Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle using proton-proton collisions at $\sqrt{s} = 13$ TeV

New measurement of $\sin^2\theta^{\ell}_{\text{eff}}$ *and* $A_{\text{FB}}(y,m)$ *at 13 TeV*

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To be submitted to Physics Letters

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On behalf of the CMS collaboration

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10 min + 5 min/questions

The CMS $\sin^2\theta_{eff}$ analysis group

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The forward-backward asymmetry in Drell–Yan production and the effective leptonic weak mixing angle are measured using a sample of proton-proton collisions at = 13 TeV collected by the CMS experiment and corresponding to an integrated luminosity of 137 fb−1. The measurement uses both dimuon and dielectron events, and is performed as a function of the dilepton's mass and rapidity. The measured value agrees with the standard model prediction. The total uncertainty using the CT18 PDF is 0.00031. This is the most precise measurement at a hadron collider, with a precision comparable to the results obtained at LEP and SLD.

To be submitted to Physics Letters

Heralding a new era of precision EW measurements at the LHC

Precision Standard Model measurements = indirect search for new physics

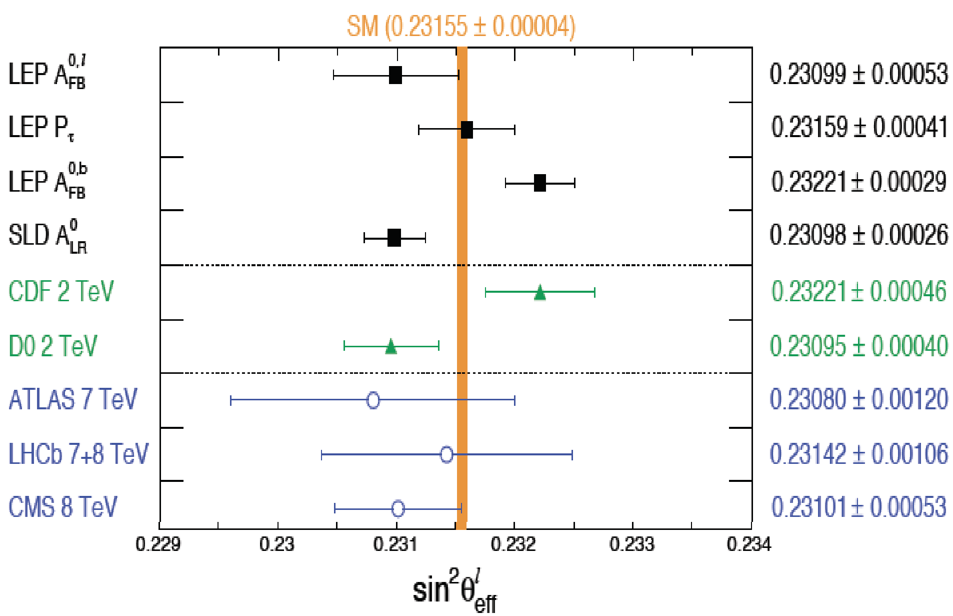
Key electroweak parameters: m_W and $\sin^2\theta^\ell_{\rm eff} = (1 - m^2_W/m^2_Z)\kappa^\ell$

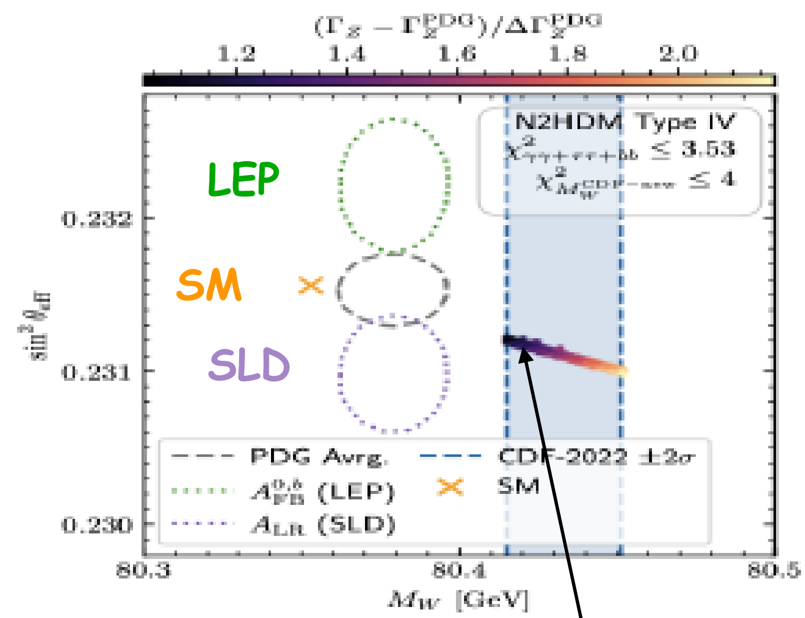
can be calculated in SM using other precise experimental inputs:

$\sin^2\theta^\ell_{\rm eff} = 0.23155 \pm 0.00004$ (SM)

Two most precise $\sin^2\theta^\ell_{\rm eff}$ results from LEP and SLD differ by $\sim 3\sigma$

Measurements at hadron colliders are now also competitive

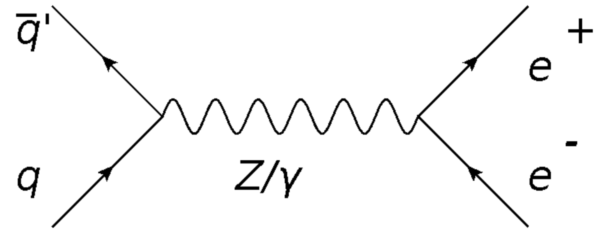




- Latest CDF m_W measurement disagrees with previous results and SM
- Models that describe CDF m_W prefer lower (SLD) value of $\sin^2\theta^\ell_{\rm eff}$

2H model with CDF m_W → $\sin^2\theta_{\rm eff}$ = 0.23110±0.00010

$\sin^2\theta_{eff}$ is extracted from the forward backward asymmetry (Afb) of Drell-Yan dileptons at the Z pole



The axial and vector neutral currents interfere

Weak neutral current strength related to $\sin^2\theta_{eff}$

$\sin^2\theta_W = \sin^2\theta_W^{on\text{-}shell} = 1 - M_w^2 / M_z^2$

What is actually measured with dilepton events is the effective lepton EW mixing angle

$$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$$

↳ ≈1.037

Precision EW measurements at LHC are now possible because of three innovative techniques

1. **Precise lepton momentum/energy scale** (and modeling resolution)
   Reduces contribution to $\Delta\sin^2\theta_{eff}$ to ±0.00008 (A. Bodek, Eur. Phys. J. C72 (2012) 2194.

2. **Angular Event weighting method for A_{FB} analyses: Most systematic errors in acceptance & efficiency cancel:** $\Delta\sin^2\theta_{eff}$ ±0.00008 The method yields the full acceptance experimental Afb (But with FSR and detector resolution smearing)
   A. Bodek. Eur. Phys. J. C67 (2010) 321. Also used as a check on the extraction of unfolded experimental A4 to Born Level A4.

3. **Most important" In situ reduction of PDF errors by PDF rewighting/profling**
   A.Bodek et al , Eur. Phys. H. (2016) C76 (2016

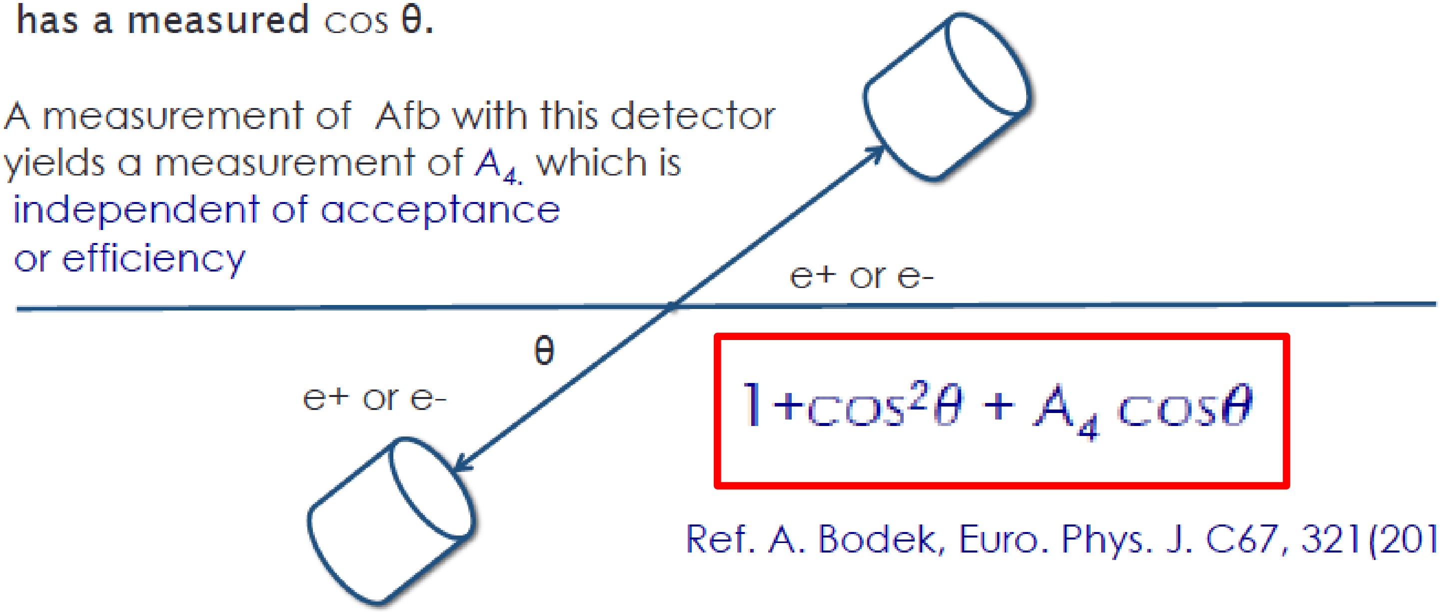
A.Bodek et al , Eur. Phys. H. (2016) C76 (2016)

In situ cancellation of experimental systematic errors by angular weighting

Event weighted A_{FB} is the same as A_{FB} for full acceptance (i.e. A4 but smeared by experimental resolution and final state radiation)

Imagine a detector with acceptance for only one value of cos θ. Each event has a measured cos θ.

A measurement of Afb with this detector yields a measurement of A_4, which is independent of acceptance or efficiency



$$1+\cos^2\theta + A_4 \cos\theta$$

Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

cos θ=1 yields best measurement of A_4. cos θ=0 yields no measurement of A_4

We can combine measurements of A_4 with different detectors at different values of by weighting events. Events with cos θ=0 have zero weight. Events with cos θ=1 have maximum weight. → obtain smaller statistical error.

Afb (all cos θ) = (3/8) A_4 → No acceptance corrections needed.

In situ reduction of PDF errors by PDF reweighting/profiling

Reducing PDF uncertainties in the measurement of $\sin^2\theta_{eff}$

At the Z peak, Afb yields a measurement of $\sin^2\theta_{eff}$. Here, Afb is is sensitive to both $\sin^2\theta_{eff}$ and PDFs.

Above and below Z peak, axial coupling known. Here Afb is not very sensitive to $\sin^2\theta_{eff}$ but is very sensitive to PDFs. In this region, measurements of Afb provide constraints on PDF using the same Drell Yan sample (but above and below the Z peak).

Note: The constrains on PDF are *statistics limited.* Therefore, the errors are reduced with with larger statistical samples (e.g. larger integrated luminosity, and/or by combing data from the three LHC experiments). With the CMS 13 TeV Drell Yan sample we get a factor of 2 reduction in $\Delta\sin^2\theta_{eff}$ from PDF uncertainties.

Reducing PDF errors in the measurements of both $\sin^2\theta_{eff}$ and m_w.

In addition, in situ measurements of W boson distributions (e.g. the W boson asymmetry, and other W boson distribution which are not sensitive to the W mass) yield a further reduction of the PDF error in the measurements of both $\sin^2\theta_{eff}$ and m_w. These additional constraints have not yet been implemented in this $\sin^2\theta_{eff}$ analysis.

Summary of PDF reweighting/profiling

Use $Z/\gamma \to \ell\ell$ events

Asymmetry in lepton decay angle:

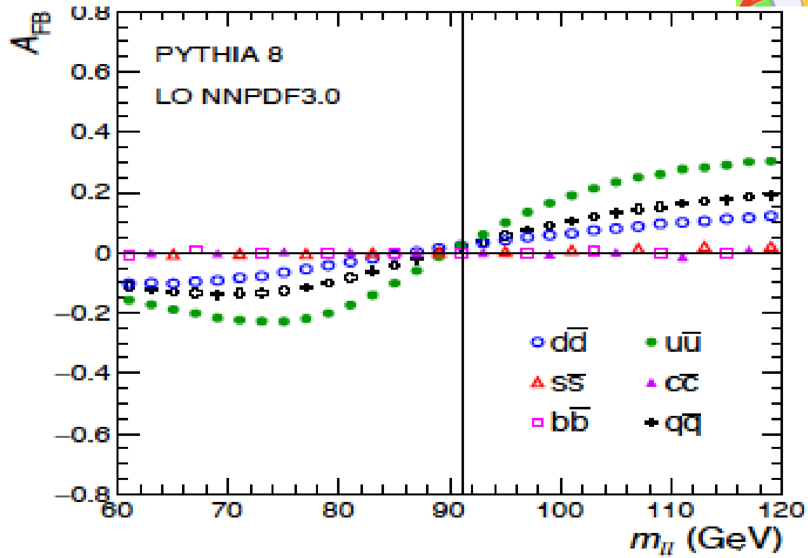
$1+\cos^2\theta+0.5A_0(1-3\cos^2\theta)+A_4\cos\theta$

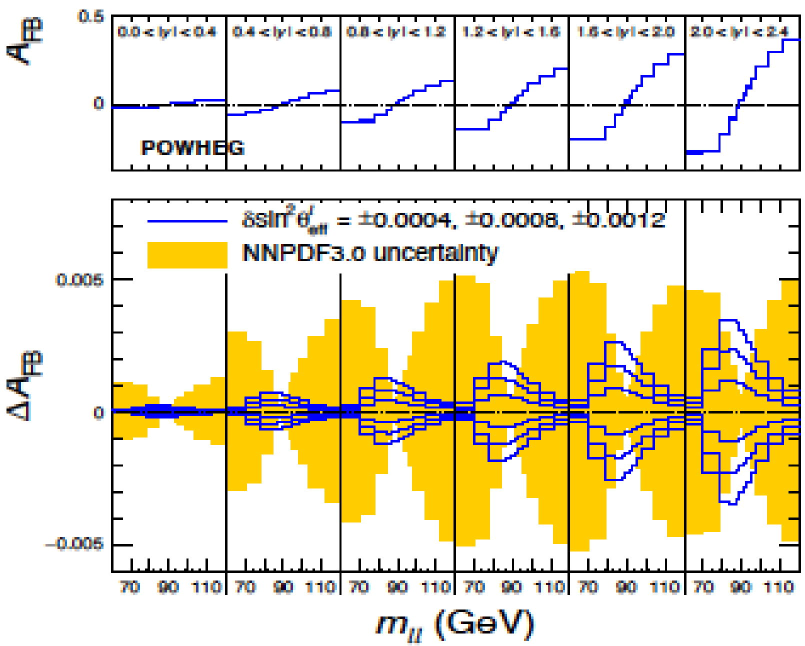
$\to A_{\mathrm{FB}} = 3/8 A_4$

$m_{\ell\ell}$ dependence from γ-Z interference

Colins-Sopper frame – reduced

theoretical and experimental unc.





1) Near m_Z, A_{FB} depends on $\sin^2\theta^\ell_{\mathrm{eff}}$

- In pp, definition of positive z direction relies on $\ell\ell$ boost (sign of $y_{\ell\ell}$)

  $\to$ only valence quarks contribute

  $\to$ significant $y_{\ell\ell}$-dependent dilution

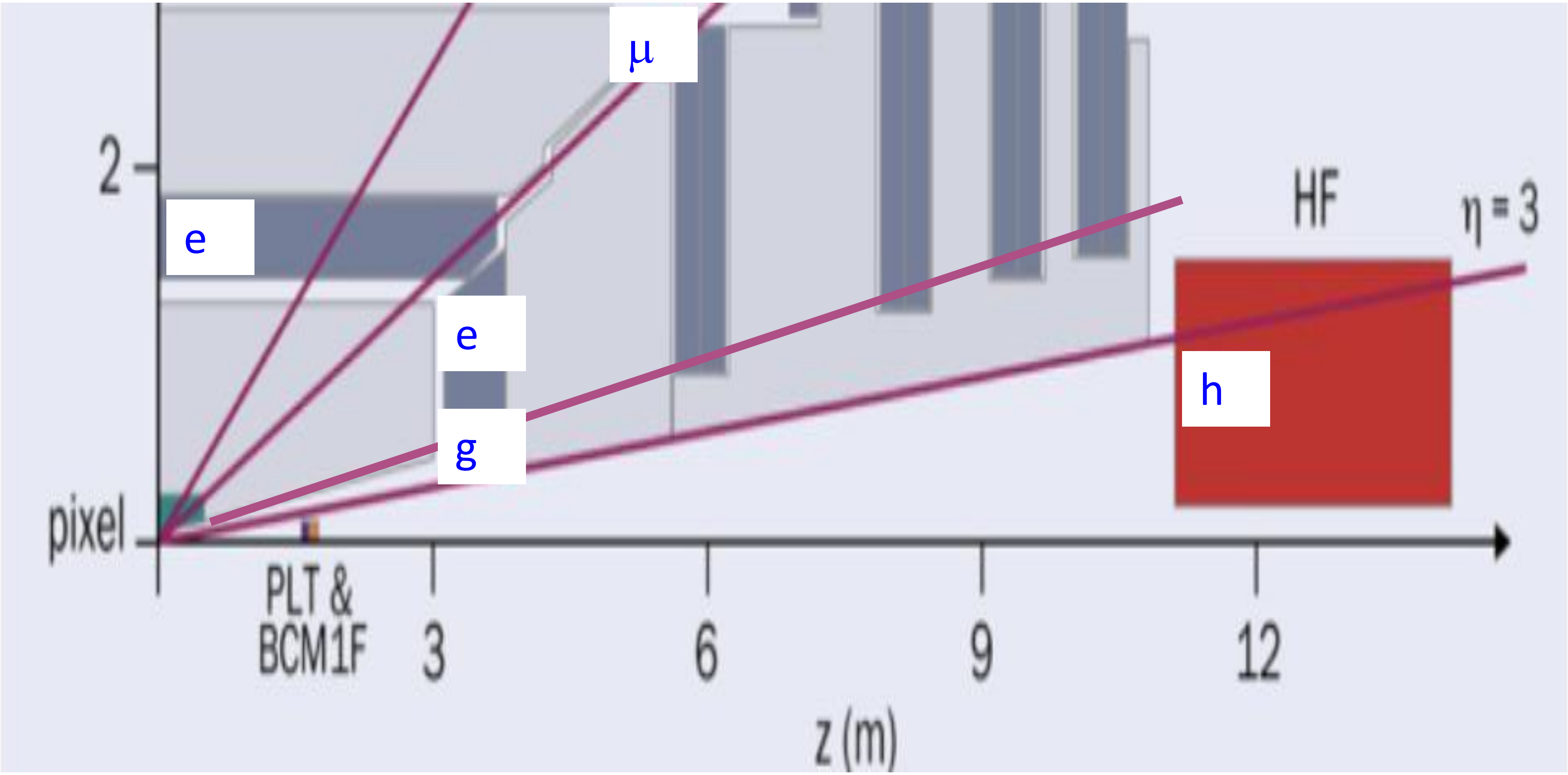
2) Strong dependence on PDFs

$\to$ Fit A_{FB} floating $\sin^2\theta^\ell_{\mathrm{eff}}$ and PDFs

- **Four dilepton channels:**
  - $\mu\mu$, ee, eg, eh

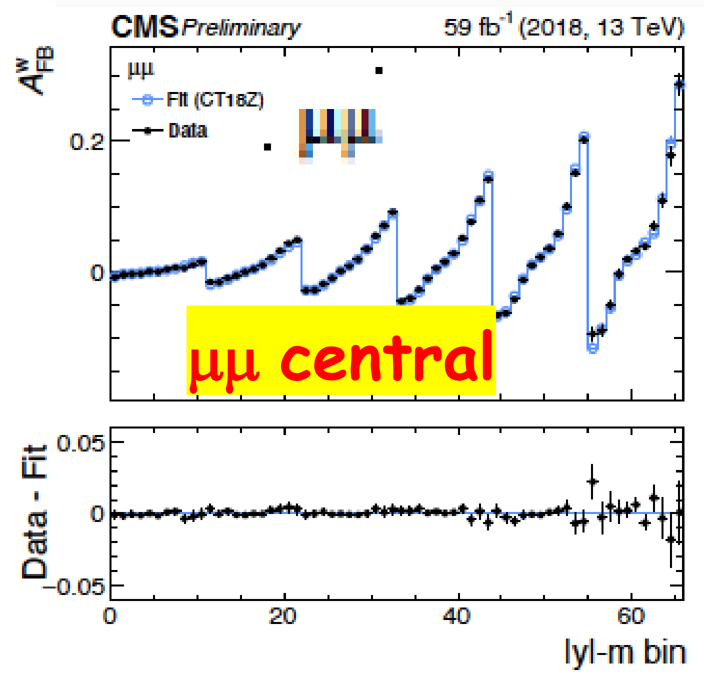
where:

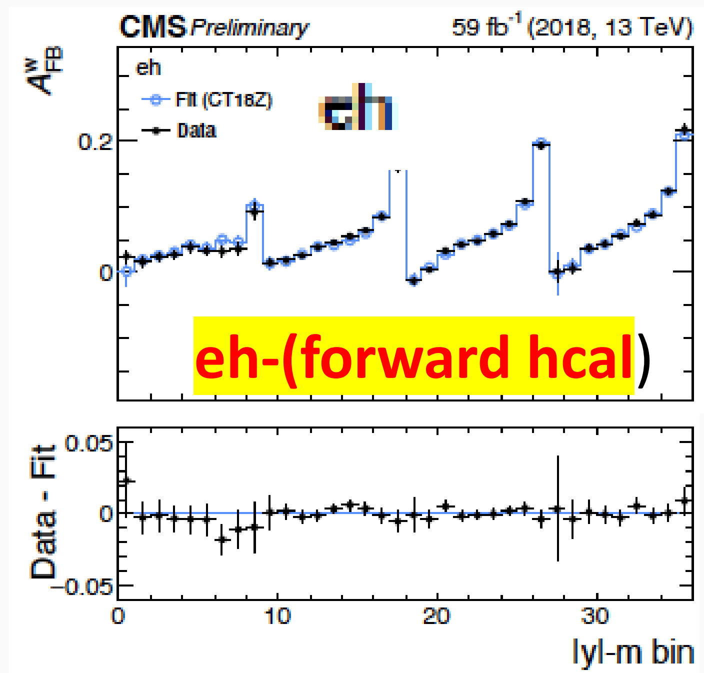
- μ – muon ($|\eta| < 2.4$)
- e – central electron ($|\eta| < 2.5$)
- g – forward ECAL (EF) electron outside tracker ($2.5 < |\eta| < 2.87$)
- h – forward HCAL (HF) electron ($3.14 < |\eta| < 4.36$)



Angular-weighted = experimental full acceptance Afb (But includes FSR and detector resolution smearing)

$\sin^2\theta^{\ell}_{\text{eff}}$ is extracted by simultaneous χ^2 fit of $A_{\text{FB}}(y, m)$ in all runs and channels





In detector level angular weighted Afb most experimental systematic level errors cancel.

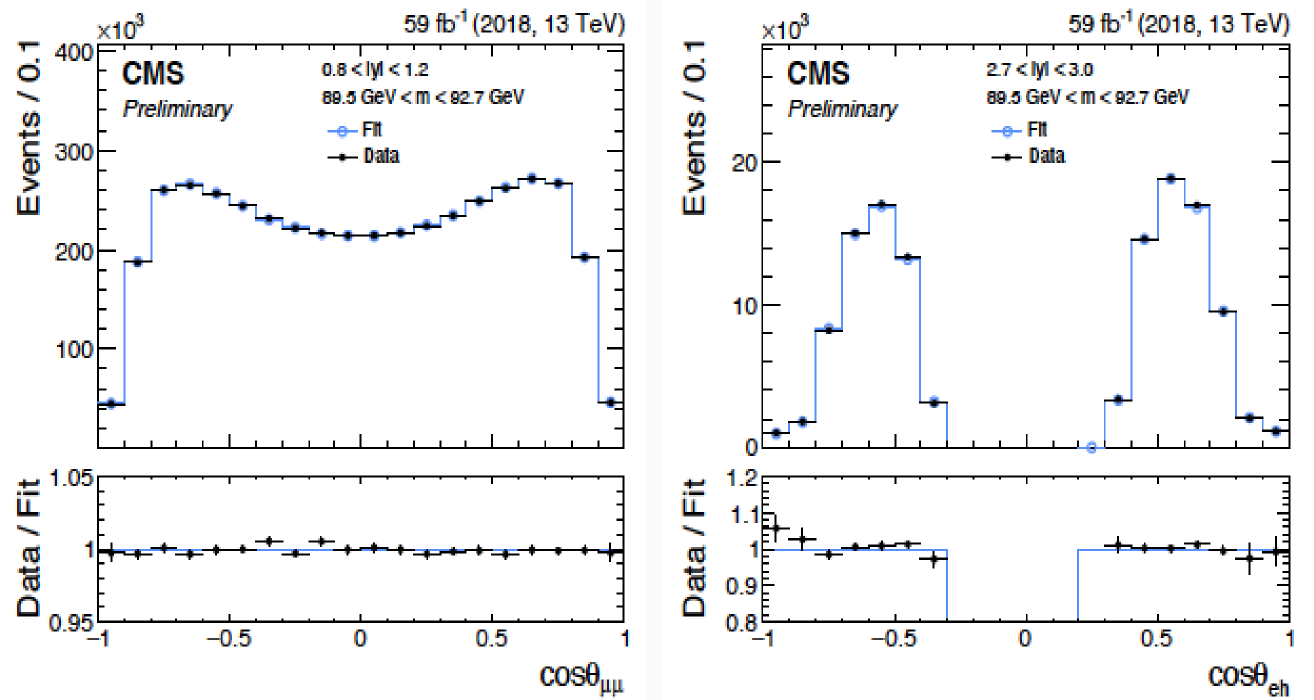
Four $\ell\ell$ channels: $\mu\mu$, ee, eg, eh

- μ – muon: $|\eta| < 2.40$
- e – central electron: $|\eta| < 2.50$
- g – EF electron: $2.50 < |\eta| < 2.87$
- h – HF electron: $3.14 < |\eta| < 4.36$

Here and in next slides, $\sin^2\theta^{\ell}_{\text{eff}}$ values and its uncertainties are in units of 10^{-5}

ch	χ^2	nbin	p(%)	$\sin^2\theta^{\ell}_{\text{eff}}$	±	σ	stat	exp	theo	pdf	mc	bkg	eff	calib	other
$\mu\mu$	241.3	264	82.7	23146	±	38	17	17	7	30	13	3	2	5	4
ee	256.7	264	59.8	23176	±	41	22	18	7	30	14	4	5	3	7
eg	119.1	144	92.8	23257	±	61	30	40	5	44	23	11	12	19	9
eh	104.6	144	99.3	23119	±	48	18	33	9	37	14	10	16	18	6
$\ell\ell$	730.7	816	98.4	23157	±	31	10	15	9	27	8	4	6	6	3

Unfolding A4: For future $\sin^2\theta_{eff}$ re-extraction with new PDFs, and for combined analysis with other data (m_w analysis, other experiments)



$A_4(y,m)$ is measured by fitting reconstructed $\cos\theta_{CS}$ distributions in y and m bins simultaneously in all runs and channels

Total $\chi^2_{min} = 14839$ for total of 14205 measurement bins and 101 free POIs

Asymmetry in lepton decay angle:

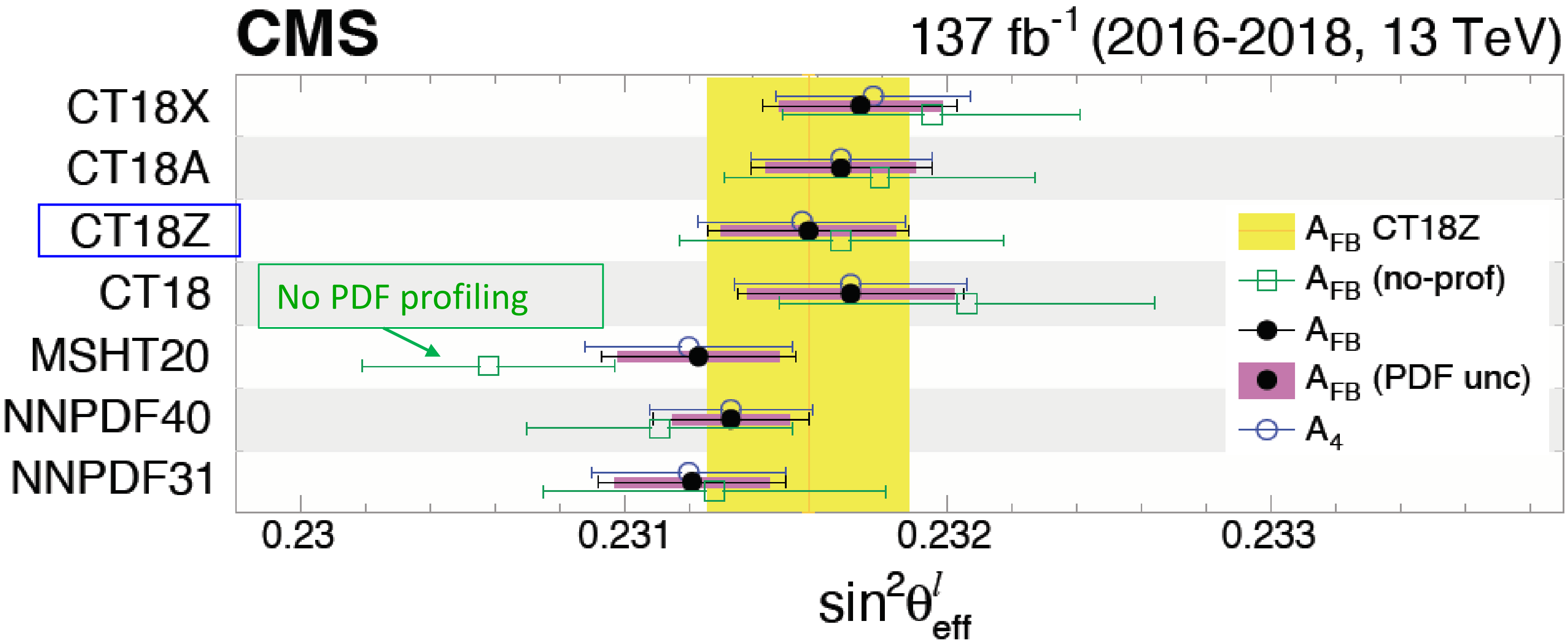
$1+\cos^2\theta+0.5A_0(1-3\cos^2\theta)+A_4\cos\theta$

$\rightarrow A_{FB} = 3/8 A_4$

A4 unfolding depends on modeling acceptance, efficiencies and resolutions. If these are properly accounted for then **$\sin^2\theta_{eff}$ extracted from A4 must** agree with **$\sin^2\theta_{eff}$ measured with detector level angle-weighted Afb**.

CT18Z PDF was chosen before unblinding (as it describes Z data at the LHC).

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23157 \pm 0.00010({\rm stat}) \pm 0.00015({\rm syst}) \pm 0.00009({\rm theo}) \pm 0.00027({\rm PDF}),$$



1. PDF reweighting/profiling reduces PDF error by a factor of 2, and results in better agreement between different PDF sets.

2. Afb and A4 analysis yield the same value of $\sin^2\theta_{eff}$ (angular-weighted Afb is a check on unfolded A4)

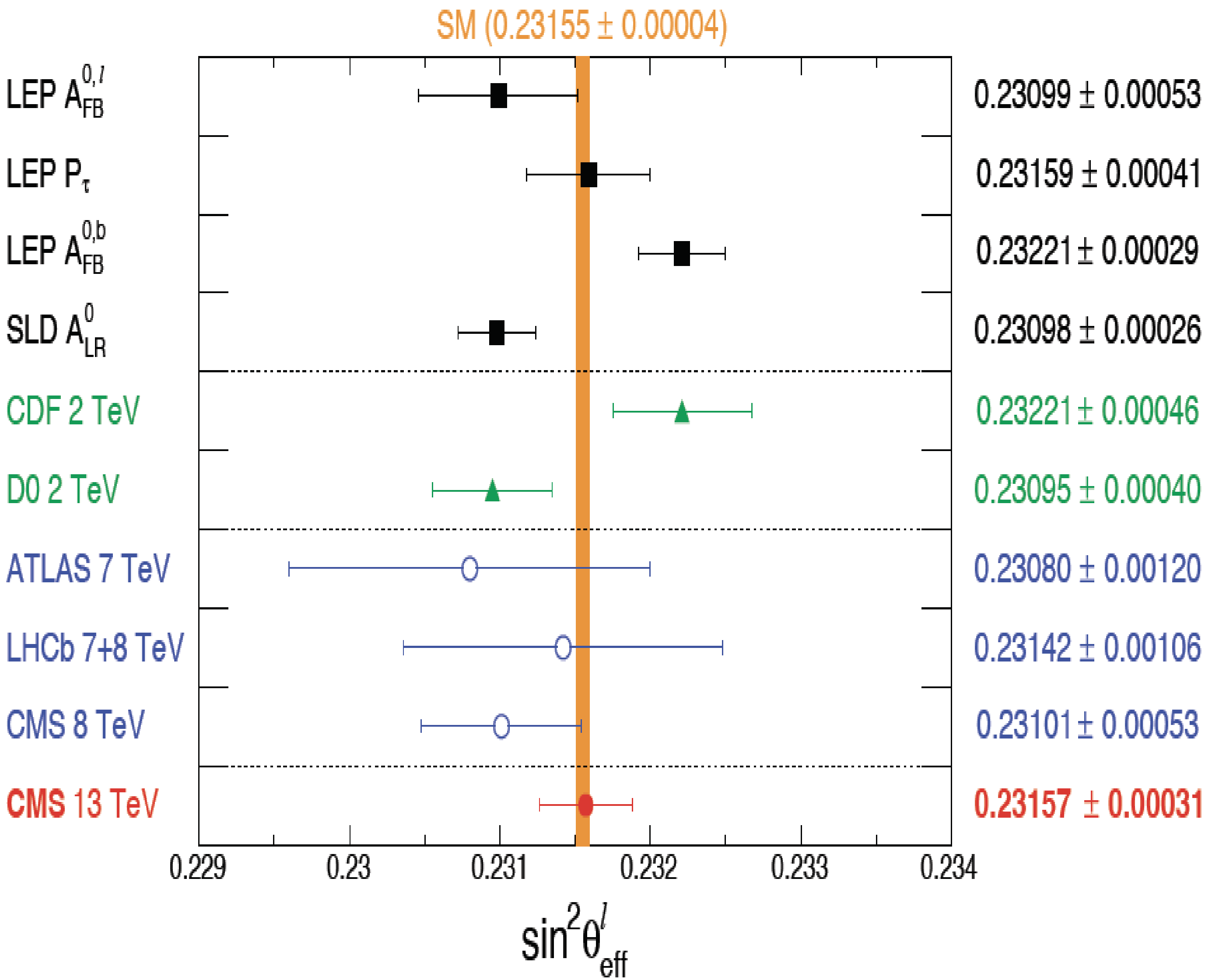
In units of 10^{-5}

PDF	A_{FB} (816 bins)		A_4 (63 bins)	
	χ^2_{min}	$\sin^2\theta^\ell_{eff}$	χ^2_{min}	$\sin^2\theta^\ell_{eff}$
NNPDF31	724.7	23121 ± 29	58.5	23120 ± 30
NNPDF40	730.5	23133 ± 24	62.6	23133 ± 25
MSHT20	735.8	23123 ± 30	71.0	23120 ± 32
CT18	728.4	23170 ± 35	62.2	23170 ± 36
CT18Z	730.7	23157 ± 31	61.3	23155 ± 32
CT18A	730.3	23167 ± 28	63.6	23167 ± 28
CT18X	728.5	23173 ± 30	61.8	23177 ± 30

$$\sin^2\theta^\ell_{eff} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{PDF}),$$

Next step: Reduce PDF error by using the values of A4 to extract **$\sin^2\theta_{eff}$** with PDF reweighting/profiling that also includes W boson asymmetry and other W boson distributions at 13 TeV.

Comparison of $\sin^2\theta_{eff}$ with previous experiments and with the SM prediction.



Conclusion: Heralding a new era of precision EW measurements at LHC

- New CMS measurement of **$\sin^2\theta_{eff.}$** with PDF reweighting/profiling is now competitive with LEP/LHC. (Experimental systematic errors cancel, PDF uncertainties remain as the dominant systematic errors)
  Further reduction in PDF errors is still needed to differentiate SM from the **2Higgs** Model

- Using the values of A4, an updated PDF reweighting/profiling analysis which also includes W boson asymmetry and W boson distributions will further reduce the PDF errors.
  PDF errors can also be reduced in a future combined analysis of A4 measurements for all three LHC experiments.

<u>Note:</u>
PDF reweighting/profiling is now also used in the CMS measurement of m_W