# Measurement of the W-boson mass with the ATLAS detector


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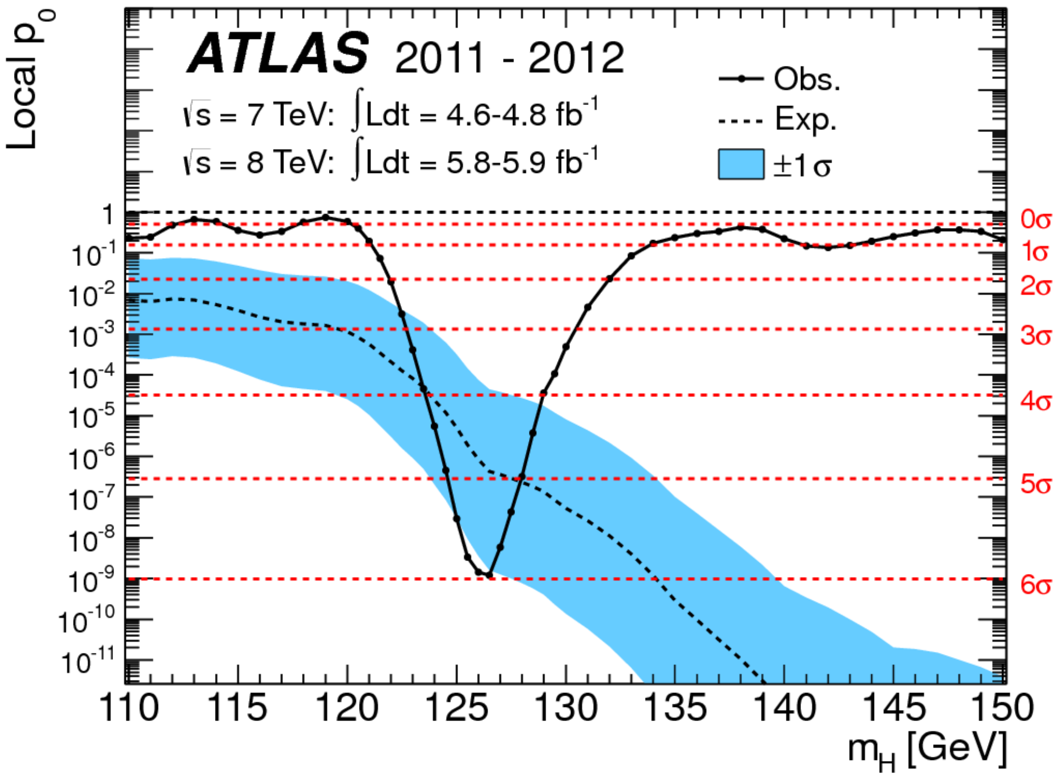
**May 3, 2017**

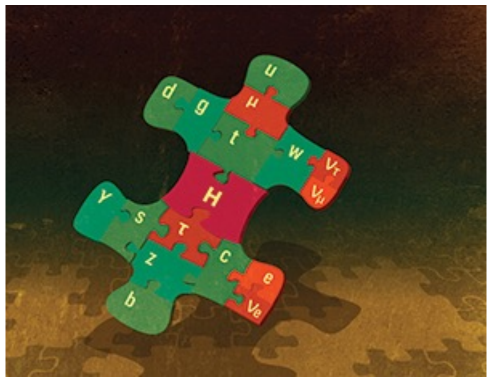
# Standard Model

Seminar 4 July 2012

Huge step in our understanding of Particle Physics:
recent discovery of the Higgs boson


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

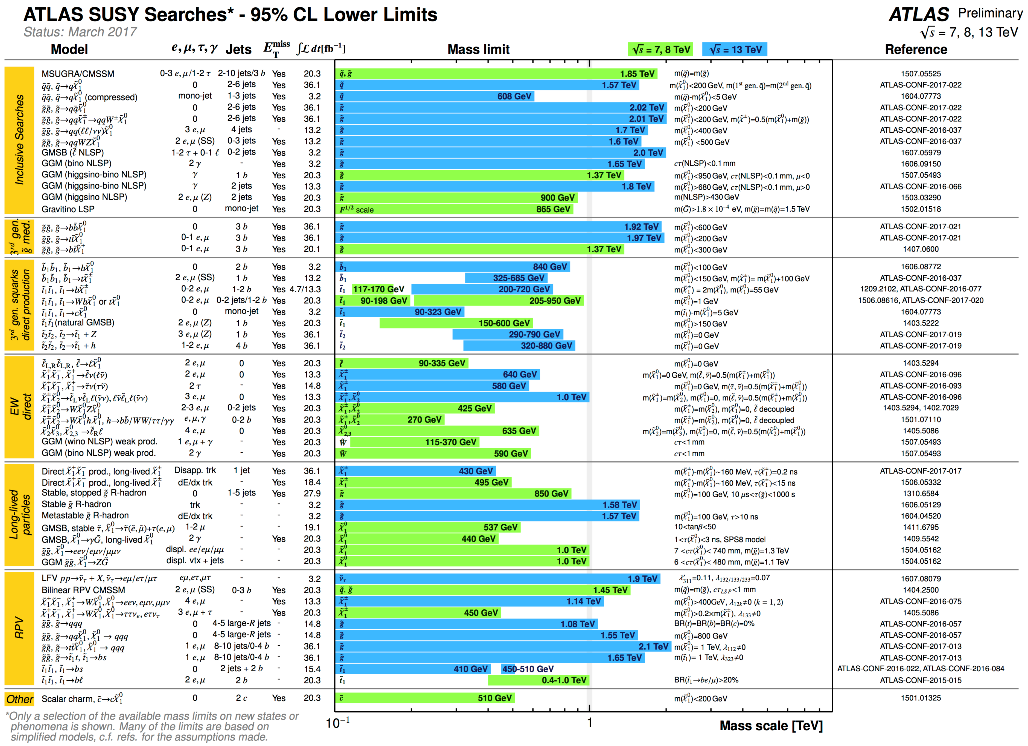


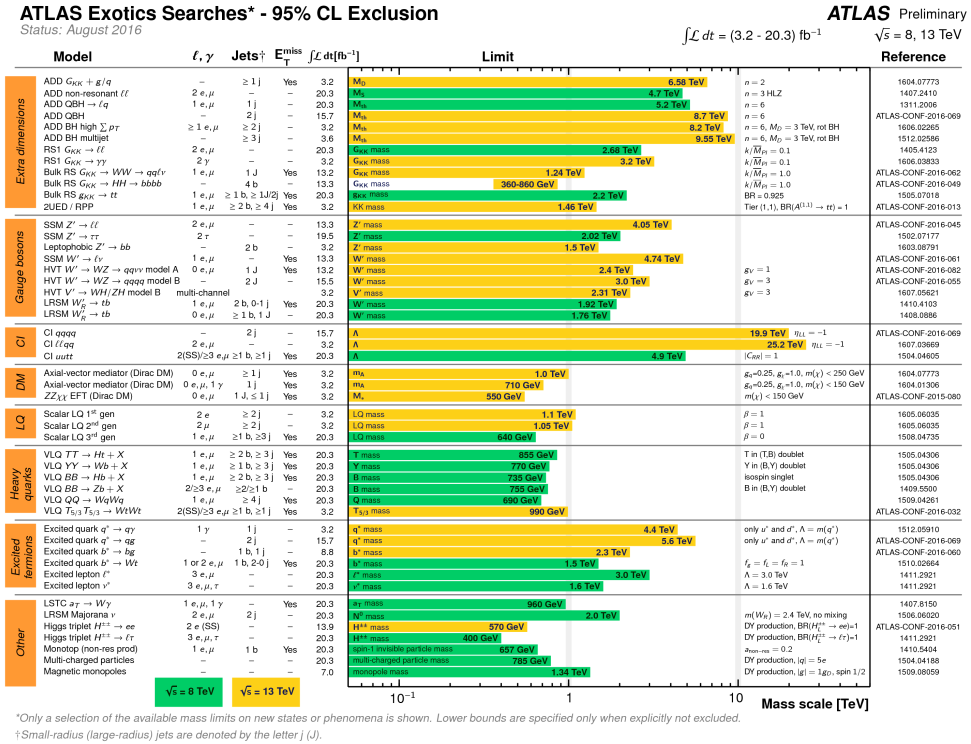



SM puzzle completed, but many open questions (mass hierarchy, baryon asymmetry, dark matter… ) remain without answers —> Search for Beyond the SM

# Beyond the Standard Model

Direct searches: huge numbers of new results - astonishing achievement. No significant signals - updated limits. More still to come with 13 TeV.



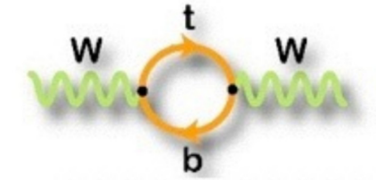




Indirect searches: precision measurements in EW sector (Higgs couplings, $\sin^2\theta$, $m_W$…)

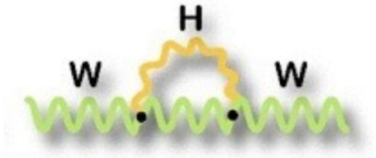
# W mass measurement

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

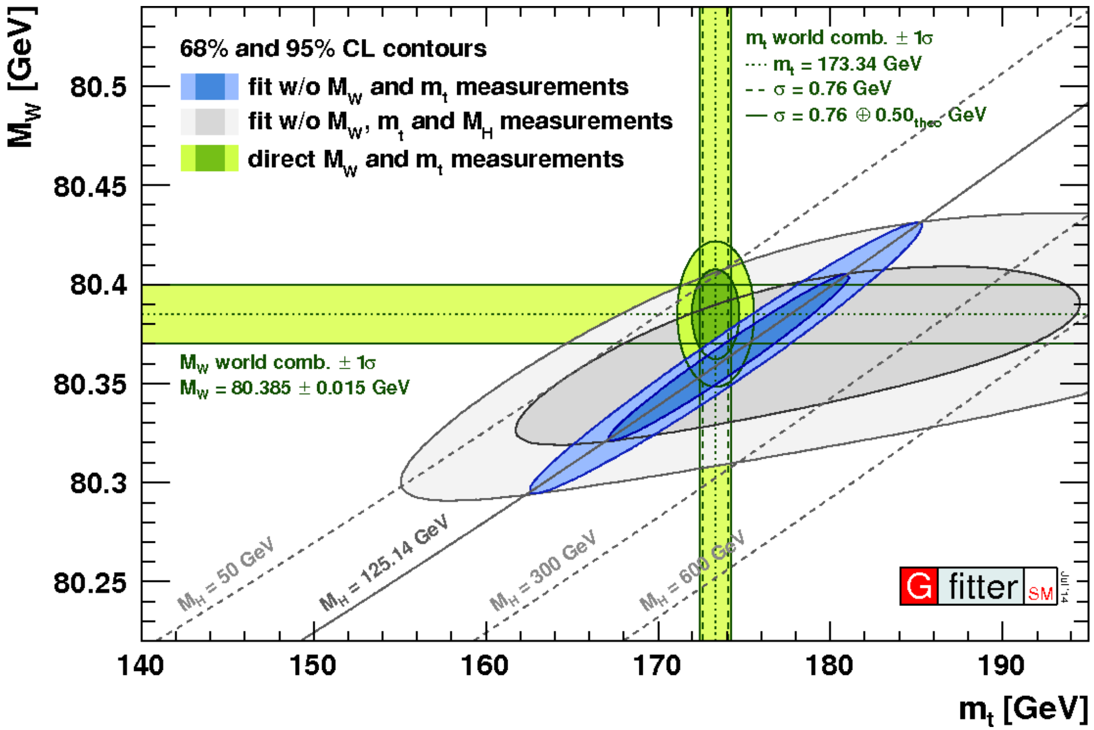
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$




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



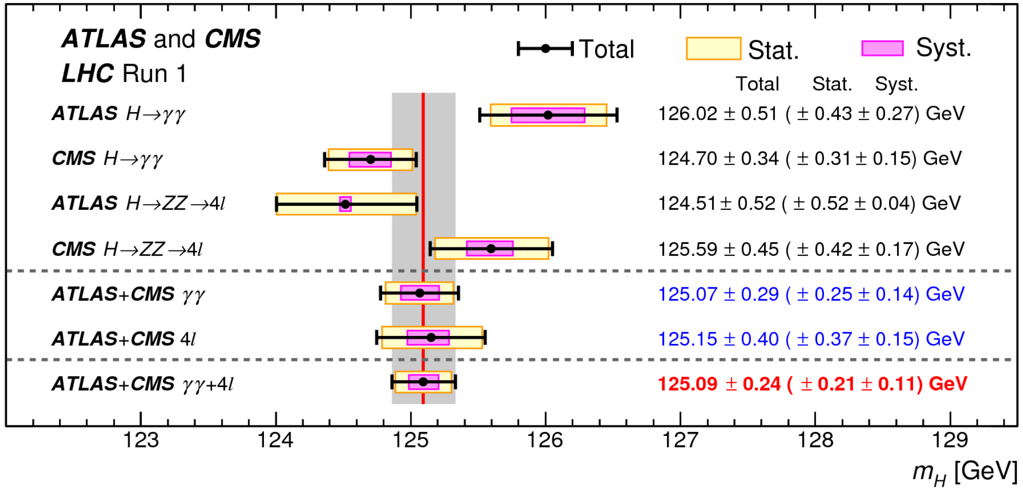

The relation between $M_W$, $m_t$, and $M_H$ provides stringent test of the SM and is sensitive to new Physics



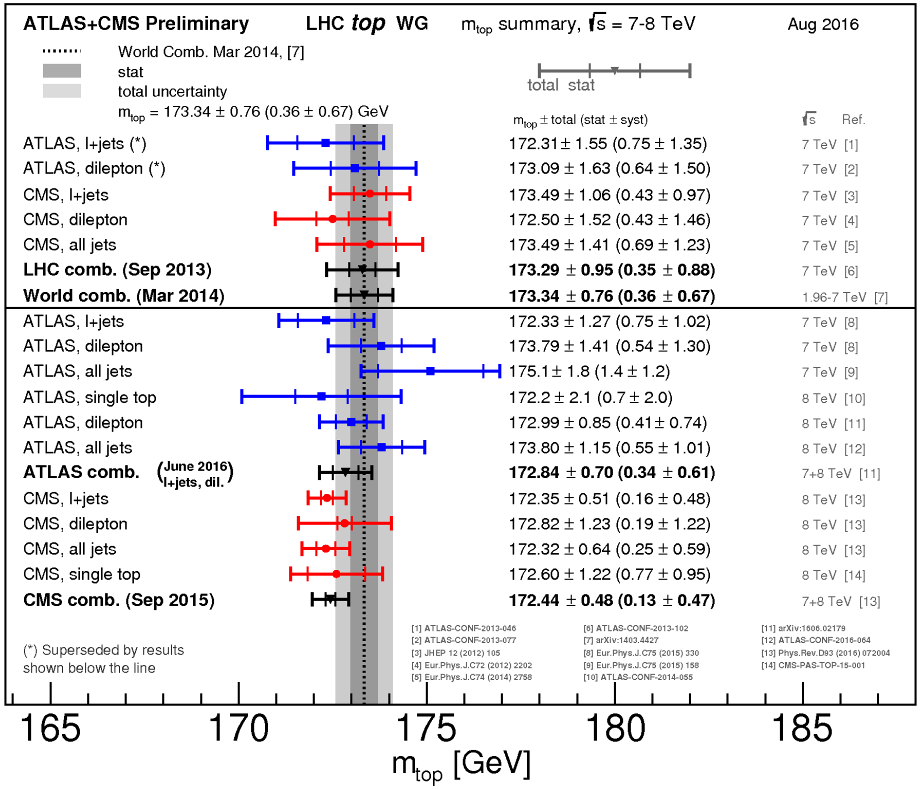
# Status of the measurements

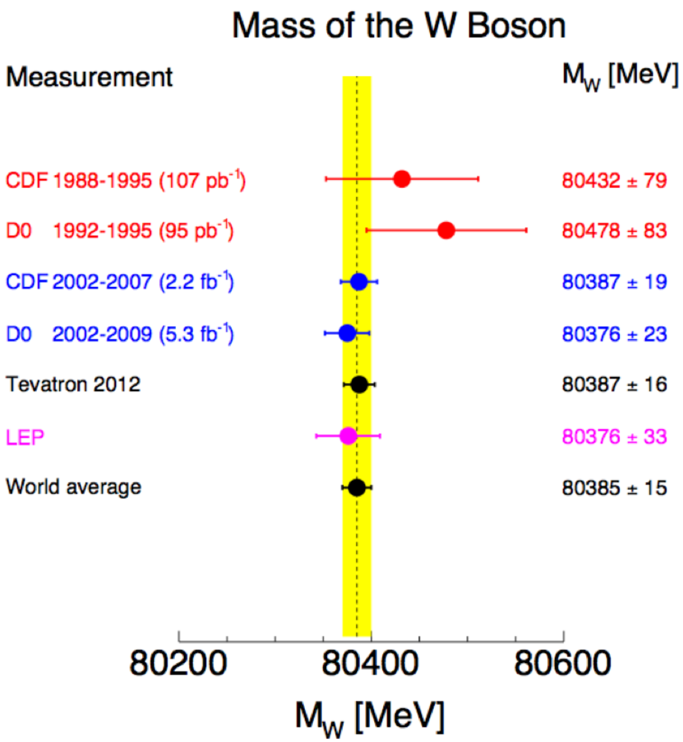
## Higgs mass

Phys. Rev. Lett. 114, 191803




## Top mass




## W mass

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

# Tevatron results

## CDF experiment:

Phys. Rev. Lett.108 (2012) 151803

electron/muon channels
2.2 $fb^{-1}$ integrated luminosity

$m_W$= 80387±12(stat)±15(syst) MeV

| Source | Uncertainty (MeV) |
|---|---|
| Lepton energy scale and resolution | 7 |
| Recoil energy scale and resolution | 6 |
| Lepton removal | 2 |
| Backgrounds | 3 |
| $p_T(W)$ model | 5 |
| Parton distributions | 10 |
| QED radiation | 4 |
| $W$-boson statistics | 12 |
| Total | 19 |

## D0 experiment:

Phys. Rev. Lett. 108 (2012) 151804

electron channel
~5.3 $fb^{-1}$ integrated luminosity

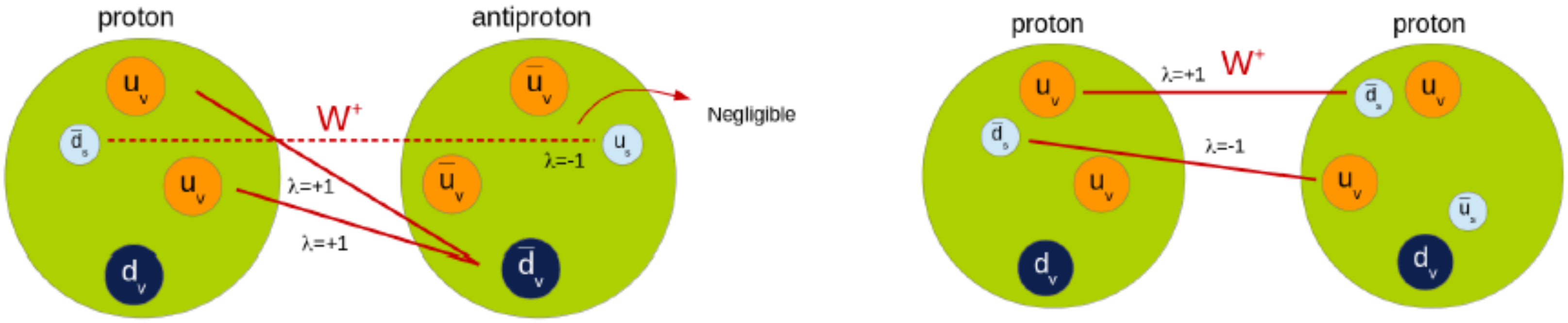
$m_W$= 80375±11(stat)±20(syst) MeV

| | $\Delta M_W$ (MeV) | | |
|---|---|---|---|
| Source | $m_T$ | $p_T^e$ | $\not{E}_T$ |
| Electron energy calibration | 16 | 17 | 16 |
| Electron resolution model | 2 | 2 | 3 |
| Electron shower modeling | 4 | 6 | 7 |
| Electron energy loss model | 4 | 4 | 4 |
| Hadronic recoil model | 5 | 6 | 14 |
| Electron efficiencies | 1 | 3 | 5 |
| Backgrounds | 2 | 2 | 2 |
| Experimental subtotal | 18 | 20 | 24 |
| PDF | 11 | 11 | 14 |
| QED | 7 | 7 | 9 |
| Boson $p_T$ | 2 | 5 | 2 |
| Production subtotal | 13 | 14 | 17 |
| Total | 22 | 24 | 29 |

$$M_W = 80\,387 \pm 16 \text{ MeV}$$

# W mass @ LHC

Challenging environment @LHC: pileup, need a high experimental precision and an accurate theoretical modelling




- $W^+/W^-$ production is asymmetric —> charge-dependent analysis

- 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).*

- The W polarisation is determined by the difference between the u, d valence and sea densities

CERN Seminar 13/12/2016

# Despite the challenge!


CERN Courier January/February 2017

## News

LHC EXPERIMENTS

## ATLAS makes precision measurement of W mass

arXiv.org > hep-ex > arXiv:1701.07240v1

arXiv:1701.07240 [hep-ex]

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High Energy Physics – Experiment

**Measurement of the $W$-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector**

ATLAS Collaboration

(Submitted on 25 Jan 2017)

paper is submitted to EPJC

New

# Strategy of the measurement (I)

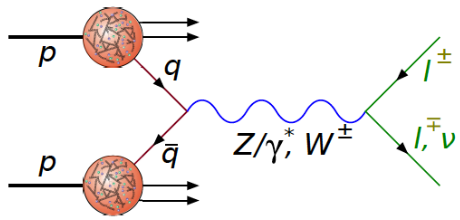
Not possible to fully reconstruct W mass

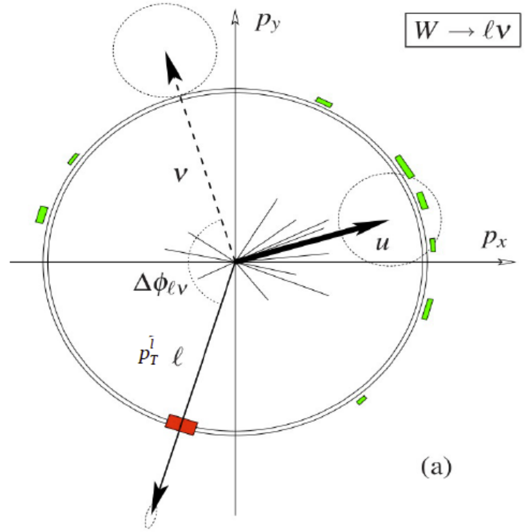
Sensitive final state distributions: **$p_T^l$, $m_T$,** $p_T^{miss*}$

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

$u_T$ being the recoil

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




Categories for the measurement:

| Decay channel | $W \to e\nu$ | $W \to \mu\nu$ |
|---|---|---|
| Kinematic distributions | $p_T^\ell$, $m_T$ | $p_T^\ell$, $m_T$ |
| 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] |

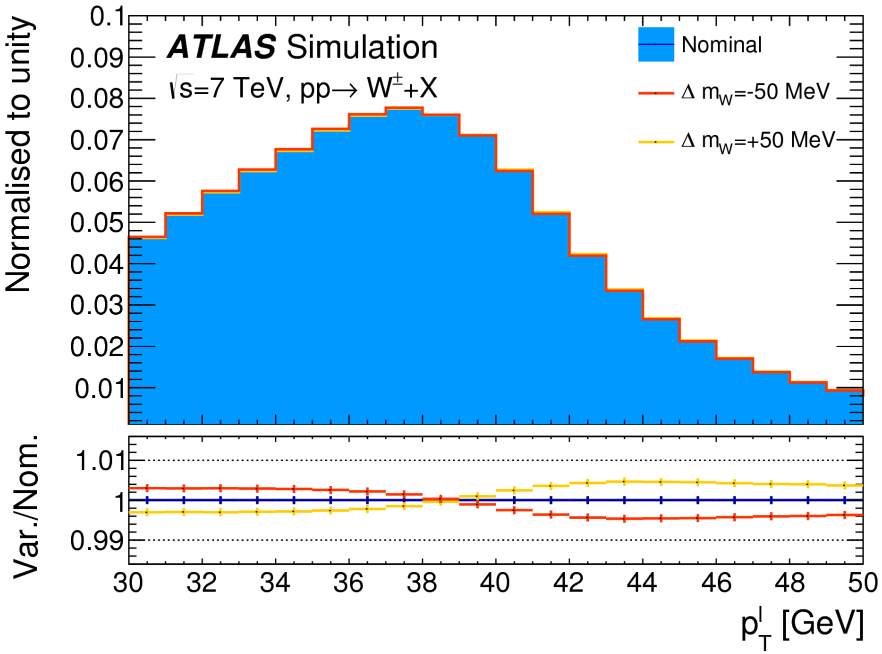
*used as cross-check only

# Strategy of the measurement (II)

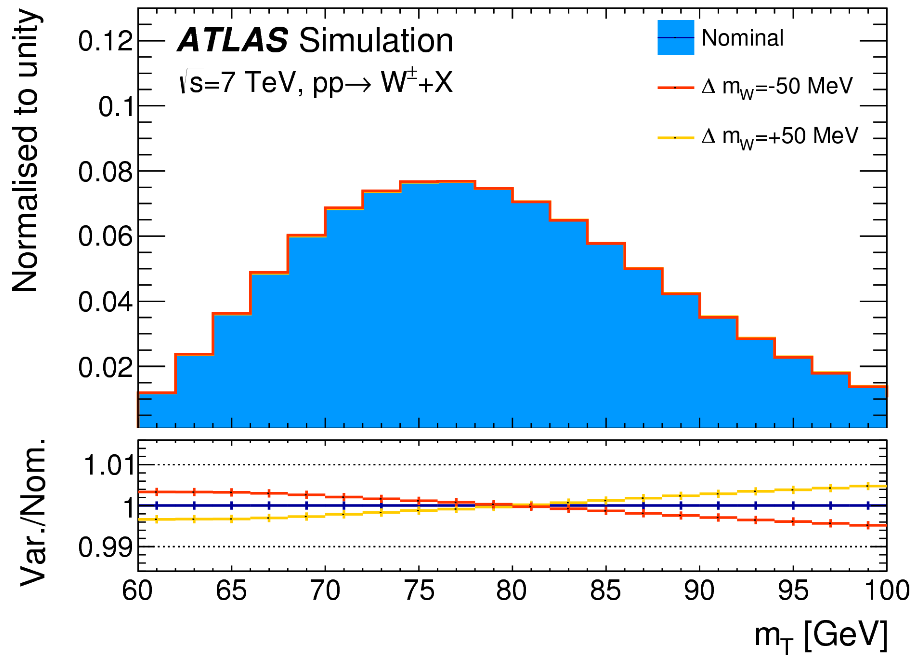
**Template fit approach:** compute the $p_T^l$ and $m_T$ distributions for different assumed values of $m_W$* —> $\chi^2$ minimisation gives the best fit template.

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.*

# Selection cuts

Lepton selections:

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

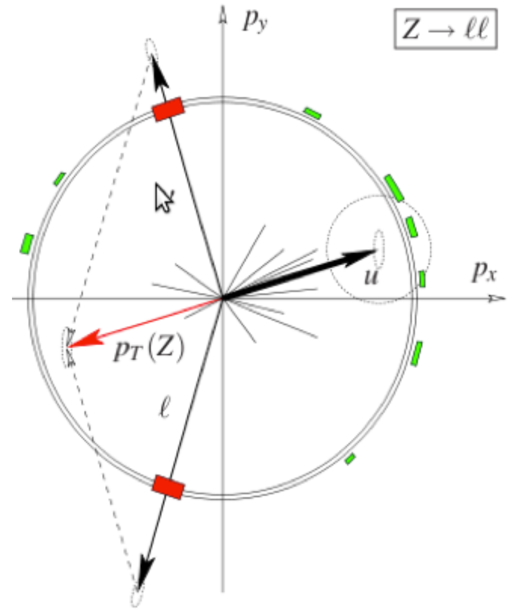
Kinematic requirements: $p_T^l>30$ GeV, $m_T>60$ GeV, MET>30 GeV and recoil($u_T$)<30 GeV

~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 |

# 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 and expected momentum balance with $p_T^{ll}$)* and theoretical constraints *(ancilliary measurements).*

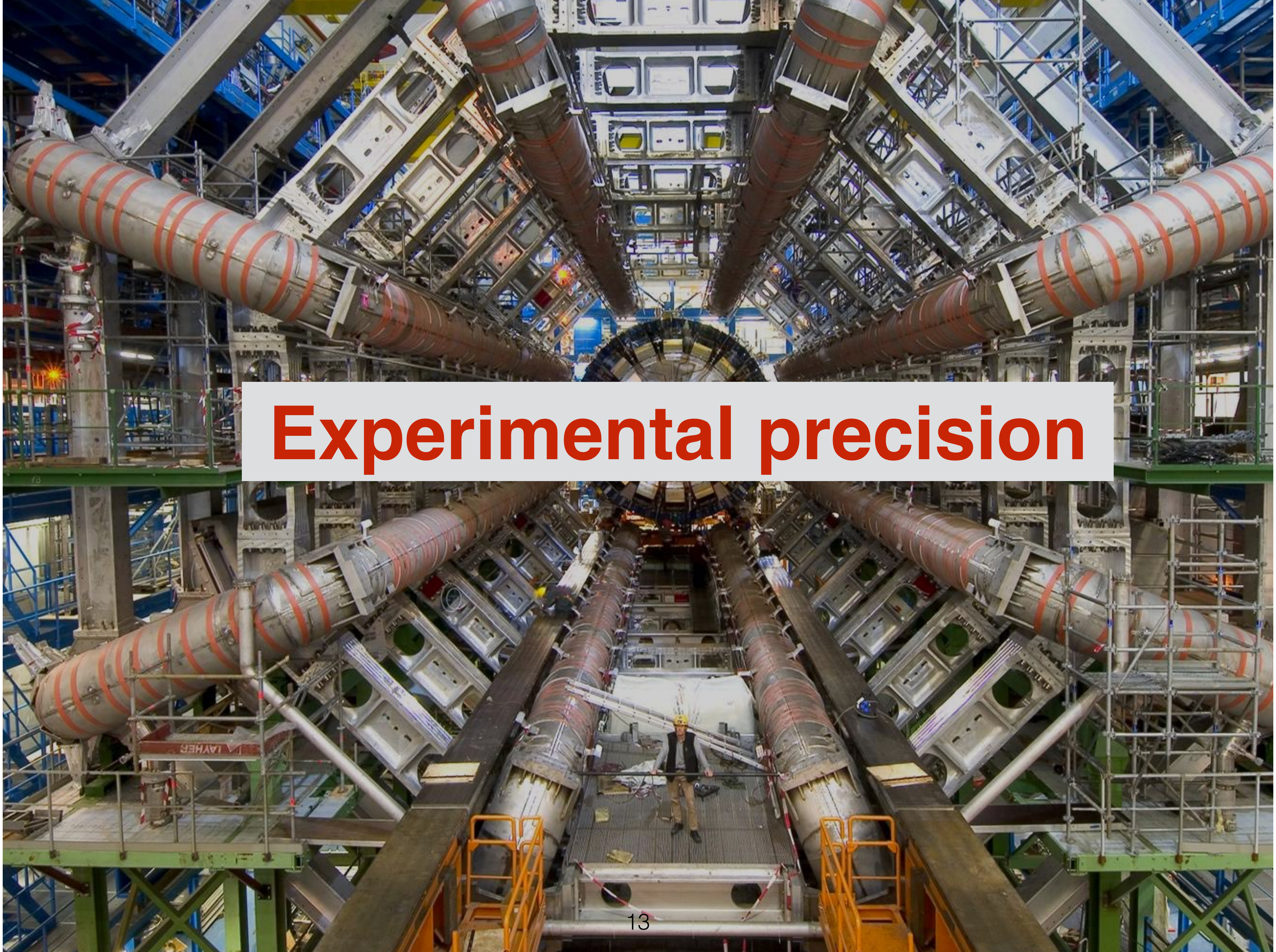



The whole analysis is checked by performing a measurement of the Z-boson mass and comparing to the LEP value, also a cross-check Z mass measurement in "W-like" i.e removing the 2nd lepton and treating it like a neutrino

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



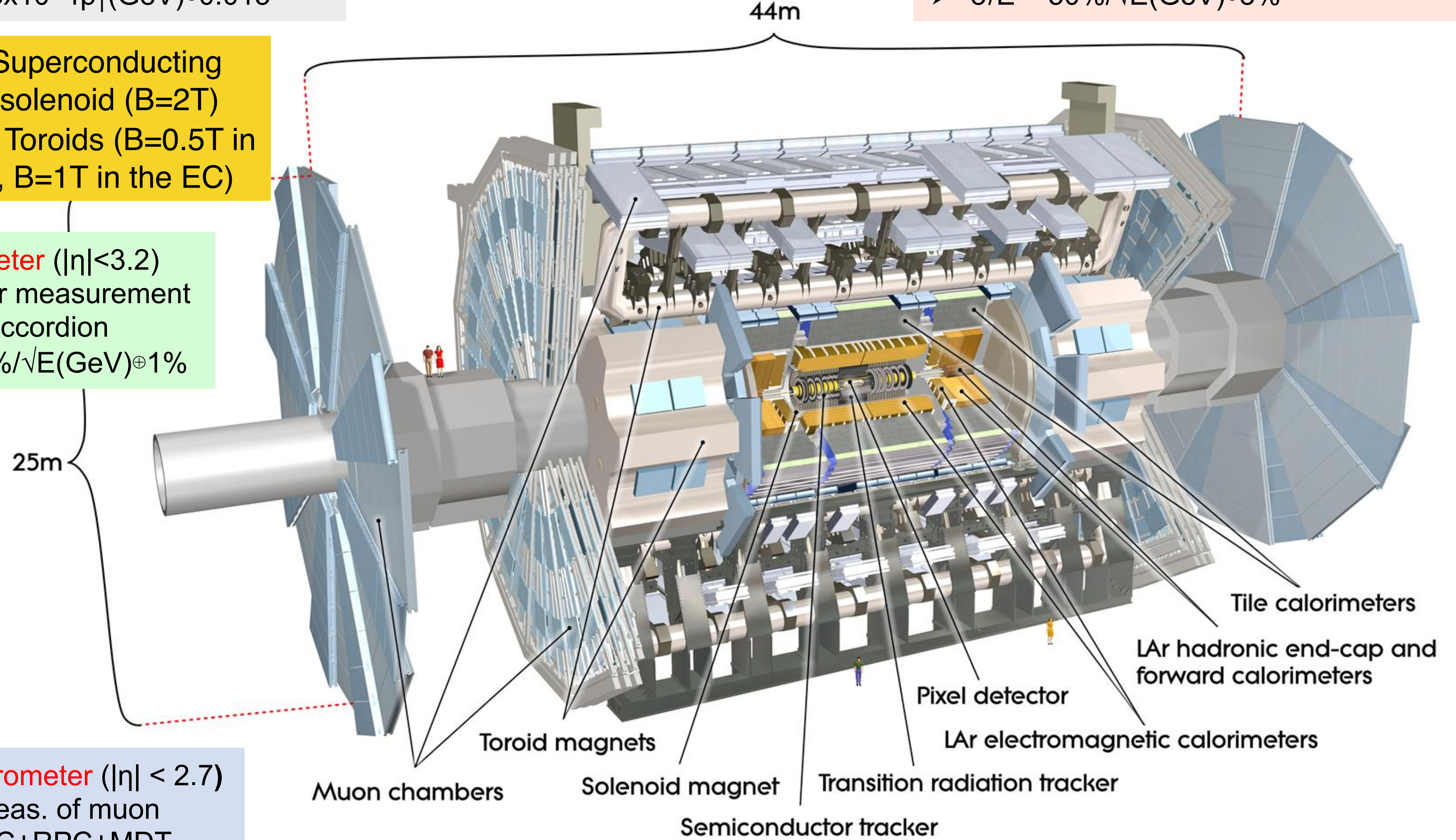
# ATLAS detector

Inner detector ($|\eta|< 2.5$, B=2T)
Tracking, vertexing, dE/dx, e/π ID
- Si pixels, Si strips, Trans. Rad. det.
- $\sigma/p_T \sim 3.8\times10^{-4} p_T(\mathrm{GeV}) \oplus 0.015$

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

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
- $\sigma/E \sim 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

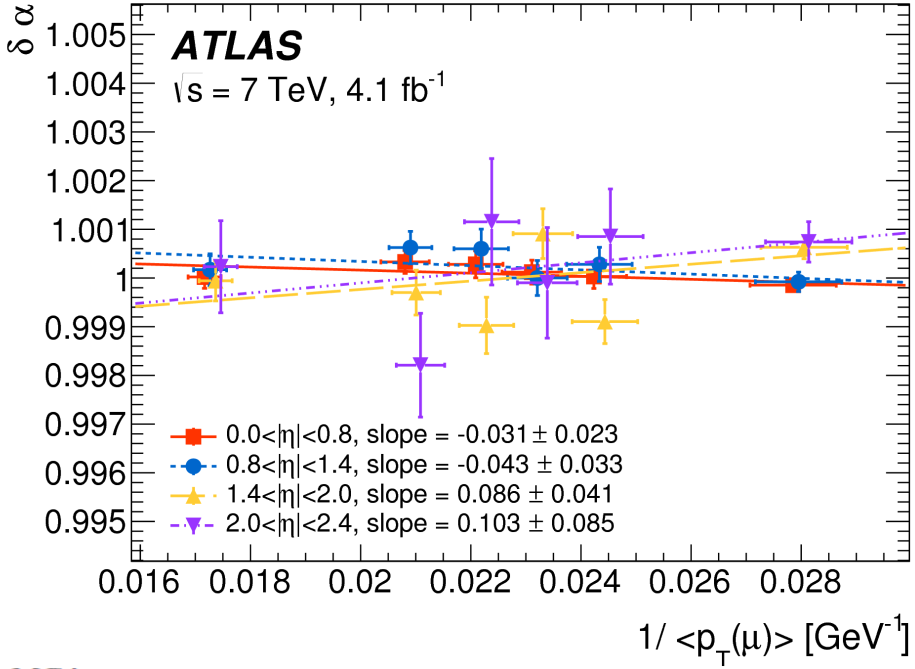



Muon spectrometer ($|\eta| < 2.7$)
Trigger & meas. of muon
- CSC+TGC+RPC+MDT
- $\sigma/p_T$ <10 % up to 1 TeV

# 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—>e$\nu$. [Eur.Phys.J.C 74 (2014) 3130]

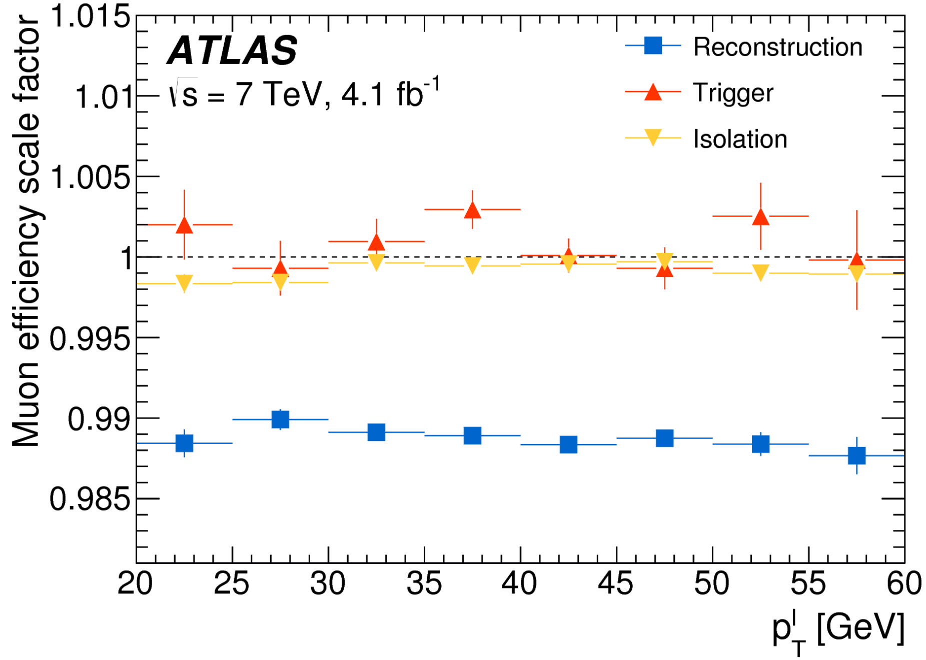



$$p_{\mathrm{T}}^{\mathrm{MC,corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times [1+\alpha(\eta,\phi)] \times \left[1+\beta_{\mathrm{curv}}(\eta)\cdot G(0,1)\cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$

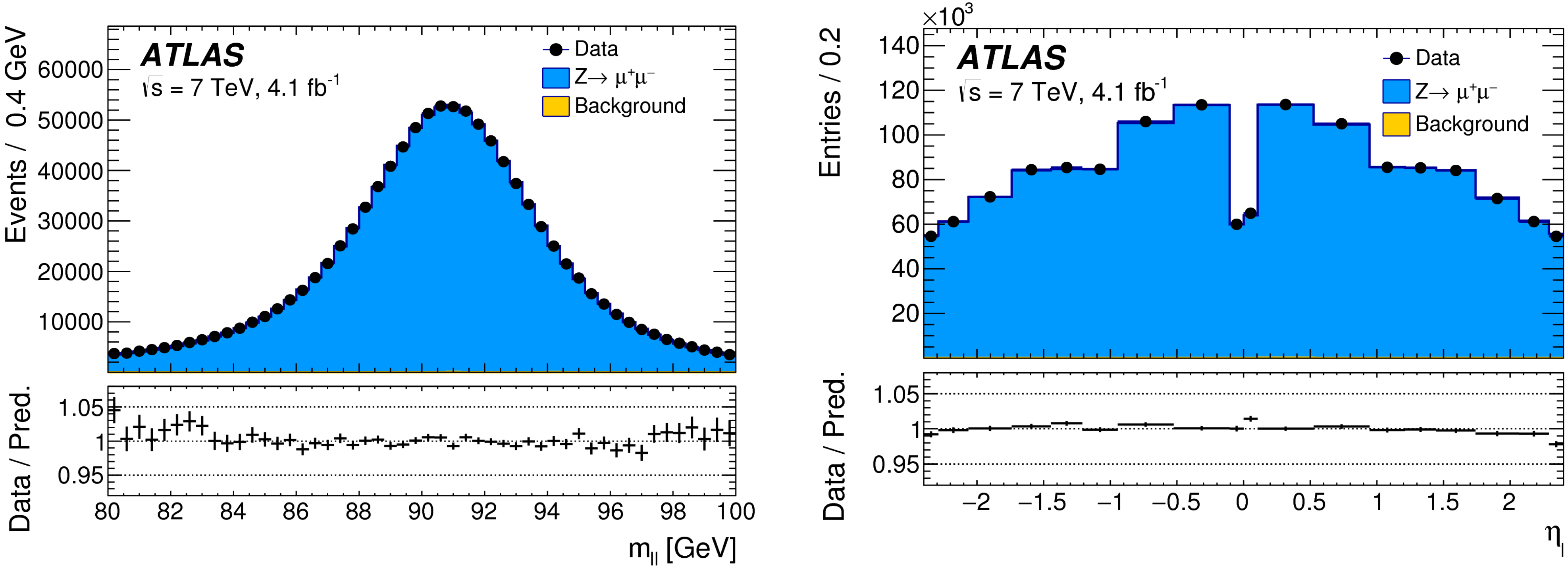
$$p_{\mathrm{T}}^{\mathrm{data,corr}} = \frac{p_{\mathrm{T}}^{\mathrm{data}}}{1+q\cdot\delta(\eta,\phi)\cdot p_{\mathrm{T}}^{\mathrm{data}}}$$

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

Dominant uncertainty is the statistical uncertainty of the Z sample.



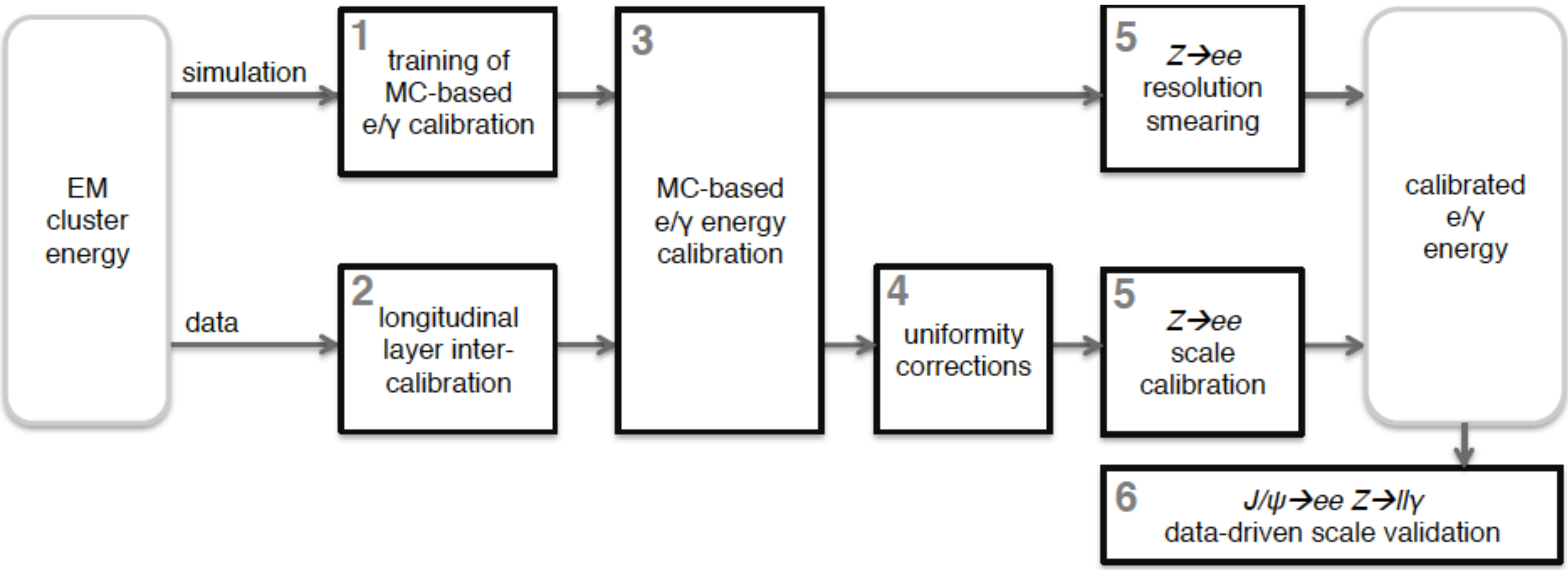
# Muon Calibration & Efficiency




| $\lvert\eta_\ell\rvert$ range | [0.0, 0.8] | | [0.8, 1.4] | | [1.4, 2.0] | | [2.0, 2.4] | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [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 Calibration & Efficiency

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



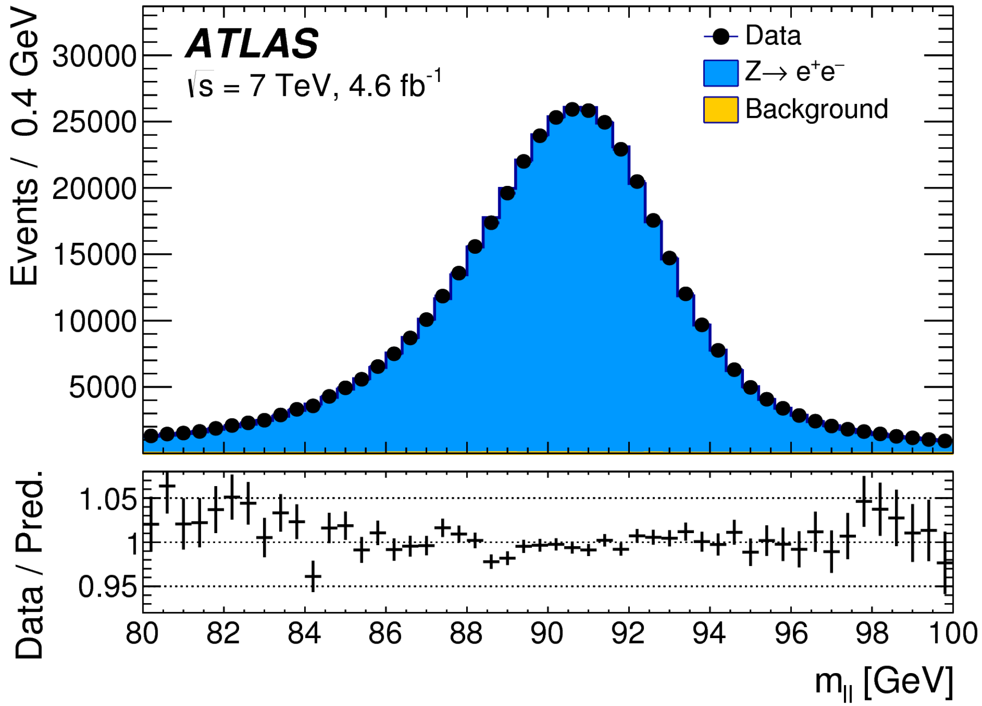

Exclude bin $1.2<|\eta|<1.82$ for the W mass measurement as the amount of passive material in front of the calorimeter and its uncertainty are largest in this region.

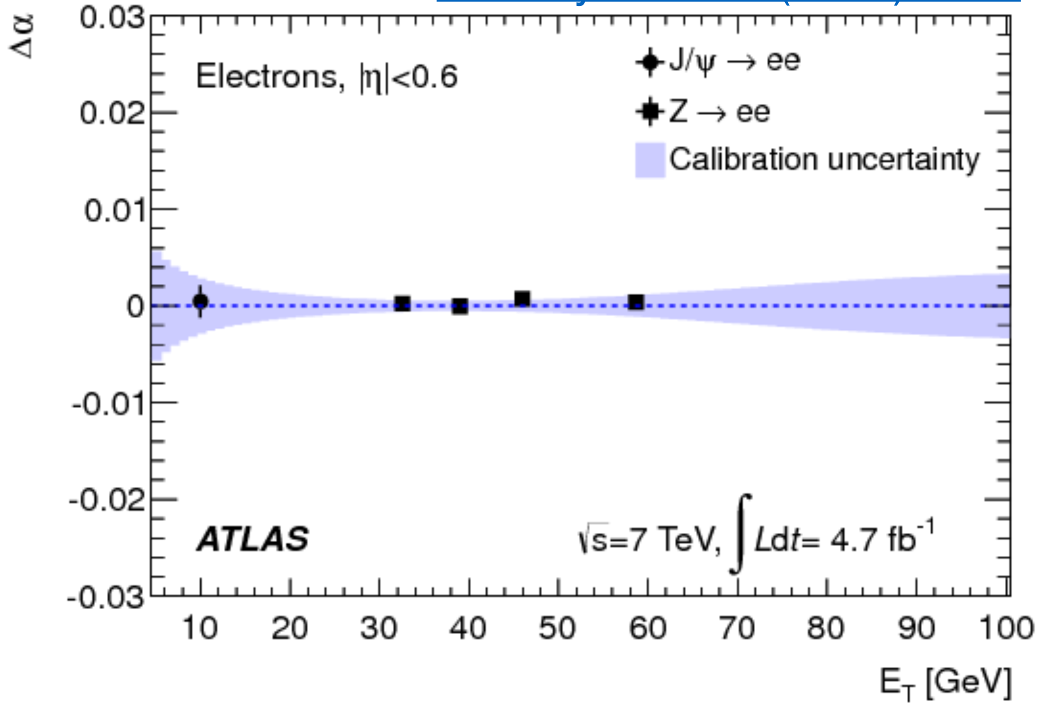
Azimuthal correction from <E/p> vs $\varphi$

Electron efficiency corrections as a function of $\eta$ and $p_T$ Eur.Phys.J.C 74 (2014) 2941

# Electron Calibration & Efficiency

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

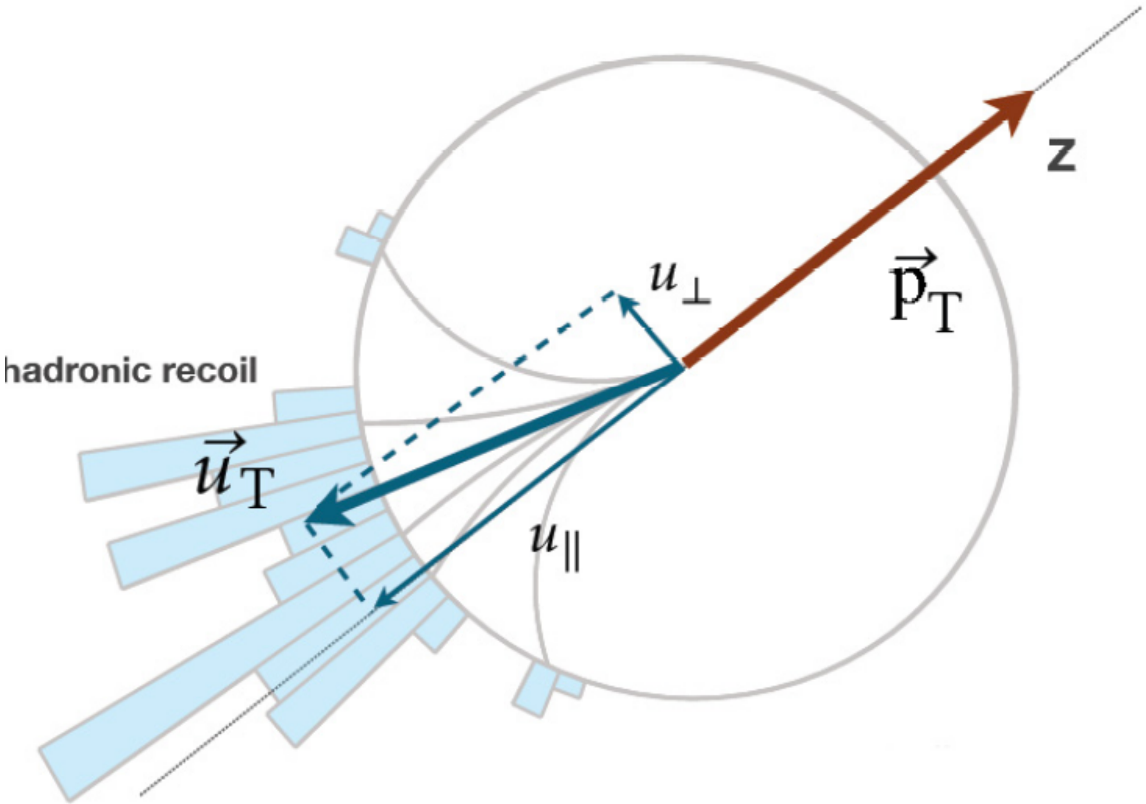



| $|\eta_\ell|$ range | [0.0, 0.6] | | [0.6, 1.2] | | [1.82, 2.4] | | Combined | |
|---|---|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [MeV] | | | | | | | | |
| Energy scale | 10.4 | 10.3 | 10.8 | 10.1 | 16.1 | 17.1 | 8.1 | 8.0 |
| Energy resolution | 5.0 | 6.0 | 7.3 | 6.7 | 10.4 | 15.5 | 3.5 | 5.5 |
| Energy linearity | 2.2 | 4.2 | 5.8 | 8.9 | 8.6 | 10.6 | 3.4 | 5.5 |
| Energy tails | 2.3 | 3.3 | 2.3 | 3.3 | 2.3 | 3.3 | 2.3 | 3.3 |
| Reconstruction efficiency | 10.5 | 8.8 | 9.9 | 7.8 | 14.5 | 11.0 | 7.2 | 6.0 |
| Identification efficiency | 10.4 | 7.7 | 11.7 | 8.8 | 16.7 | 12.1 | 7.3 | 5.6 |
| Trigger and isolation efficiencies | 0.2 | 0.5 | 0.3 | 0.5 | 2.0 | 2.2 | 0.8 | 0.9 |
| Charge mismeasurement | 0.2 | 0.2 | 0.2 | 0.2 | 1.5 | 1.5 | 0.1 | 0.1 |
| Total | 19.0 | 17.5 | 21.1 | 19.4 | 30.7 | 30.5 | 14.2 | 14.3 |

# Recoil Reconstruction

Vector sum of the momenta of all clusters measured in the calorimeters

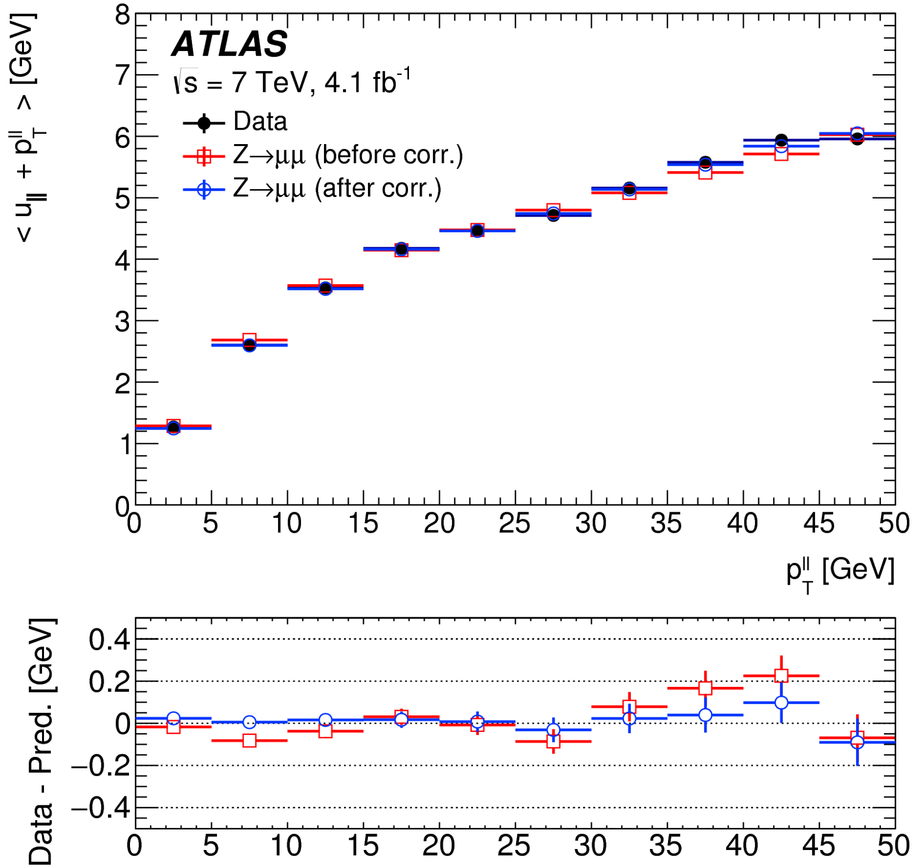


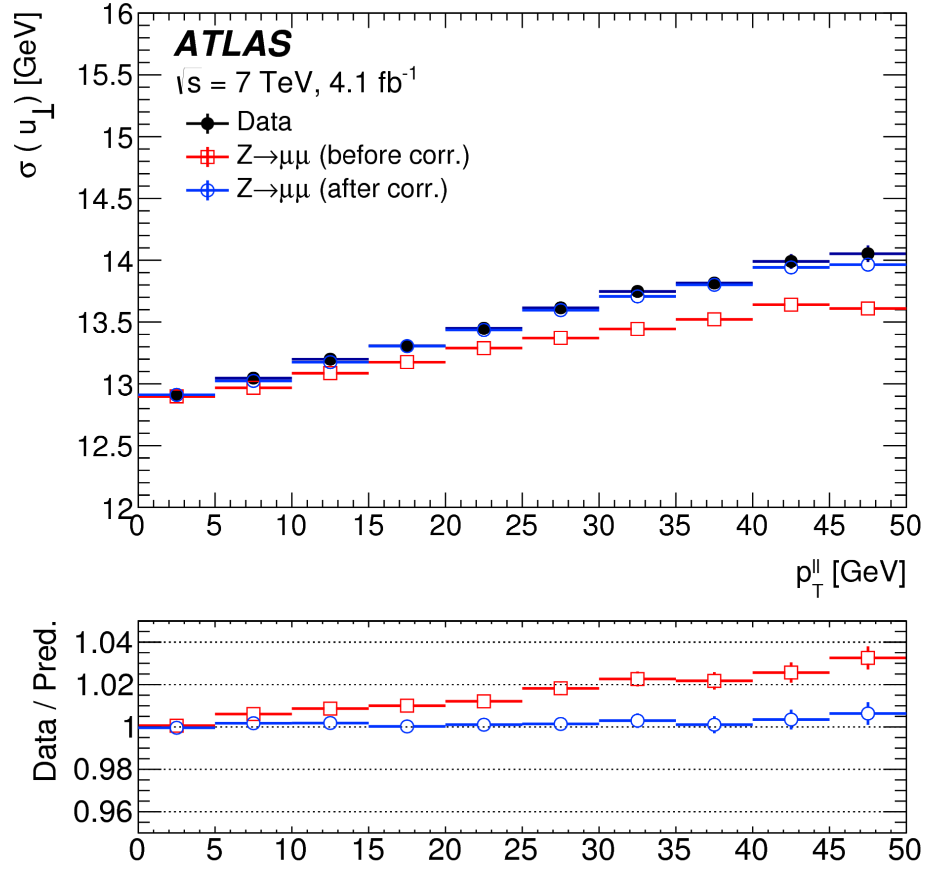

*Also : $u_{||}^l$ is the projection of the recoil along the W decay lepton direction*

# Recoil Calibration

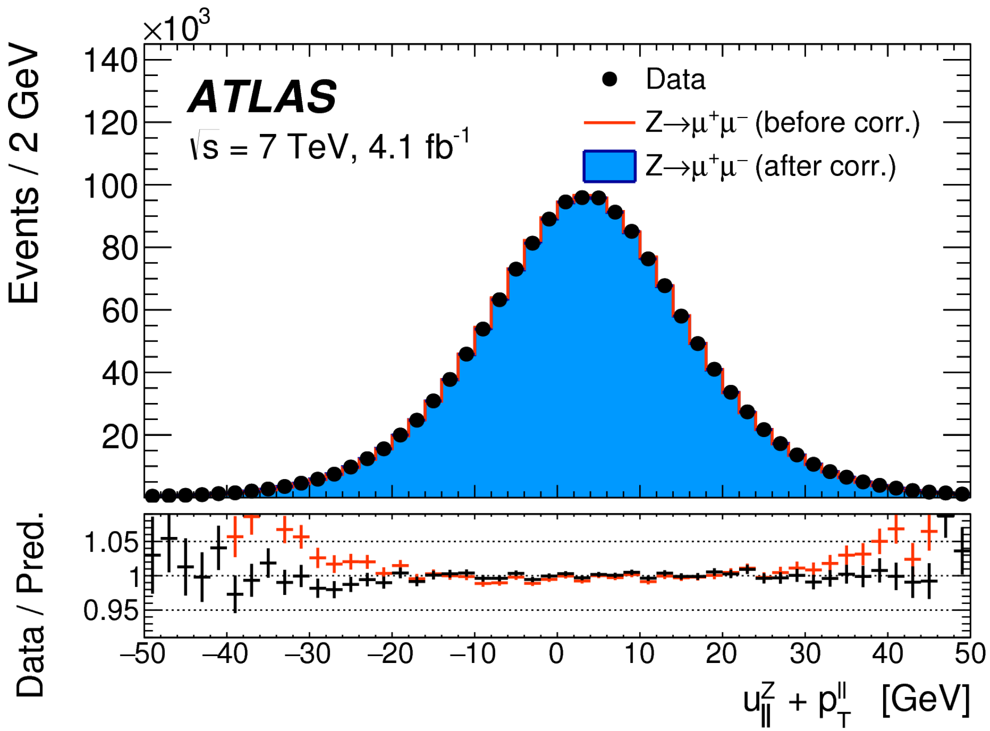
Calibrate the scale (resolution) of the recoil using $u_{||}$ ($u_{\perp}$) from Z events

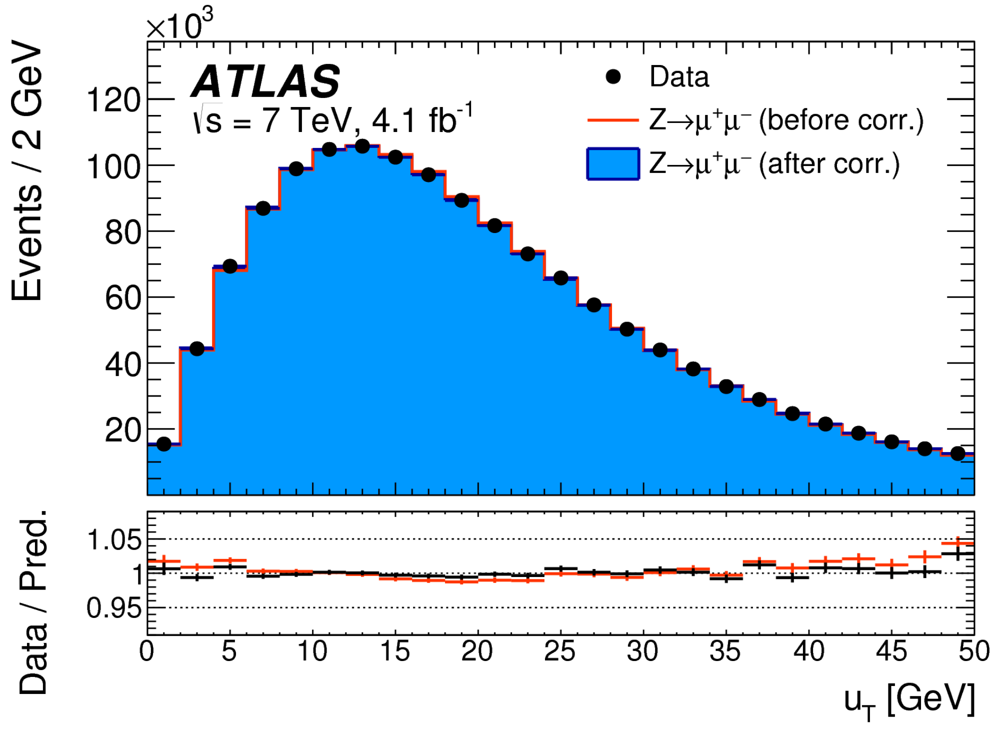
70-80% recoil response, remaining pileup dependence of the recoil resolution
cluster-based.



# Recoil Calibration

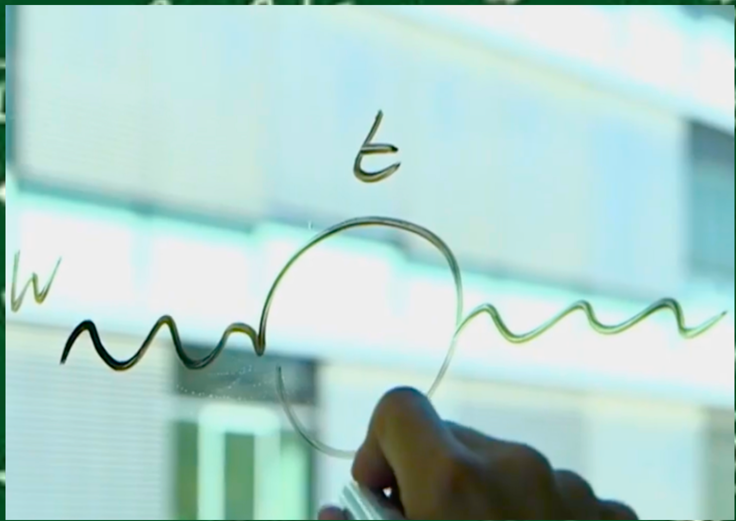



ATLAS

| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [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 |

# 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.

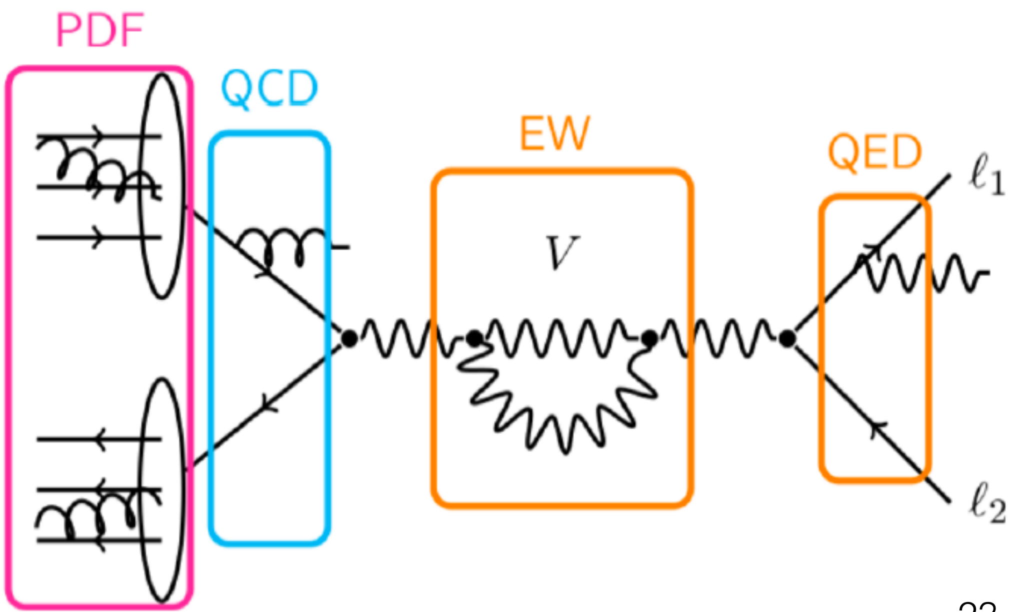
Physics modelling corrections

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 | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [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:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

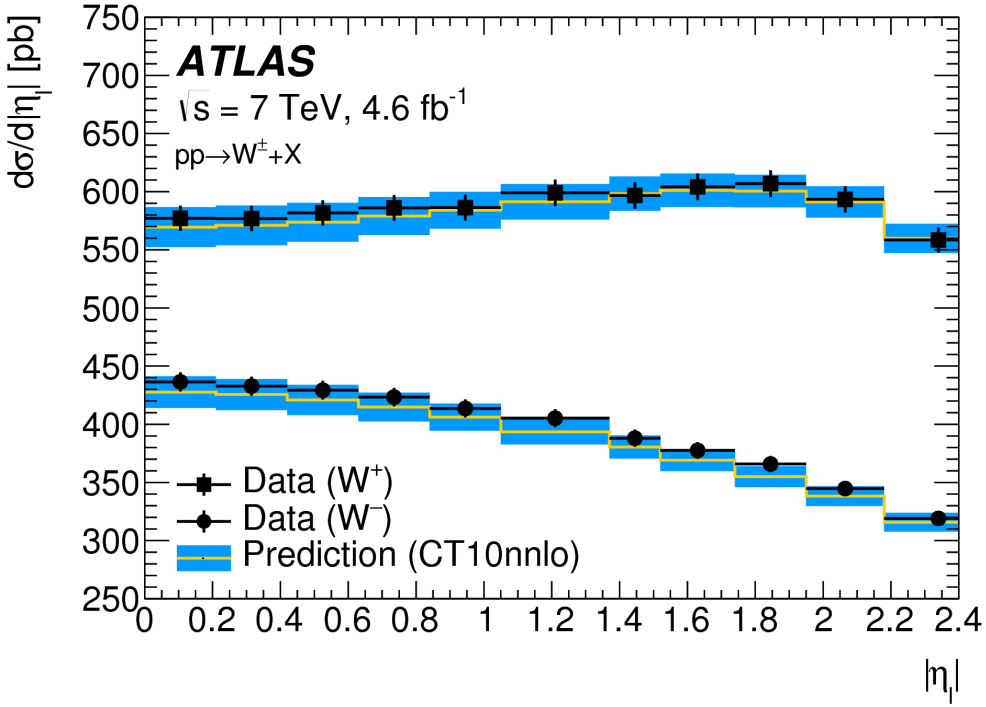
NNLO pQCD

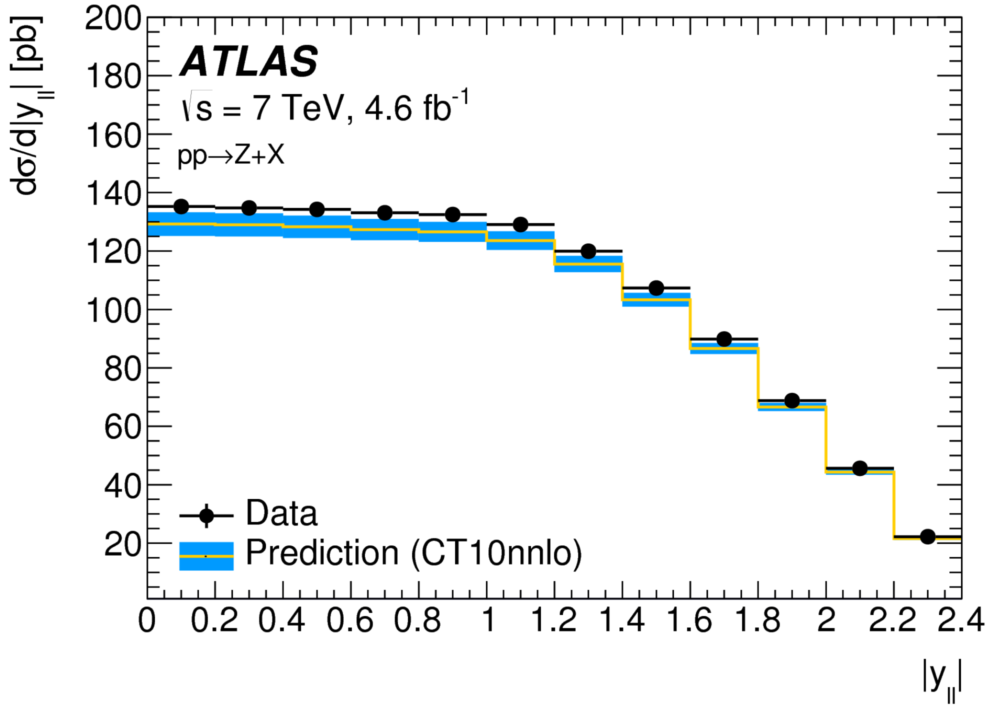
Parton Shower

$d\sigma/dm$ 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](arXiv:1612.03016)

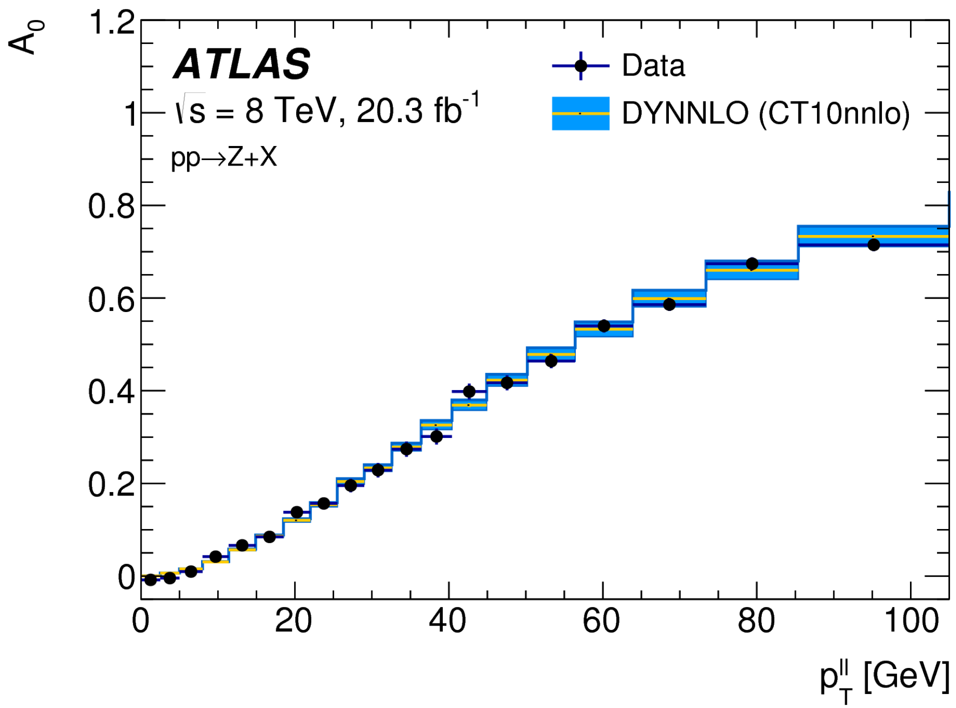


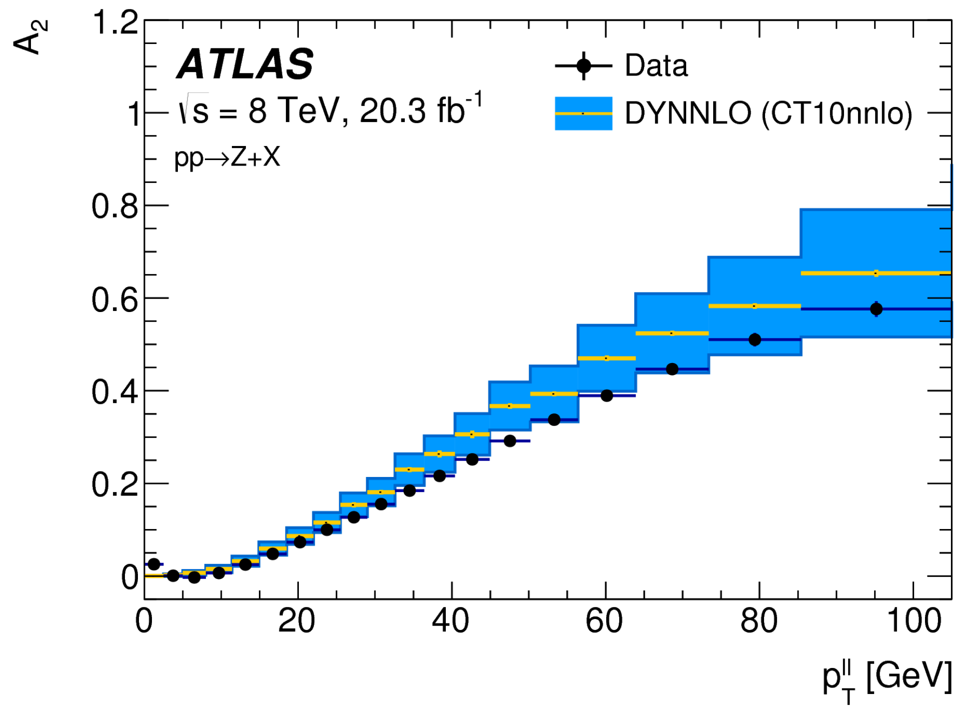




Satisfactory agreement between the theoretical prediction and the measurements is observed: $\chi^2$/dof = 45/34.

# 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

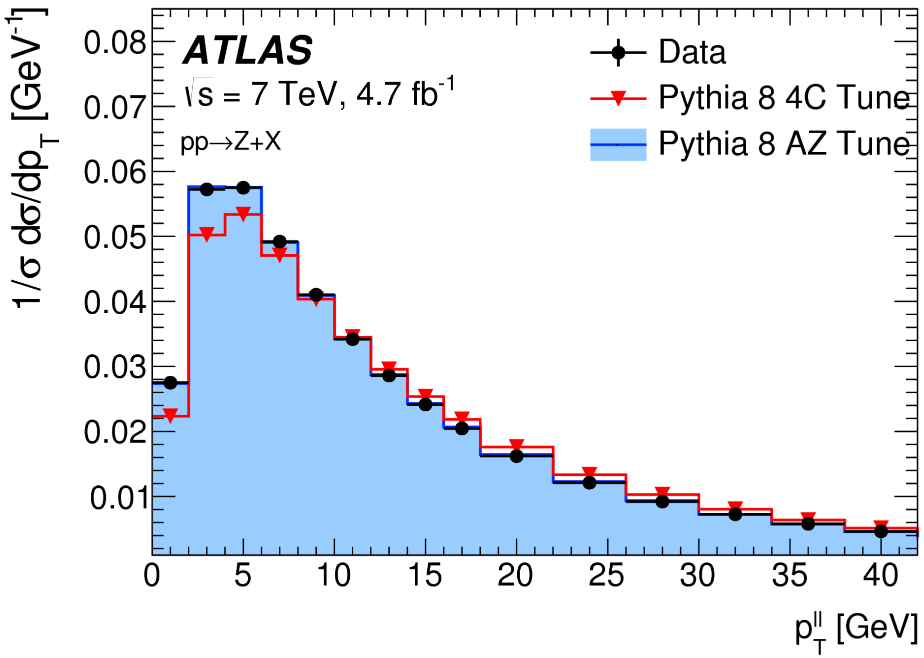
| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| Angular coefficients | 5.8 | 5.3 | 5.8 | 5.3 | 5.8 | 5.3 |

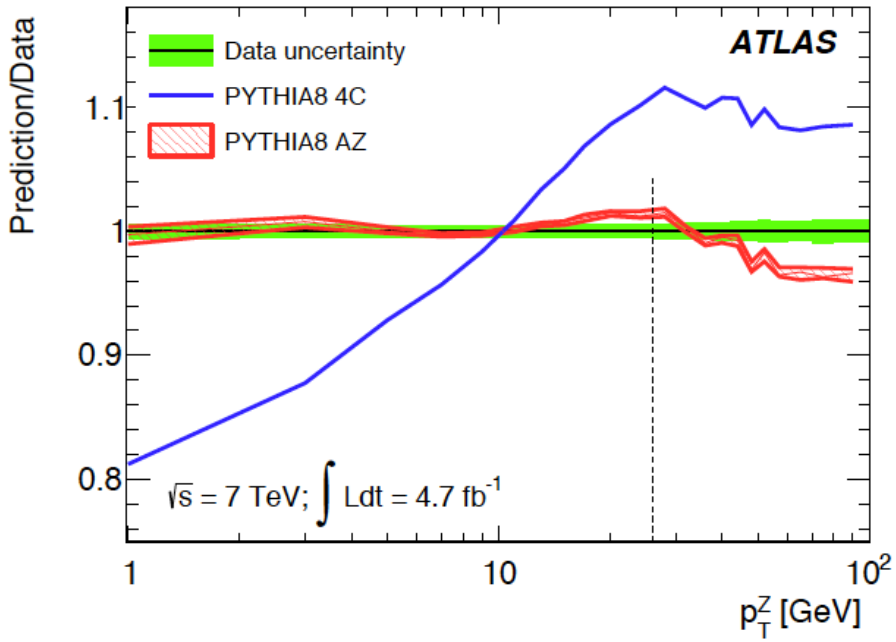
# Z transverse momentum

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] | $1.71 \pm 0.03$ |
| ISR $\alpha_S^{ISR}(m_Z)$ | $0.1237 \pm 0.0002$ |
| ISR cut-off [GeV] | $0.59 \pm 0.08$ |
| $\chi^2_{min}$/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*

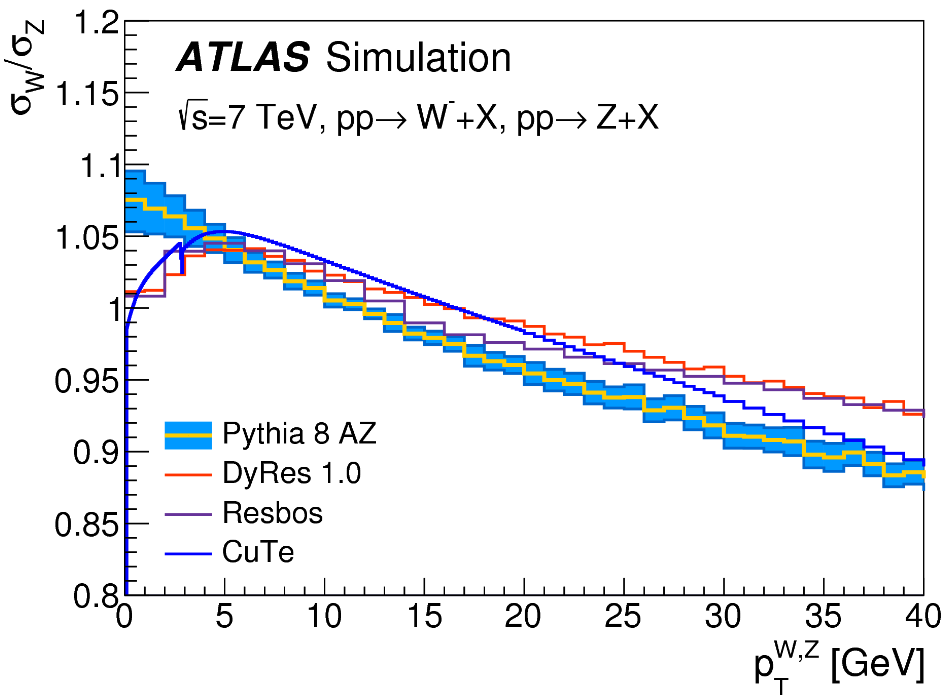
| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| AZ tune | 3.0 | 3.4 | 3.0 | 3.4 | 3.0 | 3.4 |

# W transverse momentum (I)

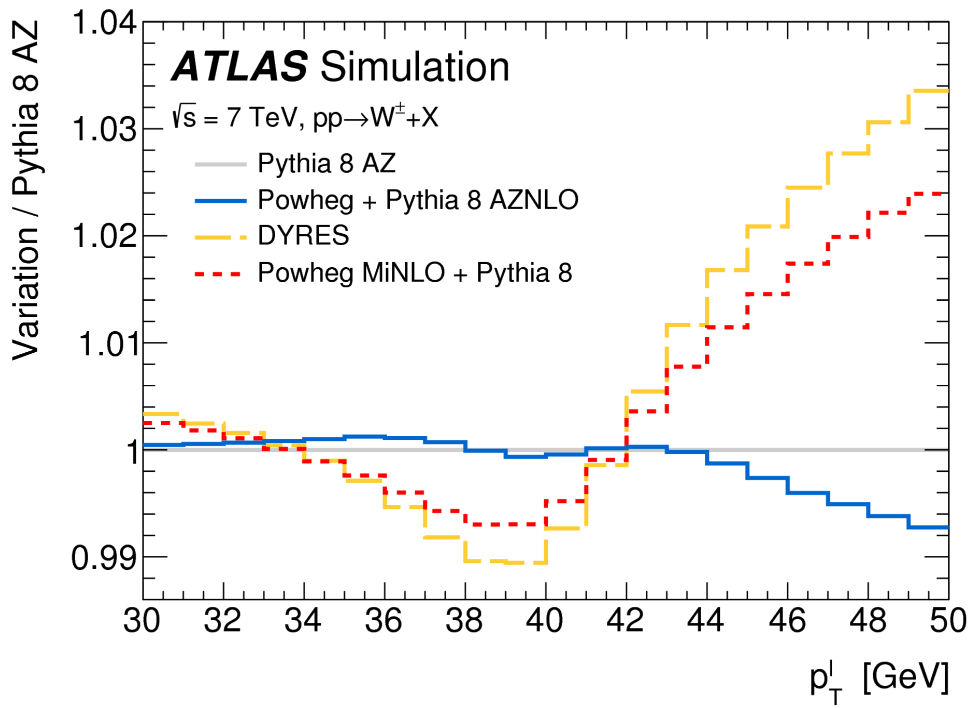
The Pythia8 AZ tune is fixed by the $p_T^Z$ data; extrapolate to W considering relative variations of the W and Z $p_T$ distributions.

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*

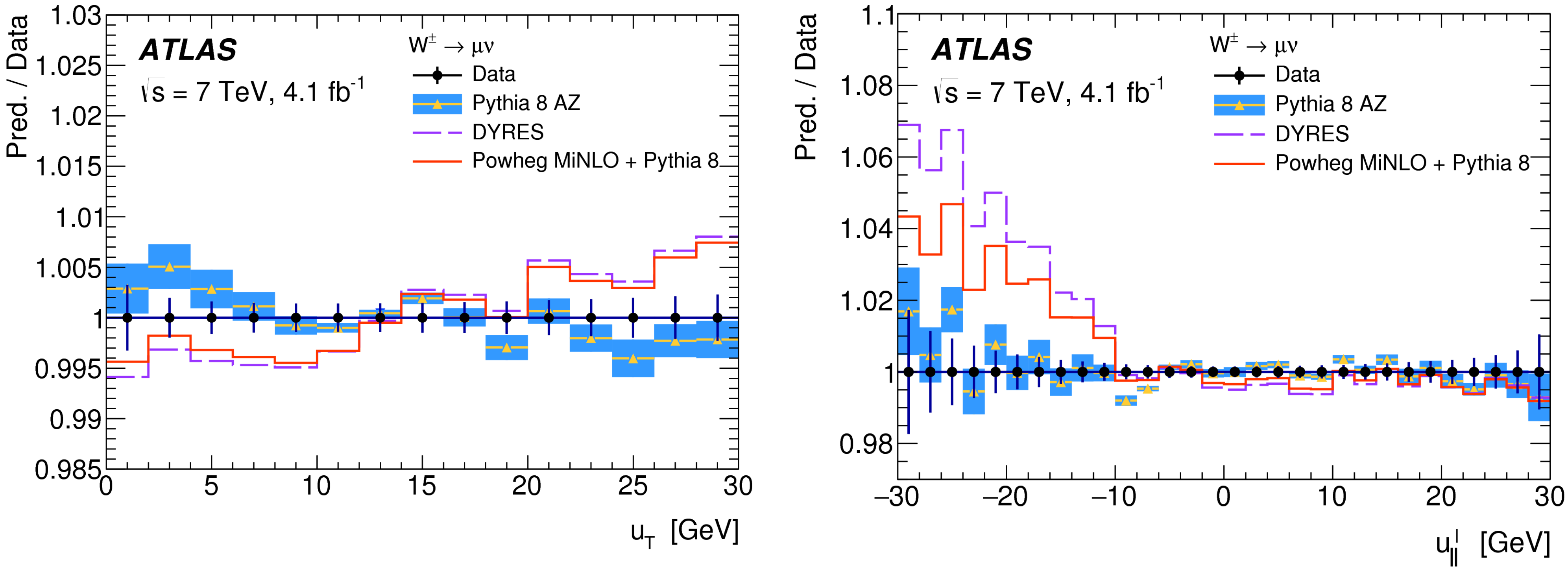



The effect on $m_W$ of using the “formally” more accurate predictions has a significant impact on the W-mass value of the order of 50-100 MeV

# 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

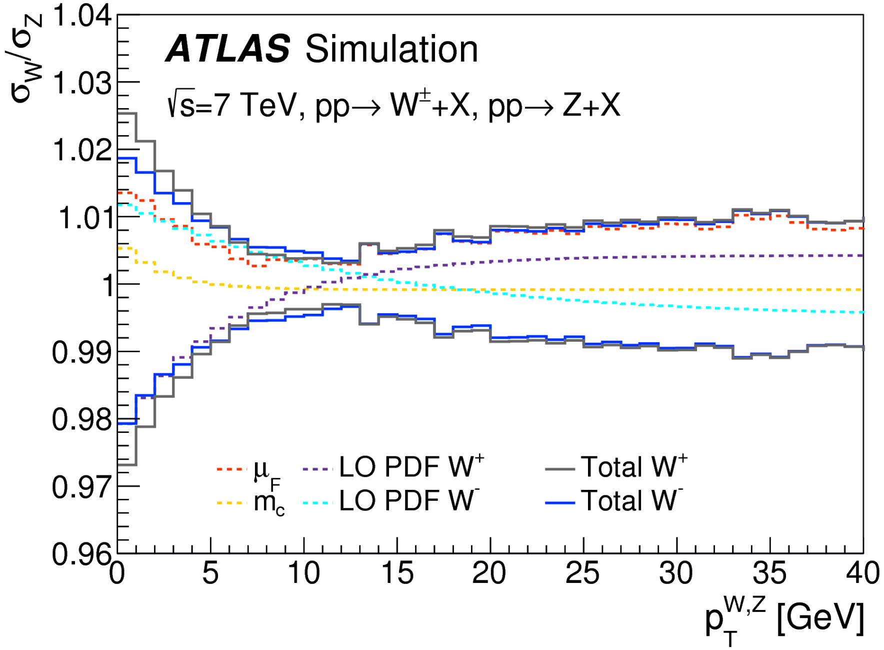
# $p_T^W$ uncertainties

**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

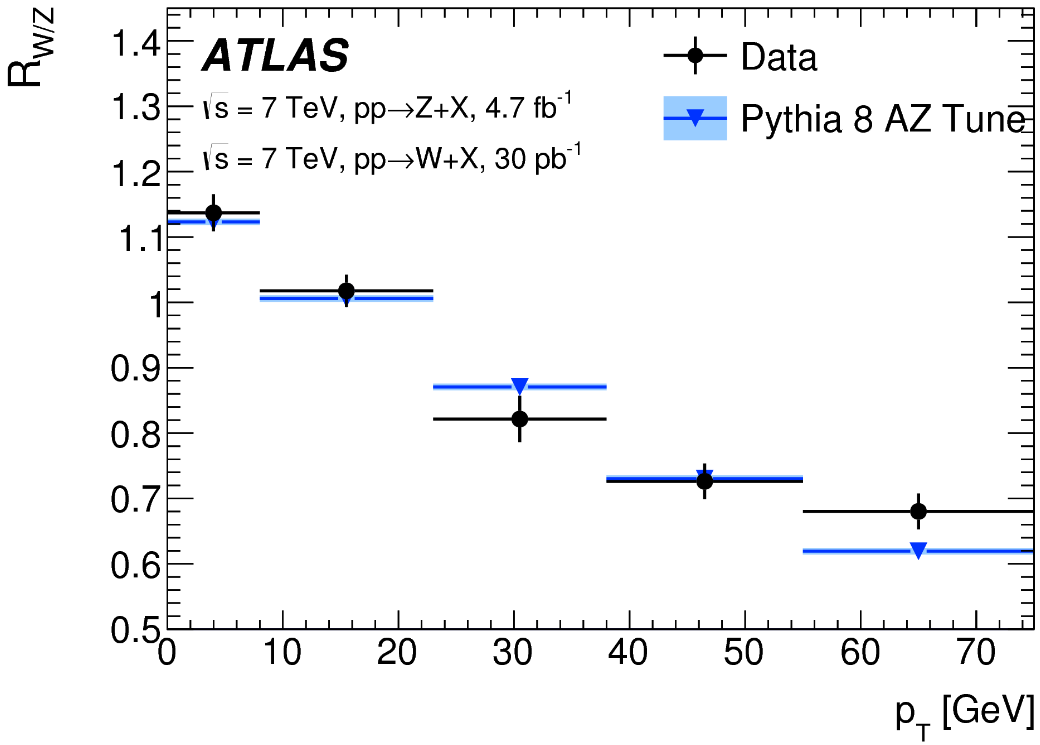



| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| Charm-quark mass | 1.2 | 1.5 | 1.2 | 1.5 | 1.2 | 1.5 |
| Parton shower $\mu_F$ with heavy-flavour decorrelation | 5.0 | 6.9 | 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



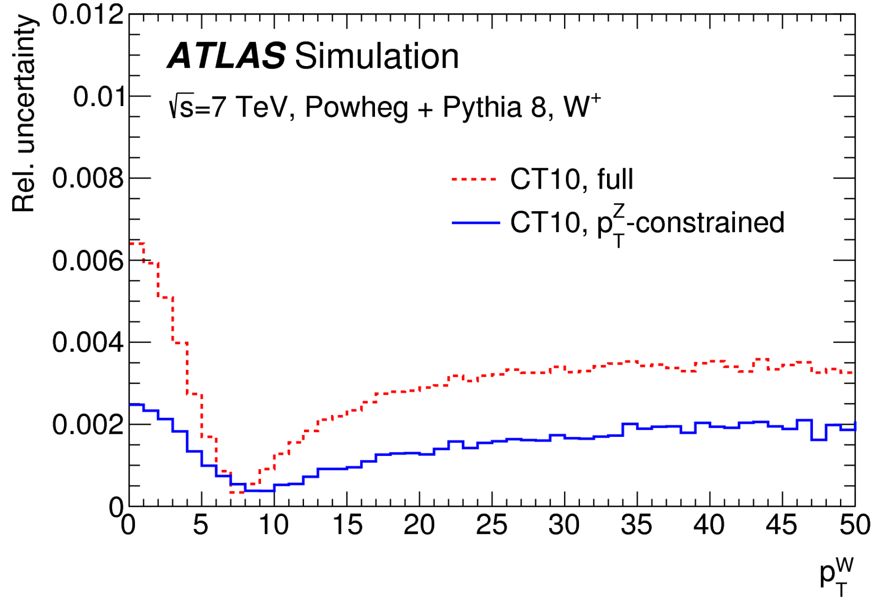

Limited precision of the data (~3%), and broad bin width (~8 GeV) limit the impact of these measurements on the systematic uncertainty.

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 | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| 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

QCD

| $W$-boson charge | $W^+$ | | $W^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [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 $\mu_F$ 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 |

EW

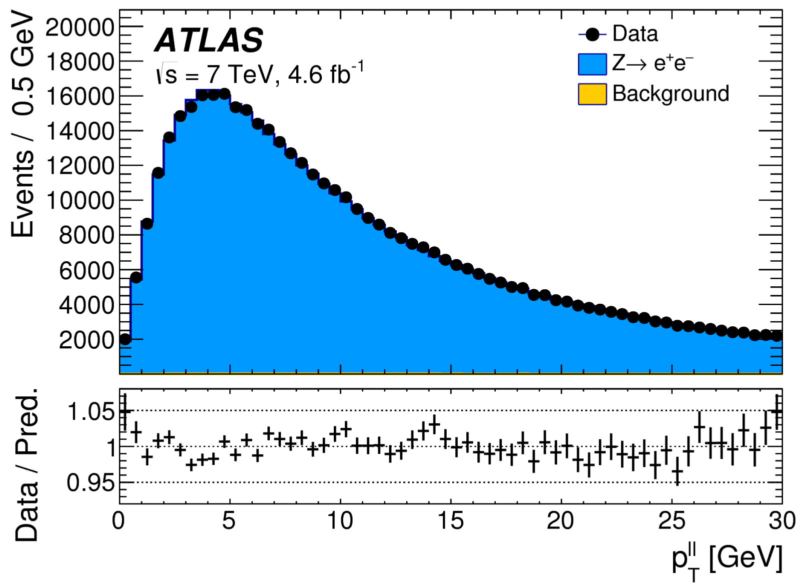
| Decay channel | $W \to e\nu$ | | $W \to \mu\nu$ | |
|---|---|---|---|---|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [MeV] | | | | |
| FSR (real) | $< 0.1$ | $< 0.1$ | $< 0.1$ | $< 0.1$ |
| Pure weak and IFI corrections | 3.3 | 2.5 | 3.5 | 2.5 |
| FSR (pair production) | 3.6 | 0.8 | 4.4 | 0.8 |
| Total | 4.9 | 2.6 | 5.6 | 2.6 |

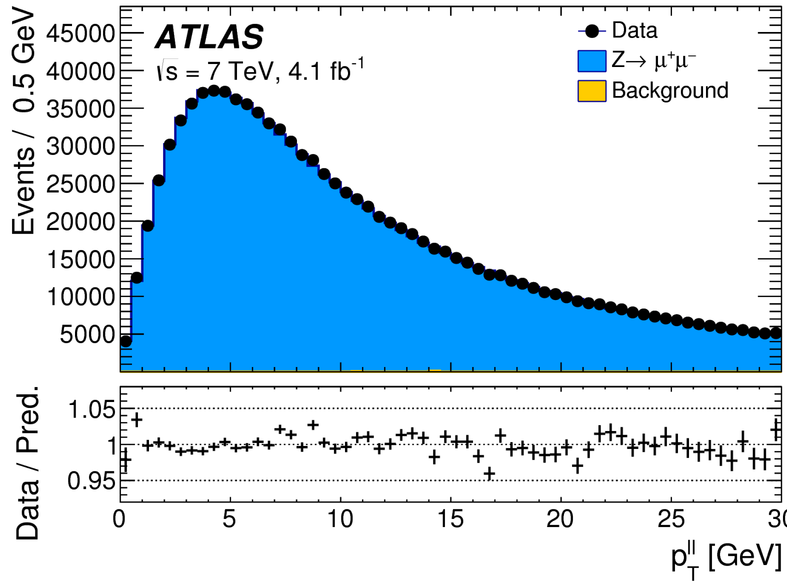
The PDF uncertainties are the dominant followed by $p_T(W)$ uncertainty due to the heavy-flavour initiated production.

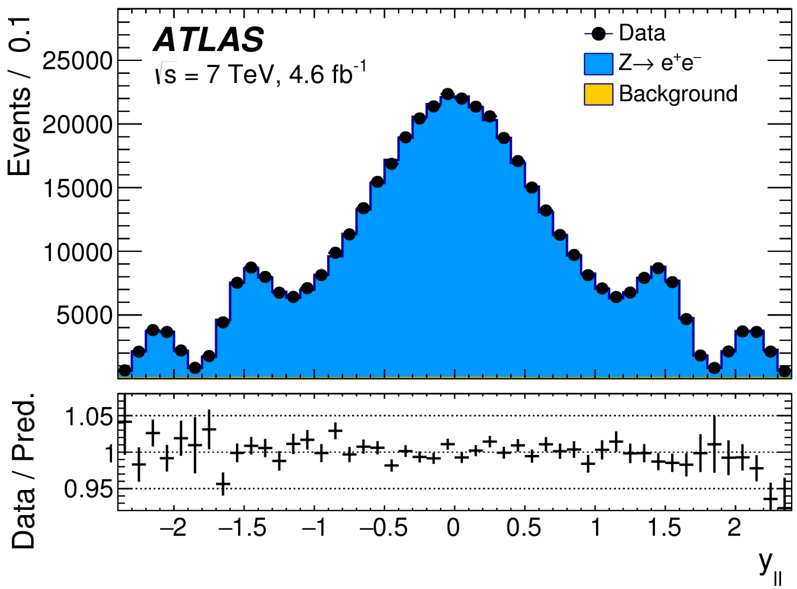
# Validation and results

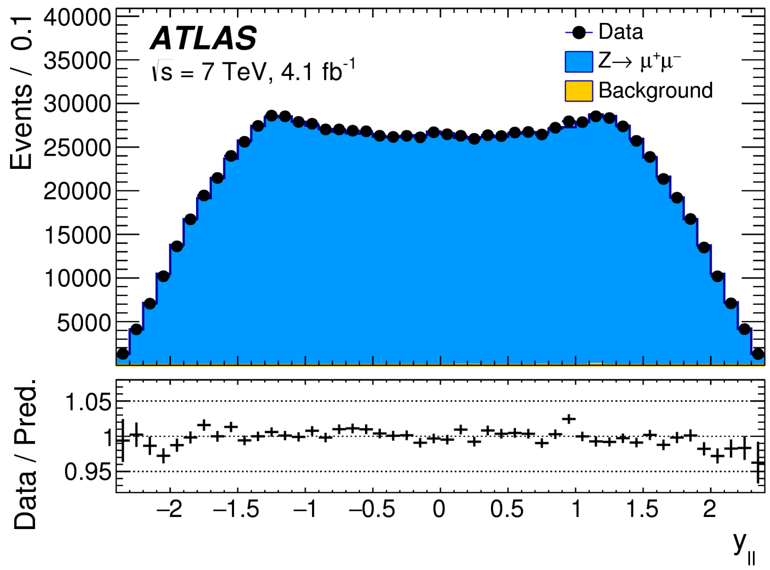
# Z control distributions: $p_T$, y

Z tranverse momentum and rapidity distributions in e, $\mu$ channels



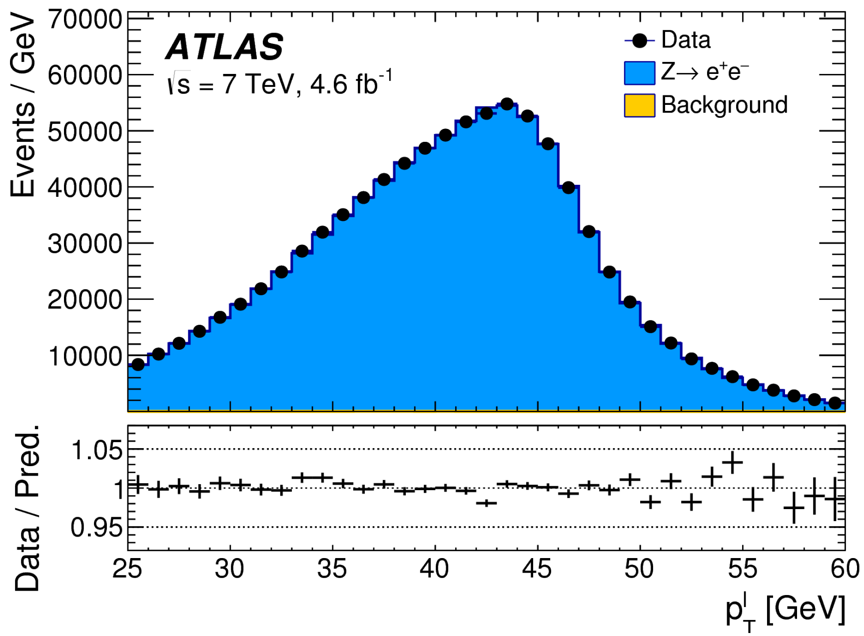



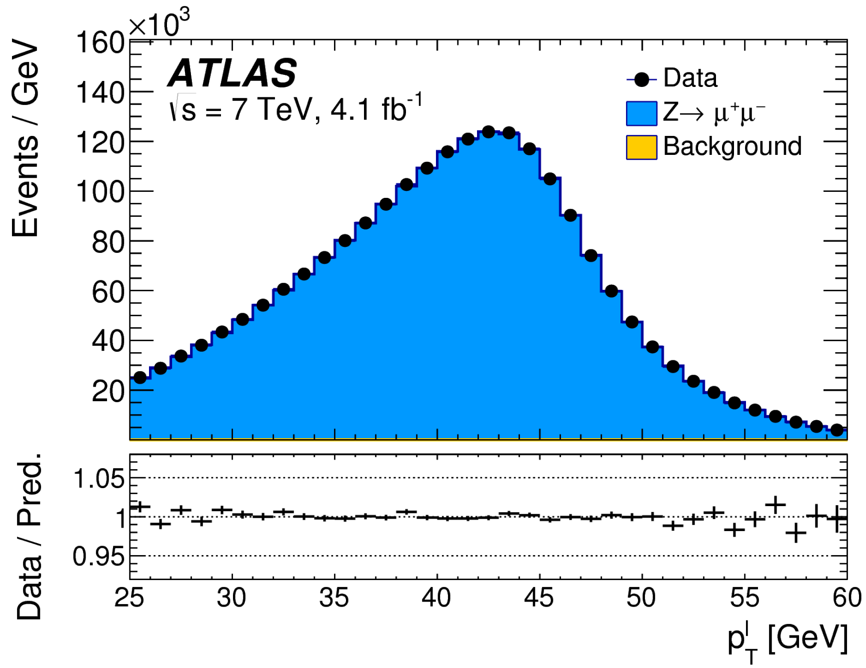



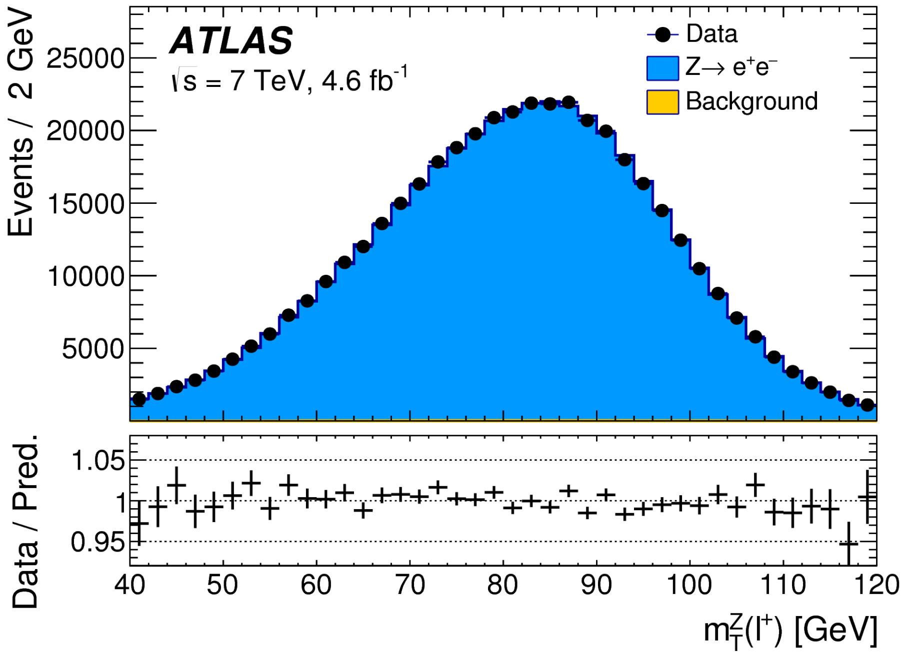

Good agreement is observed. Error bars are statistics only.

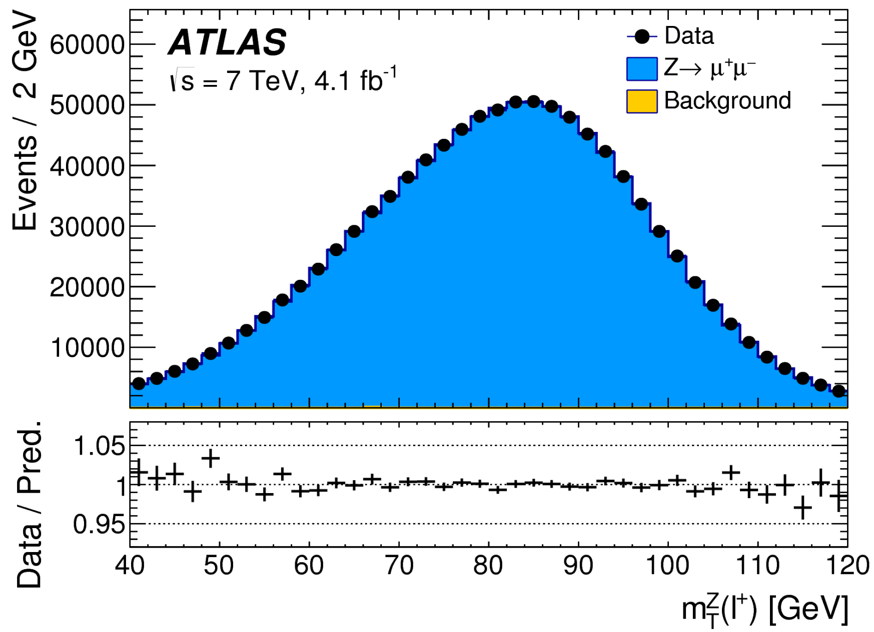
# Z mass-sensitive distributions: $p_T^l$ and $m_T$

Tranverse momentum and transverse mass distributions in e, $\mu$ channels

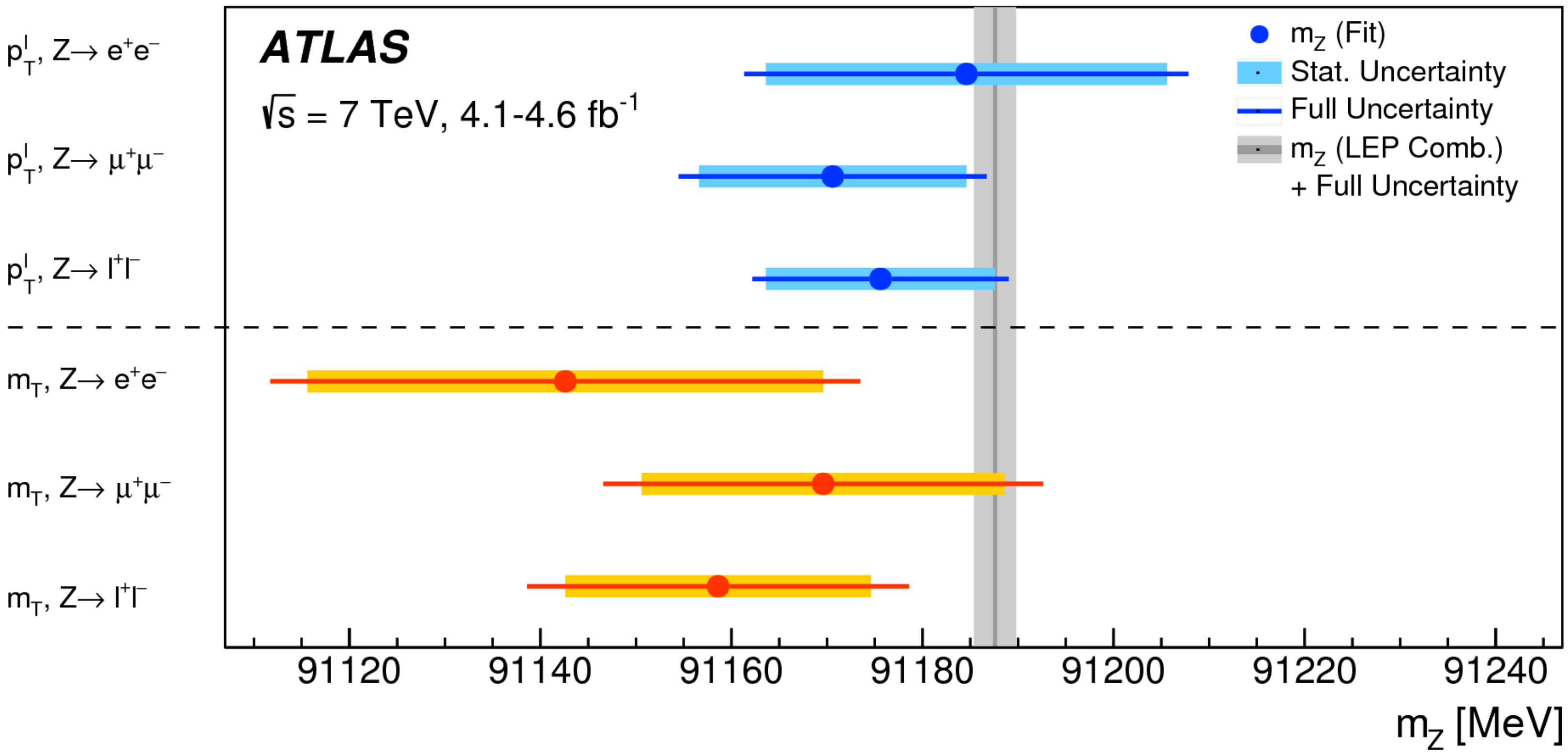


# Z mass




| Lepton charge | $\ell^+$ | | $\ell^-$ | | Combined | |
|---|---|---|---|---|---|---|
| Distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\Delta m_Z$ [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 | $5 \pm 18 \pm 6$ | $-58 \pm 23 \pm 12$ | $-31 \pm 18 \pm 6$ | $1 \pm 22 \pm 12$ | $-12 \pm 12 \pm 6$ | $-29 \pm 16 \pm 12$ |

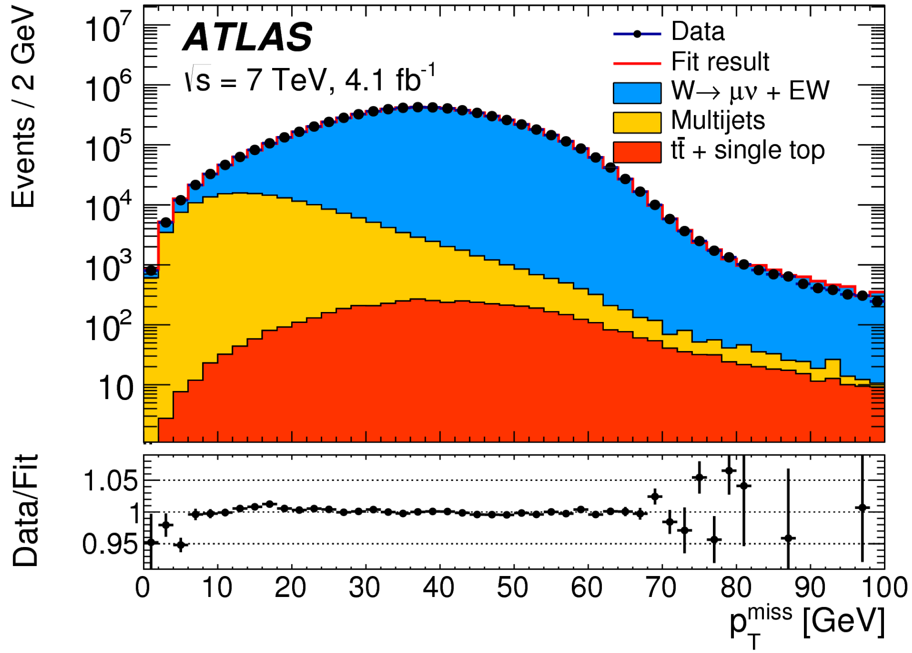
Results are consistent with the combined LEP value of $m_Z$ within experimental uncertainties

# 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



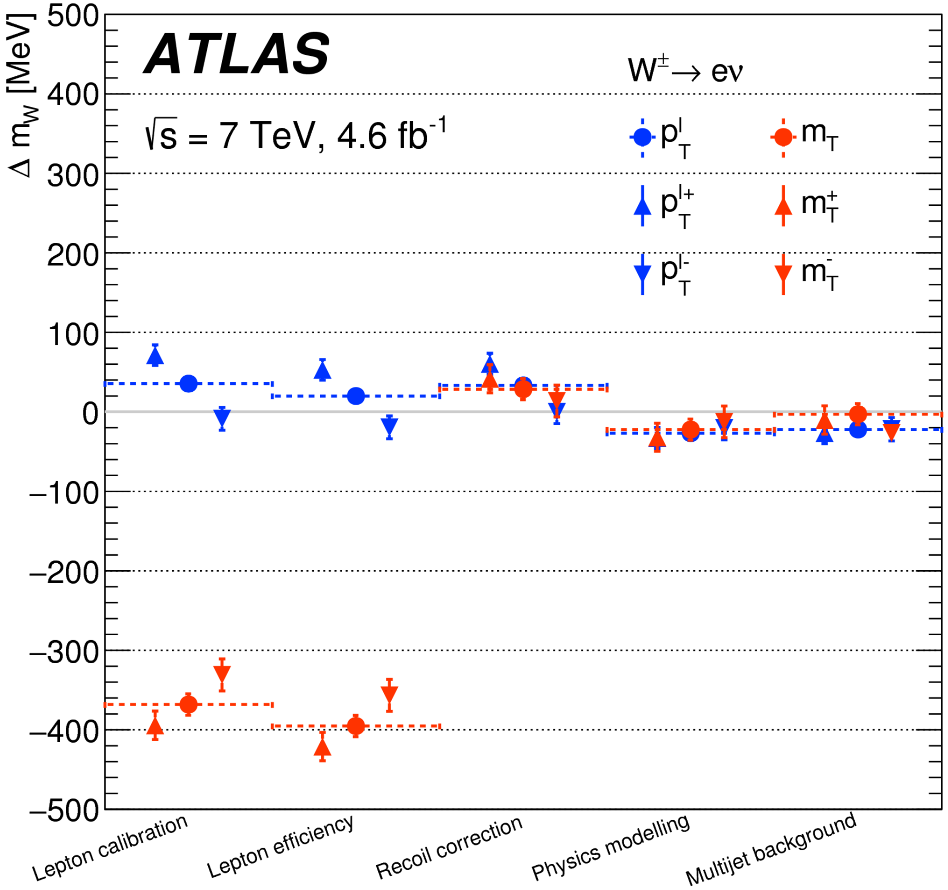

| $W \to \mu\nu$ | | | | | | |
|---|---|---|---|---|---|---|
| Category | $W \to \tau\nu$ | $Z \to \mu\mu$ | $Z \to \tau\tau$ | Top | Dibosons | Multijet |
| $W^\pm$ $0.0 < \|\eta\| < 0.8$ | 1.04 | 2.83 | 0.12 | 0.16 | 0.08 | 0.72 |
| $W^\pm$ $0.8 < \|\eta\| < 1.4$ | 1.01 | 4.44 | 0.11 | 0.12 | 0.07 | 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 $\eta$ bins | 1.01 | 5.41 | 0.11 | 0.10 | 0.06 | 0.58 |
| $W^+$ all $\eta$ bins | 0.99 | 4.80 | 0.10 | 0.09 | 0.06 | 0.51 |
| $W^-$ all $\eta$ bins | 1.04 | 6.28 | 0.14 | 0.12 | 0.08 | 0.68 |

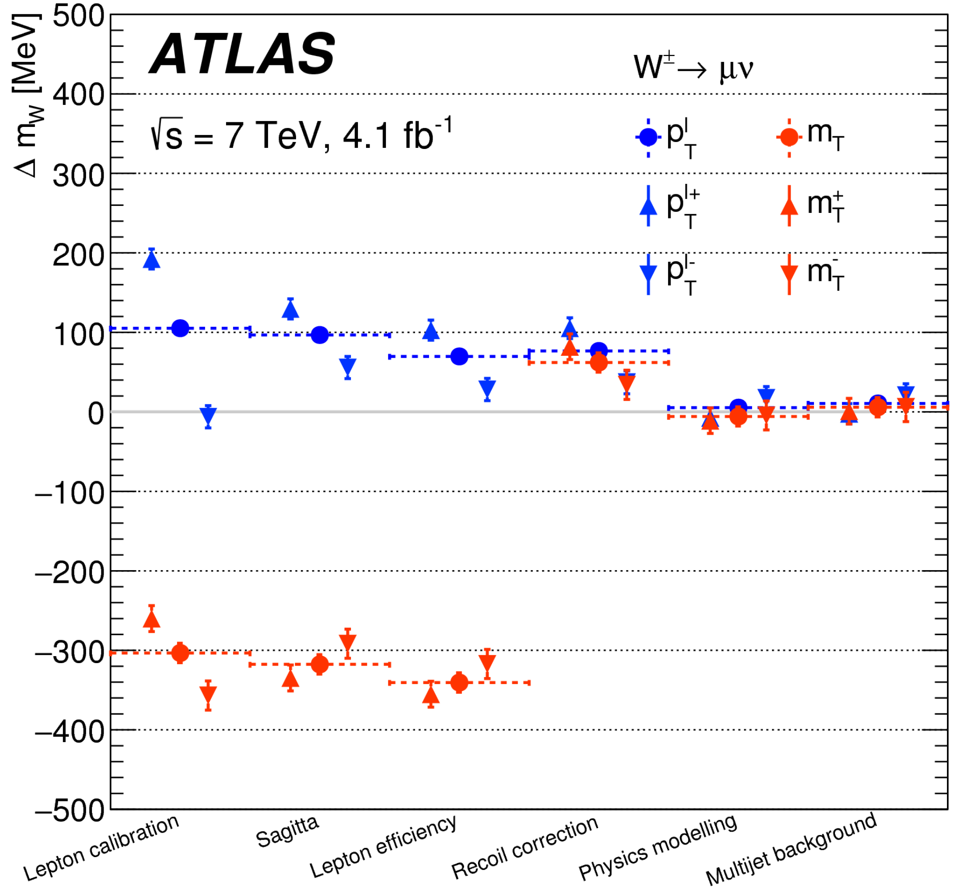
| $W \to e\nu$ | | | | | | |
|---|---|---|---|---|---|---|
| Category | $W \to \tau\nu$ | $Z \to ee$ | $Z \to \tau\tau$ | Top | Dibosons | Multijet |
| $W^\pm$ $0.0 < \|\eta\| < 0.6$ | 1.02 | 3.34 | 0.13 | 0.15 | 0.08 | 0.59 |
| $W^\pm$ $0.6 < \|\eta\| < 1.2$ | 1.00 | 3.48 | 0.12 | 0.13 | 0.08 | 0.76 |
| $W^\pm$ $1.8 < \|\eta\| < 2.4$ | 0.97 | 3.23 | 0.11 | 0.05 | 0.05 | 1.74 |
| $W^\pm$ all $\eta$ bins | 1.00 | 3.37 | 0.12 | 0.12 | 0.07 | 1.00 |
| $W^+$ all $\eta$ bins | 0.98 | 2.92 | 0.10 | 0.11 | 0.06 | 0.84 |
| $W^-$ all $\eta$ bins | 1.04 | 3.98 | 0.14 | 0.13 | 0.08 | 1.21 |

| Kinematic distribution | $p_T^\ell$ | | | | $m_T$ | | | |
|---|---|---|---|---|---|---|---|---|
| Decay channel | $W \to e\nu$ | | $W \to \mu\nu$ | | $W \to e\nu$ | | $W \to \mu\nu$ | |
| $W$-boson charge | $W^+$ | $W^-$ | $W^+$ | $W^-$ | $W^+$ | $W^-$ | $W^+$ | $W^-$ |
| $\delta m_W$ [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 |

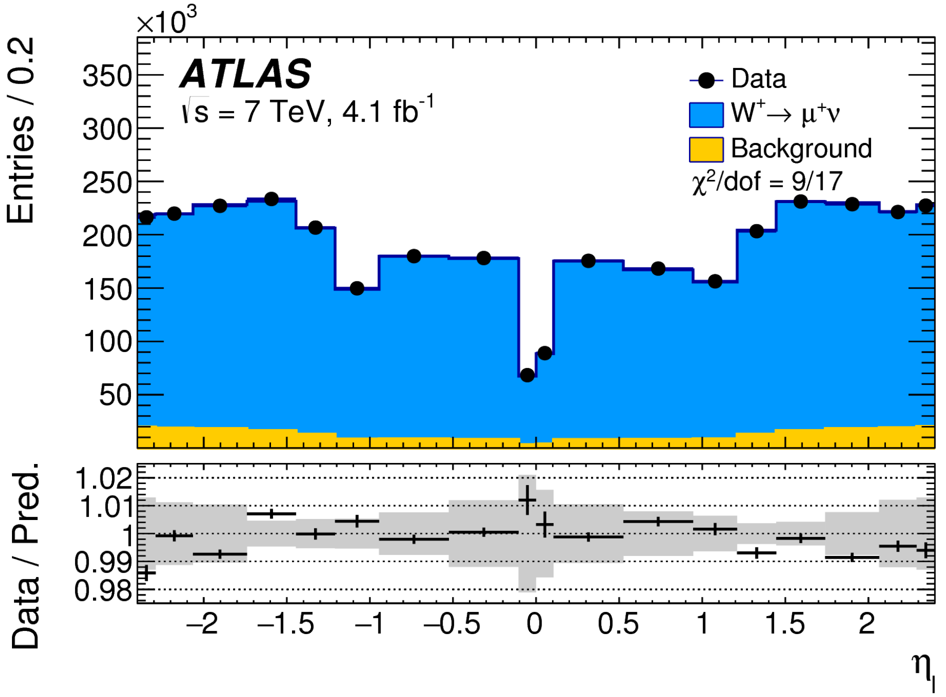
# Summary of corrections

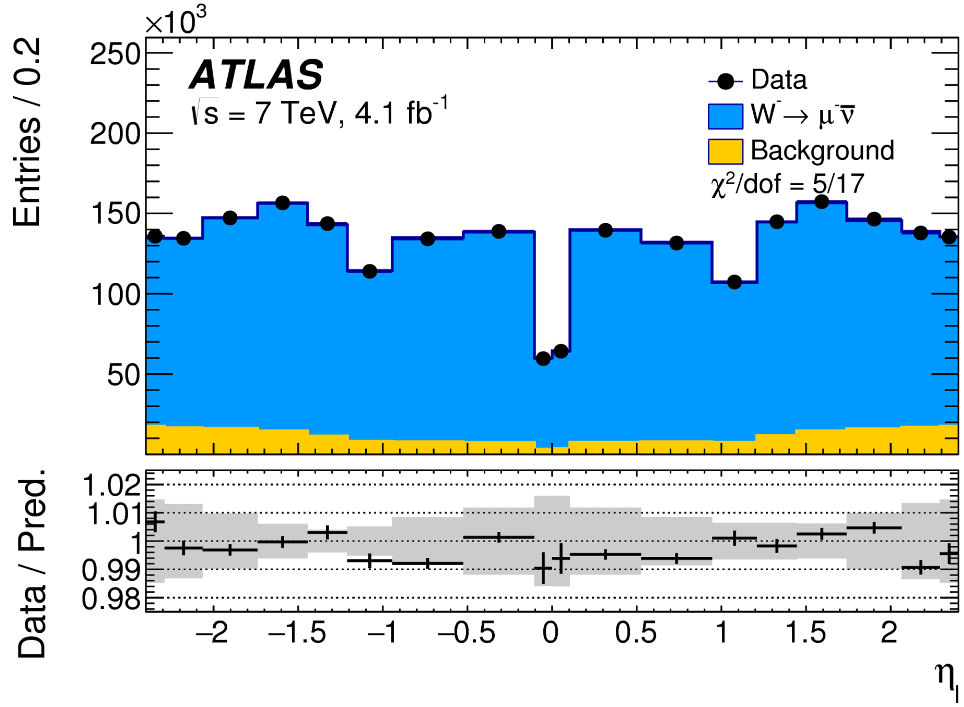
After all corrections are applied, consistent results are achieved between different channels, observables, categories, charges and only after, results were unblinded.

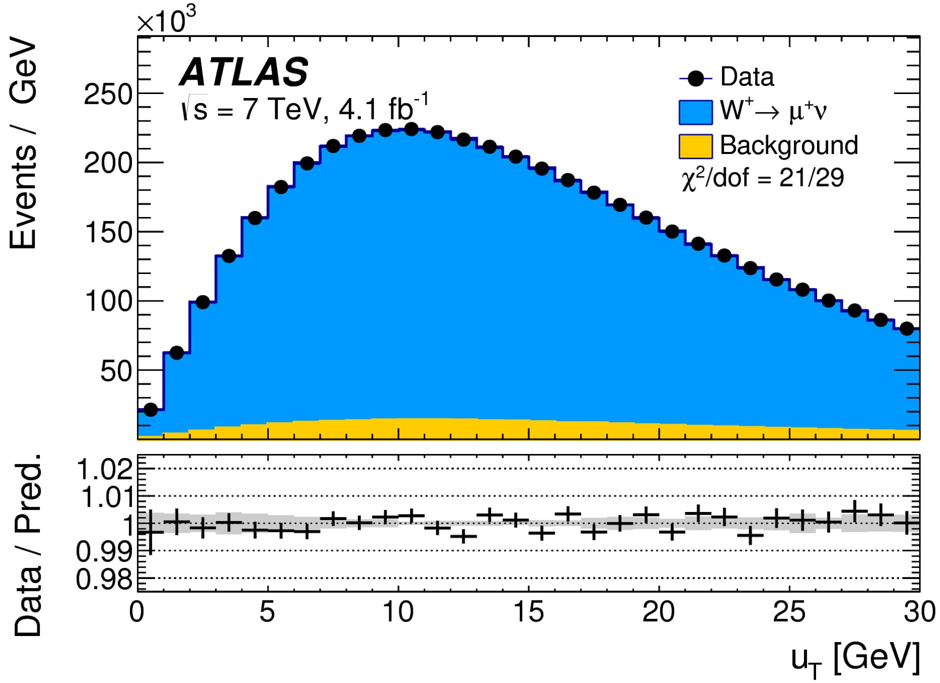


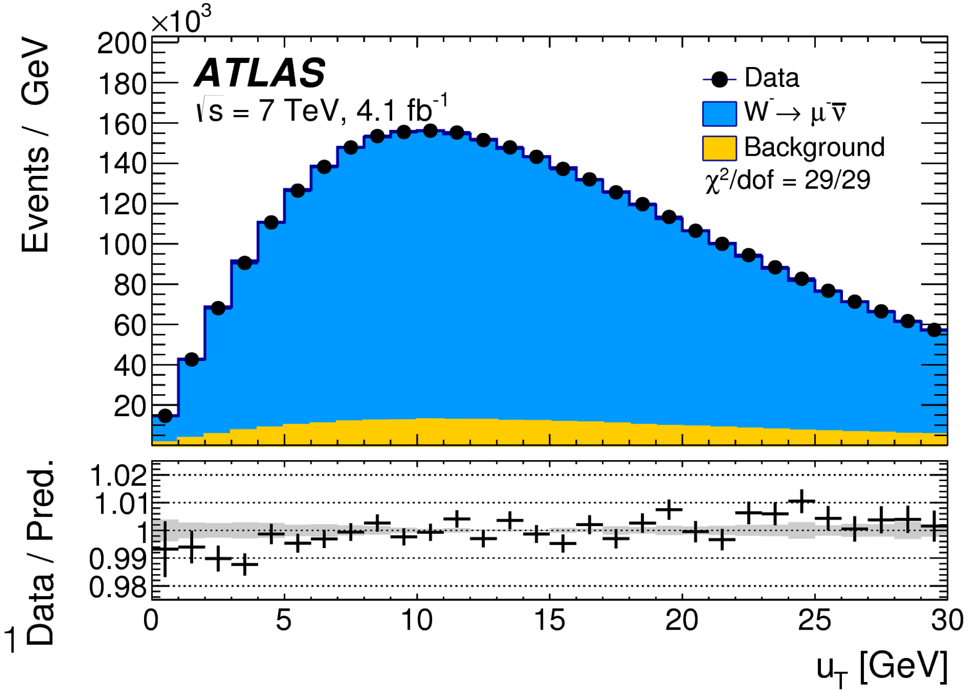



# W control distributions: η, $p_T$

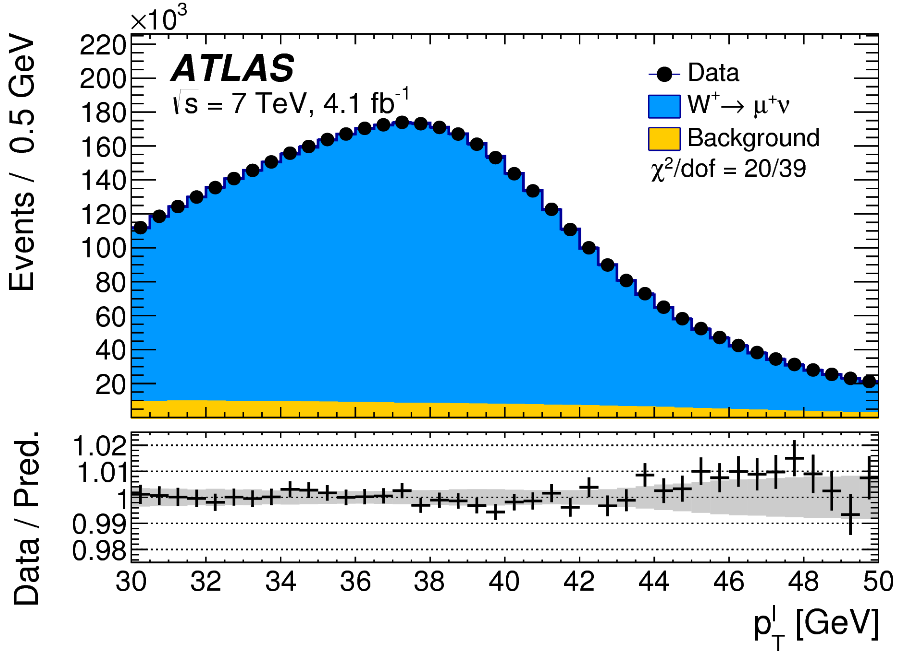


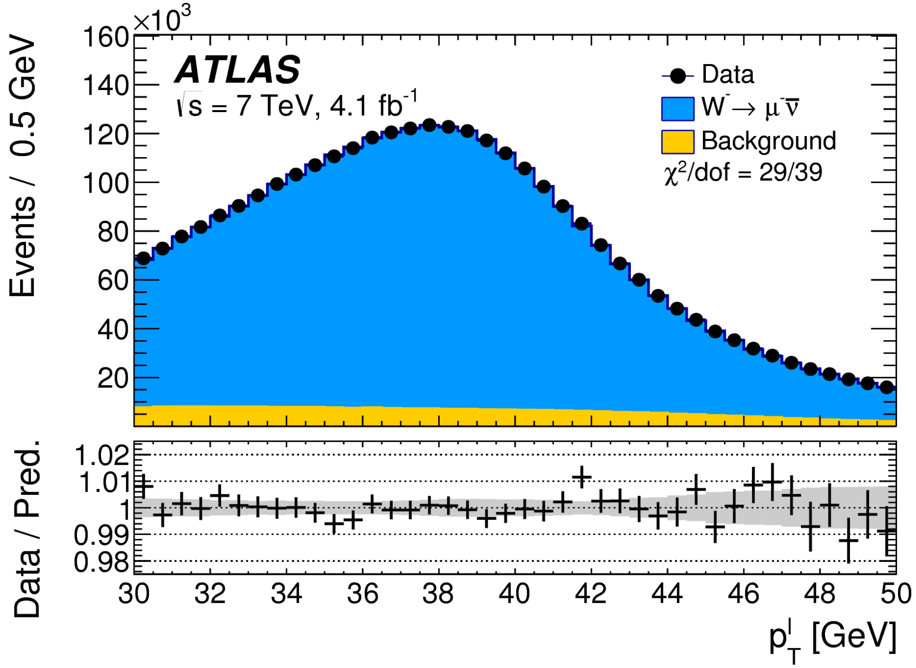



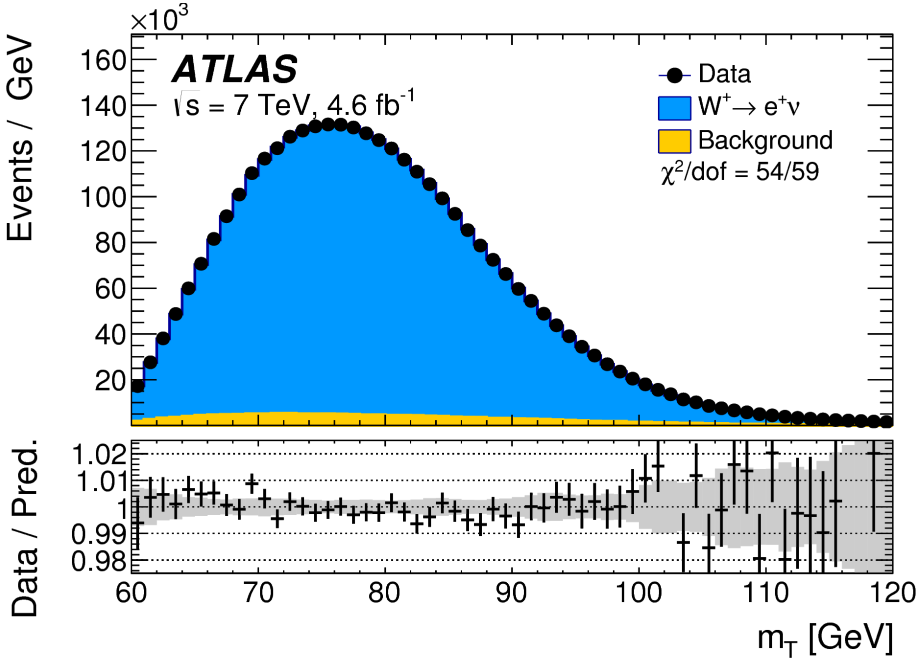



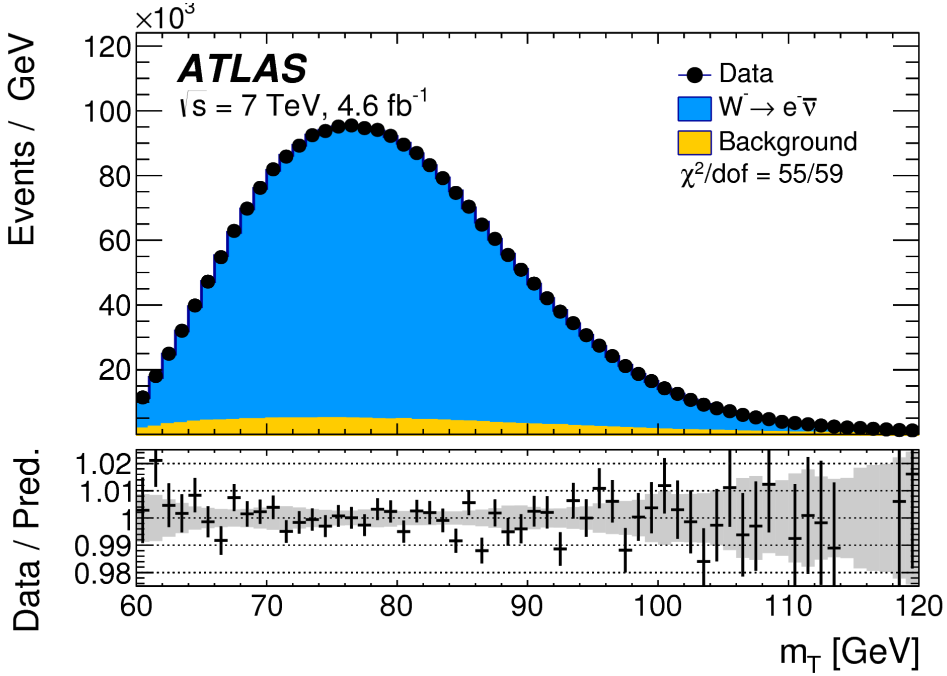



# W mass-sensitive distributions: $p_T^l$ and $m_T$



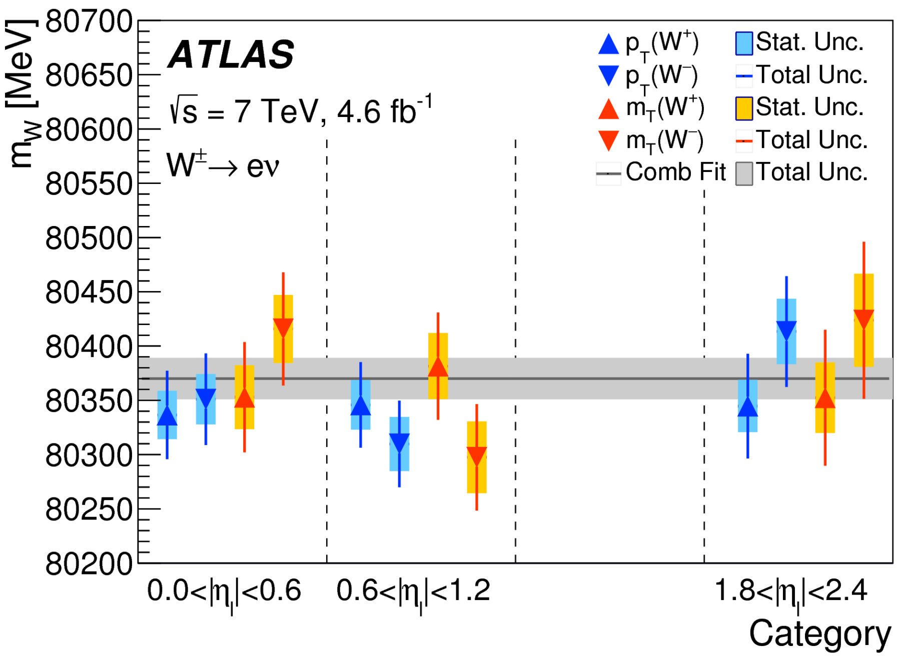



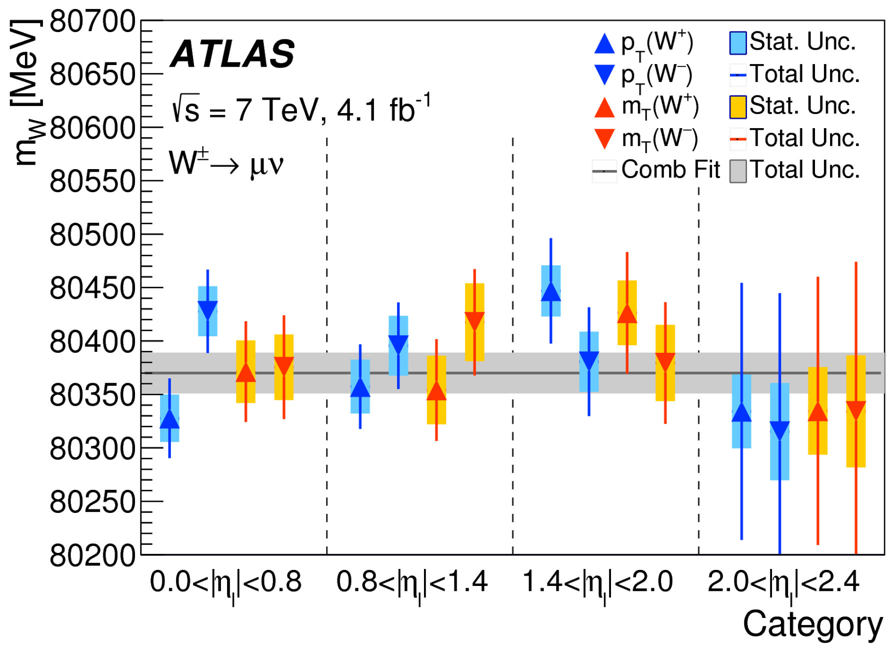



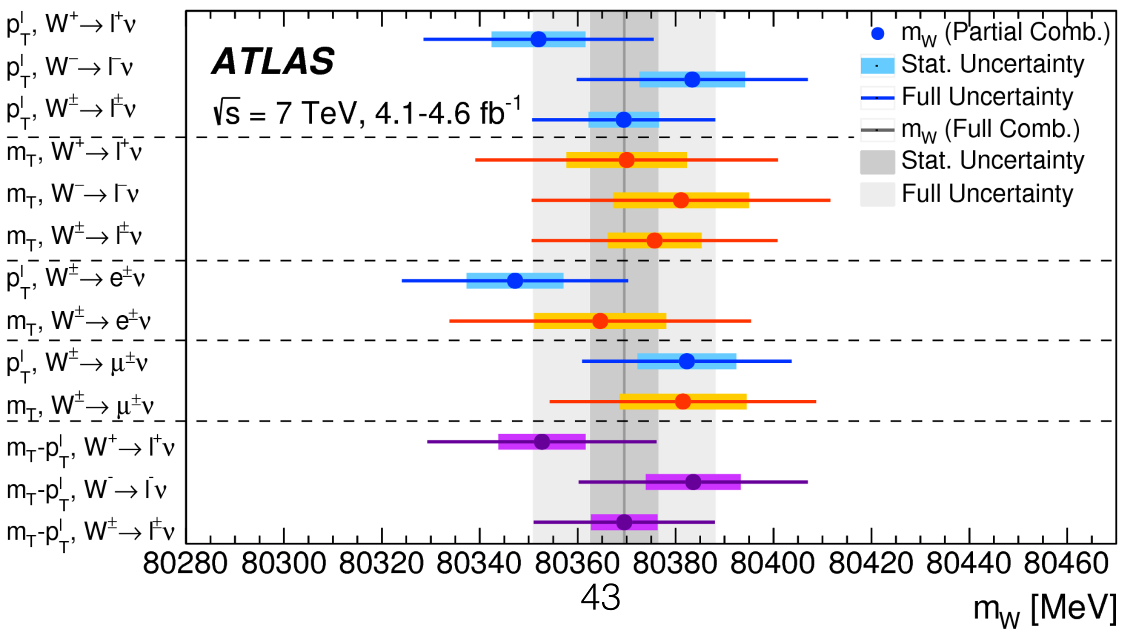



# Consistency of the results

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



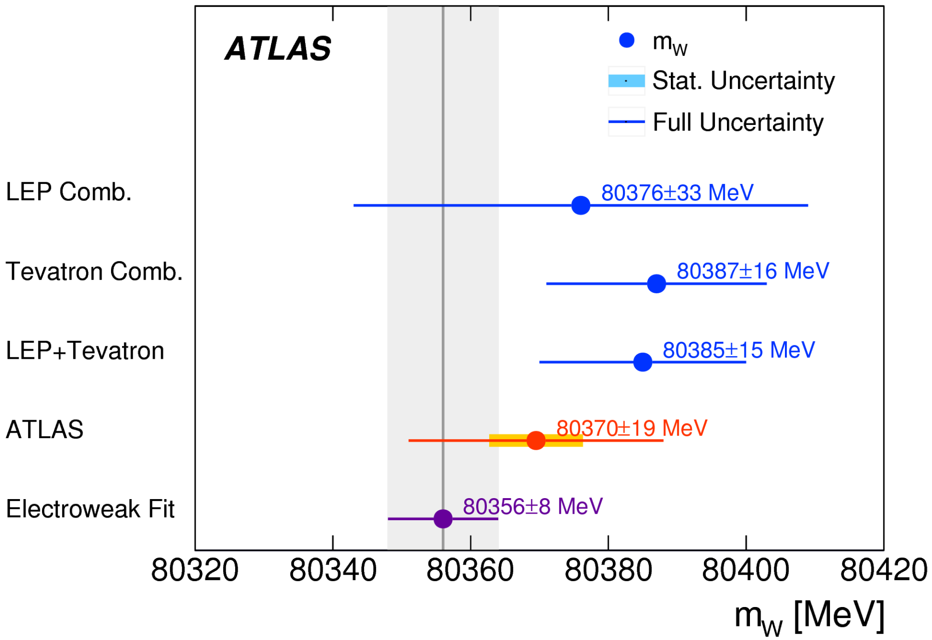



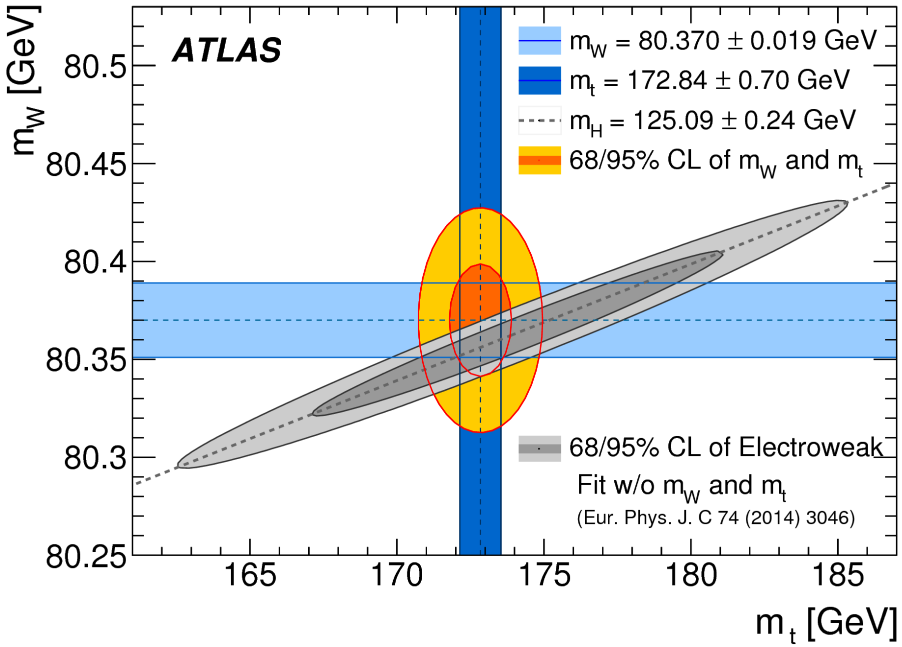

*Fitting ranges:*
*$32<p_T^l<45$ GeV,*
*$66<m_T<99$ GeV*

# 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. | $\chi^2$/dof of Comb. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $m_T$-$p_T^\ell$, $W^\pm$, e-$\mu$ | 80369.5 | 6.8 | 6.6 | 6.4 | 2.9 | 4.5 | 8.3 | 5.5 | 9.2 | 18.5 | 29/27 |



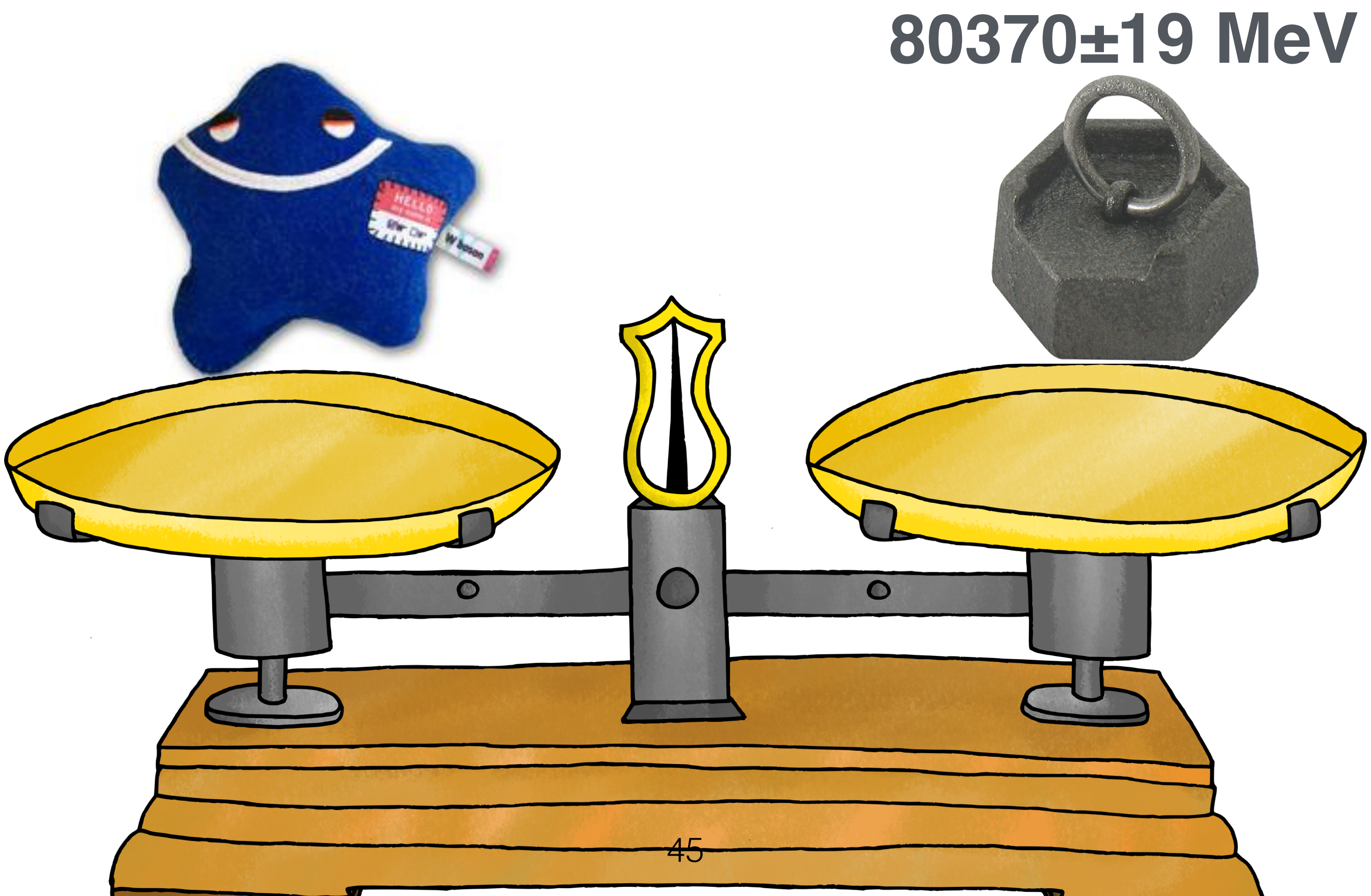




The result is consistent with the SM expectation, compatible with the world average and competitive in precision to the currently leading measurements by CDF and D0

# Conclusion

The first LHC measurement of mW = 80370+/-19 MeV is public now arXiv: 1701.07240v1 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.



# Perspectives

The uncertainty is dominated by theoretical modelling uncertainties, therefore more work in this direction is required and *a fully consistent model within one simulation tool* is needed.

The W mass measurement in CMS is ongoing. A first W-like measurement of the Z mass was performed.

More data are available with the 8 and 13 TeV datasets which can be used to improve the analysis and to further constrain the PDFs.

Experimentally, with the increase of the statistics in Z sample, most of the calibration uncertainties can be reduced. While more work is needed on the recoil with the increasing pileup.