Measurement of the W boson mass with the ATLAS detector

M. Boonekamp (IRFU)
on behalf of the ATLAS Collaboration

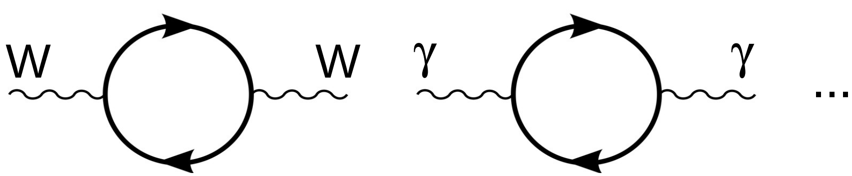
Motivation

- The electroweak gauge sector of the Standard Model is constrained by three precisely know parameters:
  - The electromagnetic coupling constant : α = 1 / 1370359999679...
  - The mun decay constant : G_μ = 1.16637 (1) $\times$ 10^{-5} GeV^{-2}
  - The Z boson mass : m_Z = 91.1876 (21) GeV

- At leading order, m_W is expressed as

$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}, \quad \sin^2\theta_W = 1 - m_W^2/m_Z^2$$

Higher-order corrections, dominantly W and γ self-energies,



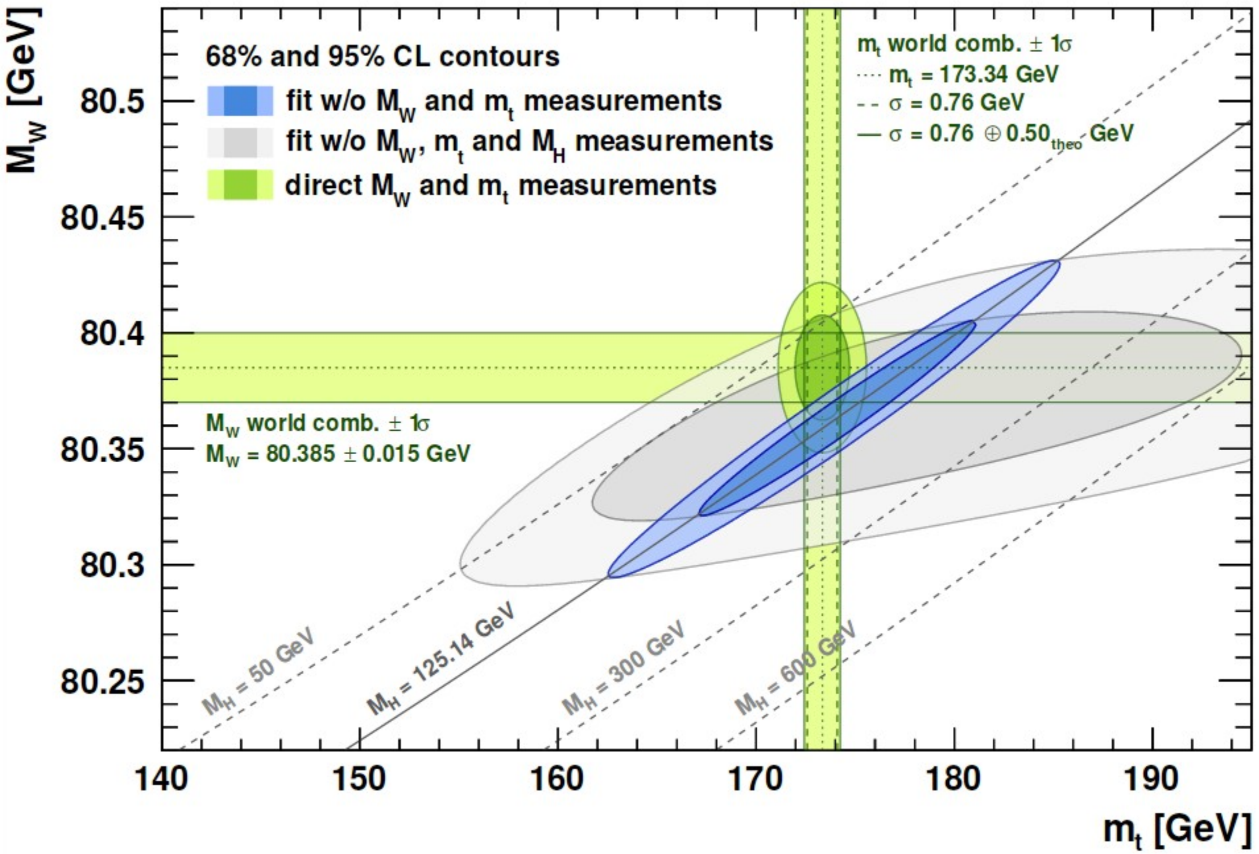
modify this relation to $$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{1-\Delta r}$$

Motivation

- Δr incorporates higher-order corrections from the SM and beyond:

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

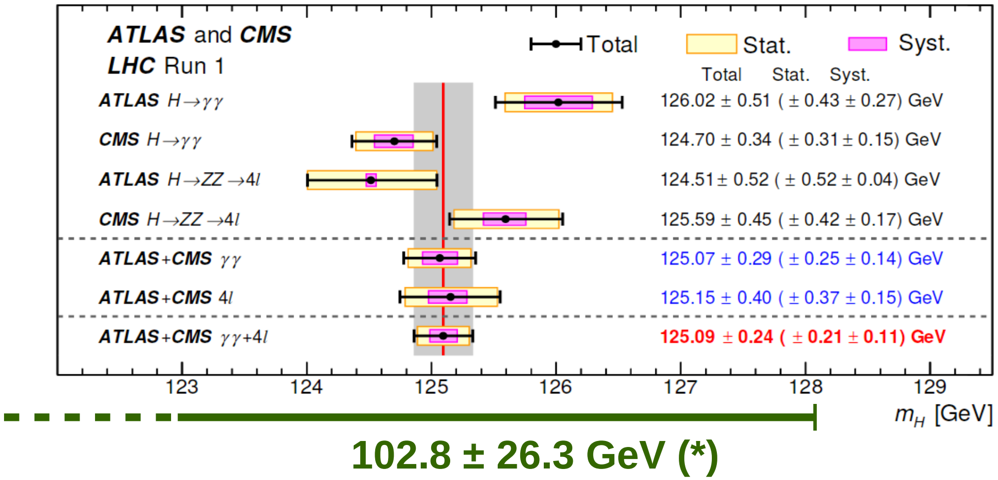
arXiv:1407.3792



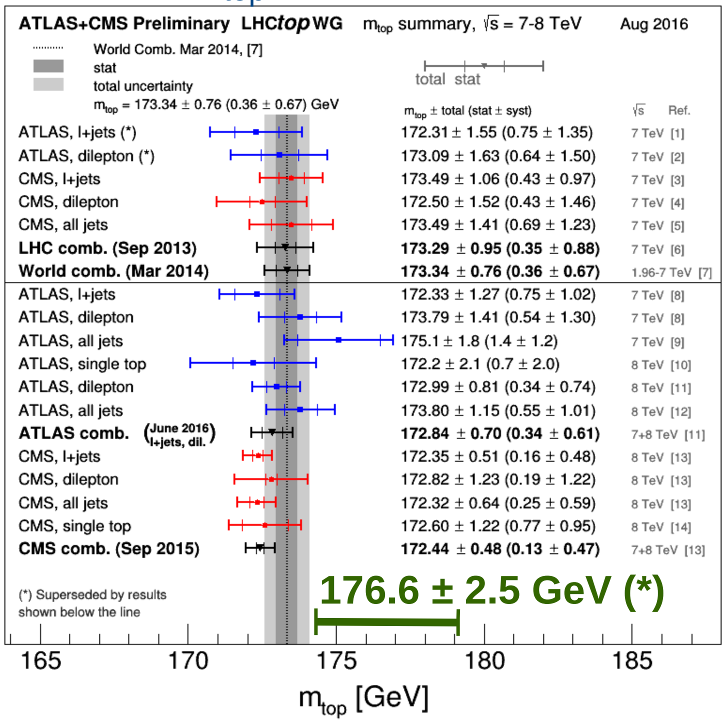
→ Consistency test of the SM, and a probe of BSM physics

Motivation

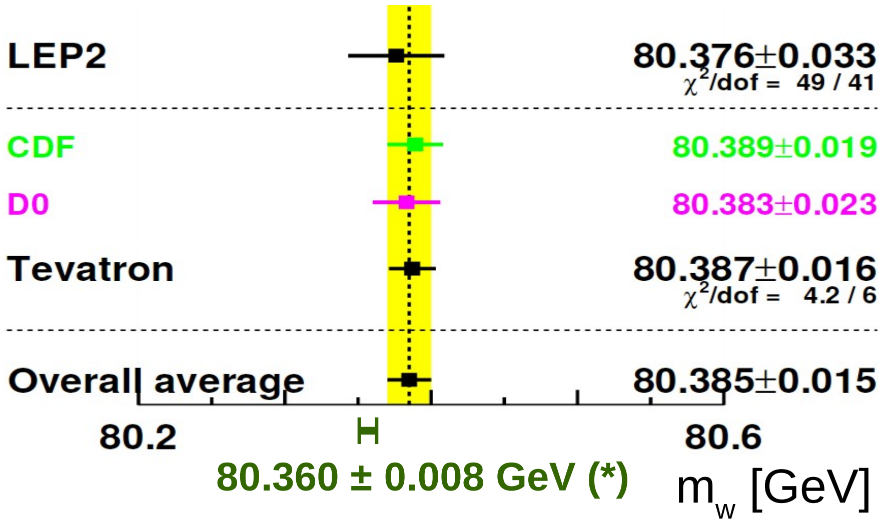
M_H 2014 – 2015



m_{top} 2012 – 2016



m_W ≤ 2012 (!)



	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

(*) arXiv:1608.01509

→ Strong constraining power. Slow progress!

TeVatron results and LHC prospects

arXiv:1203.0293

Source	m_T	p_T^e	$\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$(Experimental)	18	20	24
W Production and Decay Model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$(Model)	13	14	17
Systematic Uncertainty (Experimental and Model)	22	24	29
W Boson Statistics	13	14	15
Total Uncertainty	26	28	33

arXiv:1203.0275

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

D0 5.3 fb^{-1} 1.7×10^{6} events, W→eν

$$M_W = 80.375 \pm 0.011\ (\text{stat.}) \pm 0.020\ (\text{syst.})\ \text{GeV}$$
$$= 80.375 \pm 0.023\ \text{GeV}.$$

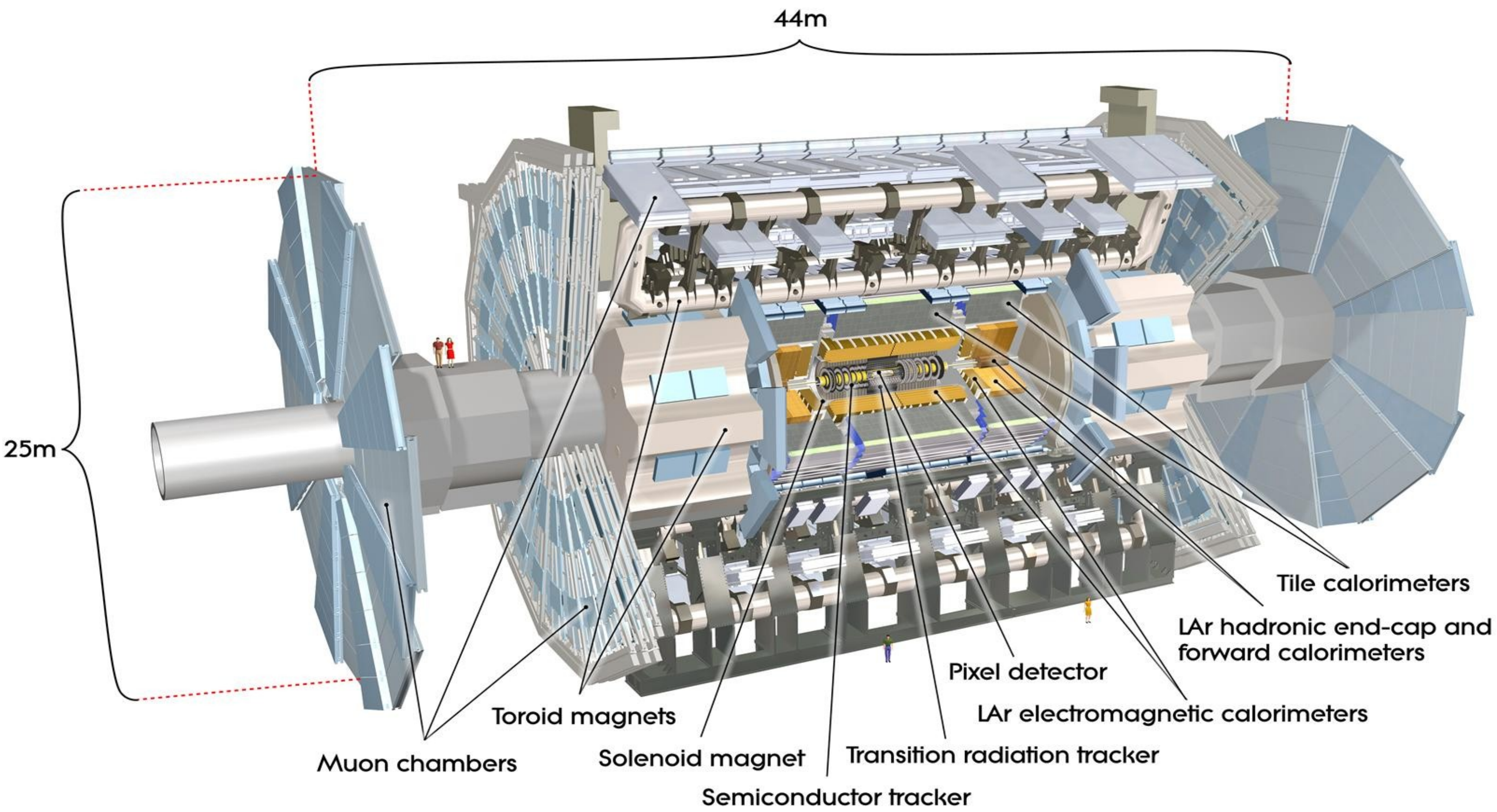
CDF 2.2 fb^{-1} 1.1×10^{6} events, W→eν,μν

$$M_W = 80\,387 \pm 12\ (\text{stat}) \pm 15\ (\text{syst})$$
$$= 80\,387 \pm 19\ \text{MeV}/c^2$$

W samples at ATLAS (W→eν, μν) :

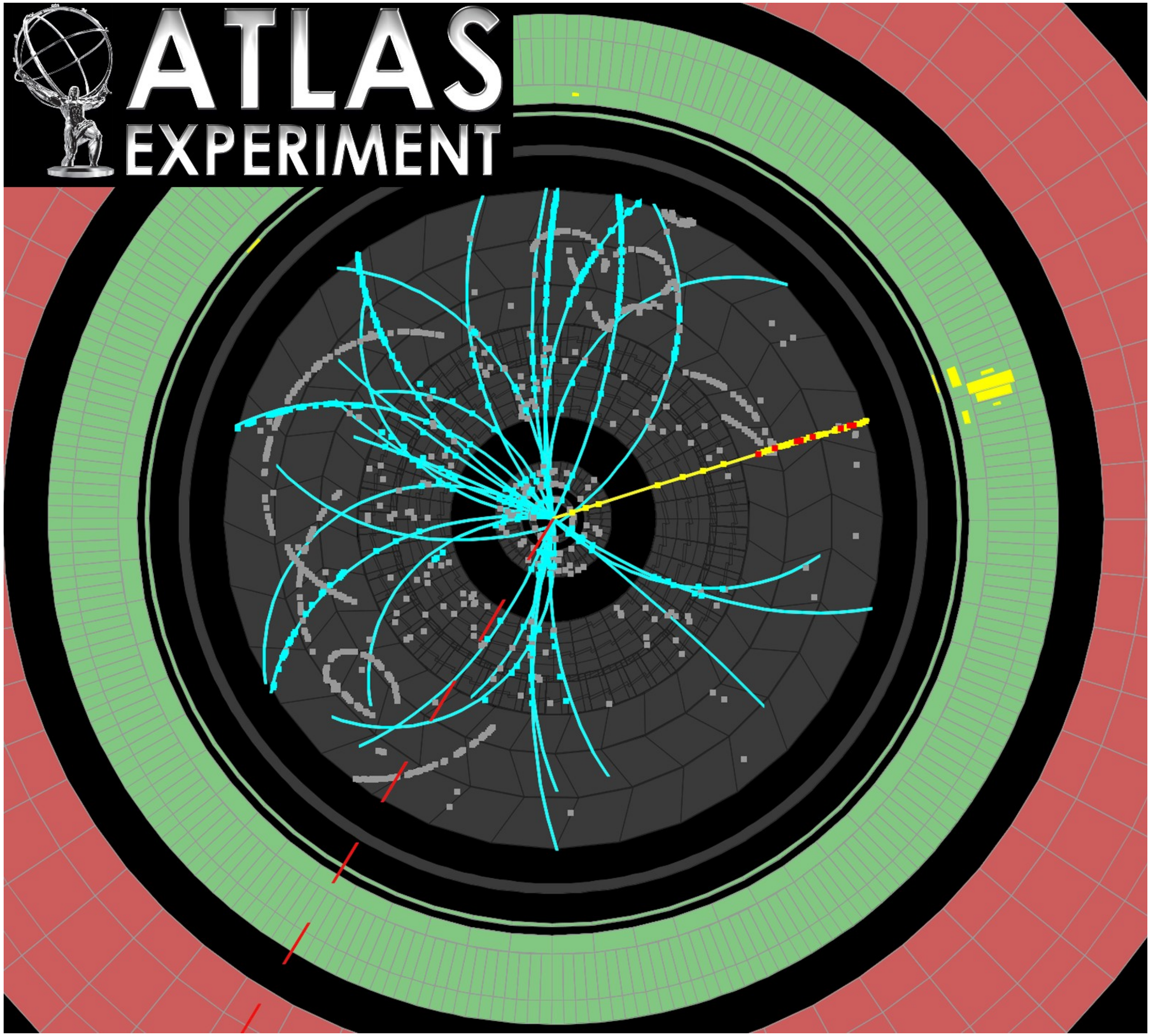
7 TeV	8 TeV	13 TeV
~4.5 fb^{-1}	~20.3 fb^{-1}	~30 fb^{-1}
15×10^{6}	80×10^{6}	190×10^{6}

The ATLAS detector



- Of particular importance to this measurement :
  - Muons (Inner Detector, Muon Spectrometer)
  - Electrons (Inner Detector, EM calorimeter)
  - Missing transverse energy (full calorimeter system)

W candidate events

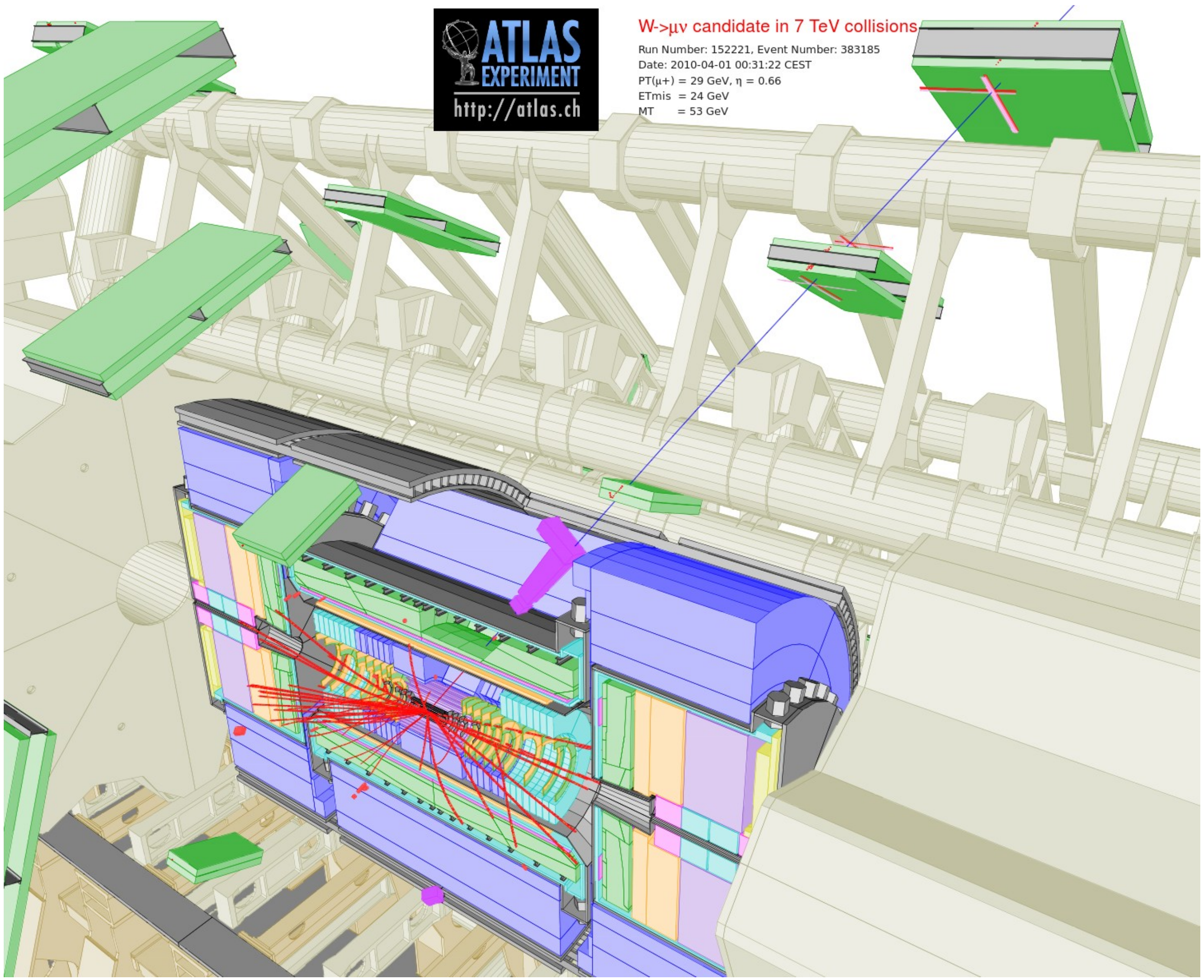


A W → eν candidate
(recorded 2010)

The electron is measured from the energy deposit in the EM calorimeter, and from the matching ID track

Missing transverse energy from the absence of additional high-p_T particles

W candidate events



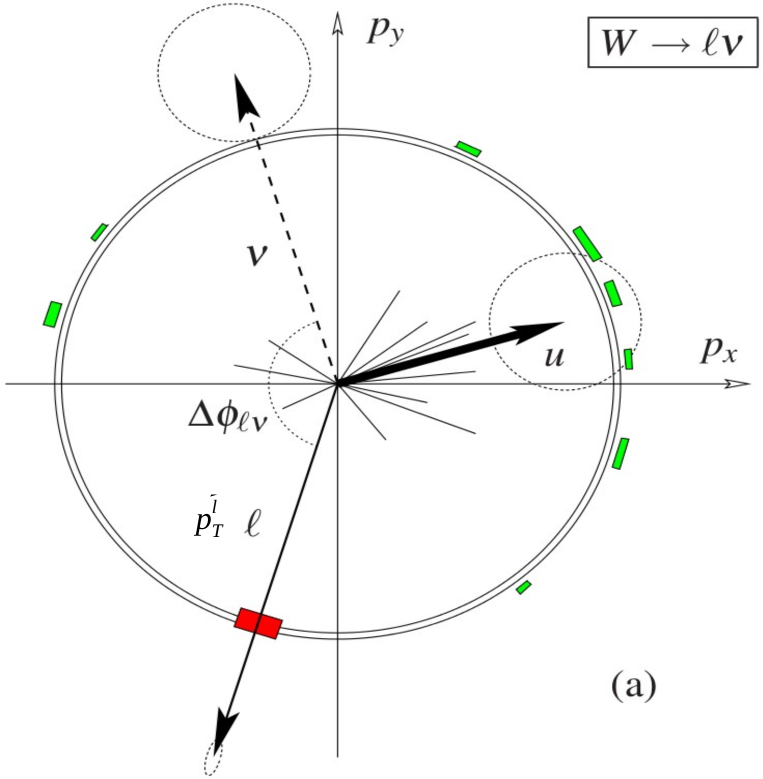
A W $\rightarrow$ $\mu\nu$ candidate (recorded 2010)

The muon is measured from matching Muon Spectrometer and ID tracks.

Missing transverse energy from the absence of additional high-p_T particles

Measurement strategy

- Event representation



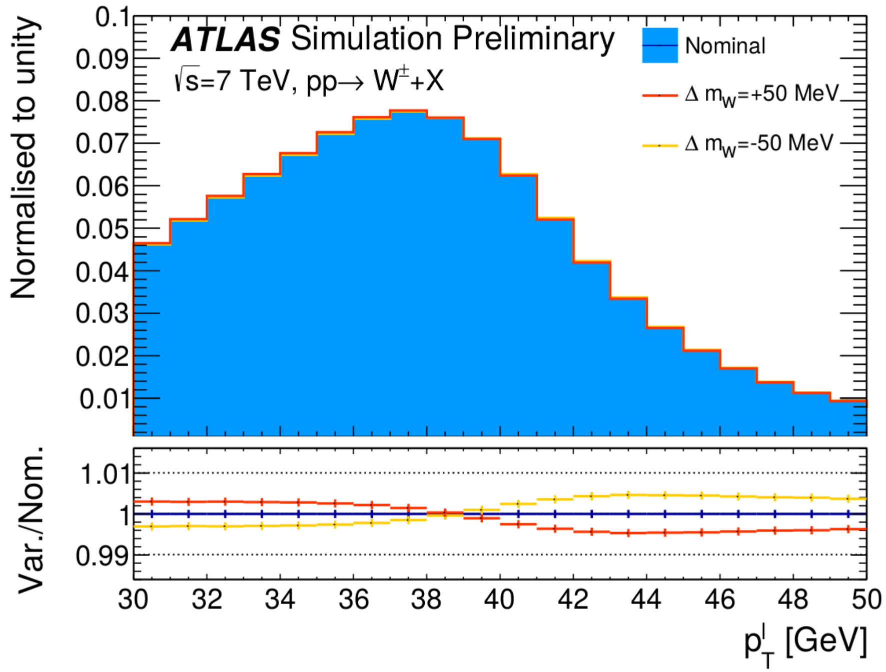
  - Main signature : final state lepton (electron or muon) : $\vec{p}_T^{\,l}$
  - Recoil : sum of "everything else" reconstructed in the calorimeters; a measure of $p_T^{W,Z}$

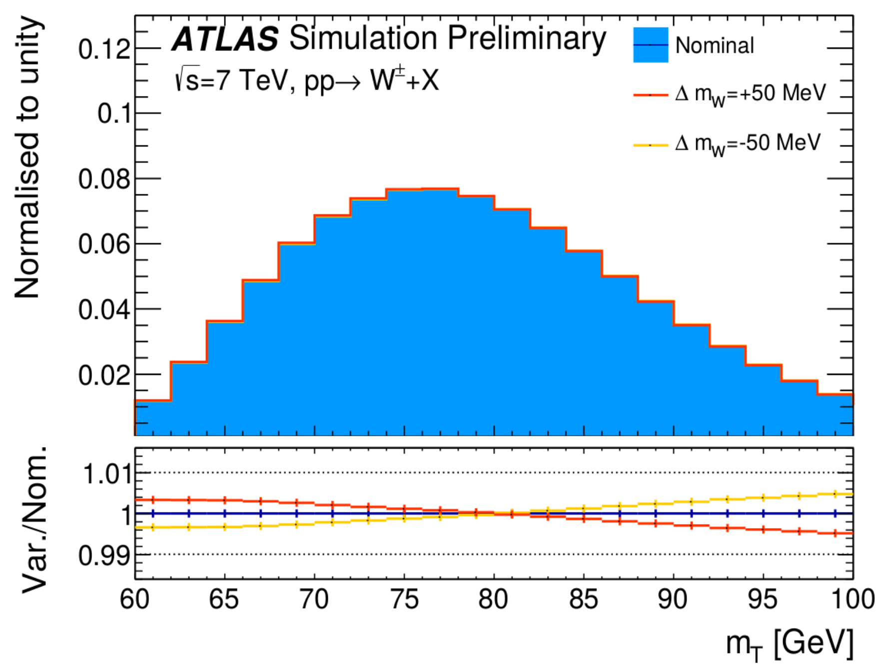
$$\vec{u}_{\rm T} = \sum_i \vec{E}_{{\rm T},i}$$ + useful projections (see later). No explicit jet reconstruction!

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

Measurement strategy

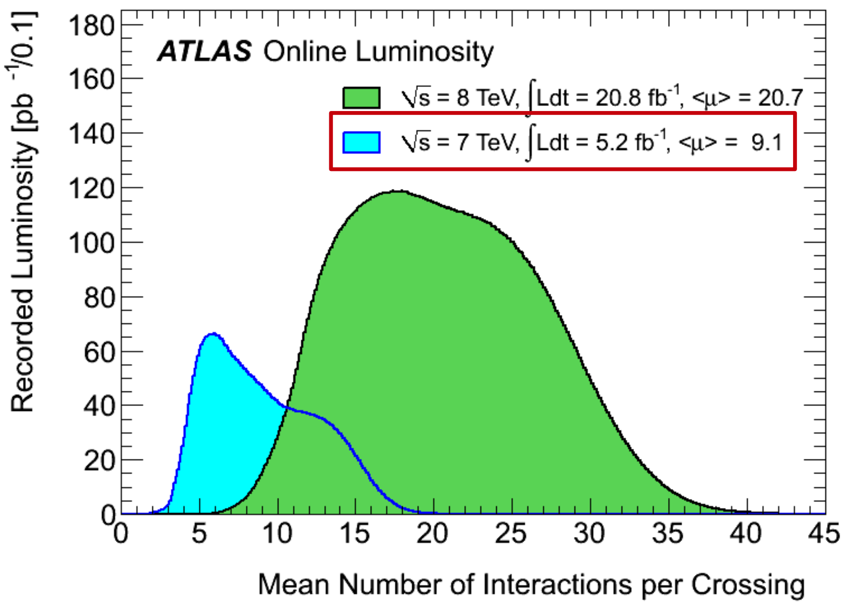
- Mass fits
  - Sensitive final state distributions : p_T^l , m_T , p_T^{miss}
  - Signal distributions contructed from a single Monte Carlo sample, reweighting the boson invariant mass distribution, and compared to data. Mass determination by χ^2 minimization
  - Resonance parametrisation : $\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$
  - A blinding offset was applied throughout the measurement, and removed when consistent results were found (compatibility among decay channels, etc).





Measurement setup

- Data : Run 1; 2011
  - √s = 7 TeV, 4.6 fb^{-1} (e), 4.1 fb^{-1} (μ)
  - Mature, well understood data;
    moderate pile-up



- Simulation
  - Single boson production : Powheg+Pythia (NLO QCD + PS); QED FSR using PHOTOS
  - Herwig and MC@NLO for EW and top backgrounds
  - Pile-up simulated using Pythia
  - Description of passive material optimized based on final ATLAS Run1 calibration results

- Residual data/MC discrepancies addressed by small corrections (~0.5% or smaller), using the known Z resonance and p_T balance constraints

Measurement setup

- Lepton selections
  - Muons : $|\eta| < 2.4$; isolated (track-based)
  - Electrons : $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated (track+calorimeter-based)
- Kinematic requirements
  - $p_T^l > 30$ GeV $p_T^{miss} > 30$ GeV
  - $m_T > 60$ GeV $u_T < 30$ GeV
- Measurement categories :

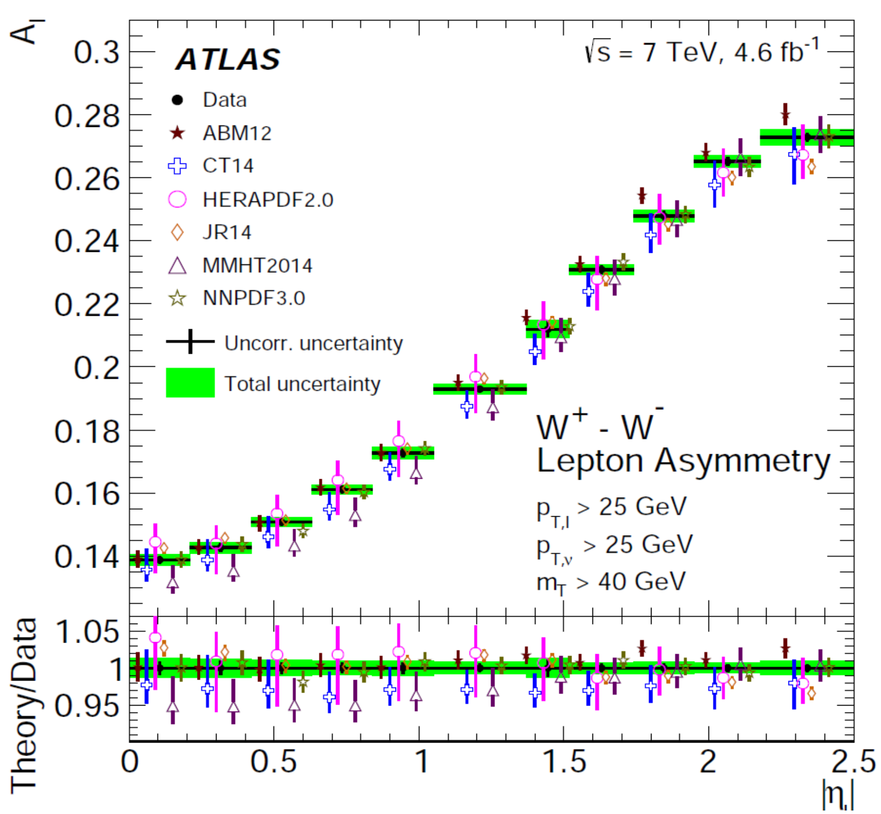
$\lvert\eta_\ell\rvert$ range	0 – 0.8	0.8 – 1.4	1.4 – 2.0	2.0 – 2.4	Inclusive	
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818	7.8 M events
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960	
$\lvert\eta_\ell\rvert$ range	0 – 0.6	0.6 – 1.2		1.8 – 2.4	Inclusive	
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716	5.9 M events
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525	

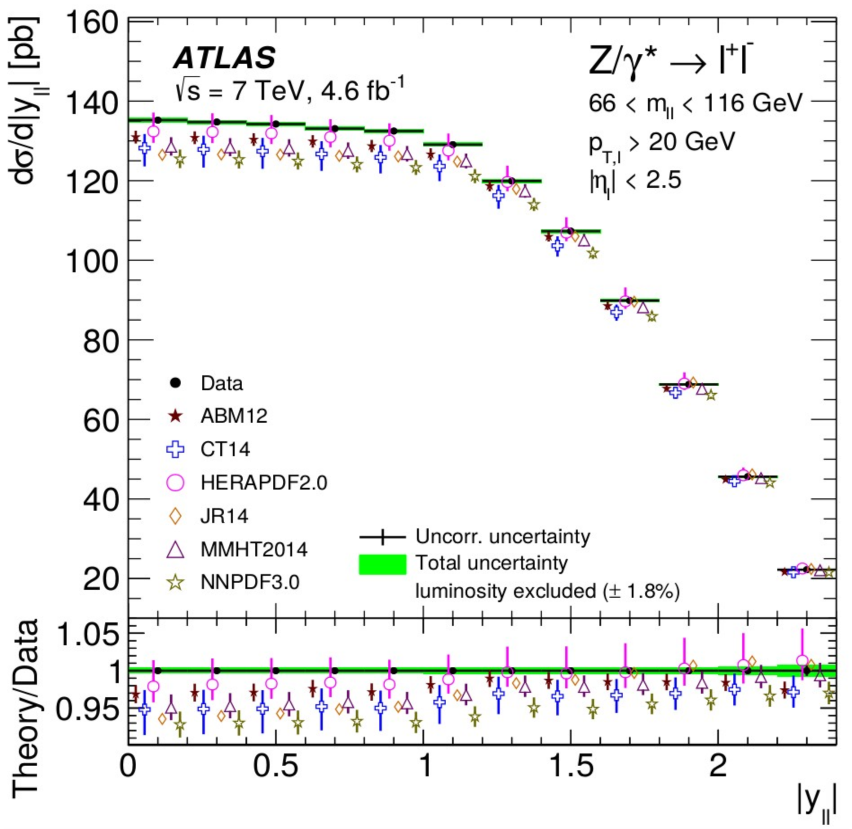
Vector boson production and decay

- QCD aspects
  - Rapidity and transverse momentum distributions;
  - Angular distributions
- EW aspects
  - ISR and FSR QED corrections
  - Missing higher-order effects

Rapidity distribution

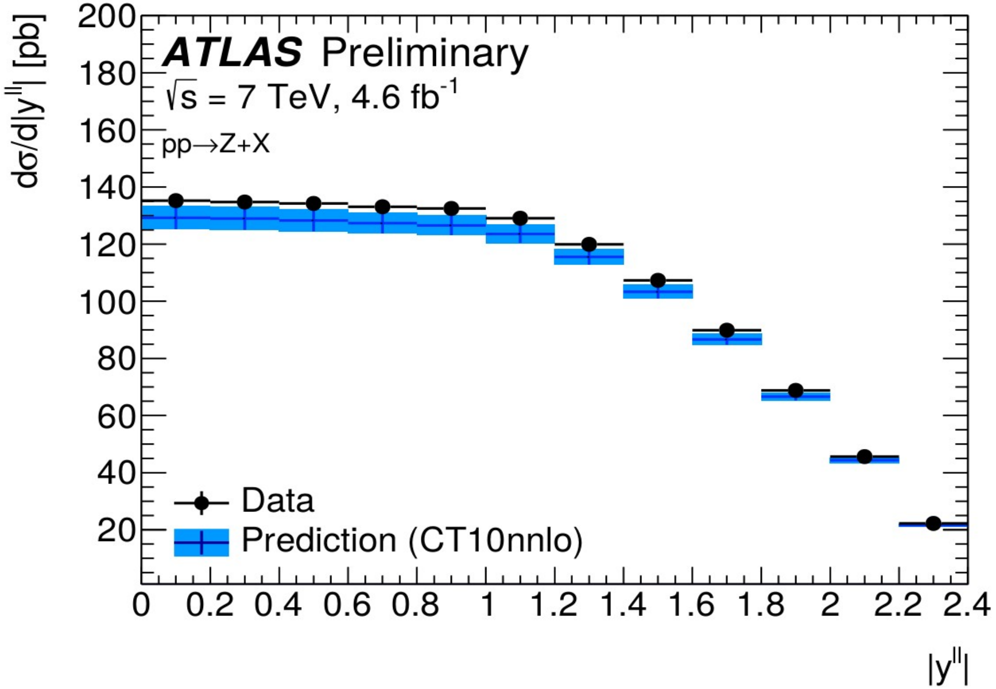
- Recent ATLAS results on W and Z cross section measurements : arXiv:1612.03016
- Integrated and differential measurements with sub-% precision
- High sensitivity to PDFs; critical to validate the predictions used for the m_W analysis

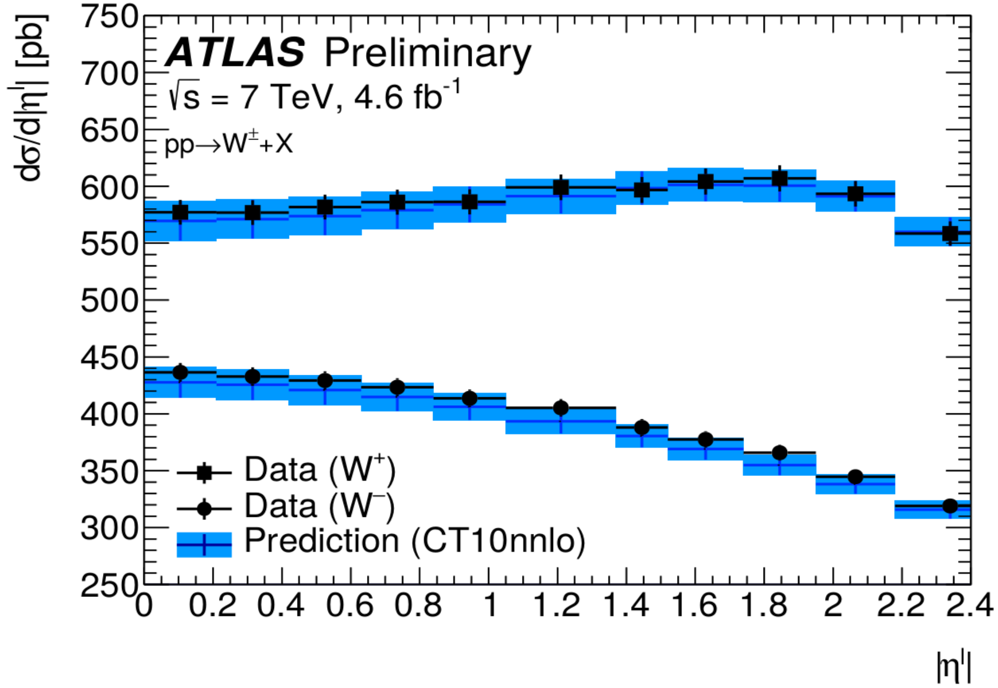




Rapidity distribution

- Dedicated predictions prepared for the m_W analysis, using DYNNLO + CT10nnlo, and compared to the W+, W- and Z peak data ($66<m_{ll}<116$ GeV)
- The resulting agreement is satisfactory : $\chi^2/n_{dof} = 45 / 34$
  - On overall normalization effect visible for Z, within one std.dev.

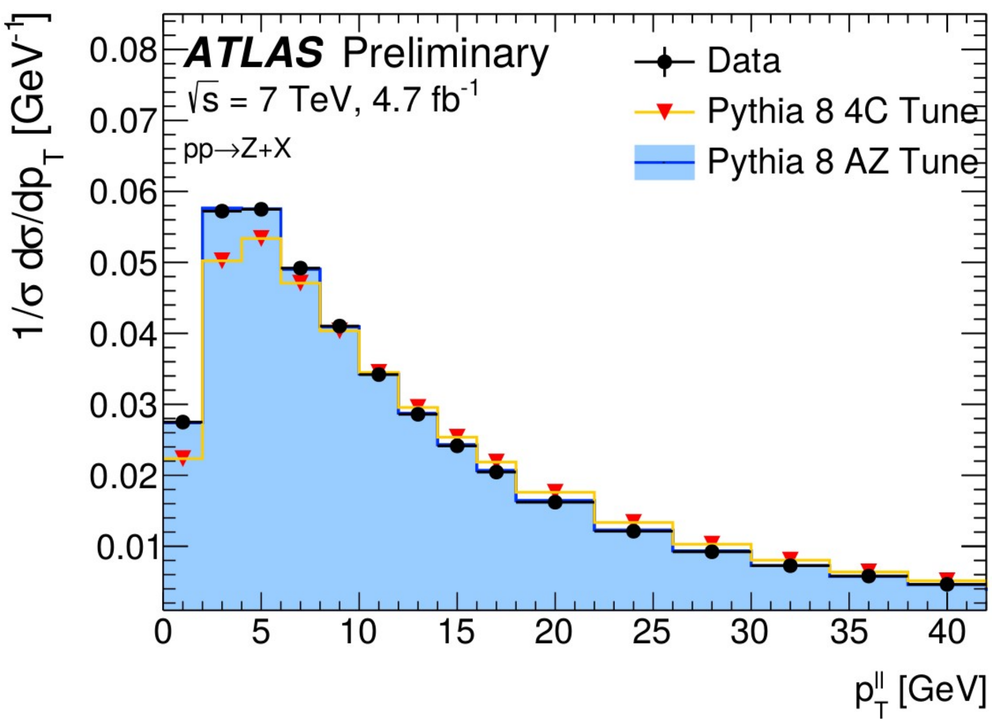


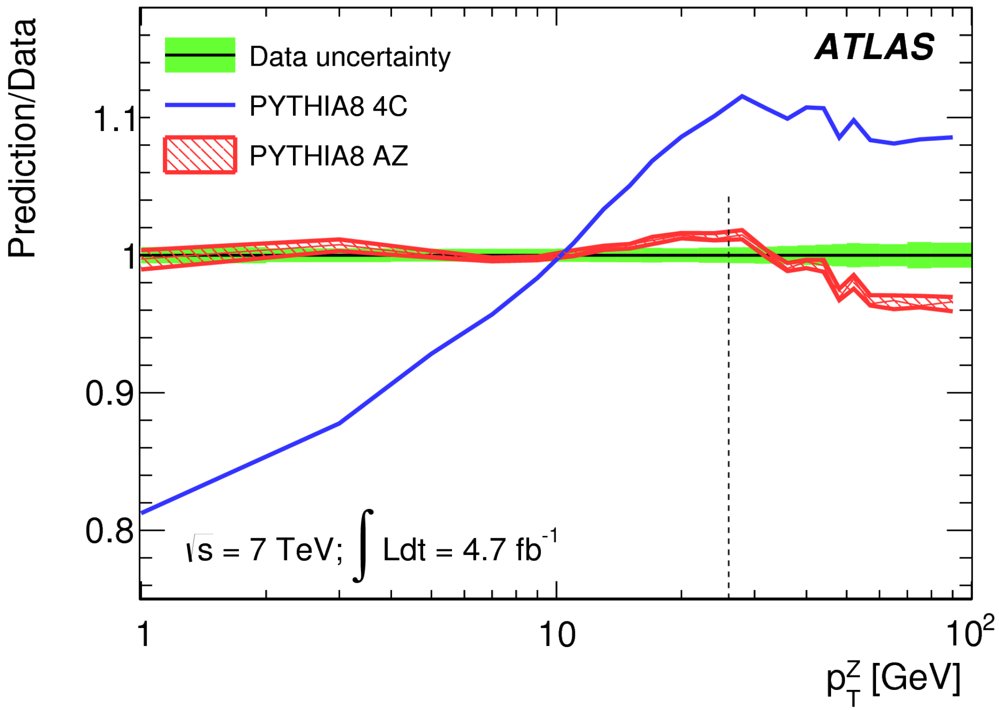


Transverse momentum distribution

- Traditional approach : fit predictions to Z data, apply to W
  - Implemented using two generators : Powheg+Pythia8, and Pythia8 standalone
  - Best description provided by the latter (better y-dependence of $d\sigma/dp_T^Z$)
  - Tuned parameters : primordial k_T; α_S^{ISR}; ISR cut-off

JHEP09(2014)145

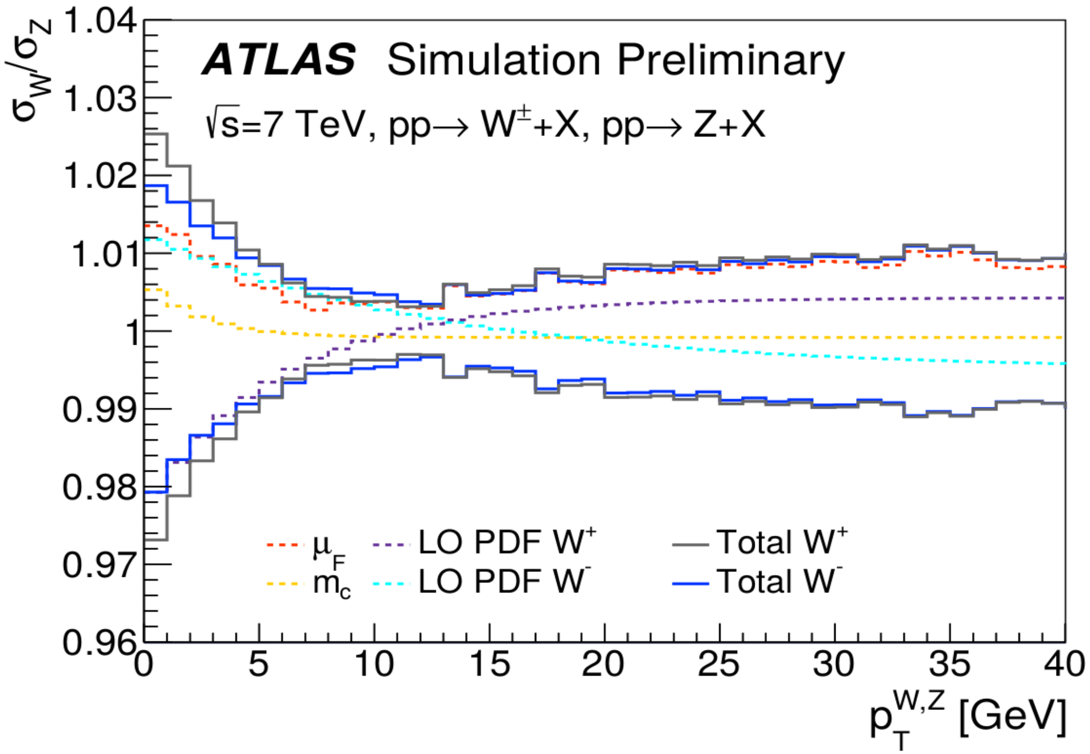




Agreement to <1% up to p_T^Z ~ 40 GeV

Transverse momentum distribution

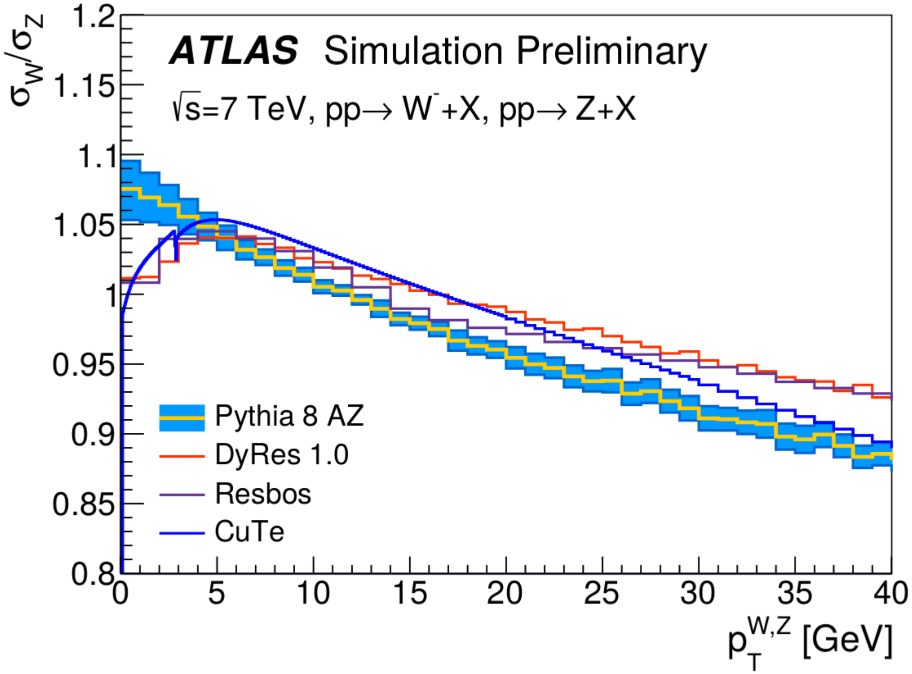
- Sources of uncertainty on $d\sigma/dp_T^W$ with Pythia 8 :
  - Accuracy of the Z data used for the tuning;
  - $Z \rightarrow W$ extrapolation : factorization scale variations (separately for light- and heavy-quark induced W and Z production); c- and b-mass uncertainties
  - Parton shower PDF variations

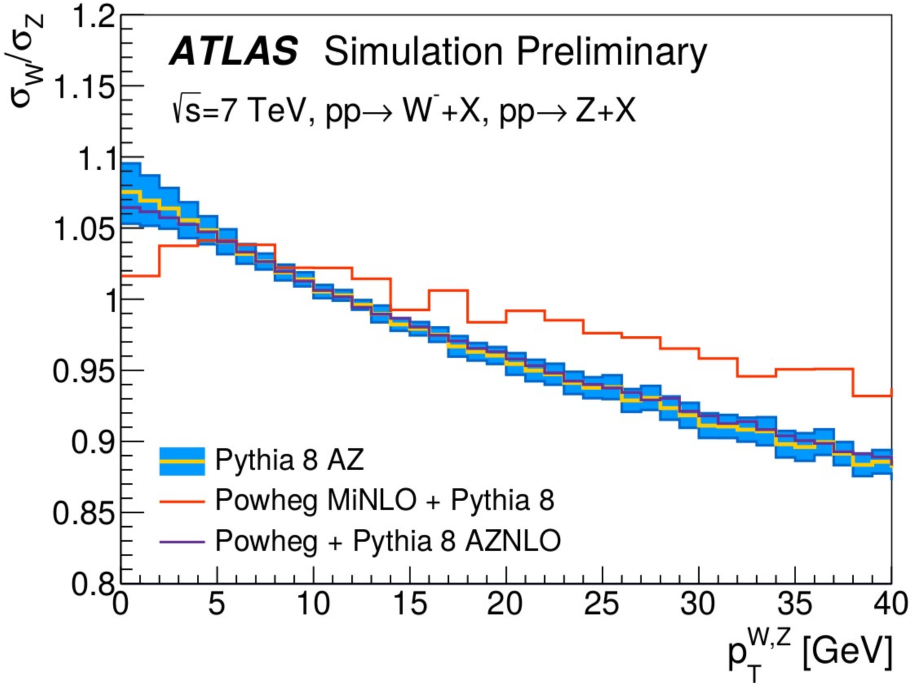


1-2% additional uncertainty on the prediction of $d\sigma/dp_T^W$

Transverse momentum distribution

- Theoretically more advanced calculations were also attempted
  - DYRES (and other resummation codes : ResBos, CuTe)
  - Powheg MiNLO + Pythia8
- All predict a significantly harder p_T^W spectrum for given p_T^Z distribution :





  - This behaviour is disfavoured by data (see later); predictions discarded for now. As a result, no explicit uncertainty from missing fixed-order terms at $O(\alpha_s^2)$, but use data to place an upper bound on this effect.

Angular distributions

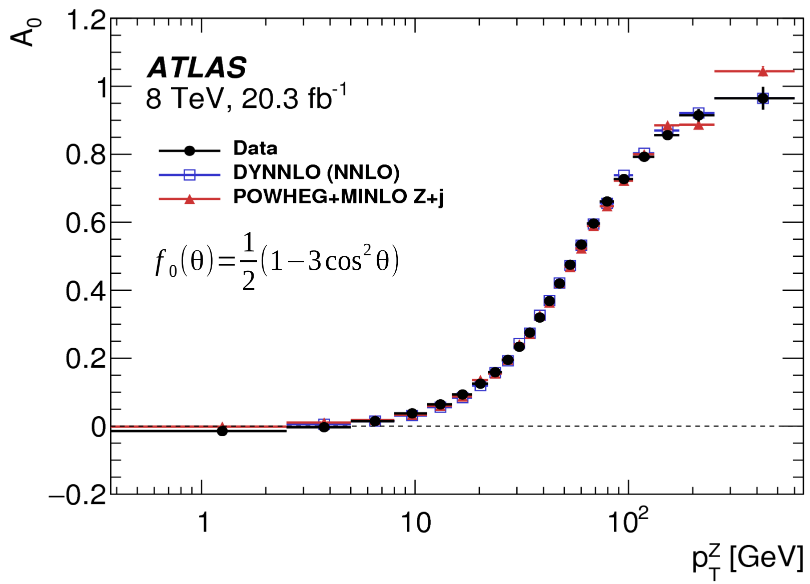
- Fully differential cross section for spin-1 boson production, to all orders:

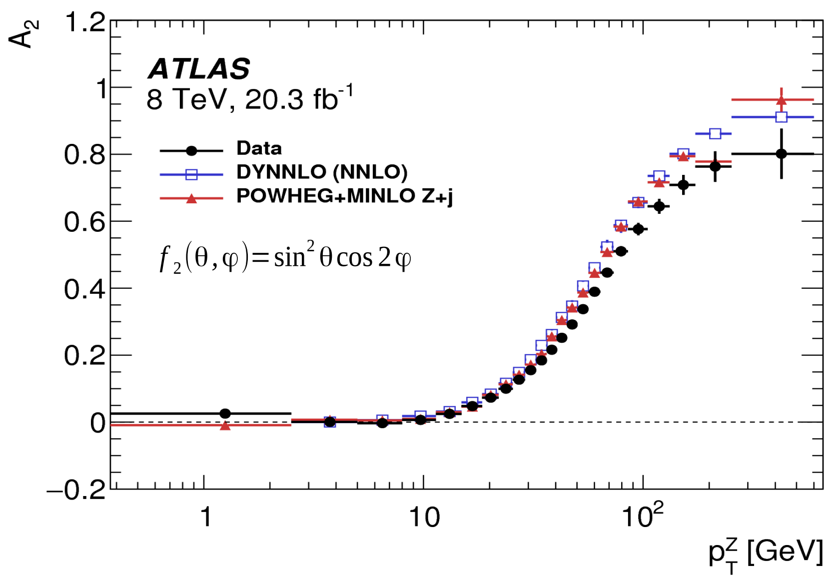
$$\frac{d\sigma}{dm\,dy\,dp_T\,d\cos\theta\,d\varphi}=\frac{d\sigma}{dm\,dy\,dp_T}\left[(1+\cos^2\theta)+\sum_i A_i(m,p_T,y)f_i(\cos\theta,\varphi)\right]$$

how accurate is the theoretical description of the A_i coefficients?

  – eg. fixed-order and resummed calculations disagree, at least at NLO (ResBos)

- ATLAS measurement : JHEP08(2016)159





- The data validate DYNNLO (fixed-order), within the measurement uncertainties

Summary of QCD predictions and uncertainties

- Baseline
  - $d\sigma/dy$, $A_i(p_T,y)$: DYNNLO+CT10nnlo (fixed-order)
  - At given y, $d\sigma/dp_T$ is predicted using Pythia 8 AZ

Validated by the data:
σ_W, σ_Z, p_T^Z, A_i ; also η_l, u_T, $u_{||}$

- Uncertainties
  - CT10nnlo uncertainties (synchronized in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT. Strong anti-correlation of uncertainties for W^+ and W-!
  - AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
  - A_i uncertainties from Z data; envelope for A2 discrepancy

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

Higher-order EW effects

- QED effects included in the simulation : ISR using Pythia8, and FSR using Photos
  - Negligible uncertainty
- Missing effects
  - NLO EW effects, evaluated in presence of QCD corrections. Available from Powheg-EW and Winhac (uncertainties from the latter).

    Impact on p_T and m_T distributions calculated in two schemes (α_0, G_μ); undertainty defined from the largest effect
  - QED emission of pairs : formally of higher order, but a significant additional source of momentum loss

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

Detector response calibration

- Lepton calibration
  - momentum calibration using the Z peak
  - efficiency corrections (not discussed – material in back up)
- Recoil calibration
  - Event activity corrections
  - Recoil response calibration using expected p_T balance between lepton pairs and u_T in Z events

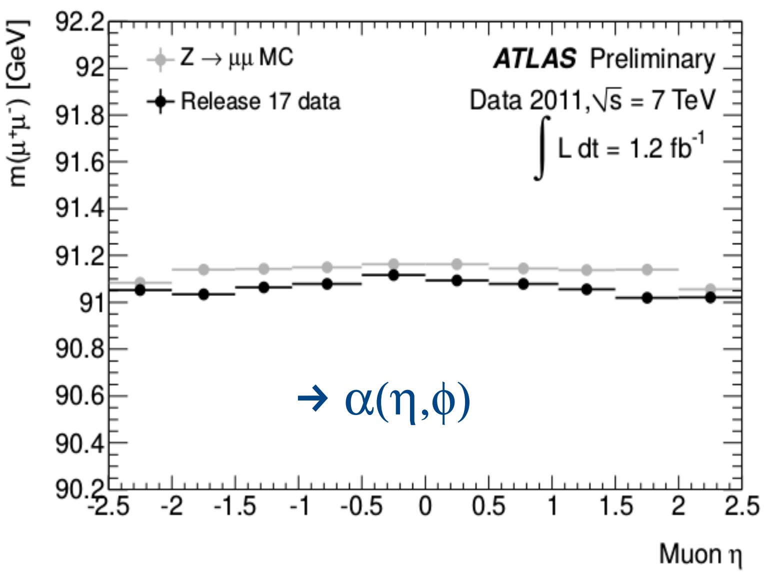
Muon response calibration

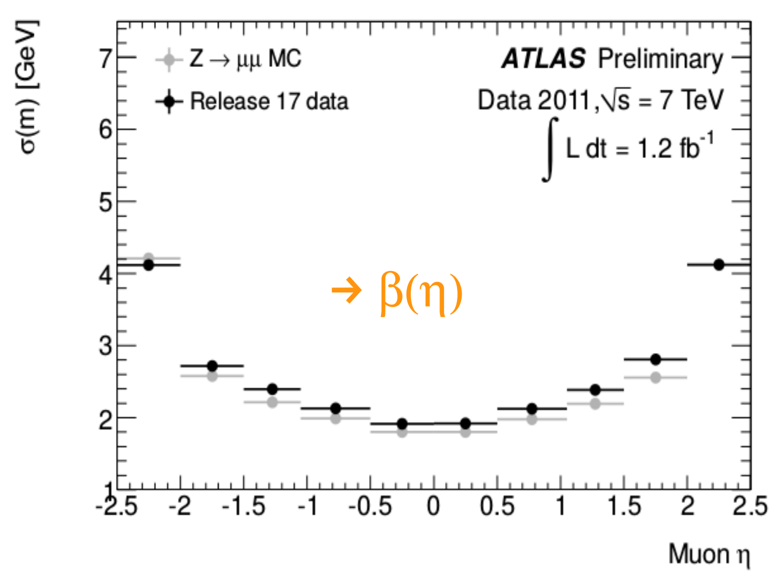
- Muon measurement
  - Identification using combined ID+MS tracks; momentum measurement from ID only : simplifies calibration; some loss in resolution (esp. at high |η|)
- Parameterisation of momentum corrections:

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

- Momentum scale and resolution corrections probed using Z → μμ events, exploiting the well-known Z boson mass and width :

ATLAS-CONF-2012-141



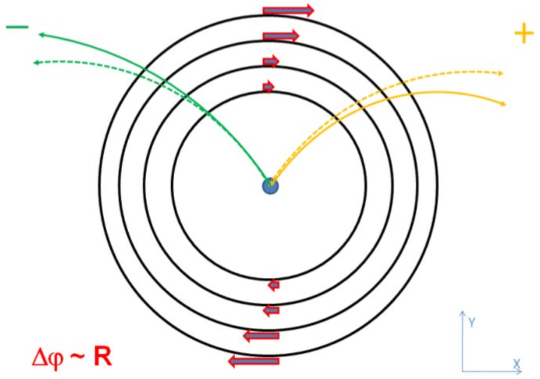


Muon response calibration

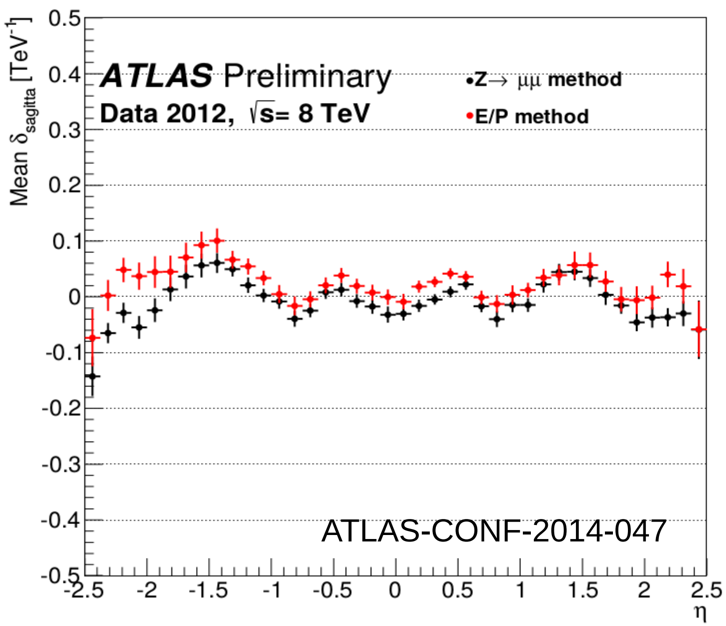
- Track sagitta bias : from rotational detector deformations

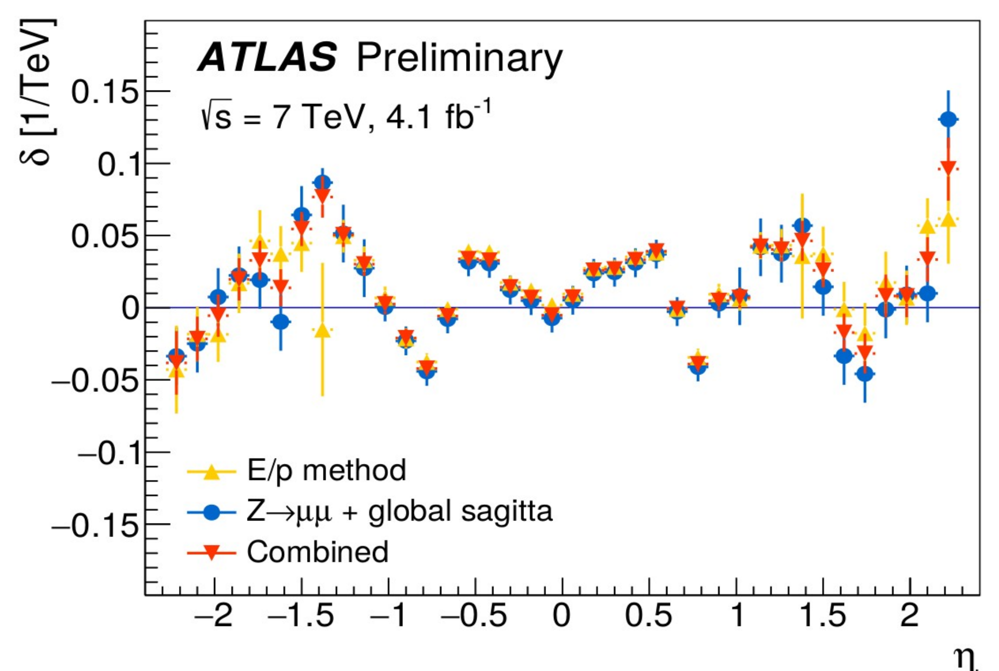
$$p_T^{\text{data,corr}} = \frac{p_T^{\text{data}}}{1 + q \cdot \boxed{\delta(\eta,\phi)} \cdot p_T^{\text{data}}}$$

(m_{W+}/m_{W-} consistency!)

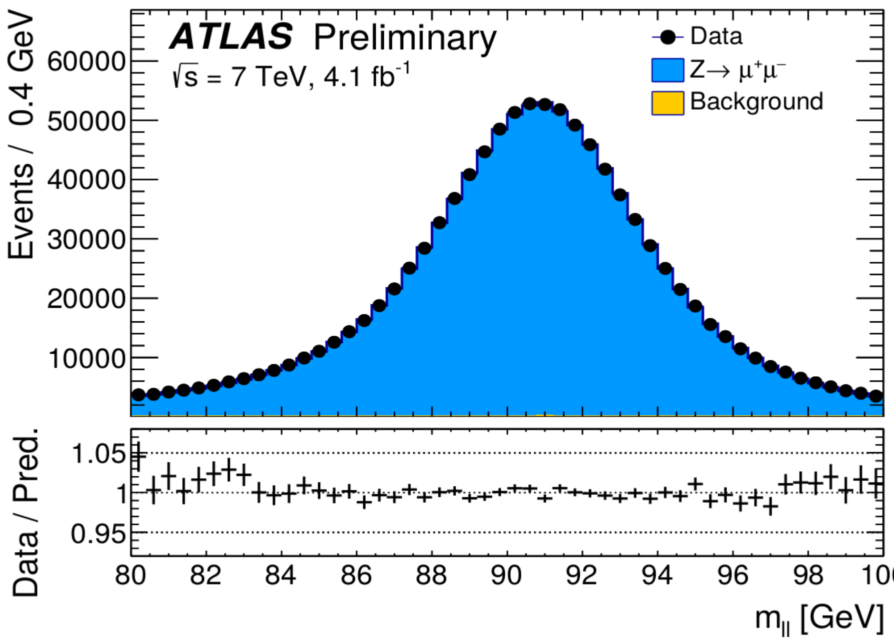


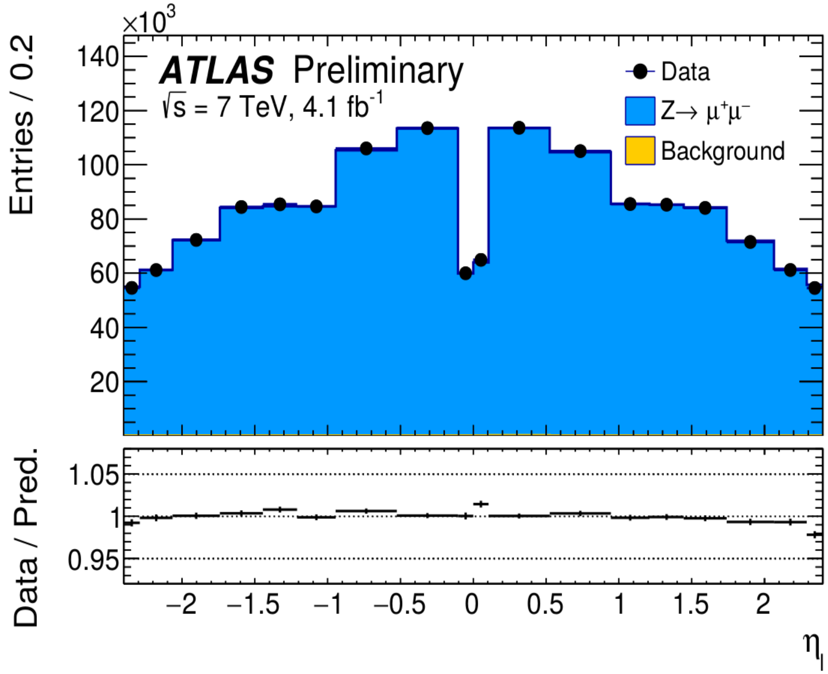
- Probed using Z → μμ and W → eν events
  - Z→μμ is sensitive to the η dependence of this effect, but blind to an overall, uniform offset
  - Comparing E/p in $W^+ \to e^+\nu$ and $W^- \to e^-\bar{\nu}$ events directly probes δ, exploiting the charge-symmetric calorimeter response





Muon calibration : performance and results





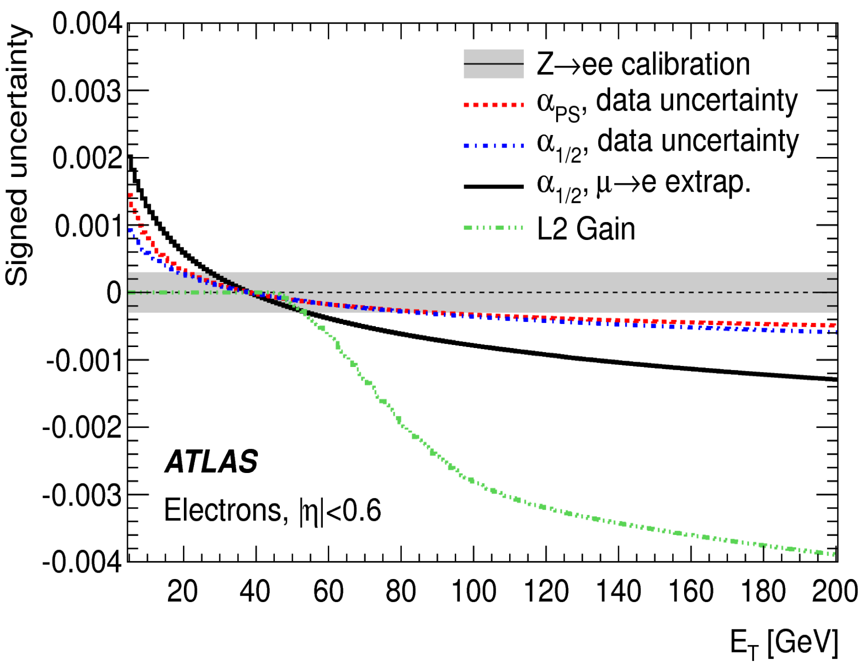
$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	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

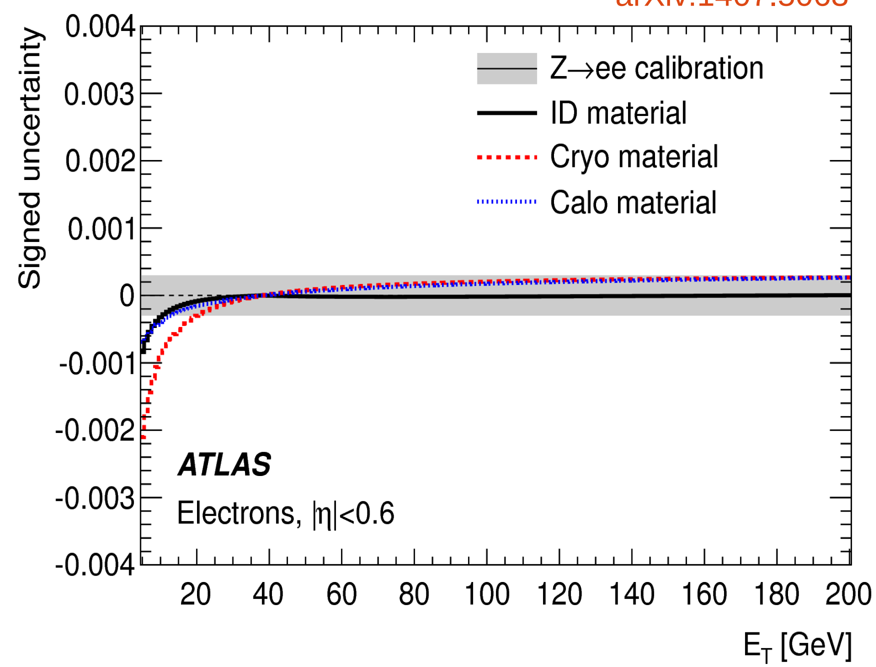
Electron response corrections

- Electron measurement : energy from the EM calorimeter; η, ϕ from the ID
- Calibration sequence :
  - Calorimeter longitudinal intercalibration using muon energy deposits
  - Passive material and presampler response corrections derived using longitudinal shower profiles of electrons and photons

  Uncertainty on the energy linearity derived from the basic components:

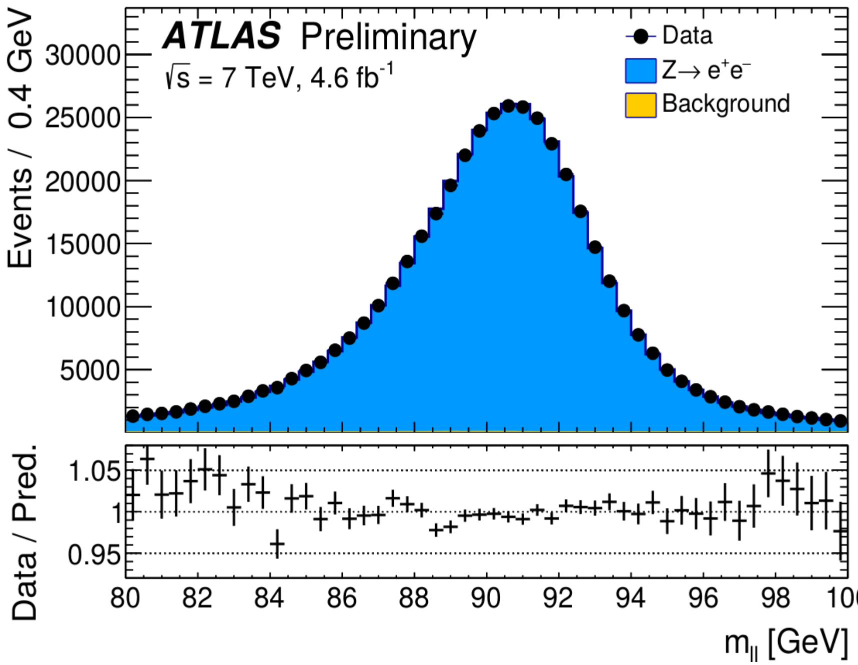
arXiv:1407.5063

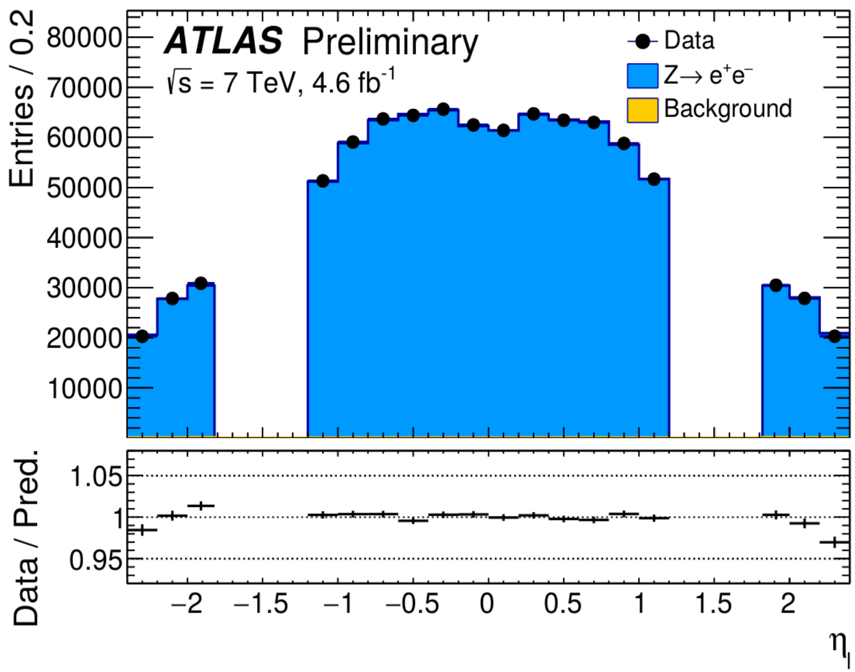




- The overall energy scale is constrained using the m_{ee} peak

Electron calibration : performance and results

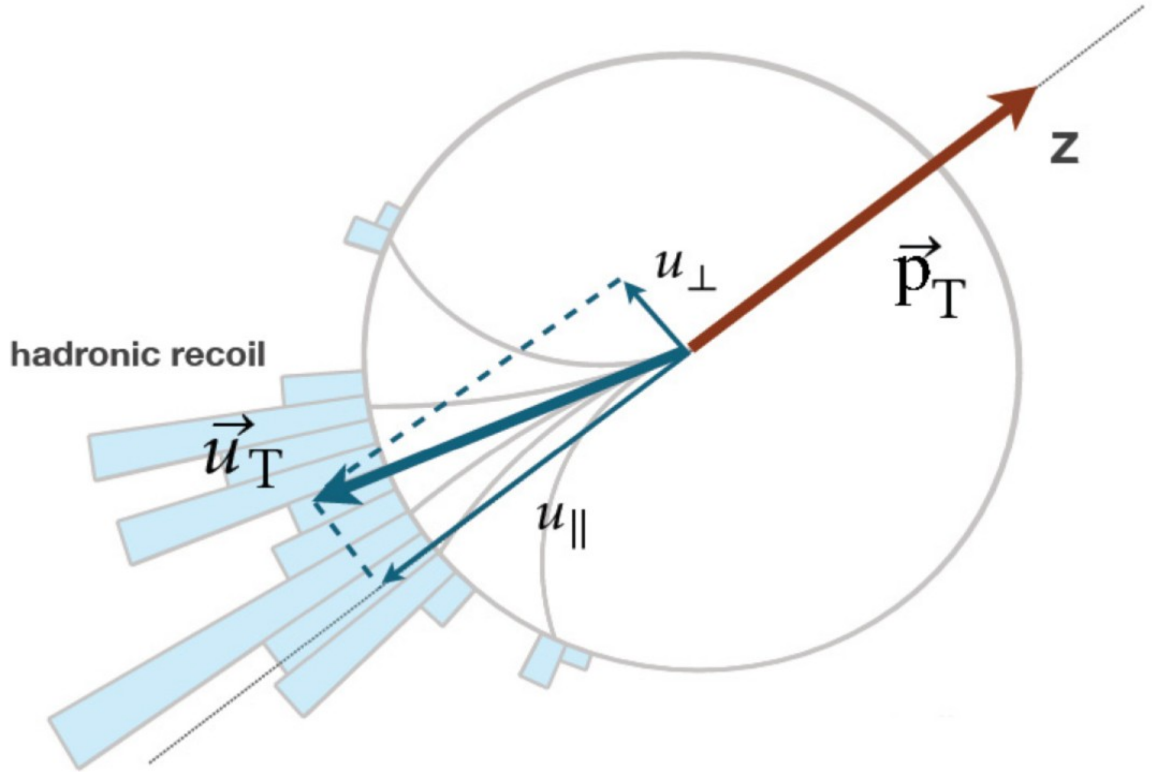




$\lvert\eta^\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	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 mis-measurement	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 response calibration

- Recoil projections useful for calibration:



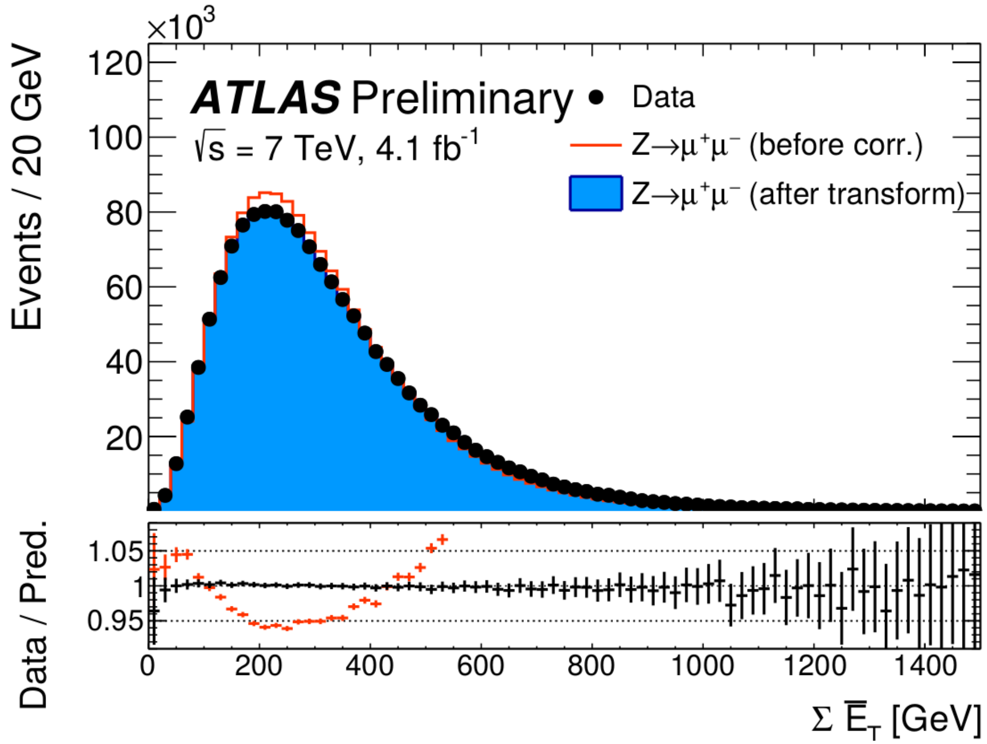
Recoil response calibration

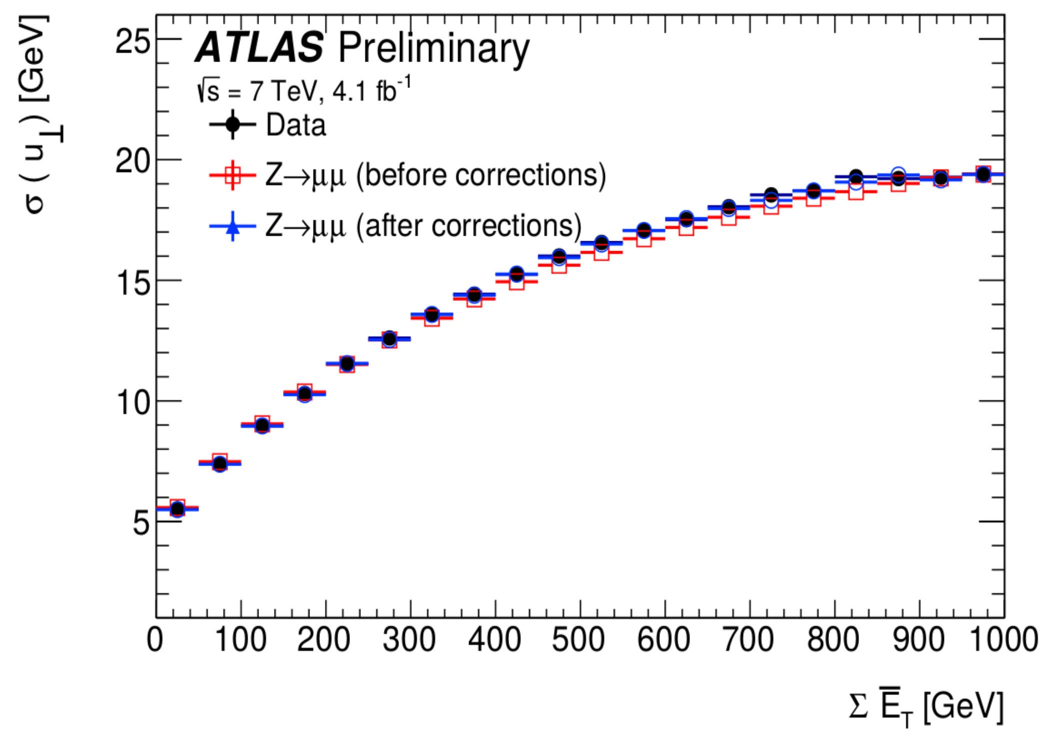
- Recoil correction steps :

  1 – Equalize pile-up multiplicity distribution in data and MC

  2 – Correct for residual differences in the ΣE_T distribution : removes u_T resolution discrepancy due to imperfect event activity mis-modeling

  Can be done directly in W events – no extrapolation systematics



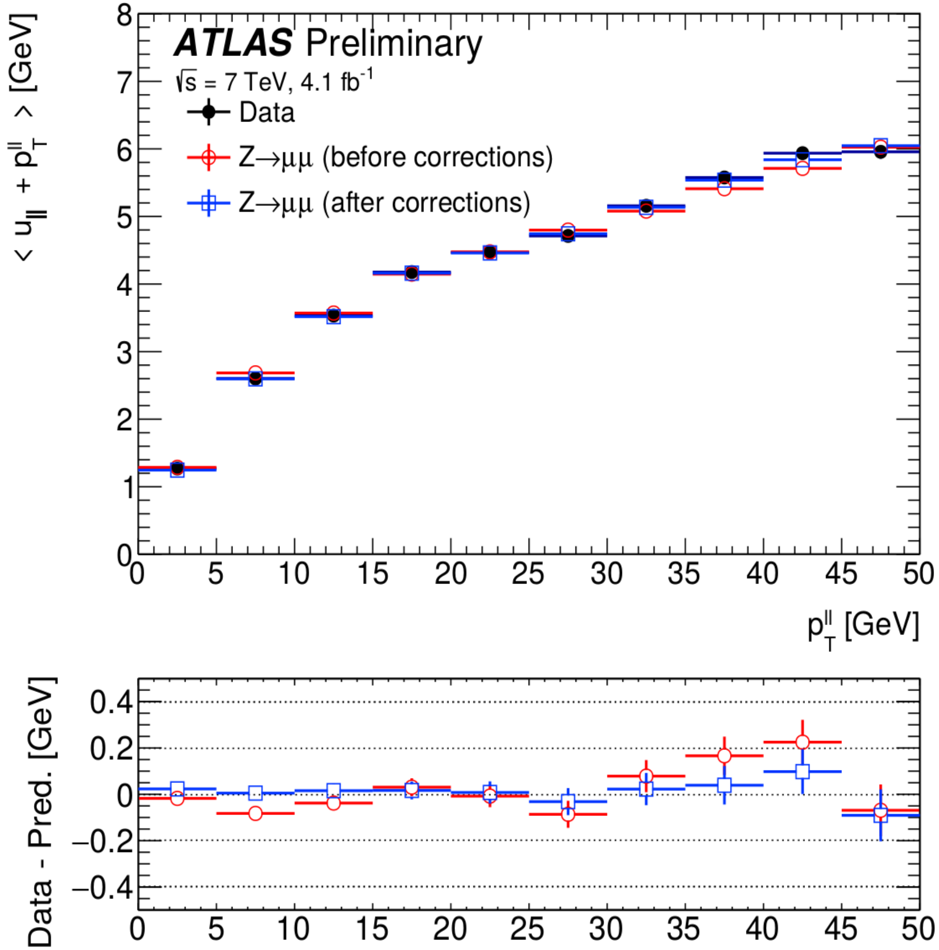


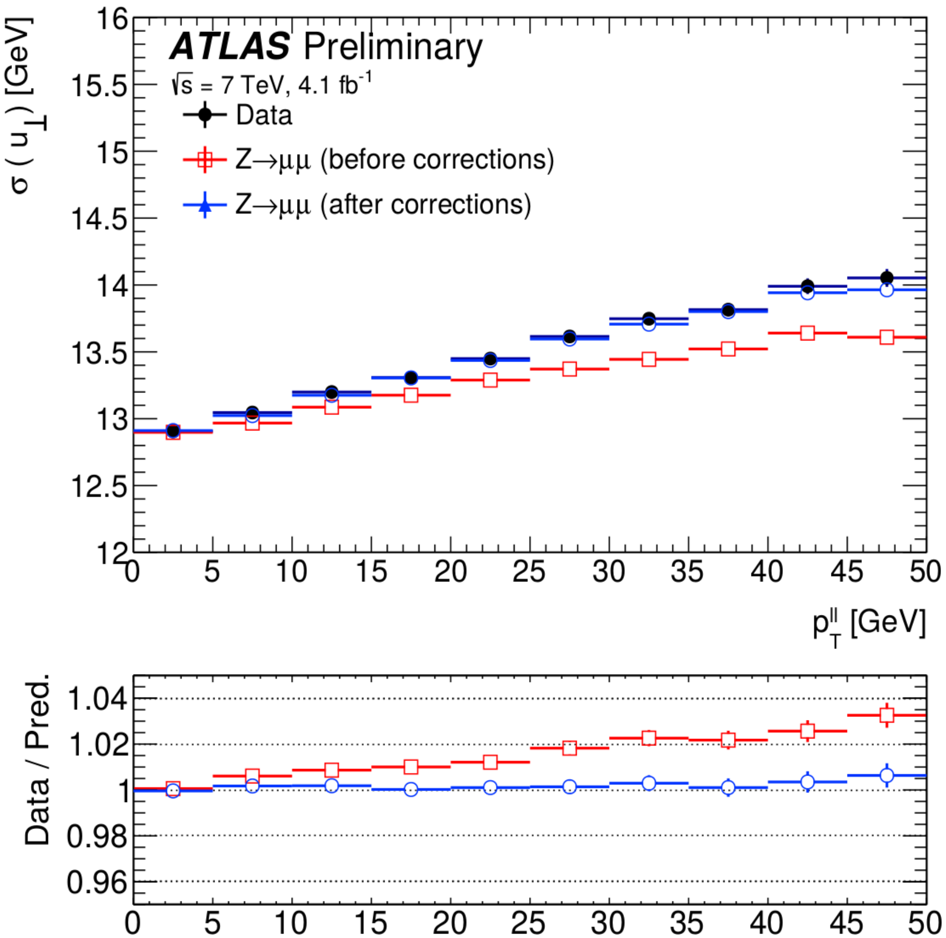
$$\Sigma E_T = \sum_i E_{T,i}$$

Recoil response calibration

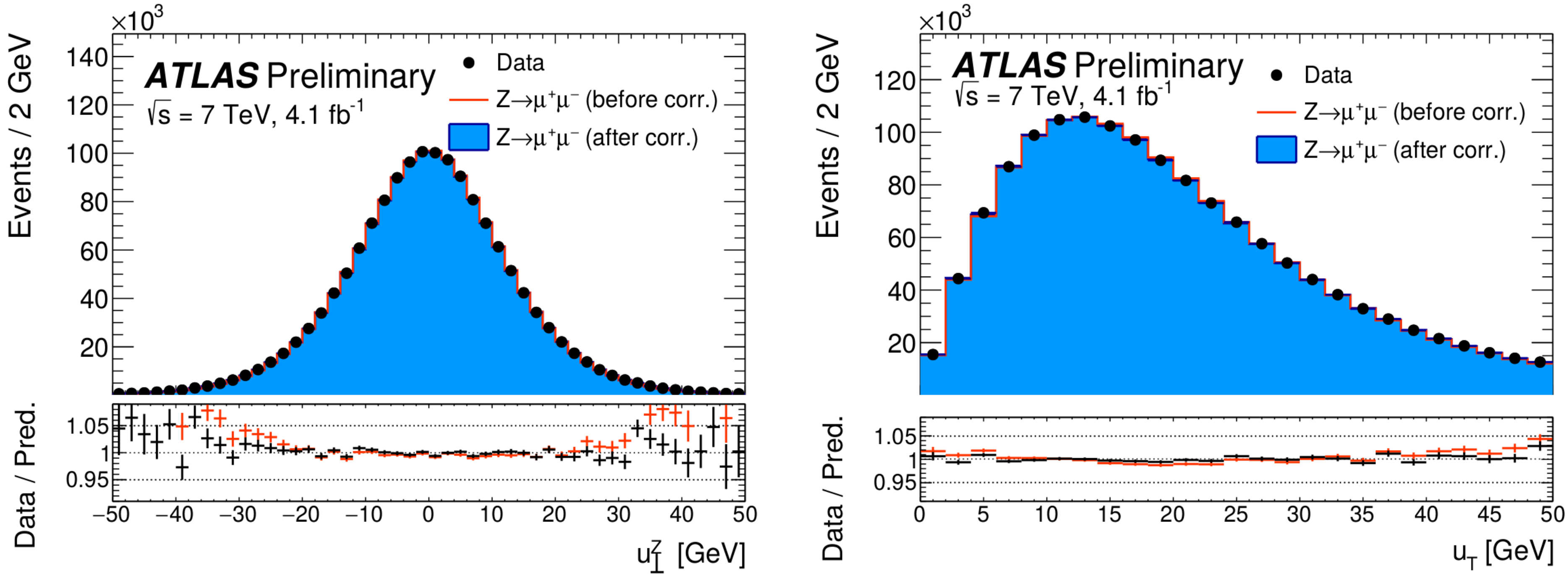
- Recoil correction steps :
  - 3 – Residual corrections using p_T balance in Z events, mapped vs (p_T^V, SumET).

    Uncertainties from Z statistics, and Z → W extrapolation





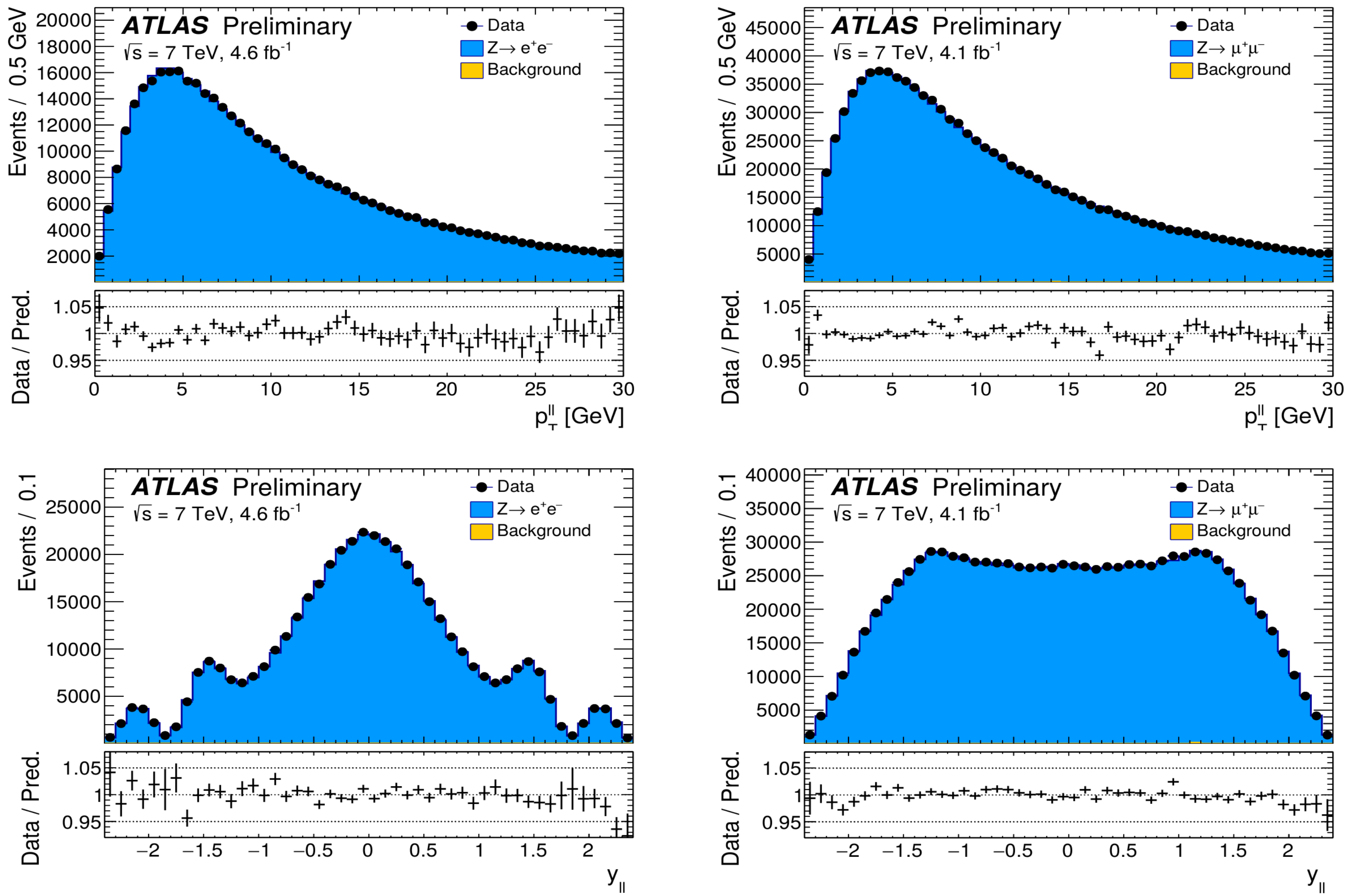
Recoil calibration : performance and results



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 checks with Z events

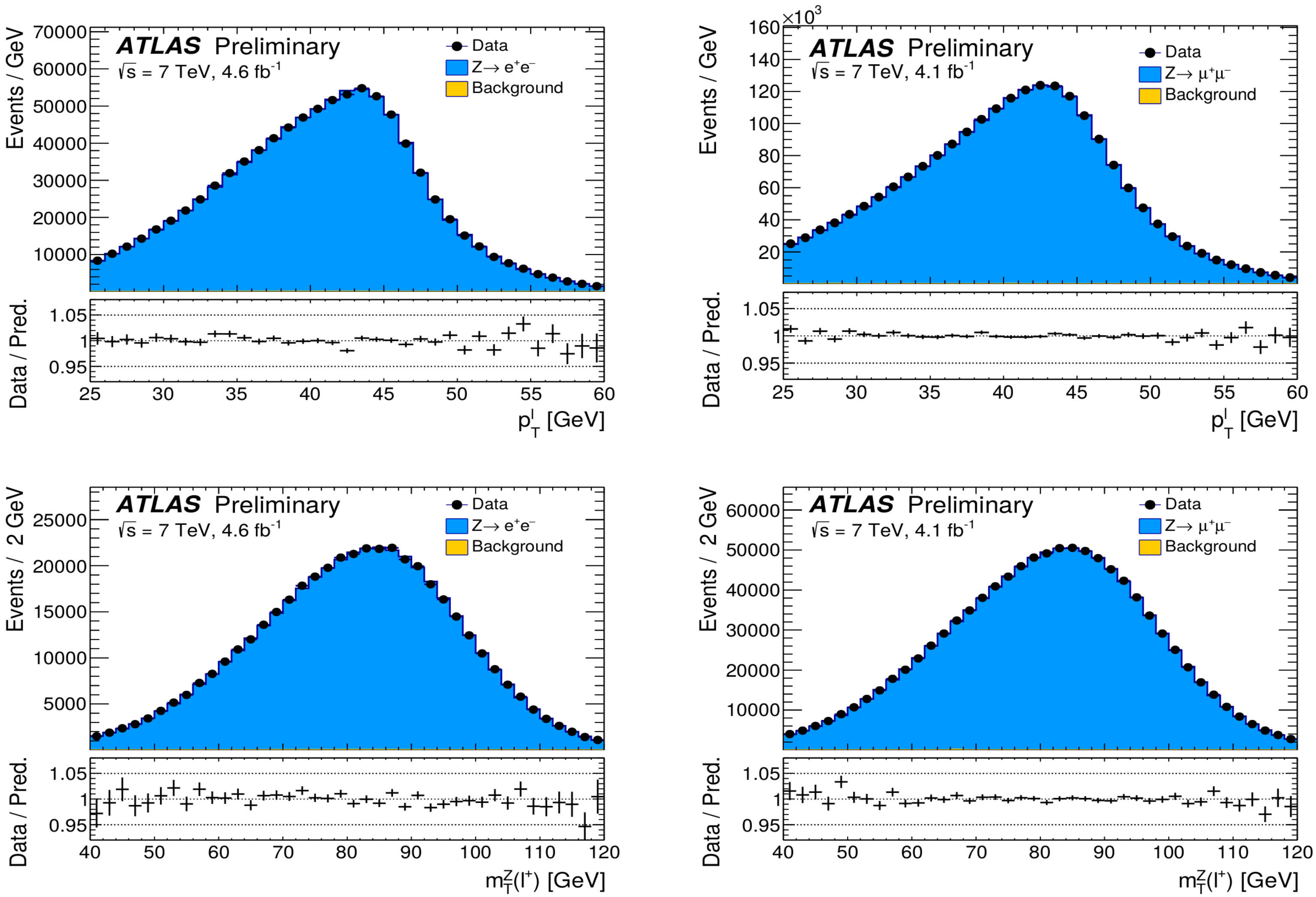
Z boson rapidity and p_T distributions :



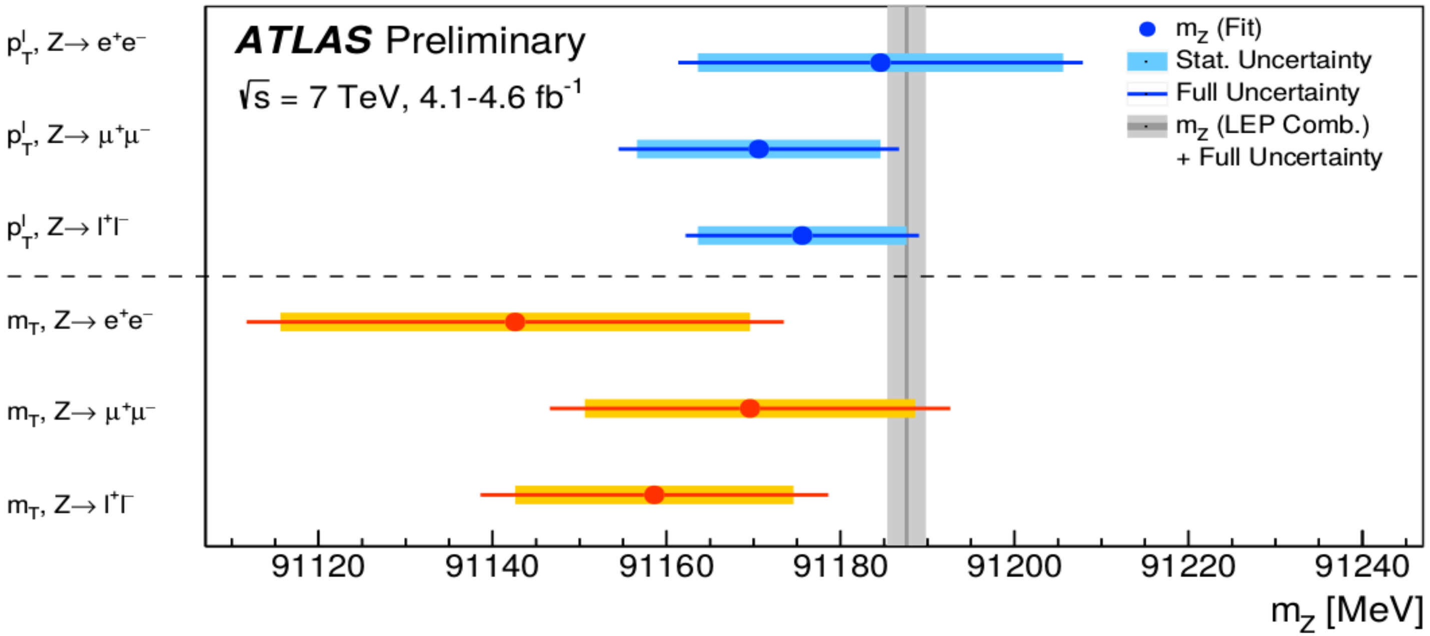
Good agreement. Error bars are statistical only

Cross checks with Z events

Trasnverse momentum and pseudo-transverse mass distributions :



Cross checks with Z events



Lepton charge	ℓ^+		ℓ^-		Combined	
Distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_Z [MeV]						
$Z \to ee$	$13 \pm 31 \pm 10$	$-93 \pm 38 \pm 15$	$-20 \pm 31 \pm 10$	$4 \pm 38 \pm 15$	$-3 \pm 21 \pm 10$	$-45 \pm 27 \pm 15$
$Z \to \mu\mu$	$1 \pm 22 \pm 8$	$-35 \pm 28 \pm 13$	$-36 \pm 22 \pm 8$	$-1 \pm 27 \pm 13$	$-17 \pm 14 \pm 8$	$-18 \pm 19 \pm 13$
Combined	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

Results consistent with m_Z, within experimental uncertainties.

Fitted values a bit low on average, but these are all from the same events – if the decay angle is a bit more forward in data, all fit results decrease simultaneously.

Backgrounds in the W sample

Most backgrounds are determined using simulation, and normalized using NNLO predictions, or measurements.

Summary of dominant components and induced uncertainties :

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

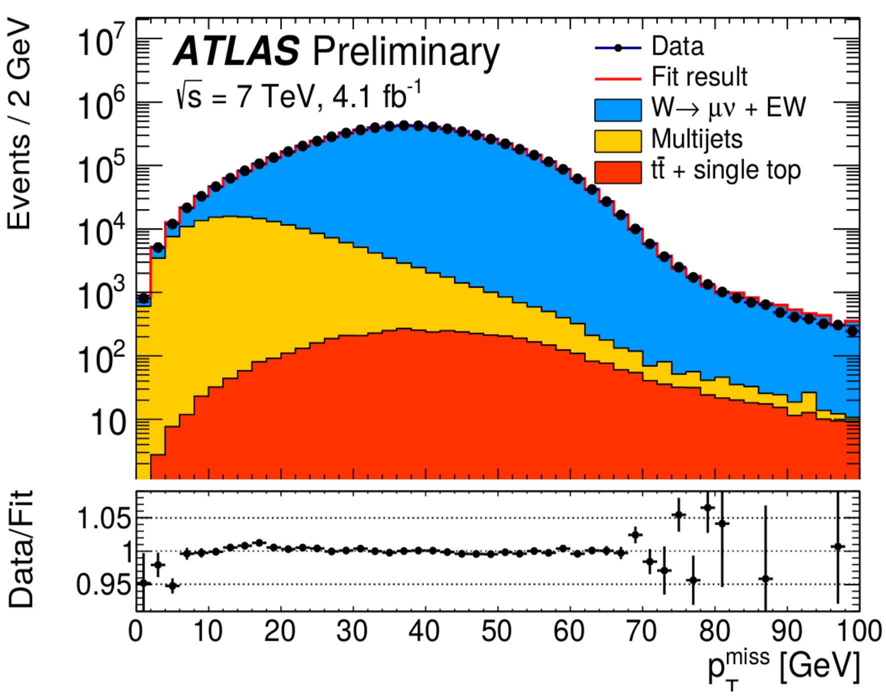
Fraction of W sample :

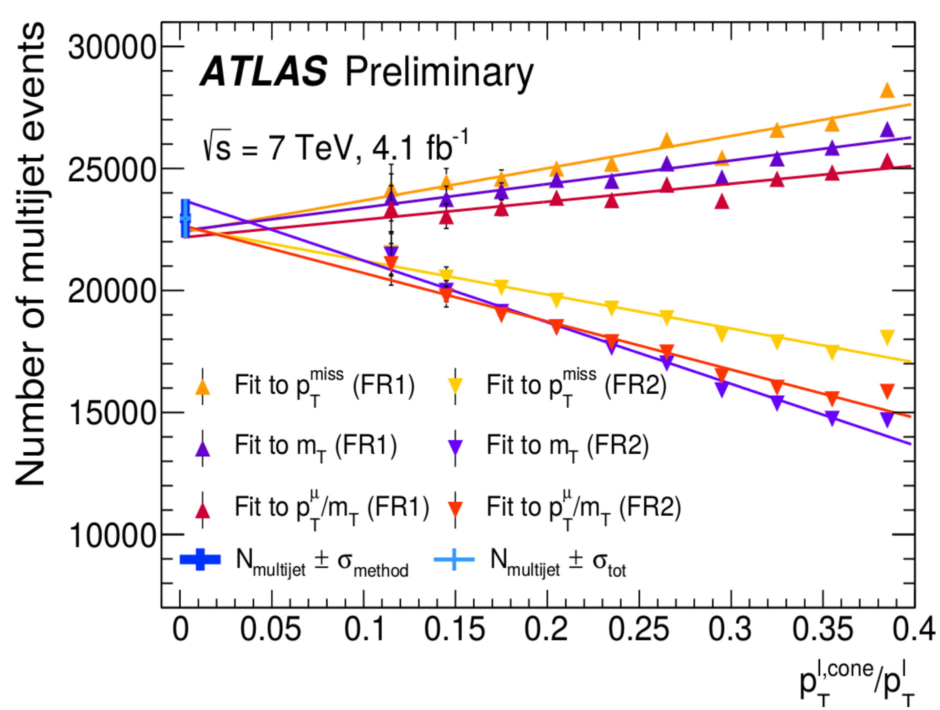
~3 – 8% (μ)
~3% (e)

~0.7 – 0.5% (μ)
~0.6 – 1.7% (e)

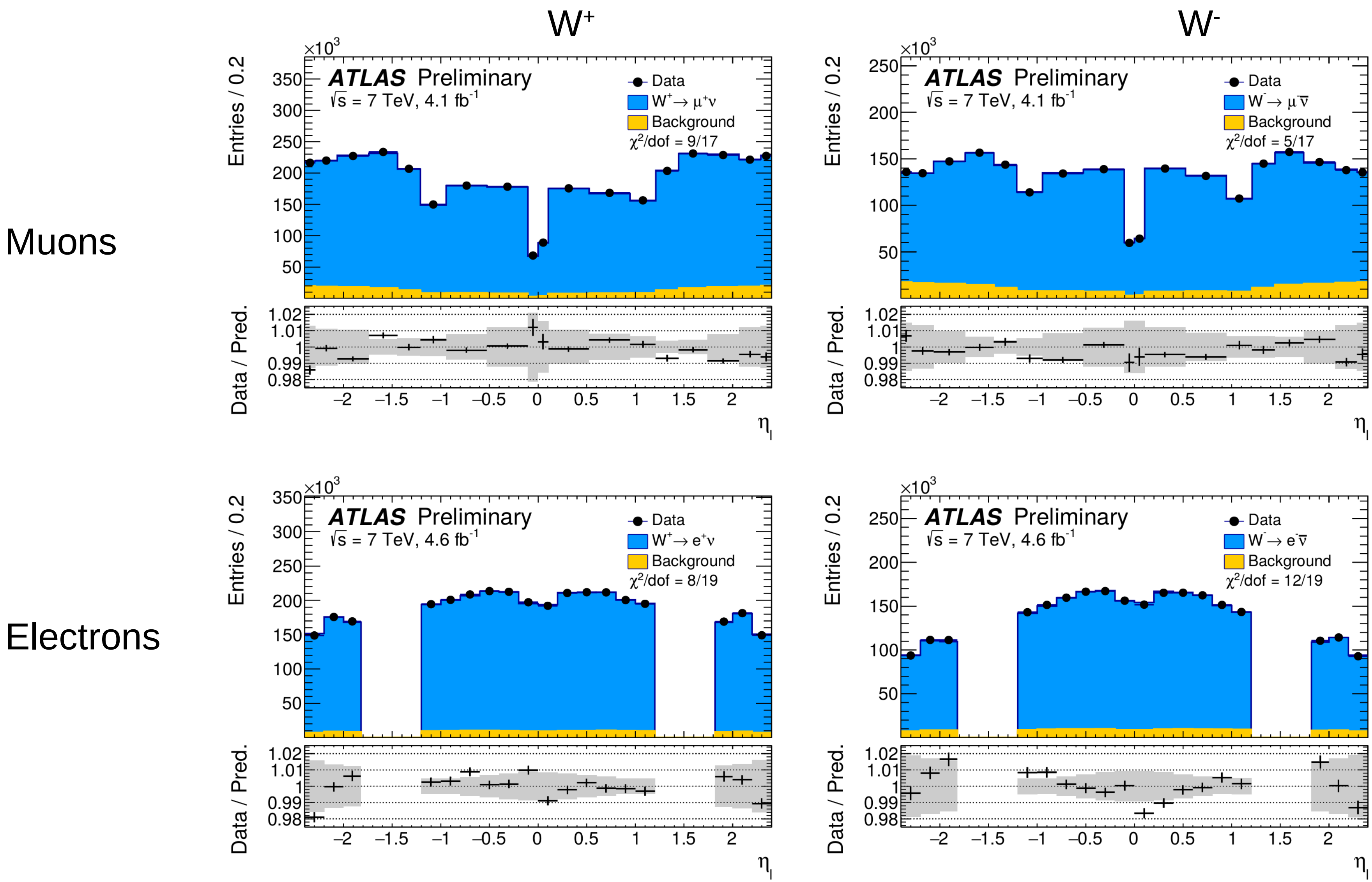
Backgrounds in the W sample

- Multijet background determined using standard data-driven techniques :
  - Define a background-dominated fit region by relaxing kinematic cut(s)
  - Signal distributions from simulation; background from a control region with inverted lepton isolation cuts
  - The multijet background yield is obtained from a fraction fit
- Variations: 3 observables (p_T^{miss} , m_T , p_T^l / m_T); two fit regions. Repeat for different anti-isolation criteria, extrapolate to the signal region





Control distributions : $\eta_{e,\mu}$



All predictions are normalized to the data

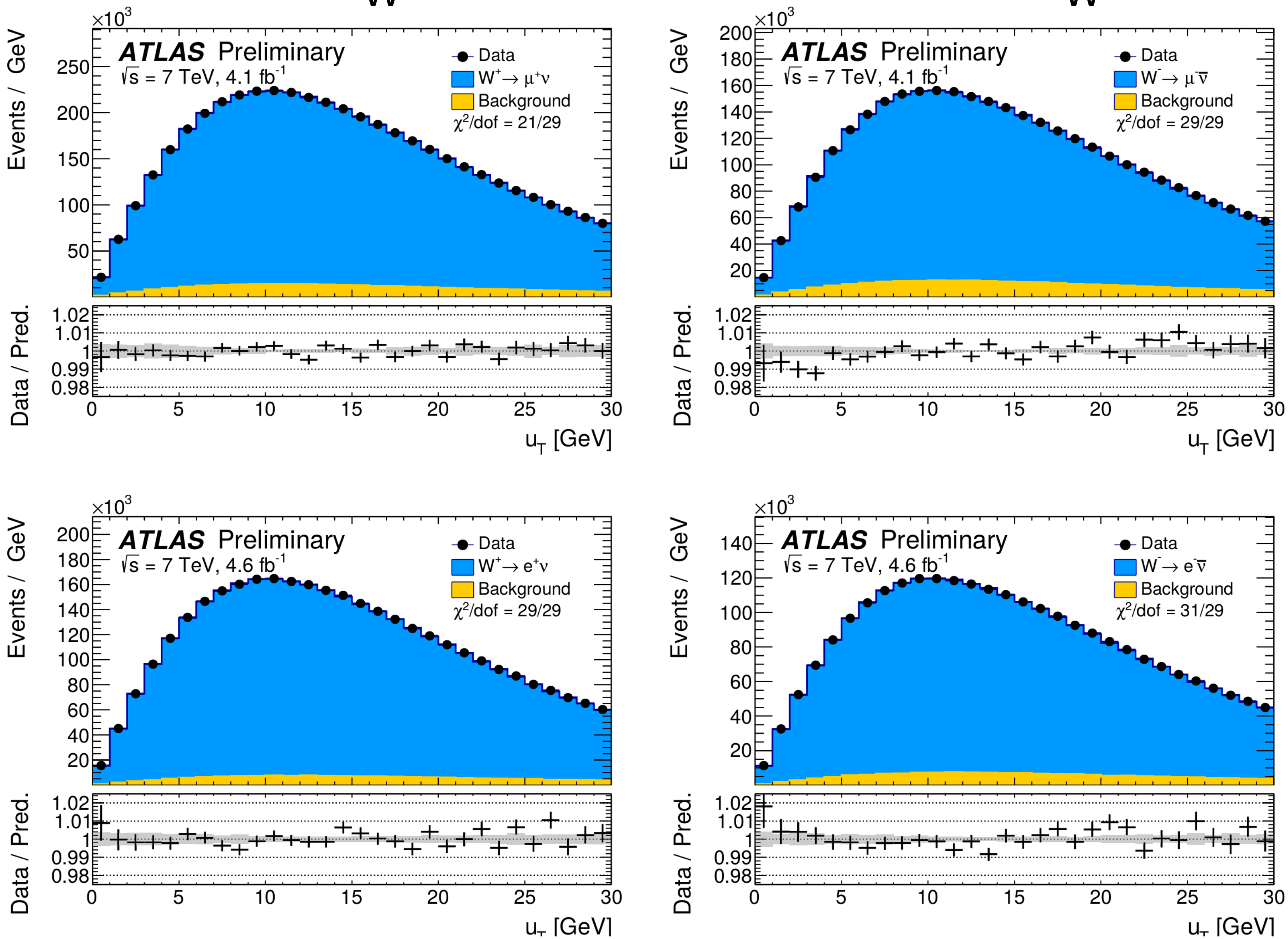
χ^2 values include the effect of bin-to-bin correlations

Control distributions : u_T

W^+ W^-

Muons

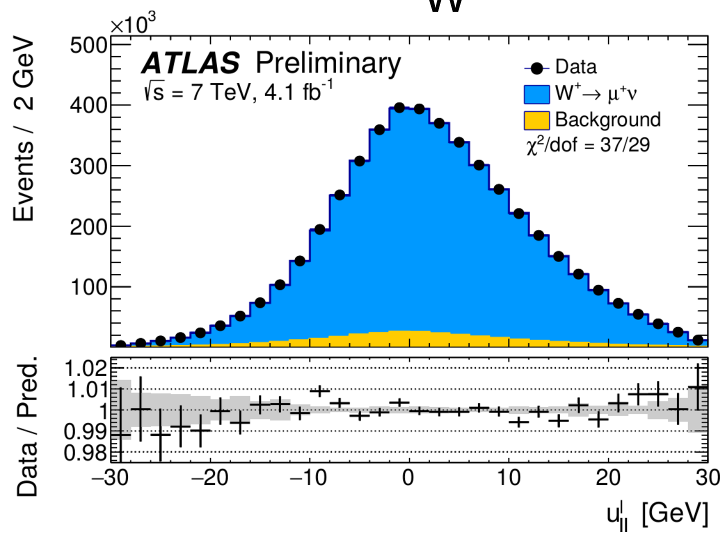
Electrons

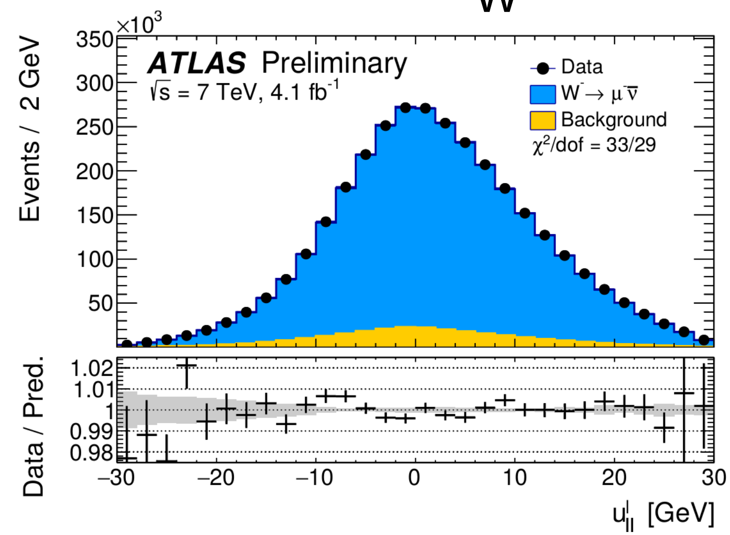


Control distributions : $u_{||}^{e}$, $u_{||}^{\mu}$

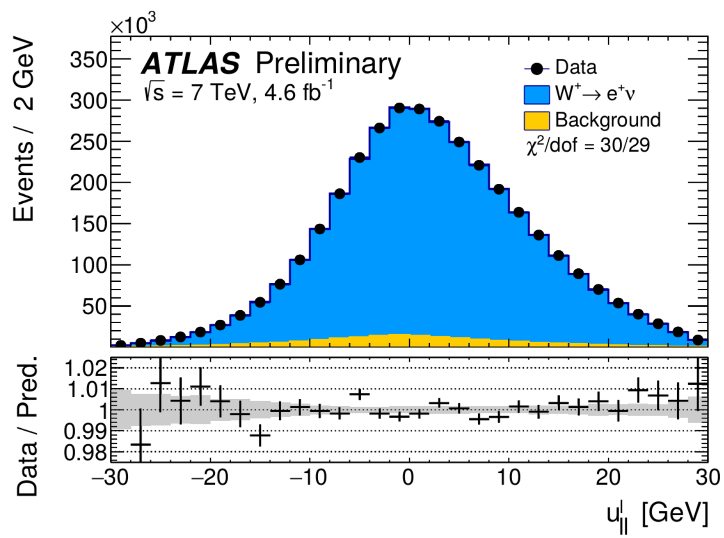
W+ | W-

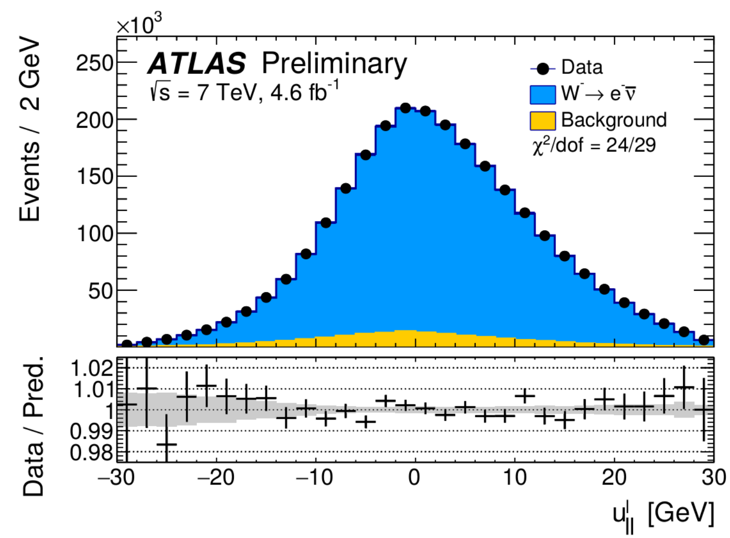
Muons





Electrons

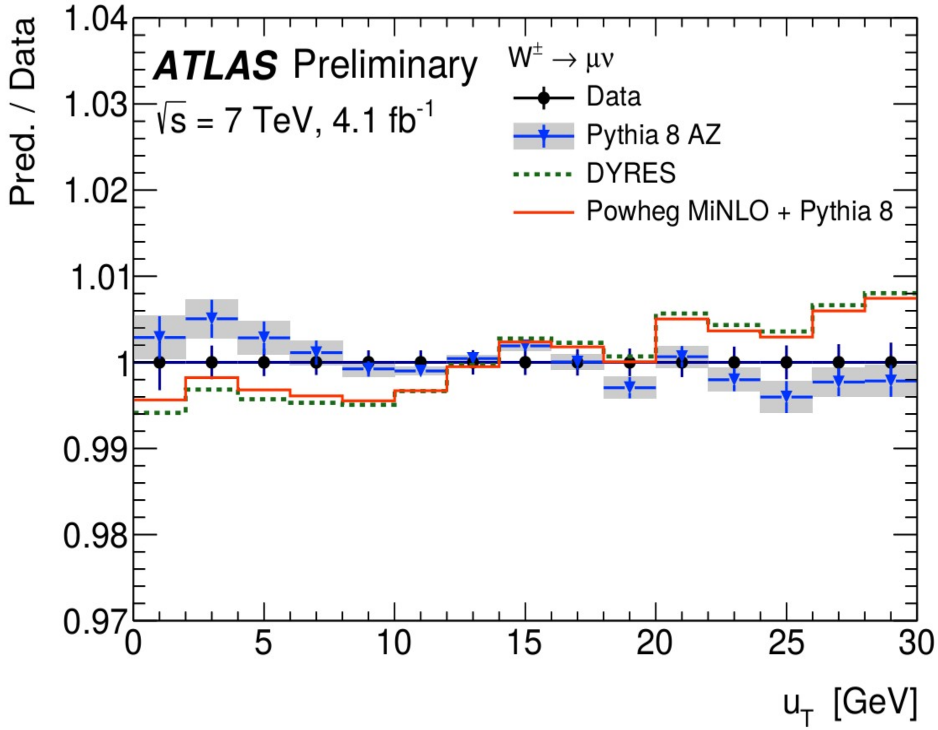


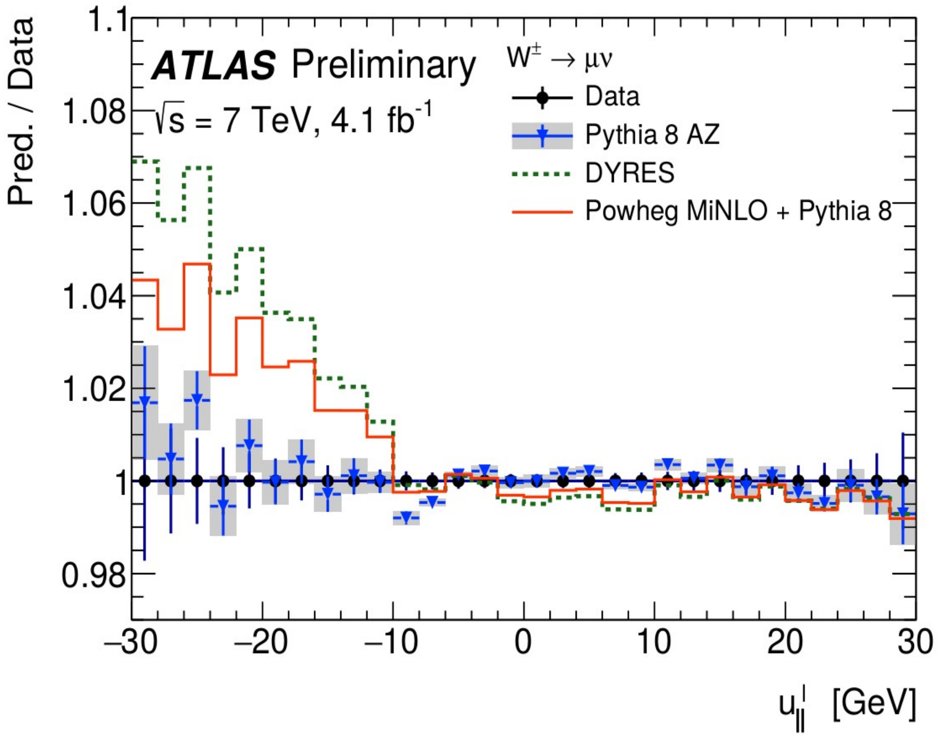


Check of the p_T^W distribution

- The $u_{||}^l$ distribution is very sensitive to the underlying p_T^W distribution, for $u_{||}^l < 0$

  Can exploit this feature to verify the accuracy of our baseline model, and compare to the alternative calculations mentioned earlier:



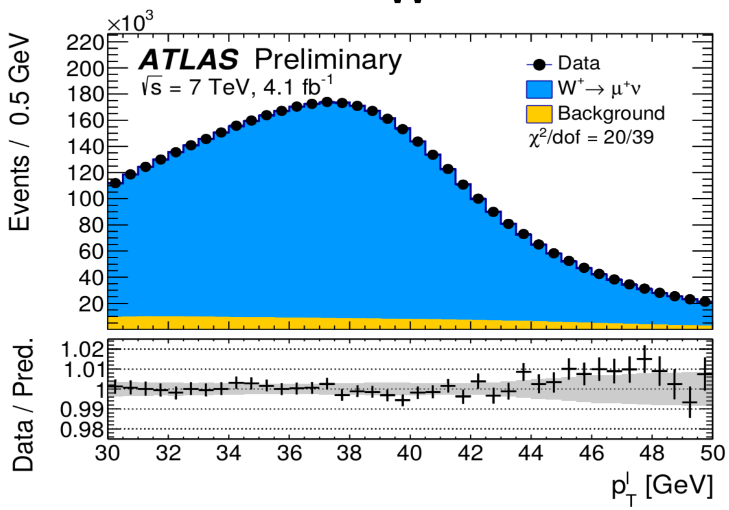


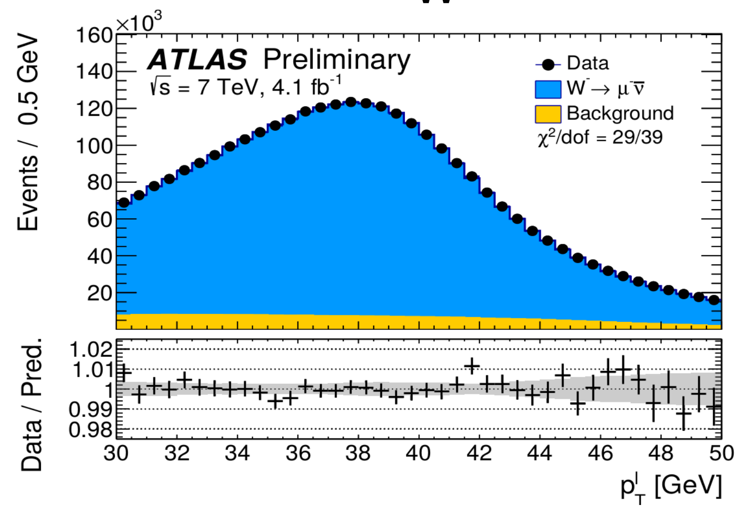
→ Pythia 8 AZ OK; DYRES, Powheg MiNLO disfavoured

Mass-sensitive distributions : p_T

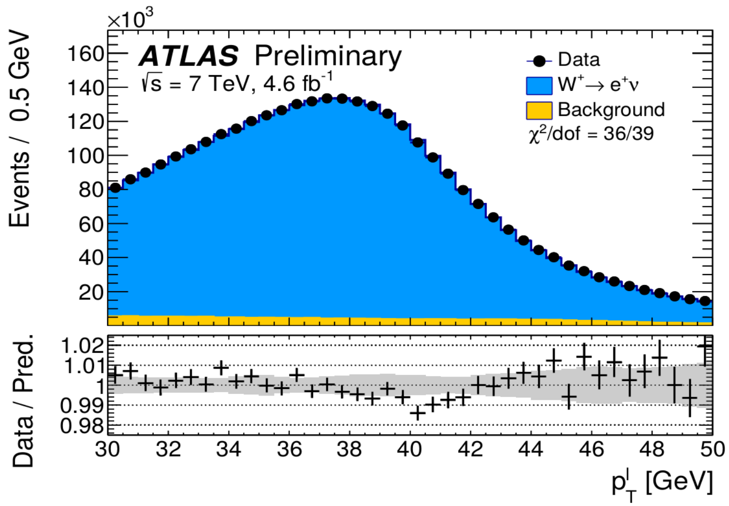
W+ W-

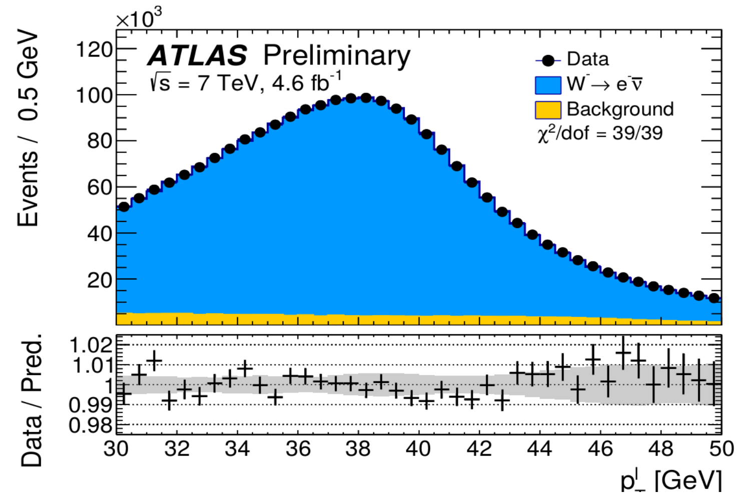
Muons





Electrons





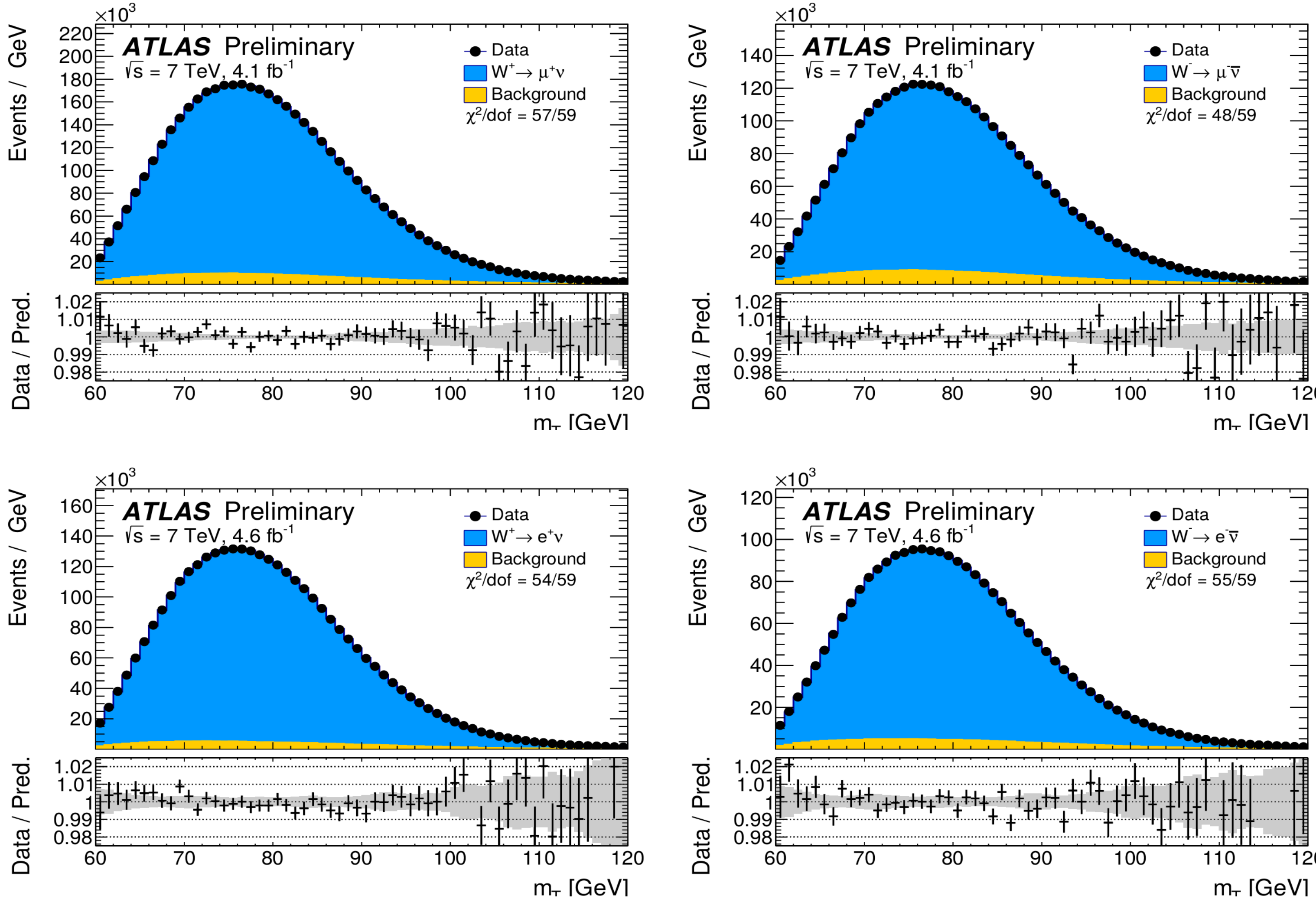
(predictions set to the result of the combined m_W fit to all distributions)

Mass-sensitive distributions : m_T

W^+ W^-

Muons

Electrons

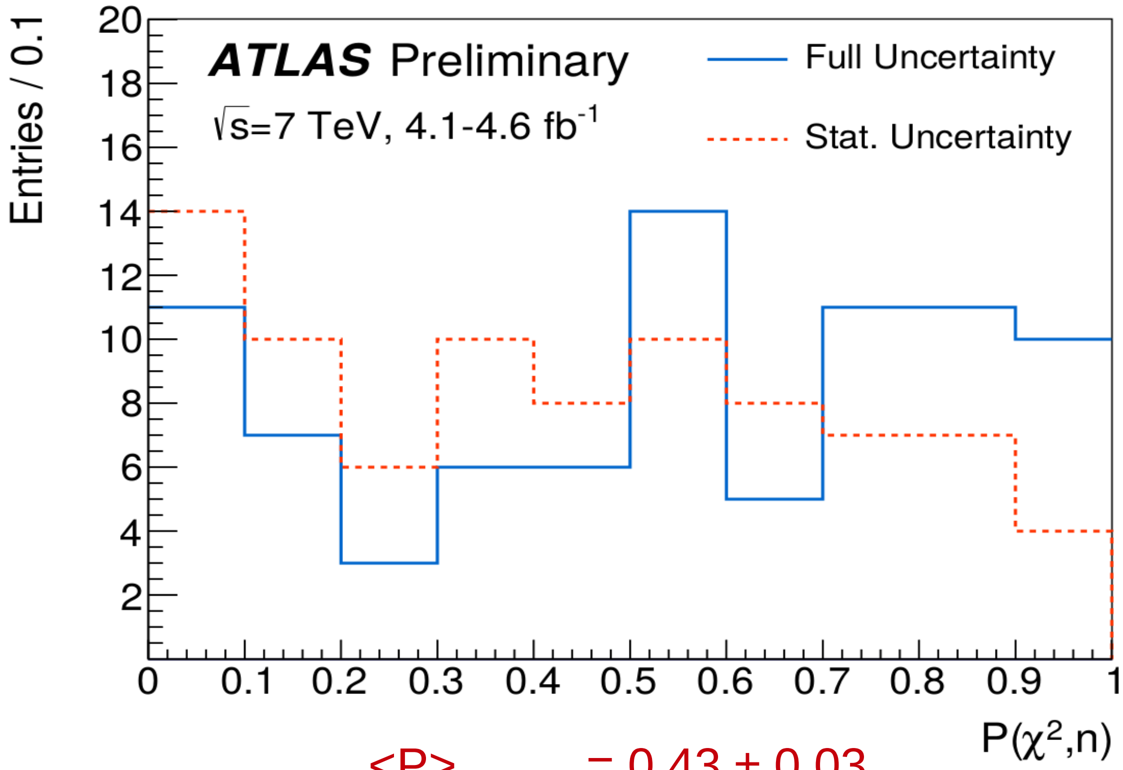


(predictions set to the result of the combined m_W fit to all distributions)

Overall modeling quality

- χ^2 / n_{dof} probability distribution from 84 data/prediction comparisons:

  Six observables, 14 measurement categories



$\langle P \rangle_{stat} = 0.43 \pm 0.03$

$\langle P \rangle_{stat+syst} = 0.54 \pm 0.03$

Results in the 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

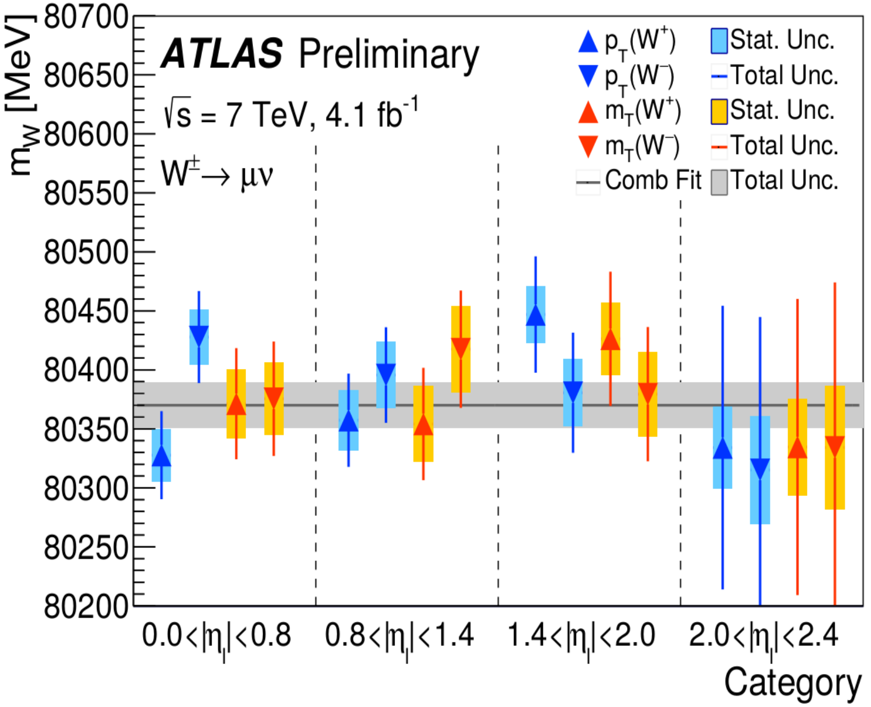
Strongly correlated

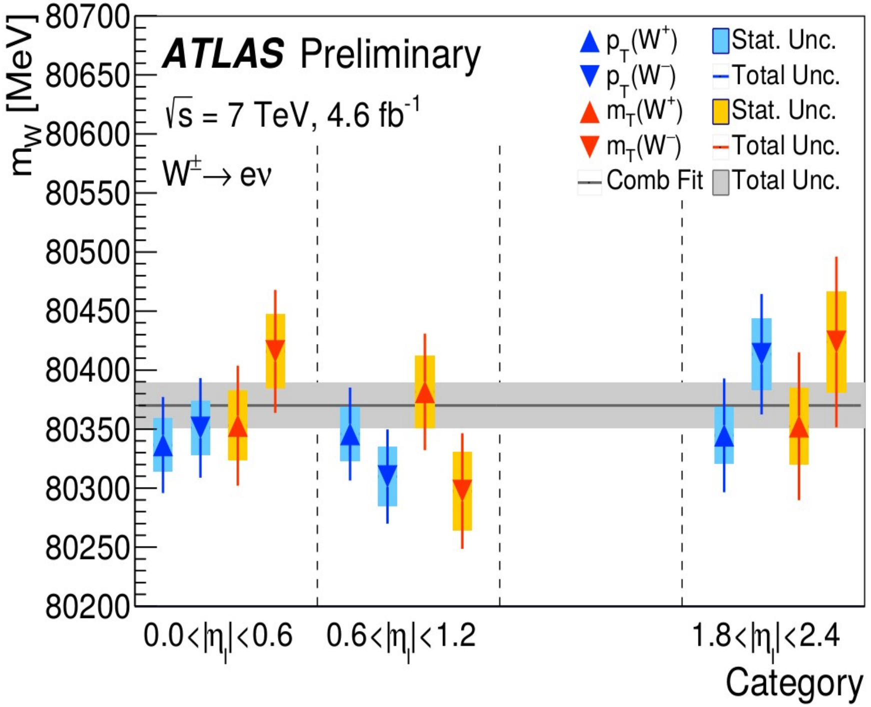
|η| comb. → ~14 MeV
W+/W- comb → ~8 MeV

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

Results : m_W

Compatibility tests, performed before unblinding :

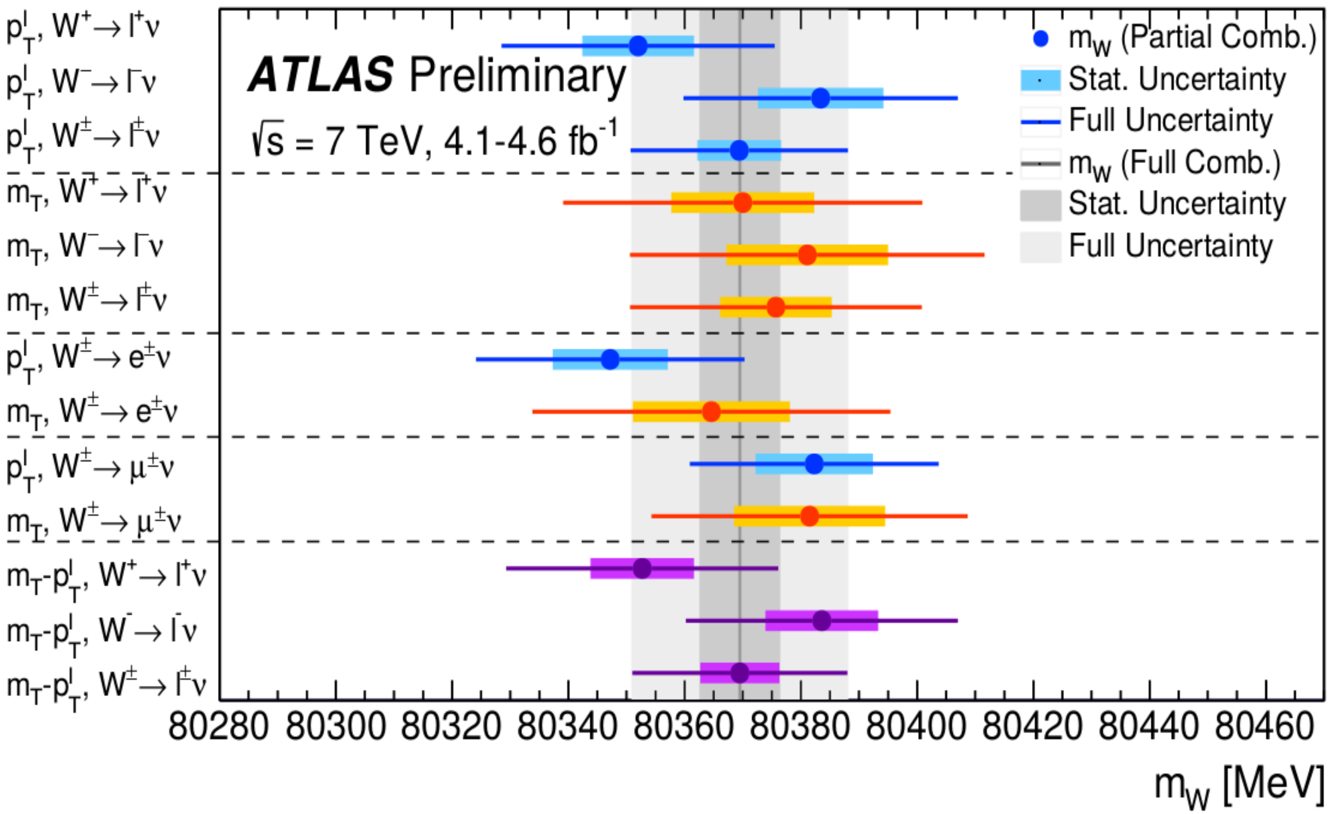




$\chi^2 / n_{dof} = 29 / 27$

Results : m_W

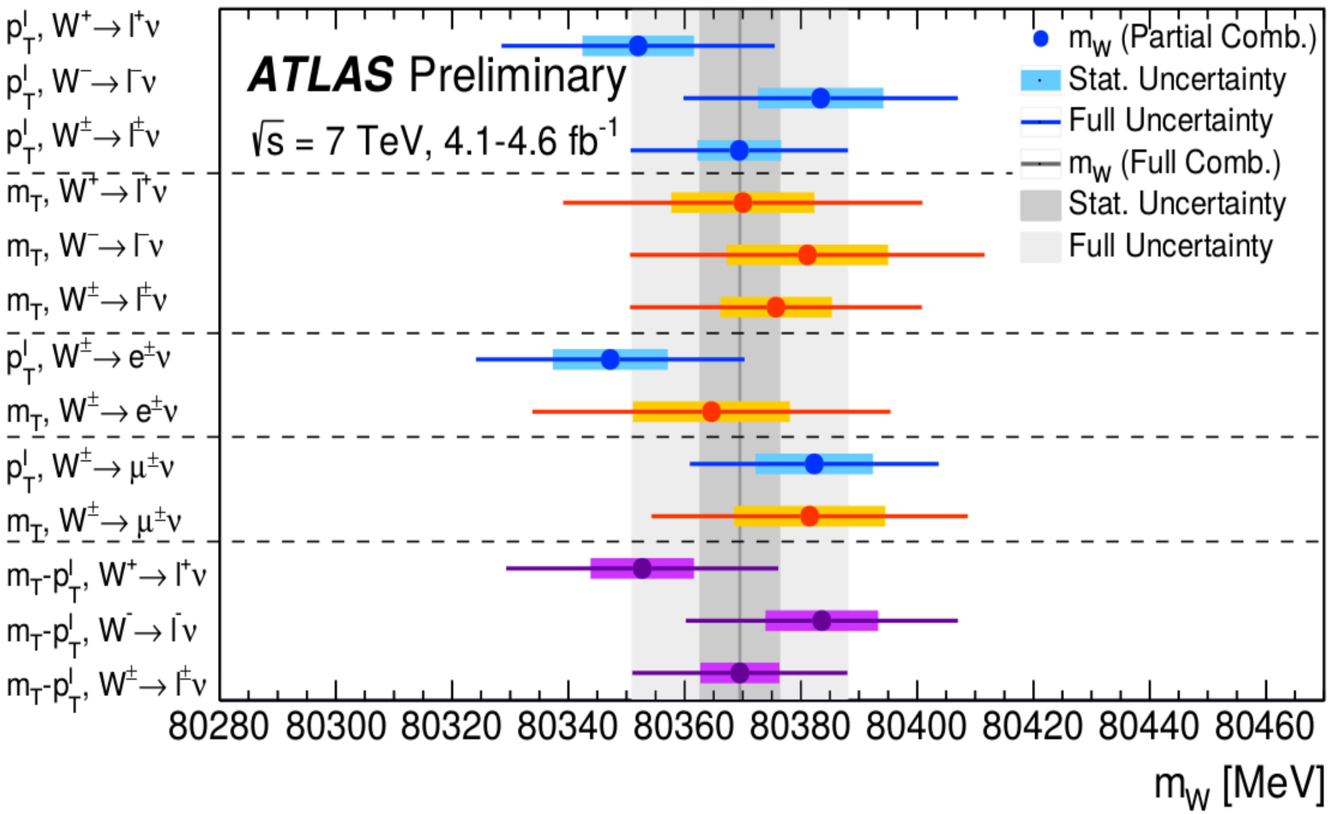
Compatibility tests, performed before unblinding :



$\chi^2 / n_{dof} = 29 / 27$

→ passed!

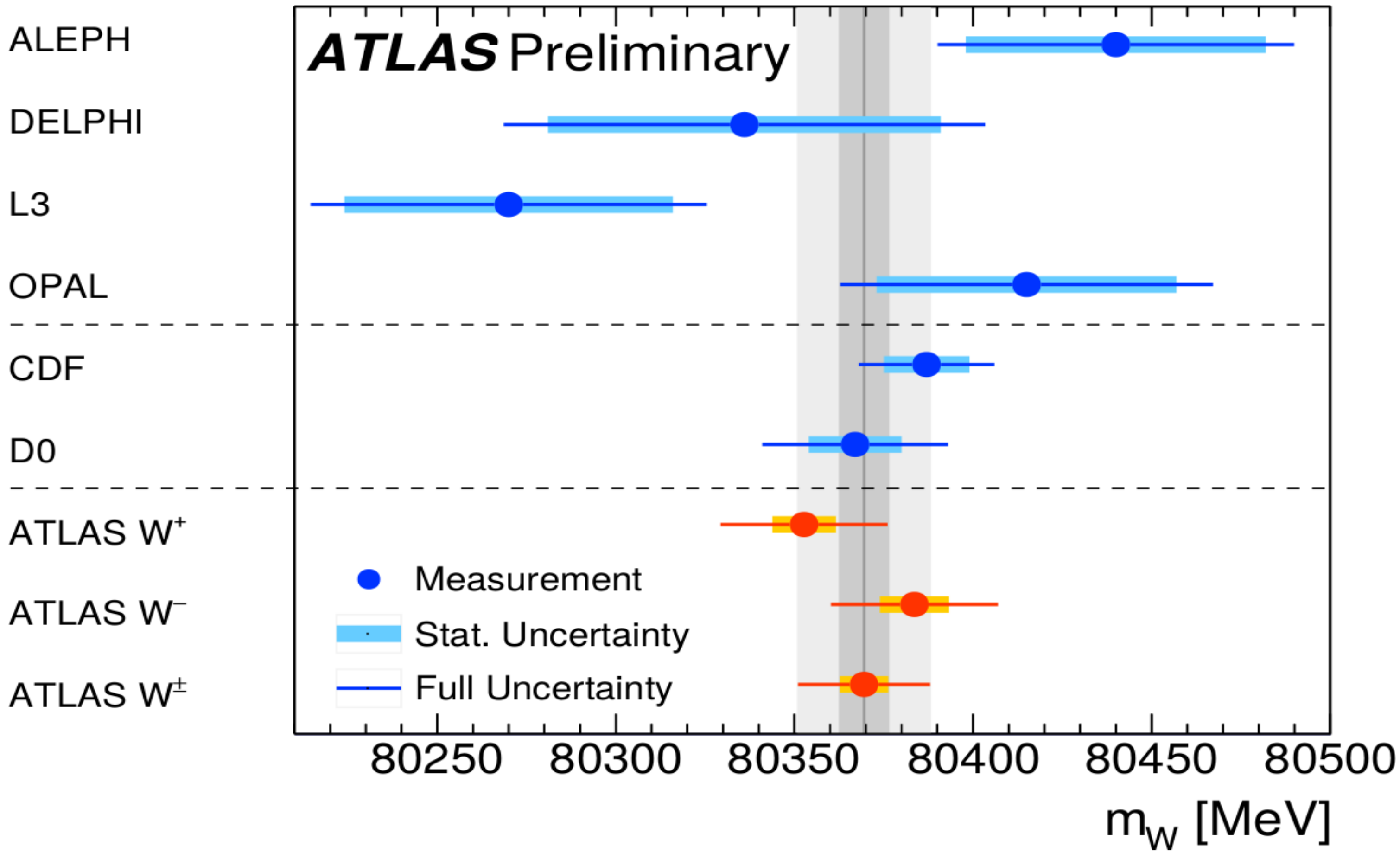
Results : m_W



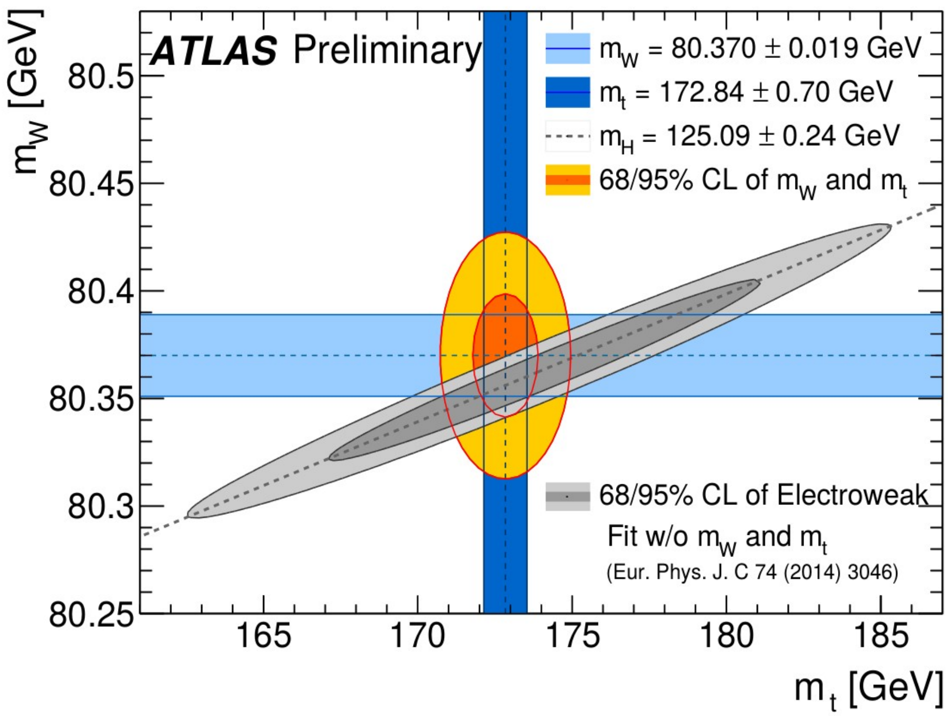
m_W = 80.370 ± 0.007 (stat.) ± 0.011 (exp.syst.) ± 0.014 (mod.syst.) GeV
= <u>80.370 ± 0.019 GeV</u>

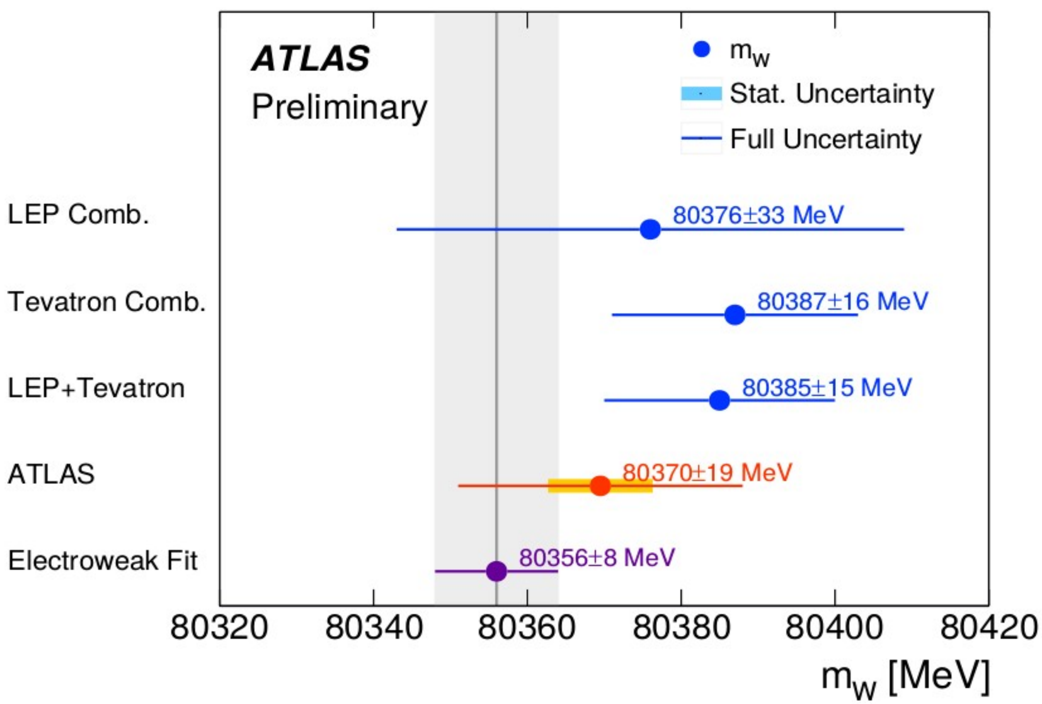
$m_{W+} - m_{W-}$ = -29 ± 13 (stat.) ± 7 (exp.syst.) ± 24 (mod.syst.) MeV
= -29 ± 28 MeV

Consistency of experimental results



Standard Model consistency





SM prediction for m_W vs m_t, assuming m_H = 125.09 ± 0.24 GeV

SM prediction for m_W, assuming
m_H = 125.09 ± 0.24 GeV
m_t = 172.84 ± 0.70 GeV

Summary

- We presented the first ATLAS measurement of m_W : $\mathbf{m_W}$ **= 80.370 ± 0.019 GeV**
  - A competitive measurement, dominated by physics modeling uncertainties as expected
  - One of the projects that ties the entire body of ATLAS data together!
  - CONF note out today : **ATLAS-CONF-2016-113**, publication to follow. We look forward to your feedback.

- Perspectives
  - We foresee to update the present result with more advanced analysis techniques and a more precise physics model, when available.
  - **Fantastic W and Z samples made available by the LHC at 8 and 13 TeV**. Modelling uncertainties need to be reduced in order to fully exploit these data.

- Many extremely interesting complications encountered : to be pursued!
  - PDF uncertainties; PDF/PS interplay; uncertainty on the W/Z p_T distribution ratio; why are the resummed predictions so hard? Angular distributions in W production? **Can we build a fully consistent model within one single tool?**
  - Could hardly discuss these questions here; we tried to address them conservatively in the analysis – concrete discussions in the near future are crucial to make real progress.

Extra material

Transmission of the predictions to the analysis samples

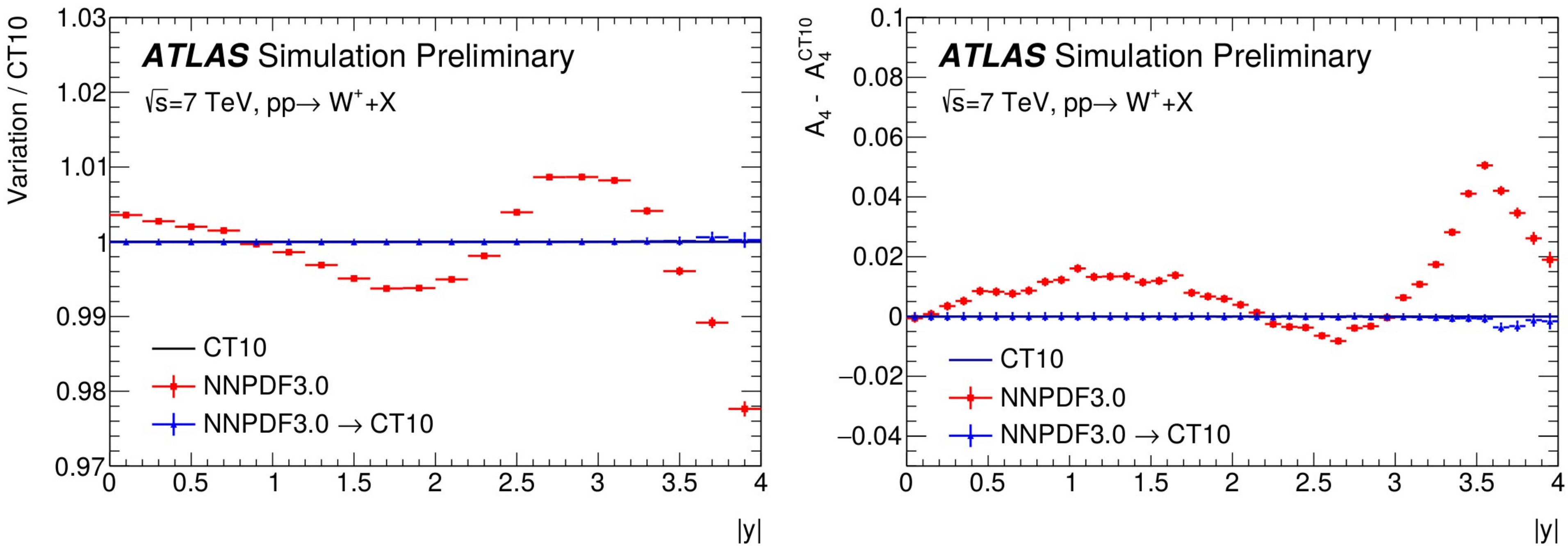
- Fully differential cross section for spin-1 boson production, to all orders:

$$\frac{d\sigma}{dm\,dy\,dp_T\,d\cos\theta\,d\varphi} = \frac{d\sigma}{dm\,dy\,dp_T}\left[\left(1+\cos^2\theta\right)+\sum_i A_i f_i(\cos\theta,\varphi)\right]$$

  Can be used to define event weights to transpose any prediction into any other.

  Inputs, neglecting *m* : a 2D (p_T,y) histogram + A_i(p_T,y) maps, i = 0 – 4

Reweighting variables :



Transmission of the predictions to the analysis samples

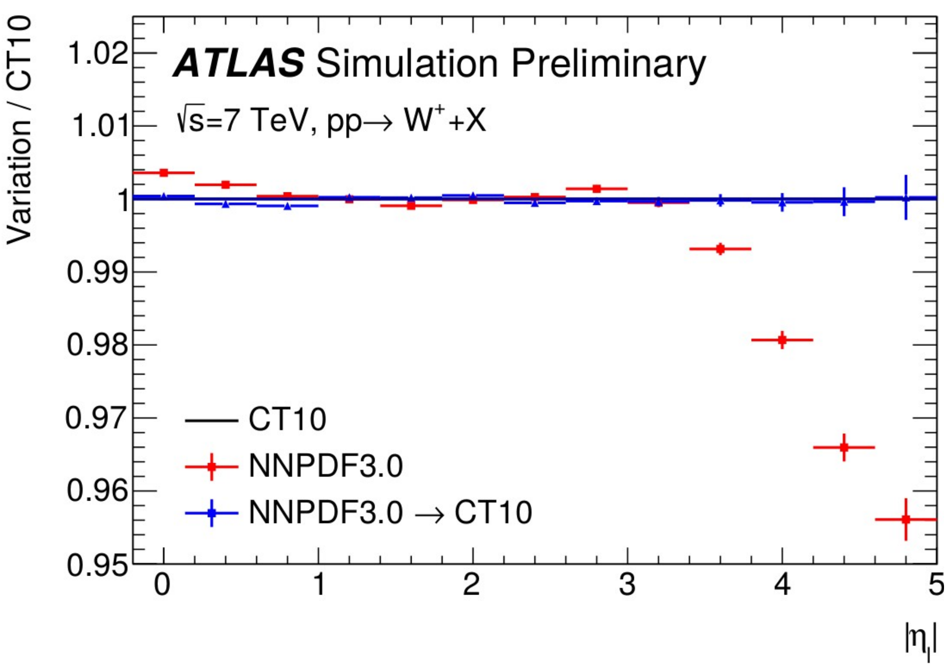
- Fully differential cross section for spin-1 boson production, to all orders:

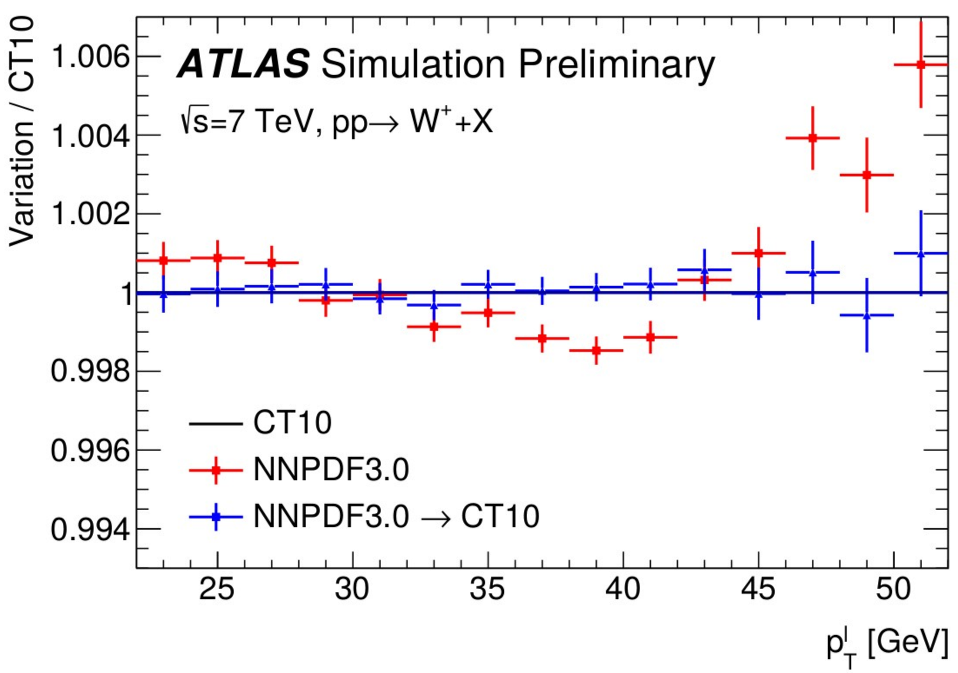
$$\frac{d\sigma}{dm\,dy\,dp_T\,d\cos\theta\,d\varphi}=\frac{d\sigma}{dm\,dy\,dp_T}\left[\left(1+\cos^2\theta\right)+\sum_i A_i f_i(\cos\theta,\varphi)\right]$$

Can be used to define event weights to transpose any prediction into any other.

Inputs, neglecting *m* : a 2D (p_T,y) histogram + A_i(p_T,y) maps, i = 0 – 4

Final state variables :

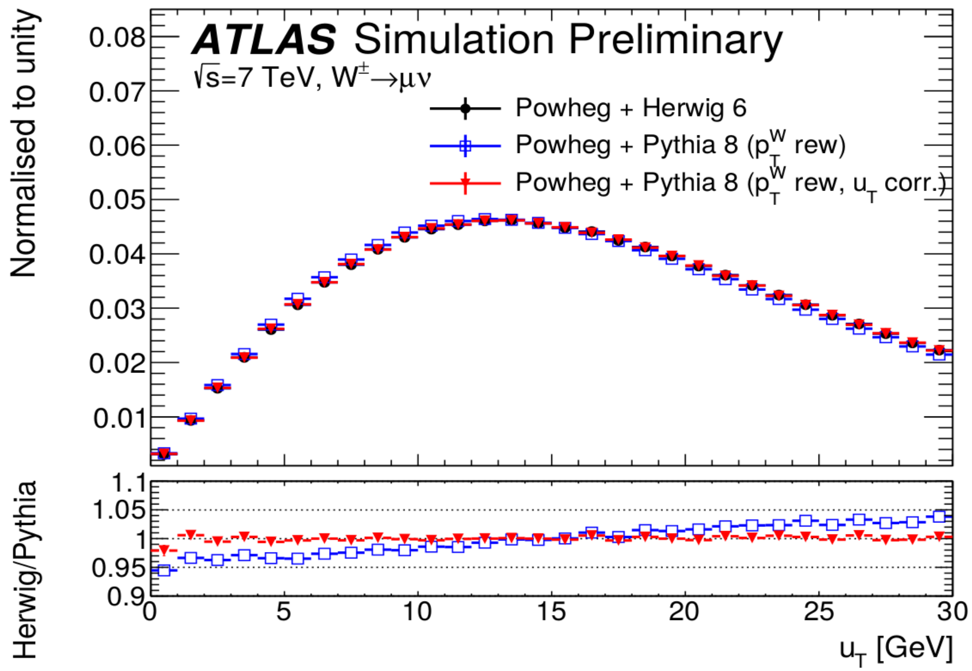


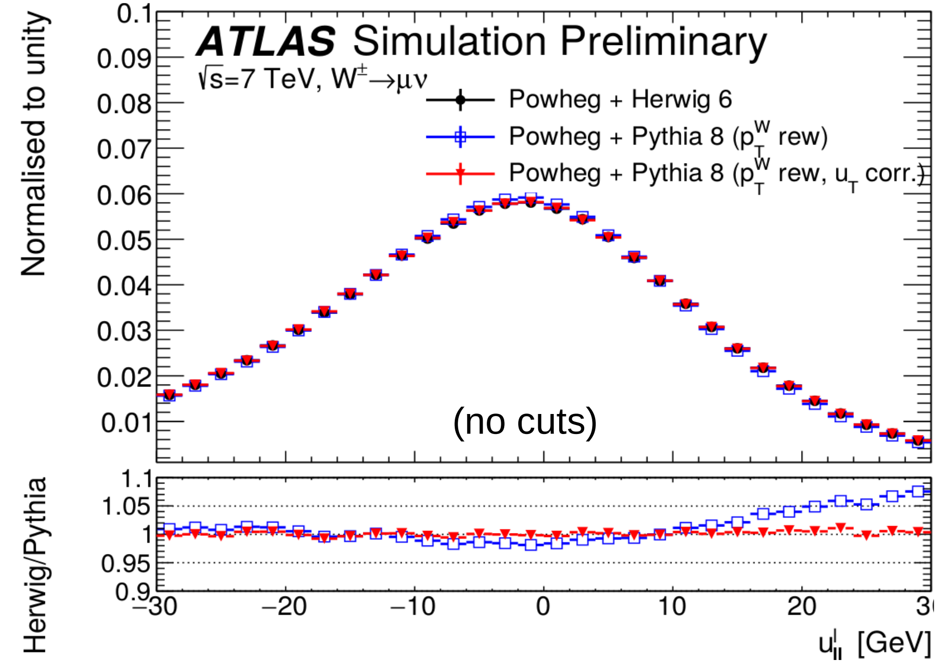


Recoil calibration

- Closure test and physics sensitivity
  - MC : Powheg + Pythia   Pseudo-data : Powheg + Herwig

    (parton shower, underlying event, hadronization models differ – everything else identical)



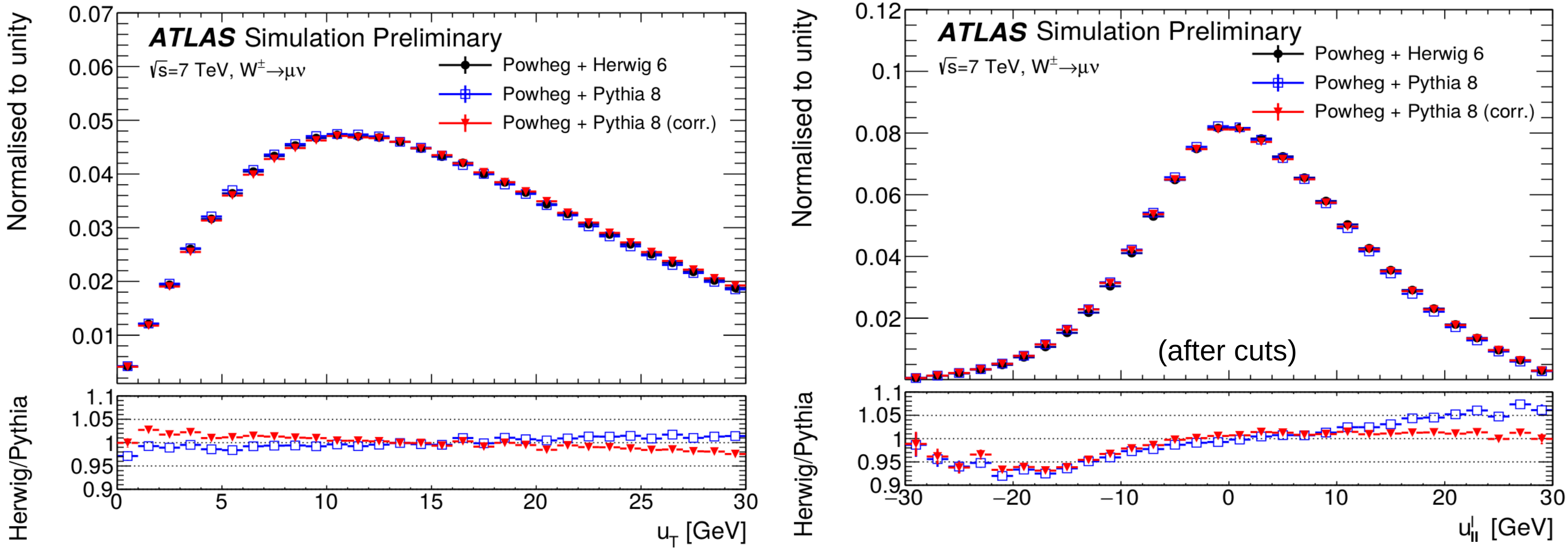


Closure : when the p_T^W distributions in both generators are made to agree, and recoil corrections are derived for Powheg+Pythia treating Powheg+Herwig as data, the resulting distributions agree perfectly

Recoil calibration

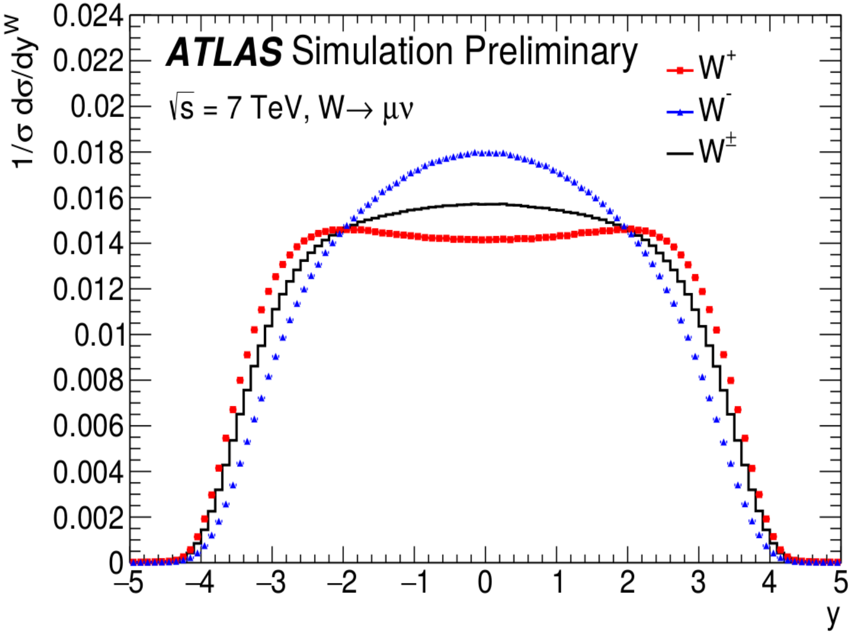
- Physics sensitivity
  - MC : Powheg + Pythia   Pseudo-data : Powheg + Herwig

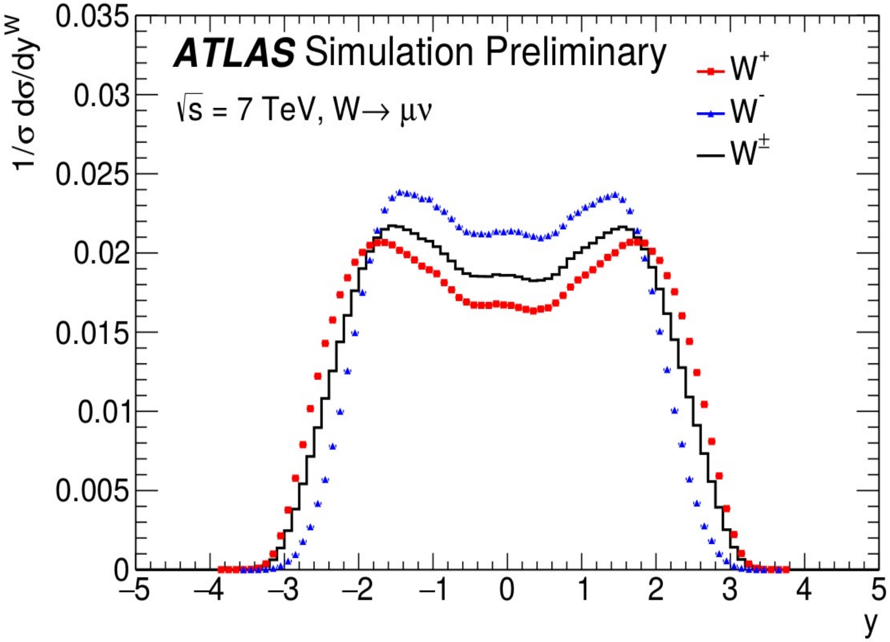
    (parton shower, underlying event, hadronization models differ – everything else identical)



Physics sensitivity of the recoil distributions, after corrections

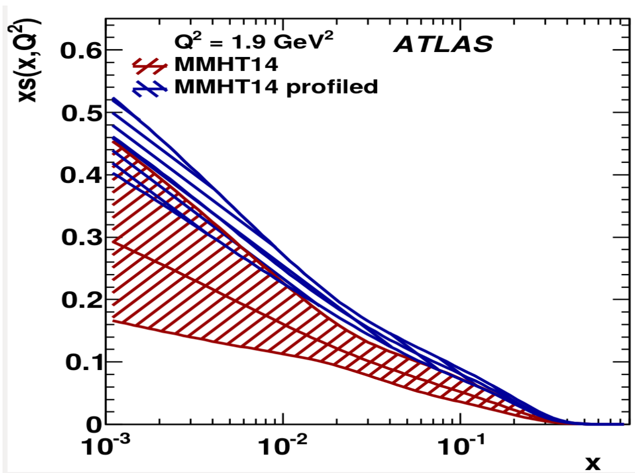
Particle-level distributions before/after analysis cuts

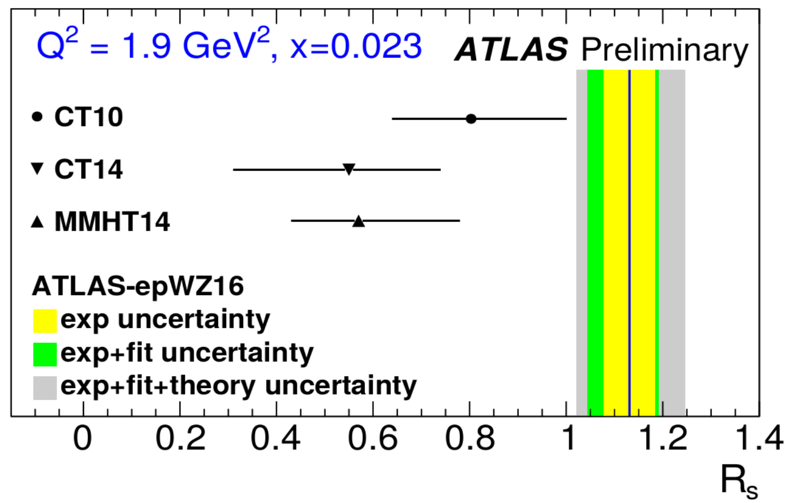




Rapidity distribution

- Prominent feature : excess of Z data at central rapidity, interpreted as due to a strange density larger than expected in most PDF sets



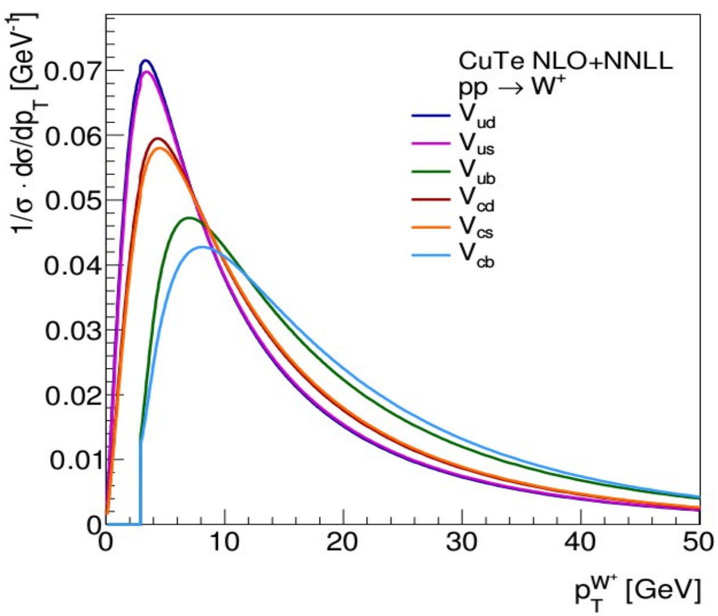


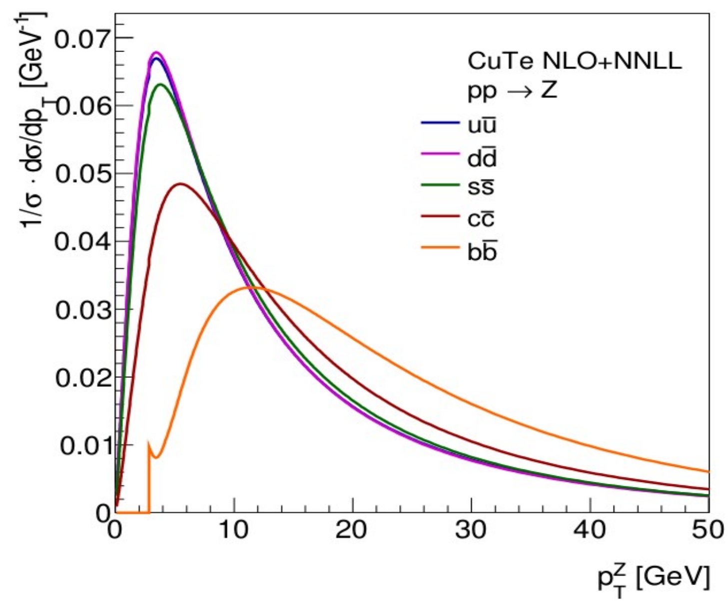
Of the global PDF sets, CT14 and MMHT provide acceptable descriptions. CT10 has highest strange density and is used as our baseline.

Data set	n.d.f.	ABM12	CT14	MMHT14	NNPDF3.0	ATLAS-epWZ12
$W^+ \to \ell^+ \nu$	11	11|21	10|26	11|37	11|18	12|15
$W^- \to \ell^- \bar{\nu}$	11	12|20	8.9|27	8.1|31	12|19	7.8|17
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 46 - 66$ GeV)	6	17|21	11|30	18|24	21|22	28|36
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	12	24|51	16|66	20|116	14|109	18|26
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 66 - 116$ GeV)	9	7.3|9.3	10|12	12|13	14|18	6.8|7.5
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	6.1|6.6	6.3|6.1	5.9|6.6	6.1|8.8	6.7|6.6
Forward $Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} = 116 - 150$ GeV)	6	4.2|3.9	5.1|4.3	5.6|4.6	5.1|5.0	3.6|3.5
Correlated χ^2		57|90	39|123	43|167	69|157	31|48
Total χ^2	61	136|222	103|290	118|396	147|351	113|159

Transverse momentum distribution

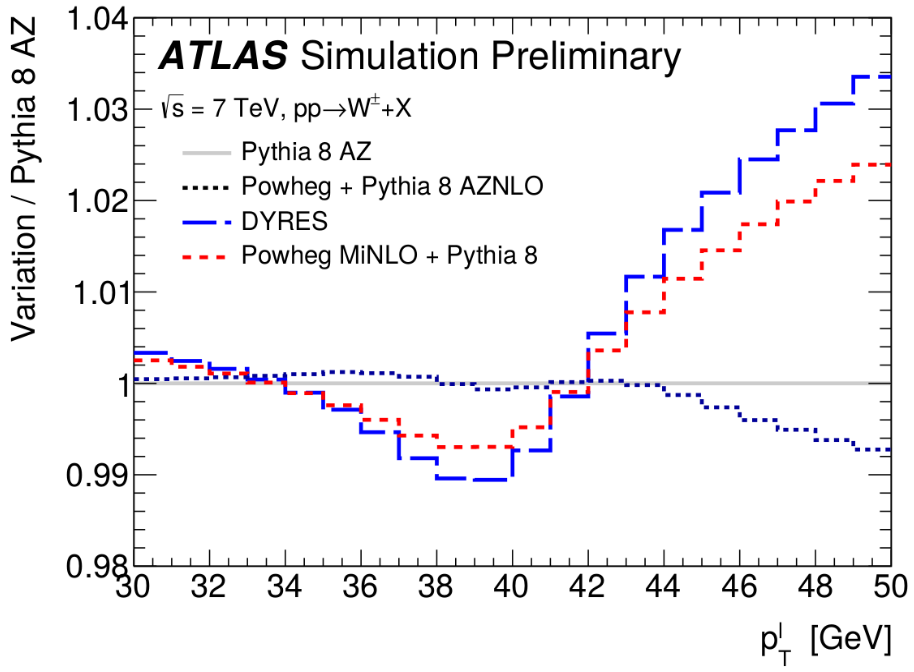
- But beyond parton shower / resummation parameters, the pT distributions also depend on the PDFs:

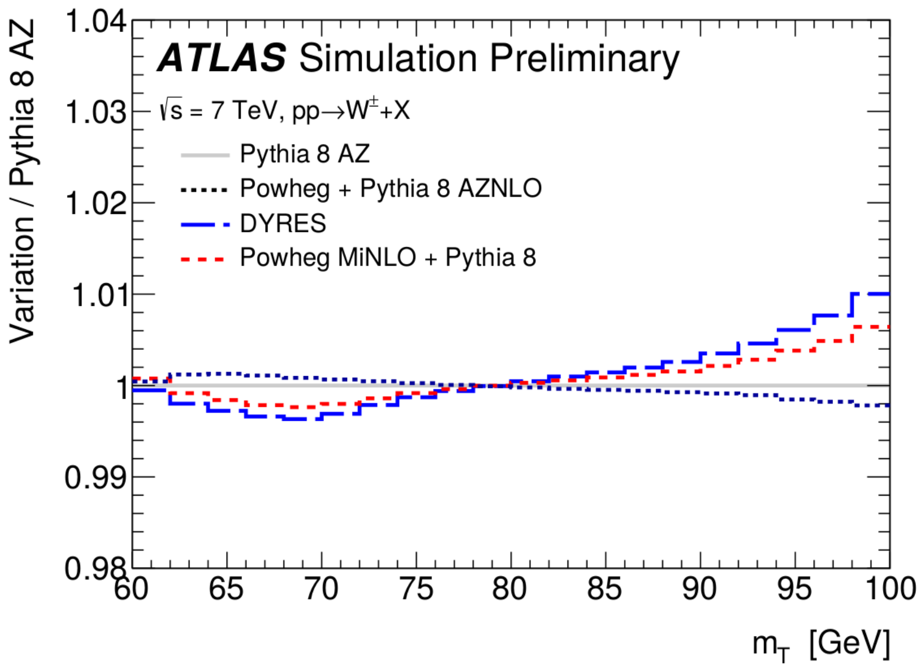




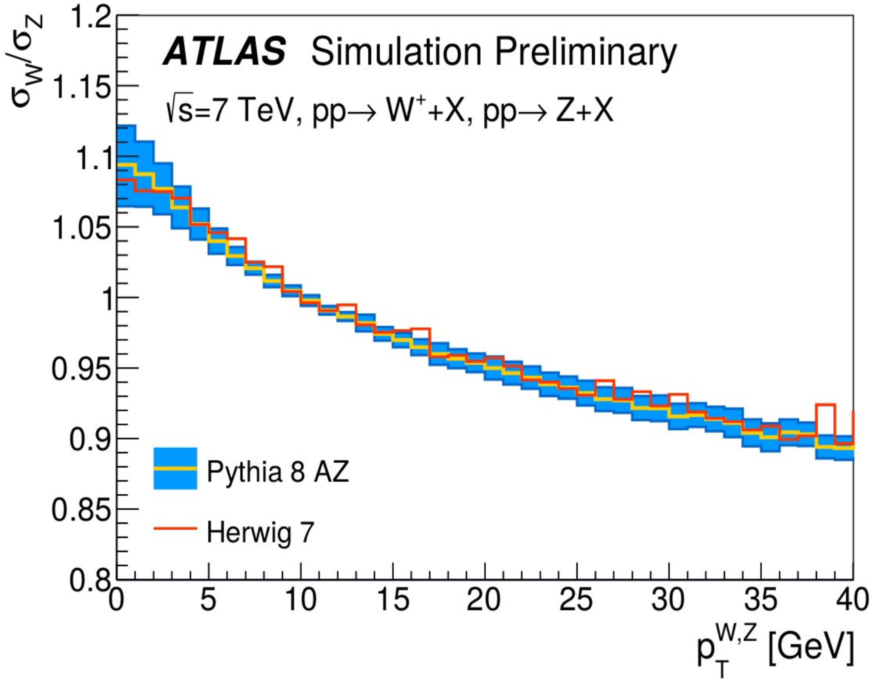
- Needs to be under control, for a proper extrapolation of the tuned predictions to W production. Uncertainty on the pT prediction for given flavour?
- Ideally, prefer a fully integrated theoretical framework, with consistent PDFs used for all aspects of the prediction (→ resummation). In shower MC's,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

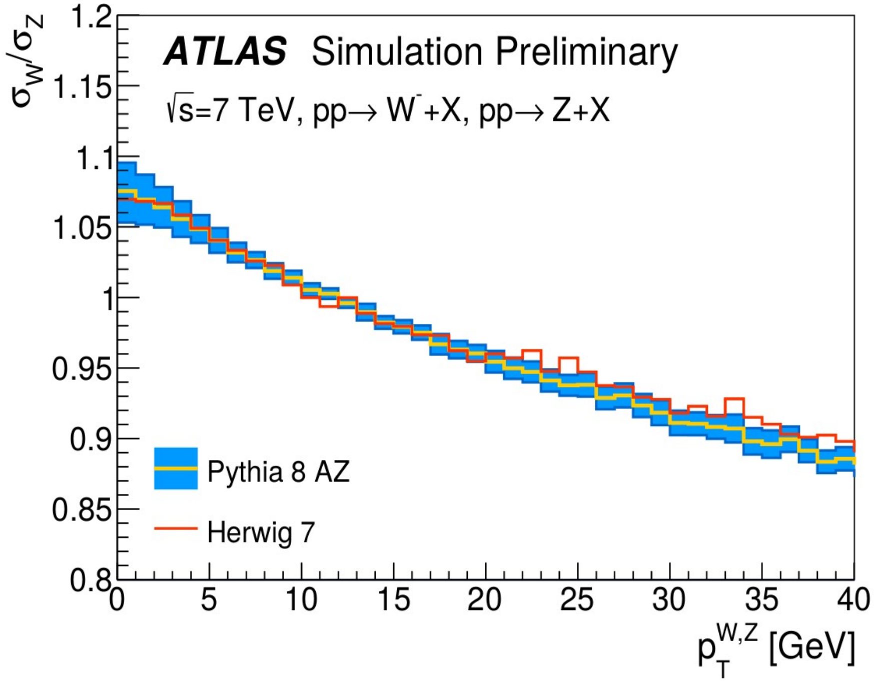
Effect of p_T^W variations on final state distributions



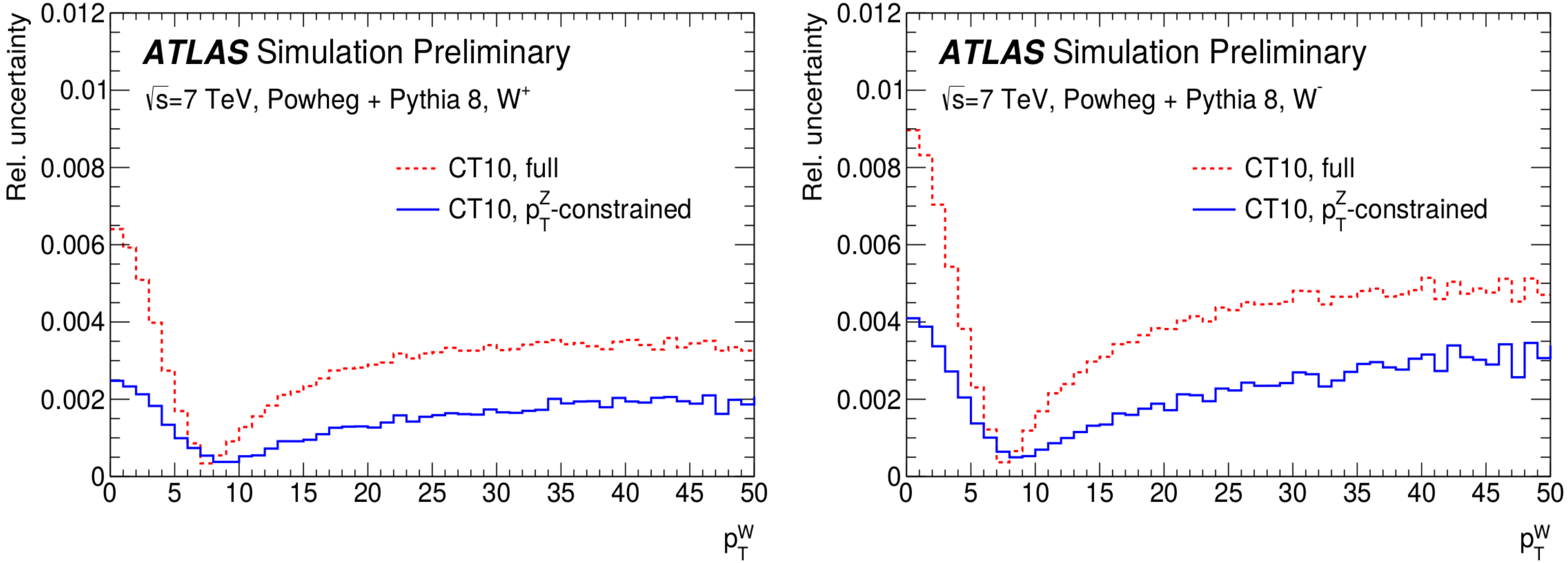


Pythia vs Herwig





PDF uncertainties on the pT distribution

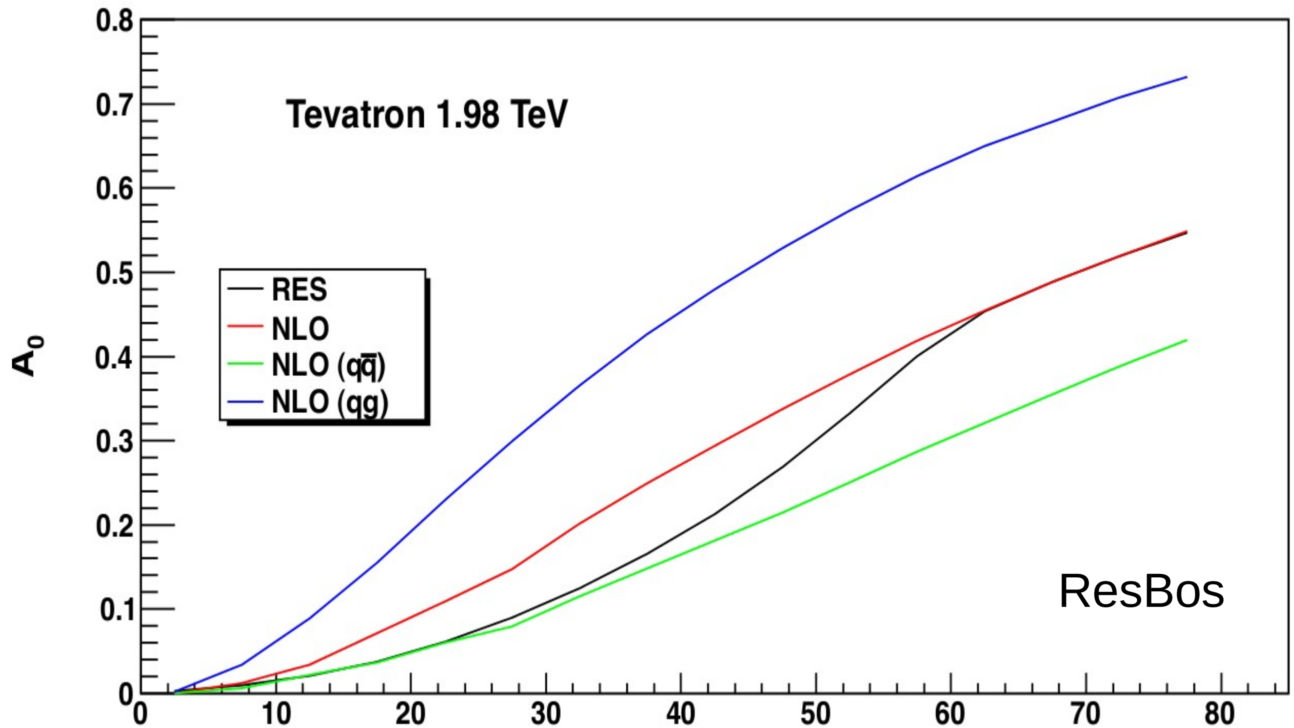


Angular distributions

- Fully differential cross section for spin-1 boson production, to all orders:

$$\frac{d\sigma}{dm\,dy\,dp_T\,d\cos\theta\,d\varphi} = \frac{d\sigma}{dm\,dy\,dp_T}\left[(1+\cos^2\theta) + \sum_i A_i(m, p_T, y) f_i(\cos\theta, \varphi)\right]$$

- Consider for example A_0, coefficient of $f_0(\theta) = \frac{1}{2}(1-3\cos^2\theta)$



From lectures by C-P Yuan

qg → W

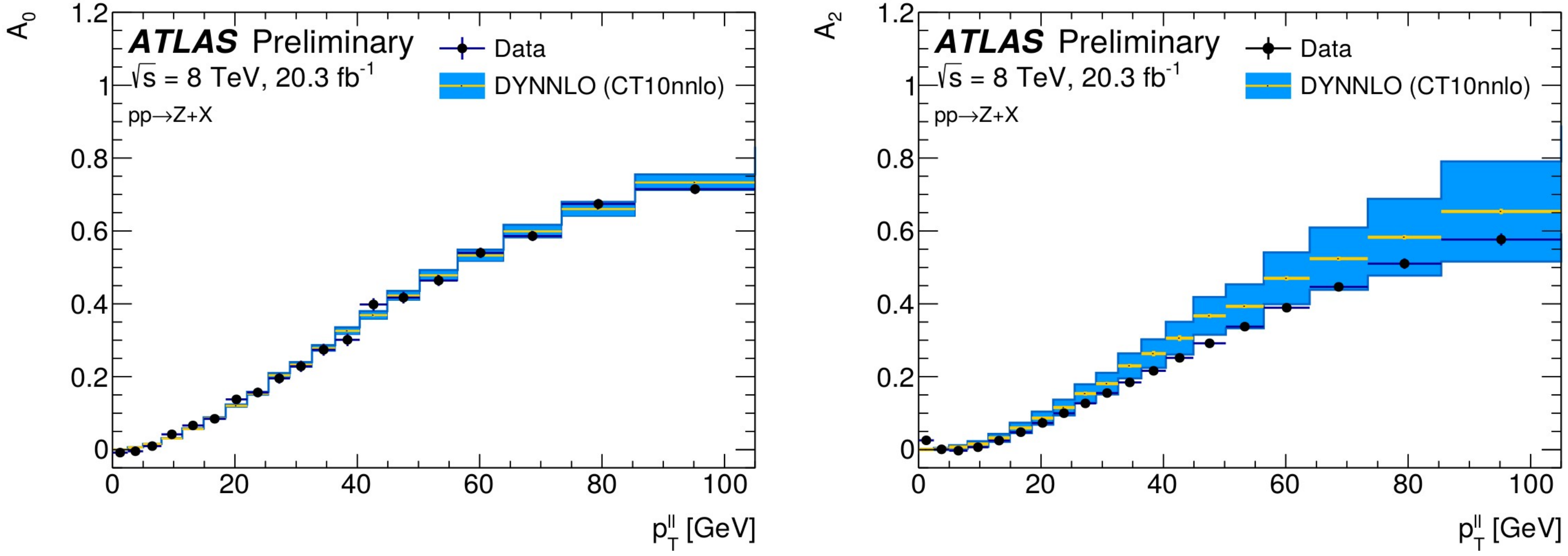
qq → W

qq+qg → W, fixed-order

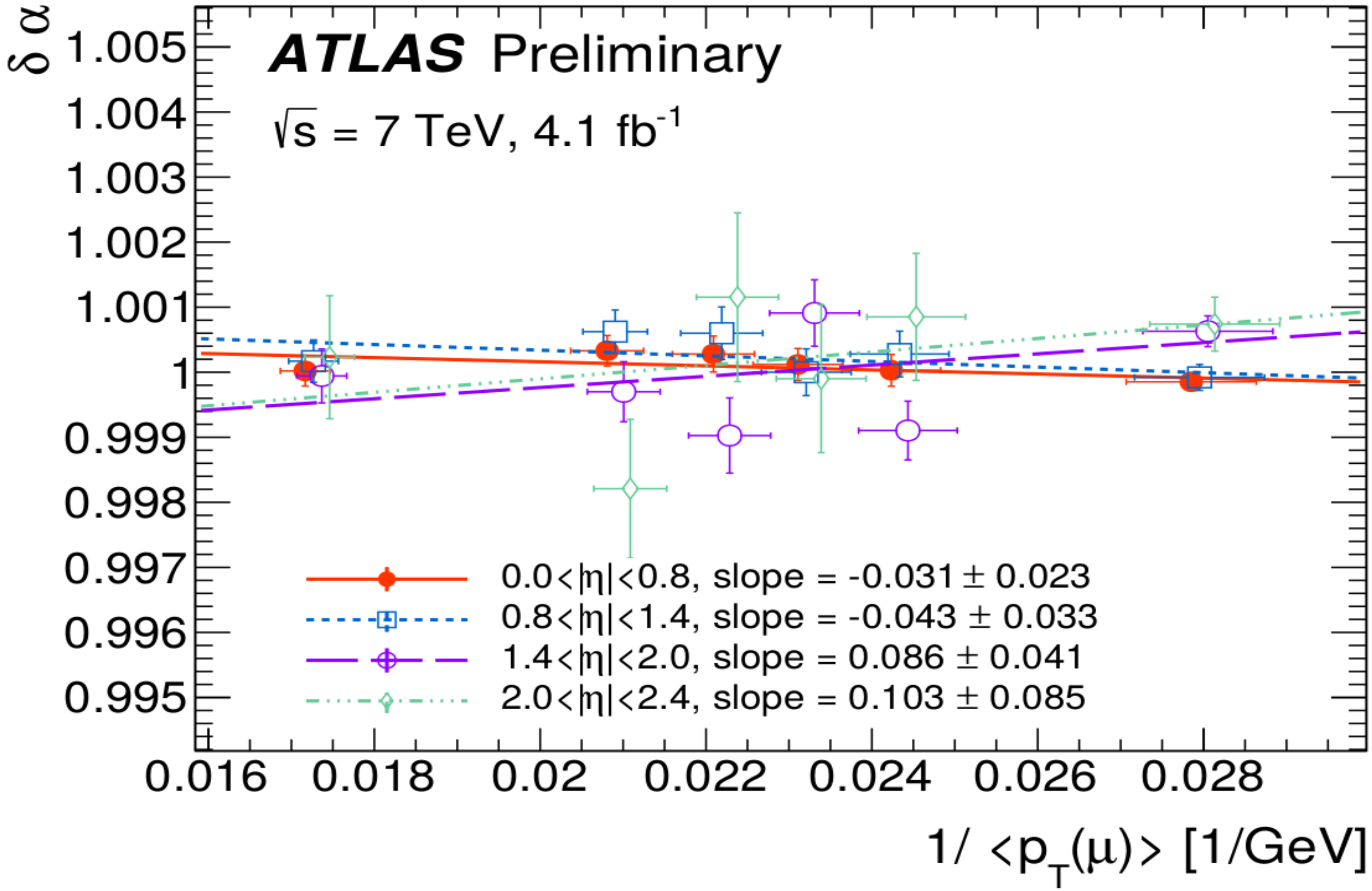
qq+qg → W, resummed

Is boson production at finite pT fundamentally gluon-induced, or quark-induced + ISR?

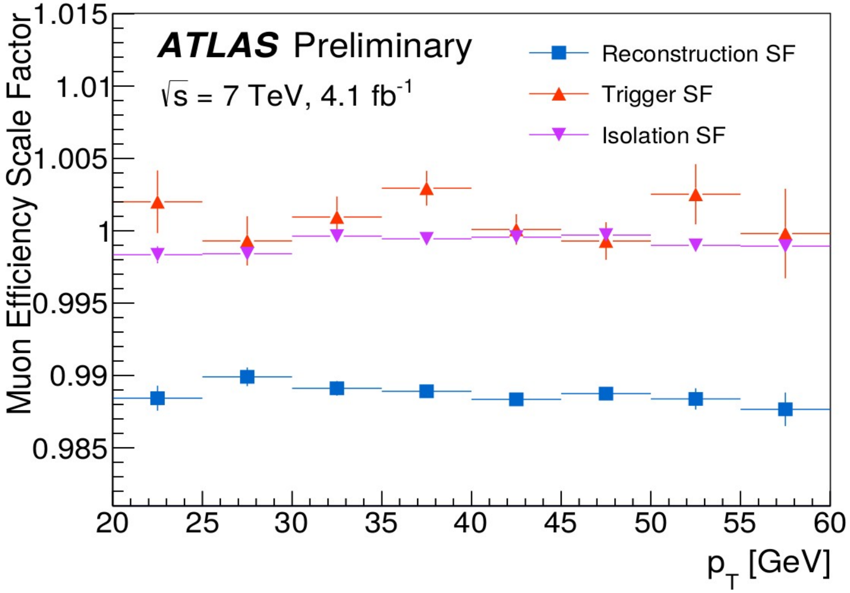
A0, A2 uncertainty variations

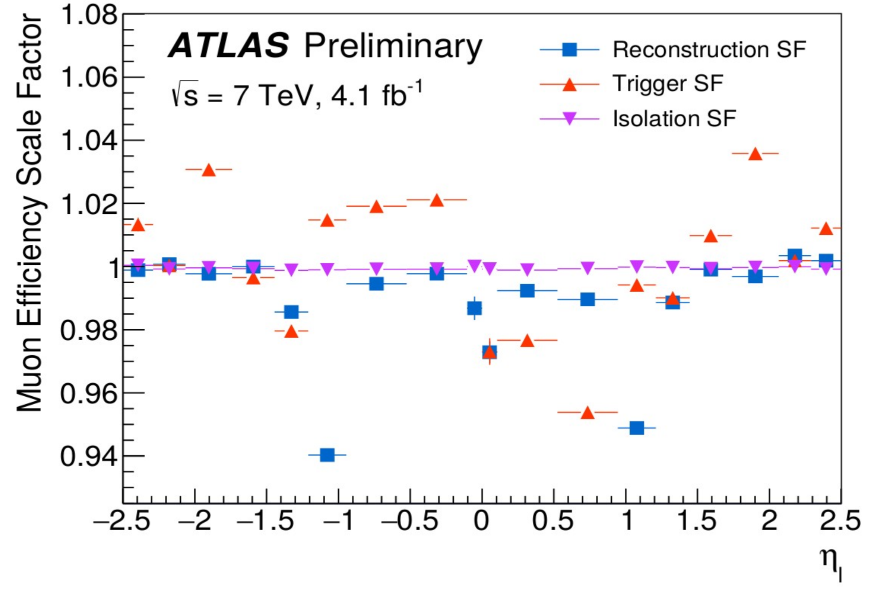


More muon plots

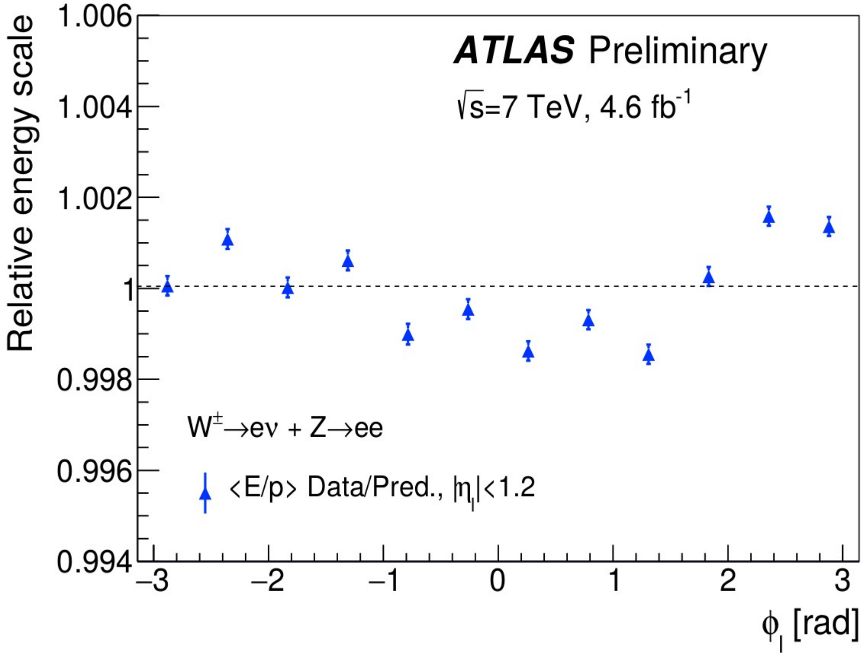


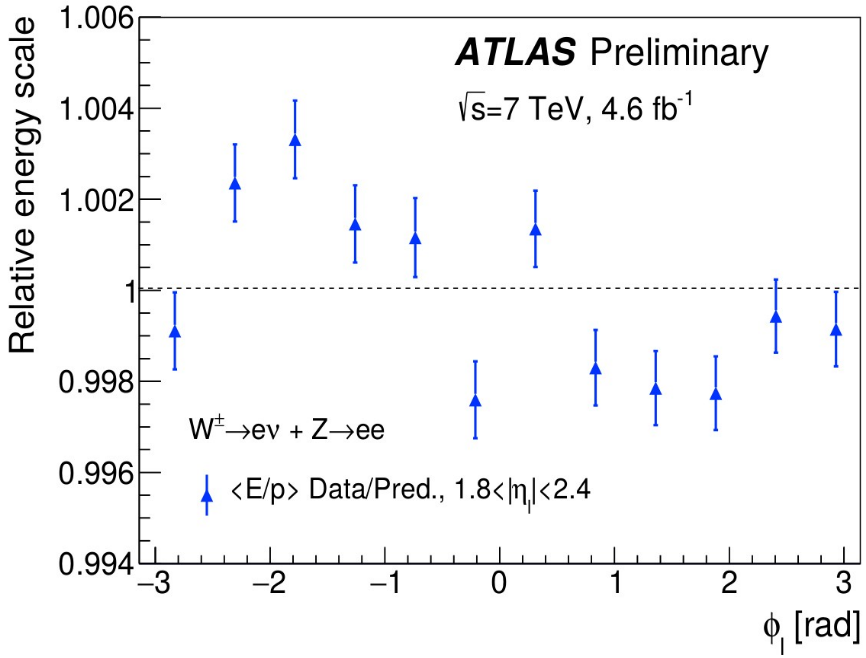
More muon plots





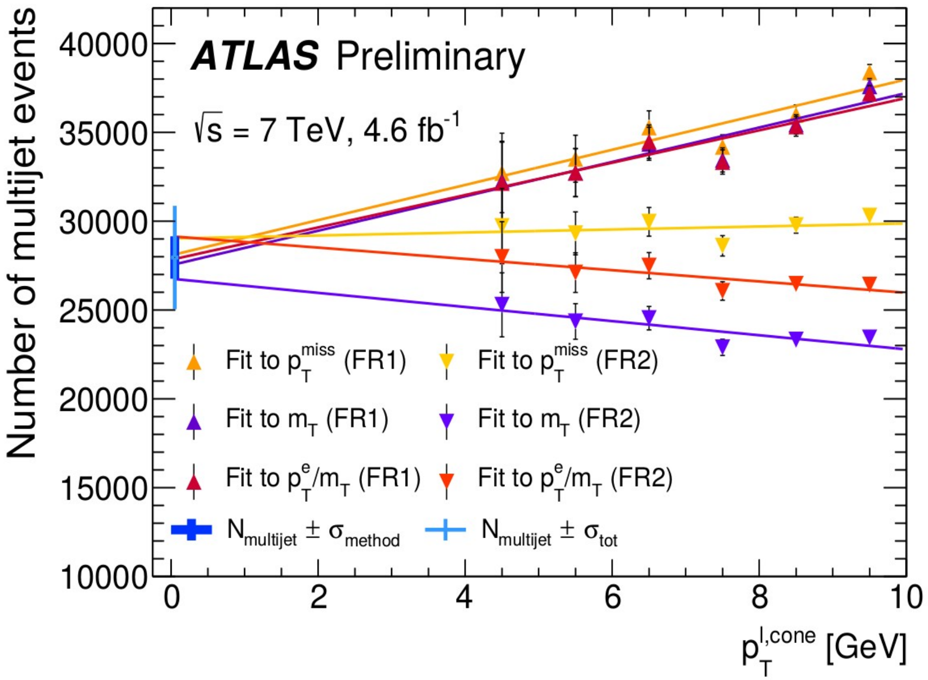
More electron plots

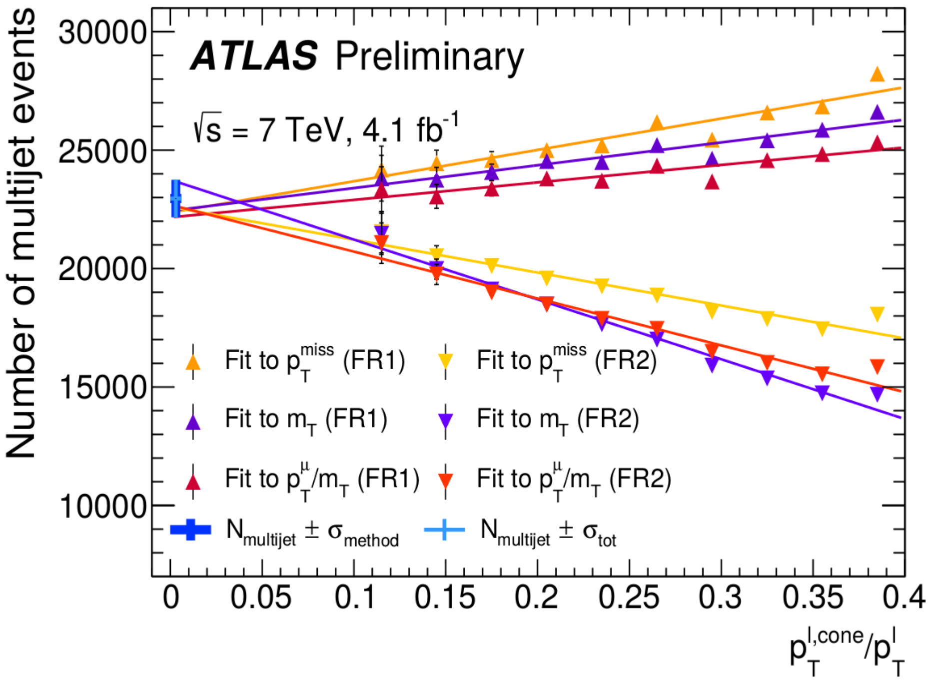




Backgrounds in the W sample

- Refinement : dependence on anti-isolation criterion
  - The 6 fraction fit results differ by up to 40% at large anti-isolation
  - Nice convergence is observed when extrapolating each fit to the isolation range used for the signal selection
  - Final accuracy on the MJ yield : 3% / 9% in the muon / electron channels





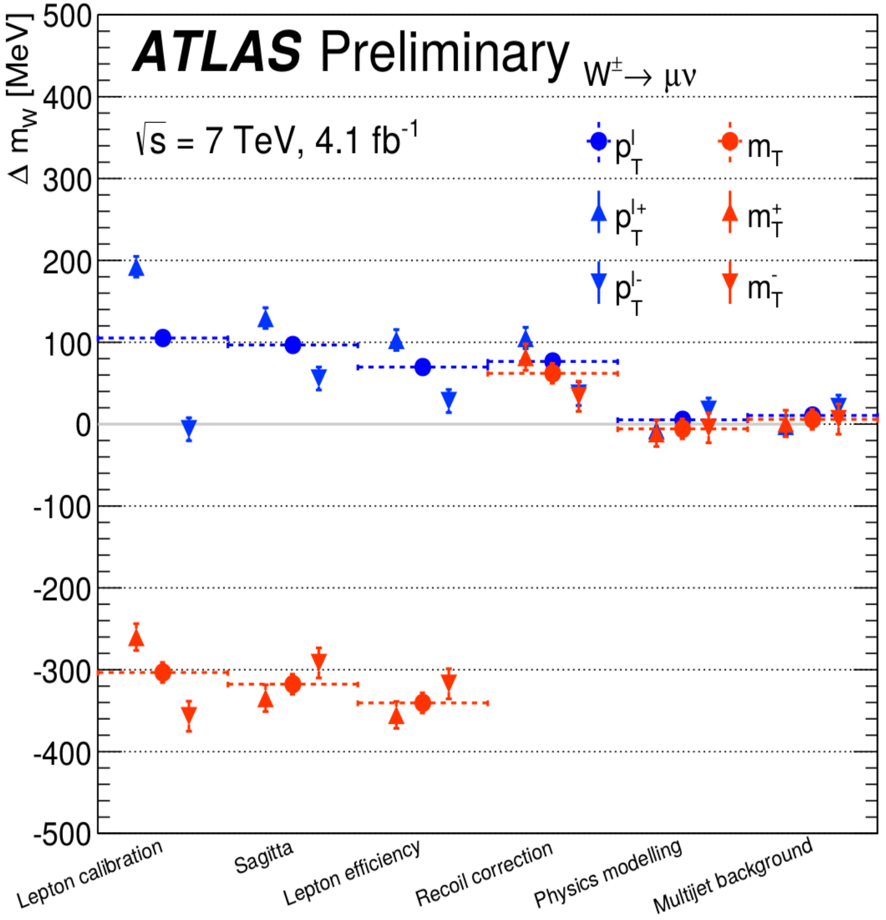
Backgrounds in the W sample

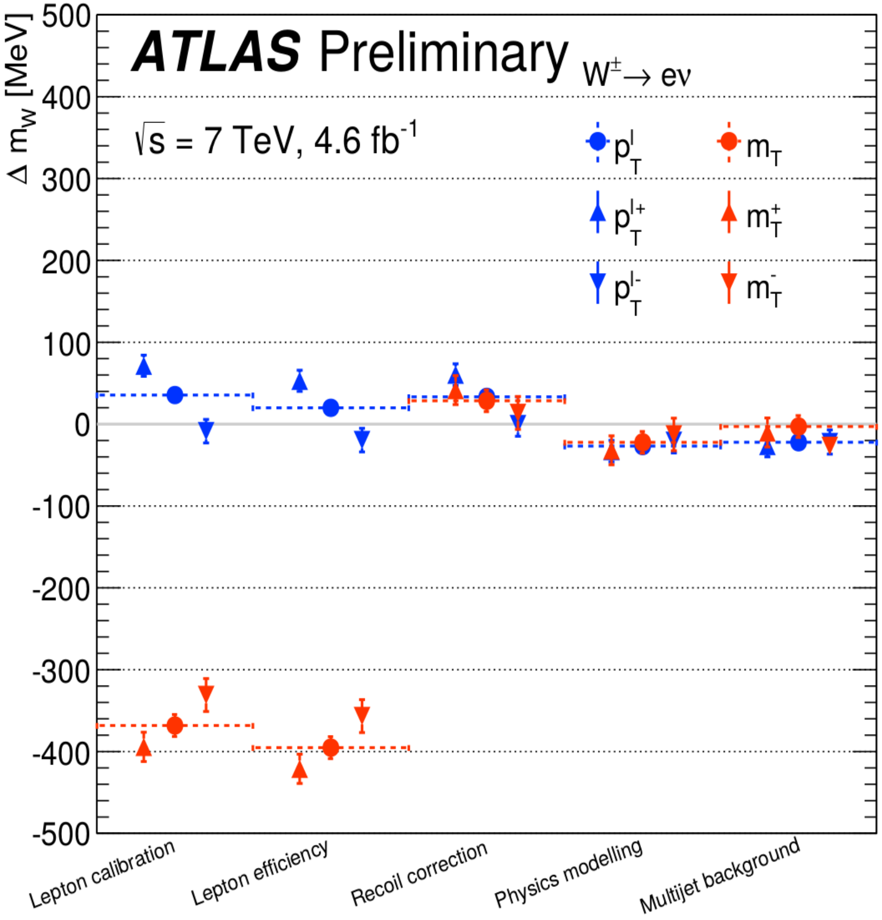
Summary of background fractions (%):

$W \to \mu\nu$						
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

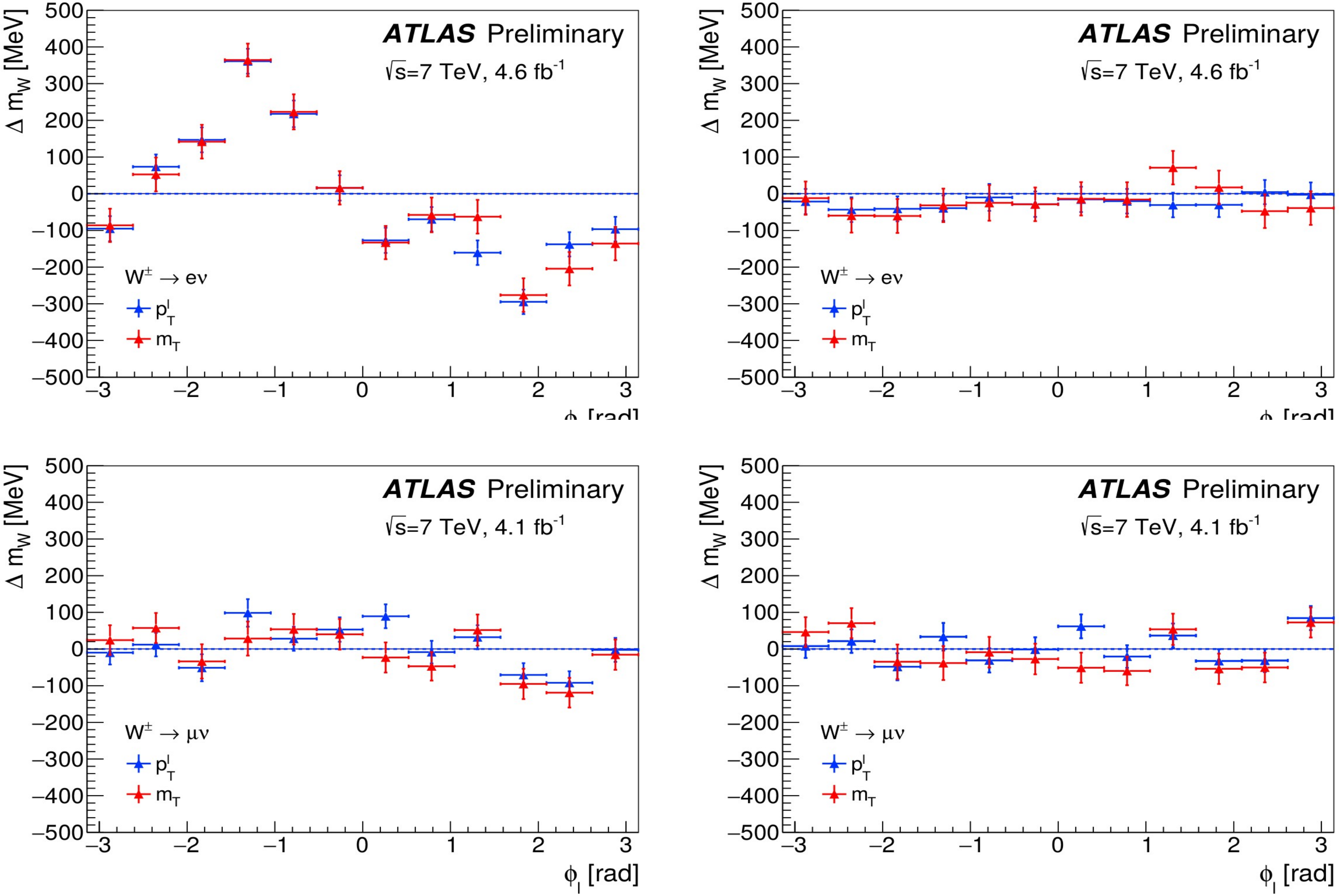
Mass fits after successive corrections



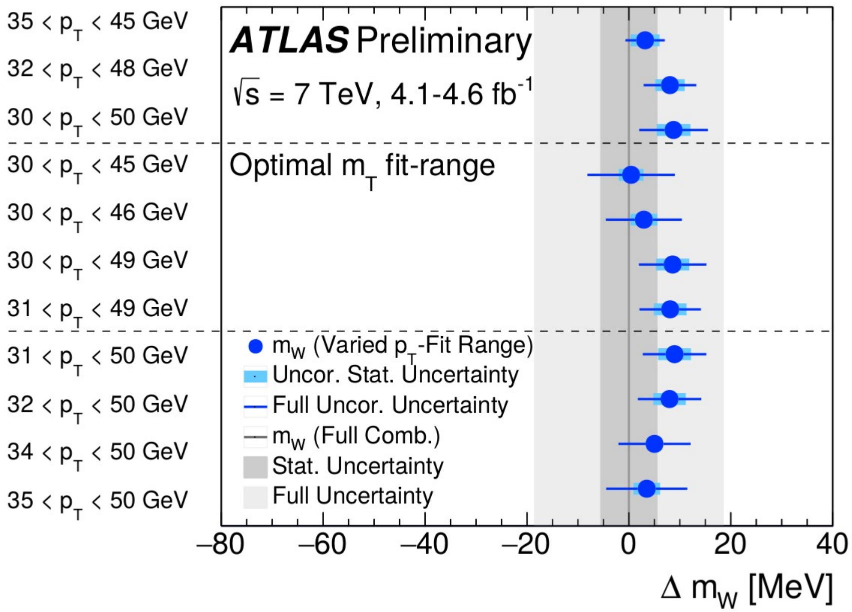


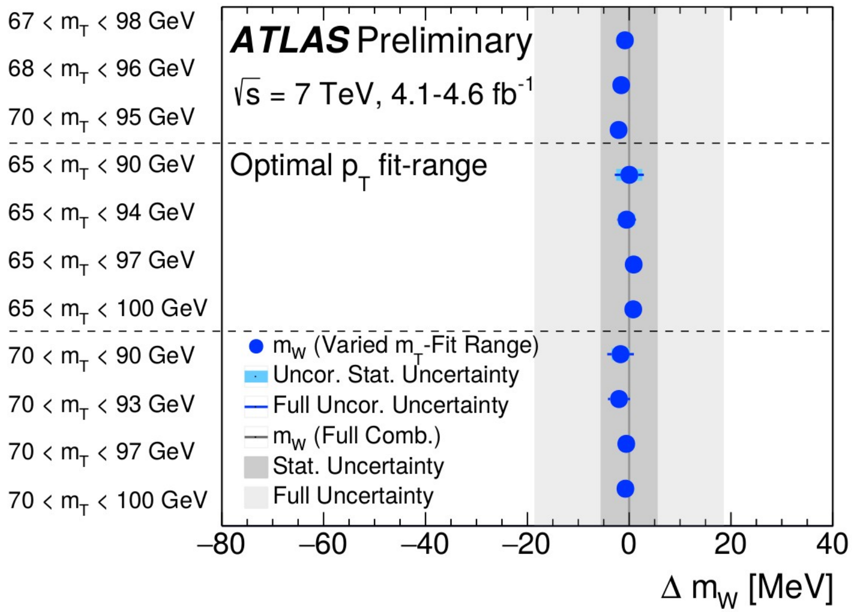
All correction steps play a critical role in achieving compatibility between decay channels, boson charge and fit observables.

Fit stability vs phi



Fit stability





Fit stability

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 $p_{\mathrm{T}}^{\mathrm{miss}}$-cut	14 ± 9	-1 ± 13	10 ± 8	-6 ± 12	12 ± 6	-4 ± 9

Combination weights

Combination	Weight
Electrons	0.427
Muons	0.573
m_{T}	0.144
p_{T}^{ℓ}	0.856
W^{+}	0.519
W^{-}	0.481

W^+ / W^- mass difference

- Strongly constrained off-shell using μ and τ decays :

  other CPT tests are extremely tight
- Existing results :
  - CDF (in PDG) : $m_{W+} - m_{W-} = -0.2 \pm 0.6$ GeV (!!)
  - In their 2.2 fb^{-1} paper, CDF quotes 71 ± 70 ($W \to \mu\nu$) and -49 ± 42 MeV ($W \to e\nu$) as cross checks
- Meas^t constructed from difference of W+ and W- results in each category, and combined
  - Not the same as the difference of W+ and W- combined measurements!
- Not tuned, but not blinded!

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK 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

$$m_{W+} - m_{W-} = -29 \pm 13\ \text{(stat.)} \pm 7\ \text{(exp.syst.)} \pm 24\ \text{(mod.syst.) MeV}$$
$$= -29 \pm 28\ \text{MeV}$$