Precision measurements of Standard Model parameters with the ATLAS detector

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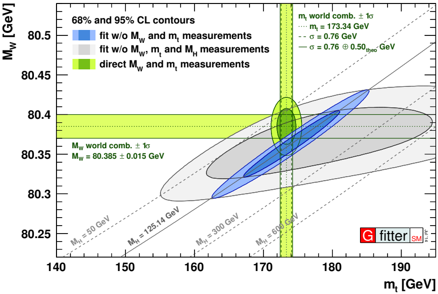
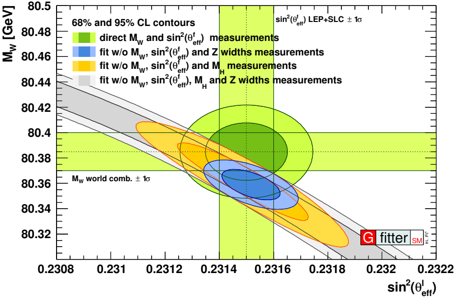
Introduction

- Standard Model is over-constrained (with the Higgs boson discovery)
- The precision measurements are of great importance for testing the Standard Model
- Indirect information of new physics
- Figures show scans of M_W vs m_t and M_W vs $\sin^2(\theta^l_{eff})$ for the direct measurement (green band) compared to the fit including direct M_H (blue band)
- M_W and $\sin^2(\theta^l_{eff})$ have become the sensitive probe for new physics (both are "tree" level SM predictions)
- **This talk will focus on**:
  - ATLAS measurement of the weak mixing angle
  - Towards the M_W measurement





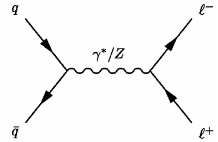
Weak mixing angle

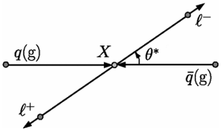
Measurement of the forward-backward asymmetry of electron and muon pair-production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

`http://arxiv.org/pdf/1503.03709v1.pdf` (submitted to JHEP)

Leptons produced in $q\bar{q} \to Z/\gamma^* \to l^+l^-$ are expected to have a forward-backward asymmetry with respect to the quark direction in the rest frame of the dilepton system (Collins-Soper frame)

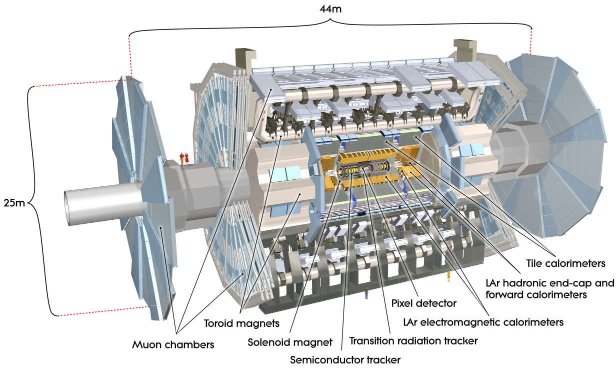
- The angle between the lepton and the quark in CS frame:
  $$\cos\theta^*_{\mathrm{CS}} = \frac{p_{z,ll}}{|p_{z,ll}|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m_{ll}\sqrt{m_{ll}^2+p_{\mathrm{T},ll}^2}}, \text{ where } p_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{i,z})$$
- The direction of the incoming quark needs to be known.
- The asymmetry:
  $$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$
  where σ_{F} and σ_{B} are the cross sections for forward and backward configurations, is measured as a function of the invariant mass of the dilepton system.
- The electroweak mixing angle can be extracted from the asymmetry.
- Forward direction is defined as the longitudinal boost of the resulting lepton pair
  - probability of misidentifying the quark direction decreases with with increasing boost of the dilepton system
  - valence quarks





ATLAS Detector and Event Selection

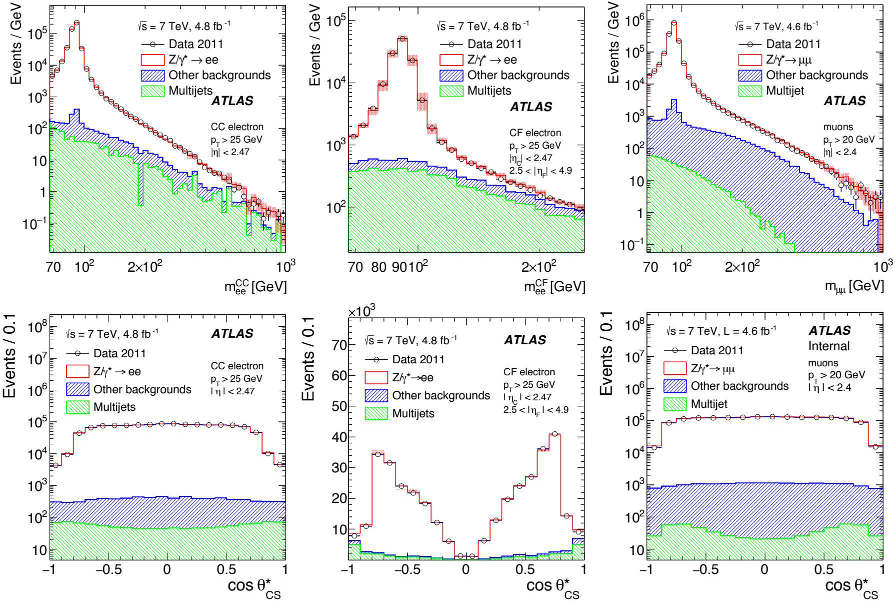
- $Z \to ee$ and $Z \to \mu\mu$ decays in 2011 data with $4.8\,\text{fb}^{-1}$ for electron and $4.6\,\text{fb}^{-1}$ for muon channel.
  - Central Electrons: $|\eta| < 2.47$ (ID+Calo)
  - Forward Electrons: $2.5 < |\eta| < 4.9$ (Calo)
  - Muons: $|\eta| < 2.4$ (ID+MS)



- MC signal samples: PYTHIA 6.4 (MSTW2008 LO) + POWHEG
  FSR from QED taken using PHOTOS
  cross-section at NNLO using PHOZPR (MSTW2008 NNLO)
- Background:
  - $Z/\gamma^* \to \tau\tau$: PYTHIA 6.4
  - WW, ZZ, WZ: HERWIG 6.510
  - $\tau\bar{\tau}$: MC@NLO 4.01 + HERWIG
  - Multi-jet: Data-driven methods

Invariant Mass and $\cos\theta^*_{CS}$ Distributions

CC Electrons **CF Electrons** **Muons**



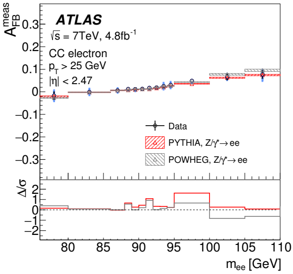
Detector-Level Forward-Backward Asymmetry

A_{FB} is number of forward and backward events for each invariant mass bin:

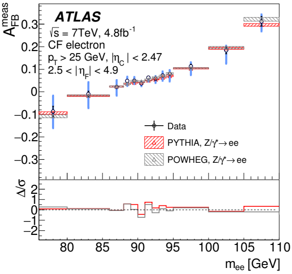
$$A_{\mathrm{FB}} = \frac{N_{\cos\theta^*_{CS}\geq 0} - N_{\cos\theta^*_{CS}<0}}{N_{\cos\theta^*_{CS}\geq 0} + N_{\cos\theta^*_{CS}<0}}$$

after background subtraction.

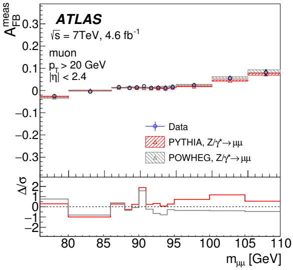
CC Electrons



CF Electrons



Muons



- Good agreement between Data and simulation.

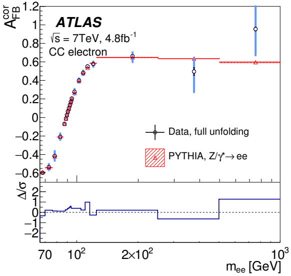
Particle-Level Forward-Backward Asymmetry

Iterative Bayesian unfolding method must correct for :

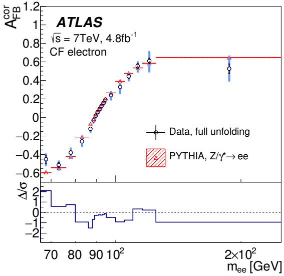
- Detector effects
- QED radiative corrections
- Remove dilution effects (wrong choice is made for the direction of the incoming quark):
  - depends on the generator
  - the contribution from the PDFs becomes the dominant systematic uncertainty

The fully corrected spectra for Born-level leptons:

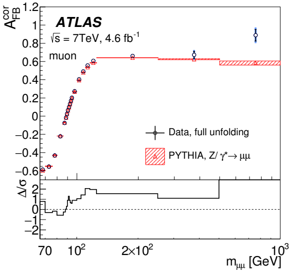
CC Electrons



CF Electrons



Muons



Systematics on Forward-Backward Asymmetry

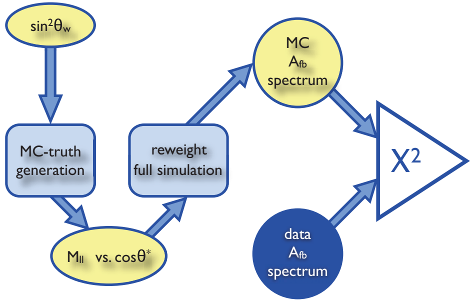
CC electrons			
Uncertainty	66–70 GeV	70–250 GeV	250–1000 GeV
Unfolding	$\boxed{\sim 1\times10^{-2}}$	$\boxed{(2\text{–}5)\times10^{-3}}$	$\sim 4\times10^{-4}$
Energy scale/resolution	$\sim 7\times10^{-3}$	$(0.5\text{–}2)\times10^{-3}$	$\boxed{\sim 2\times10^{-2}}$
MC statistics	$\sim 5\times10^{-3}$	$(0.1\text{–}1)\times10^{-3}$	$(3\text{–}20)\times10^{-3}$
PDF	$\sim 2\times10^{-3}$	$(1\text{–}8)\times10^{-4}$	$(0.7\text{–}3)\times10^{-3}$
Other	$\sim 1\times10^{-3}$	$(0.1\text{–}2)\times10^{-3}$	$(5\text{–}9)\times10^{-3}$

CF electrons			
Uncertainty	66–70 GeV	70–250 GeV	250–1000 GeV
Unfolding	$\sim 2\times10^{-2}$	$\boxed{(0.5\text{–}2)\times10^{-2}}$	–
Energy scale/resolution	$\sim 1\times10^{-2}$	$\boxed{(0.5\text{–}7)\times10^{-2}}$	–
MC statistics	$\sim 1\times10^{-2}$	$(1\text{–}7)\times10^{-3}$	–
Background	$\boxed{\sim 3\times10^{-2}}$	$\boxed{(0.5\text{–}1)\times10^{-2}}$	–
PDF	$\sim 4\times10^{-3}$	$(2\text{–}6)\times10^{-4}$	–
Other	$\sim 1\times10^{-3}$	$(1\text{–}5)\times10^{-4}$	–

Muons			
Uncertainty	66–70 GeV	70–250 GeV	250–1000 GeV
Unfolding	$\boxed{\sim 1\times10^{-2}}$	$(1\text{–}4)\times10^{-3}$	$\sim 5\times10^{-4}$
Energy scale/resolution	$\sim 8\times10^{-3}$	$\boxed{(3\text{–}6)\times10^{-3}}$	$\sim 5\times10^{-3}$
MC statistics	$\sim 5\times10^{-3}$	$(0.1\text{–}1)\times10^{-3}$	$\boxed{(2\text{–}30)\times10^{-3}}$
PDF	$\sim 2\times10^{-3}$	$(1\text{–}8)\times10^{-4}$	$(0.3\text{–}3)\times10^{-3}$
Other	$\sim 1\times10^{-3}$	$(0.5\text{–}1)\times10^{-3}$	$(3\text{–}10)\times10^{-3}$

- Unfolding uncertainty:
  reweight spectrum to data and then use response matrix to fold and unfold the spectrum
- Multi-jet background modelling:
  difference between two methods
- Other experimental systematic uncertainties:
  energy scaling and resolution are the largest contributions
- PDF uncertainties:
  reweighted to eigenvalues in the CT10 PDF set (at 68% CL)

Measurement of The Effective Weak Mixing Angle



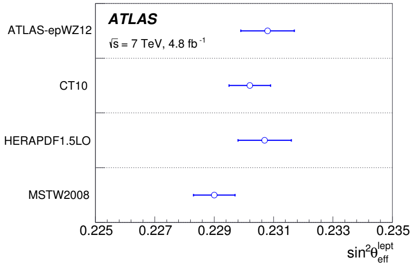
- $\sin^2(\theta^l_{\text{eff}})$ was extracted from each of the measured A_{FB} spectra by comparing the detector-level asymmetry to Monte Carlo predictions produced with varying initial values of the weak mixing angle
- PYTHIA templates with initial values $0.218 \le \sin^2(\theta^l_{\text{eff}}) \le 0.238$
- χ^2 fits in the mass range $70 - 250\,\text{GeV}$

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

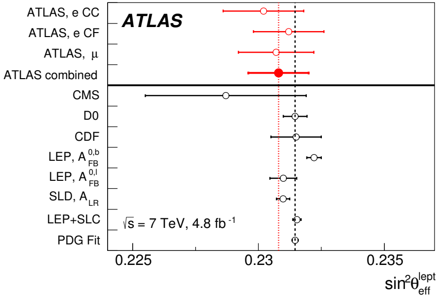
Systematics on The Effective Weak Mixing Angle

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

- Final uncertainty dominated by PDF (ATLAS-epWZ12 LO PDF set)
  - Variation of PDF set leads to significant shifts
  - MSTW2008 shifts down the value by 0.002
  - precision measurements are needed to constrain PDFs
    W/Z cross-section measurement, Angular distributions



Results for The Effective Weak Mixing Angle



- $\boxed{\sin^2(\theta^{l}_{\text{eff}}) = 0.2308 \pm 0.0012}$
- Agreement with PDG global fit (0.6σ): $\sin^2(\theta^{l}_{\text{eff}}) = 0.23146 \pm 0.00012$
- Result is about 10 times less precise than LEP+SLC
  - limited by the PDF uncertainty

Determination of **Muon Asymmetry Parameter** A_μ:

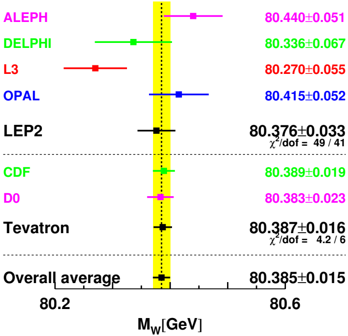
- can be estimated from A_{FB}, assuming the SM value for A_q and estimation

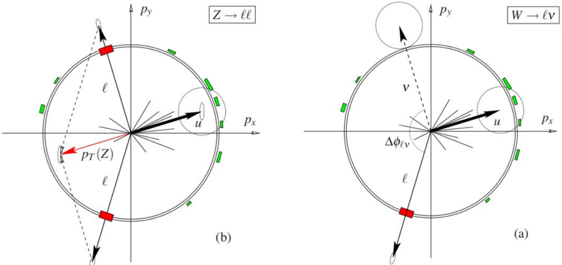
$$\sin^2\theta^{q}_{\text{eff}} = \sin^2\theta^{\mu}_{\text{eff}} = \sin^2\theta^{\text{lept}}_{\text{eff}} \text{ (valid up to } 1.5\cdot 10^{-3}\text{)}: A_\mu = \frac{2(1-4\sin^2\theta^{\text{lept}}_{\text{eff}})}{1+(1-4\sin^2\theta^{\text{lept}}_{\text{eff}})}$$

- $\boxed{A_\mu = 0.153 \pm 0.007(stat.) \pm 0.009(syst.) = 0.153 \pm 0.012}$
- in agreement with measurements from LEP/SLD (0.142 ± 0.015)
  `http://arxiv.org/pdf/hep-ex/0509008v3.pdf`

Towards the M_W Measurement

- Among electroweak observables, the W mass is the least constrained by current experimental data
- indirect determination better by factor of ~ 2
- world average $\delta M_W = 15\,\text{MeV}$
- natural goal at the LHC $\delta M_W < 10\,\text{MeV}$
- Measurement is dominated by physics modeling (PDFs)
- Basic objects: **lepton** and **hadronic recoil**
- Z events can be used for calibration
- M_W is extracted from the comparison of data with MC templates of the mass-sensitive distributions: p_T^l and M_T





Summary

ATLAS measurement of the weak mixing angle

- $\sin^2(\theta^{l}_{\mathrm{eff}}) = 0.2308 \pm 0.0005(stat.) \pm 0.0006(syst.) \pm 0.0009(PDF) = 0.2308 \pm 0.0012$
- Good agreement with other measurements
- Uncertainty is dominated by the PDFs ($\sim 75\%$)
- Determined value of muon asymmetry parameter is in good agreement with previous measurements

Towards the M_W Measurement

- Detector calibration is under control:
  - Electron Calibration: Eur.Phys.J. C74 (2014) 10, 3071
  - Muon Calibration: Eur.Phys.J. C74 (2014) 11, 3130
- Physics modeling of W production is a challenge

Further electroweak measurements are important in order to constrain the models:

- W/Z cross-section measurement[1], W charge asymmetry, W+ charm production
- p_{T}^{Z} measurement[2]
- p_{T}^{W} measurement (needs low pile-up Data sample)

[1]Phys. Rev. D 85, 072004, 2012; Phys. Rev. Lett. 109, 012001, 2012
[2]Phys. Lett. B 738, 25, 2014; Phys. Lett. B 720, 32, 2013

Backup

Standard Model - Fit Results

Pull values for SM fit defined as deviations to the indirect determinations, divided by total error:

- Direct measurement (data)
- Full fit result
- Fit result without using corresponding direct constraint from the measurement

- Total error: error of direct measurement plus error from indirect determination

- The prediction is often more precise then the **measurement**, exceptions: $M_H, M_Z, m_t, \Delta\alpha^{(5)}_{had}(M_Z^2)$