Precision measurements of inclusive and differential Drell-Yan cross sections with the ATLAS detector

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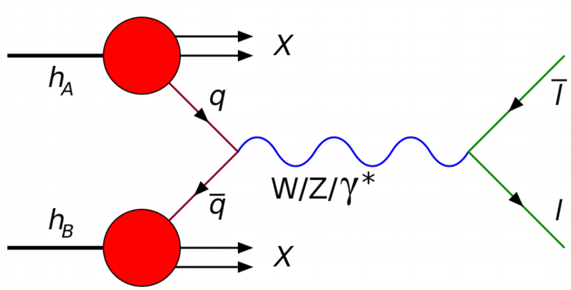
Outline

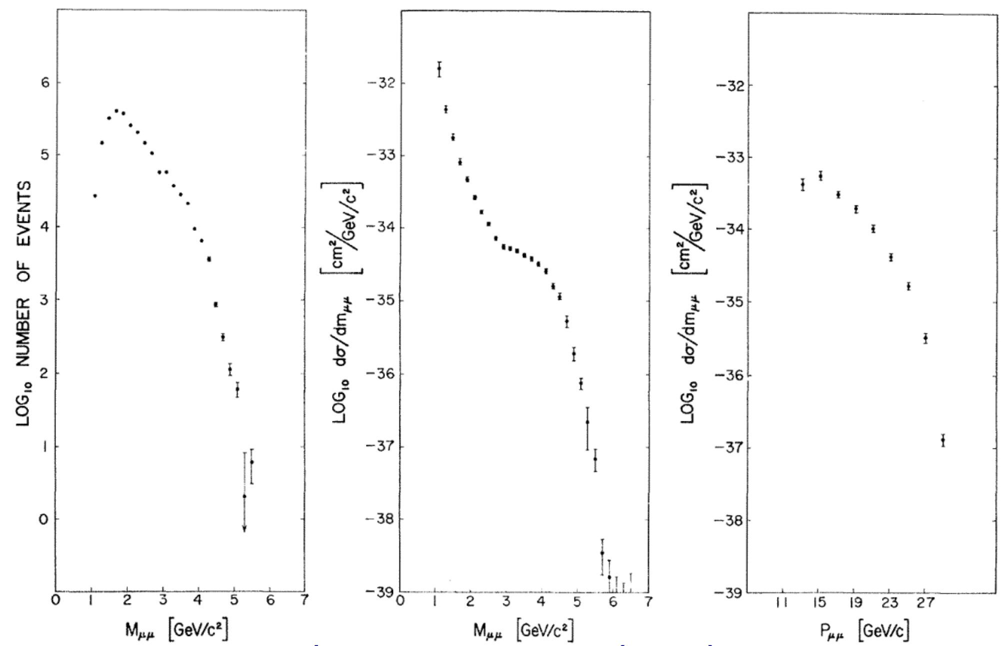
- Introduction and motivation for precision measurements of Drell-Yan processes
- W and Z inclusive cross section measurements
- Differential DY cross sections:
  - Measurements of Z pT and ϕ^*_η
  - Measurements of Angular coefficients in Z
  - High mass Drell Yan

Introduction

- The Drell Yan process denotes the: “Massive lepton pair production in hadron-hadron collisions at high energies” Phys. Rev.Lett.25, 316 (1970)
- The Drell-Yan mechanism was proposed and observed in 1970. It was a milestone in the building of QCD as the theory of the strong interation
- In 1983 lead to the discovery of W and Z bosons, which confirmed the theory of the electroweak unification



After 45 years, why is this process still of interest and what can we learn from it?



Phys. Rev. Lett. 25 (1970) 1523

Motivation

The Drell Yan process at the LHC nowadays allows:

- Stress testing of the factorization theorem at higher energies
- Probing the proton PDFs, by providing valuable information on the d-valence PDF and the dv/uv ratio, and unique information of the light sea decomposititon, in particular on the s/d ratio
- Measuring fundamental electroweak parameters, as the mass of the W boson, and the weak-mixing angle
- Searching for new physics in high dilepton mass final states

The measurements presented in this talk are crucial inputs for precise measurements of the EW parameters, see f.i. Jakub Cuth's talk on W mass

W and Z production cross section at 13 TeV

- Integrated luminosity L = 81 pb^{-1}
- Event selection: ℓ = e, mu

  Z → $\ell\ell$: pT(ℓ)> 25; $|\eta(\ell)|$ < 2.5; 66 < $m\ell\ell$ < 116

  W → $\ell\nu$: pT(ℓ) > 25; $|\eta(\ell)|$ < 2.5; pT(ν) > 25; mT > 50

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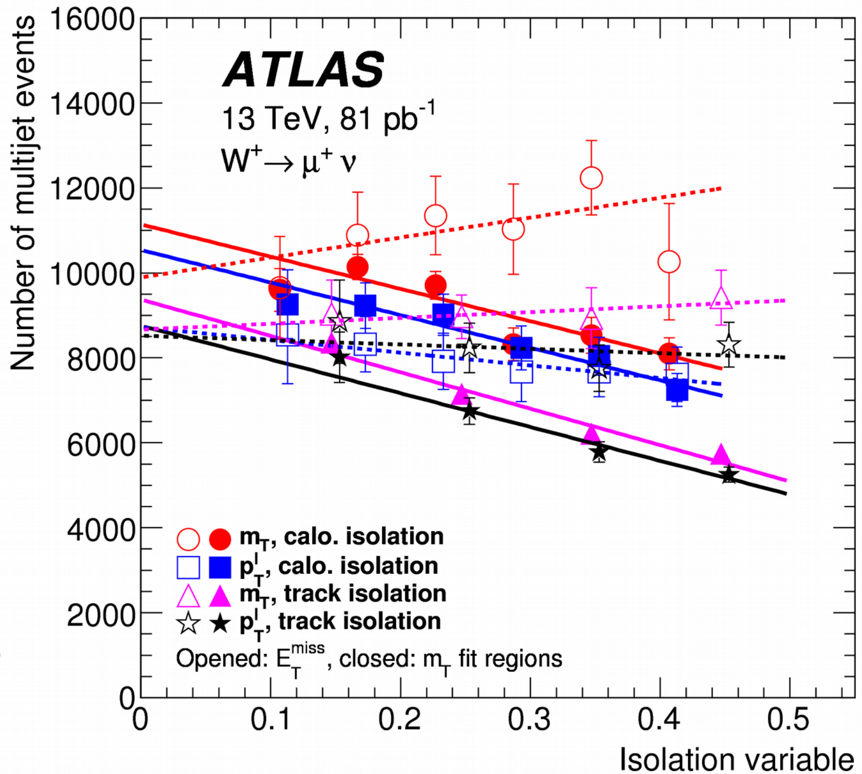
- Multijet background in W events is estimated by extrapolating the anti-isolation requirement to the signal region



- Dominant uncertainties are:

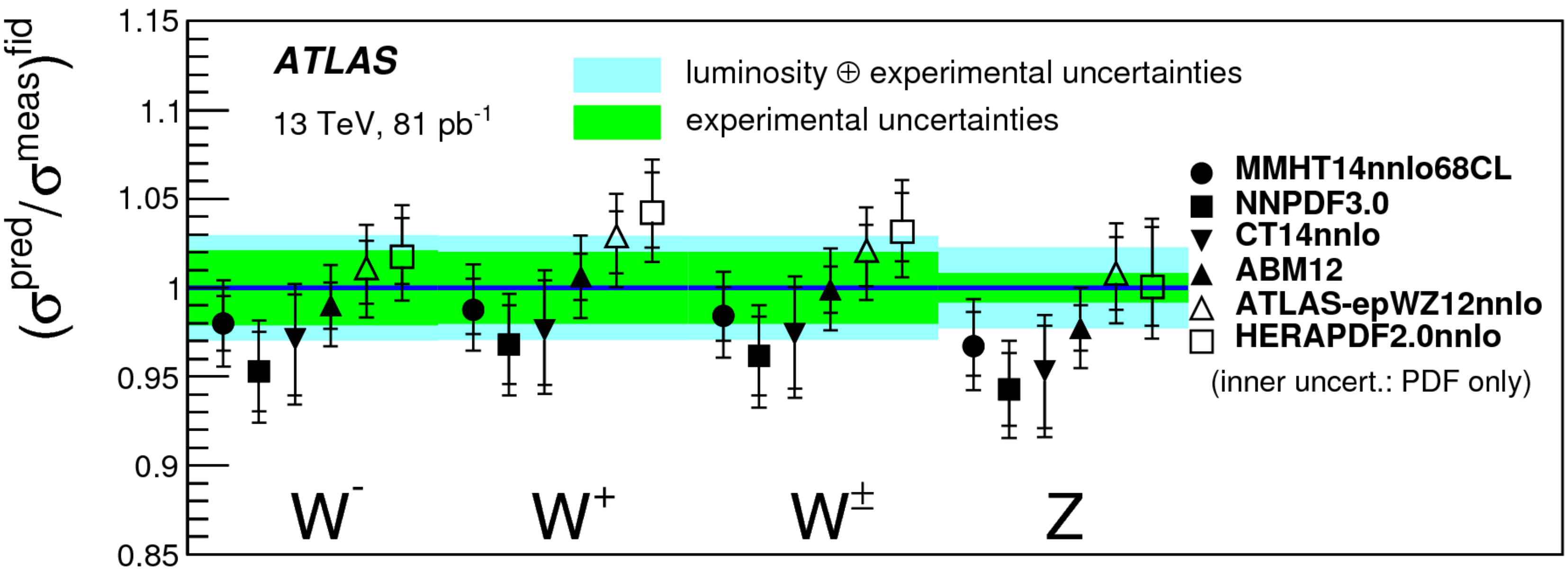
  Lepton ID (Z) : 0.9%

  JES and JER for ETmiss (W): 1.7%

  Luminosity (Common): 2.1%

W and Z production cross section at 13 TeV

- Total W and Z cross sections are compared to various PDF sets



- Provides valuable constraints for the determination of PDFs

- Uncertainties:

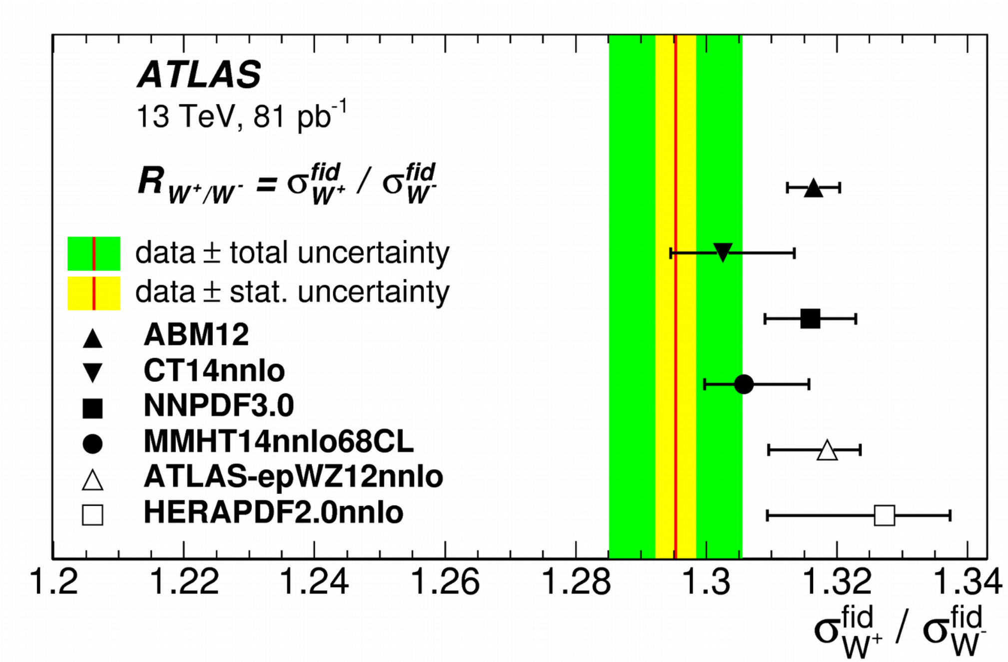
  Luminosity: 2.1%

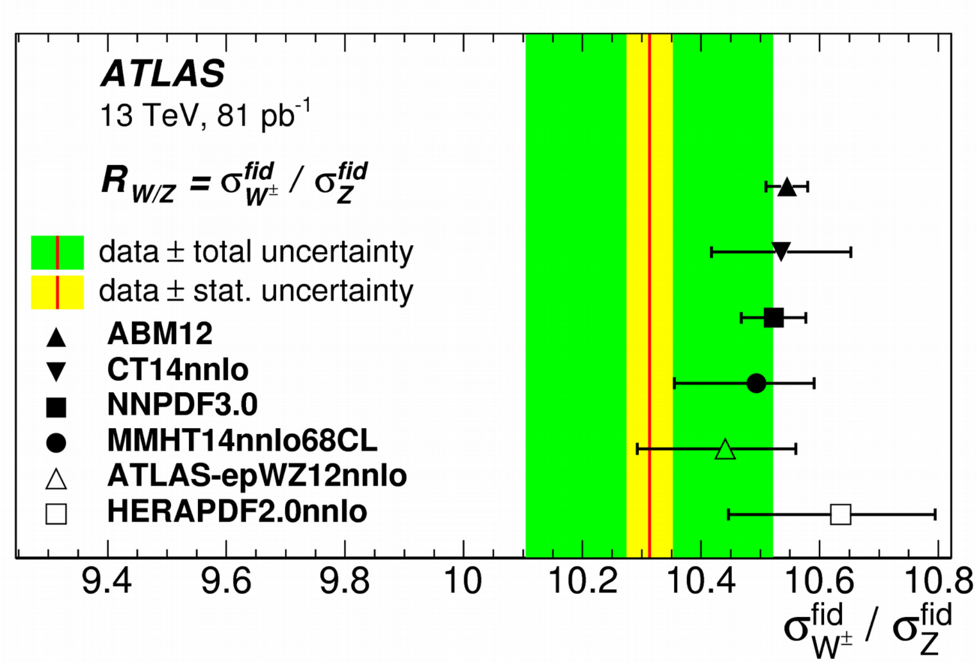
  experimental W: ~2%

  experimental Z: ~1%

W and Z production cross section at 13 TeV

- Ratios of W/Z and W+/W- cross sections are a sensitive probe of PDFs
- Luminosity uncertainty cancels in the ratio





- The W+/W- ratio is sensitive to the uv/dv ratio at low Bjorken-x
- The W/Z ratio is sensitive to the strange PDF

  The results show a mild preference for unsuppressed strangeness, that is s/d ~ 1 at low Bjorken-x

Anatomy of DY differential cross sections

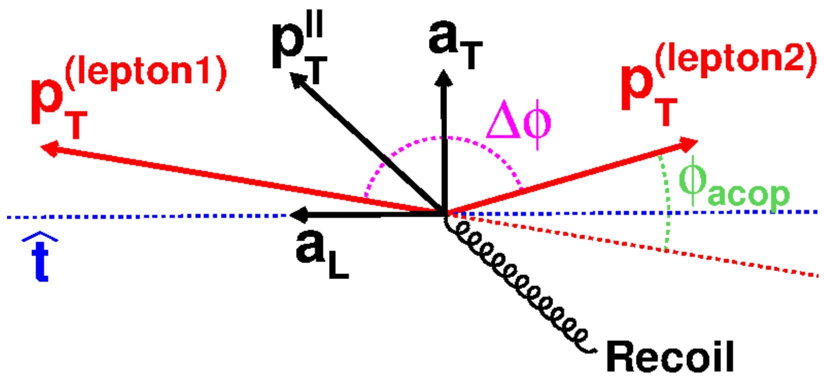
- A convenient way of expressing the radiation-inclusive DY cross section is through the factorisation of the production dynamic and the decay kinematic properties of the dilepton system

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

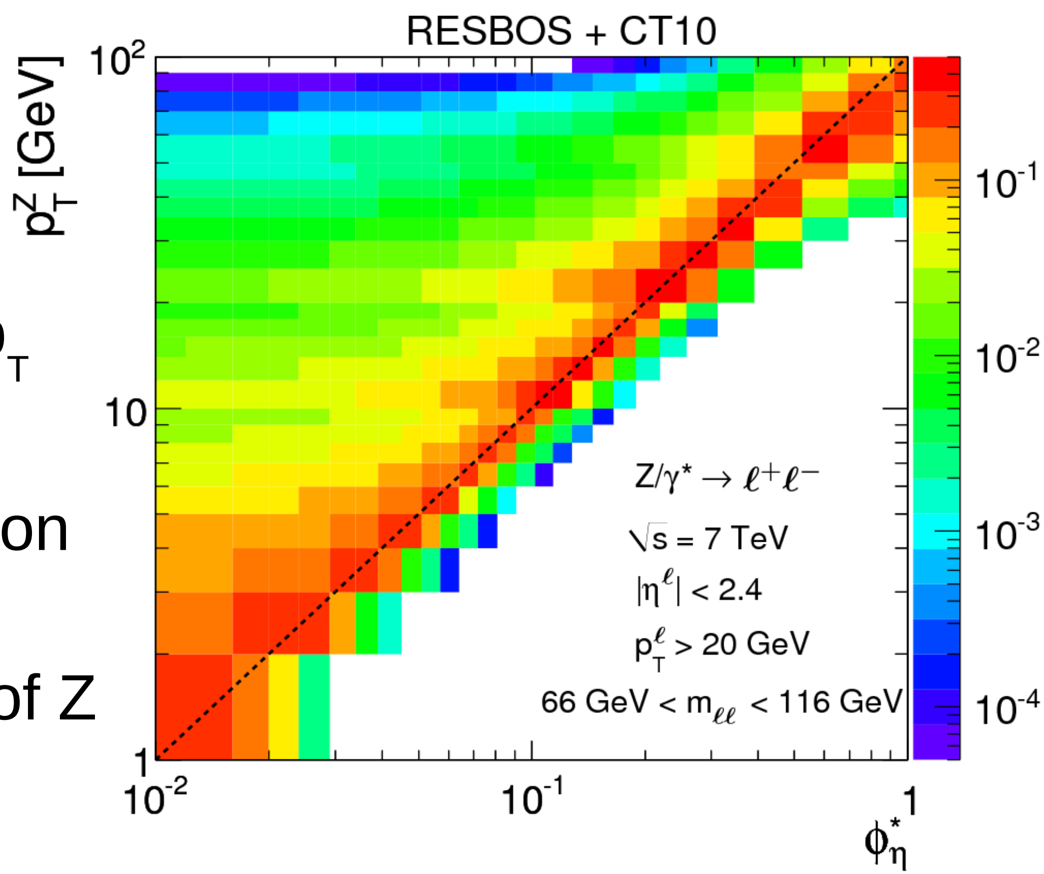
- dσ/dy allows probing of the longitudinal dynamic (PDFs)
- dσ/dpt allows probing of the transerve dynamic of non-perturbative and perturbative QCD
- dσ/dm allows probing of PDFs, and searching for new physics
- The Ai coefficients allows testing of the QCD and EW helicity structure, for instance the FB asymmetry induced by the V-A interference, which is sensitive to $\sin^2\theta_W$, and of violation of the Lam-Tung relation in QCD

Transverse momentum of Z bosons at 8 TeV

- Measurement of $d\sigma/dpt$ and $d\sigma/d\phi^*_\eta$
- Integrated luminosity L = 20.3 fb^{-1}



$$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$$



- Z ϕ^*_η is strongly correlated to Z p_T $\to \phi^*_\eta \sim p_T^Z / M_{ll}$
- Ideal for probing the low Z p_T region
- Measurement performed in bins of Z rapidity, and in bins of dilepton invariant mass, on- and off-peak

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Transverse momentum of Z bosons at 8 TeV

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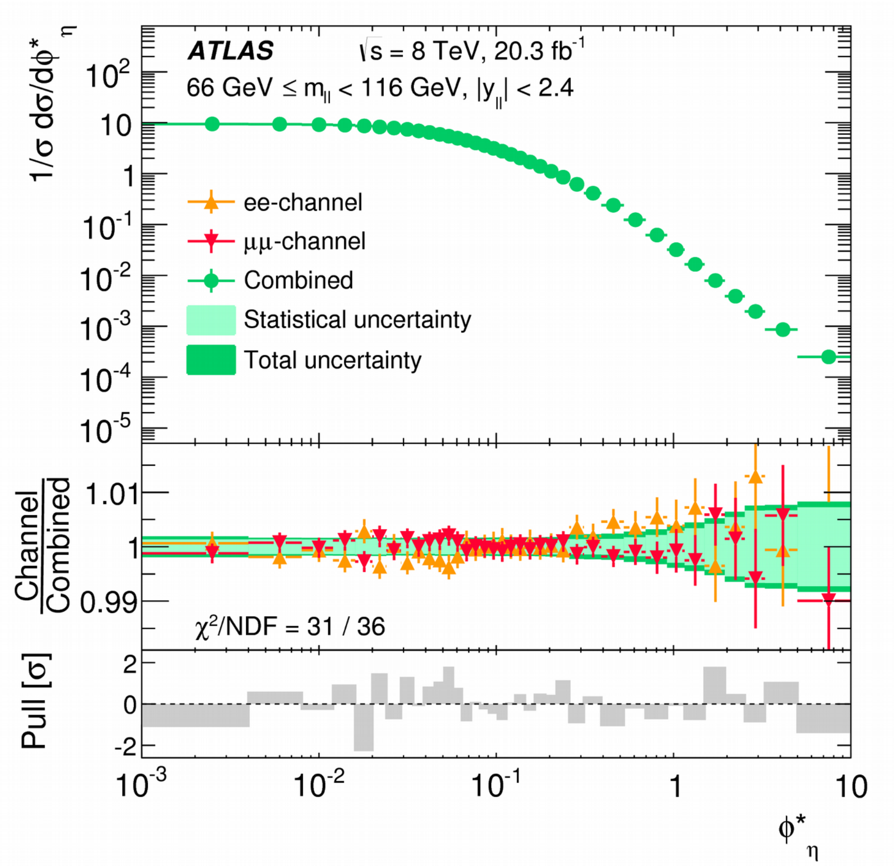
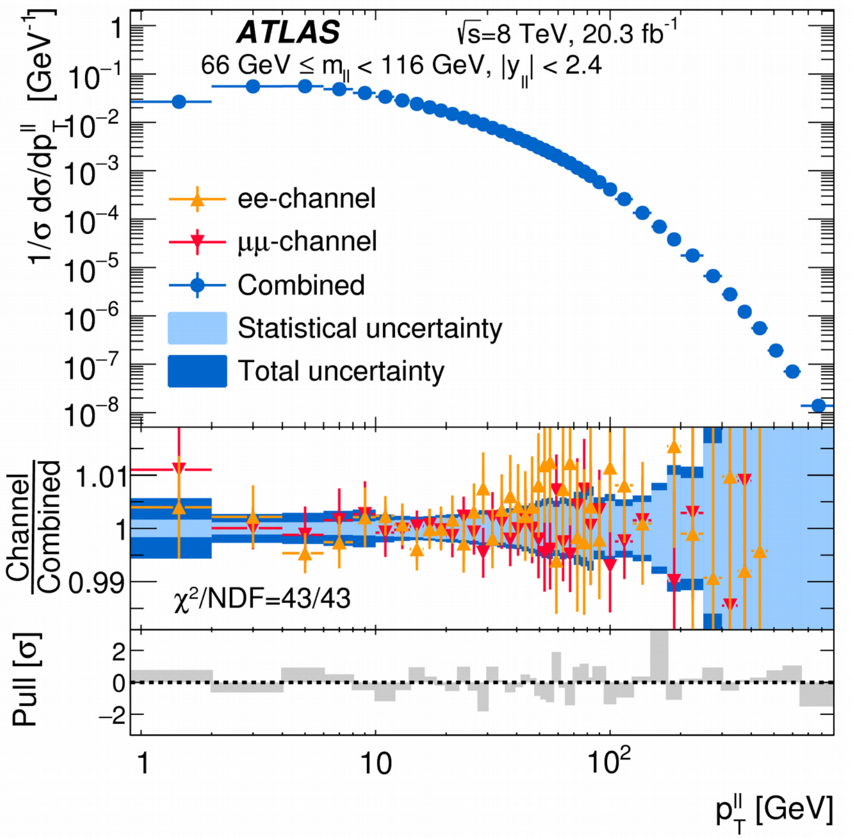
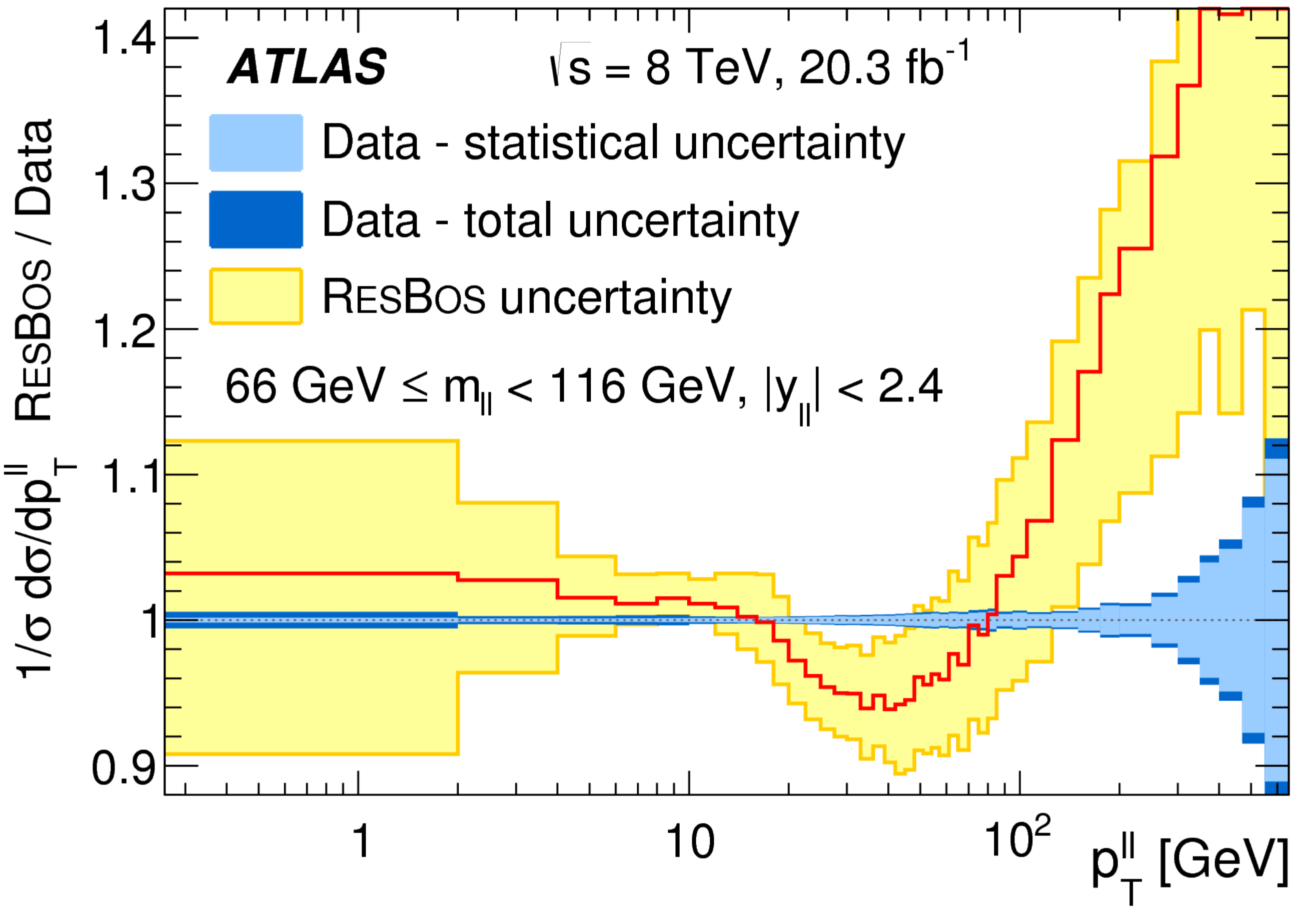




- Electron and muon decay channels are combined

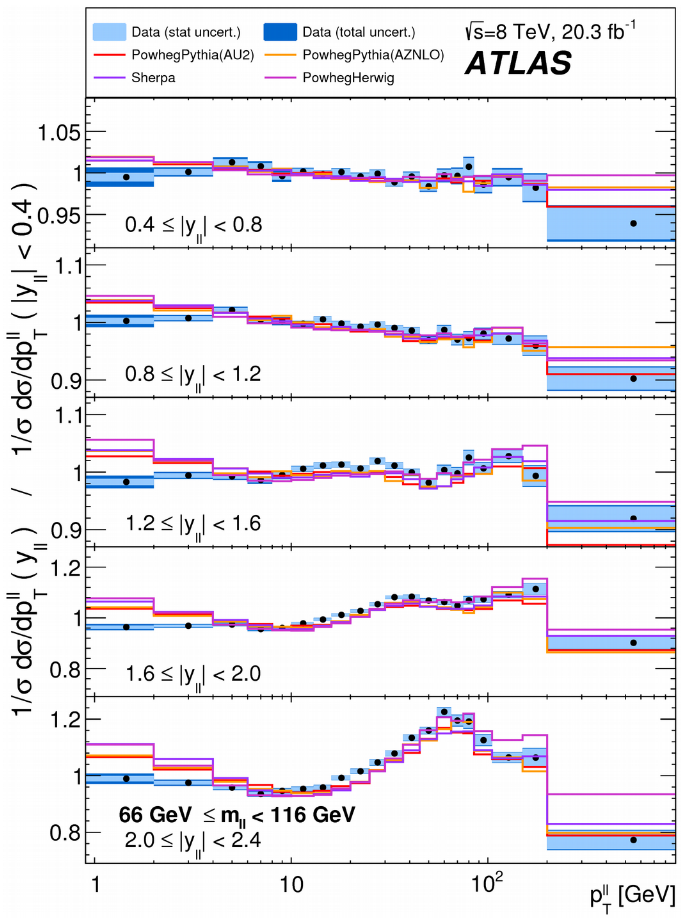
Transverse momentum of Z bosons at 8 TeV

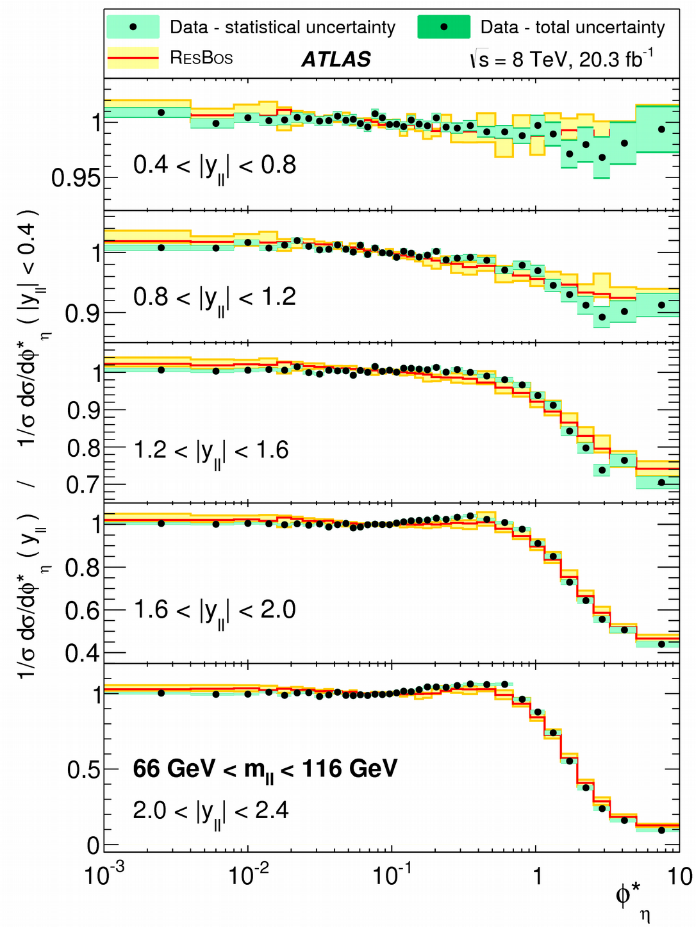


- Stringent probe of perturbative and non-perturbative QCD
- Typical accuracy for pT < 30 GeV: ~0.3-0.4%
- Highest pt bin reaches 650-900 GeV, with ~18% uncertainty

Transverse momentum of Z bosons at 8 TeV

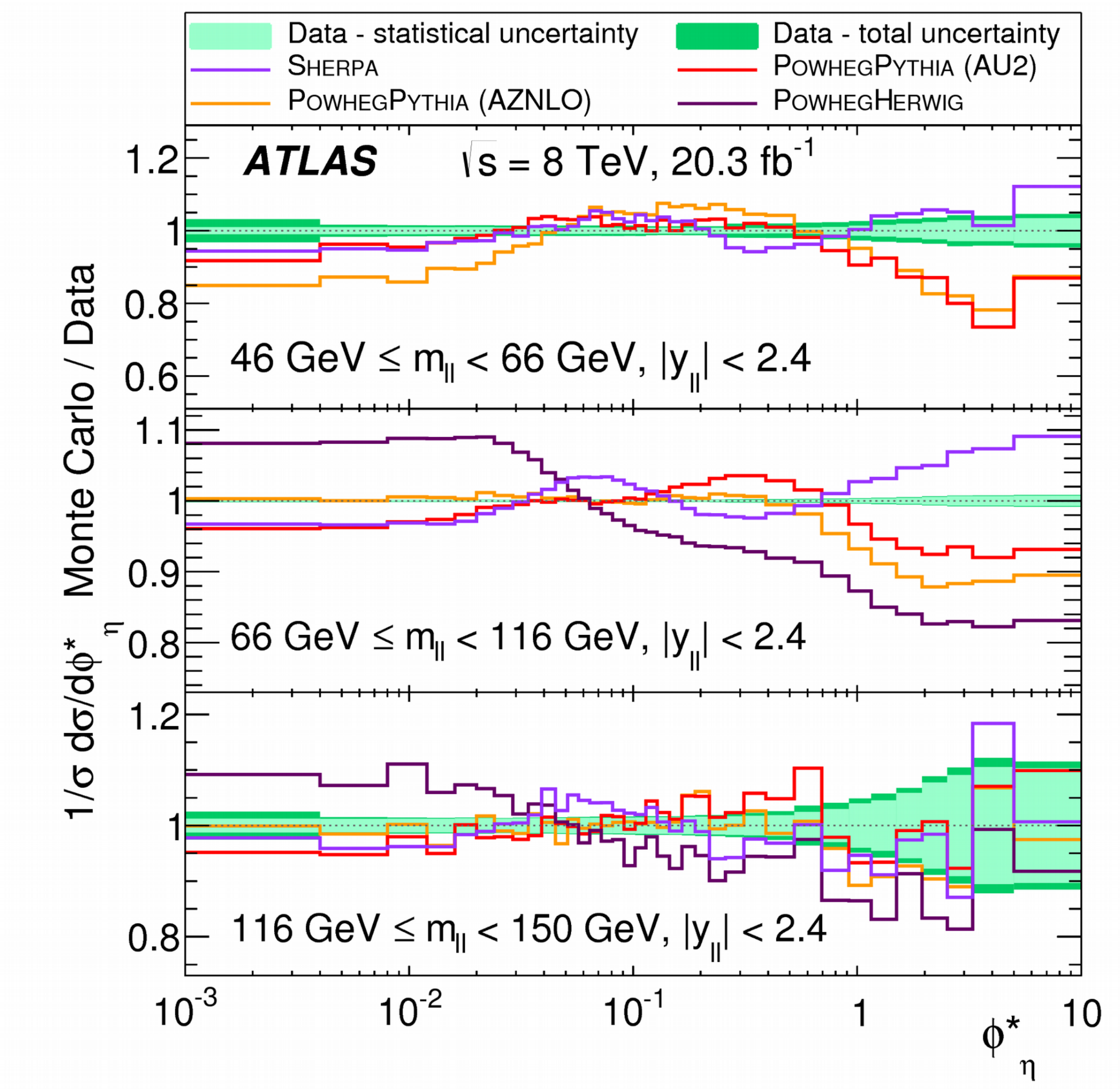
- Rapidity dependence of dσ/dpt and dσ/dφ*$_\eta$ allows to test low-x broadening, and the x-dependence of the non-perturbative transverse form factor





- Analytic resummation (RESBOS) and Pythia (not shown) describe the y-dependence well
- Powheg and Sherpa are in less good agreement

Transverse momentum of Z bosons at 8 TeV

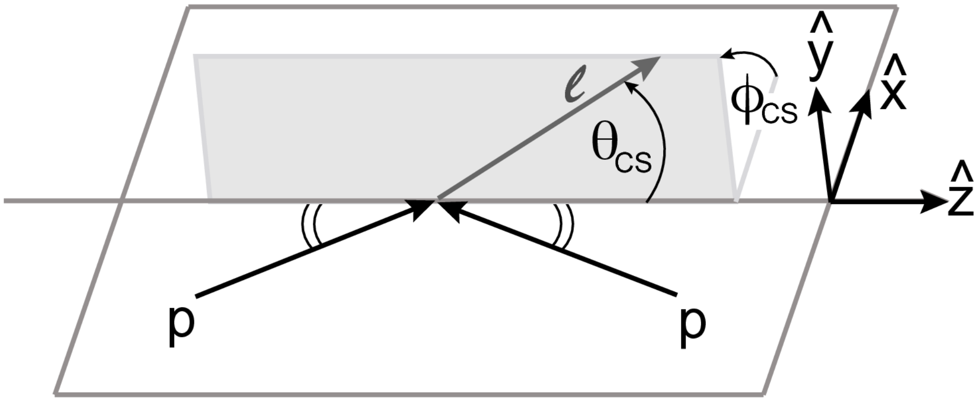


- On-peak and off-peak Z/γ^* production processes have different heavy-quark-initiated composition
- Invariant mass dependence of $d\sigma/dpt$ and $d\sigma/d\phi^*_\eta$ allows testing of the transverse momentum dynamic properties of heavy-flavour-initiated processes
- Crucial inputs for a precise measurement of the W mass at the LHC

Z-boson angular coefficients at 8 TeV

- The angular coefficients are ratios of helicity cross sections

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1 + \cos^2\theta + \sum_{i=0}^{7} A_i(y, p_T, m) P_i(\cos\theta, \phi)\right)$$

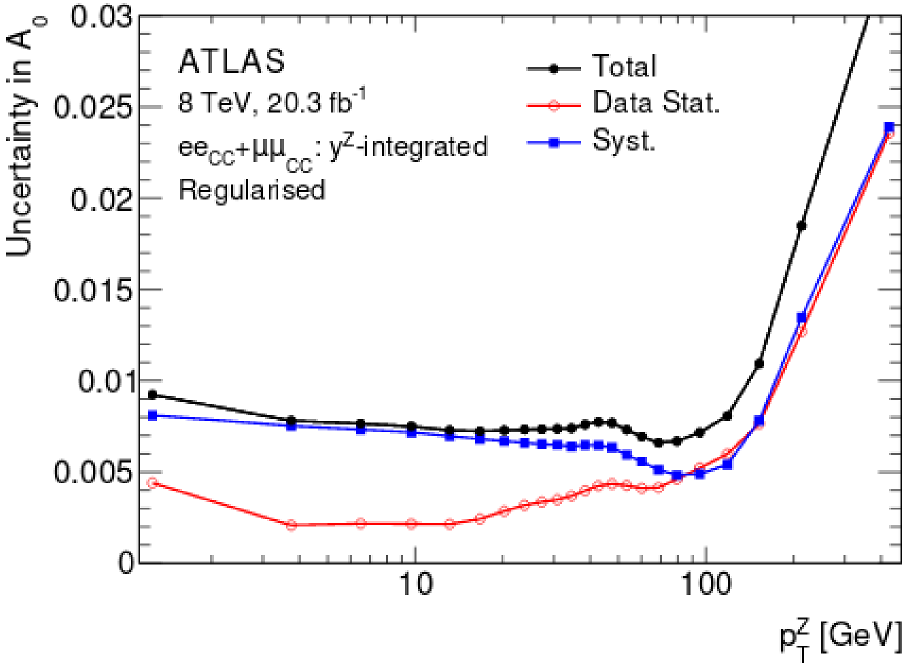


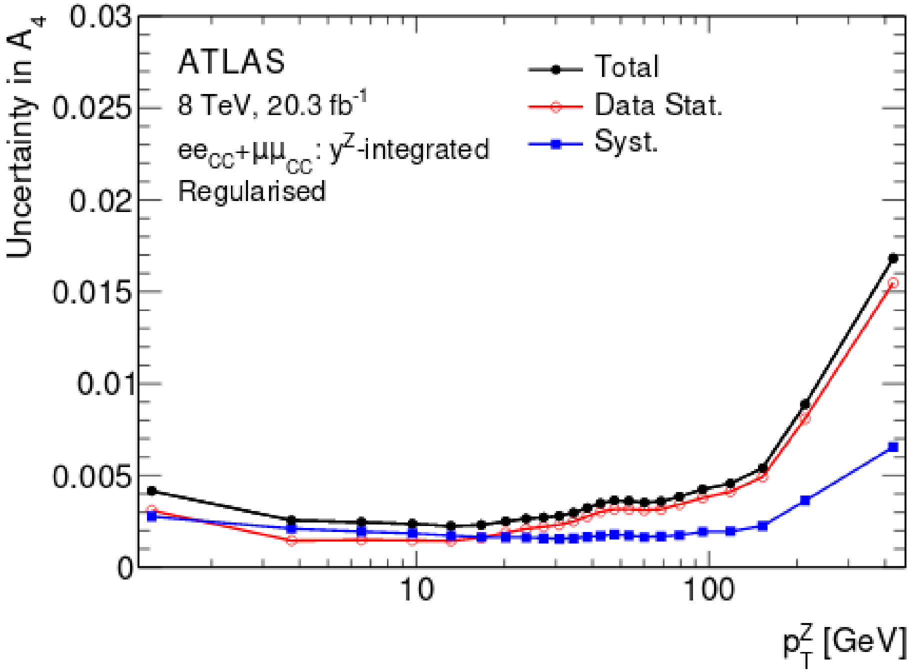
$$\begin{aligned}
P_0(\cos\theta,\phi) &= \frac{1}{2}(1 - 3\cos^2\theta) \\
P_1(\cos\theta,\phi) &= \sin 2\theta \cos\phi \\
P_2(\cos\theta,\phi) &= \frac{1}{2}\sin^2\theta\cos 2\phi \\
P_3(\cos\theta,\phi) &= \sin\theta\cos\phi \\
P_4(\cos\theta,\phi) &= \cos\theta \\
P_5(\cos\theta,\phi) &= \sin^2\theta\sin 2\phi \\
P_6(\cos\theta,\phi) &= \sin 2\theta\sin\phi \\
P_7(\cos\theta,\phi) &= \sin\theta\sin\phi
\end{aligned}$$

- Coefficients defined in the Collins-Soper frame

Z-boson angular coefficients at 8 TeV

- For the first time, all the 8 coefficients, including A5, A6, A7 have been measured
- The coefficients are extracted with a simultaneous likelihood fit based on 2D cosθ-ϕ templates
- An typical uncertainty of 1% or less is achieved in the range of pt from 0 to 100 GeV

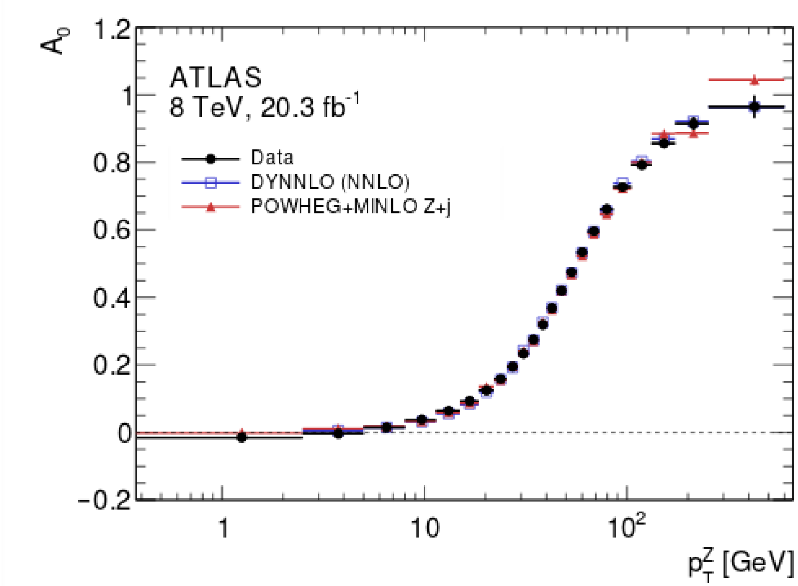


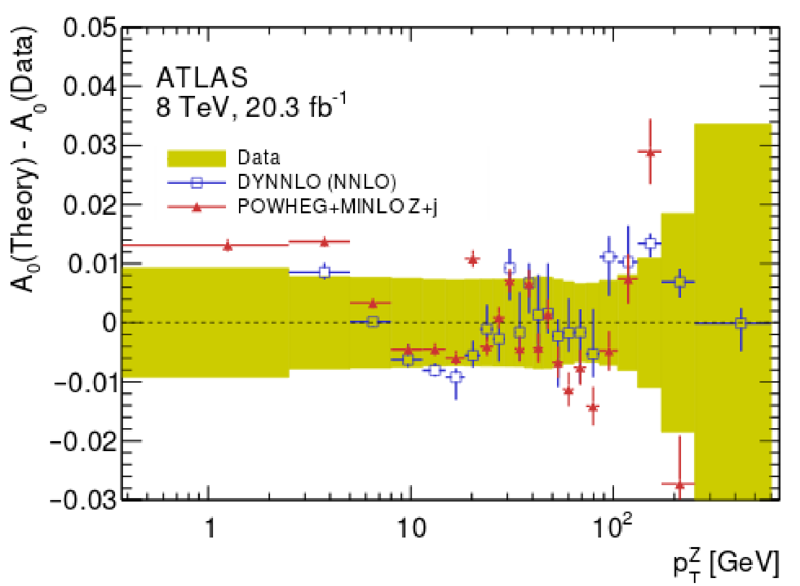


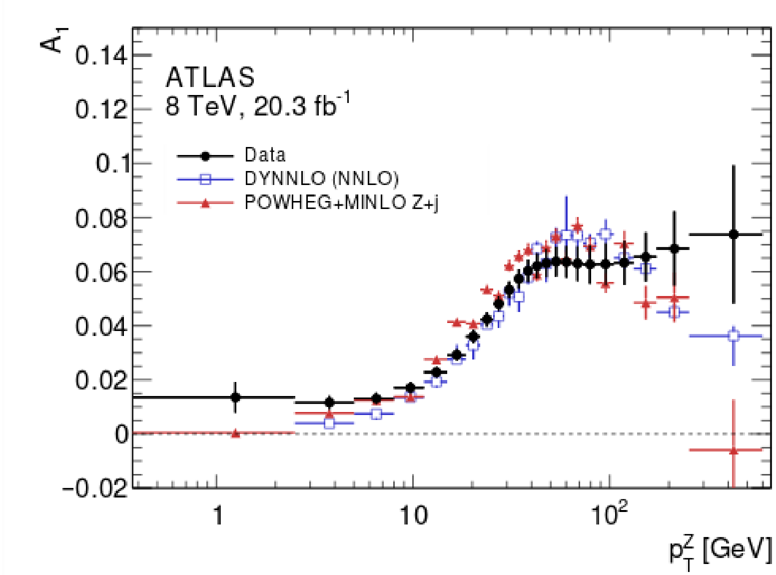
arXiv:1606.00689

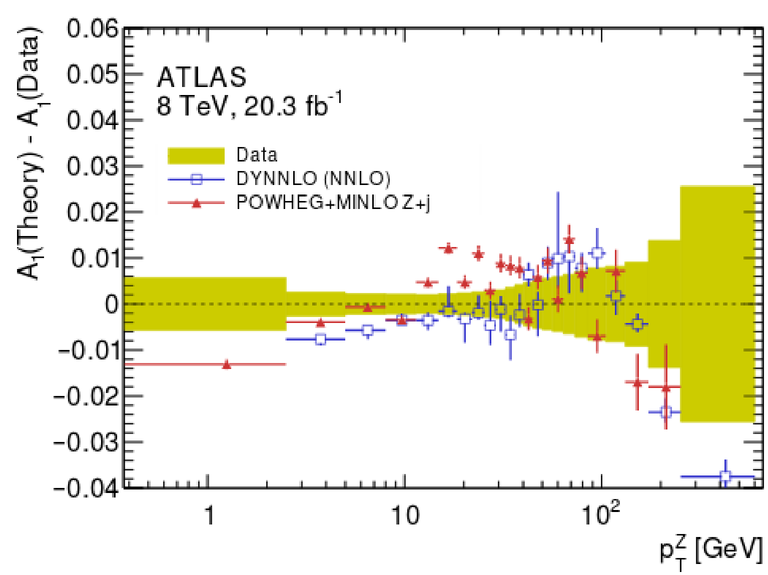
Z-boson angular coefficients at 8 TeV

- NNLO perturbative QCD predictions are in good agreement with the data for A0, A1



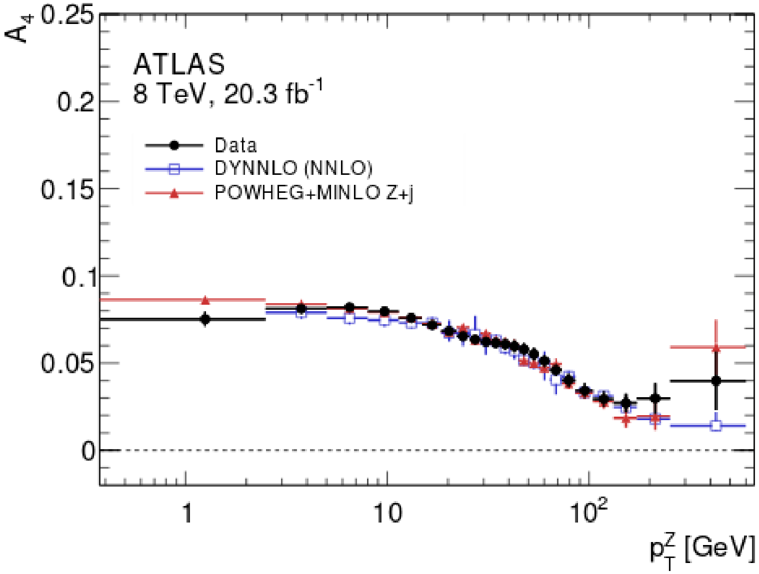


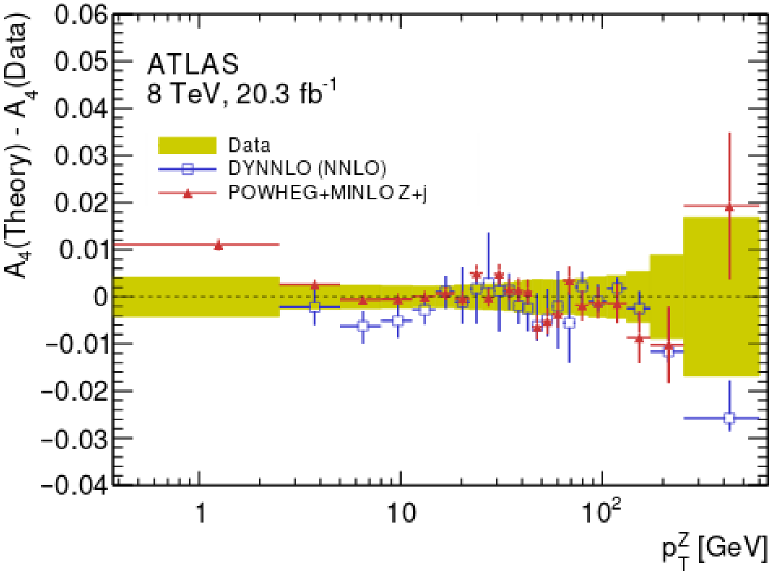


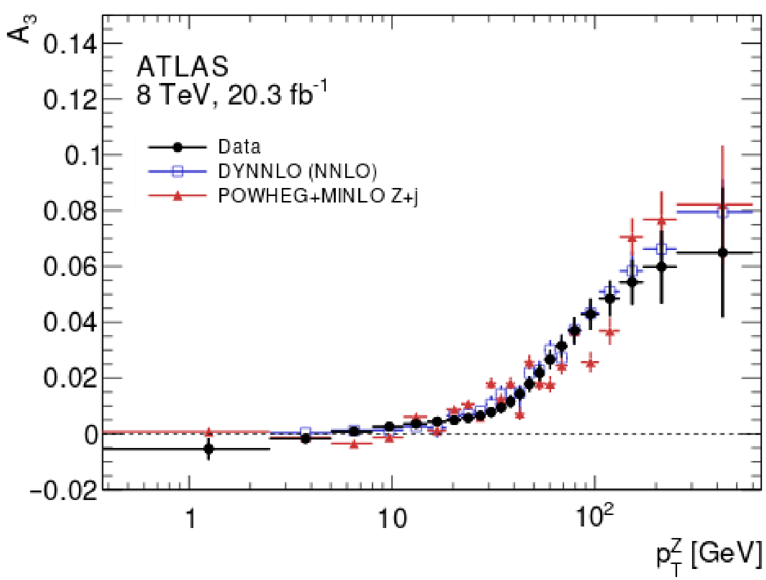


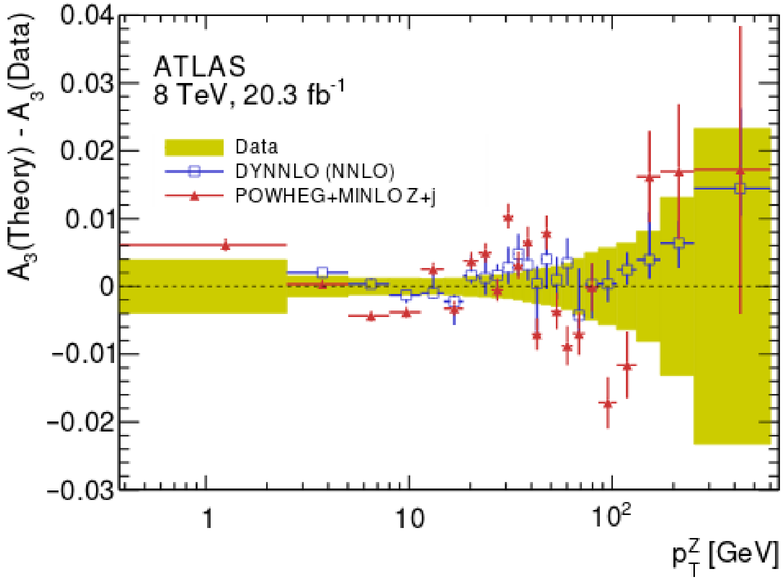
Z-boson angular coefficients at 8 TeV

- NNLO perturbative QCD predictions are in good agreement with the data for A3, A4. These coefficients are sensititive to $\sin^2\theta_W$



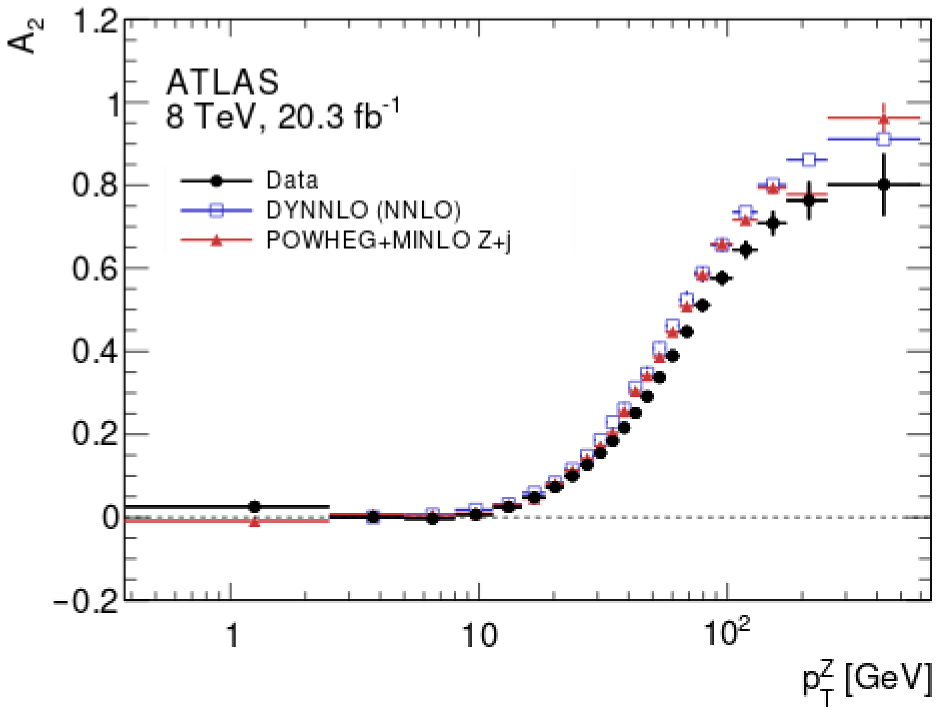


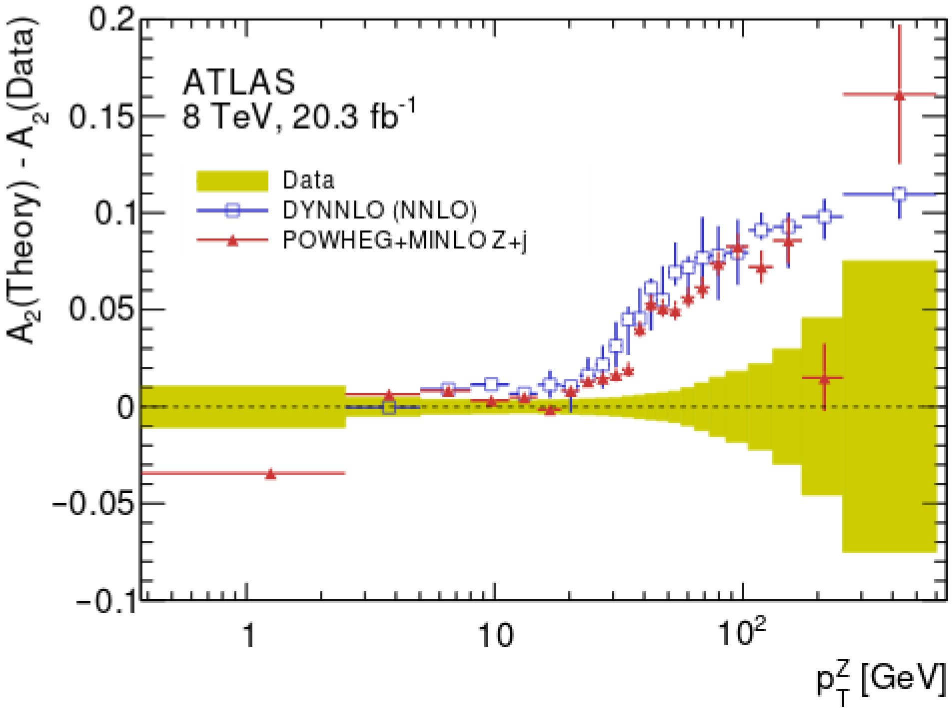




Z-boson angular coefficients at 8 TeV

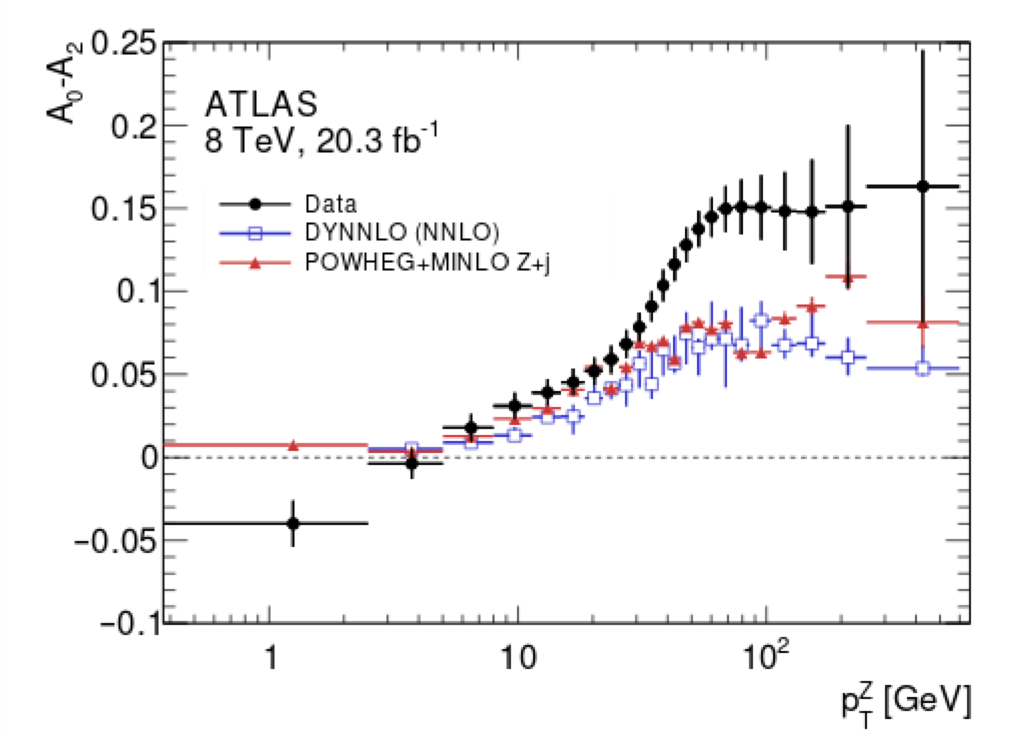
- Some disagreement at very low and at high pt between NNLO perturbative QCD predictions and data for A2

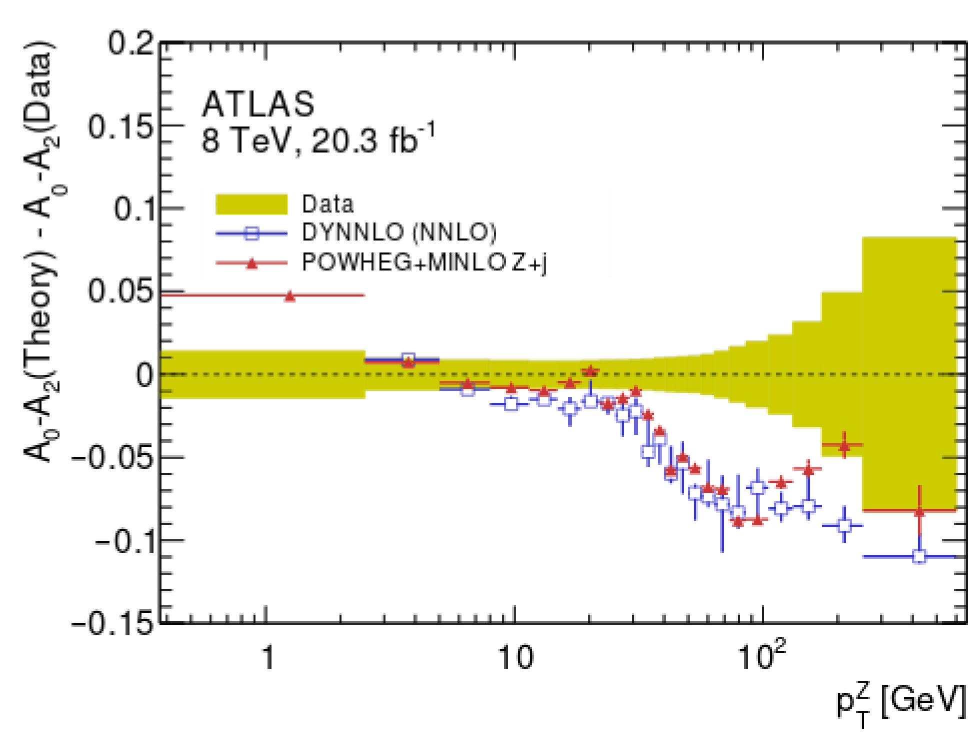




Z-boson angular coefficients at 8 TeV

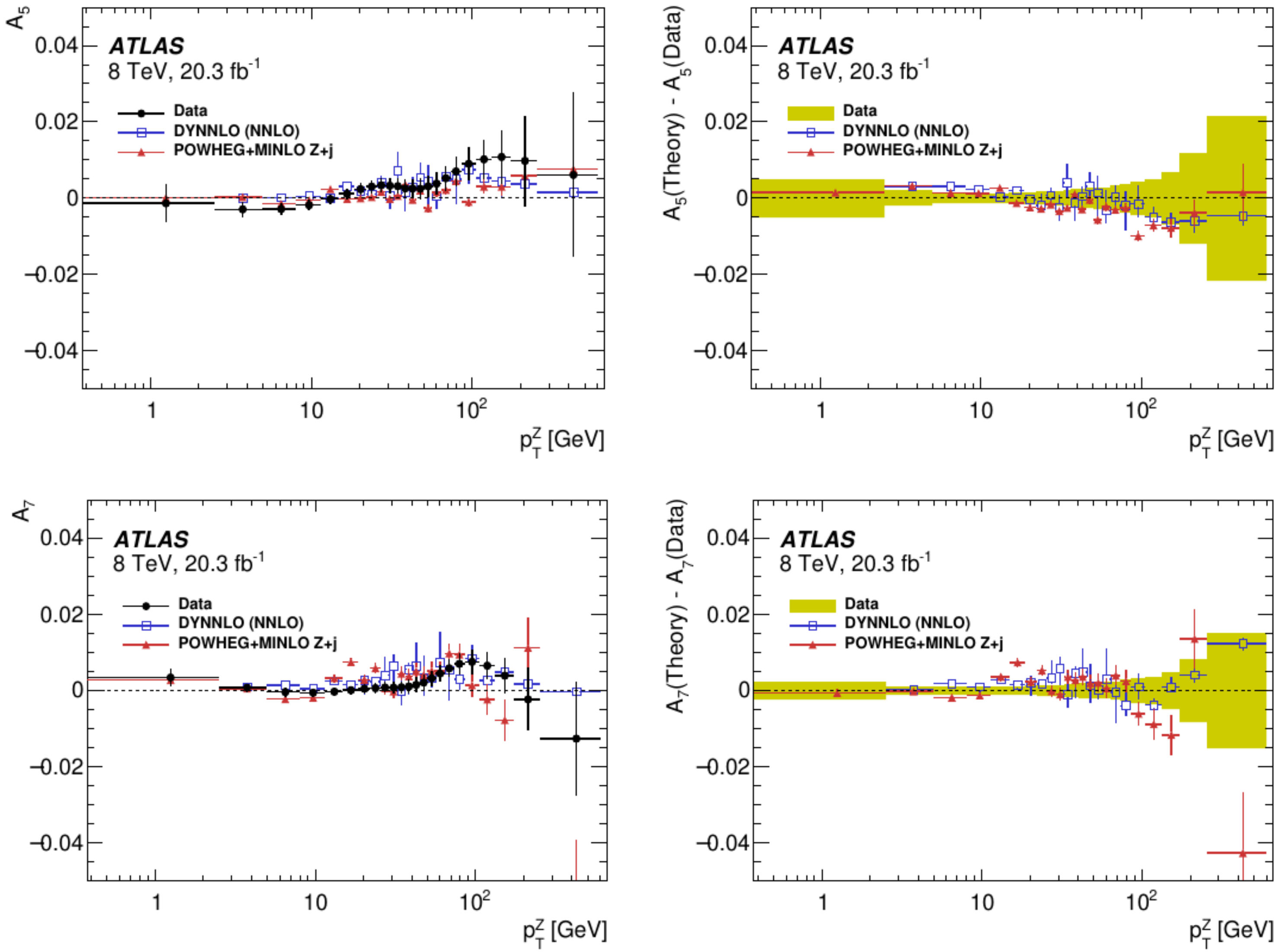
- The Lam-Tung relation predicts A0-A2 = 0
- Perturbative QCD predicts a violation at order O(alphas^2) and higher, in the high pt region
- The data shows positive A0-A2 at high pt larger than the prediction, and negative A0-A2 at low pt.





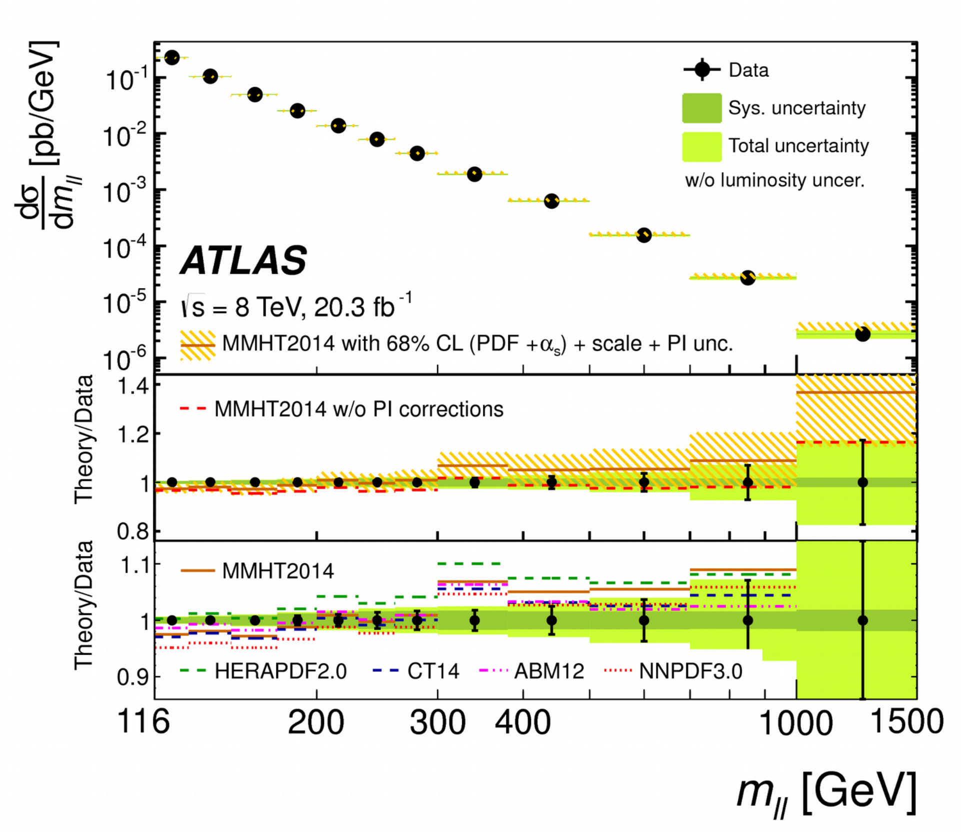
Z-boson angular coefficients at 8 TeV

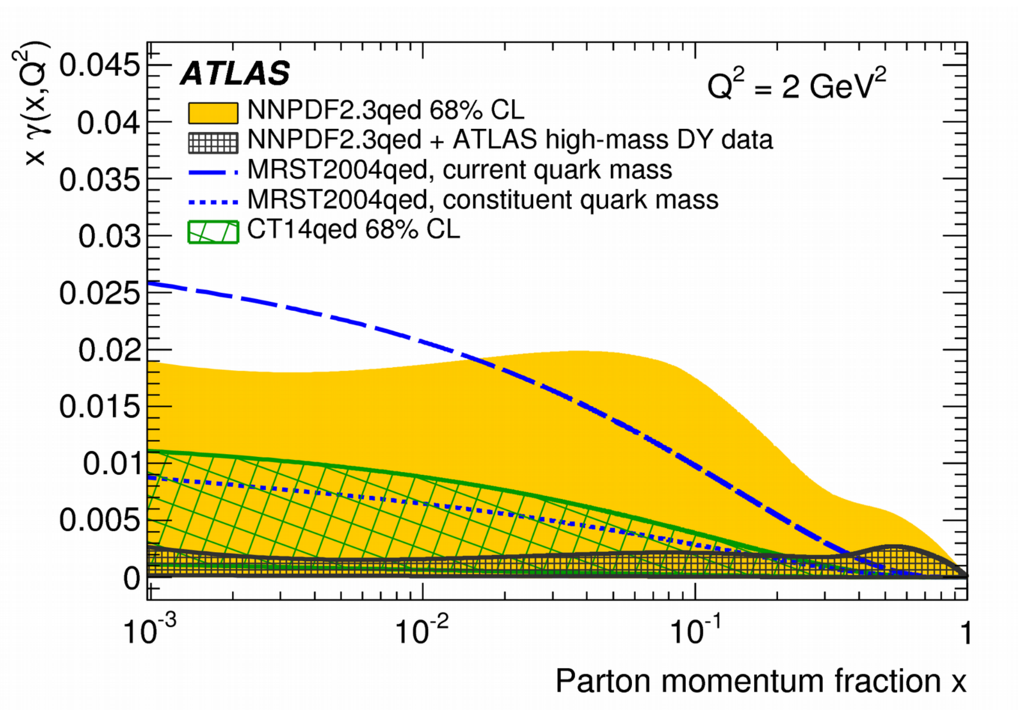
- Measured the A5, A6, A7 coefficients for the first time
- Allows a full decomposition of the cross section in spherical harmonics



High mass DY at 8 TeV

- Test higher order QCD and EW corrections
- Probe photon PDF





- More details in Eram Rizvi's talk in the PDF session

Summary

- After 45 years, the DY process is still an important measurement, which allows fundamental tests of the SM, precise determination of QCD and EW parameters, searching for new physics
- ATLAS has an extensive programme of DY measurements, which has reached unprecedented precision, and allows a reach assortment of phenomenological studies, including PDF determination and extraction of EW parameters
- DY measurements will benefit from the large data sample which is being collected in Run 2. Larger statistic will allow exploring new corners of the phase space, and reducing the systematic uncertainties related to the calibration of the detector

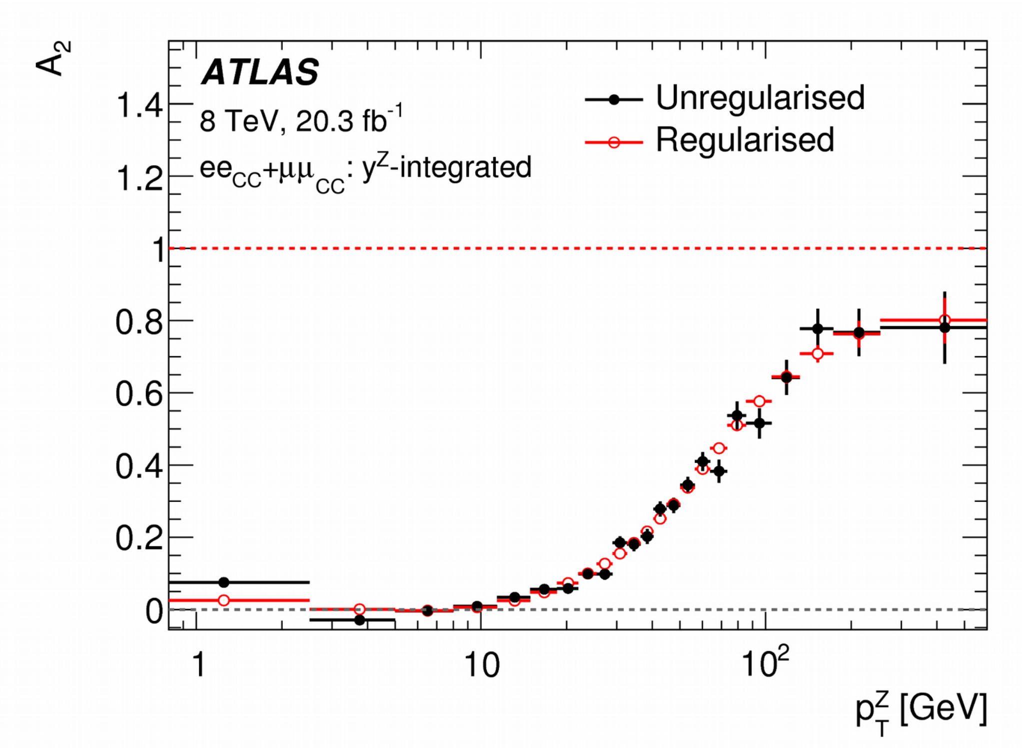
BACKUP

Z-boson angular coefficients at 8 TeV

- A cos(2ϕ) asymmetry which violates the Lam-Tung relation at low pt was observed in fixed target experiments

$$P_2(\cos\theta, \phi) = \frac{1}{2}\sin^2\theta\cos 2\phi \qquad \frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

→ $\nu = A2$



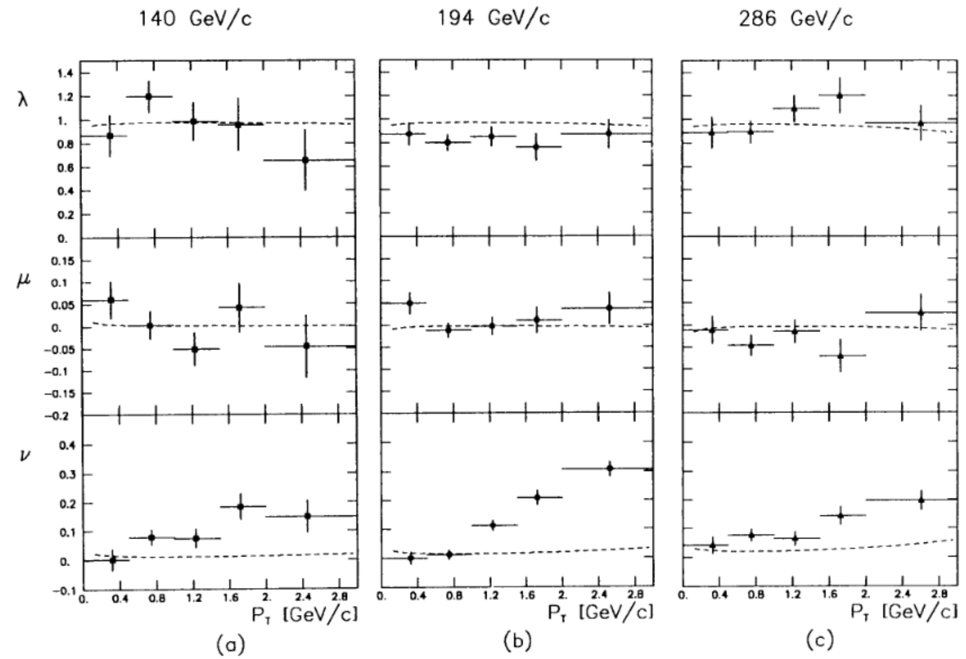
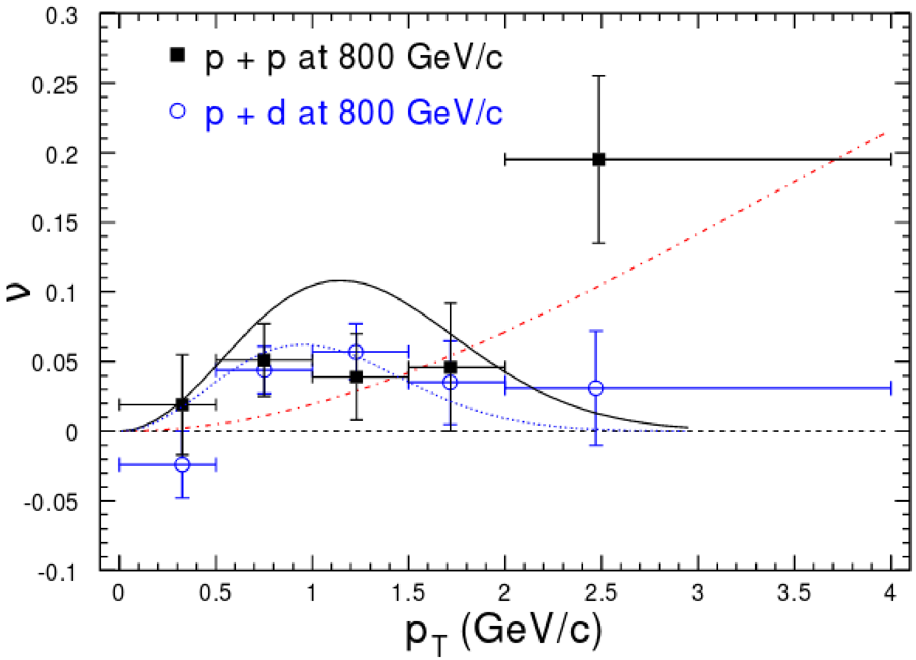


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. a 140 GeV/c; b 194 GeV/c; c 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

Z-boson angular coefficients at 8 TeV

- A cos(2ϕ) asymmetry which violates the Lam-Tung relation at low pt was observed in fixed target experiments
- The effect can be explained by higher twist effects, QCD vacuum effects, or by the Boer-Mulders TMD functions, which describe a correlation between transverse momentum and transverse spin of quarks



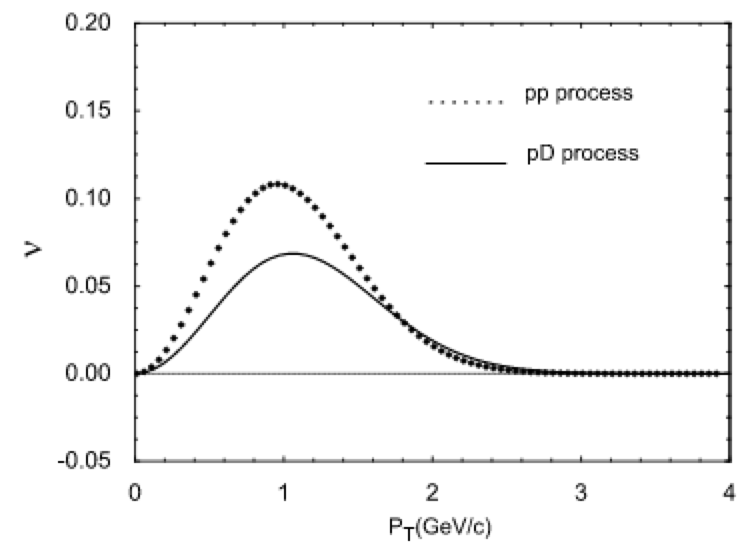
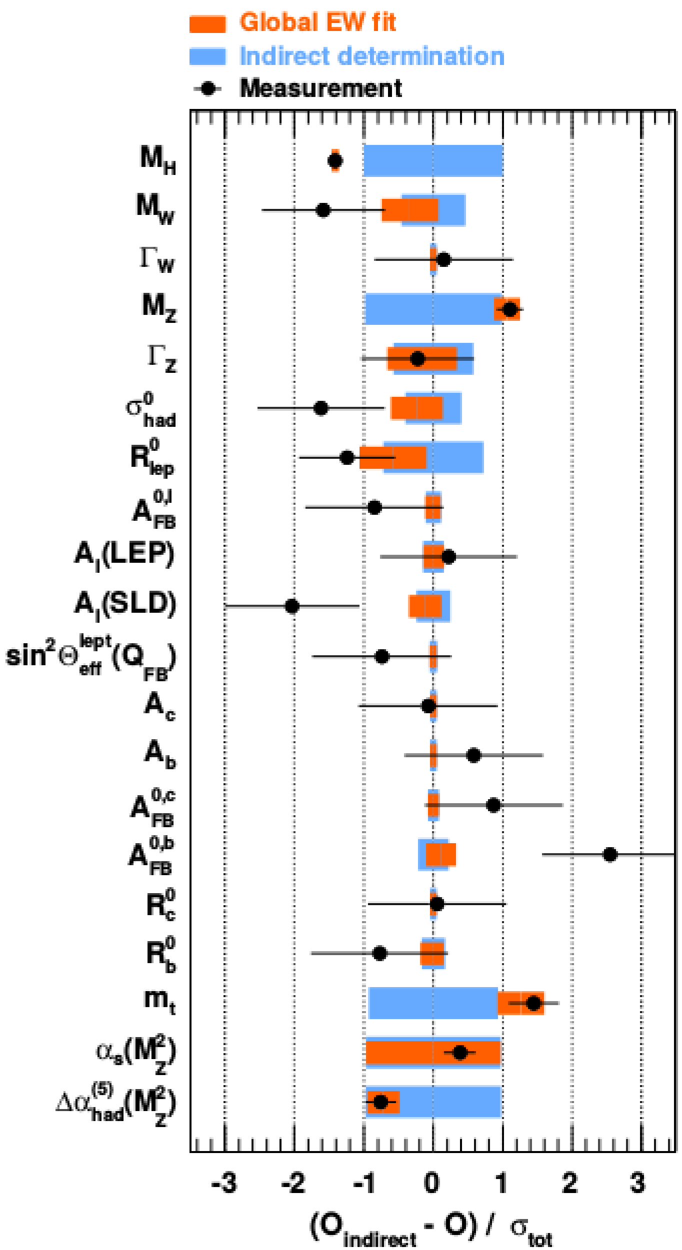


FIG. 4: The p_T-dependent $\cos 2\phi$ asymmetries ν in both pp (dotted curve)and pD(solid curve) Drell-Yan processes at FNAL E866/NuSea, calculated with the fitted Boer-Mulders functions presented in Table I.

Precision measurements of EW parameters

- After the measurement of the Higgs mass, all the free parameters of the Standard Model are known
- Relations between electroweak observables can be predicted (almost) at 2-loop level



Eur.Phys.J. C74 (2014) 3046

Precise measurements of the EW parameters allow

- Stringent test of self consistency of the SM
- Look for hints of BSM physics

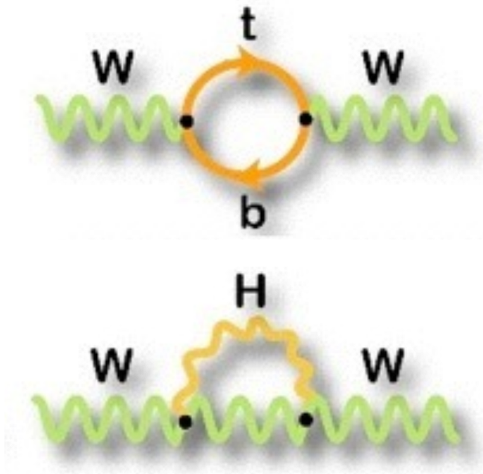
Measurement of the W mass

A milestone of the LHC physics program

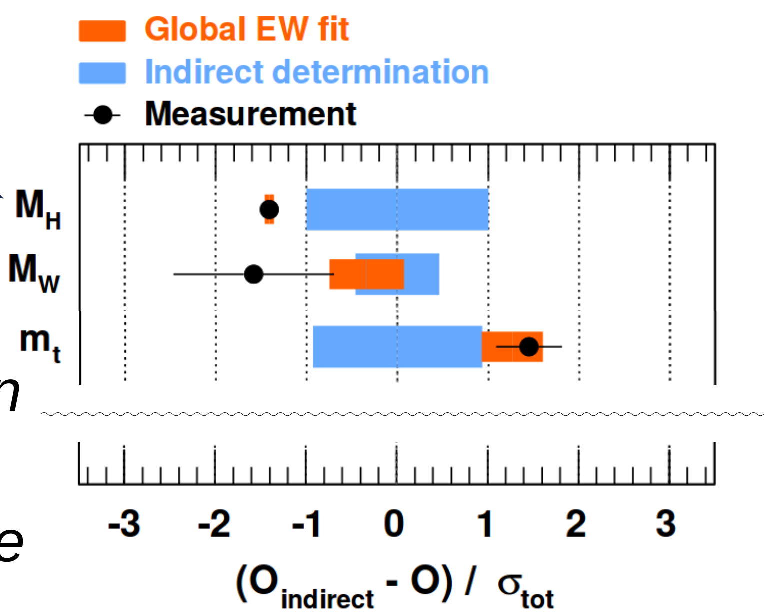
The EW sector of the SM, relates M_W to α, G_F, and $\sin^2\theta_W$

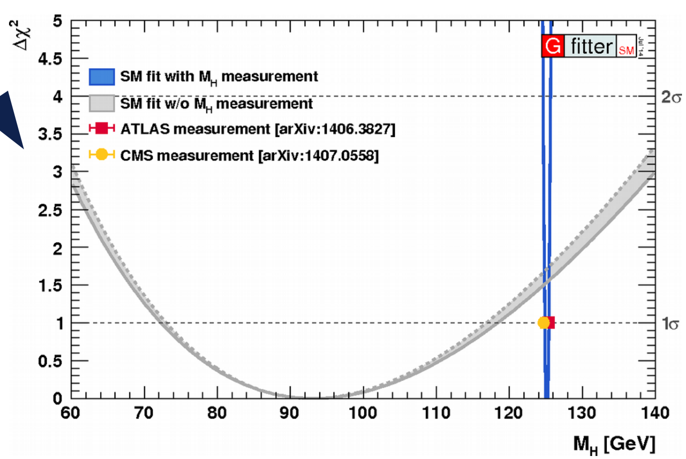
$$M_W^2 = \frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F\,(1 - M_W^2/M_Z^2)\,(1-\Delta r)}$$

Radiative corrections Δr are dominated by Top and Higgs loops



- The relation between M_{top}, M_H and M_W provides a stringent test of the SM
- The comparison between the measured M_H and the predicted M_H is sensitive to new physics





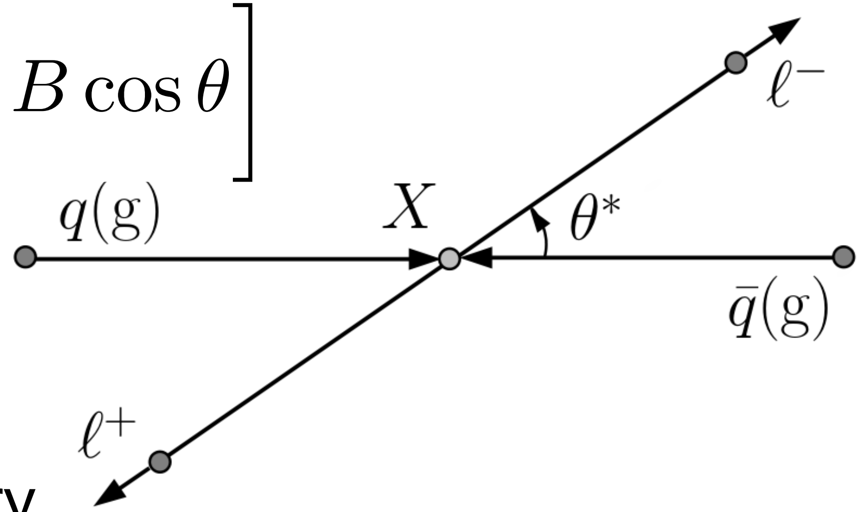
Indirect determination of M_W (±8 MeV) is more precise than the experimental measurement

Call for $\delta M_W^{exp} < 10$ MeV

Z forward-backward asymmetry and θ_W

The Drell-Yan production cross section
as function of the scattering angle θ

$$\frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}(A(1+\cos^2\theta) + B\cos\theta\right]$$



- Coefficients A and B depend on the weak mixing angle θ_W
- Linear term in cos(θ) gives rise to non-vanishing forward-backward asymmetry

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F = \sigma(\cos\theta > 0)$$
$$\sigma_B = \sigma(\cos\theta < 0)$$

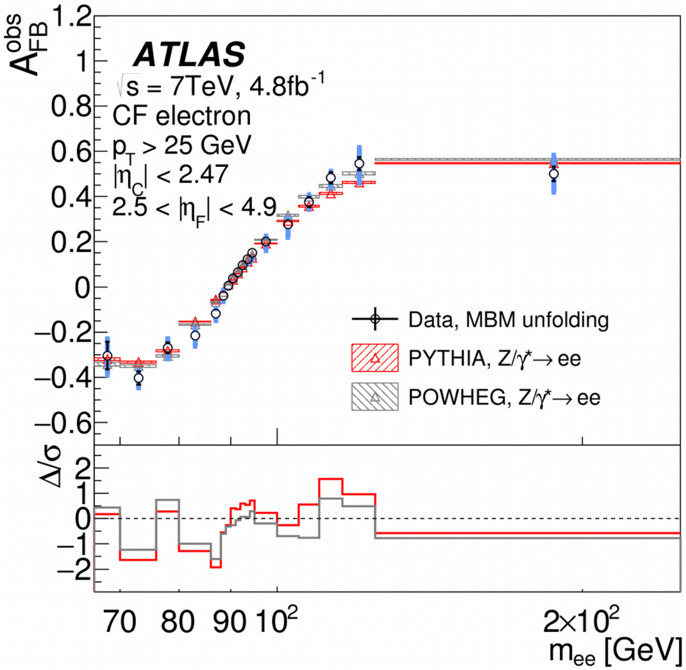
$B \propto s - m_Z^2$ → A_{FB} changes sign at the Z pole

The direction of the incoming quark is unknown

- Only valence quarks determine a detectable asymmetry
- Asymmetry is diluted, effect related to PDF
- Use θ^* scattering angle, defined in the Collins-Soper frame

Measurement of weak-mixing angle θ_W

- $\sin^2\theta_W$ extracted from template fits to Z AFB as a function of dilepton invariant mass M_{ll}
- Uncertainties evaluated with the offset method



	$\sin^2(\theta_W^{eff})$
ATLAS 7 TeV 4.8 fb^{-1}	0.2308 ± 0.0005(stat) ± 0.0006(syst) ± 0.0009(PDF)
LEP+SLD	0.23153 ± 0.00016

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 10 times worst than LEP+SLD
- $\sin^2\theta_W$ measurement limited by PDF uncertainty