JOHANNES GUTENBERG UNIVERSITÄT MAINZ

W mass and transverse momentum measurements at the LHC

Samuel Webb

on behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

Johannes Gutenberg University Mainz

samuel.webb@cern.ch

Outline

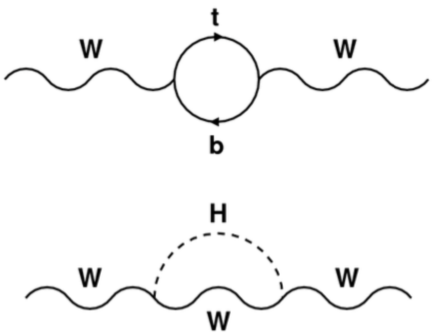
- Introduction to W mass measurements at the LHC
  - Focus on **ATLAS 7 TeV result**
    - issues affecting **hadronic recoil resolution**
      - for transverse mass template fits
    - and affecting **lepton p_T modelling**
      - theoretical model for W p_T spectrum

- How future experimental uncertainty could be reduced
  - Measuring W p_T in low pile-up environment

- Summary

W mass introduction

- Theoretical uncertainty on W boson mass smaller than world average experimental
  - 8 MeV compared to 15 MeV
  - potential to constrain new physics
  - improve understanding of PDFs and higher order corrections

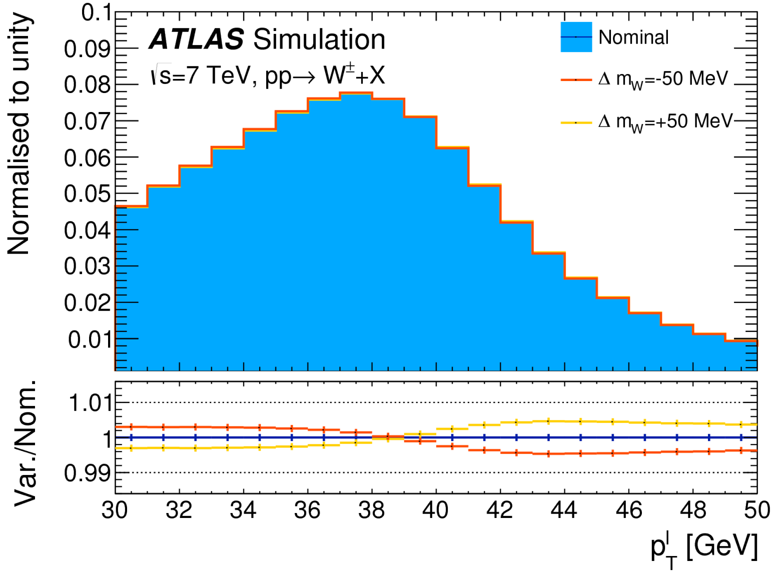


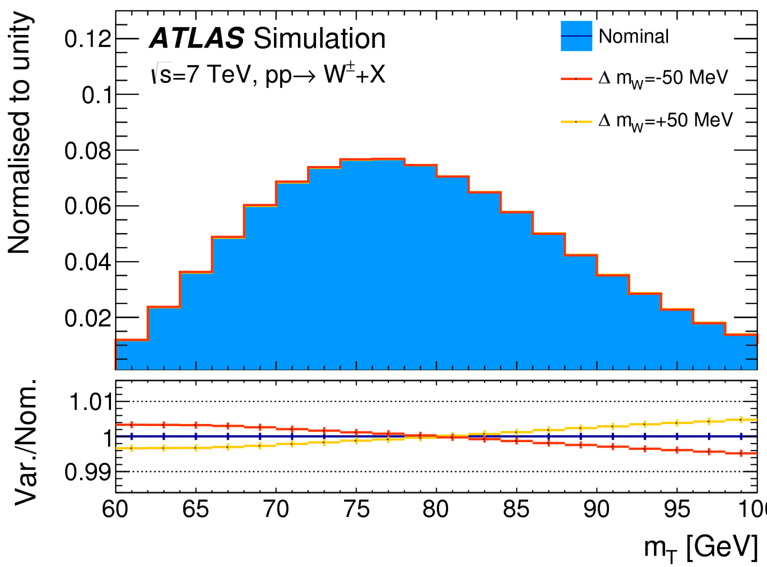
$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r)$$

- Measurements at LHC strongly affected by uncertainties on strange and charm quark PDF
  - 25% of W's induced by charm and strange - 5% at Tevatron
- However larger statistics at LHC
  - allows a more precise detector calibration

W mass measurement at 7 TeV

- Currently one published measurement of the W boson mass at the LHC
  - ATLAS @ 7 TeV - *Eur. Phys. J. C 78 (2018) 110*
- Template fit method in two kinematic variables
  - p_T of decay lepton (e or μ), W transverse mass





  - Also separated by W^+, W^- , and bins of lepton η
  - 28 categories total

W mass measurement
Systematic sources

- A large number of systematic sources to consider, each with many sub-contributions
  - Statistical uncertainties
  - Experimental calibration
    - Muon calibration
    - Electron calibration
    - Recoil calibration
  - Electroweak and multi jet background modelling
  - Physics modelling uncertainties
    - fixed order prediction
    - higher order EW corrections
    - PDF modelling

All of these have to be carefully controlled to get a precise measurement

Eur. Phys. J. C 78 (2018) 110

Physics modelling

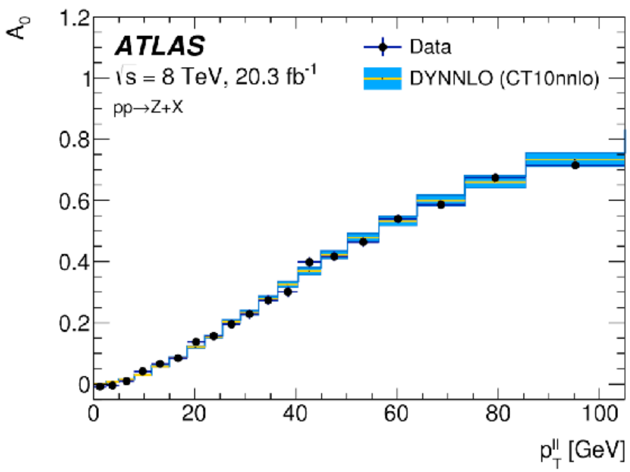
- Model used for fitting obtained by re-weighting NLO MC prediction from Powheg+Pythia to an improved higher order prediction

factorisation of cross section:

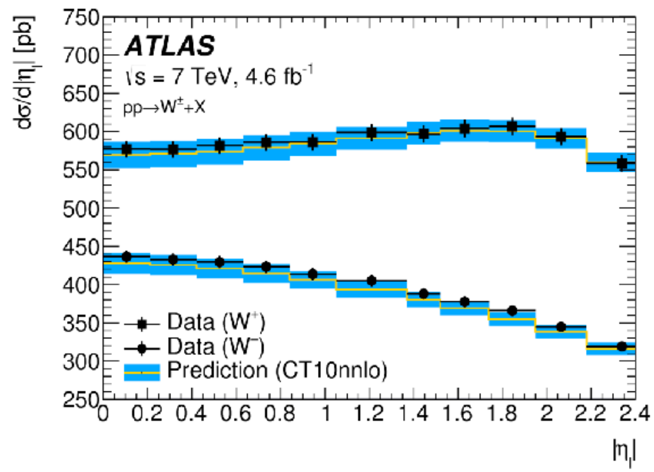
[mass] [rapidity] [angular coefficients] [p_T]

Breit-Wigner · **NNLO pQCD** · **Parton Shower**

- **NNLO predictions** cross-checked with published results



A_0 coefficient



lepton pseudorapidity (W decays)

large uncertainty from PDF modelling for fixed order prediction
~8 MeV

Eur. Phys. J. C 78 (2018) 110

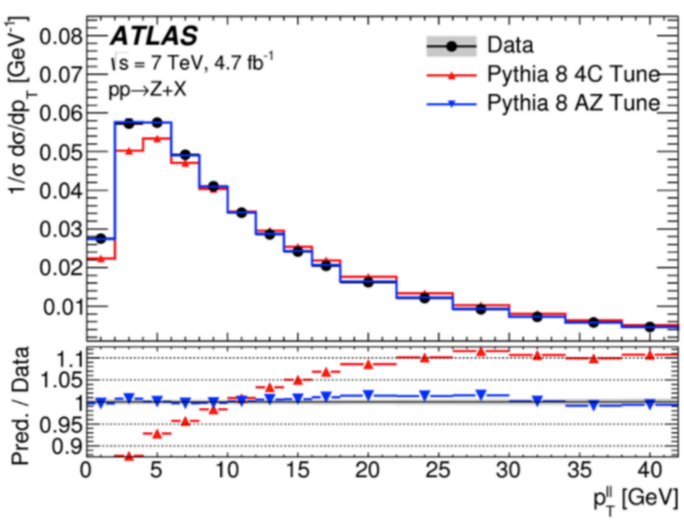
Physics modelling

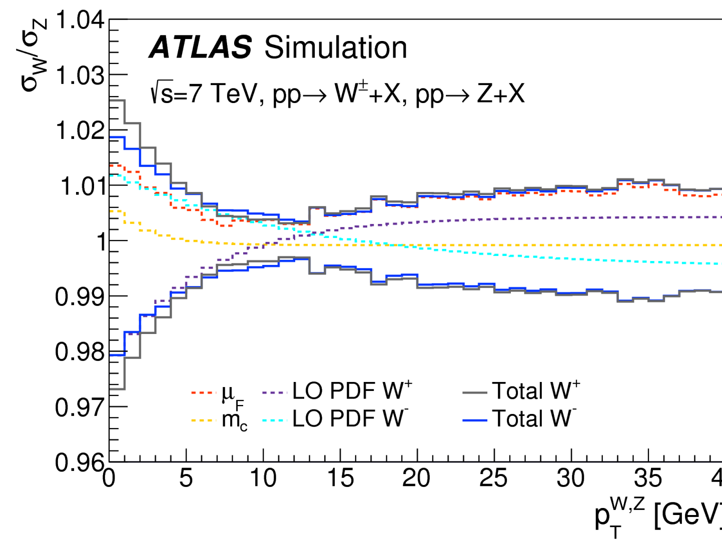
factorisation of cross section:

[mass] [rapidity] [angular coefficients] [p_T]

Breit-Wigner (mass) — **NNLO pQCD** (rapidity, angular coefficients) — **Parton Shower** (p_T)

- Tune Pythia8 p_T distribution using Z boson **p_T measurement** at 7 TeV
- Use Pythia8 to evaluate theory uncertainties on ratio W p_T / Z p_T (large **~6 MeV**)





Eur. Phys. J. C 78 (2018) 110

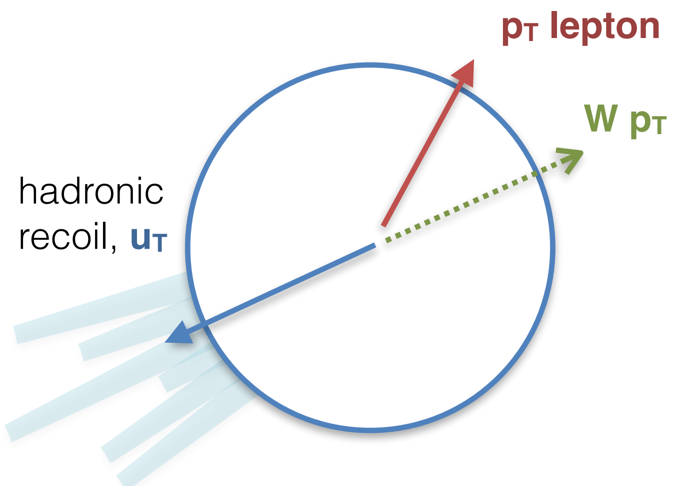
Transverse mass fit

- Transverse mass fit

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

  - depends on calibration of the hadronic recoil, **u_T**

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$



The recoil is reconstructed from the vector sum of the transverse energy of all clusters reconstructed in the calorimeters

- Three calibrations steps
  - correct pile-up profile in MC to match data
  - correct for residual differences in transverse energy sum distributions
  - Scale and resolution corrections from $Z \rightarrow \mu\mu$ sample

Transverse mass fit

- Transverse mass fit

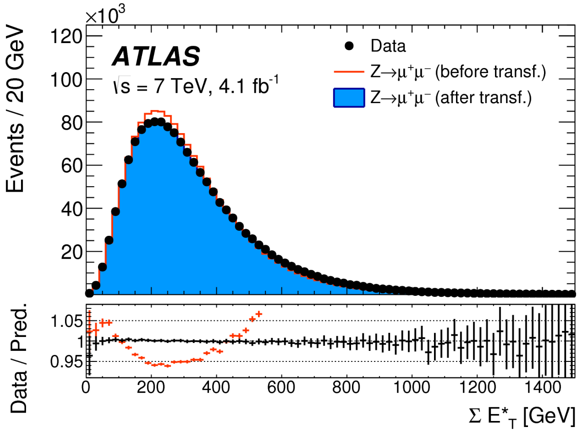
$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)}$$

  - Resolution of the hadronic recoil a limiting factor for m_T measurement - 13 MeV (total 25 MeV) -

m_w [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1

Combined W mass measurement, using transverse mass fit

- Mainly due to transverse energy sum re-weighting and transfer of calibration from Z events
  - **pile-up** large contributing factor



Lepton p_T fit

- Lepton p_T fit
  - Effect of the recoil calibration much smaller with respect to transverse mass fit
  - however strongly affected by modelling of W p_T in the prediction

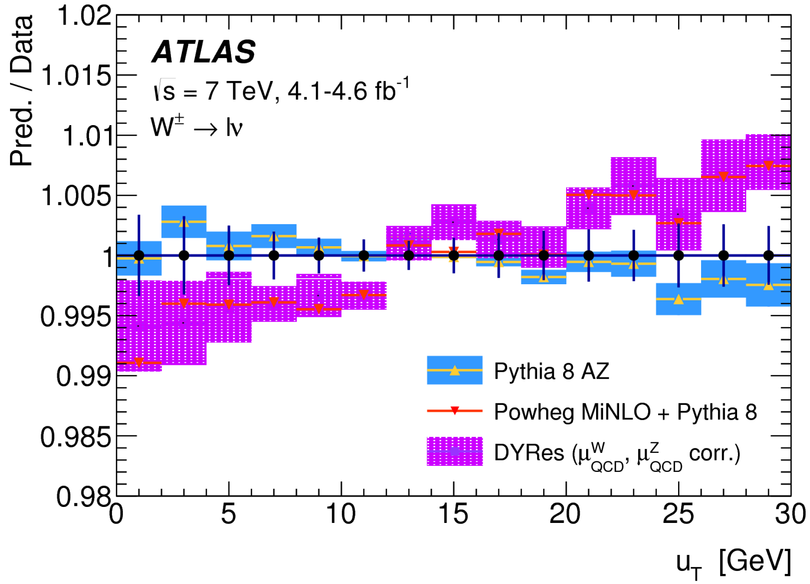
m_w [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7

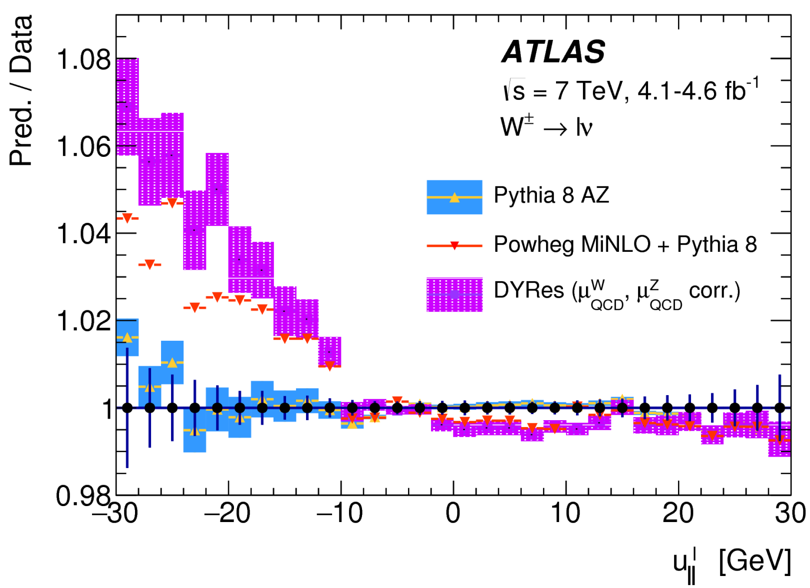
- PDF uncertainty anti-correlated between W^+ W^-
  - reduced in combination

Eur. Phys. J. C 78 (2018) 110

Boson p_T modelling

- Many tests of the p_T modelling show Pythia8 provides a good description (within the large uncertainties)





Component of hadronic recoil transverse to lepton direction

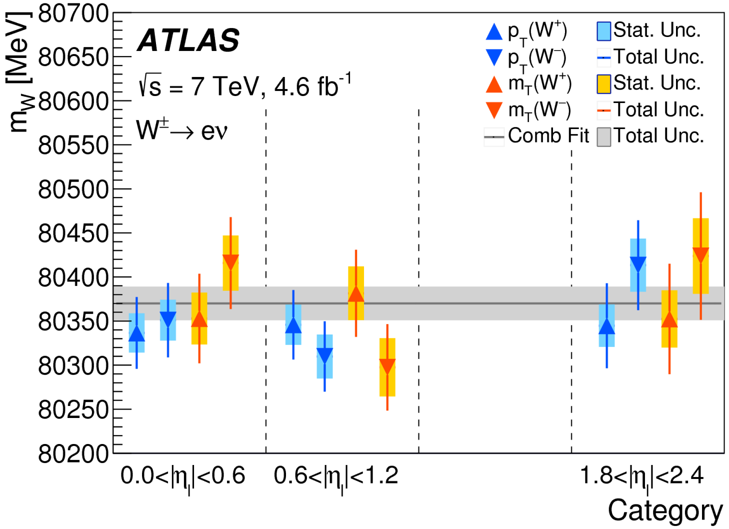
Component of hadronic recoil parallel to lepton direction

- NNLO+NNLL predictions do not describe data
  - due to incomplete heavy flavour treatment?

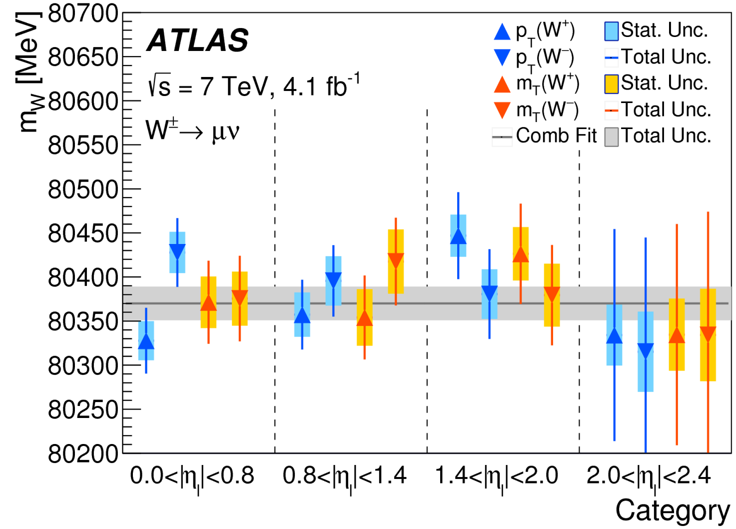
Eur. Phys. J. C 78 (2018) 110

Final combined result

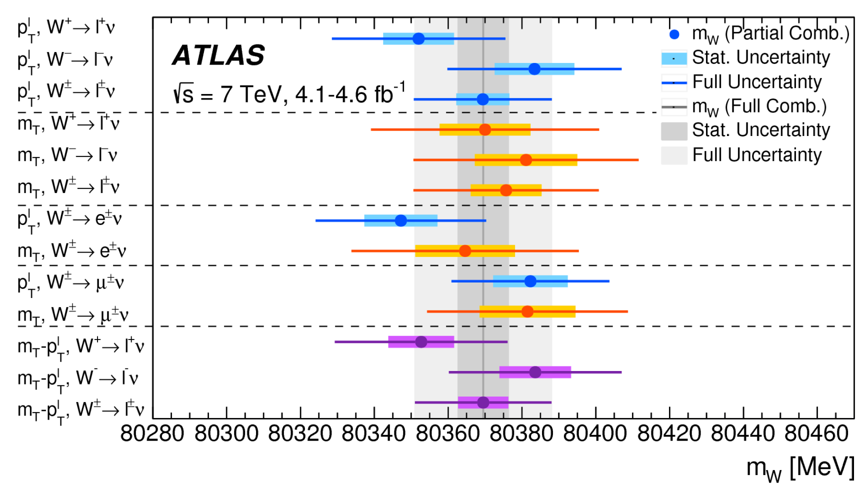
electron channel fits



muon channel fits



- Measurements consistent
  - in each category
  - in combinations of categories

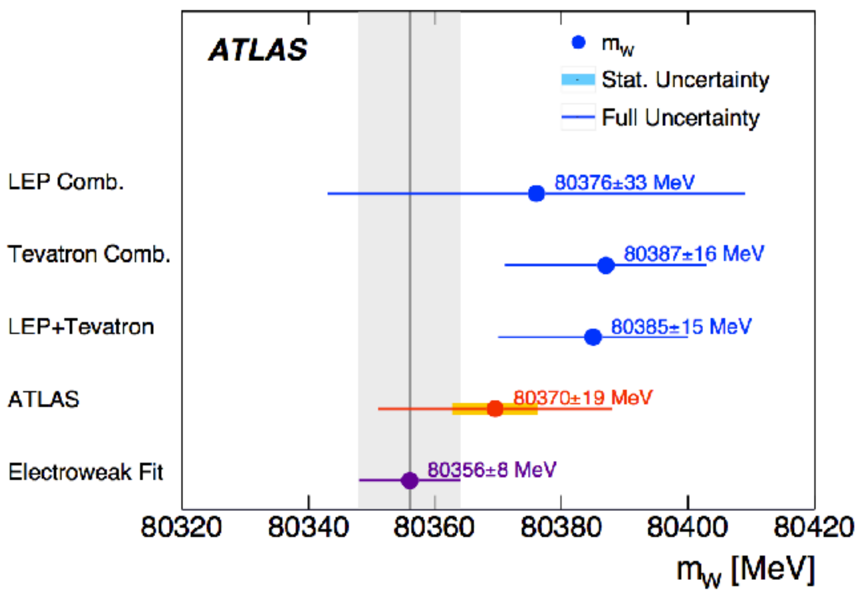


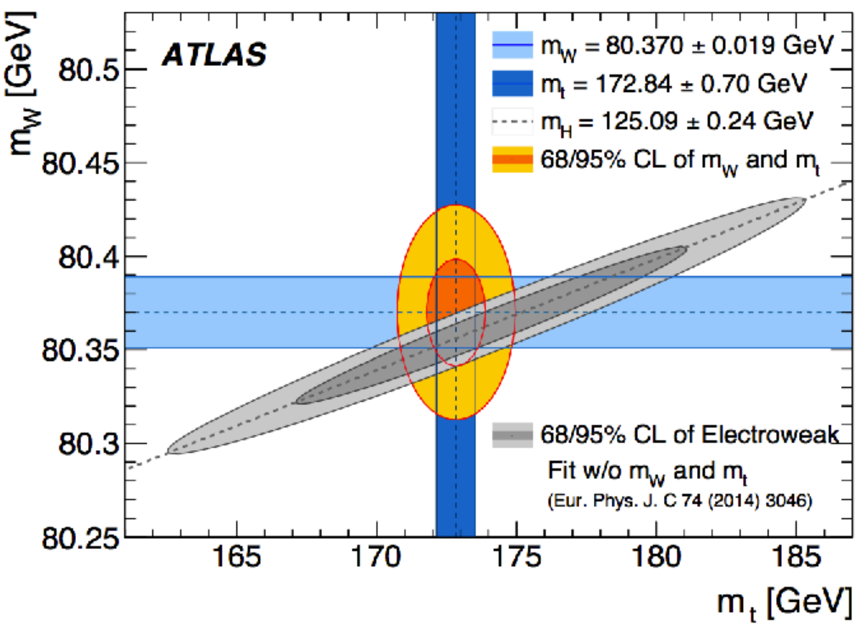
Eur. Phys. J. C 78 (2018) 110

Final combined result

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

- **Final result consistent with theory and previous measurements**
  - Uncertainty, 18.5 MeV, dominated by physics modelling uncertainties



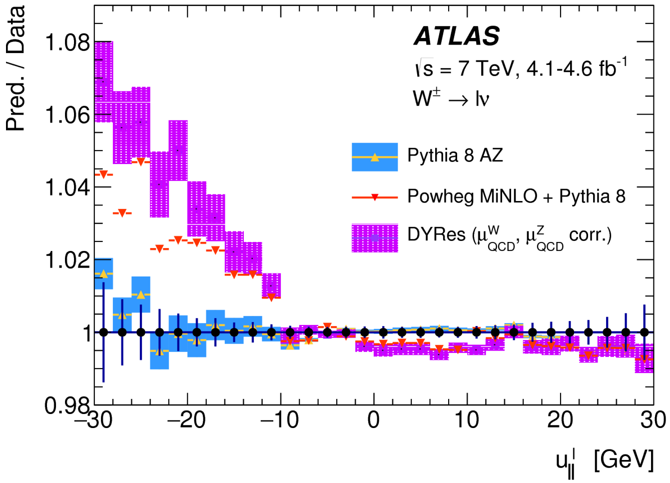


Improvements for future measurements

- One of the dominant uncertainties in ATLAS measurement arises from W p_T modelling
  - tune Pythia8 to Z p_T distribution
  - evaluate uncertainties related to the difference between W and Z transverse momentum distributions

- 1) Improve theoretical modelling of W p_T and ratio between W p_T and Z p_T
  - (experimental uncertainty on Z p_T small)

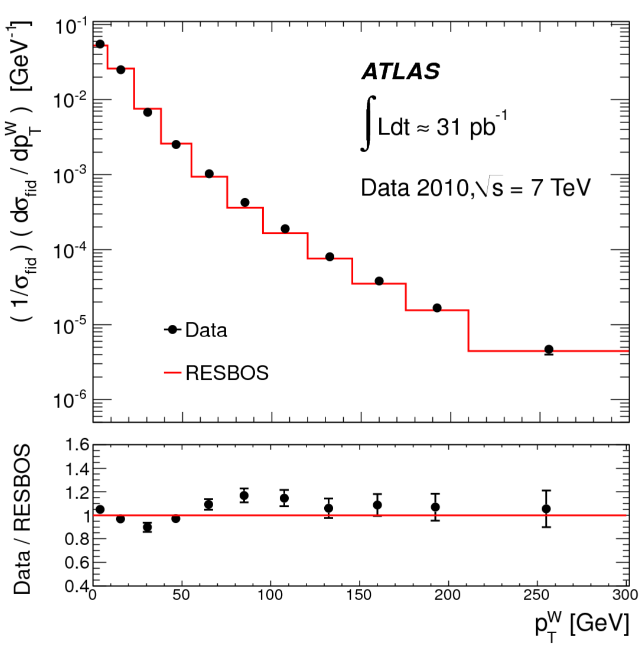
- 2) Directly measure W p_T distribution in data
  - removes the need for a transfer from Z

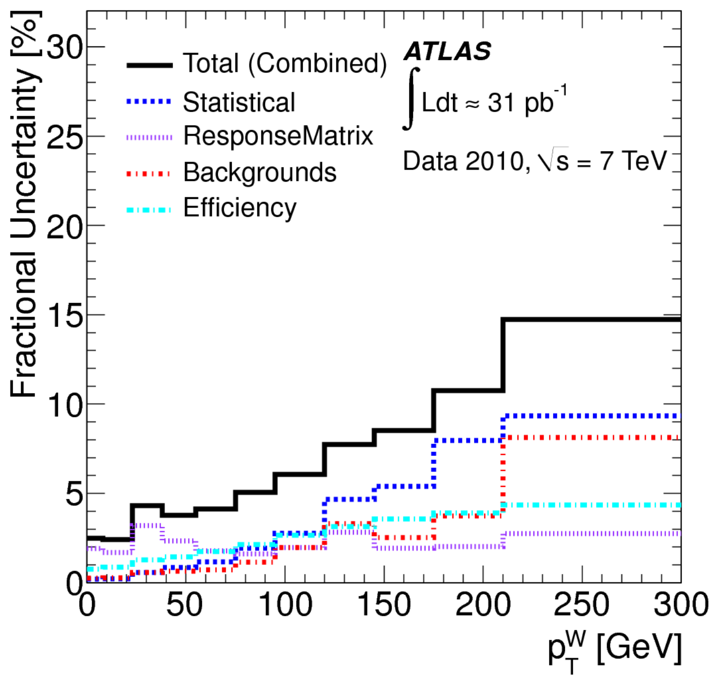


Previous W p_T measurements - ATLAS

Phys.Rev. D85 (2012) 012005

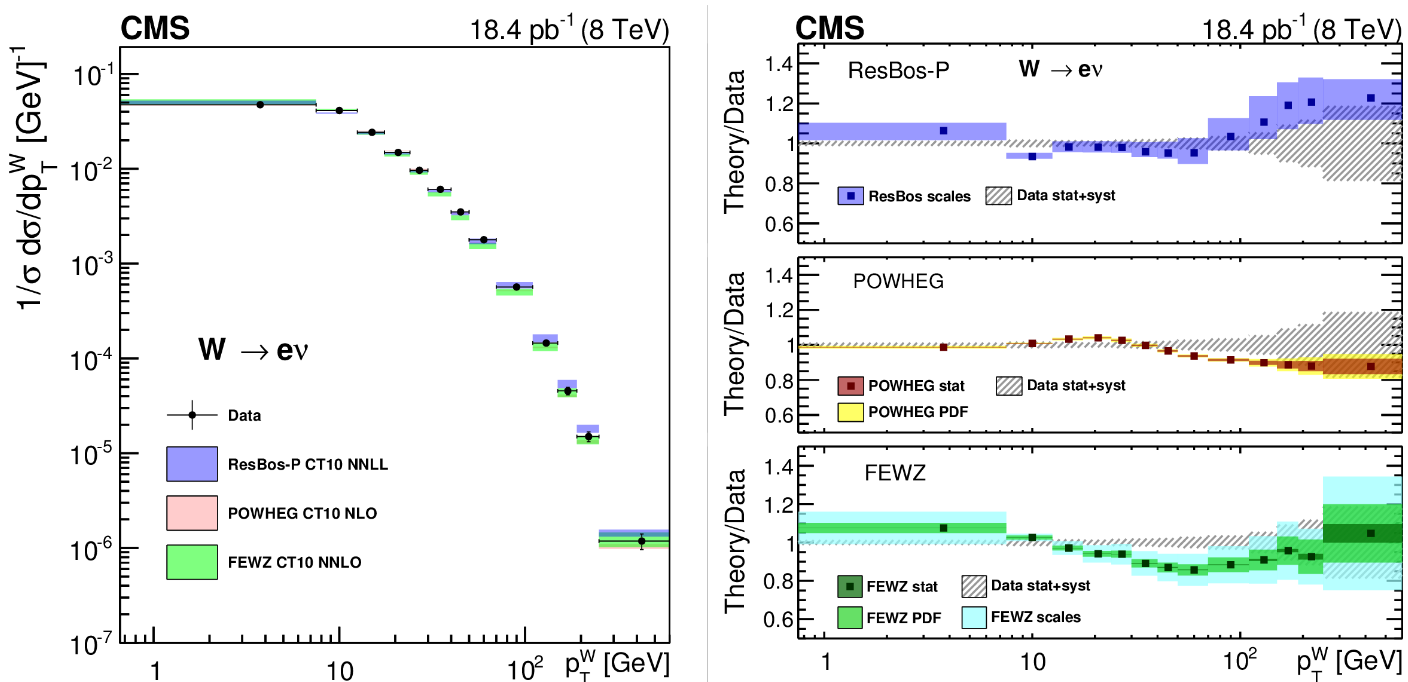
- ATLAS 7 TeV W p_T measurement from 2010 (low pile-up, μ=2)
  - combined electron + muon channels
  - uncertainty dominated by low statistics at high p_T (31 pb^{-1})
    - low statistics also affects efficiency and calibration sample size
    - for example for the data-driven hadronic recoil calibration





Previous W p_T measurements - CMS

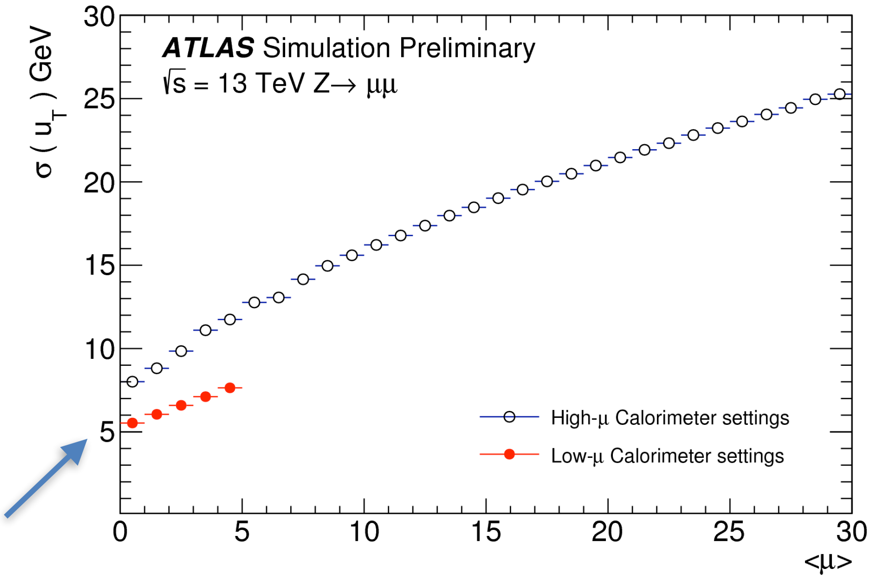
- More recent CMS 8 TeV W p_T measurement (also low pile-up, $\mu=4$)
  - combined electron + muon channels
  - uncertainty again dominated by low statistics at high p_T (18.4 pb^{-1})
    - as well as modelling of background from multi-jet processes



Prospects for new W p_T measurements

- To reduce uncertainty from p_T modelling by ~factor of two
  - need measurements of W p_T in bin sizes of 5 GeV or less (for W p_T < 30 GeV)
  - only possible if recoil resolution is comparable or better than 5 GeV

low pile-up run required

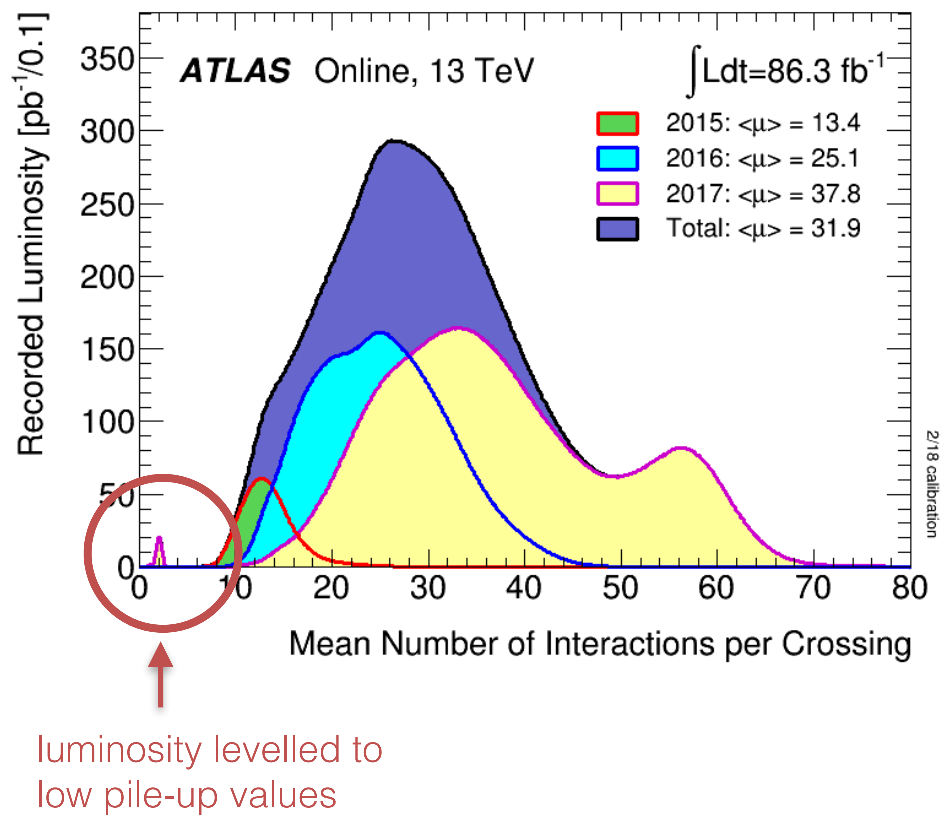


- In November 2017, ATLAS+CMS collected ~280 pb^{-1} of low-pile-up data at $\sqrt{s}$ = 5 TeV, and ~160 pb^{-1} at $\sqrt{s}$ = 13 TeV in each case with $\langle \mu \rangle$ of ~2.
  - Many times more data than previous measurements

Low pile-up data

- The better recoil resolution may also allow for a W mass measurement in which the **transverse mass fit has a larger contribution to the final value**
  - complementary to previous measurement at 7 TeV

- W p_T measurements at 5 TeV and 13 TeV could probe how the **importance of heavy quark initiated processes** increases with centre of mass energy



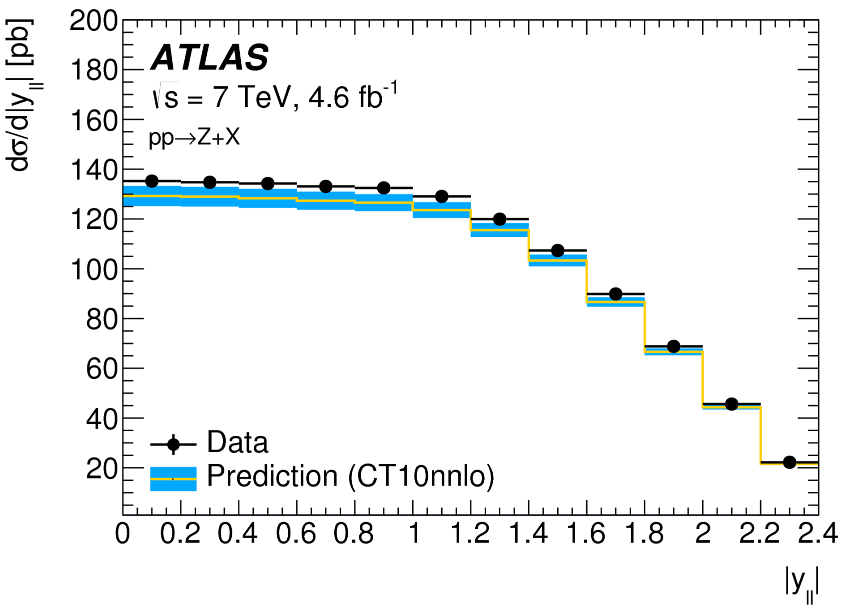
Summary

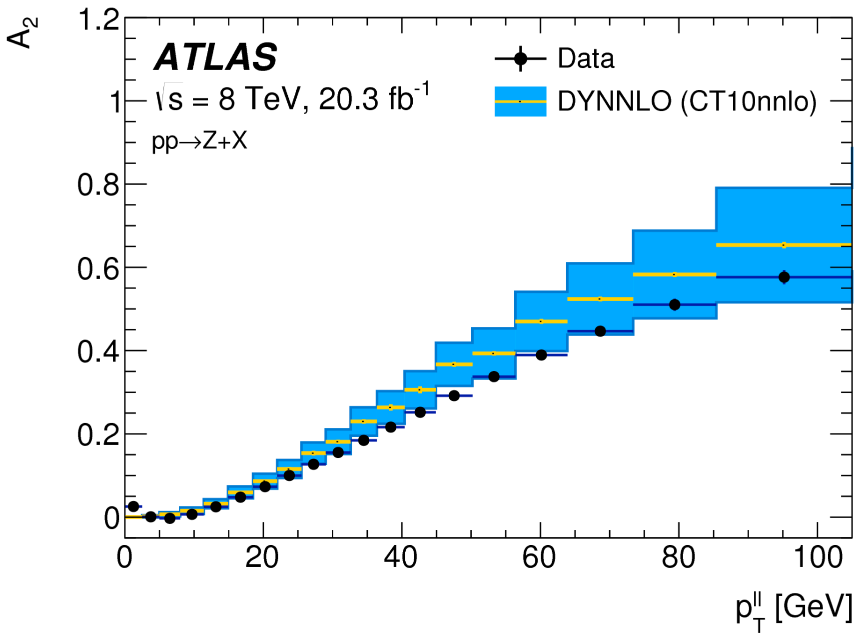
- ATLAS W mass measurement at 7 TeV reached experimental uncertainty of 18.5 MeV
  - theoretical uncertainty 8 MeV - still room to improve measurement
  - dominant uncertainties on the measurement from
    - imperfect knowledge of PDFs in fixed order prediction
    - theoretical description of W p_T / Z p_T ratio

- Uncertainties could be reduced with a direct measurement of W p_T
  - bin sizes < 5 GeV required
  - previous measurements suffered from low data statistics
  - 280 pb^{-1} of low-pile-up data at $\sqrt{s}$ = 5 TeV, and 160 pb^{-1} at $\sqrt{s}$ = 13 TeV now available

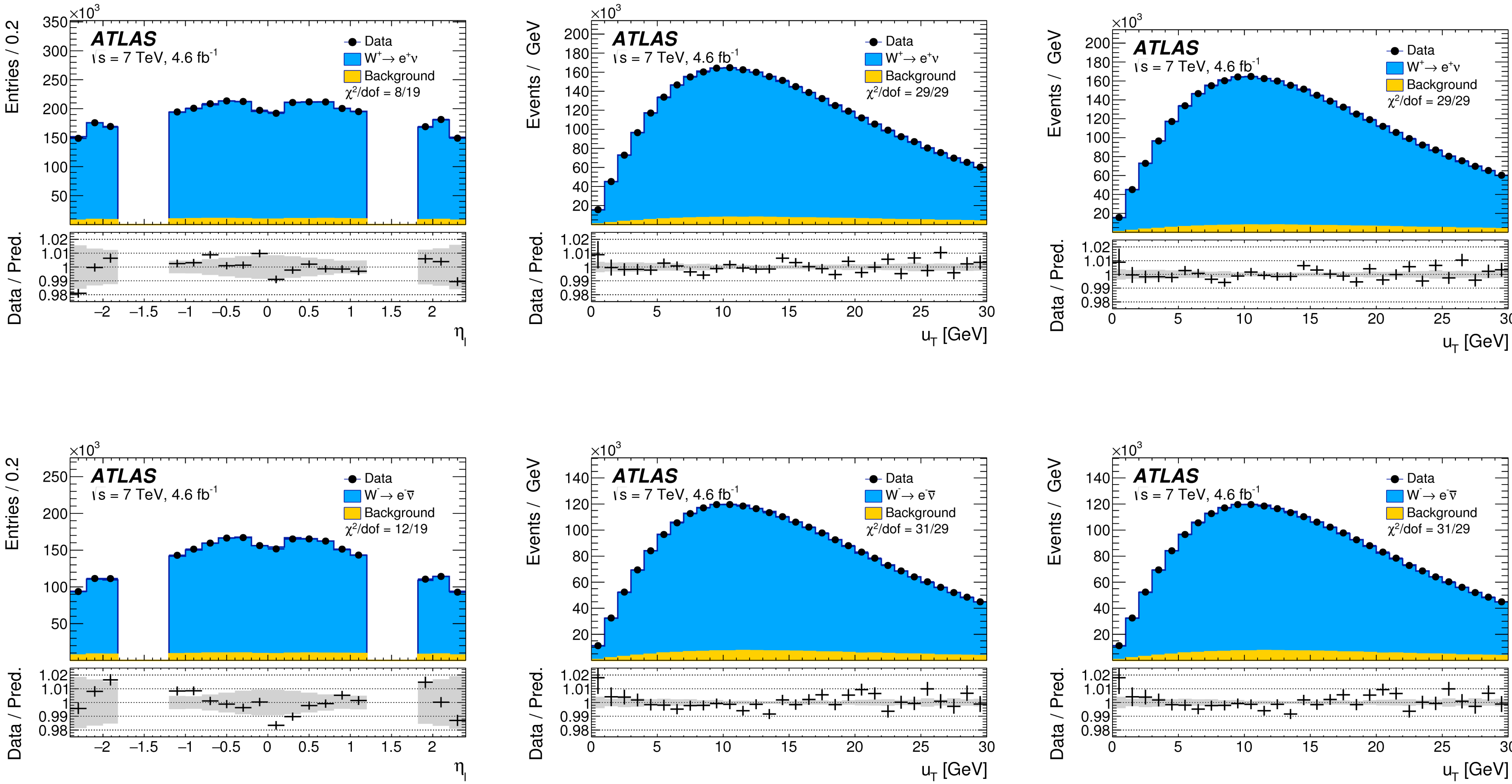
Additional Material

DYNNLO predictions

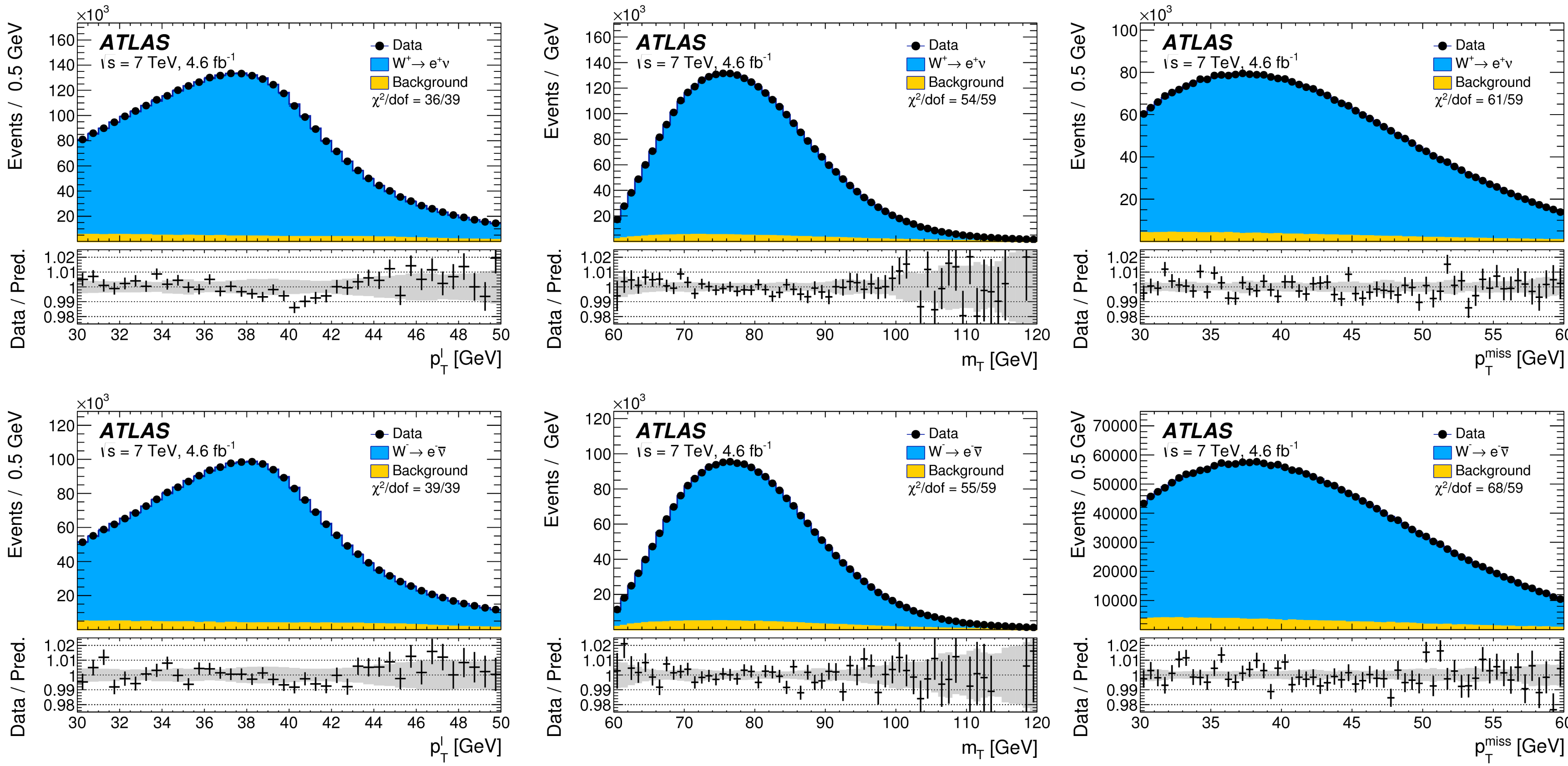




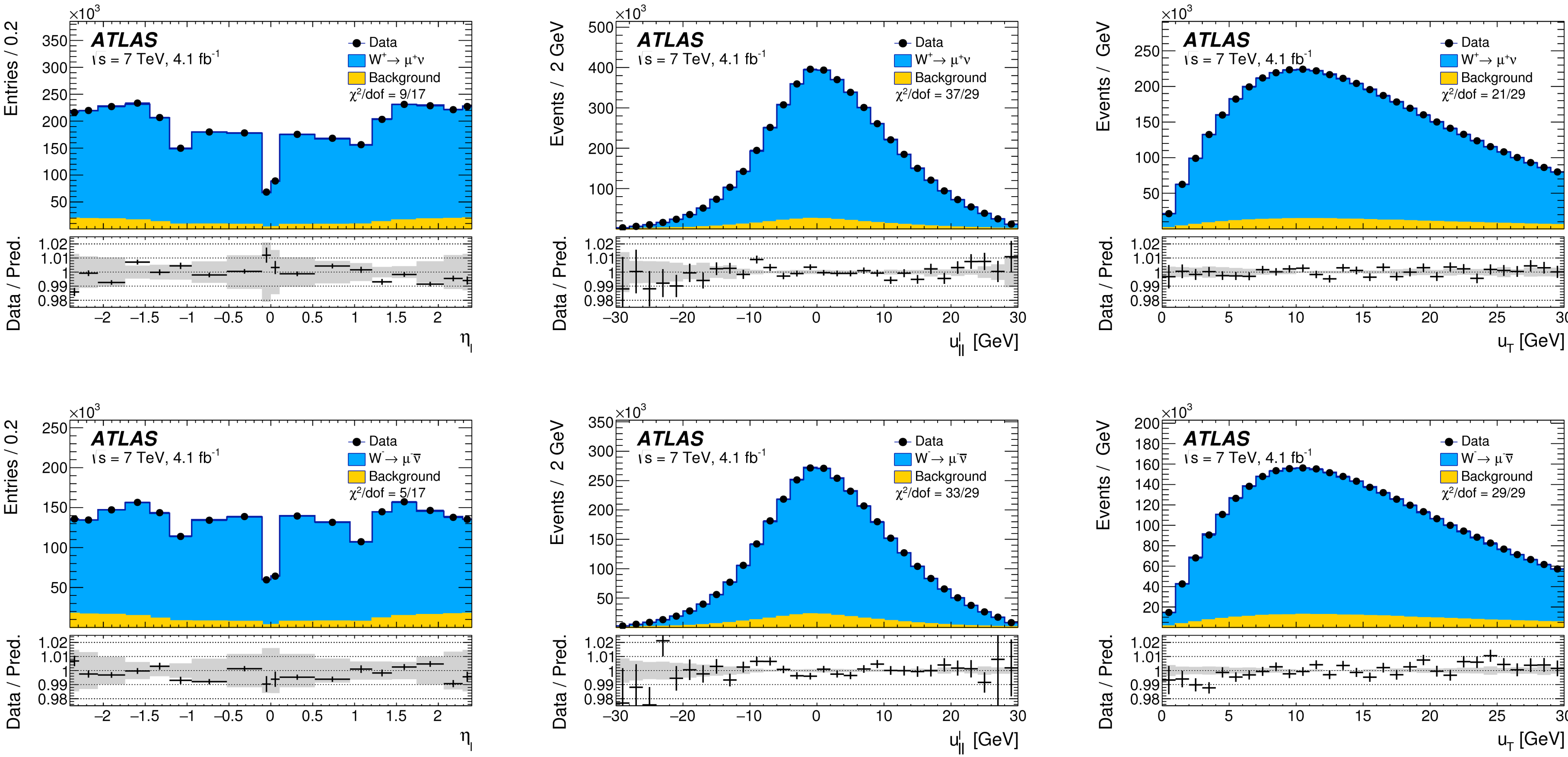
Control distributions electron channel



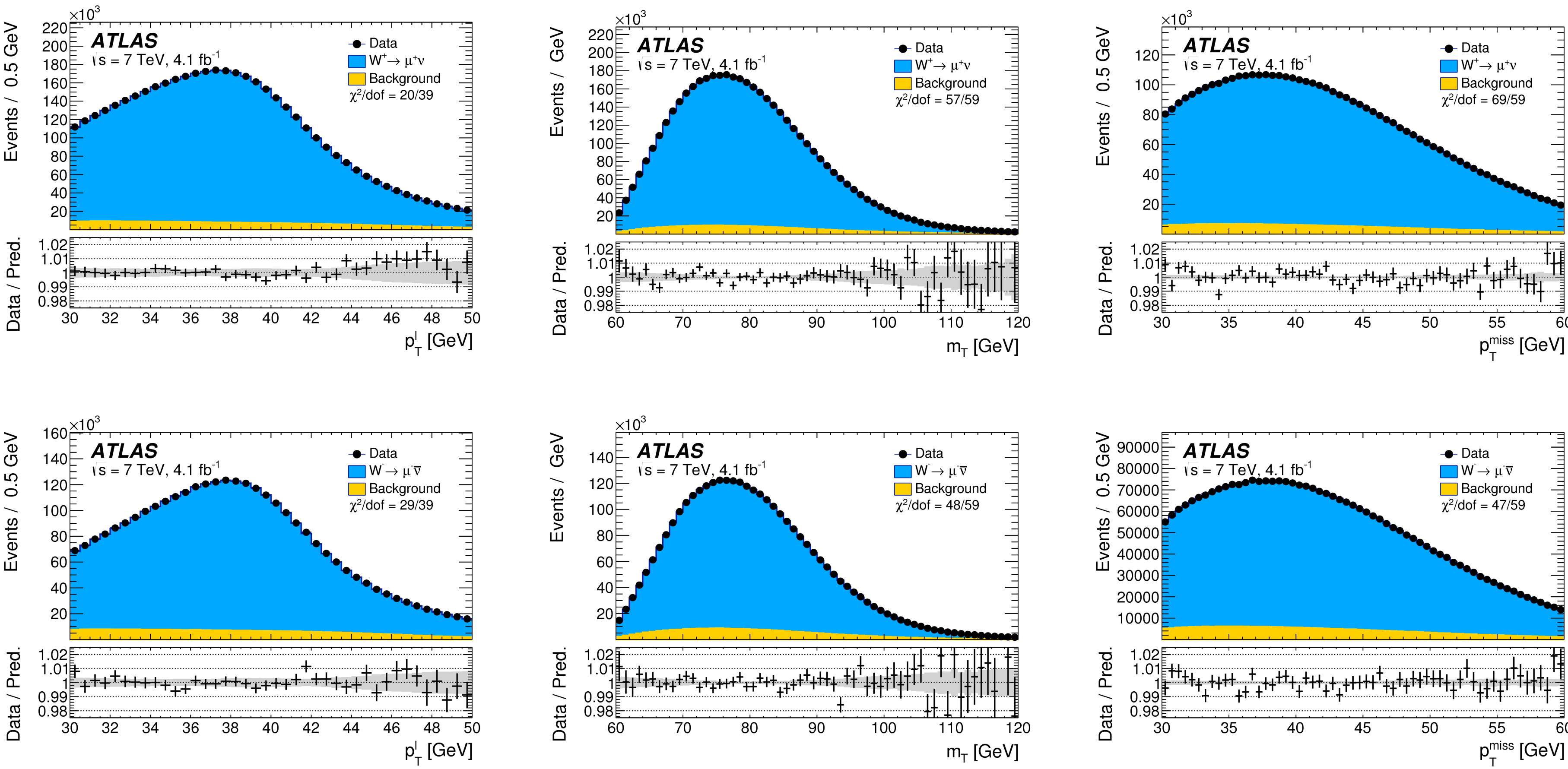
Control distributions electron channel



Control distributions muon channel



Control distributions muon channel



Uncertainties due to QCD modelling

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

Uncertainties due to muon calibration

$\lvert\eta_\ell\rvert$ 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

Uncertainties due to electron calibration

$\lvert\eta_\ell\rvert$ 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

Uncertainties due to recoil corrections

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

Number of selected W bosons

$\|\eta_\ell\|$ 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