Measurement of the W-boson mass with the ATLAS detector

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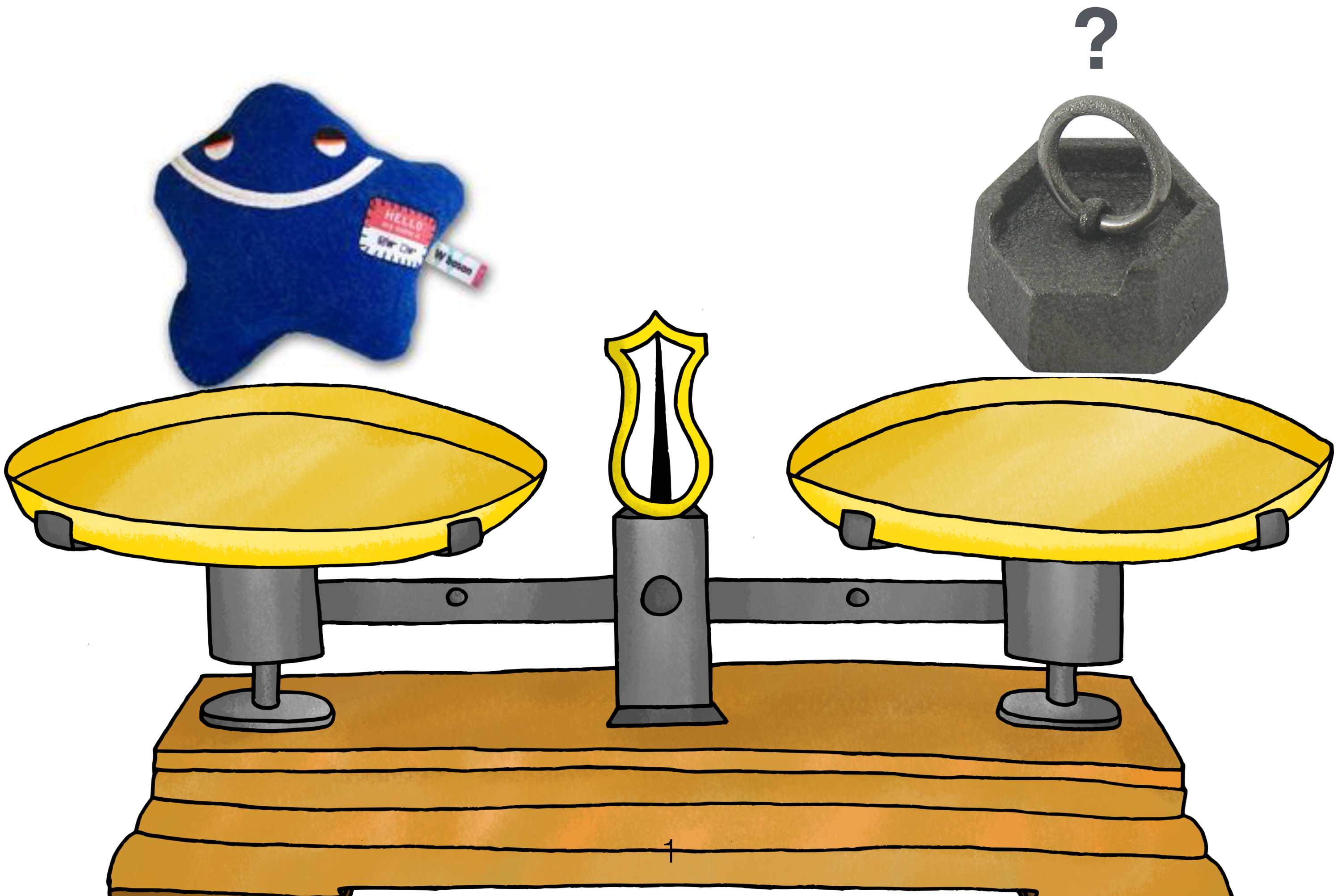
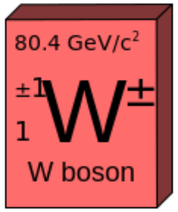
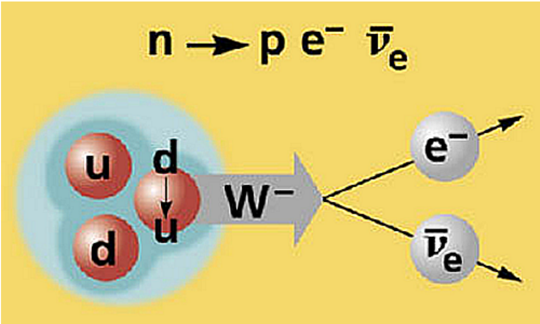


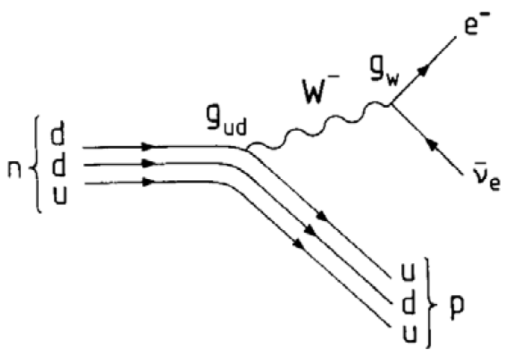
What is the W boson?



It is an elementary charged particle that carries the weak force.

Example: radioactive β-decay

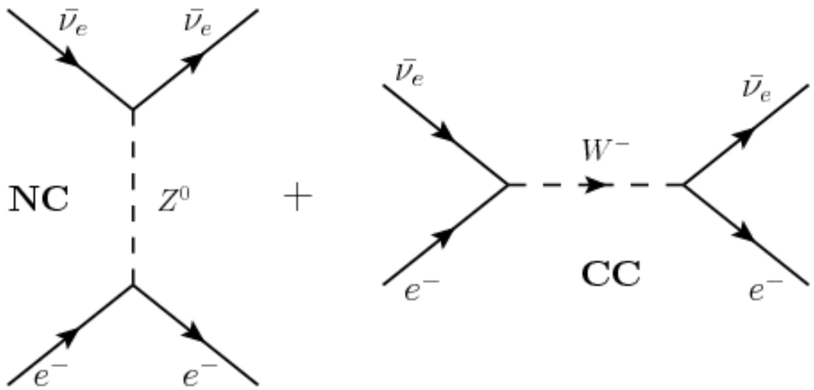




Weinberg - Glashow - Salam

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Neutral Current Charged Current



mediated by exchange of Z and W± bosons
with masses of ~91.2 GeV and 80.4 GeV resp.

Electroweak theory: 3 fundamental parameters

$$\alpha_{em} = \frac{e^2}{4\pi}, \quad \frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}, \quad \sin\theta_W$$

Mass of W and Z related:

$$M_{Z^0}^2 = M_W^2 / \cos^2\theta_W$$

Discovery of the W boson

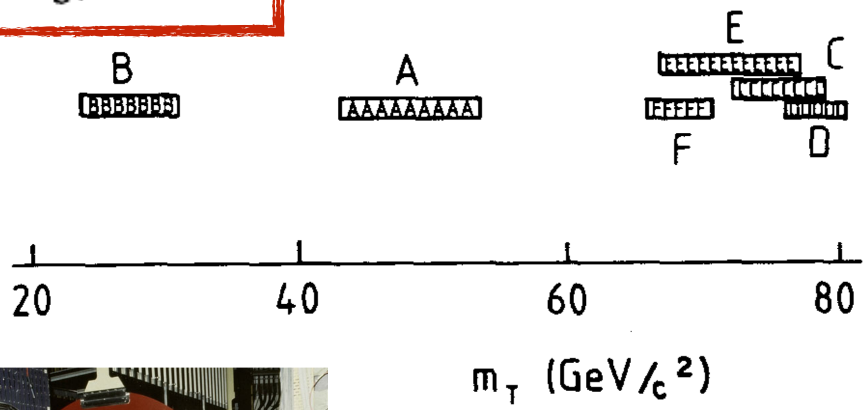
The W boson was discovered by the UA1 and UA2 experiments at the SPS at CERN √s=540 GeV (world's first proton-antiproton collider) in 1983.

On the 20th of January 1983, 6 candidate W events were published by UA1 and 5 days later, 4 candidate W events were published by UA2.

https://www.sciencedirect.com/science/article/pii/0370269383911772
https://www.sciencedirect.com/science/article/pii/0370269383916052

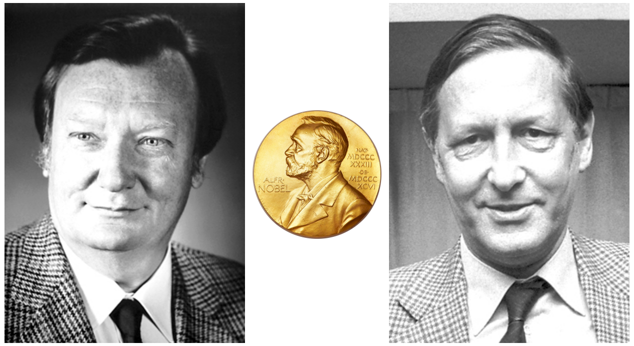
$$\boxed{m_W = (81\,^{+5}_{-5})\ \mathrm{GeV}/c^2}$$

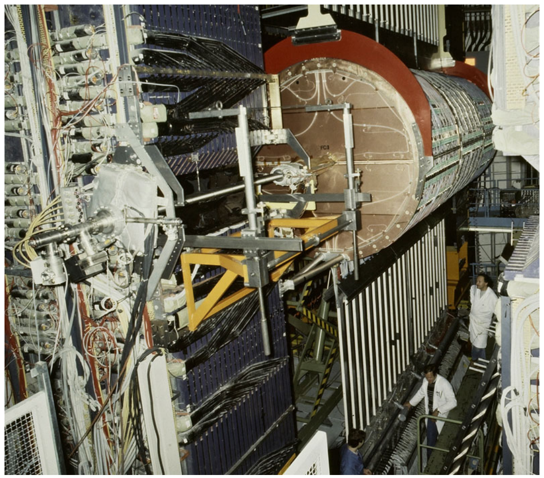
UA1 result



The Nobel Prize in Physics 1984

Carlo Rubbia, Simon van der Meer





The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*

Carlo Rubbia, who had and developed the idea, and Simon Van der Meer, whose invention made it feasible.

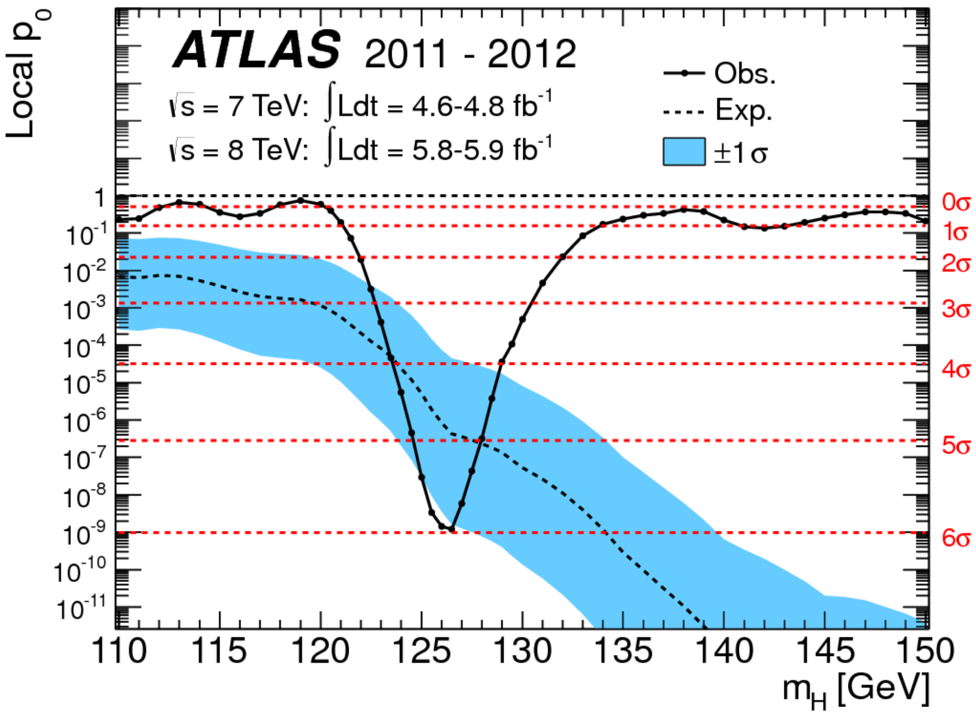
Nice video: https://videos.cern.ch/record/1004828

Higgs discovery: another success of the SM

Seminar 4 July 2012

Huge step in our understanding of Particle Physics:
recent discovery of the Higgs boson
at the LHC by the ATLAS and CMS experiments

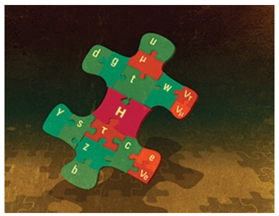
Phys. Lett. B 716 (2012) 1-29



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

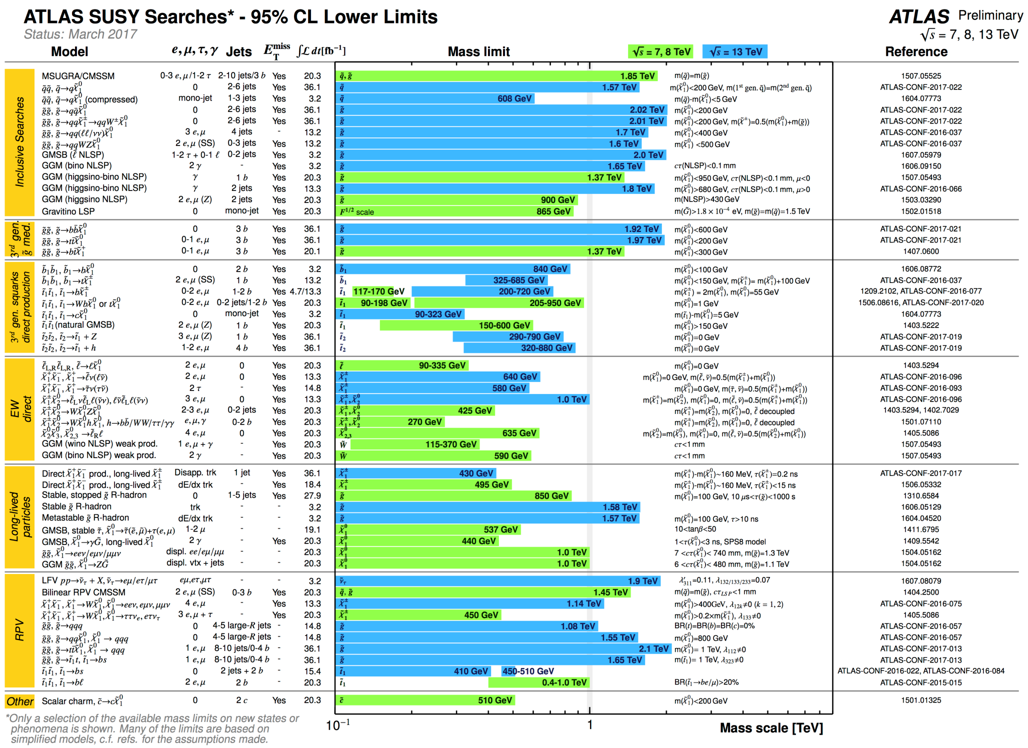
SM puzzle completed, but many open questions (mass hierarchy, baryon asymmetry, dark matter…) remain without answers

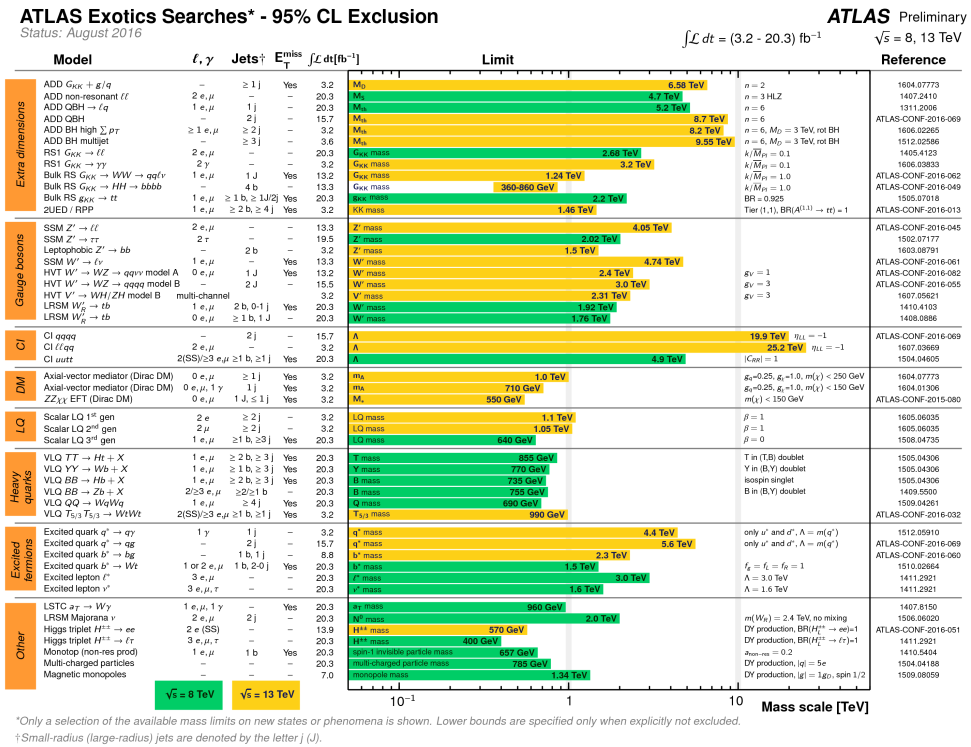
—> Search for Beyond the SM



Beyond the Standard Model

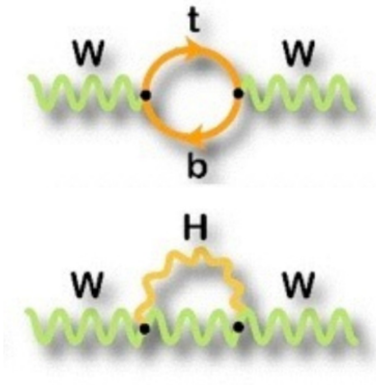
Direct searches: huge numbers of new results from the LHC - astonishing achievement. No significant signals - updated limits. More still to come with future data.





Indirect searches: precision measurements in EW sector (Higgs couplings, $\sin^2\theta_W$, m_W…)

W-boson mass



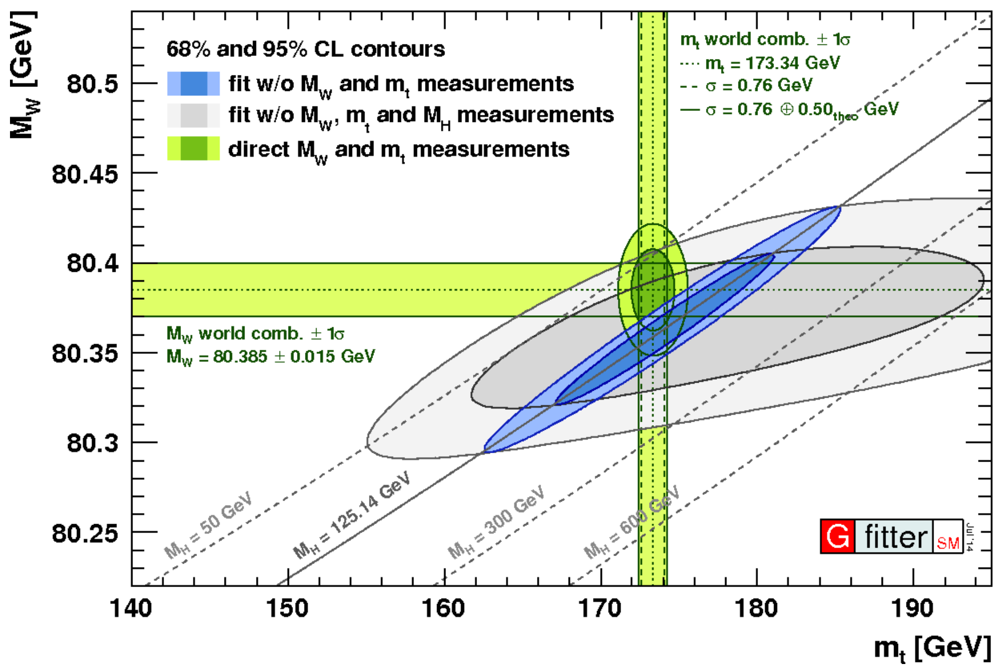
In the electroweak sector of the SM, the W mass at the tree level:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}$$

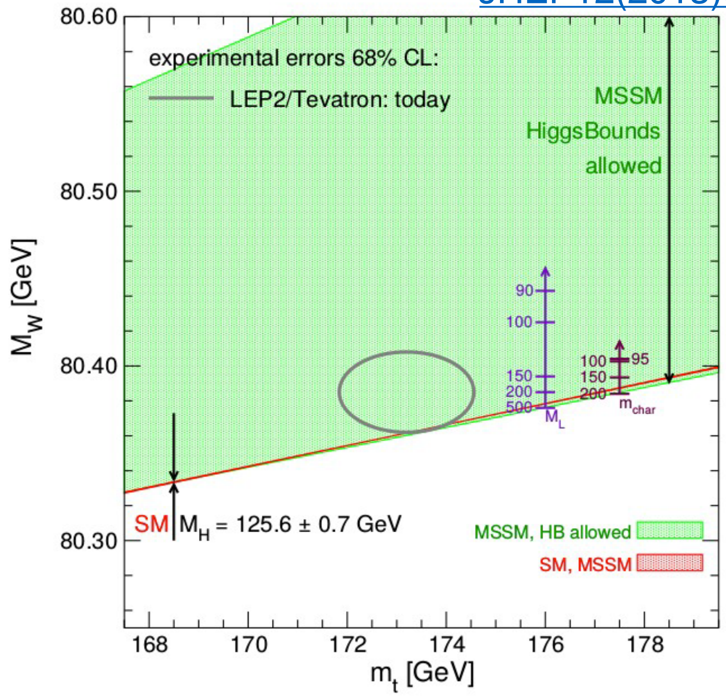
at the loop level: $$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

In SM, Δr reflects loop corrections and depends on m_t^2 and $\ln m_H$

The relation M_W, m_t, and M_H provides stringent test of the SM and is sensitive to NP

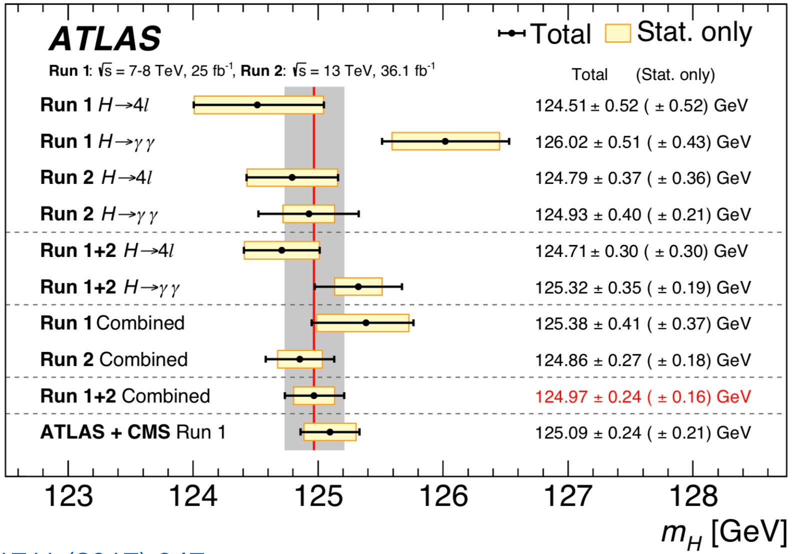


JHEP12(2013)084



Status of the measurements

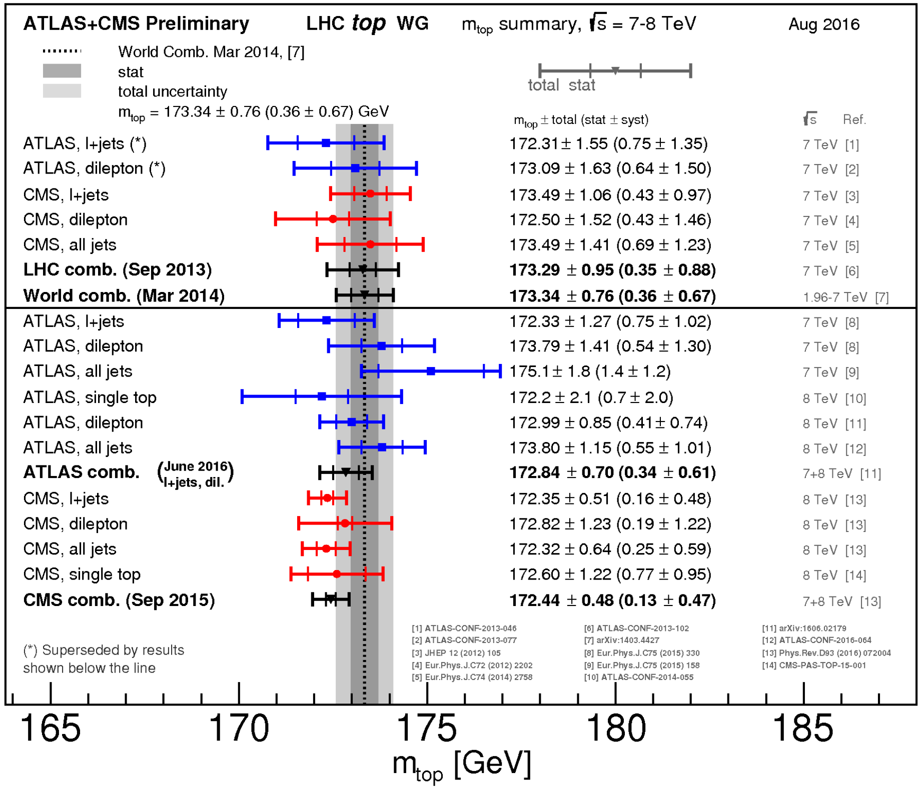
Higgs mass [Phys. Lett. B 784 (2018) 345]

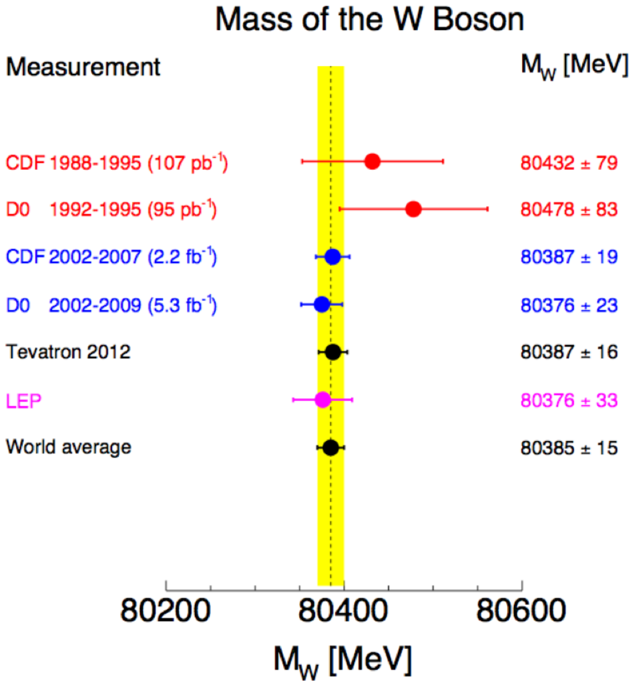


[JHEP 1711 (2017) 047]

CMS new: $125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})$ GeV

Top mass





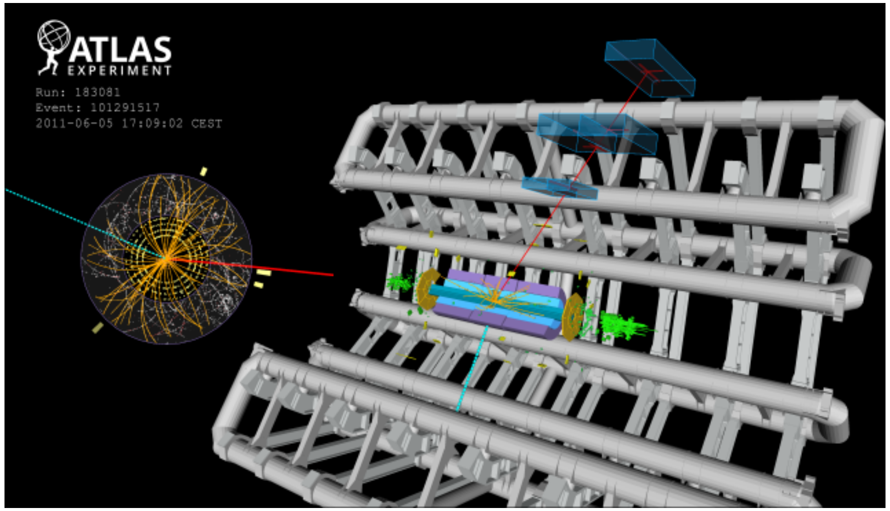
W mass

LEP+Tevatron: M_W uncertainty~ 15 MeV
Best individual measurement:
CDF M_W uncertainty 19 MeV

First W mass measurement at the LHC

Recently published in EPJC Eur.Phys.J.C (2018) 78:110

Seminar 13/12/2016

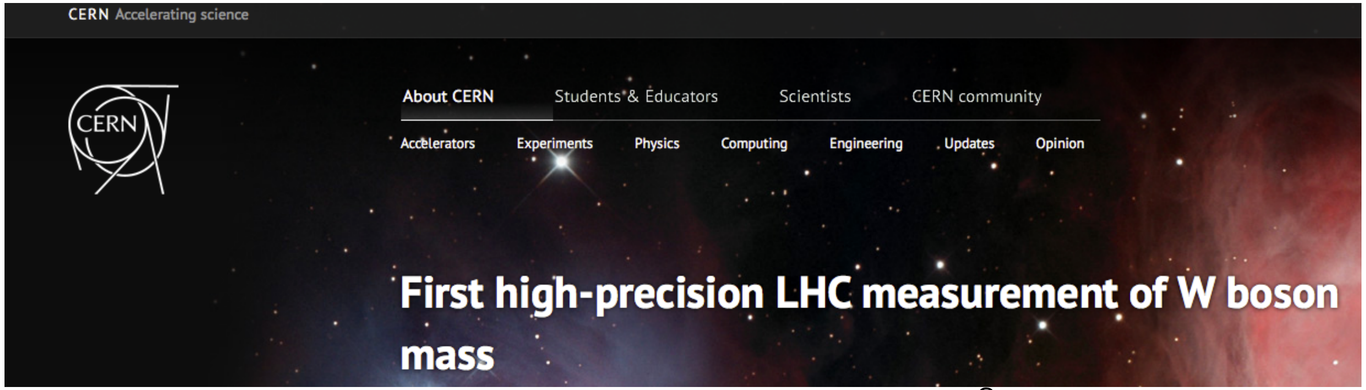


CERN Courier January/February 2017

News

LHC EXPERIMENTS

ATLAS makes precision measurement of W mass



The Guardian International edi

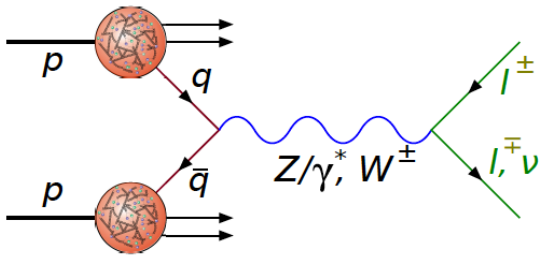
Tribune de Genève

SWI swissinfo.ch

ASTROPAGE.EU

How to measure the W mass

Consider leptonic decay: electron and muon channels

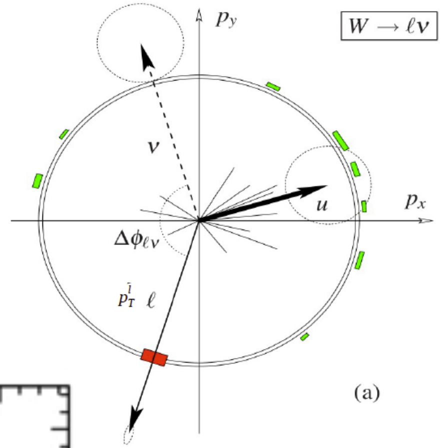


Not possible to fully reconstruct W mass

Sensitive final state distributions: **p_T^l, m_T,** p_T^{miss}

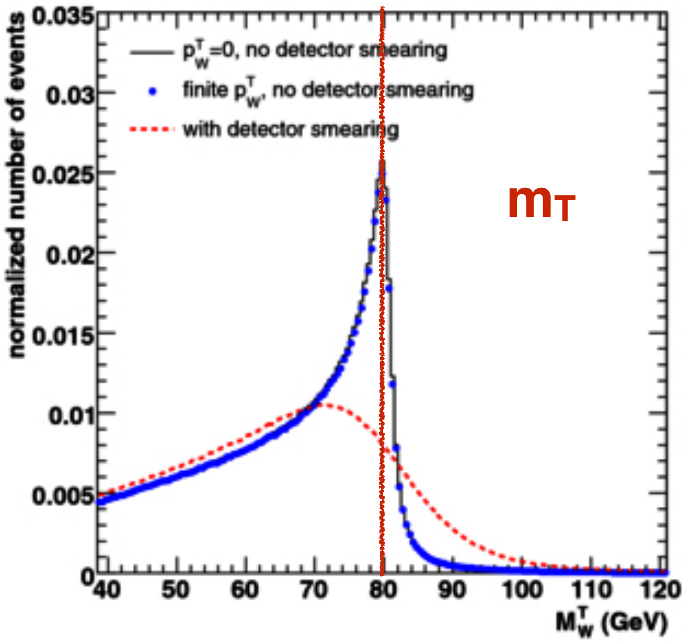
$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right), \quad m_T = \sqrt{2p_T^{\ell} p_T^{miss}(1-\cos\Delta\phi)}$$

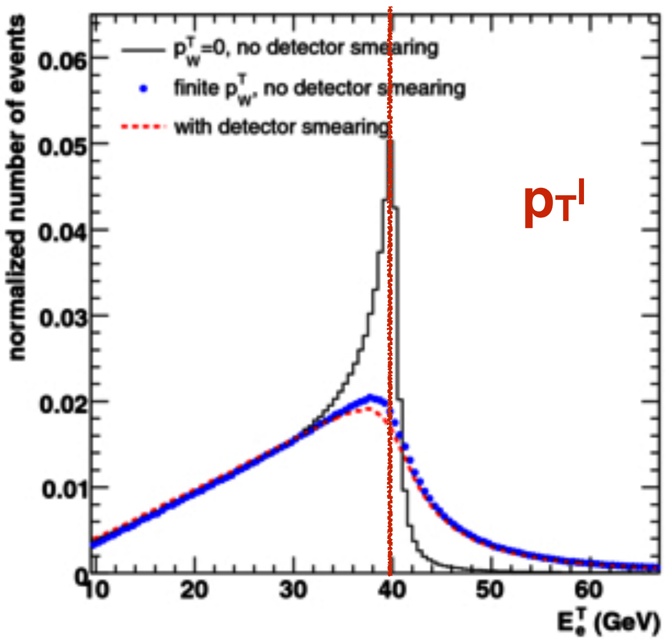
u_T being the recoil



$-u_T$ provides an estimate of the boson p_T

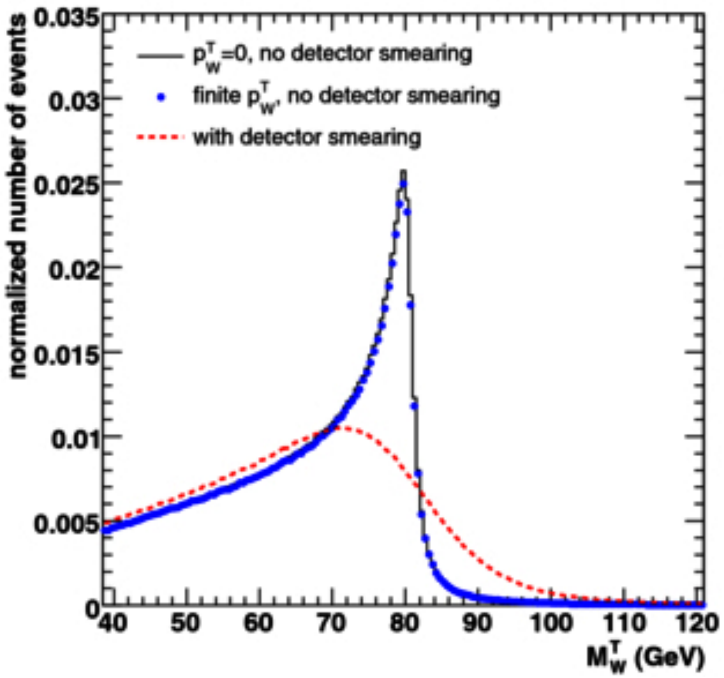
Jacobian edge at: m_W $m_W/2$

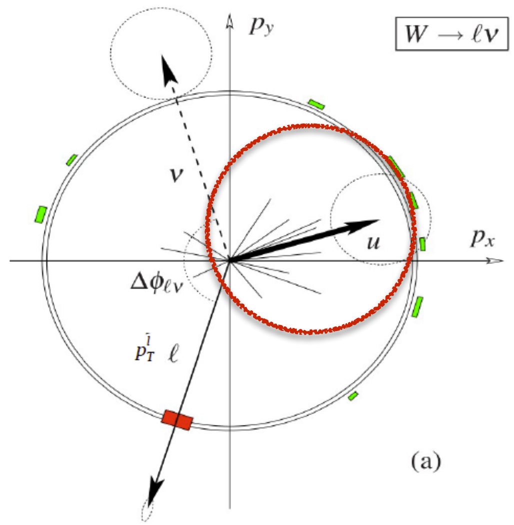


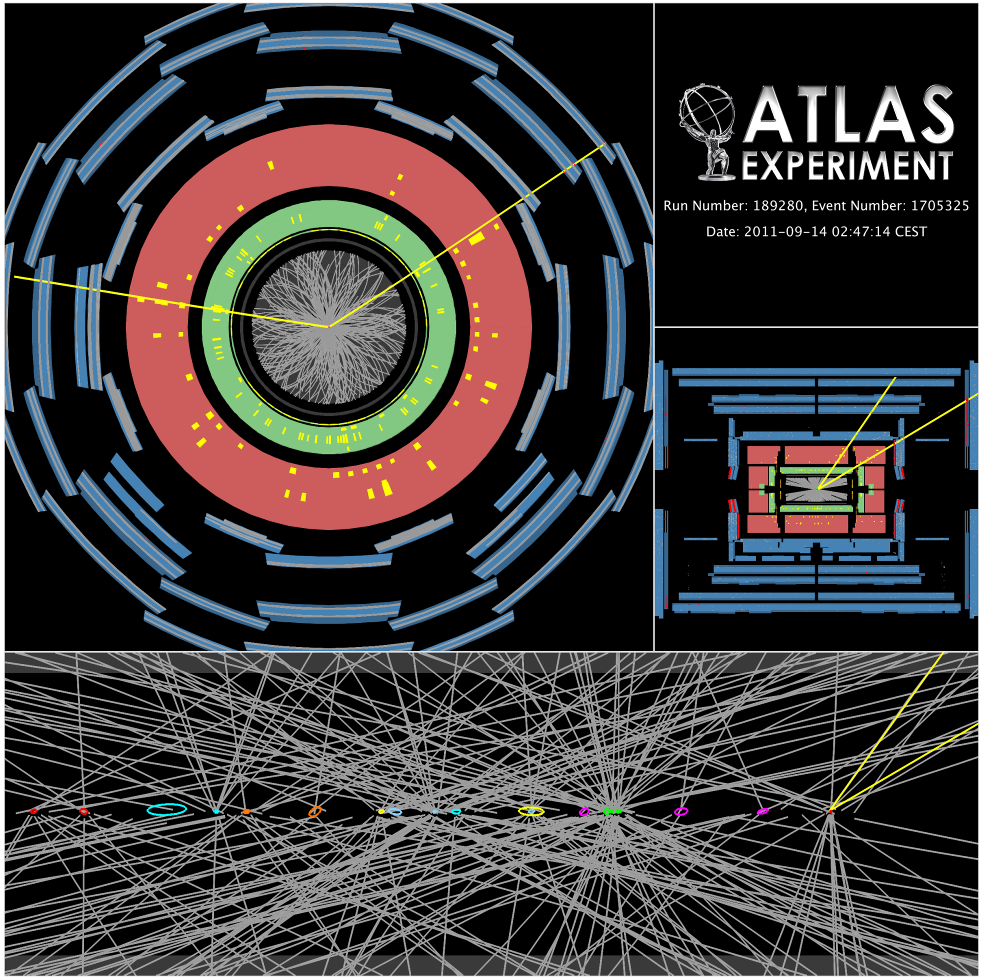


W transverse mass

Sensitive to the modelling of the recoil: pileup, UE.. effects





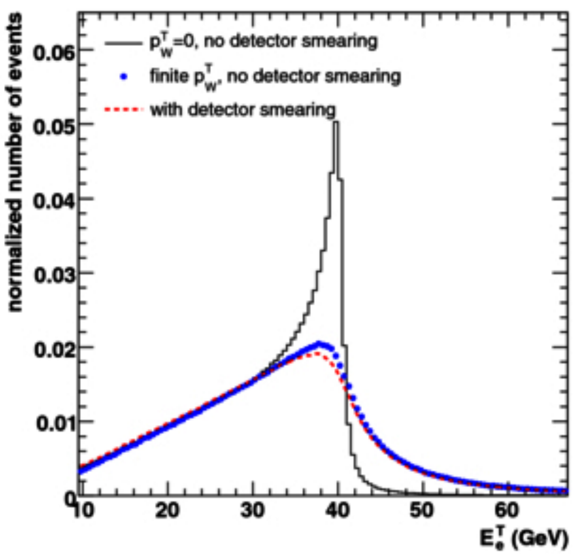


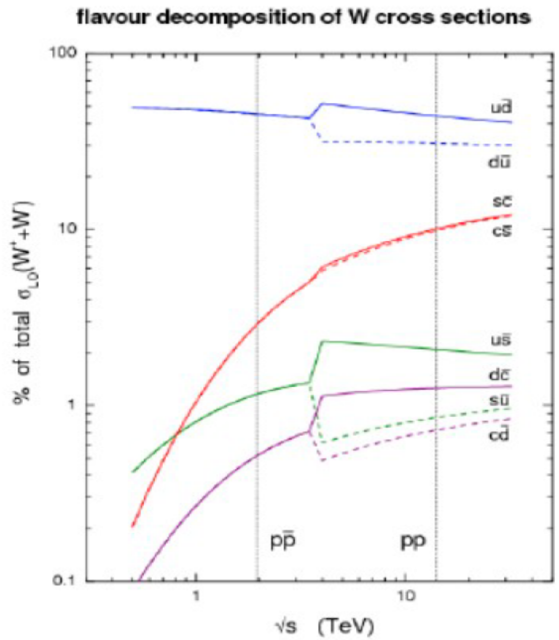
Z—>$\mu\mu$ event with 20 reconstructed vertices

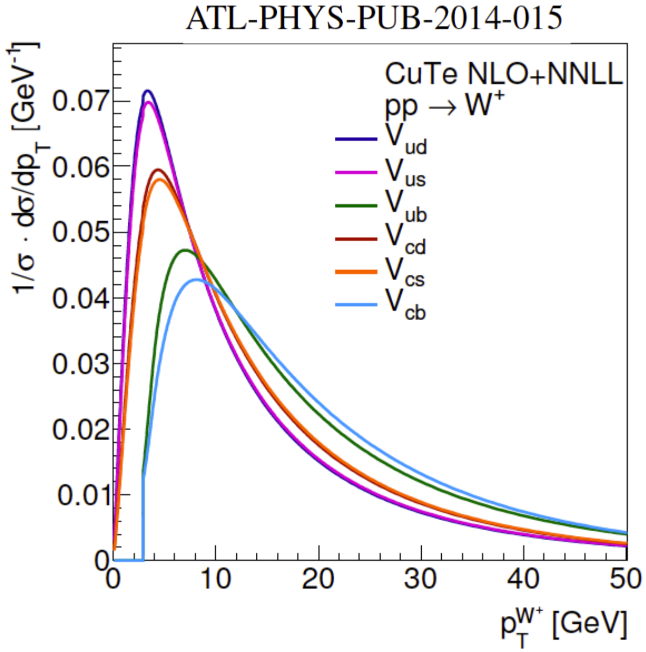
(recorded in September 2011)

Lepton transverse momentum

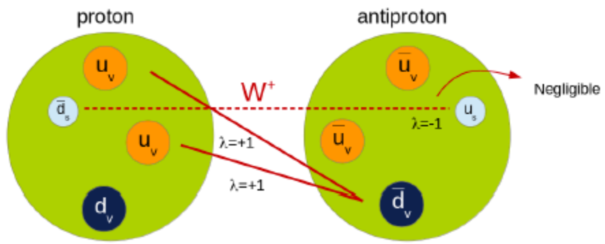
Strong impact of the W boson transverse momentum distribution on p_T^l

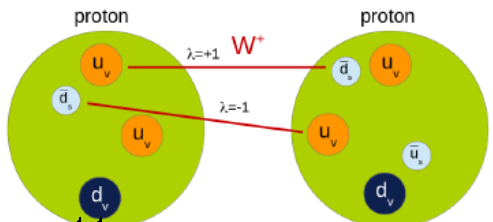


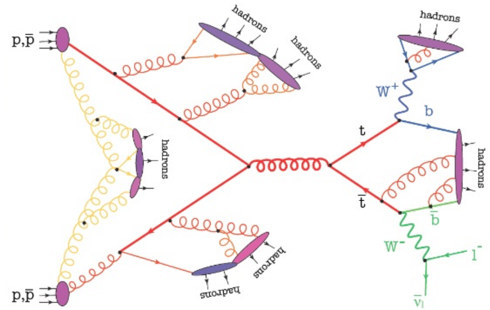




- Second generation quark PDFs play a larger role at the LHC *(25% of the W-boson production is induced by at least one second generation quark s or c)* than at the Tevatron.
- The W polarisation is determined by the difference between the u, d valence and sea densities







Strategy of the measurement in ATLAS

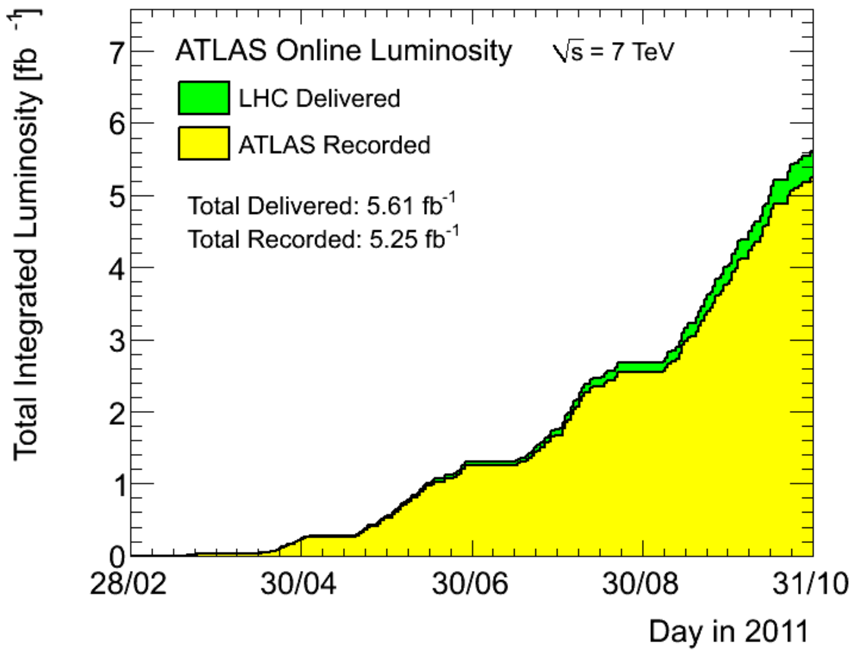
Sensitive final state distributions: **p_T^l, m_T,** p_T^{miss}*

$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right), \quad m_T = \sqrt{2 p_T^{\ell} p_T^{miss}(1-\cos\Delta\phi)}$$

u_T being the recoil

In W, Z events $-u_T$ provides an estimate of the boson p_T

2011 data is used for the measurement recorded at $\sqrt{s}$= 7 TeV



Categories for the measurement:

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

**used as cross-check only*

Selection cuts

Lepton selections:

- muons isolated (track-based) $|\eta|<2.4$
- electrons isolated (track+calorimeter-based) tight identified $0<|\eta|<1.2$, $1.8<|\eta|<2.4$

Kinematic requirements: $p_T^l>30$ GeV, $m_T>60$ GeV, MET>30 GeV and recoil(u_T)<30 GeV

~6M/8M observed in the electron/muon channel

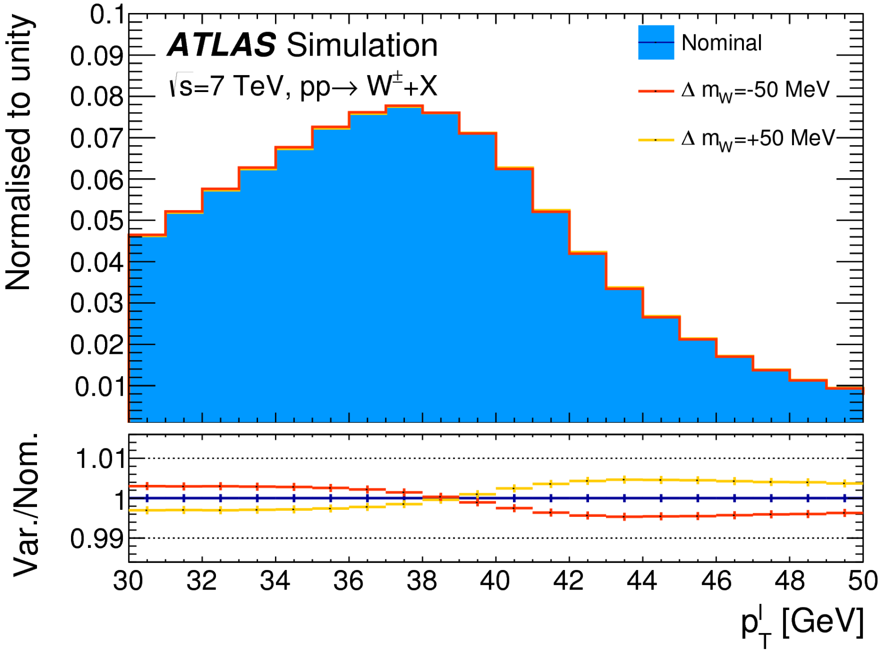
$\|\eta_\ell\|$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3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

Template fit

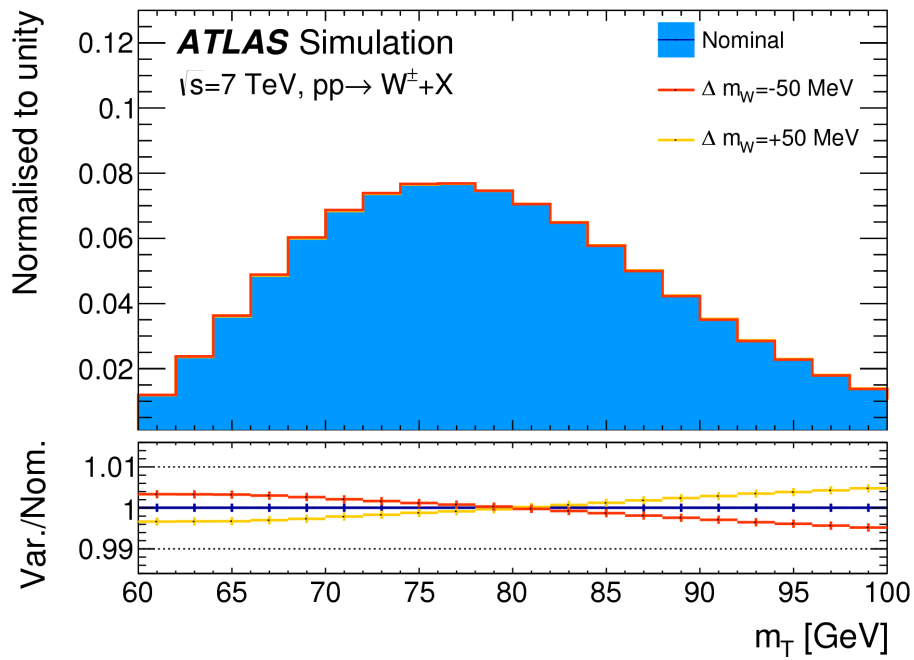
Template fit approach: compute the p_T^l and m_T distributions for different assumed values of m_W* —> χ^2 minimisation gives the best fit template.

Predictions for different m_W values are obtained by reweighting the boson invariant mass distribution according to the BW parameterisation.

$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$



p_T^l has a Jacobian edge at $m_W/2$

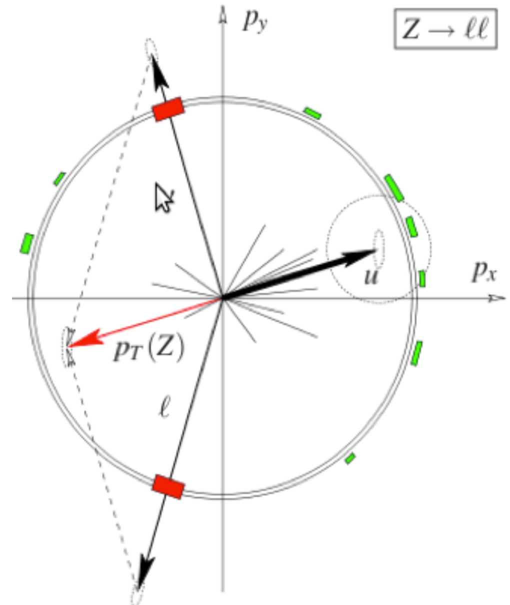


m_T has a Jacobian edge at m_W

* *A blinding offset was applied throughout the measurement and removed when consistent results were found.*

Z-boson sample

Benefit from the fully reconstructed mass in Z-boson sample to validate the analysis and to provide significant experimental *(lepton and recoil calibration using resp. m_Z measured at LEP = 91187.5±2.1 MeV and expected momentum balance with p_T^{ll})* and theoretical constraints *(ancilliary measurements).*

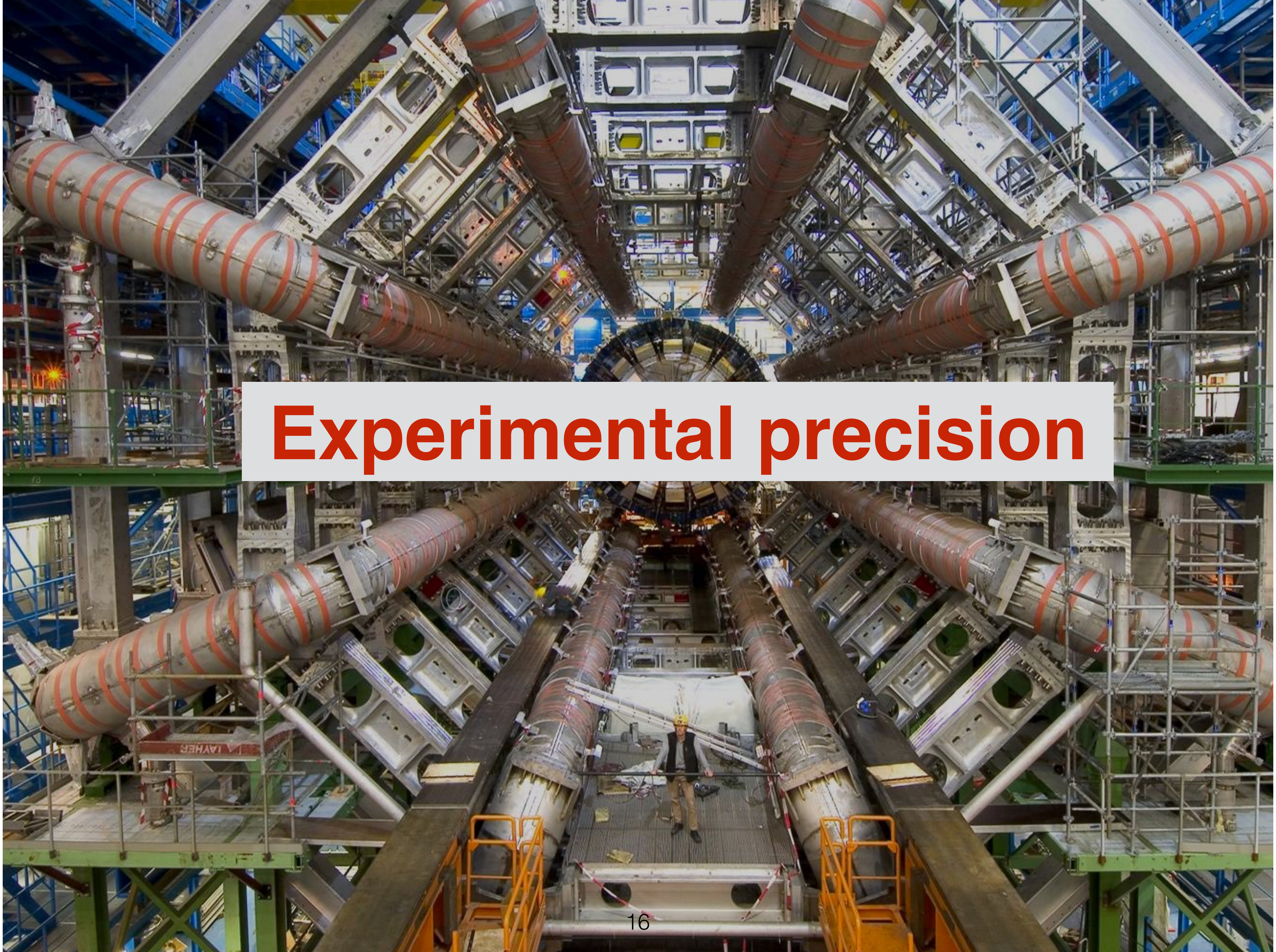


The whole analysis is checked by performing a measurement of the Z-boson mass and comparing to the LEP value, also a cross-check Z mass measurement in “W-like” i.e removing the 2nd lepton and treating it like a neutrino

A similar W-like analysis was also done by CMS **CMS PAS SMP-14-007**

Need to consider additional systematics for W mass measurement (*theory uncertainties, Z—>W extrapolation and background)*

Experimental precision



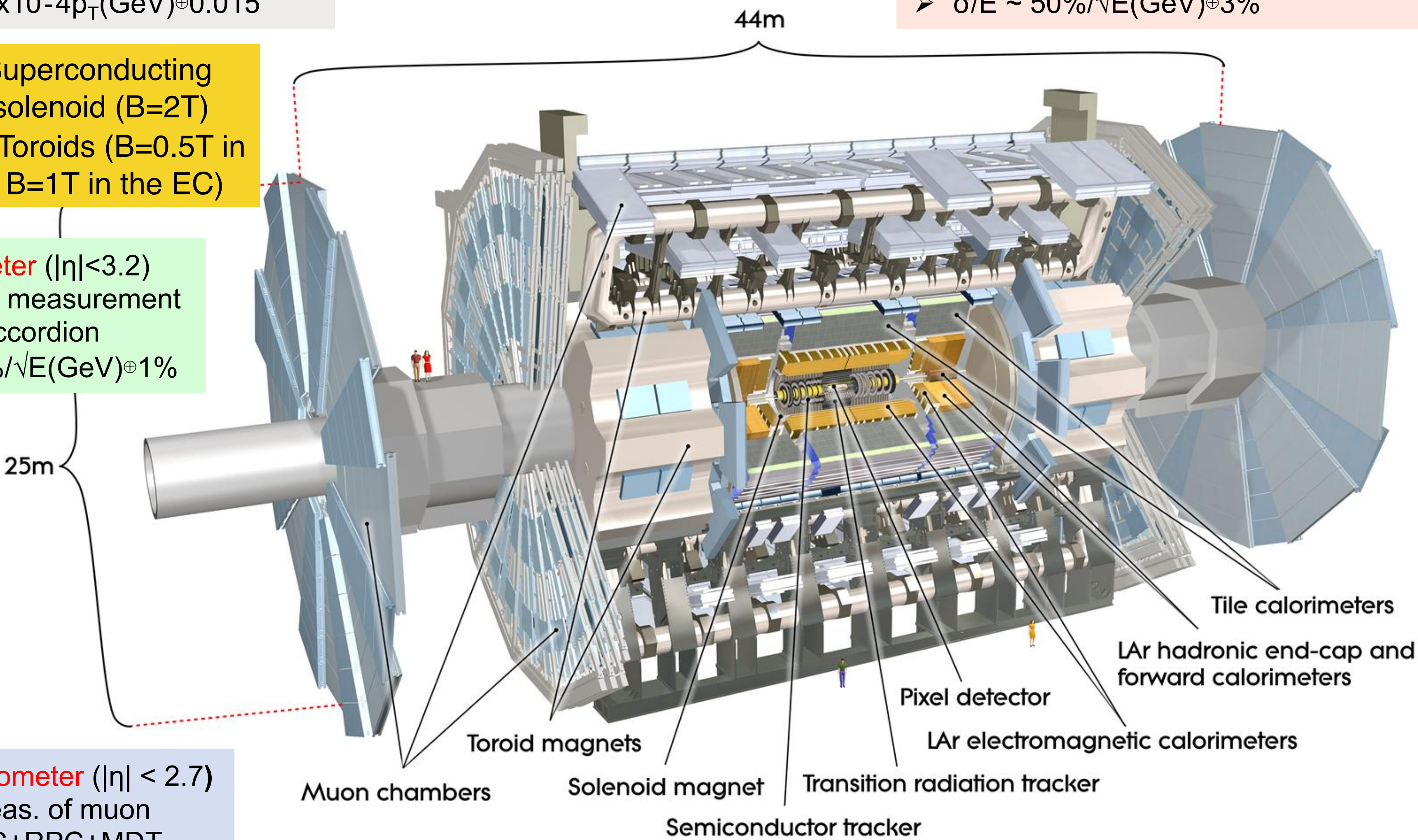
ATLAS detector

Inner detector ($|\eta|< 2.5$, B=2T)
Tracking, vertexing, dE/dx, e/π ID
- Si pixels, Si strips, Trans. Rad. det.
- $\sigma/p_T \sim 3.8x10\text{-}4 p_T(\text{GeV}) \oplus 0.015$

Hadron Calorimeter ($|\eta|<5$)
Trigger and meas. of jet/Emiss
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(\text{GeV})} \oplus 3\%$

4 Magnets Superconducting
- 1 Central solenoid (B=2T)
- 3 Air core Toroids (B=0.5T in the barrel, B=1T in the EC)

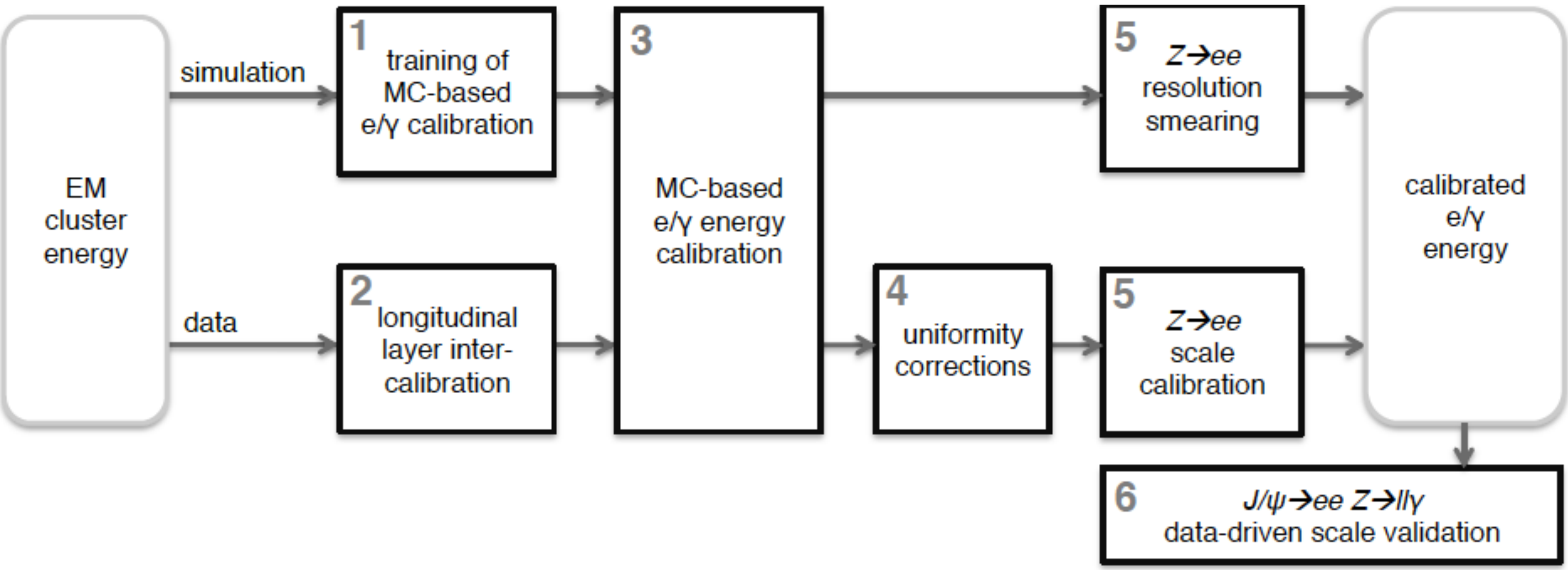
EM Calorimeter ($|\eta|<3.2$)
e/γ ID trigger measurement
- Pb-Lar accordion
- $\sigma/E \sim 10\%/\sqrt{E(\text{GeV})} \oplus 1\%$



Muon spectrometer ($|\eta| < 2.7$)
Trigger & meas. of muon
- CSC+TGC+RPC+MDT
- σ/p_T <10 % up to 1 TeV

Electron Calibration & Efficiency

Calibration for electrons closely follows the Run I calibration paper [Eur.Phys.J.C 74 (2014) 3071]

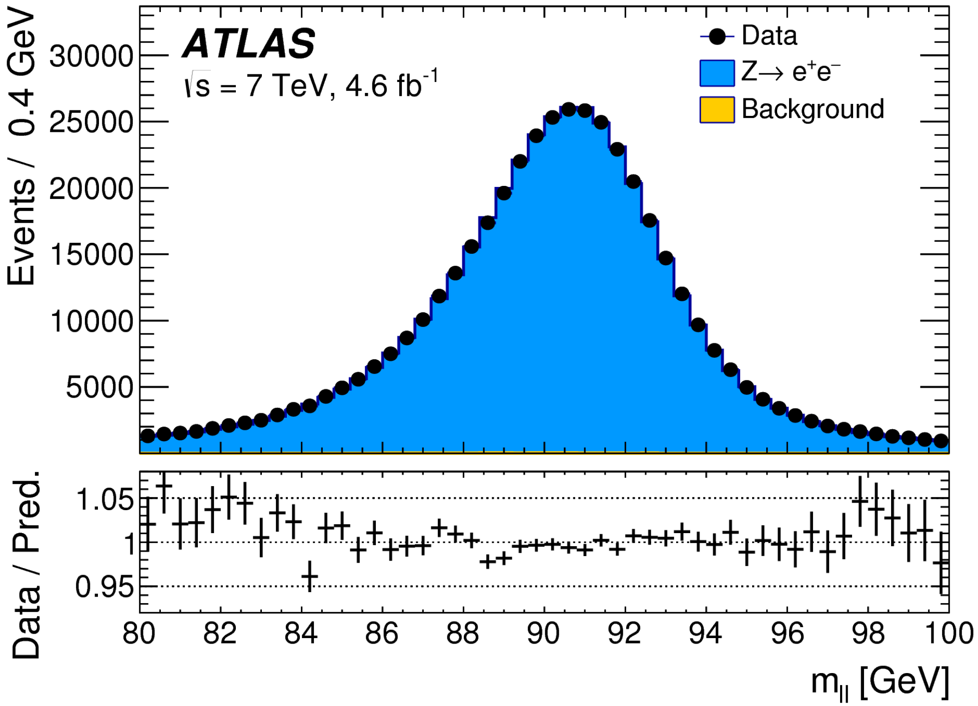


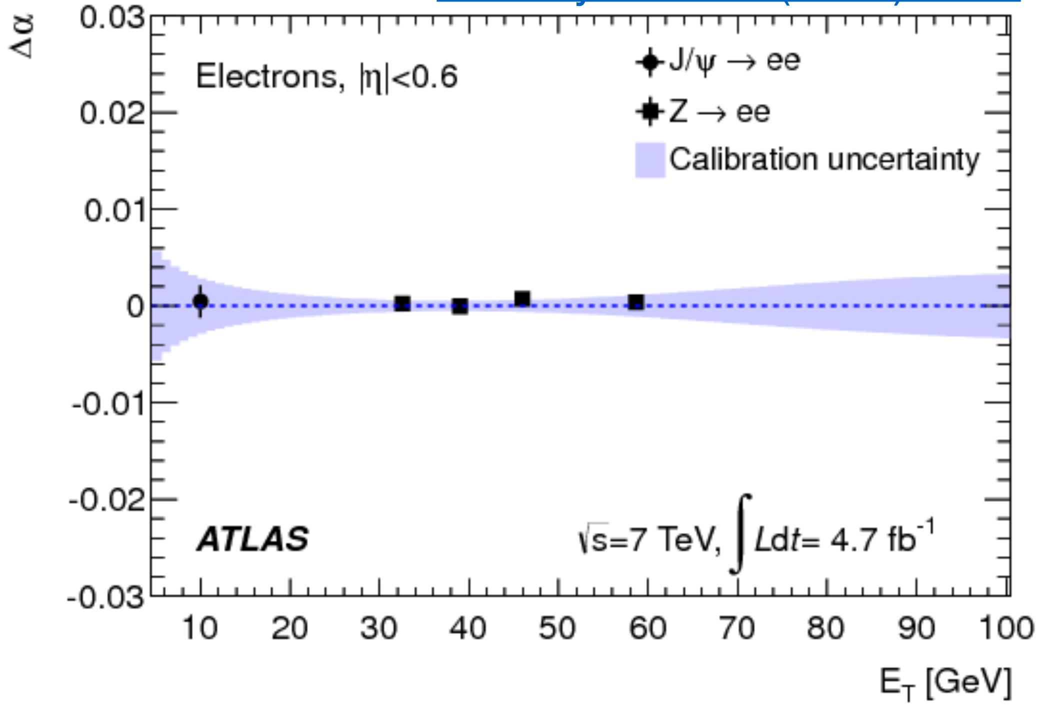
Exclude bin $1.2<|\eta|<1.82$ for the W mass measurement as the amount of passive material in front of the calorimeter and its uncertainty are largest in this region.
Azimuthal correction from <E/p> vs φ

Electron efficiency corrections as a function of η and p_T [Eur.Phys.J.C 74 (2014) 2941]

Electron Calibration & Efficiency

Eur.Phys.J.C 74 (2014) 3071



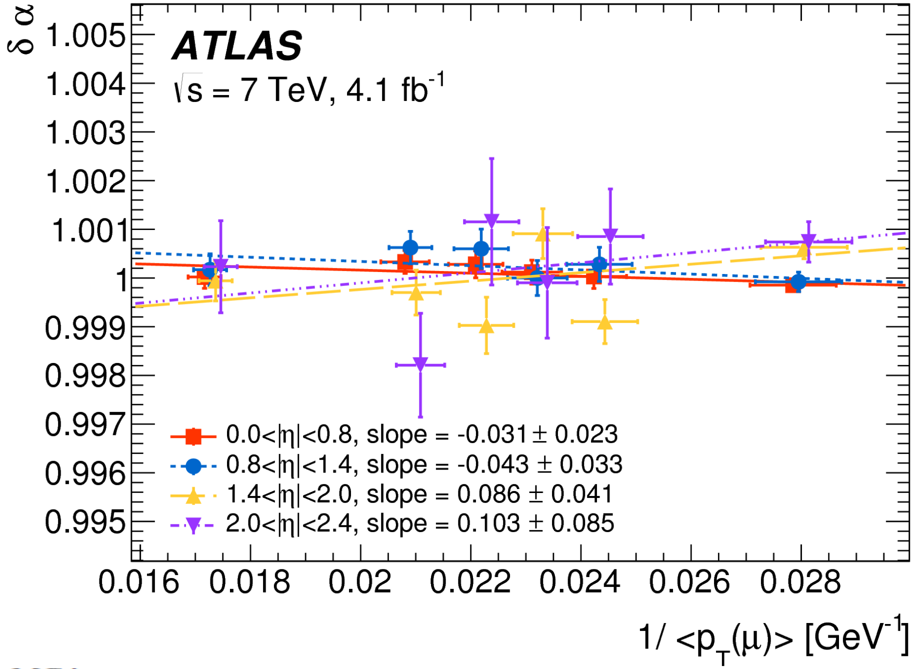


$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6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

Muon Calibration & Efficiency

Muon identified using combined ID+MS tracks, momentum measurement from ID only.

Calibration factors for ID-only muons derived from Z—>$\mu\mu$ and sagitta bias charge-dependent corrections from Z—>$\mu\mu$ and E/p of W—>eν. Eur.Phys.J.C 74 (2014) 3130

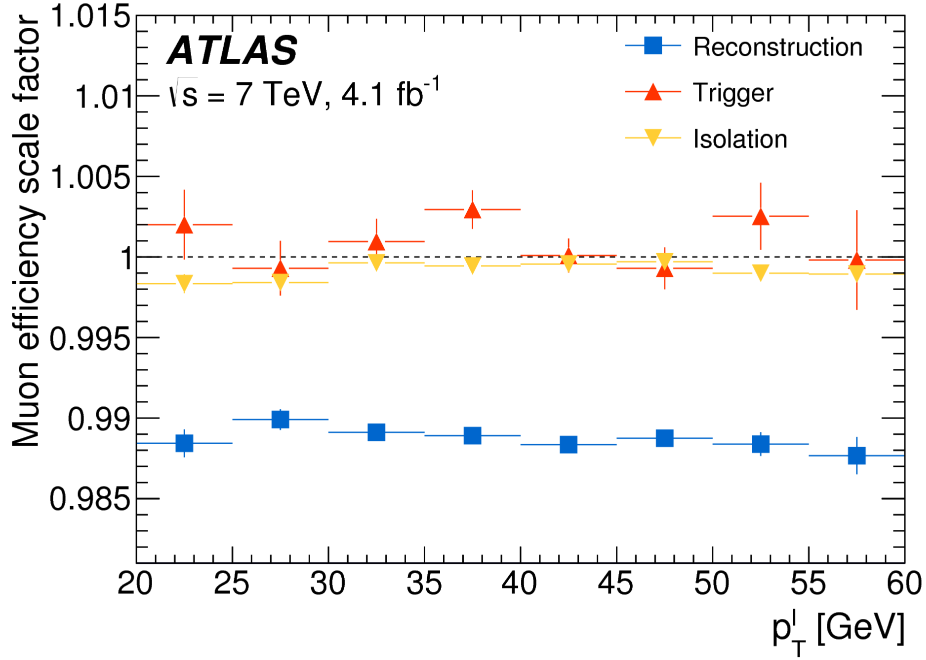


$$p_{\mathrm{T}}^{\mathrm{MC,corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times [1 + \alpha(\eta,\phi)] \times \left[1 + \beta_{\mathrm{curv}}(\eta) \cdot G(0,1) \cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$

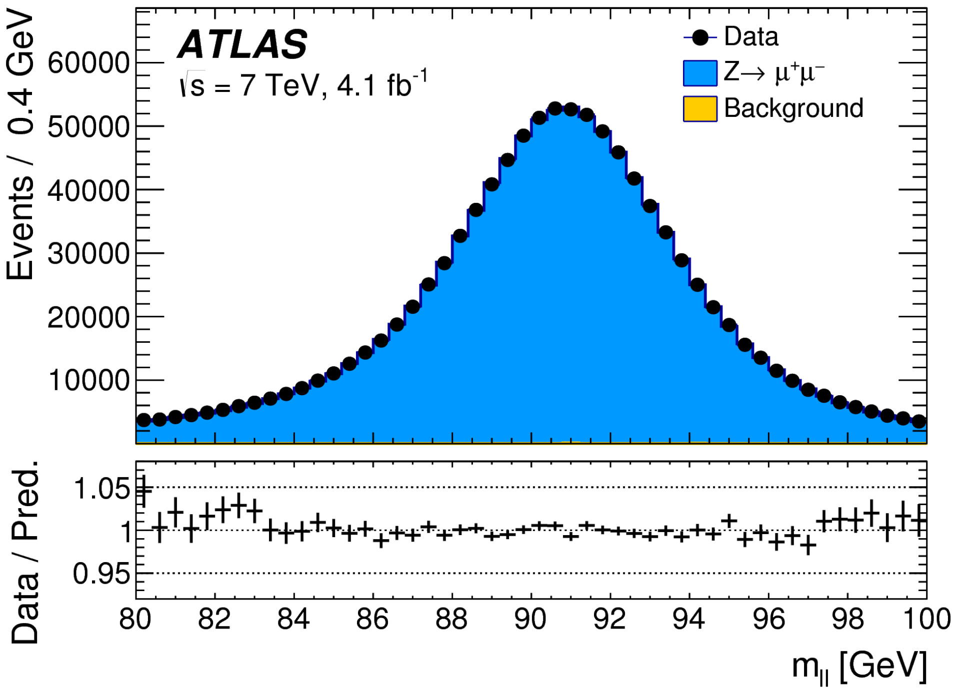
$$p_{\mathrm{T}}^{\mathrm{data,corr}} = \frac{p_{\mathrm{T}}^{\mathrm{data}}}{1 + q \cdot \delta(\eta,\phi) \cdot p_{\mathrm{T}}^{\mathrm{data}}}$$

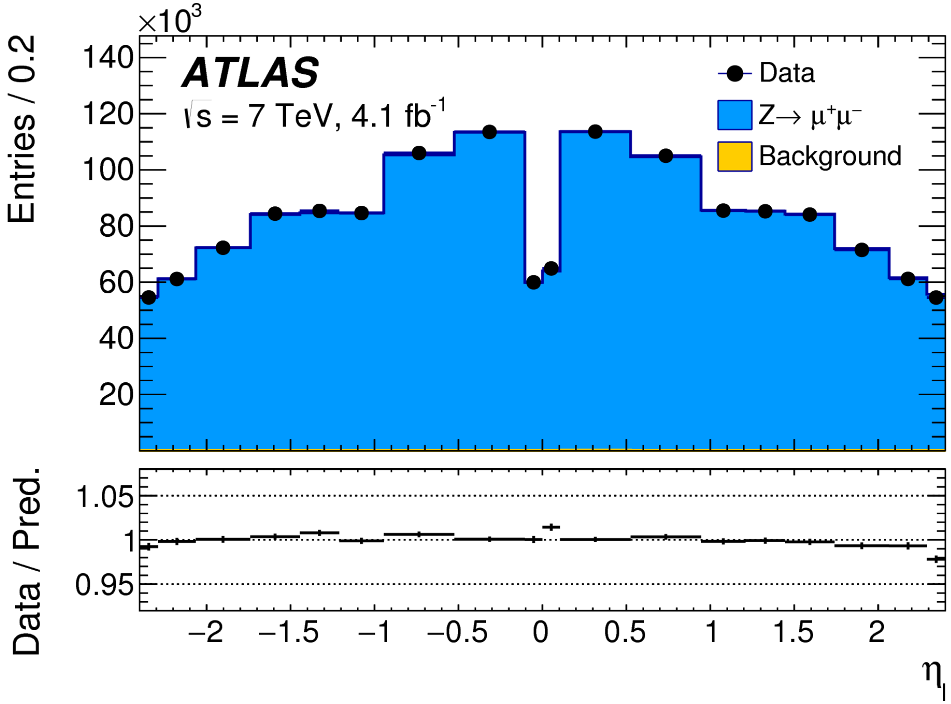
Muon trigger/id/iso efficiency corrections data/MC evaluated in bins of p_T^l, η and charge.

Dominant uncertainty is the statistical uncertainty of the Z sample.



Muon Calibration & Efficiency

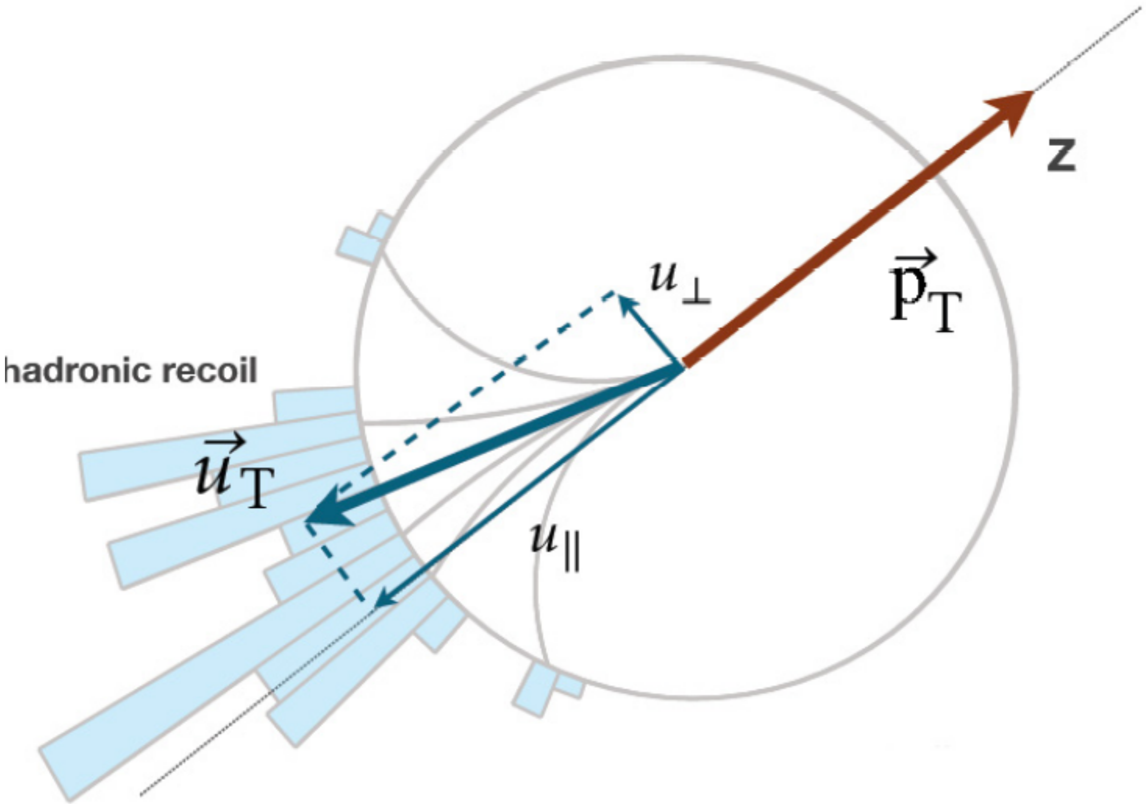




$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0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

Recoil Reconstruction

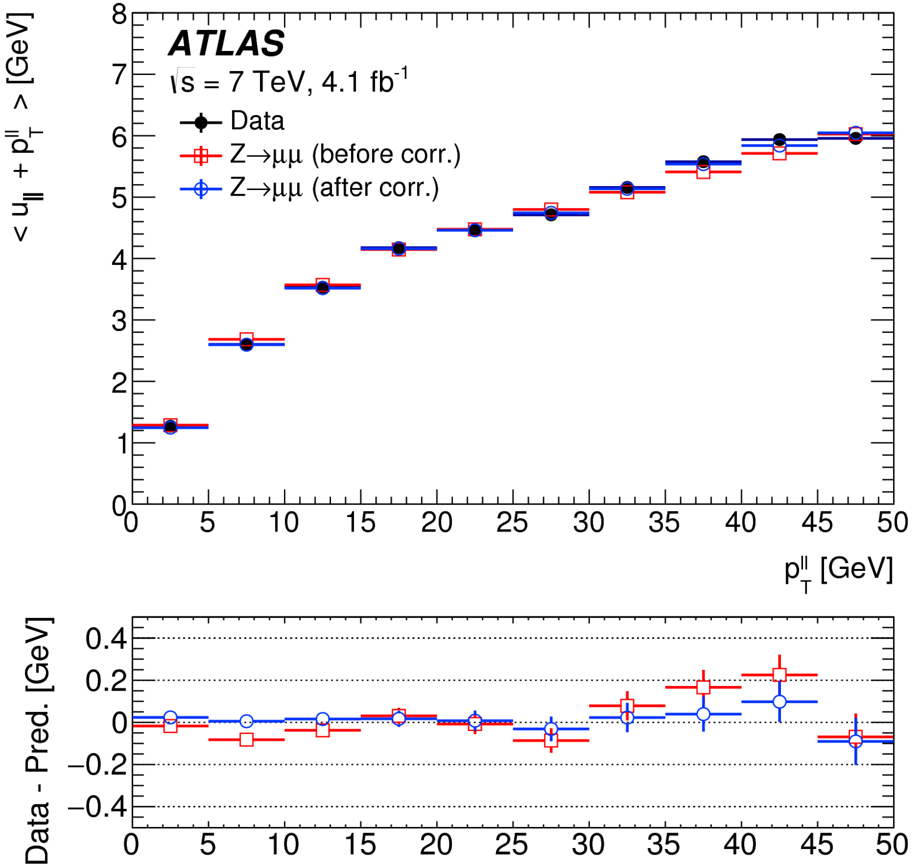
Vector sum of the momenta of all clusters measured in the calorimeters excluding energy deposits associated with the decay leptons

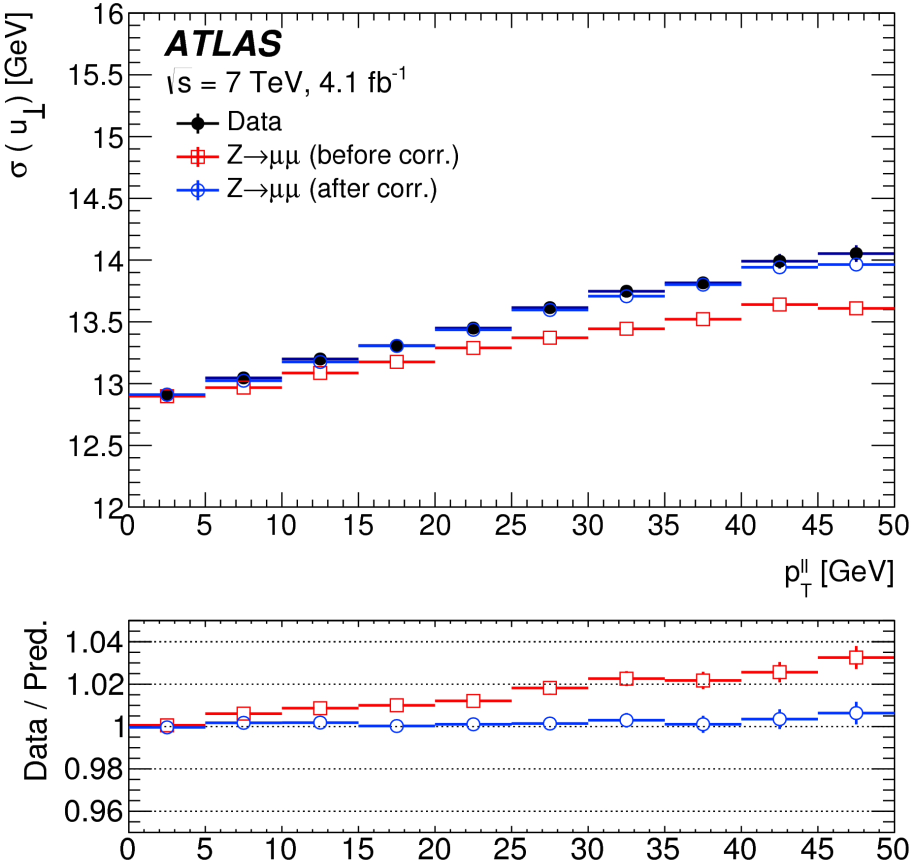


Also : $u_{||}^{l}$ is the projection of the recoil along the W decay lepton direction

Recoil Calibration

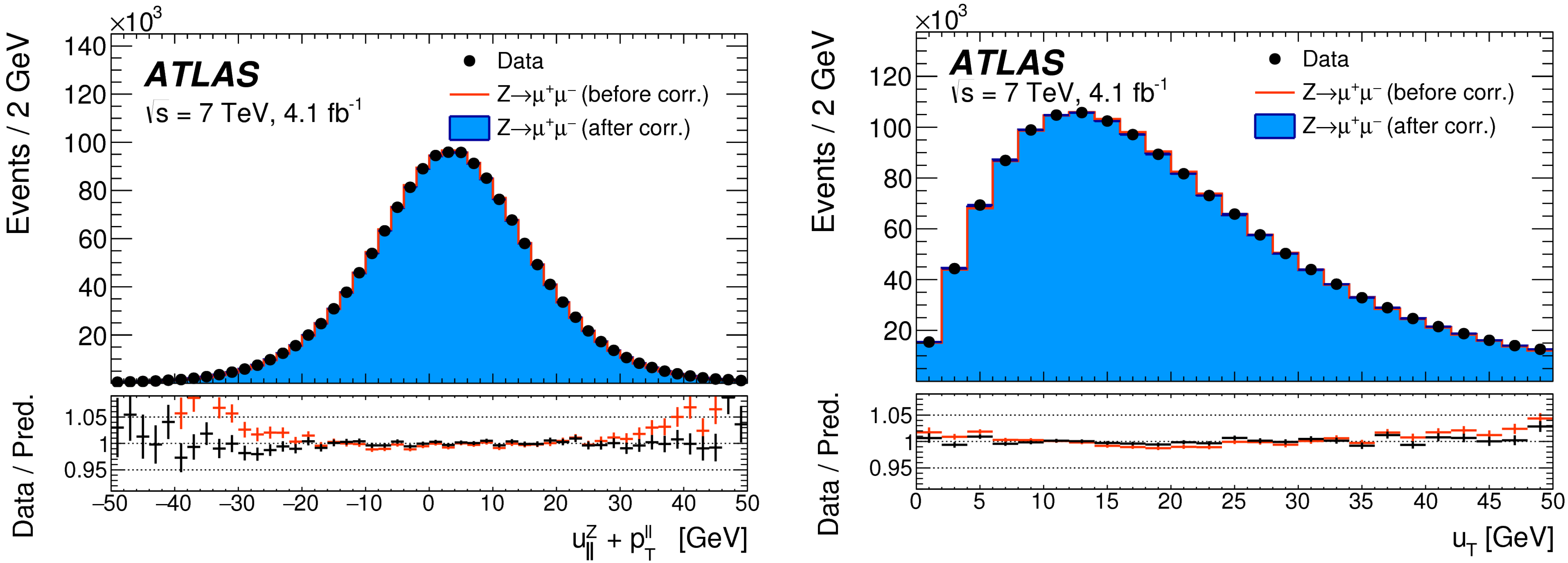
Calibrate the scale (resolution) of the recoil using $u_{||}$ ($u_{\perp}$) from Z events





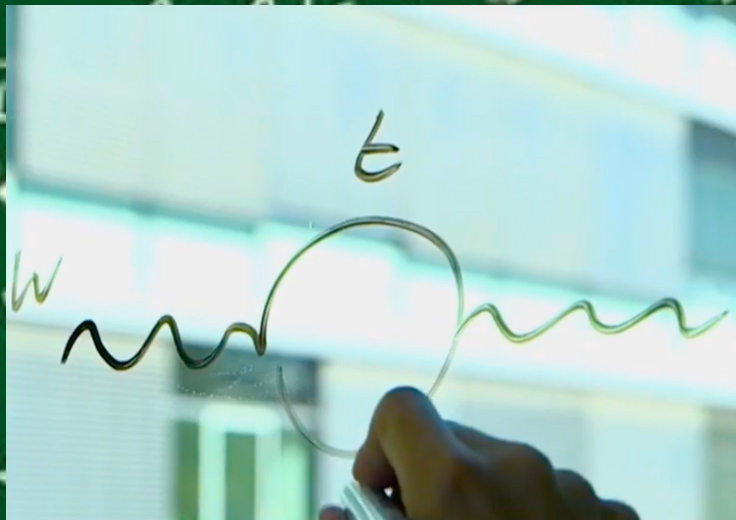
70-80% recoil response, remaining pileup dependence of the recoil resolution cluster-based.

Recoil Calibration



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	$\boxed{2.6}$	$\boxed{13.0}$

Physics modelling



Physics Modelling

No single generator able to describe all observed distributions.

Start from the Powheg+Pythia8 and apply corrections. Use ancillary measurements of Drell-Yan processes to validate (and tune) the model and assess systematic uncertainties.

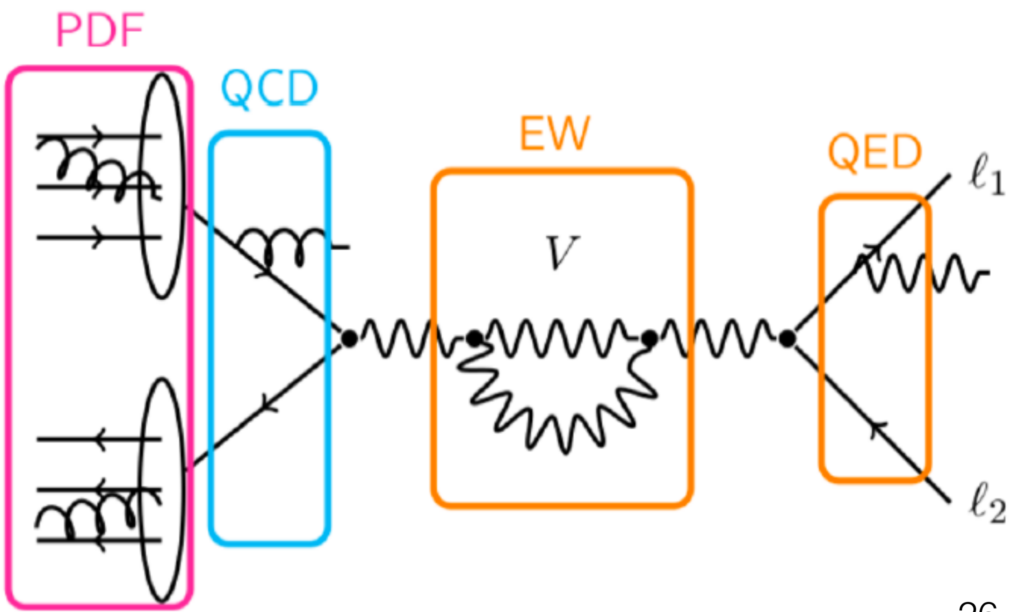
Physics modelling corrections

Electroweak corrections

- *QED FSR and ISR (included)*
- *missing higher order effects and FSR pair production (uncertainties)*

QCD corrections

- *pT distribution*
- *polarisation*
- *rapidity*



EW corrections

QED effects: FSR *(dominant correction)* included in the simulation with PHOTOS, negligible uncertainty. QED ISR included through Pythia8 parton shower.

NLO EW effects: taken as uncertainties, pure weak corrections evaluated in the presence of QCD corrections, estimated using Winhac. ISR-FSR interference.

FSR lepton pair production estimated and added as an uncertainty. Formally higher order correction but a significant additional source of energy 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

QCD corrections

The Drell-Yan cross-section can be decomposed by factorising the dynamic of the boson production and the kinematic of the boson decay.
An approximate decomposition is given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1\,\mathrm{d}p_2} = \left[\frac{\mathrm{d}\sigma(m)}{\mathrm{d}m}\right]\left[\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right]\left[\frac{\mathrm{d}\sigma(p_\mathrm{T},y)}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}\left(\frac{\mathrm{d}\sigma(y)}{\mathrm{d}y}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_\mathrm{T},y)P_i(\cos\theta,\phi)\right]$$

Breit-Wigner

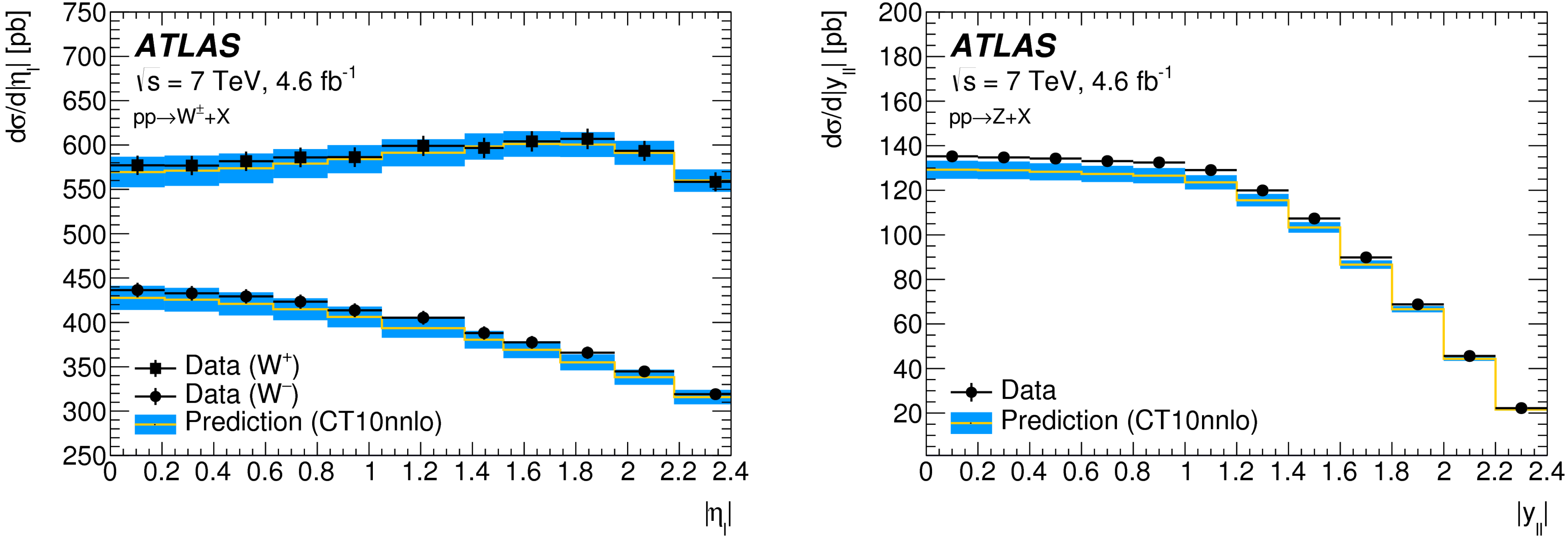
NNLO pQCD

Parton Shower

$d\sigma/dm$ is modelled with a BW parameterisation (+ EW corrections)
$d\sigma/dy$ and the Ai coefficients are modelled with fixed order pQCD at NNLO
$d\sigma/dp_T$ is modelled with parton shower (tried analytic resummation)

Rapidity distribution

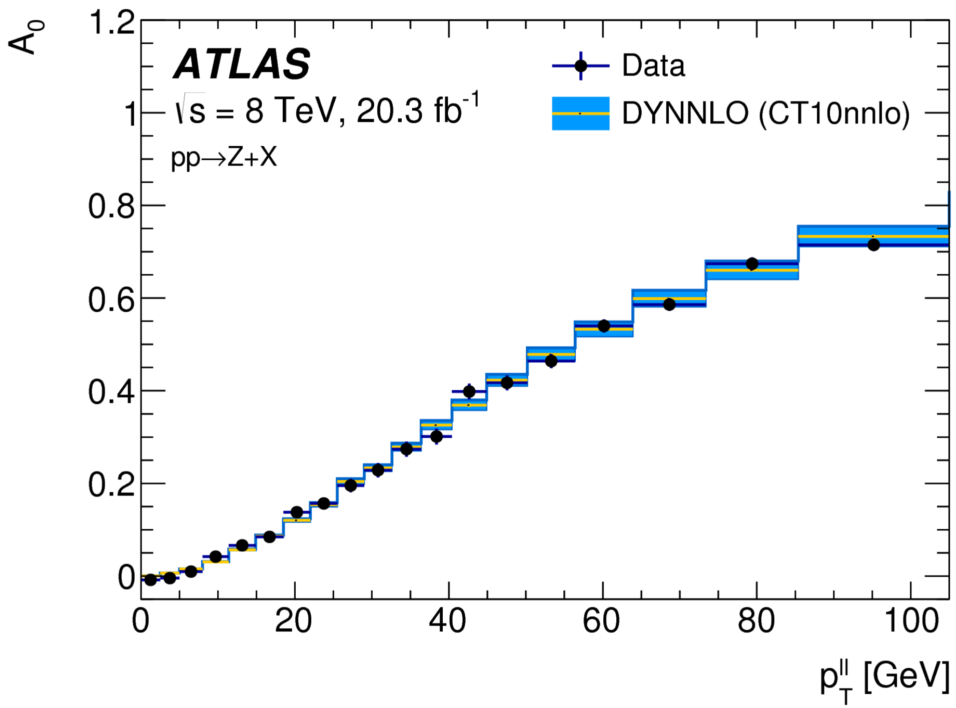
The rapidity distribution is modelled with NNLO predictions and the CT10nnlo PDF set. PDF choice validated on the observed weaker suppression of the strange quark in the W,Z cross-section data as published in [arXiv:1612.03016](https://arxiv.org/abs/1612.03016)

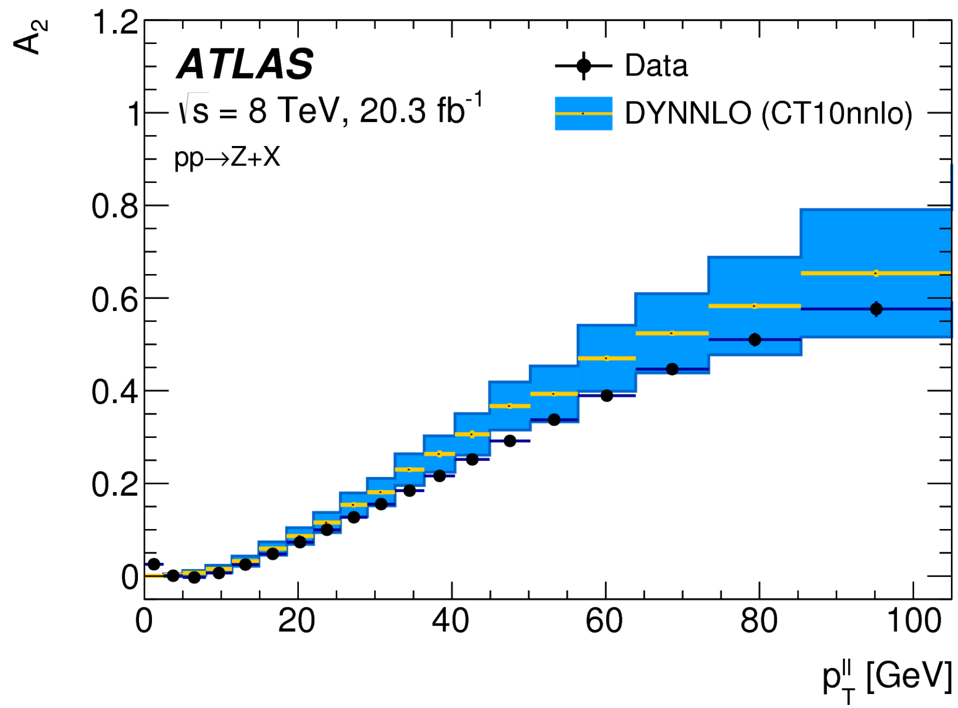


Satisfactory agreement between the theoretical prediction and the measurements is observed: χ^2/dof = 45/34.

Polarisation coefficients

The Ai coefficients are modelled with fixed order pQCD at NNLO.
The predictions (DYNNLO) are validated by comparison to the Ai measurements in 8 TeV Z-boson data JHEP08(2016)159





Uncertainties on Ai modelling: experimental uncertainty of the measurement and observed discrepancy for A2 coefficient

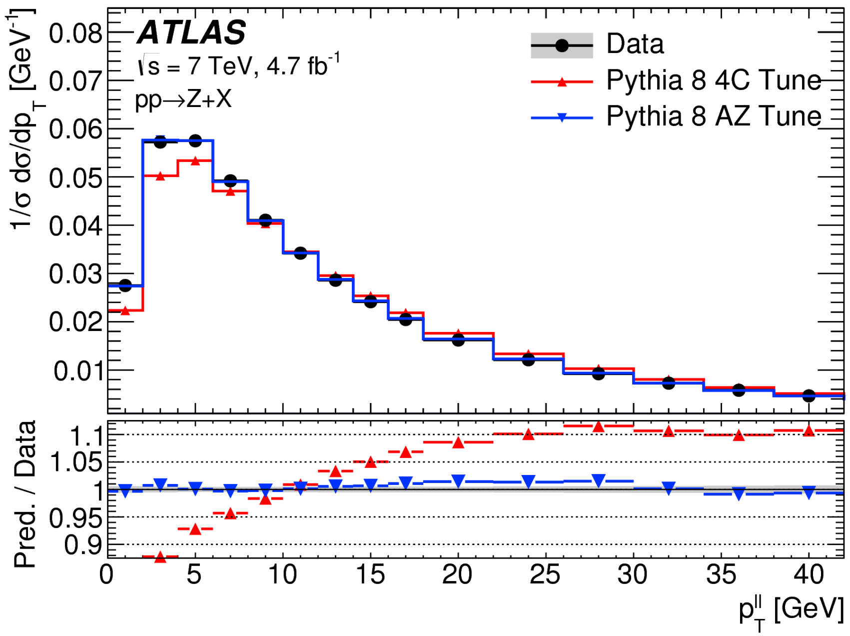
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3

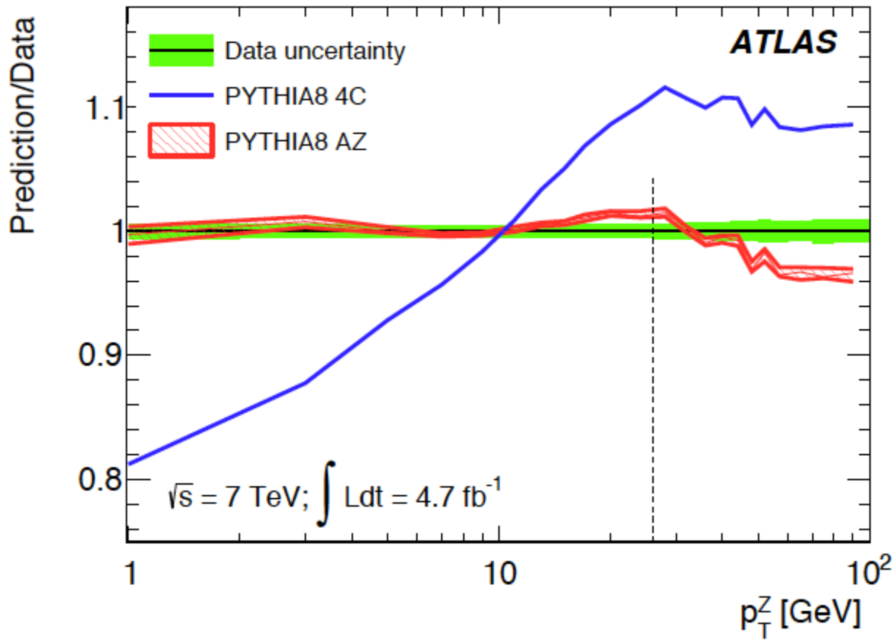
Z transverse momentum

Parton shower MC Pythia 8 tuned to the 7 TeV data AZ tune (better description in rapidity bins than the AZNLO tune of Powheg+Pythia) [JHEP09(2014)145]

	PYTHIA8
Tune Name	AZ
Primordial k_T [GeV]	1.71 ± 0.03
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002
ISR cut-off [GeV]	0.59 ± 0.08
χ^2_{min}/dof	45.4/32

The agreement between data and Pythia AZ is better than 1% for p_T<40 GeV





The accuracy of Z data is propagated and considered as an uncertainty

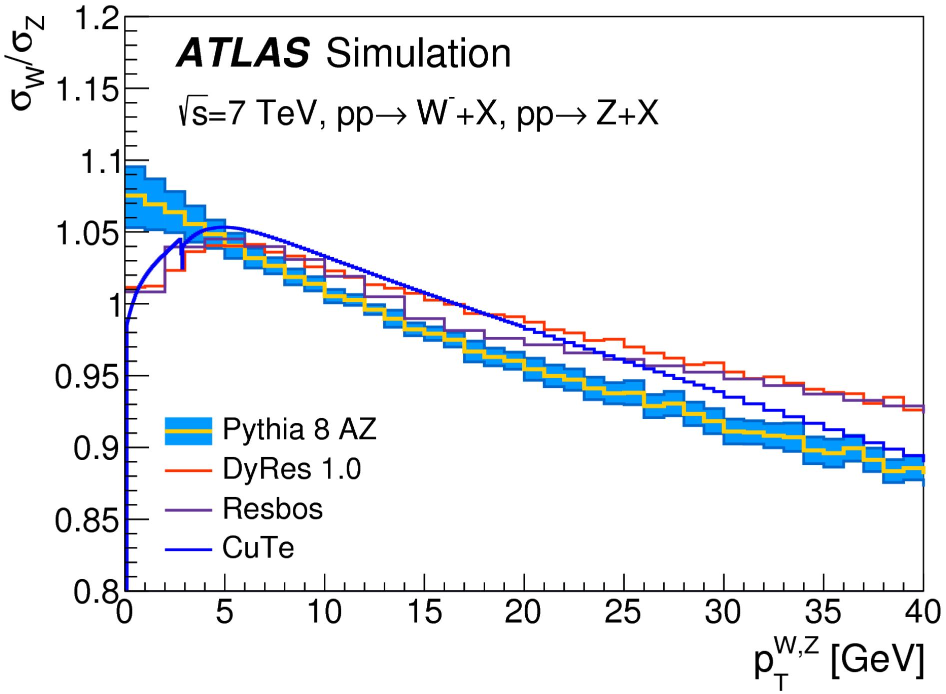
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4

W transverse momentum (I)

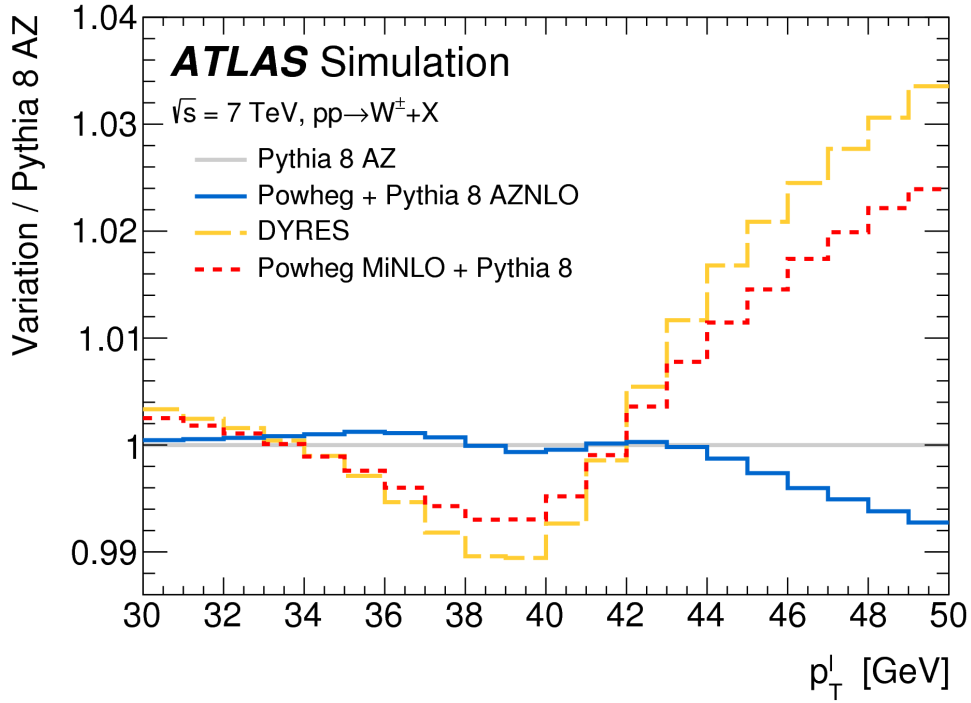
The Pythia8 AZ tune is fixed by the p_T^Z data; extrapolate to W considering relative variations of the W and Z p_T distributions.

Resummed predictions (DYRES, ResBos, CuTe) and Powheg MiNLO+Pythia8 were tried but they predict harder W p_T spectrum for a given p_T (Z) spectrum.

truth-level



reco-level

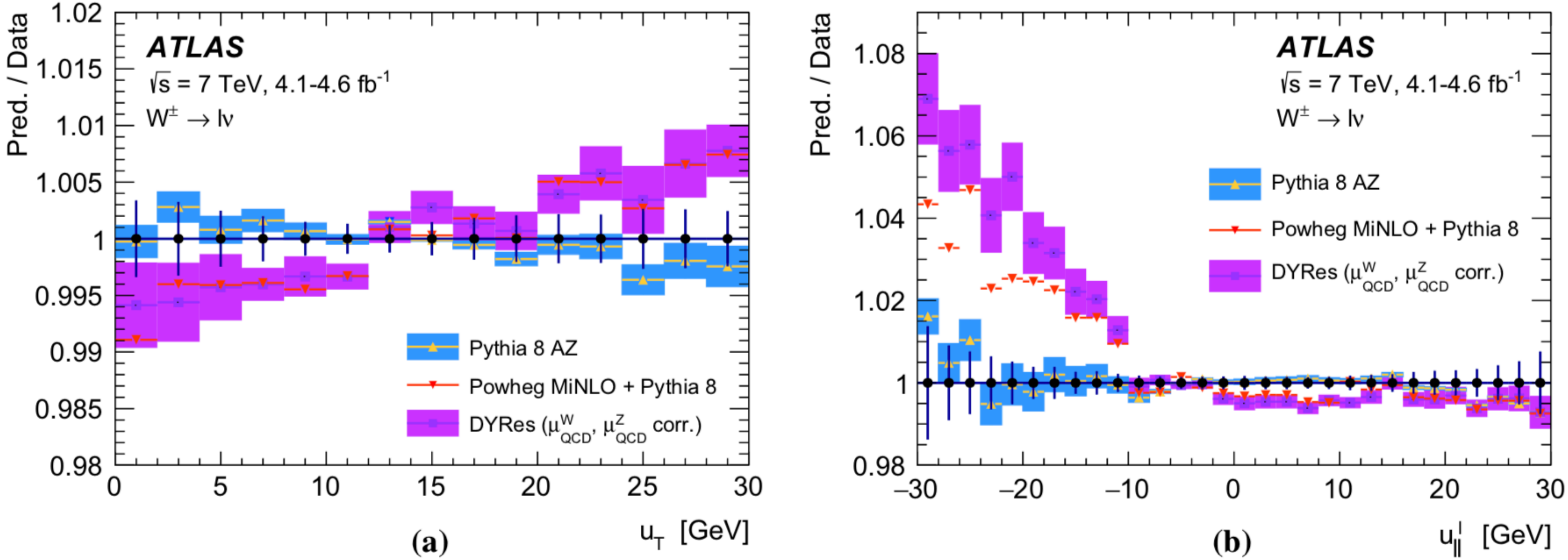


The effect on m_W of using the "formally" more accurate predictions has a significant impact on the W-mass value of the order of 50-100 MeV

W transverse momentum (II)

To validate the choice of Pythia8 AZ for the baseline, use $u_{||}^{l}$ distribution which is very sensitive to the underlying p_T^W distribution

—> provide a data-driven validation of the accuracy of our Pythia8 AZ model and compare to other calculations



NNLL resummed predictions and Powheg+MiNLO strongly disfavoured by the data however PS MC are in a good agreement; tested using Pythia8 , Herwig7 and Powheg+Pythia8

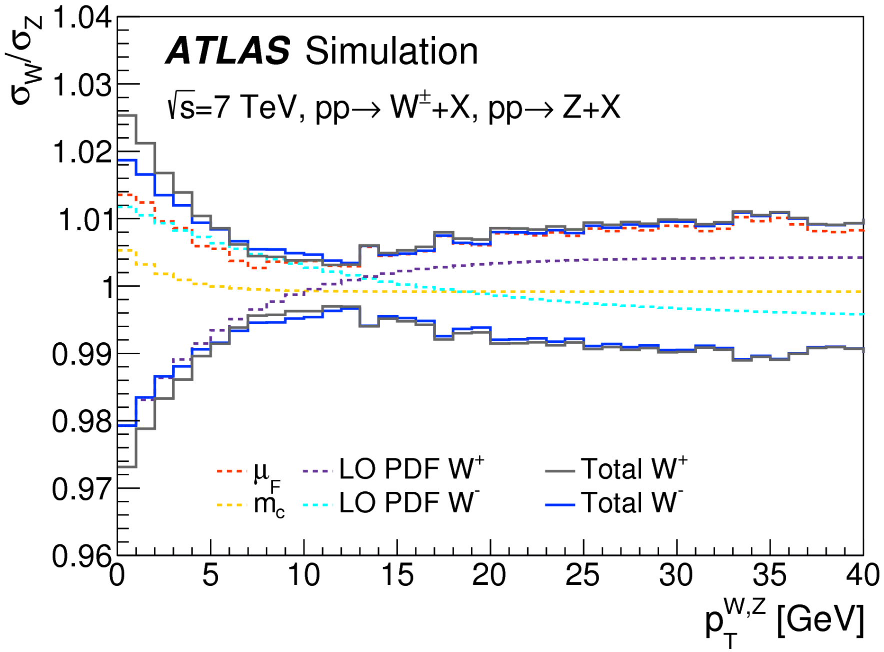
p_T^W uncertainties

Heavy flavour initiated production (HFI) introduces differences between Z and W and determines a harder pT spectrum, expect certain degree of decorrelation.
However higher-order QCD expected to be largely correlated between W and Z produced by light quarks

Consider relative variations on $p_T(W)/p_T(Z)$ under uncertainty variations.

Uncertainty: heavy quark mass variations *(varying m_c by ±0.5 GeV),* factorisation scale variations in the QCD ISR *(separately for light and heavy-quark induced production)*

Largest deviation of $p_T(W)/p_T(Z)$ for the parton shower PDF variation: CTEQ6L1 LO (nominal) to CT14lo, MMHT2014lo and NNPDF2.3lo

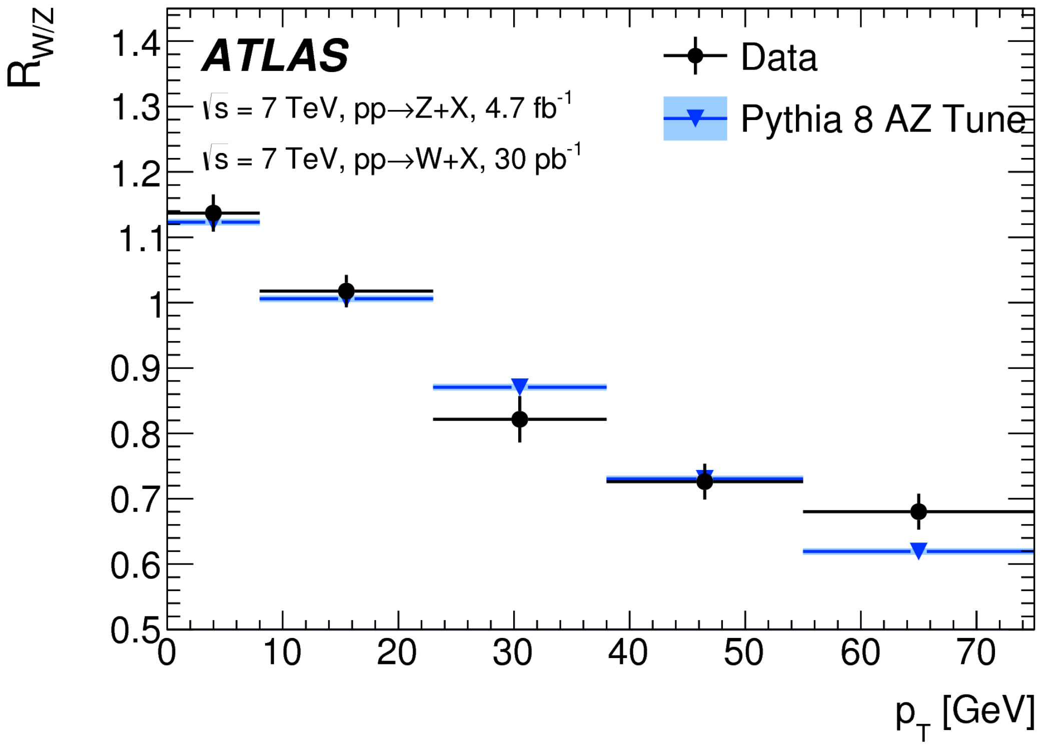


W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6

Reducing p_T^W uncertainties

The ratio of the W and Z pT distributions has been measured

Phys. Rev. D 85, 012005 arXiv:1701.07240



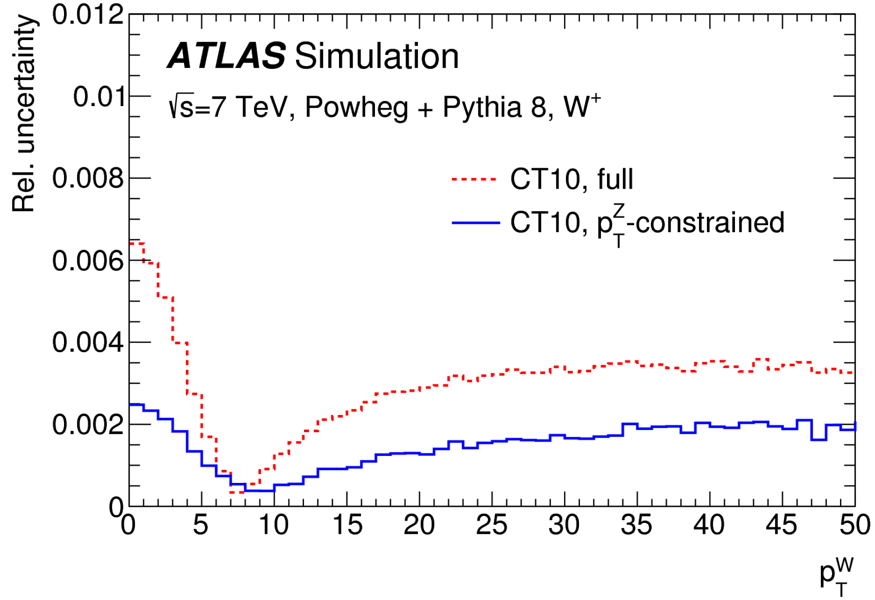
Limited precision of the data (~3%), and broad bin width (~8 GeV) limit the impact of these measurements on the systematic uncertainty.

Further measurements would be useful, ideally with low pile-up, targeting bin width <5 GeV and a precision about ~1%.

PDF uncertainties

PDF variations (25 error eigenvectors) of CT10nnlo are applied simultaneously to the boson rapidity, Ai, and p_T distributions.

Only relative variations of the $p_T(W)$ and $p_T(Z)$ induced by PDFs are considered.



W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7

The PDF uncertainties are very similar between p_T^l and m_T but strongly anti-correlated between W^+ and W^-. Envelope taken from CT14 and MMHT2014~3.8 MeV.

Summary of physics modelling 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

QCD

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

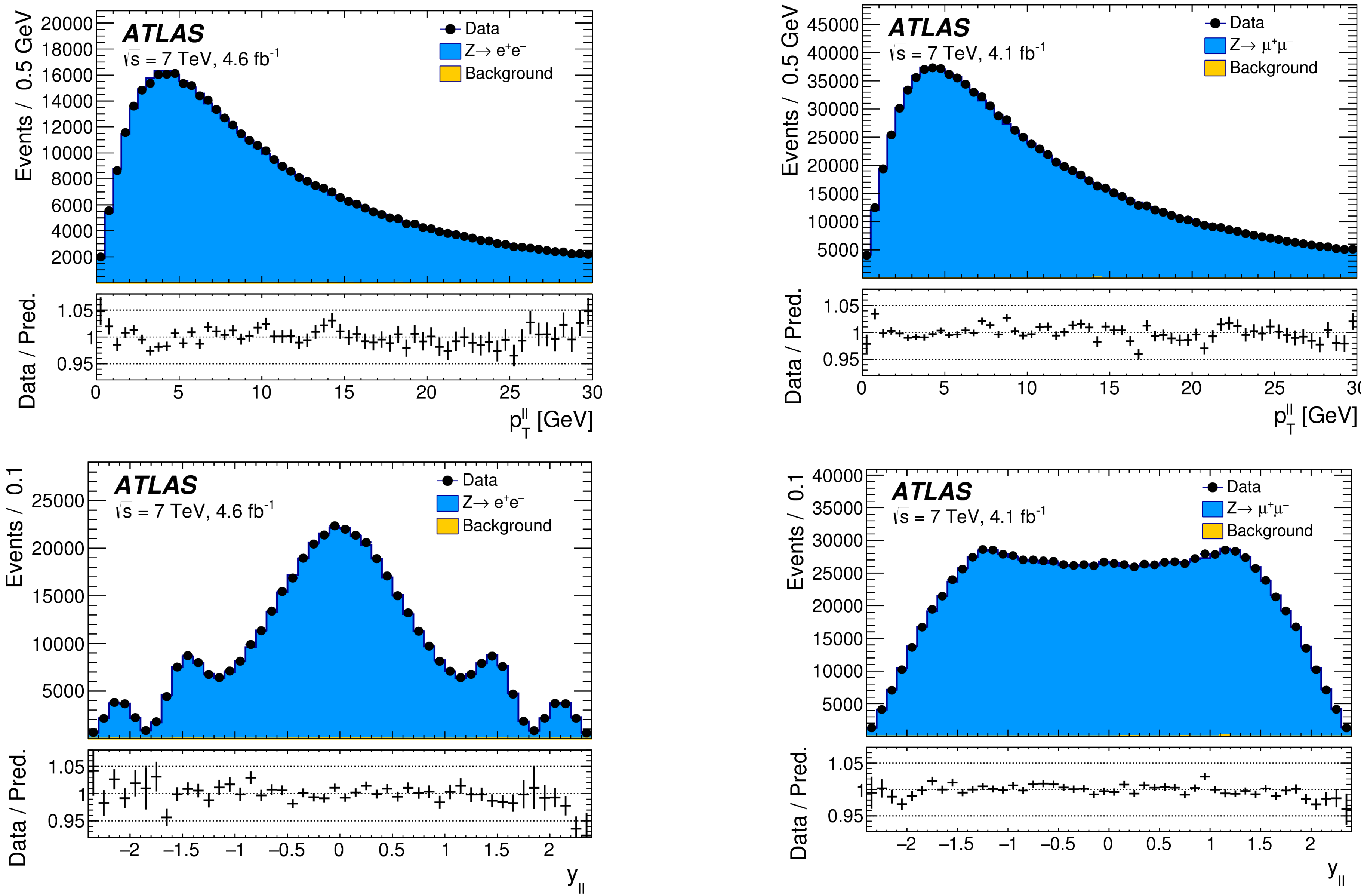
EW

The PDF uncertainties are the dominant followed by $p_T(W)$ uncertainty due to the heavy-flavour initiated production.

Validation and results

Z control distributions: p_T, y

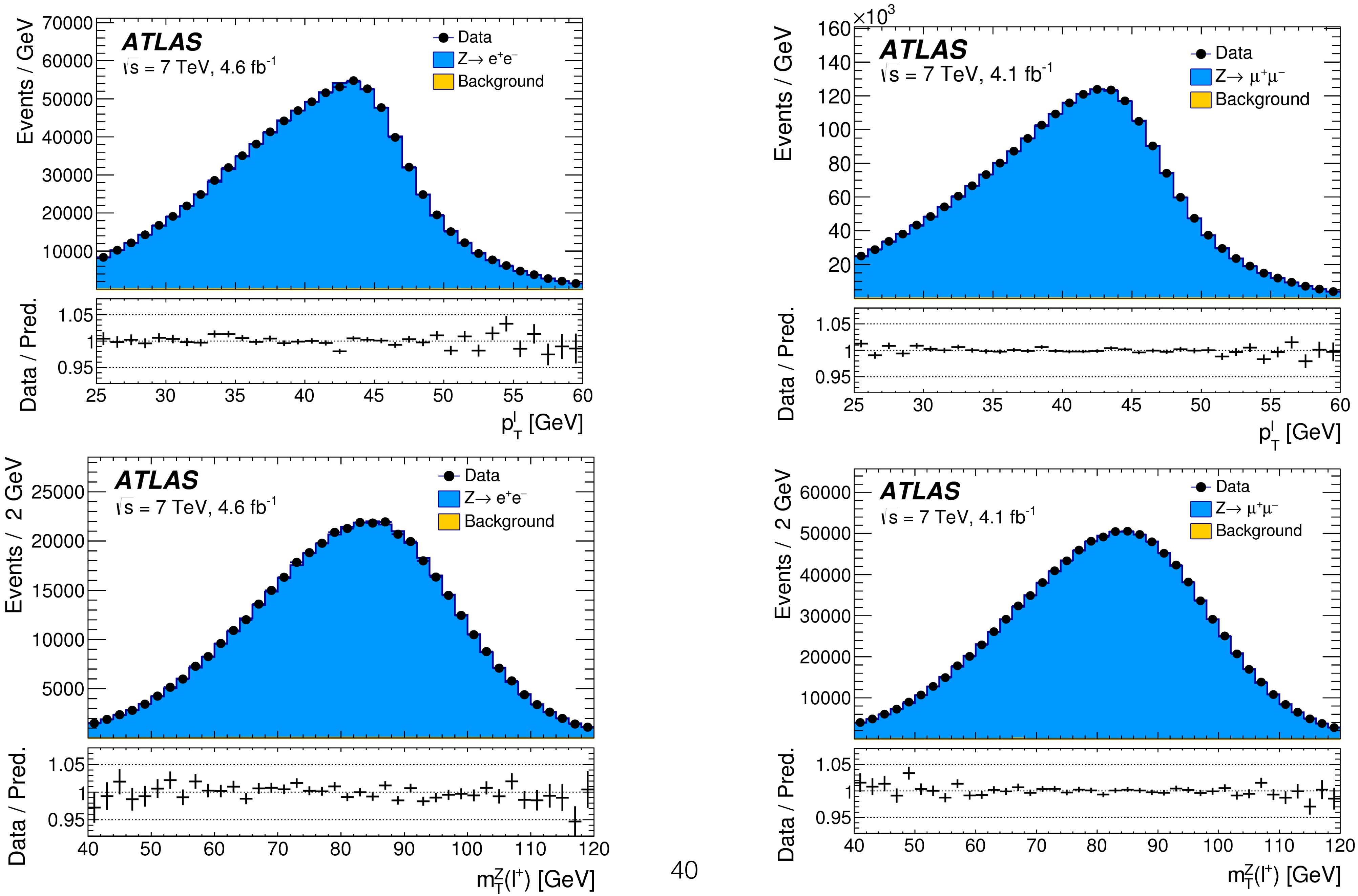
Z tranverse momentum and rapidity distributions in e, μ channels



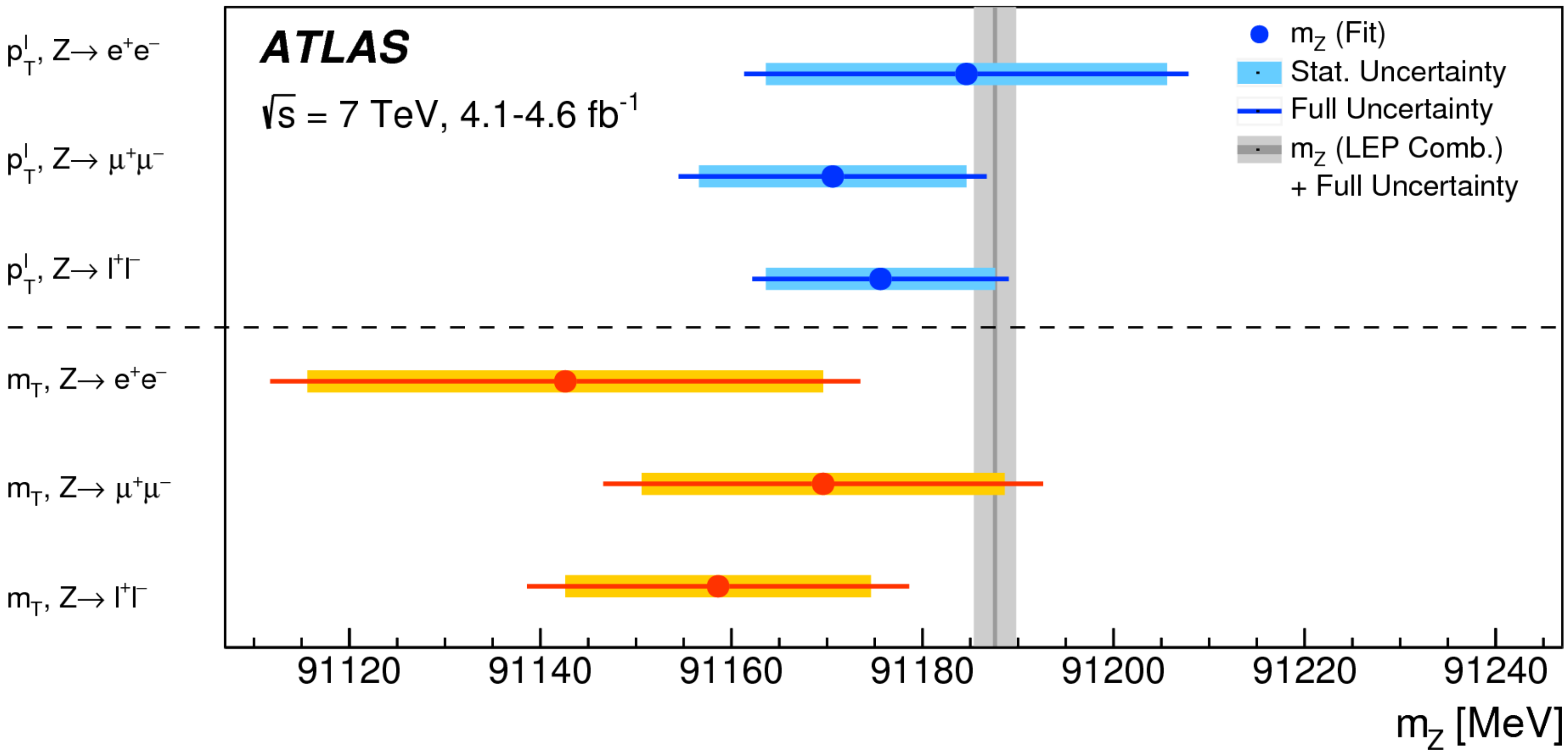
Good agreement is observed. Error bars are statistics only.

Z mass-sensitive distributions: p_T^l and m_T

Tranverse momentum and transverse mass distributions in e, μ channels



Z mass measurement



Lepton charge Distribution	ℓ^+ p_T^ℓ	 m_T	ℓ^- p_T^ℓ	 m_T	Combined 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	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

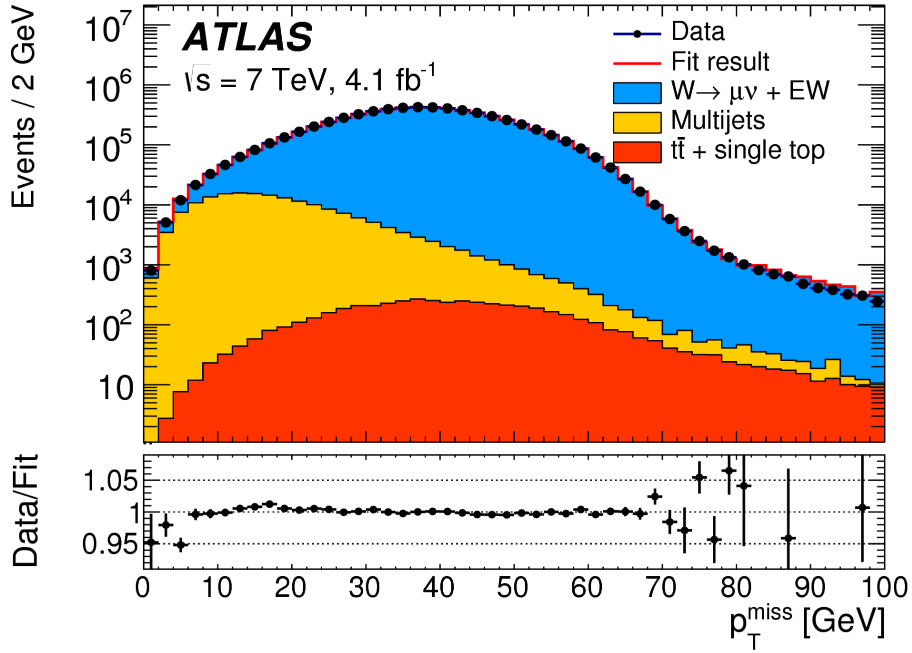
Results are consistent with the combined LEP value of m_Z within experimental uncertainties

Backgrounds in W

Electroweak and top-quark backgrounds are determined from simulation

Multijet background is determined using data-driven techniques:

- define background-dominated fit regions with relaxed cuts of the event selection
- template fits in these regions to 3 observables: p_T^{miss}, m_T and p_T^l/m_T
- control regions are obtained by inverting the lepton isolation requirements



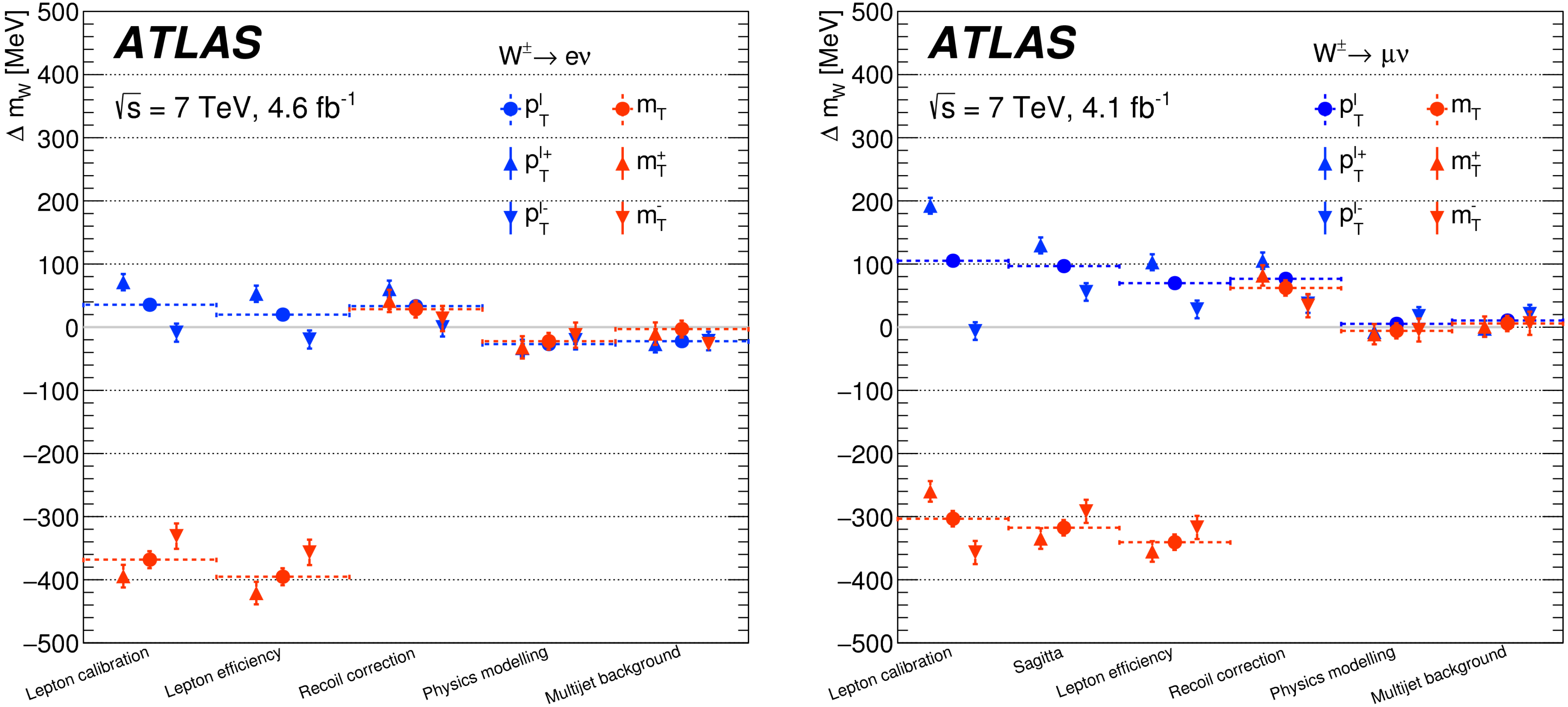
$W \to \mu\nu$						
Category	$W \to \tau\nu$	$Z \to \mu\mu$	$Z \to \tau\tau$	Top	Dibosons	Multijet
$W^{\pm}$ $0.0 < \lvert\eta\rvert < 0.8$	1.04	2.83	0.12	0.16	0.08	0.72
$W^{\pm}$ $0.8 < \lvert\eta\rvert < 1.4$	1.01	4.44	0.11	0.12	0.07	0.57
$W^{\pm}$ $1.4 < \lvert\eta\rvert < 2.0$	0.99	6.78	0.11	0.07	0.06	0.51
$W^{\pm}$ $2.0 < \lvert\eta\rvert < 2.4$	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
$W^{\pm}$ $0.0 < \lvert\eta\rvert < 0.6$	1.02	3.34	0.13	0.15	0.08	0.59
$W^{\pm}$ $0.6 < \lvert\eta\rvert < 1.2$	1.00	3.48	0.12	0.13	0.08	0.76
$W^{\pm}$ $1.8 < \lvert\eta\rvert < 2.4$	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

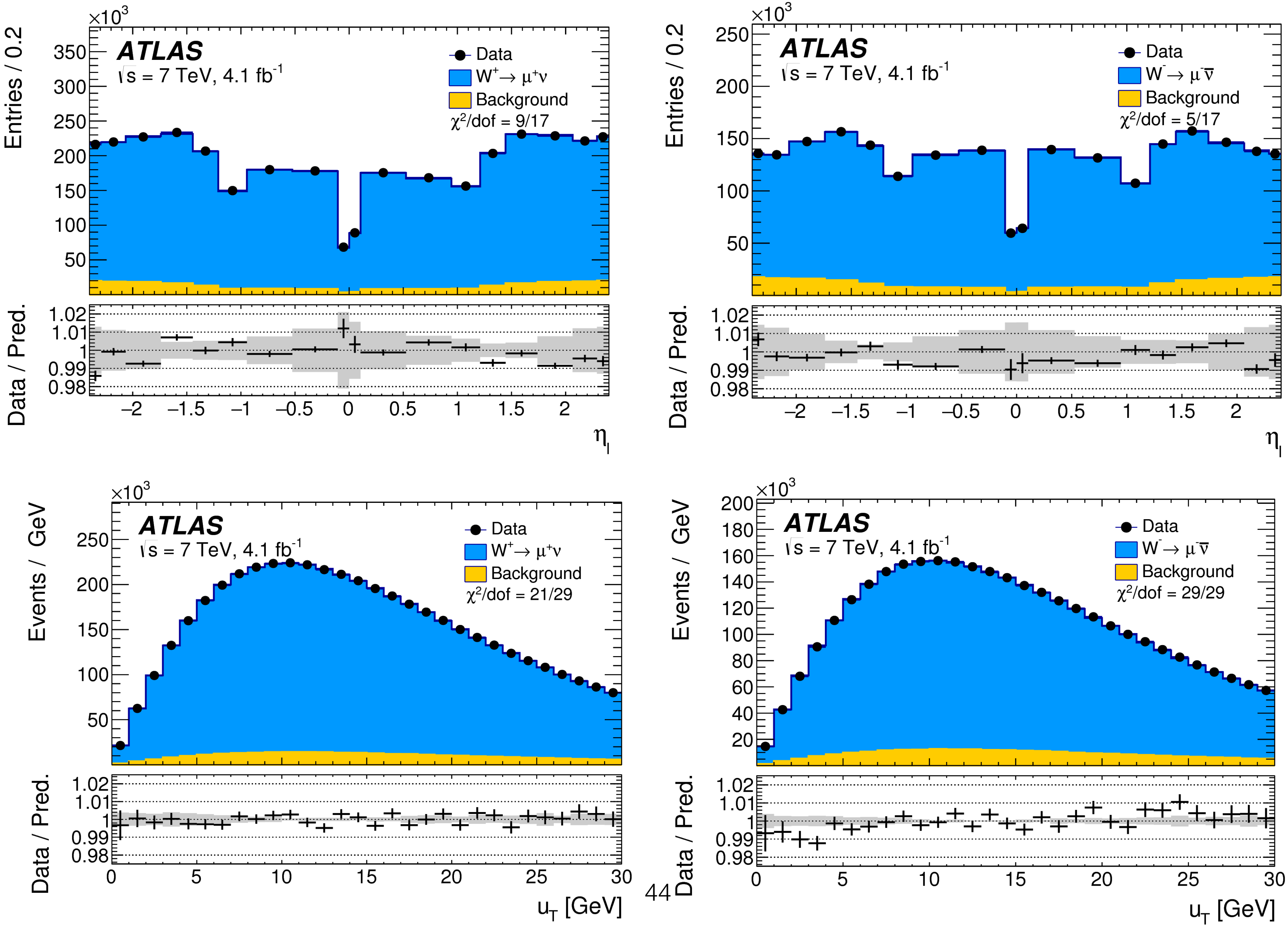
Kinematic distribution	p_T^{ℓ}				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (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

Summary of corrections

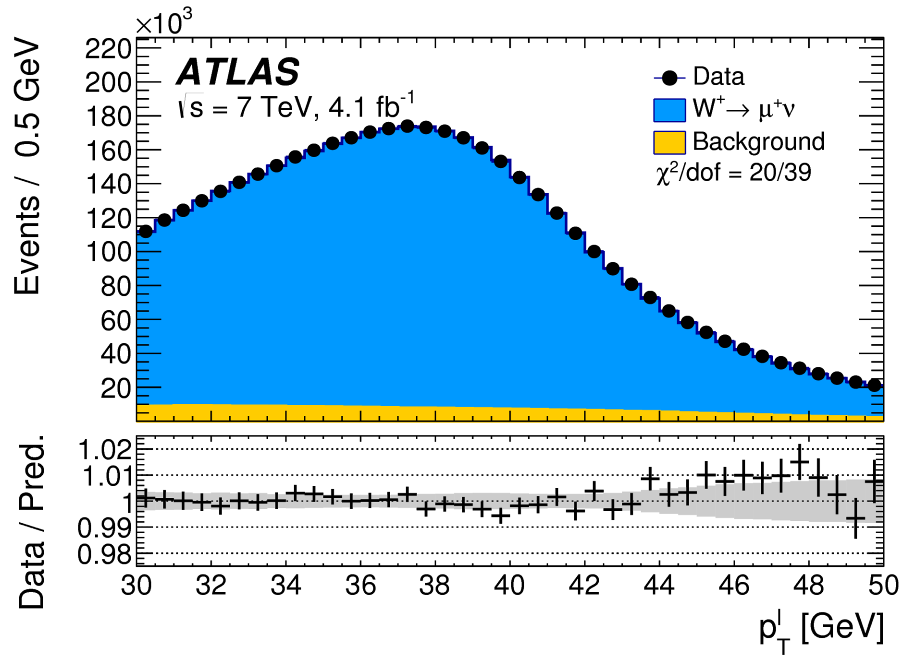
After all corrections are applied, consistent results are achieved between different channels, observables, categories, charges and only after, results were unblinded.

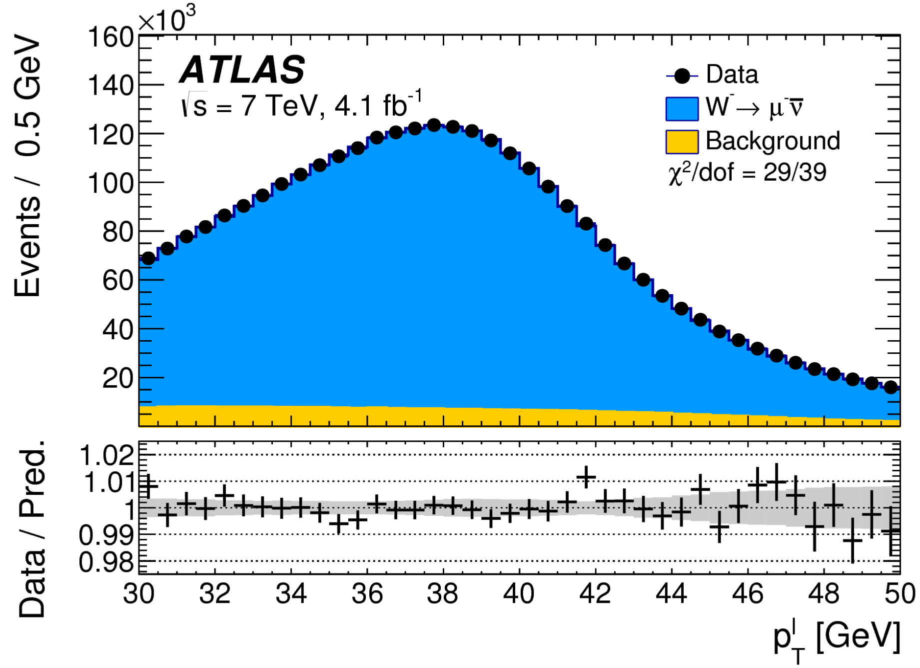


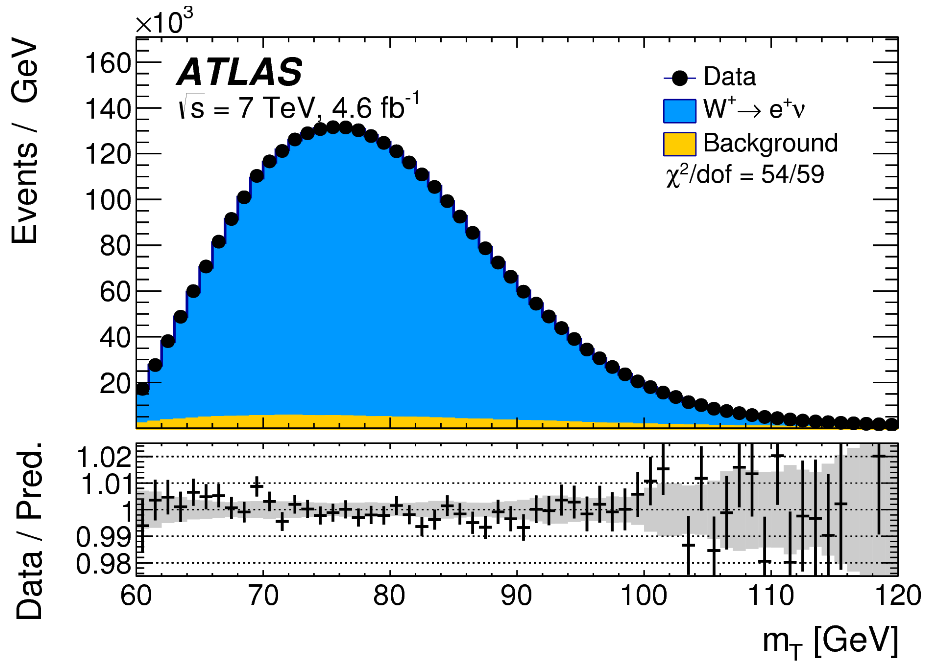
W control distributions: η, p_T

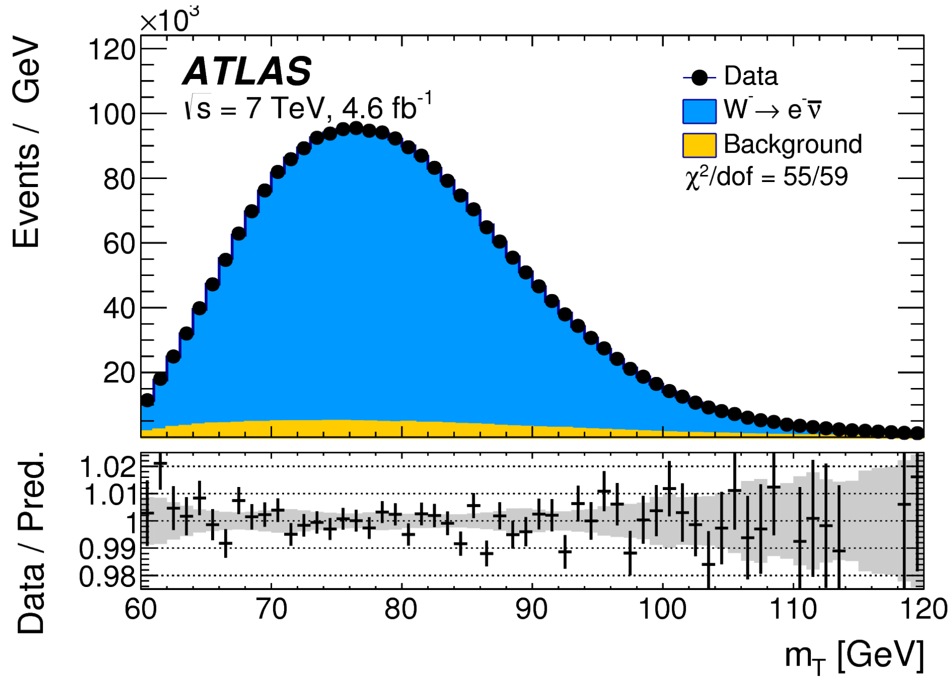


W mass-sensitive distributions: p_T^l and m_T



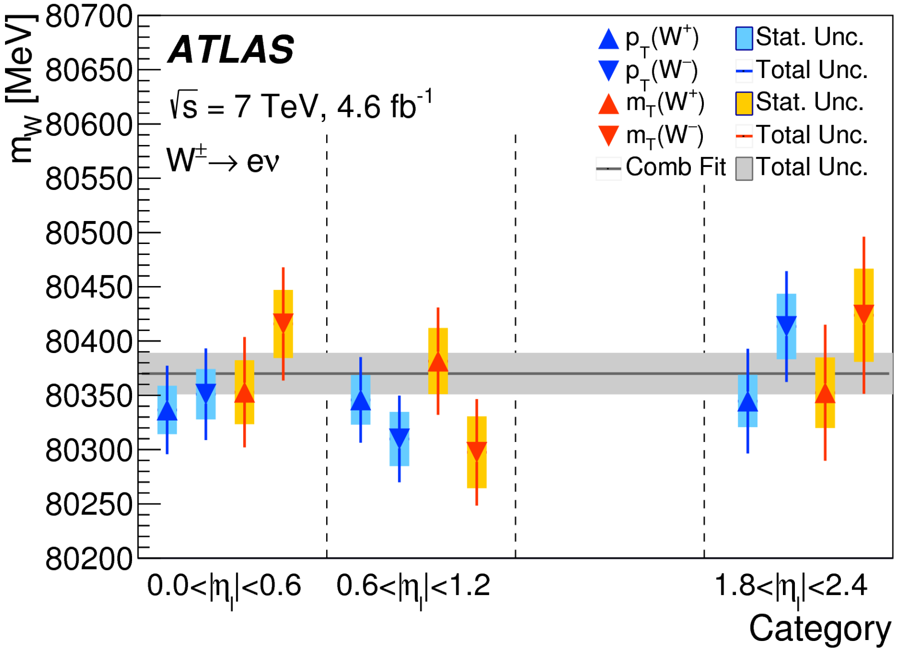


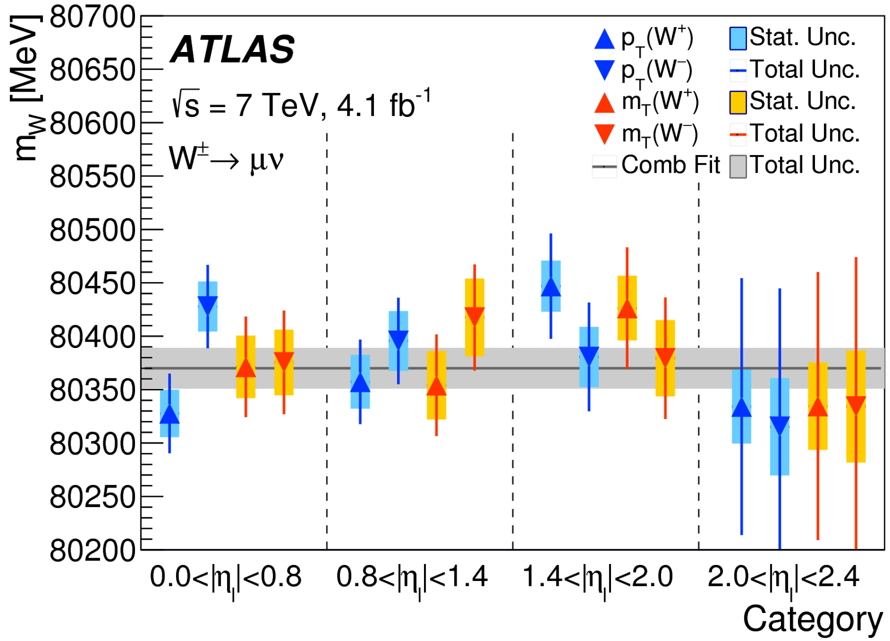


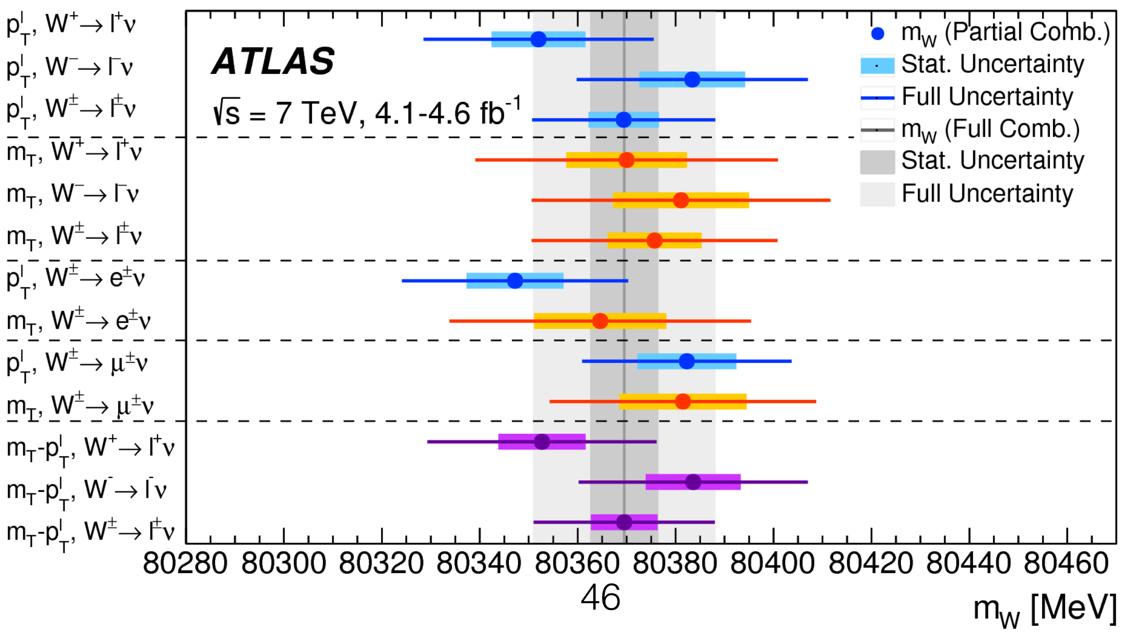


Consistency of the results

The consistency of the results was checked in the different categories but also in different pileup, u_T and $u_{//}$ bins





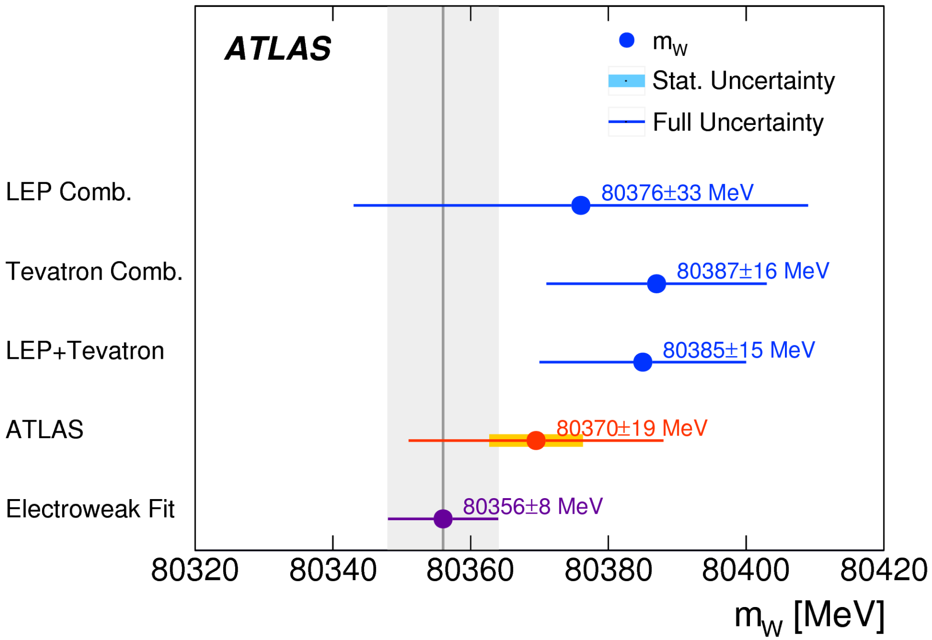


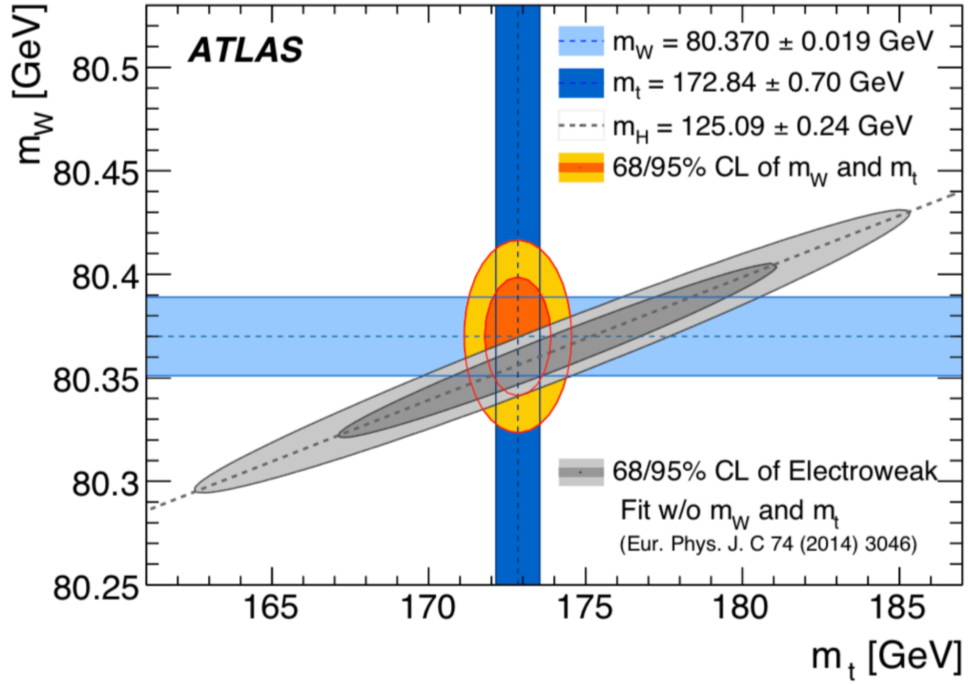
Fitting ranges:
$32<p_T^l<45$ GeV,
$66<m_T<99$ GeV

Results

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

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27





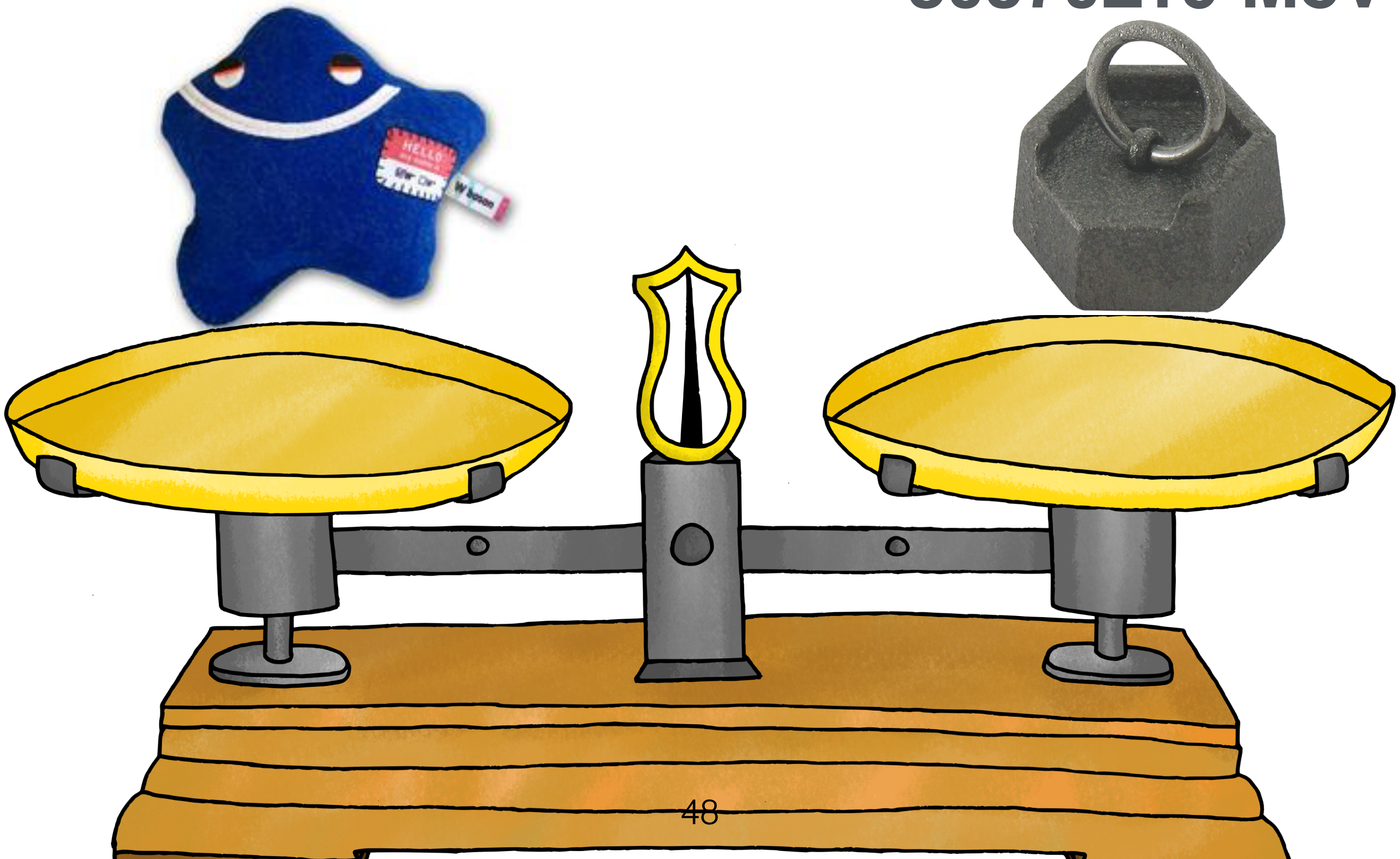
The result is consistent with the SM expectation, compatible with the world average and competitive in precision to the currently leading measurements by CDF

Conclusion

The first LHC measurement of mW = 80370+/-19 MeV is public now [Eur. Phys. J. C (2018) 78:110] after many years of effort in the ATLAS collaboration.

The central value is consistent with the SM prediction and with the current world average value.

80370±19 MeV



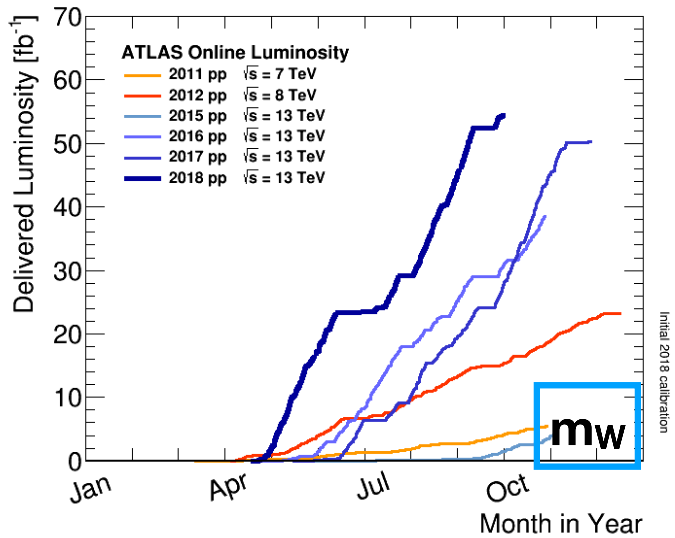
Prospects for improvement

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

- **Stat uncertainty:** add more data available

- **Experimental uncertainty:** improve the experimental precision - calibration and reconstruction

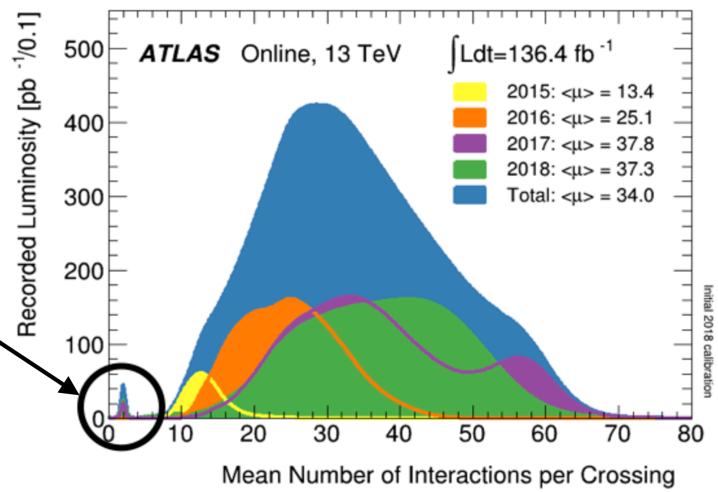
- **Theory-related uncertainties:** reduce PDF and modelling uncertainties by adding information from auxiliary measurements



Low pile-up runs

In November 2017 special low pile-up runs of a few days:
- ~250 pb^{-1} @5 TeV mu=0.5~ 4
- ~150 pb^{-1} @13 TeV mu = 2 (levelled)

In 2018: ~ 190 pb^{-1} @13 TeV mu=2 (levelled)

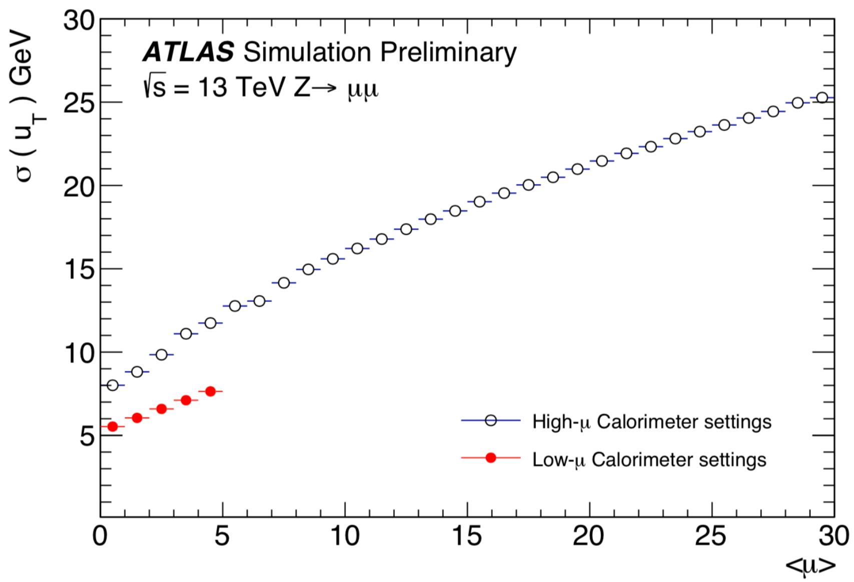


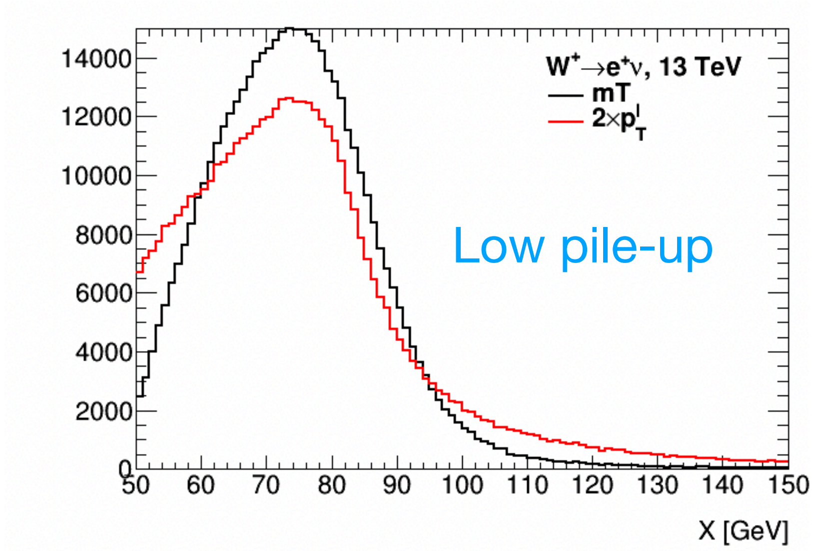
Low pile-up runs

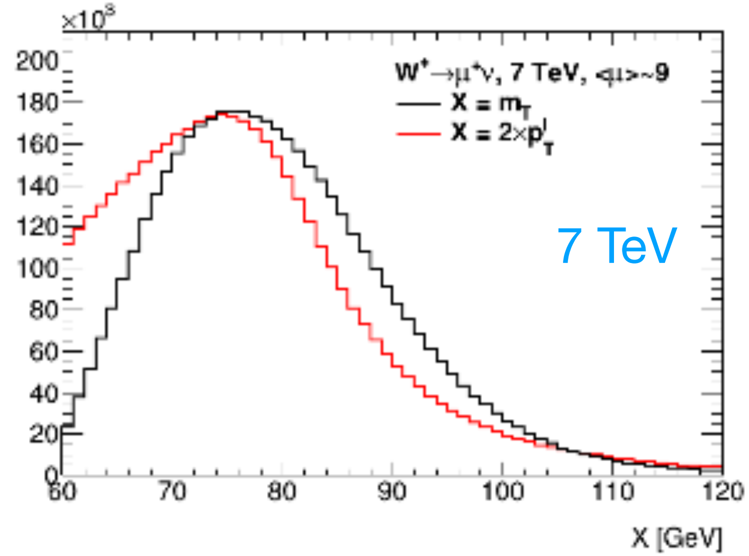
ATLAS-PUB-2017-021

Needed for W mass measurement:

- Increase sensitivity from m_T
- Direct p_T^W measurement —> use information to reduce p_T modelling uncertainties also in high pile-up runs
- Used for calibration studies







Stay tuned for future interesting measurements !

Thank you for your attention!