Measurement of the weak mixing angle in ATLAS

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Outline

- Introduction
- Z F/B asymmetry measurement in ATLAS
  - Event selection
  - Unfolding
- Weak mixing angle (wma) extraction

Z asymmetries

- They arise from the parity violation of EW interactions
- Three non-vanishing observables:
  - Longitudinal polarization asymmetry, A_{LR}
  - Polarized FB asymmetry
  - Unpolarized FB asymmetry
- The Z production+decay cross section gains a term proportional to the cosine of the scattering angle
  - Coefficient depends on the couplings

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

A_{FB}

- Will focus here on the unpolarized FB asymmetry, defined as

$$A_{\mathrm{FB}} \equiv \frac{\int_0^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta - \int_{-1}^0 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta}{\int_{-1}^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\,\mathrm{d}\cos\theta} = \frac{B}{A}$$

$$A = Q_l^2 Q_q^2 + 2 Q_l Q_q g_V^q g_V^l Re(\chi(s)) + ({g_V^l}^2 + {g_A^l}^2)({g_V^q}^2 + {g_A^q}^2)|\chi(s)|^2$$

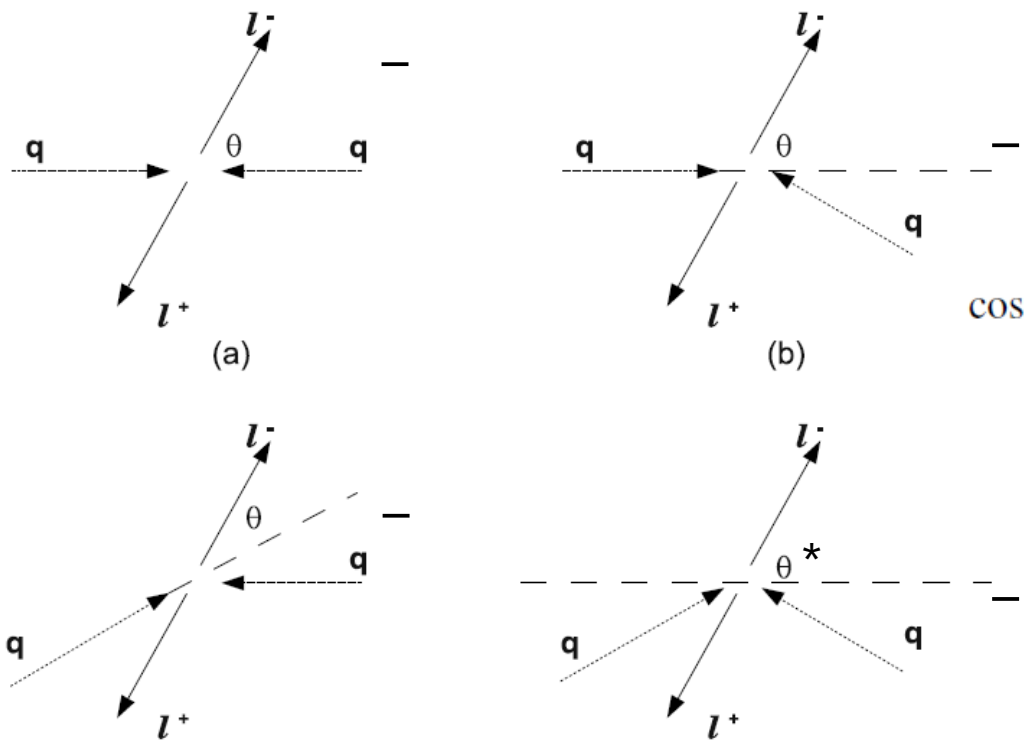
$$B = \frac{3}{2} g_A^q g_A^l (Q_l Q_q Re(\chi(s)) + 2 g_V^q g_V^l |\chi(s)|^2)$$

$$\chi(s) = \frac{1}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z}$$

- A_{FB} has direct dependence on the wma, as well as on the invariant mass of the lepton pair

Collins-Soper frame

- An ambiguity in the definition of the angle is present when the transverse momentum of the lepton pair in the lab frame is not negligible
  - Use a reference frame (Collins-Soper) which resolves this ambiguity by using a symmetric axis wrt the incoming partons



$$\cos\theta^* = \frac{2}{m(Z/\gamma^*)\sqrt{m(Z/\gamma^*)^2 + p_T(Z/\gamma^*)^2}}(P_1^+P_2^- - P_1^-P_2^+)$$

$$P_i^\pm = \frac{1}{\sqrt{2}}(E_i \pm P_{z,i})$$

Dilution

- In *pp* colliders, one extra complication arises from the fact that one does not know which beam the quark belonged to
  - Result is that A_{FB} is diluted
  - Dilution less important if one limits the measurement to lepton pairs with high rapidity
  - In this case, one of the partons had high x, i.e. it was most likely a quark: assume that the direction of flight of the Z/γ^* coincides with the direction of the quark
- Extension of the analysis reach to high Z-boson rapidities allows to select a sample of events with less diluted asymmetry
  - Leads to reduced errors on the weak mixing angle
- Both experiments are now exploiting the capabilities of their forward calorimetry to detect electrons with rapidities up to 5

Overview of recent results

- CMS A_{FB} <u>and weak mixing angle measurement</u>
  - Muon final state, 7TeV, 1.1/fb [**Phys. Rev. D 84, 112002 (2011)**]
- CMS A_{FB}
  - Muon and electron final states, 7TeV, 5/fb [**Phys. Lett. B 718 (2013) 752**]
- ATLAS A_{FB} <u>and weak mixing angle measurement</u>
  - Muons, electrons, and forward electrons, 7TeV, 5/fb [**JHEP09(2015)049**]
- CMS A_{FB}
  - Muons, electrons, and forward electrons, 8TeV, 19.7/fb [**CMS-PAS-SMP-14-004**]
- CMS angular coefficients of Z decays
  - Muons, 8TeV, 19.7/fb [**arXiv:1504.03512, submitted to Phys. Lett. B**]

Analysis strategy

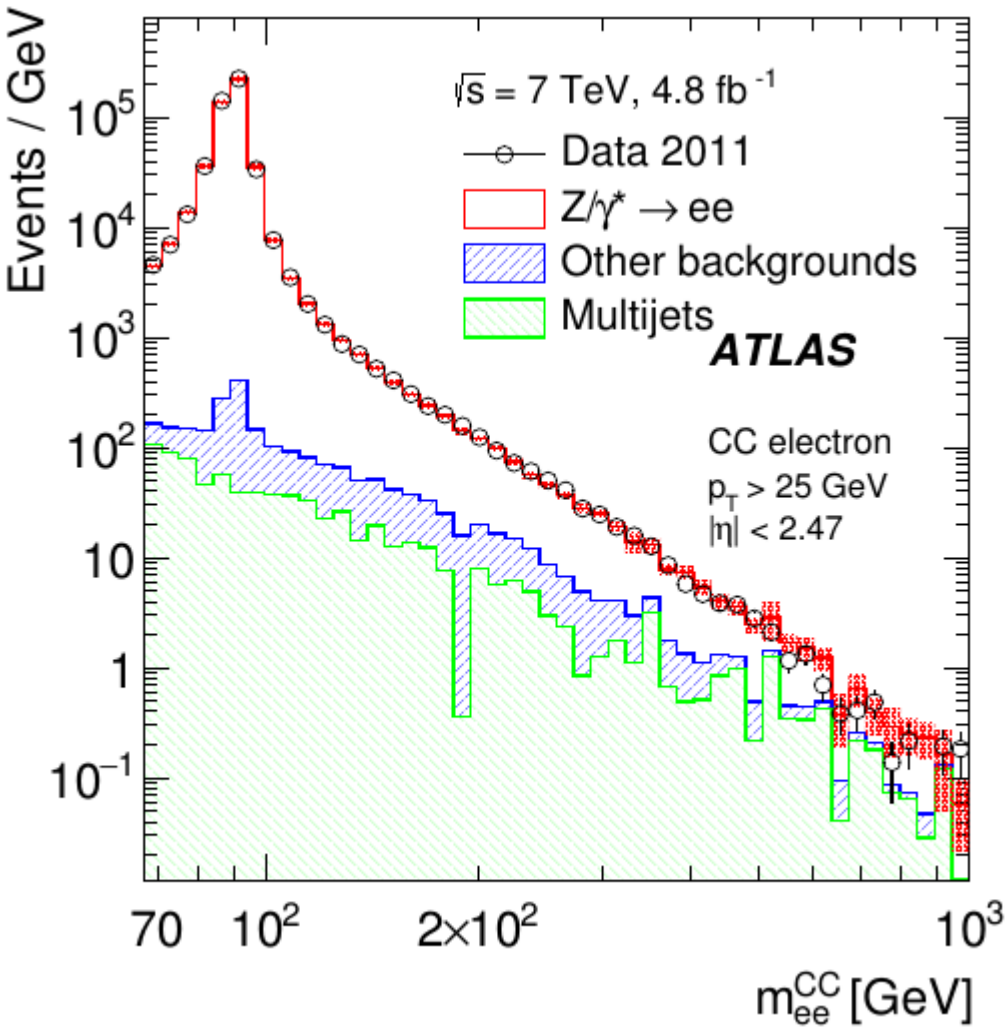
- Select events with pairs of high-p_T, isolated leptons
- Measure the A_{FB} spectra with two central electrons (CC), one central and one forward electron (CF) and two muons
  - Raw
  - MC-based unfolding
- Measure the wma
  - Use template fits on raw spectra

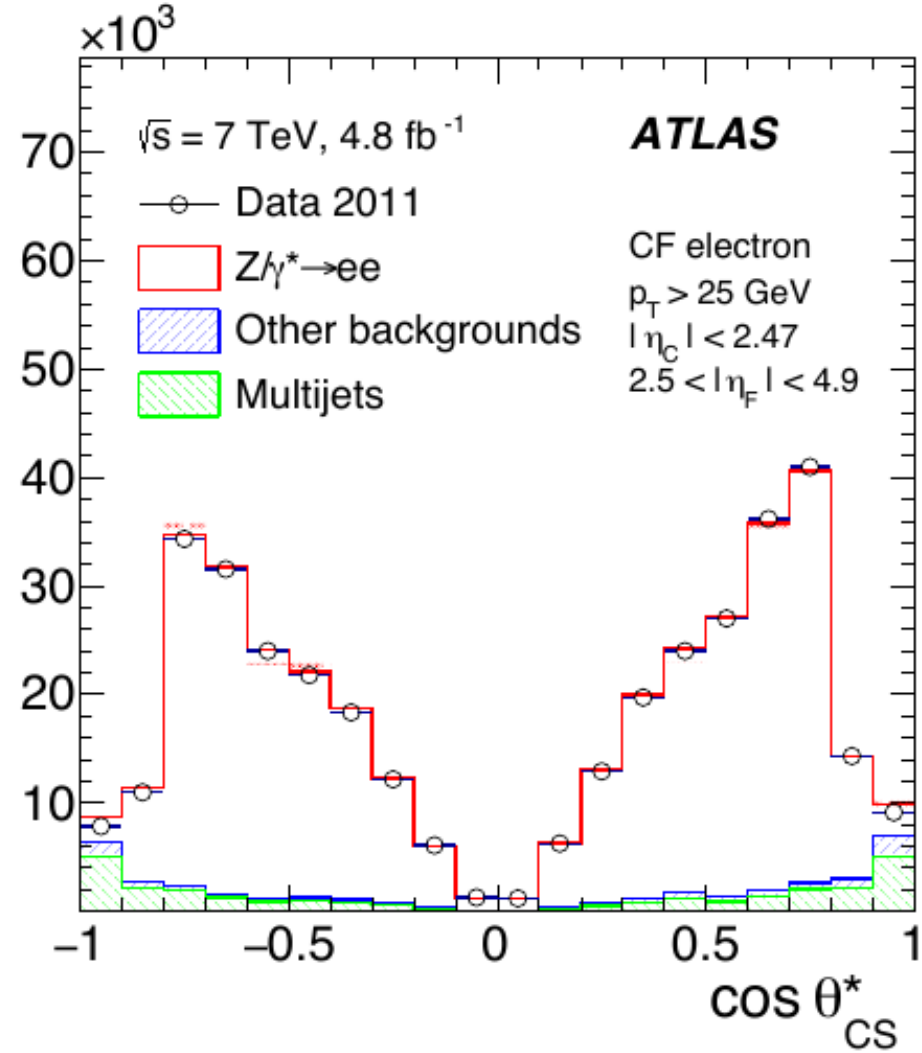
Backgrounds

- EWK background is taken from MC
- For QCD multijet and other fake-related backgrounds (like W+j) the electron channels use data-driven methods
  - QCD/fake bg prediction completely dominates CF channel for masses above 250GeV, where *data stat is fairly low*
  - ATLAS decided to limit the measurements in CF channel to masses below 250GeV
- In muon channel, QCD multijet background contribution is determined in control region (reversed isolation cuts) and transferred to the signal region using MC-based transfer factors

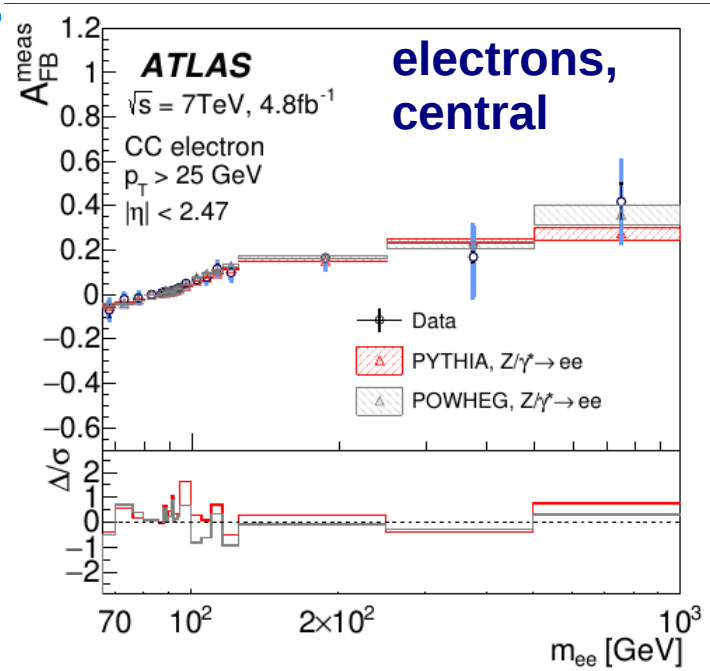
Control plots

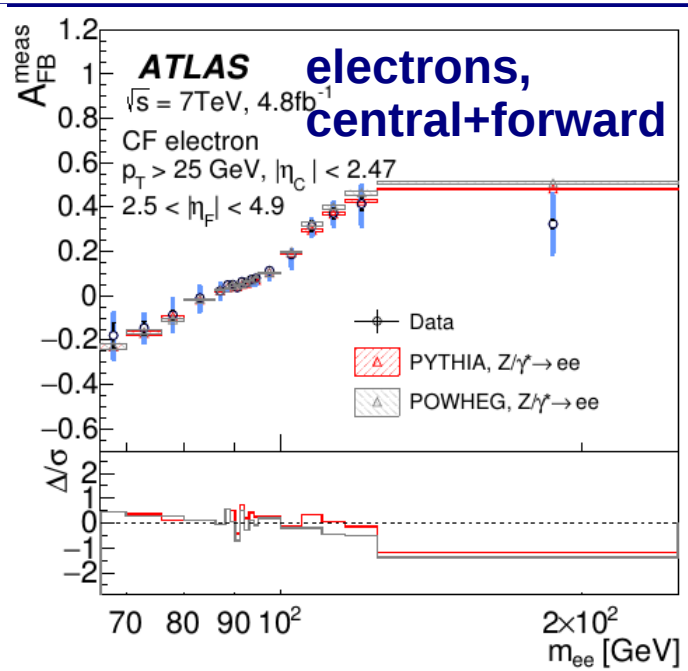
- Left: central electrons, invariant mass
- Right: central-forward electrons, cosθ*

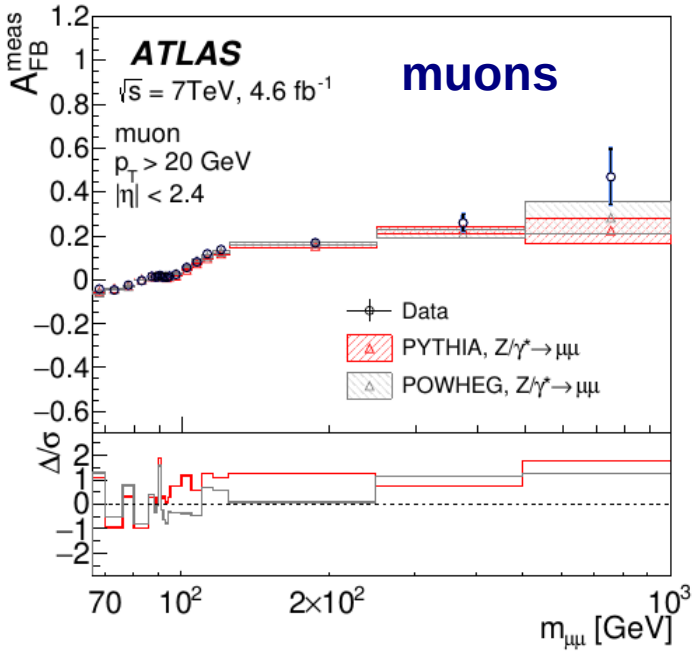




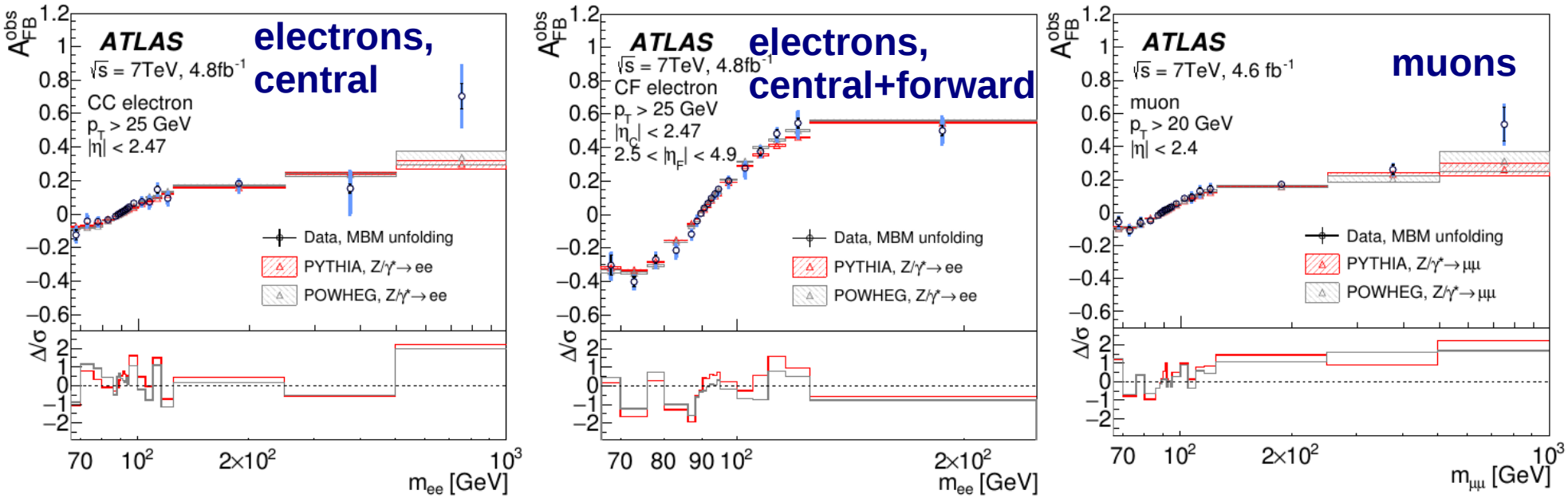
Raw AFB spectra







Unfolded A_{FB} spectra



- Asymmetry spectra unfolded for detector effects and extrapolated to the fiducial volume
  - Comparison with Pythia and POWHEG yields overall good agreement

A_{FB}: systematics

- Systematics on unfolded A_{FB} spectra shown in previous slide include:
  - FSR: estimated using alternate modeling
  - Limited statistics in MC used to obtain the unfolding matrices: effect estimated using toyMCs
  - PDF: effect estimated using PDF reweighting
  - Detector misalignment
  - Background modeling
  - Pileup
  - Trigger/Reco/ID efficiencies

wma measurement

- Strategy is to use simulated samples to perform template fit on *raw* A_{FB} spectra
  - Baseline generator for the templates is Pythia
- Samples with different wma values are obtained using a reweighting technique, validated using simulated samples
- In general, systematics on A_{FB} are propagated to the wma
- A few specific additional studies were added
  - Effect of QCD NLO on wma extraction: studied using MCFM, alternating between LO and NLO results and quoting the difference as systematics on the wma
  - Effect of EW NLO on wma extraction: similar procedure as for QCD NLO, but using HORACE
- As a cross check, the wma extraction is also repeated on the unfolded particle-level asymmetries, using MCFM+APPLGRID
  - Results compatible with the ones extracted at the detector level using Pythia

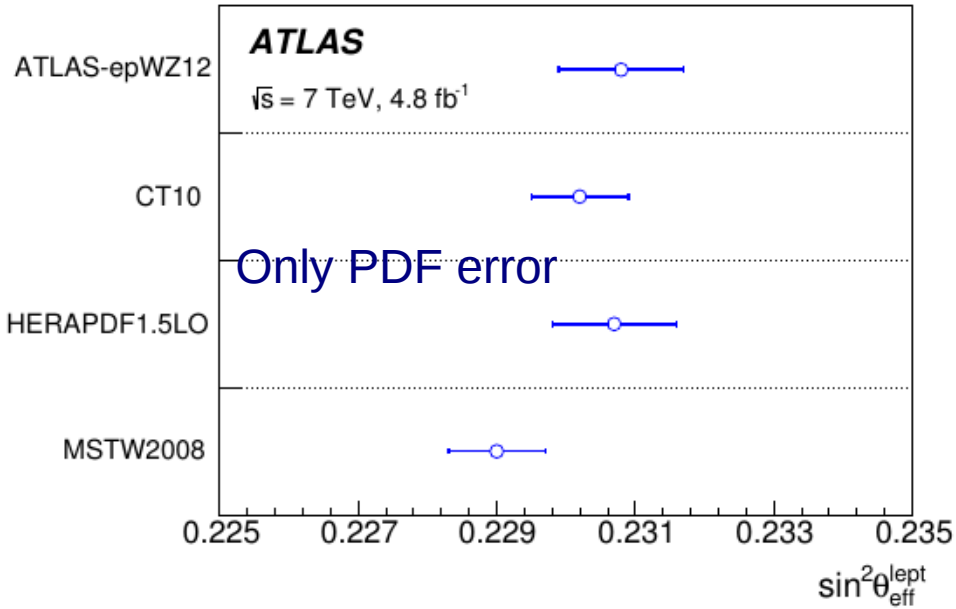
wma: combination

- ATLAS obtains three statistically independent measurements of $\sin^2\theta_W$, which can be combined
  - Combine together the two electron channels (CC and CF)
    - All systematics (but MC-stats and detector-related ones) are treated as fully correlated
  - Combine the electron result with the muon one
    - At this stage, the only correlated systematics are PDF and HO corrections

	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
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	$0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2308 \pm 0.0012$

Wma and PDFs

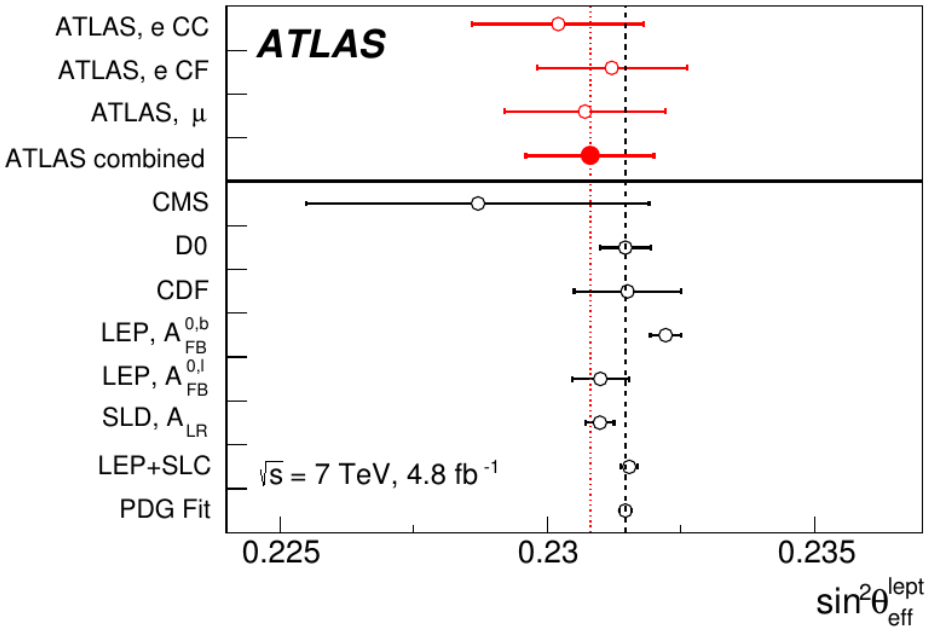
- A_{FB} depends on flavour and charge of the initial partons → wma extraction is sensitive to (valence) PDFs
  - In addition, dilution introduces a sensitivity to the sea-to-valence quark ratio
- ATLAS measurement of inclusive W and Z production sensitive to same effects
  - Indicate that some of the existing PDFs don't provide a good description of data
- For this measurement, a LO version of the ATLAS-epWZ fits was prepared, and used for the baseline result
  - Other PDFs are also used, and results quoted for comparison/cross check
- Note: ATLAS W/Z data suggests symmetric light quark sea ($\bar{s}/\bar{d}$~1)
  - Tests done with "special" $\bar{s}/\bar{d}$=0.5 showed, however, negligible impact on the wma measurement



Wma: results

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

	$\sin^2\theta_{\rm eff}^{\rm lept}$	Δ/σ (wrt LEP+SLC)	Δ/σ (wrt ATLAS)
ATLAS	0.2308 ± 0.0012	-0.6	–
CMS [5]	0.2287 ± 0.0032	-0.9	-0.6
D0 [4]	0.23146 ± 0.00047	-0.1	0.5
CDF [3]	0.2315 ± 0.0010	-0.03	0.4
LEP, $A_{\rm FB}^{0,b}$ [2]	0.23221 ± 0.00029	–	1.2
LEP, $A_{\rm FB}^{0,l}$ [2]	0.23099 ± 0.00053	–	-0.1
SLC, $A_{\rm LR}$ [2]	0.23098 ± 0.00026	–	-0.1
LEP+SLC [2]	0.23153 ± 0.00016	–	0.6
PDG global fit [45]	0.23146 ± 0.00012	-0.4	0.6



Conclusions

- Latest measurements of the A_{FB} spectra and of the wma by ATLAS have been presented
- The spectra cover a large mass range and, thanks to the use of forward electrons, also an unprecedented rapidity range
- The spectra were used to derive measurements of the weak mixing angle
- Wma value is consistent with previous experiments

Backup

EW parameters and $\sin^2\theta_W$

- SM only needs three input parameters
  - All other observables can be predicted from these
- The most common prescription uses the Z mass, the fine structure constant and the Fermi constant
  - In this context, $\sin^2\theta_W$ and the W mass can be calculated (given some value of m_t and m_H)
- At tree level, all is nice and simple
- The problem arises when incorporating higher orders
  - Depending on where one decides to “hide” HO contributions in the formulas, one ends up having different predictions for the calculated quantities
    - with different dependence on m_t
  - A striking consequence of this is that the PDG lists not one, but FIVE different possible values of the weak mixing angle

Normalization schemes

- The most relevant normalization scheme for A_{FB} measurements is the *Effective* one, since it is directly related to the coupling of Z to fermions

Scheme	Notation	Value
On-shell	s_W^2	0.2233
NOV	$s_{M_Z}^2$	0.2311
$\overline{\text{MS}}$	$\hat{s}_Z^2$	0.2313
$\overline{\text{MS}}$ ND	$\hat{s}_{\text{ND}}^2$	0.2315
Effective angle	$\bar{s}_f^2$	0.2316

- Bulk of EW corrections is absorbed into *effective* couplings
- One then defines an *effective* weak mixing angle in such a way that the new couplings are proportional to the tree-level ones
  - The predictions for the asymmetries stay *formally identical* to the tree-level expressions, modulo using the effective angle instead of the “bare” one