Measurement of m_W

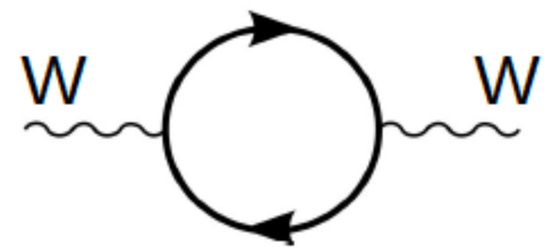
Massimo Corradi (INFN Roma-1)
on behalf of the ATLAS Collaboration

Main topics :

- ATLAS measurement of m_W (Eur.Phys.J. C (2018) 78:110)
- Prospects for a measurement of p_T^W using low-pileup runs (ATL-PHYS-PUB-2017-021)

Motivations

- In the SM at LO the W boson mass can be expressed as a function of three parameters known with high precision: α_{em} , G_μ , m_Z



$$\sin^2\theta_W = 1 - m_W^2 / m_Z^2$$

$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2} G_\mu} \frac{1}{1-\Delta r}$$

$$\Delta r = \Delta\alpha - \tan\theta_W \Delta\rho(m_{top}) + \Delta r_{rem}^{SM}(m_{top}, m_H) + \ldots$$

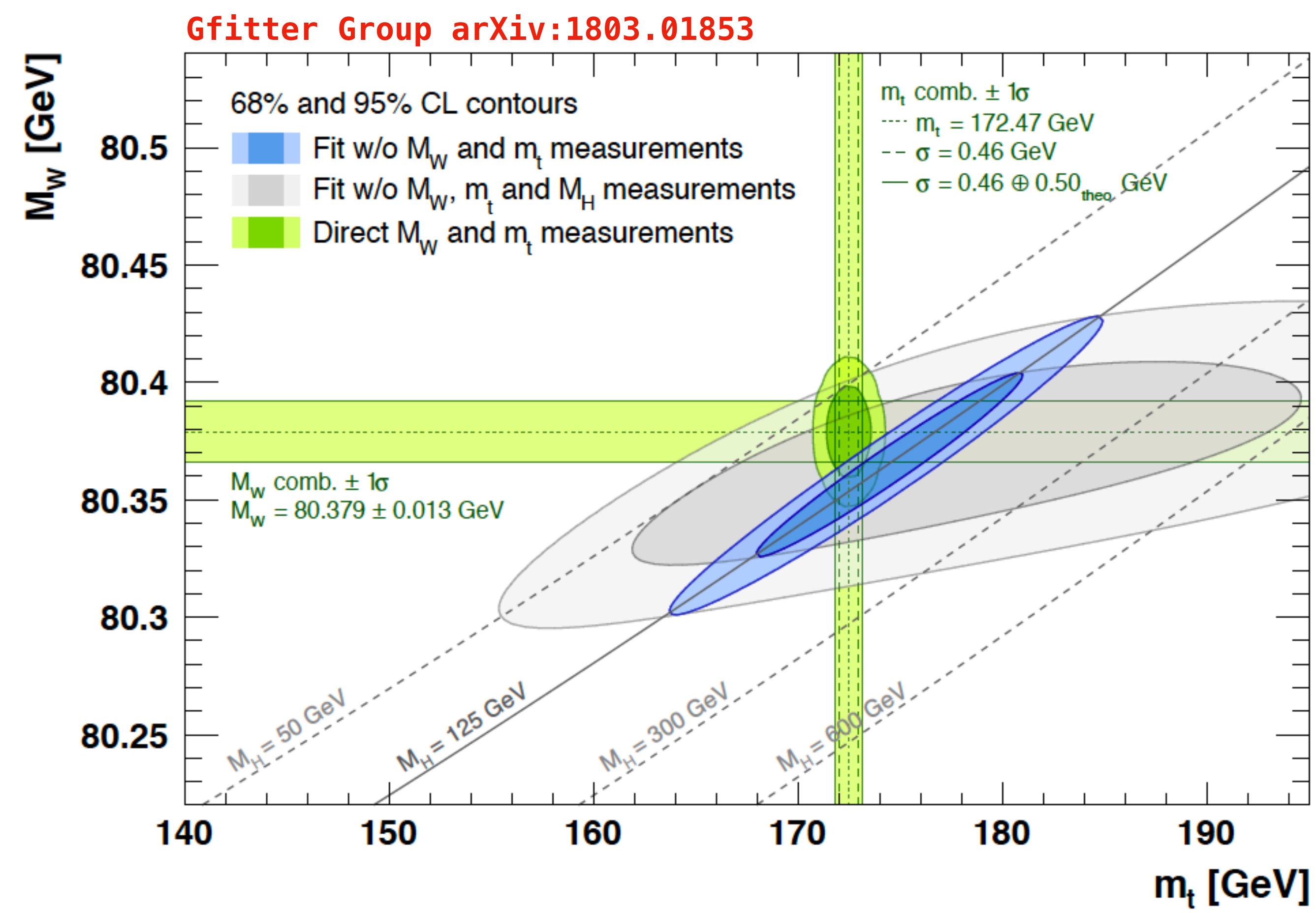
- Beyond LO : corrections depending on m_H and m_{top}

- Test of SM: compare measured m_W to prediction from SM EWK fit

- SM fit without m_W:
  m_W = 80354 +- 7 MeV (arXiv:1803.01853)

- Previous combined measurements :
  LEP m_W = 80376 +- 33 MeV
  Tevatron m_W = 80387 +- 16 MeV

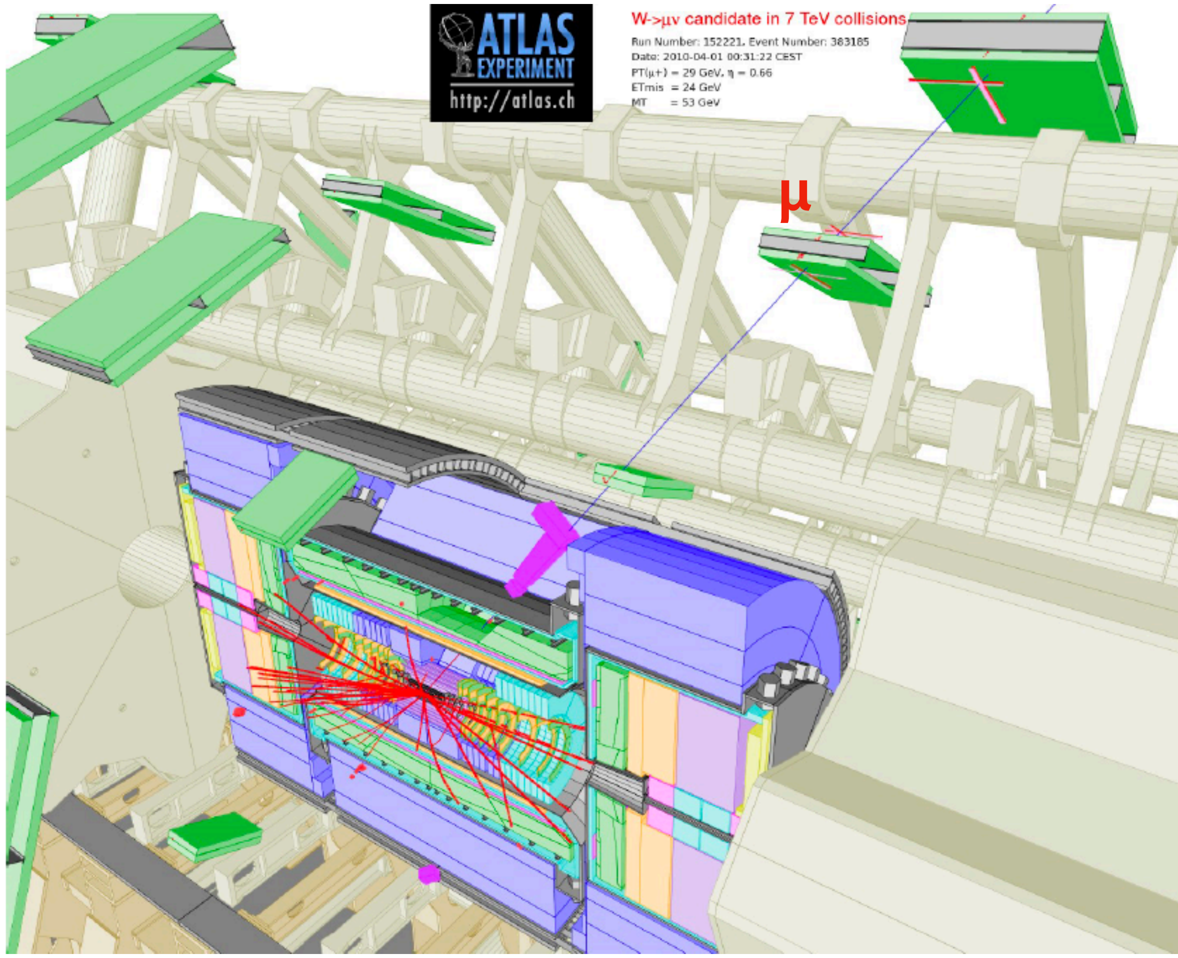
=> can we improve with LHC data ?



W reconstruction with ATLAS

W->$l\nu$ (l=**e**,μ) decays reconstructed in ATLAS :

- Muons identified and measured by the inner detector (ID) and Muon Spectrometer;
- Electrons are identified and measured by the ID and the Liquid Argon EM calorimeters;
- The missing transverse momentum is measured with the whole calorimeter system.

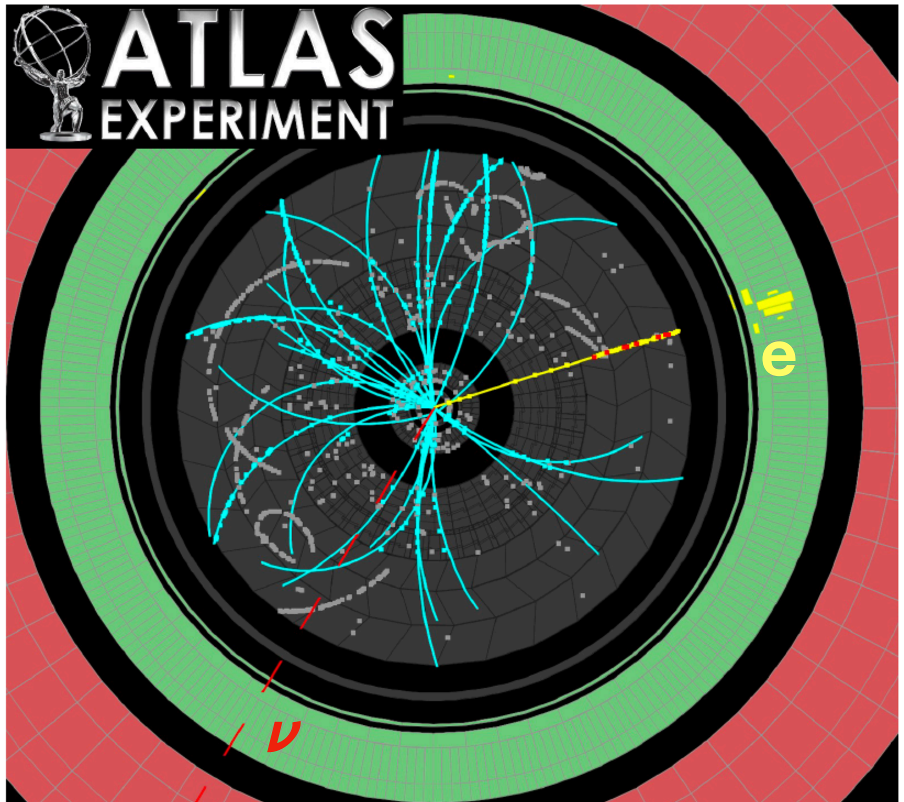


The m_W measurement is based on data collected in 2011 :

$\sqrt{s}$ = 7 TeV

$\int dL$ = 4.6 (4.1) fb^{-1} for **e** (**μ**) sample,

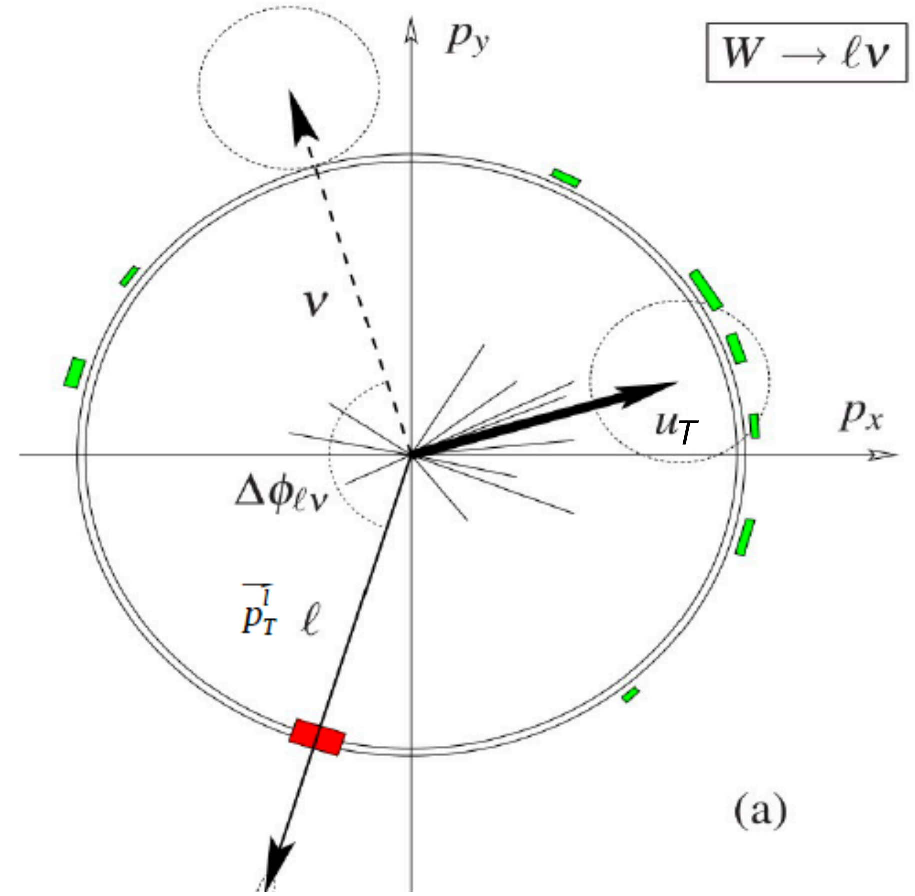
Average number of inelastic pp collisions per bunch crossing <μ>= 9.1



Selection and reconstruction

Main variables:

- Lepton transverse momentum: $\overrightarrow{p_T}^{\,l}$
- Recoil: $\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$
- Missing-p_T: $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$.
- Transverse mass: $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$



Event selection:

- Muons: $|\eta|<2.4$
- Electrons : $|\eta|<1.2$ OR $1.8<|\eta|<2.4$
- Lepton isolation
- $p_T^l>30$ GeV
- $p_T^{miss}>30$ GeV
- $u_T<30$ GeV
- $m_T>60$ GeV

	Events
$W^+ \to \mu^+\nu$	4 609 818
$W^- \to \mu^-\bar{\nu}$	3 234 960
$W^+ \to e^+\nu$	3 397 716
$W^- \to e^-\bar{\nu}$	2 487 525

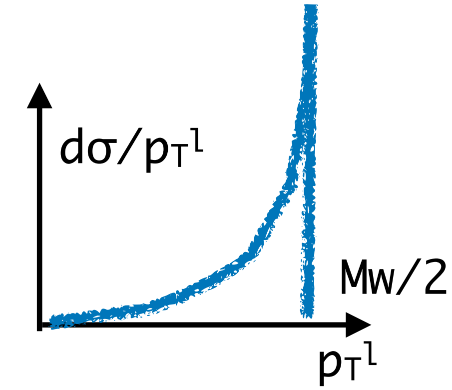
Sample of 13.7 M events: 5 times larger than combined (D0+CDF) Tevatron sample.

Z->ll selection used to MC tuning and cross check

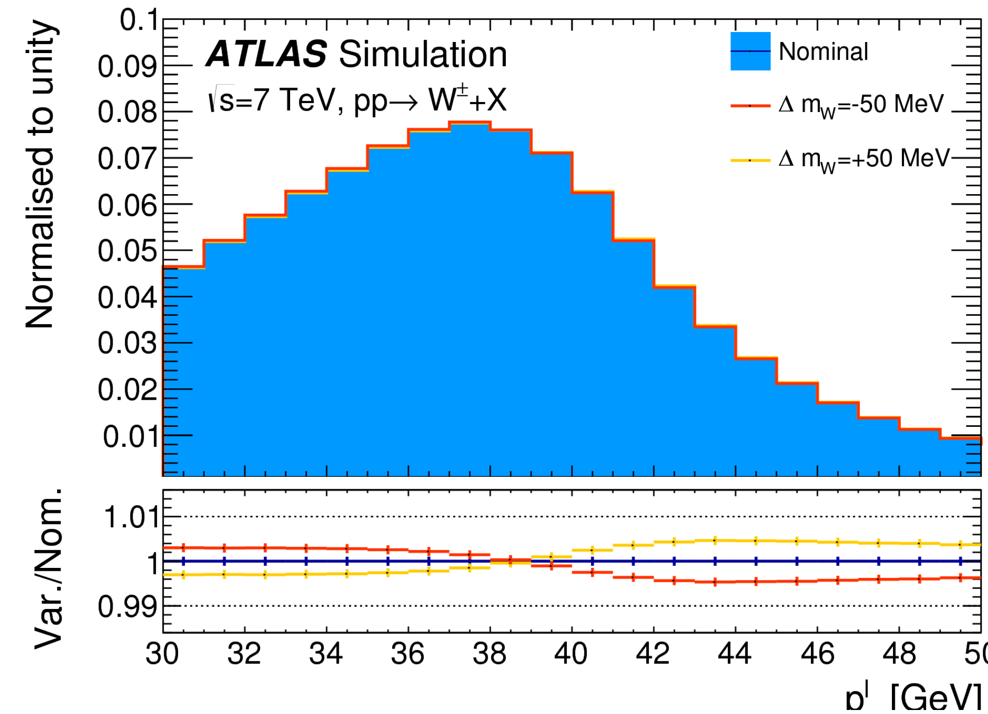
m_W measurement strategy

At LO p_T^l has a Jacobian peak at $m_W/2$,
m_T has an endpoint at m_W

LO :
$d\sigma/d\cos\vartheta^* \propto (1+\cos^2\vartheta^*)$

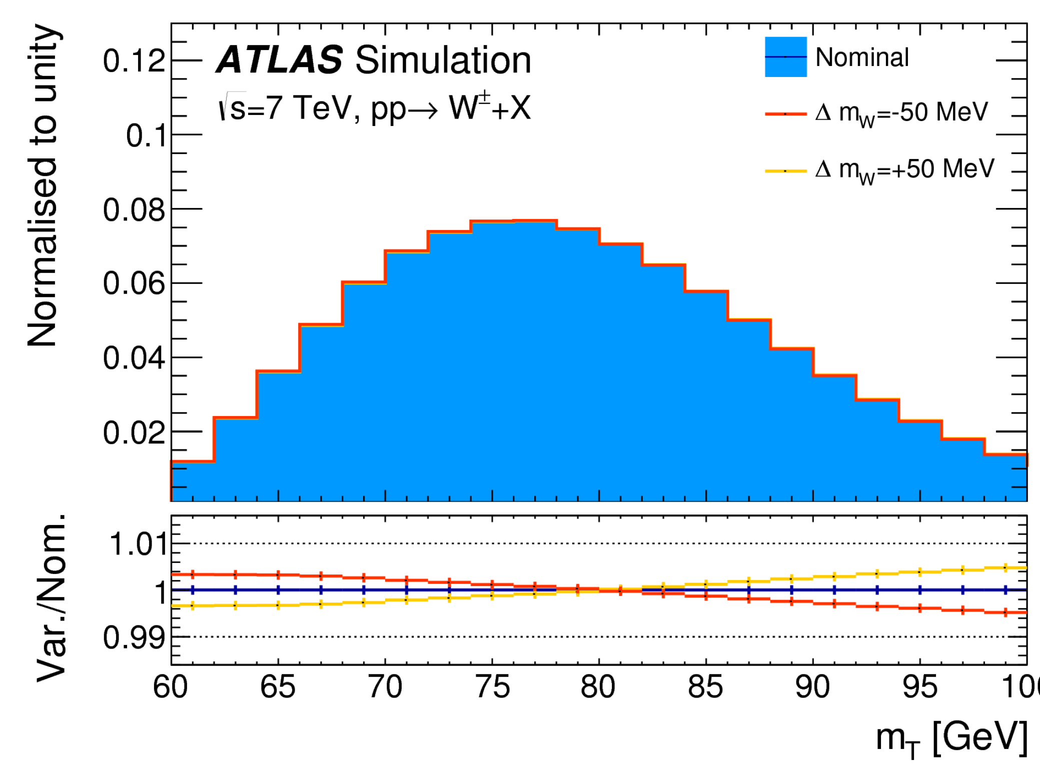


Different effects modify the reconstructed p_T^l and m_T distributions:
- Initial and final state radiation (QED);
- The W boson p_T^W distribution (QCD);
- Detector response.



Method:
Fit the distribution of p_T^l and m_T using MC templates generated with different m_W.

- m_T less sensitive to W boson p_T, but more sensitive to hadronic recoil
- p_T^l not directly dependent on recoil, but more sensitive to p_T^W



Construction of MC samples

MC is generated using PowHeg+Pythia8 and reweighed to the optimal theoretical model exploiting this cross section factorisation :

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]$$

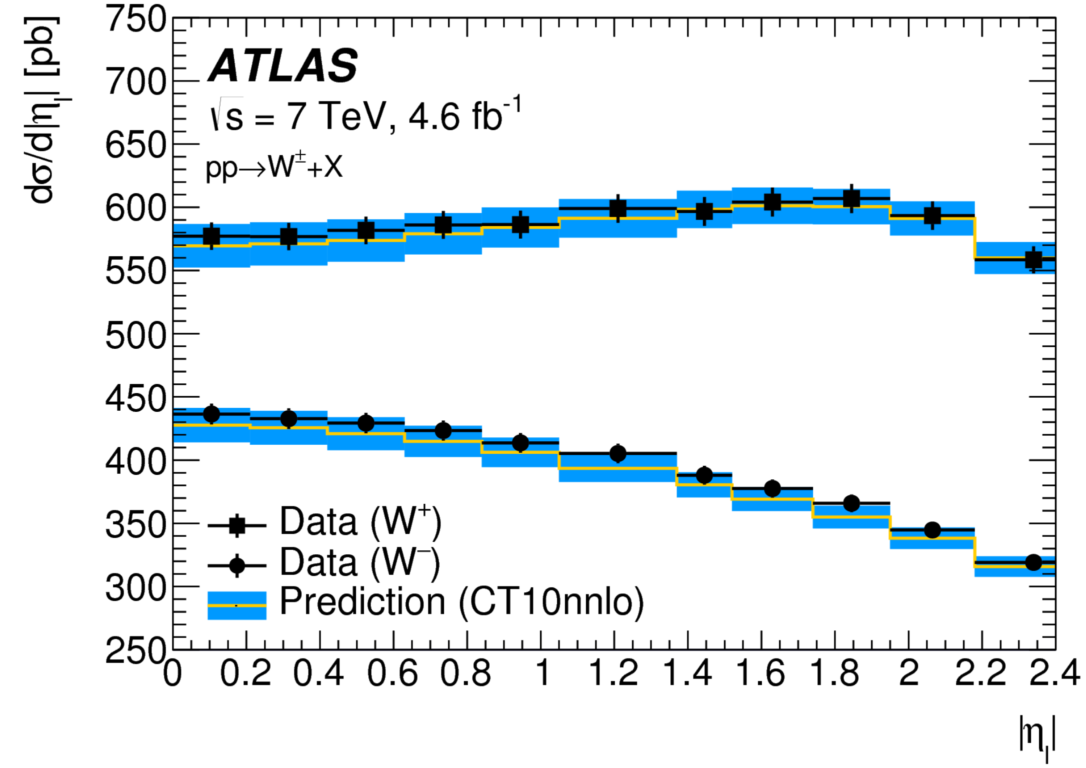
$$\times \left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

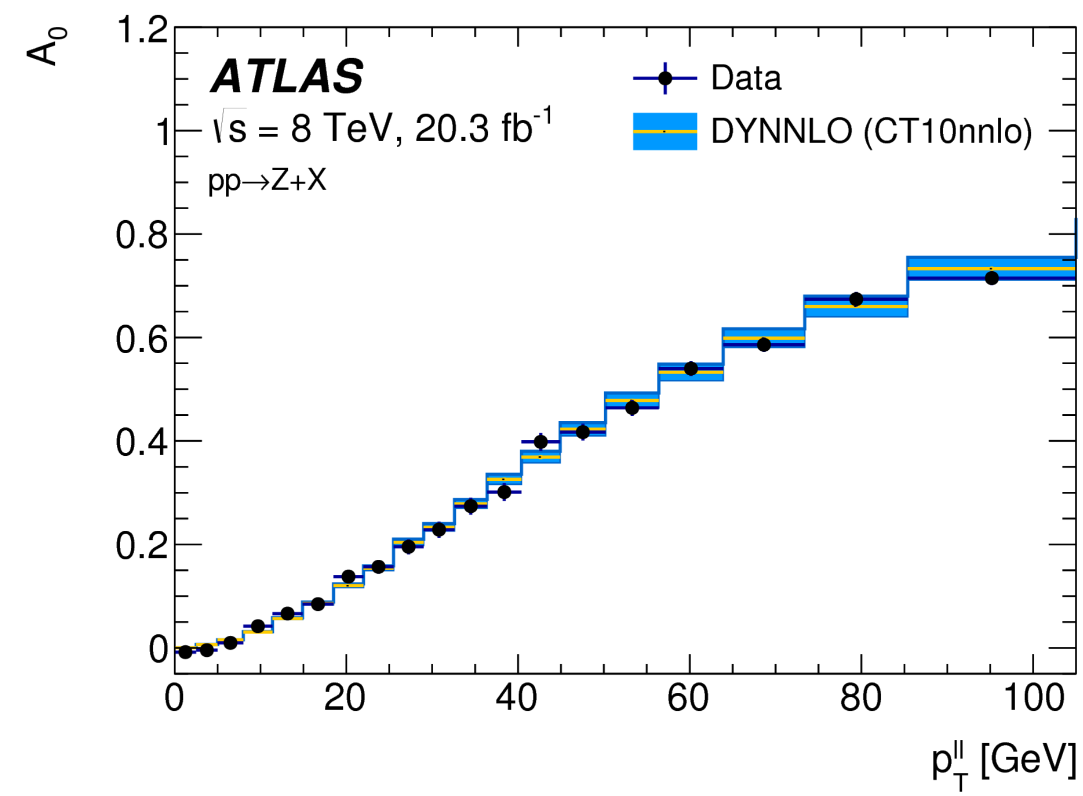
- dσ/dy and angular coefficients A_i (p_T,y) are taken from Fixed-order NNLO theory: DYNNLO + CT10nnlo PDFs, good agreement with ATLAS Z and W data

- dσ/p_T (in y bins) is taken from Pythia8 + AZ tune (next slide)

QED effects:

- ISR/FSR simulated in MC using Pythia8 QED ISR / Photos

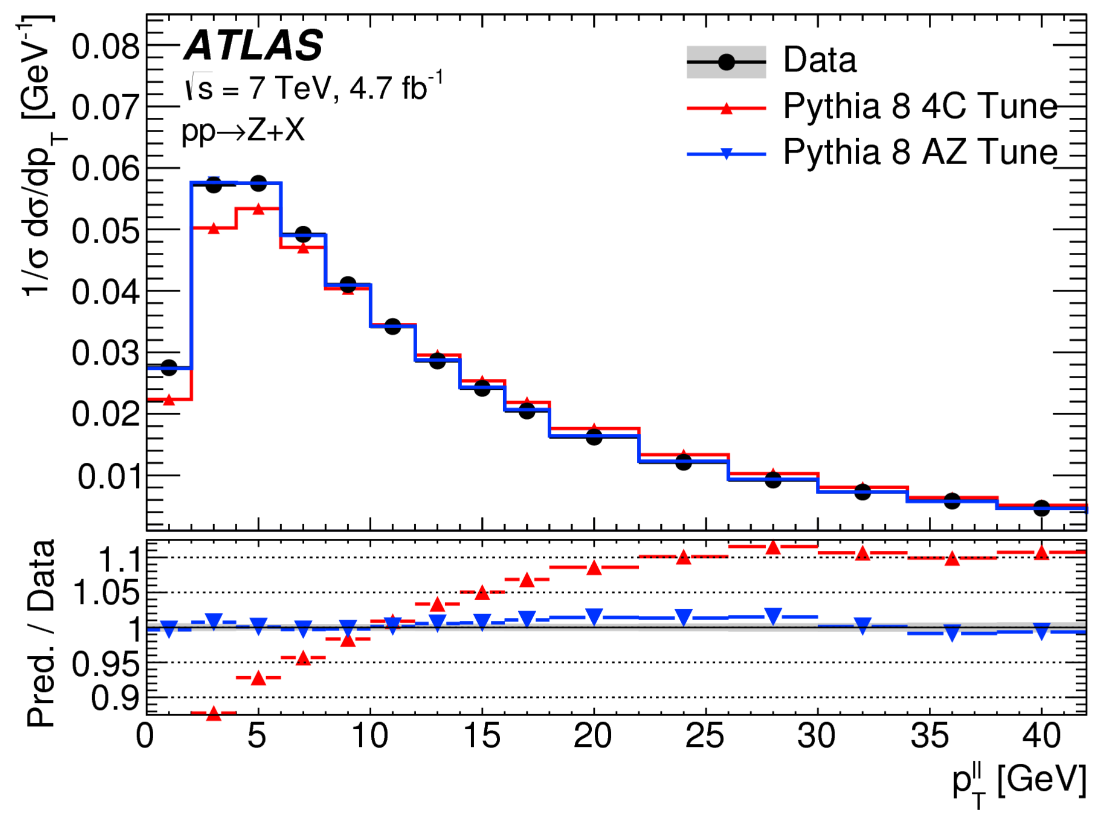




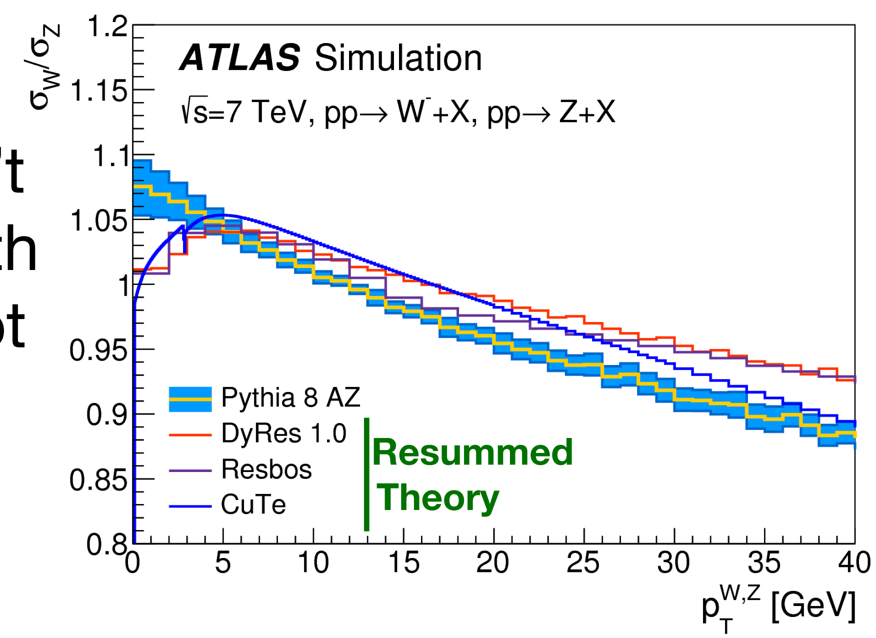
p_T^W distribution

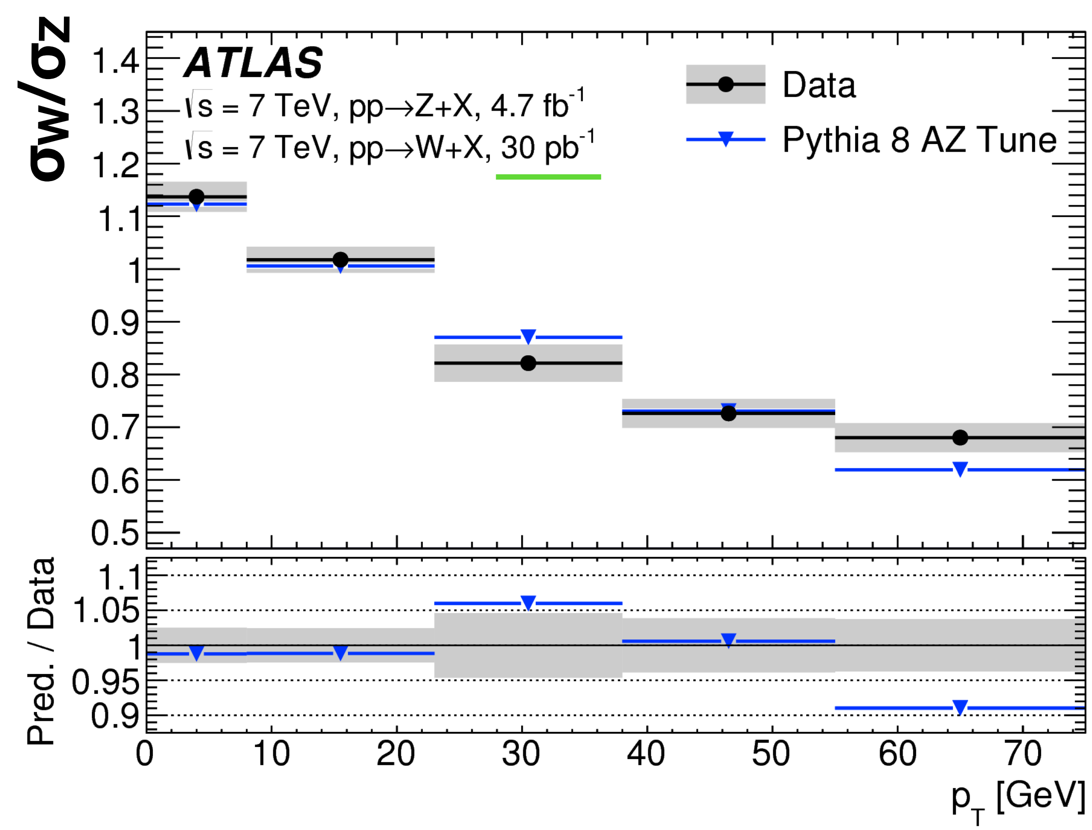
- Fixed order NNLO calculations can not predict accurately the p_T^W spectrum at low-p_T^W because of large logs of *(p_T^W/M_W):* resummation is needed (analytical or effectively through parton shower MC).

- The Pythia-8 "AZ tune" is used, tuned to the ATLAS measurement of p_T^Z, which gives a good description of Z and W data.
  Tuned parameters:
  intrinsic parton k_T,
  the cutoff and the α_S used in QCD ISR.



- Resummed theory doesn't agree well with W, Z data. Not used.

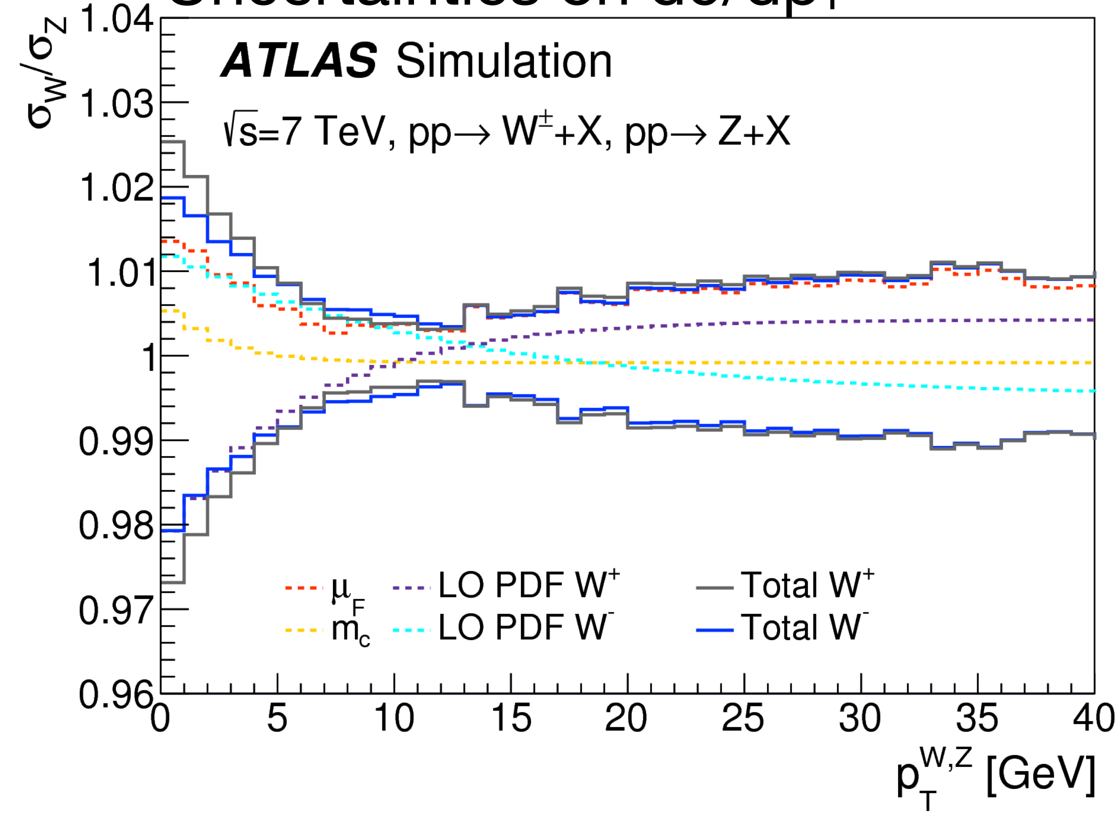




Physics modelling uncertainties

- QCD uncertainties are evaluated by varying parameters of Pythia-8 AZ tune and of the NNLO calculation.
- Largest uncertainties on m_W from PDF variations in NNLO calculation: 13-15 MeV, largely anti-correlated between W^+ and W^-
- Uncertainties from missing higher-order electroweak corrections are small.

Uncertainties on $d\sigma/dp_T$

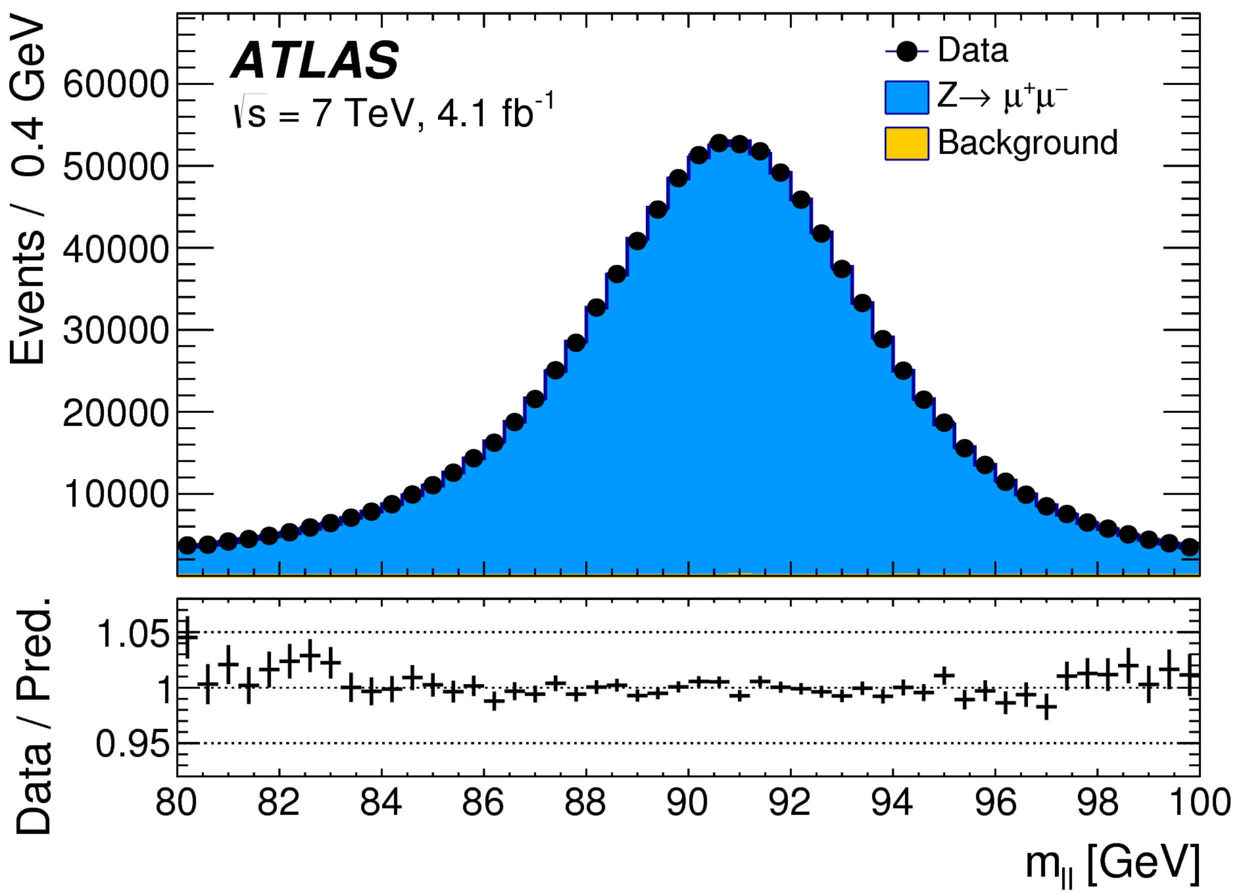


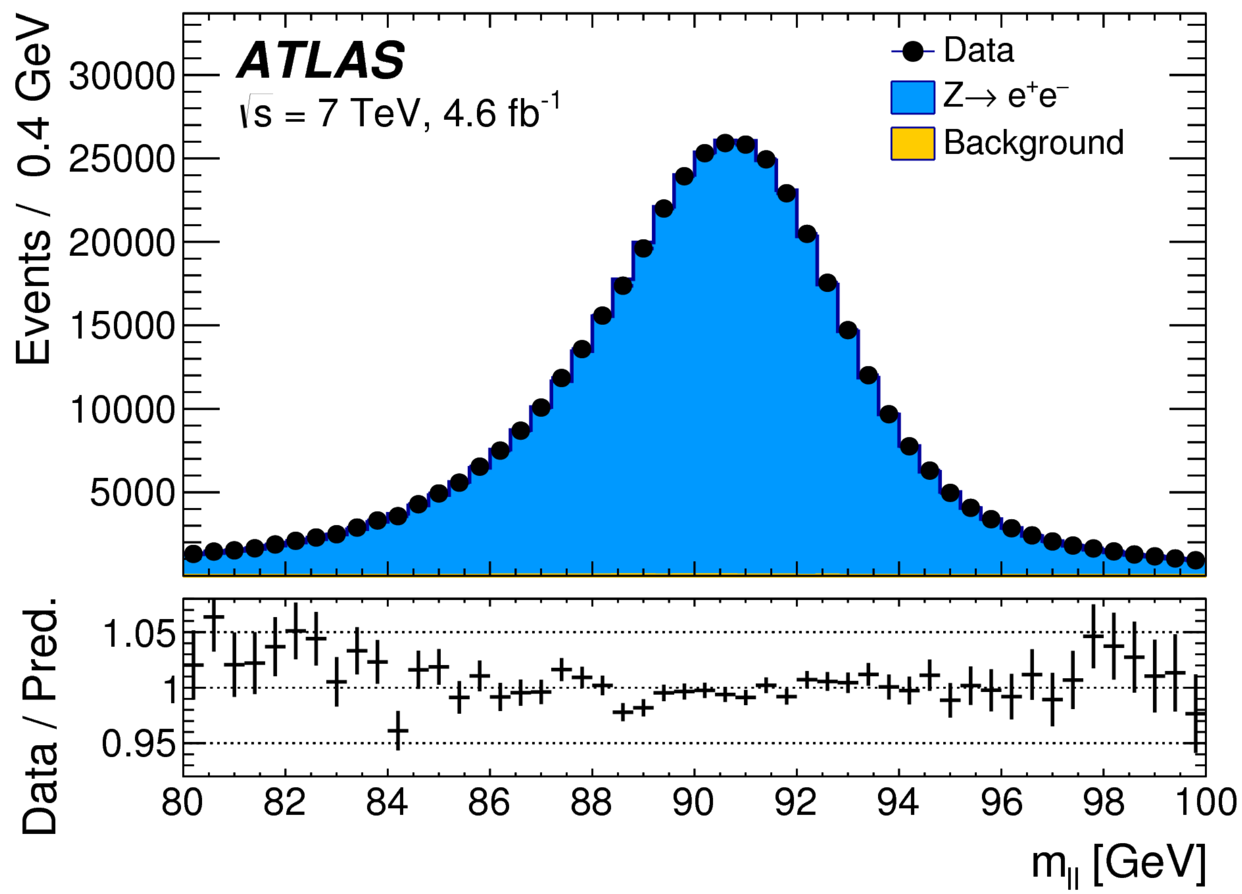
QCD uncertainties

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

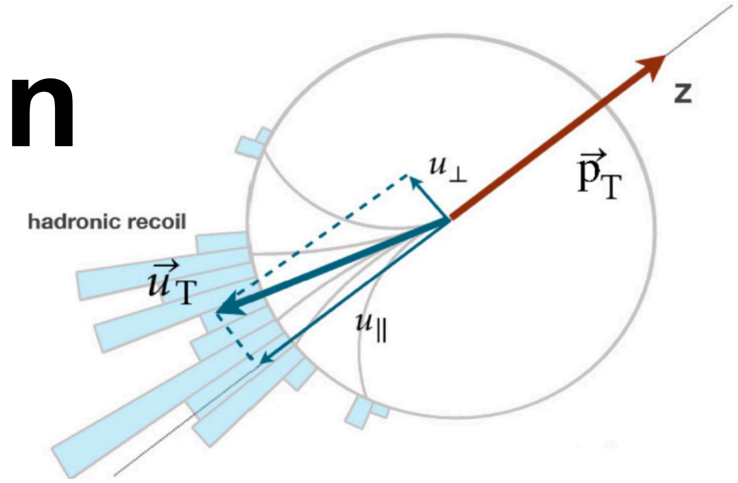
Lepton energy/momentum scale calibration

- Lepton momentum scales are measured using Z->ll and events and corrected in MC
- Scale known better than ~2 x 10^{-4} (except for muons at highest rapidity)
- Translates into an uncertainty on m_W of approx. 8-9 MeV
- Reconstruction, identification and trigger efficiency studied from Z sample, small effects for muon, of similar size as the energy scale for electrons.





Recoil reconstruction



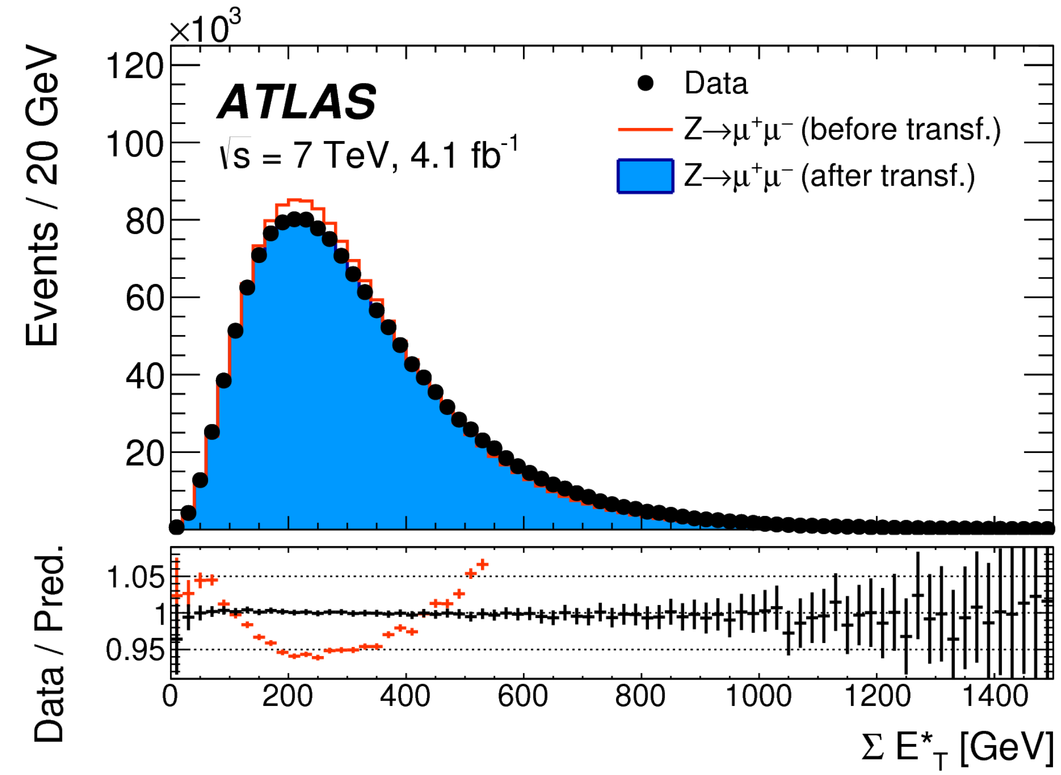
The reconstruction of the hadronic recoil depends strongly on the total E_T in the event, three corrections are needed:

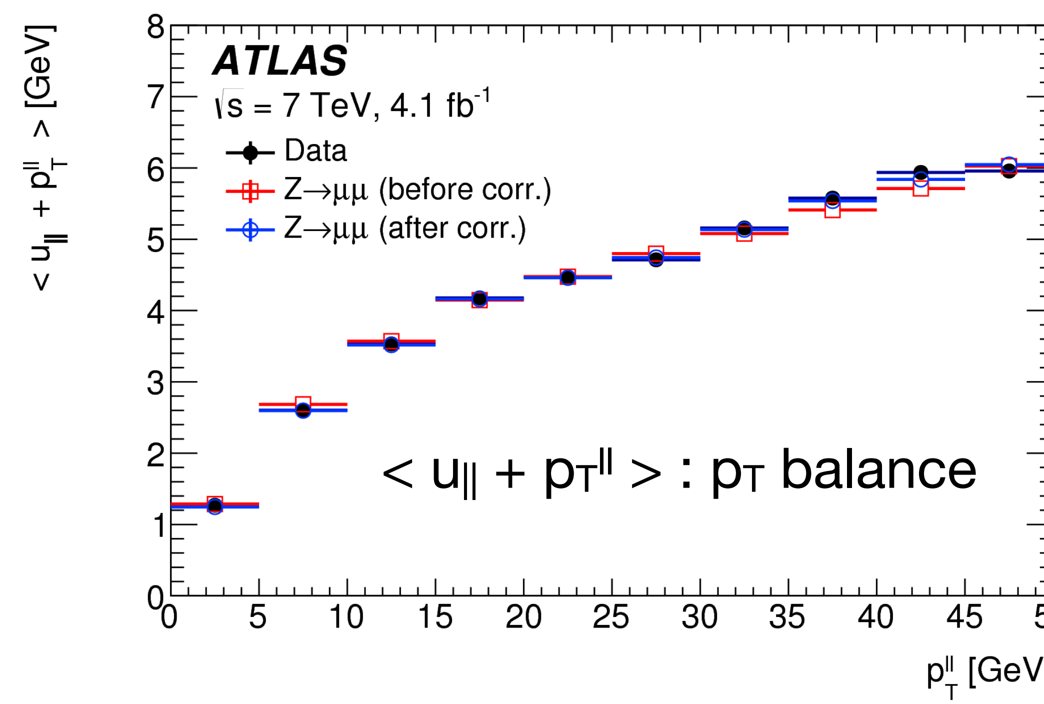
1- Pileup distribution: data/MC equalisation.

2- Correction of residual differences in the total E_T distribution (activity mis-modeling)

3- Calibration obtained by the p_T balance in Z event

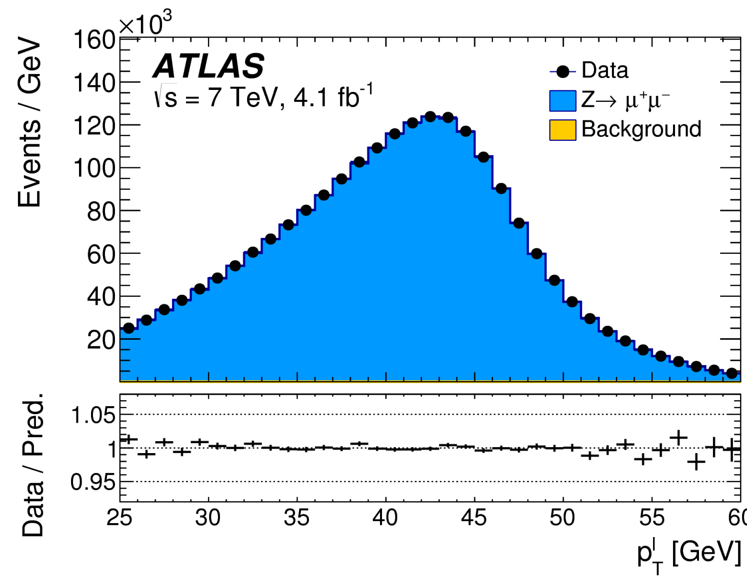
Uncertainty on m_W ~ 11 MeV for m_T fits (smaller for p_T^l), dominated by the total E_T correction.

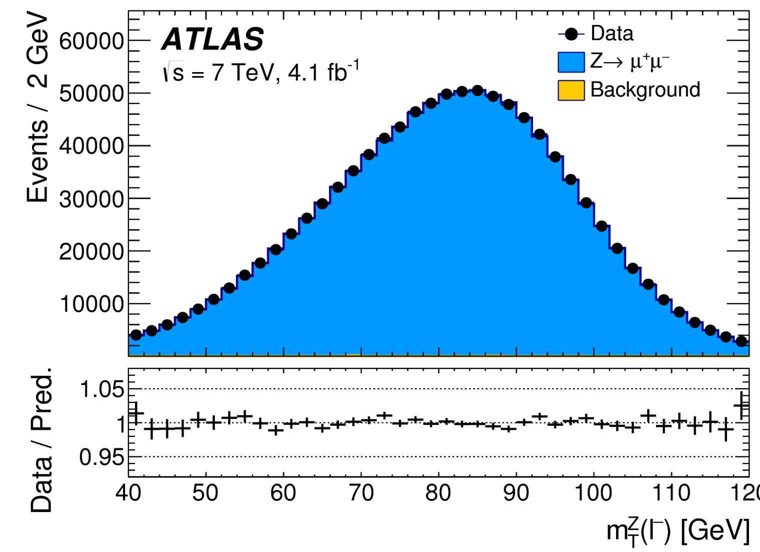


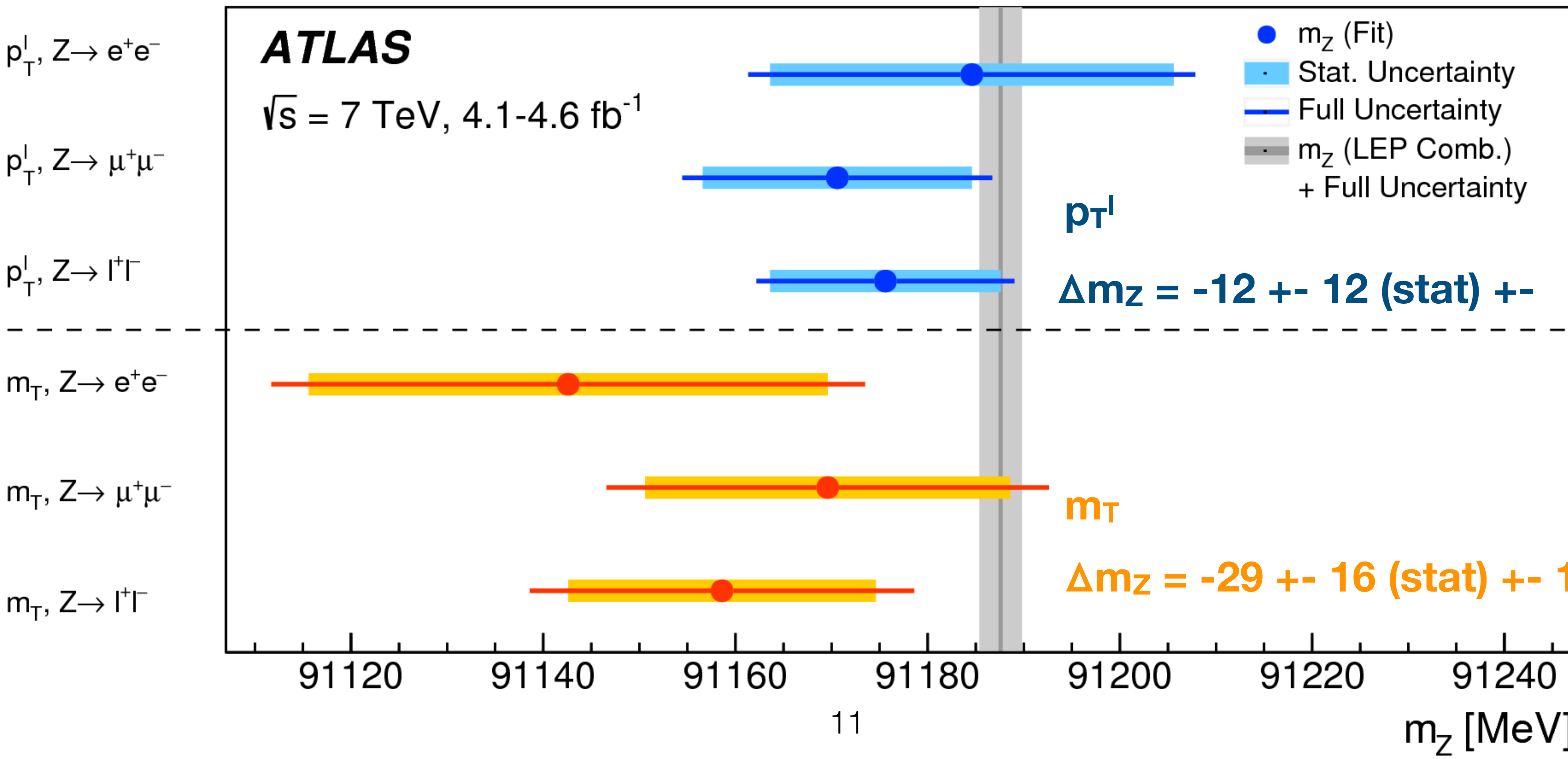


Z cross check

- Good data/MC agreement in Z->ll
- Test: m_Z from fits to m_T and p_T^l
- Result consistent with m_Z within experimental 1/1.5 $\boldsymbol{\sigma}$. (Note the correlation of m_T and p_T^l)







p_T^l

Δm_Z = -12 +- 12 (stat) +- 6 (syst) MeV

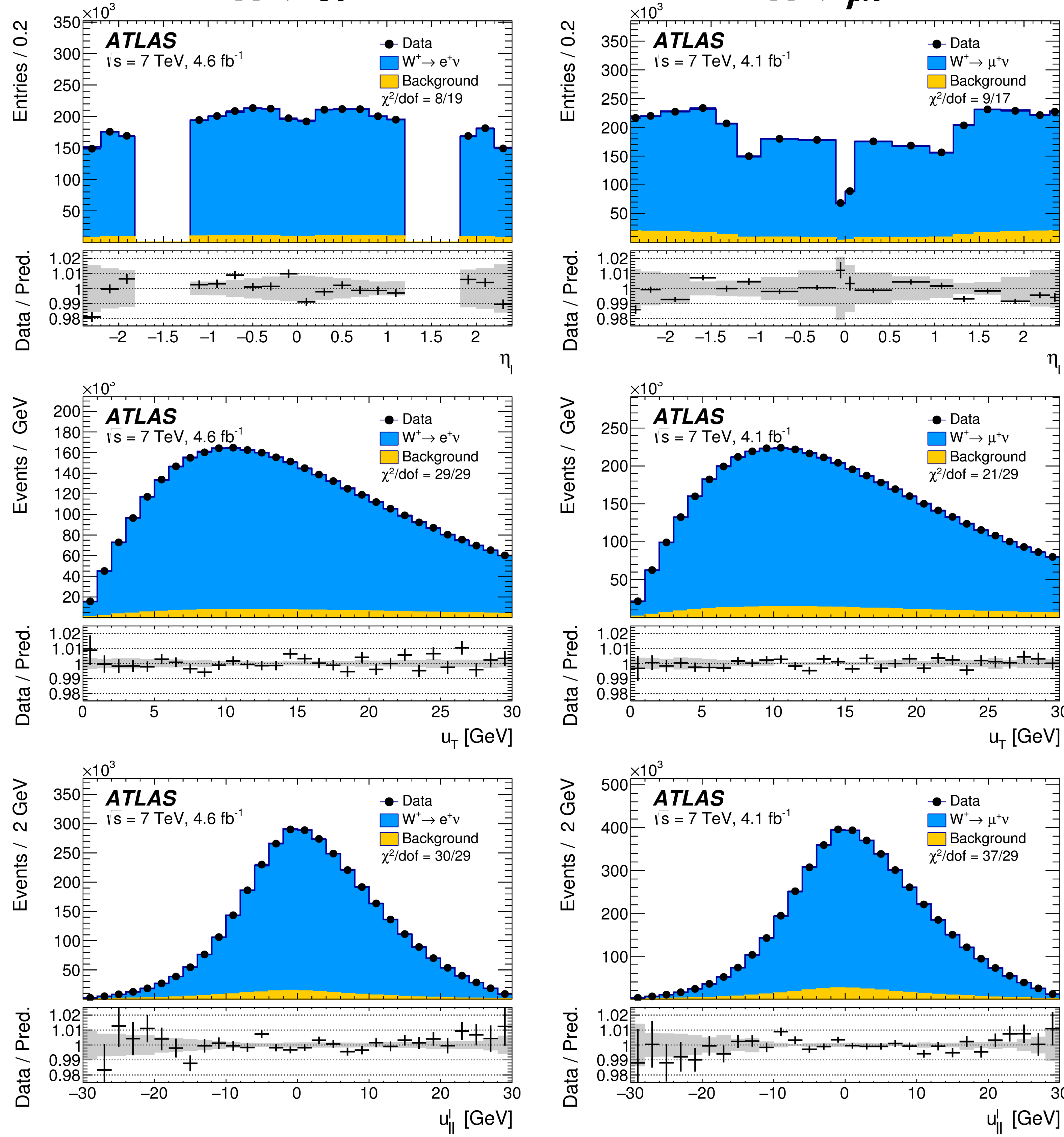
m_T

Δm_Z = -29 +- 16 (stat) +- 12 (syst) MeV

W : Data - MC comparison

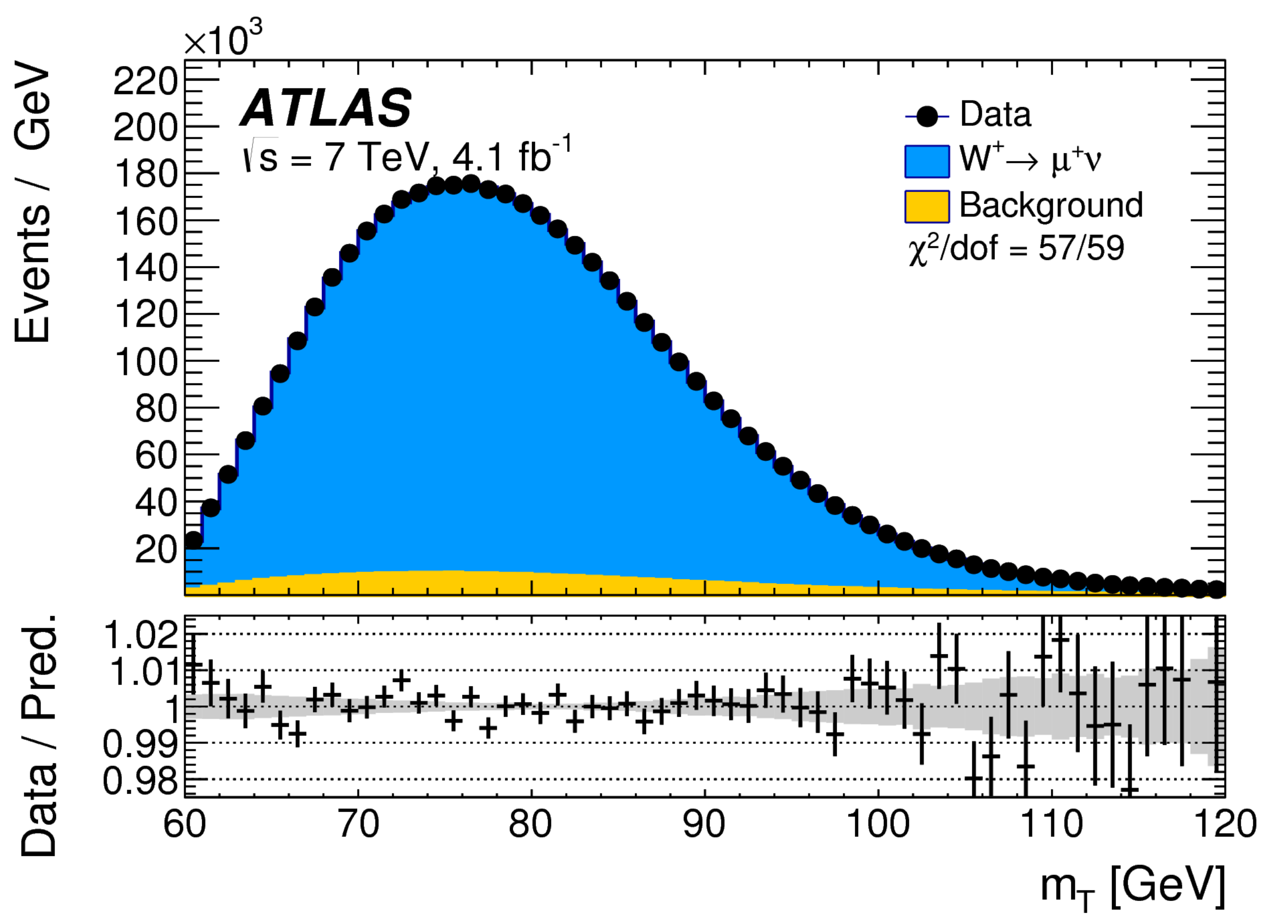
- Backgrounds: EWK+top from MC Multijet data-driven
- Good data /MC agreement observed over many tested distributions

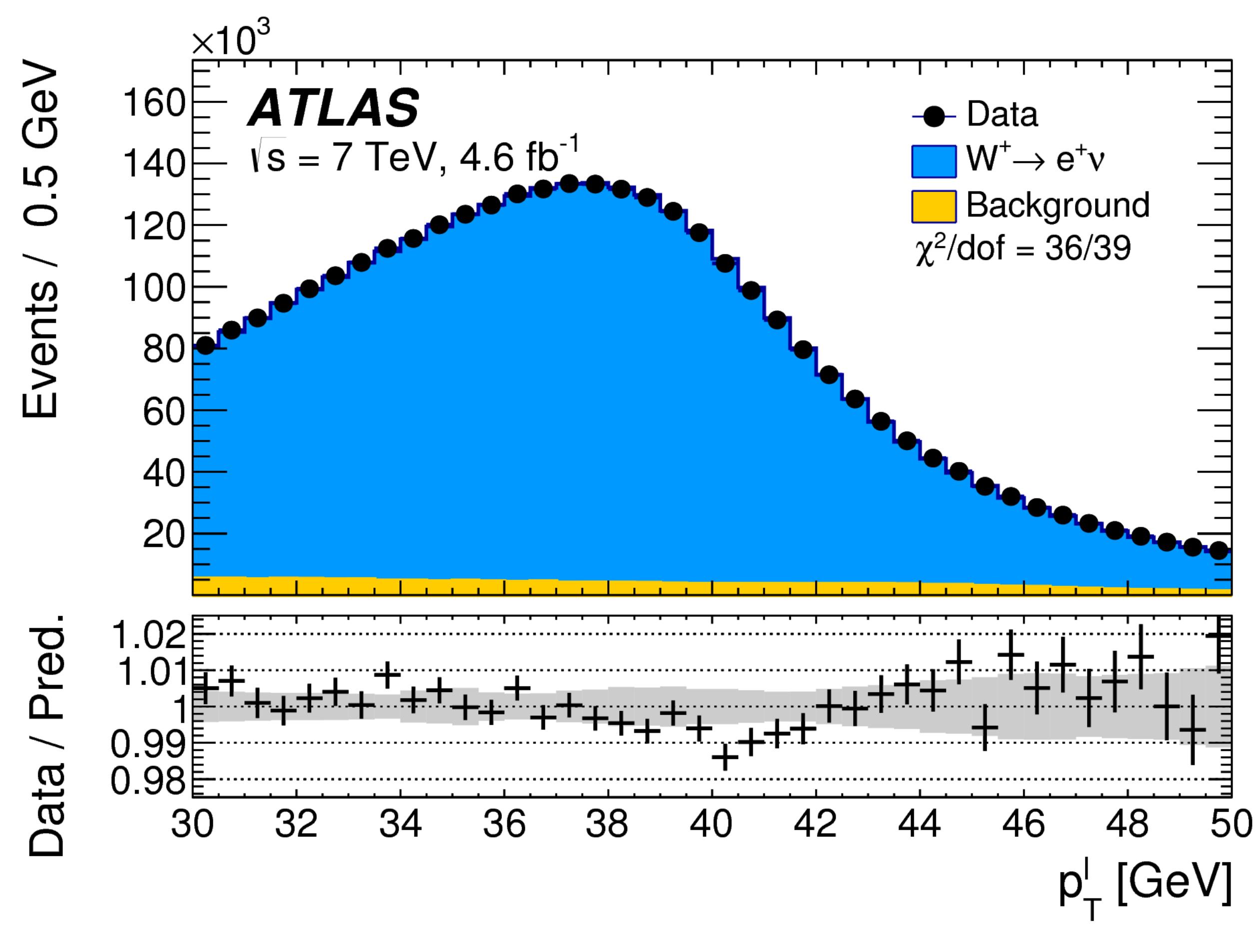
W->$e\nu$ W->$\mu\nu$



Mass Fits

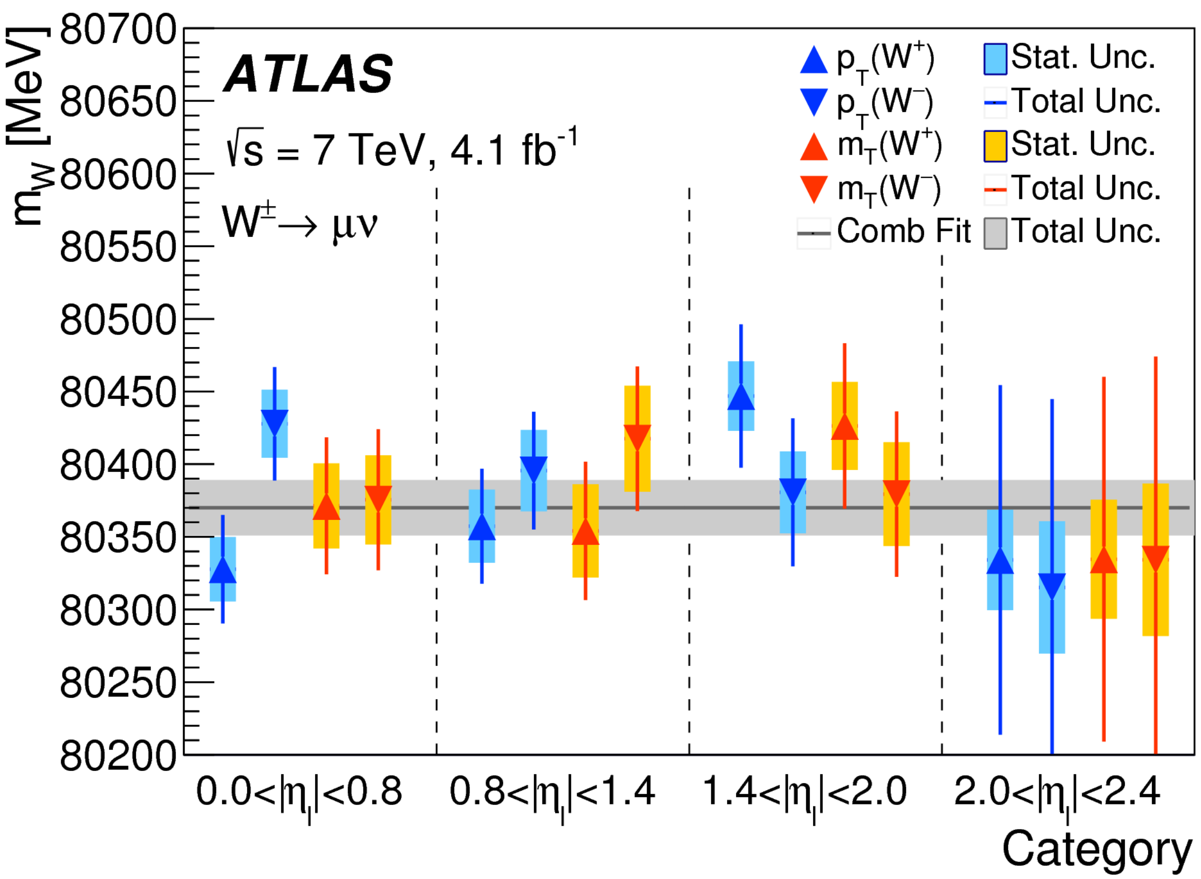
- MC templates with different mass are generated in steps of 1-10 MeV
- 28 χ^2 fits, separated by lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e), fit variable (m_T, p_T^l).
- Many other fits were performed as consistency checks by varying the fit range, varying the range of u_T etc.

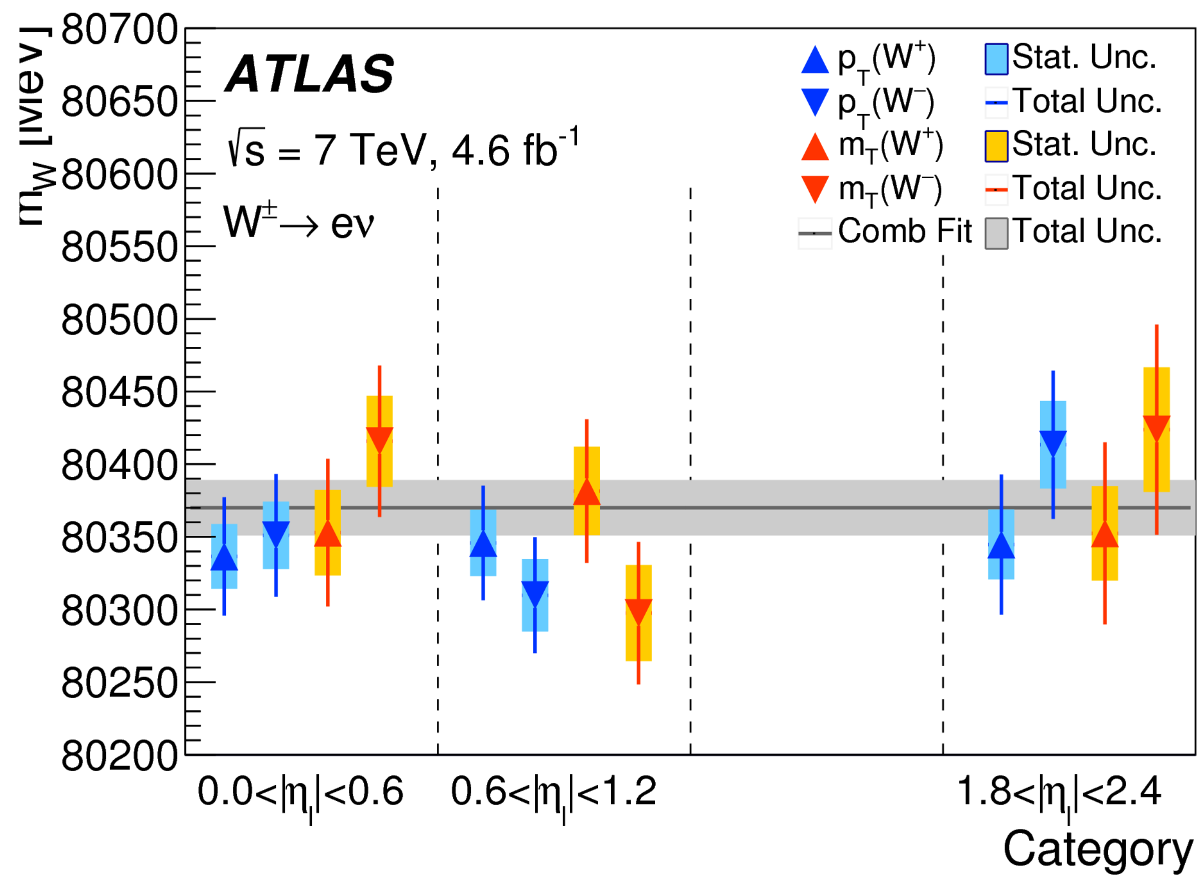




Mass Fits

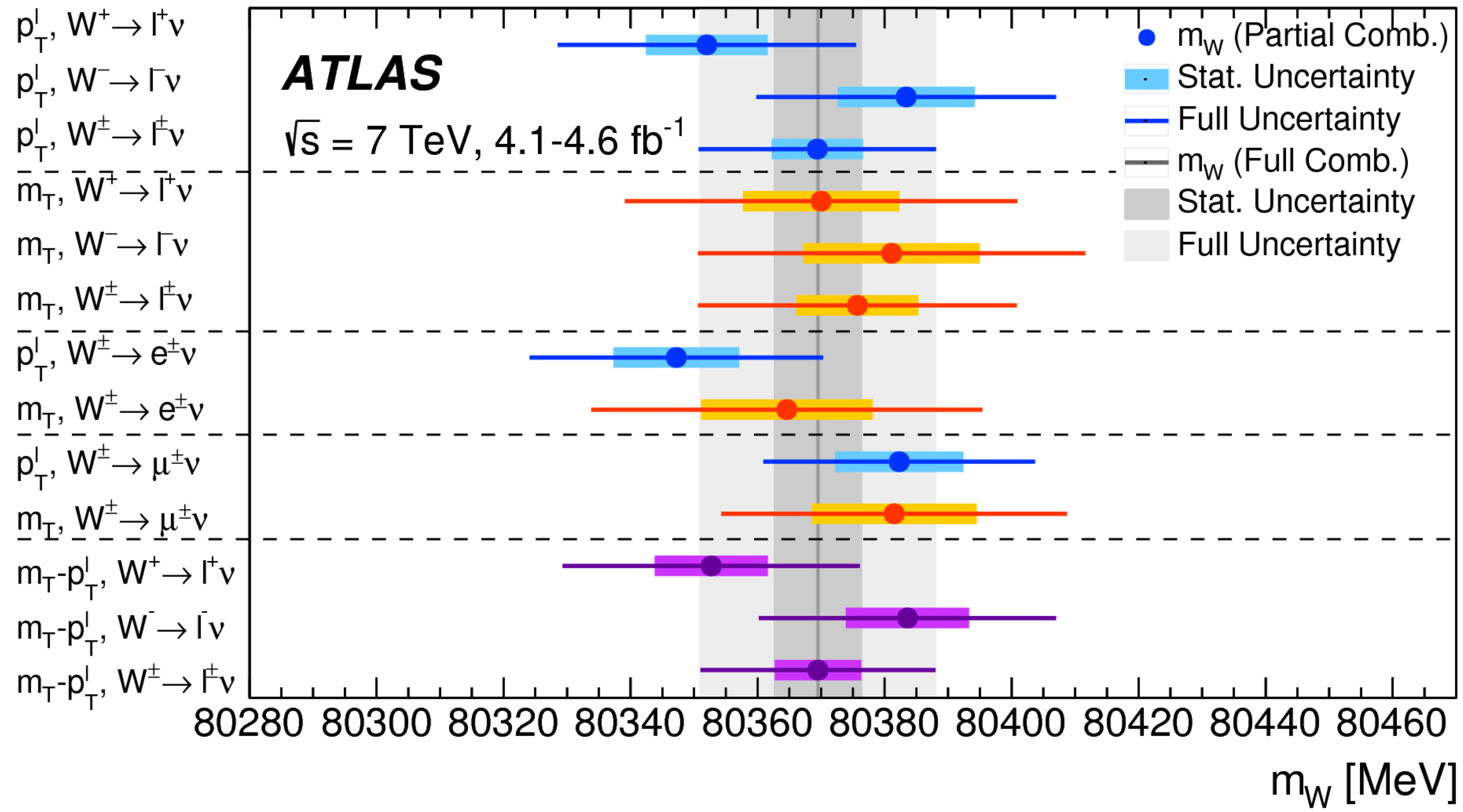
- MC templates with different mass are generated in steps of 1-10 MeV
- 28 χ^2 fits, separated by lepton type (μ,e), W charge (+/-), rapidity interval (4 for μ, 3 for e), fit variable (m_T, p_T^l).
- Many other fits were performed as consistency checks by varying the fit range, varying the range of u_T etc.





Combined Result

Different combinations are performed, taking into account the correlation of m_T and p_T^l (approx. 50%) and of systematics.



The final combination gives (assuming same mass for W^+ and W^-) :

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.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

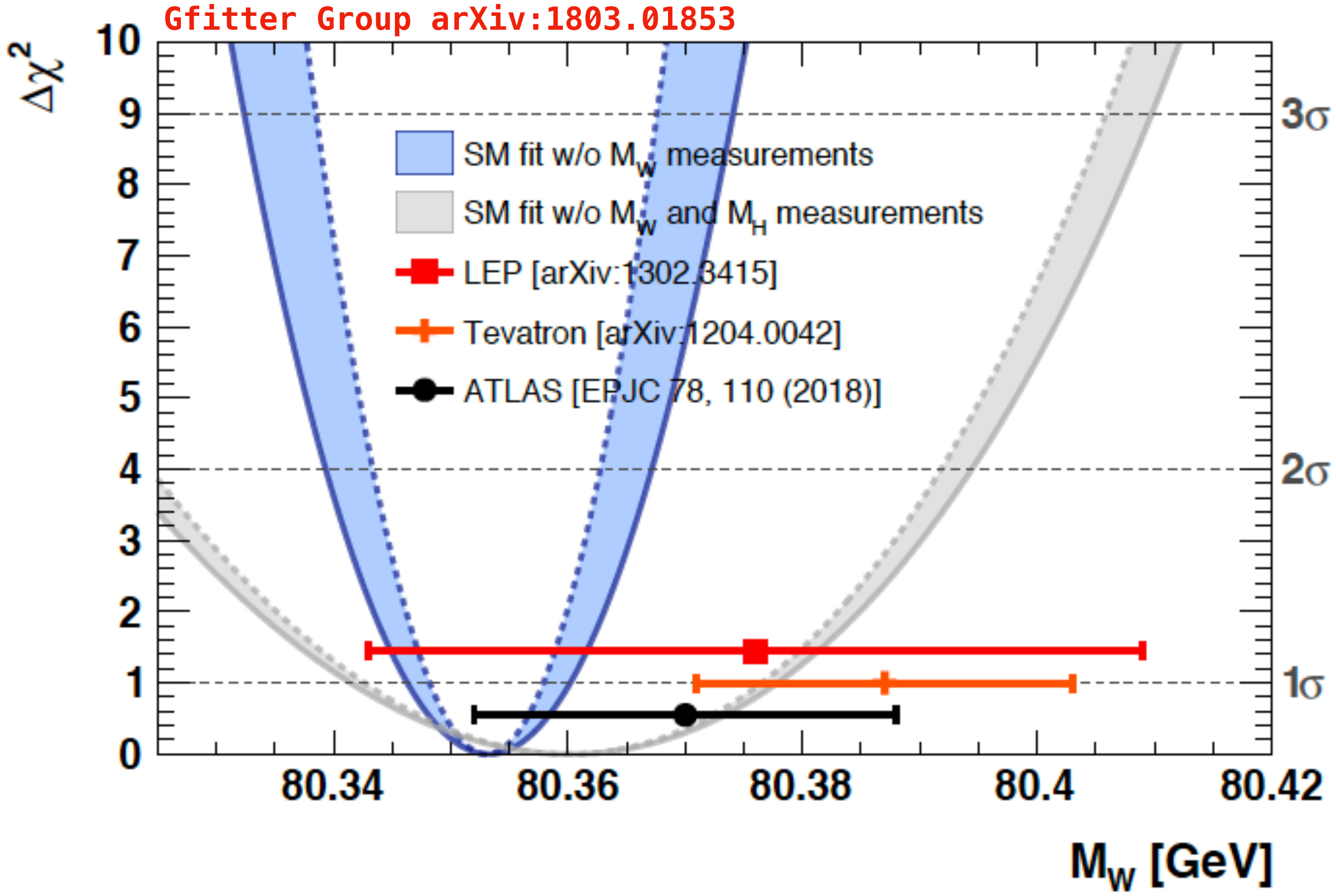
stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV

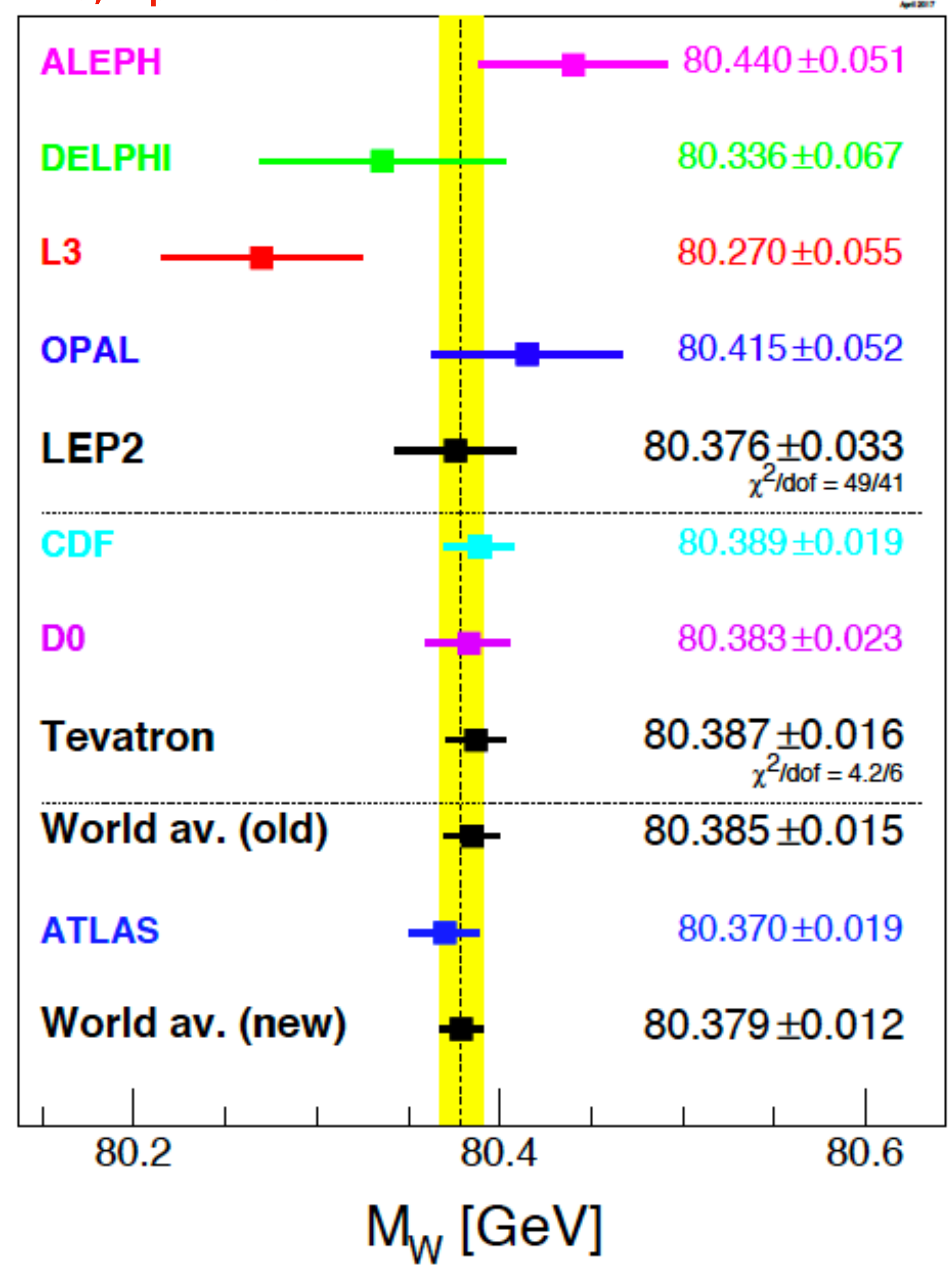
Comparison with previous results and SM

- The ATLAS measurement has the same precision of the previous most-precise single measurement (CDF) and is consistent with previous result.
- Word Combination uncertainty varies between 11 and 14 MeV, depending on assumed correlation between ATLAS and Tevatron. PDG assumes 7 MeV of correlated uncertainty (J. Erler, Moriond 2017). A detailed study of this correlation (mainly PDFs) would be very important.
- Good agreement with predicted m_W from SM EWK fit.

Gfitter Group arXiv:1803.01853



PDG, April 2017



W^+ - W^-

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

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

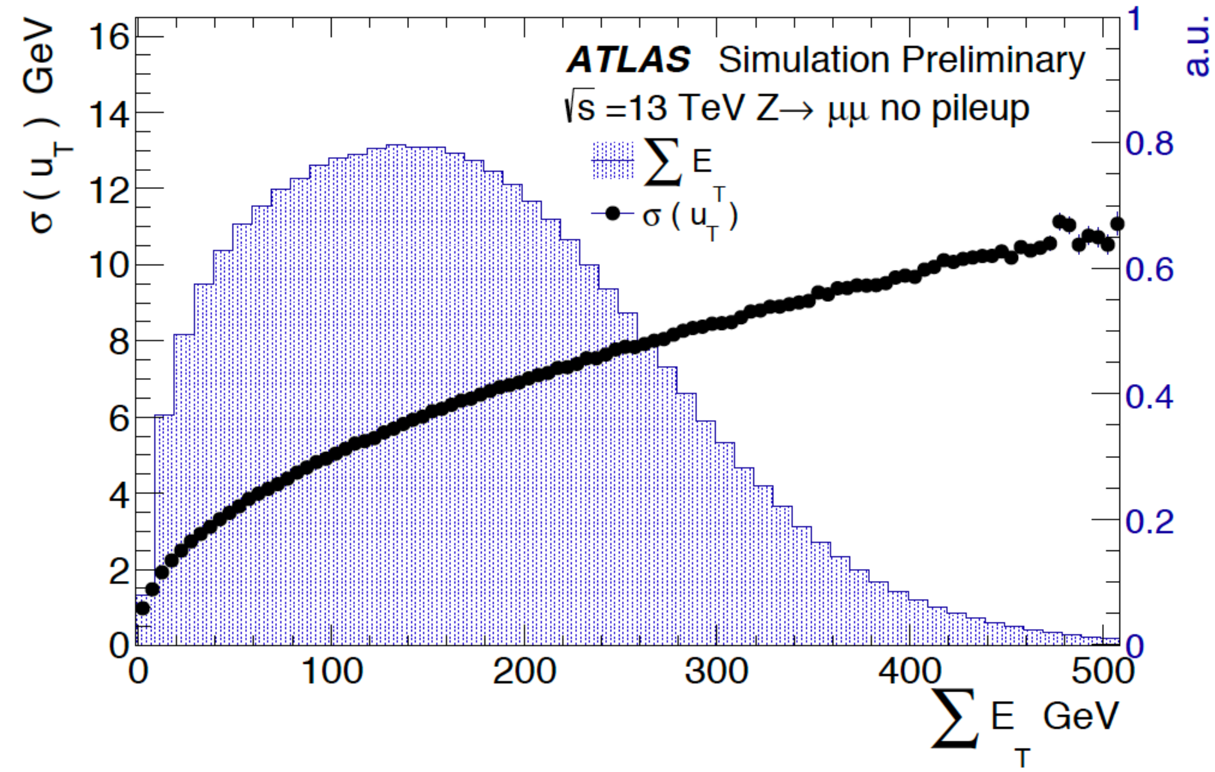
Prospects for p_T^W measurement

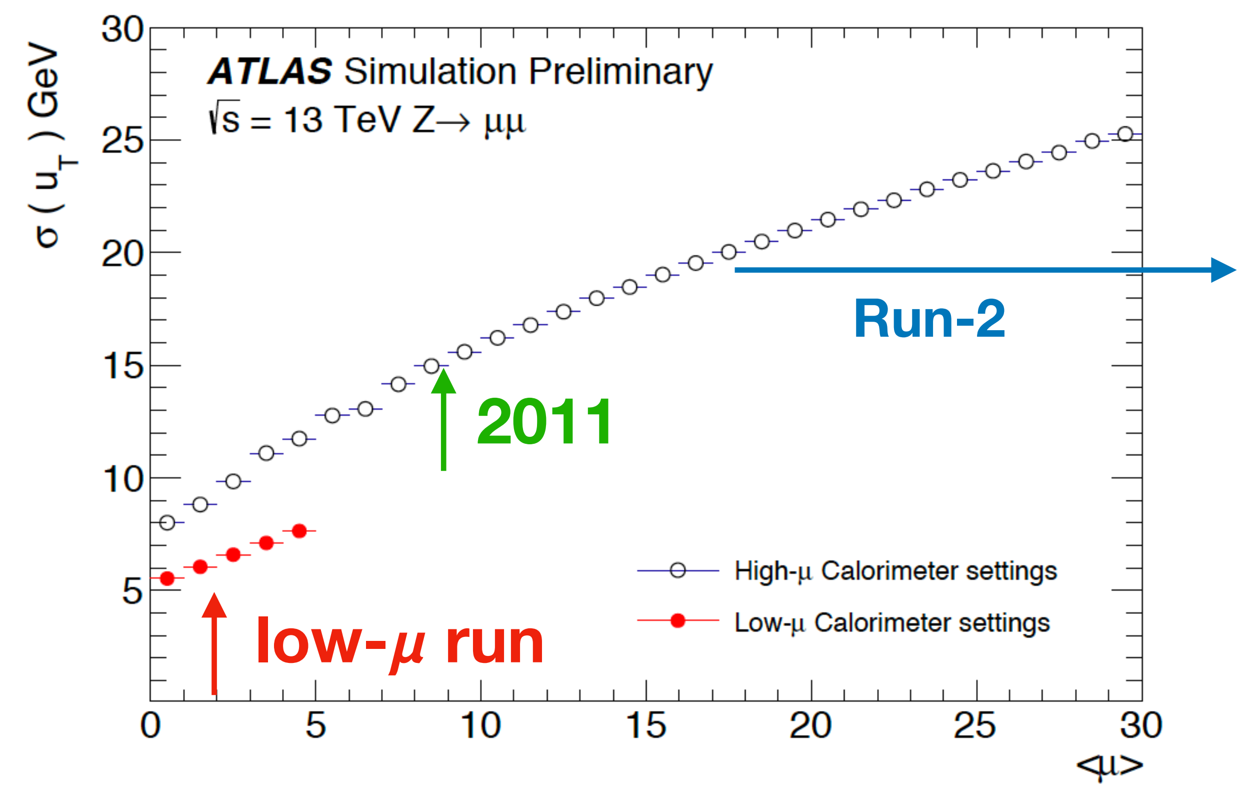
- One of the largest uncertainties comes from the QCD modelling of the p_T^W distribution
- p_T^W can be measured directly from recoil, provided experimental resolution is good enough.
- For the pileup level of 2011 data ($<\mu>=9$) $\sigma(u_T)$=13 GeV, not good enough.
- Special runs taken in 2017 at $<\mu>=2$

  $\sqrt{s}$ = 5 TeV $\int L = 280\ pb^{-1}$
  $\sqrt{s}$ = 13 TeV $\int L = 160\ pb^{-1}$

- Lowered calorimeter thresholds and "particle flow" reconstruction will further improve the recoil reconstruction beyond simple pileup reduction
- Target: measure p_T^W with ~1% uncertainty in 5 GeV bins for p_T^W<30 GeV

ATL-PHYS-PUB-2017-021





Conclusions and perspectives

ATLAS measurement of m_W : m_W = 80370 +- 19 MeV

Competitive result, uncertainty dominated by physics modelling

Perspectives:

- Huge W and Z samples available from LHC run-1 and run-2

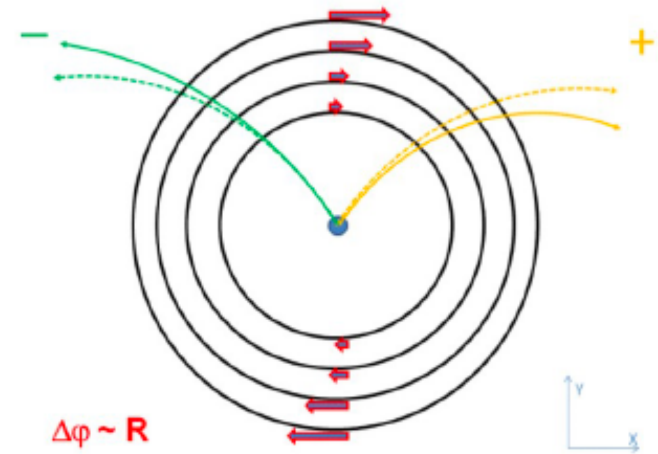
- Modelling systematics need to be reduced to exploit this sample (e.g. reducing PDF uncertainty with new measurements, a fully consistent model incorporating NNLO + resummation ?)

- Uncertainties from p_T^W can be reduced with a direct measurement in 2017 runs with low pileup.

BACKUP

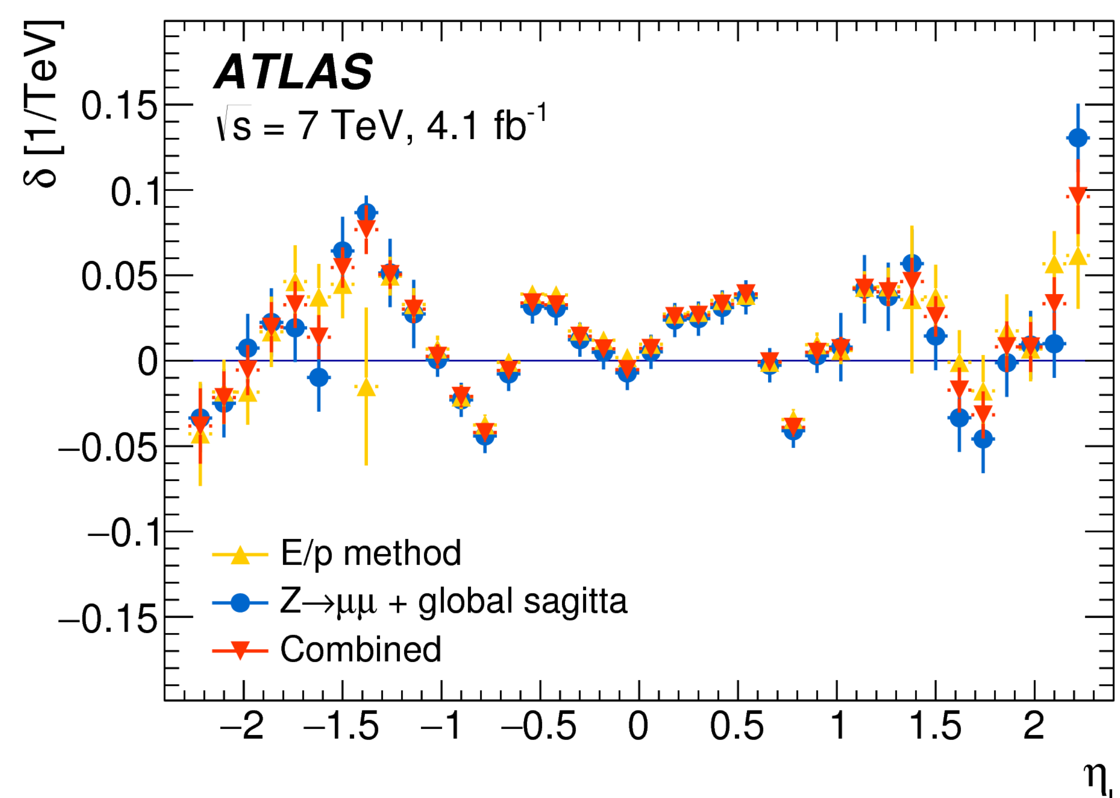
Muon momentum reconstruction

- Muons are identified using the Muon Spectrometer, momentum is reconstructed using Inner Detector: this gives a smaller momentum scale uncertainty at the price of worse resolution, in particular at large rapidity.



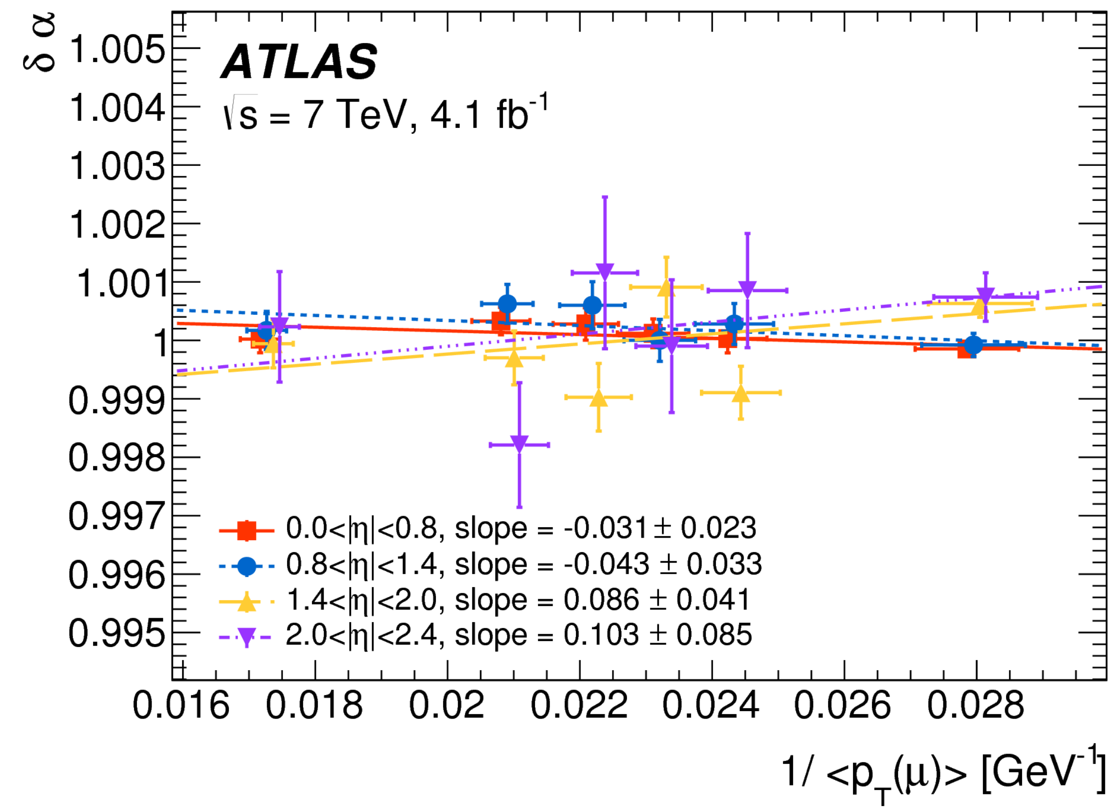
- Global alignment weak modes, not seen by standard track-based alignment, introduce p_T-dependent momentum biases. They are corrected based on $Z \to \mu\mu$ and $W \to e\nu$ E/p data.

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



Muon momentum scale calibration

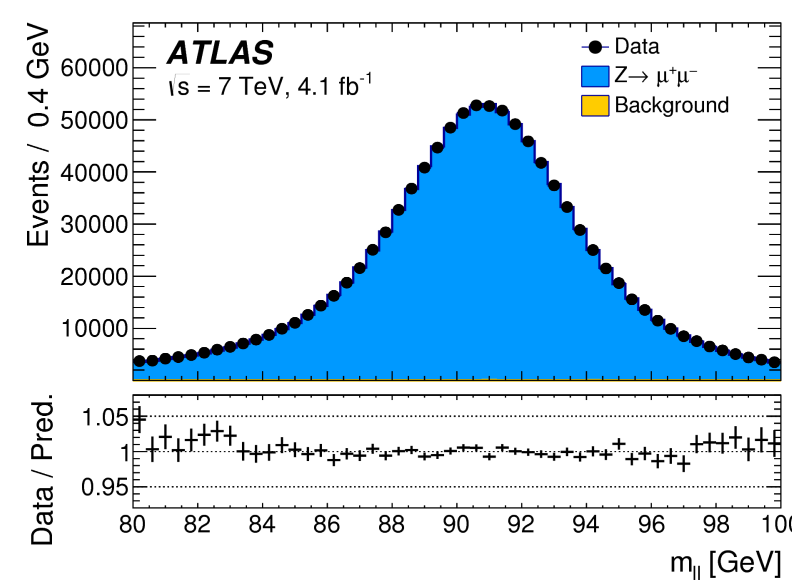
- Muon momentum is reconstructed using Inner Detector only: this gives a smaller momentum scale uncertainty at the price of worse resolution with respect to using the Muon Spectrometer too, in particular at large rapidity.
- Momentum scale and resolution measured using Z->***μμ*** events and corrected in MC
- Momentum scale known better than 2 x 10^{-4} (except at high rapidity)
- Reconstruction and trigger efficiency studied from Z sample, small effects.



$$p_{\mathrm{T}}^{\mathrm{MC,corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times [1 + \alpha(\eta,\phi)] \times \left[1 + \beta_{\mathrm{curv}}(\eta) \cdot G(0,1) \cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$

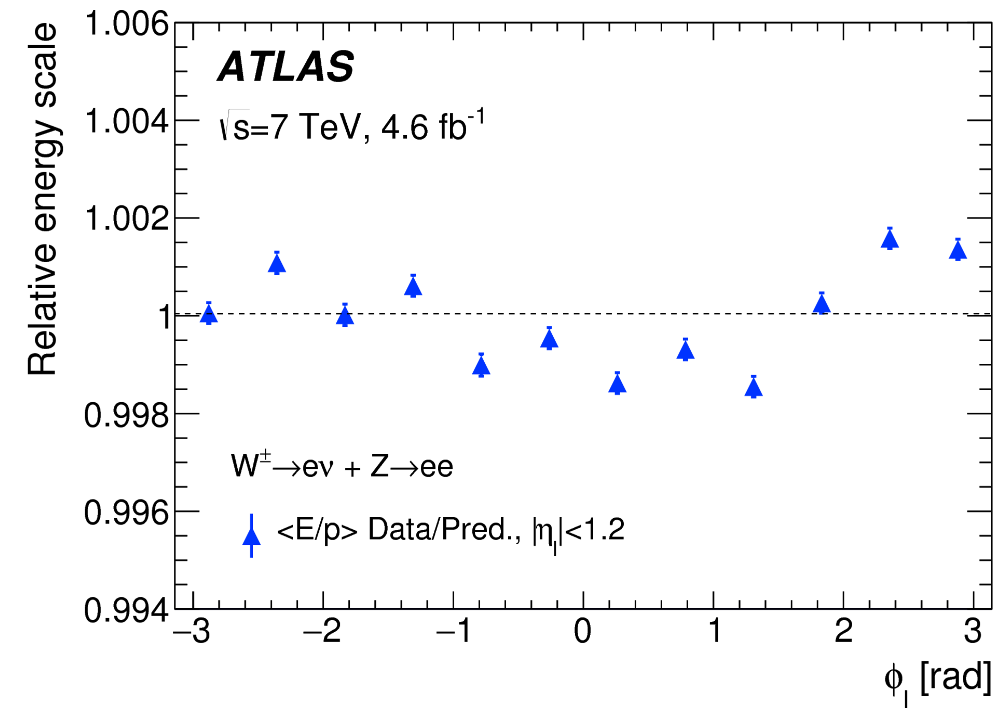
Muon uncertainties

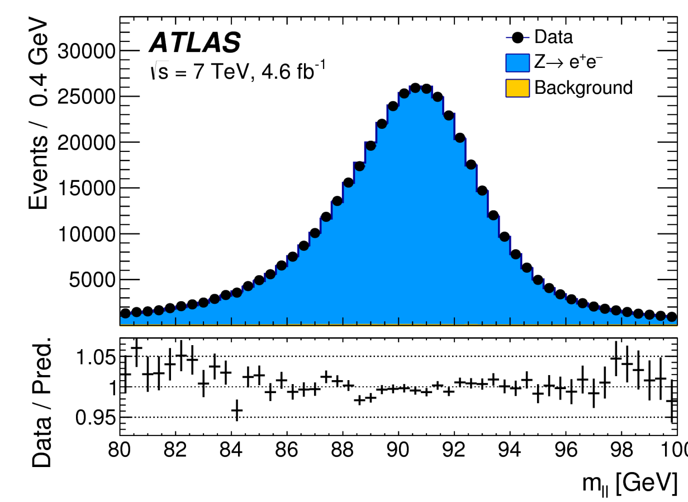
$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_{T}^{ℓ}	m_{T}	p_{T}^{ℓ}	m_{T}	p_{T}^{ℓ}	m_{T}	p_{T}^{ℓ}	m_{T}	p_{T}^{ℓ}	m_{T}
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	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

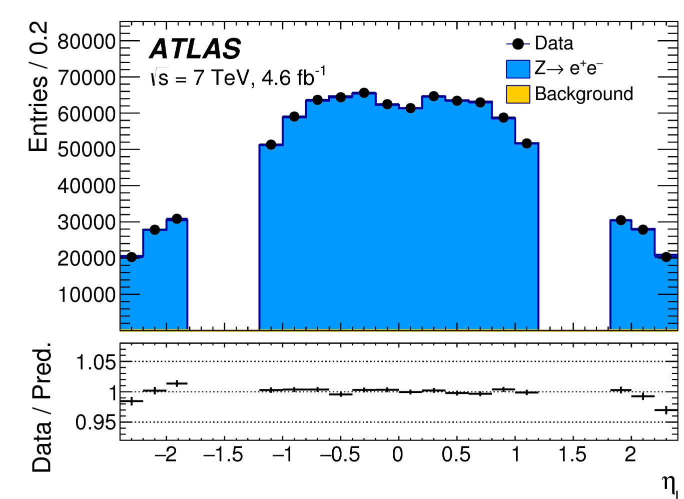


Electron reconstruction and energy scale

- Electron energy measured using the LAr calorimeter and presamplers
- The energy calibration is based on the Z mass taken as a reference and corrected in MC
- Energy scale known at 2 x 10^{-4}
- Reconstruction and identification efficiency from Z, uncertainties not negligible.





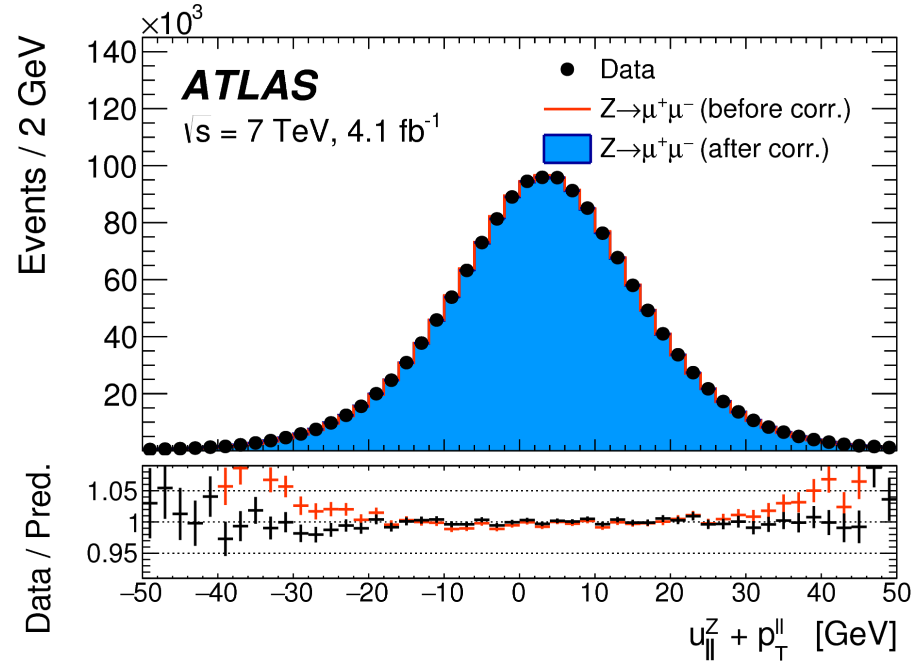


Electron uncertainties

$\lvert\eta_\ell\rvert$ 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

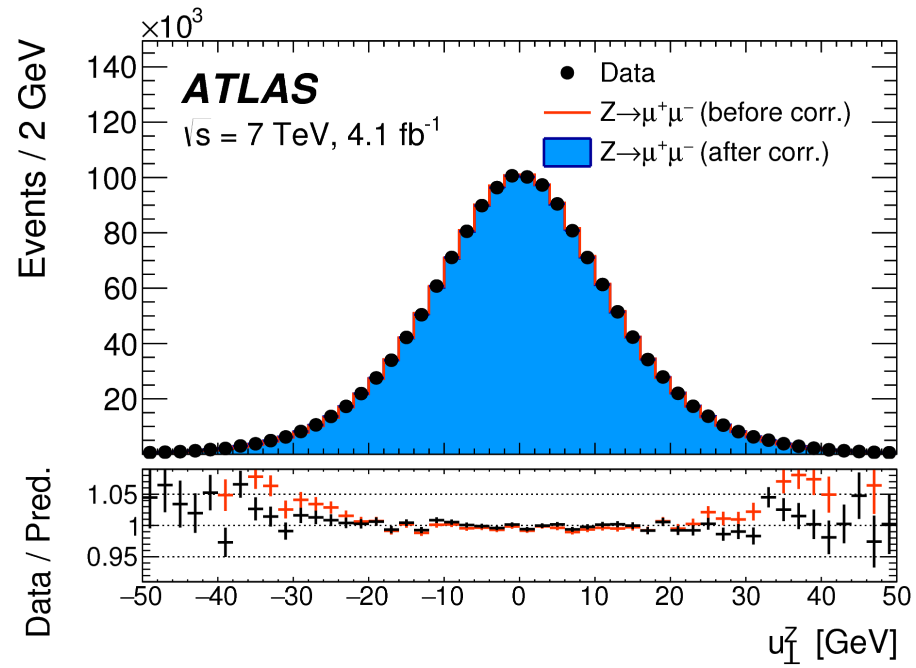
Recoil reconstruction uncertainties

- Sum E_T correction is the largest contribution,



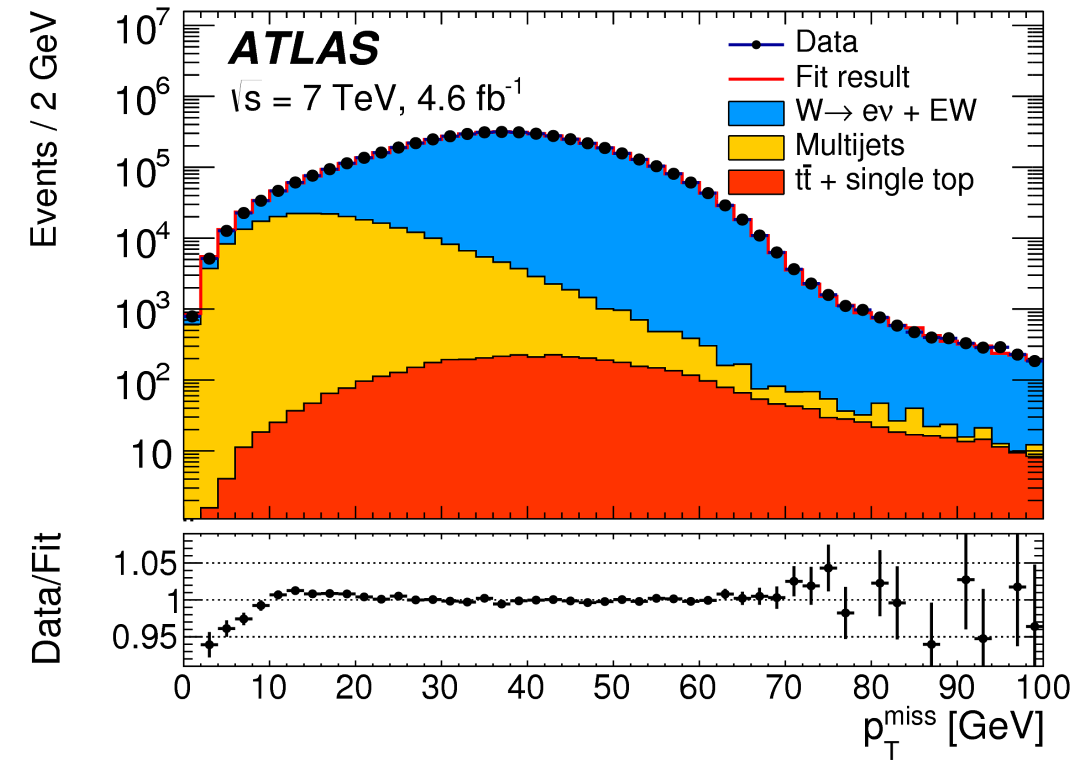
Recoil uncertainties

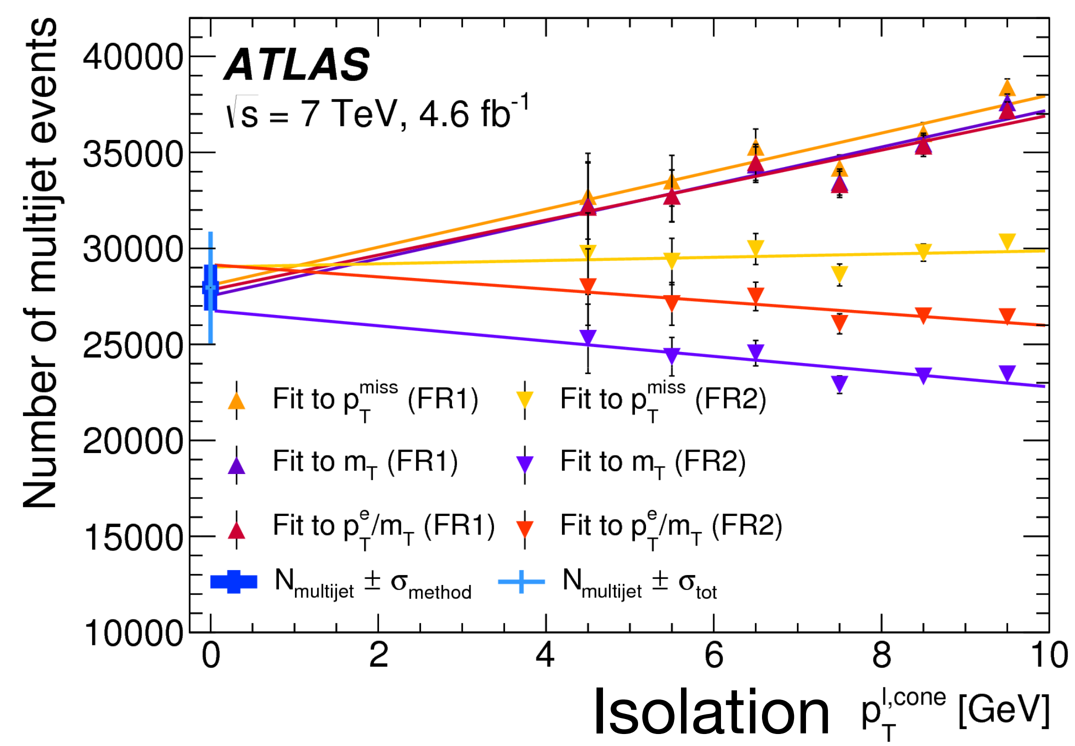
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_T^* correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	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



Backgrounds

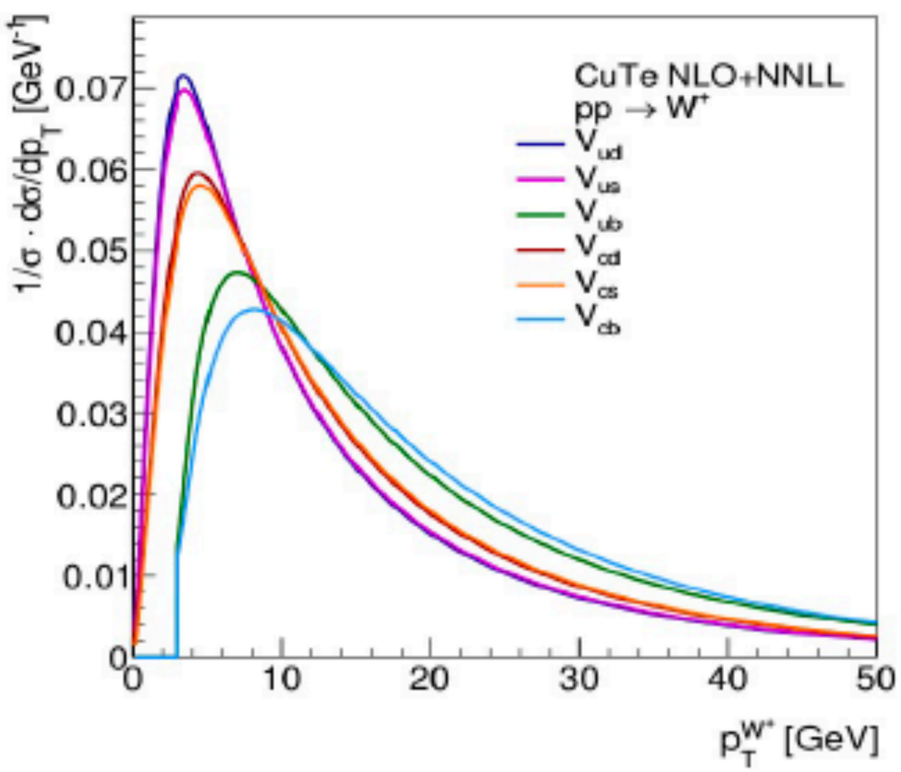
- Backgrounds from Z, diboson production, top, estimated from MC
- The Multijet background is estimated from data by relaxing the selection cuts on p_T^{miss}, m_T, isolation (and u_T) and fitting sensitive distributions (p_T^{miss}, m_T, p_T^l/m_T).
- The multijet background is order 1%.

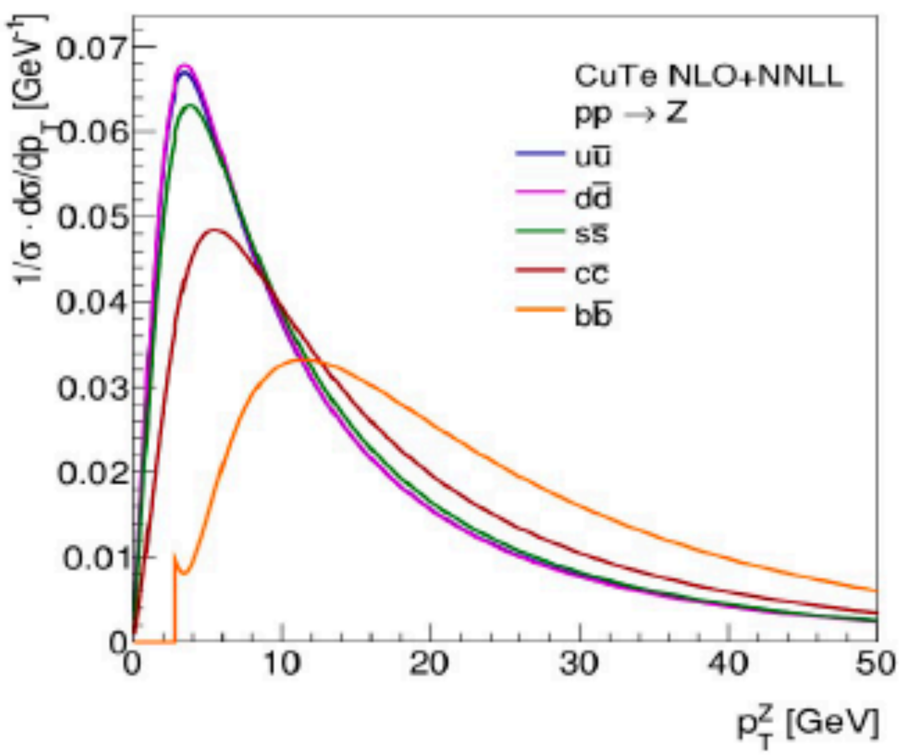




Transverse momentum distribution

- But beyond parton shower / resummation parameters, the pT distributions also depend on the PDFs:





- Needs to be under control, for a proper extrapolation of the tuned predictions to W production. Uncertainty on the pT prediction for given flavour?
- Ideally, prefer a fully integrated theoretical framework, with consistent PDFs used for all aspects of the prediction (→resummation). In shower MC's, the "parton shower PDF" is an additional degree of freedom