Measurement of the W boson mass with the ATLAS detector

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DIS 2017

Outline

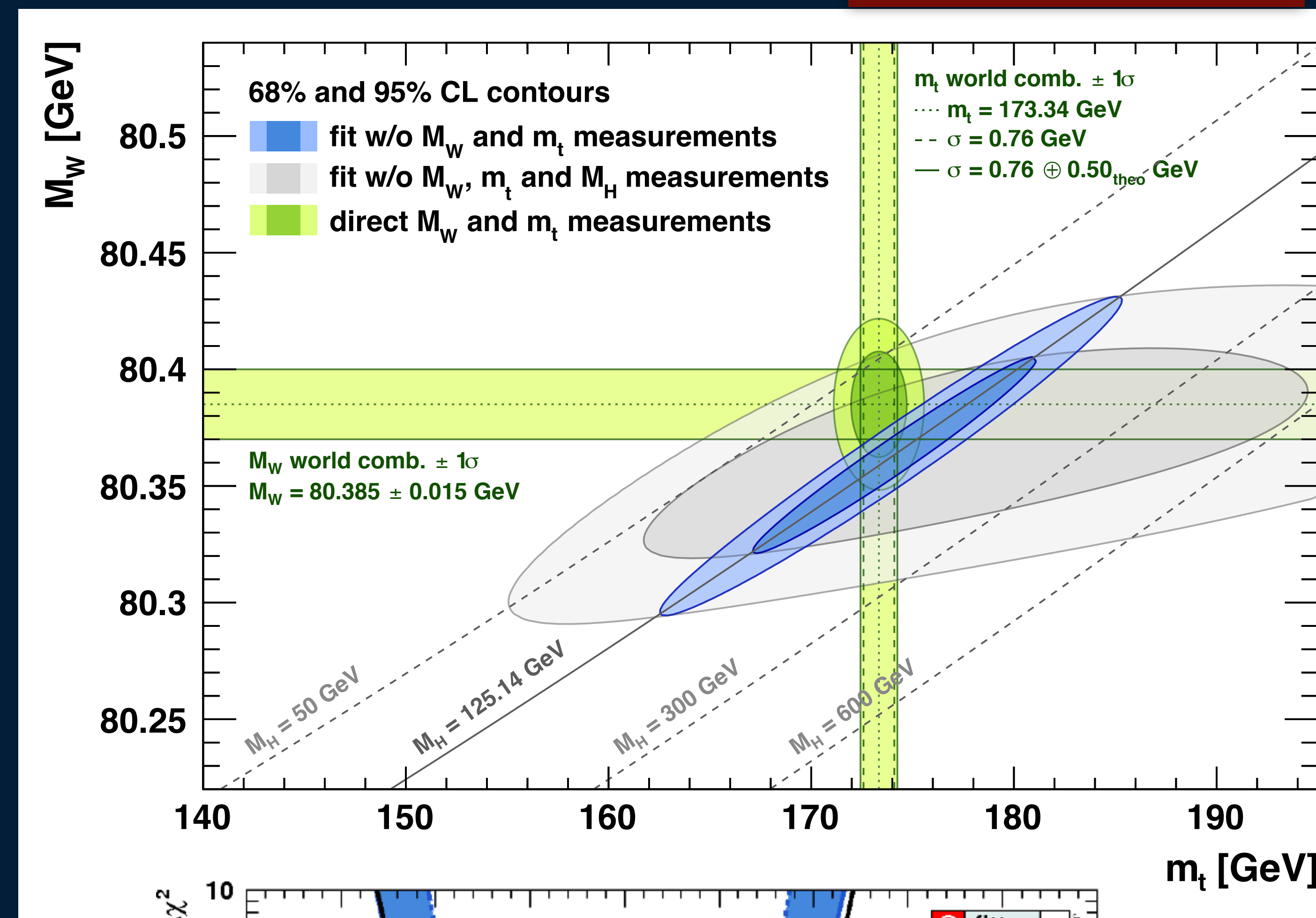
- Introduction
- Experimental aspects
- Modeling aspects
- Conclusion and summary

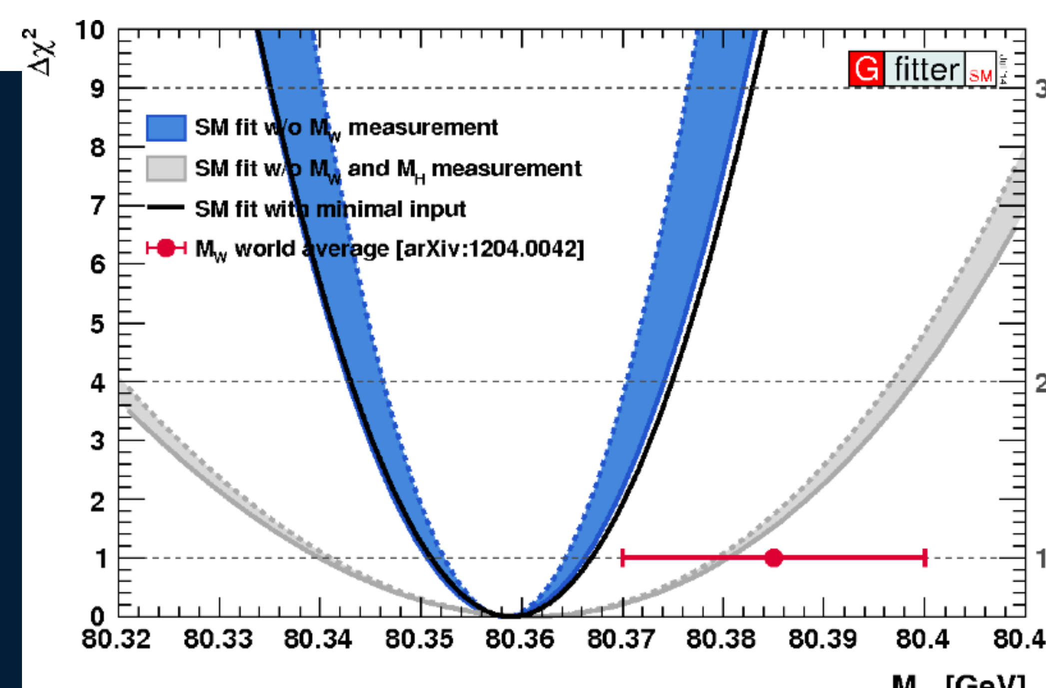
arXiv : 1701.07240
Submitted to EPJC

Introduction

arXiv:1407.3792

- Motivation for **precise** W mass measurement (‱)
  - Electroweak fit (possible values for m_W from SM predictions) : natural goal of 8 MeV
  - Constraints on new physics (NP) : biggest impact on indirect searches — target 5 MeV
- A lot of efforts from lepton colliders, Tevatron…

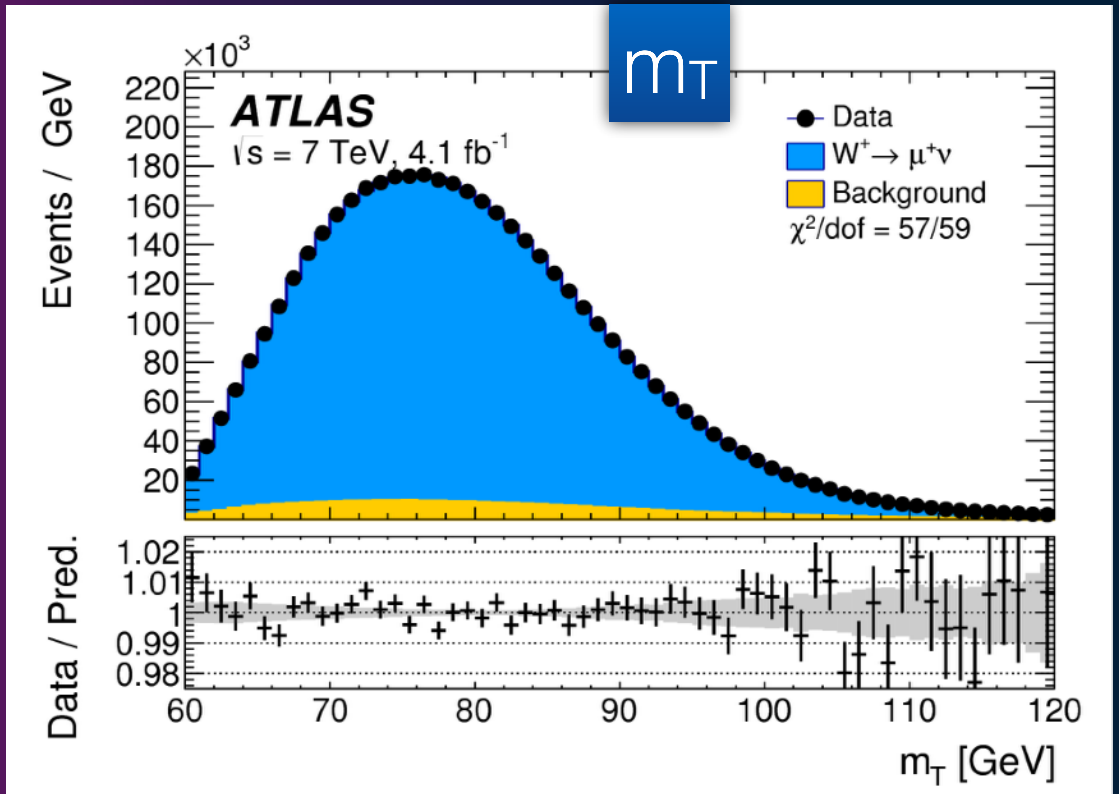


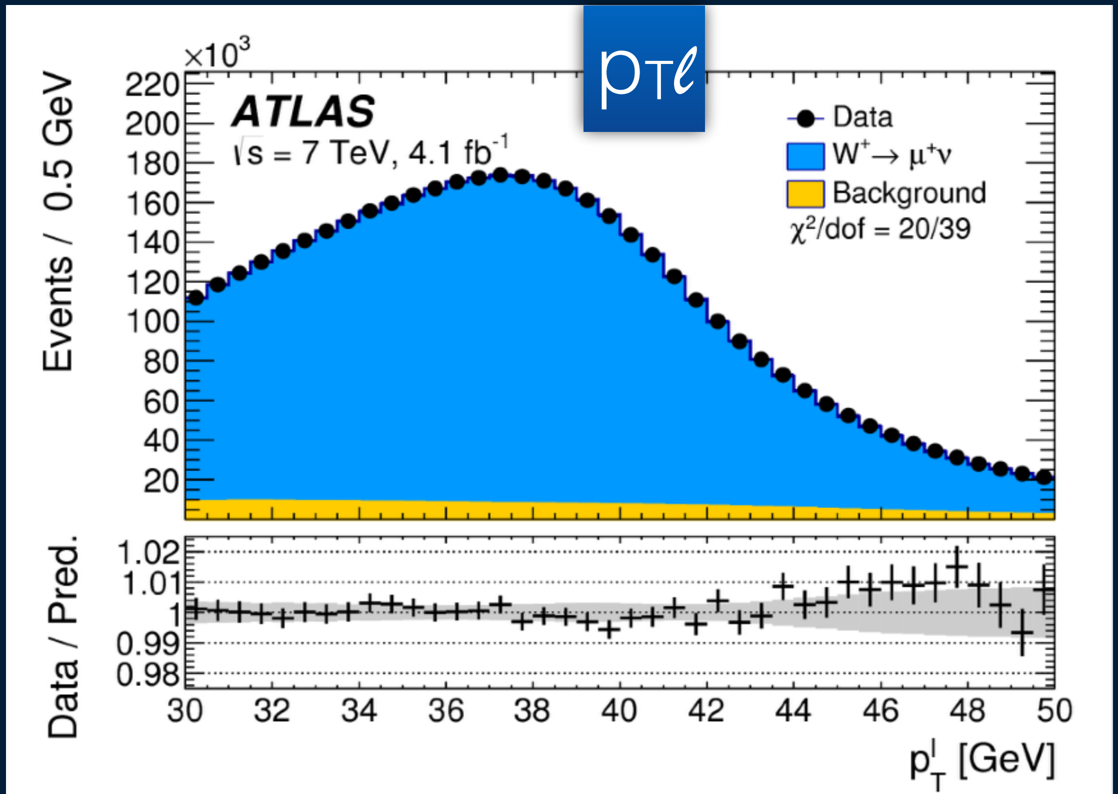


Current world average (Tevatron):
m_W = 80.385 ± 0.015 GeV

Introduction

- Strategy :
  - obtain predictions with simulated events for signal and background (except data-driven multijet background)
  - to extract the result, compare data and predictions for distributions sensitive to mW :
    - lepton transverse momentum ($p_{T\ell}$)
    - transverse boson mass (m_T)
    - missing transverse momentum, p_T^{miss} (more difficult at LHC)





Introduction

Long way to get there

- Strategy :
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    - lepton transverse moment
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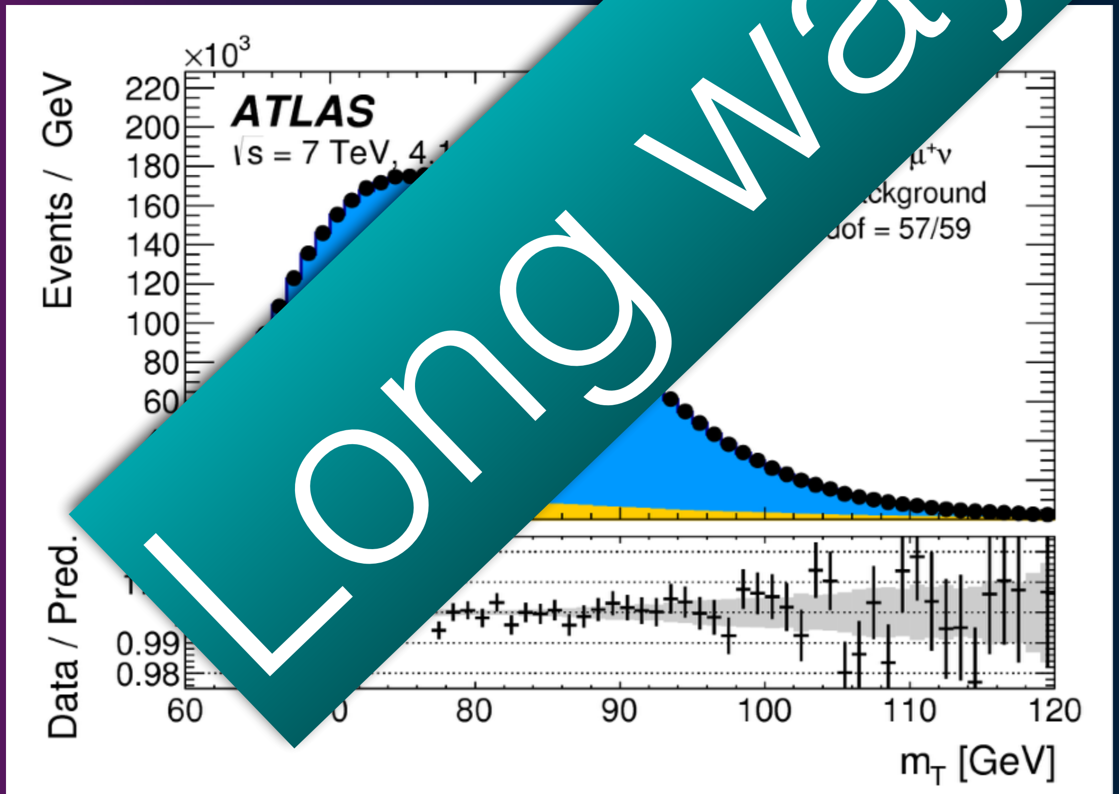
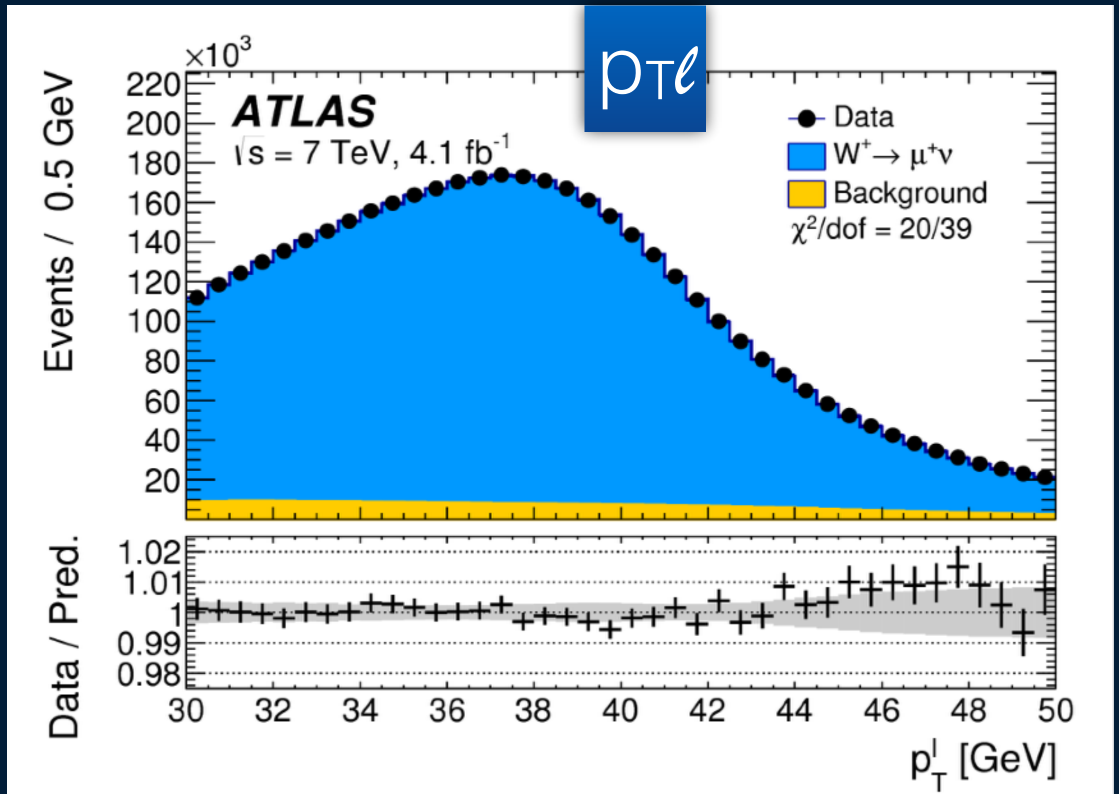


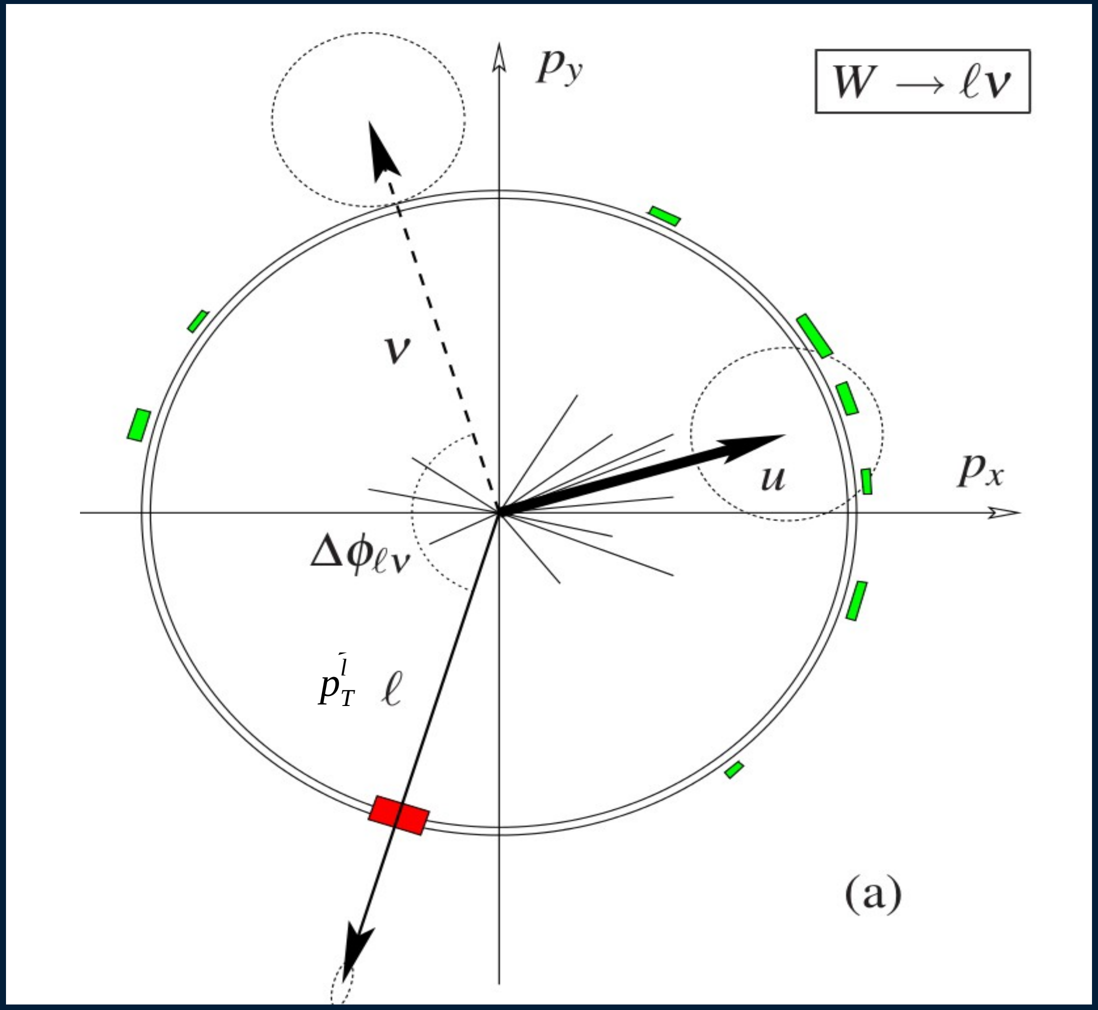


EXPERIMENTAL ASPECTS

Event selection

Lepton selection

- muon : $p_T > 30$ GeV, $|\eta| < 2.4$, track-based isolation
- electron : $p_T > 30$ GeV, $|\eta| < 1.2$ or $1.8 < |\eta| < 2.4$, track and calorimeter-based isolation



- Recoil : $u_T < 30$ GeV
- $m_T > 60$ GeV, $p_T^{miss} > 30$ GeV

$\vec{u}_T$: vector sum of calorimeter deposit excluding lepton deposits

$\vec{p}_T^{miss} = -(\vec{u}_T + \vec{p}_{T\ell})$

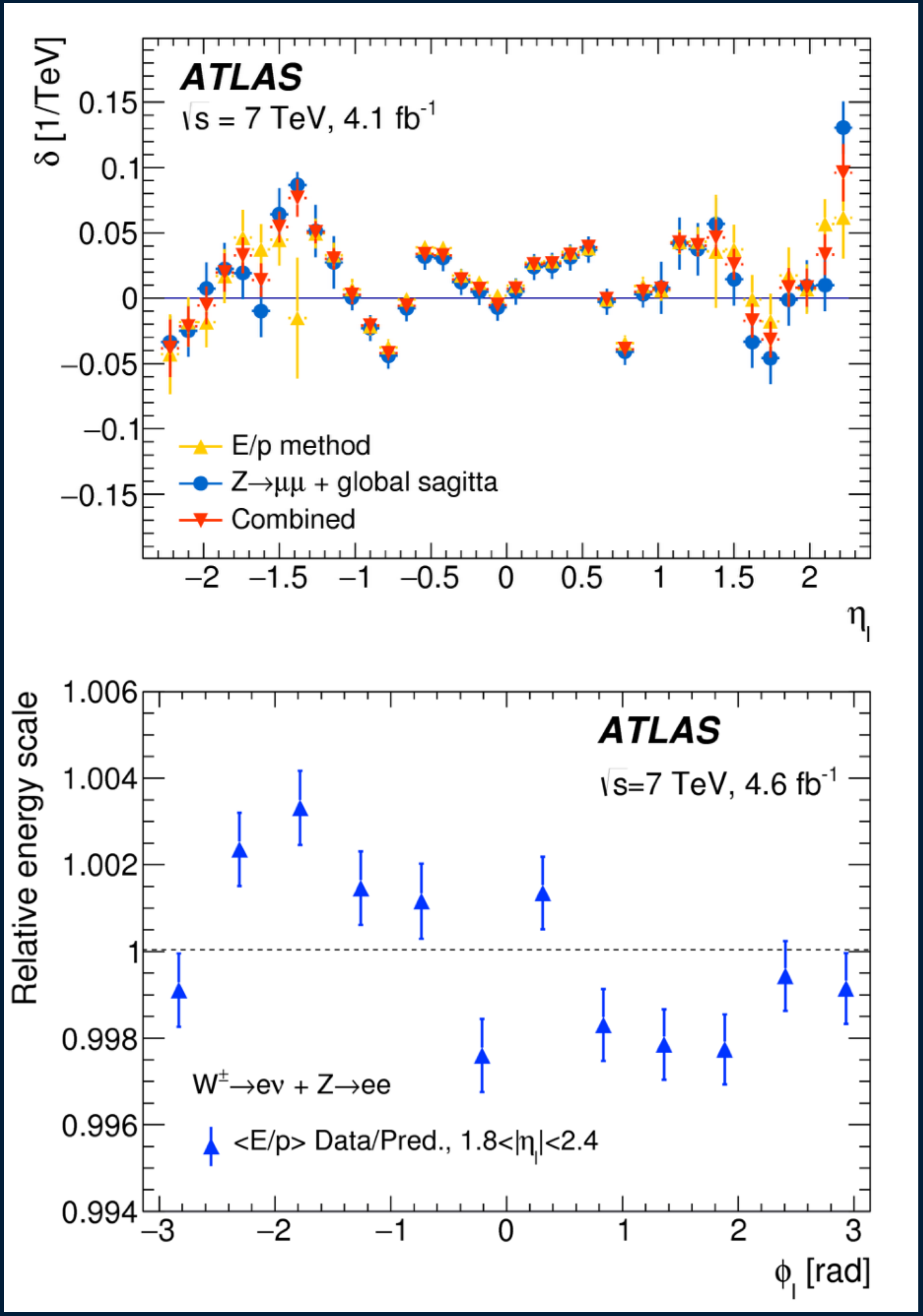
$m_T = \sqrt{[2\, p_{T\ell}\, p_T^{miss}\, (1-\cos\Delta\phi)]}$

Lepton calibration

- muon momentum scale calibration using Z, extrapolation to W using $p_T\ell(W)$ spectrum
- muon sagitta bias calibration uses W events (E/p) and Z events

$$p_T^{\text{data,corr}} = \frac{p_T^{\text{data}}}{1 + q \cdot \delta(\eta, \phi) \cdot p_T^{\text{data}}}$$

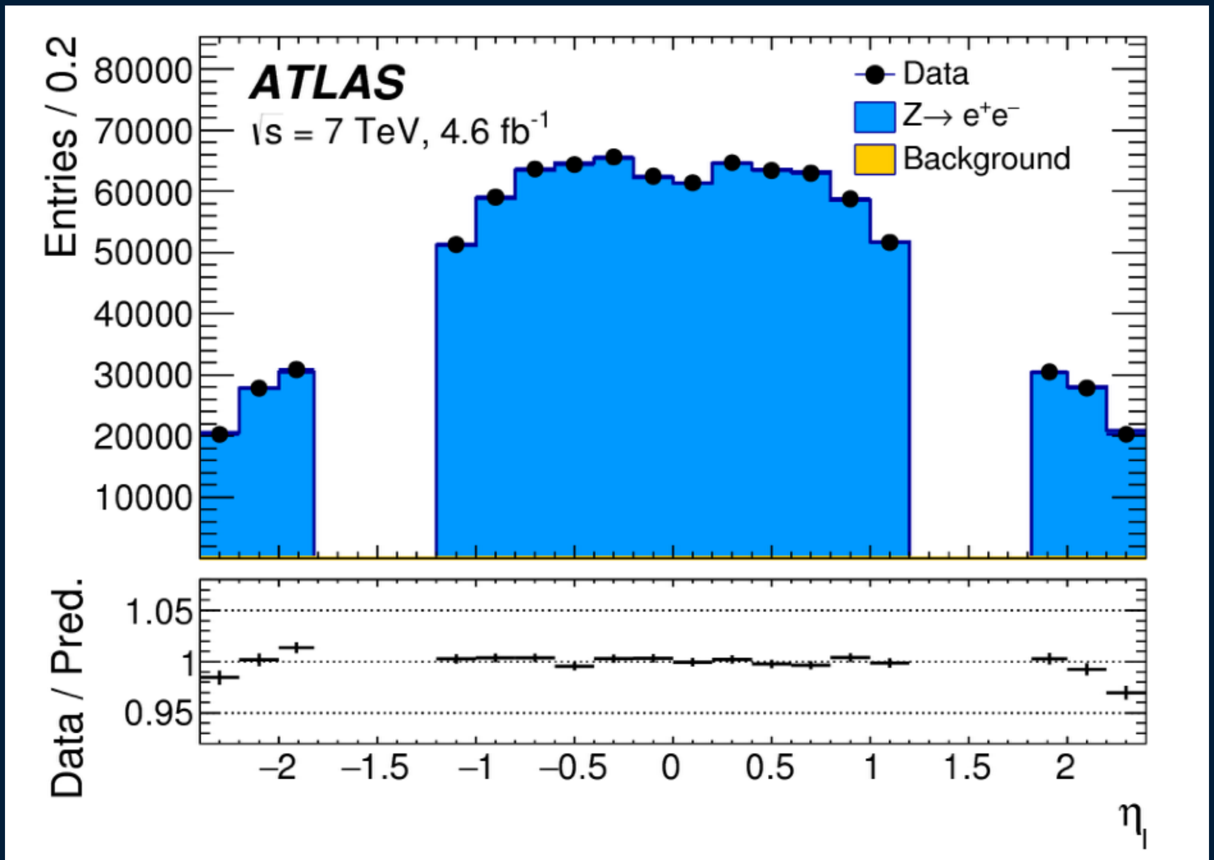
- electron calibration uses Z events
    - Overall average relative uncertainty 9.4 x 10^{-5}
    - ϕ modulation due to mechanical deformation under gravity corrected with W and Z events

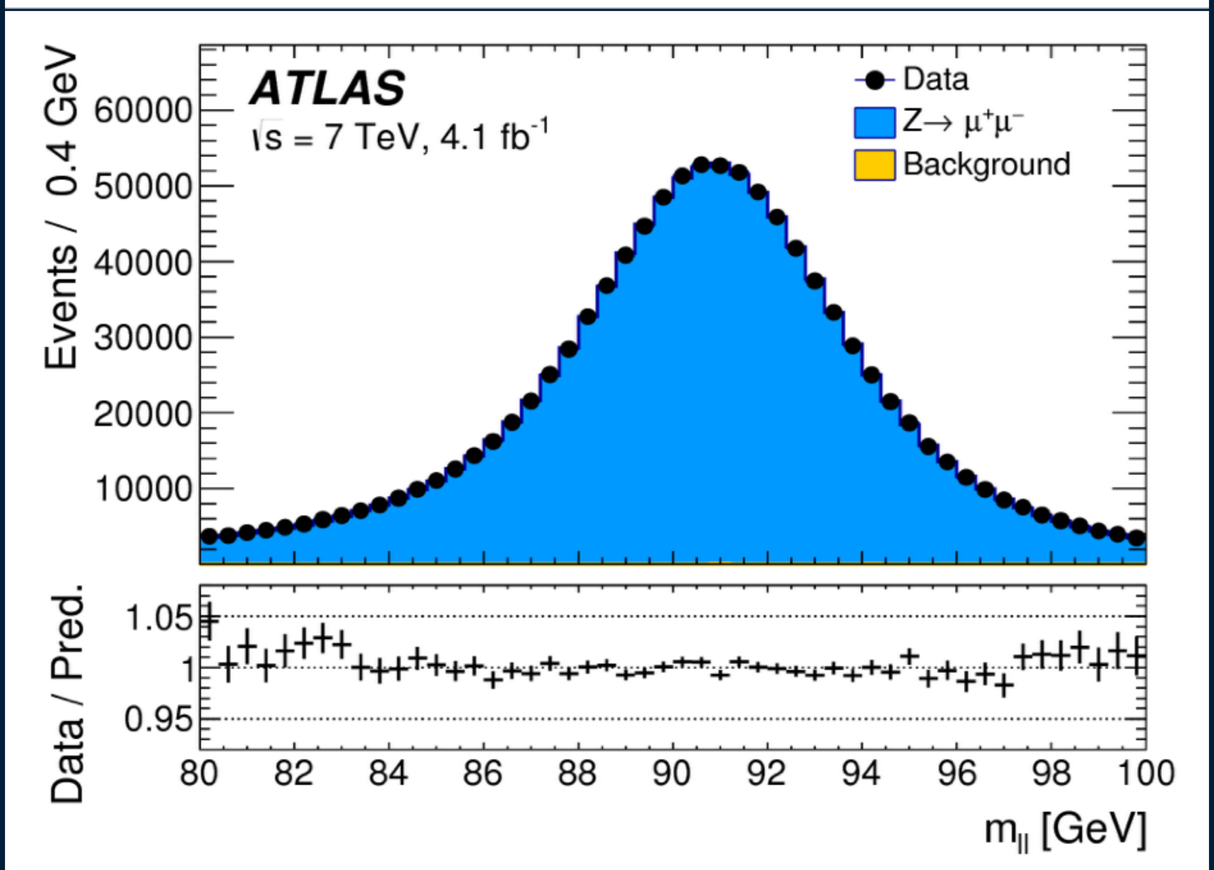


Lepton calibration

- Selection efficiencies for reconstruction, identification, trigger, isolation ~10(8) MeV for $p_{T\ell}(m_T)$ fit

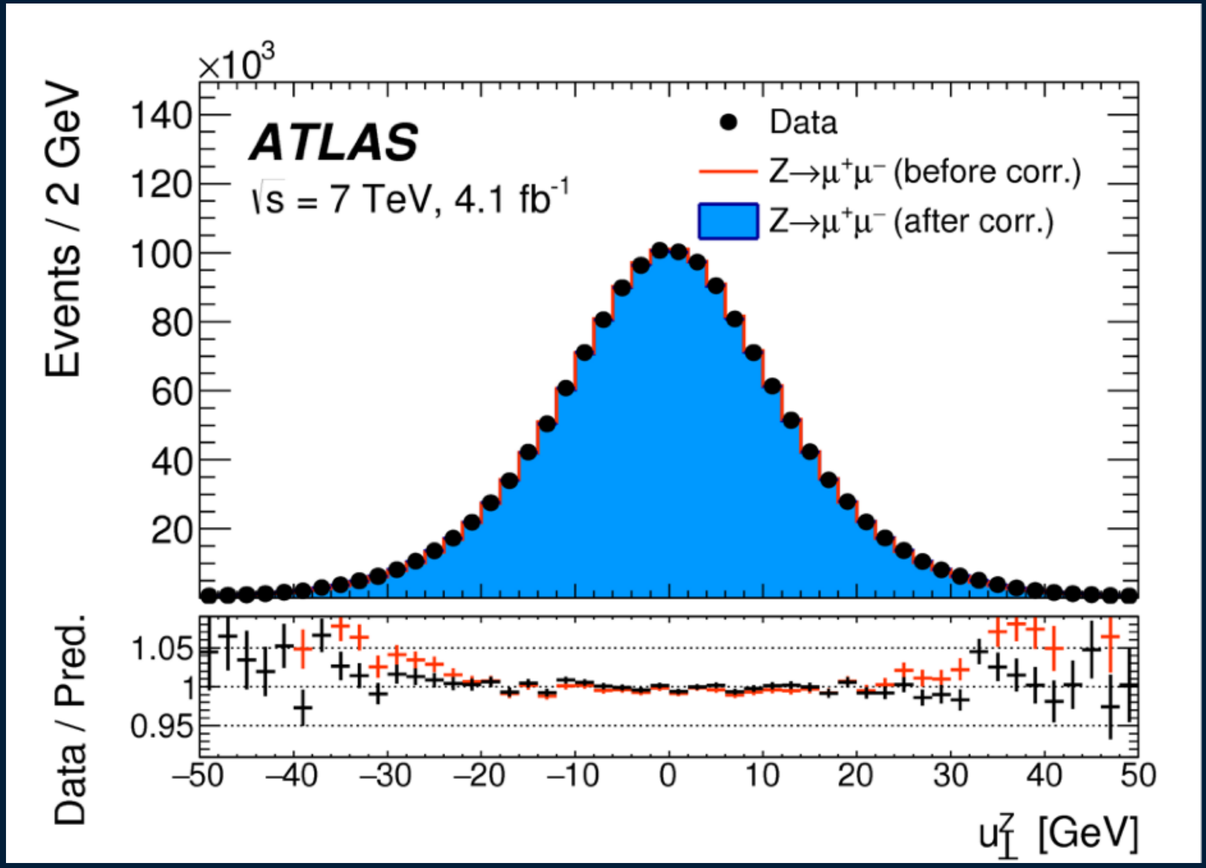
- Total lepton uncertainty ~10 MeV (muon) and 14 MeV (electron)

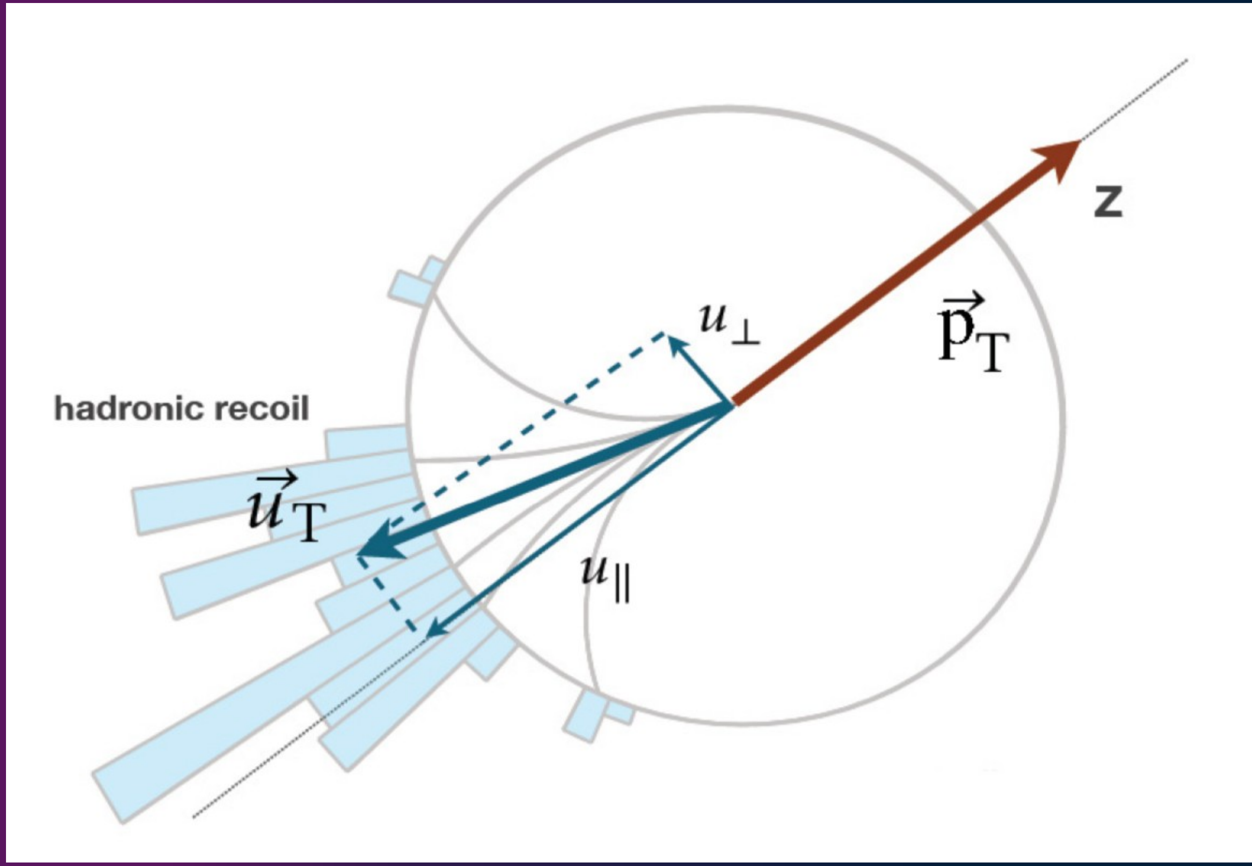


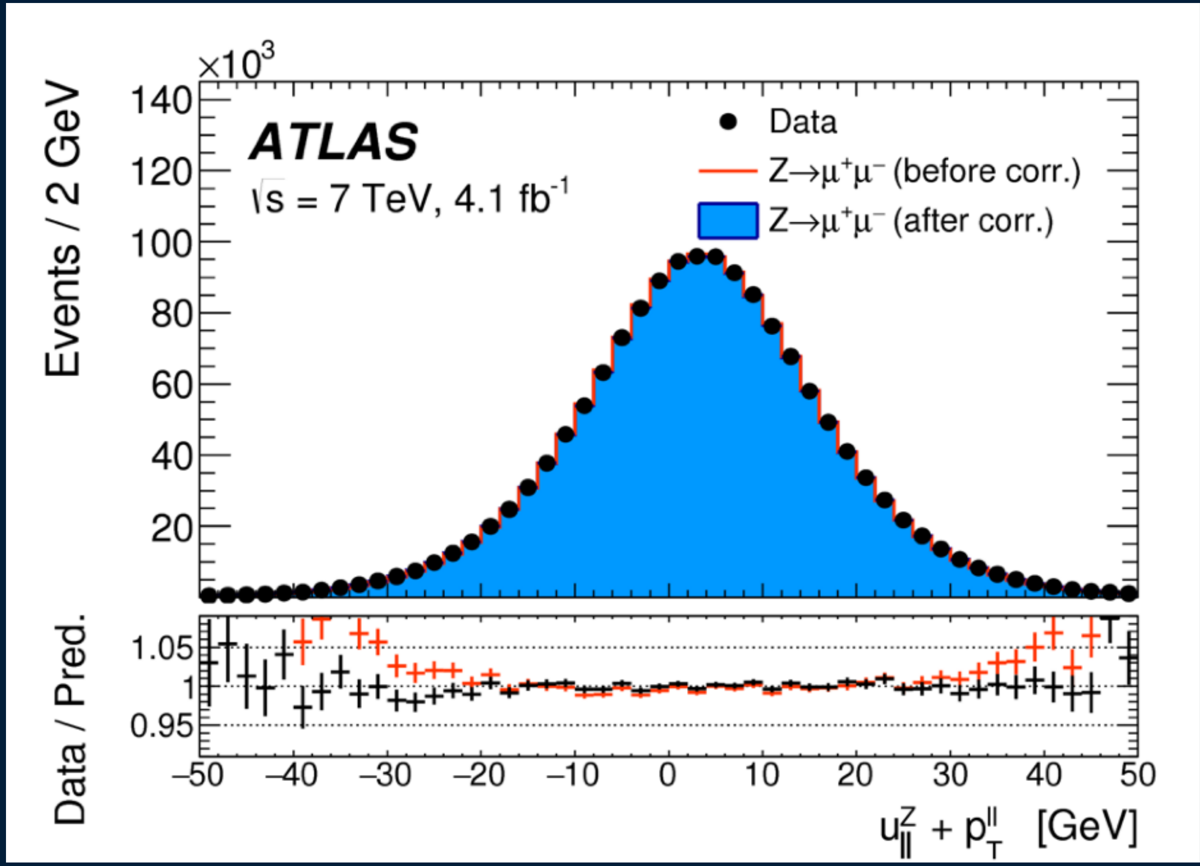


Hadronic recoil calibration

- Several steps of the correction :
  - Correct pile-up activity
  - Correct ΣE_T distribution
  - residual response and resolution corrections in Z events, extrapolated to W
- 2.6/13.0 MeV uncertainty on $p_T\ell/m_T$ fit



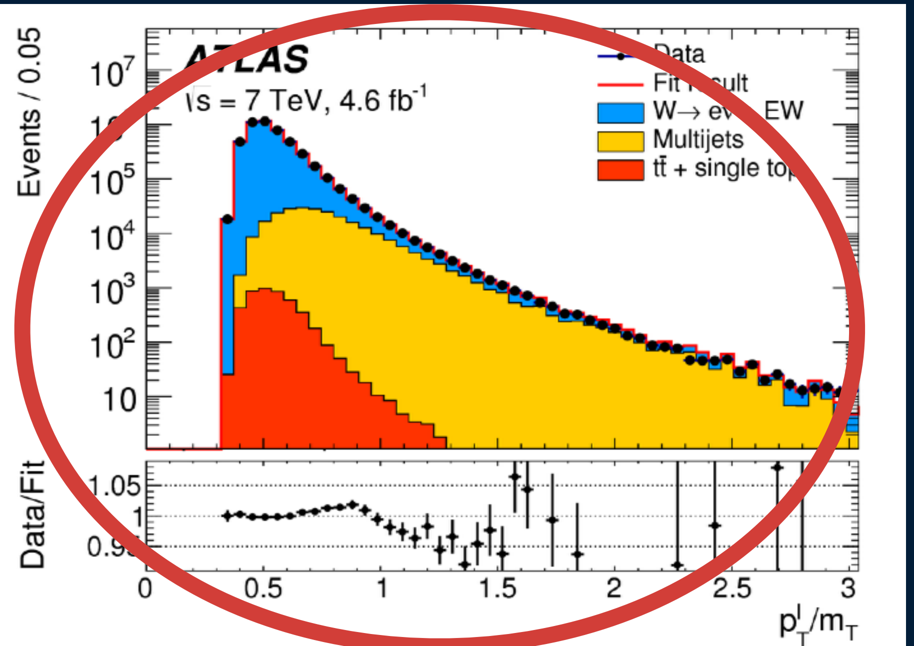


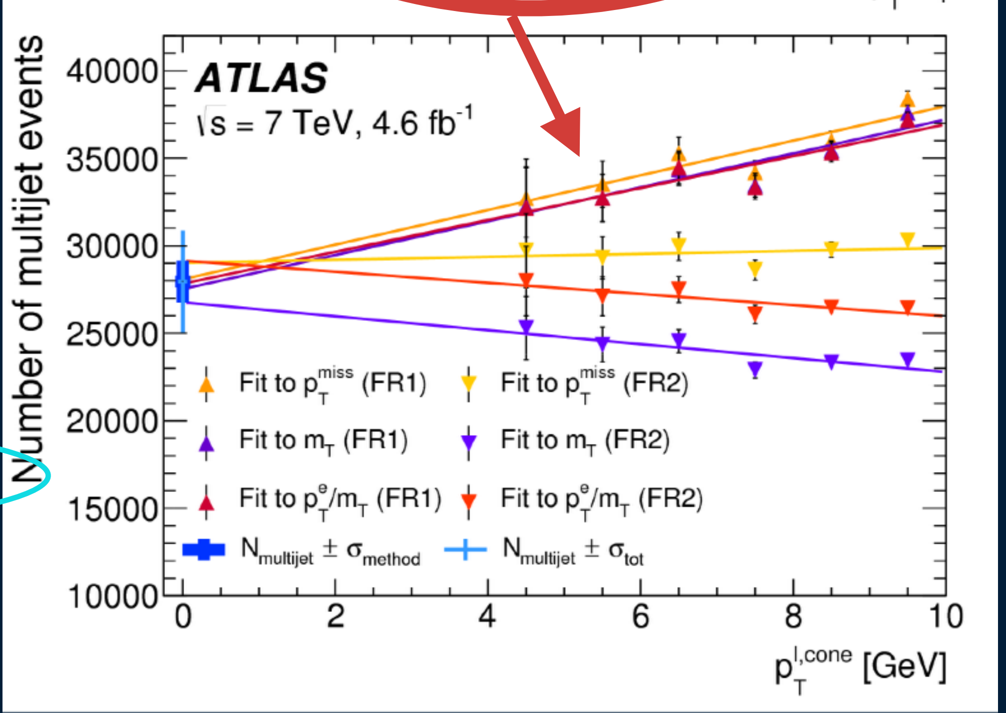


Multijet background

- data-driven technique :
  - 2 different background enriched regions to fit multijet fraction
    - EW and top contamination subtracted with MC estimation
  - 3 different observables : m_T, p_T^ℓ/m_T, p_T^{miss}
  - scan in isolation variable
  - linear extrapolation to signal region

0.6 - 1.7 % (e channel)
0.5 - 0.7 % (mu channel)





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

MODELING ASPECTS

Introduction to the modeling

- Factorisation of cross-section under 4 terms
    - Approximation checked and valid at 2 MeV level for m_W

spherical harmonics

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

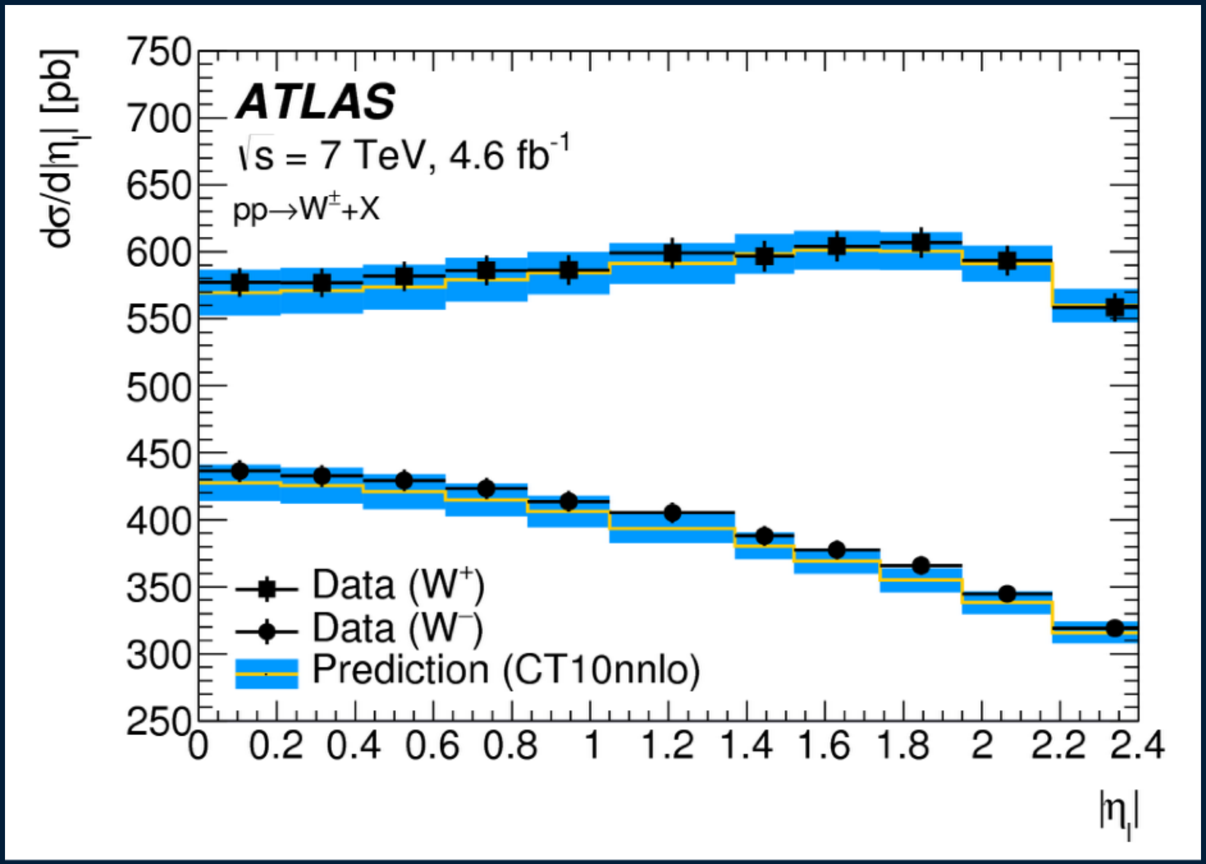
- $d\sigma(m)/dm$ modeled with Breit Wigner
- Other terms : reweight MC according to various predictions
    1. dσ(y)/dy : fixed-order NNLO prediction
    2. p_T at a given y : Pythia8 AZ
    3. polarisation Ai : fixed-order NNLO prediction

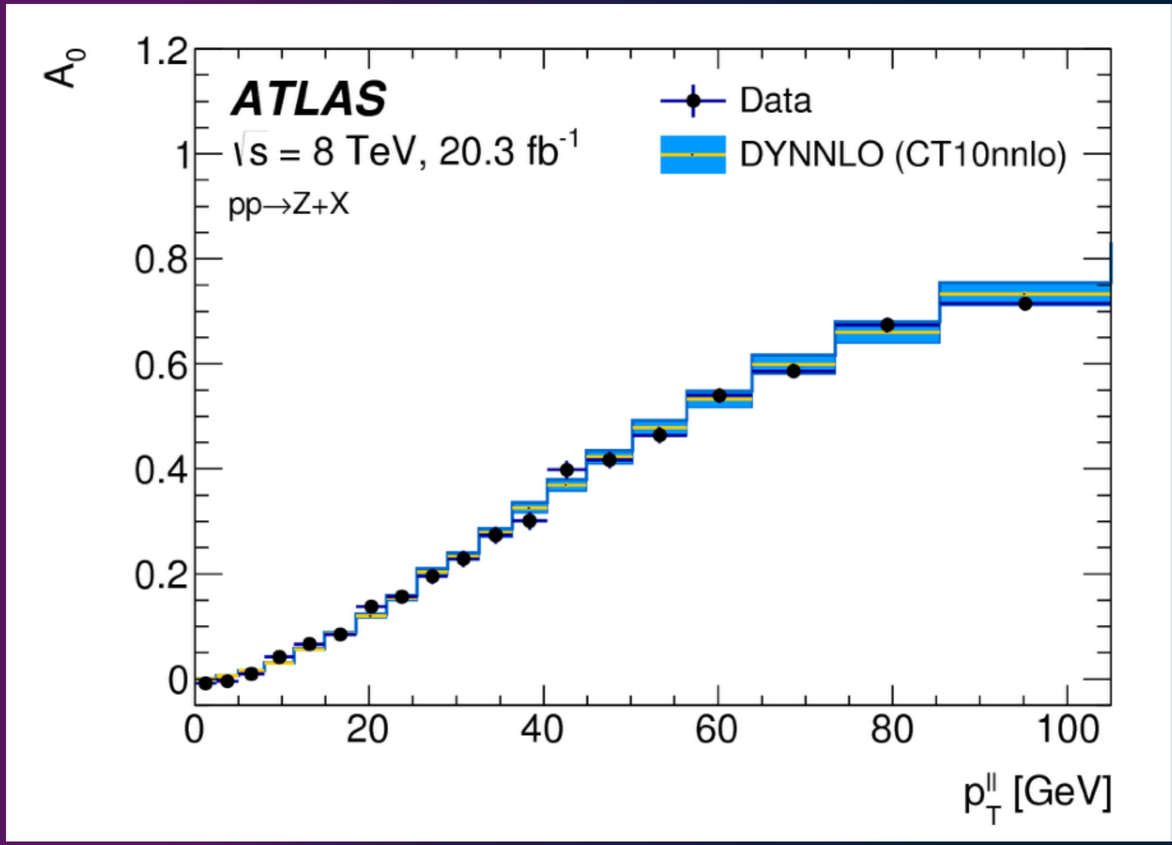
Polarisation and rapidity

- Use of DYNNLO (Fixed-order NNLO)
- Validate against 7 TeV ATLAS W, Z cross-section measurements

arXiv:1612.03016
submitted to EPJC

- PDF : CT10nnlo (best agreement), MMHT14nnlo and CT14nnlo used for uncertainties (others disfavoured by the data)





- ATLAS Z polarisation measurement validates fixed-order prediction

JHEP 08 (2016) 159

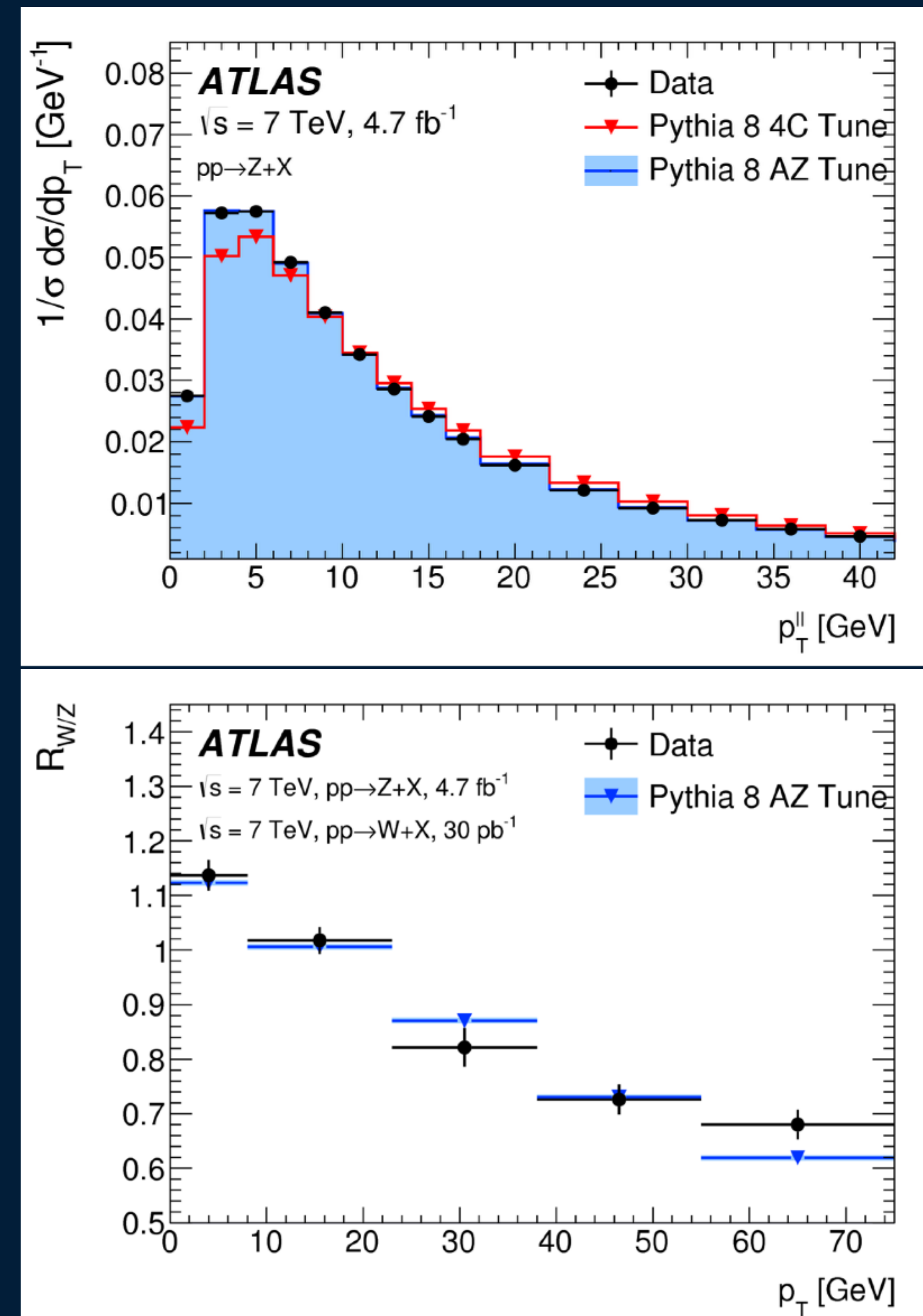
  - except for A_2 : additional uncertainty
  - uncertainties propagated from Z to W

Boson transverse momentum

- Use Pythia8 AZ tuned on Z p_T ATLAS data JHEP 09 (2014) 145
  - Good agreement for

$$R_{W/Z}(p_T) = \left(\frac{1}{\sigma_W} \cdot \frac{d\sigma_W(p_T)}{dp_T}\right)\left(\frac{1}{\sigma_Z} \cdot \frac{d\sigma_Z(p_T)}{dp_T}\right)^{-1}$$

- Uncertainties on PS include
  - tune uncertainties
  - c and b masses uncertainties
  - factorisation scale variation
  - LO PS PDF uncertainty



Electroweak and QCD uncertainties

- QED/EW effects : mainly FSR photons, implemented with Photos
  - NLO EW corrections from Winhac — taken as uncertainty
  - FSR pair production impact checked with Photos and Sanc

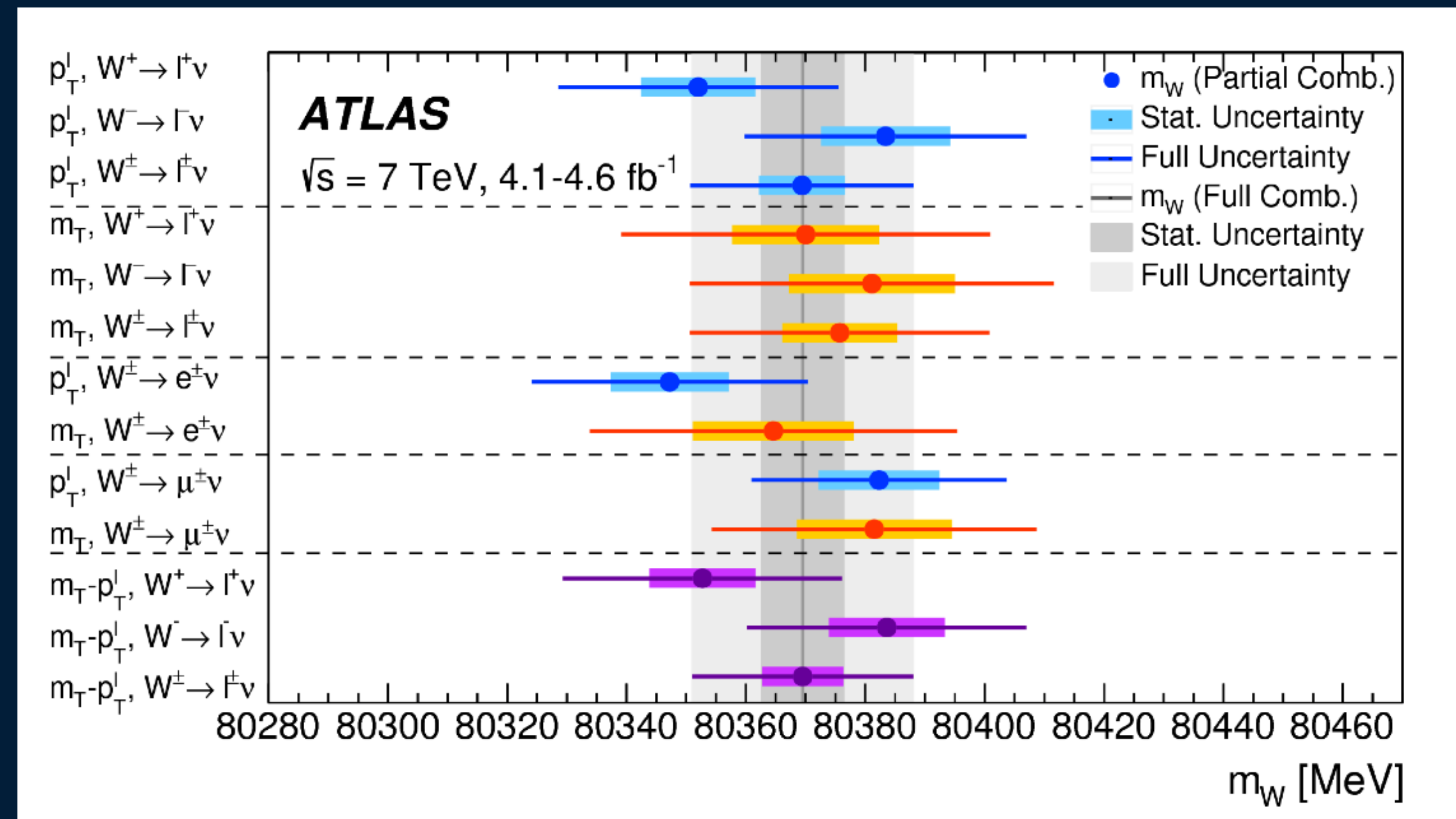
Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

- PDFs uncertainties to NNLO predictions are dominant : may do better in the future with profiled sets (incorporating parton shower)

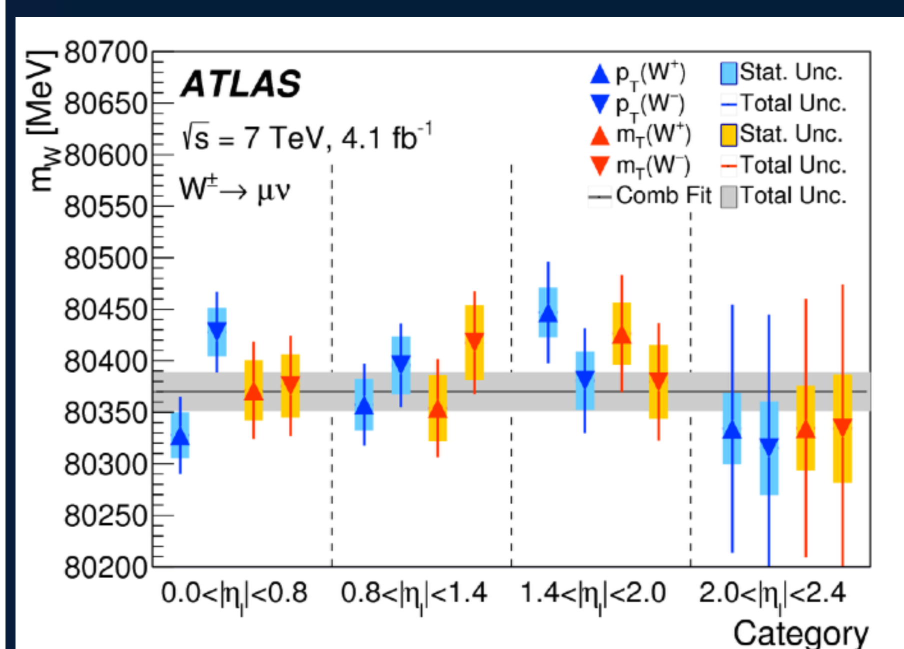
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

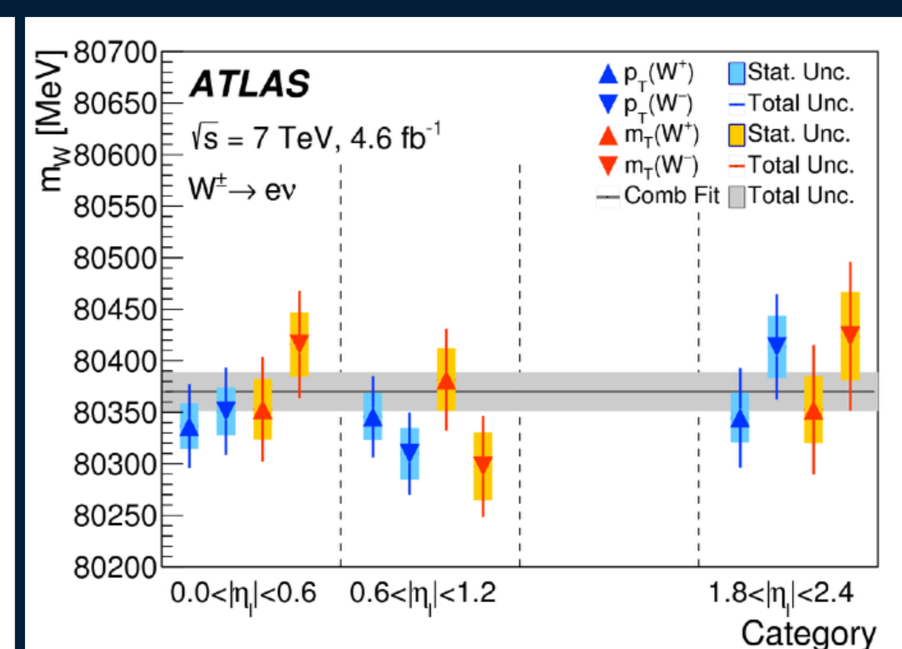
m_W extraction

- $\chi 2$ template fit to the data in each category (distribution, charge, lepton channel, η_ℓ bin)
- All categories give consistent result —> strength of detector calibration and physics modelling
- combination using BLUE method



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



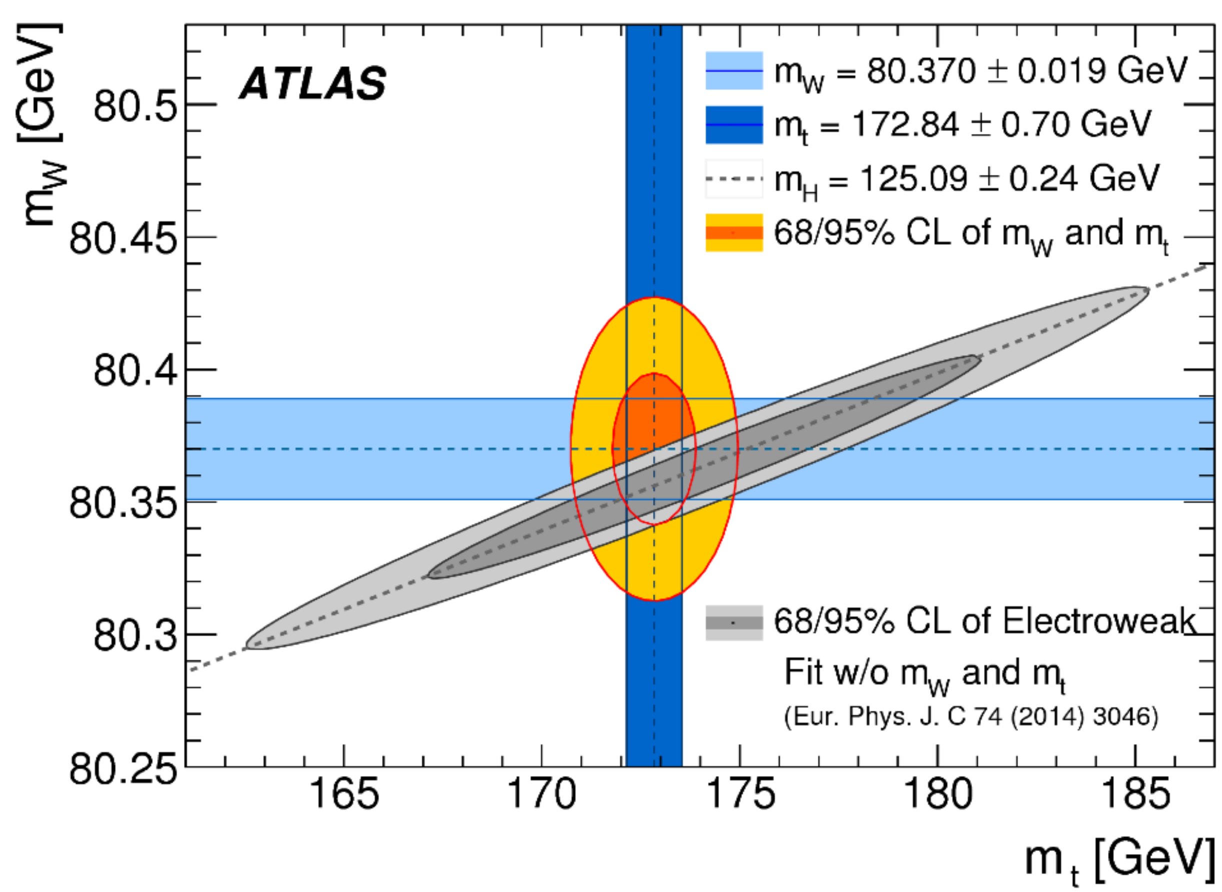


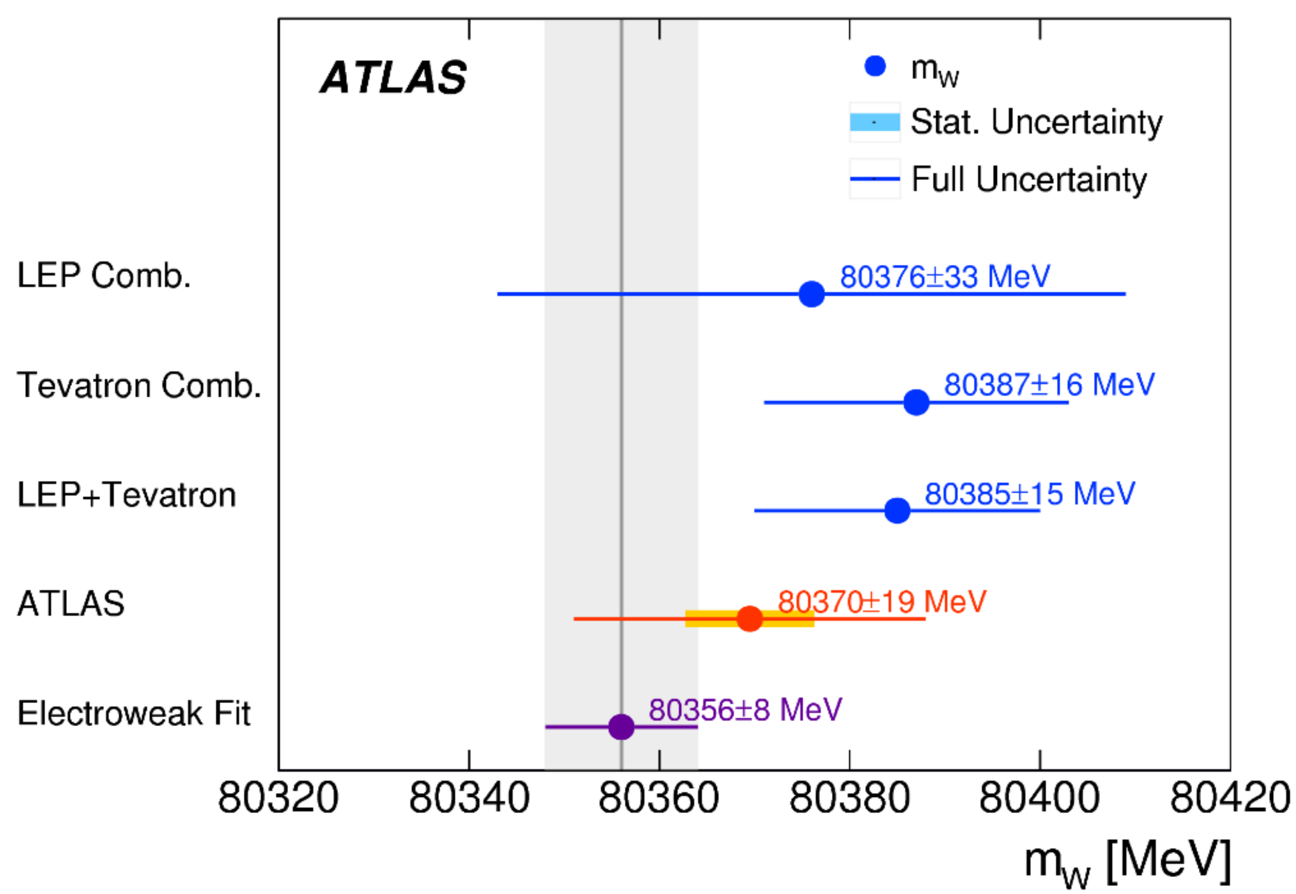
CONCLUSION AND SUMMARY

$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W+} - m_{W-} = -29 \pm 28\ \text{MeV}$$

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-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





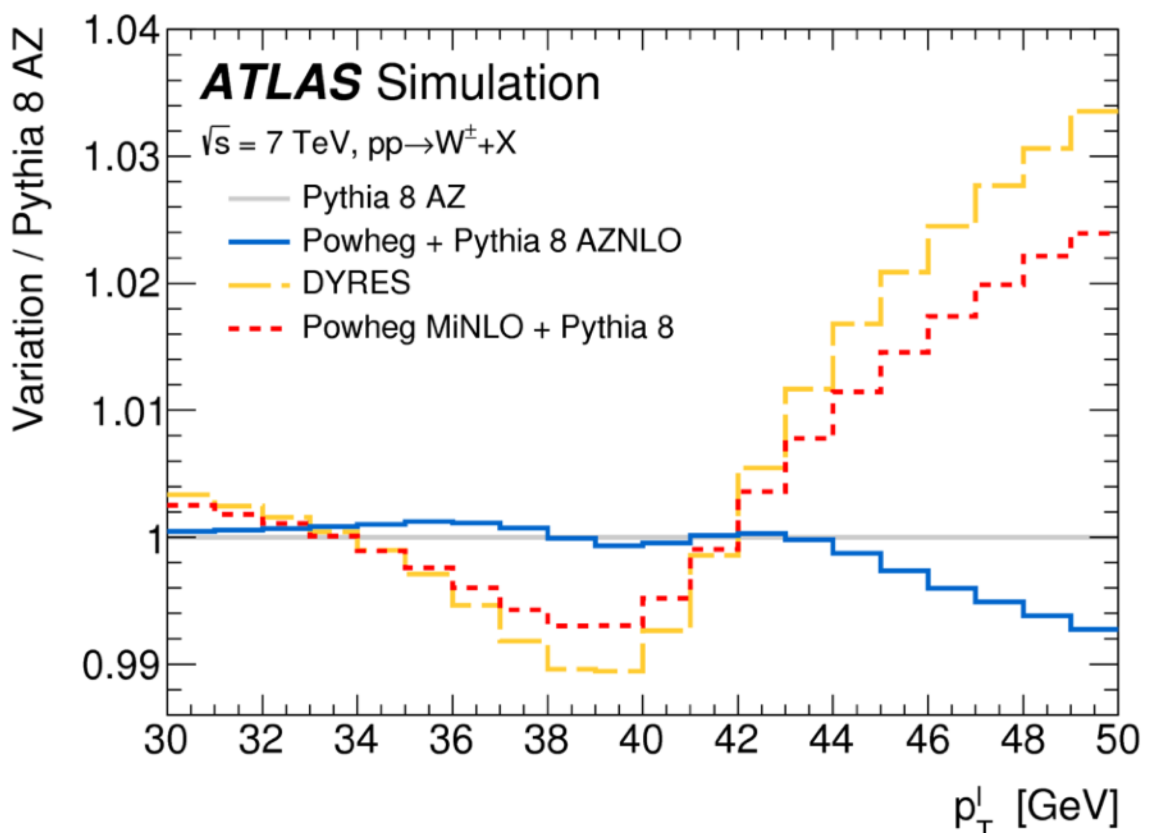
What’s next ?

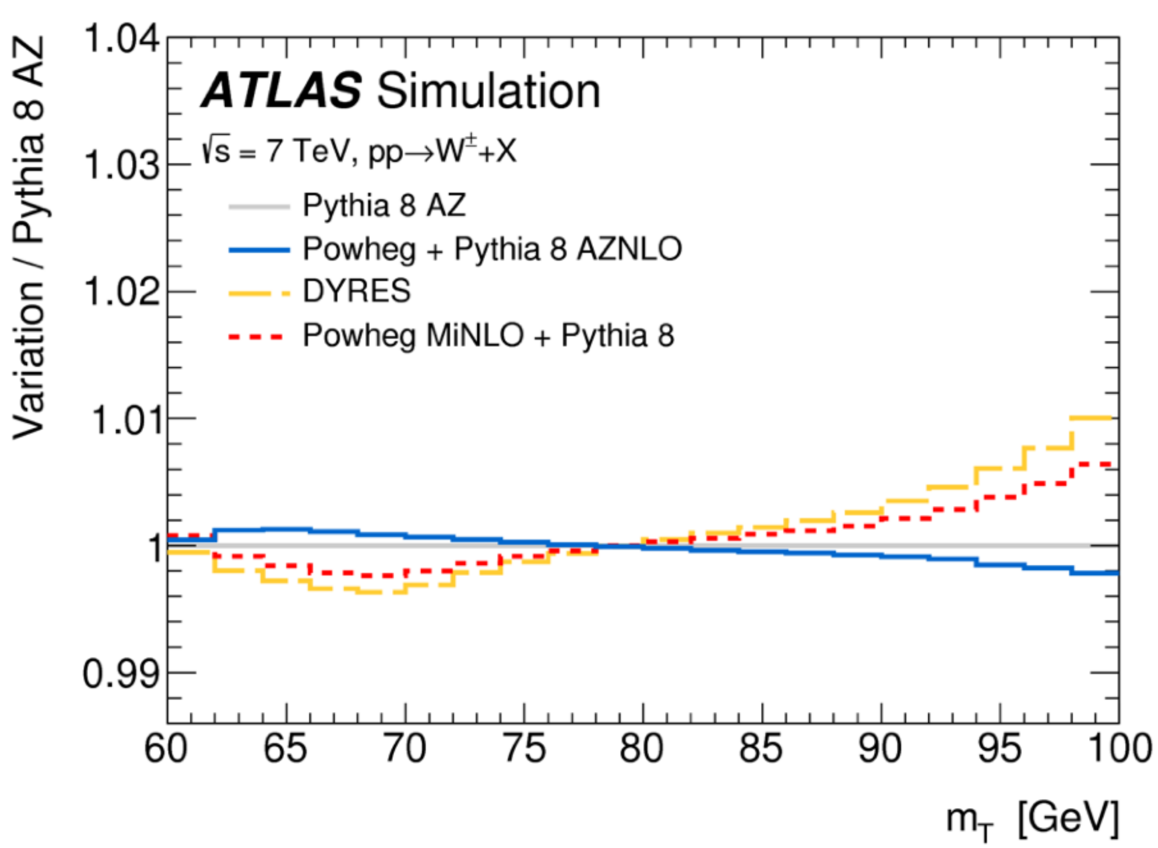
- What can be done to improve the precision in the coming (<10) years ?
  - 8 and 13 TeV data analyses : challenging (more pile-up, more radiations), but probing different kinematic regions
    - —> e.g. PDF sensitivity differences good for combination
  - **More progress on theory side : resummation, better handle on PDFs**
  - Experimental innovations : e.g. pile-up mitigation techniques, more and more ancillary measurements like W pT, polarisation…
  - Combinations with existing measurements (*e.g* Tevatron)

Thank you for your attention!!

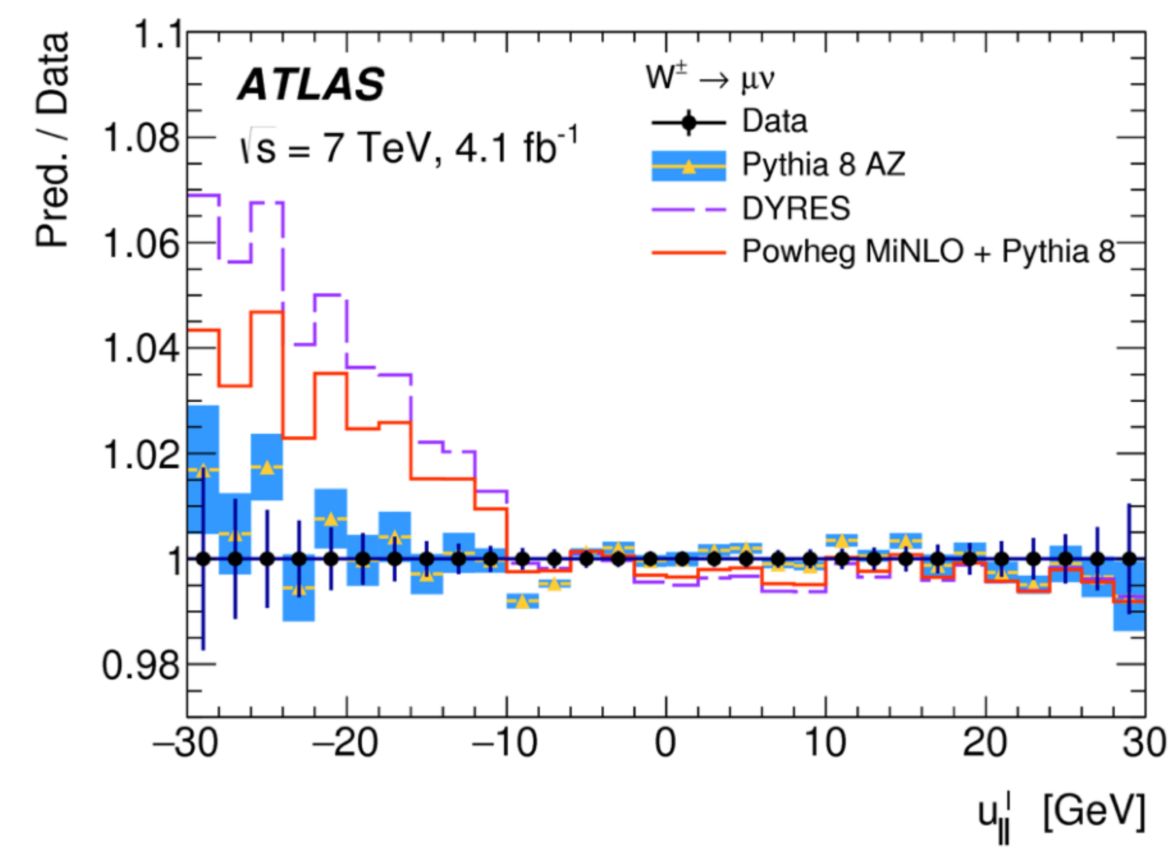
BACKUP

pT modeling strategy

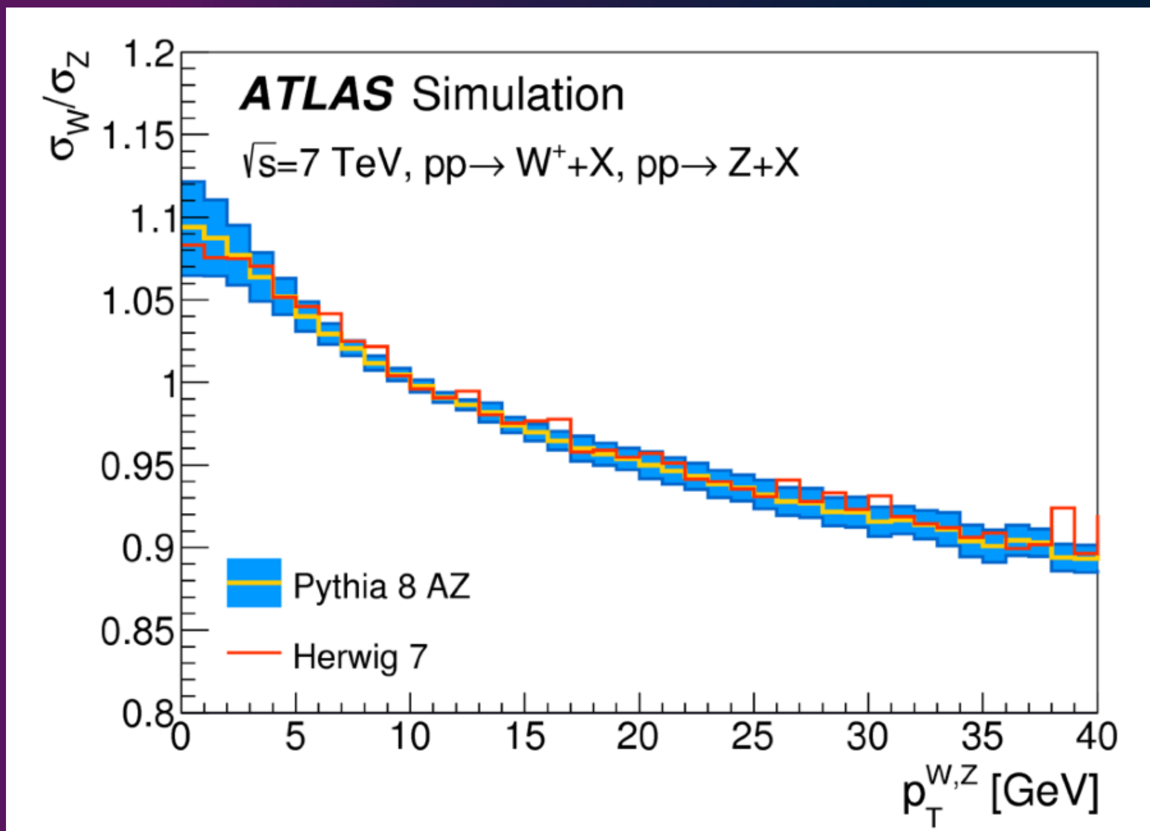


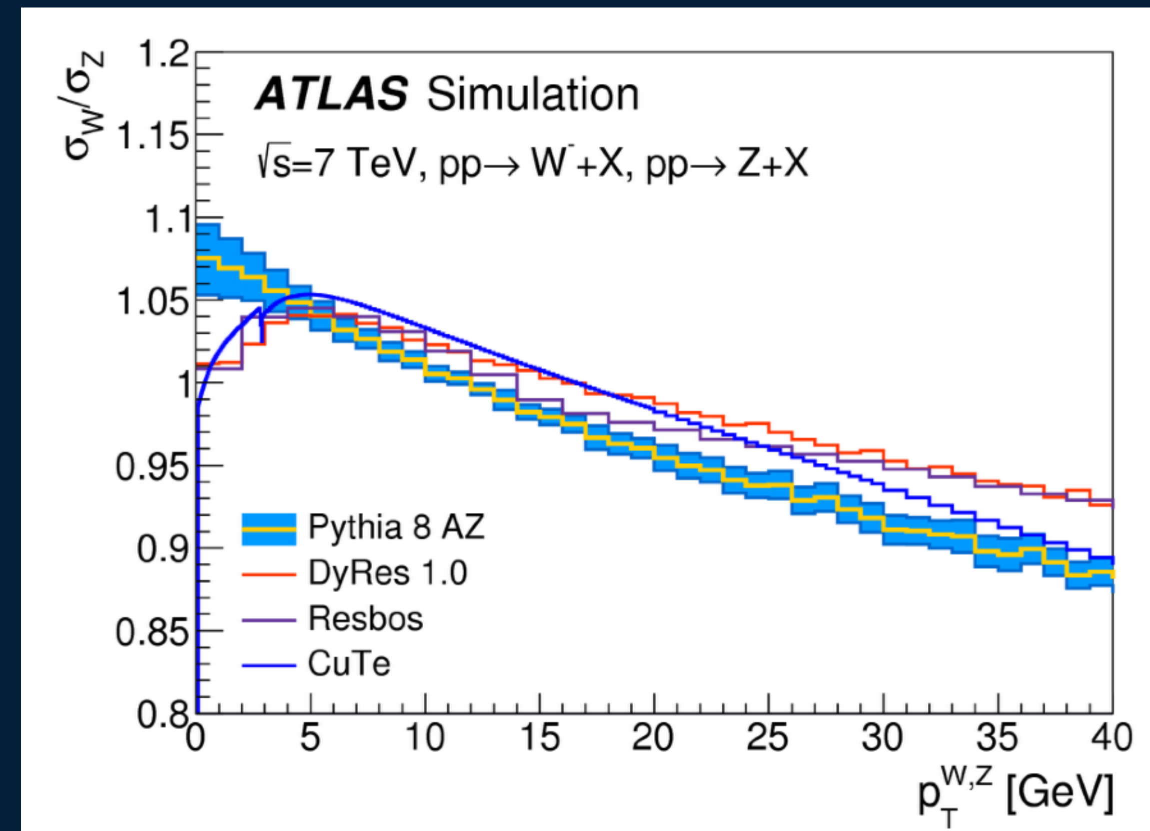


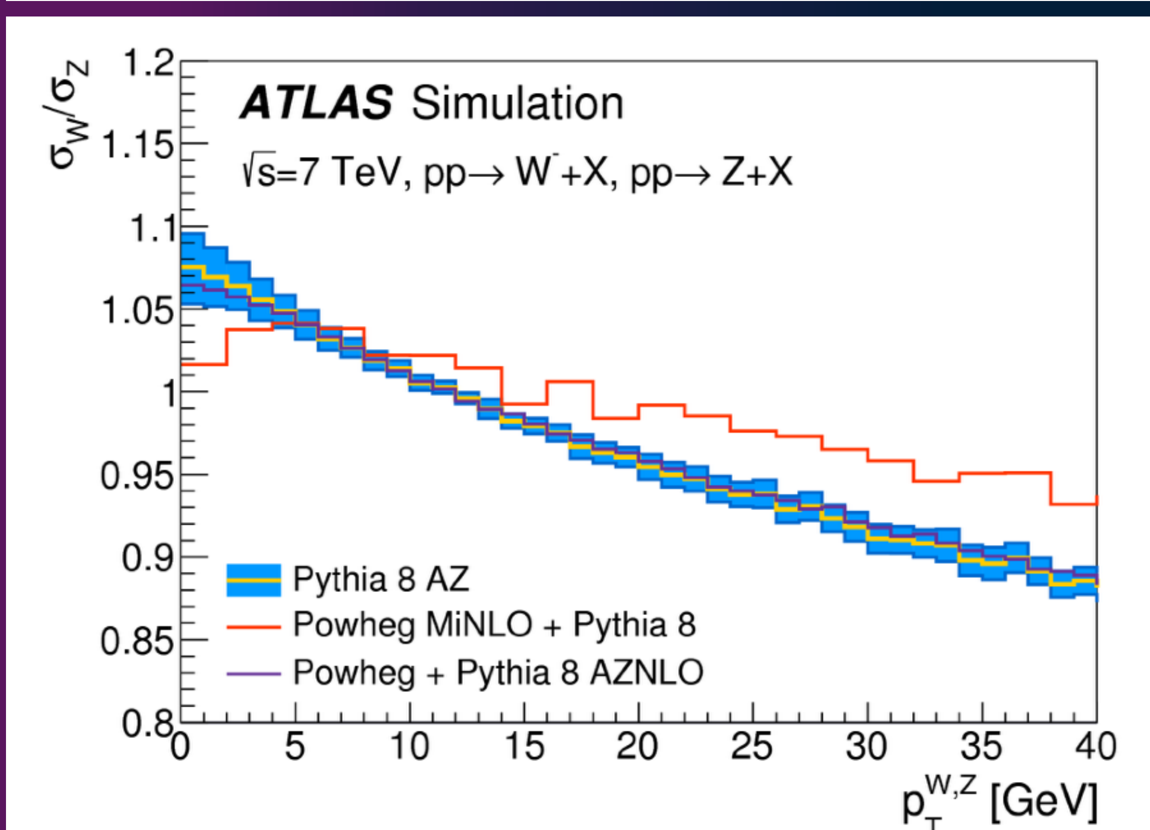
- Very different prediction of pTW/pTZ for DYRES and Powheg MiNLO + Pythia8 with respect to Pythia 8 AZ
- Strongly disfavoured by the data in $u_{//}$



pT modeling strategy



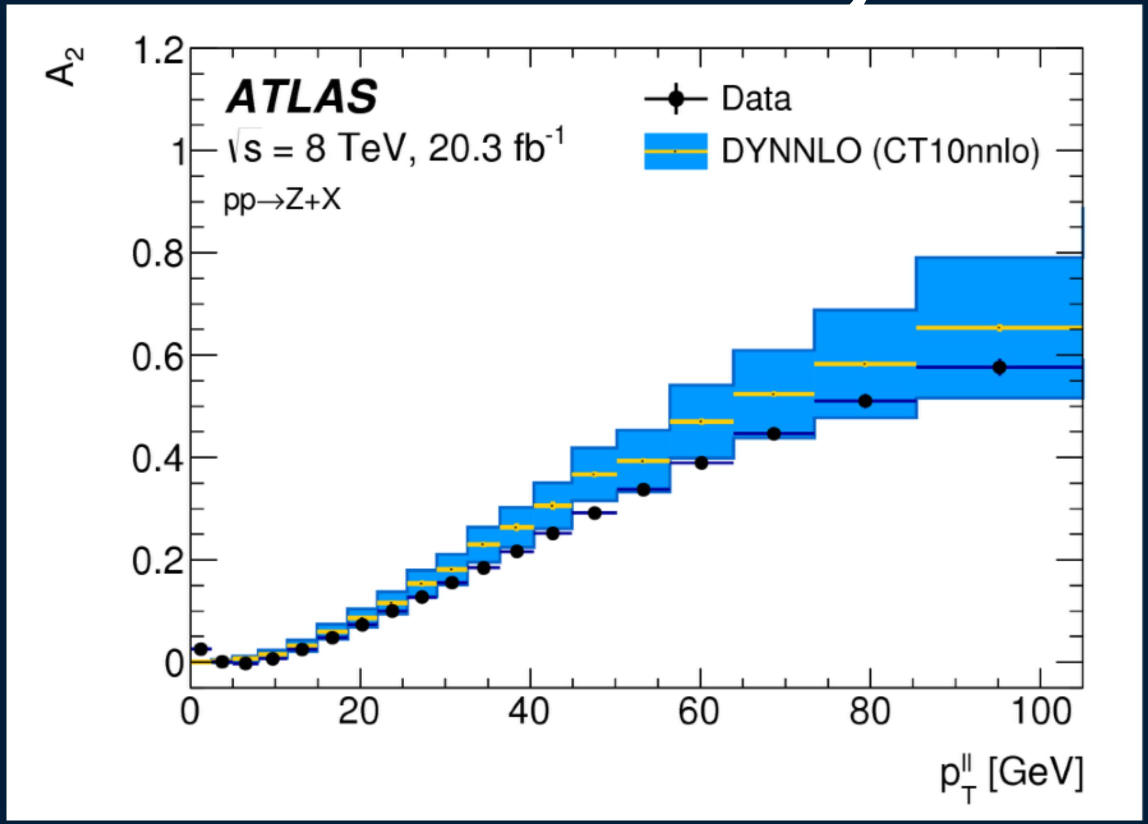


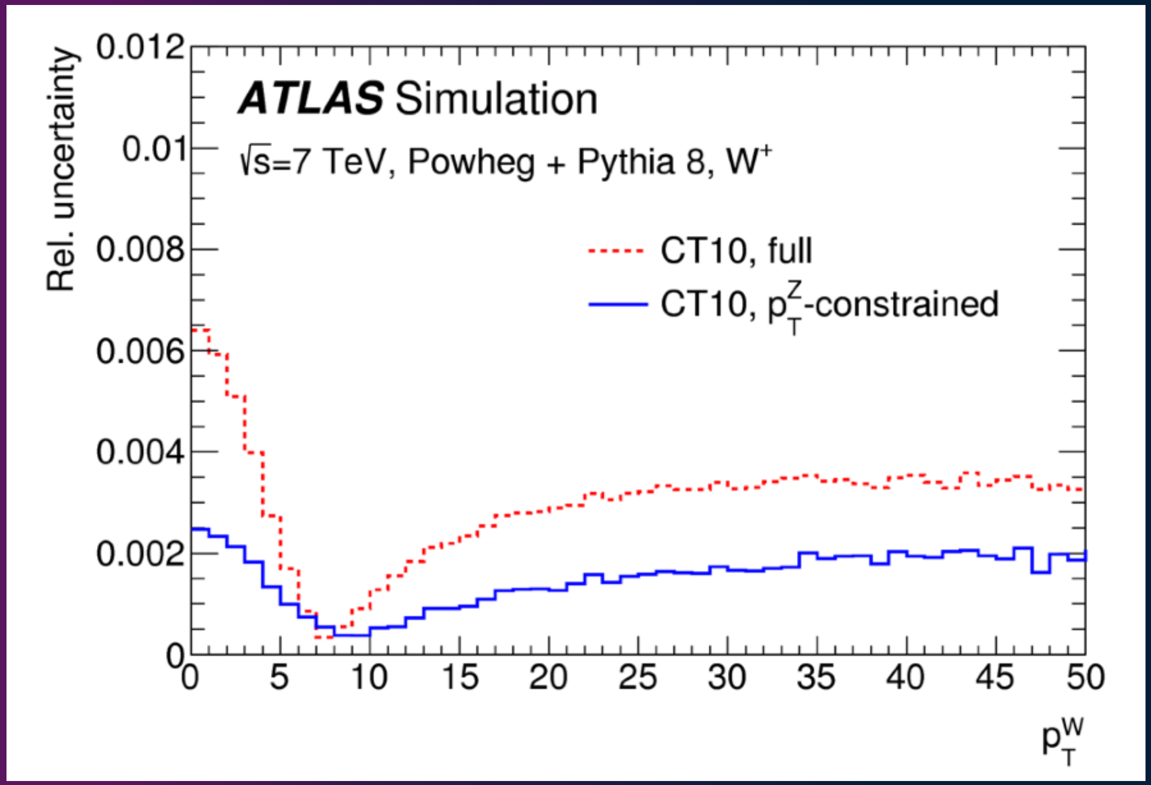


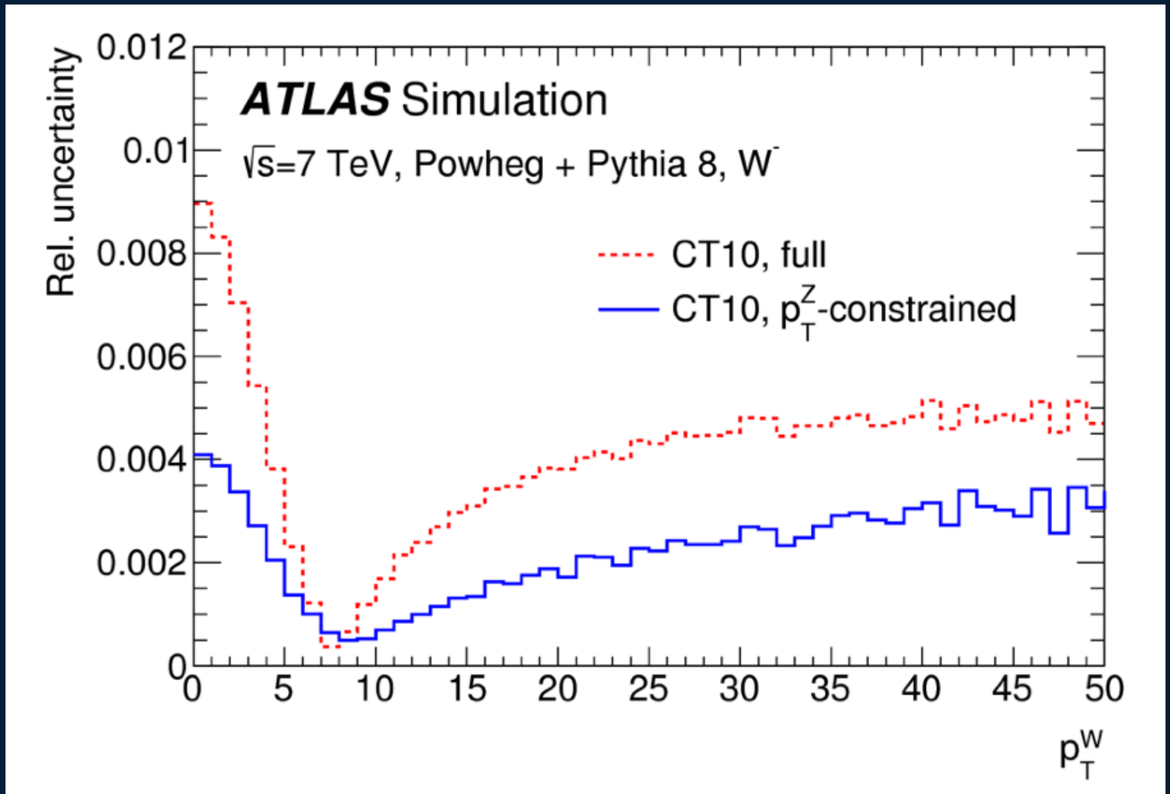
- p_T ratios for several generators : big difference from resummation and MiNLO vs Pythia 8 AZ
- Negligible impact of the PS model (Herwig 7)

fixed-order uncertainty

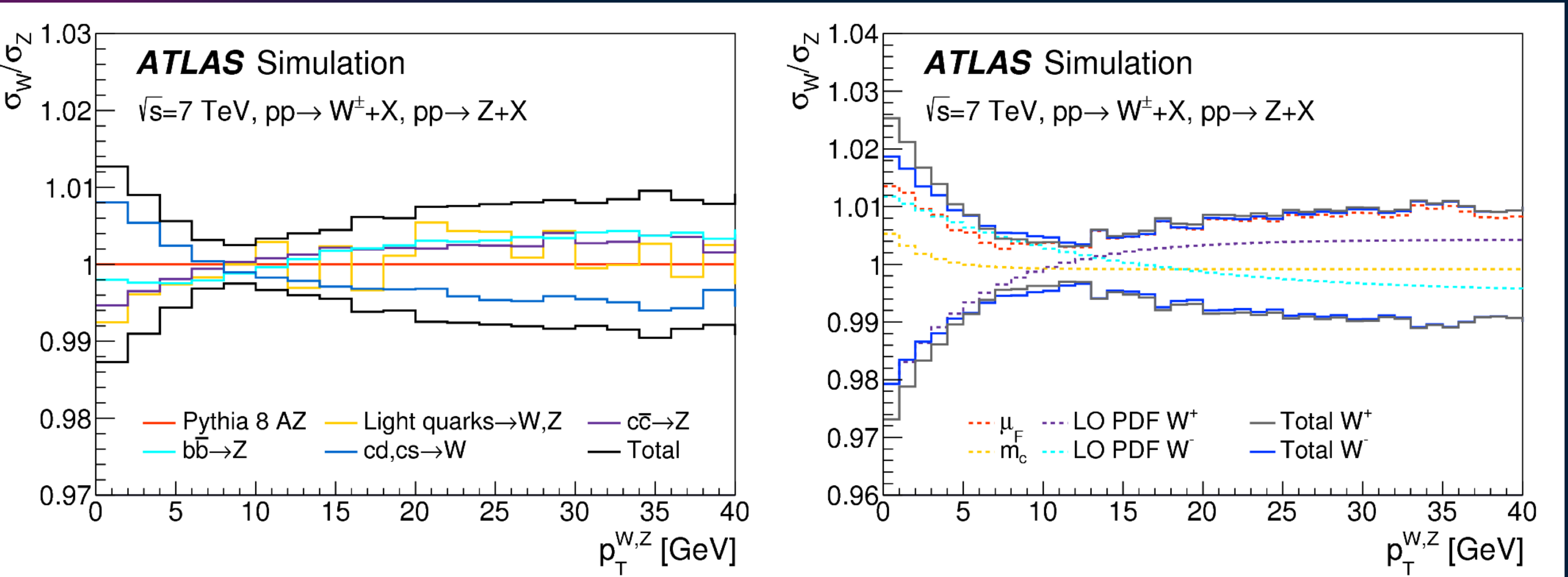
- Experimental polarisation uncertainties from Z measurement propagated to W, additional uncertainty for A2 (disagreement with DYNNLO)
- CT10nnlo relative variations of p_T^W and p_T^Z are considered





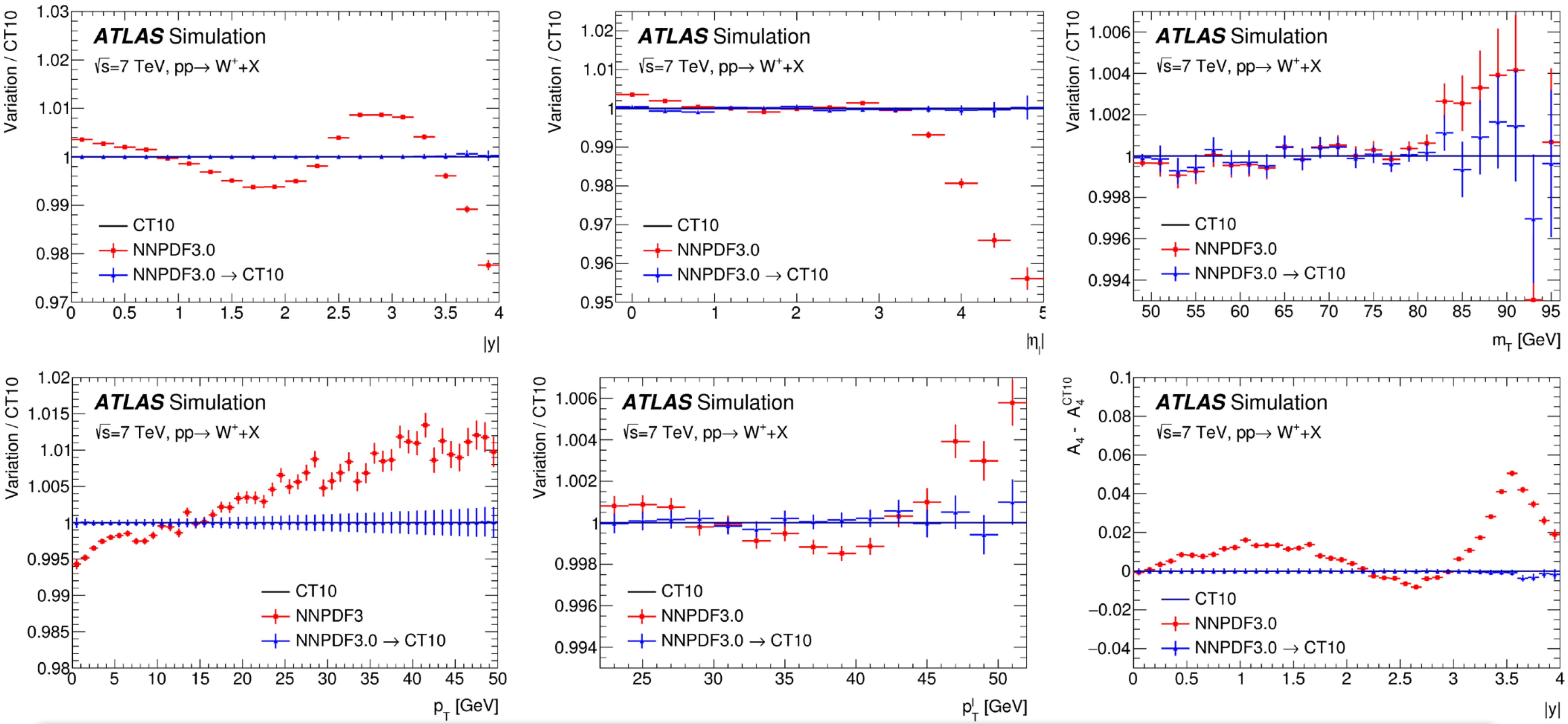


Parton shower uncertainty



- factorisation scale variations correlated between W/Z for light quark, uncorrelated for heavy quarks
- other sources : m_C, parton shower LO PDF

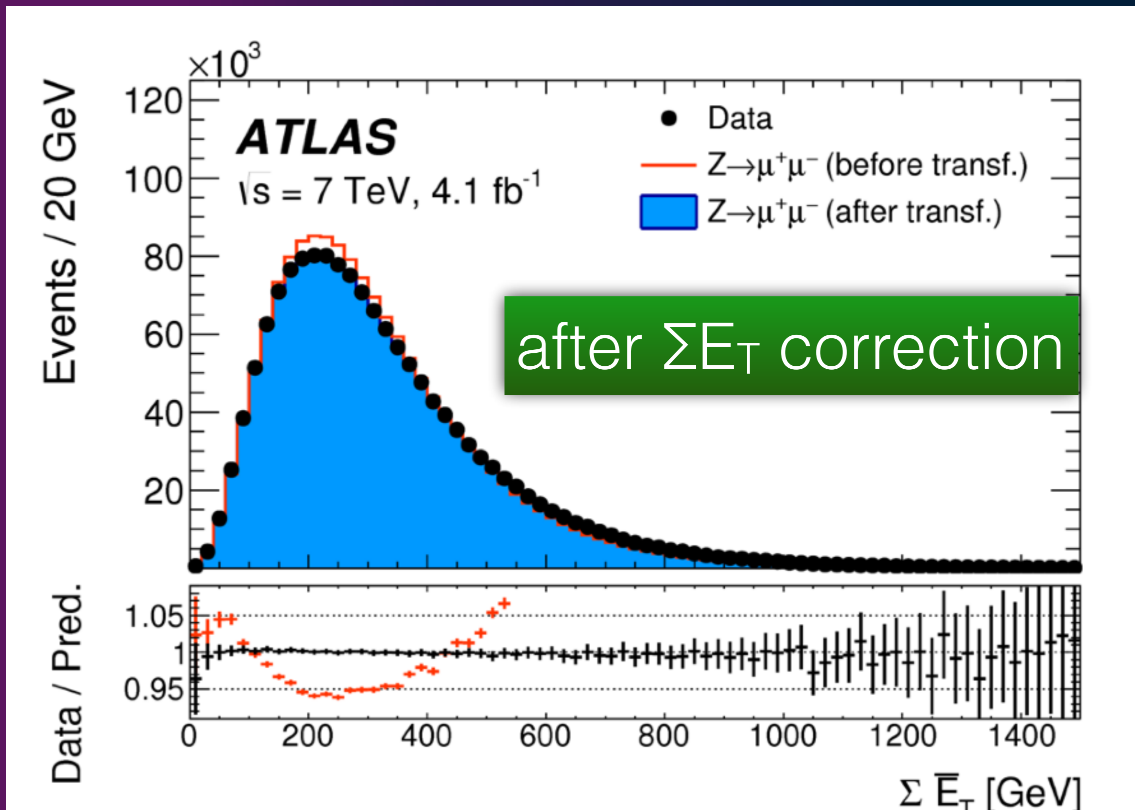
Modeling tests

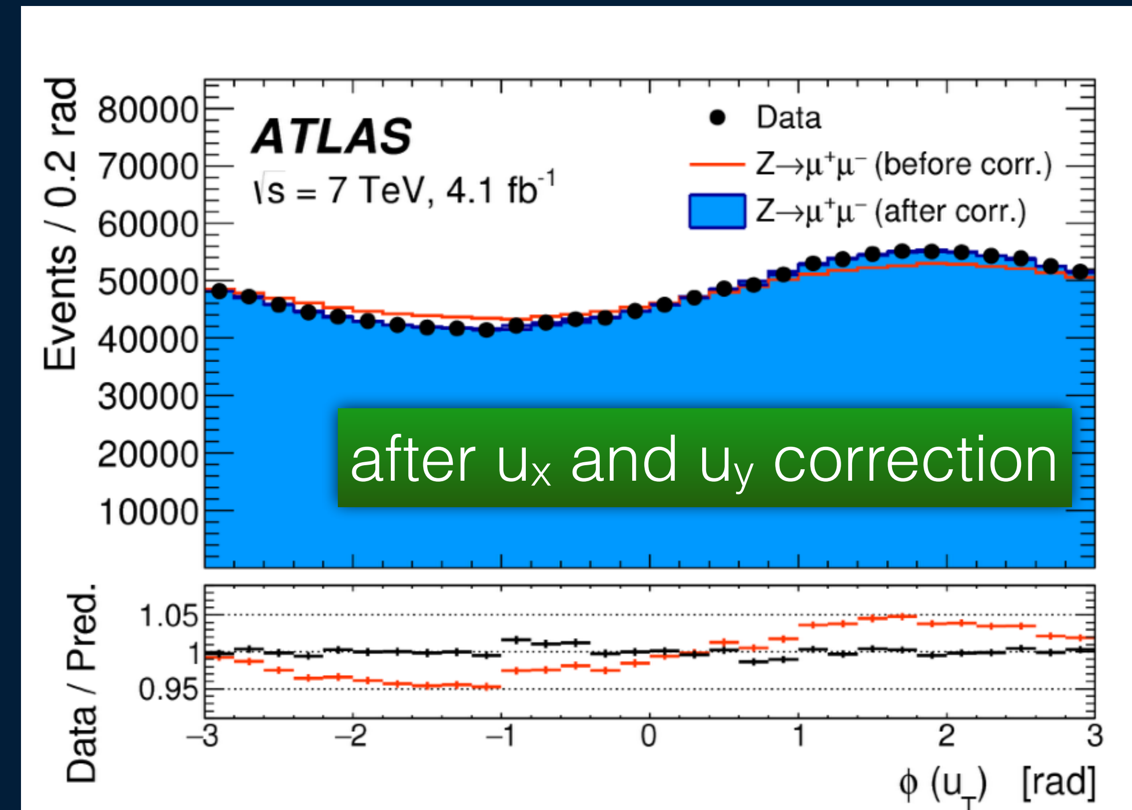


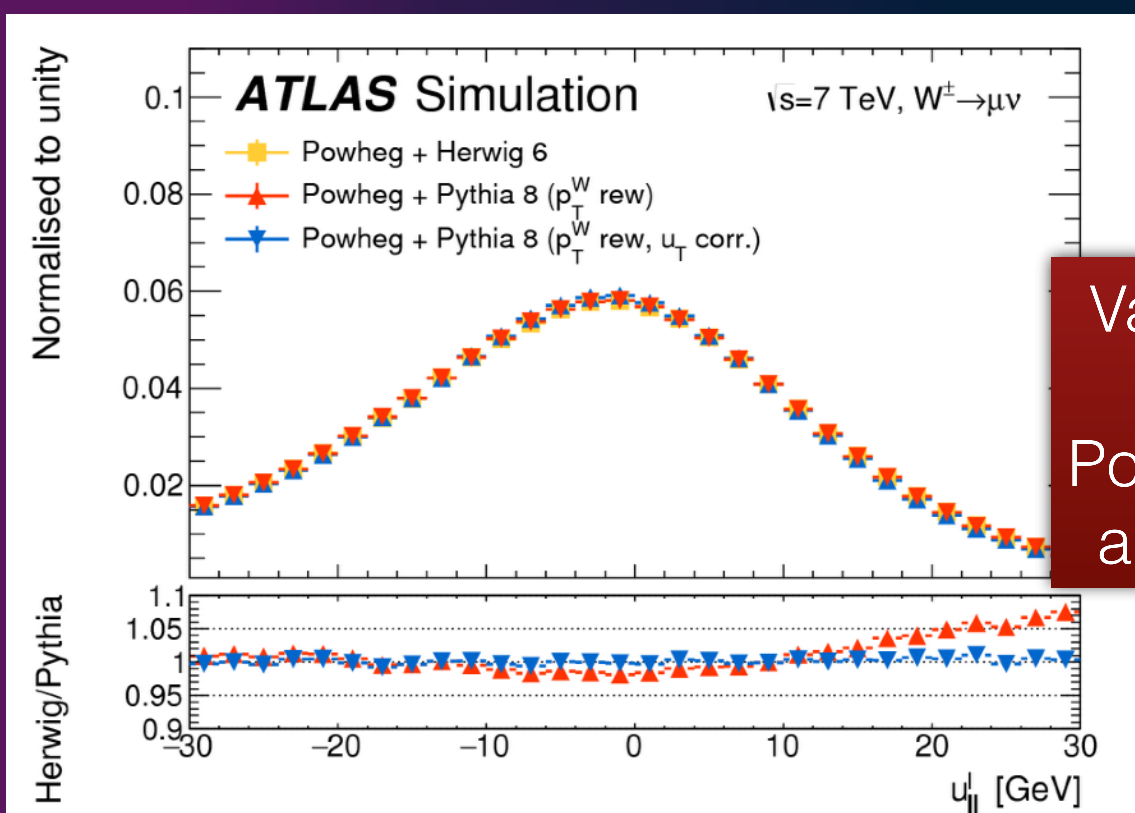
Use NNPDF3 prediction as pseudo-data, perform the various reweightings (y, p_T, polarisation) to CT10 sample : strongly validates the modeling procedure

$\Delta m_W = 1.5 \pm 2.0$ MeV

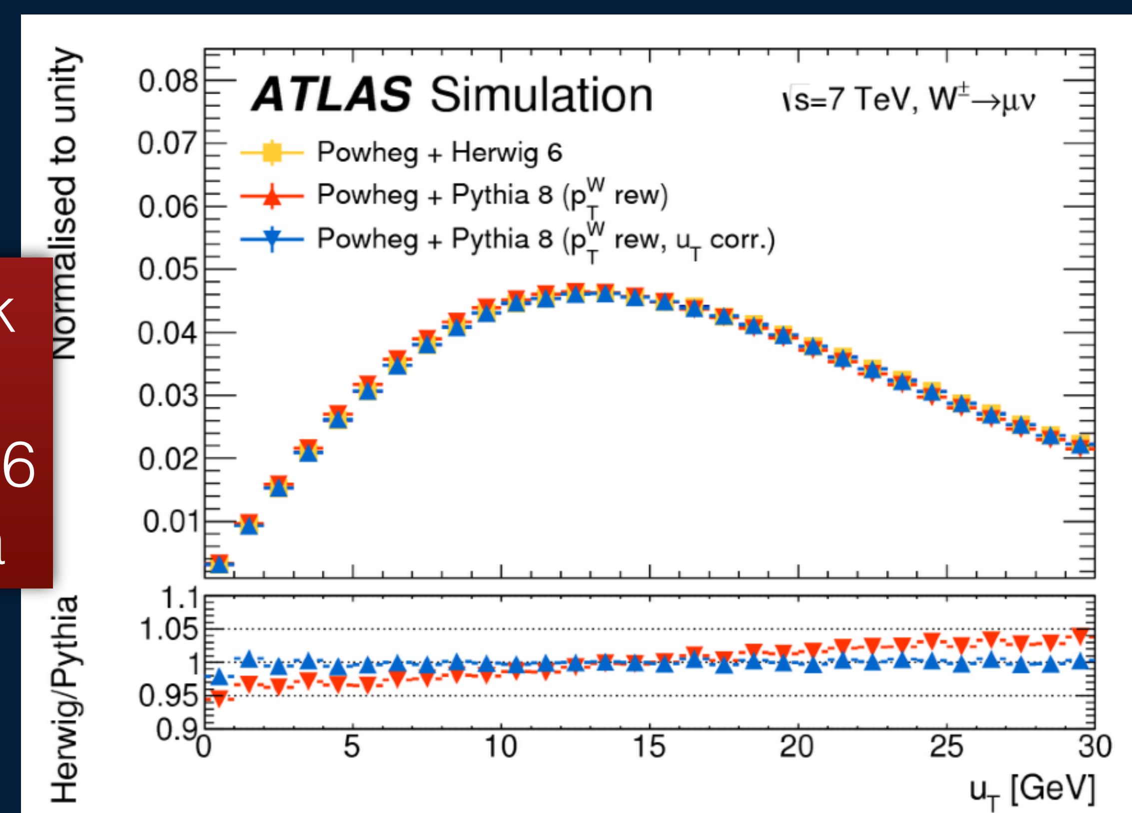
Recoil calibration



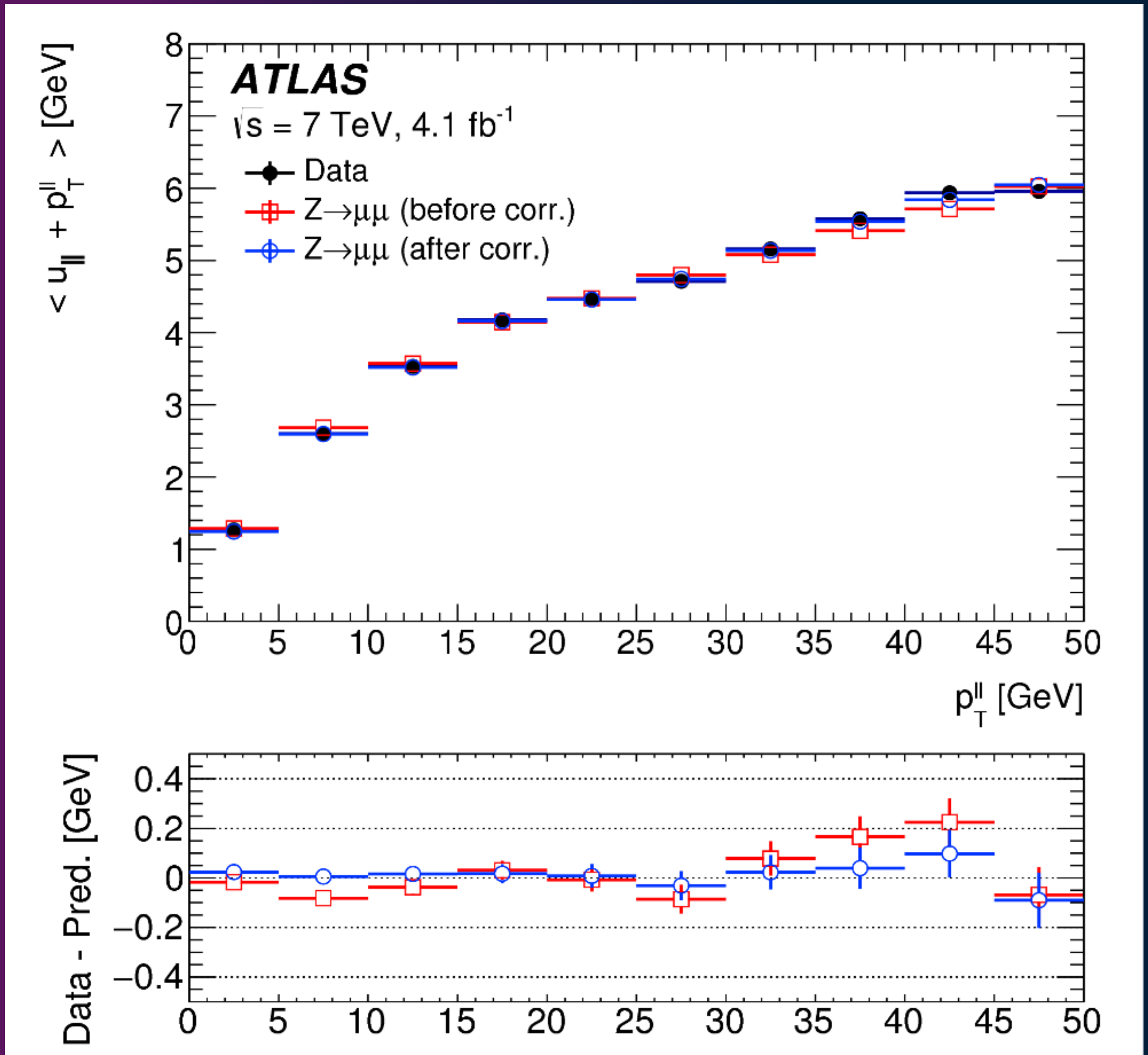




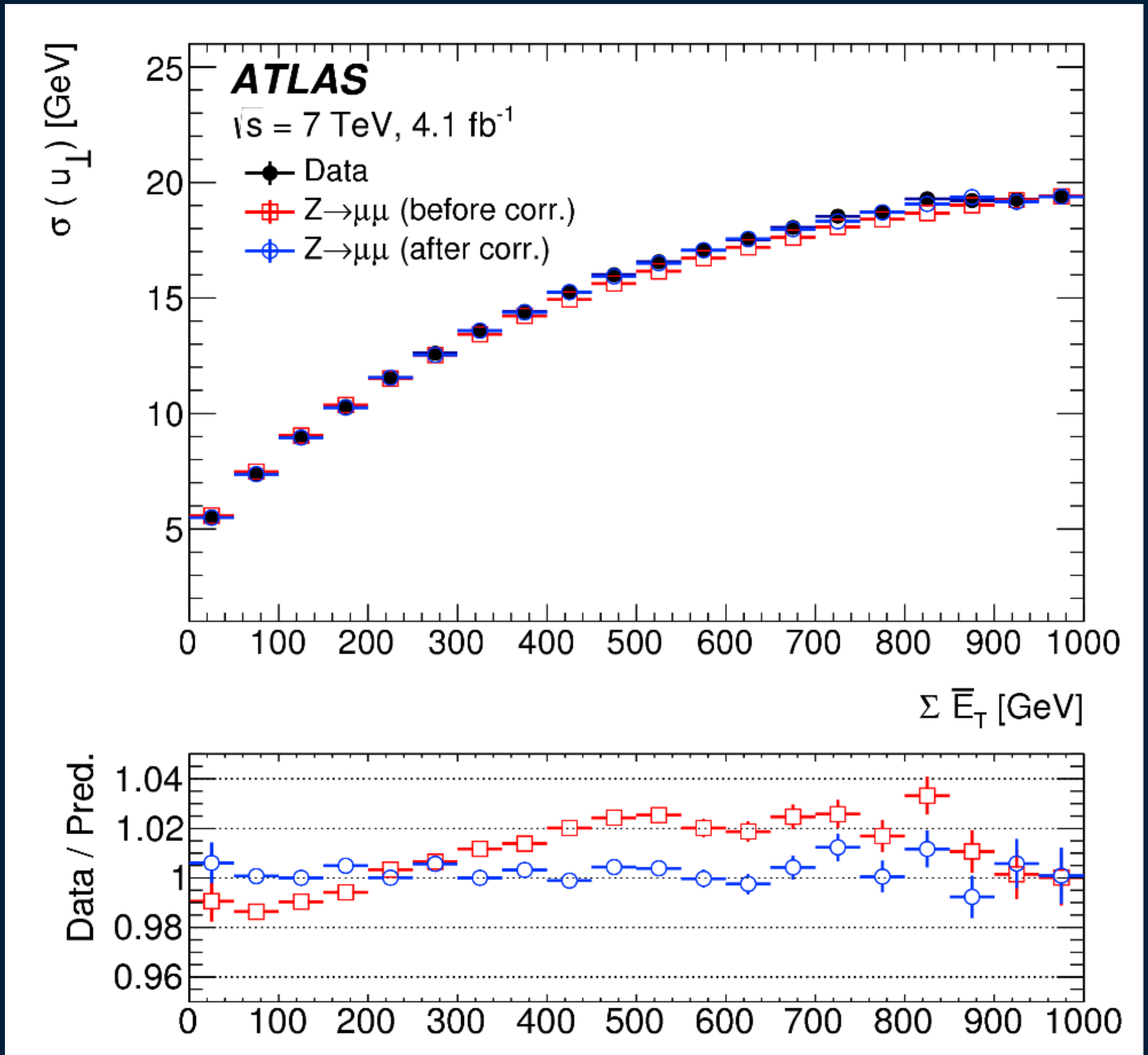
Validation check using Powheg+Herwig6 as pseudo-data



Recoil calibration

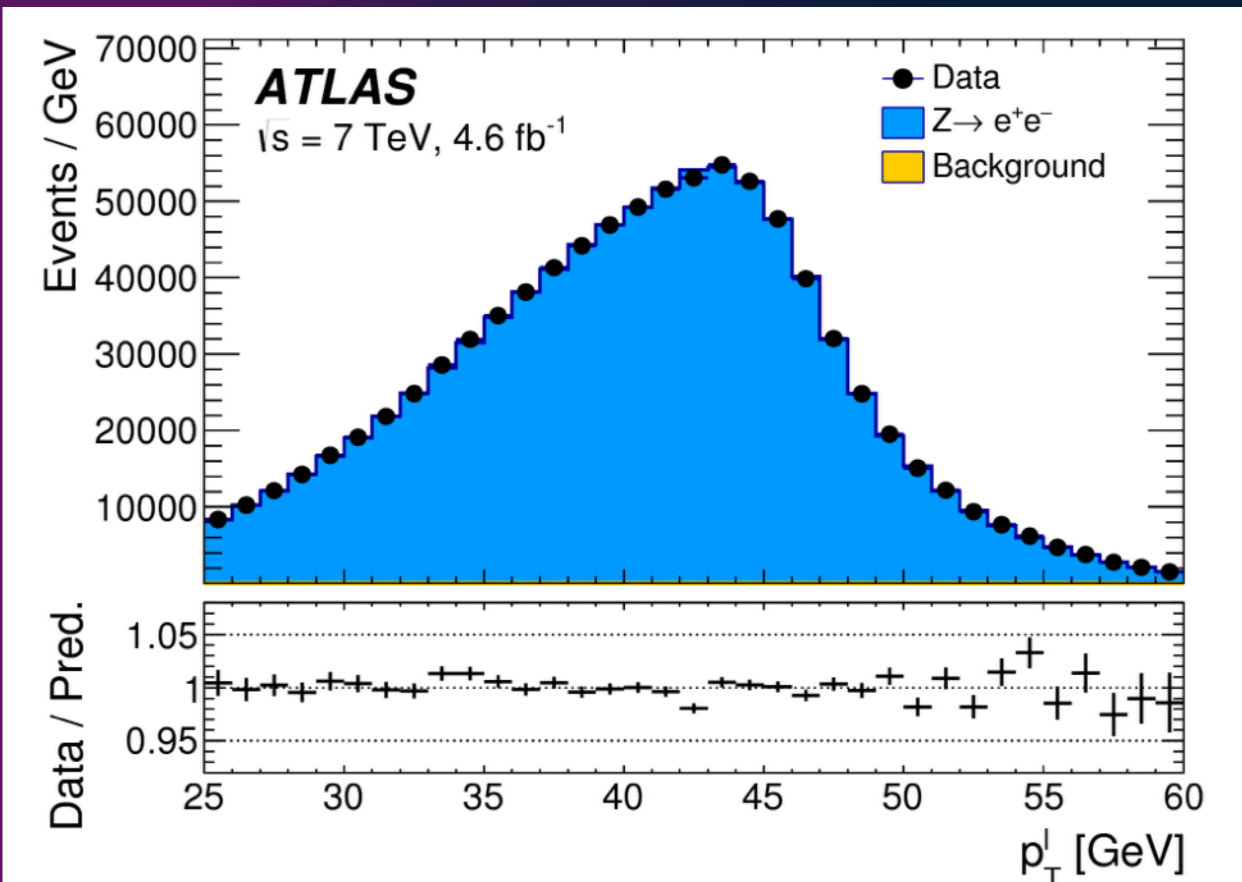


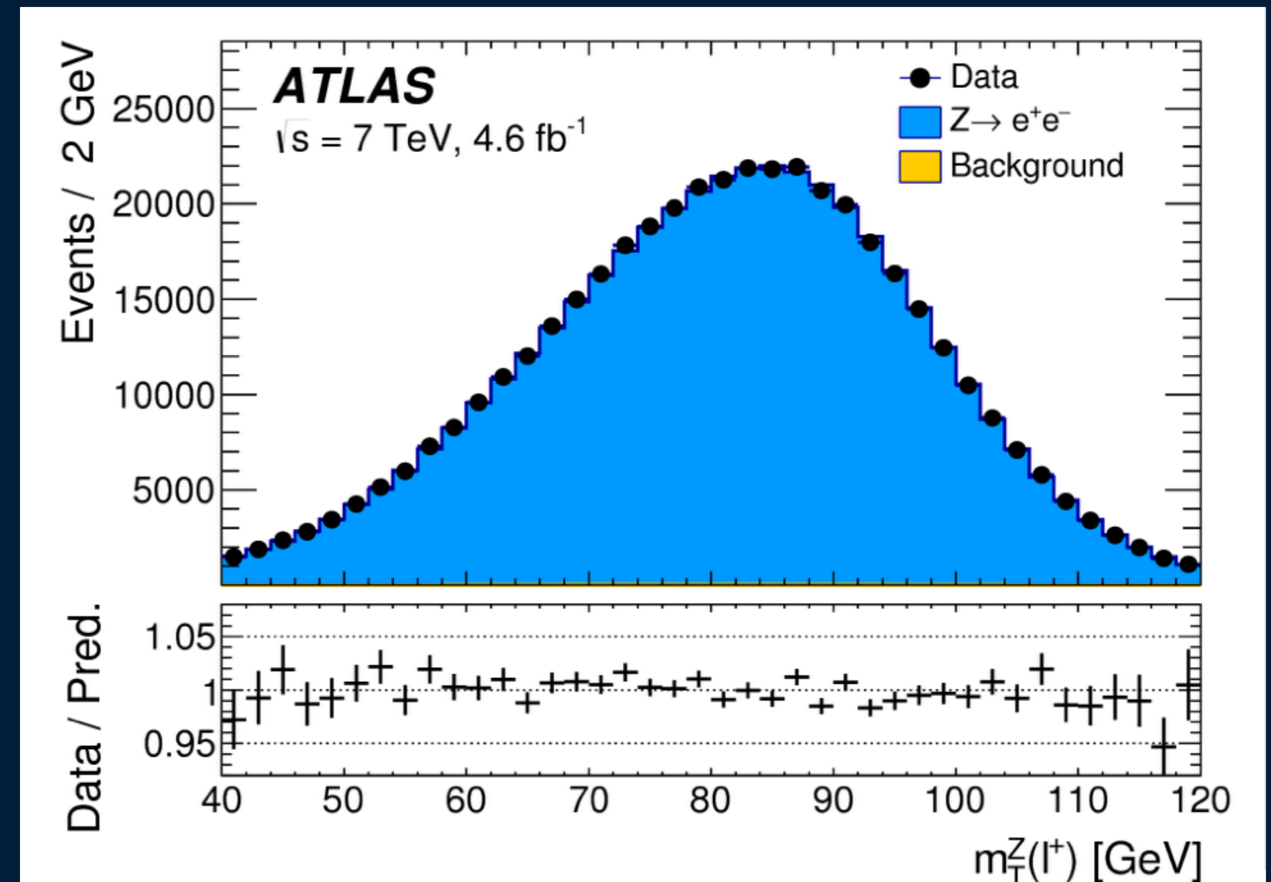
Recoil bias vs p_T^Z

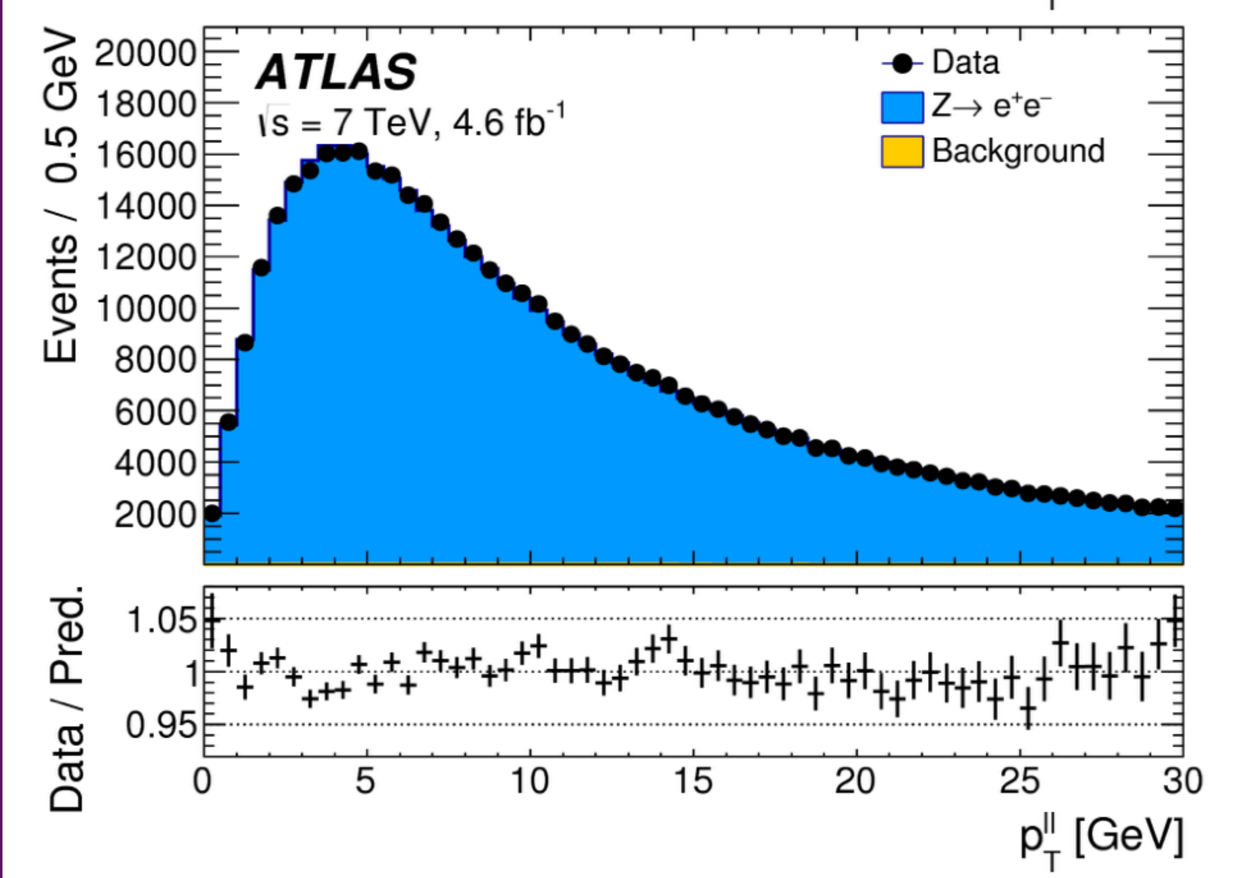


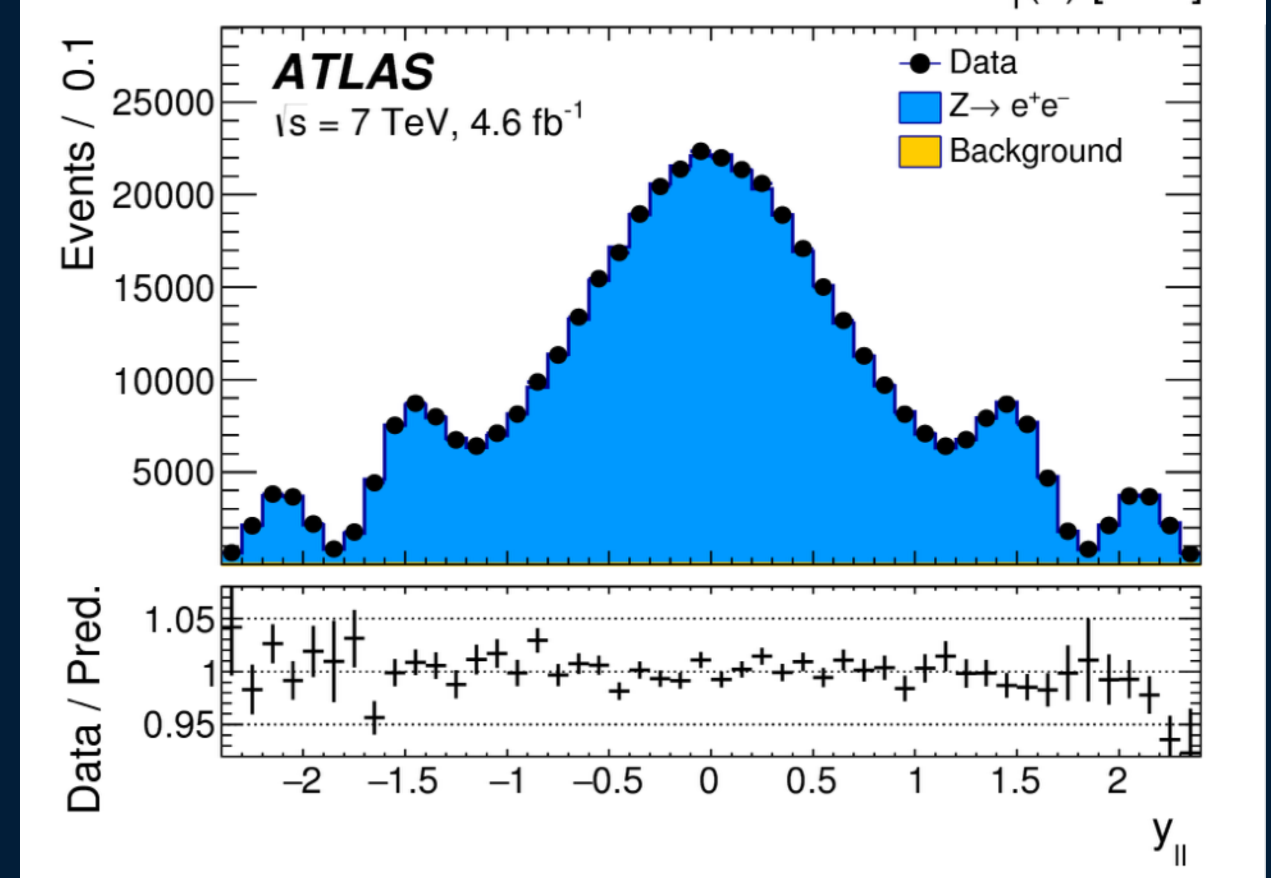
Recoil resolution vs ΣE_T

Z ee plots after all corrections

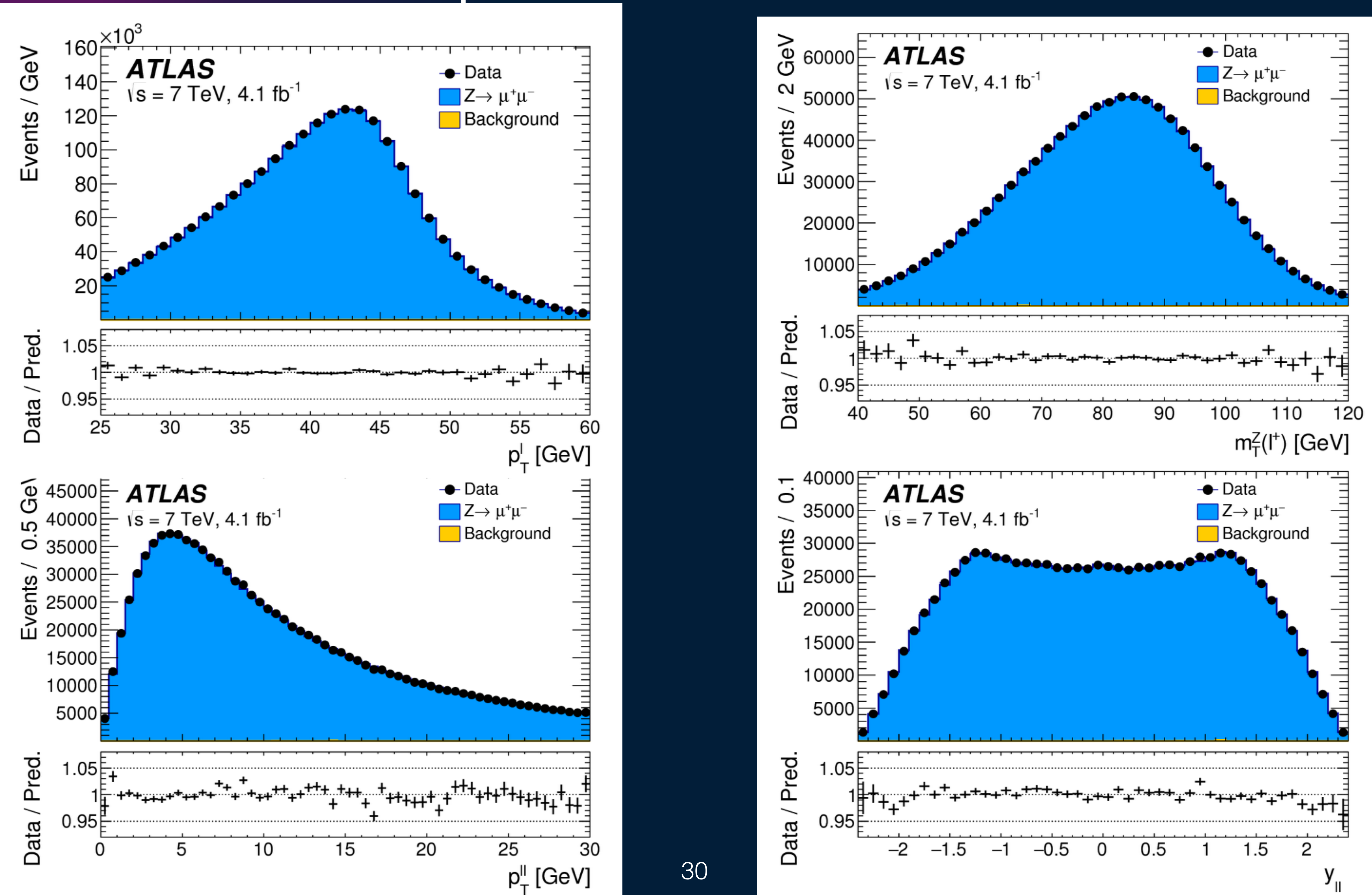




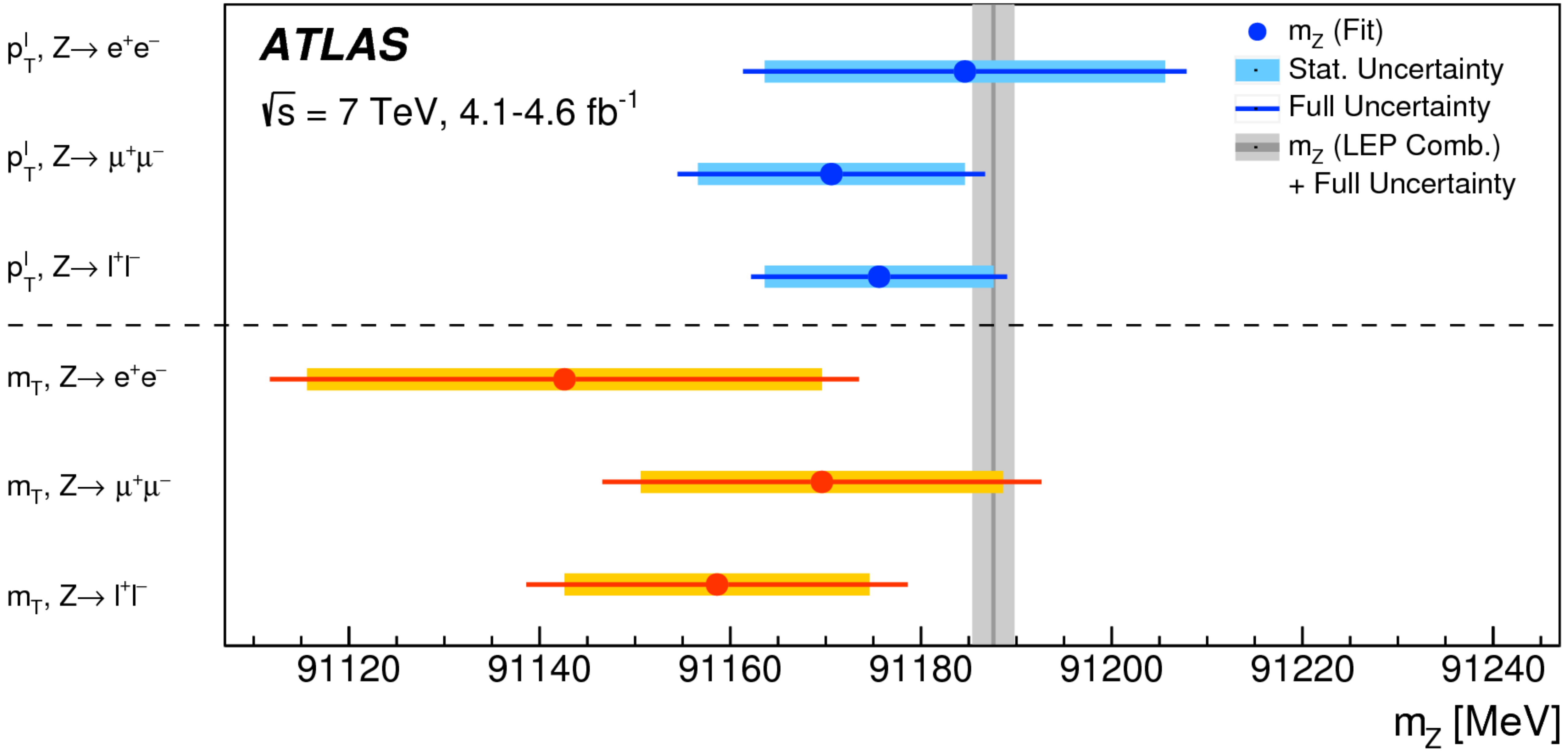




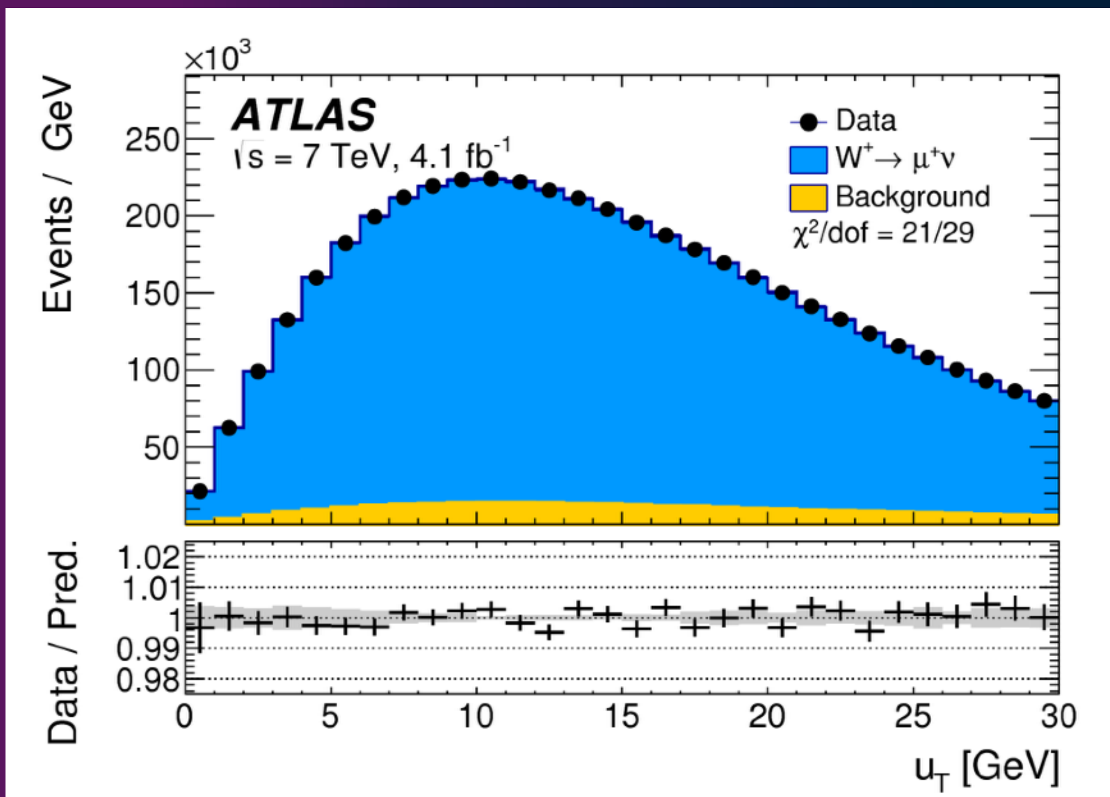
Z mumu plots after all corrections

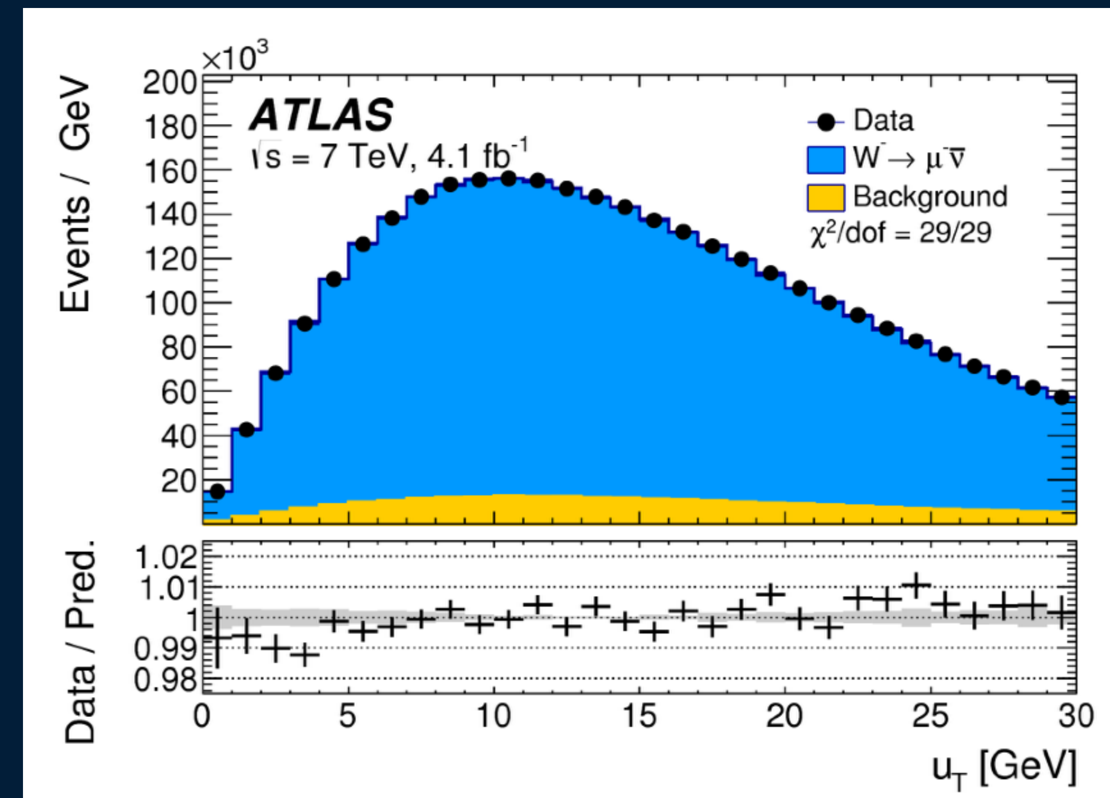


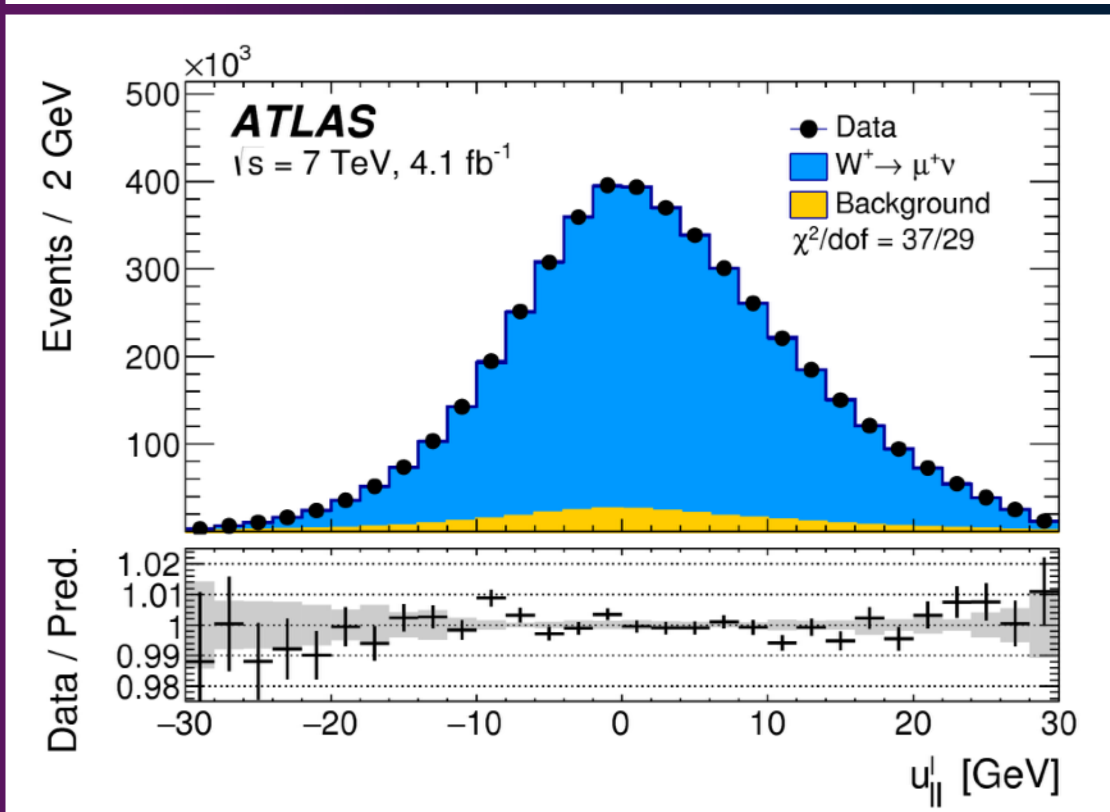
Z mass measurement

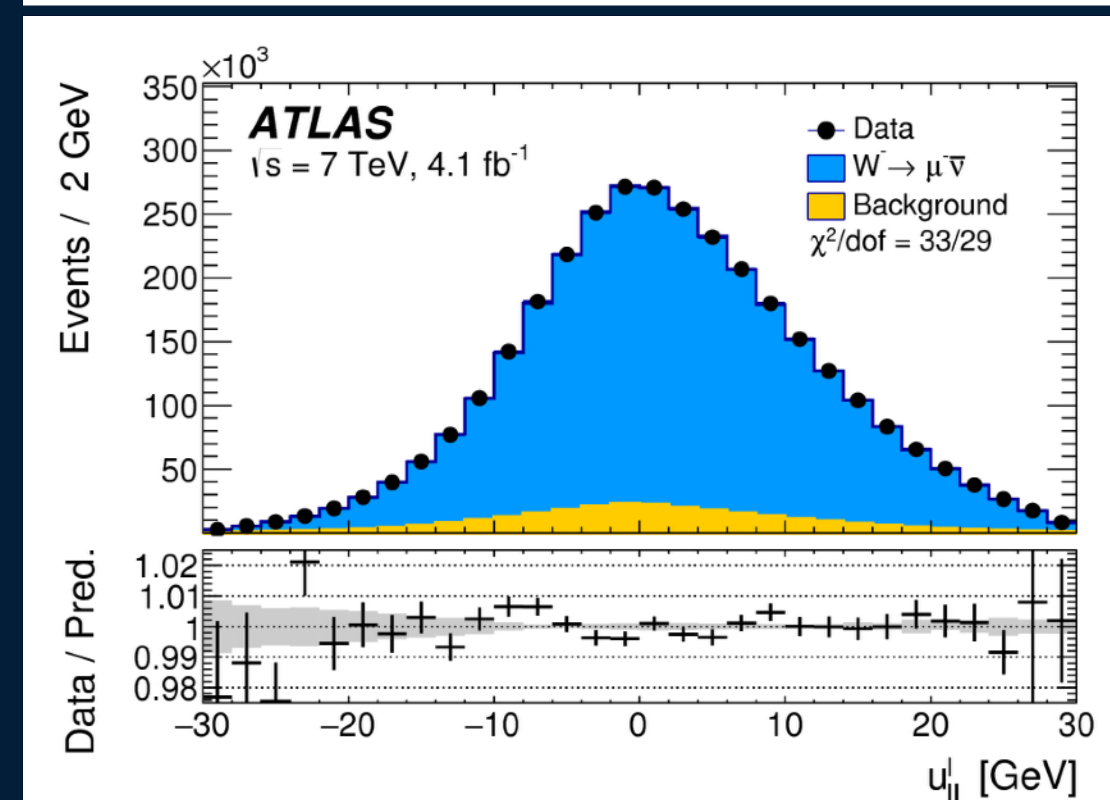


Hadronic recoil

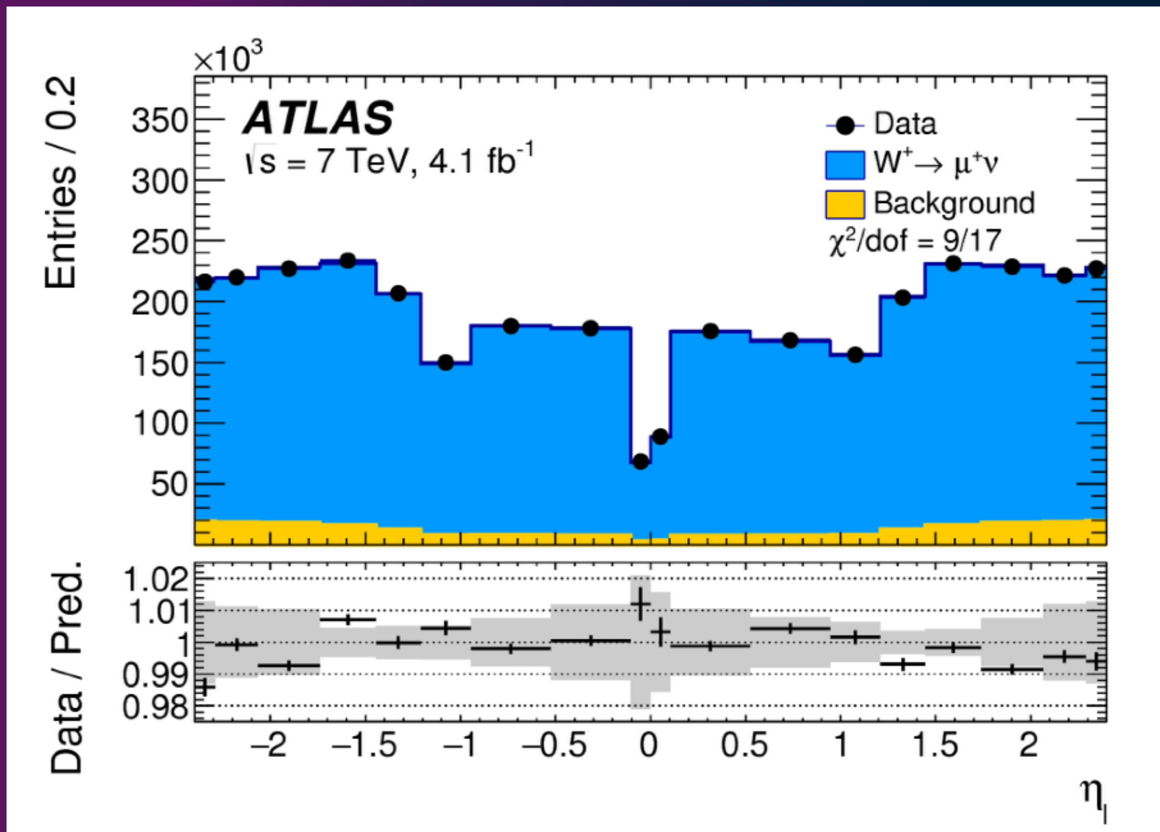


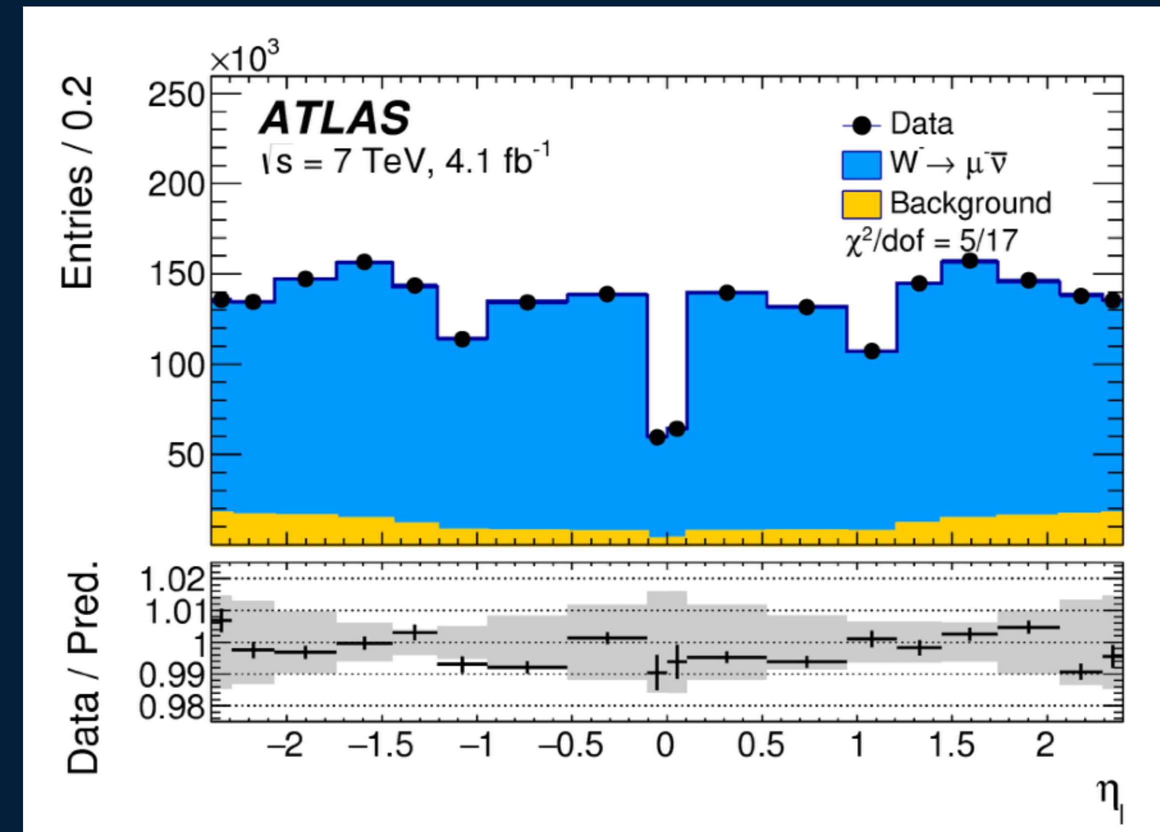


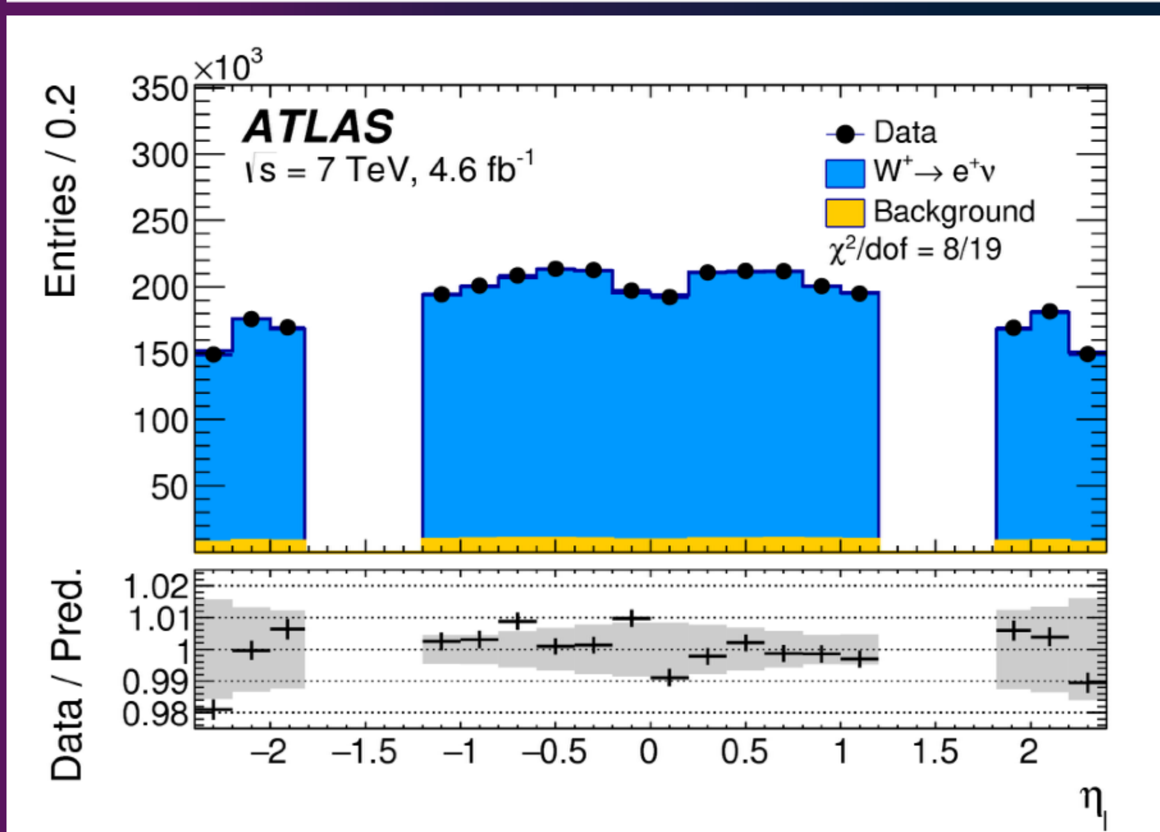


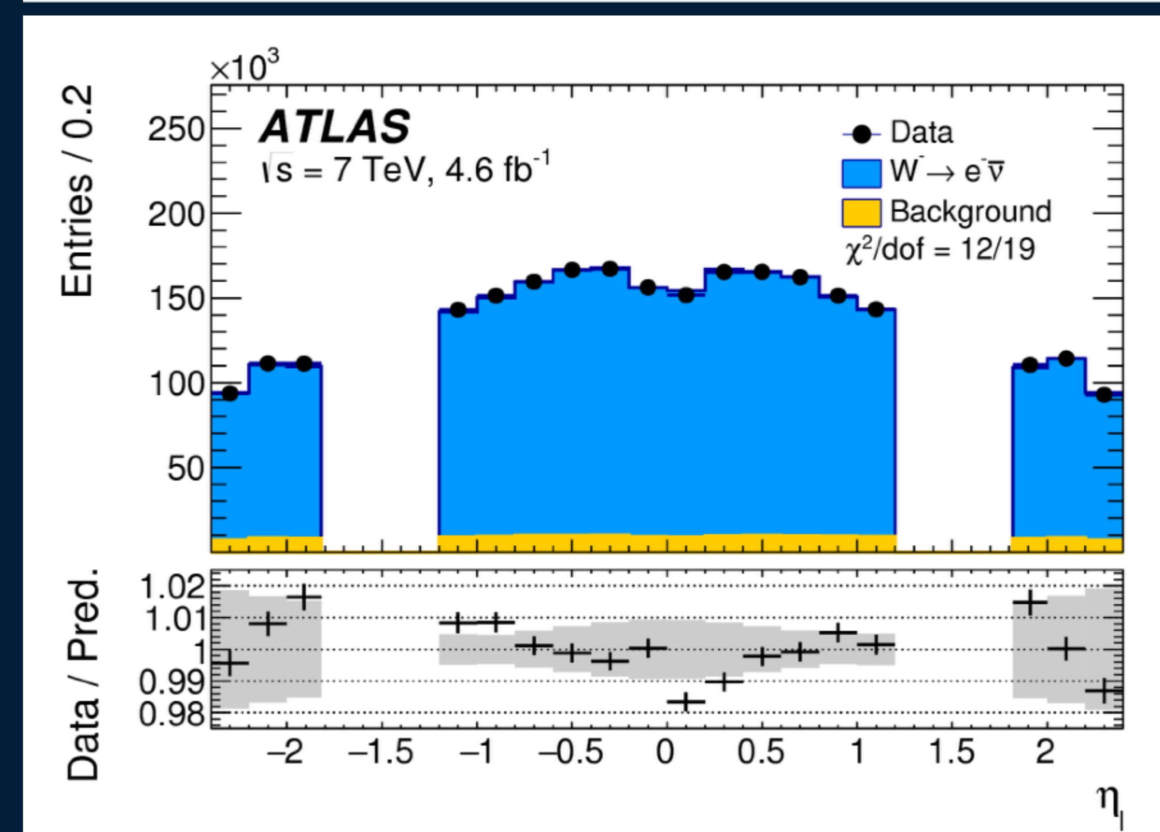


Lepton eta

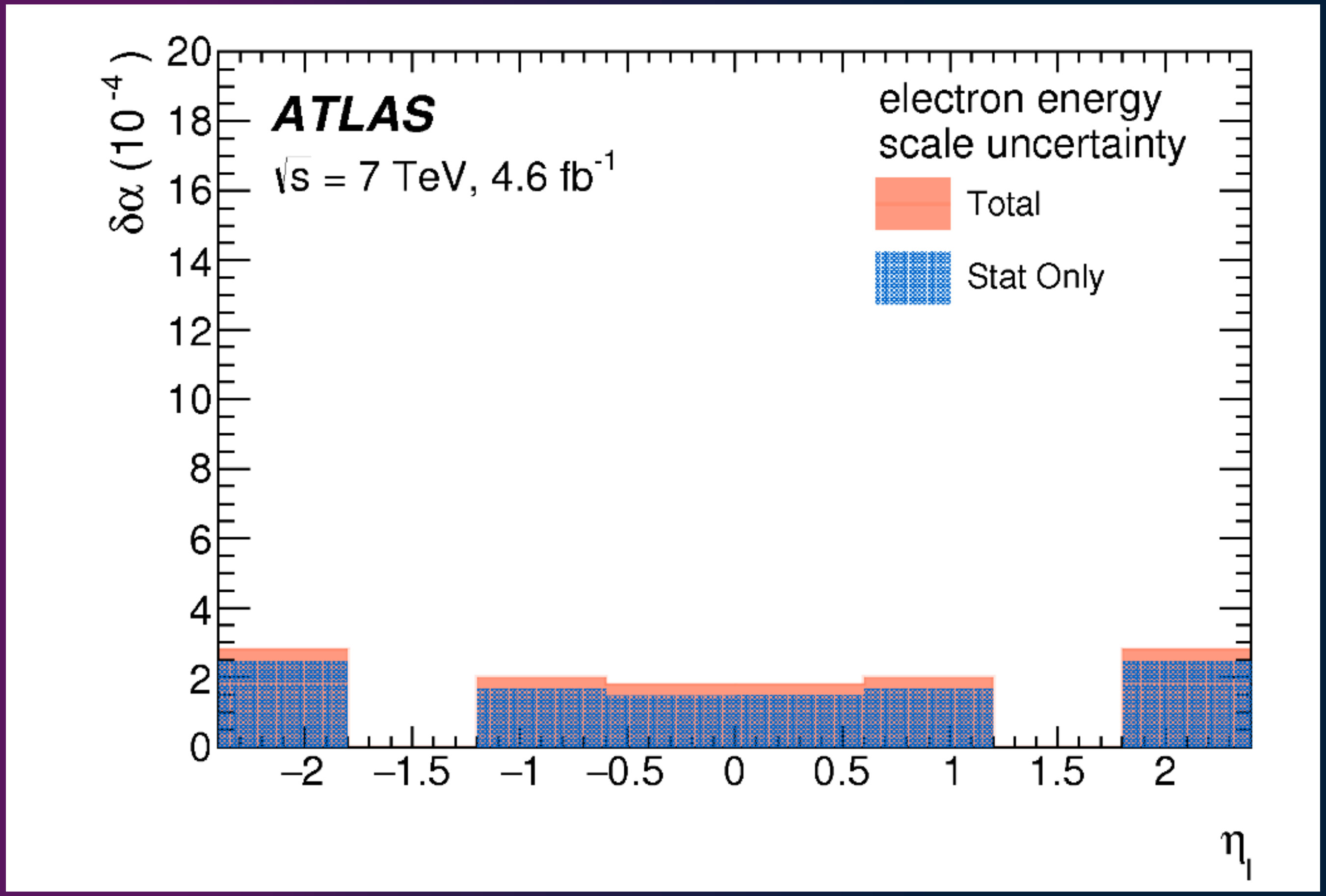

ATLAS
√s = 7 TeV, 4.1 fb⁻¹
Data
W⁺→ μ⁺ν
Background
χ²/dof = 9/17
Entries / 0.2
Data / Pred.
η_l

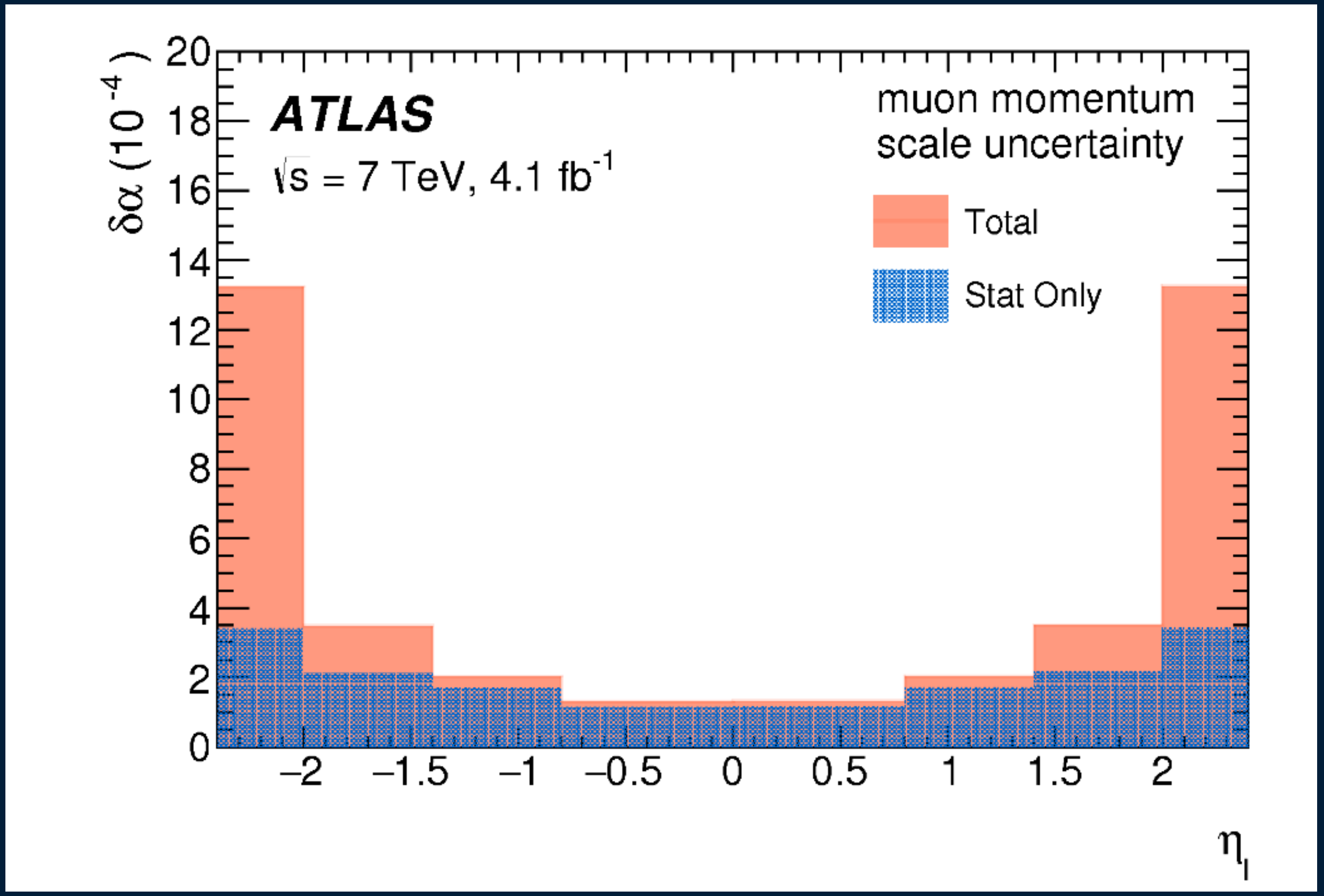

ATLAS
√s = 7 TeV, 4.1 fb⁻¹
Data
W⁻→ μ⁻ν̄
Background
χ²/dof = 5/17
Entries / 0.2
Data / Pred.
η_l


ATLAS
√s = 7 TeV, 4.6 fb⁻¹
Data
W⁺→ e⁺ν
Background
χ²/dof = 8/19
Entries / 0.2
Data / Pred.
η_l


ATLAS
√s = 7 TeV, 4.6 fb⁻¹
Data
W⁻→ e⁻ν̄
Background
χ²/dof = 12/19
Entries / 0.2
Data / Pred.
η_l

Lepton scale uncertainties





Background fractions

			$W \to \mu\nu$			
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

Full uncertainty table

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

lepton uncertainty tables

$|\eta_\ell|$ 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

$|\eta_\ell|$ 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

Weights of all categories

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