Measurement of W-boson Mass in ATLAS

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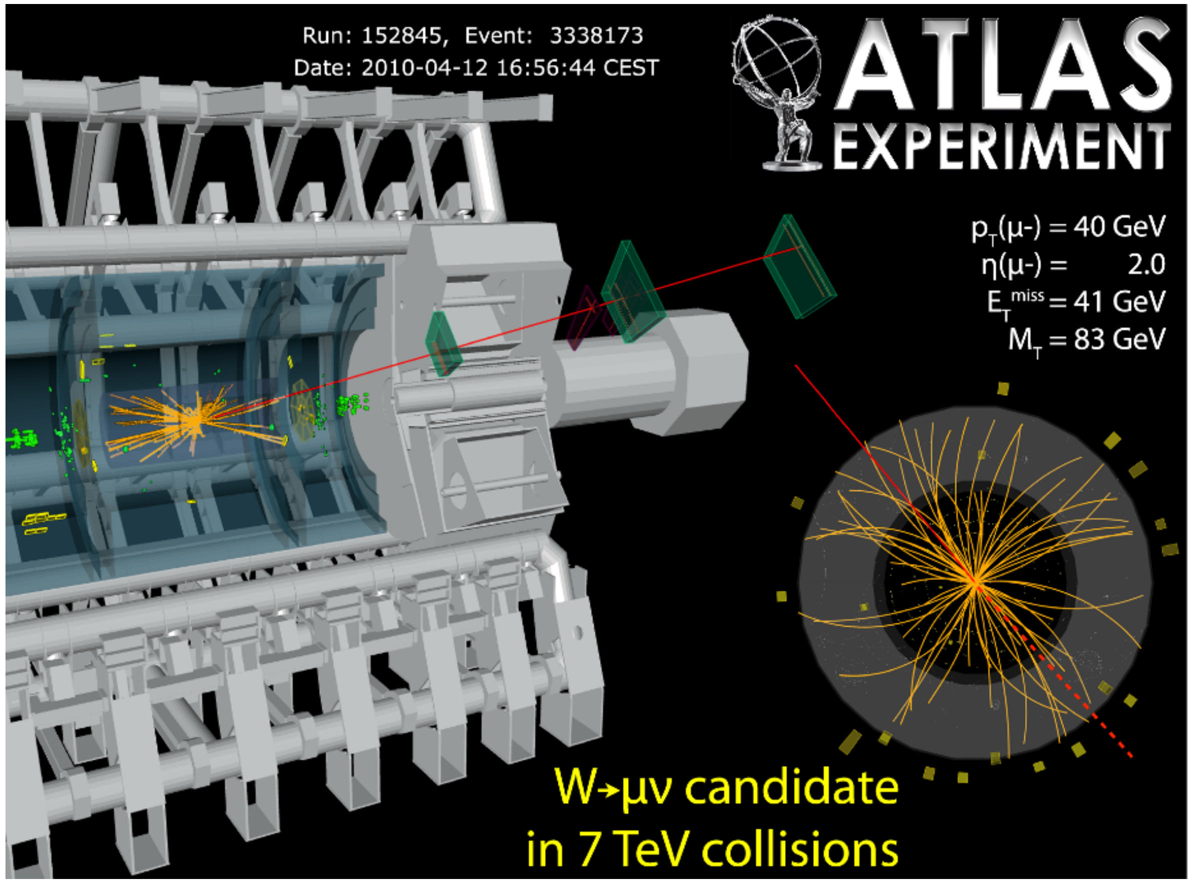
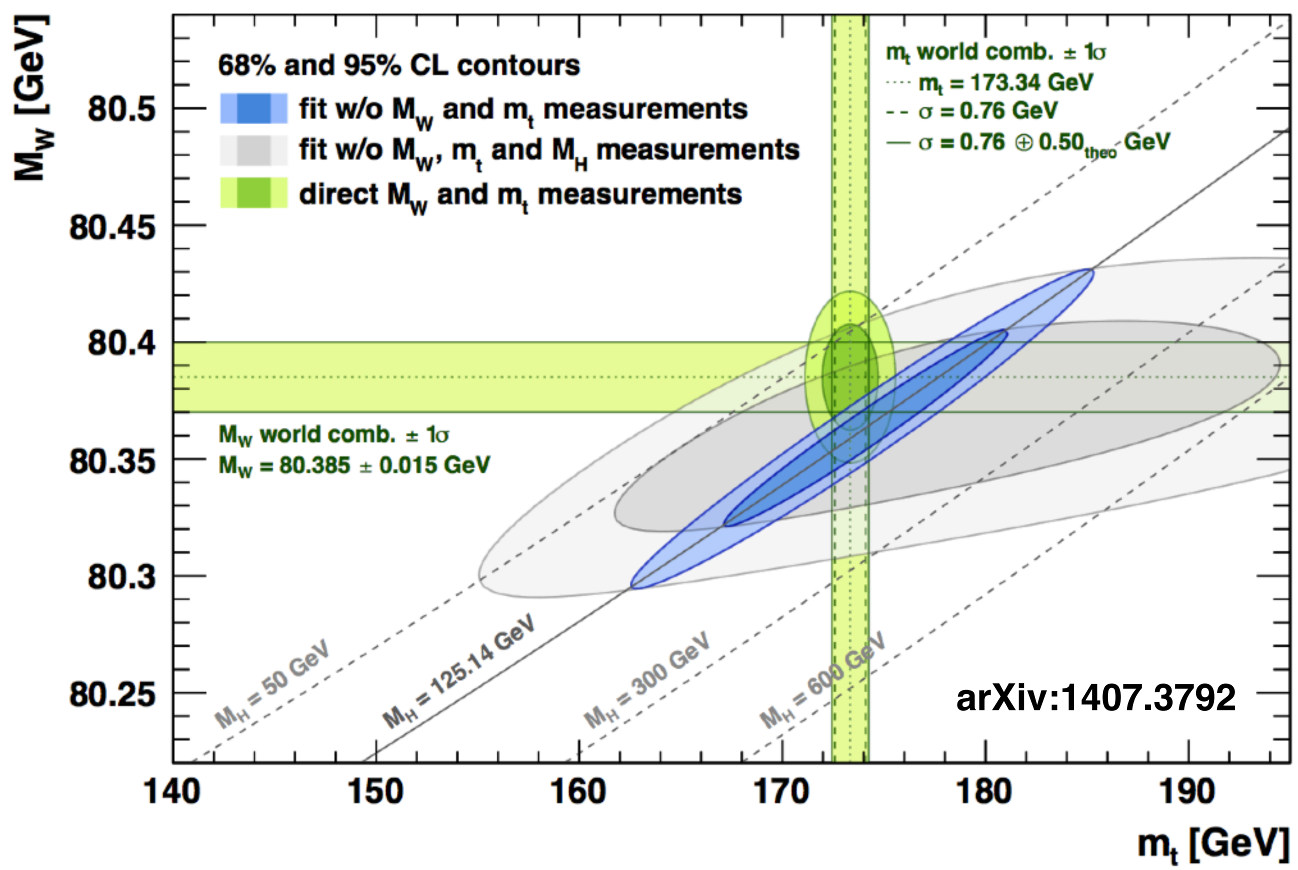
Outline

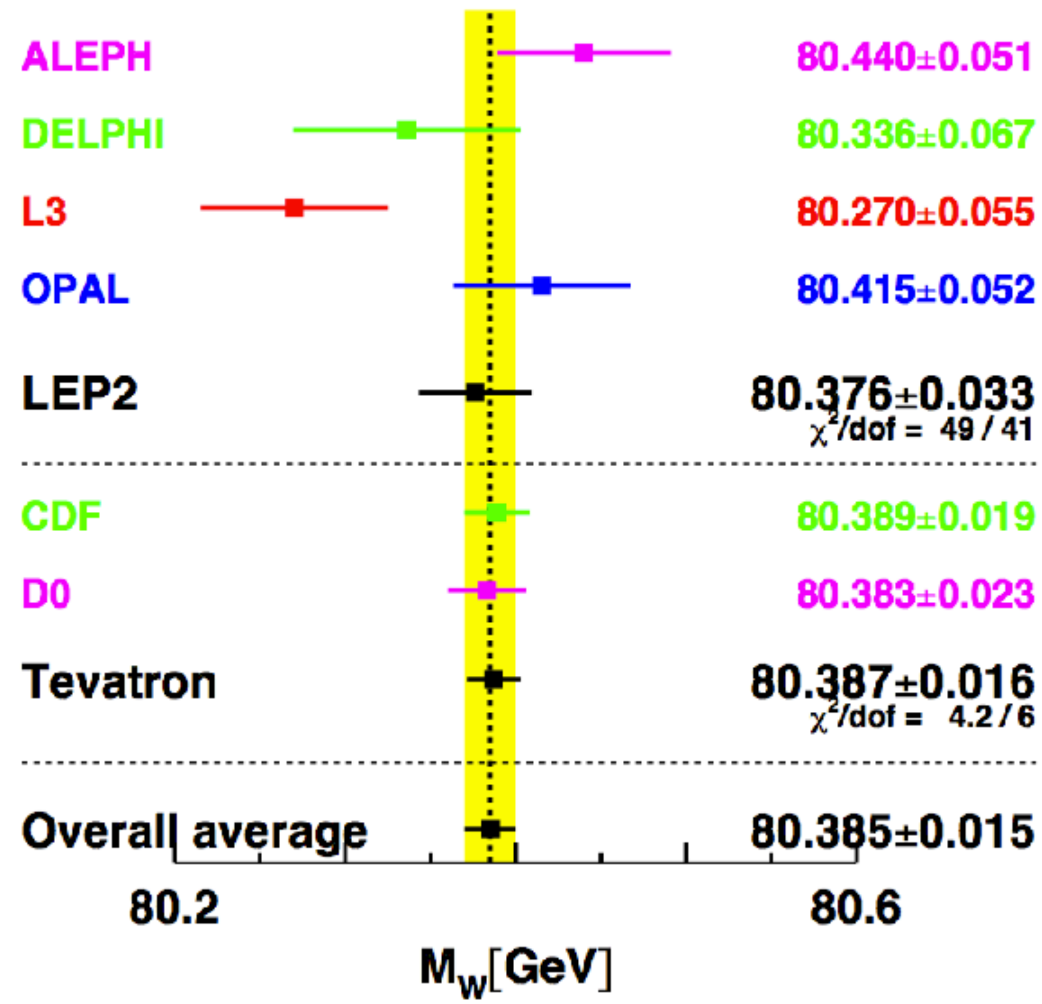
- Motivation for W mass measurement
- Measurement Strategy
  Method: Monte Carlo Templates Fits
- Event Selection and Calibration
  ATLAS 7TeV datasets in 2011
- Physics Modelling
- Measured Results
  arXiv:1701.07240



Motivation

Chin. Phys. C. 40. 100001 (2016)



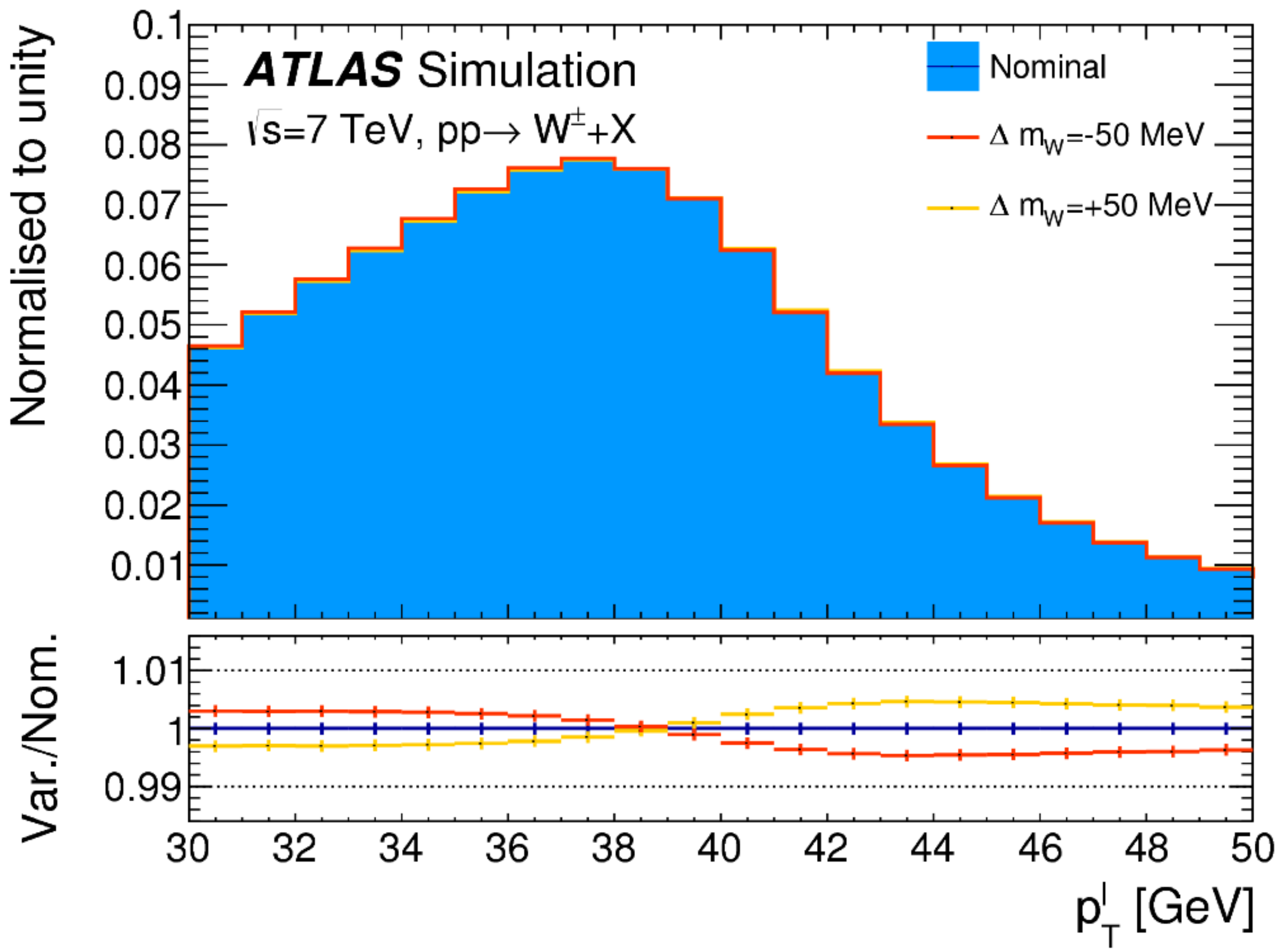


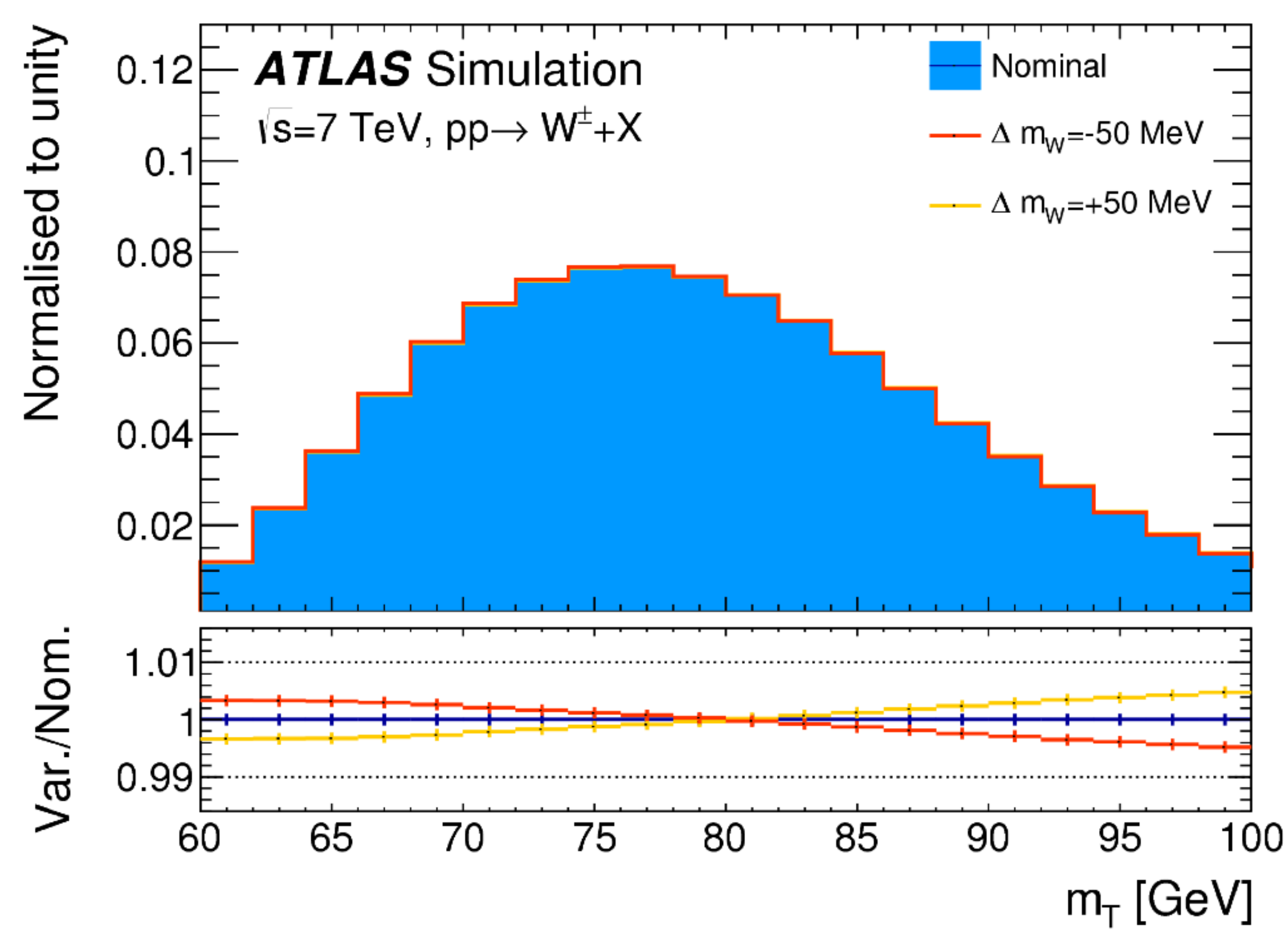
- W boson mass is fundamental parameter of the Standard Model which is particularly sensitive to top and Higgs bosons' masses

- The measurement of the W boson mass provides a consistency test of the Standard Model and a probe of Beyond Standard Model physics

- The Standard Model prediction (arXiv:1608.01509): 80.360±0.008 GeV
  The world average experimental measurement: 80.385±0.015 GeV
  Improvement of W mass measurement allows to challenge the SM prediction

Measurement Strategy

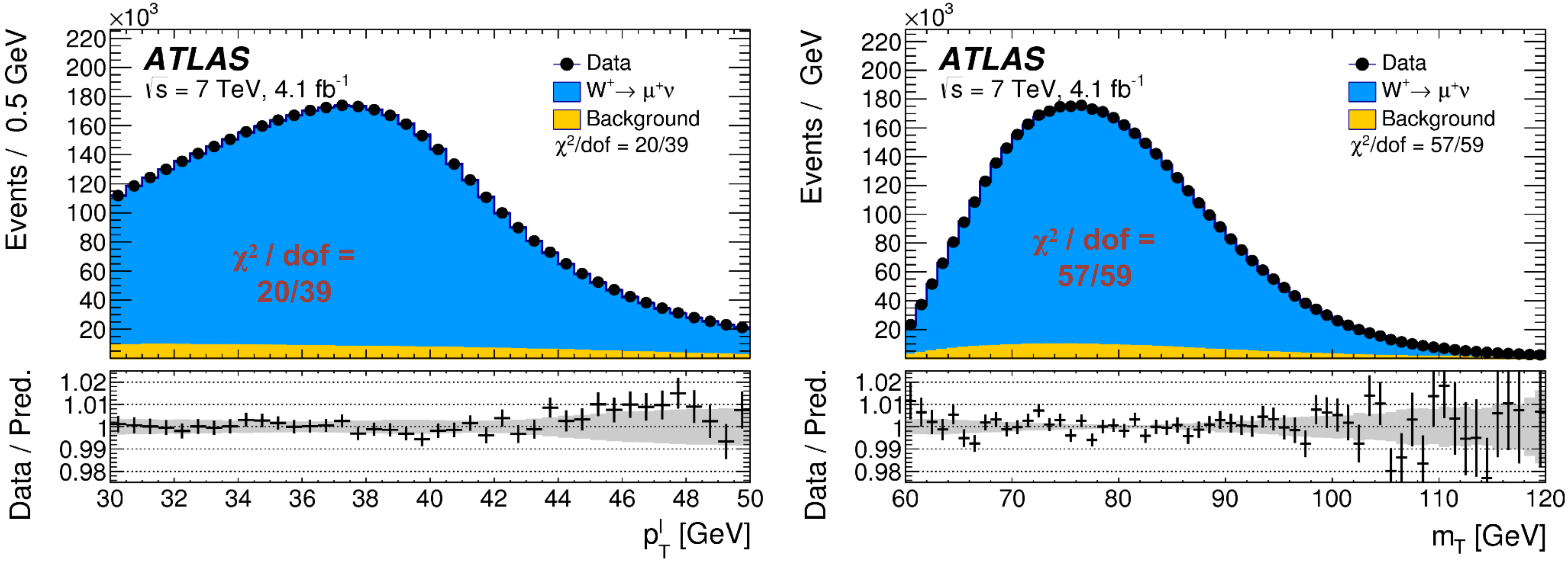




- Create Monte Carlo templates with different W mass values by re-weighting. Then perform Monte Carlo template fit to data with $\chi 2$ minimisation to extract mass in data.

- Sensitive final state distributions: p_T^l, m_T, p_T^{miss} are tested. (p_T^{miss} is only used as a cross check)

Measurement Strategy

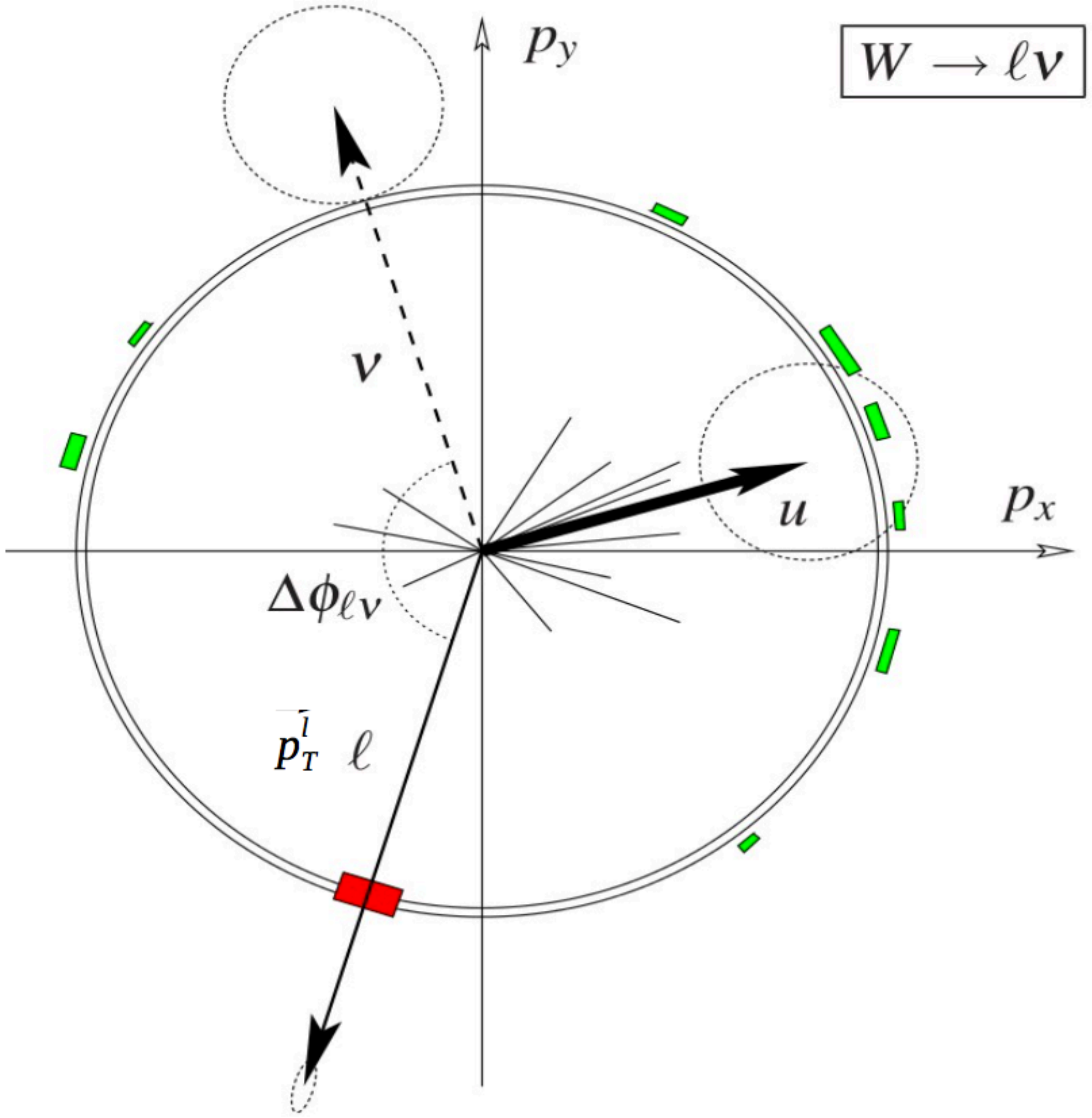


- Fits performed in categories to enhance the fit sensitivity
  - electron / muon decays (different detector effect)
  - p_T^l fit / m_T fit (different detector effect)
  - positive / negative lepton charges (different impact of physics modelling uncertainties)
  - different lepton pseudorapidity $|\eta|$ ranges (different impact of physics modelling uncertainties)

- A blinding offset of W mass was applied throughout the measurement and removed when consistent results were found.

Event Selection

- ATLAS 7TeV datasets in 2011
- Electron channel selection
  - $|\eta| < 2.4$
    (exclude $1.2 < |\eta| < 1.82$
    due to large amount of passive material)
  - $p_T > 30$ GeV
  - isolation requirements
  - 5.89×10^6 W-boson candidates,
    0.58×10^6 Z boson candidates
  - 4.6 fb^{-1} of integrated luminosity



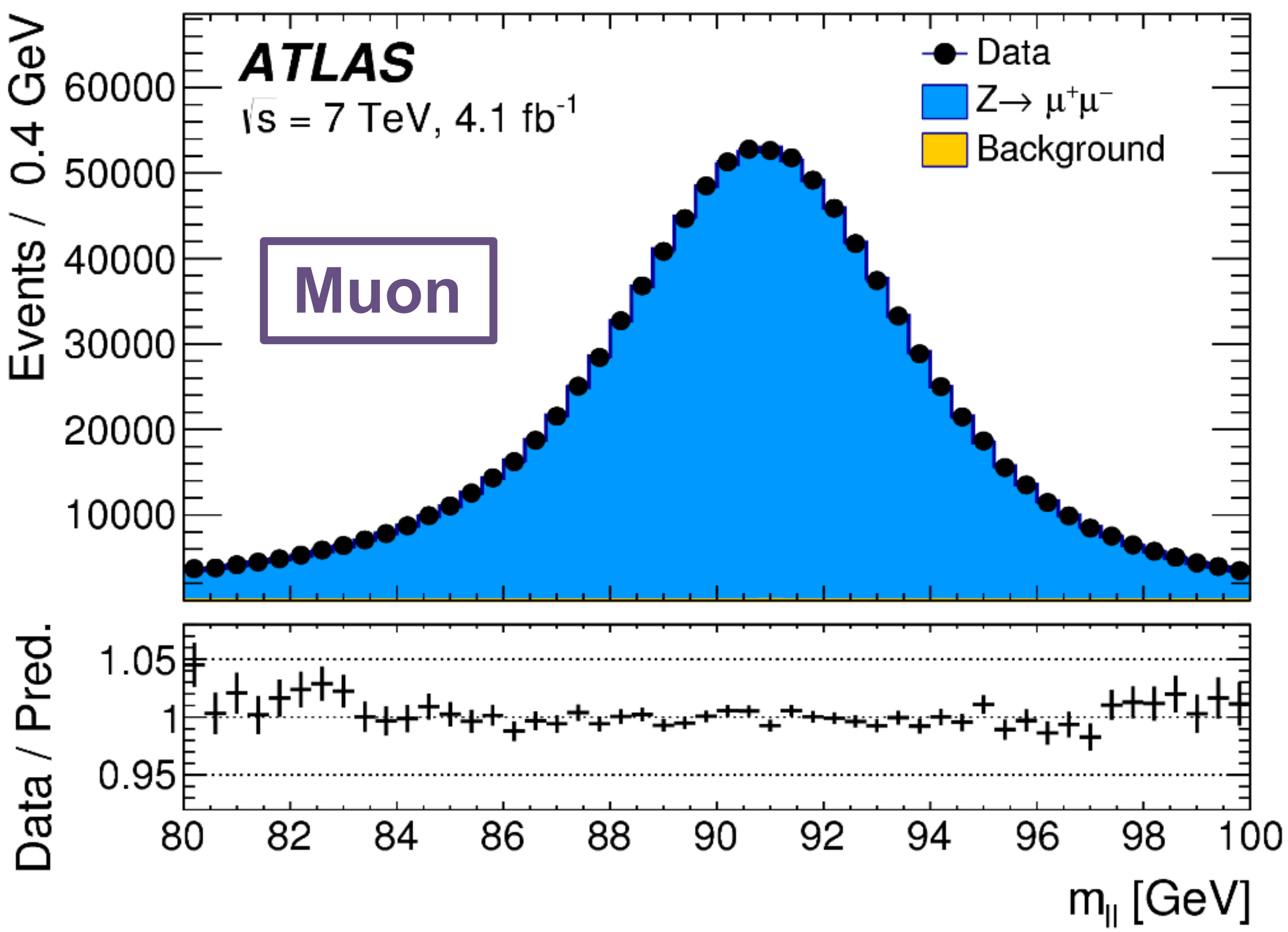
- Muon channel selection
  - $|\eta| < 2.4$ and $p_T > 30$ GeV
  - isolation requirements
  - 7.84×10^6 W-boson candidates,
    1.23×10^6 Z boson candidates
  - 4.1 fb^{-1} of integrated luminosity
    (some data discarded due to a timing problem in the resistive plate chambers)

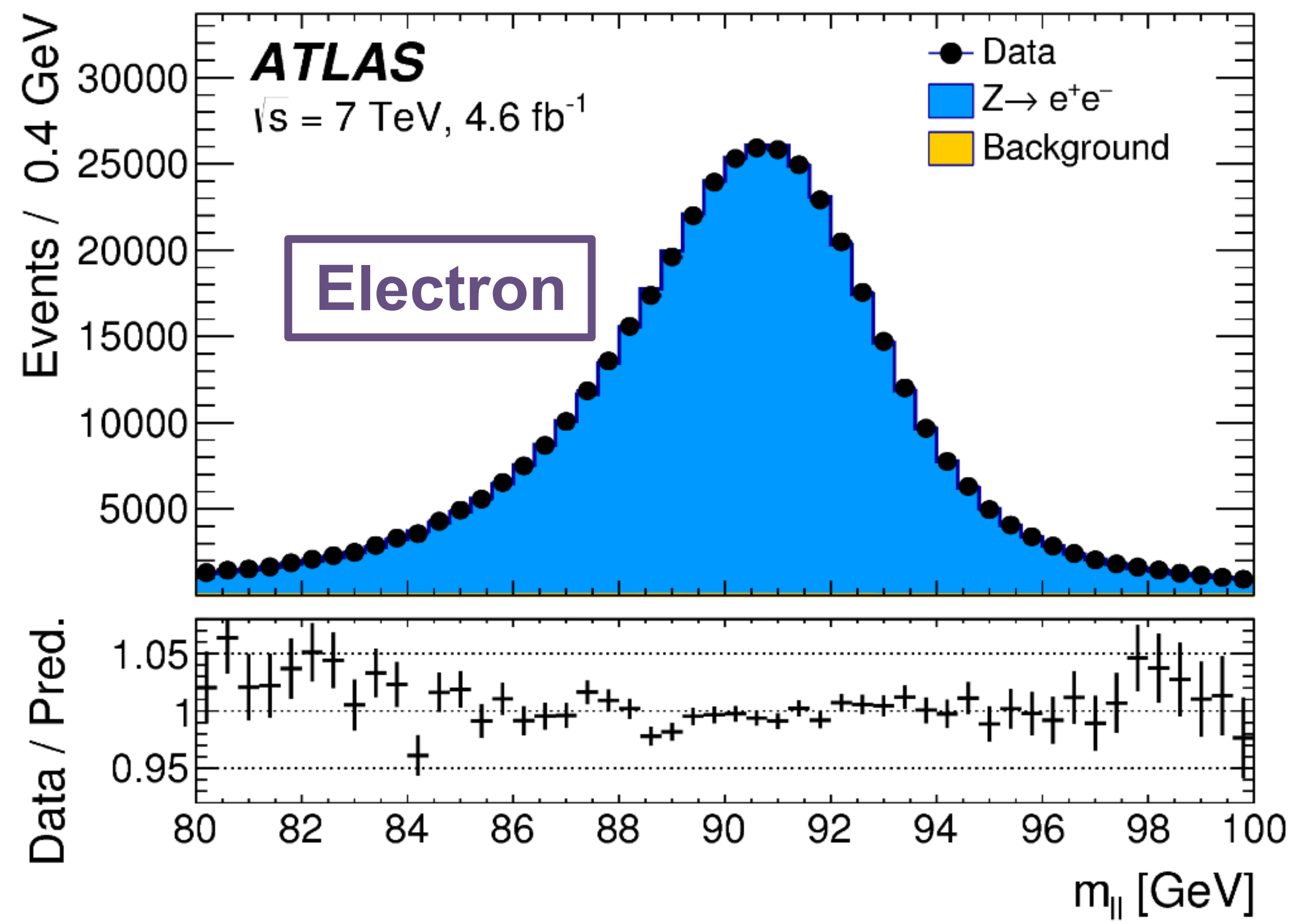
- Recoil
  - Vector sum of the transverse energy of all clusters measured in the calorimeters
    (range $|\eta| < 4.9$)
  - u_T<30 GeV, m_T>60 GeV

Detector Calibration - Leptons

- Calibration of detector response to electrons and muons by using Z boson decays
  - momentum / energy scale and resolution
  - selection efficiencies

- Momentum calibration by using the Z peak





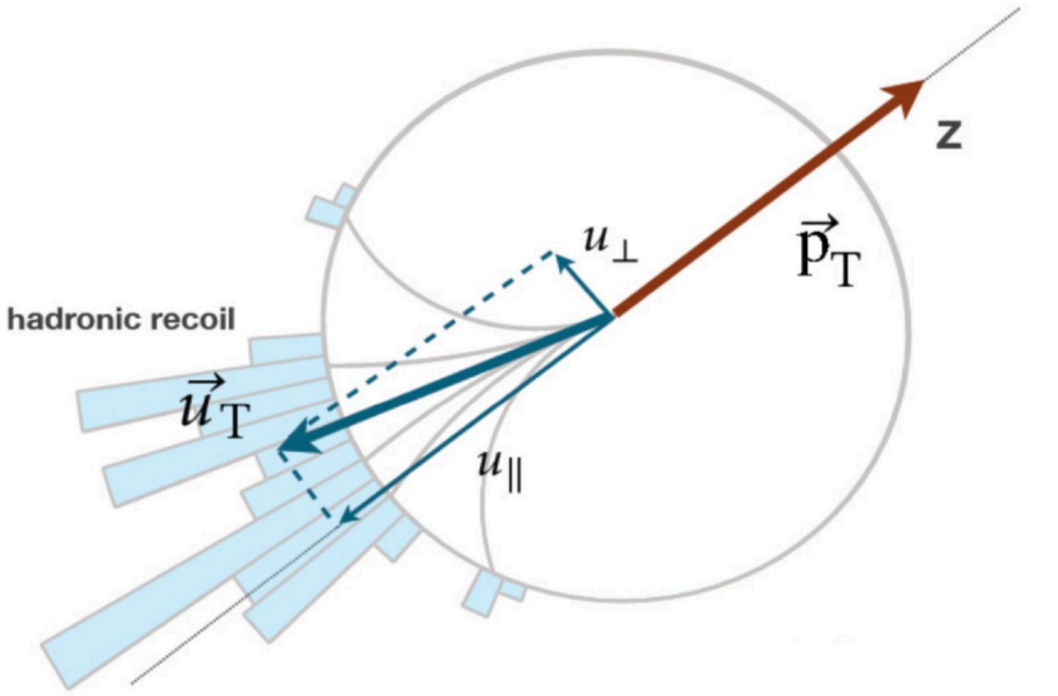
Calibration uncertainties (Shift on m_W)

Muon 7 MeV (19 MeV Total)

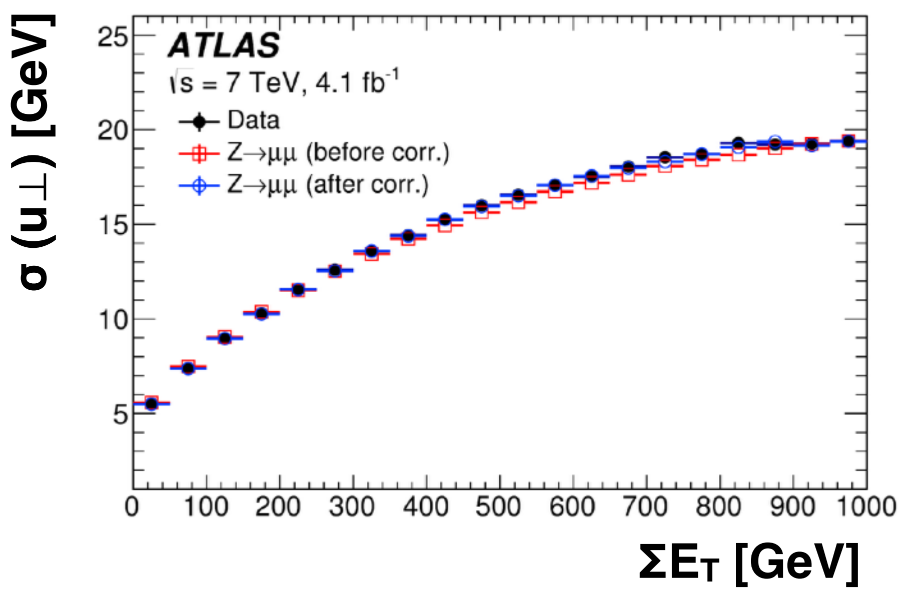
Electron 6 MeV (19 MeV Total)

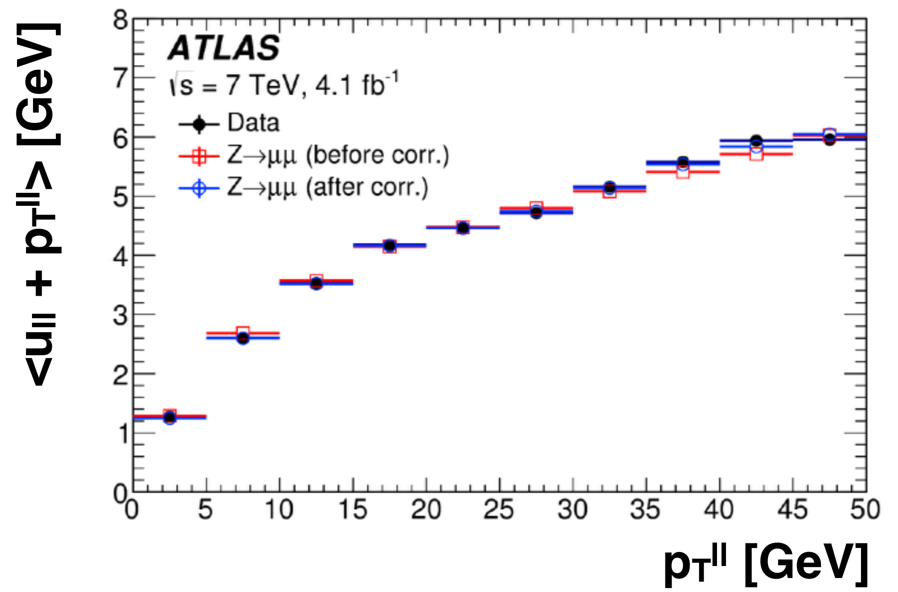
Detector Calibration - Recoil

- Calibration of recoil
  - event activity correction
  - recoil response calibration
    using expected p_T balance between lepton pairs and u_T in Z boson decay events

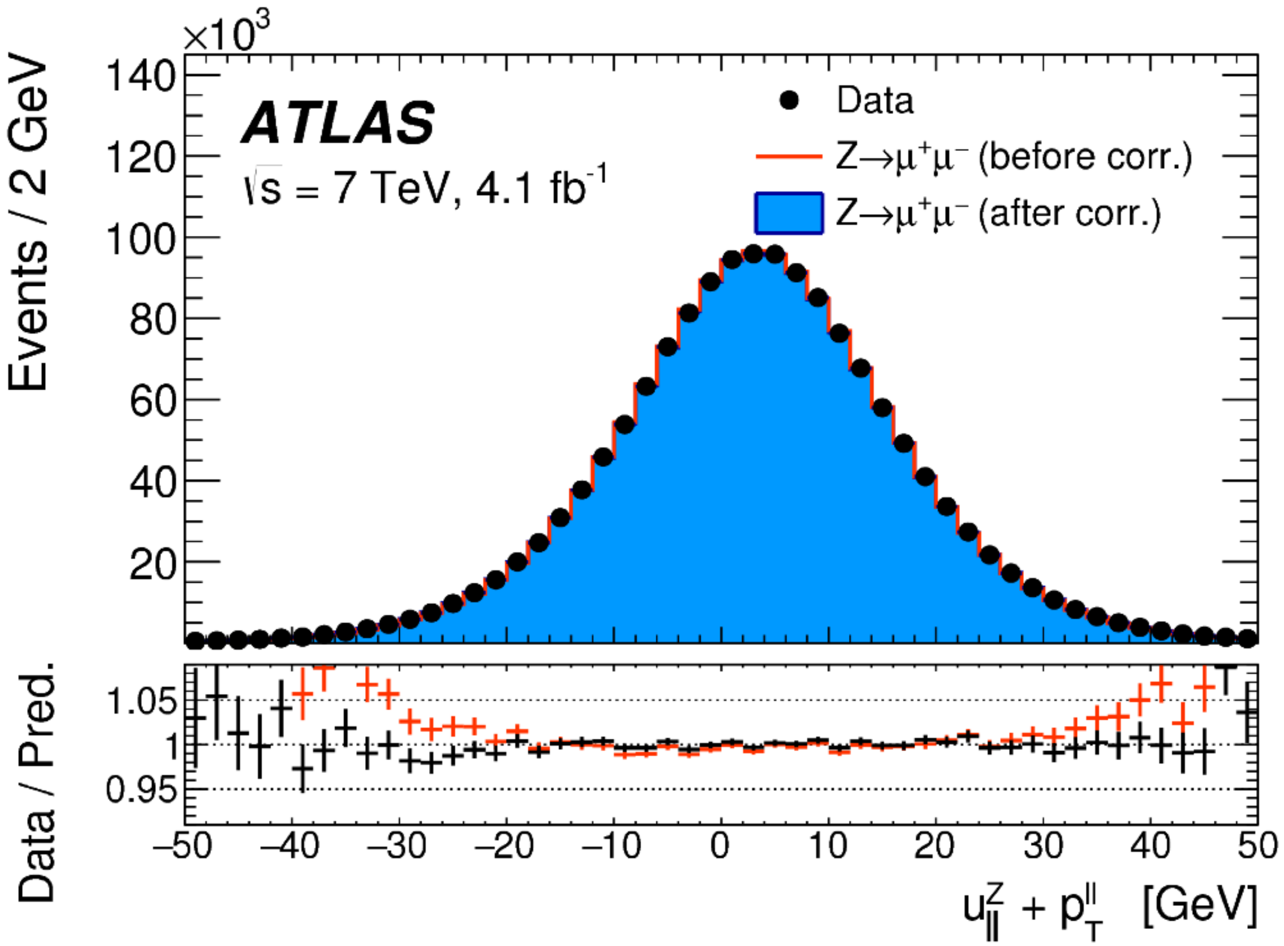


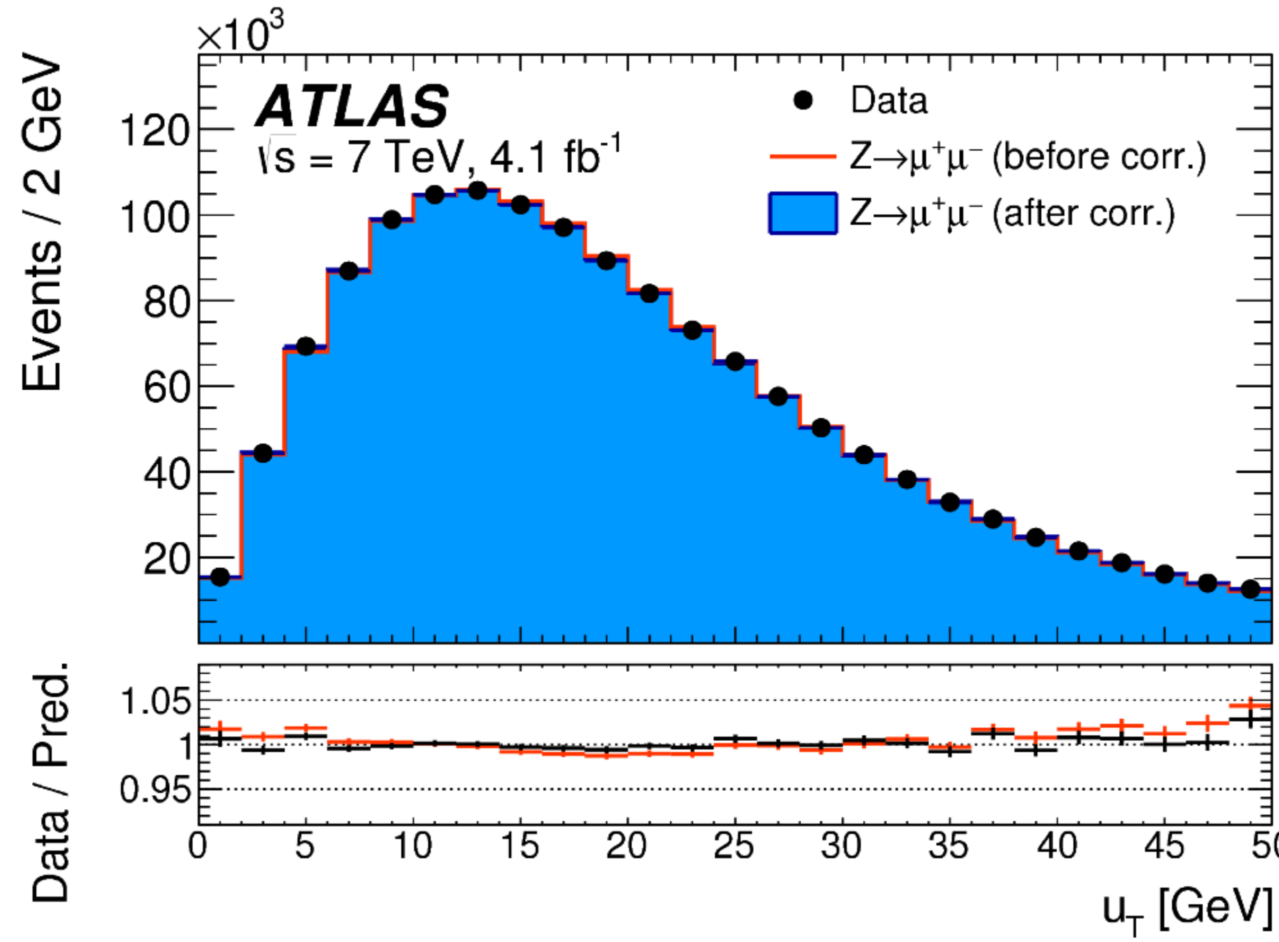
- Recoil correction steps:
  - Equalise pile-up multiplicity distribution in data and MC
    (done directly in W events)
  - Correct for residual difference in the ΣE_T distribution
    (done directly in W events)
    removes u_T resolution discrepancy due to imperfect event activity mis-modelling
  - Residual corrections using p_T balance in Z events, mapped vs p_T^V and ΣE_T
    (done in Z events, uncertainties from Z statistics and Z to W extrapolation)





Detector Calibration - Recoil





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

Calibration uncertainties

m_T and p_T^l comb.
2.9 MeV Total

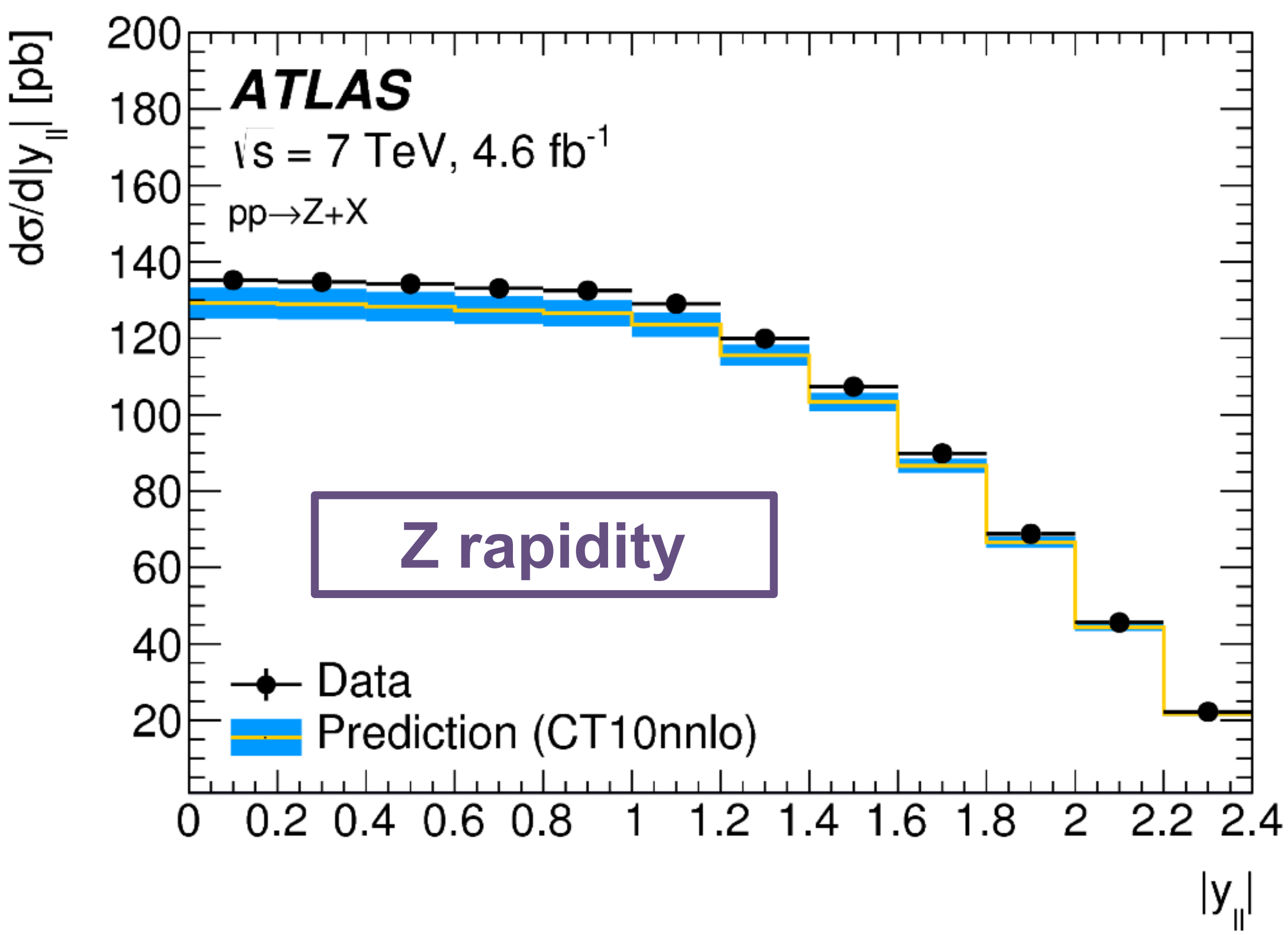
Physics Modelling

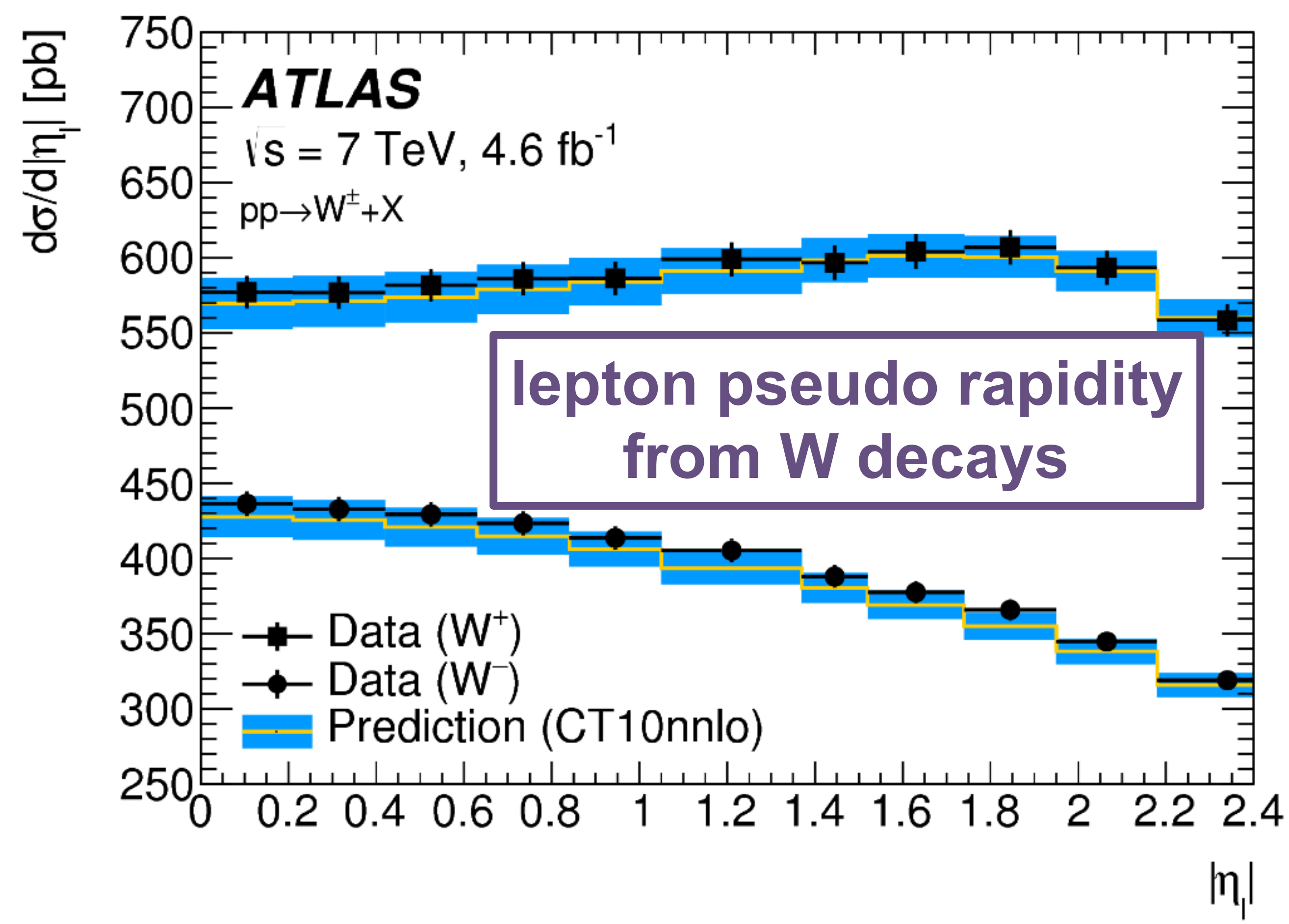
- No available generator describes all observed distribution
  — choose extensive re-weighting approach

- Re-weighted baseline MC (Powheg + Pythia 8) to more precise model
  - with higher order QCD effects
  - with electroweak corrections

factorisation of cross section: **[mass] [rapidity] [angular coefficients] [p_T]**

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





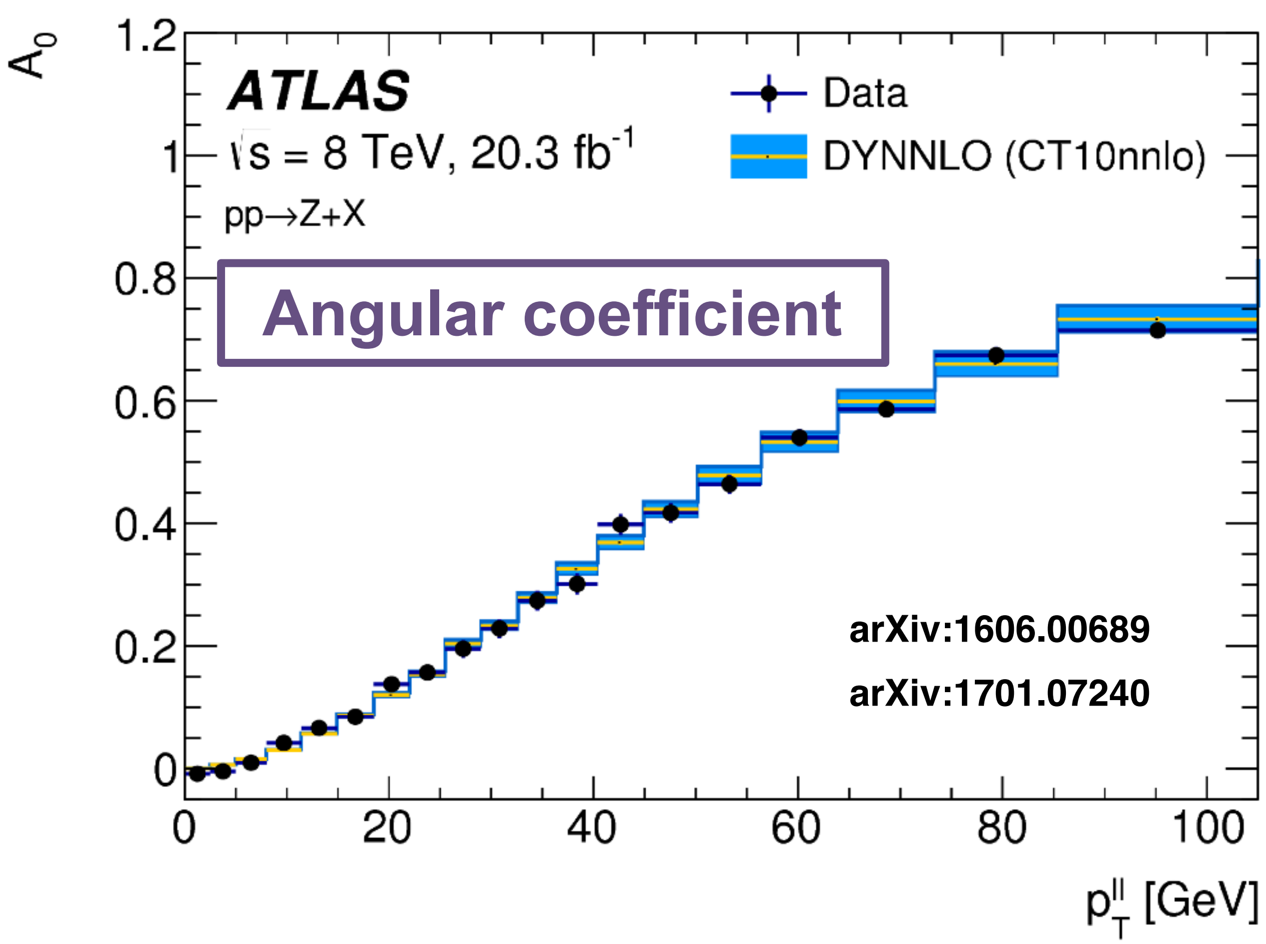
Physics Modelling

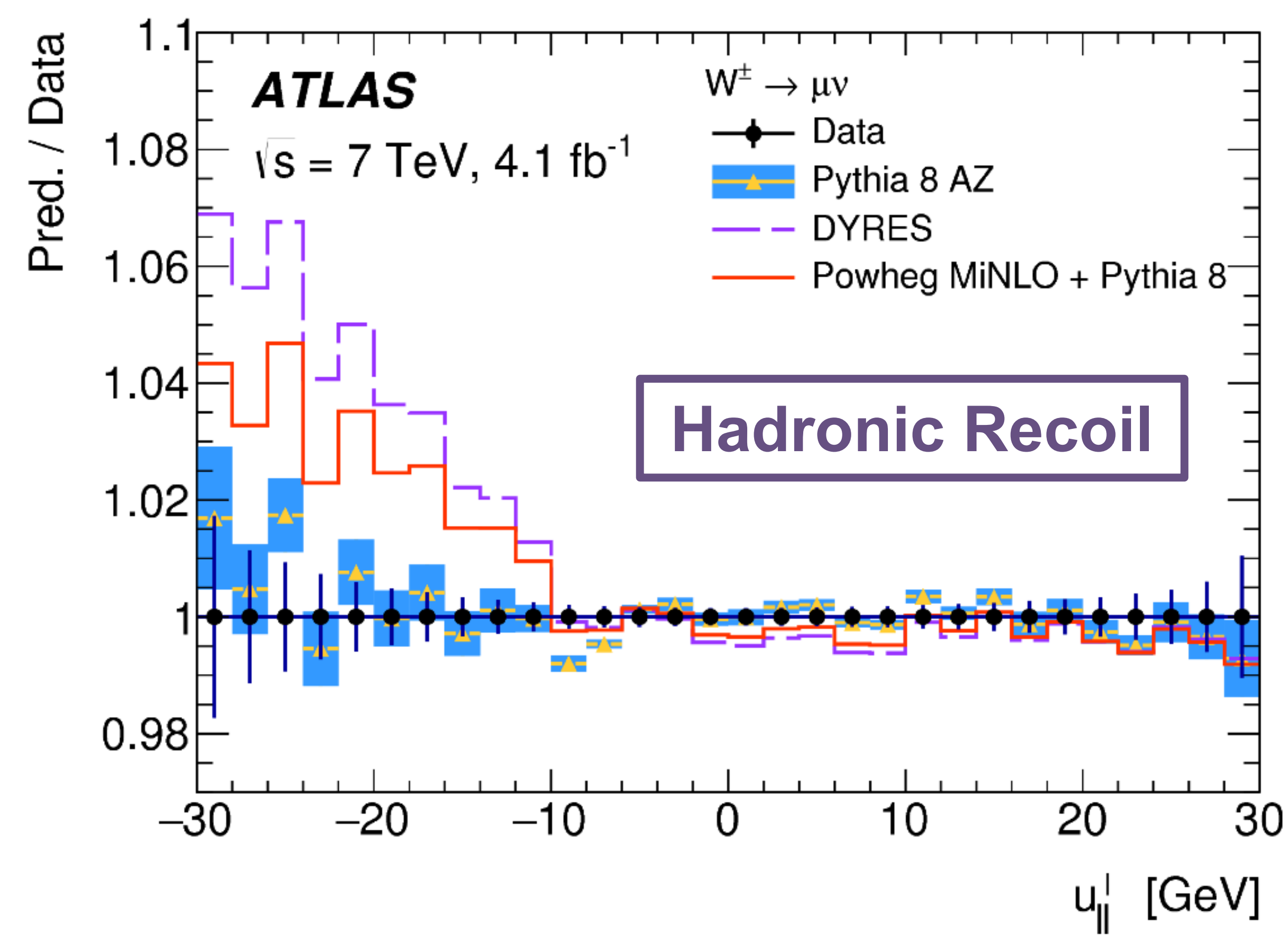
- The theoretical description of the angular coefficient A_i are not described well by ResBos at NLO for fixed-order and resummed calculations but satisfactorily by DYNNLO
- Hadronic recoil parameter $u_{||}^{l}$ is sensitive to the Wp_T
  DyRes and MiNLO do not describe data well, therefore not used

factorisation of cross section:

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

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





Results in Measurement Categories

Channel m_T-Fit	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK 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

|η| comb e → ~15 MeV
μ → ~11 MeV

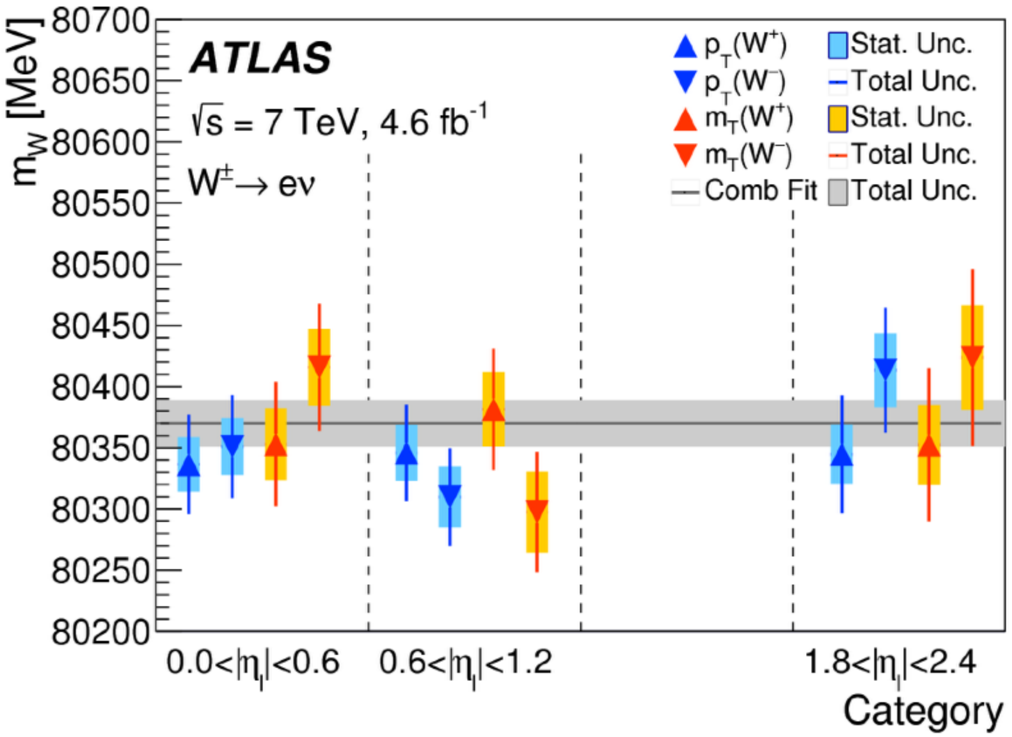
Strongly correlated

Strongly correlated

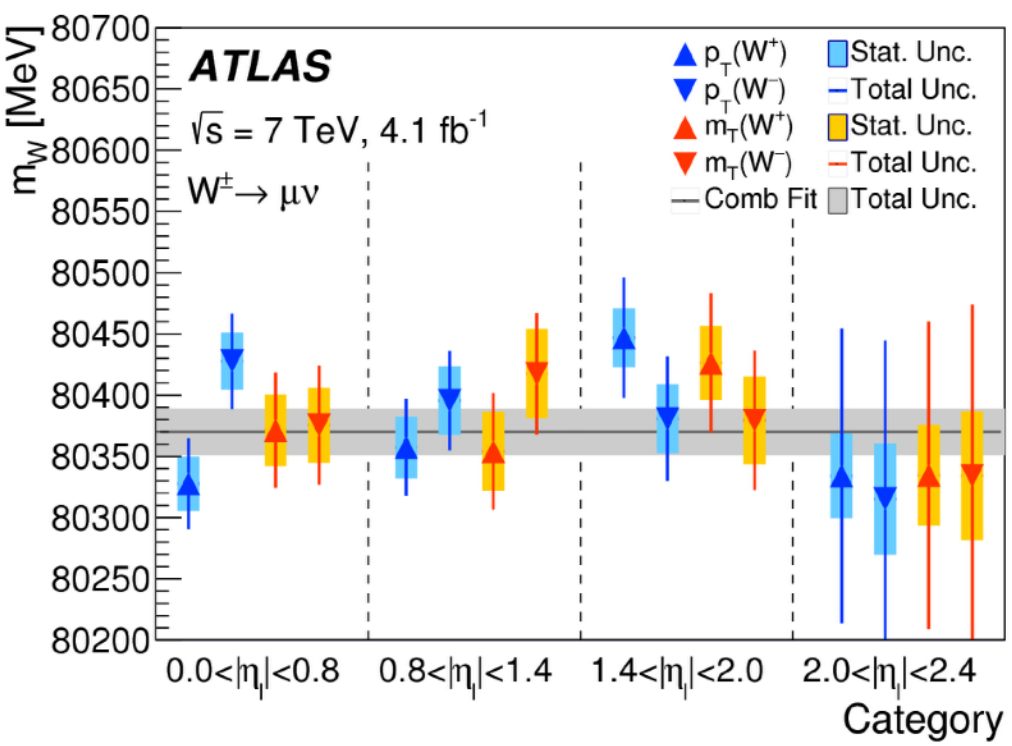
|η| comb. → ~14 MeV
W+/W- comb → ~8 MeV

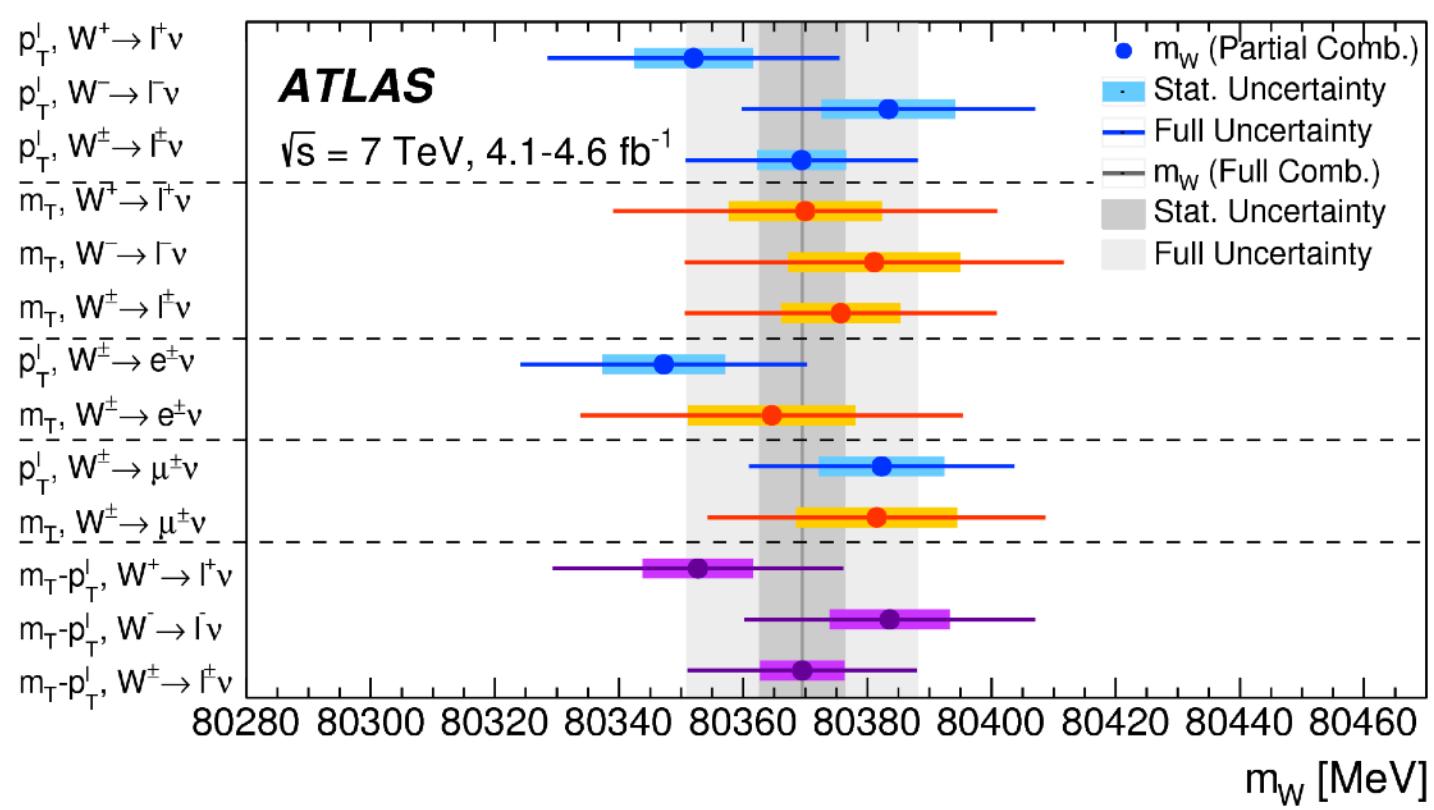
Fit ranges : $32<p_T^l<45$ GeV; $66<m_T<99$ GeV, minimizing total expected measurement uncertainty

Results in Measurement Categories

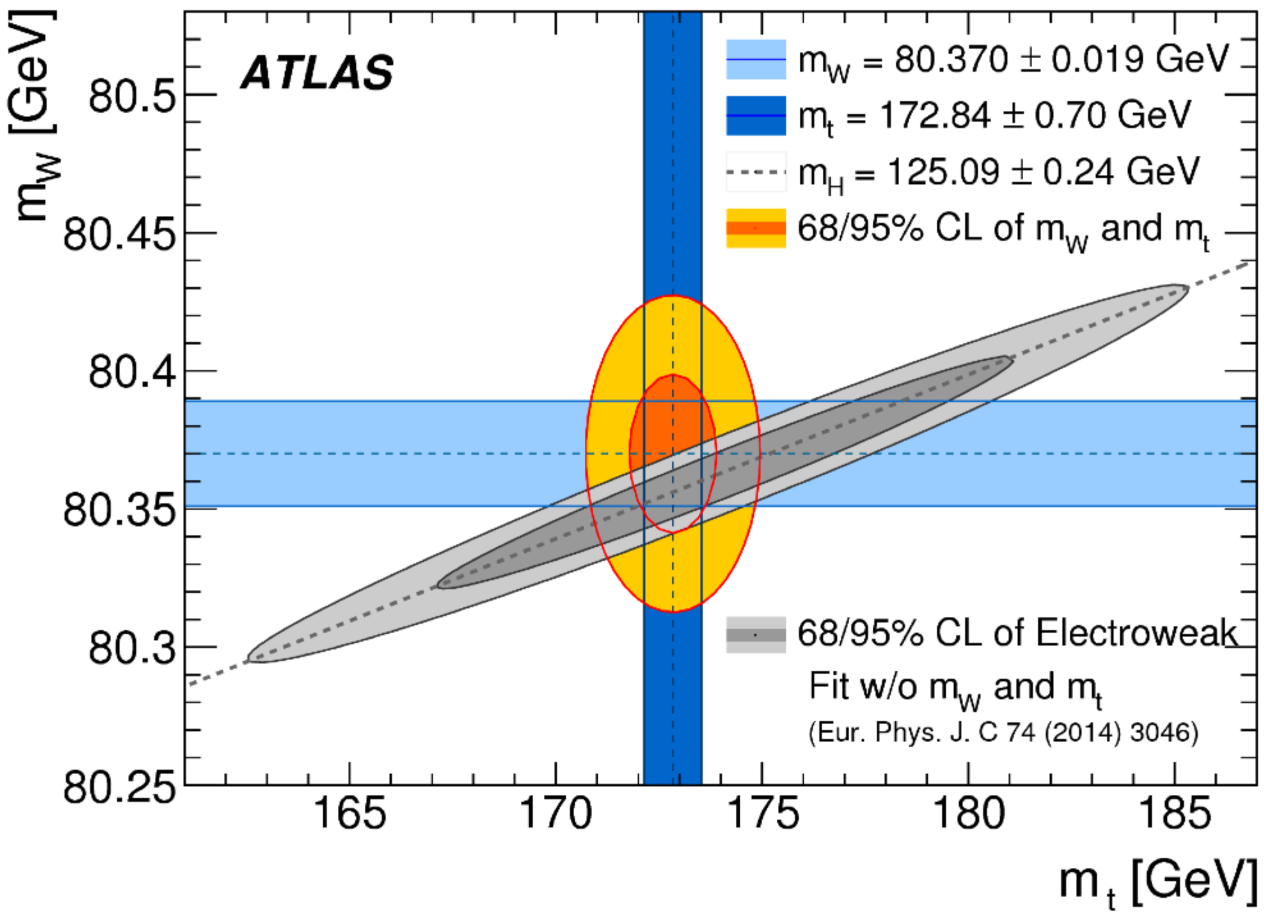


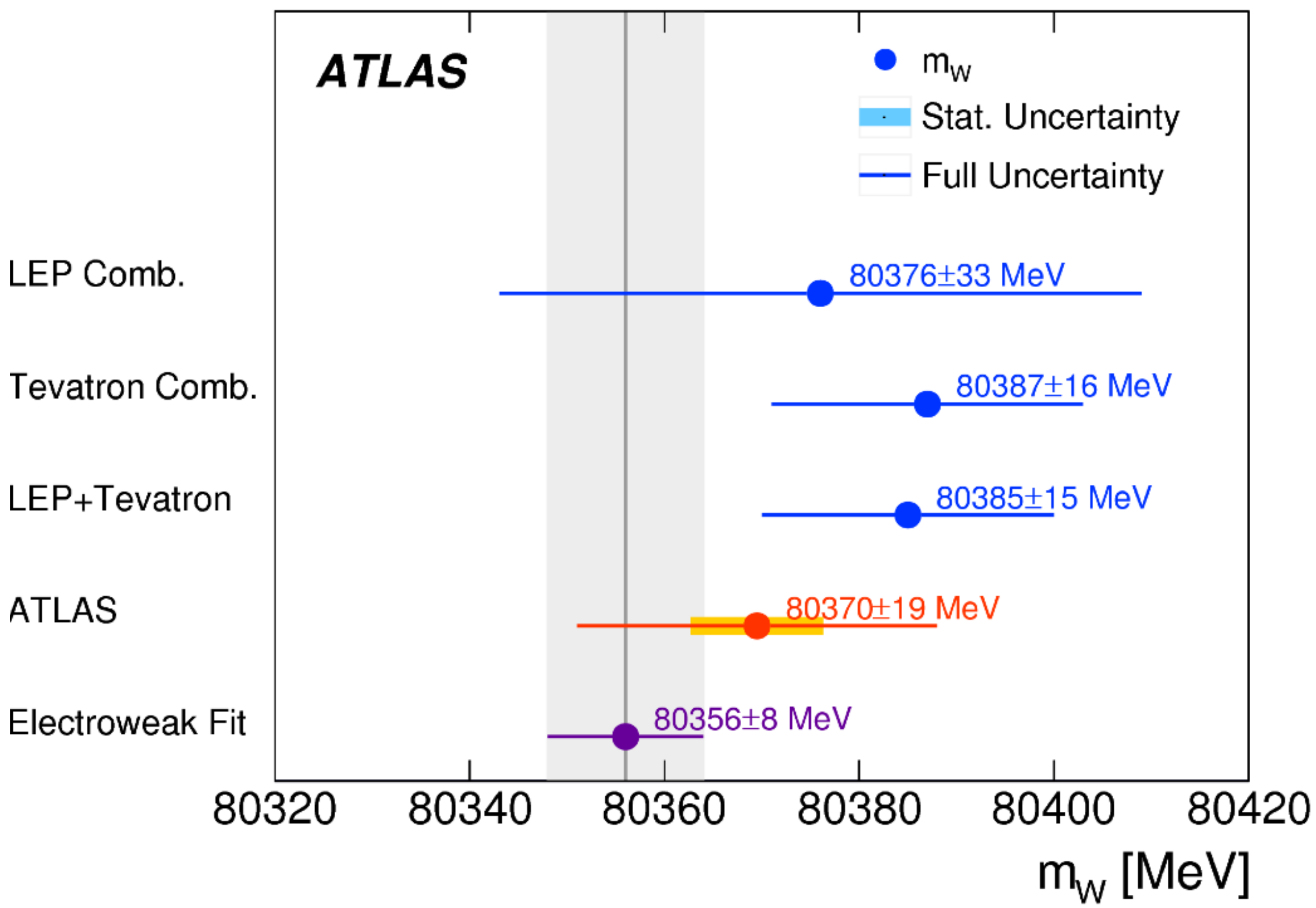
- Measurements consistent
  - in each category
  - in combinations of categories
- Fulfils the requirement to be unblinded





Final Combined Results





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

- Final uncertainty dominated by physics modelling uncertainties
  - e.g. PDF uncertainty in fixed order prediction - 8 MeV on p_T^l fit
  - parton shower factorisation scale - 5 MeV
- ATLAS result competitive with previous measurements and consistent with SM prediction

W+ W- Mass Difference

- Auxiliary measurement: Mass difference between W+ and W-
(zero difference in the SM)

$$m_{W^+} - m_{W^-} = -29.2 \pm 12.8\ \text{MeV(stat.)} \pm 7.0\ \text{MeV(exp. syst.)} \pm 23.9\ \text{MeV(mod. syst.)}$$
$$= -29.2 \pm 28.0\ \text{MeV},$$

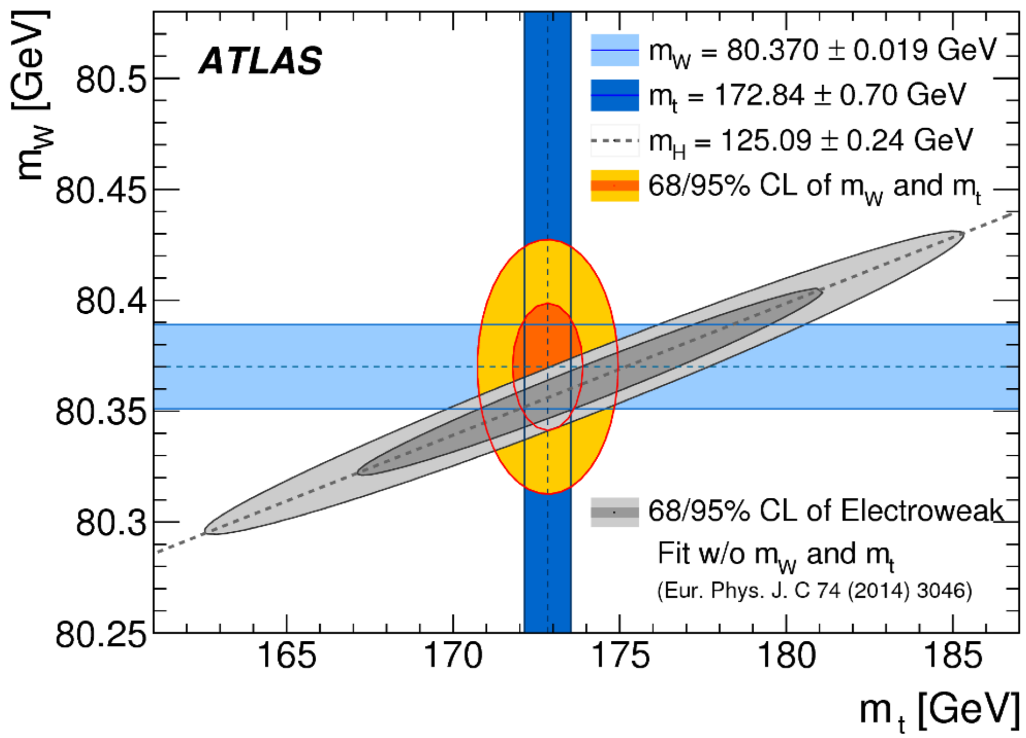
- Same measurement methodology but mass difference was not blinded

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

PDF uncertainties anti-correlated between W^+ and W^-

Conclusion

- First W-boson mass measurement at the LHC
- Consistent and competitive with previous measurements
- In agreement with prediction from global electroweak fit
- arXiv:1701.07240



Backup Results in Measurement Categories

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

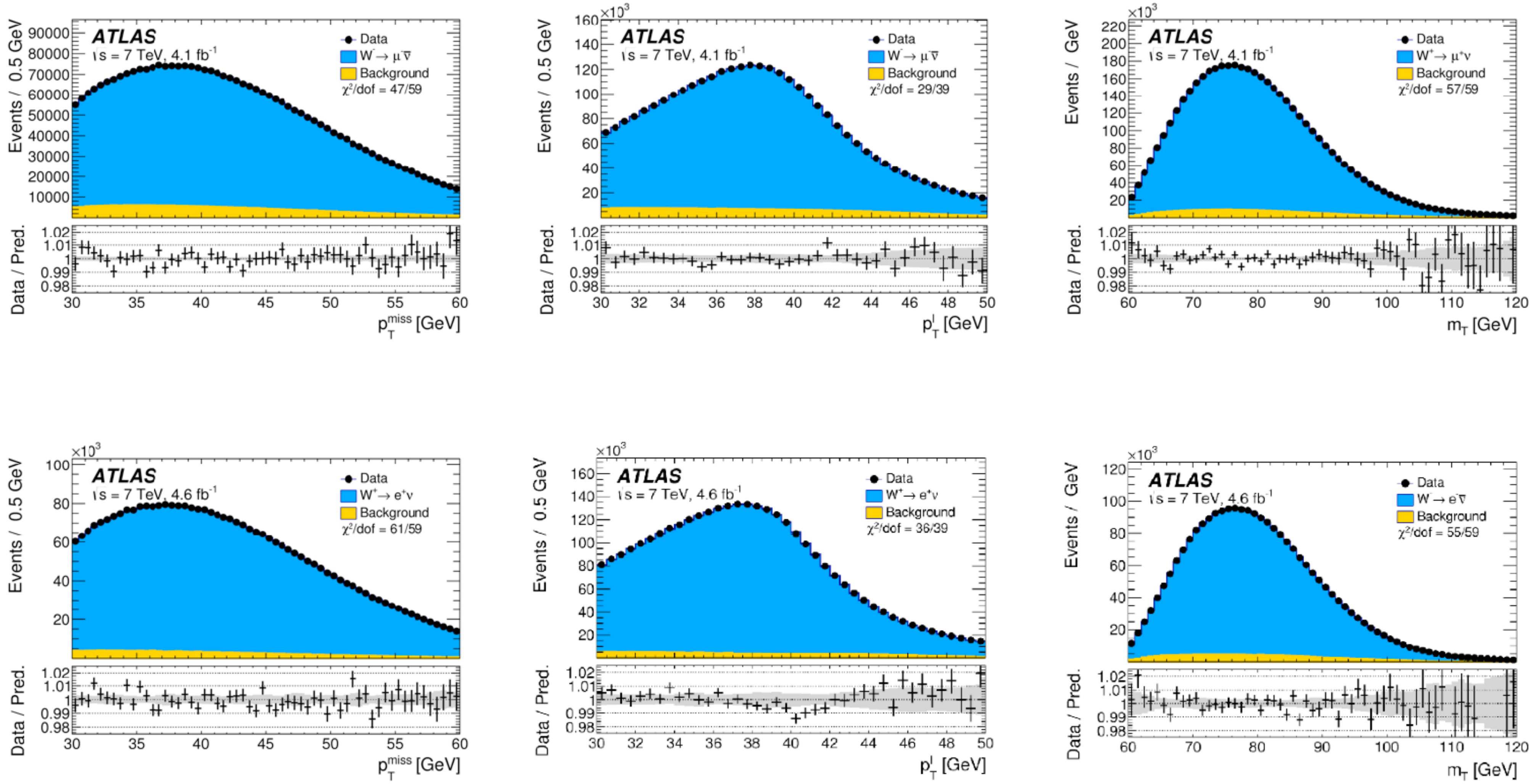
Backup

- Samples of inclusive vector-boson production are produced using the Powheg MC generator interfaced to Pythia 8
- EW Corrections
  - QED final-state radiation simulated with Photos (dominant correction)
  - The effect of QED initial-state radiation (ISR) is also included through the Pythia 8 parton shower.
  - The effect of NLO EW corrections are estimated using Winhac
- Rapidity distribution and angular coefficients
  - dσ(y)/dy, and the angular coefficients, Ai, are modelled with fixed-order pQCD predictions, at $O(\alpha^2_s)$ and using the CT10nnlo PDF set
  - An optimised version of DYNNLO is used
- Transverse momentum distribution
  - Modelled with Pythia 8
  - QCD parameters used in Pythia 8 were determined from fits to the Z-boson transverse momentum distribution measured with the ATLAS detector at a centre-of-mass energy of √s = 7 TeV (AZ tune)

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

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

Backup


ATLAS
√s = 7 TeV, 4.1 fb⁻¹
Data
W⁻→ μ⁻ν̄
Background
χ²/dof = 47/59
Events / 0.5 GeV
Data / Pred.
p_T^miss [GeV]
χ²/dof = 29/39
p_T^l [GeV]
W⁺→ μ⁺ν
χ²/dof = 57/59
Events / GeV
m_T [GeV]
√s = 7 TeV, 4.6 fb⁻¹
W⁺→ e⁺ν
χ²/dof = 61/59
χ²/dof = 36/39
W⁻→ e⁻ν̄
χ²/dof = 55/59

Backup

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

The angular coefficients depend in general on p_T, y and m. The A_5–A_7 coefficients are non-zero only at order $O(\alpha_s^2)$ and above. They are small in the p_T region relevant for the present analysis, and are not considered further. The angles θ and ϕ are defined in the Collins–Soper (CS) frame [82].

Backup