

Electroweak Precision Measurements in ATLAS



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This talk covers some of EW results reported in the following 3 publications:

1. Tau polarisation in Z boson decays at 8 TeV,
EPJC78 (2018) 163, arXiv:1709.03490
2. Triple-differential cross-section of Drell-Yan events at 8 TeV,
JHEP 12 (2017) 069, arXiv:1710.05167
3. W boson mass measurement at 7 TeV,
EPJC78 (2018) 110, arXiv:1701.07240

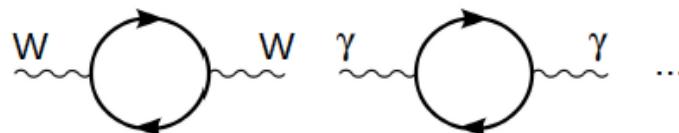
Introduction

- The EW gauge sector of the SM is constrained by 3 precisely known parameters:
 - Fine-structure constant: $\alpha=1/137.035\,999\,139(31)$ $\rightarrow 0.23 \text{ ppb}$ (relative precision)
 - Fermi coupling constant: $G_F=1.166\,378\,7(6) \times 10^{-5} \text{ GeV}^{-2}$ $\rightarrow 0.5 \text{ ppm}$
 - Z boson mass: $m_Z=91.1876(21) \text{ GeV}$ $\rightarrow 23 \text{ ppm}$

- At leading order, m_W is expressed as

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

- At higher-orders, dominant W and γ self-energies contribution



modifies the relation to

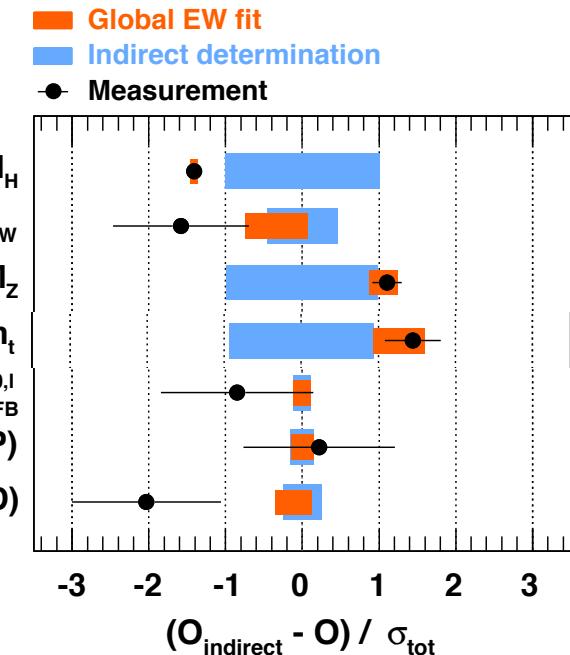
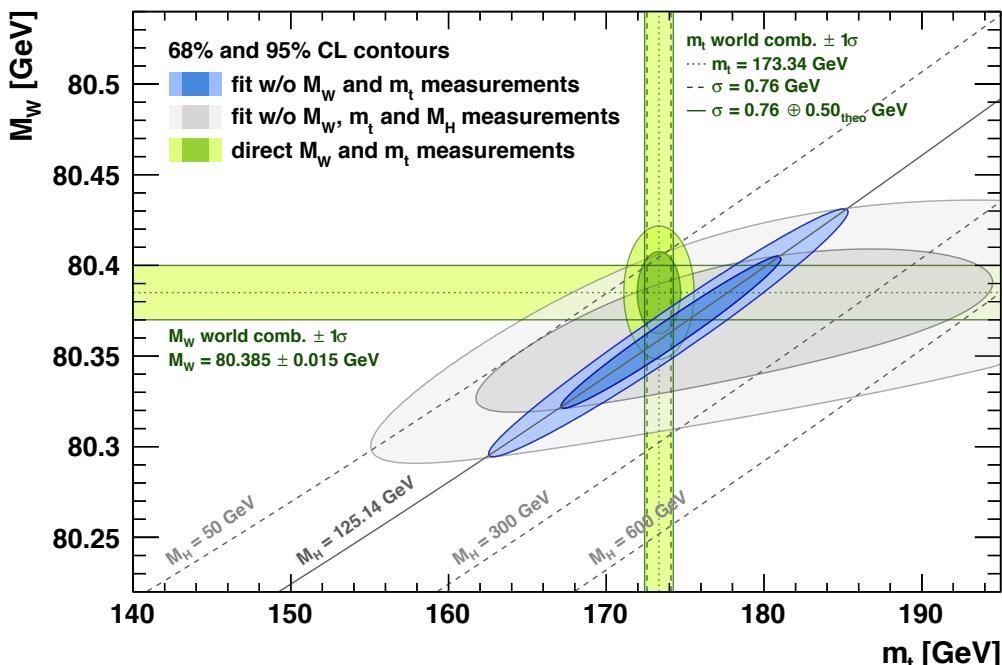
$$m_W^2 \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} \frac{1}{1 - \Delta r(\alpha, m_W, m_Z, m_t, m_H, \dots)}$$

Motivation

Plots from gFitter arXiv:1407.3792

For m_W , A_{FB} [Forward-Backward Asymmetry] and A_I [lepton asymmetry parameter $\sim \tau$ polarisation]:

- The indirect determinations have better precision than the measurements
- Limiting factors in global analysis

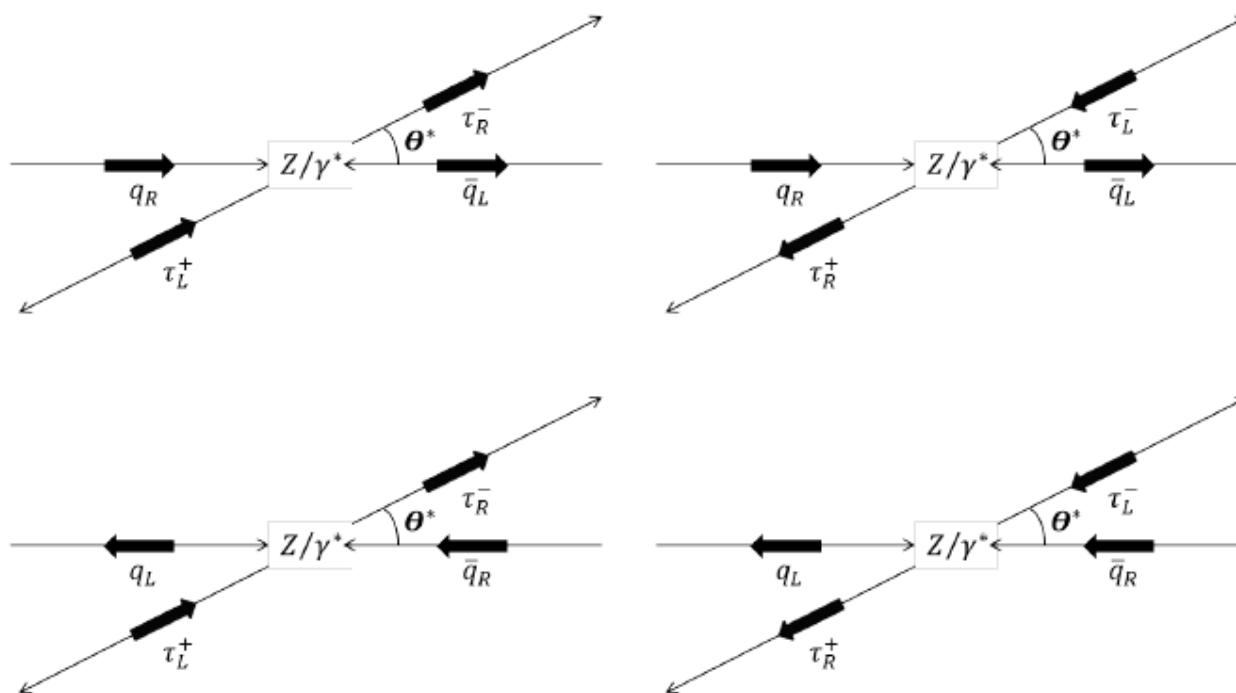


- Precision EW measurements allow for consistency tests of the SM
- They are sensitive to new physics/particles independent of direct searches

Tau Polarisation in Z Boson Decays (1)

- Tau (τ): the heaviest lepton in the SM
- Tau polarisation is a measure of parity violation & probes Lorentz structure of the interactions

$$P_\tau = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto 2(1 - 4 \sin^2 \theta_{\text{eff}}), \quad \sin^2 \theta_{\text{eff}} = \kappa \sin^2 \theta_W$$



Tau Polarisation in Z Boson Decays (2)

□ Based on 8 TeV data with 20.2 fb^{-1}

□ $Z/\gamma^* \rightarrow \tau\tau$:

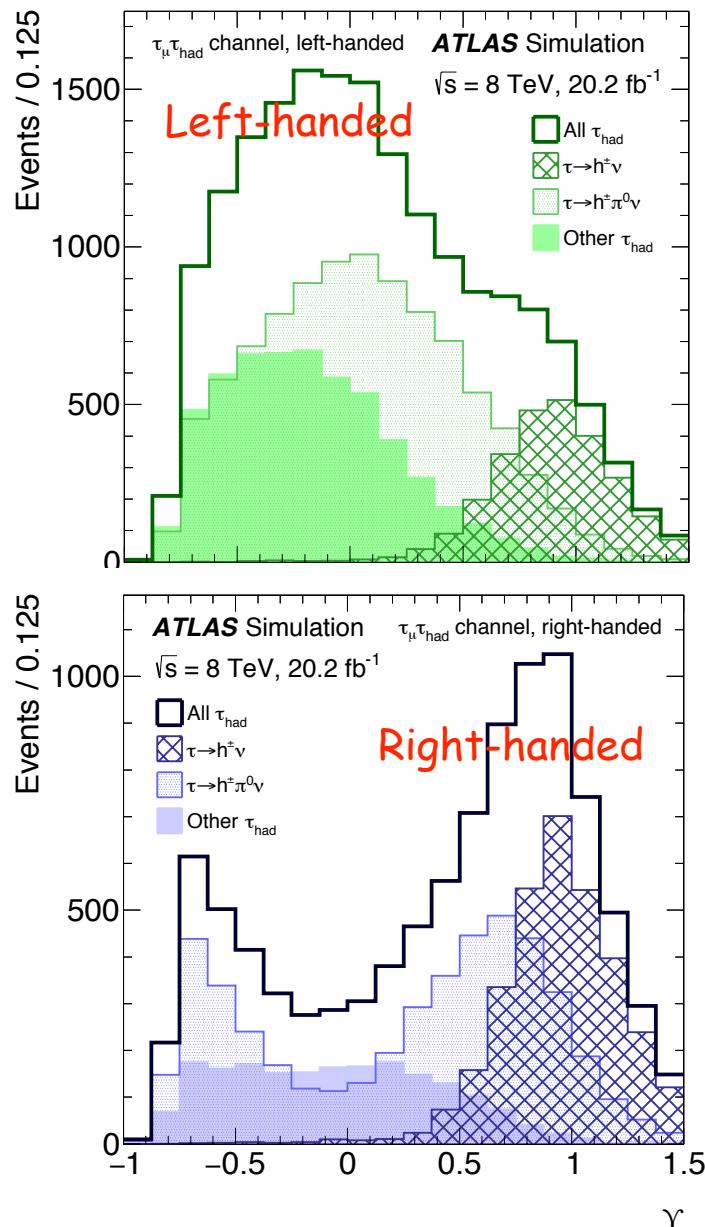
- one $\tau \rightarrow \nu_\tau e/\mu \nu_{e/\mu}$ as tag [μ -tagged plotted]
- one τ in one-prong hadronic decay mode as the polarisation analyser

$$\Upsilon_{\text{theory}} = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}$$

$$\Upsilon_{\text{exp}} = \frac{E_T^{\pi^\pm} - E_T^{h^0}}{E_T^{\tau_{\text{had-vis}}}} = \frac{2p_T^{\text{track}}}{E_T^{\tau_{\text{had-vis}}}} - 1$$

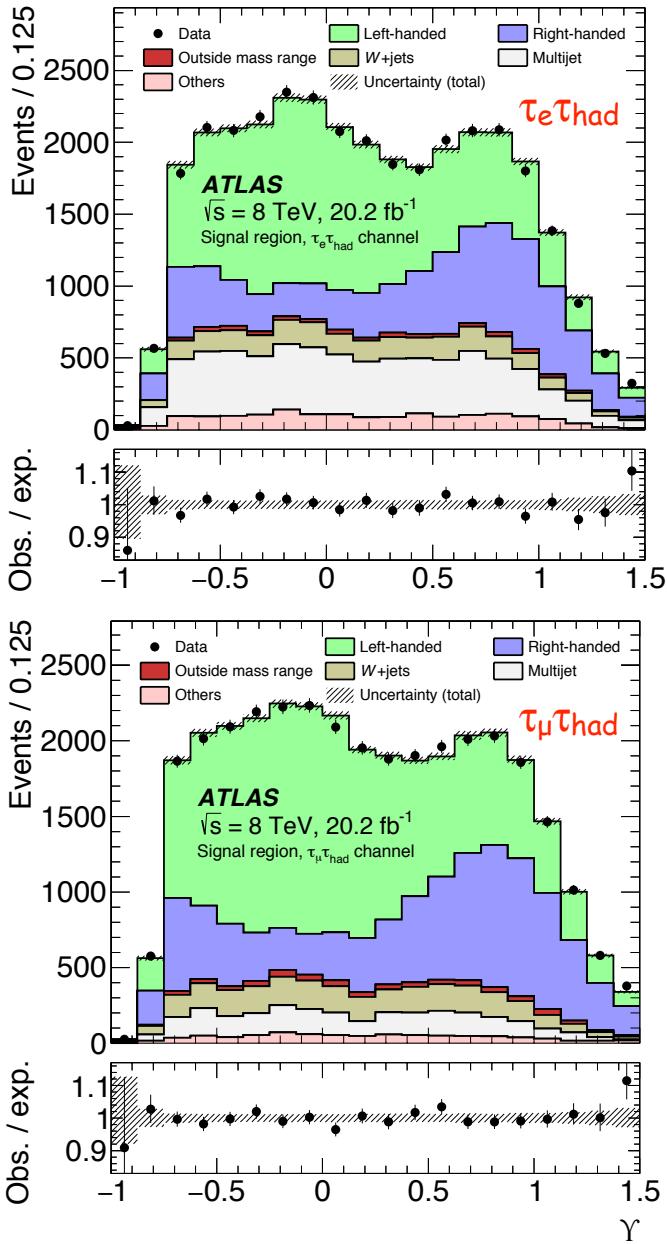
- Extracted in Z/γ^* mass region $[66, 116] \text{ GeV}$
- As well as in fiducial region

One τ_{lep} decay	One single-prong τ_{had} decay
$p_{T,\text{lepton}} > 26 \text{ GeV}$	$p_{T,\tau_{\text{had-vis}}} > 20 \text{ GeV}$
$ \eta_e < 2.47$ and not $1.37 < \eta_e < 1.52$ or $ \eta_\mu < 2.5$	$ \eta_{\tau_{\text{had-vis}}} < 2.47$
$m_T < 30 \text{ GeV}$	$40 < m_{\text{vis}} < 85 \text{ GeV}$

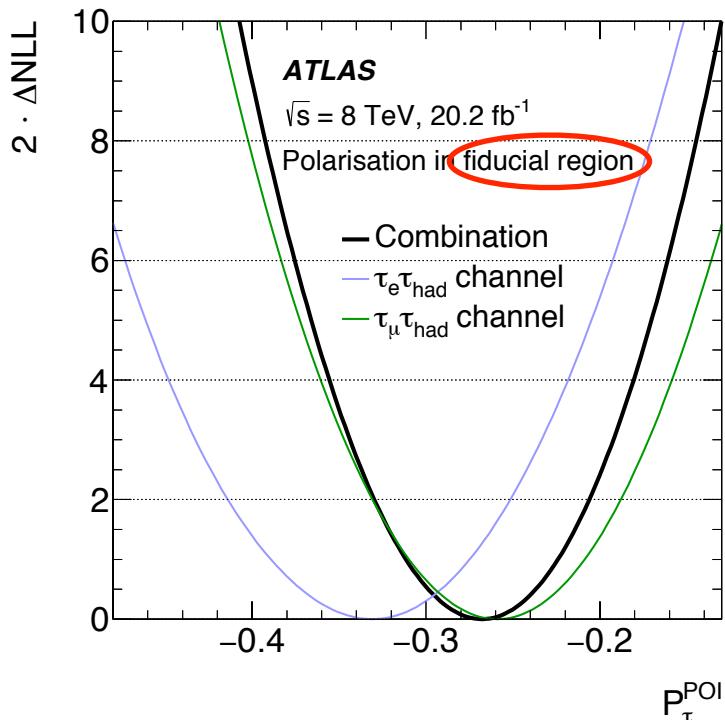
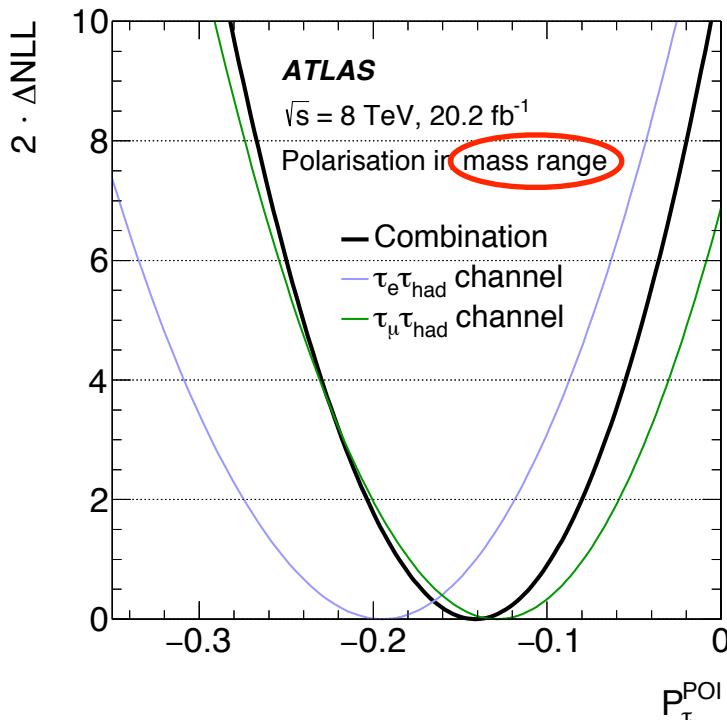


Tau Polarisation in Z Boson Decays (3)

- Dominant background, multijet & W+jets, estimated with data-driven techniques:
 - multijet with same-sign control region
 - W+jets with dedicated W+jets control region
- Minor background estimated from simulation
- Template fit used to extract the polarisation following ATLAS $W \rightarrow \tau\nu$ analysis at 7 TeV [link]
 - Simultaneous fit to the signal and same-sign control regions
- Uncertainties include:
 - Shape of the templates (signal shape being the dominant source)
 - Acceptance, efficiency, i.e. normalisation



Tau Polarisation in Z Boson Decays (4)



Channel	P_{τ} in mass-selected region	P_{τ} in fiducial region
$\tau_e - \tau_{\text{had}}$	$-0.20 \pm 0.02 \text{ (stat)} \pm 0.05 \text{ (syst)}$	$-0.33 \pm 0.03 \text{ (stat)} \pm 0.05 \text{ (syst)}$
$\tau_\mu - \tau_{\text{had}}$	$-0.13 \pm 0.02 \text{ (stat)} \pm 0.05 \text{ (syst)}$	$-0.26 \pm 0.02 \text{ (stat)} \pm 0.05 \text{ (syst)}$
Combination	$-0.14 \pm 0.02 \text{ (stat)} \pm 0.04 \text{ (syst)}$	$-0.27 \pm 0.02 \text{ (stat)} \pm 0.04 \text{ (syst)}$

in excellent agreement with

Prediction* -0.1517 ± 0.0019

-0.270 ± 0.006

* based on Alpgen interfaced with Pythia6 & Tauola

3D Cross-Section of Drell-Yan Events at 8 TeV (1)

Based on the same 8 TeV data sample

$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\ell}s} \sum_q P_q [f_q(x_1, Q^2)f_{\bar{q}}(x_2, Q^2) + (q \leftrightarrow \bar{q})]$$

$$P_q = e_\ell^2 e_q^2 (1 + \cos^2 \theta^*) \quad \gamma \text{ exchange}$$

$$+ e_\ell e_q \frac{2m_{\ell\ell}^2(m_{\ell\ell}^2 - m_Z^2)}{\sin^2 \theta_W \cos^2 \theta_W [(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]} [v_\ell v_q (1 + \cos^2 \theta^*) + 2a_\ell a_q \cos \theta^*] \quad \gamma Z \text{ interf}$$

$$+ \frac{m_{\ell\ell}^4}{\sin^4 \theta_W \cos^4 \theta_W [(m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2]} [(a_\ell^2 + v_\ell^2)(a_q^2 + v_q^2)(1 + \cos^2 \theta^*) + 8a_\ell v_\ell a_q v_q \cos \theta^*]$$

Z exchange

$$a_{\ell,q} = \frac{1}{2} I_{\ell,q}^3 \quad v_{\ell,q} = I_{\ell,q}^3 - 2e_{\ell,q} \sin^2 \theta_W$$

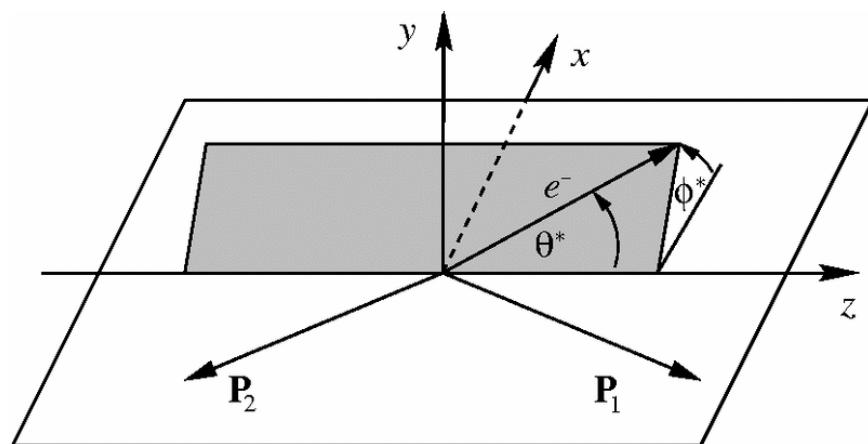
- PDFs typically dominates $\sin^2 \theta_W$ at hadron colliders
- $d^3\sigma$ attempts to constrain both simultaneously

Dominant term inducing forward-backward asymmetry, A_{FB}

This terms takes over at $m_{||} \sim m_Z$

3D Cross-Section of Drell-Yan Events at 8 TeV (2)

- Initial state QCD radiation
 - Quark directions may no longer align with initial proton directions
- Define decay angle θ^* in the Collins-Soper reference frame
- It is measured from an axis symmetric wrt the two incoming partons



$$\cos \theta^* = \frac{p_{z,\ell\ell}}{m_{\ell\ell} |p_{z,\ell\ell}|} \frac{p_1^+ p_2^- - p_1^- p_2^+}{\sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}}$$

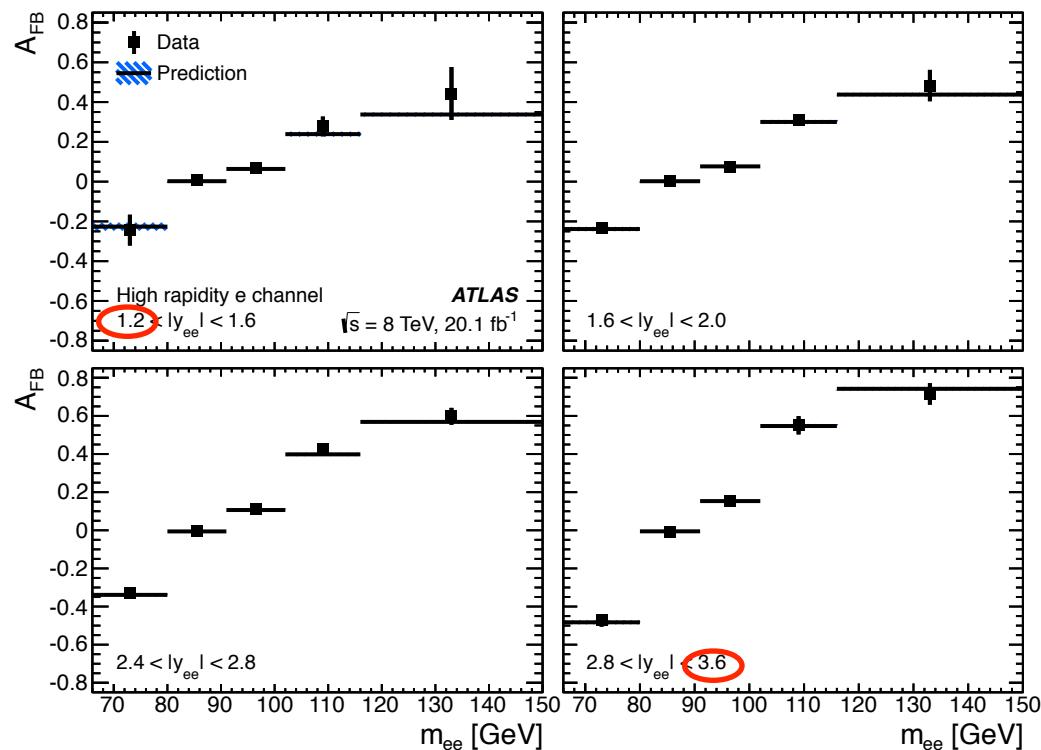
$$p_i^\pm = E_i \pm p_{z,i}$$

3D Cross-Section of Drell-Yan Events at 8 TeV (3)

$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

Forward-Backward Asymmetry A_{FB}
is $y_{||}$ dependent

The largest asymmetry at large $y_{||}$
with ee channel



- Reduced syst errors wrt $d^3\sigma$
- Stat errors dominate everywhere
- Data agree with Born-level prediction from Powheg including NNLO QCD & NLO EW corrections with input $\sin^2\Theta_W=0.23113$

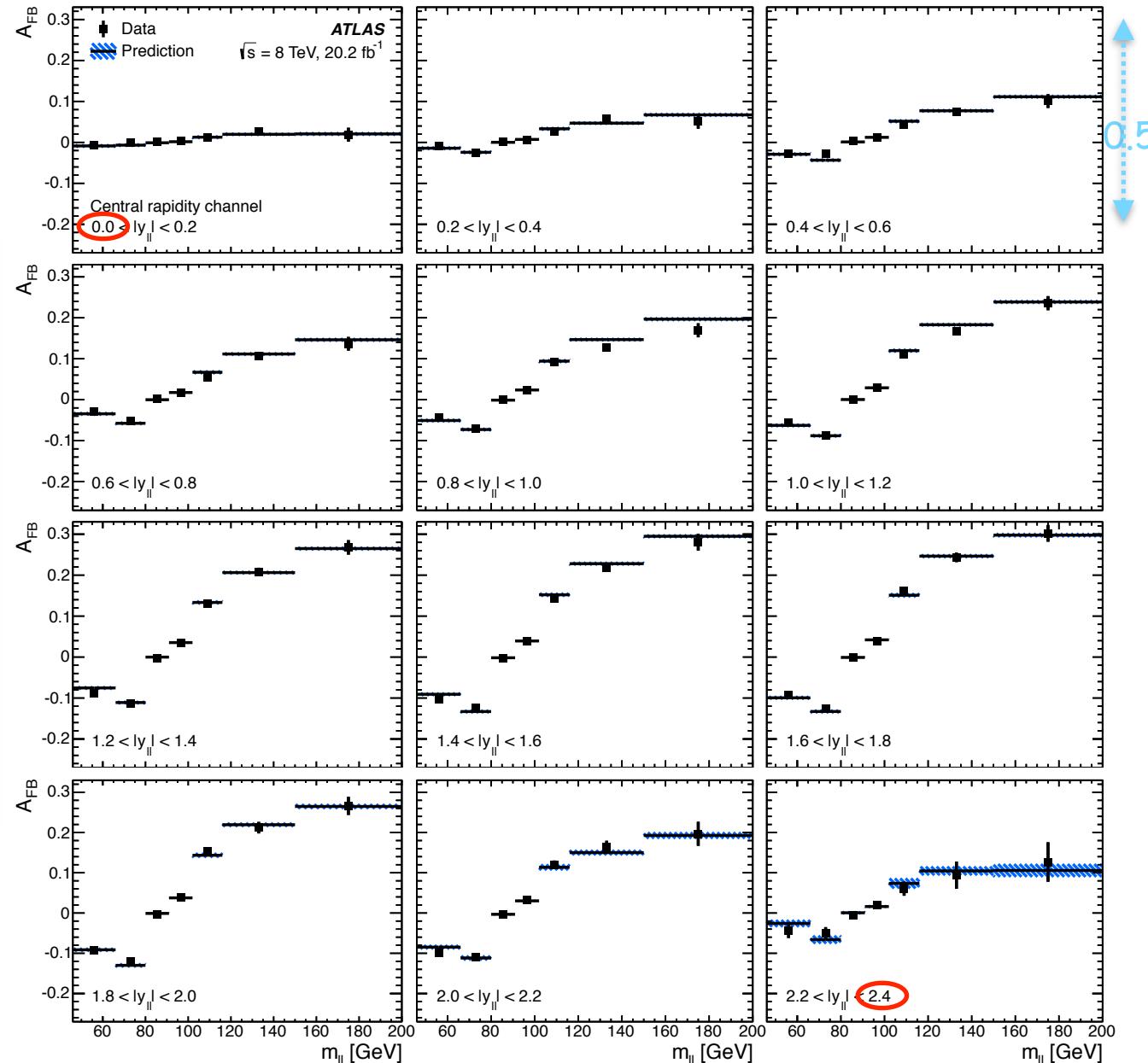
See Ulla Blumenschein's talk for 3d cross section measurement

3D Cross-Section of Drell-Yan Events at 8 TeV (4)

Even better precision
with combined ee & $\mu\mu$
channels in central
rapidity region

However with reduced
asymmetry (reduced
 y range wrt previous plot)

The data can be used
to extract $\sin\theta_W$ &
PDFs



W Boson Mass Measurement at 7 TeV (1)

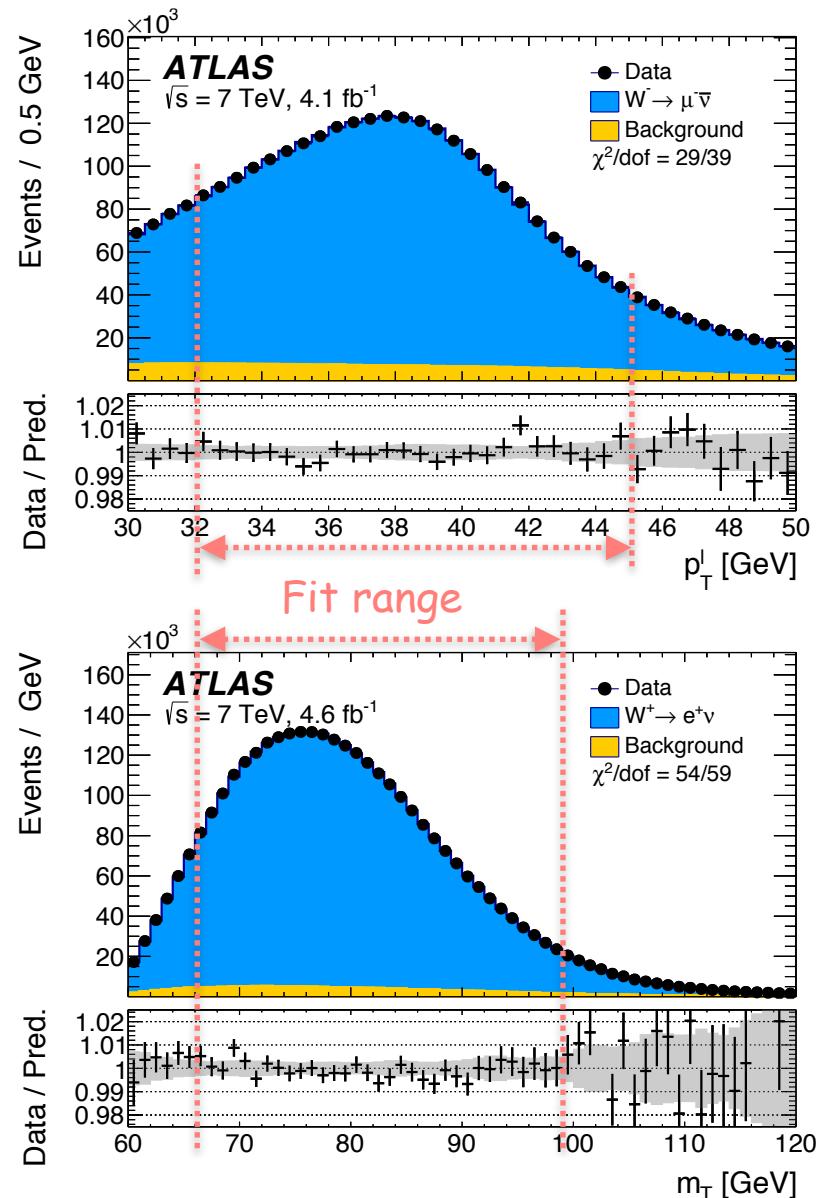
- Based on 7 TeV data with up to 4.6 fb^{-1}
 - Signal samples: $W \rightarrow e/\mu v_{e/\mu}$ decays
 - Calibration samples: $Z \rightarrow ee, \mu\mu + W$ samples
 - Favorable pileup condition ($\langle \mu \rangle \sim 9$)
 - Resolution less affected by pileup

- Extremely challenging measurement
 - Strongly affected by PDFs (s, c PDFs)
 - Difficult modelling @ low p_T^W
 - Precise lepton, recoil (u) system calibration

- Template fits to charged lepton transverse momentum (p_T^ℓ) and W boson transverse mass (m_T) distributions

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

$$\vec{p}_T^{\text{miss}} = -(\vec{P}_T^\ell + \vec{u}_T)$$



W Boson Mass Measurement at 7 TeV (2)

In addition to p_T^l , m_T , W^+ , W^- , e , μ categories, several pseudo-rapidity categories defined

Uncertainties are evaluated in all these categories and with their correlation taken into account in the combination

Muon channel:

Momentum scale error
dominates

Electron channel:

Energy scale, reconstruction
and identification efficiencies
are equally important
dominant error sources

$ \eta_\ell $ 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								
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

$ \eta_\ell $ 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

W Boson Mass Measurement at 7 TeV (3)

Recoil:

The recoil correction
dominates & contributes
essentially only to m_T

W-boson charge Kinematic distribution	W^+		W^-		Combined	
	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle \mu \rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_T^* correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \rightarrow W$ 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

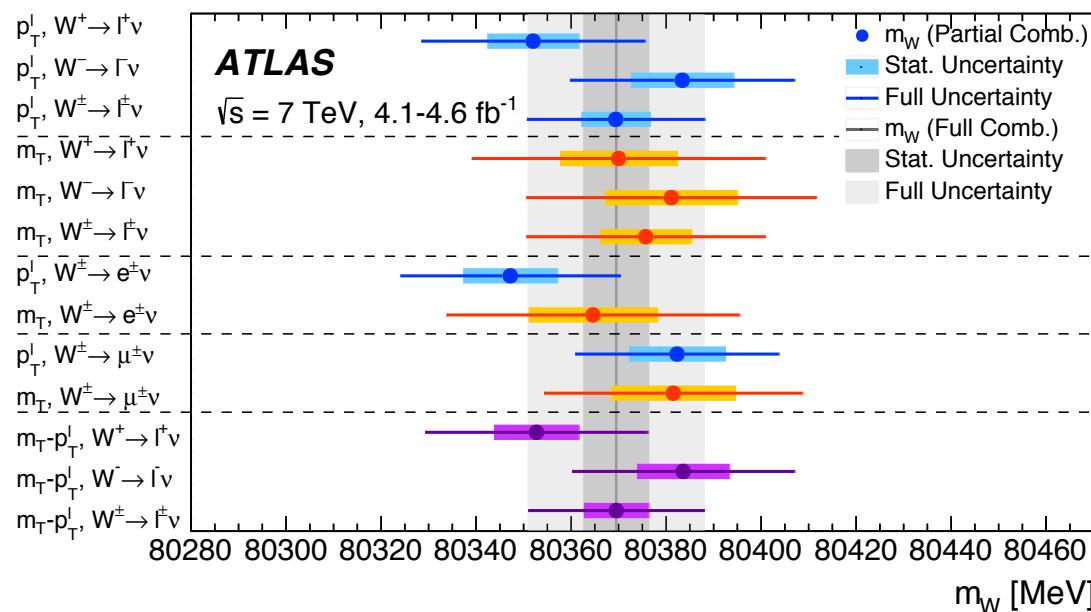
W-boson charge Kinematic distribution	W^+		W^-		Combined	
	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

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

W Boson Mass Measurement at 7 TeV (4)

Tests:

A large number of closure/consistency/validation tests performed in additions to the existing categories: extract m_Z from Z samples, extract m_W in different $\langle\mu\rangle$ /recoil intervals, in different p_T^l and m_T fit ranges, by removing p_T^{miss} cut etc

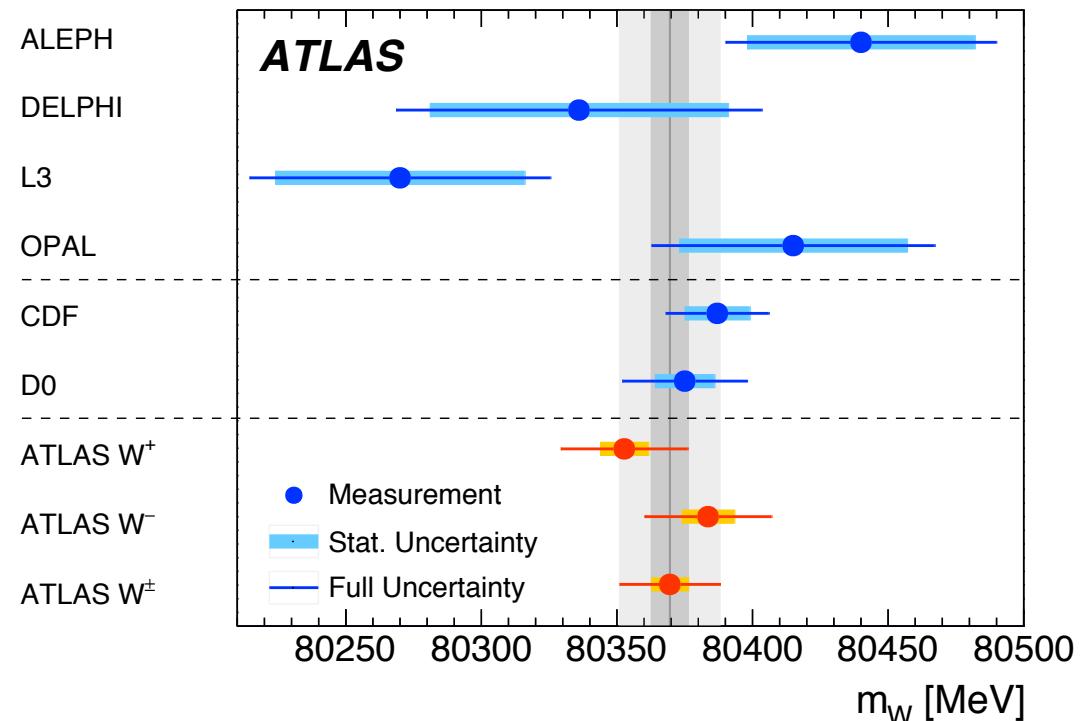


→ The consistency e vs μ channels tests of experimental calibrations
the consistency W^+ vs W^- & different rapidity categories tests W production model

W Boson Mass Measurement at 7 TeV (5)

Results:

- In good agreement with other single experiment measurement
- Precision matches other best one



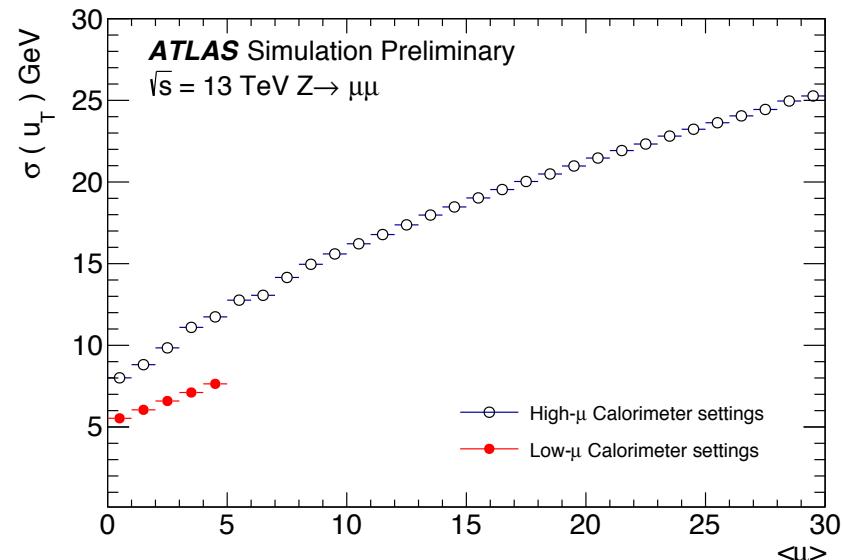
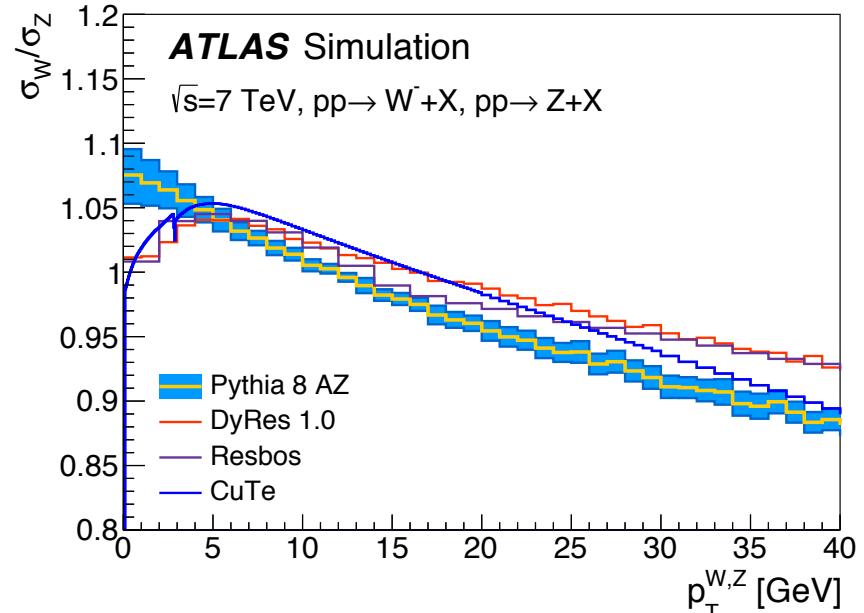
Impact of ATLAS measurement in global fit (arXiv:1803.01853):

- The uncertainty of world average improved from 15 MeV to 13 MeV
- The precision of the indirect determination reduced from 8 MeV to 7 MeV

W Boson P_T Measurement Perspective

ATL-PHYS-PUB-2017-021

- ❑ Dedicated low pileup data available
- ❑ These data could help for a better understanding/modelling of low $p_T^{W,Z}$ region
- ❑ At low pileup, we also have best recoil resolution, thus could improve the sensitivity of the m_T observable



Summary

- ❑ EW precision measurements at the LHC are very challenging
- ❑ They have been achieved with good and competitive precision
 - Tau polarisation is sensitive to $\sin\theta_W$, the technique may be used to distinguish SM and BSM signals
 - 3d DY cross sections are being used to constrain both $\sin\theta_W$ and PDFs, the latter is needed for improving the precision of m_W
 - m_W measured with best precision from a single experiment but needs improvement to match the precision of the indirect determination
- ❑ Stay tuned for new EW results with much improved precision based on high statistics and dedicated data samples