Electroweak precision measurements with Z and W bosons at the LHC

Moriond EW Session, 2017

Aram Apyan

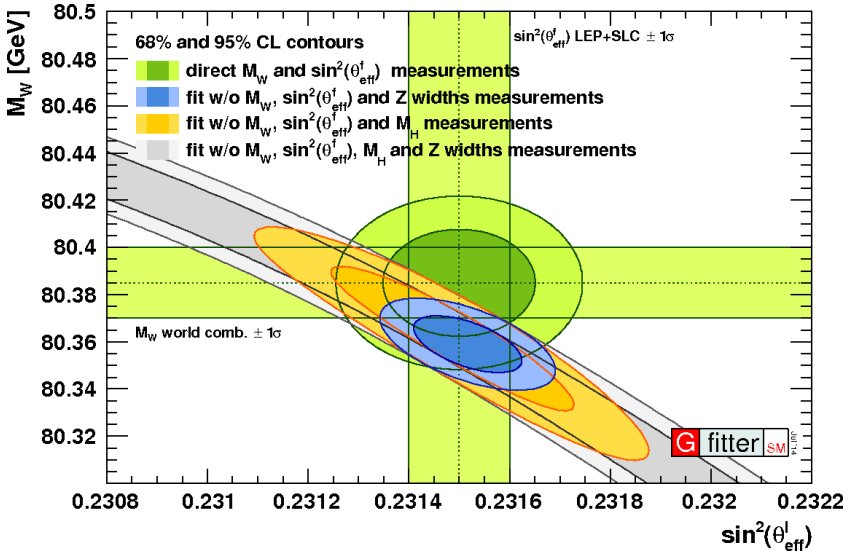
On behalf of ATLAS, CMS, and LHCb collaborations

Overview of the Electroweak Sector

- Electroweak (EW) precision observables
  - $\alpha_{\mathrm{em}}, \mathrm{G_F}, m_{\mathrm{W}}, m_{\mathrm{Z}}, \sin^2\theta_{\mathrm{W}}, m_h$
- Not independent but related through Standard Model (SM)

$$m_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}} = \frac{\pi\alpha}{\sqrt{2}\mathrm{G_F}} \qquad \sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2} \qquad \text{(Tree level)}$$

- Precision EW measurements
  - Testing the consistency of the SM
  - Probing beyond SM contributions
- Focus on $\sin^2\theta_{\mathrm{W}}$ in this talk
  - Non-abelian Gauge structure discussed in the next talk
  - W mass discussed tomorrow morning

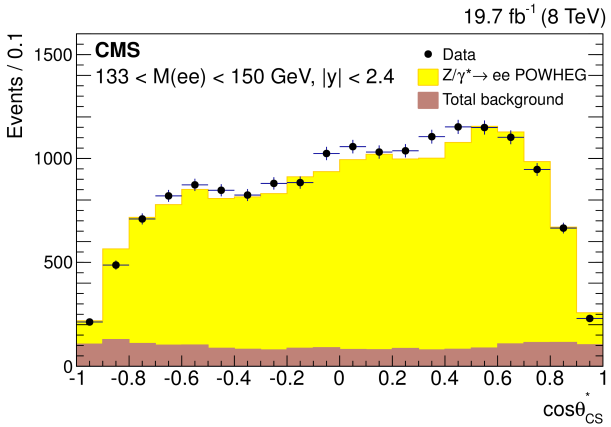


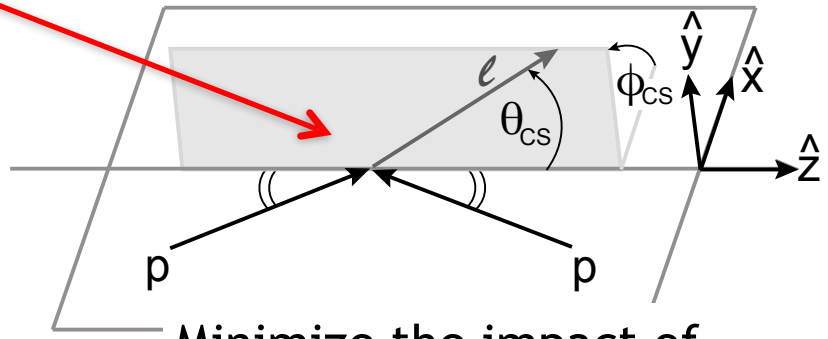
Forward-backward Asymmetry

- Neutral current process: $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$
- Z boson couplings are different for left and right-handed fermions
- Forward-backward asymmetry (A_{FB}) in the polar angle distribution of negatively charged lepton in the rest frame of di-lepton system
  - Defined with respect to the incoming quark

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta} = \frac{3}{8}\frac{d\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta\right\}$$

- A_{FB} defined in Collin-Soper (CS) frame $A_{\mathrm{FB}} = \dfrac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$





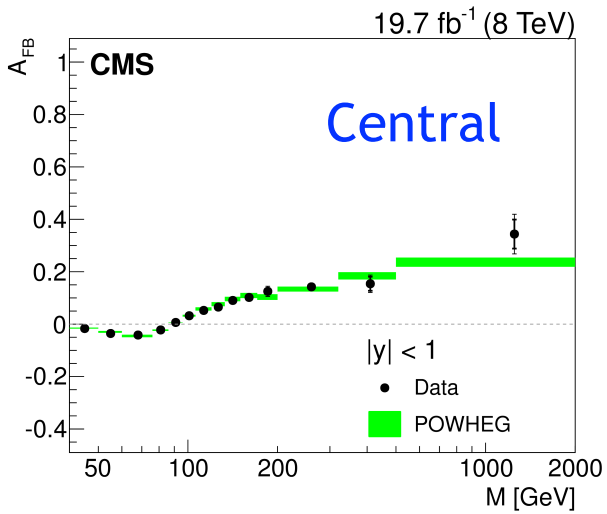
Minimize the impact of incoming quark transverse momentum

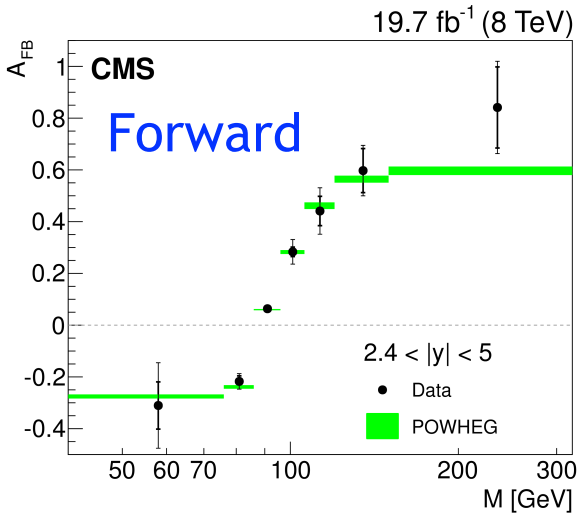
Eur.Phys.J.C76(2016)

Forward-backward Asymmetry 2

- A_{FB} measured as function of di-lepton mass in muon (LHCb) and electron/muon final states (ATLAS/CMS)
- Proton-proton collisions: where is the quark?
  - Direction of longitudinal boost of the di-lepton system in the laboratory frame chosen as the positive axis
    - Quark direction is not always along the positive axis
      - Dilution of A_{FB}
    - Dilution is smaller at large absolute rapidities of di-lepton system

Eur.Phys.J.C76(2016)





Effective weak mixing angle

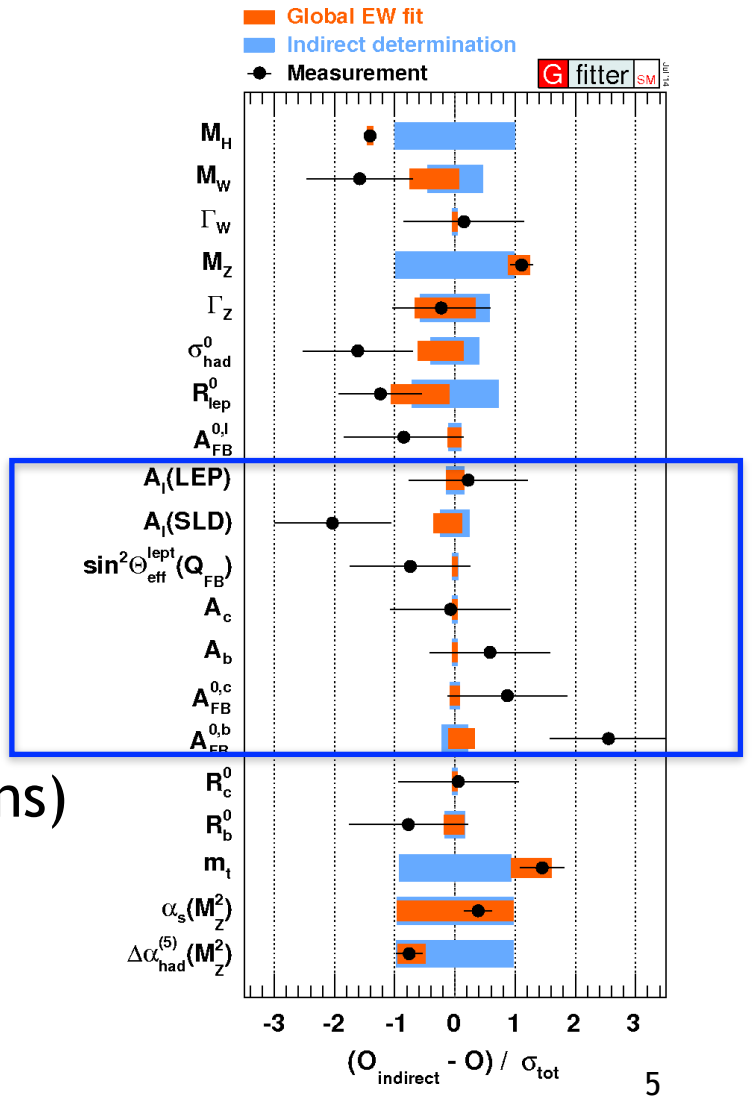
- A_{FB} is sensitive to $\sin^2\theta_W$ near Z peak
  - Product of vector and axial couplings
- Electroweak corrections:
  - Tree level couplings are replaced by effective couplings

$$\sin^2\theta^{\mathrm{f}}_{\mathrm{eff}} = \kappa^{\mathrm{f}}_Z \sin^2\theta_{\mathrm{W}}$$

$$g^{\mathrm{f}}_{\mathrm{A}} = \sqrt{\rho_{\mathrm{f}}}\, t^{\mathrm{f}}_{3L}$$

$$g^{\mathrm{f}}_{\mathrm{V}} = \sqrt{\rho_{\mathrm{f}}}\,(t^{\mathrm{f}}_{3L} - 2Q_{\mathrm{f}}\kappa_{\mathrm{f}}\sin^2\theta_{\mathrm{W}})$$

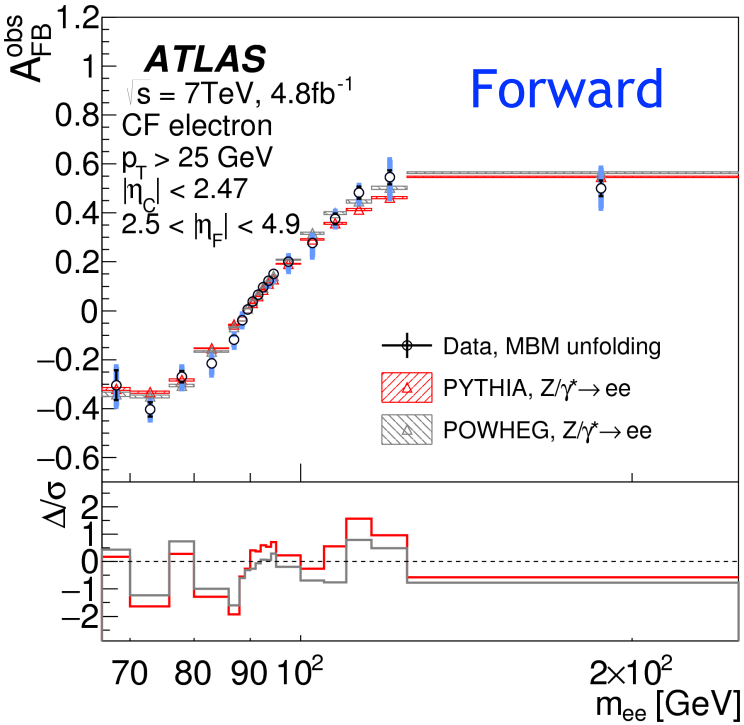
- Template fit to extract the $\sin^2\theta^{\ell}_{\mathrm{eff}}$
- Large discrepancy (~3 standard deviations) between the two most precise LEP/SLD measurements

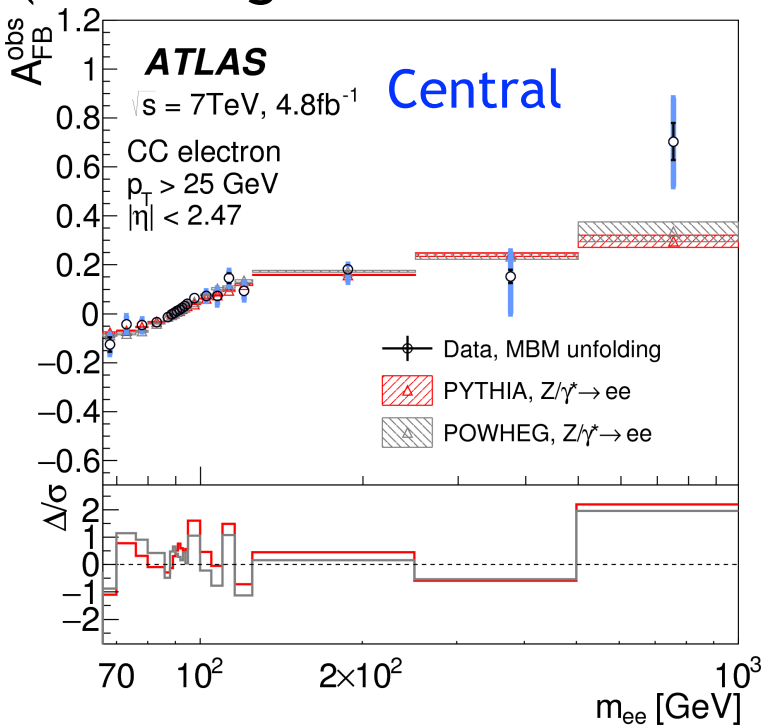


A_{fb} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$

JHEP 1509 (2015) 049

- ATLAS 7 TeV measurement
- Muon and electron final states are used (including forward electrons)





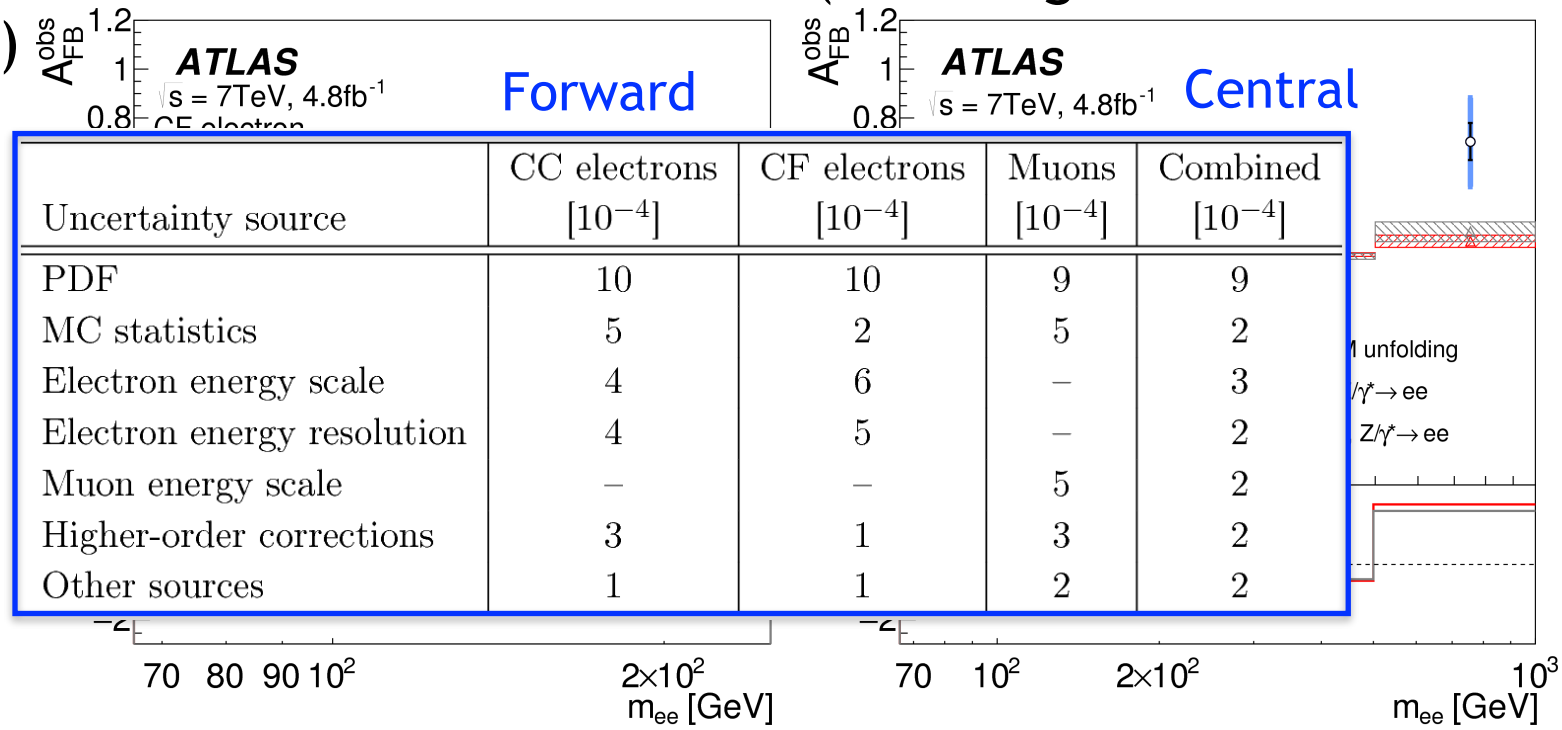
Leading uncertainties are from PDF

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

A_{fb} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$

JHEP 1509 (2015) 049

- ATLAS 7 TeV measurement
- Muon and electron final states are used (including forward electrons)



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

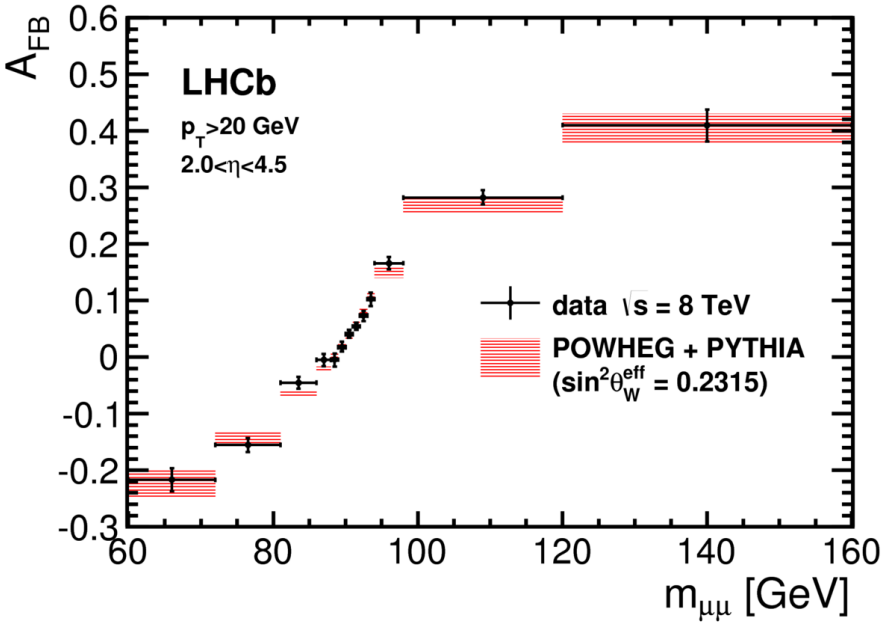
Leading uncertainties are from PDF

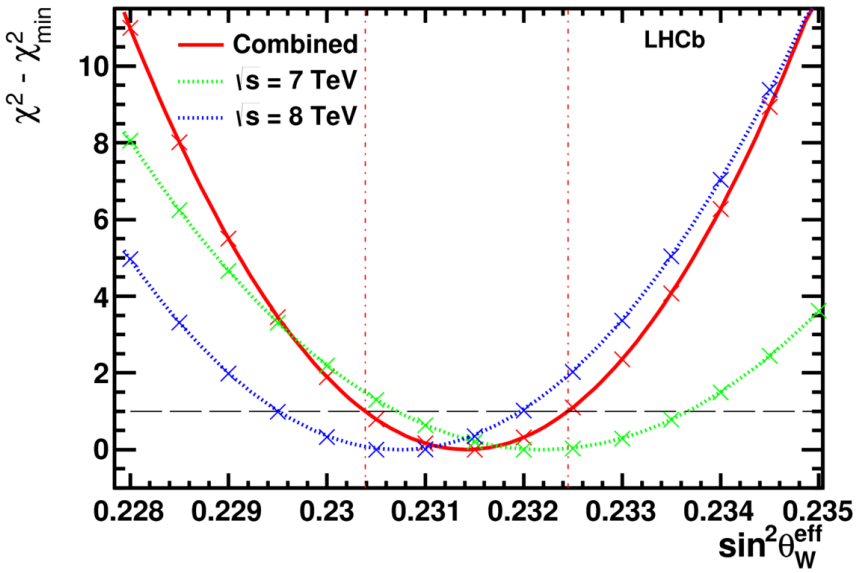
	$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$	
CC electron	$0.2302 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm$	$0.0010(\mathrm{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm$	$0.0010(\mathrm{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307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

A_{fb} and $\sin^2\theta^{\ell}_{\text{eff}}$

JHEP 1511 (2015) 190

- LHCb 7 and 8 TeV measurements using di-muon
- Assignment of forward and backward decays is correct 90% of the time





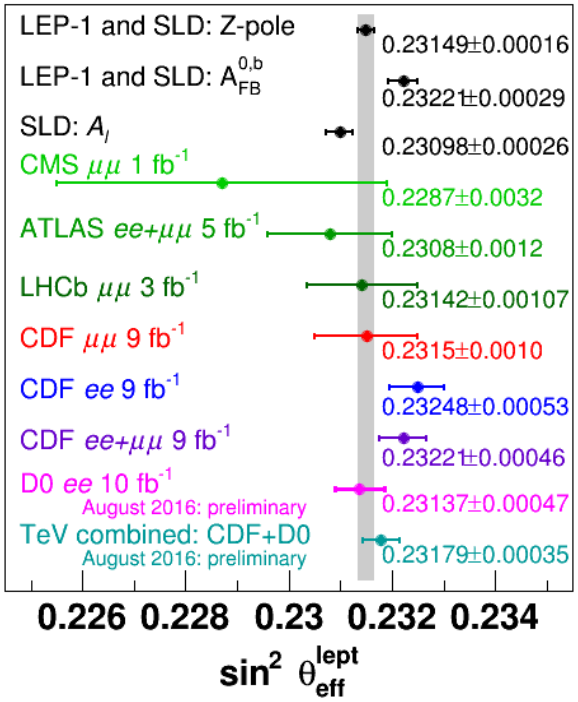
- Smaller theoretical uncertainty due to forward di-muon events

$$\sin^2\theta^{\text{eff}}_{\text{W}} = 0.23142 \pm \underbrace{0.00073}_{\text{(stat)}} \pm \underbrace{0.00052}_{\text{(exp)}} \pm \underbrace{0.00056}_{\text{(theory+pdf)}}$$

A_{fb} and $\sin^2\theta^{\ell}_{\mathrm{eff}}$

FERMILAB-CONF-16-295-E

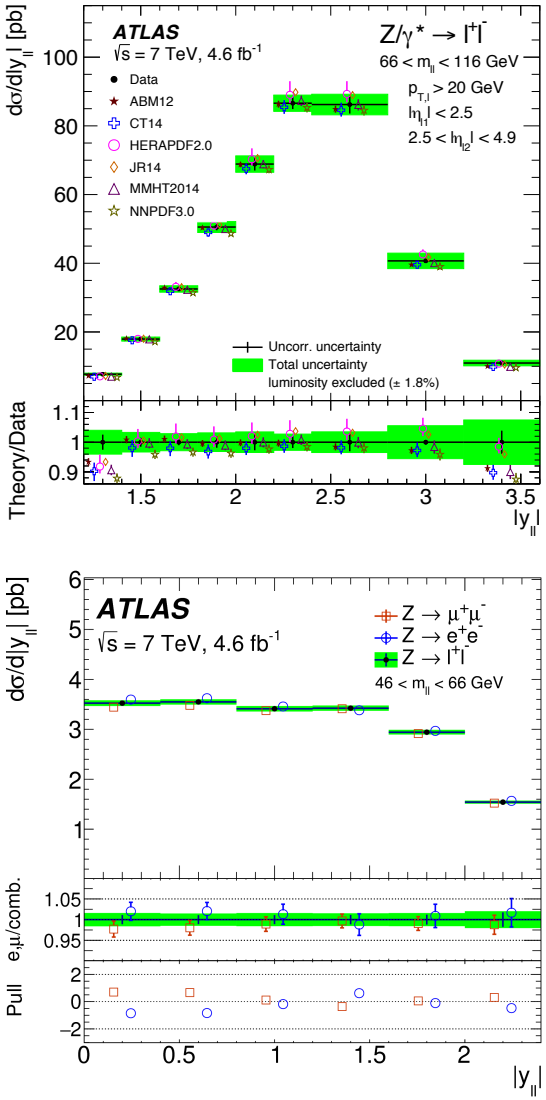
- Hadron collider measurements are becoming more precise
  - LEP and SLD measurements are still most precise measurements
- Dominating PDF uncertainties at the LHC
  - PDF uncertainties will be smaller if the measurements were repeated with recent PDFs
- Future improvements? Profiling PDF uncertainties in a combined fit to extract $\sin^2\theta^{\ell}_{\mathrm{eff}}$ and constrain PDFs



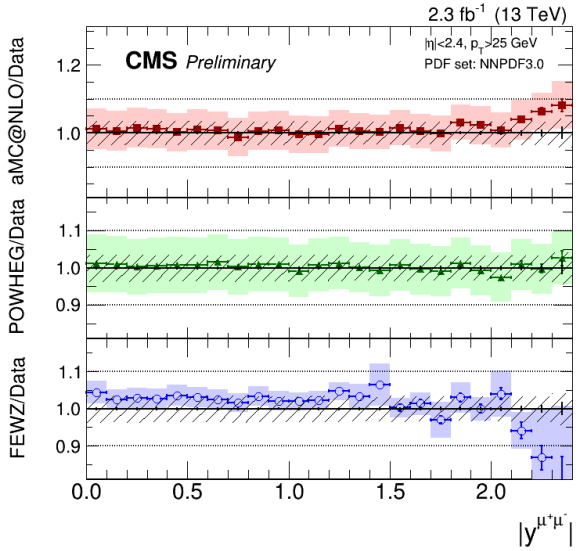
PDF related measurements

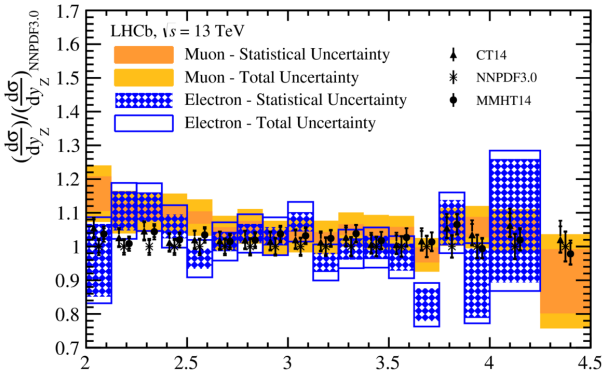
- Single boson production cross section measurements constrain the PDFs
  - Differential W/Z measurements are important (including the forward region)
- Measurements at 7, 8, and 13 TeV are performed

Arxiv:1612.03016



CMS-PAS-SMP-15-011



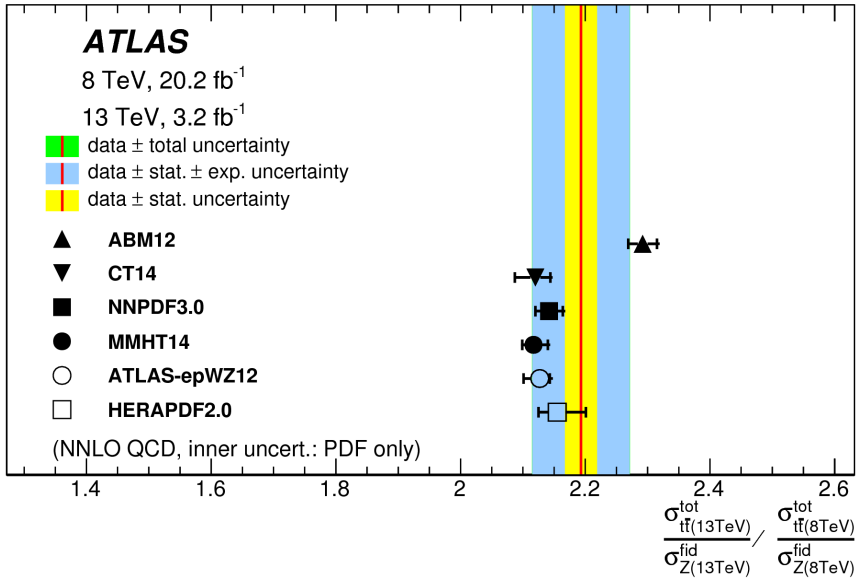


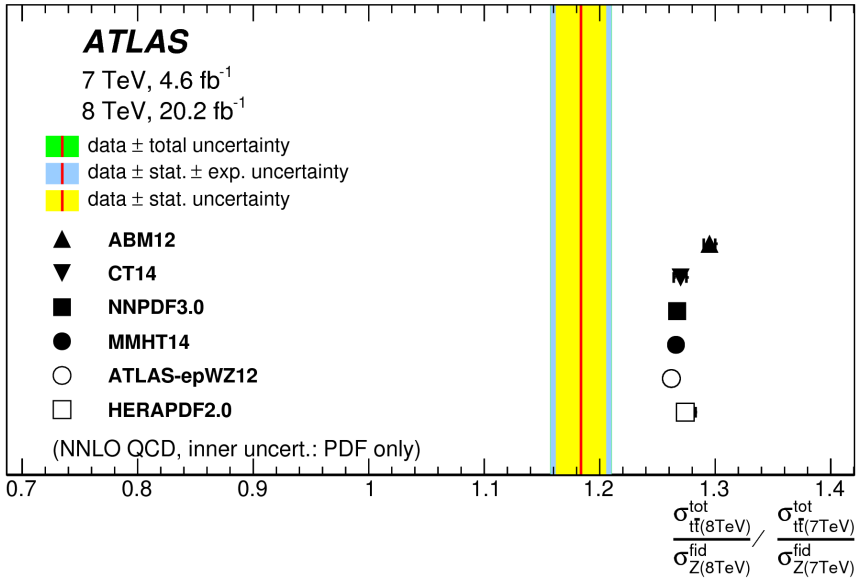
JHEP 09 (2016) 136

Cross section ratios

JHEP 02 (2017) 117

- Measurements of top-quark pair to Z boson cross section ratios
  - Center of mass energies of 7, 8, and 13 TeV
- Constrains on PDFs, strong coupling constant, and top-quark mass





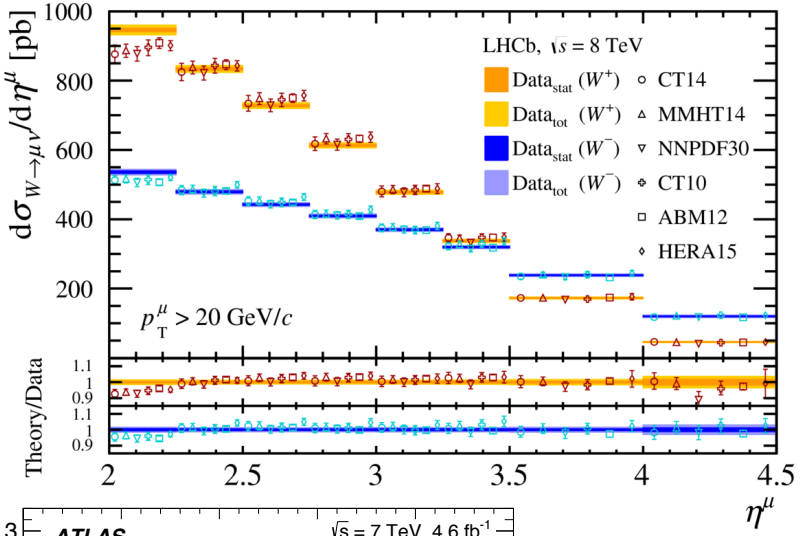
- Significant power to constrain the gluon distribution functions near x of 0.1

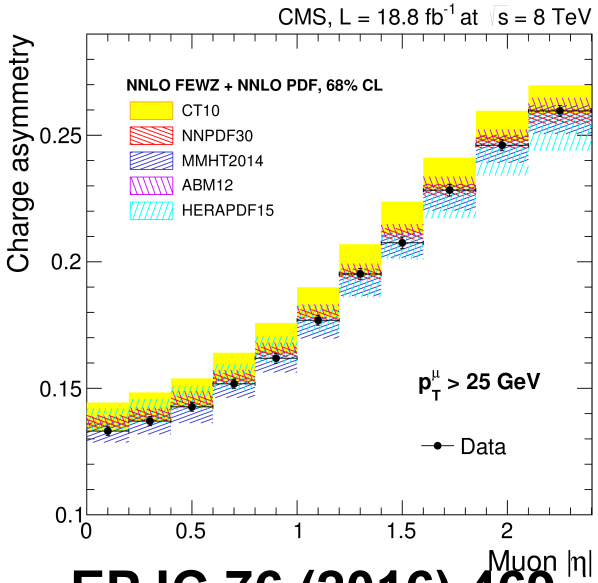
W charge asymmetry

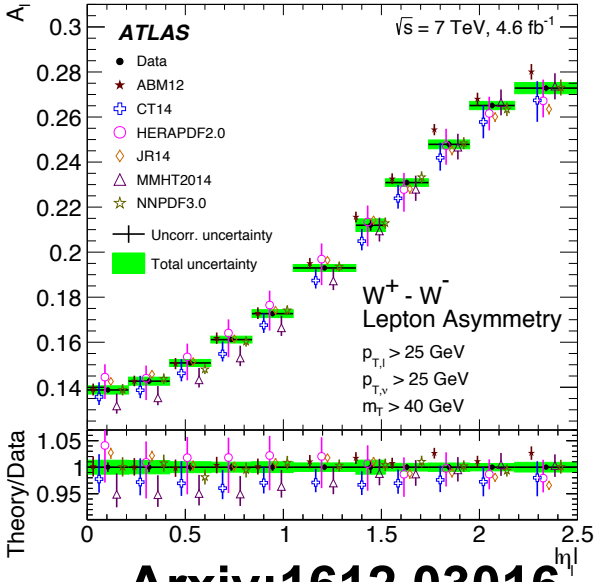
JHEP 01 (2016) 155

- Constraints on the valence and sea quark distributions
- General good agreement with theory predictions

$$A_e \equiv \frac{\sigma_{W^+\to e^+\nu_e} - \sigma_{W^-\to e^-\overline{\nu}_e}}{\sigma_{W^+\to e^+\nu_e} + \sigma_{W^-\to e^-\overline{\nu}_e}}$$







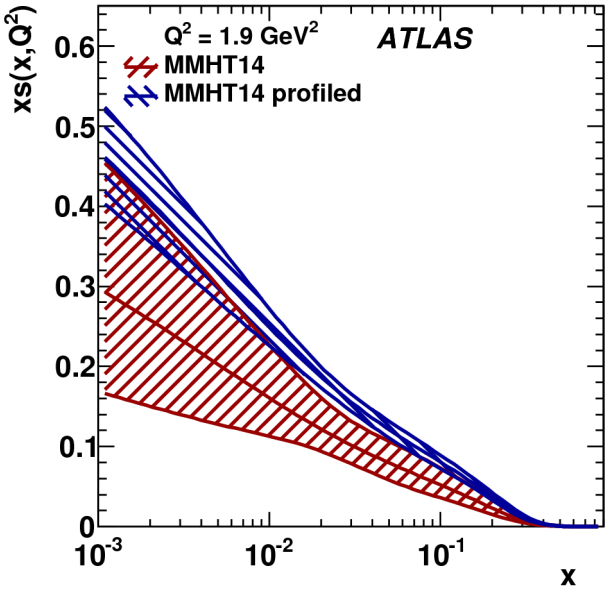
EPJC 76 (2016) 469

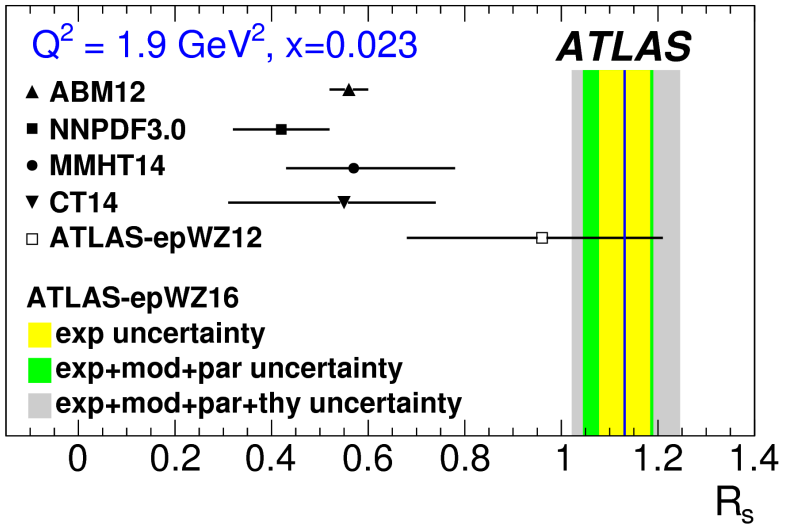
Arxiv:1612.03016

Impact on PDFs

Arxiv:1612.03016

- Data can be interpreted in combination with HERA data within perturbative QCD
- For example: more sensitivity to the flavor composition of sea quark
  - Ratio of strange to light quark sea densities
    - Close to unity in the sensitivity range of data





- Heavy flavor PDF can also be tested via V+c-jet measurements

Angular coefficients

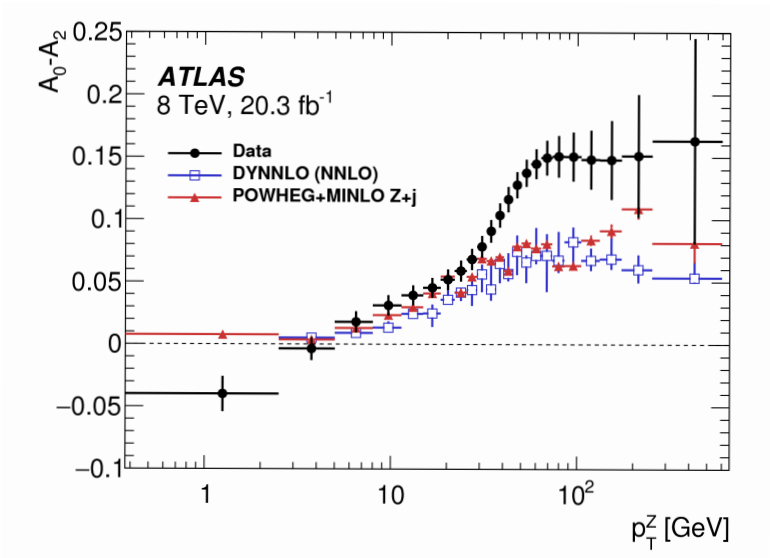
- Accurate modeling of QCD effects is crucial to perform the EW precision measurements
- Factorizing the Drell-Yan production cross section from the decay kinematics

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

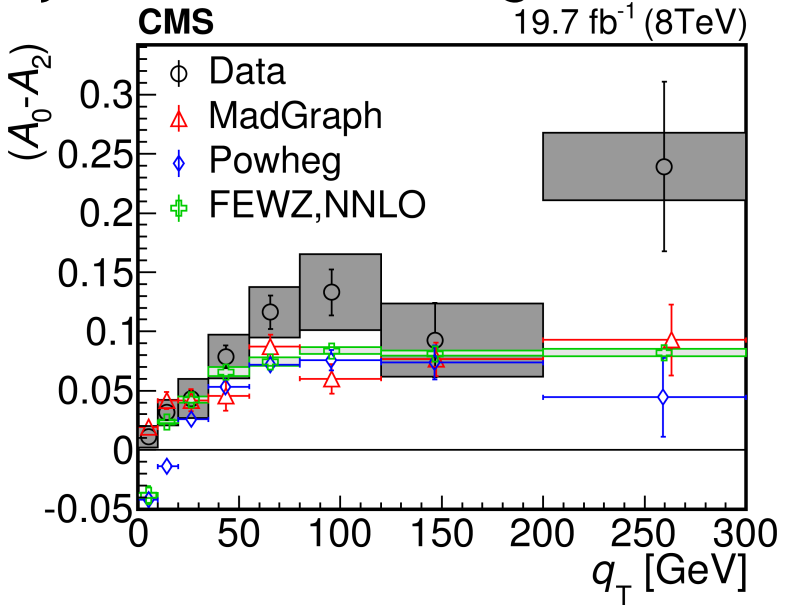
CS frame

$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi + \frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta + A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}$$

A_0-A_2 is non-zero for QCD calculations beyond NLO: Lam-Tung relation violated



JHEP 08 (2016) 159



Phys. Lett. B 750 (2015) 154

Summary

- Electroweak precision measurements at the LHC
- Precise measurements of the effective weak mixing angle
  - PDF and statistical uncertainties dominate
  - Experimental uncertainties are under control
- PDF uncertainties will improve with more data
  - Precise measurements of W/Z production cross sections and their ratios available
- Many more results to come with new data