Dilepton Forward-Backward Asymmetry and electroweak mixing angle in ATLAS and CMS

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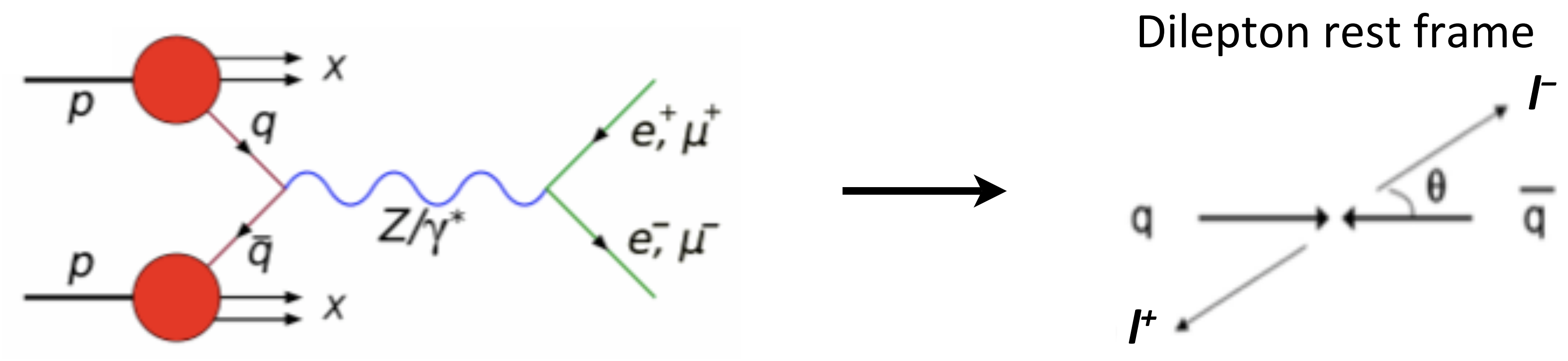
Introduction

- Forward-Backward asymmetry (A_{FB}) of Drell-Yan process



✓ Forward-Backward asymmetry is defined as

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$: F (B) denotes cosθ>0 (<0)

✓ A_{FB} originate from the interference of vector and axial coupling

✓ A_{FB} has strong dependence on dilepton mass (M)

- A_{FB} is close to zero near Z boson mass peak
- A_{FB} is large and negative at low M, but large and positive at high M

✓ A_{FB}(M) is sensitive to the electroweak mixing angle, $\sin^2\theta_W$

- A_{FB}(M) is used to extract the effective weak mixing angle

A_{FB} in LHC

- Differential cross section as a function of cosθ* in leading order (LO) :

$$\frac{d\sigma}{d(\cos\theta^*)} = A(1+\cos^2\theta^*) + \boxed{B\cos\theta^*}$$

Asymmetric term

- A_{FB} is calculated in Collins-Soper (CS) frame
  - ✓ CS frame reduces the uncertainties due to p_T of the incoming quarks
  - ✓ The quark direction(positive z-axis) is determined based on the rapidity direction

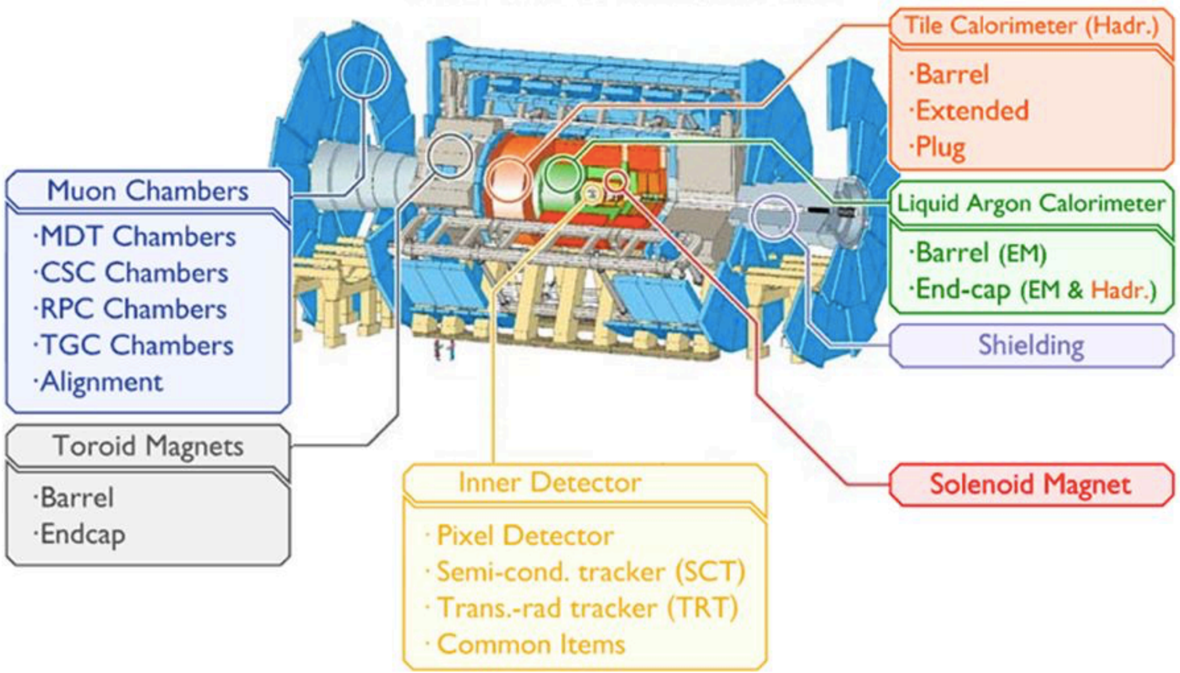
$$\cos\theta^*_{CS} \rightarrow \frac{|Q_z|}{Q_z}\cos\theta^*_{CS}$$

: where Q_z is the longitudinal momentum of the dilepton

  - In pp collision, the quark(*q*) and anti-quark(*qbar*) directions are not known
  - *q* carries more momentum than *qbar* as *qbar* must originate from the parton sea
  - On average, Z boson is boosted into *q* direction
- ✓ The ambiguity in the quark direction increases at low rapidity
  - A_{FB} in LHC has strong rapidity dependence
  - A_{FB} is more pronounced at large rapidity due to better identification of *q* direction
  - Extending the measurement in higher rapidity is important

This talk will cover ATLAS and CMS measurements ***(LHCb result in Xabier's talk)***

ATLAS and CMS Detector



ATLAS detector

Good muon coverage up to |η|=2.4

EM calorimeter : |η|<3.2

Forward calorimeter covers the region of 3.1<|η|<4.9

CMS detector

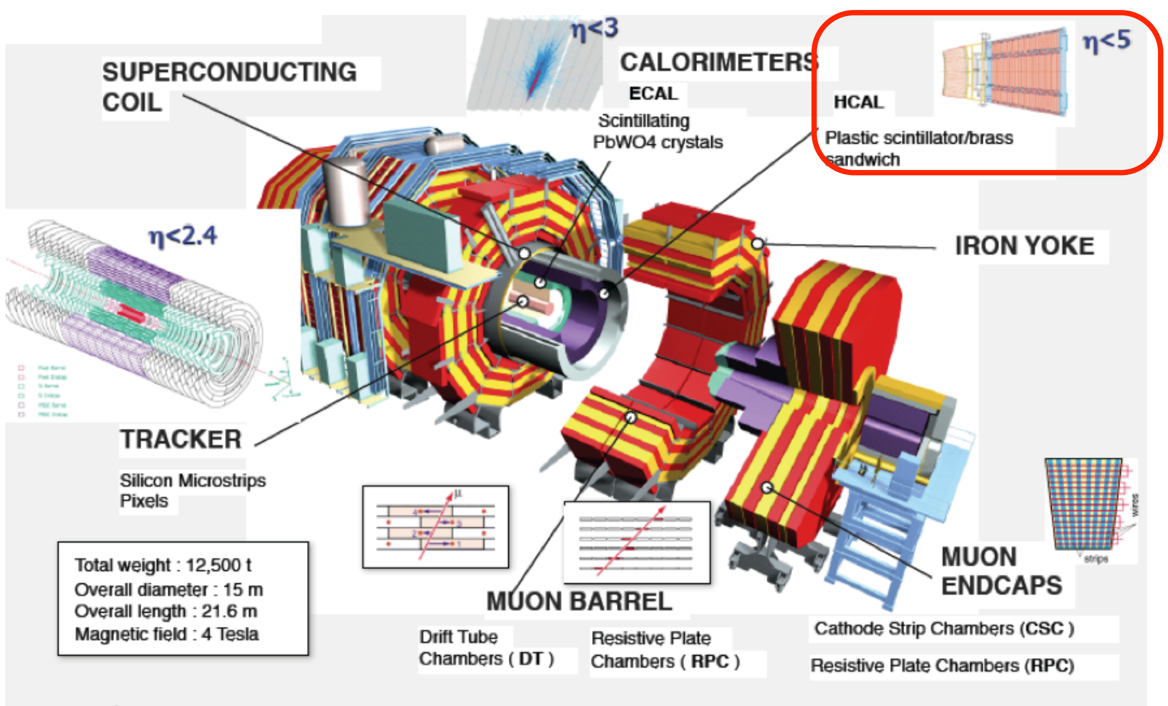
Muon coverage up to |η|=2.4

⇒ Good tracking coverage

EM calorimeter : |η|<3

HF calorimeter extends η coverage up to |η|=5

⇒ Forward events have smaller dilution of A_{FB}



Data and Event selection : ATLAS

- ATLAS uses 7 TeV data, $\int Ldt = 4.8\ (4.6)\ \mathrm{fb}^{-1}$ for electron (muon) channel
  - ✓ Single lepton (electron or muon) trigger is used
    - $E_T(e)>20$ or 22 GeV (depending on instantaneous luminosity), $p_T(\mu)>18$ GeV
- Electron selection : $E_T>25$ GeV
  - ✓ Central (C) electron ($|\eta|<2.47$) : candidates are matched to a track
    - ID selection is required based on shower shape and track quality cut
  - ✓ Forward (F) electron ($2.5<|\eta|<4.9$) :
    - 'medium' quality criteria optimized for forward electron are required
  - ✓ Event topology :
    - CC events : two central electrons passing 'medium' ID selection
      - Oppositely charged electrons
    - CF events : one 'tight' central electron + one 'medium' forward electron
      - Required isolation energy cut (<5 GeV) on the central electron
- Muon selection : $p_T>20$ GeV and $|\eta|<2.4$
  - ✓ ID selection is required based on quality requirement in sub-detectors
  - ✓ Fractional tracker isolation ($\Sigma p_T^{track}/p_T^{\mu} < 0.1$) is required

Data and Event selection : CMS

- CMS uses 8 TeV data, $\int Ldt$ = 19.7 fb^{-1} for both electron and muon channels
  - ✓ Dilepton (electron or muon) trigger or single electron trigger is used
    - Dilepton trigger : $E_T(e)$ or $p_T(\mu)$ >17(leading), 8(sub-leading) GeV with $|\eta|<2.4$
    - Single electron trigger for forward events : $E_T(e)>27$ GeV with $|\eta|<2.4$
- Electron selection :
  - ✓ Central (C) electron ($|\eta|<2.4$) : $E_T>20$ or 30 GeV, candidates are matched to a track
    - ID selection and fractional PF isolation requirements are used
  - ✓ Forward (F) electron ($3<|\eta|<5$) : $E_T>20$ GeV
    - Quality criteria (based on isolation) optimized for forward electron are required
  - ✓ Event topology :
    - CC events : two central electrons with $E_T>20$ GeV, oppositely charged electrons
    - CF events : one central electron ($E_T>30$ GeV) + one forward electron ($E_T>20$ GeV)
      - Both electrons are required to be the same side of detector ($\eta_{e1}\cdot\eta_{e2} > 0$)
- Muon selection : $p_T>20$ GeV and $|\eta|<2.4$
  - ✓ ID selection is required based on quality requirement in sub-detectors
  - ✓ Fractional tracker isolation ($\Sigma p_T^{track}/p_T^{\mu} < 0.1$) is required

Simulations

- Signal MC sample (Z/ɣ* → ee or μμ)
  - ✓ ATLAS : PYTHIAv6.4 with MSTW2008(LO) PDFs with $\sin^2\theta^{lept}_{eff} = 0.232$
    - FSR from QED is taken into account using PHOTOS
  - ✓ CMS : POWHEG with CT10(NLO) PDFs with $\sin^2\theta^{lept}_{eff} = 0.2312$
    - Parton showering, hadronization are simulated using PYTHIA with Z2* tune
- Background MC samples
  - ✓ ATLAS :
    - Z/ɣ*→$\tau\tau$ (PYTHIA), Diboson (HERWIG), ttbar (MC@NLO)
    - multi-jet and W+jets background are estimated by data-driven method
  - ✓ CMS :
    - Z/ɣ*→$\tau\tau$, ttbar, tW (POWHEG), inclusive W (MadGraph), Diboson (PYTHIA)
    - Z/ɣ*→$\tau\tau$, ttbar, multi-jet background are also measured by data-driven method
- MC simulations are fully simulated for detector effect based on GEANT4
- MC simulations are tuned to describe data for
  - ✓ pileup distribution and efficiencies (trigger, ID, reconstruction)
  - ✓ Lepton energy/momentum scale and resolution

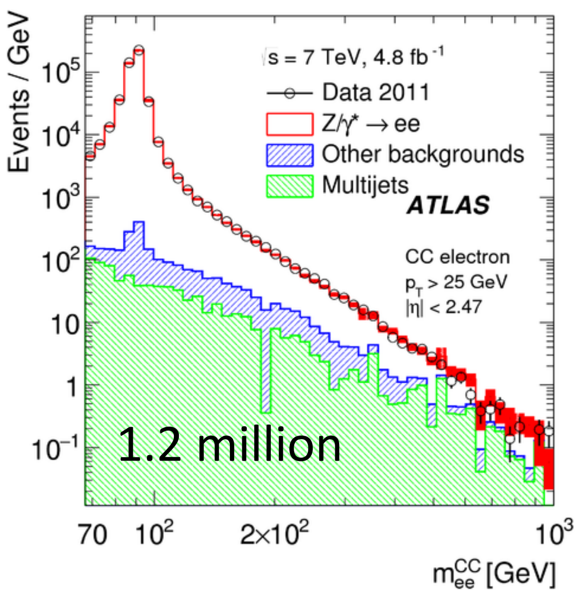
Background estimation

- Major backgrounds in low and high mass are $Z/\gamma^* \rightarrow \tau\tau$ and ttbar process
- Multi-jet background is one of dominant sources in electron channel
- Background measurement in ATLAS
  - ✓ $Z/\gamma^* \rightarrow \tau\tau$, ttbar, and diboson(WW/WZ/ZZ) are measured using MC
  - ✓ Multi-jet background is estimated using a combination of data-driven technique
    - CC electron topology :
      - the reverse ID method in $M<125$ GeV + fake-factor method in high mass
    - CF electron topology : only the reverse ID method is used
    - Muon channel : control region(anti-isolation) vs. signal region method used
- Background measurement in CMS
  - ✓ Multi-jet background for CC and muon channel : same charged events method used
  - ✓ Multi-jet background for CF events : Fitting of kinematic distributions used
  - ✓ $Z/\gamma^* \rightarrow \tau\tau$, ttbar, W_jets, tW for muon channel : $e\mu$ method is used
    - Overall rate for $\mu\mu$ background events is proportional to observed $e\mu$ events
  - ✓ Other remaining backgrounds are estimated using MC

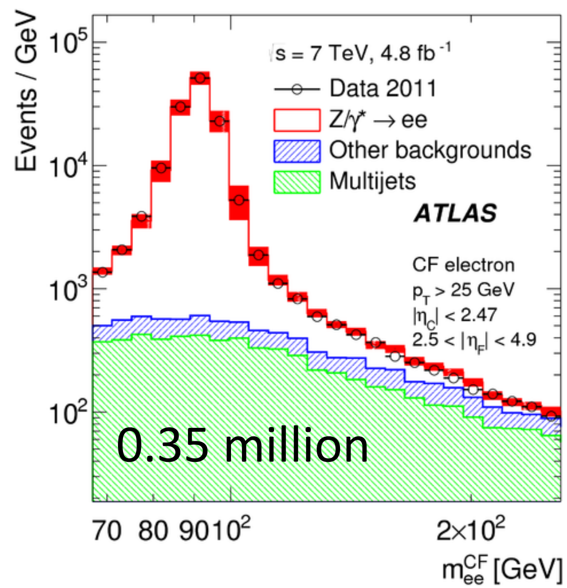
Dilepton mass distributions

- Dilepton mass comparison between data and MC

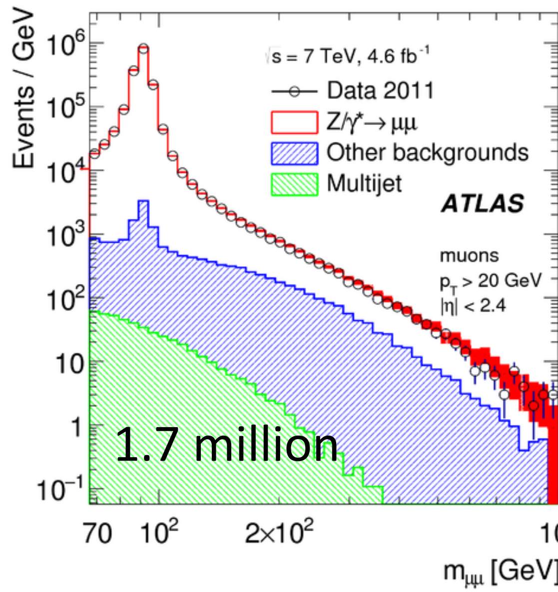
ee(CC) events

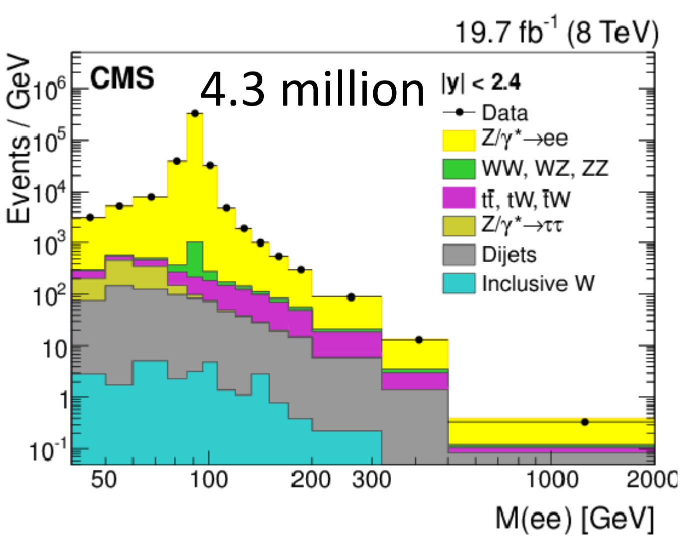


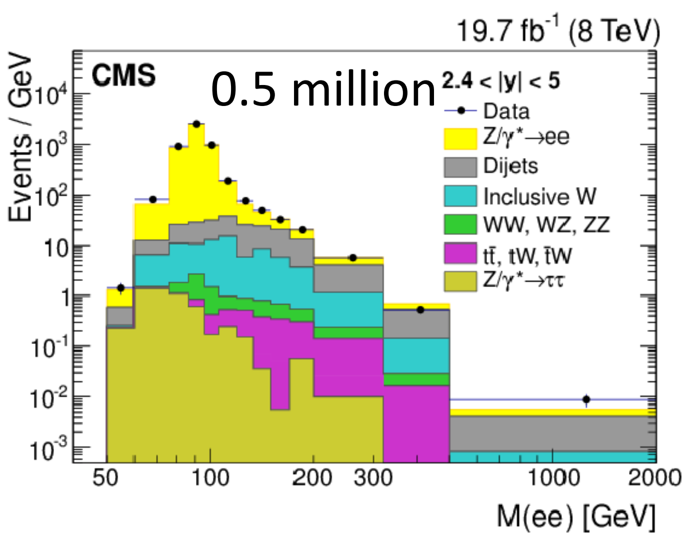
ee(CF) events

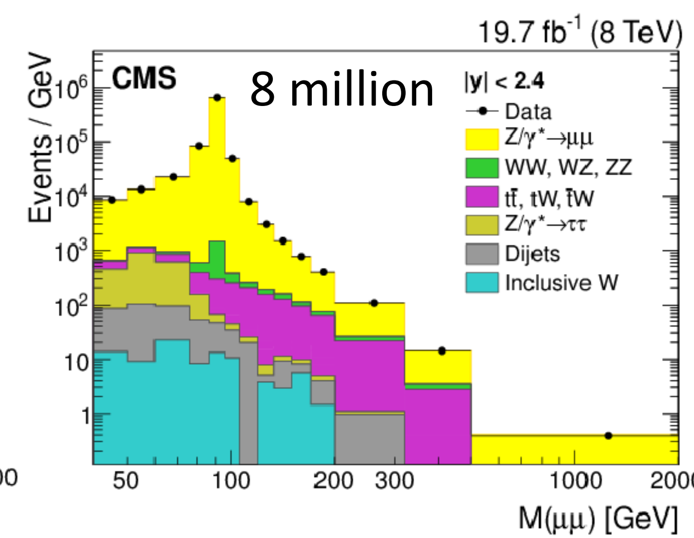


μμ events









*** CMS mass spectrum is normalized by bin width

Unfolding A_{FB}

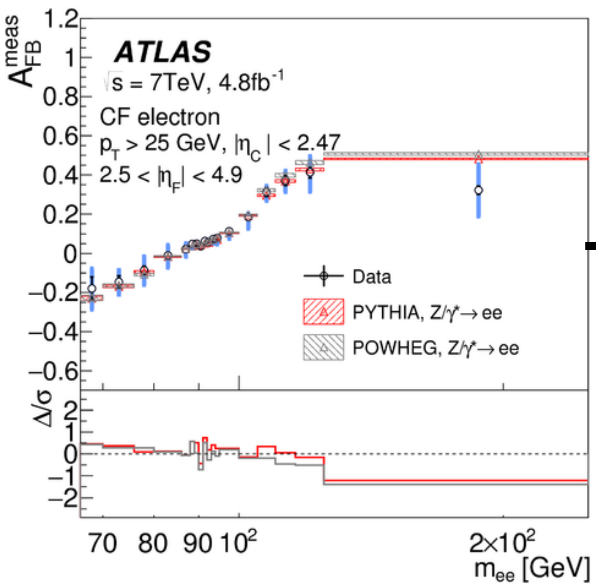
- The measured A_{FB} in the reconstructed level is defined as

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

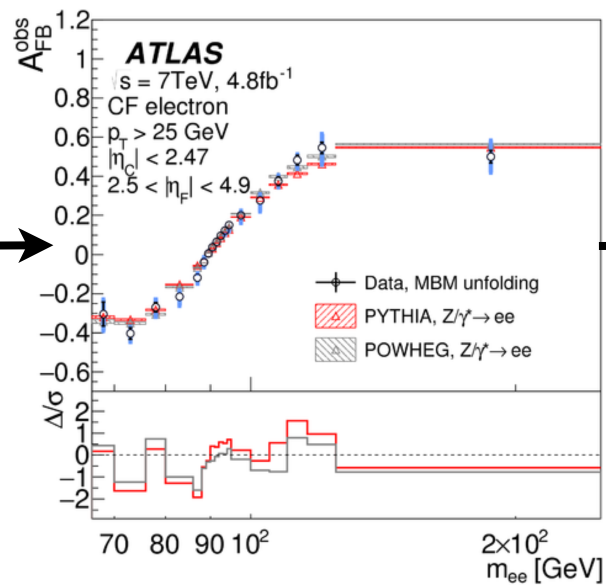
ATLAS measures A_{FB} in mass for ee(CC), ee(CF), μμ
CMS measures A_{FB} in mass, y

- The measured A_{FB} is unfolded using iterative Bayesian method for
  - ✓ Detector effect (efficiencies, detector resolution, acceptance (CMS only))
  - ✓ QED radiation corrections
- ATLAS result is further corrected for the dilution and acceptance effect
  - ✓ PYTHIA signal sample is used to estimate the correction factors

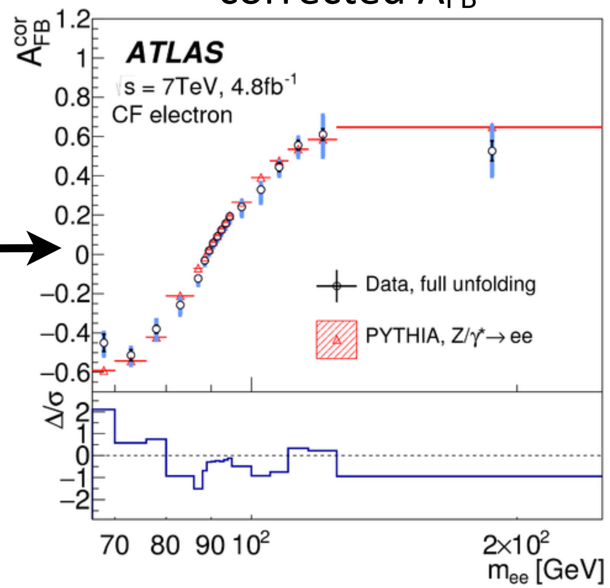
Measured A_{FB}



Unfolded A_{FB}

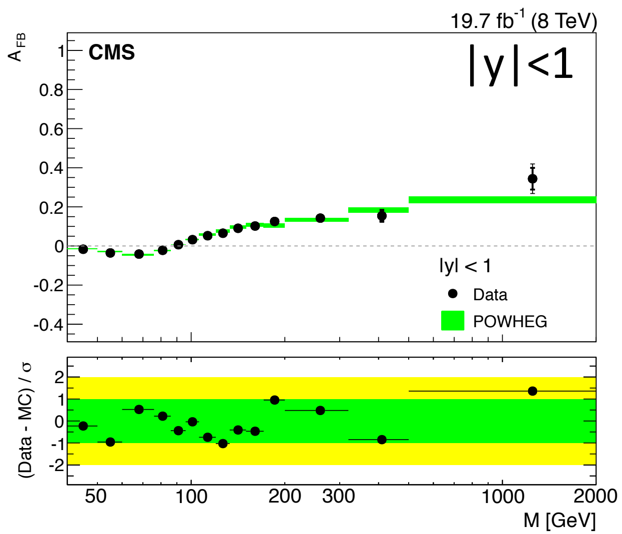


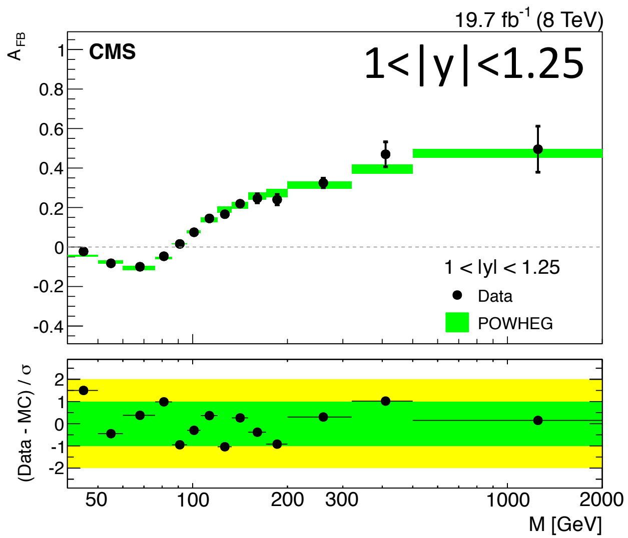
Dilution, Acceptance corrected A_{FB}



Unfolded A_{FB} in CMS

- A_{FB} is measured as a function of dilepton mass and rapidity
- CMS measures A_{FB} for ee and μμ, then combines both channel up to |y|=2.4





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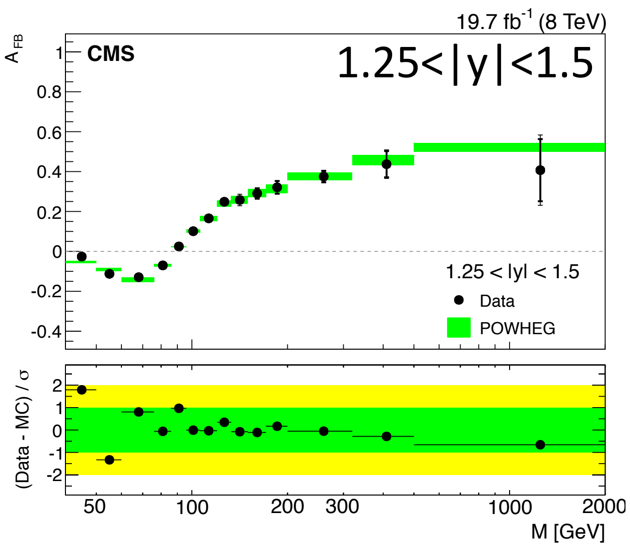
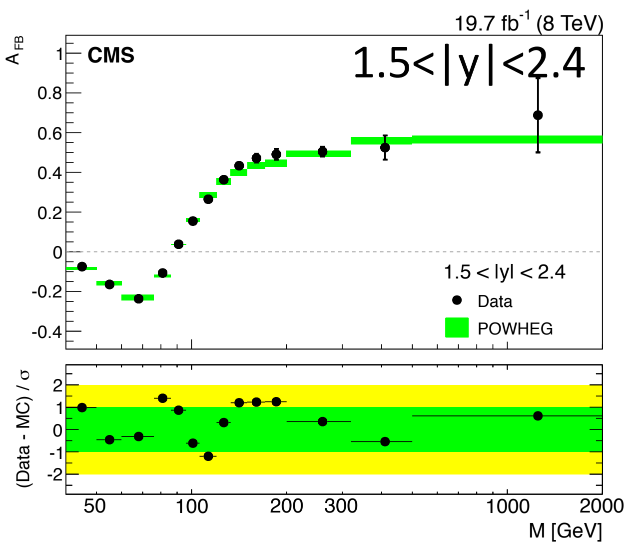
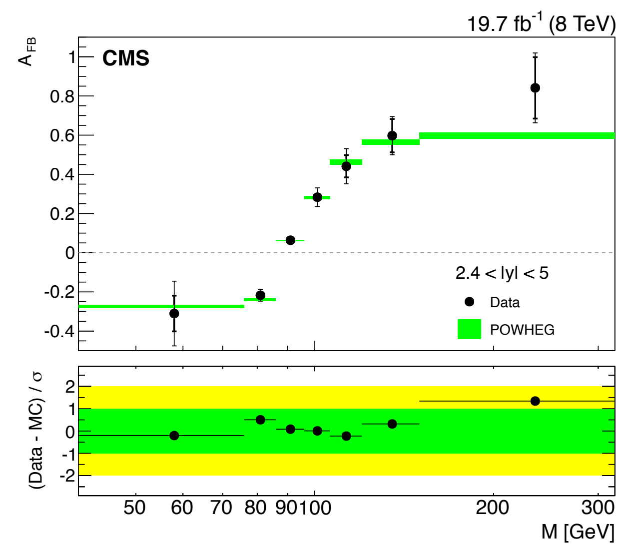
Measured A_{FB} in mass and rapidity agrees with POWHEG prediction with $\sin^2\theta^{lept}_{eff} = 0.2312$

A_{FB} in forward region (2.4<|y|<5) is statistical uncertainty dominant







Unfolded A_{FB} in ATLAS

- ATLAS measures A_{FB} for ee(CC), ee(CF), μμ, respectively
- A_{FB} is corrected up to the Born level including the dilution and acceptance
- Unfolding procedure and energy scale/resolution are leading source of syst. error
  - ✓ Background is also dominant source for CF electrons

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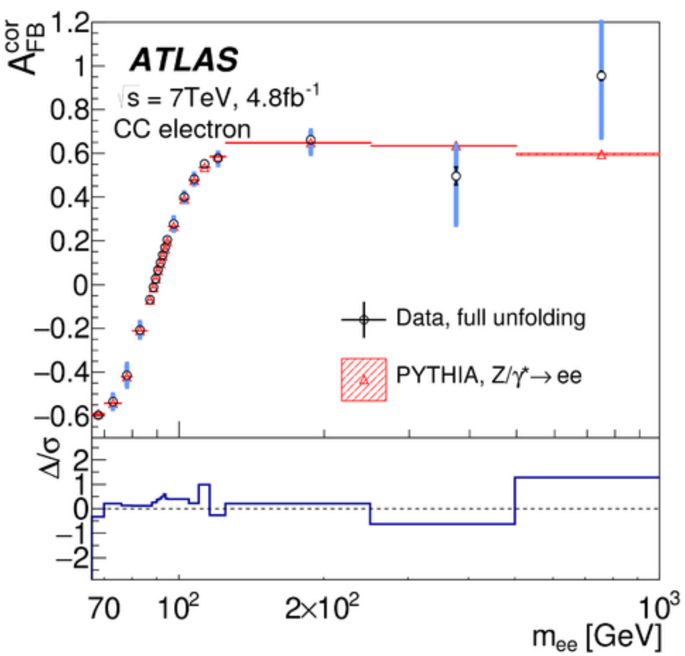
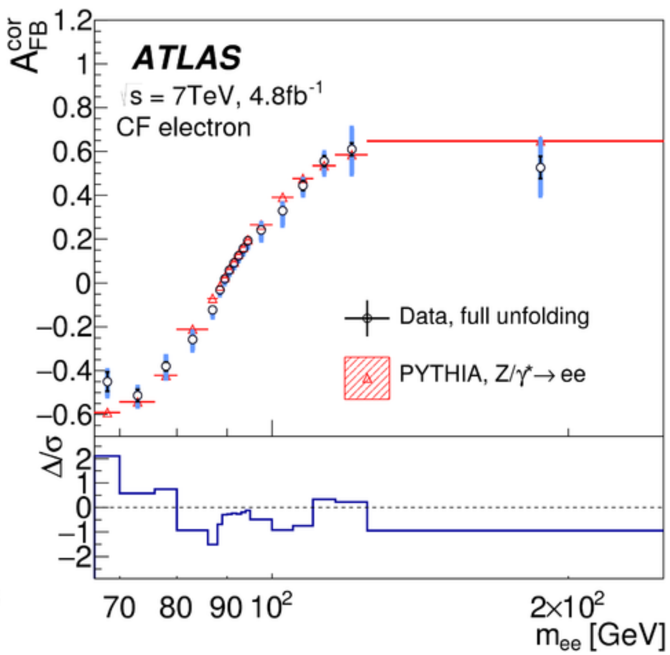
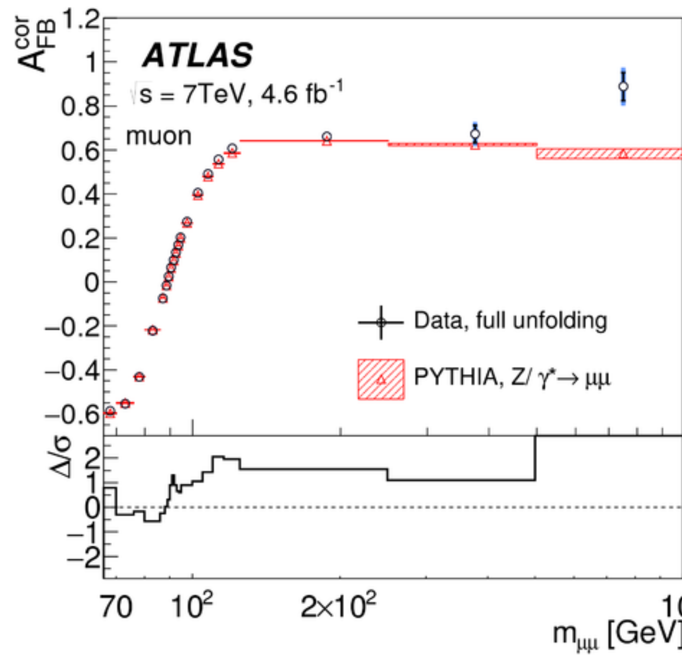
CC electron



CF electron



muon



- Measured A_{FB} agrees with PYTHIA prediction with $\sin^2\theta_{eff}^{lept} = 0.232$
  - ✓ Muon channel shows more deviation in high mass, but within 2σ

Measurement of $\sin^2\theta_{eff}^{lept}$

- The extraction of effective weak mixing angle, $\sin^2\theta_{eff}^{lept}$
  - ✓ The extraction is done using the detector level A_{FB} (raw A_{FB})
  - ✓ PYTHIA is used to produce the template of A_{FB} for each $\sin^2\theta_{eff}^{lept}$ value
    - Varying $\sin^2\theta_{eff}^{lept}$ in the region of $0.218 \leq \sin^2\theta_{eff}^{lept} \leq 0.236$: 17 MC samples
    - Weights are calculated in gen. level, in bins of dilepton mass and $\cos\theta^*_{CS}$
    - The A_{FB}^{raw} values obtained from the reweighted sample are compared with data
      - χ^2 test over the mass range of 70 ~ 250 GeV is used

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

CF electron has smallest error even though less statistics due to smaller dilution effect

PDF uncertainty is dominant source : ATLAS-epWZ12 LO PDFs is used as default

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

Summary

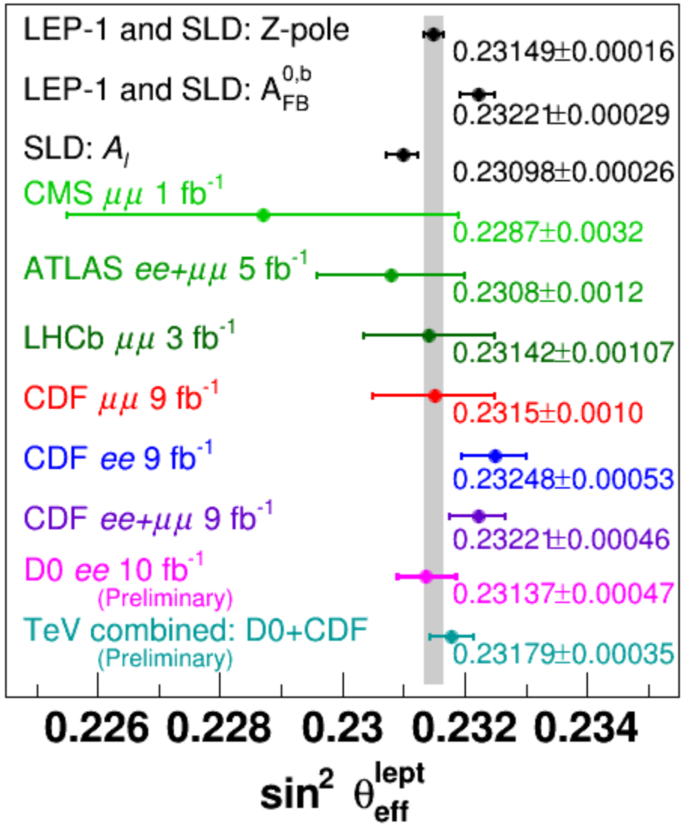
- Forward-Backward asymmetry of Drell-Yan process is measured using RunI data
  - ✓ ATLAS uses √s = 7 TeV data (4.8 fb^{-1}) and CMS uses √s = 8 TeV data (19.7 fb^{-1})
    - ATLAS measures $A_{FB}(M)$ up to Born level including dilution correction
    - CMS measures $A_{FB}(M)$ up to particle level as a function of rapidity
    - The measured A_{FB} shows a good agreement with predictions (PYTHIA, POWHEG)
  - ✓ ATLAS A_{FB} measurement is used to extract the effective weak mixing angle
    - Combined result : $\boxed{\sin^2\theta^{lept}_{eff} = \mathbf{0.2308 \pm 0.0005(stat.) \pm 0.0006(syst.) \pm 0.0009(PDF)}}$

World average is dominated by the most precise measurements (LEP-1 and SLD)
Two most precise measurements differ by 0.00122 (3.2σ)

LHC has already reached an impressive precision on $\sin^2\vartheta_W$, but it still has large uncertainty to distinguish the tension between LEP-1 and SLD
⇒ We will improve the precision further

Most precise hadron collider result is Tevatron combination

Tevatron and LHCb talks will follow after this talk !!
(See Willis' and Xabier's talk)



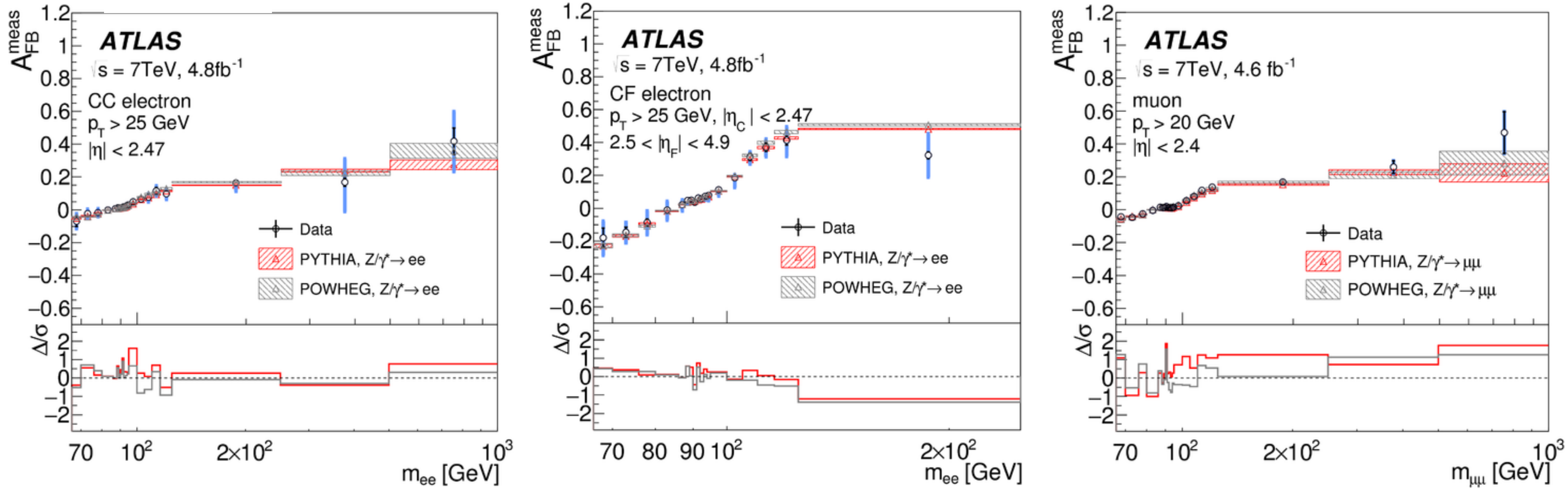
ATLAS (ee) : 1.3 per mill

Tevatron (ee) : 0.5 per mill

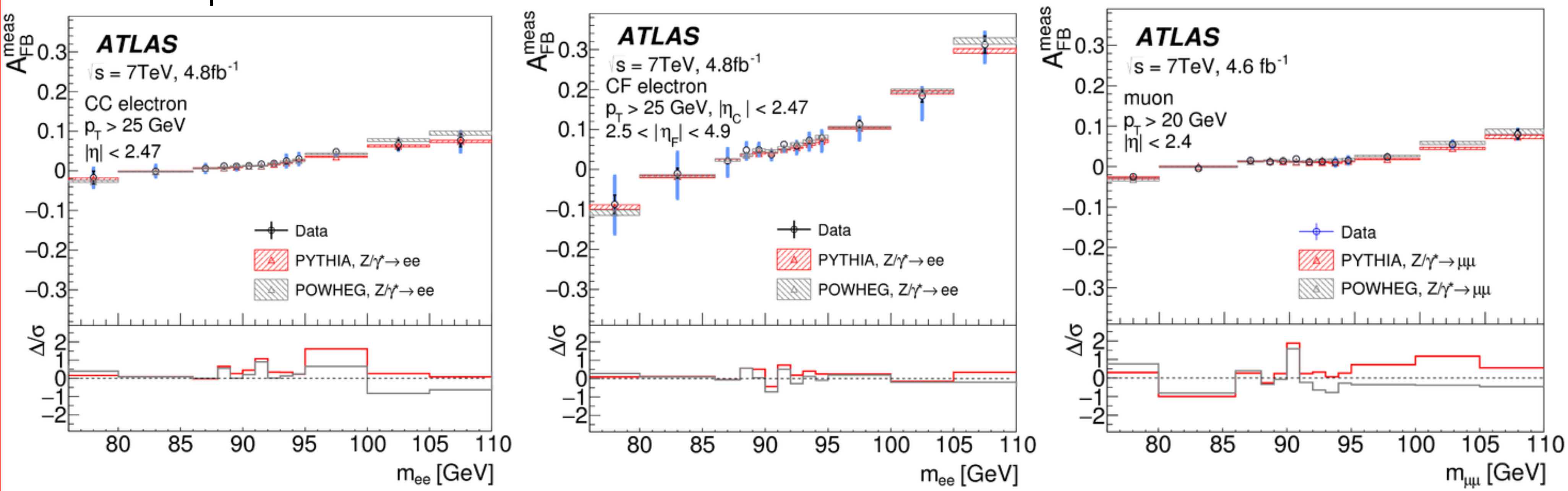
Backup Slides

A_{FB} in ATLAS : raw A_{FB}

Full mass

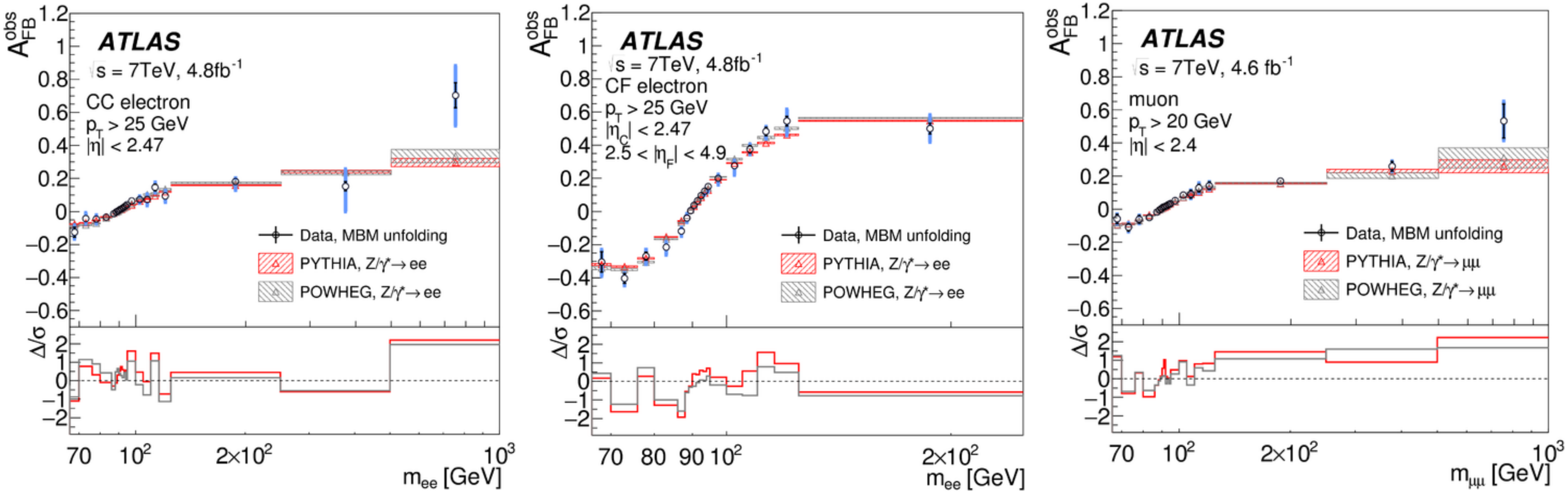


Near Z peak



A_{FB} in ATLAS : unfolded A_{FB}

- Unfolded A_{FB} in fiducial region



Systematic uncertainty summary : ATLAS

- Summary table for the systematic uncertainties

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

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

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

Major contributions are unfolding and background

Systematic uncertainty of unfolding procedure is estimated using a partially data-driven method (modeling effect in mass and cosθ*)

Systematic uncertainty summary : CMS

- Summary table for the systematic uncertainties : maximum deviation in mass

Muon channel

Systematic uncertainty	$\lvert y \rvert$ bins			
	0–1	1–1.25	1.25–1.5	1.5–2.4
Background	0.062	0.080	0.209	0.051
Momentum correction	0.006	0.015	0.020	0.022
Unfolding	0.001	0.003	0.004	0.003
Pileup reweighting	0.002	0.004	0.003	0.004
Efficiency scale factors	<0.001	0.002	0.003	0.005
PDFs	0.001	0.004	0.008	0.047
FSR	<0.001	0.001	0.001	0.002

Electron channel

Systematic uncertainty	$\lvert y \rvert$ bins				
	0–1	1–1.25	1.25–1.5	1.5–2.4	2.4–5
Background	0.064	0.015	0.008	0.004	0.033
Energy correction	0.011	0.015	0.012	0.012	0.123
Unfolding	0.005	0.007	0.006	0.004	0.001
Pileup reweighting	0.003	0.002	0.002	0.001	0.007
Efficiency scale factors	<0.001	<0.001	<0.001	<0.001	0.008
Forward η scale factor	—	—	—	—	0.002
Forward η asymmetry	—	—	—	—	0.029
Global normalization factor	—	—	—	—	0.060
PDFs	0.002	0.004	0.005	0.008	0.014
FSR	<0.001	0.001	0.001	0.001	0.002

Major contributions are background and p_T,E_T scale/resolution

Table summarizes the maximum deviation in $A_{FB}(M)$
$\Rightarrow$ Some of contribution comes from the high mass region due to the fluctuation effect

Weak mixing angle

- In Drell-Yan process,
  - ✓ Virtual photon coupling : fermions(f) couple to γ^* via vector coupling, $Q_f\gamma_\mu$
  - ✓ Z boson coupling : fermion coupling to Z boson has $g_V{}^f\gamma_\mu + g_A{}^f\gamma_\mu\gamma_5$

    Born couplings : $g_V^f = T_3^f - 2Q_f \sin^2\theta_W, g_A^f = T_3^f$ → affect angular distributions
  - ✓ Asymmetry in cosθ distribution is induced from
    - γ^* and Z interference : depends on $g_A(T_3)$
    - Z boson vector and axial-vector interference : includes g_V

    ⇒ A_4 contribution is proportional to $g_V{}^l g_V{}^q$
- Loop and vertex electroweak radiative correction modify $\sin^2\theta_W$ by few %

  ⇒ "effective" coupling ($\sin^2\theta_{eff}{}^{lept}$) is observed
  - A4 is most sensitive to the effective lepton-Z coupling ($\sin^2\theta_{eff}{}^{lept}$)

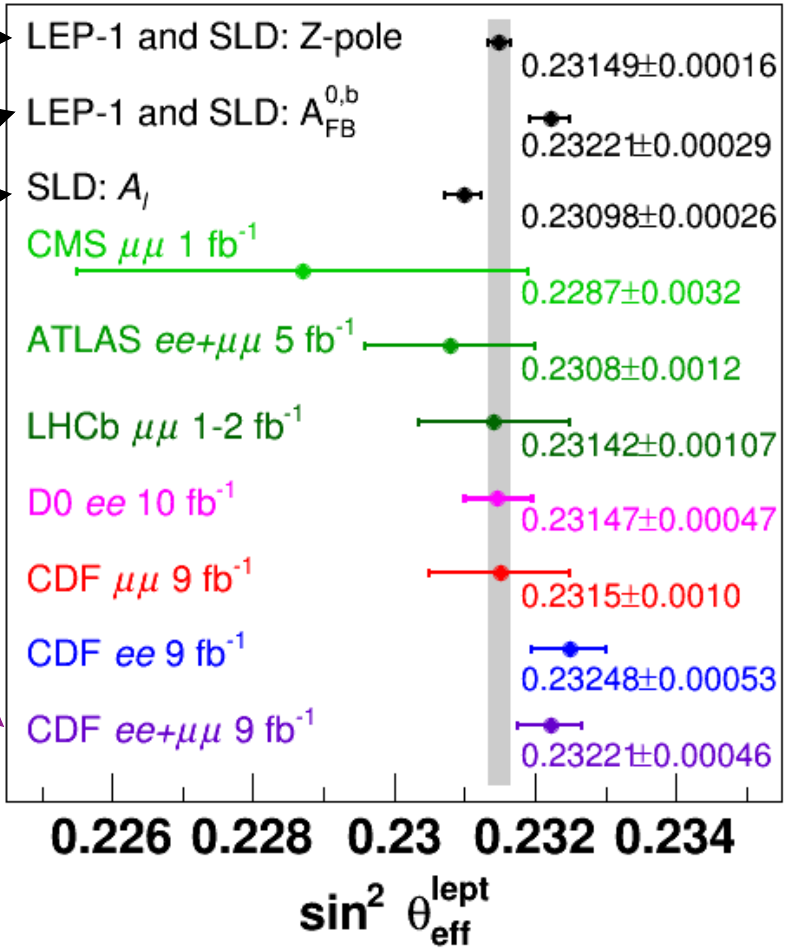
Electroweak mixing angle measurement

World average is dominated by the average of two most precise measurements (LEP-1, SLD)

Two most precise measurements of $\sin^2\theta_W$ differ by 0.00122 which is 3.2 σ

LHC result(ATLAS and LHCb) still has larger error, more than factor of 2 than Tevatron

Most precise hadron collider measurements (CDF and D0) have a errors of 0.00047



Electroweak mixing angle results

- Electroweak mixing angle measurements at Hadron collider

CMS (μ)	1.1/fb	0.22870 $\pm$ 0.00200(stat) $\pm$ 0.00250(syst+pdf)
ATLAS (e+μ)	4.5/fb	0.23080 $\pm$ 0.00050(stat) $\pm$ 0.00060(syst) $\pm$ 0.00090(pdf)
D0 (e)	9.7/fb	0.23138 $\pm$ 0.00043(stat) $\pm$ 0.00008(syst) $\pm$ 0.00017(pdf)
CDF (e+μ)	**9.7/fb**	**0.23221 $\pm$ 0.00043(stat) $\pm$ 0.00018(syst+pdf)**
LHCb(μ)	**7&8TeV**	**0.23142 $\pm$ 0.00073(stat) $\pm$ 0.00052(syst) $\pm$ 0.00017(theo)**

✓ PDF uncertainty is already dominant source at LHC

- PDF error in ATLAS result is already ~2 times of statistical error

✓ CDF measurement used χ^2 weighting technique to reduce PDFs error