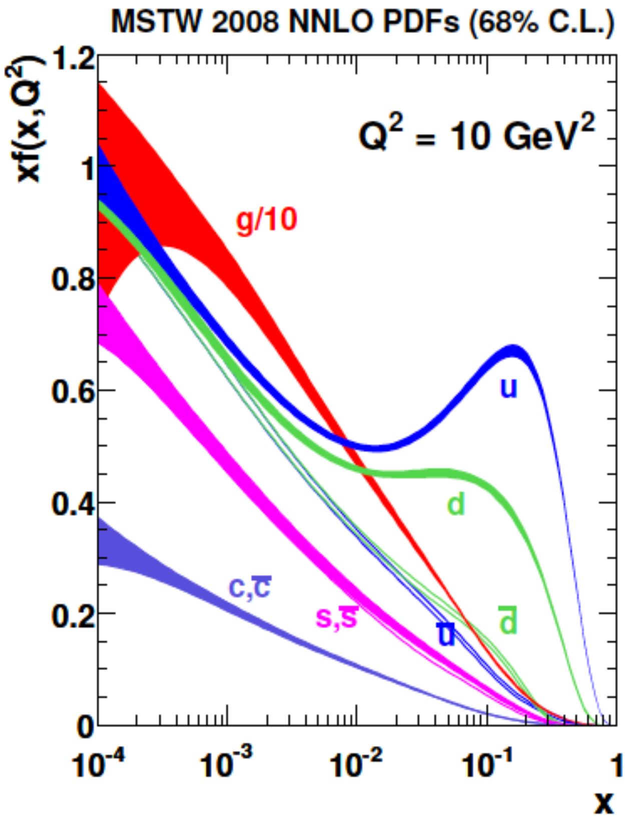


$$
\begin{aligned}
M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \\
&\quad \pm 0.0018_{\Delta\alpha_{\rm had}} \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \\
&\quad \pm 0.0040_{\delta_{\rm theo} M_W}\ \text{GeV}, \\
&= 80.358 \pm 0.008_{\rm tot}\ \text{GeV},
\end{aligned}
$$

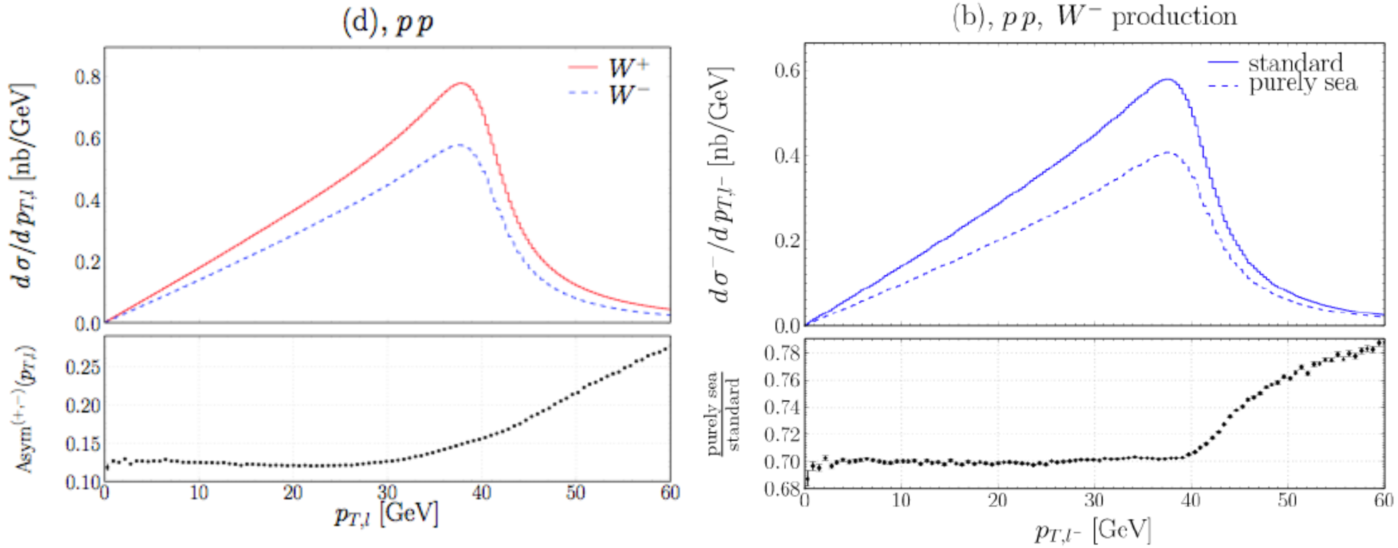
Parameter	$\delta_{\rm meas}$	$\delta^{\rm tot}_{\rm fit}$	$\delta^{\rm theo}_{\rm fit}$	$\delta^{\rm exp}_{\rm fit}$	Experimental uncertainty source [$\pm 1\sigma$]					
					δM_W	δM_Z	δm_t	$\delta \sin^2\theta^f_{\rm eff}$	$\delta\Delta\alpha_{\rm had}$	$\delta\alpha_S$
Present uncertainties										
M_H [GeV]	0.2	$^{+33}_{-27}$	$^{+10}_{-8}$	$^{+31}_{-26}$	$^{+28}_{-23}$	$^{+5}_{-4}$	$^{+10}_{-7}$	$^{+29}_{-23}$	$^{+7}_{-5}$	$^{+4}_{-3}$
M_W [MeV]	15	7.8	5.0	6.0	–	2.5	4.3	5.1	1.6	2.5
M_Z [MeV]	2.1	12.0	3.7	11.4	10.5	–	3.5	11.2	2.2	1.4
m_t [GeV]	0.8	2.5	0.6	2.4	2.3	0.4	–	2.3	0.5	0.6
$\sin^2\theta^\ell_{\rm eff}$ [a]	16	6.6	4.9	4.5	3.7	1.2	2.0	–	3.4	1.2
$\Delta\alpha_{\rm had}$ [a]	10	44	13	42	31	6	10	41	–	2
LHC prospects										
M_H [GeV]	< 0.1	$^{+21}_{-18}$	$^{+4}_{-3}$	$^{+20}_{-18}$	$^{+17}_{-14}$	$^{+6}_{-5}$	$^{+8}_{-7}$	$^{+18}_{-16}$	$^{+3}_{-2}$	$^{+5}_{-4}$
M_W [MeV]	8	5.5	1.8	5.2	–	2.5	3.5	4.8	0.8	2.6
M_Z [MeV]	2.1	7.2	1.4	7.0	6.0	–	2.8	5.9	0.8	1.9
m_t [GeV]	0.6	1.5	0.2	1.5	1.3	0.4	–	1.2	0.2	0.5
$\sin^2\theta^\ell_{\rm eff}$ [a]	16	3.0	1.1	2.8	2.5	1.1	1.4	–	1.5	0.9
$\Delta\alpha_{\rm had}$ [a]	4.7	36	6	36	25	9	12	35	–	5
ILC/GigaZ prospects										
M_H [GeV]	< 0.1	$^{+7.3}_{-6.9}$	$^{+2.5}_{-2.4}$	$^{+6.8}_{-6.5}$	$^{+2.5}_{-3.6}$	$^{+4.3}_{-4.0}$	$^{+0.3}_{-0.2}$	$^{+3.4}_{-2.9}$	$^{+4.3}_{-4.0}$	$^{+0.3}_{-0.3}$
M_W [MeV]	5	2.3	1.3	1.9	–	1.7	0.1	1.2	0.6	0.3
M_Z [MeV]	2.1	2.7	1.0	2.5	2.4	–	0.1	1.3	1.9	0.2
m_t [GeV]	0.1	0.8	0.2	0.7	0.6	0.5	–	0.3	0.4	0.2
$\sin^2\theta^\ell_{\rm eff}$ [a]	1.3	2.3	1.0	2.0	1.7	1.2	0.1	–	1.5	0.1
$\Delta\alpha_{\rm had}$ [a]	4.7	6.4	3.0	5.6	2.6	4.2	0.2	3.8	–	0.2

[a] In units of 10^{-5}

Valence vs sea quarks

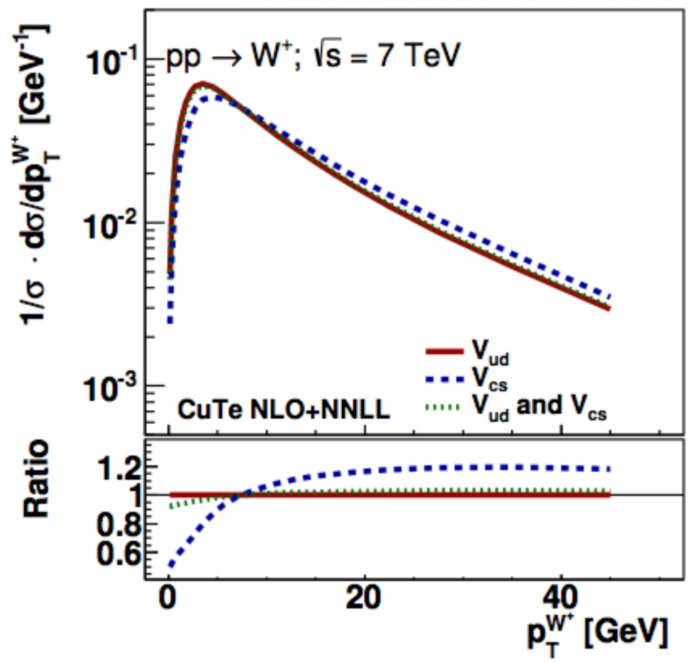


arXiv:1004.2597



The uncertainty in u and d valence and sea PDF —> an uncertainty in helicity axis of the W —> on p_T^l spectrum

ATL-PHYS-PUB-2014-015



Strange quark pdf uncertainty —> uncertainty on the relative fraction of charm-initiated W boson production —> uncertainty on $p_T(W)$

The amount of charm initiated W production will also alter the balance between valence quark and sea quark —> W polarisation —> p_T^l

Mass-sensitive distributions

In a traditional template fit analysis, Mw can be extracted from:

➢ Lepton transverse momentum: p_T^l

- insensitive to recoil
- sensitive to pTW modelling, higher order QCD, PDF, W polarisation, charm mass

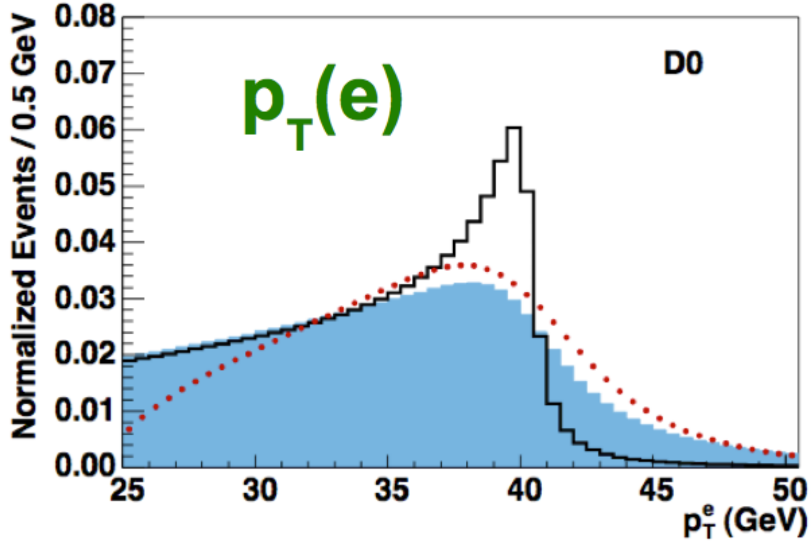
➢ Neutrino transverse mass p_T^ν

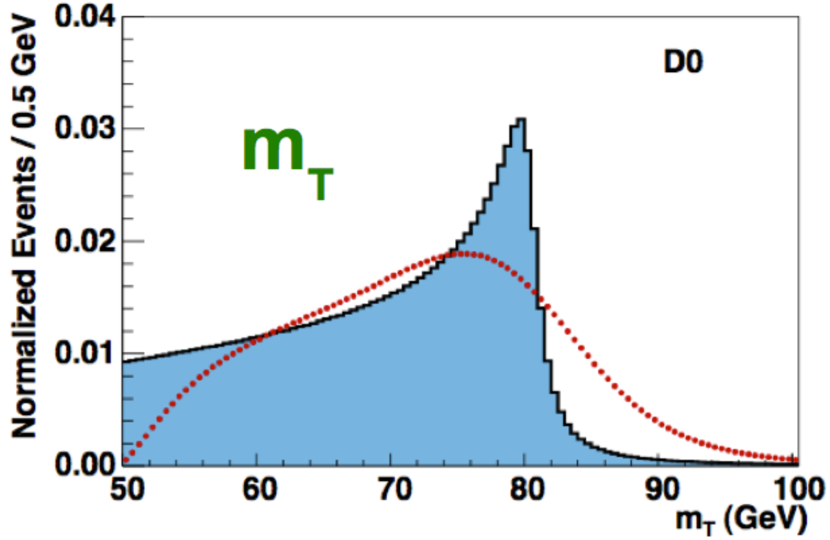
$$\vec{p}_T^{\,\nu} = -(\vec{p}_T^{\,l} + \vec{u})$$

u: the recoil measured as the sum of the energies in topoclusters excluding the lepton itself -->sensitive to pile-up, UE

➢ W transverse mass $m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi(l,\nu))}$

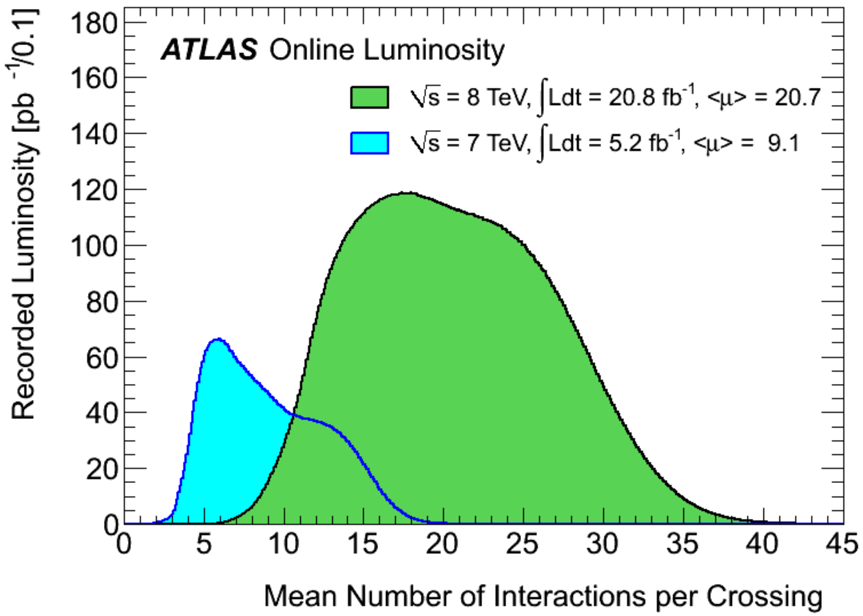
- low sensitivity to pTW, smaller pdf uncertainties
- smaller non-pQCD uncertainties
- Recoil modelling crucial, sensitivity to pile-up, UE





ATLAS selection

Data Run I in 2011:
centre-of-mass energy: **7 TeV**
4.6 fb^{-1} for the electron channel
4.1 fb^{-1} for the muon channel
(part of the data discarded due to timing problem in the resistive plate chambers)
bunch spacing: 50 ns



Lepton selections:

- muons isolated (track-based) $|\eta|<2.4$
- electrons isolated (track+calorimeter-based) tight identified $0<|\eta|<1.2$, $1.8<|\eta|<2.4$

Kinematic requirements: $p_T^l>30$ GeV, $m_T>60$ GeV, MET>30 GeV and recoil(u_T)<30 GeV
~6M/8M observed in the electron/muon channel

$\|\eta_\ell\|$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

Z selection: pTl>25 GeV 80<mll<100 GeV 0.58 M (1.23 M) e/mu channels

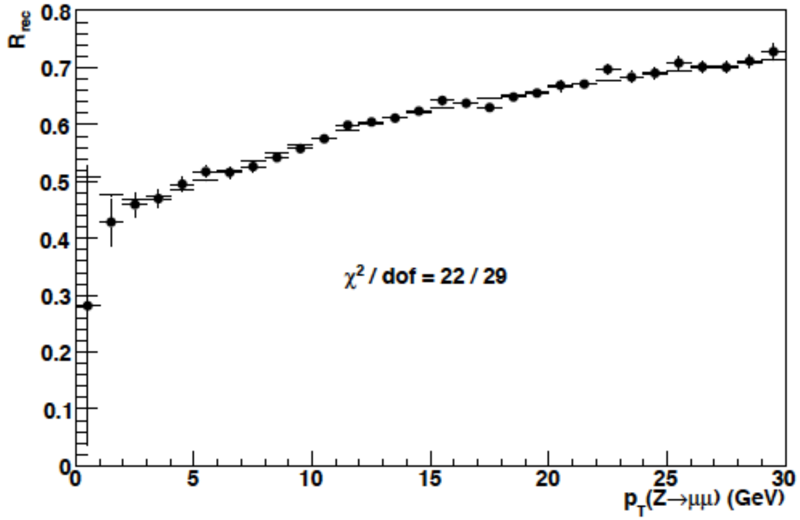
CDF&D0

qq-bar-->W+X, W-->lv

RESBOS used to model pTZ/W (NNLO+NNLL no decay) Fit non-pQCD parameters to pTZ data.
Use of CTEQ6.6 PDF
Use PHOTOS to simulate FSR

Experiment	CDF	D0
Luminosity	2.2fb-1	4.3 fb-1
Channels	W-->eν, W-->μν	W→eν
p(E)-scale	J/psi, Y	Z-->ee
Detector	tracker	calorimeter
Result MW	80387+/12(stat) +/-15(syst) MeV	80375+/-11(stat)+/-20(syst) MeV

CDF



$$M_W = 80\,387 \pm 16 \text{ MeV}$$

CMS selection

2 OS isolated muons $M_{\mu\mu}$>50 GeV

d_{xy}<0.2cm (d_{xy}: distance of closest approach between the muon and the beam line in the transverse plane)

trigger: $|\eta|$<0.9, p_T>30 GeV while the other muon p_T>10 GeV and $|\eta|$<2.1

30<p_T<50 GeV, 30<MET<55 GeV, 60<m_T<100 GeV, u<15 GeV and p_T^Z<30 GeV

Z events with an even number: recoil calibration
Z events with an odd number: measurement

181 985/180 554 events in the positive/negative W-like events
(47% of the events are common among the 2 samples)

J/ψ and Υ(1S): trigger OS muon pair $|y_{\mu\mu}|$<1.25

J/ψ: 2.8<M<3.35 GeV, di-muon p_T>9.9 GeV

Υ(1S): 8.5<M<11.5 GeV, di-muon p_T>5 or 7 GeV

Muons high quality $|\eta|$<2.4, p_T>4 GeV and d_{xy}<0.2cm.

3.5 M (1M) J/ψ (Υ(1S))

Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	**NO**	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
μ momentum scale	✓ YES	✓ YES
μ tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	**NO**	✓ YES
Background to 1-l	**NO**	✓ YES

CMS muon calibration

Magnetic field: $A_1+A_2\eta^2$

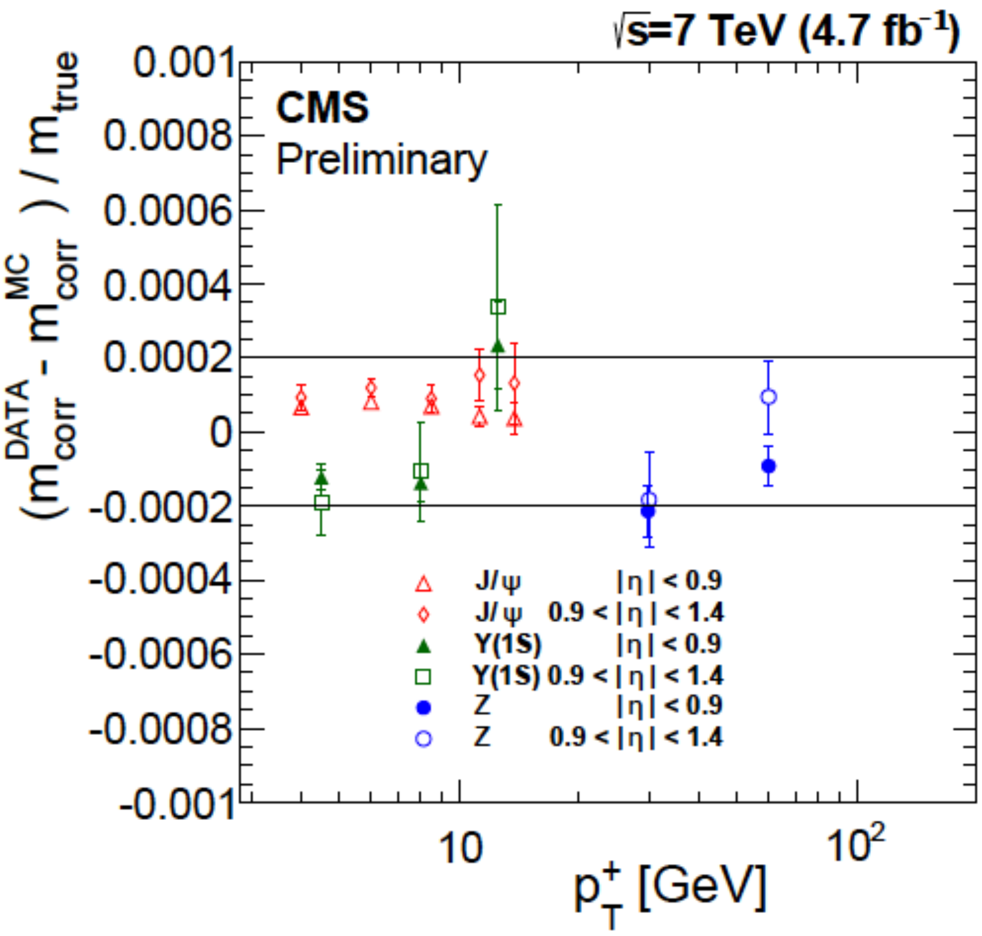
Energy loss: ε is derived in12 η bins

Misalignment: first terms of a Fourier series, in φ, in 6 η bins

Total number of parameters in the fitting model: 44

A differs from 1 by less than 0.0005; M less than 10^{-4} GeV^{-1} and ε is of the order of 4 MeV

For the resolution calibration: fit to J/ψ, correcting the resolution for multiple scattering and hit position effects in different bins of η —> 10% relative agreement between data and MC



CMS recoil calibration (I)

To measure the W boson mass 10-20 MeV, need recoil precision of 0.5%

$$\vec{E\!\!\!/}_T = -\vec{u}_T - \vec{p_T}^{\mu}$$

$m_T^2 = 2p_T E_T^{miss}(1 - cos(\Delta\phi))$

$m_W \sim 2p_T + h_{||}$

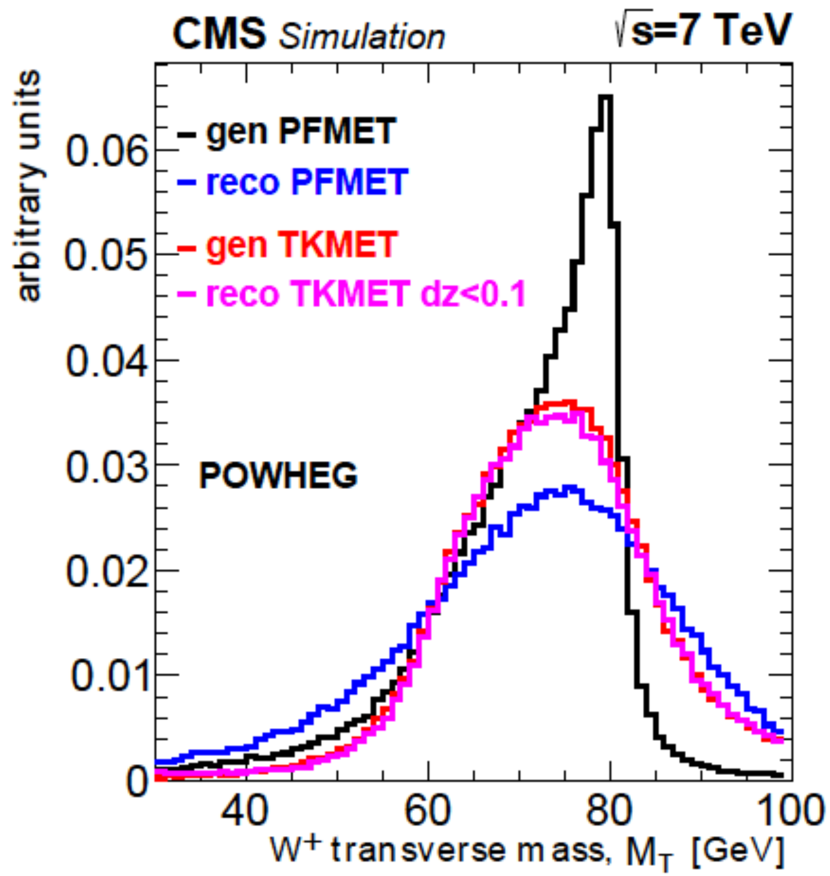
Where $h_{||}$ is the projection of the recoil on lepton axis

40 GeV	few GeV	←typical values
10^-4	10^-3	←target precision

$u_{||}$ should be proportional to the boson p_T, proportionality coefficient depending on the MET definition. $u_{\perp}$ is expected to be distributed around 0.

The optimal MET choice (tkMET):
all reco charged tracks compatible with the PV, dz(track,PV)<0.1cm, $|\eta|<2.4$

retains only 40% of the hadronic recoil ($\langle u_{||}\rangle/p_T^Z$) probed with pfMET (all stable particules within $|\eta|<5$) but has the advantage of better data/MC agreement and of being essentially insensitive to pileup.



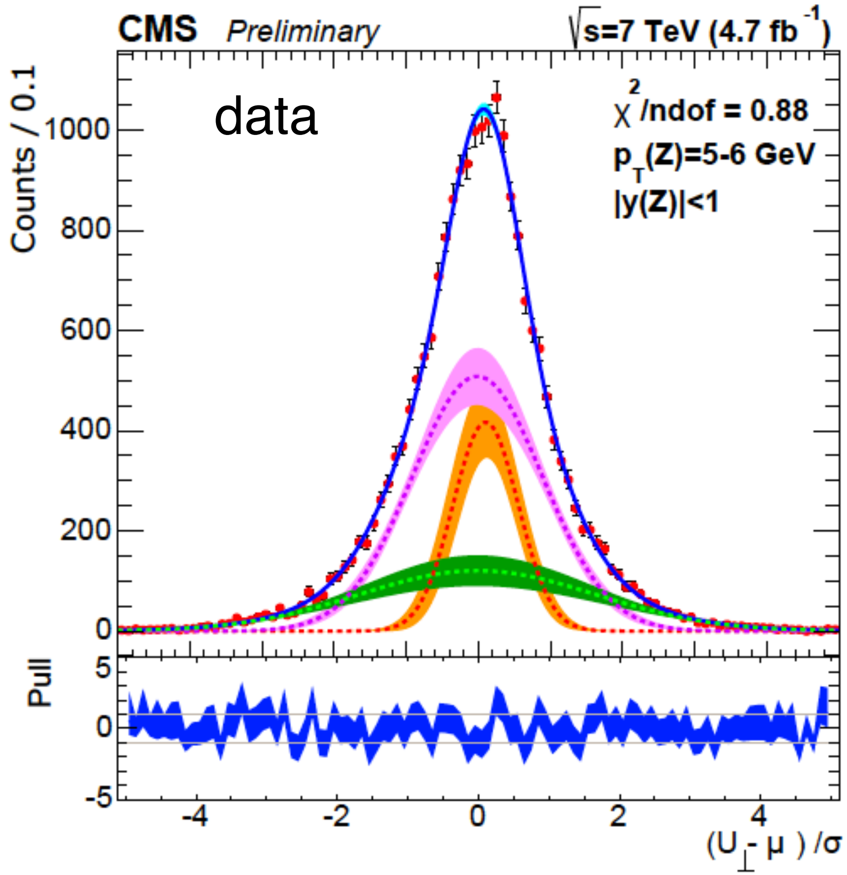
CMS recoil calibration (II)

Recoil calibration is performed in bins of boson rapidity (to minimise the systematic uncertainties from PDF and polarisation when applying the calibration to W events.

The recoil projection distributions are modelled by a sum of 3 Gaussians, whose parameters are polynomial functions of p_T^Z.

The models (from data and MC) are used to derive corrections using probability integral transforms of the models for the source (MC) and target distributions.

The projections are defined wrt the axis in the transverse plane: direction of p_T^Z.



CMS mass fits and systematic uncertainties

Fitting ranges p_T^l: 32-45 GeV, m_T: 65-100 GeV. Binned-template likelihood-ratio

Table 1: Correlation between the W-like fitting variables.

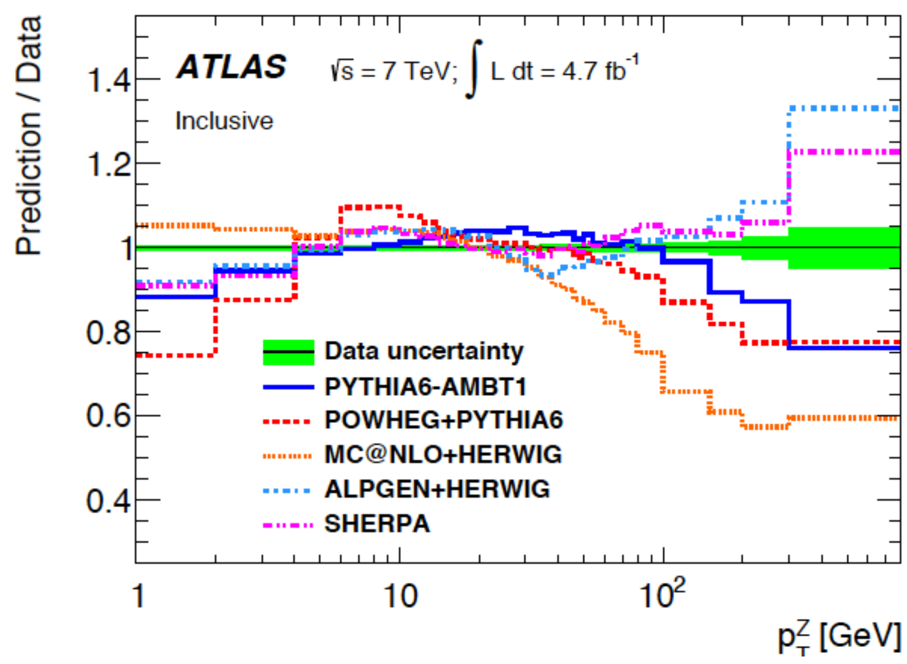
Variable	1	2	3
1. Lepton transverse momentum (p_T)	1.00		
2. Transverse mass (m_T)	0.67	1.00	
3. Missing transverse energy ($\not{E}_T$)	0.34	0.70	1.00

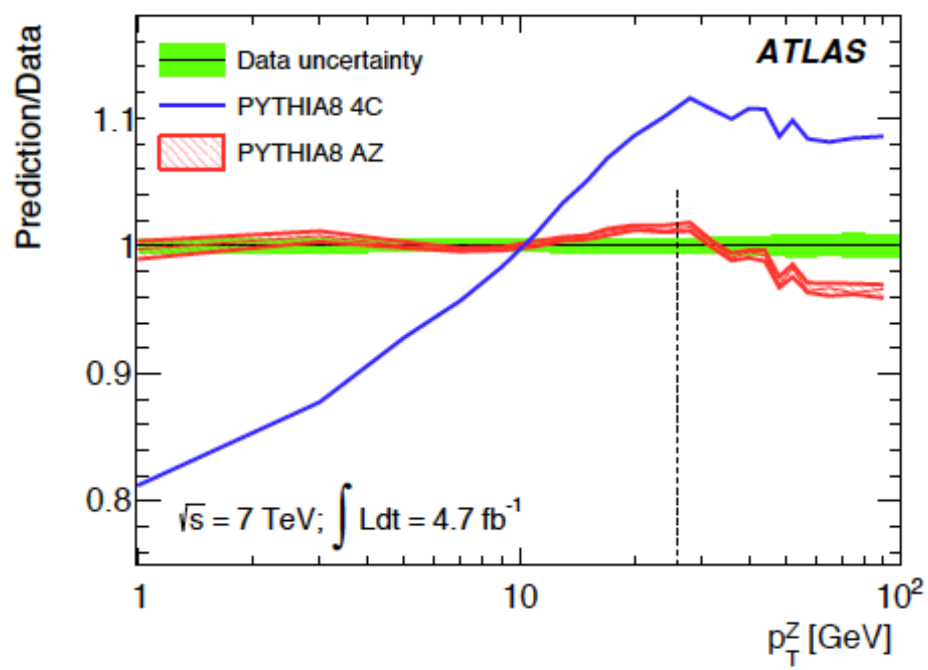
jackknife delete-d resampling

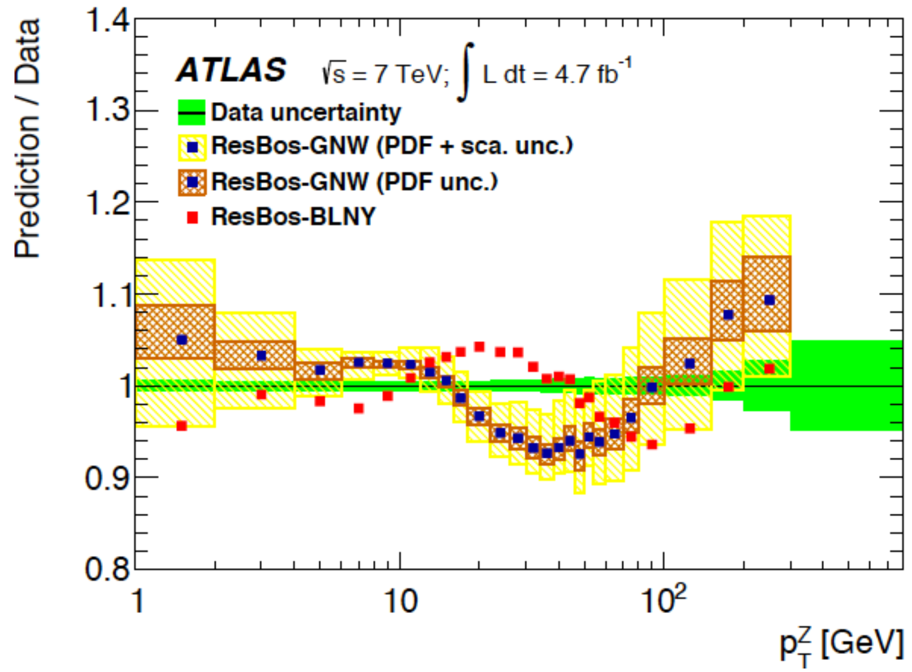
Efficiencies: uncorrelated bin-to-bin stat and 1% sys from tag and probe
Calibration: deviation from perfect closure and stat
Recoil: stat of the recoil fits, deviation from perfect closure of the calibration fits, the bkg modelling (on/off)
PDF: NNPDF2.3 NLO (100 members)
QED: Powheg NLO EW+QCD (on/off EW)
Rew: independent estimation from odd/even event number

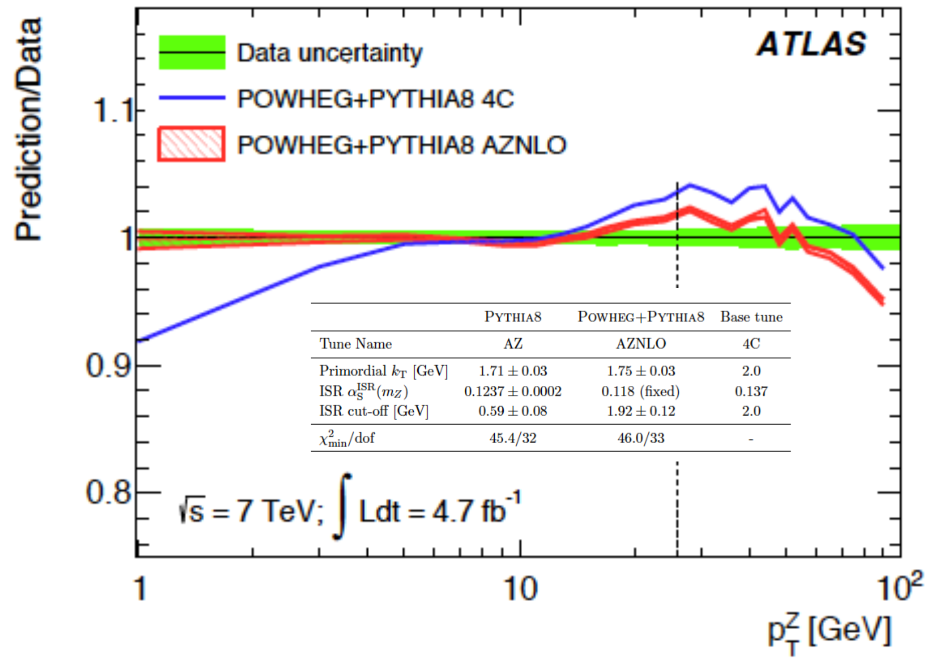
	$M_Z^{W\text{like}+}$			$M_Z^{W\text{like}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

ATLAS pTZ measurement 7 TeV (I)



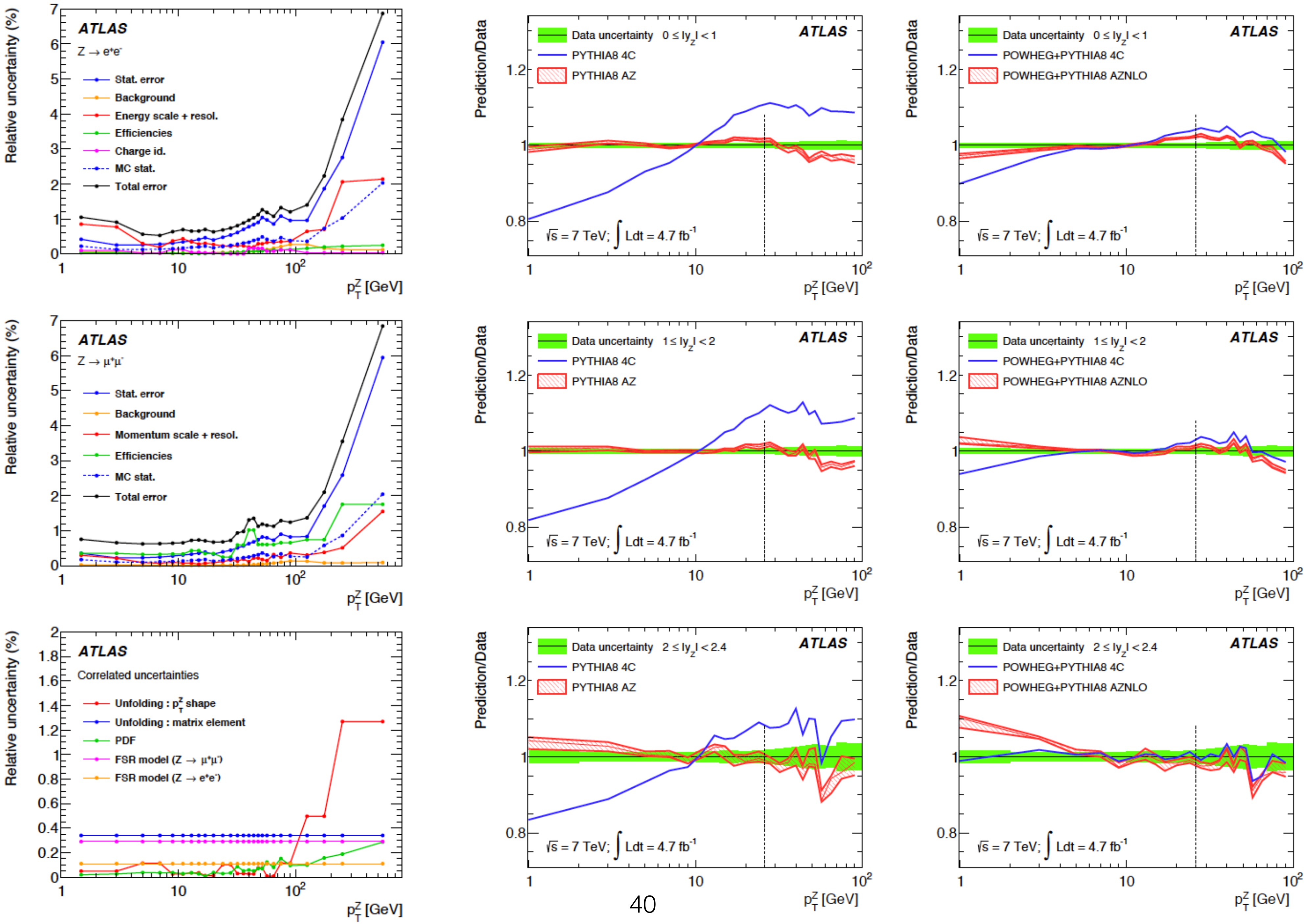




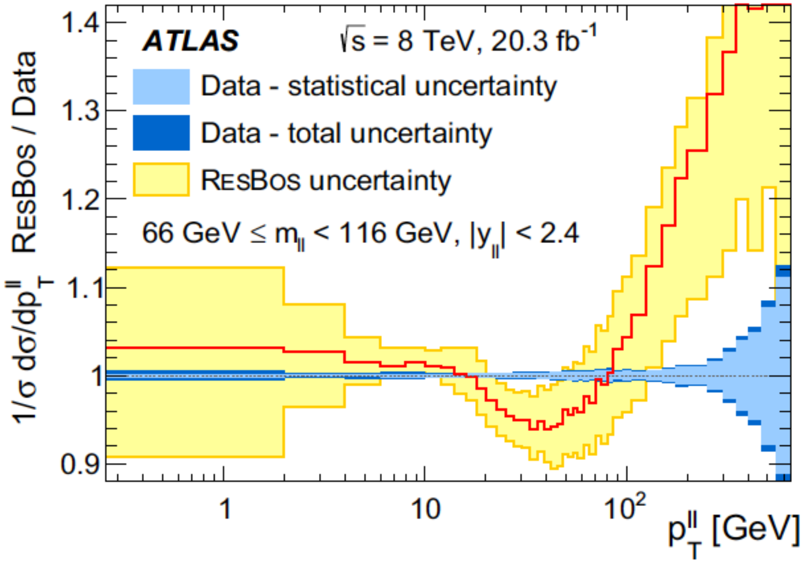


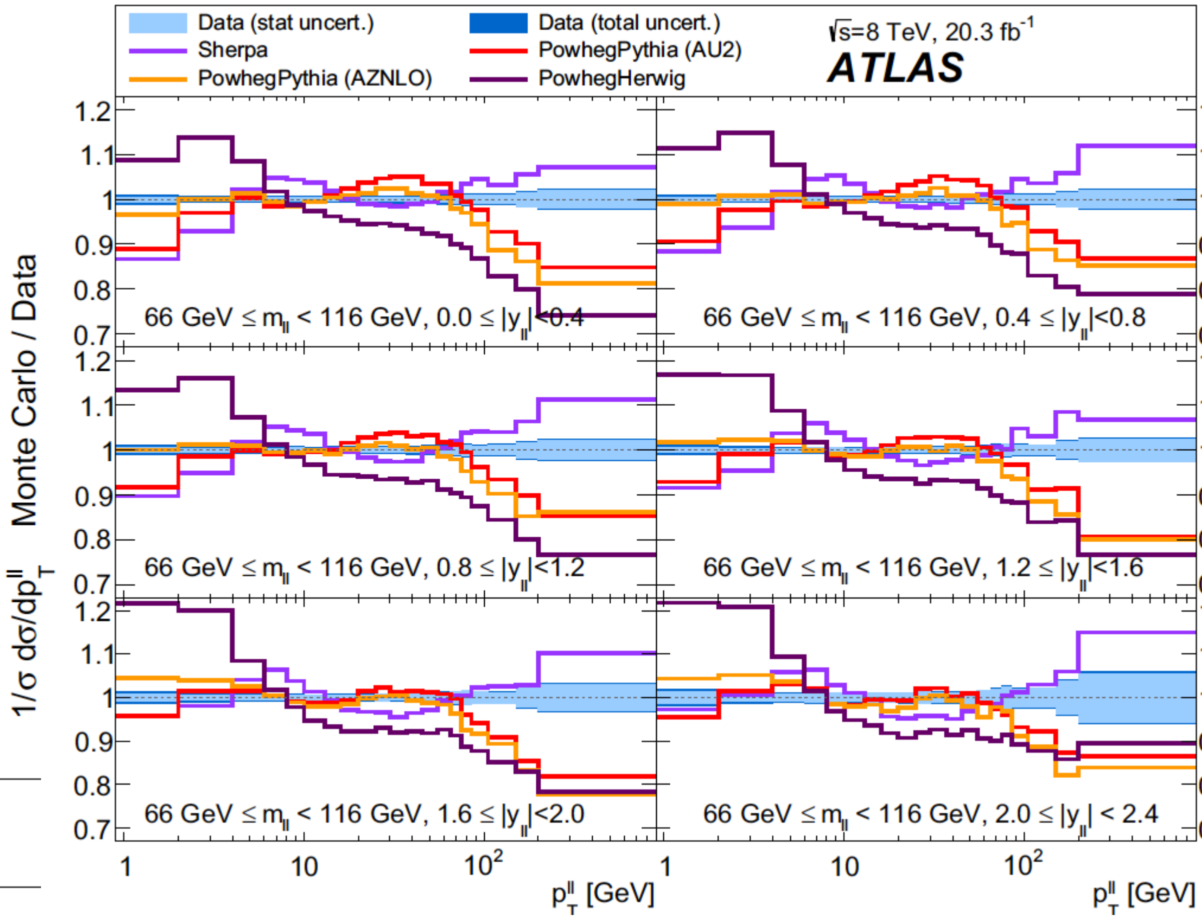
	PYTHIA8	POWHEG+PYTHIA8	Base tune
Tune Name	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-

ATLAS pTZ measurement 7 TeV (II)

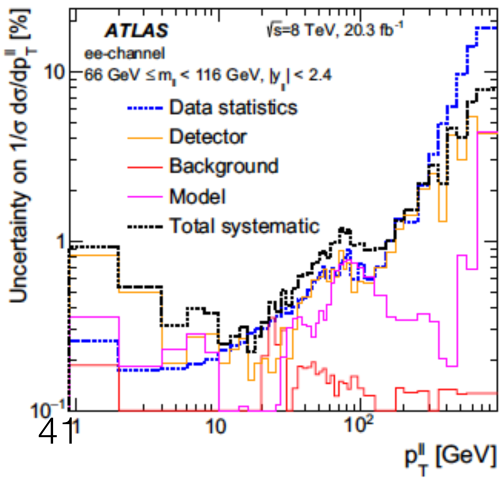


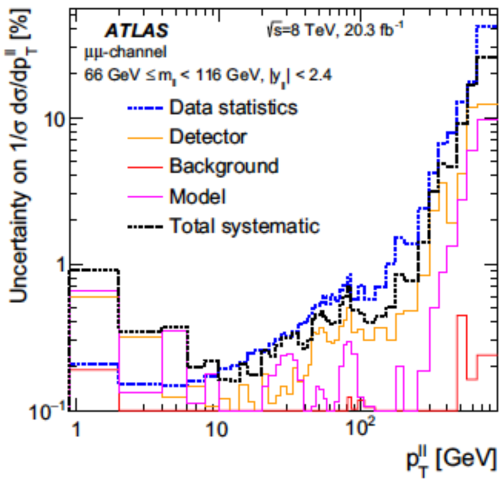
ATLAS pTZ measurement 8 TeV





Particle-level definitions (*treatment of final-state photon radiation*)	
Electron pairs	Dressed; Born
Muon pairs	Bare; dressed; Born
Combined	Born
Fiducial region	
Leptons	$p_T > 20$ GeV and $\lvert\eta\rvert < 2.4$
Lepton pairs	$\lvert y_{\ell\ell}\rvert < 2.4$
Mass and rapidity regions	
46 GeV $< m_{\ell\ell} <$ 66 GeV	$\lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.4$ (ϕ^*_η measurements only)
	$\lvert y_{\ell\ell}\rvert < 2.4$
66 GeV $< m_{\ell\ell} <$ 116 GeV	$\lvert y_{\ell\ell}\rvert < 0.4$; $0.4 < \lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.2$; $1.2 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.0$; $2.0 < \lvert y_{\ell\ell}\rvert < 2.4$; $\lvert y_{\ell\ell}\rvert < 2.4$
116 GeV $< m_{\ell\ell} <$ 150 GeV	$\lvert y_{\ell\ell}\rvert < 0.8$; $0.8 < \lvert y_{\ell\ell}\rvert < 1.6$; $1.6 < \lvert y_{\ell\ell}\rvert < 2.4$ (ϕ^*_η measurements only)
	$\lvert y_{\ell\ell}\rvert < 2.4$
Very-low mass regions	
12 GeV $< m_{\ell\ell} <$ 20 GeV 20 GeV $< m_{\ell\ell} <$ 30 GeV 30 GeV $< m_{\ell\ell} <$ 46 GeV	$\lvert y_{\ell\ell}\rvert < 2.4$, $p_T^{\ell\ell} > 45$ GeV, $p_T^{\ell\ell}$ measurements only

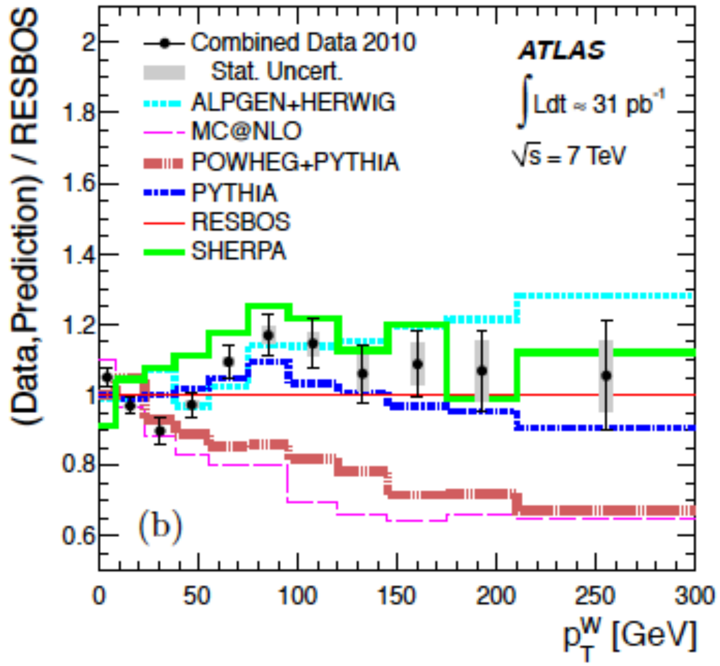




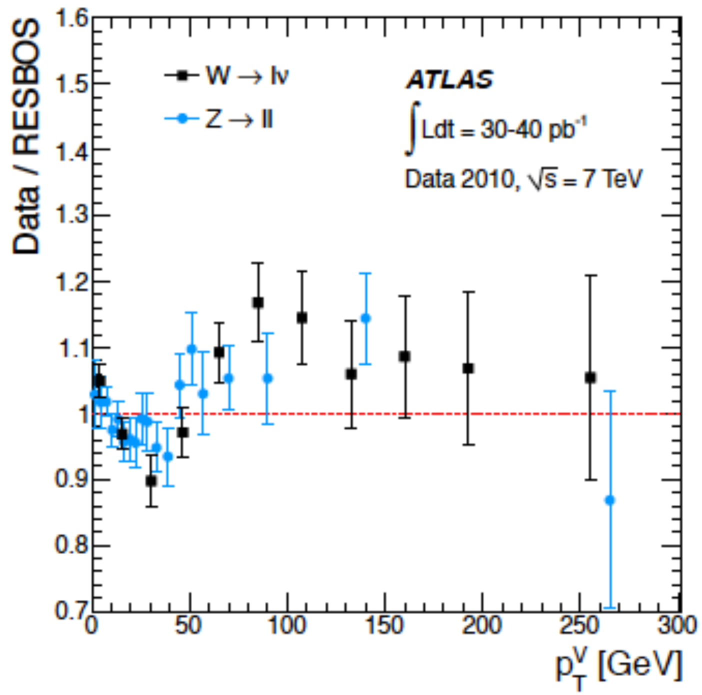
ATLAS pTW measurement 7 TeV

- **ATLAS : 7 TeV, 31 pb-1**
  - 11 bins: 0 – 8 – 23 – 38 – 55 – 75 – 95 – 120 – 145 – 175 – 210 – 300 GeV
  - E, mu: common fiducial volumes
    - |η|<2.4, pT>20 GeV, MET>25 GeV, MT>40 GeV
  - Charge-blind; shape measurement only

The measurement is compared to a selection of predictions. The ALPGEN+HERWIG, PYTHIA, RESBOS, and SHERPA predictions match the data within 20% over the entire p_T^W range. MC@NLO provides the closest description of the data for $p_T^W < 38$ GeV, but MC@NLO and POWHEG+PYTHIA both underestimate the data at higher p_T^W.



p_T^W Bin [GeV]	$(1/\sigma_{\rm fid})(d\sigma_{\rm fid}/dp_T^W)$ (GeV^{-1})	ResponseMatrix uncert. (%)	Backgrounds uncert. (%)	Efficiency uncert. (%)	Statistical uncert. (%)	Total uncert. (%)
0 – 8	$5.510 \cdot 10^{-2}$	1.91	0.26	0.76	0.22	2.48
8 – 23	$2.512 \cdot 10^{-2}$	1.69	0.28	0.87	0.24	2.42
23 – 38	$6.766 \cdot 10^{-3}$	3.20	0.57	1.28	0.57	4.31
38 – 55	$2.523 \cdot 10^{-3}$	2.34	0.65	1.44	0.84	3.78
55 – 75	$1.025 \cdot 10^{-3}$	1.78	0.74	1.74	1.19	4.09
75 – 95	$4.263 \cdot 10^{-4}$	1.61	1.15	2.13	1.91	4.94
95 – 120	$1.896 \cdot 10^{-4}$	1.98	1.94	2.67	2.68	5.99
120 – 145	$7.985 \cdot 10^{-5}$	2.84	3.30	3.16	4.78	7.91
145 – 175	$3.710 \cdot 10^{-5}$	1.98	2.66	3.66	5.72	9.31
175 – 210	$1.692 \cdot 10^{-5}$	2.00	3.72	3.84	7.75	10.56
210 – 300	$4.803 \cdot 10^{-6}$	2.69	7.81	4.26	9.28	14.40



CMS pTW measurement 8 TeV

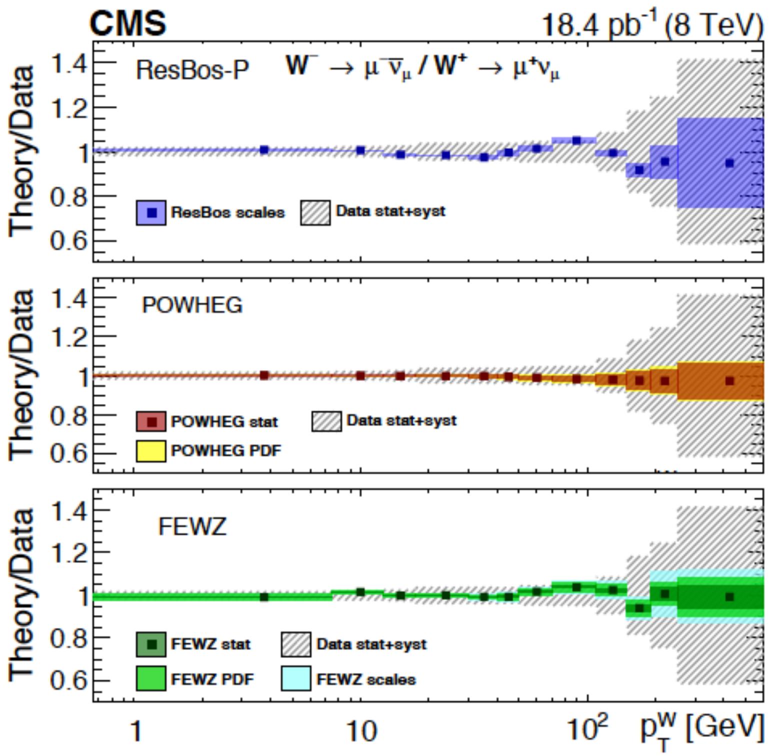
8 TeV 18.4 pb^{-1} μ=4

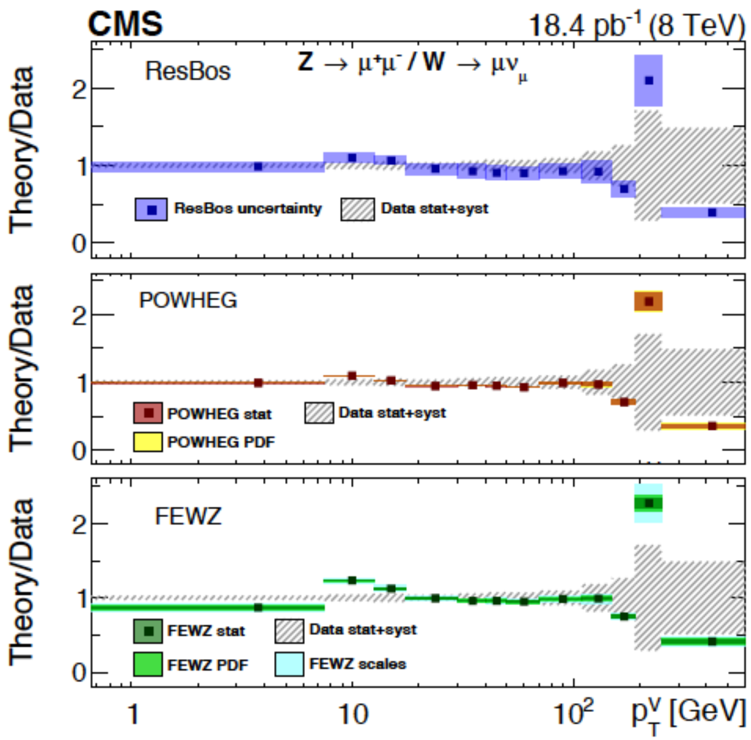
Z selection: muons pT>20 GeV |eta|<2.1

W selection: electrons pT>25 GeV, muons pT>20 GeV

12 bins: 0-7.5-12.5-17.5-30-40-50-70-110-150-190-250-600

Bin (GeV)	W^-/W^+	Z/W
0–7.5	0.961 ± 0.019	0.962 ± 0.025
7.5–12.5	0.994 ± 0.024	0.890 ± 0.038
12.5–17.5	1.017 ± 0.028	0.982 ± 0.052
17.5–30	1.028 ± 0.041	1.081 ± 0.041
30–40	1.056 ± 0.043	1.101 ± 0.064
40–50	1.069 ± 0.041	1.149 ± 0.085
50–70	1.065 ± 0.050	1.216 ± 0.085
70–110	1.064 ± 0.052	1.206 ± 0.115
110–150	1.061 ± 0.093	1.274 ± 0.232
150–190	1.106 ± 0.204	1.820 ± 0.479
190–250	1.002 ± 0.247	0.641 ± 0.454
250–600	0.912 ± 0.379	3.865 ± 1.881

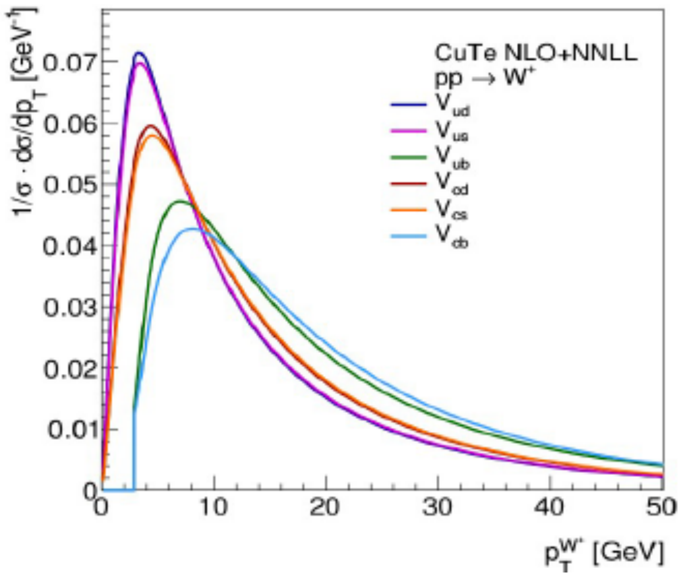


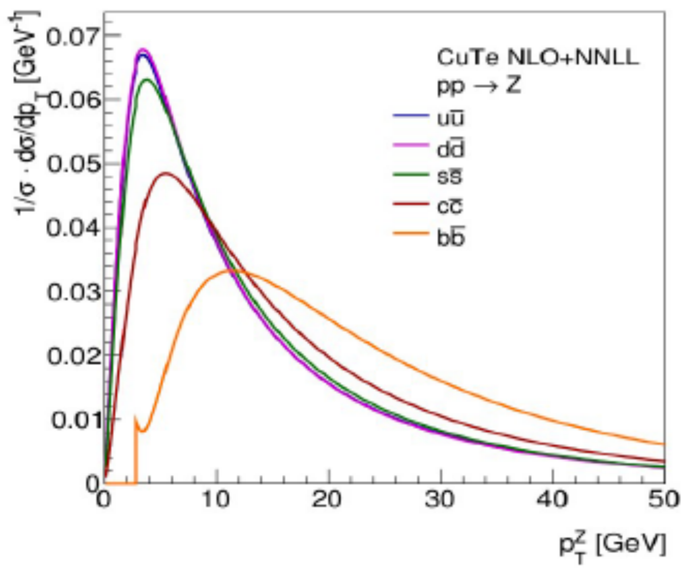


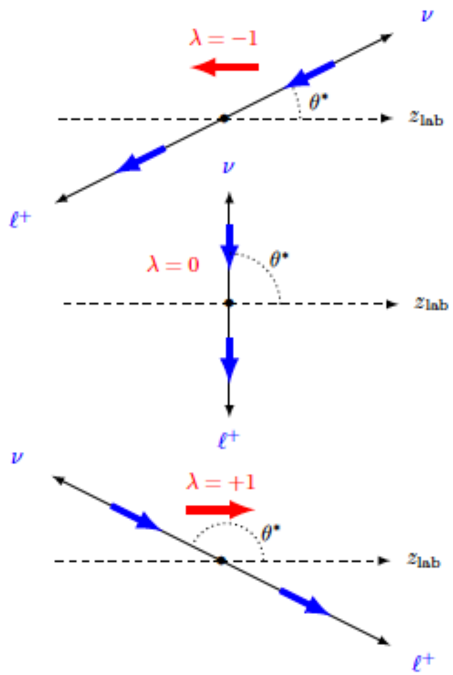
	Uncertainty or size	Analytic resummation	Pythia	Leftover effect on W/Z
Singular resummation	5-10%	$\surd\surd\surd$	$\surd$	$\lesssim$ % (?)
Power corrections	few %	$(\times)$	$(\surd)$?	?
Nonperturbative	few %	$(\surd)$	$(\surd)$	?
Massive quarks	few % (?)	$\times$ $(\to \surd)$	?	few % (?)
QED	$\lesssim$ % (?)	$\times$	$\surd$ (?)	$\lesssim$ % (?)
PDFs	2%	$\surd$	$\surd$	$\surd$
$\alpha_s(m_Z)$	up to 5%??	$\surd$	$\surd$	$\surd$

- Most ? could be addressed (some just mean that I don't know ...)
- Though it is a bit unsettling it is not unbelievable that in the end plain Pythia currently seems to describe the W/Z ratio best
  - Question of the uncertainty when used as prediction remains

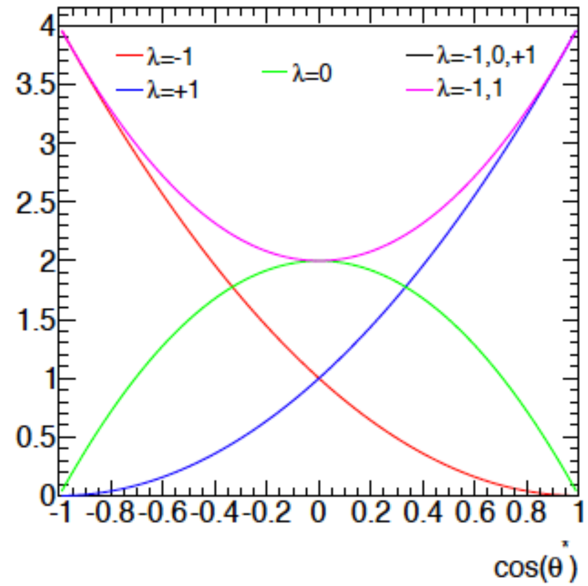
More on pTW





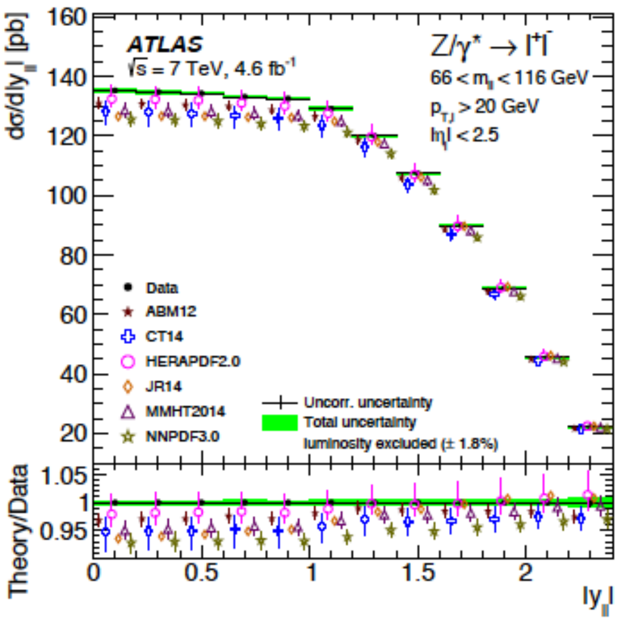


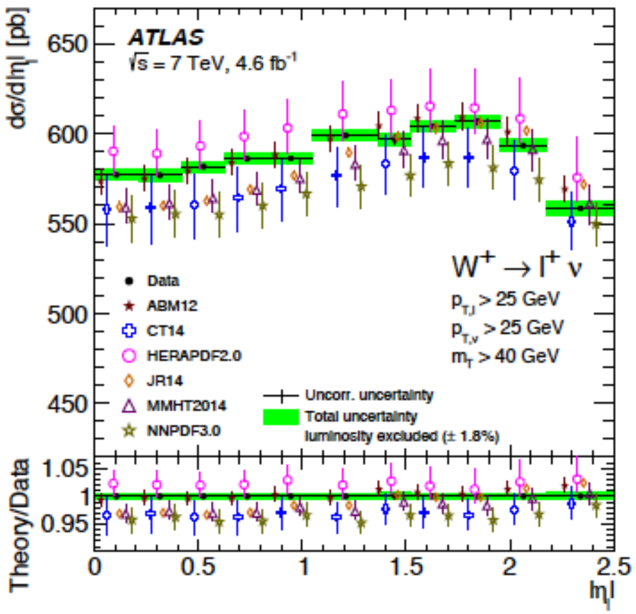
(a)

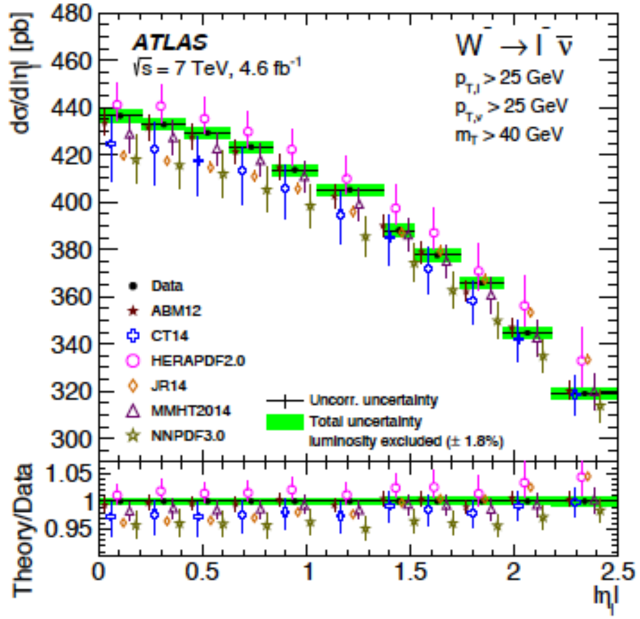


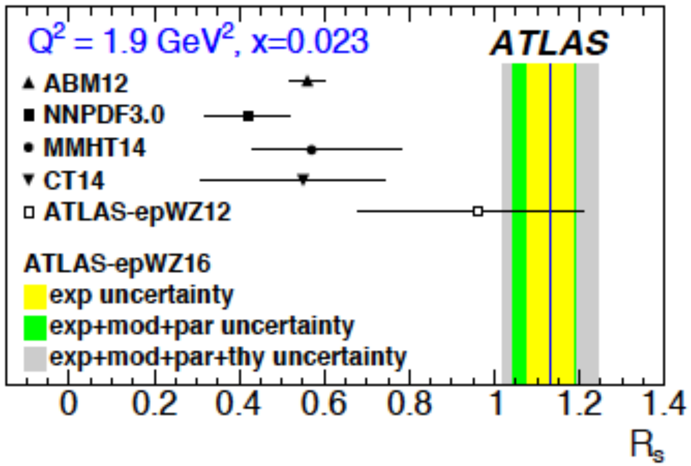
(b)

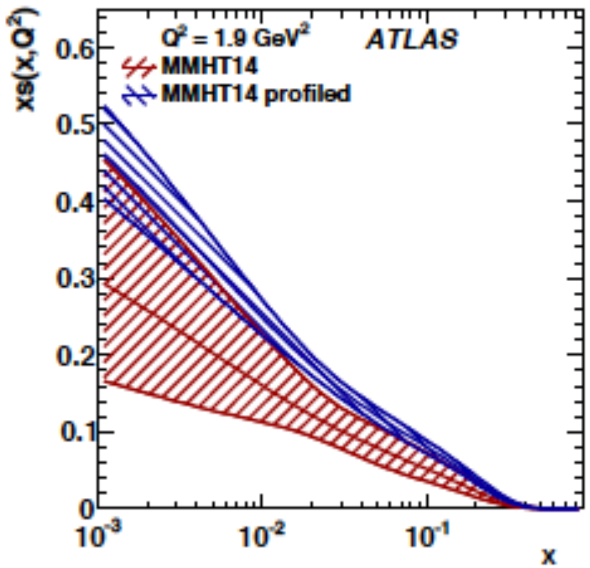
ATLAS W, Z cross section measurement





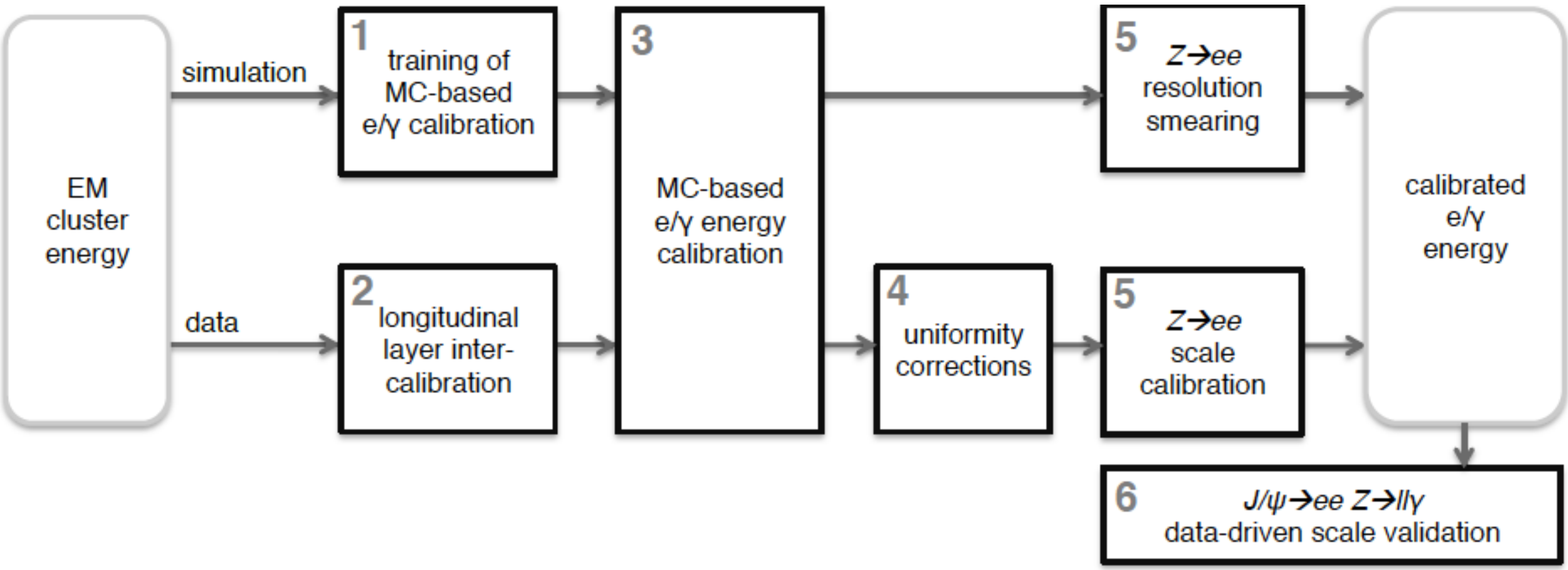






Electron calibration and efficiency

Calibration for electrons closely follows the Run I calibration paper Eur.Phys.J.C 74 (2014) 3071

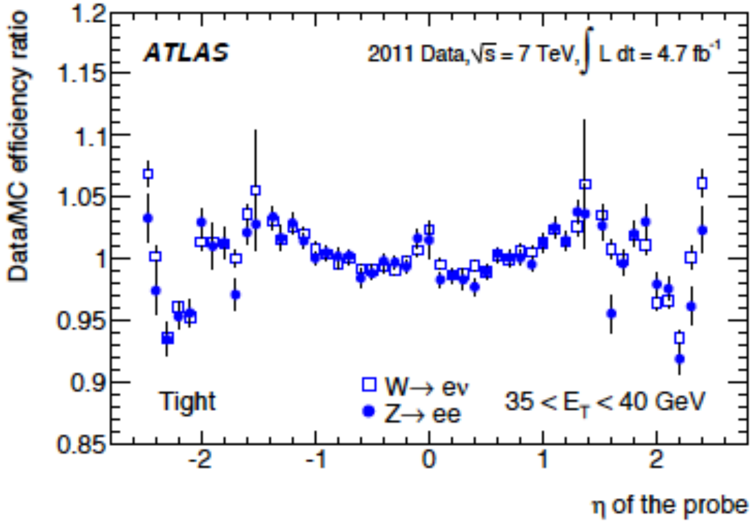


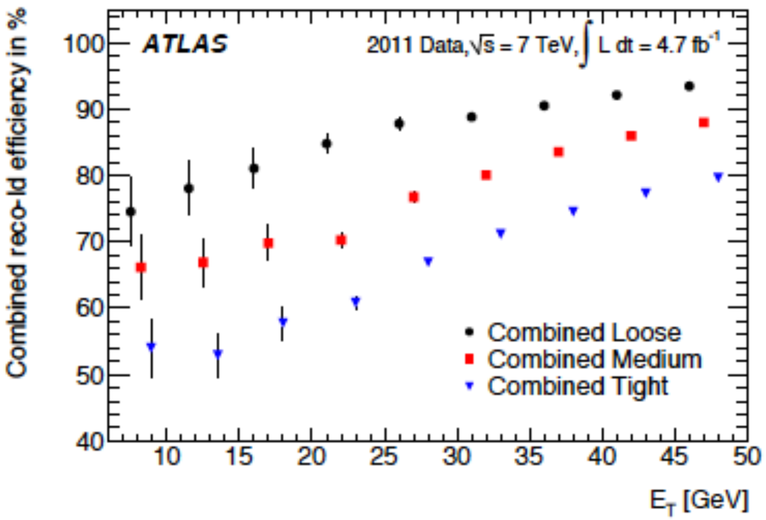
Exclude bin 1.2<|eta|<1.82 for the W mass measurement as the amount of passive material in front of the calorimeter and its uncertainty are largest in this region.
Azimuthal correction from <E/p> vs phi

Electron efficiency corrections as a function of eta and p_T Eur.Phys.J.C 74 (2014) 2941

Electron efficiency

- Electron detection complicated by large amount of material in the detector and significant background from jets
- Efficiency controlled in several steps using "tag-and-probe": relies mostly on $Z \to \ell\ell$ events selected with looser criteria on one leg
- Simulation not perfect $\to$ correct simulation double-differentially in (η^ℓ, p_T^ℓ) by measured $\epsilon_{\mathrm{data}}/\epsilon_{\mathrm{MC}}$, known to typically $\sim 0.2 - 1\%$ in relevant range $p_T^\ell > 25$ GeV
- Directly relevant as systematics for cross-section measurement, important to control p_T^ℓ-dependent slopes for m_W
- Muon efficiencies controlled in similar way, just easier





ATLAS mW paper

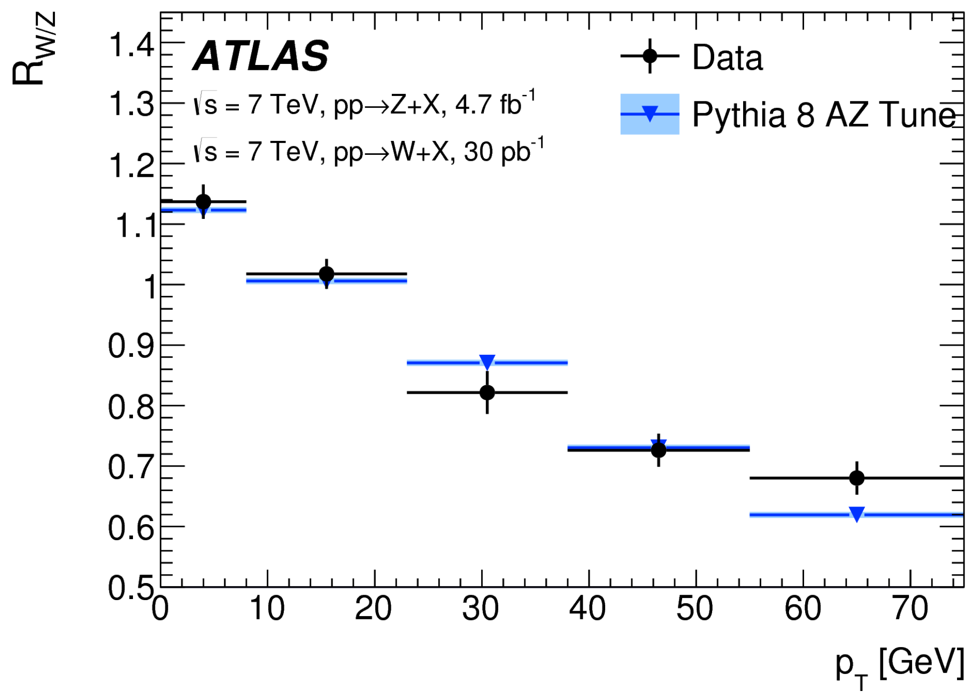
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta,\phi)\right],$$

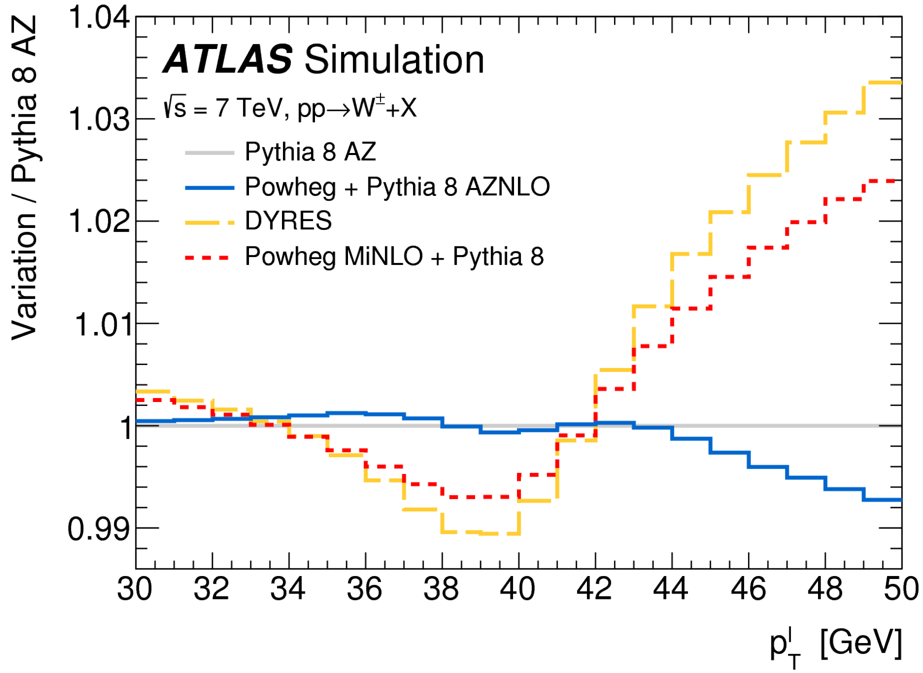
$$\begin{aligned}\frac{d\sigma}{dp_T^2\,dy\,dm\,d\cos\theta\,d\phi} &= \frac{3}{16\pi}\frac{d\sigma}{dp_T^2\,dy\,dm} \times [(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) \\ &+ A_1\ \sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\ \sin\theta\cos\phi + A_4\ \cos\theta \\ &+ A_5\ \sin^2\theta\sin 2\phi + A_6\ \sin 2\theta\sin\phi + A_7\ \sin\theta\sin\phi].\end{aligned}$$

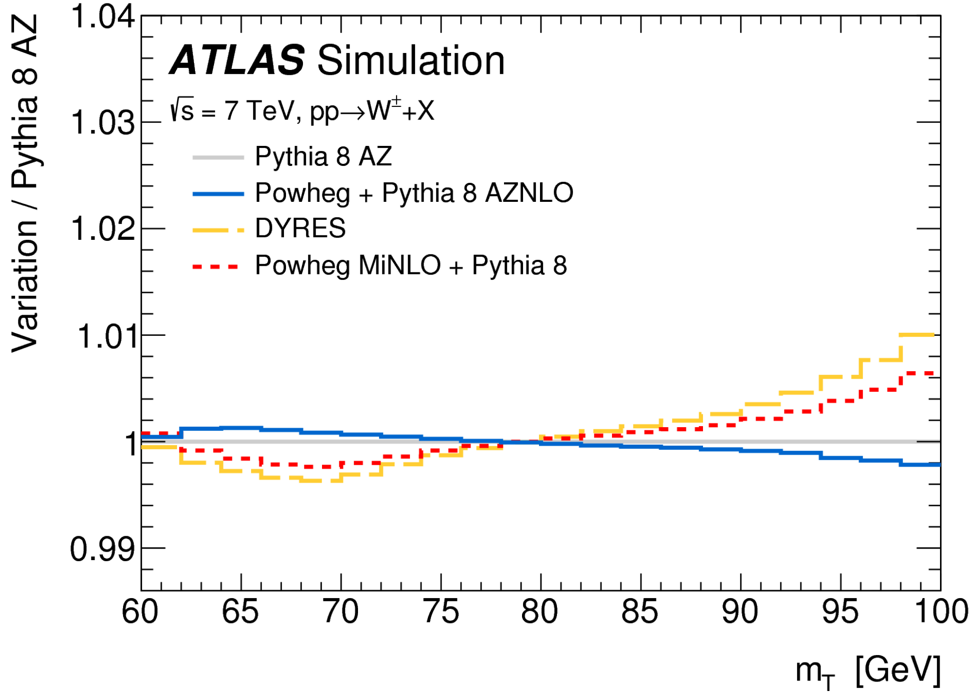
$$\begin{aligned} p_T^{\mathrm{MC,corr}} &= p_T^{\mathrm{MC}} \times [1+\alpha(\eta,\phi)] \times \left[1 + \beta_{\mathrm{curv}}(\eta)\cdot G(0,1)\cdot p_T^{\mathrm{MC}}\right], \\ p_T^{\mathrm{data,corr}} &= \frac{p_T^{\mathrm{data}}}{1 + q\cdot\delta(\eta,\phi)\cdot p_T^{\mathrm{data}}}, \end{aligned}$$

$$\delta\alpha = p_0 + \frac{p_1}{\left\langle p_T^{\ell}(W)\right\rangle},$$

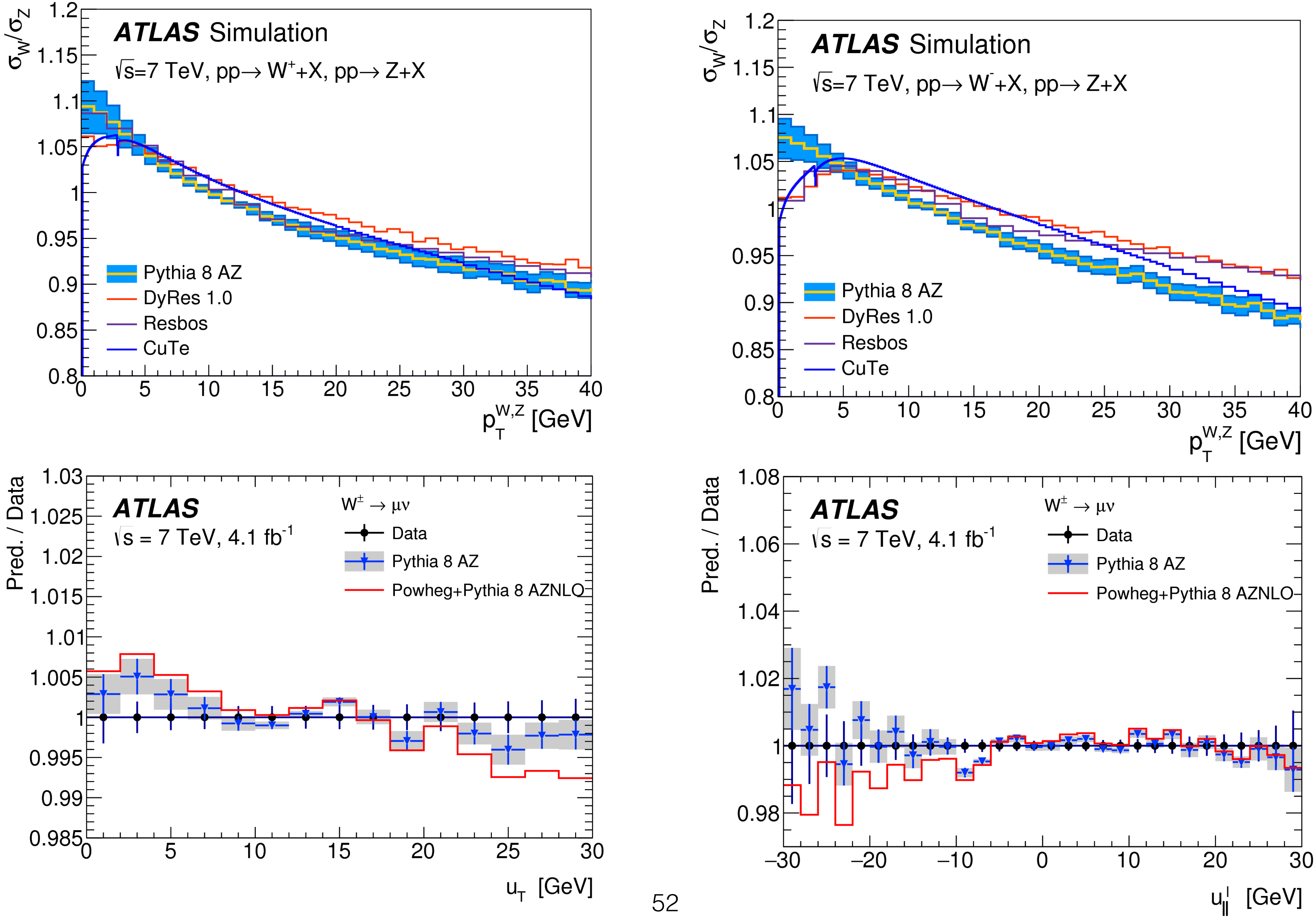
Transverse momentum



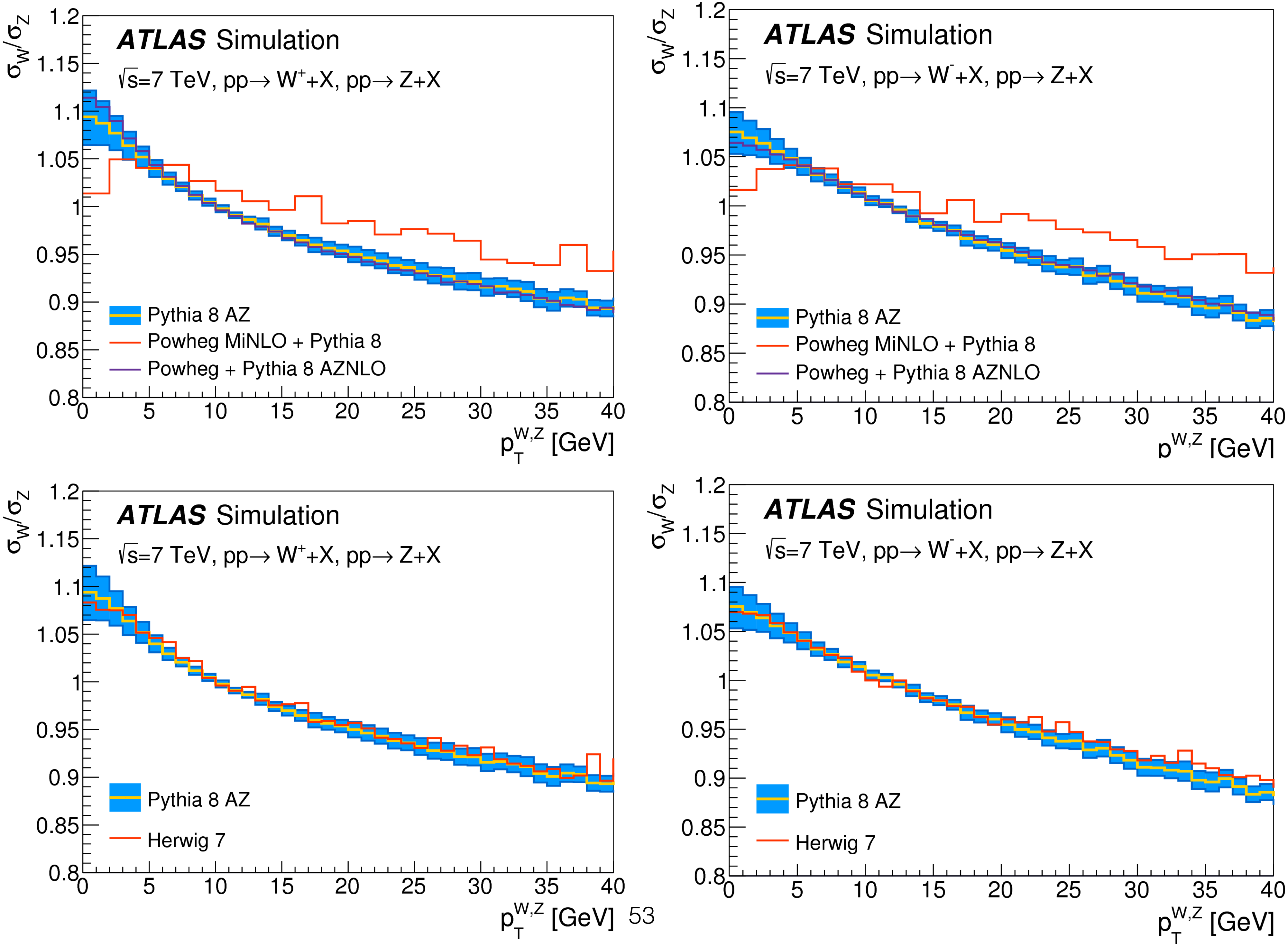




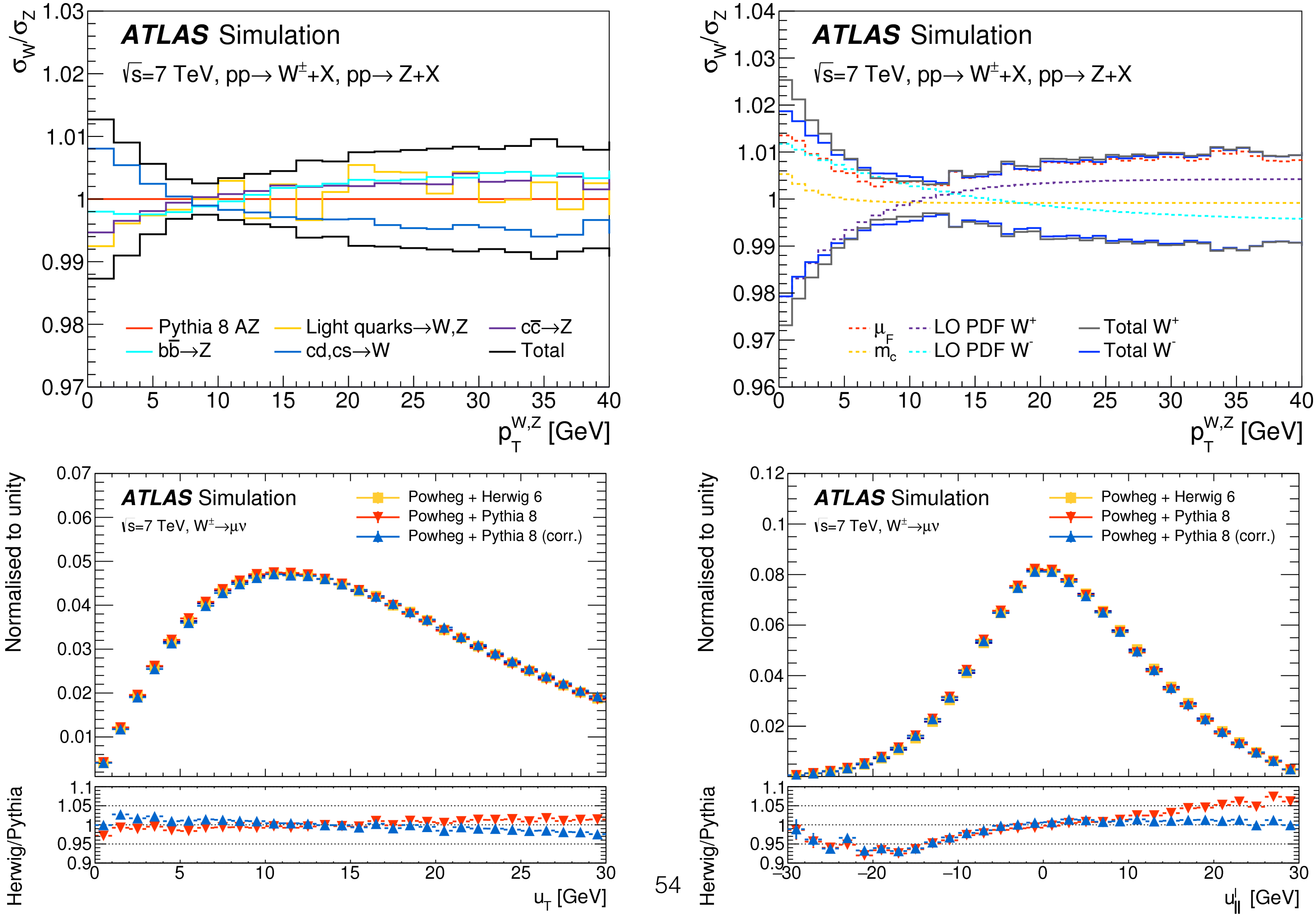
Transverse momentum

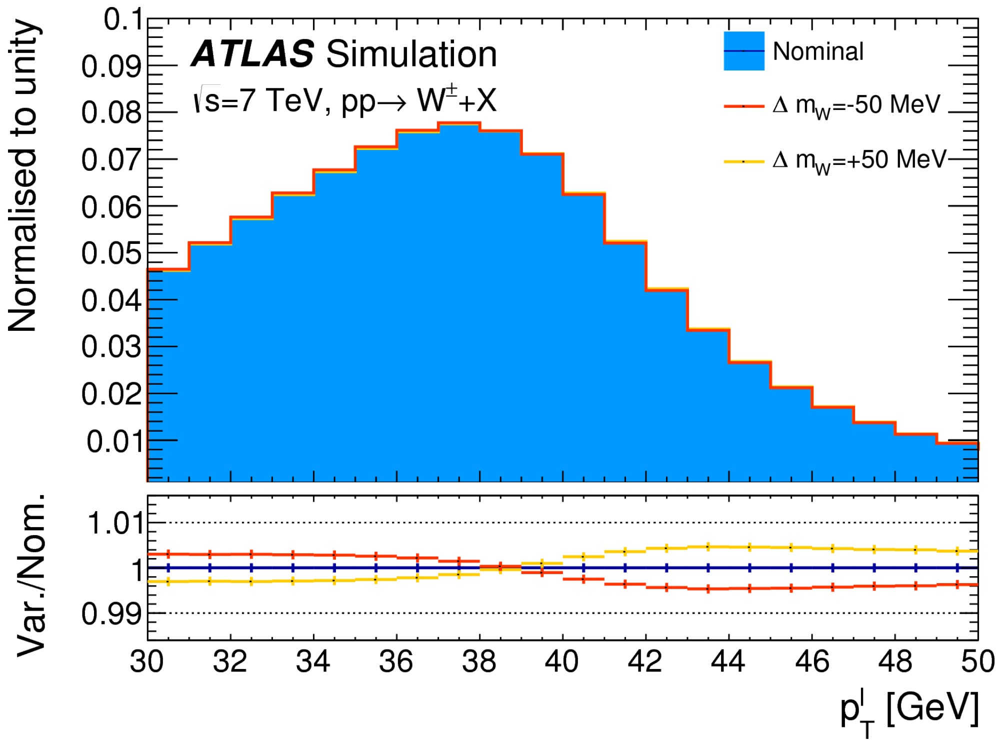


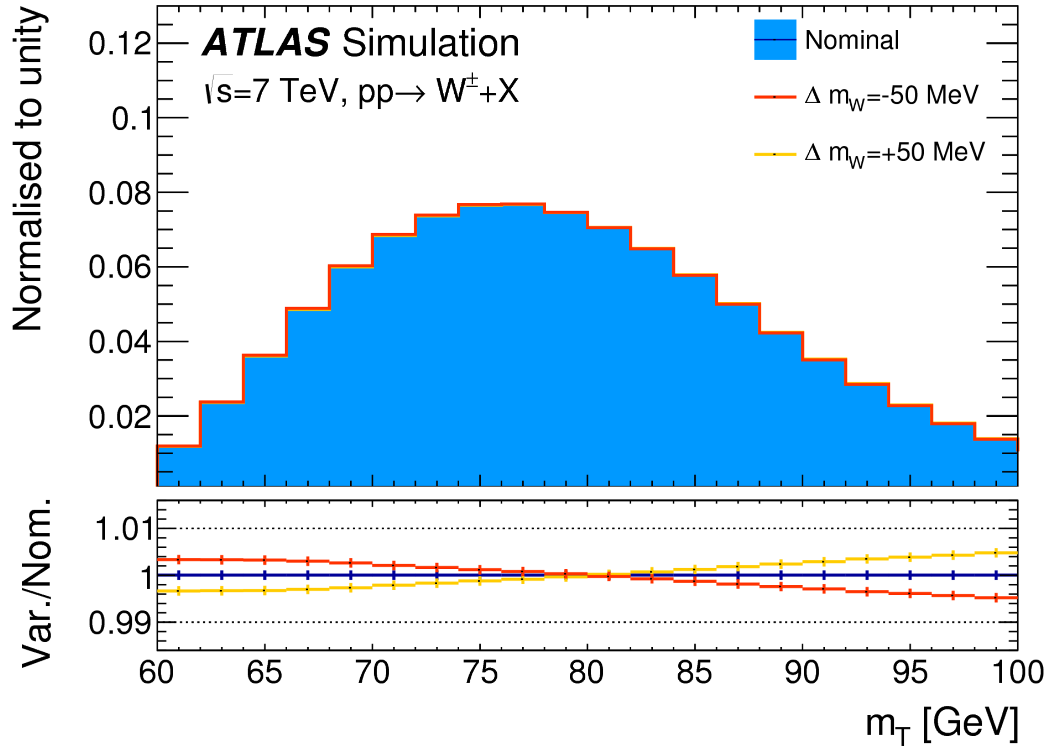
Transverse momentum

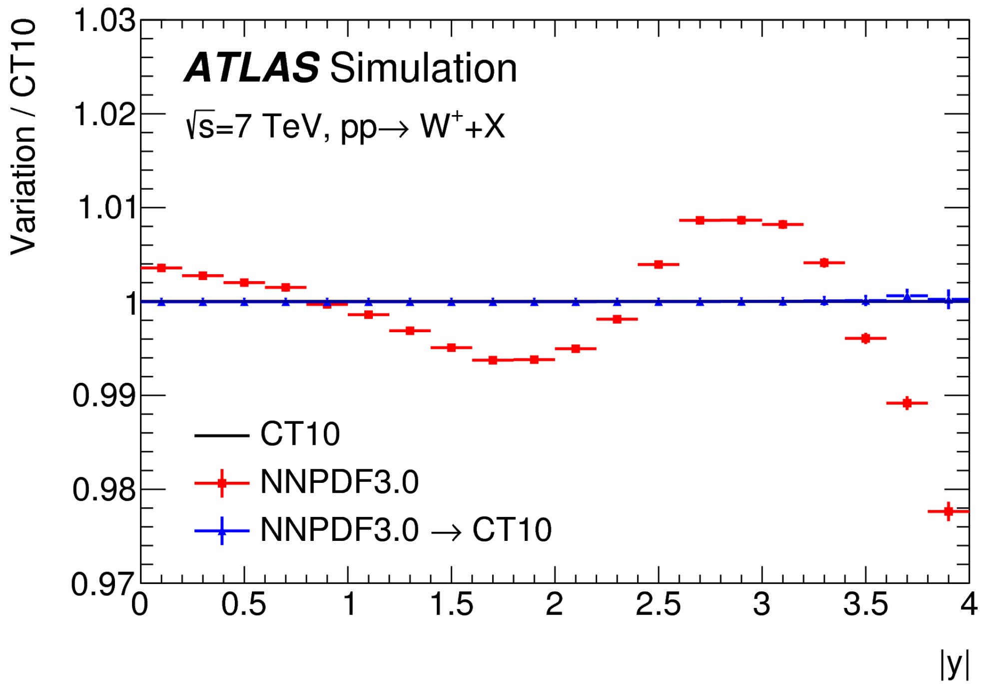


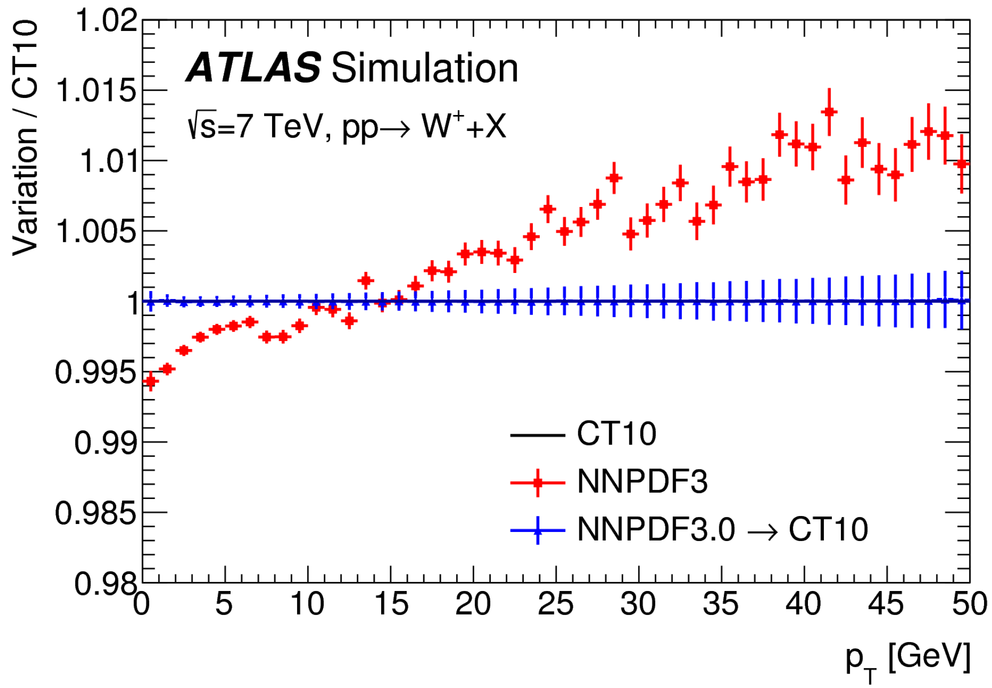
Transverse momentum

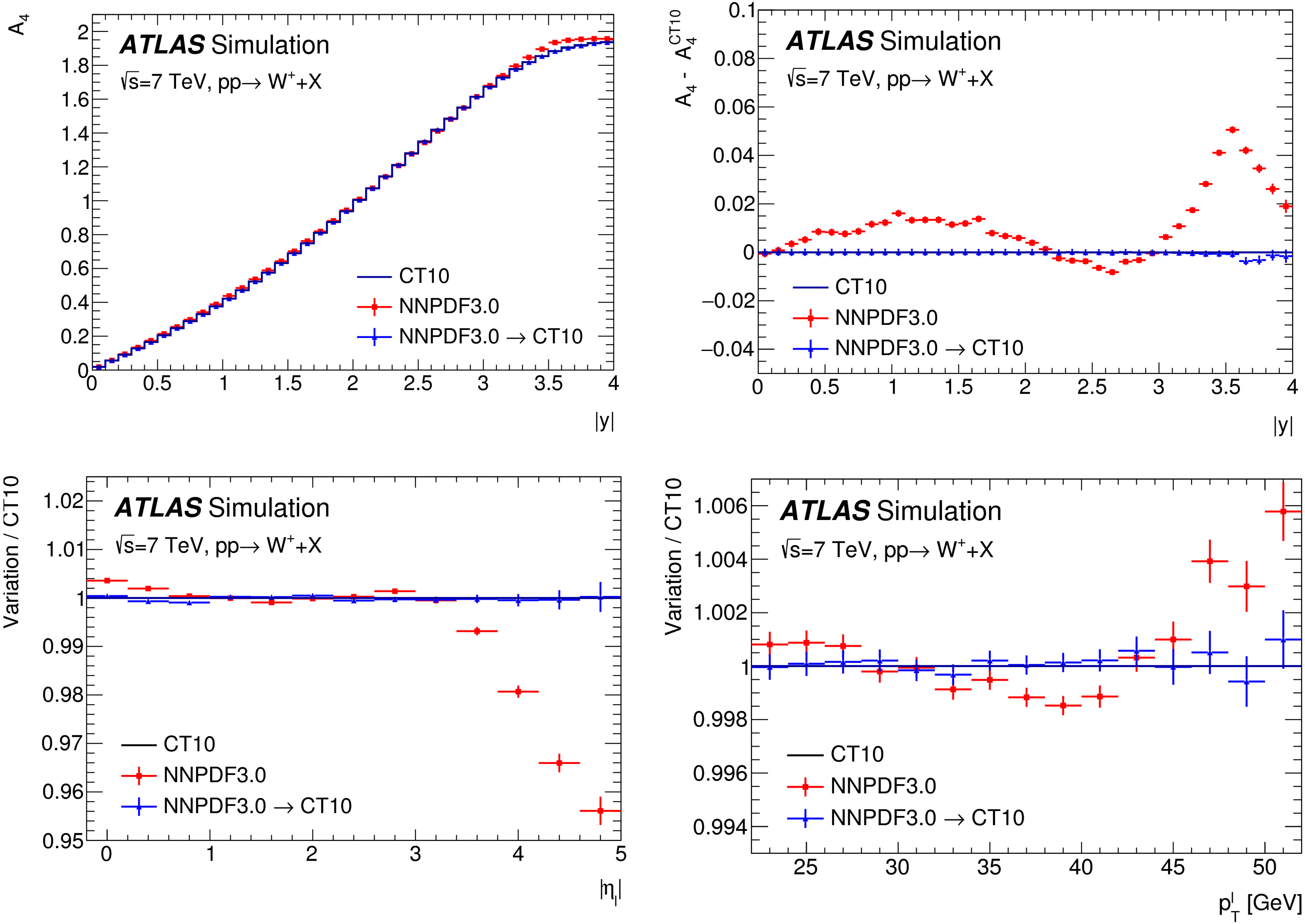


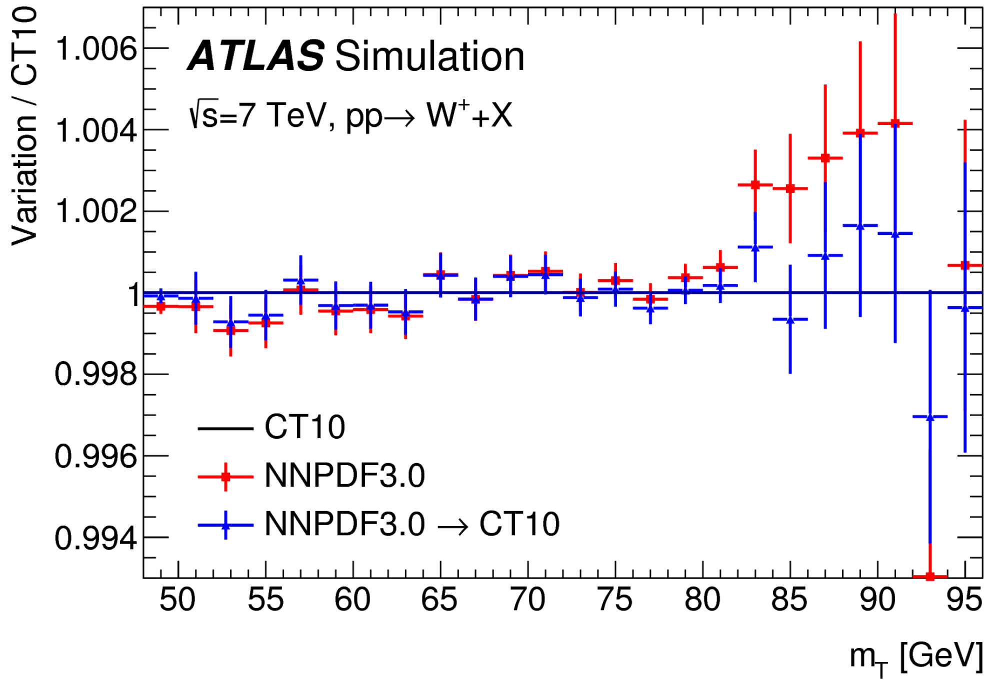

ATLAS Simulation
√s=7 TeV, pp→ W±+X
Nominal
Δ mW=-50 MeV
Δ mW=+50 MeV
Normalised to unity
Var./Nom.
pT^l [GeV]


ATLAS Simulation
√s=7 TeV, pp→ W±+X
Nominal
Δ mW=-50 MeV
Δ mW=+50 MeV
Normalised to unity
Var./Nom.
mT [GeV]

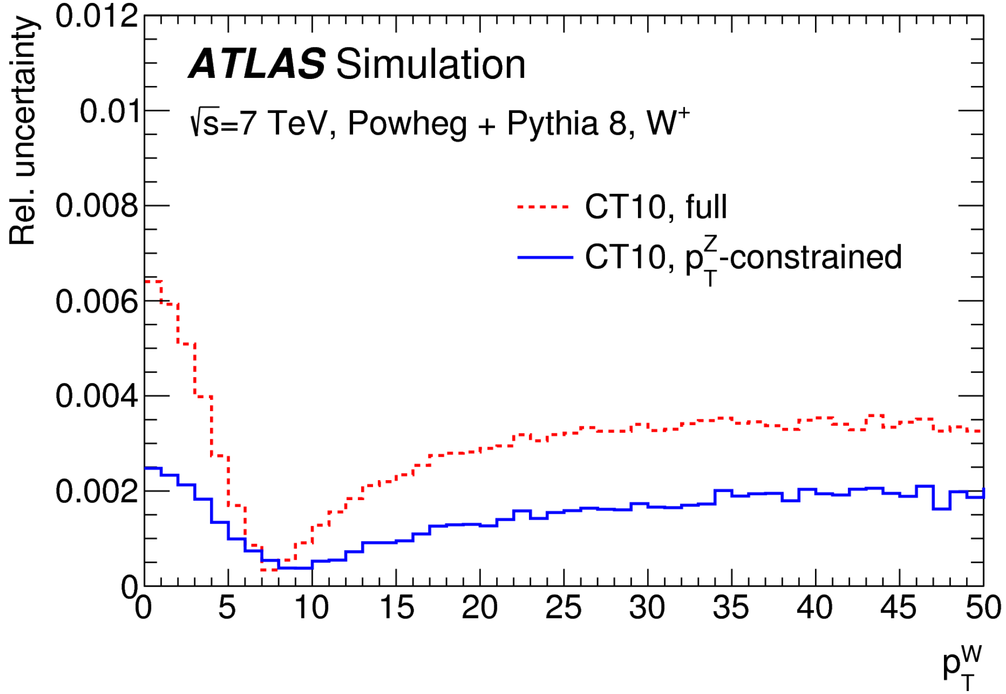

ATLAS Simulation
√s=7 TeV, pp→ W+ +X
CT10
NNPDF3.0
NNPDF3.0 → CT10
Variation / CT10
|y|


ATLAS Simulation
√s=7 TeV, pp→ W+ +X
CT10
NNPDF3
NNPDF3.0 → CT10
Variation / CT10
pT [GeV]

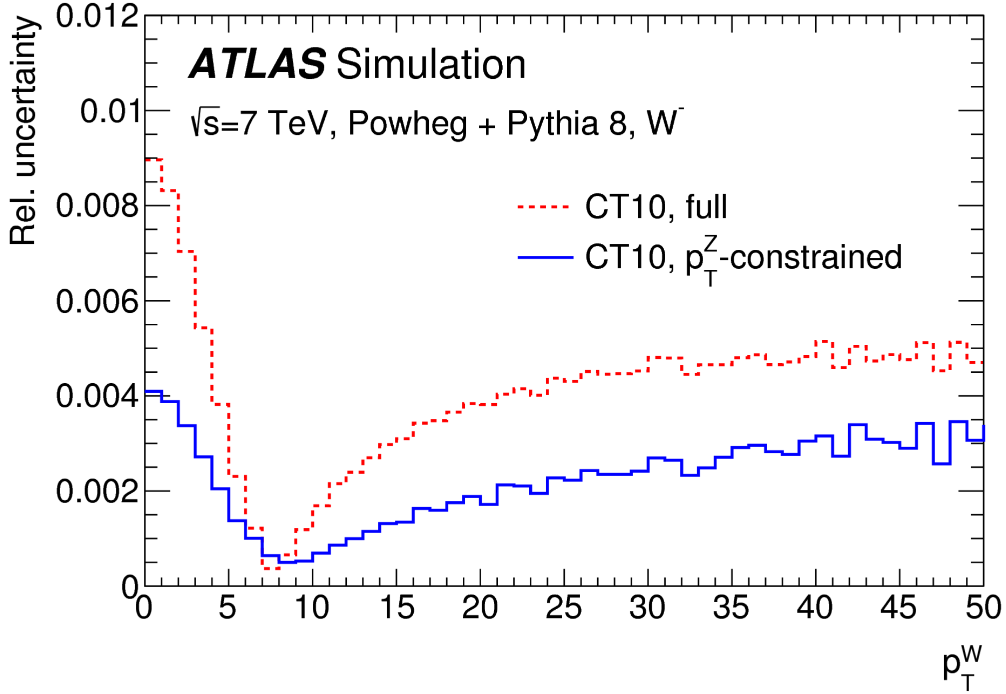

ATLAS Simulation
√s=7 TeV, pp→ W⁺+X
CT10
NNPDF3.0
NNPDF3.0 → CT10
A_4
$A_4 - A_4^{CT10}$
|y|
Variation / CT10
$|\eta_l|$
p_T^l [GeV]



ATLAS Simulation
√s=7 TeV, pp→ W⁺+X
Variation / CT10
CT10
NNPDF3.0
NNPDF3.0 → CT10
m_T [GeV]

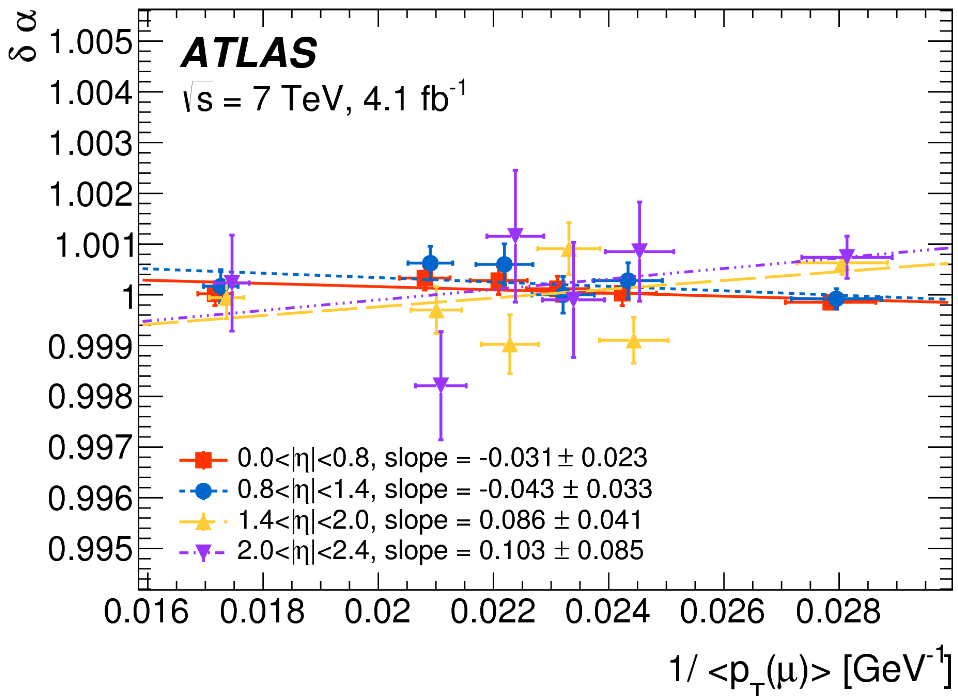


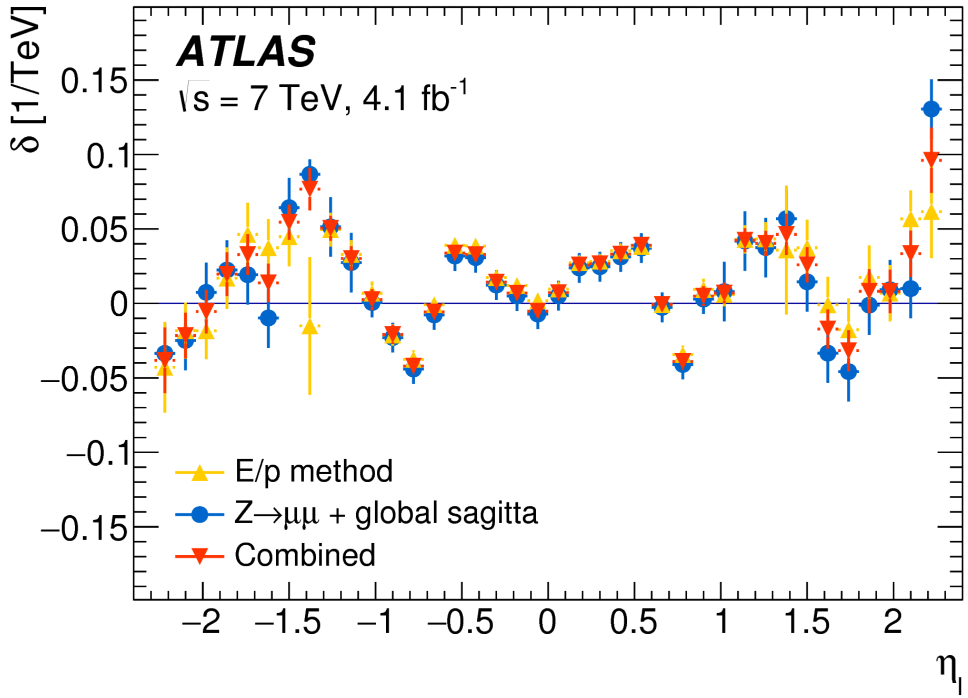
ATLAS Simulation
√s=7 TeV, Powheg + Pythia 8, W⁺
Rel. uncertainty
CT10, full
CT10, p_T^Z-constrained
p_T^W

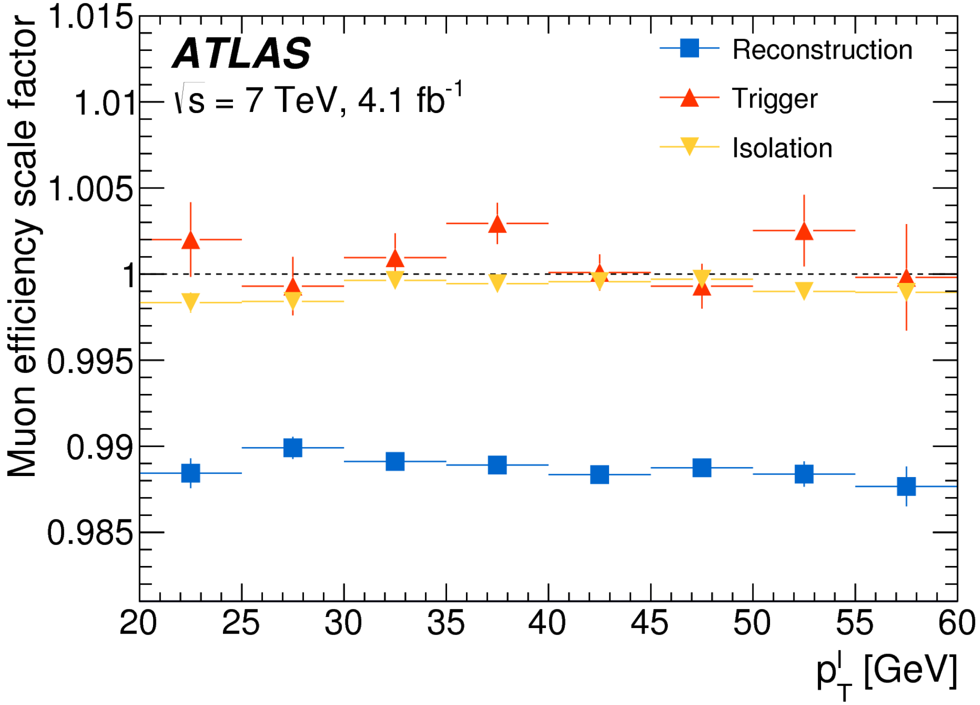


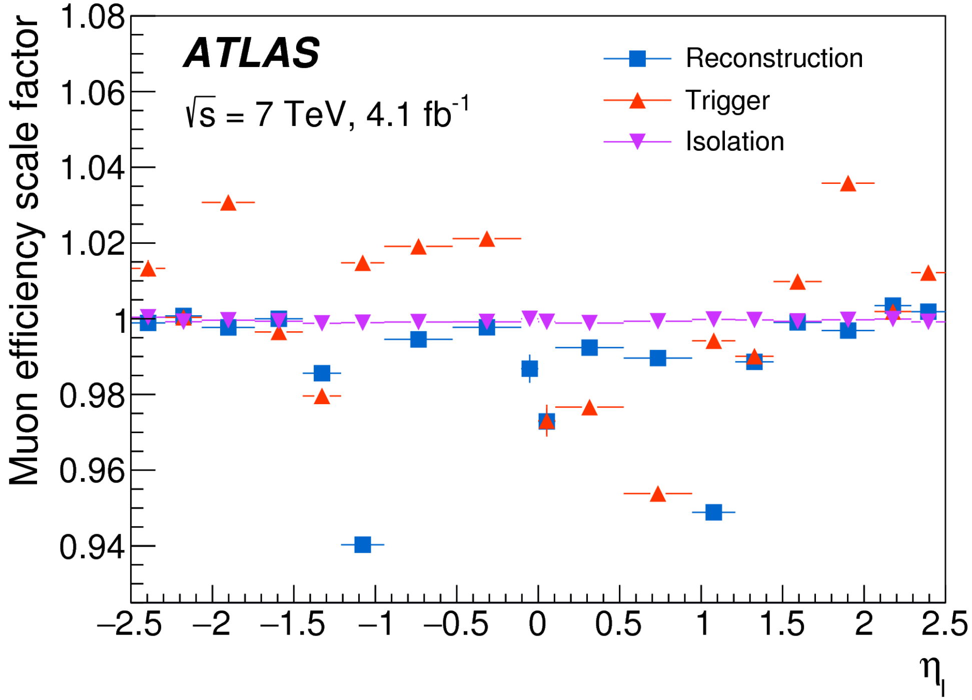
ATLAS Simulation
√s=7 TeV, Powheg + Pythia 8, W⁻
Rel. uncertainty
CT10, full
CT10, p_T^Z-constrained
p_T^W

Muon Calibration

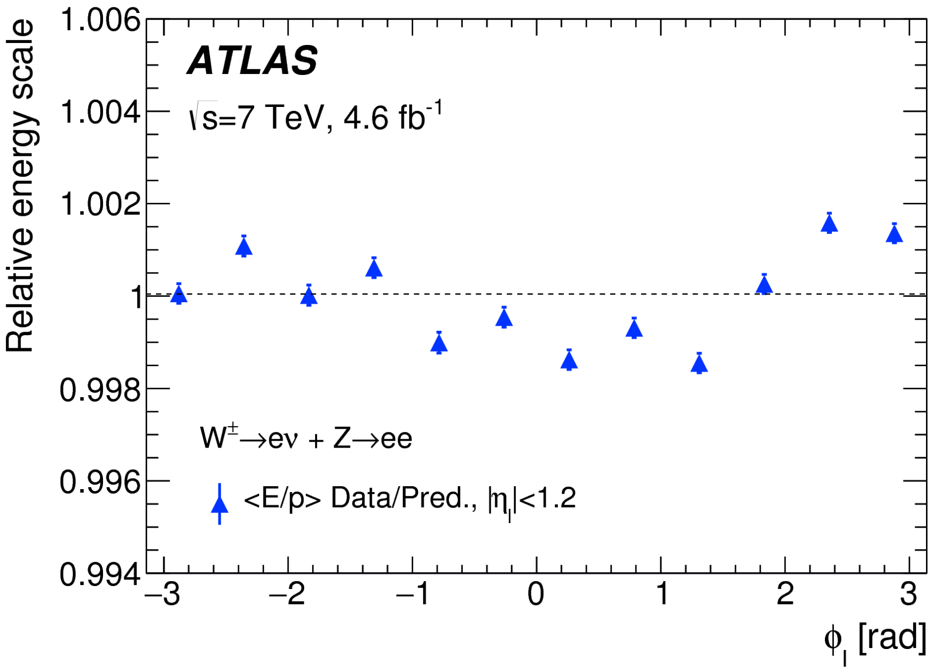


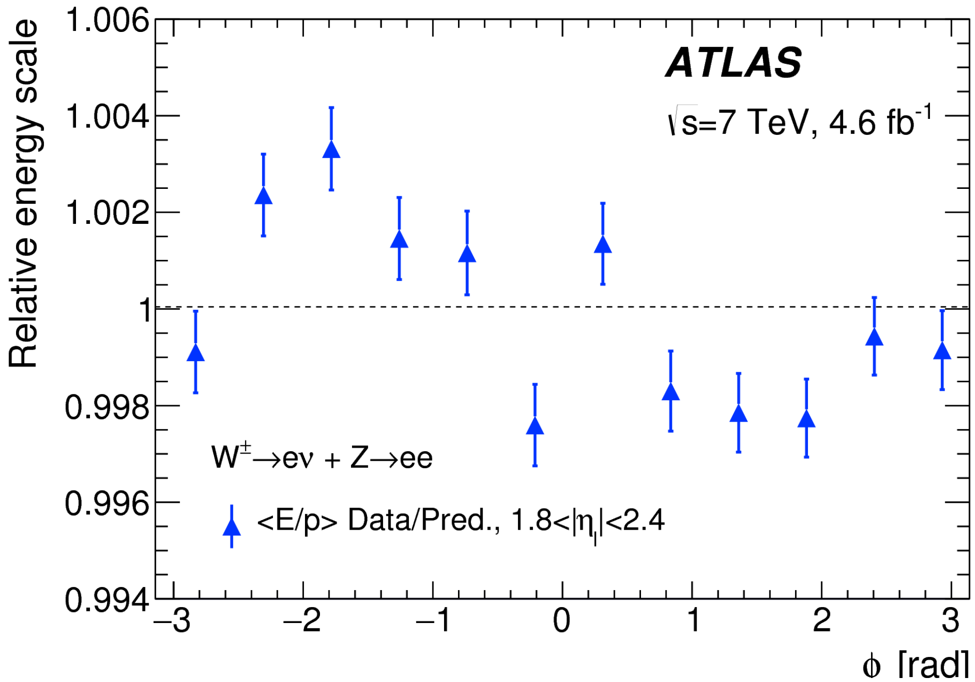


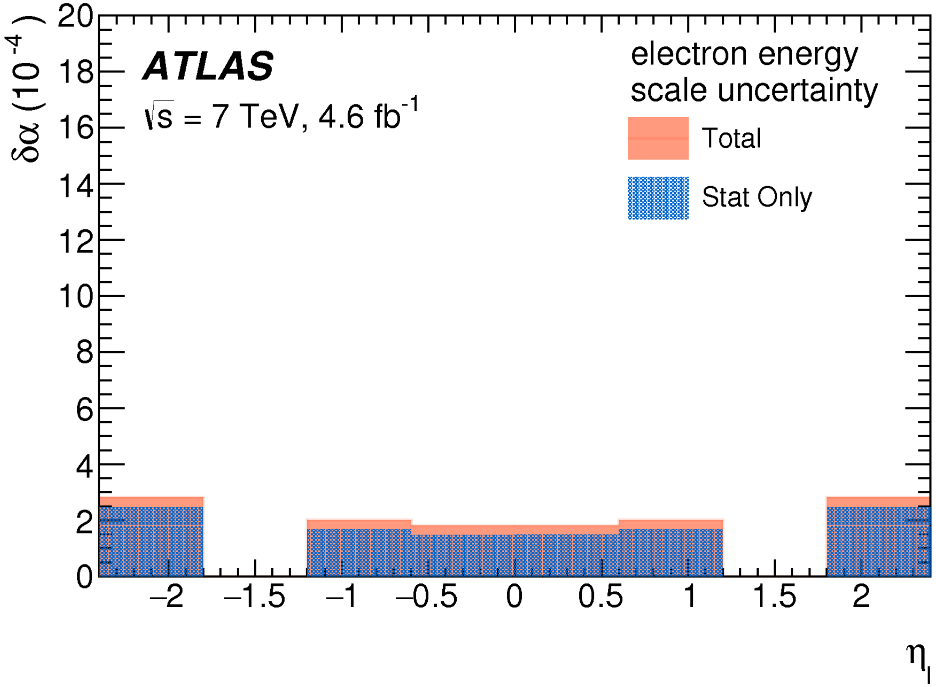


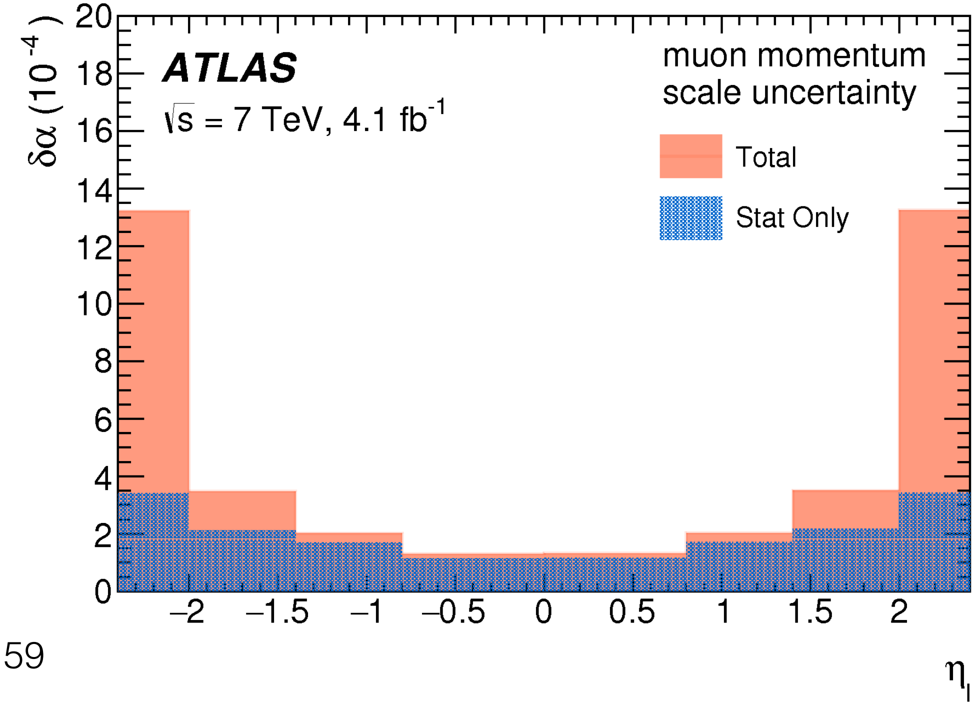


Electron Calibration

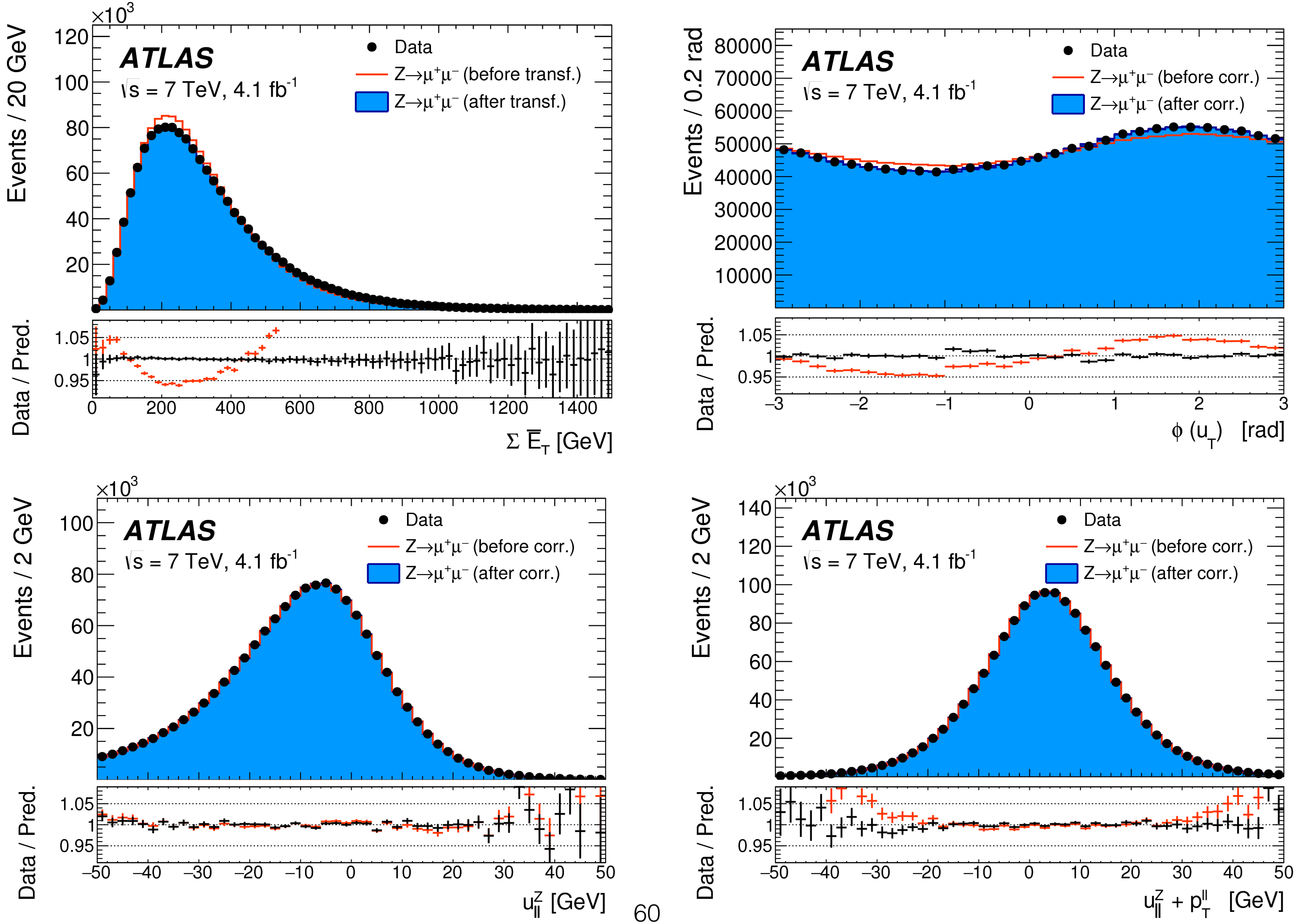




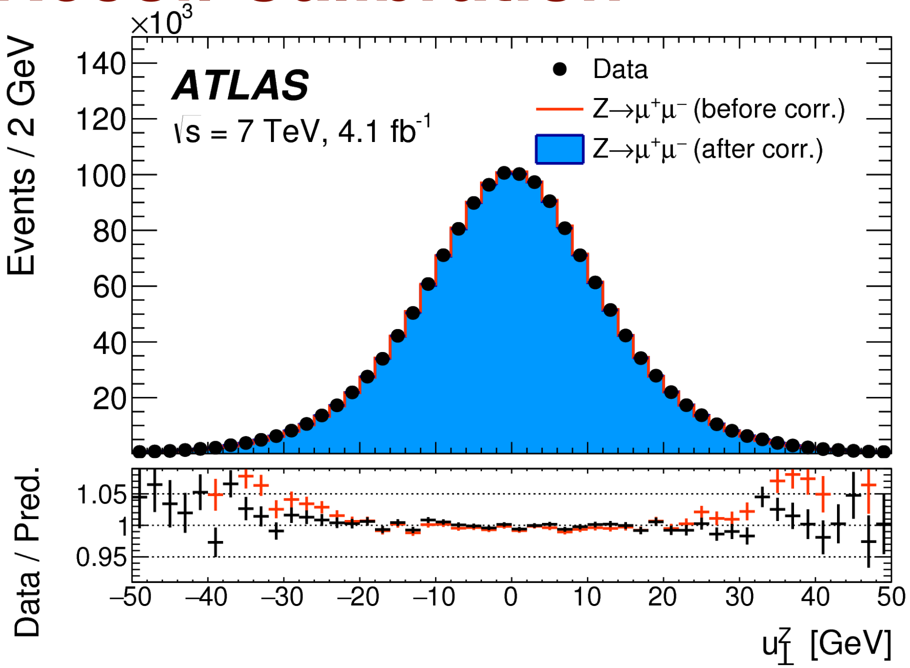


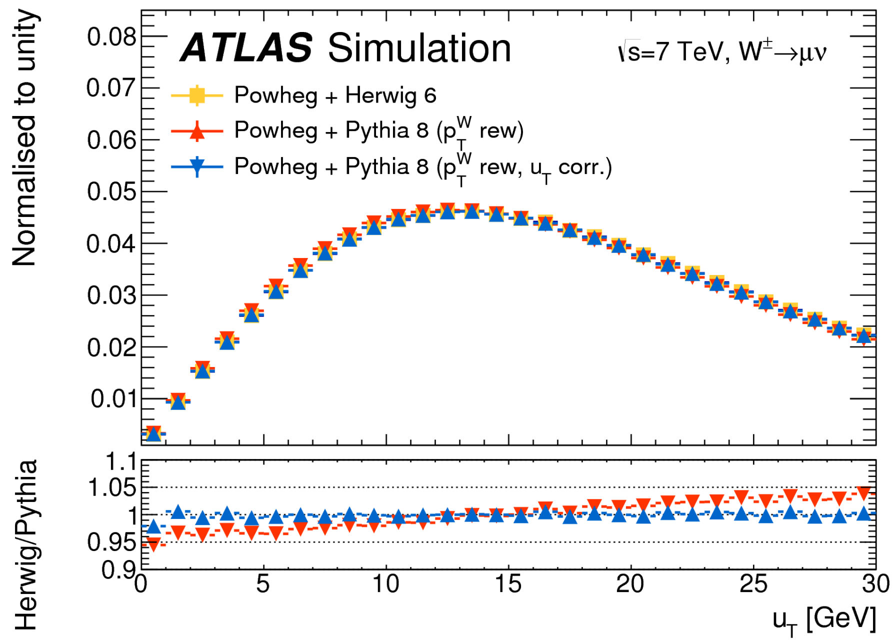


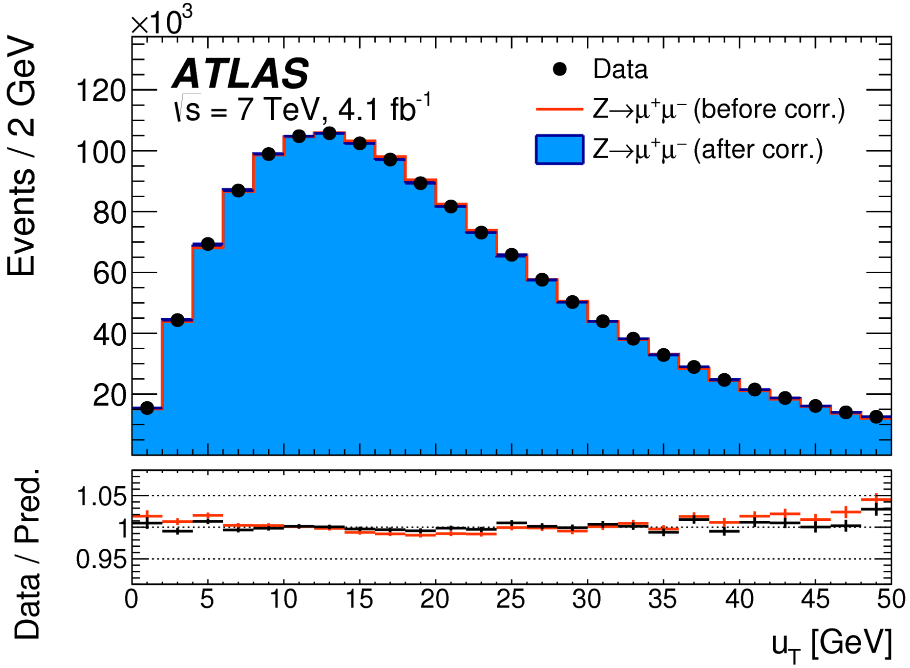
Recoil Calibration

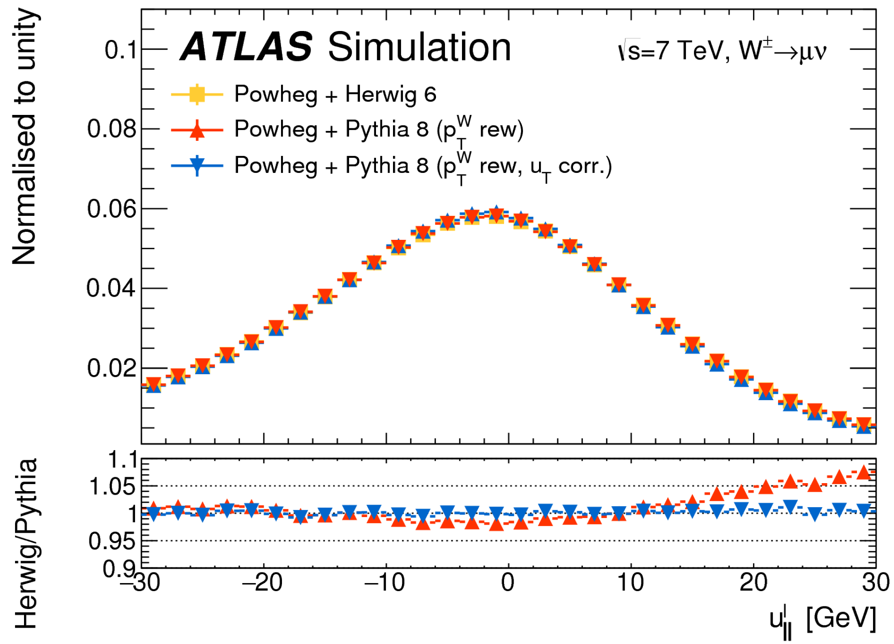


Recoil Calibration

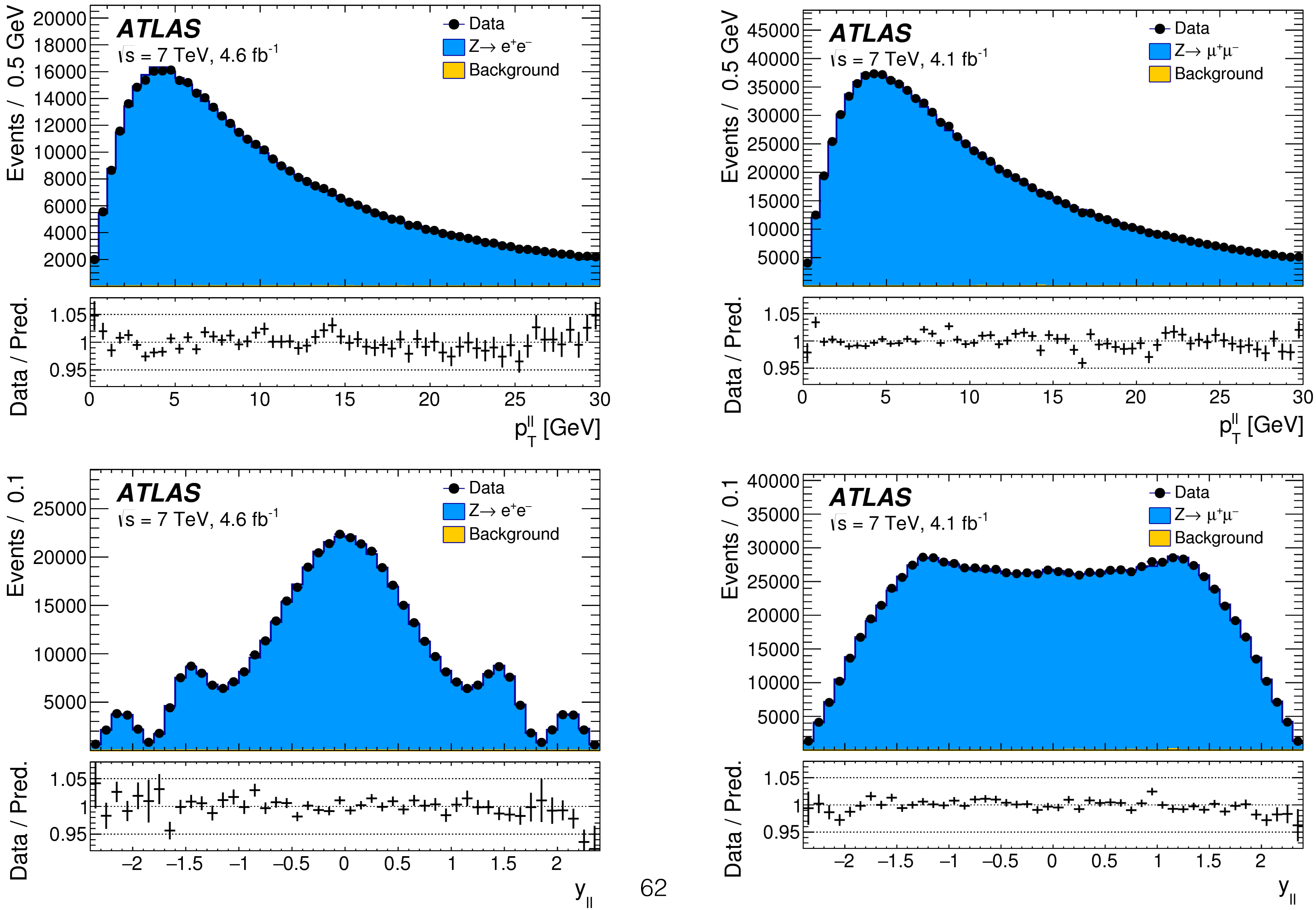




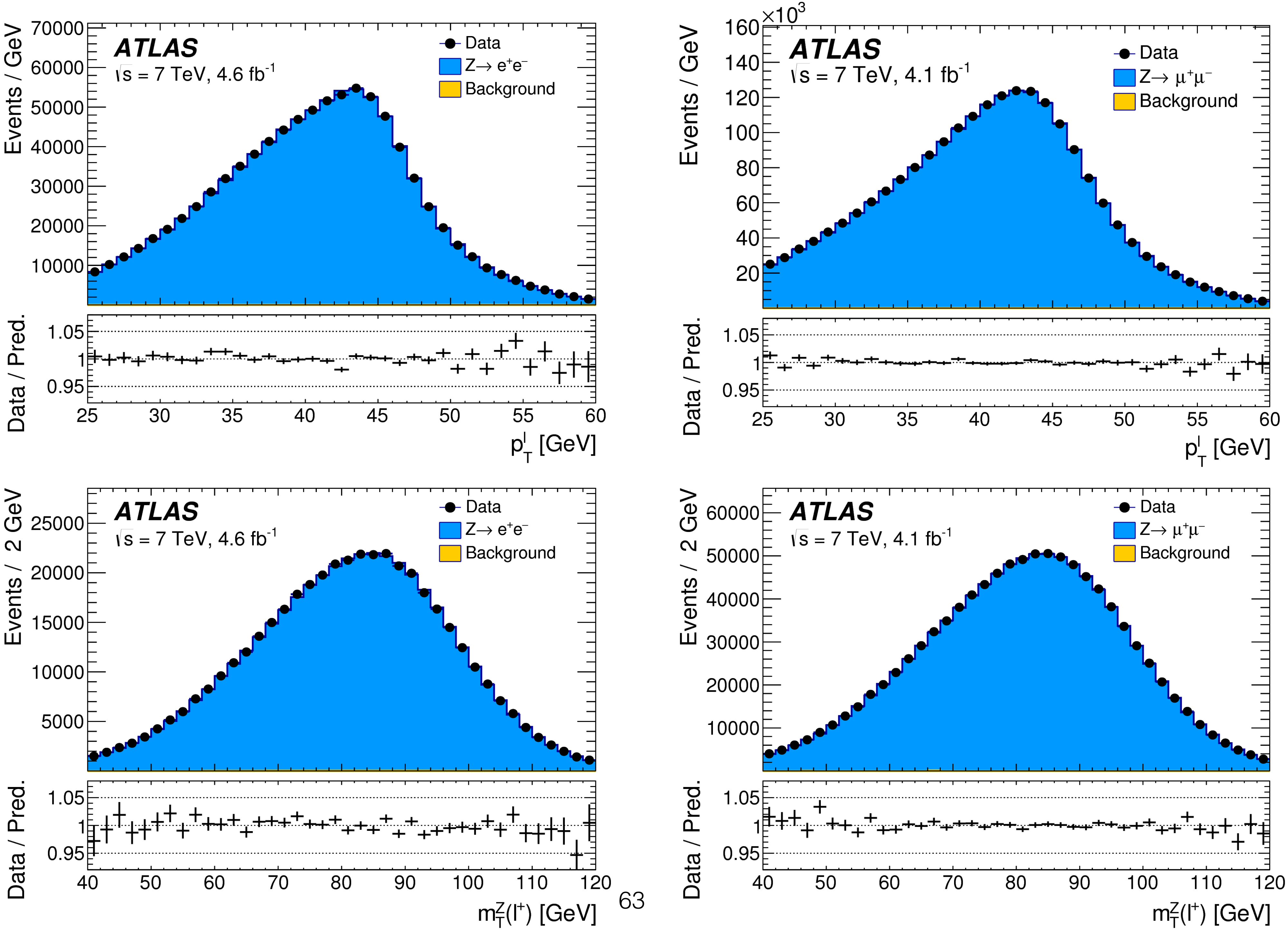




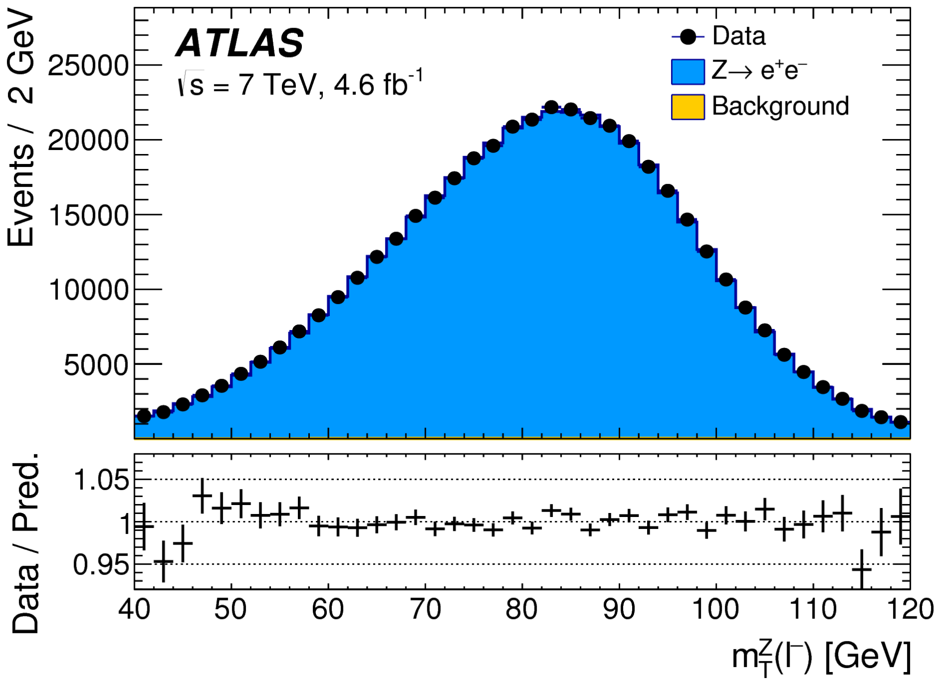
Z control distributions

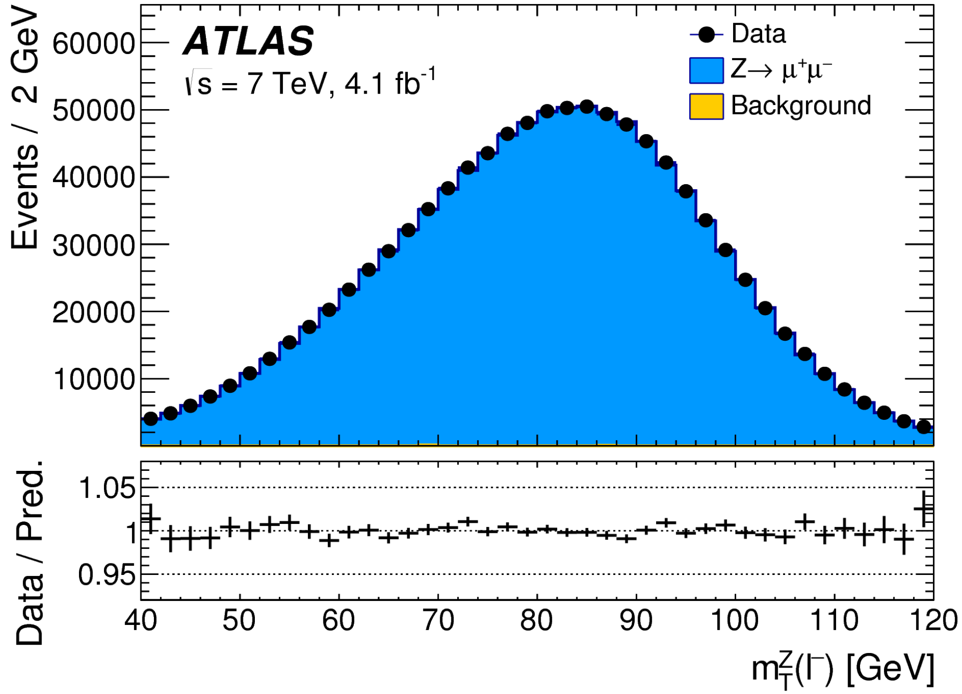


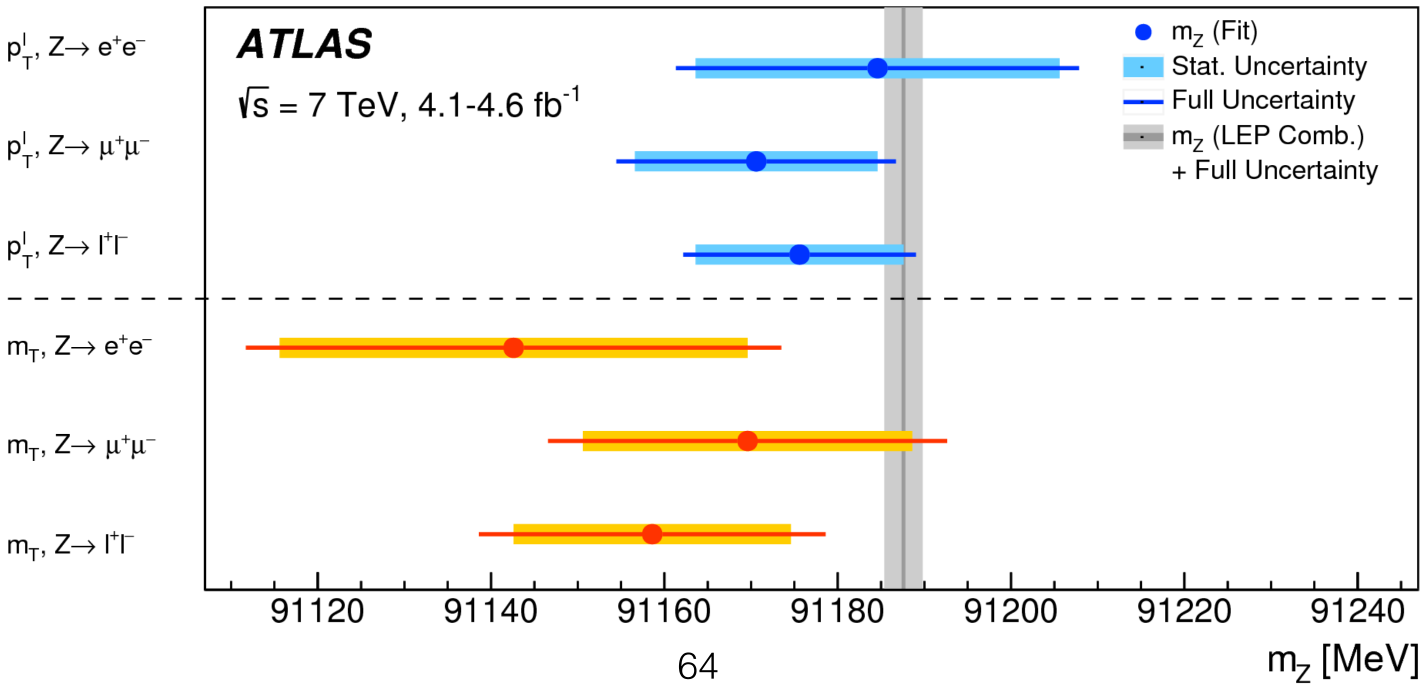
Z control distributions



Z control distributions





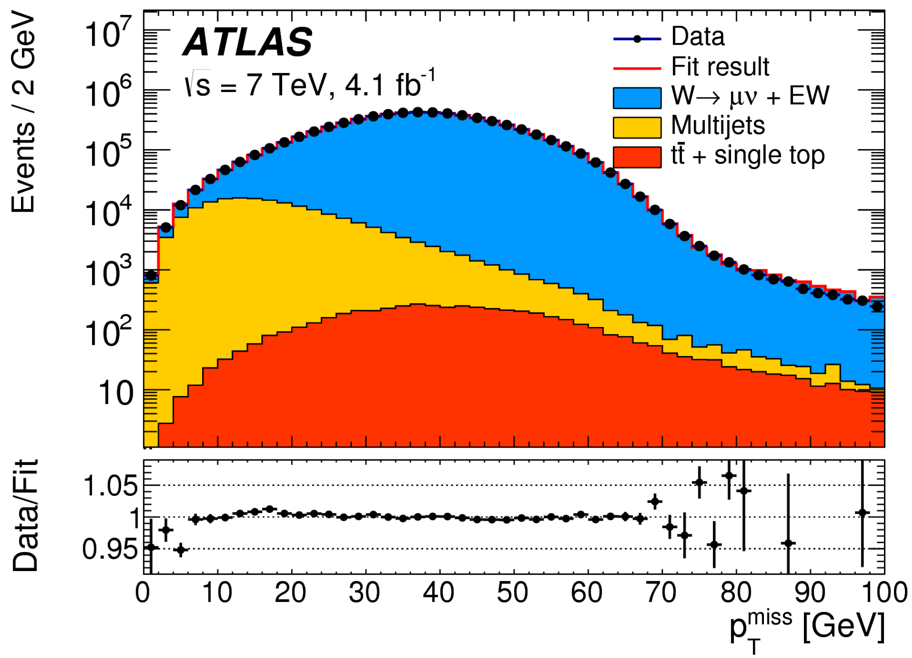


Backgrounds in W

Electroweak and top-quark backgrounds are determined from simulation

Multijet background is determined using data-driven techniques:

- define background-dominated fit regions with relaxed cuts of the event selection
- template fits in these regions to 3 observables: p_T^{miss}, m_T and p_T^l/m_T
- control regions are obtained by inverting the lepton isolation requirements



$W \to \mu\nu$

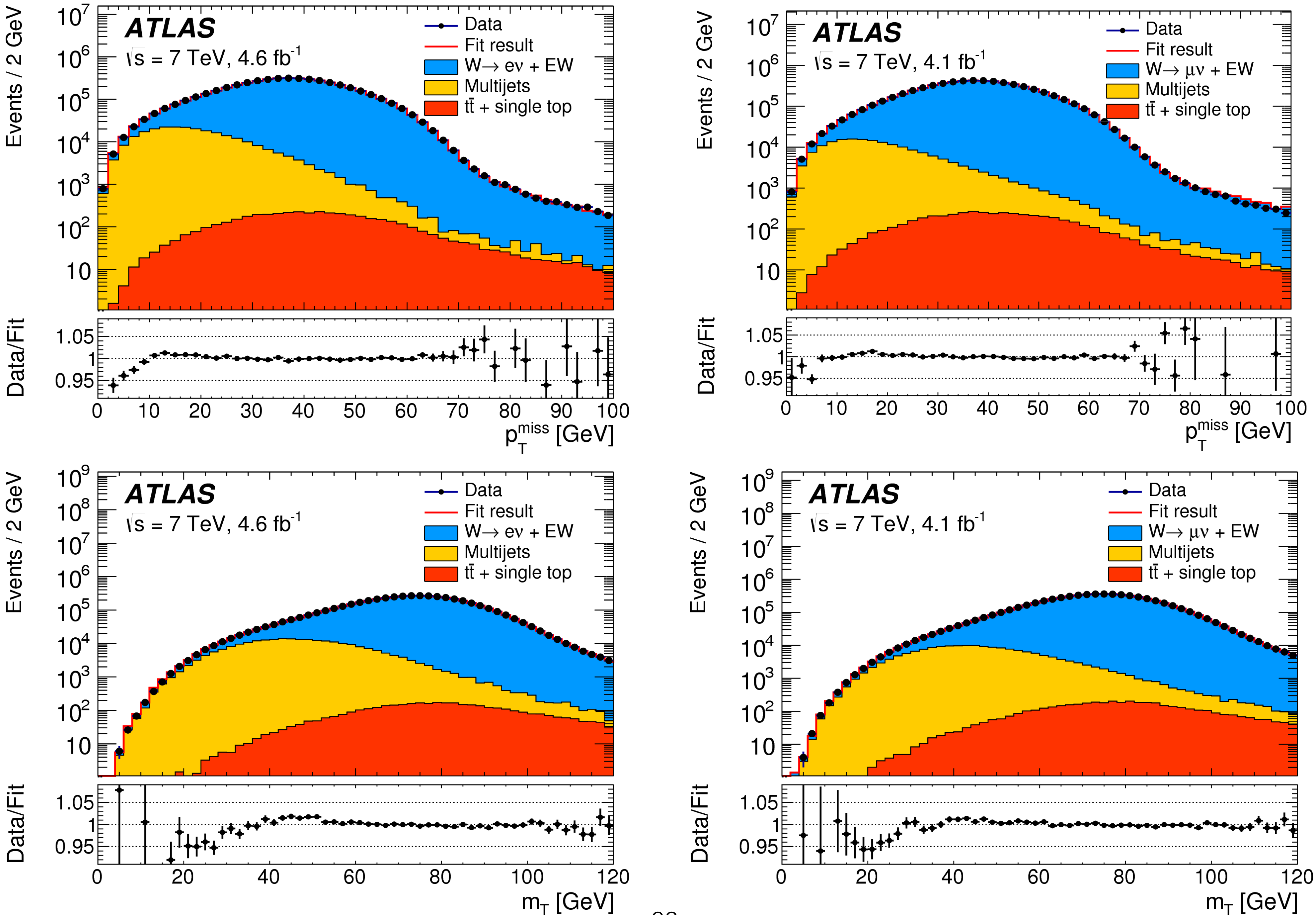
Category	$W \to \tau\nu$	$Z \to \mu\mu$	$Z \to \tau\tau$	Top	Dibosons	Multijet
$W^\pm$ $0.0 < \|\eta\| < 0.8$	1.04	2.83	0.12	0.16	0.08	0.72
$W^\pm$ $0.8 < \|\eta\| < 1.4$	1.01	4.44	0.11	0.12	0.07	0.57
$W^\pm$ $1.4 < \|\eta\| < 2.0$	0.99	6.78	0.11	0.07	0.06	0.51
$W^\pm$ $2.0 < \|\eta\| < 2.4$	1.00	8.50	0.10	0.04	0.05	0.50
$W^\pm$ all η bins	1.01	5.41	0.11	0.10	0.06	0.58
W^+ all η bins	0.99	4.80	0.10	0.09	0.06	0.51
W^- all η bins	1.04	6.28	0.14	0.12	0.08	0.68

$W \to e\nu$

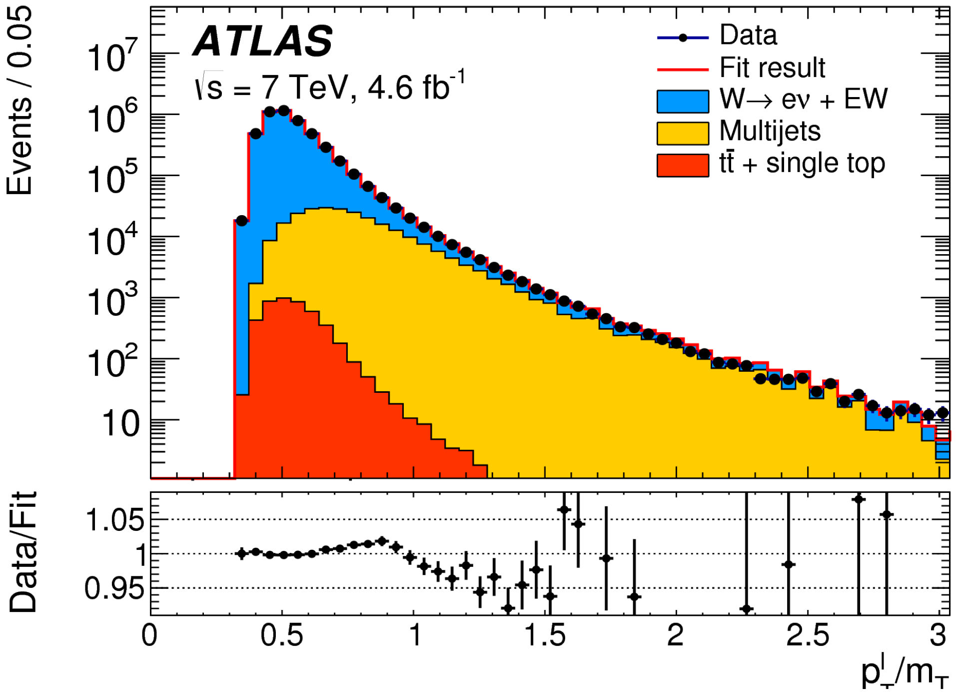
Category	$W \to \tau\nu$	$Z \to ee$	$Z \to \tau\tau$	Top	Dibosons	Multijet
$W^\pm$ $0.0 < \|\eta\| < 0.6$	1.02	3.34	0.13	0.15	0.08	0.59
$W^\pm$ $0.6 < \|\eta\| < 1.2$	1.00	3.48	0.12	0.13	0.08	0.76
$W^\pm$ $1.8 < \|\eta\| < 2.4$	0.97	3.23	0.11	0.05	0.05	1.74
$W^\pm$ all η bins	1.00	3.37	0.12	0.12	0.07	1.00
W^+ all η bins	0.98	2.92	0.10	0.11	0.06	0.84
W^- all η bins	1.04	3.98	0.14	0.13	0.08	1.21

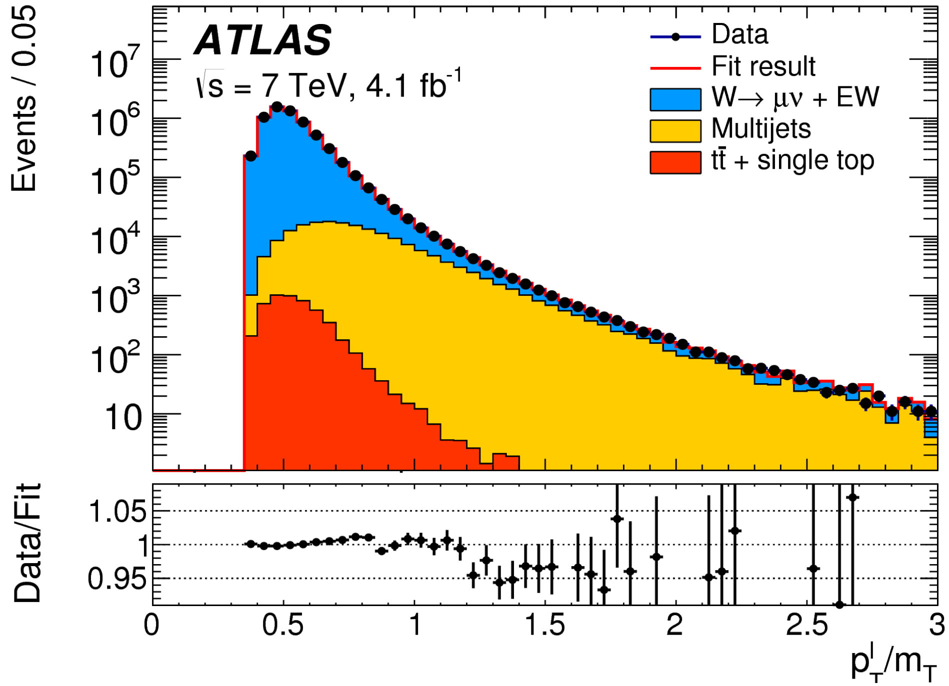
Kinematic distribution	p_T^ℓ				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	3.5	4.5	–	–	4.3	5.2
$Z \to \tau\tau$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
WW, WZ, ZZ (fraction)	0.1	0.1	0.1	0.1	0.4	0.4	0.3	0.4
Top (fraction)	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
Multijet (fraction)	3.2	3.6	1.8	2.4	8.1	8.6	3.7	4.6
Multijet (shape)	3.8	3.1	1.6	1.5	8.6	8.0	2.5	2.4
Total	6.0	6.8	4.3	5.3	12.6	13.4	6.2	7.4

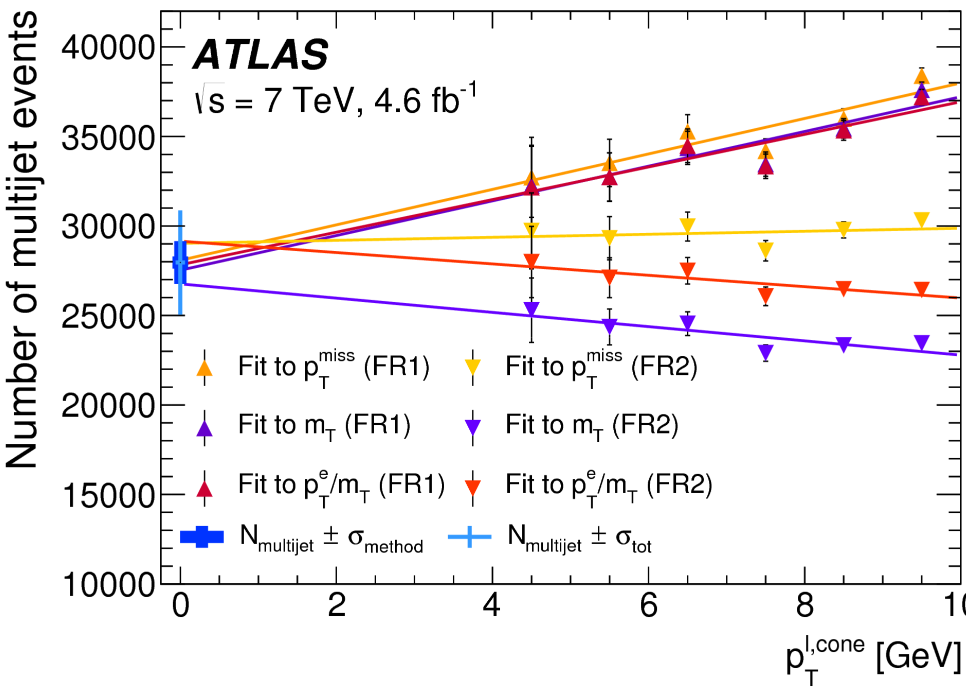
W background

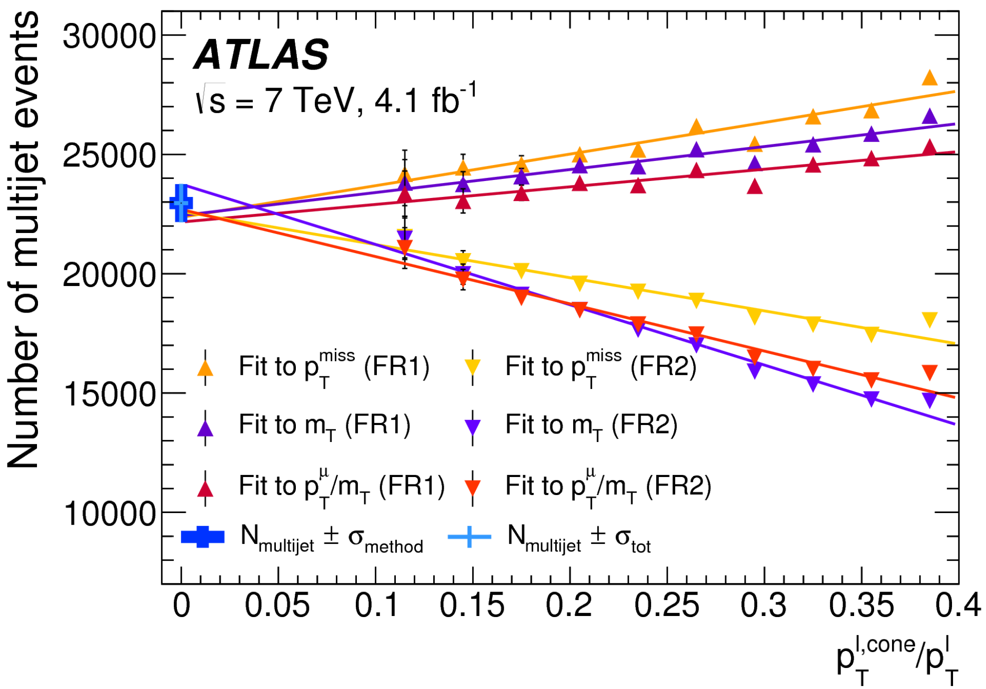


W background

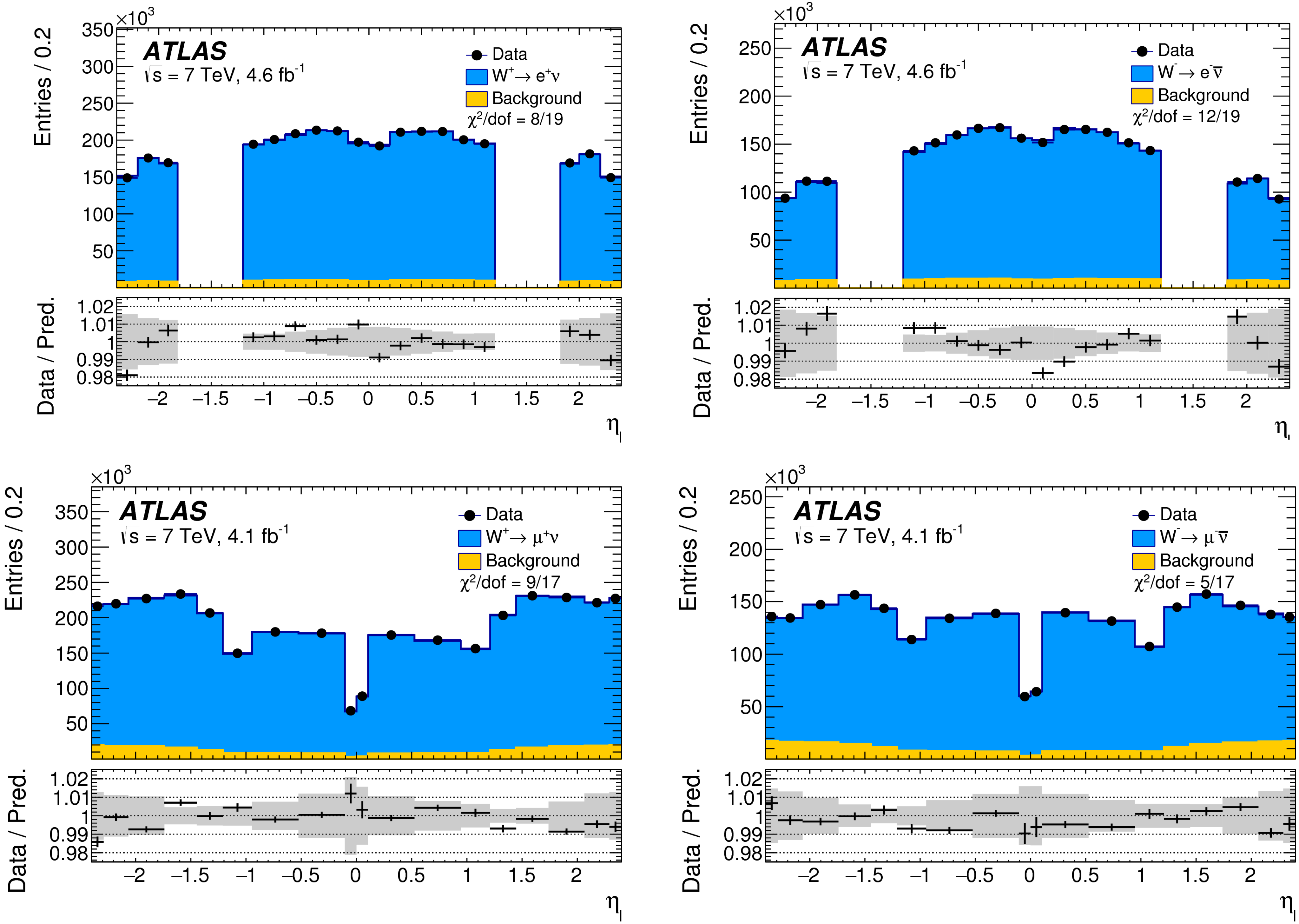




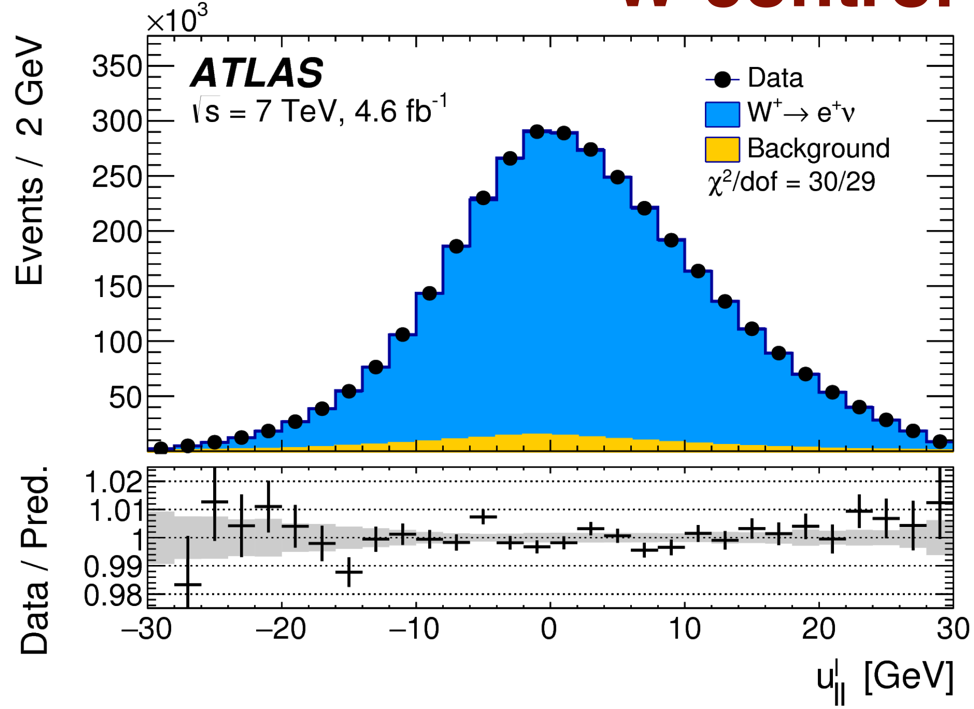


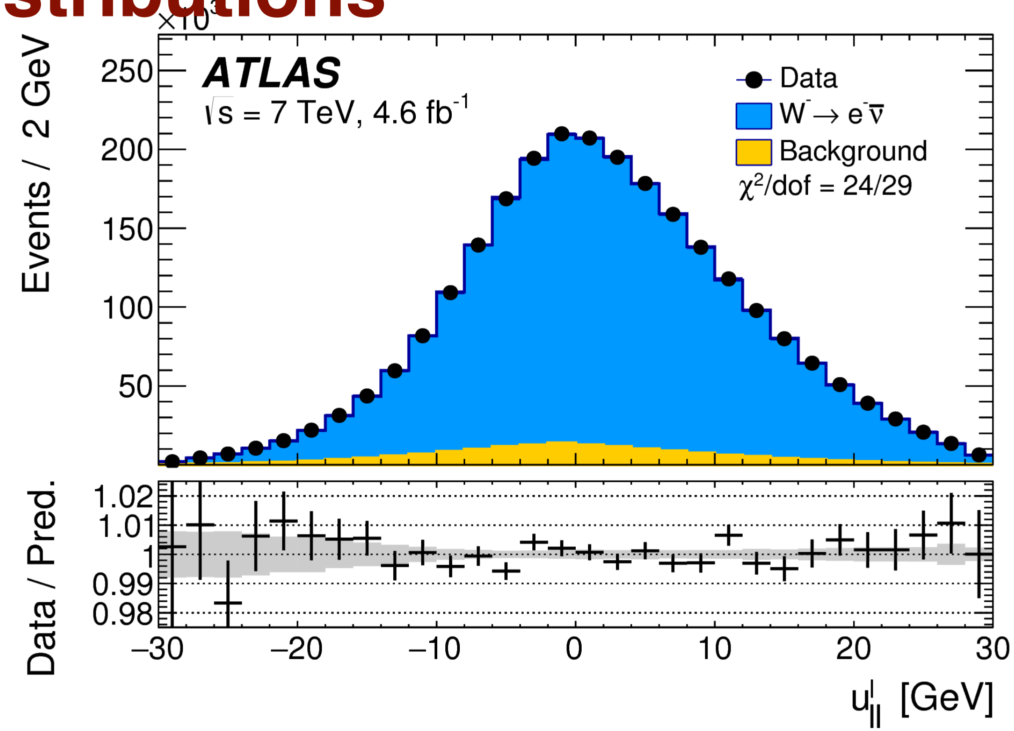


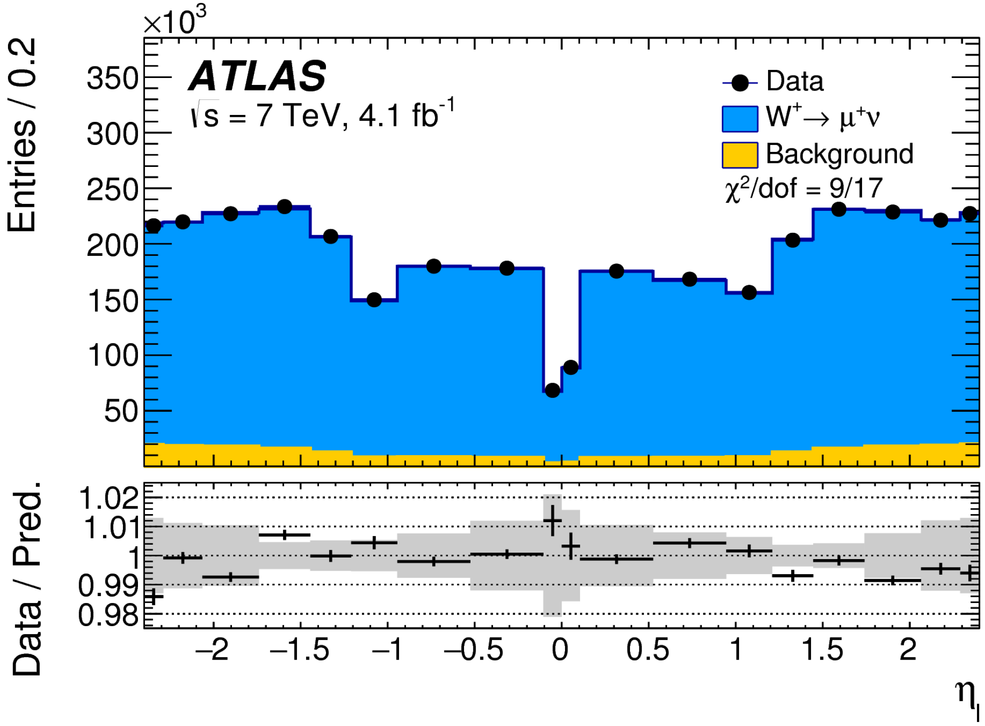
W control distributions

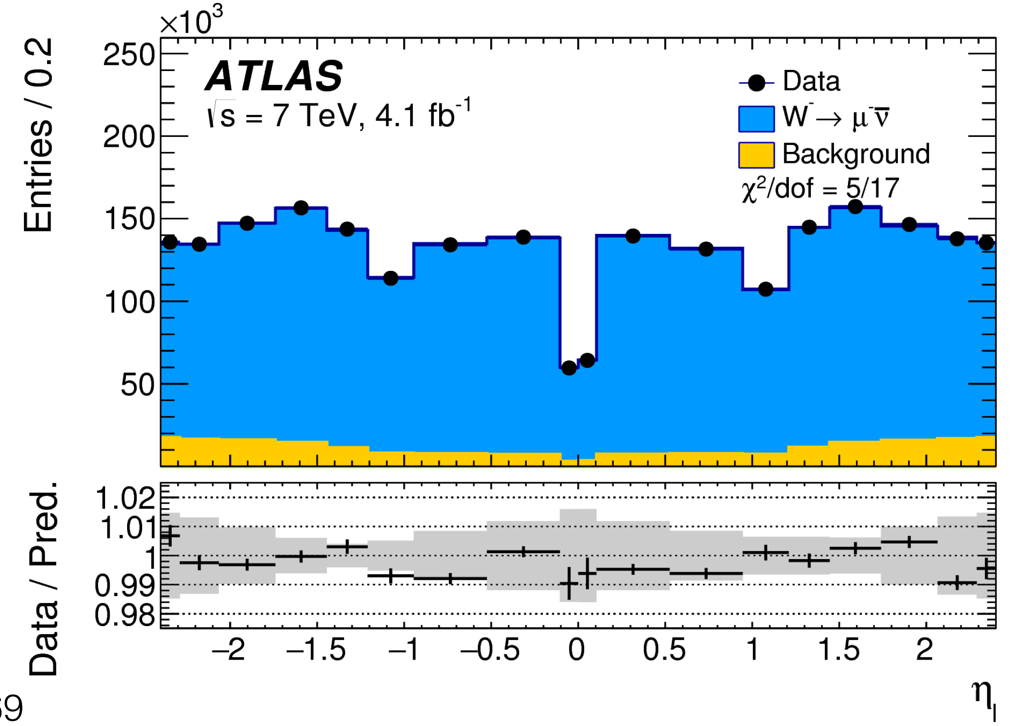


W control distributions

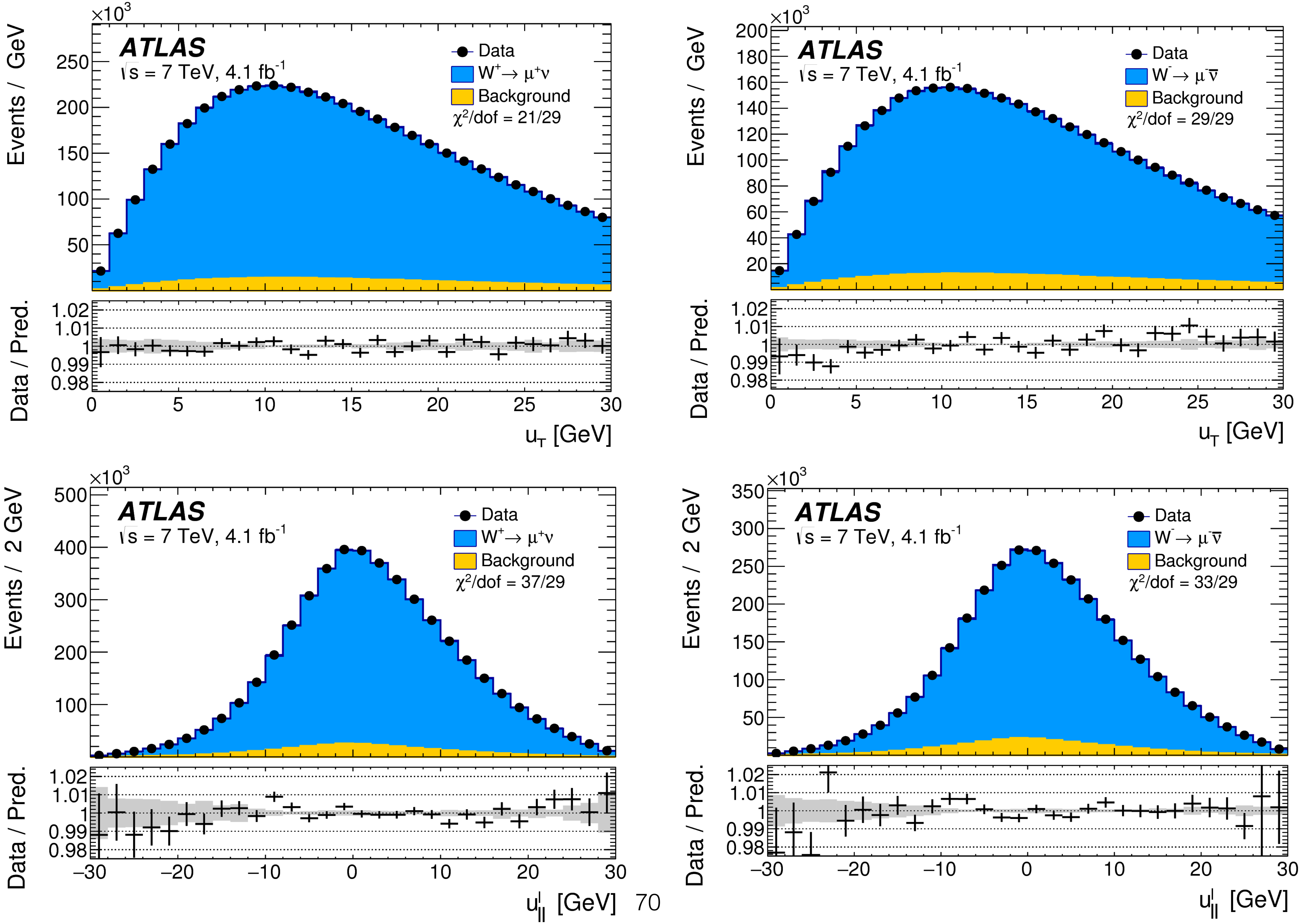




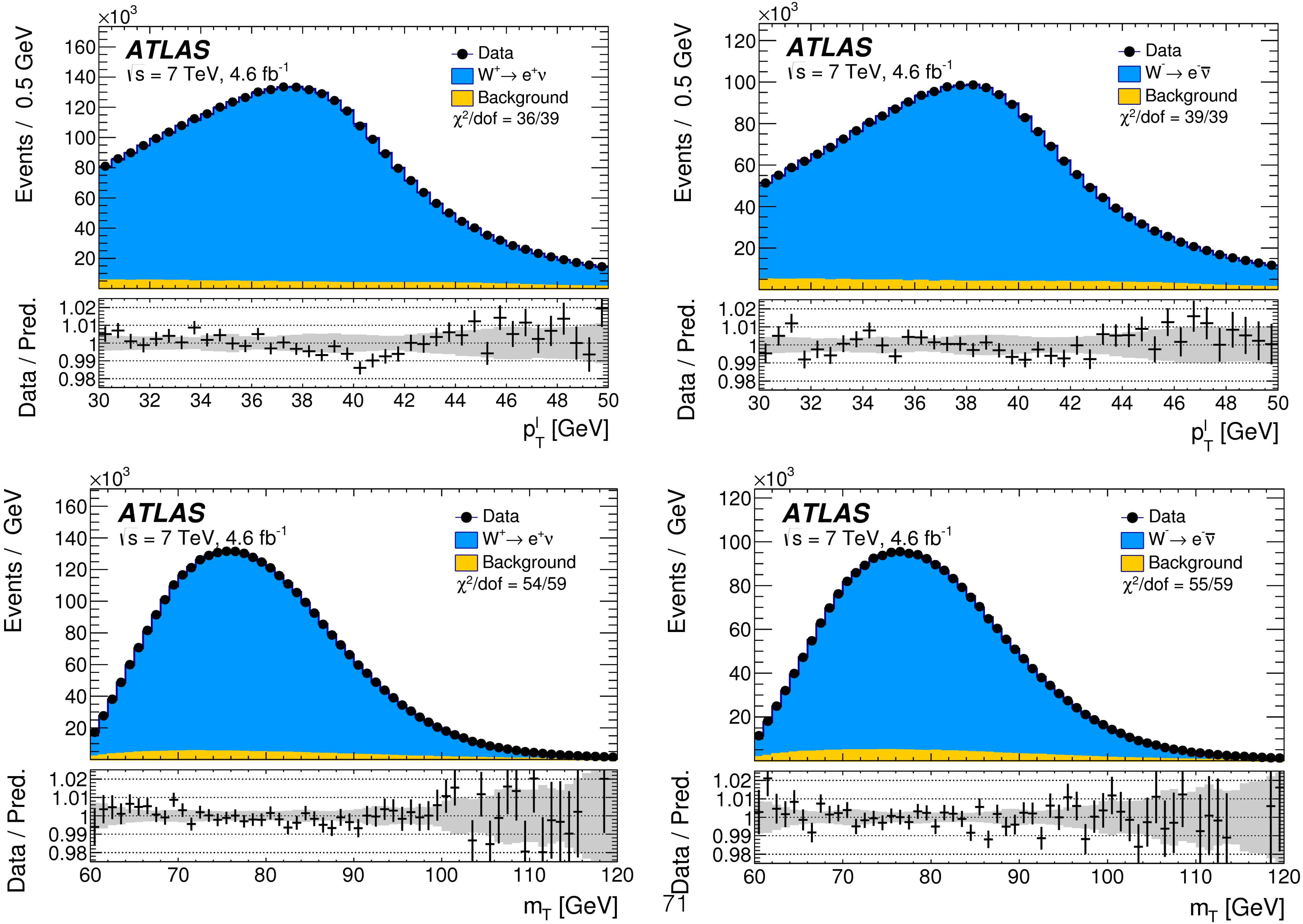




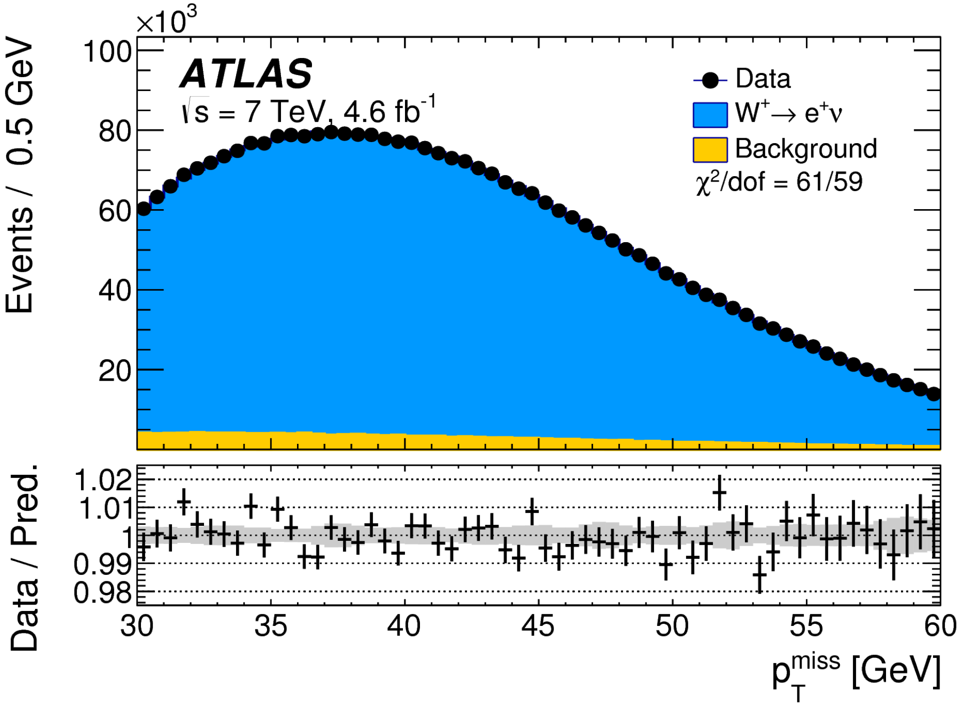
W control distributions

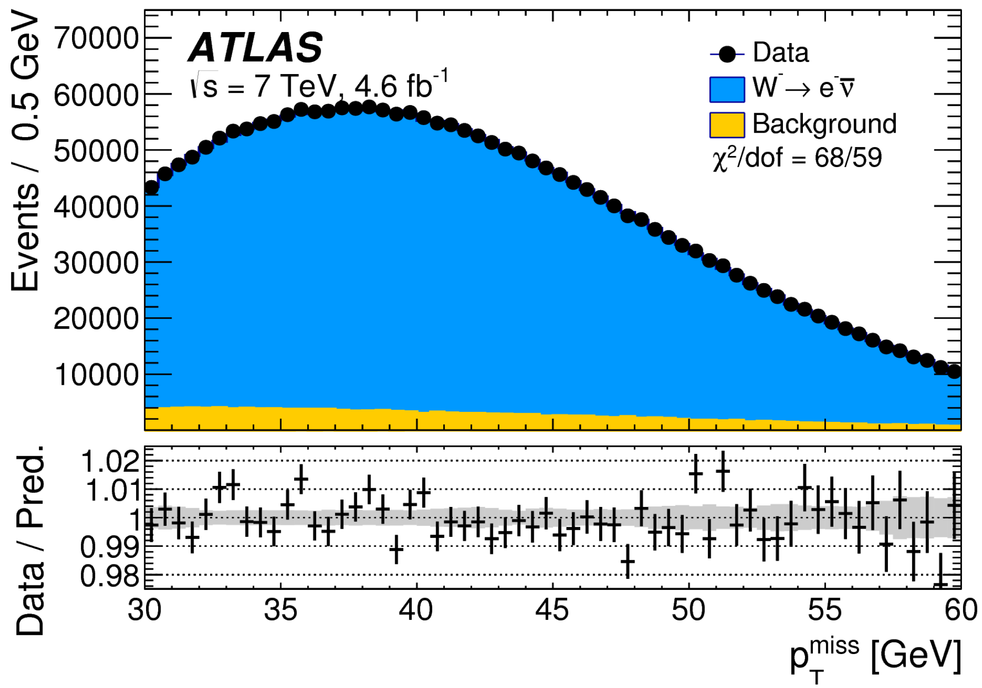


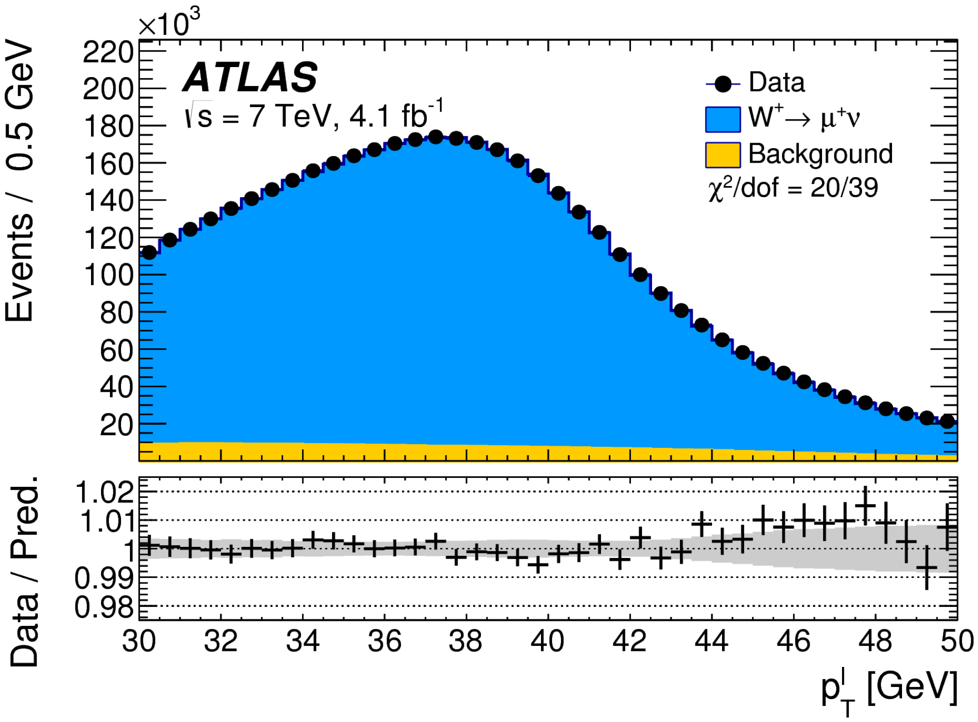
W control distributions

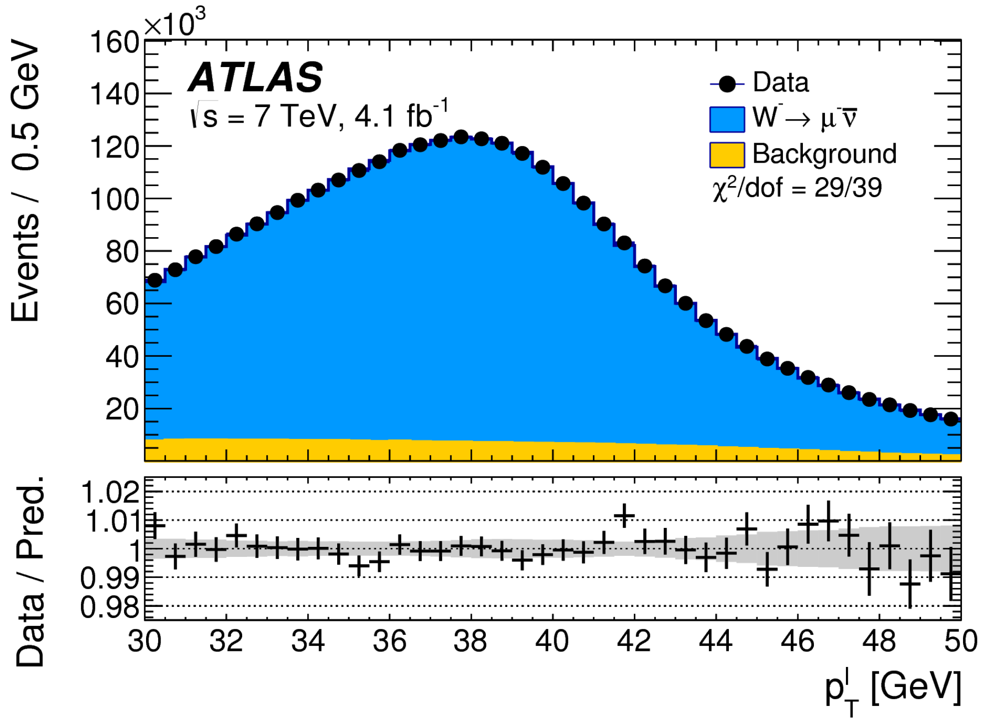


W control distributions

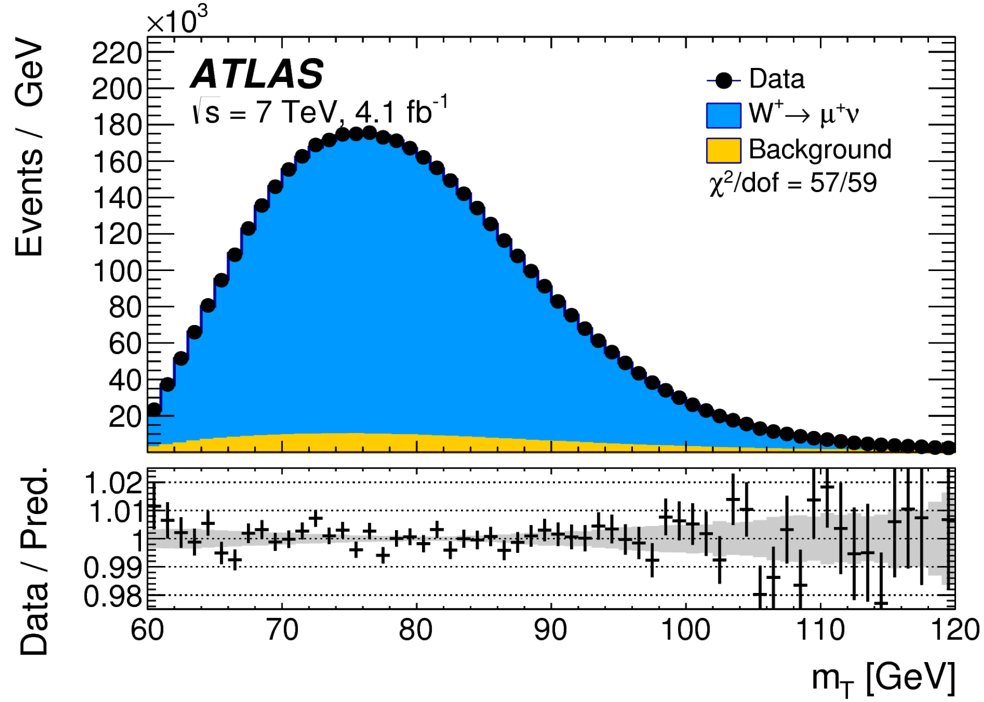


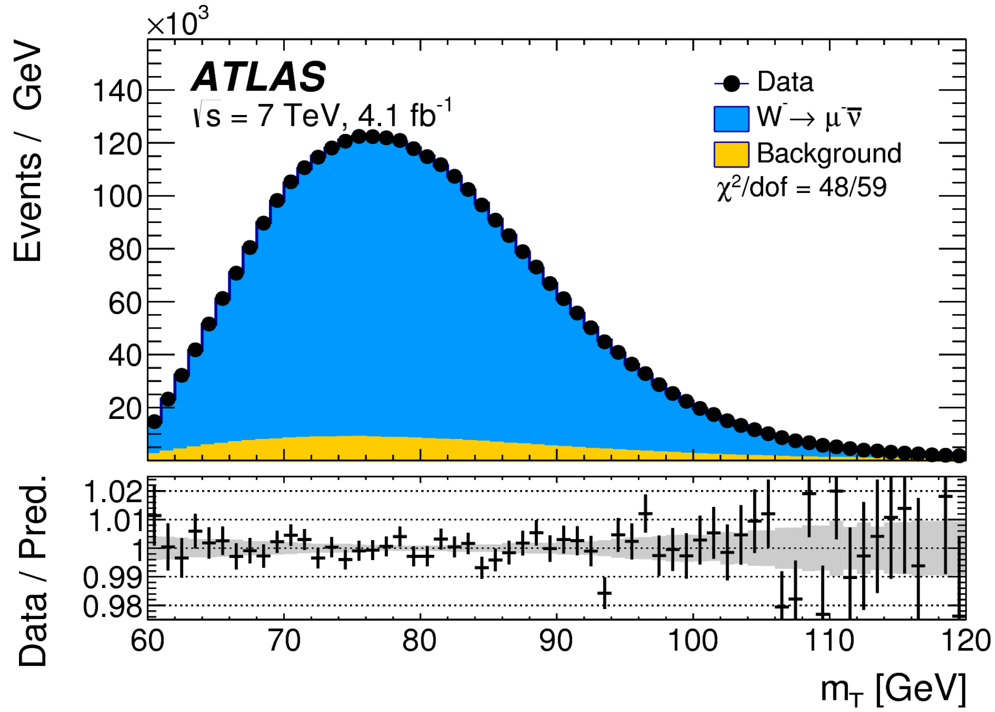


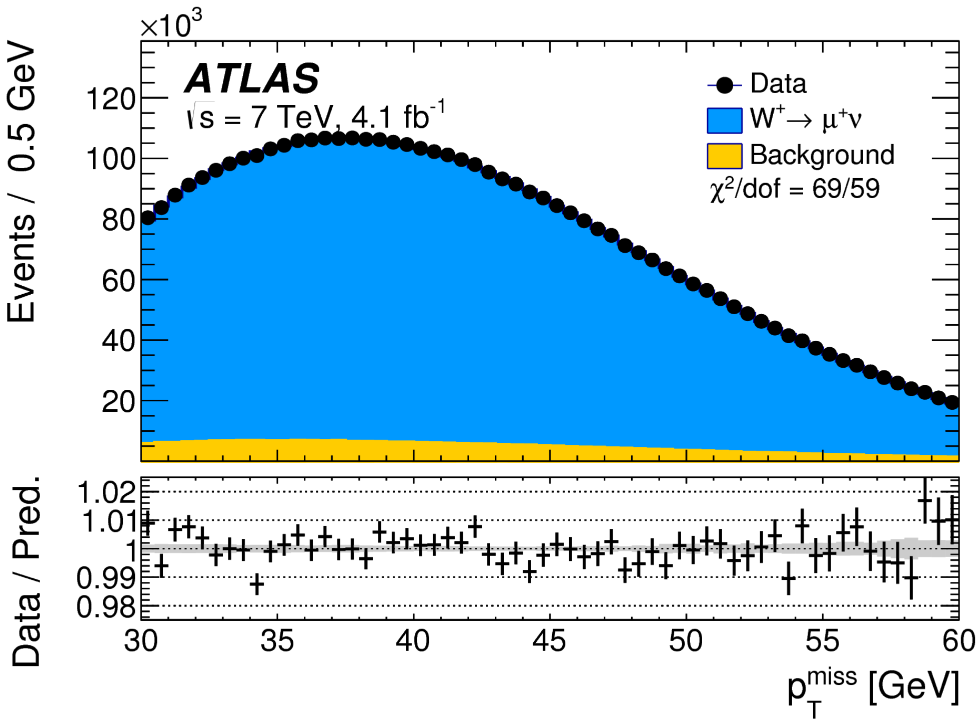


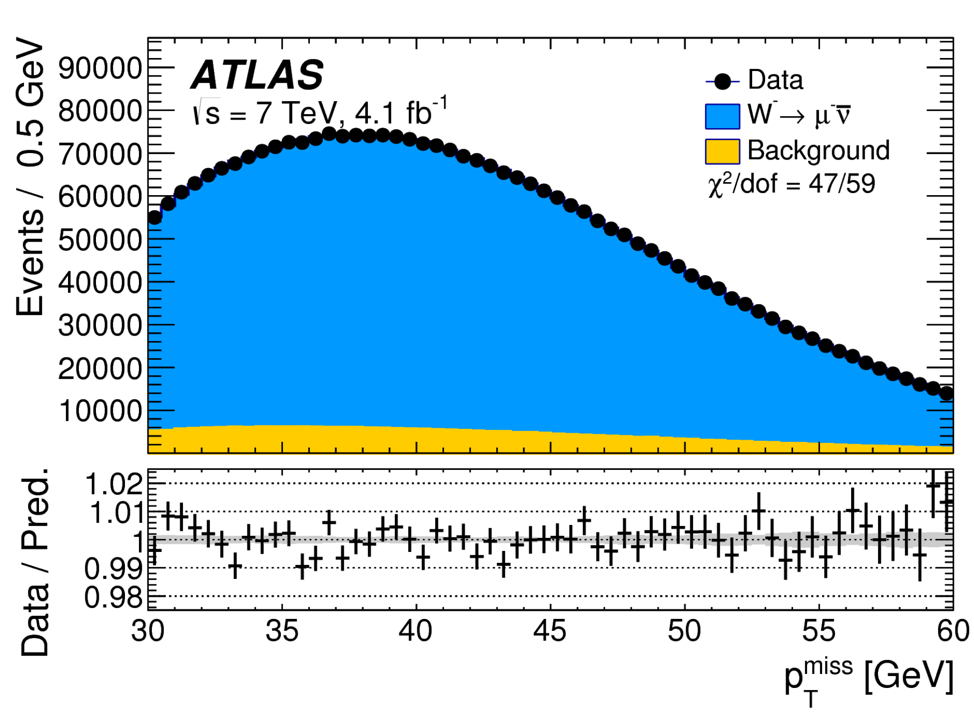


W control distributions

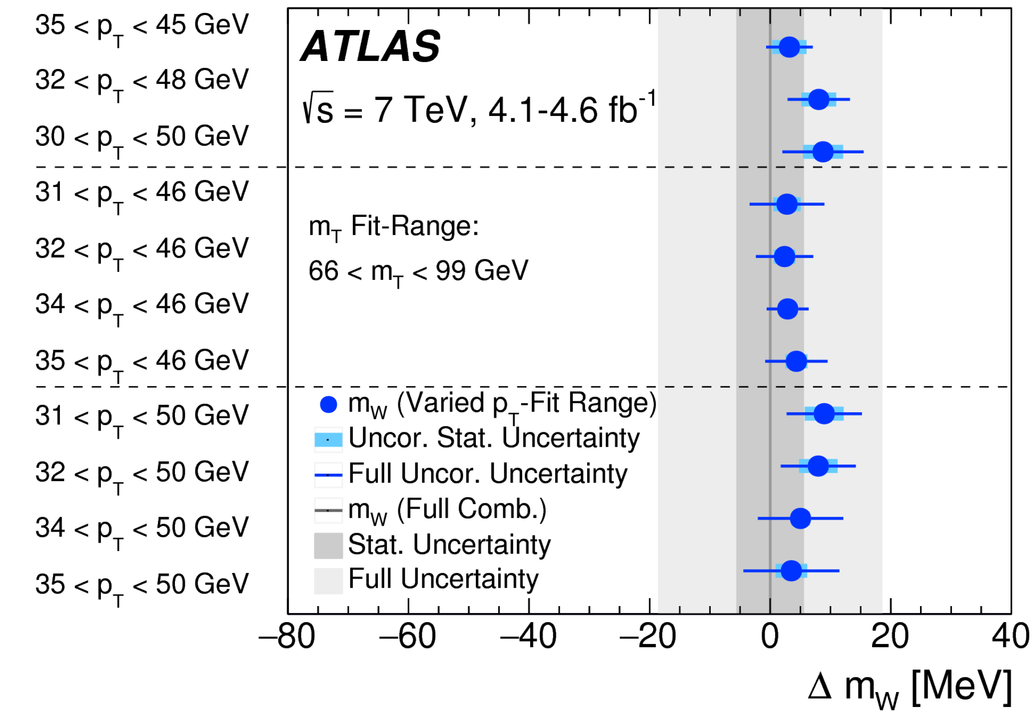


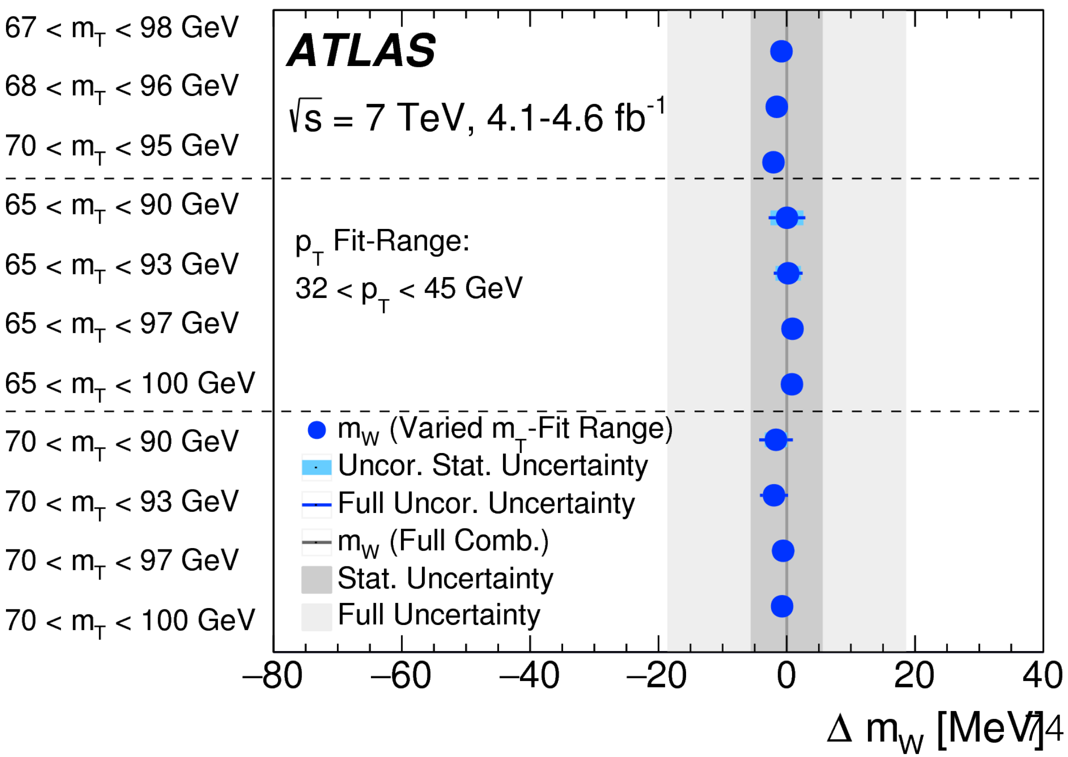


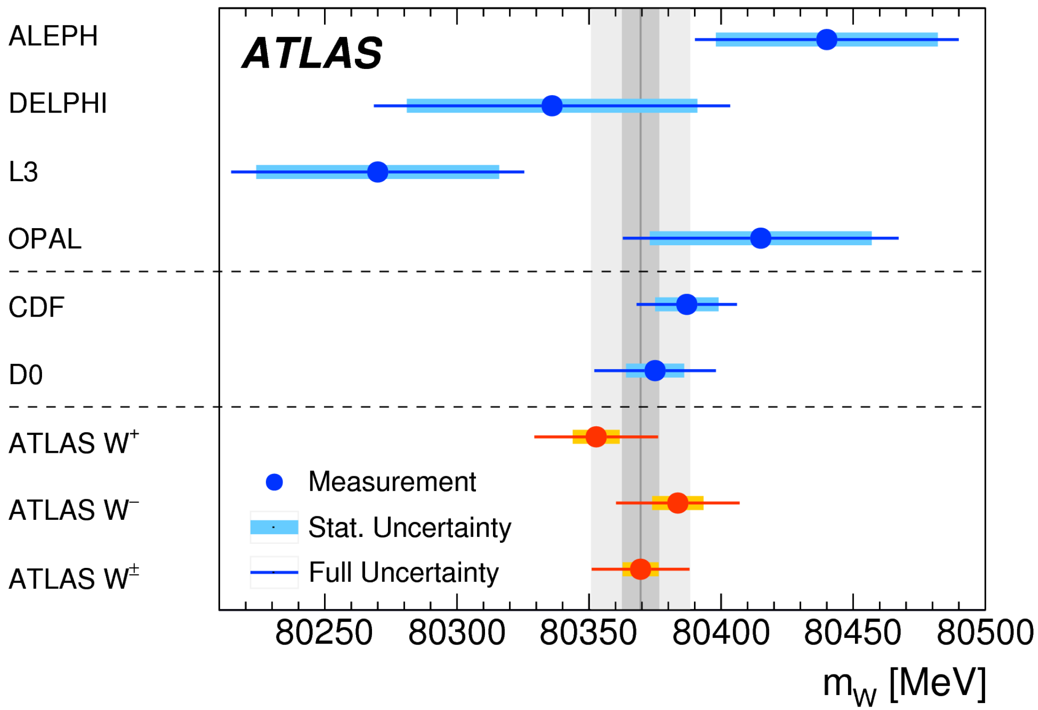




W mass results







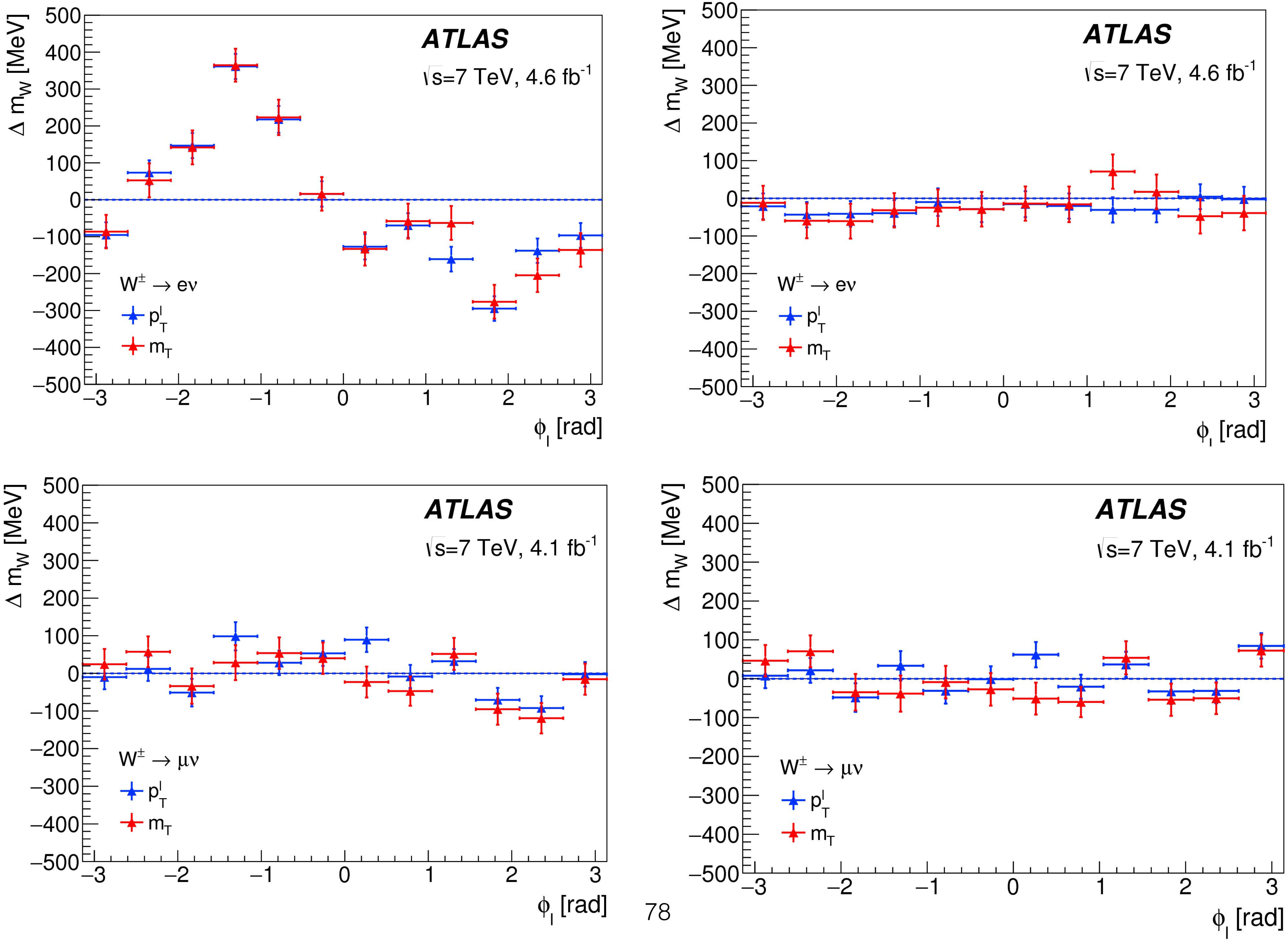
Channel m_{T}-Fit	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80371.3	29.2	12.4	0.0	15.2	8.1	9.9	3.4	28.4	47.1
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80354.1	32.1	19.3	0.0	13.0	6.8	9.6	3.4	23.3	47.6
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80426.3	30.2	35.1	0.0	14.3	7.2	9.3	3.4	27.2	56.9
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.6	40.9	112.4	0.0	14.4	9.0	8.4	3.4	32.8	125.5
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80375.5	30.6	11.6	0.0	13.1	8.5	9.5	3.4	30.6	48.5
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80417.5	36.4	18.5	0.0	12.2	7.7	9.7	3.4	22.2	49.7
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80379.4	35.6	33.9	0.0	10.5	8.1	9.7	3.4	23.1	56.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.2	52.4	123.7	0.0	11.6	10.2	9.9	3.4	34.1	139.9
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80352.9	29.4	0.0	19.5	13.1	15.3	9.9	3.4	28.5	50.8
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80381.5	30.4	0.0	21.4	15.1	13.2	9.6	3.4	23.5	49.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80352.4	32.4	0.0	26.6	16.4	32.8	8.4	3.4	27.3	62.6
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80415.8	31.3	0.0	16.4	11.8	15.5	9.5	3.4	31.3	52.1
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80297.5	33.0	0.0	18.7	11.2	12.8	9.7	3.4	23.9	49.0
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80423.8	42.8	0.0	33.2	12.8	35.1	9.9	3.4	28.1	72.3
p_{T}-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80327.7	22.1	12.2	0.0	2.6	5.1	9.0	6.0	24.7	37.3
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80357.3	25.1	19.1	0.0	2.5	4.7	8.9	6.0	20.6	39.5
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80446.9	23.9	33.1	0.0	2.5	4.9	8.2	6.0	25.2	49.3
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.1	34.5	110.1	0.0	2.5	6.4	6.7	6.0	31.8	120.2
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80427.8	23.3	11.6	0.0	2.6	5.8	8.1	6.0	26.4	39.0
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80395.6	27.9	18.3	0.0	2.5	5.6	8.0	6.0	19.8	40.5
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80380.6	28.1	35.2	0.0	2.6	5.6	8.0	6.0	20.6	50.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80315.2	45.5	116.1	0.0	2.6	7.6	8.3	6.0	32.7	129.6
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80336.5	22.2	0.0	20.1	2.5	6.4	9.0	5.3	24.5	40.7
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80345.8	22.8	0.0	21.4	2.6	6.7	8.9	5.3	20.5	39.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80344.7	24.0	0.0	30.8	2.6	11.9	6.7	5.3	24.1	48.2
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80351.0	23.1	0.0	19.8	2.6	7.2	8.1	5.3	26.6	42.2
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80309.8	24.9	0.0	19.7	2.7	7.3	8.0	5.3	20.9	39.9
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80413.4	30.1	0.0	30.7	2.7	11.5	8.3	5.3	22.7	51.0

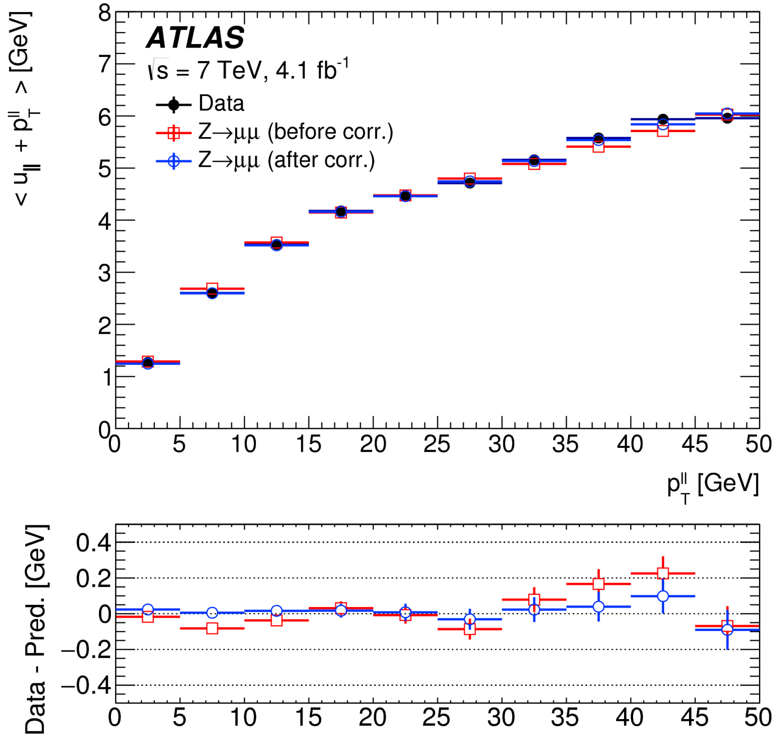
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_{T}, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_{T}, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_{T}, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_{T}^{ℓ}, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_{T}^{ℓ}, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_{T}^{ℓ}, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_{T}^{ℓ}, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_{T}, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_{T}-p_{T}^{ℓ}, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_{T}-p_{T}^{ℓ}, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_{T}-p_{T}^{ℓ}, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_{T}^{ℓ}, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_{T}, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_{T}-p_{T}^{ℓ}, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_{T}-p_{T}^{ℓ}, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_{T}-p_{T}^{ℓ}, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_{T}-p_{T}^{ℓ}, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_{T}-p_{T}^{ℓ}, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_{T}-p_{T}^{ℓ}, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

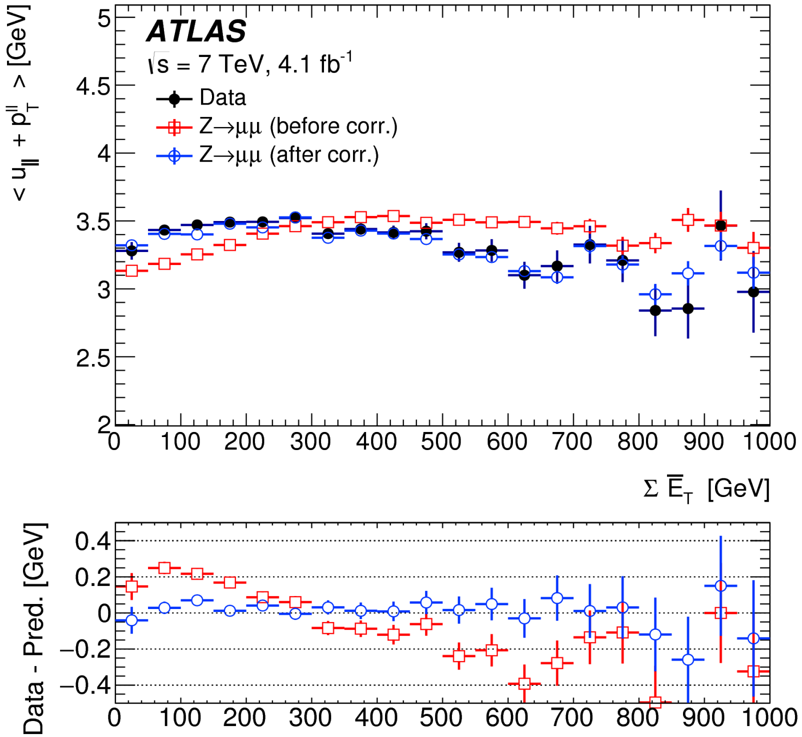
Decay channel	$W \to e\nu$		$W \to \mu\nu$		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_W [MeV]						
$\langle\mu\rangle$ in $[2.5, 6.5]$	8 ± 14	14 ± 18	-21 ± 12	0 ± 16	-9 ± 9	6 ± 12
$\langle\mu\rangle$ in $[6.5, 9.5]$	-6 ± 16	6 ± 23	12 ± 15	-8 ± 22	4 ± 11	-1 ± 16
$\langle\mu\rangle$ in $[9.5, 16]$	-1 ± 16	3 ± 27	25 ± 16	35 ± 26	12 ± 11	20 ± 19
u_T in $[0, 15] GeV$	0 ± 11	-8 ± 13	5 ± 10	8 ± 12	3 ± 7	-1 ± 9
u_T in $[15, 30] GeV$	10 ± 15	0 ± 24	-4 ± 14	-18 ± 22	2 ± 10	-10 ± 16
$u_\parallel^\ell < 0\, GeV$	8 ± 15	20 ± 17	3 ± 13	-1 ± 16	5 ± 10	9 ± 12
$u_\parallel^\ell > 0\, GeV$	-9 ± 10	1 ± 14	-12 ± 10	10 ± 13	-11 ± 7	6 ± 10
No p_T^{miss}-cut	14 ± 9	-1 ± 13	10 ± 8	-6 ± 12	12 ± 6	-4 ± 9

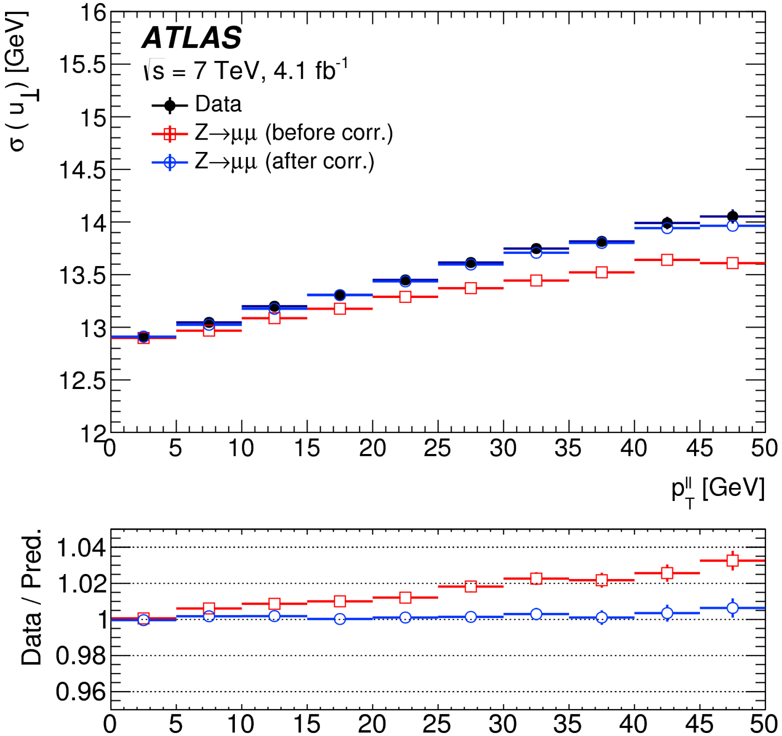
Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	-29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	-28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	-29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

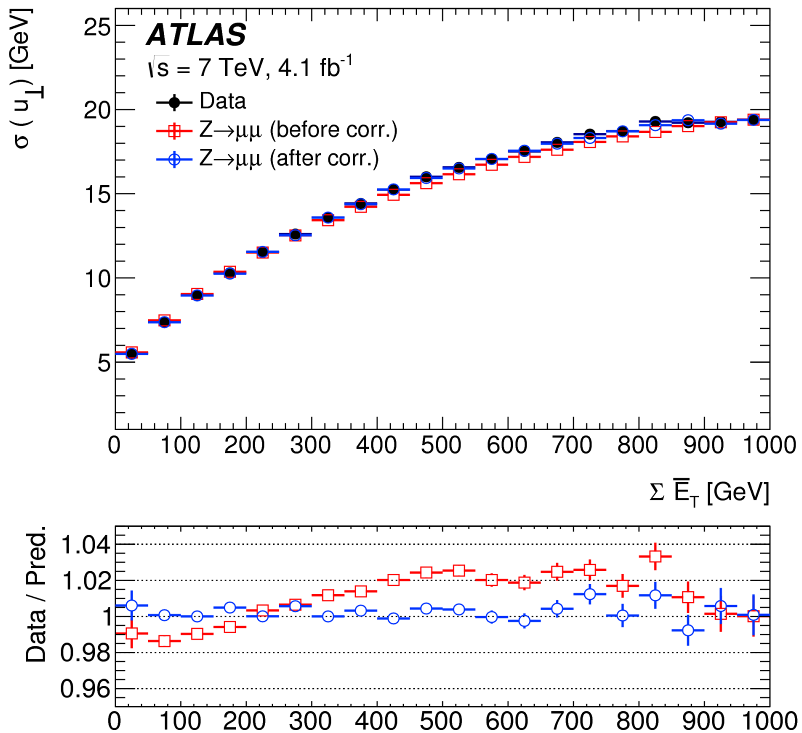
W mass results

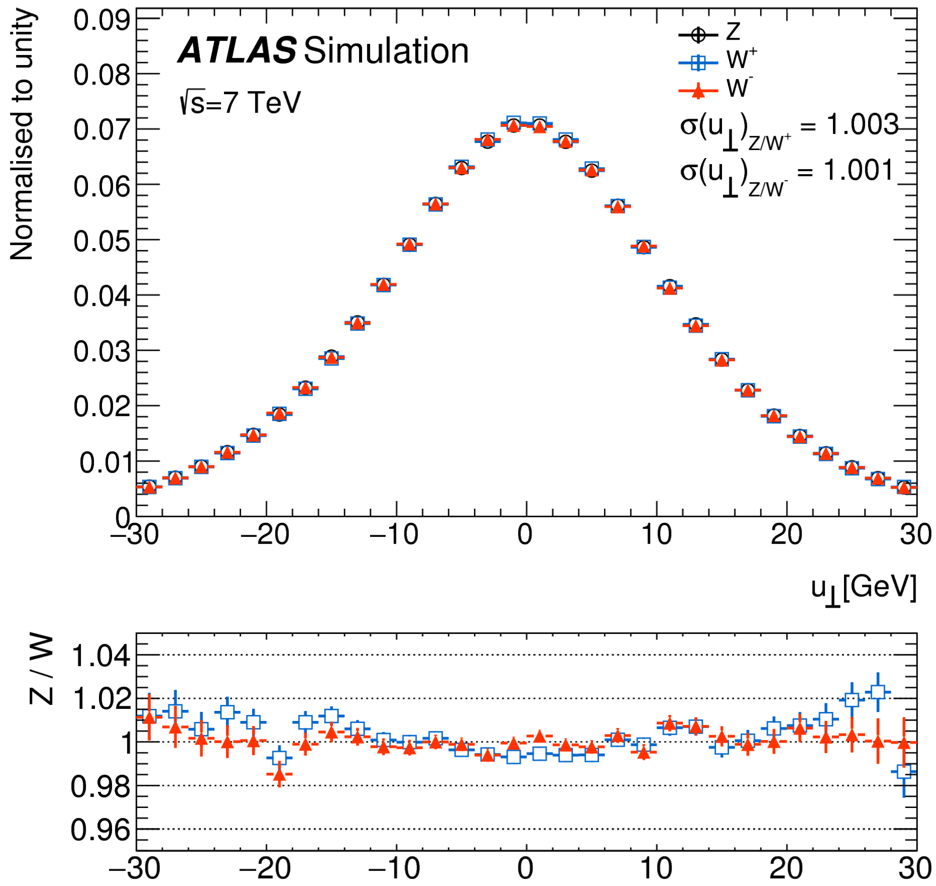


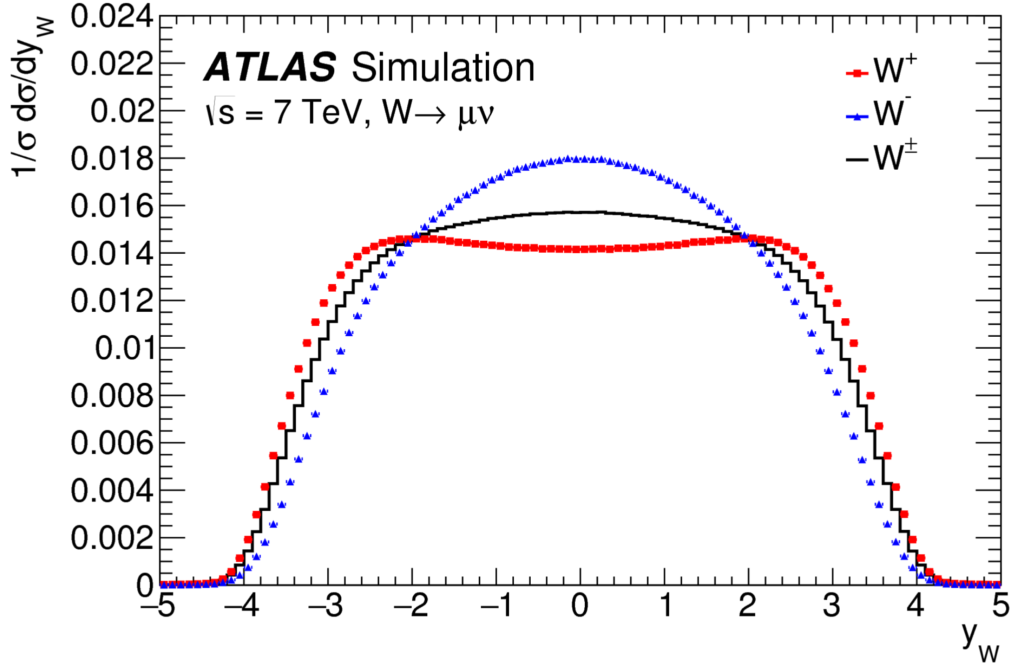

ATLAS
√s = 7 TeV, 4.1 fb^{-1}
Data
Z→μμ (before corr.)
Z→μμ (after corr.)
< $u_{\parallel} + p_T^{ll}$ > [GeV]
p_T^{ll} [GeV]
Data - Pred. [GeV]

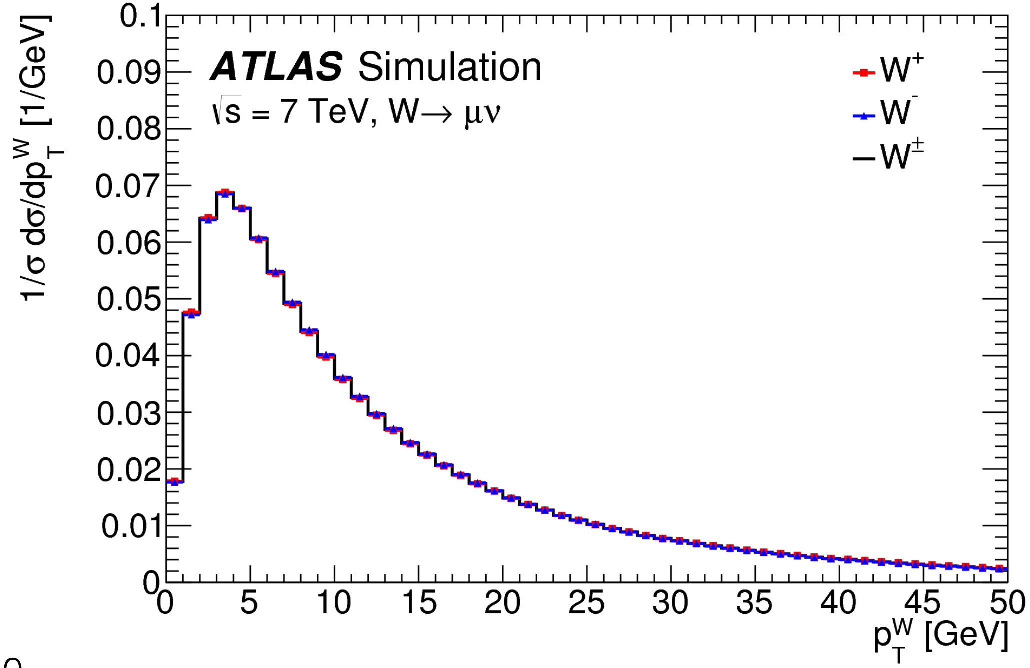

ATLAS
√s = 7 TeV, 4.1 fb^{-1}
Data
Z→μμ (before corr.)
Z→μμ (after corr.)
< $u_{\parallel} + p_T^{ll}$ > [GeV]
$\Sigma \bar{E}_T$ [GeV]
Data - Pred. [GeV]

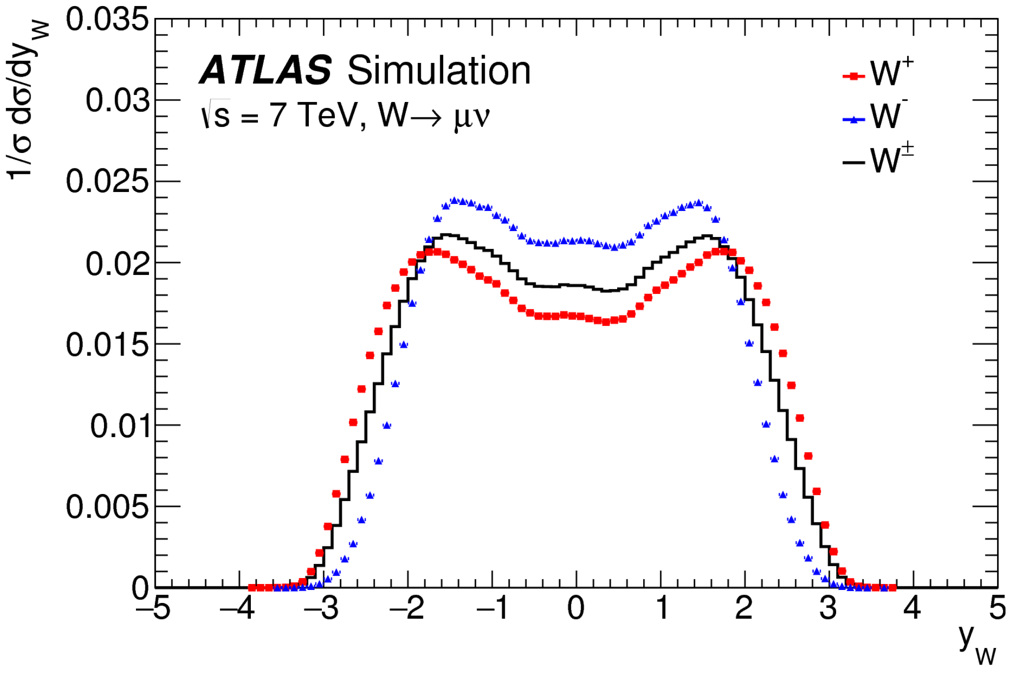

ATLAS
√s = 7 TeV, 4.1 fb^{-1}
Data
Z→μμ (before corr.)
Z→μμ (after corr.)
σ ($u_{\perp}$) [GeV]
p_T^{ll} [GeV]
Data / Pred.

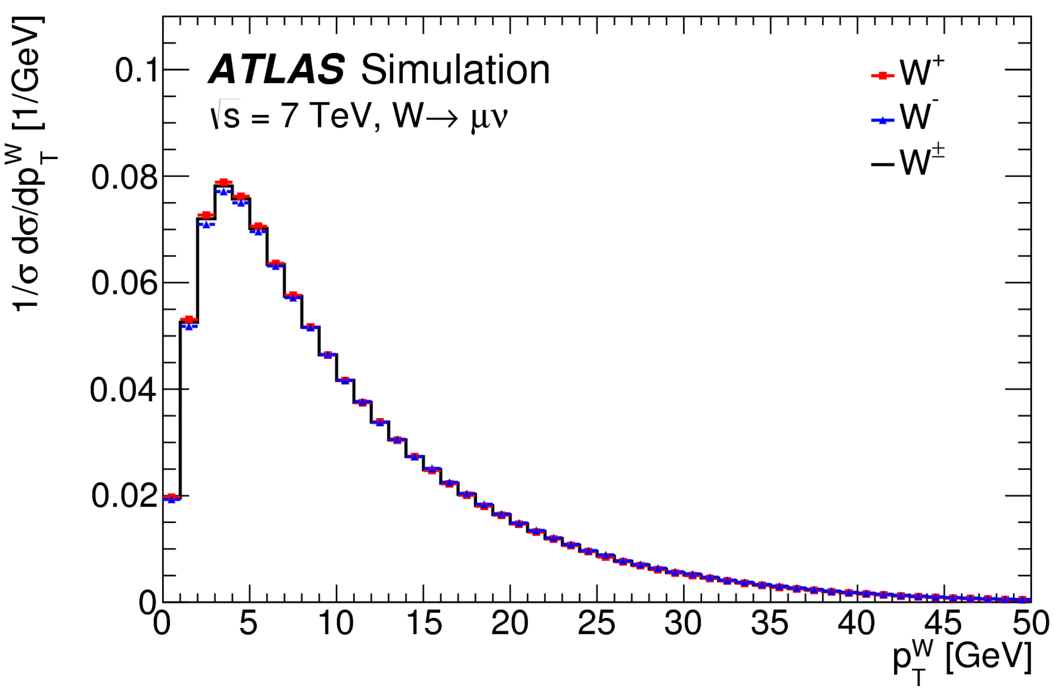

ATLAS
√s = 7 TeV, 4.1 fb^{-1}
Data
Z→μμ (before corr.)
Z→μμ (after corr.)
σ ($u_{\perp}$) [GeV]
$\Sigma \bar{E}_T$ [GeV]
Data / Pred.

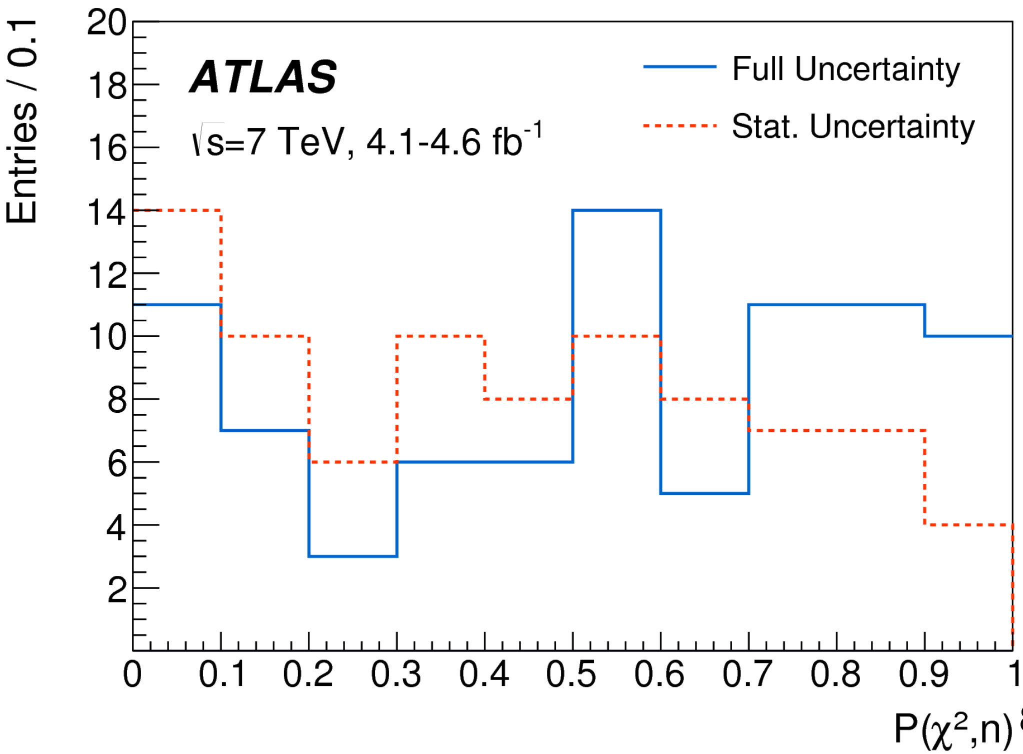

ATLAS Simulation
√s=7 TeV
Z
W+
W-
σ(u⊥)Z/W+ = 1.003
σ(u⊥)Z/W- = 1.001
Normalised to unity
u⊥[GeV]
Z / W

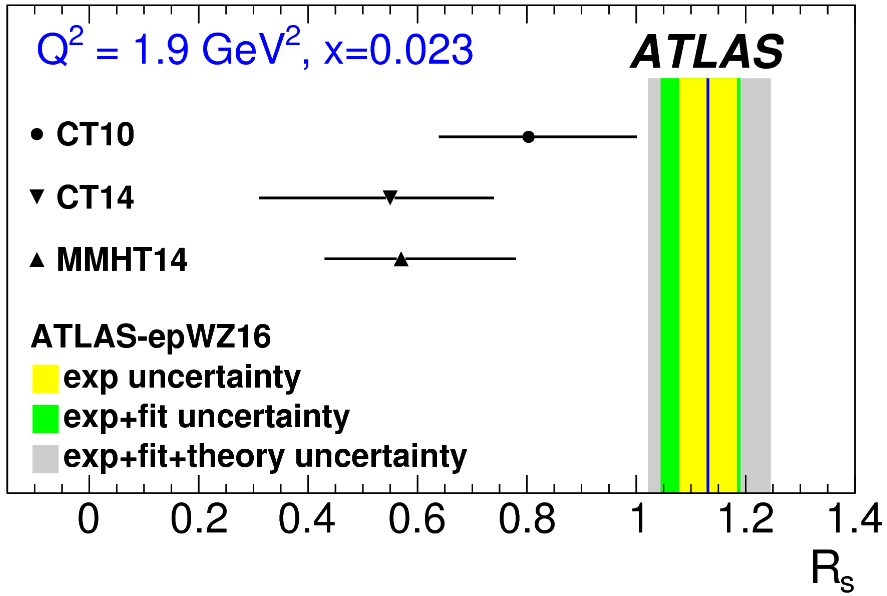

ATLAS Simulation
√s = 7 TeV, W→ μν
W+
W-
W±
1/σ dσ/dyW
yW


ATLAS Simulation
√s = 7 TeV, W→ μν
W+
W-
W±
1/σ dσ/dpTW [1/GeV]
pTW [GeV]


ATLAS Simulation
√s = 7 TeV, W→ μν
W+
W-
W±
1/σ dσ/dy_W
y_W


ATLAS Simulation
√s = 7 TeV, W→ μν
W+
W-
W±
1/σ dσ/dp_T^W [1/GeV]
p_T^W [GeV]


ATLAS
√s=7 TeV, 4.1-4.6 fb-1
Full Uncertainty
Stat. Uncertainty
Entries / 0.1
P(χ2,n)


Q2 = 1.9 GeV2, x=0.023
ATLAS
CT10
CT14
MMHT14
ATLAS-epWZ16
exp uncertainty
exp+fit uncertainty
exp+fit+theory uncertainty
R_s

Observable	Channel	η range	Weight
m_T	$W^+ \to \mu\nu$	$\|\eta\| < 0.8$	0.018
		$0.8 < \|\eta\| < 1.4$	0.022
		$1.4 < \|\eta\| < 2.0$	0.003
		$2.0 < \|\eta\| < 2.4$	0.006
	$W^- \to \mu\nu$	$\|\eta\| < 0.8$	0.020
		$0.8 < \|\eta\| < 1.4$	0.018
		$1.4 < \|\eta\| < 2.0$	0.022
		$2.0 < \|\eta\| < 2.4$	0.001
	$W^+ \to e\nu$	$\|\eta\| < 0.6$	0.013
		$0.6 < \|\eta\| < 1.2$	0.001
		$1,8 < \|\eta\| < 2.4$	0.010
	$W^- \to e\nu$	$\|\eta\| < 0.6$	0.008
		$0.6 < \|\eta\| < 1.2$	0.000
		$1.8 < \|\eta\| < 2.4$	0.002
p_T^ℓ	$W^+ \to \mu\nu$	$\|\eta\| < 0.8$	0.101
		$0.8 < \|\eta\| < 1.4$	0.076
		$1.4 < \|\eta\| < 2.0$	0.050
		$2.0 < \|\eta\| < 2.4$	0.011
	$W^- \to \mu\nu$	$\|\eta\| < 0.8$	0.097
		$0.8 < \|\eta\| < 1.4$	0.071
		$1.4 < \|\eta\| < 2.0$	0.047
		$2.0 < \|\eta\| < 2.4$	0.010
	$W^+ \to e\nu$	$\|\eta\| < 0.6$	0.056
		$0.6 < \|\eta\| < 1.2$	0.071
		$1,8 < \|\eta\| < 2.4$	0.081
	$W^- \to e\nu$	$\|\eta\| < 0.6$	0.062
		$0.6 < \|\eta\| < 1.2$	0.056
		$1.8 < \|\eta\| < 2.4$	0.067

Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481