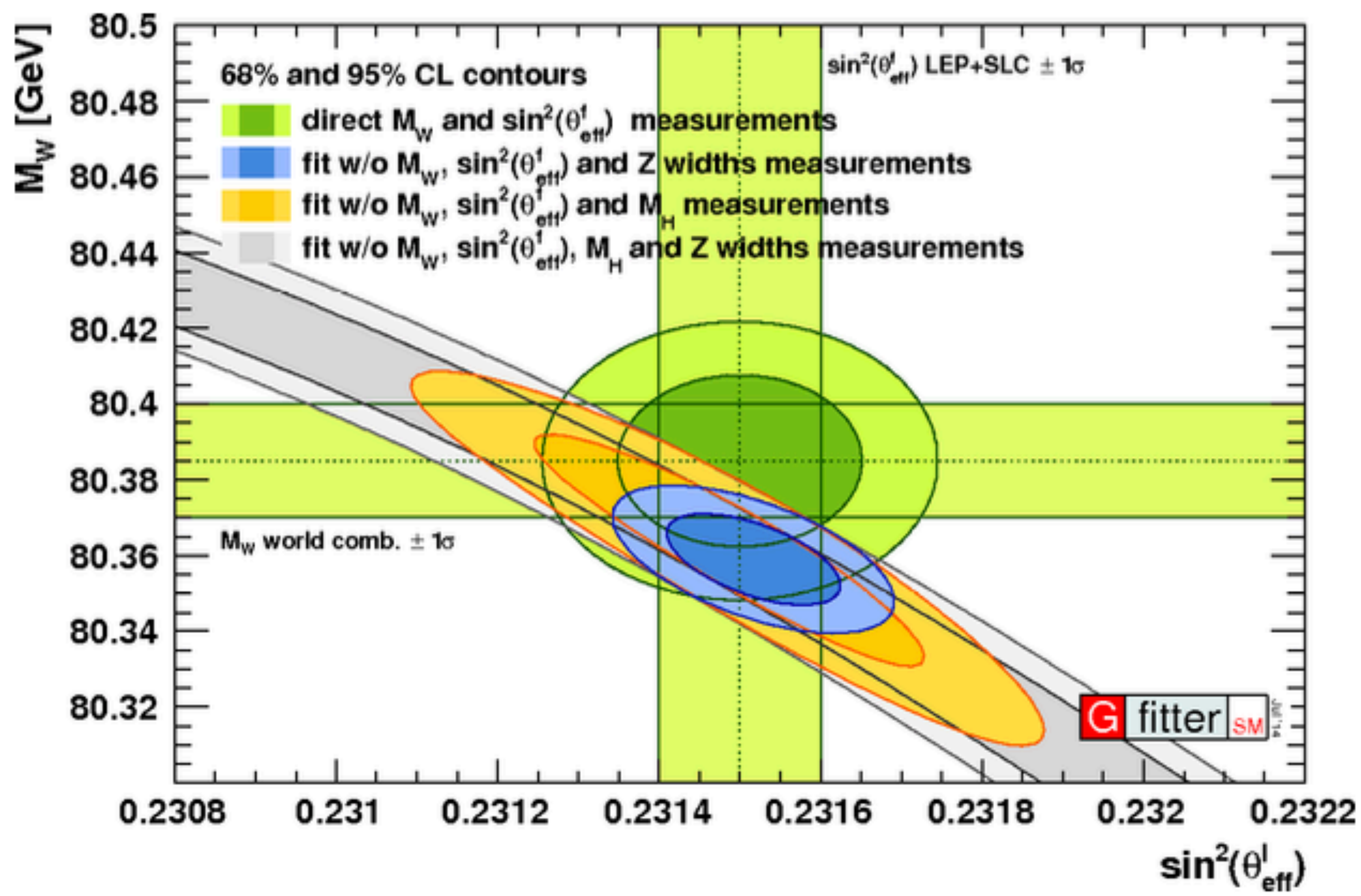
Electroweak precision measurements at ATLAS



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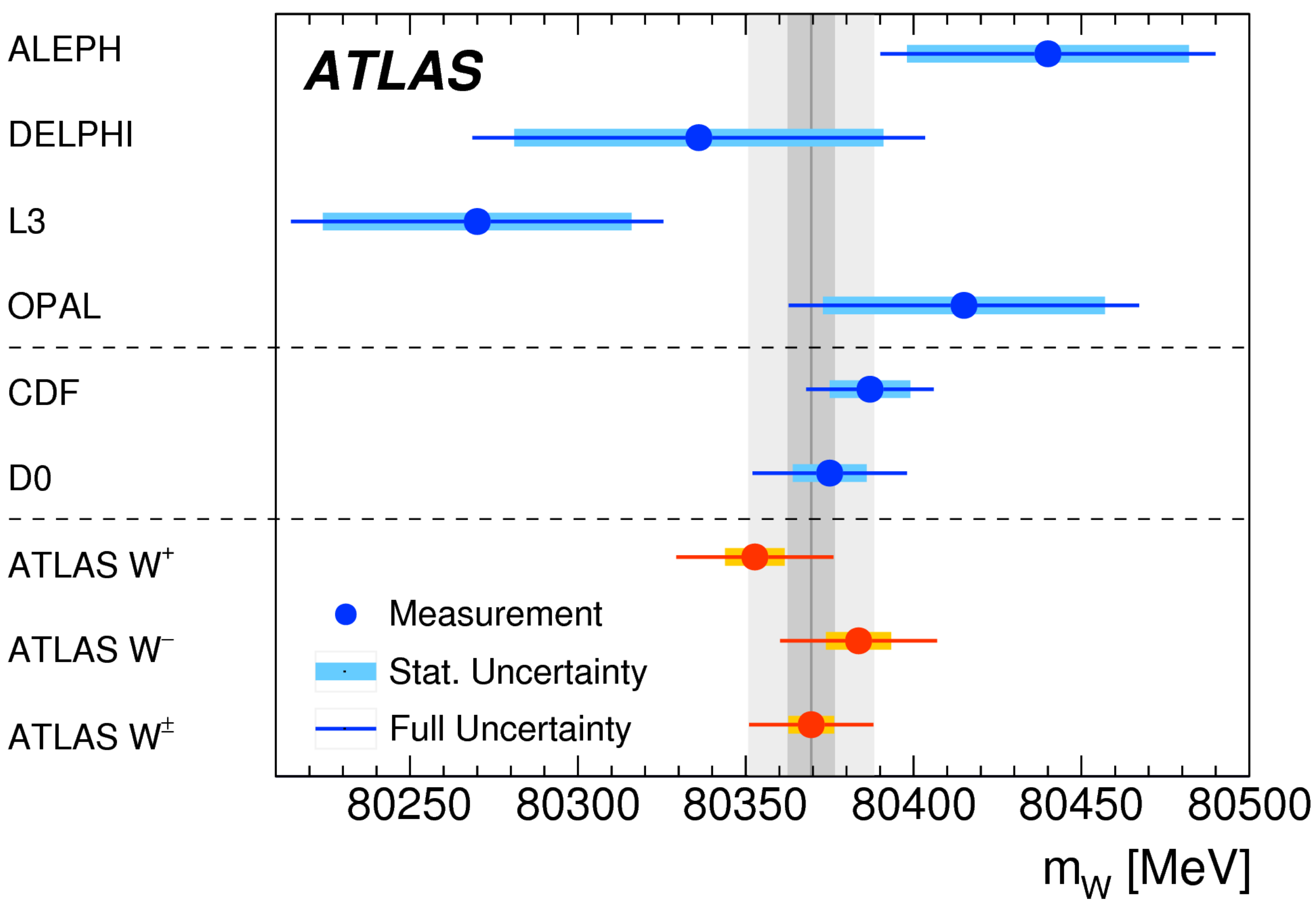
On behalf of the ATLAS Collaboration

18/05/2017

ATLAS EXPERIMENT

Introduction

- Nice recent m_W results!
  - see Maarten's talk yesterday
- Challenge on many experimental aspects to keep uncertainties under control
  - Years of work for experimentalists
  - Not the scope of this talk



Electrons

$\lvert\eta_\ell\rvert$ 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

Muons

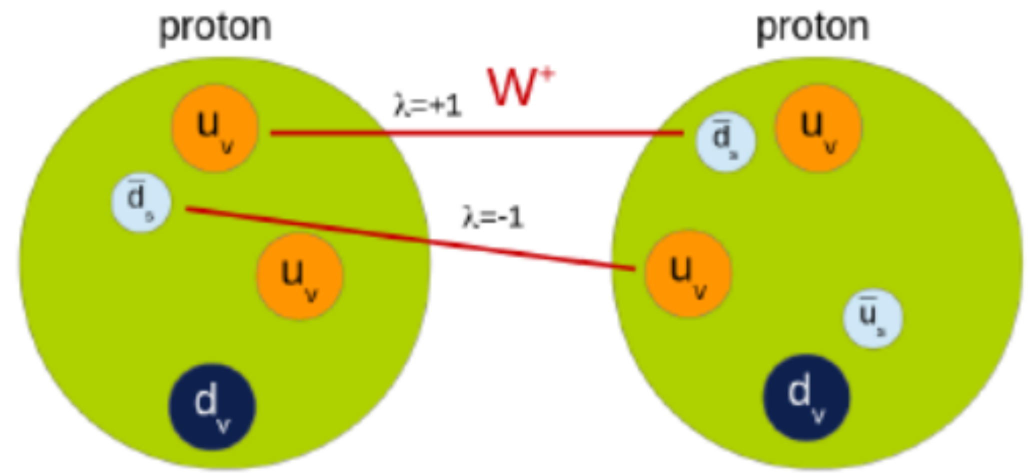
$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0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

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

$$m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}$$

Introduction (2)



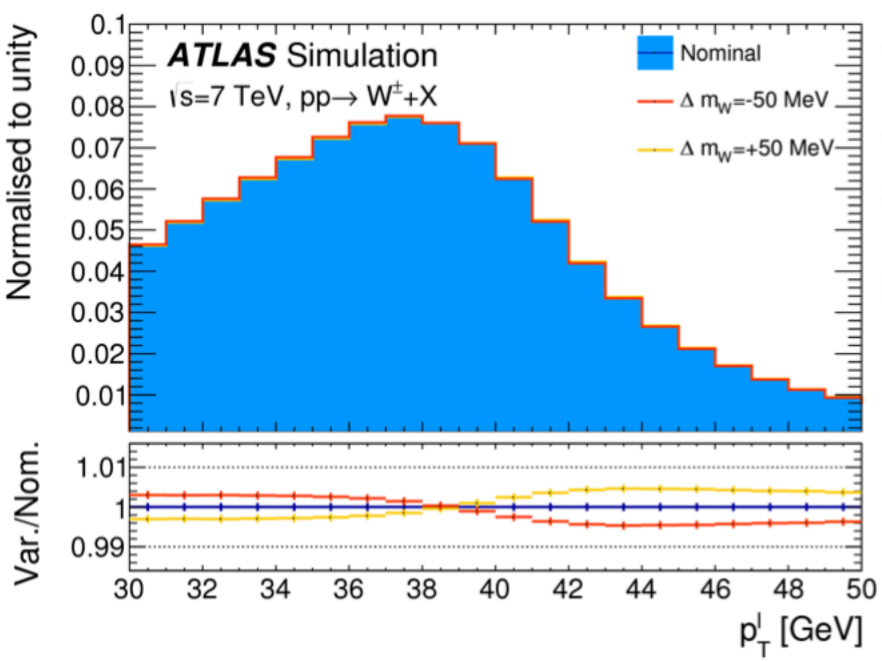
- Nice recent m_W results!
  - see Maarten's talk yesterday
  - Sensitive sensitive to potential BSM physics
- Extremely complicated measurement
  - More complicated with proton-proton (because of the larger participation of sea quarks) than previous analyses with p-p̄ at Tevatron (see talk by Alexander)
    - Charge-asymmetric W production
    - Larger role of 2nd generation quarks (involved in ~25% of the production)
    - Ambiguity in the average helicity (W polarisation uncertainty)
    - For a longer discussion of PDF constraints, see Juan's talk
  - Relies on a few dedicated ancillary studies…
    - Will focus here on the $p_T(W)$
  - …and best/improved Monte Carlo programs
- Other interesting results on $\sin^2\theta_W$

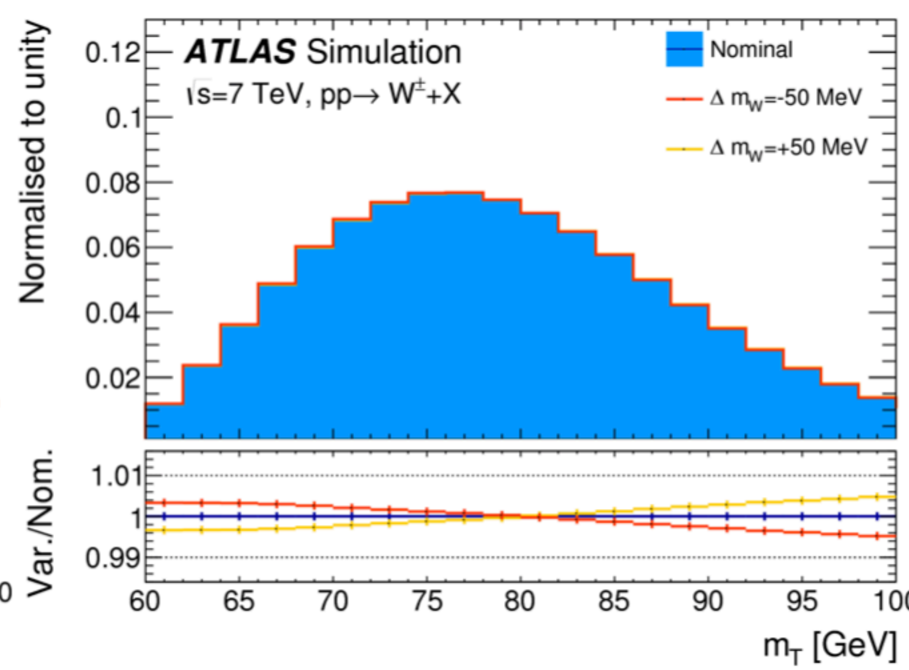
ATLAS m_W measurement recap

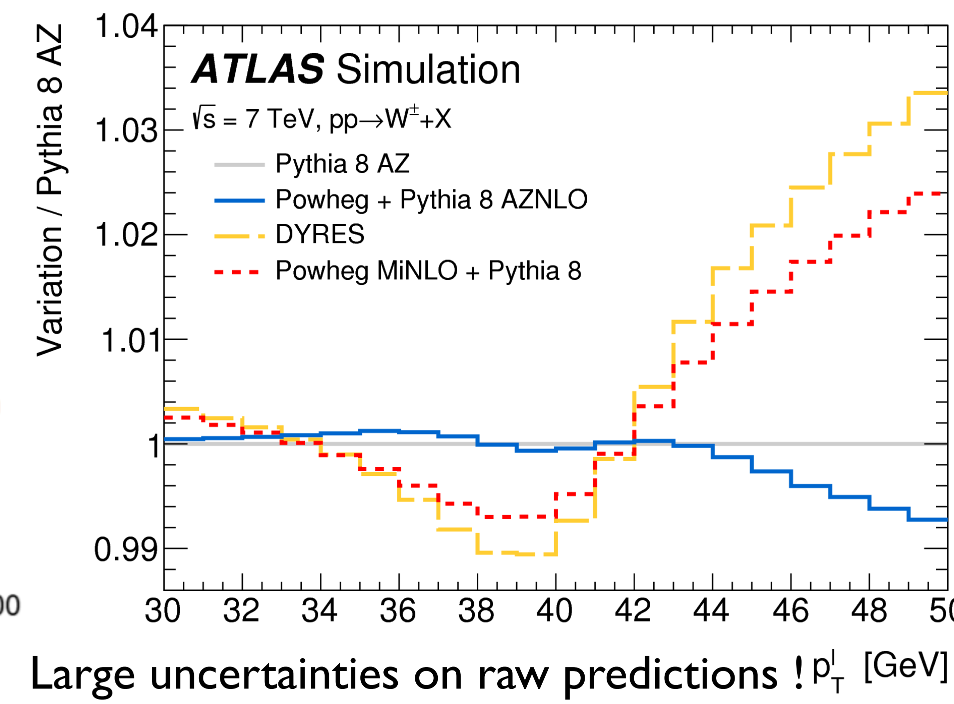
- ATLAS uses both electrons and muons in the precision region ($|\eta|<2.4$) with the $\sqrt{s}$=7 TeV data
- Split events in charge and pseudo-rapidity categories

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	$[0, 0.6]$, $[0.6, 1.2]$, $[1.8, 2.4]$	$[0, 0.8]$, $[0.8, 1.4]$, $[1.4, 2.0]$, $[2.0, 2.4]$

- Relies on template fit of $p_T(l)$ and transverse mass m_T distributions



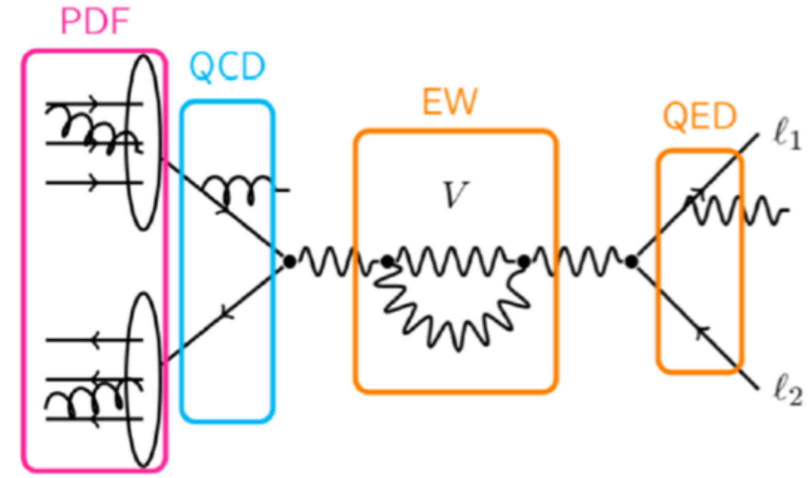




Large uncertainties on raw predictions !

- Calls for precise template (and m_W-dependence) predictions !

Modelling uncertainties



- Impossible to find a generator dealing with all critical aspects at the same time

- Electroweak corrections:

Decay channel Kinematic distribution	$W \to e\nu$ p_T^ℓ	 m_T	$W \to \mu\nu$ 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

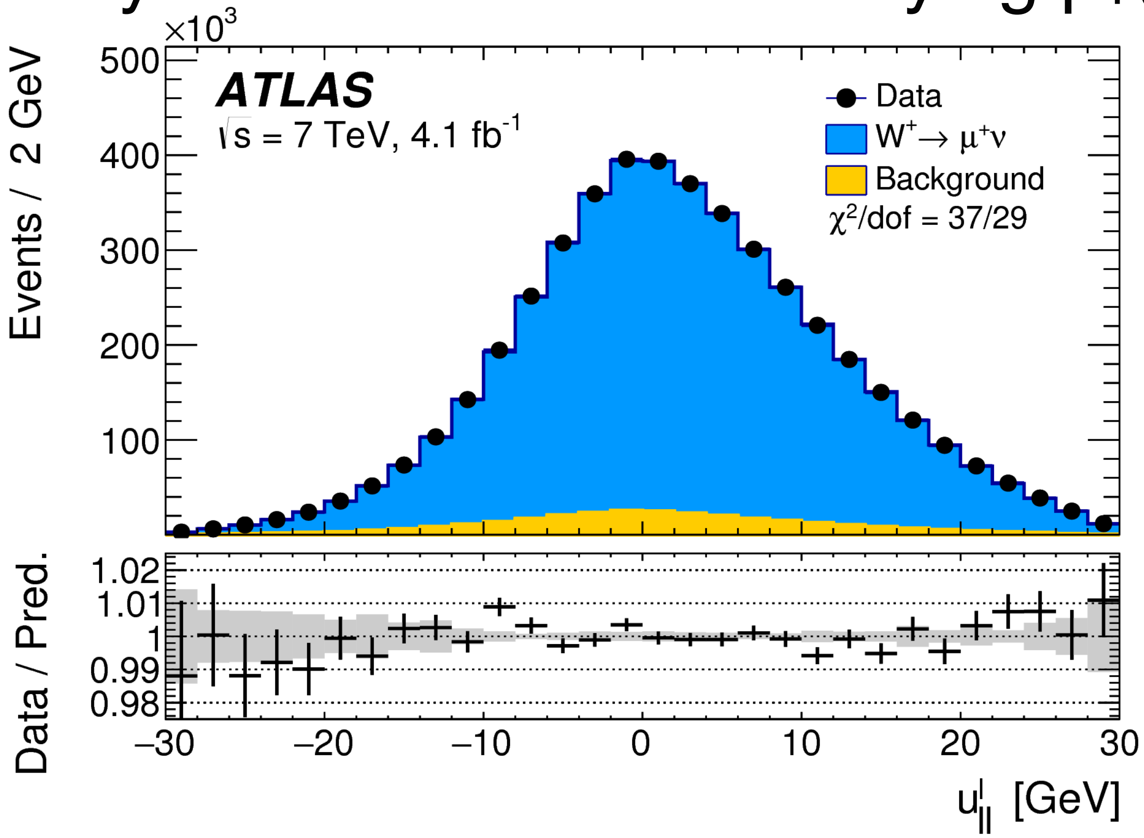
- Photos include QED FSR emission
- (Small) ISR and ISR/FSR interference effects can be evaluated with dedicated tools
- Gets complicated for multiple and mixed QED/QCD emissions
- Ways to compute size of these effects to be added as uncertainty
- See talk by Alessandro Vicini

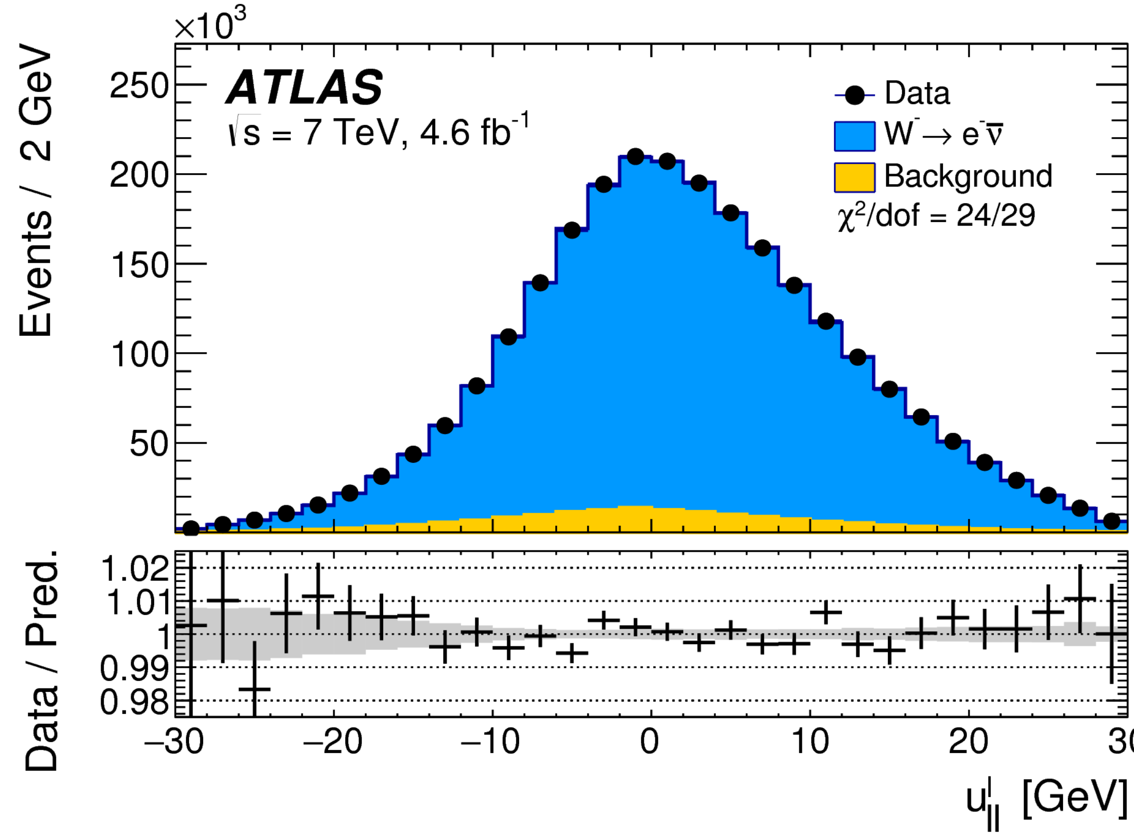
- QCD corrections:
  - Large impact on $p_T(W)$ distributions
  - Polarisation
  - Rapidity
  - Taking the best from NNLO pQCD + PS

W-boson charge Kinematic distribution	W^+ p_T^ℓ	 m_T	W^- p_T^ℓ	 m_T	Combined 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

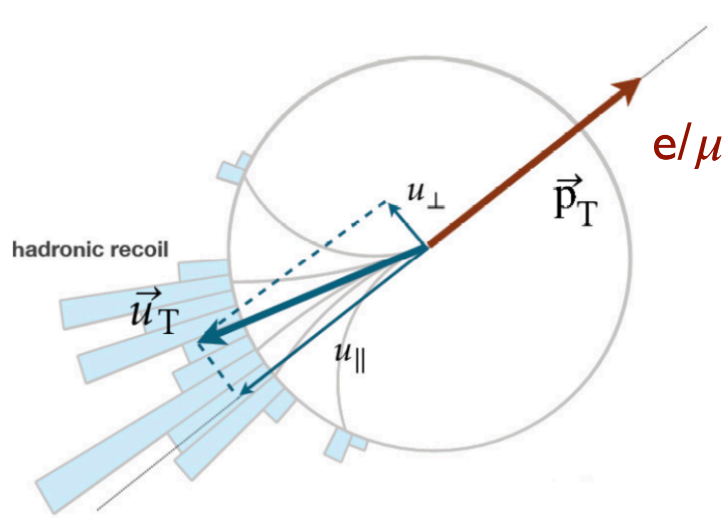
Control of W observables

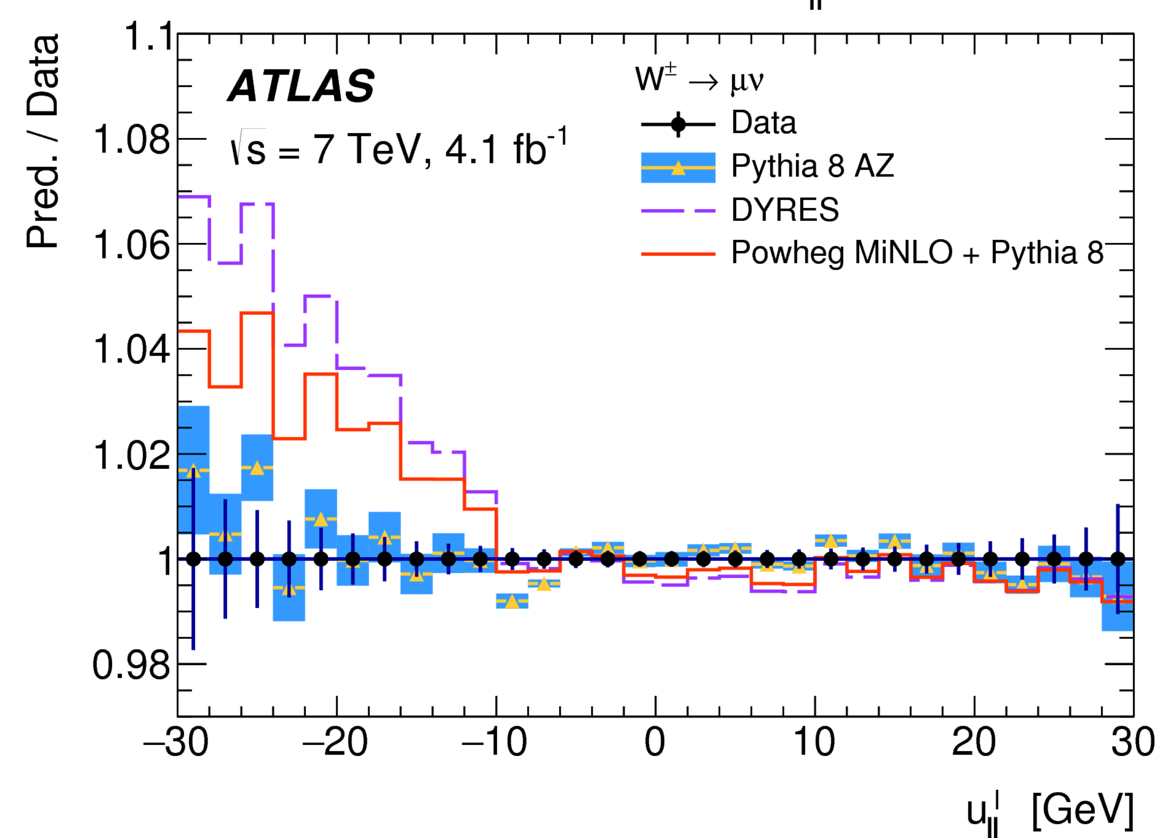
- Although difficult experimentally (calibrated in-situ from Z events), the recoil is very sensitive to the underlying $p_T(W)$ distribution





- In particular the region <0 disfavours strongly Powheg MiNLO and DYRES Pythia8 tuned to Z seems Ok





Understanding of Z

- Another way to assess the quality of the modelling of the $p_T(W)$ distribution is to look at what works and what is to be improved for the Z
- Factorising the Drell-Yan production cross-section from the decay kinematics

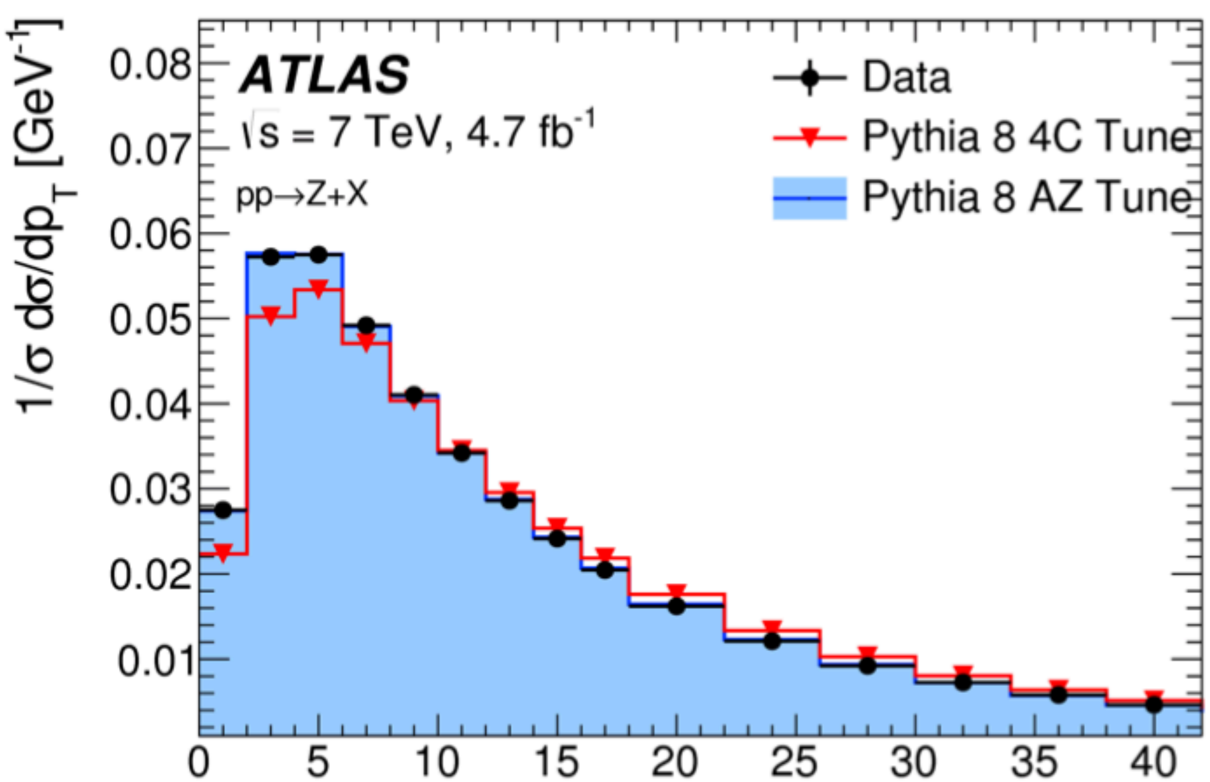
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower

- For instance, A_0-A_2 is non-zero starting from NNLO QCD



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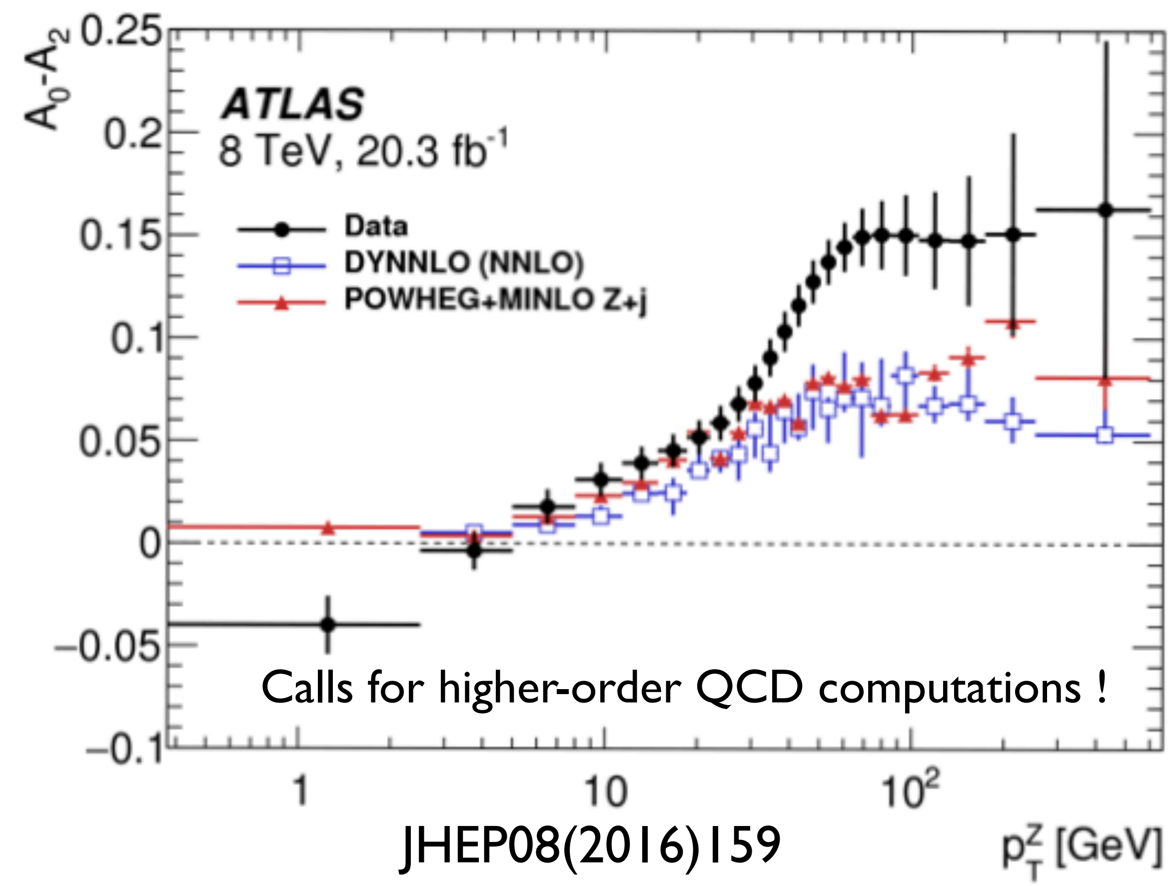

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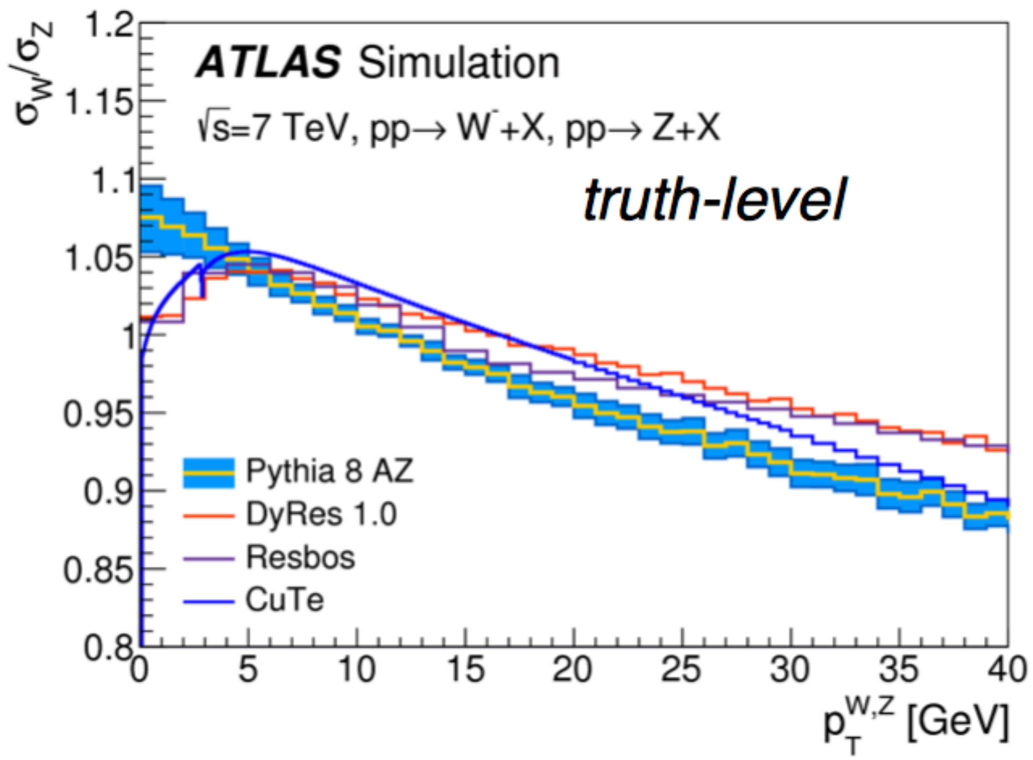
- May be possible to do a similar A_i measurement on W data ?

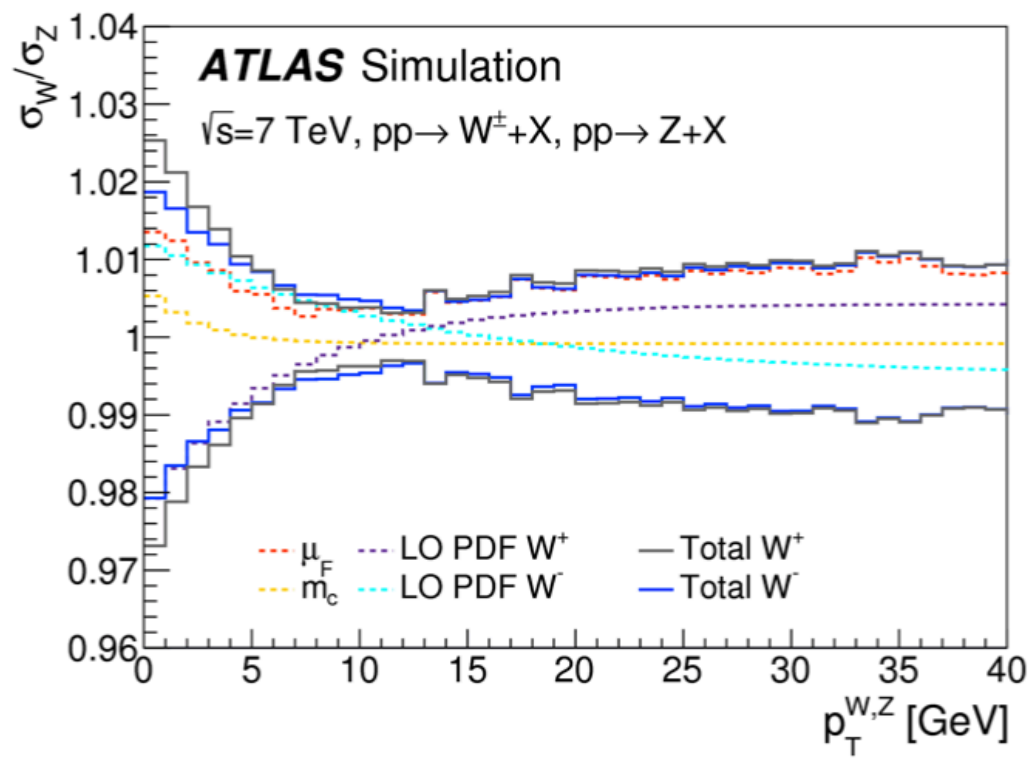
(Eur.Phys.J. C77 (2017) no.2, 111)

Extrapolating from the Z

- The accuracy of Z data can be propagated as an uncertainty on m_W
  - Pythia8 AZ tune determined on $p_T(Z)$ data
  - Extrapolation to W considering relative variations of the W and Z p_T distributions
    - Would benefit from new $p_T(Z)$ and W/Z p_T ratio measurements with more / low pile-up statistics

- Higher-order QCD expected to be mostly correlated between W and Z ?
- Heavy flavours for example introduce some decorrelation between Z and W





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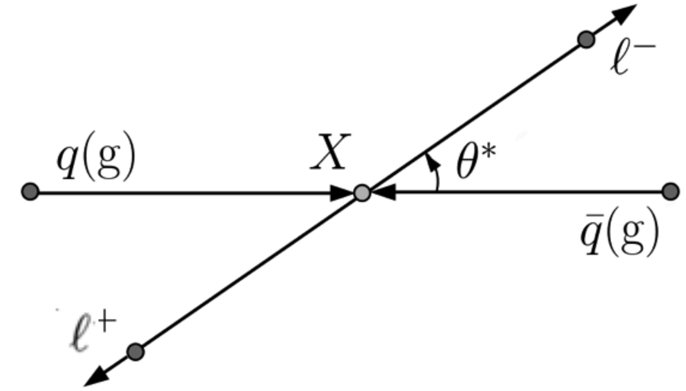
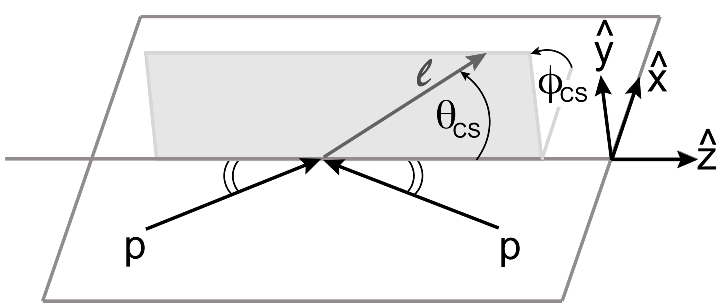
$\sin^2\theta_W$ and A_{FB}



- At tree level $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$, intrinsically linked to m_W !
- DY cross-section vs the scattering angle $\frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}\mathcal{A}(1+\cos^2\theta) + \mathcal{B}\cos\theta\right]$.

  Z/γ^* & V-A interference → linear term leading to forward-backward asymmetry
  - The V-A interference contribution depends on $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$
  - The Z/γ^* interference is proportional to $(s-m_Z^2)$
- LHC beams are « symmetric » → ambiguous direction of incoming quark

  → dilution of A_{FB} (largest for central rapidity, decreasing with $|y_Z|$)

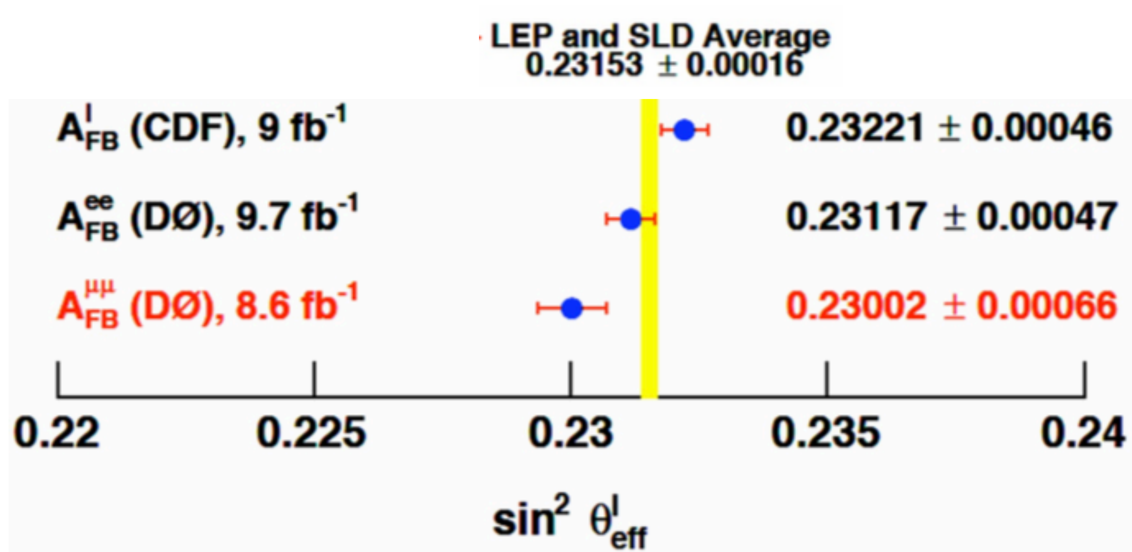


$\cos\theta^*_{CS} \geq 0$ F

$\cos\theta^*_{CS} < 0$ B

→ $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ changes sign at the Z pole

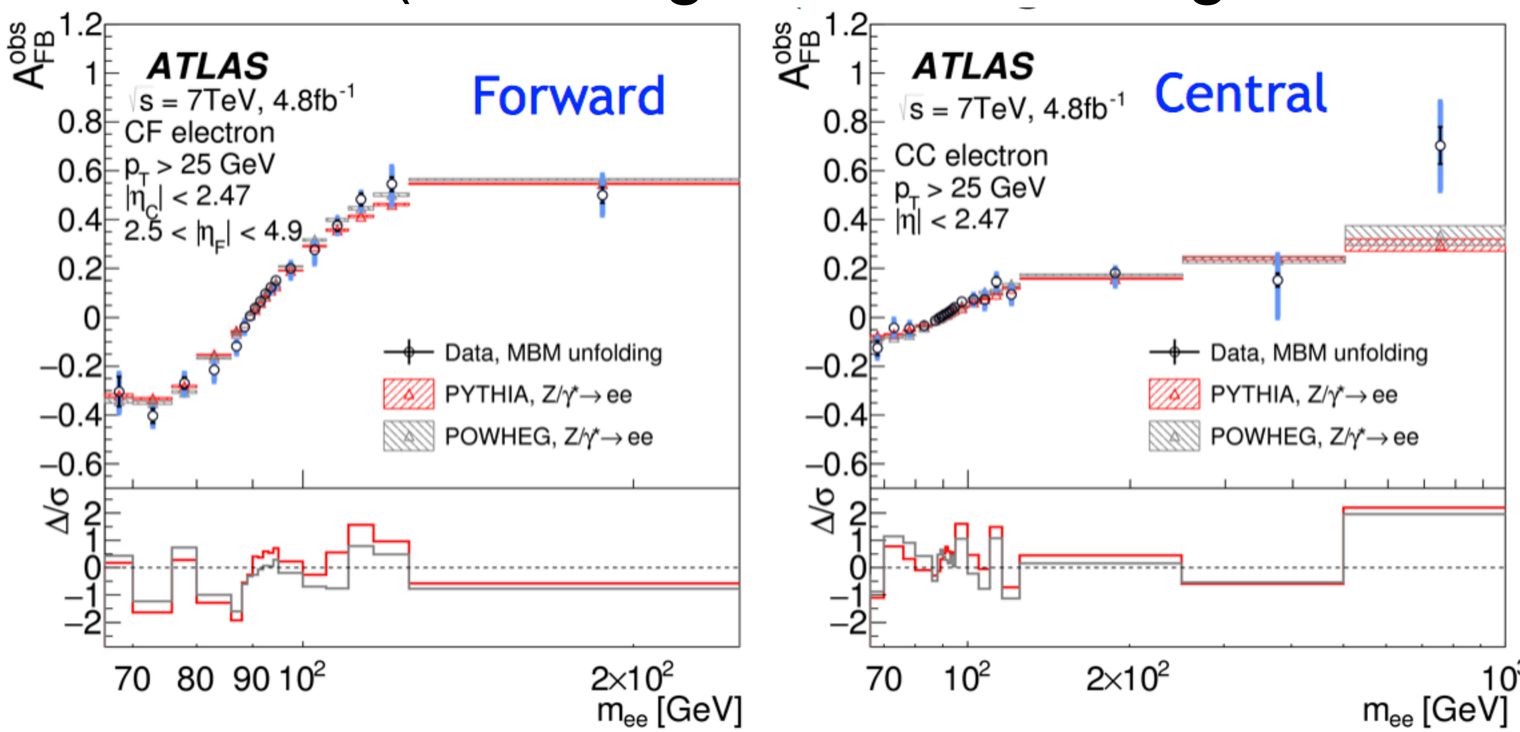
- Even more important measurement to make at LHC that Tevatron ones have some tension



ATLAS Z A_{FB}

JHEP 1509 (2015) 049

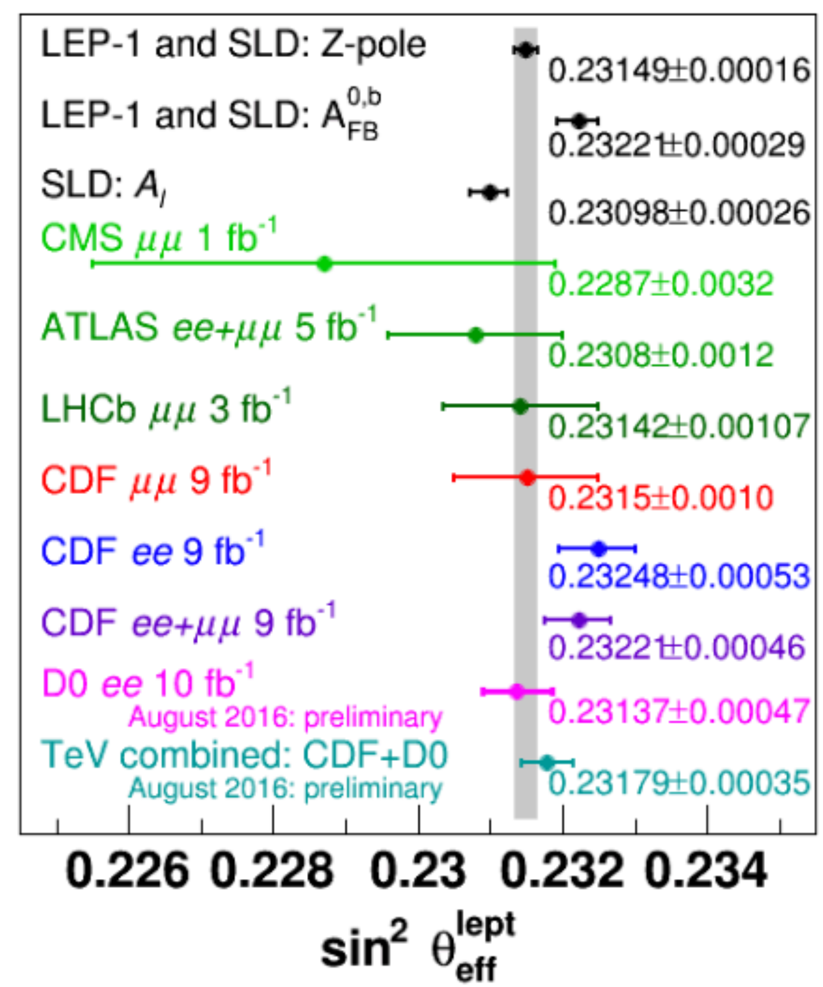
- ATLAS did such measurement in the 7 TeV dataset using both muons and electrons (including the forward region to be more sensitive)



	$\sin^2\theta^{\text{lept}}_{\text{eff}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

- Leading systematic from the PDF

Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2



- Still some large stat uncertainties (will decrease) but already comparable result !

Remember the A_i ?

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

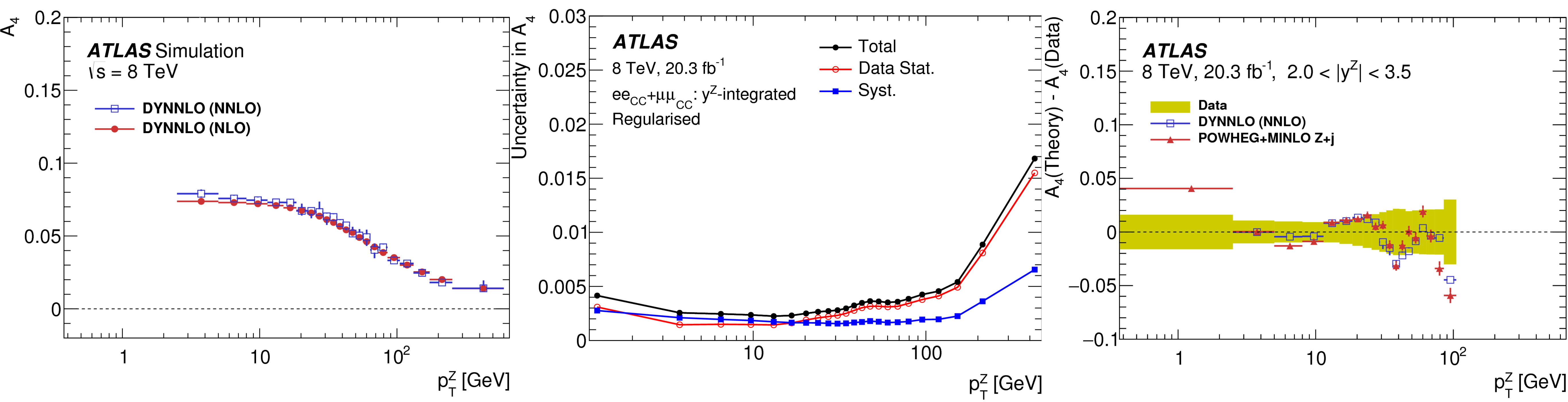
Breit-Wigner

NNLO pQCD

Parton Shower

A_i	Polynomials P_i
A_0	$P_0 = [1-3\cos^2\theta]/2$
A_1	$P_1 = \sin 2\theta \cos\varphi$
A_2	$P_2 = [\sin^2\theta \cos 2\varphi]/2$
A_3	$P_3 = \sin\theta \cos\varphi$
A_4	$P_4 = \cos\theta$
A_5	$P_5 = \sin^2\theta \sin 2\varphi$
A_6	$P_6 = \sin 2\theta \sin\varphi$
A_7	$P_7 = \sin\theta \sin\varphi$

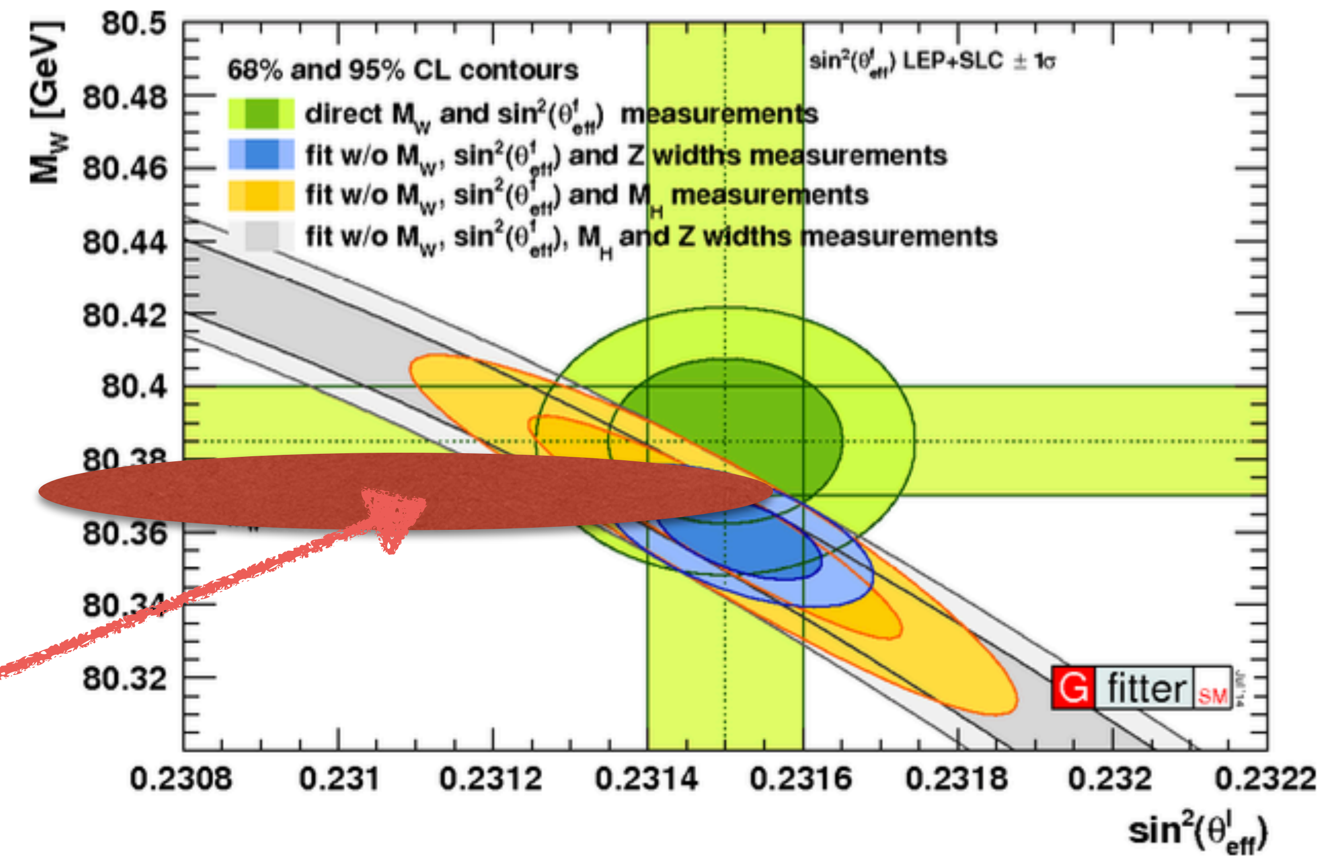
- $\cos\theta$ linear term multiplied in the decomposition by A_4
- Value for A_4 driven by the Z/γ^* interference far from the Z pole
  - But pure Z component has some sensitivity on $\sin^2\theta_W$
- Although these are same events, the methodology is very different from the A_{FB}



- Can potentially reach some interesting precision using the power of the forward region and more statistics

Conclusions

- A loooooot of very precise measurements have already been done by the ATLAS Collaboration to probe the Electroweak sector
- Some more needs to be done or redone with a larger dataset in order to serve the W mass measurement
- New techniques and methodologies are being developed to probe fundamentals quantities such as $\sin^2\theta_W$
  - Collaboration between experimentalists and theorists is crucial on this ! In particular to help the making of better Monte Carlo programs
- Stay tuned!



Next ATLAS result ?