Precision measurements of Standard Model parameters with the ATLAS detector

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

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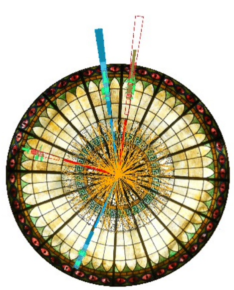

ATLAS
EXPERIMENT

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Introduction

- With m_H all parameters of the Standard Model are now known.
- Now we need to measure them with higher precision to test consistency.
- Presenting a new ATLAS measurement of the weak mixing angle $\sin\theta_W$

$$\sin^2\theta_{\rm W} = \left(\frac{e}{g}\right)^2 = 1 - \frac{m_{\rm W}^2}{m_{\rm Z}^2}$$ at tree level.

- The weak mixing angle θ_W can be measured from Drell-Yan *Z* production $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ using

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

where A and B depend on $\sqrt{\hat{s}}$ and the ew. couplings.

- Linear term leads to asymmetry A_{FB} in polar angle distribution of the lepton

$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}}$$

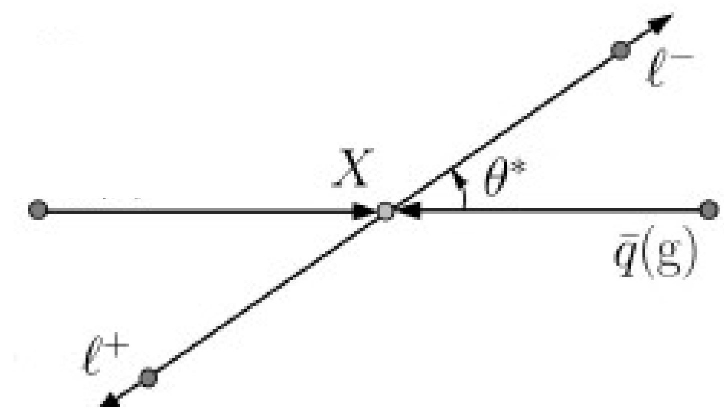
where forward (f) and backward (b) are defined with respect of the incoming quark

Measuring A_{FB} in *pp* collisions

- In *pp* collisions the incoming quark 4-momentum can not be measured if not collinear with the beam (if $p_T^Z > 0$)
- Measure in the rest frame of the lepton pair $\ell^+\ell^-$ (Collins-Soper frame)

$$\cos\theta^*_{CS} = \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}\frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}}$$

with $p_i^\pm = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$

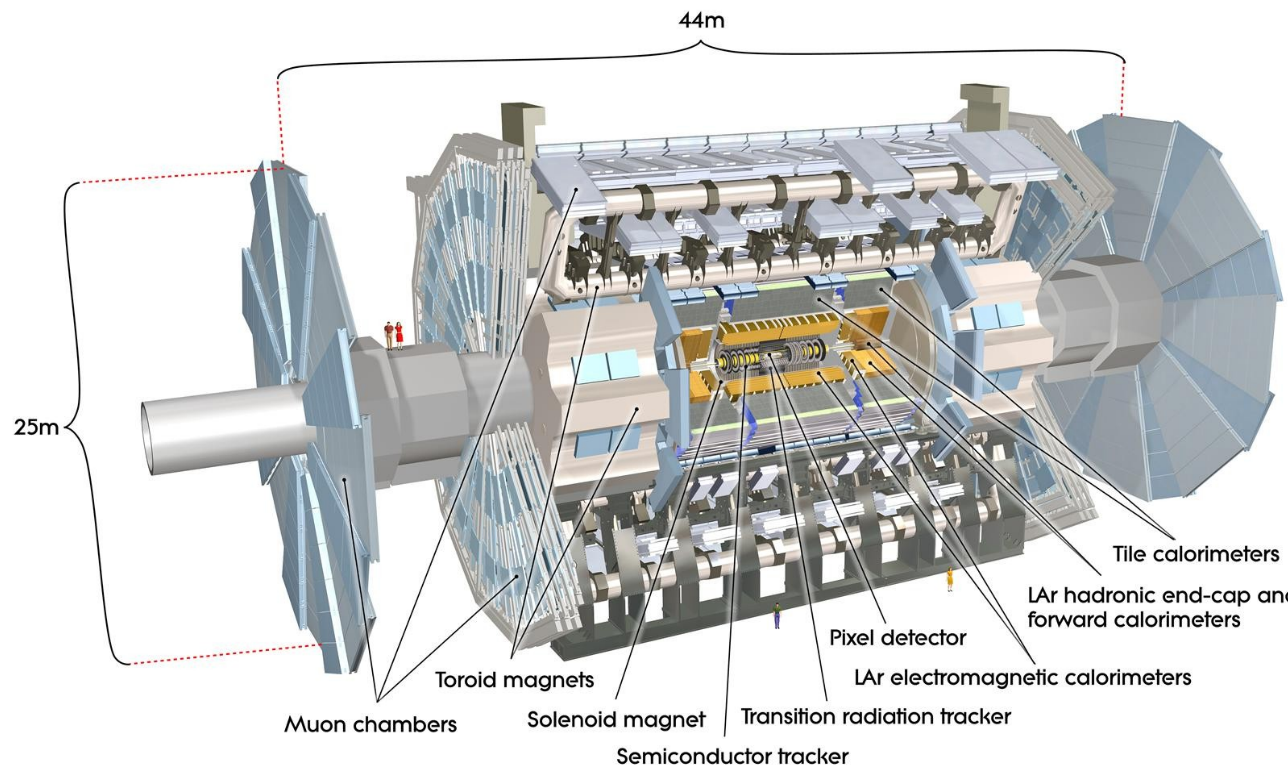


- Forward direction assumed to be the direction of the boost of the lepton
  - In some cases this is wrong: **Dilution**
  - Only valence quarks give rise to an asymmetry: **PDF dependence**

Electron and Muon ID with the ATLAS Detector

- Analysis uses 4.8 fb^{-1} of 7 TeV data

- Measuring *Z* decays in two electron final state topologies (central-central, CC and central-forward, CF) and in the muon final state



- Central electrons $|\eta| < 2.47$ tracking via Inner detector + calorimeters (em. Lar + had. Tile)
- Forward electrons $2.5 < |\eta| < 4.9$ calorimetric info only Lar, Tile and forward Cal ($3.1 < |\eta| < 4.9$)
- Muons $|\eta| < 2.7$ muon spectrometer

Signal and Background Modelling

- Signal from PYTHIA 6.4 (MSTW2008LO) + POWHEG
  - Final state radiation usingPHOTOS
  - Normalized to cross section at NNLO from PHOZPR (MSTW2008 NNLO)

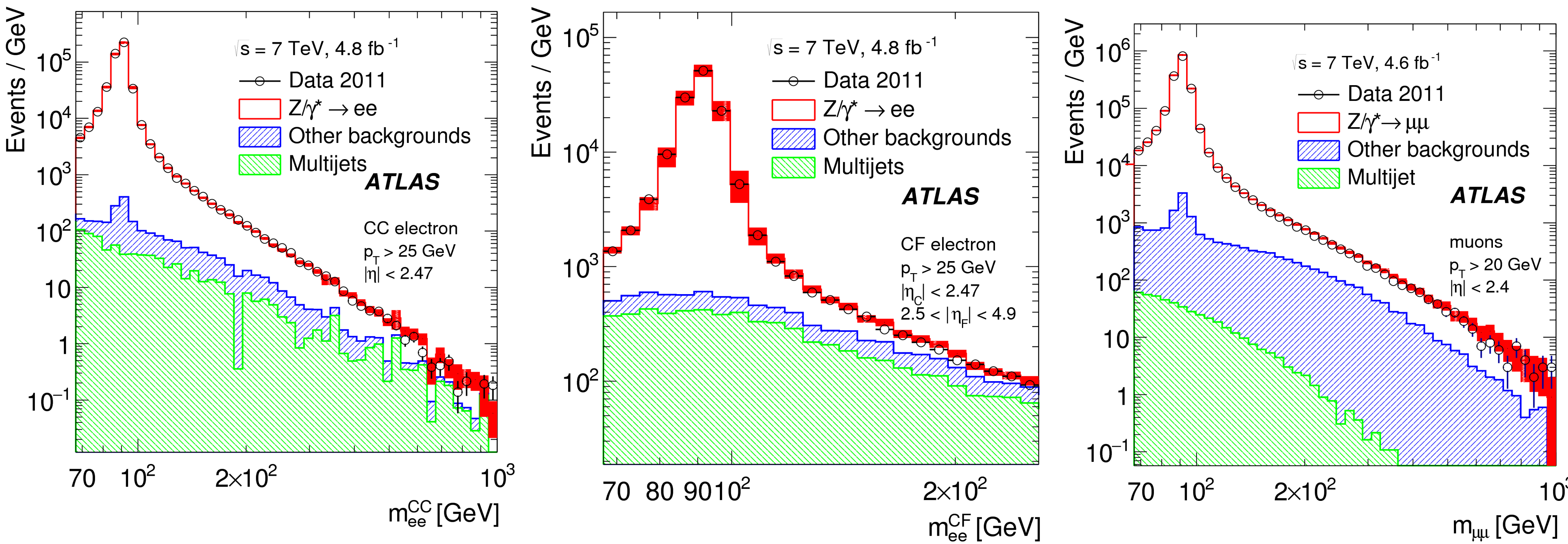
- Backgrounds estimated from MC simulations at (N)NLO

• Z --> tau tau	PYTHIA 6.4 (like signal)
• Diboson	HERWIG 6.510 (MRSTMCal)
• Top quark pair-production	MC@NLO 4.01 (CTEQ6L1) + HERWIG

- Multijet and W+jets Backgrounds estimated together from data-driven Methods

• CC electron	
• $m_{ll} < 125$ GeV:	Reverse identificaton
• $m_{ll} > 125$ GeV:	Fake-factor method
• $110 < m_{ll} < 200$ GeV:	Both methods combined
• CF electron ($m_{ll} < 250$ GeV):	Reverse identification
• Muon	Inverted isolation criterium

Di-Lepton Invariant Mass Distributions

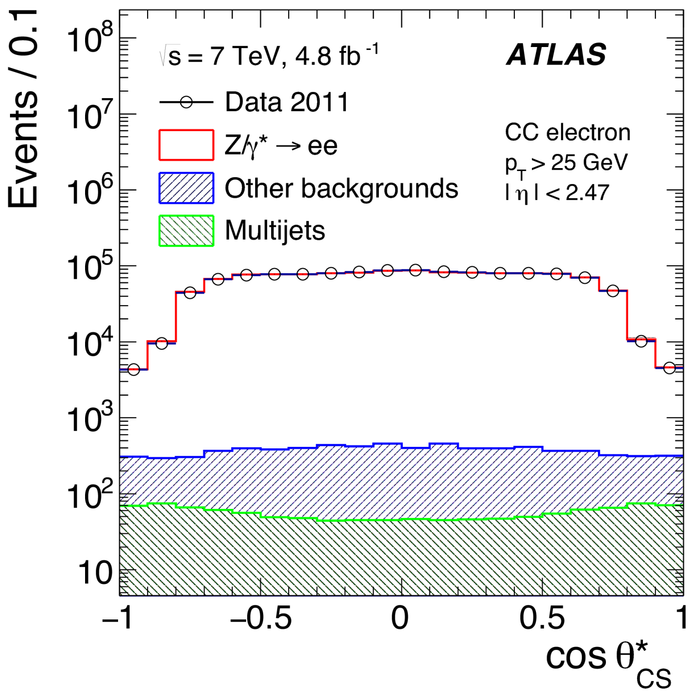


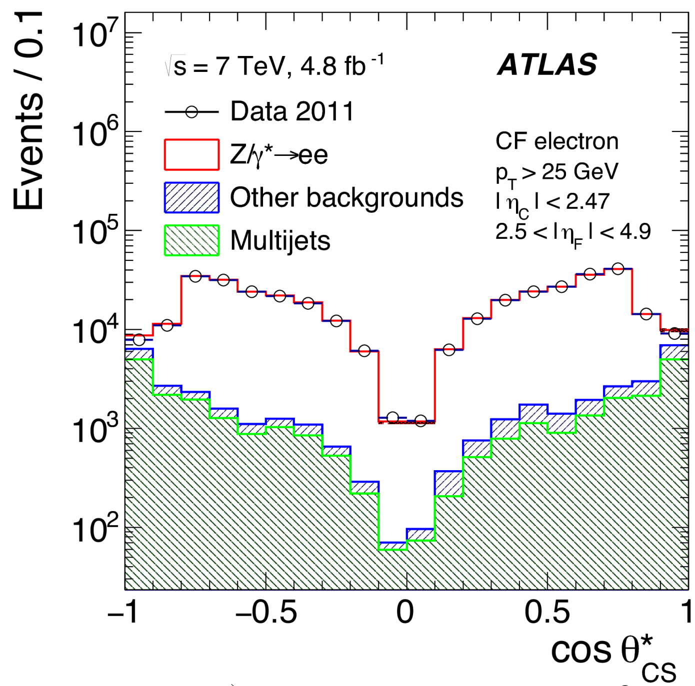
- Detector Level Distributions
  - Red bands contain all experimental systematic uncertainties

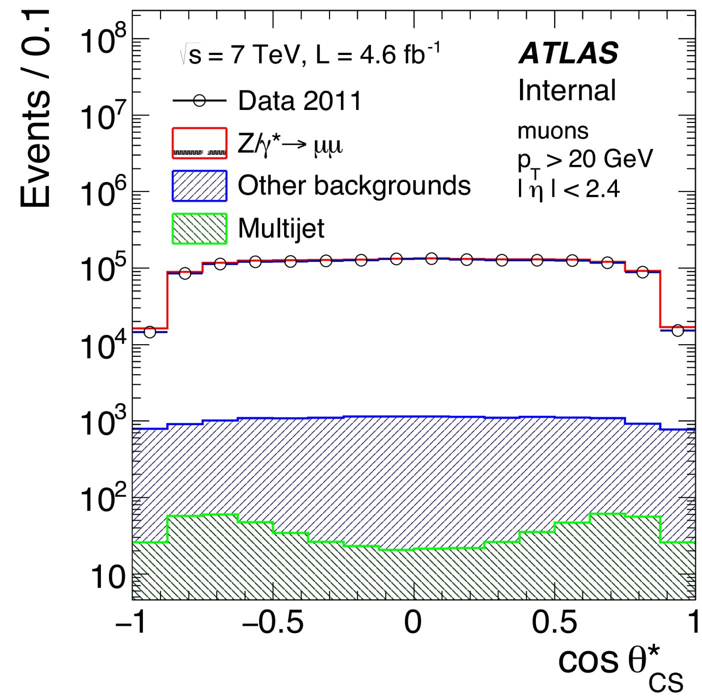
- CC and muon channel measure up to $m_{ll} < 1000$ GeV
  - Backgrounds in *Z* peak region ~ 1%

- CF electron only up to $m_{ee}^{CF} < 250$ GeV due to large backgrounds above
  - Backgrounds in *Z* peak region ~ 5%

Cosine of Polar Angle in Collins-Soper frame

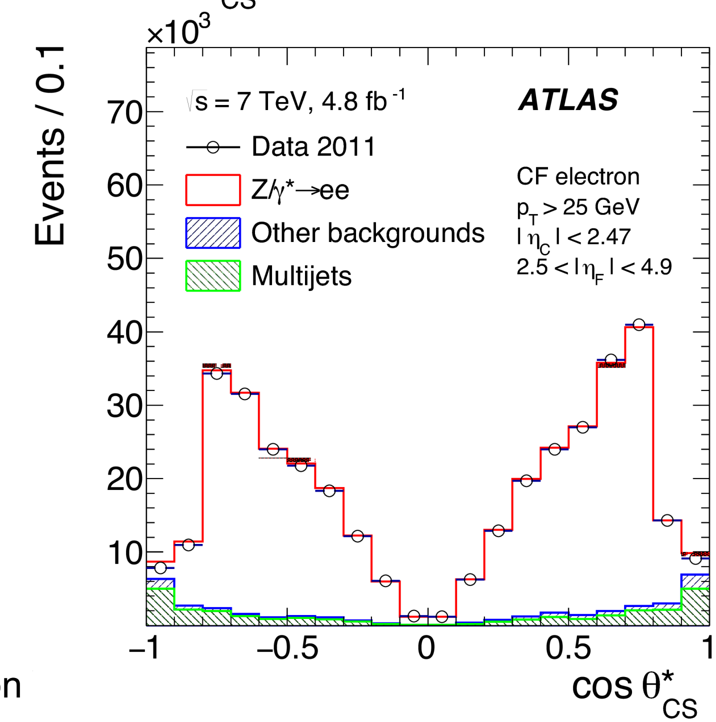






- $\cos\theta^*_{CS}$ distributions at detector level

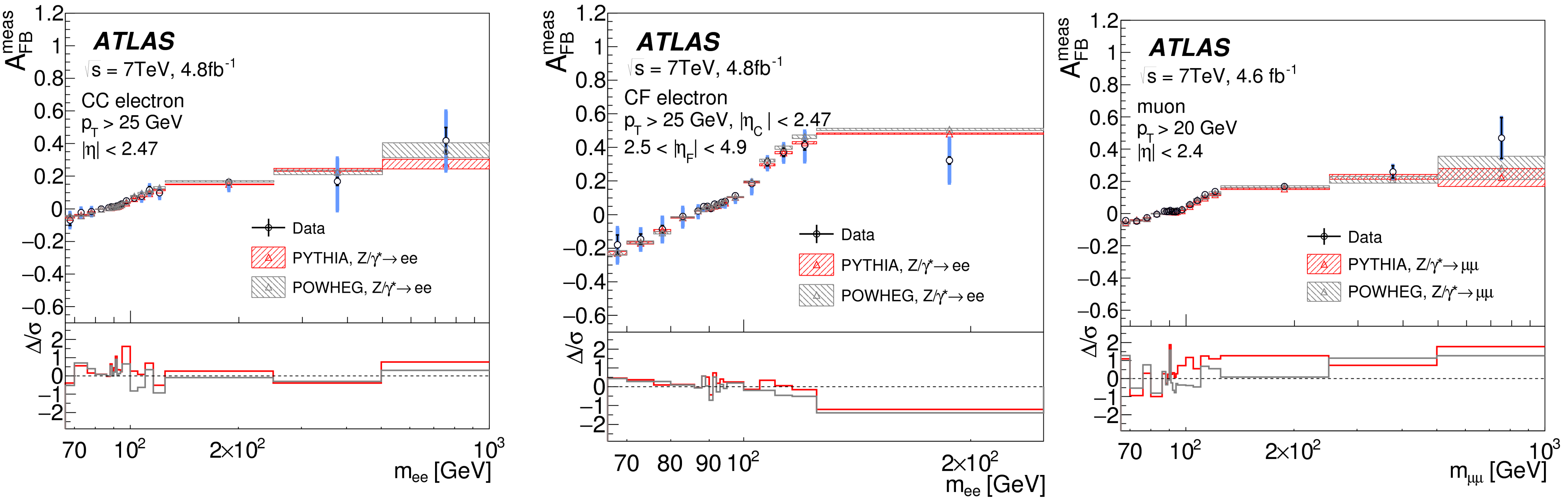
CF electrons:
In linear scale asymmetry
is directly visible on the plot



Detector Level A_{FB}^{meas}

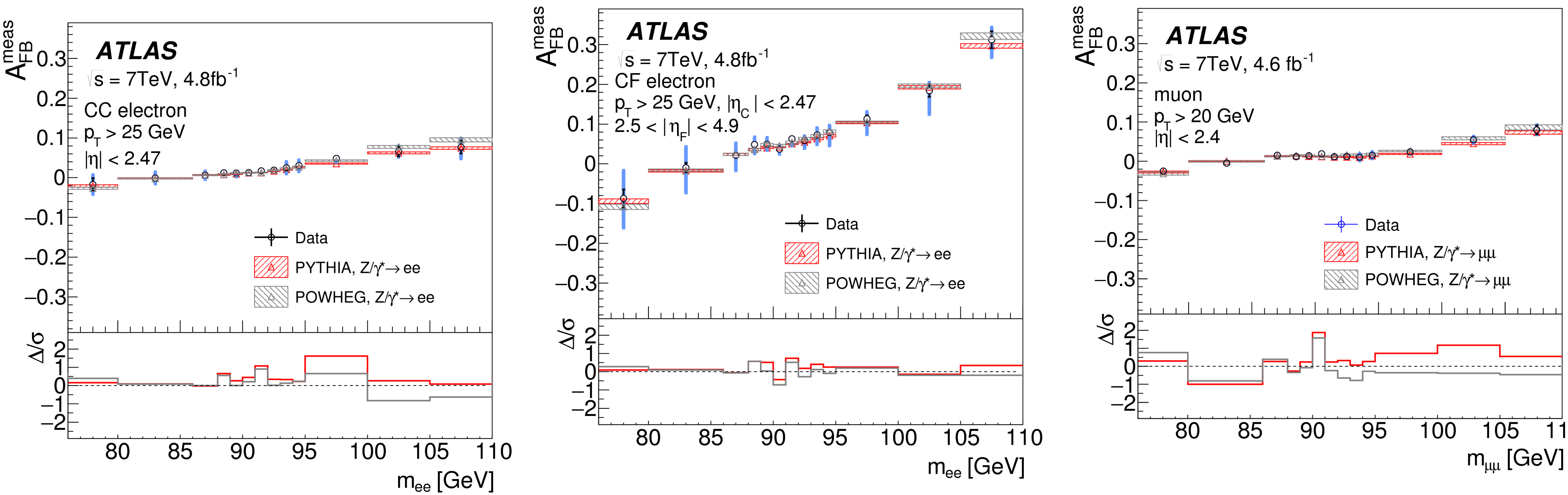
- Calculate A_{FB} from cos θ^*_{CS} distributions at detector level after background subtraction

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



- Good agreement of data with PYTHIA and POWHEG predictions

Detector Level A_{FB}^{meas} around Z-pole

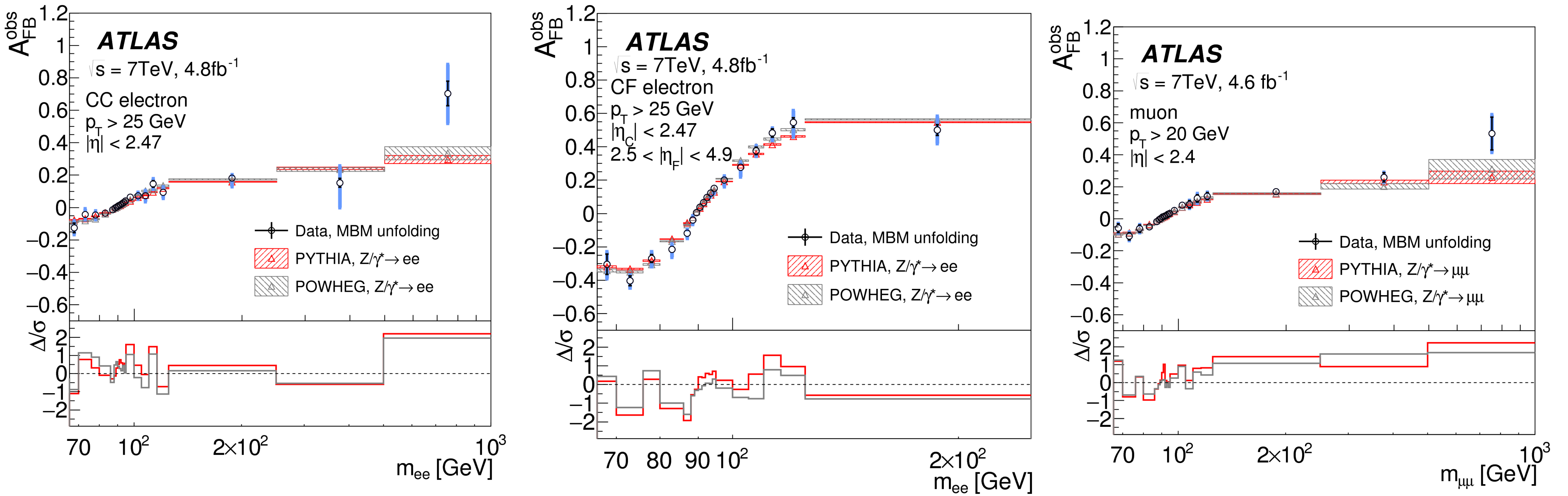


- A closer look around the Z peak
- Good agreement of data with PYTHIA and POWHEG predictions

Unfolding to Particle Level: A_{FB}^{obs}

- Use Bayesian iterative procedure using PYTHIA signal sample to correct for
  - Detector effects
    - Cross checked with PYTHIA LO
  - QED Final State Radiation (back to "Born level")
    - Cross checked with SHERPA + PHOTONS++
  - Cross check on EWK corrections using HORACE MC
  - Cross check on NLO QCD effects using POWHEG pseudo data

→ All cross check effects smaller than statistical unfolding error!



- Good agreement of A_{FB}^{obs} and PYTHIA, POWHEG predictions

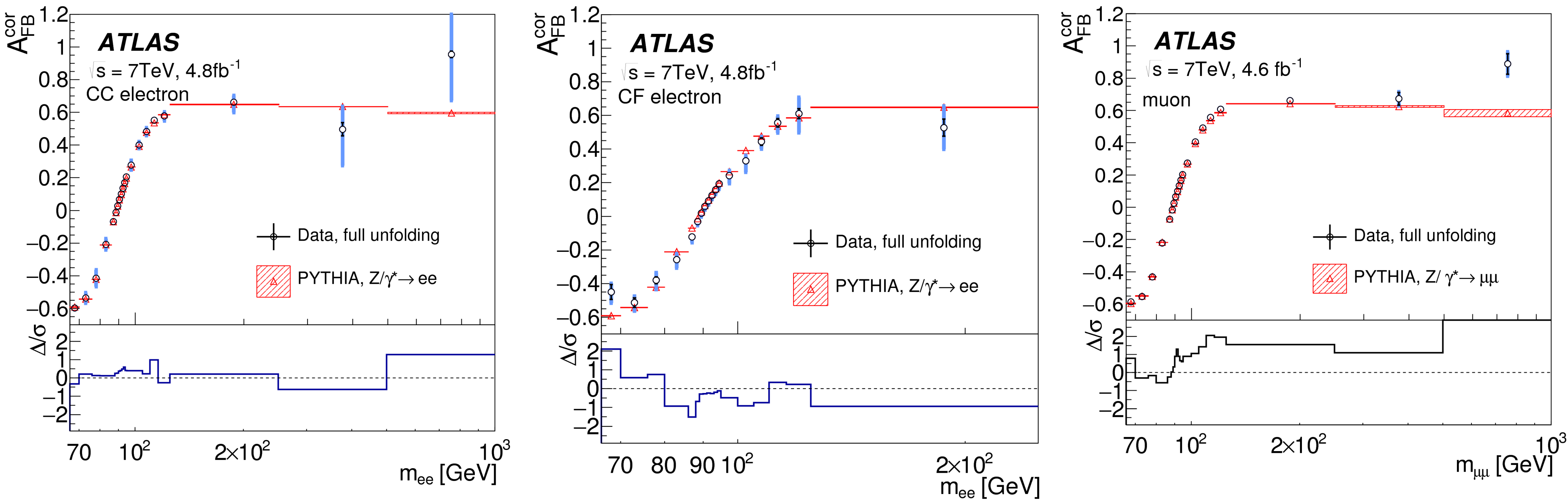
Summary of Systematic Uncertainties on A_{FB}^{obs}

- Unfolding uncertainty from data reweighting and response matrix statistics
- PDF from response matrix reweighted to CT10 eigenvectors at 68%CL
- "Other" contains experimental uncertainties
- Background uncertainty from difference between methods (negligible in CC *e* and muons)
- No single dominating uncertainty overall

CC electrons			
Uncertainty	66–70 GeV	70–250 GeV	250–1000 GeV
Unfolding	$\sim 1\times10^{-2}$	$(2\text{–}5)\times10^{-3}$	$\sim 4\times10^{-4}$
Energy scale/resolution	$\sim 7\times10^{-3}$	$(0.5\text{–}2)\times10^{-3}$	$\sim 2\times10^{-2}$
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	$\sim 2\times10^{-2}$	$(0.5\text{–}2)\times10^{-2}$	–
Energy scale/resolution	$\sim 1\times10^{-2}$	$(0.5\text{–}7)\times10^{-2}$	–
MC statistics	$\sim 1\times10^{-2}$	$(1\text{–}7)\times10^{-3}$	–
Background	$\sim 3\times10^{-2}$	$(0.5\text{–}1)\times10^{-2}$	–
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	$\sim 1\times10^{-2}$	$(1\text{–}4)\times10^{-3}$	$\sim 5\times10^{-4}$
Energy scale/resolution	$\sim 8\times10^{-3}$	$(3\text{–}6)\times10^{-3}$	$\sim 5\times10^{-3}$
MC statistics	$\sim 5\times10^{-3}$	$(0.1\text{–}1)\times10^{-3}$	$(2\text{–}30)\times10^{-3}$
PDF	$\sim 2\times10^{-3}$	$(1\text{–}8)\times10^{-4}$	$(0.3\text{–}3)\times10^{-3}$
Other	$\sim 1\times10^{-3}$	$(0.5\text{–}1)\times10^{-3}$	$(3\text{–}10)\times10^{-3}$

Dilution and Acceptance Correction: A_{FB}^{cor}

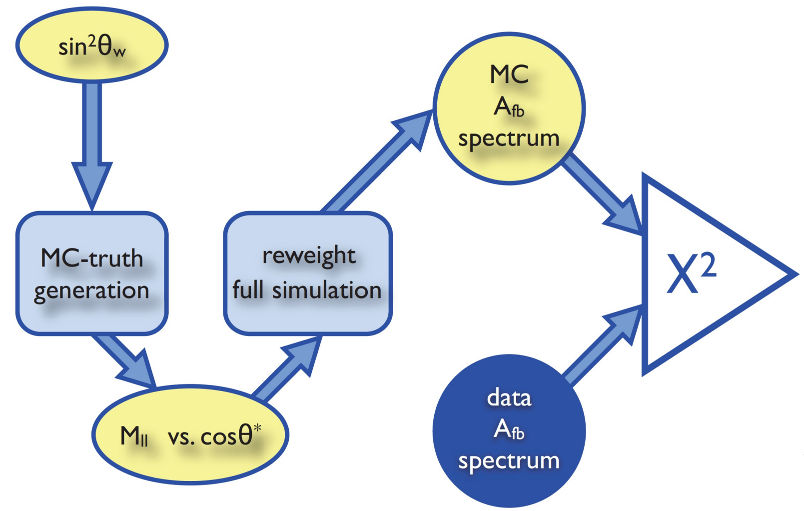
- Unfold A_{FB}^{obs} again to A_{FB}^{cor} using PYTHIA signal MC sample to correct for
  - Dilution
  - Geometrical acceptance
- Introduces large dependence on generator
- PDFs become dominant systematic uncertainty



- Discrepancy at $m_{ll} > m_Z$ in the muon channel enhanced by unfolding
- Possibly from incomplete knowledge of PDFs and higher-order effects in MC used for correction (dilution unfolding only meaningful at LO)

Measurement of $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$

- Use PYTHIA templates to extract the weak angle from A_{FB}^{meas}
- Reweight to a set of A_{FB}^{rew} using different weak angles at generator level
- Perform χ^2 fits in the mass range 70 – 250 GeV



Some notes on cross checks and systematics:

- FSR effects (estimated with SHERPA): negligible
- NLO QCD corrections uncertainty (estimated with MCFM)
- Background uncertainty (estimated by extraction before subtraction): ~10%
- Impact of PDFs
  - A_{FB} depends on flavour and charge of initial partons -> sensitive to PDFs
  - A special LO PDF fit based on ATLAS-epWZ NNLO and NLO using the latest ATLAS data was prepared:

ATLAS-epWZ12 LO

ATLAS Results for $\sin^2\theta_{\text{eff}}^{\text{lept}}$

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

- Combination of channels by quadratic error weighting
  - Experimental uncertainties taken as completely uncorrelated (due non-overlapping detector regions or statistical origin)
  - Theoretical uncertainties taken as completely correlated

- Final uncertainty dominated by PDF uncertainty
  - Evaluated from ATLAS-epWZ12 LO PDF eigenvalue set

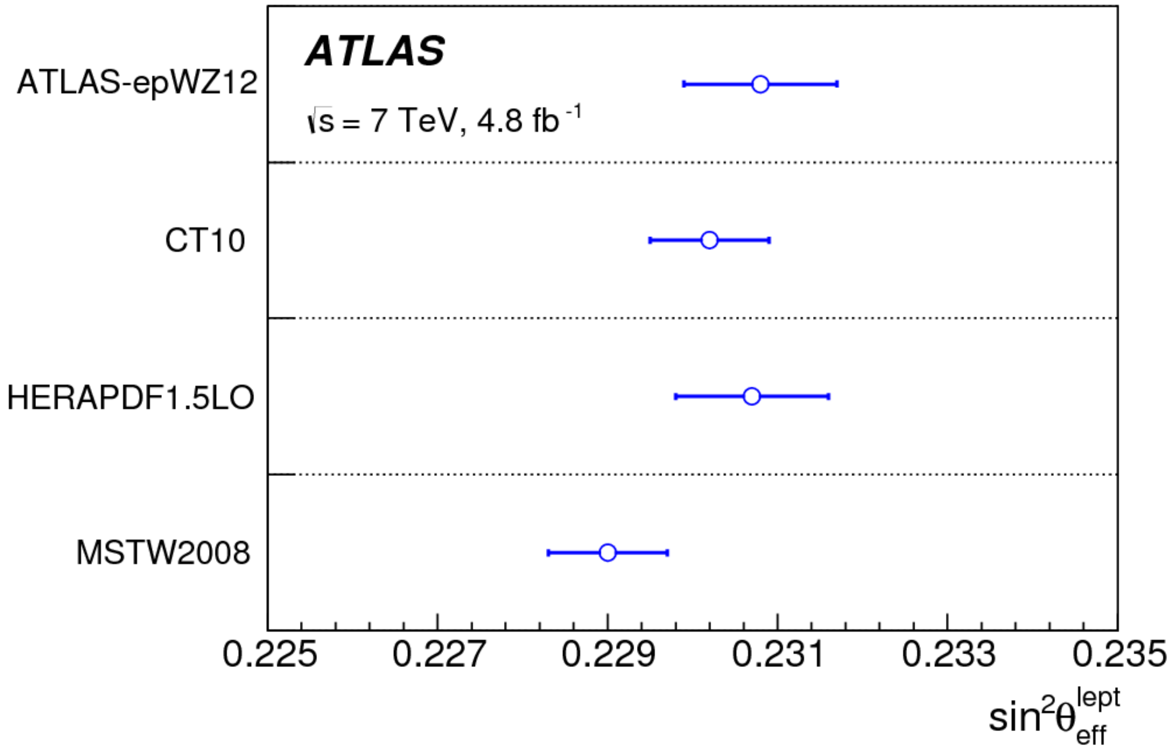
- Most accurate result from CF electrons
  - Direction of incoming quark is constrained best – least dilution

Syst. Uncertainties on $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$

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

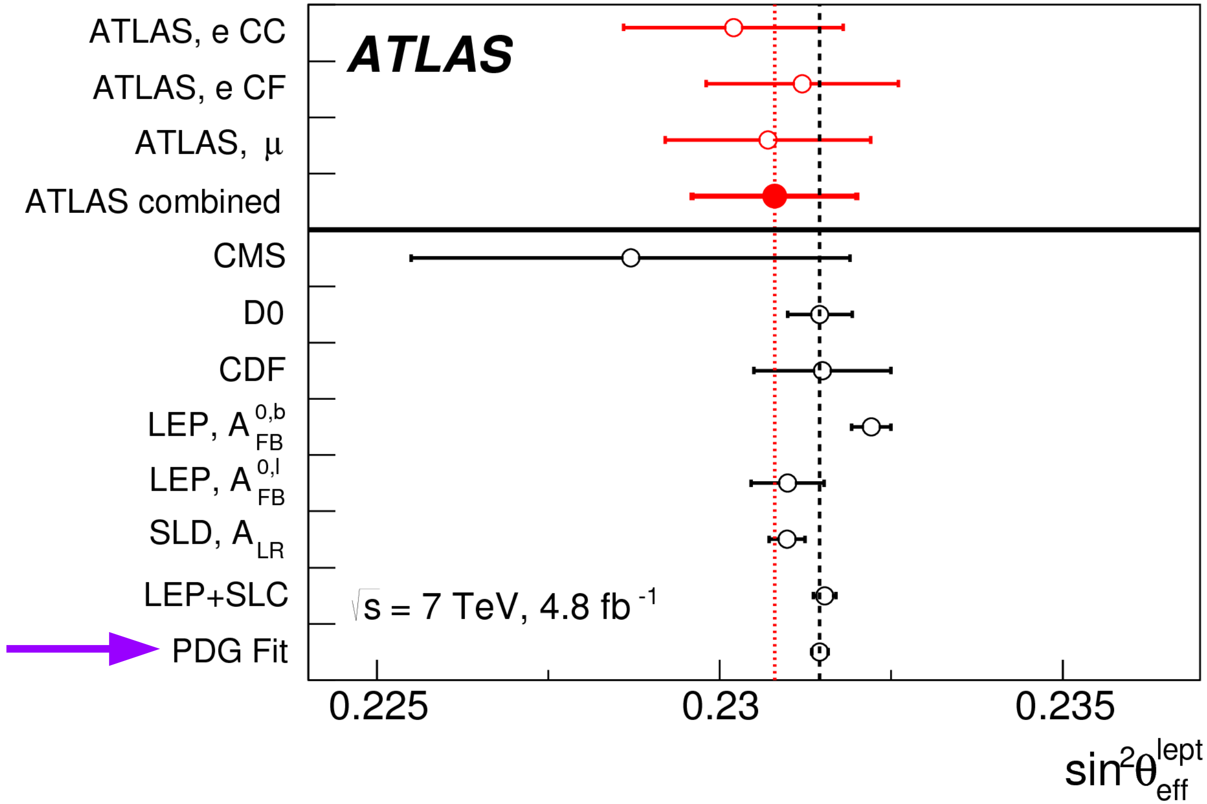
- Main error from PDF
  - Can be constrained better using future LHC electroweak measurements (W, Z cross sections, esp. angular distributions)
  - Will also help reduce theoretical uncertainties (angles not well modelled)

Impact of different PDF sets on $\sin^2\theta_{\text{eff}}^{\text{lept}}$



- Variation of PDF set itself leads to significant shifts in $\sin^2\theta_{\text{eff}}^{\text{lept}}$
  - Eg. by choosing MSTW2008 sin2th shifts down by ~ -0.002
  - How serious is this? In this PDF, there are known deficiencies --> Need further precision measurements to constrain PDFs
  - For example W and Z rapidity distributions and W,Z+heavy flavour production

Comparison to other experiments



- Agreement with **PDG global fit** at 0.6σ level
- ATLAS result still 10 times less precise than LEP+SLC result
  - Limited by PDF uncertainty

	$\sin^2\theta_{\text{eff}}^{\text{lept}}$	Δ/σ (wrt LEP+SLC)	Δ/σ (wrt ATLAS)
ATLAS	0.2308 ± 0.0012	-0.6	–
CMS [6]	0.2287 ± 0.0032	-0.9	-0.6
D0 [5]	0.23146 ± 0.00047	-0.1	0.5
CDF [4]	0.2315 ± 0.0010	-0.03	0.4
LEP, $A_{\text{FB}}^{0,b}$ [3]	0.23221 ± 0.00029	–	1.2
LEP, $A_{\text{FB}}^{0,l}$ [3]	0.23099 ± 0.00053	–	-0.1
SLC, A_{LR} [3]	0.23098 ± 0.00026	–	-0.1
LEP+SLC [3]	0.23153 ± 0.00016	–	0.6
PDG global fit [46]	0.23146 ± 0.00012	-0.4	0.6

Extraction of Asymmetry Parameter A_μ

- Asymmetry parameters are related to ew. couplings

$$A_{q/\mu} = \frac{2 g_V^{q/\mu} g_A^{q/\mu}}{(g_V^{q/\mu})^2 + (g_A^{q/\mu})^2} = \frac{2 g_V^{q/\mu} / g_A^{q/\mu}}{1 + (g_V^{q/\mu} / g_A^{q/\mu})^2}$$

  and to the weak angle via

$$g_V^{q/\mu} / g_A^{q/\mu} = 1 - 4|Q_{q/\mu}| \sin^2 \theta_{\text{eff}}^{q/\mu}$$

- Can be estimated from $A_{FB}^{0,\ell} = \frac{3}{4} A_q A_\ell$
- Need to assume SM value of A_q
- Using the estimate $\sin^2\theta_{\text{eff}}^q = \sin^2\theta_{\text{eff}}^\mu = \sin^2\theta_{\text{eff}}^{\text{lept}}$ we get

$$A_\mu = \frac{2(1 - 4\sin^2\theta_{\text{eff}}^{\text{lept}})}{1 + (1 - 4\sin^2\theta_{\text{eff}}^{\text{lept}})^2}$$

$$A_\mu = 0.153 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.}) = 0.153 \pm 0.012(\text{tot.})$$

- Compatible with and similar precision as the most precise measurement

  0.142 ± 0.015 (SLD Phys.Rept.427:257-454,2006 arXiv:hep-ex/0509008)

Summary

- ATLAS has measured the forward-backward asymmetry A_{FB} from Z/γ^* decays in 7 TeV pp collisions in electron and muon channels

- The measurement is used to extract the weak mixing angle

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

- Good agreement of this result with results from e^+e^- colliders, TeVatron and CMS

- Uncertainty dominated by knowledge of PDFs
  - Reduction possible using future ewk. measurements from LHC

- Extraction of the asymmetry parameter A_μ from the muon channel data and yields

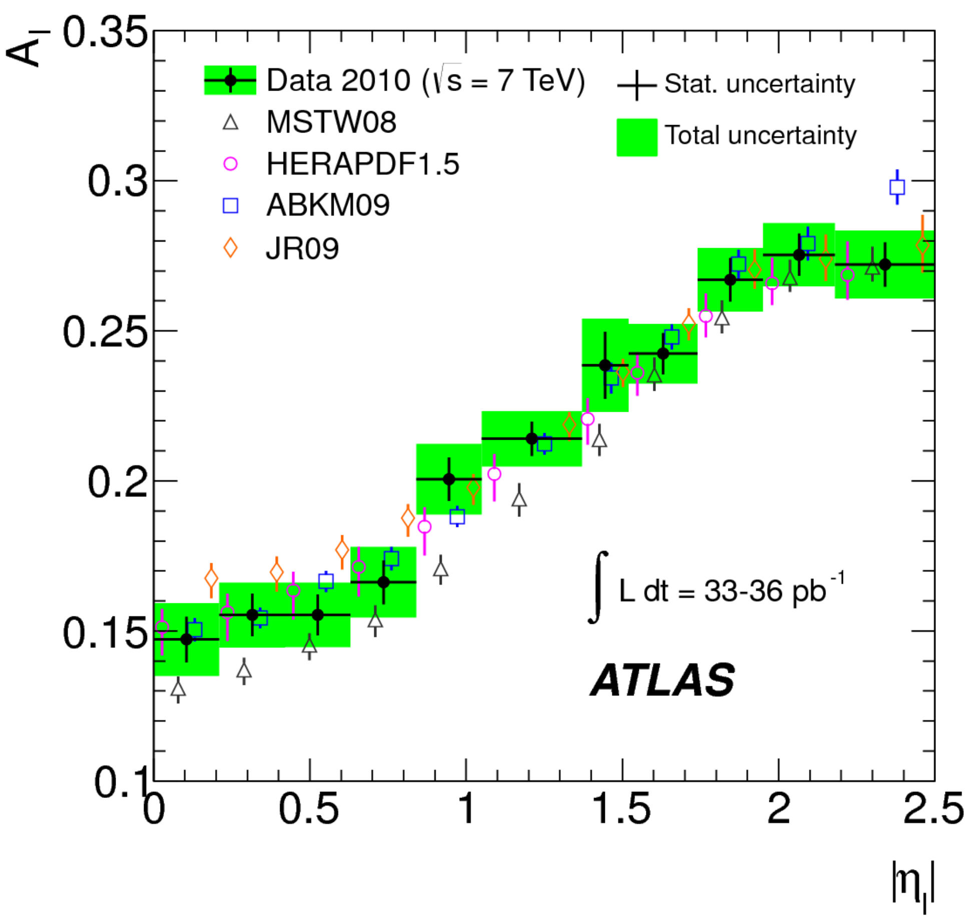
- Good agreement with best previous measurements

$$A_\mu = 0.153 \pm 0.007(\mathrm{stat.}) \pm 0.009(\mathrm{syst.}) = 0.153 \pm 0.012(\mathrm{tot.})$$

BACKUP

$\sin^2\theta_W$ measured using MSTW2008

- Using MSTW2008 produces a significant shift of -0.002 in $\sin^2\theta_W$
- Well known problems of this pdf to describe low x as well as u- and d-valence quark distributions
- Visible in W asymmetry which depends on (u-d) valence distribution at LO



- Similar effect in custom LO pdf used for this measurement