Measurement of the effective leptonic weak mixing angle in proton-proton collisions at $\sqrt{s}$ = 13 TeV

On behalf of the CMS collaboration

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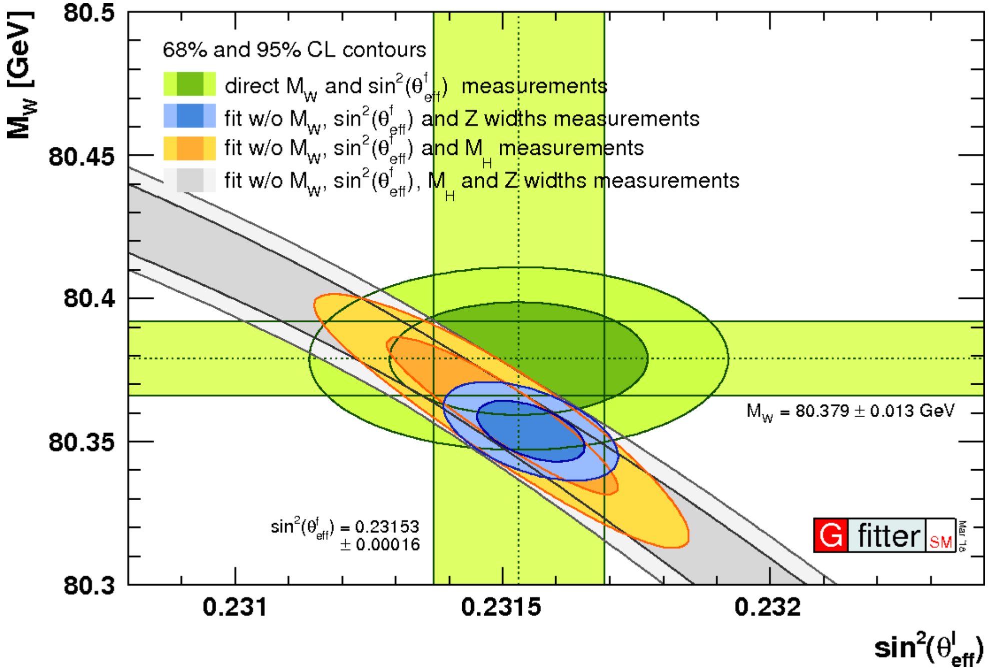
Weak mixing angle

- The weak mixing angle is a fundamental parameter in the Standard model related to the unification of the electromagnetic and weak forces
- $\sin^2\theta_W = \frac{g'^2}{g^2+g'^2} = 1 - \left(\frac{m_W}{m_Z}\right)^2 = \frac{1}{4|Q_f|}\left(1 - \frac{g_V^f}{g_A^f}\right)$

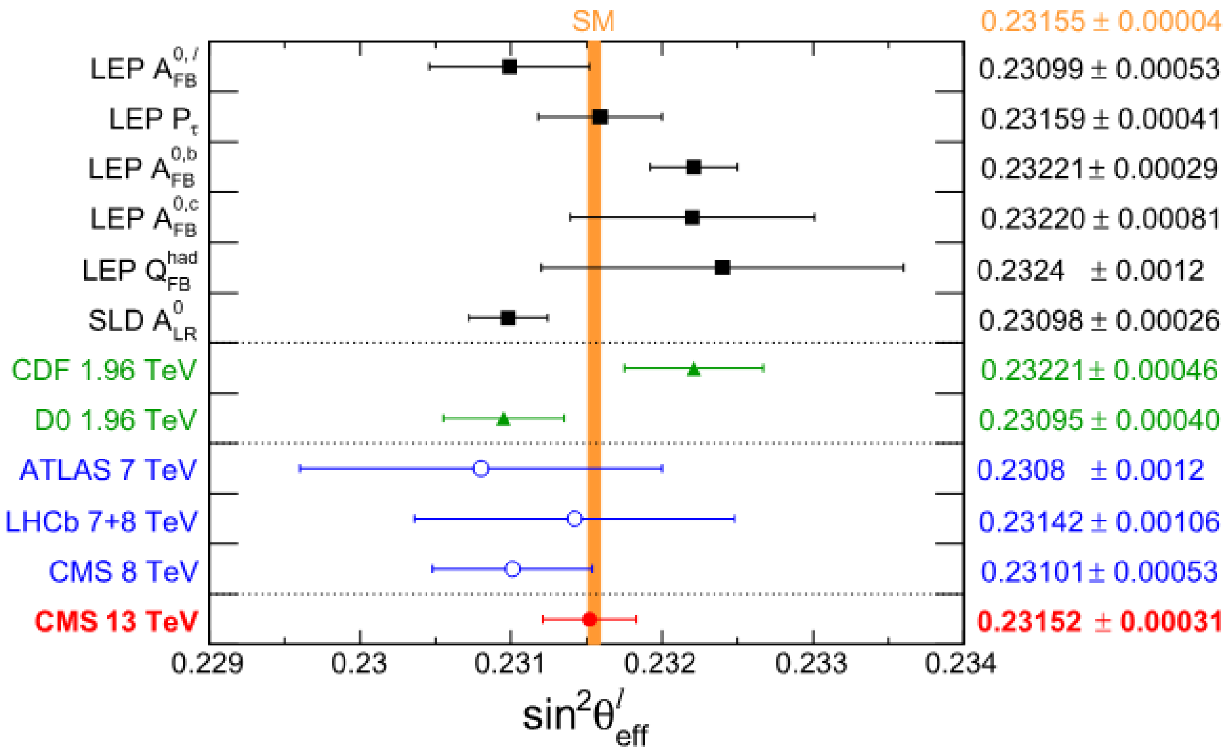
- Measurement of mixing angle
  - consistency check of the Standard model
  - powerful tool for searching for new phenomena

- Effective leptonic mixing angle
  - $\sin^2\theta_{eff}^l = \frac{1}{4}\left(1 - \frac{g_V^l}{g_A^l}\right)$
  - Includes loop corrections and reflects actual Z-lepton couplings



$\sin^2\theta^l_{eff}$ measurement at CMS 13 TeV

- $\sin^2\theta^l_{eff} = 0.23152 \pm 0.00031$ with CMS Run2 data (138 fb^{-1})
- The most precise measurement at hadron collider
- With a precision comparable to LEP and SLD
- Published in Phys. Lett. B (2025)

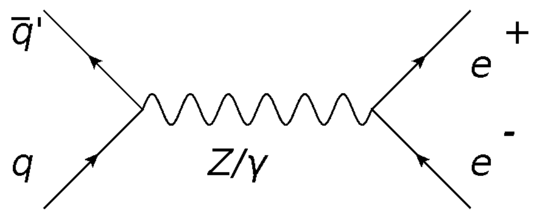


The CMS experiment at CERN measures a key parameter of the Standard Model

With this measurement the LHC is again demonstrating its ability to provide very high-precision measurements and bringing new insights into an old mystery

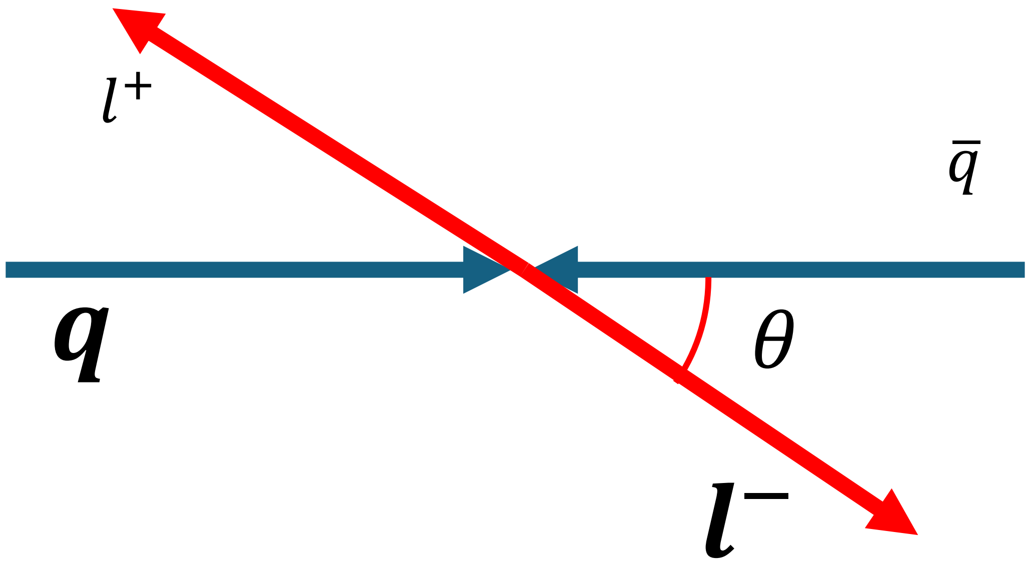
3 APRIL, 2024

Forward-backward asymmetry ($\boldsymbol{A_{FB}}$)



$\boldsymbol{\theta}$: Angle btw incoming and outgoing particles
$\cos\theta > 0$, forward event (F)
$\cos\theta < 0$, backward event (B)

CM frame



$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Forward-backward asymmetry ($\boldsymbol{A_{FB}}$)

- If incoming and outgoing particles have

same helicity → **forward** event is preferred

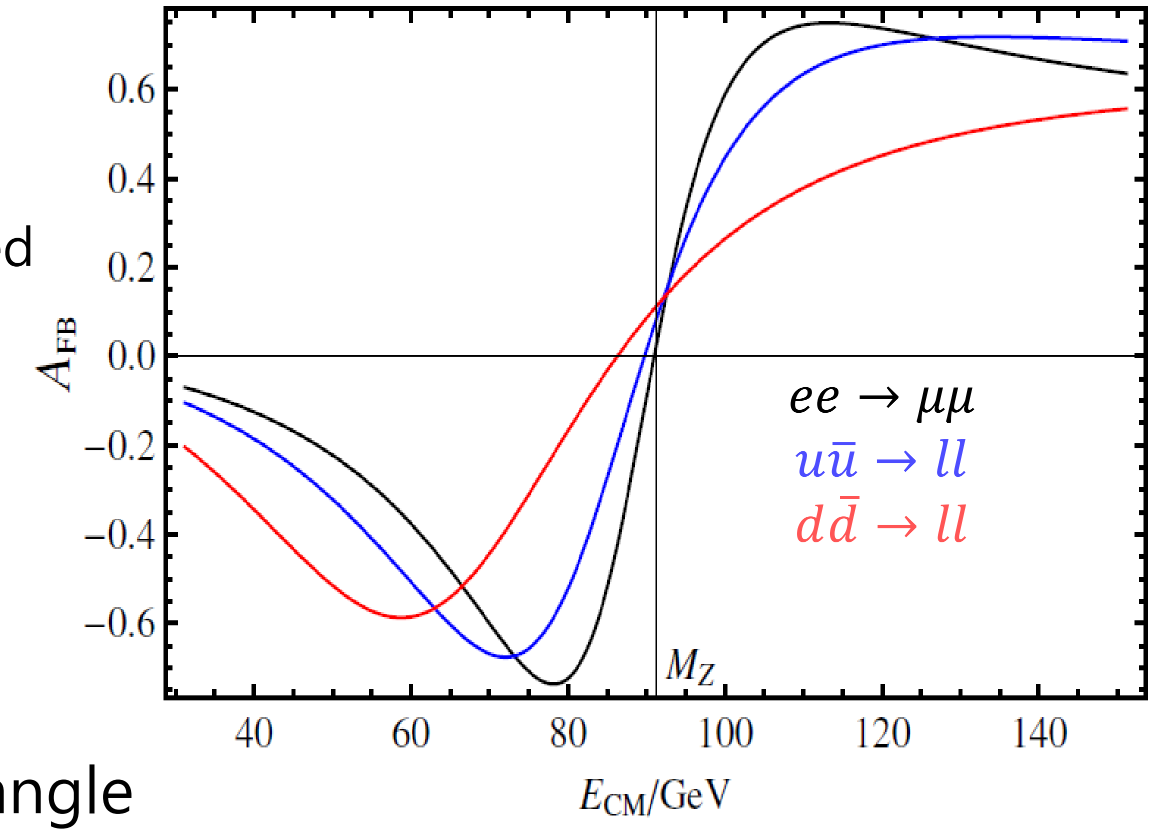
$$\sigma_{L\to L}, \sigma_{R\to R} \propto (1+\cos\theta)^2$$

opposite helicity → **backward** event is preferred

$$\sigma_{L\to R}, \sigma_{R\to L} \propto (1-\cos\theta)^2$$

due to angular momentum conservation

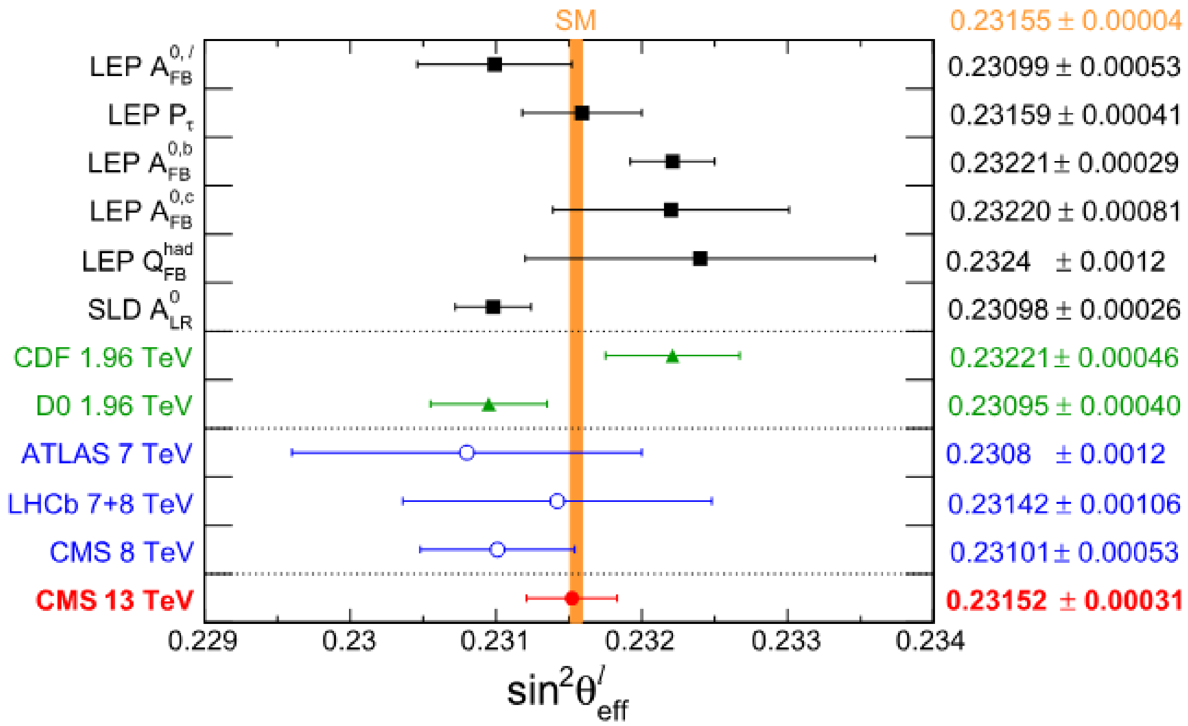
$$\frac{d\,\sigma_{DY}}{d\cos\theta} \propto (1+\cos^2\theta) + A_4\cos\theta$$



- $A_4 = \frac{8}{3}A_{FB}$ is sensitive to weak mixing angle

Challenges in hadron collision

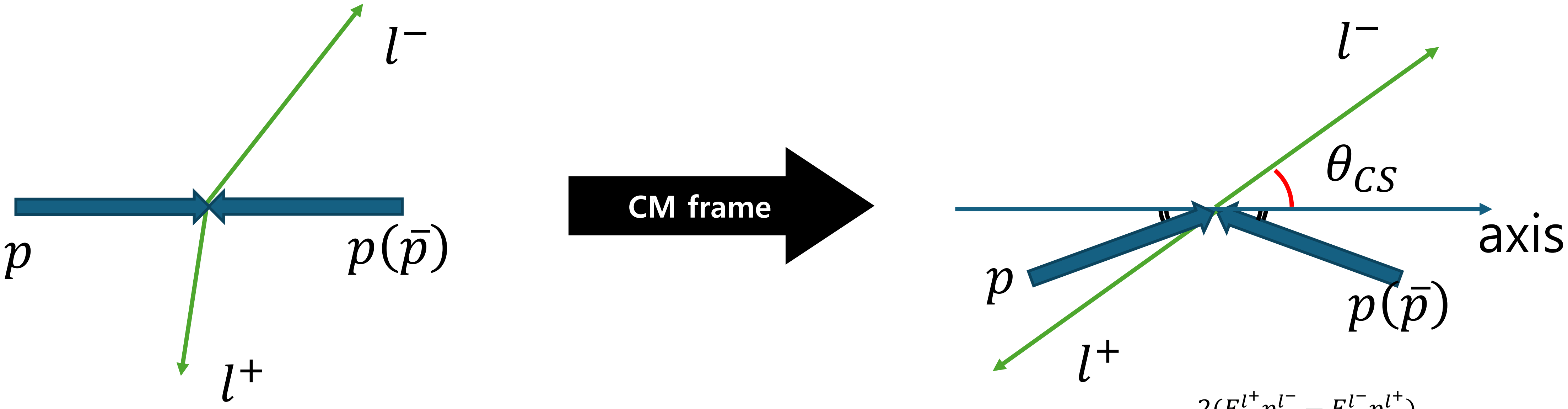
- Electron-positron (LEP, SLD)
  - Forward axis = electron direction
- Proton-antiproton (Tevatron)
  - Forward axis ≈ proton direction
    → PDF uncertainty
  - Dilution from ISR recoil: Collins-Soper (CS) frame
- Proton-Proton (LHC):
  - Forward axis ~ dilepton rapidity direction
    → Larger PDF uncertainty
  - Dilution from ISR recoil: Collins-Soper (CS) frame



Analysis strategy 1

Collins-Soper (CS) frame

- Two beam directions are not parallel in dilepton CM frame
- Due to recoil from ISR (Initial State Radiation)
- Bisect of beams is used as forward axis to minimize dilution of A_{FB}



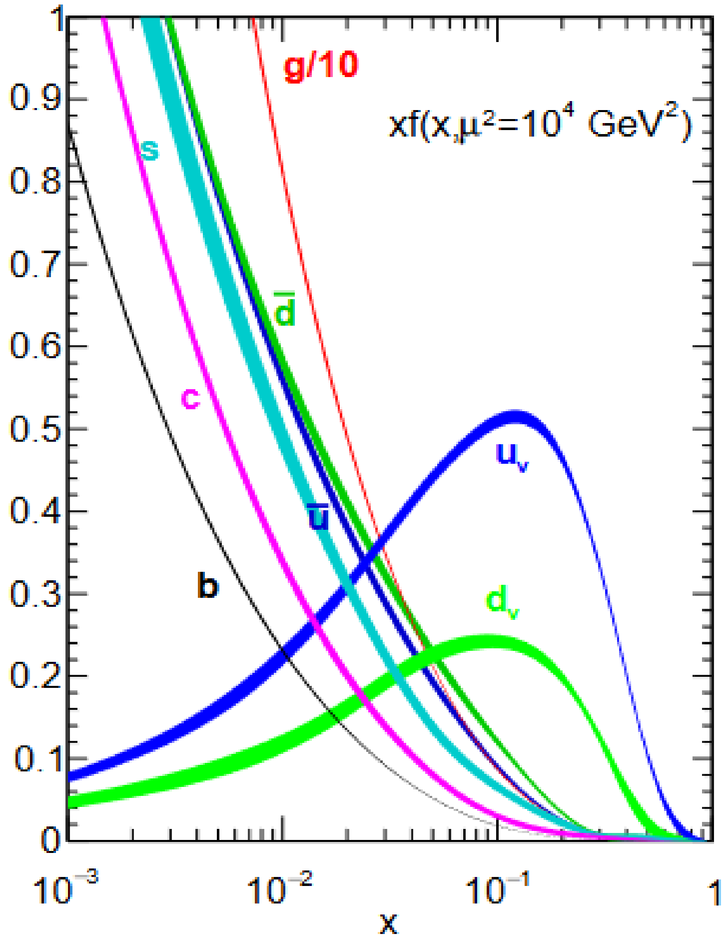
$$\cos\theta_{CS} = \frac{2(E^{l^+}p_z^{l^-} - E^{l^-}p_z^{l^+})}{m_{ll}\sqrt{m_{ll}^2 + p_{T,ll}^2}}$$

Analysis strategy 2

Forward axis guess using dilepton rapidity

- In pp collision, it's more challenging to determine forward axis than $p\bar{p}$
- Because we need to infer which proton provided the particle and which provided the antiparticle
- Typically, valence quarks carry more momentum than sea quarks
- Forward axis ~ dilepton rapidity direction

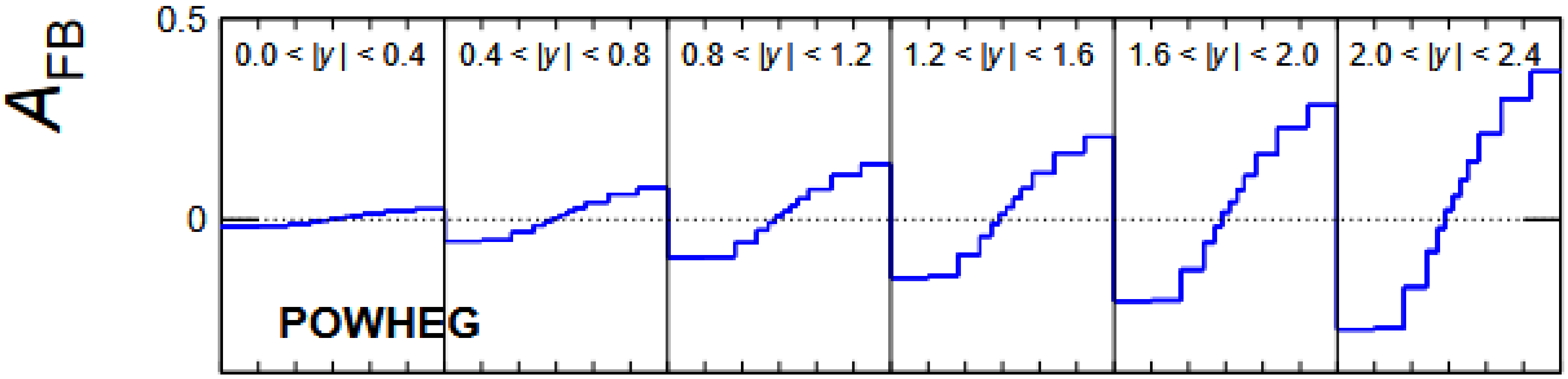
$$\cos\theta_{CS} = \frac{2(E^{l^+}p_z^{l^-} - E^{l^-}p_z^{l^+})}{m_{ll}\sqrt{m_{ll}^2 + p_{T,ll}^2}}\frac{\boldsymbol{y_{ll}}}{|\boldsymbol{y_{ll}}|}$$



Analysis strategy 3

Dilepton rapidity binning

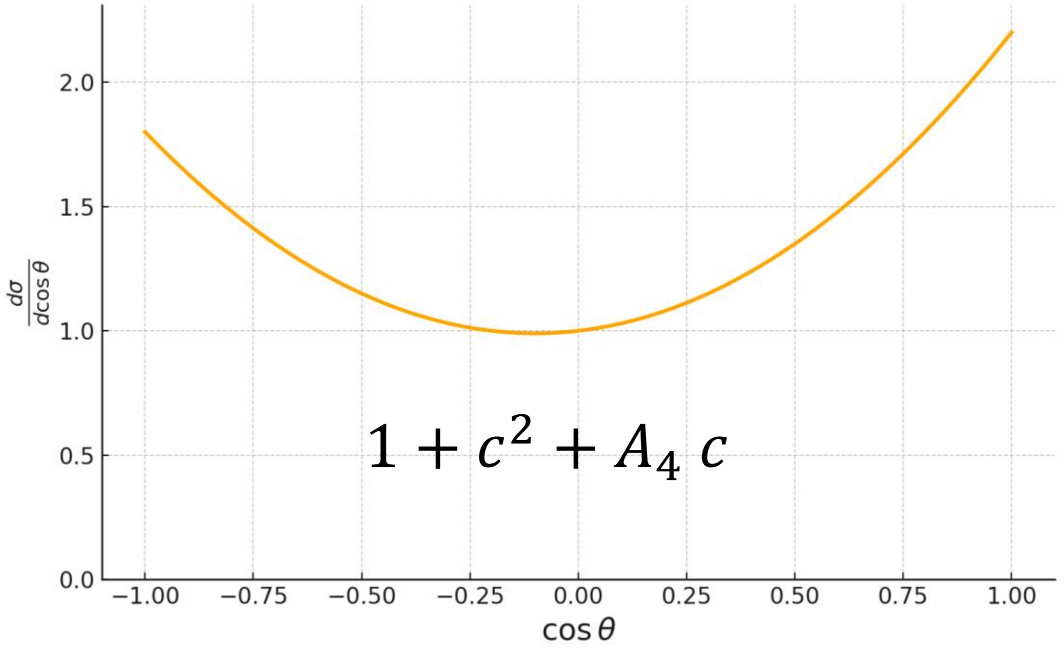
- Forward direction guess is more precise as rapidity get larger
- A_{FB} is measured in bins of rapidity to maximize sensitivity

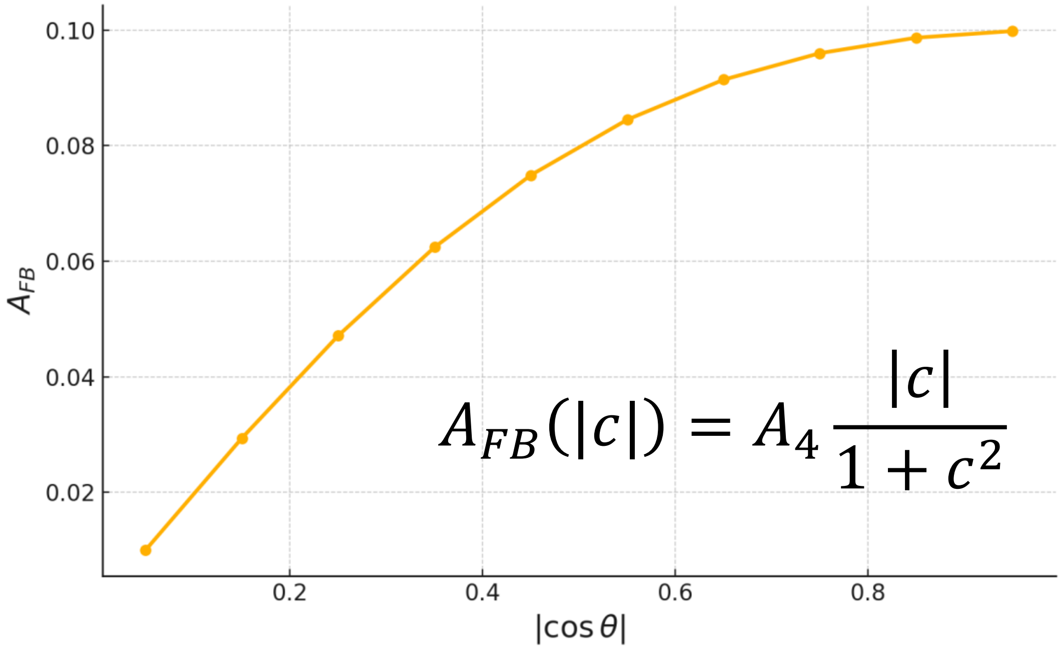


Analysis strategy 4

Angular-weighted asymmetry A_{FB}^{w}

- High $|\cos\theta_{CS}|$ region has larger sensitivity





Analysis strategy 4

Angular-weighted asymmetry A_{FB}^{w}

- One can measure A_{FB} in bins of $|\cos\theta_{CS}|$ to increase sensitivity
- But we apply weights based on DY angular distribution, which effectively achieves same sensitivity improvement as $|\cos\theta_{CS}|$ binning
- With this technique, systematic errors in acceptance and efficiency cancel

$$A_{FB}^{raw} = \frac{\sum_F 1 - \sum_B 1}{\sum_F 1 + \sum_B 1}$$

$$A_{FB}^{w} = \frac{3}{8}\frac{\sum_F w_N - \sum_B w_N}{\sum_F w_D + \sum_B w_D}$$

$$w_N = \frac{\mathbf{1}}{|\boldsymbol{c}|}\left(\frac{\boldsymbol{c}}{\mathbf{1}+\boldsymbol{c}^{\mathbf{2}}}\right)^{\mathbf{2}}$$

$$w_D = \frac{\mathbf{1}}{\mathbf{1}+\boldsymbol{c}^{\mathbf{2}}}\left(\frac{\boldsymbol{c}}{\mathbf{1}+\boldsymbol{c}^{\mathbf{2}}}\right)^{\mathbf{2}}$$

RED: $A_{FB}(c) \rightarrow A_4$

GREEN: Weight appropriately based on statistical power

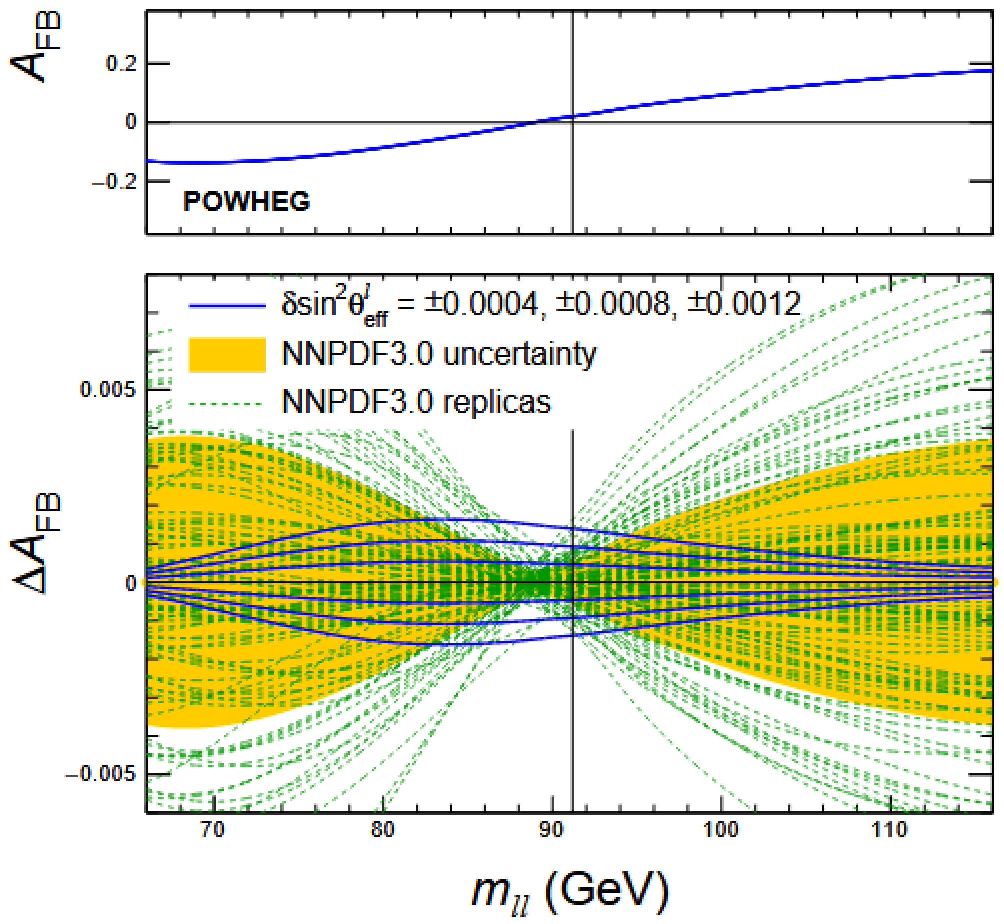
- In actual analysis, there is higher-order term h

$1 + \mathrm{c}^2 \rightarrow 1 + c^2 + h$

Analysis strategy 5

PDF profiling

- A_{FB} at Z peak is most sensitive region to mixing angle
- The sideband region, on the other hand, is sensitive to PDF
- We can constrain PDF using A_{FB} in sideband region to reduce PDF uncertainty, which is the largest systematic uncertainty



Analysis strategy 6

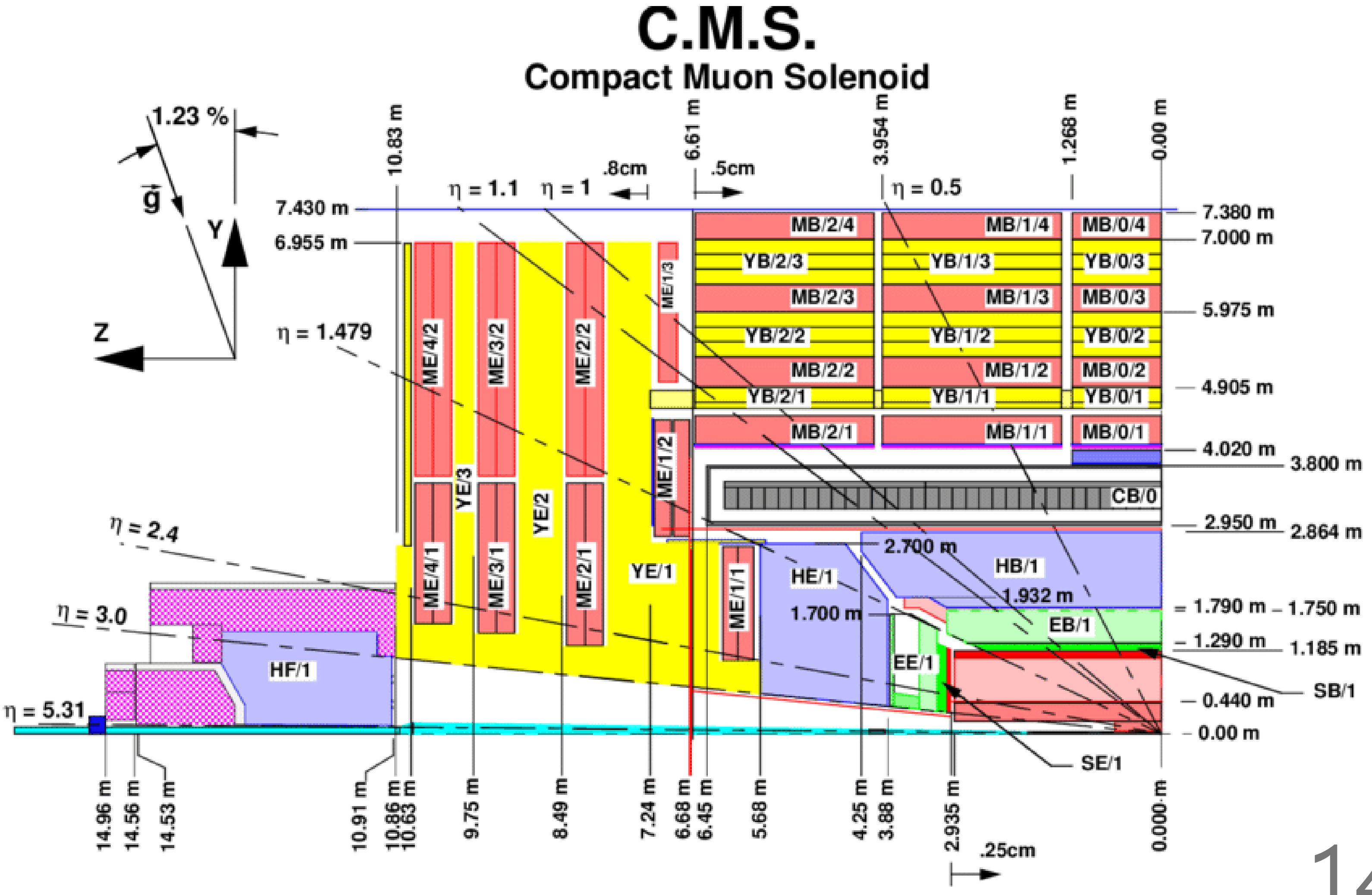
Forward electron

- Central lepton (with tracker)

μ: $|\eta| < 2.4$
e: $|\eta| < 2.5$

- Forward electron

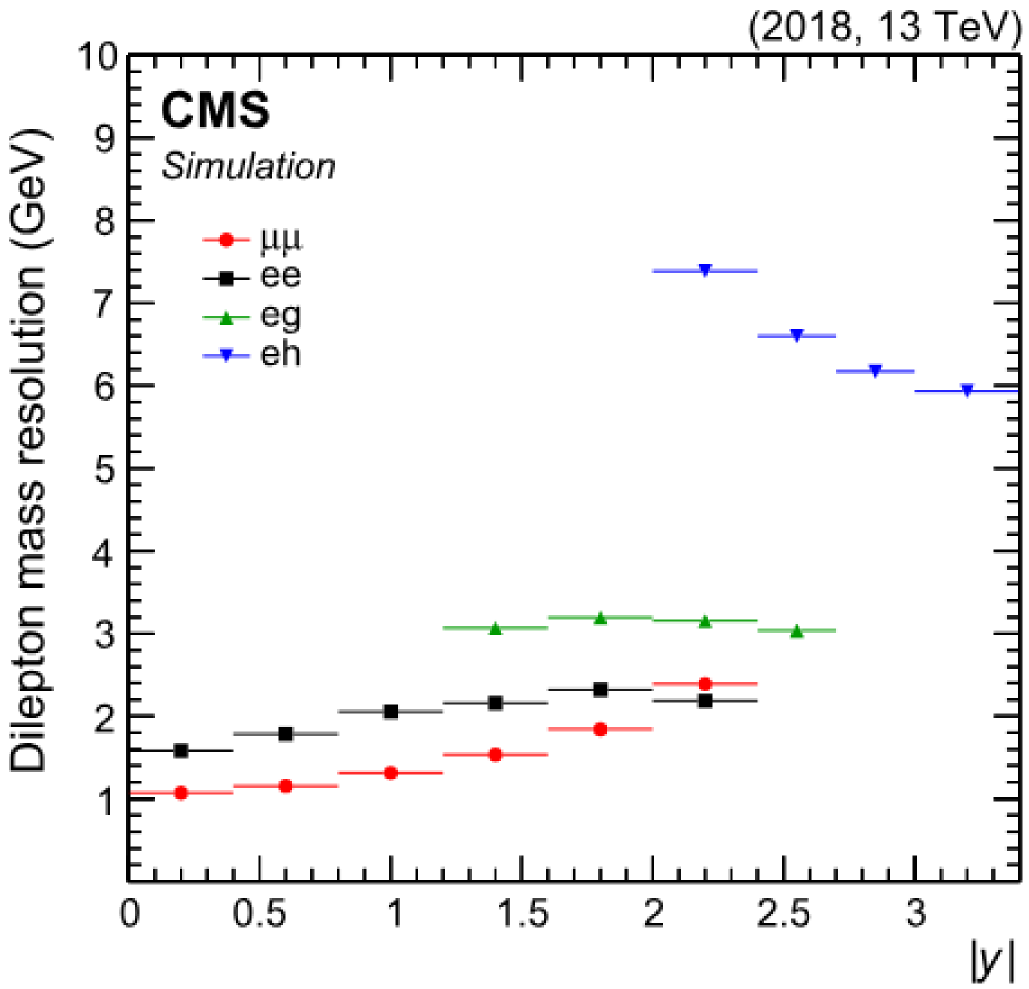
g: $2.5 < |\eta| < 2.87$
h: $3.14 < |\eta| < 4.36$



Analysis strategy 6

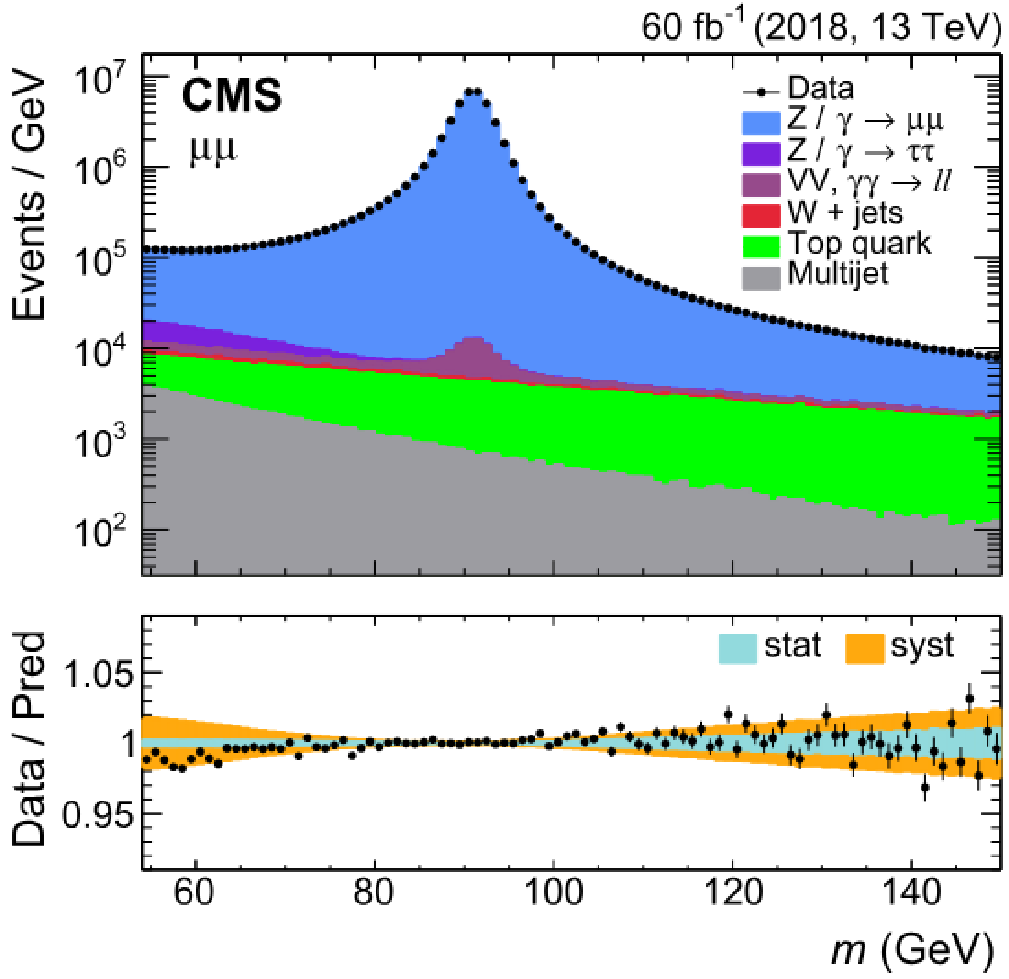
Forward electron

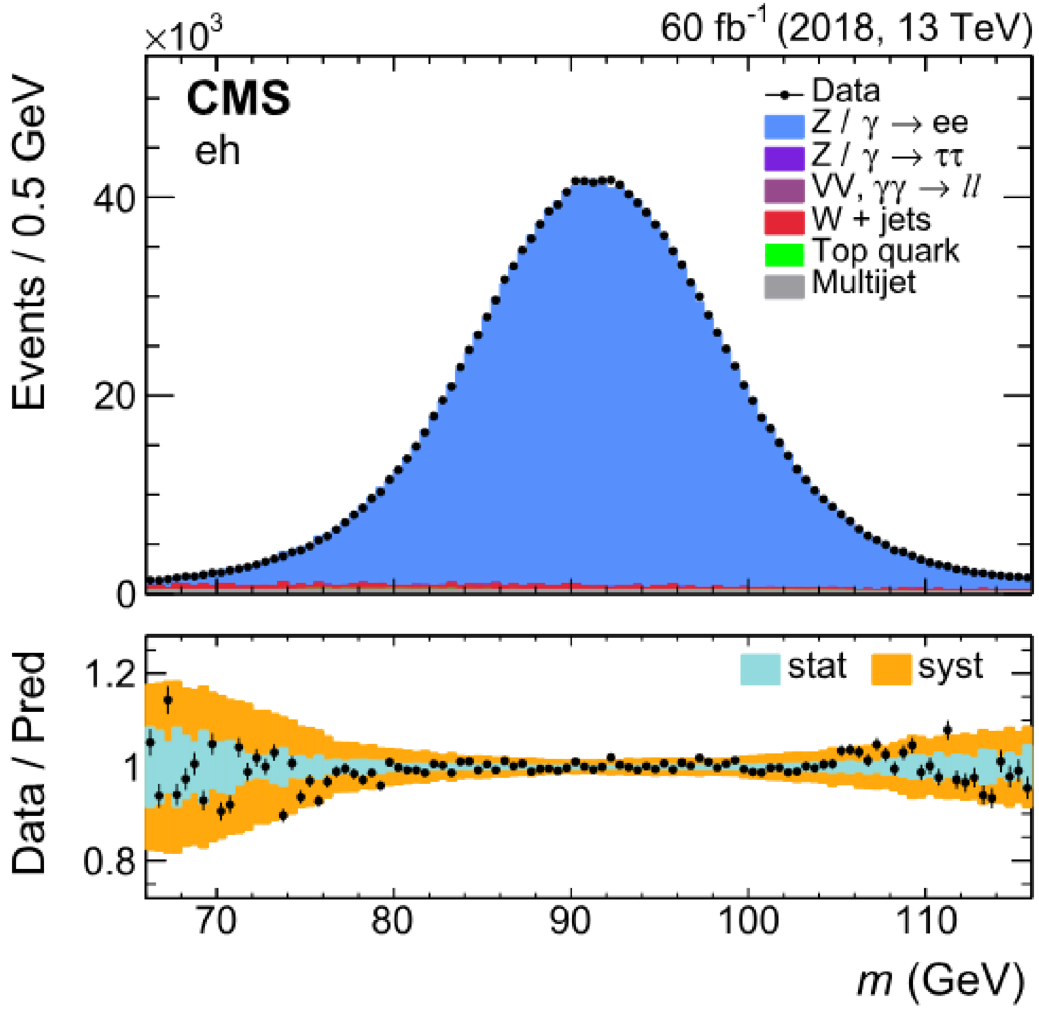
	$\|\eta\|$		$p_{T,min}^{leading}$	$p_{T,min}^{trailing}$
μμ	0.00–2.40		20 GeV	10 GeV
ee	0.00–2.50		25 GeV	15 GeV
	$\|\eta_e\|$	$\|\eta_{g,h}\|$	$p_{T,min}^{e}$	$p_{T,min}^{g,h}$
eg	0.00–2.50	2.50–2.87	30 GeV	20 GeV
eh	1.57–2.50	3.14–4.36	30 GeV	20 GeV



Extend the measurement to higher rapidity region

Dilepton mass distributions





Extracting $\sin^2 \theta_{eff}^{l}$

- Interpretation model: (NNLO QCD) + (NLO+HO EW) + PS +α
  - $MiNNLO_{PS}$ Powheg + Photos + Pythia8
  - NLO+HO weak correction
  - Z p_T reweight

- Three methods
  - **Fit $\boldsymbol{A_{FB}^{w}(|y|, m)}$**
  - Fit unfolded $A_4(|y|, m)$: $\frac{d^3\sigma}{d|y|\, dm\, d\cos\theta_{CS}} \rightarrow A_4(|y|, m) \rightarrow \sin^2 \theta_{eff}^{l}$
  - Fit $\cos\theta_{CS}$ distributions: $\frac{d^3\sigma}{d|y|\, dm\, d\cos\theta_{CS}} \rightarrow \sin^2 \theta_{eff}^{l}$

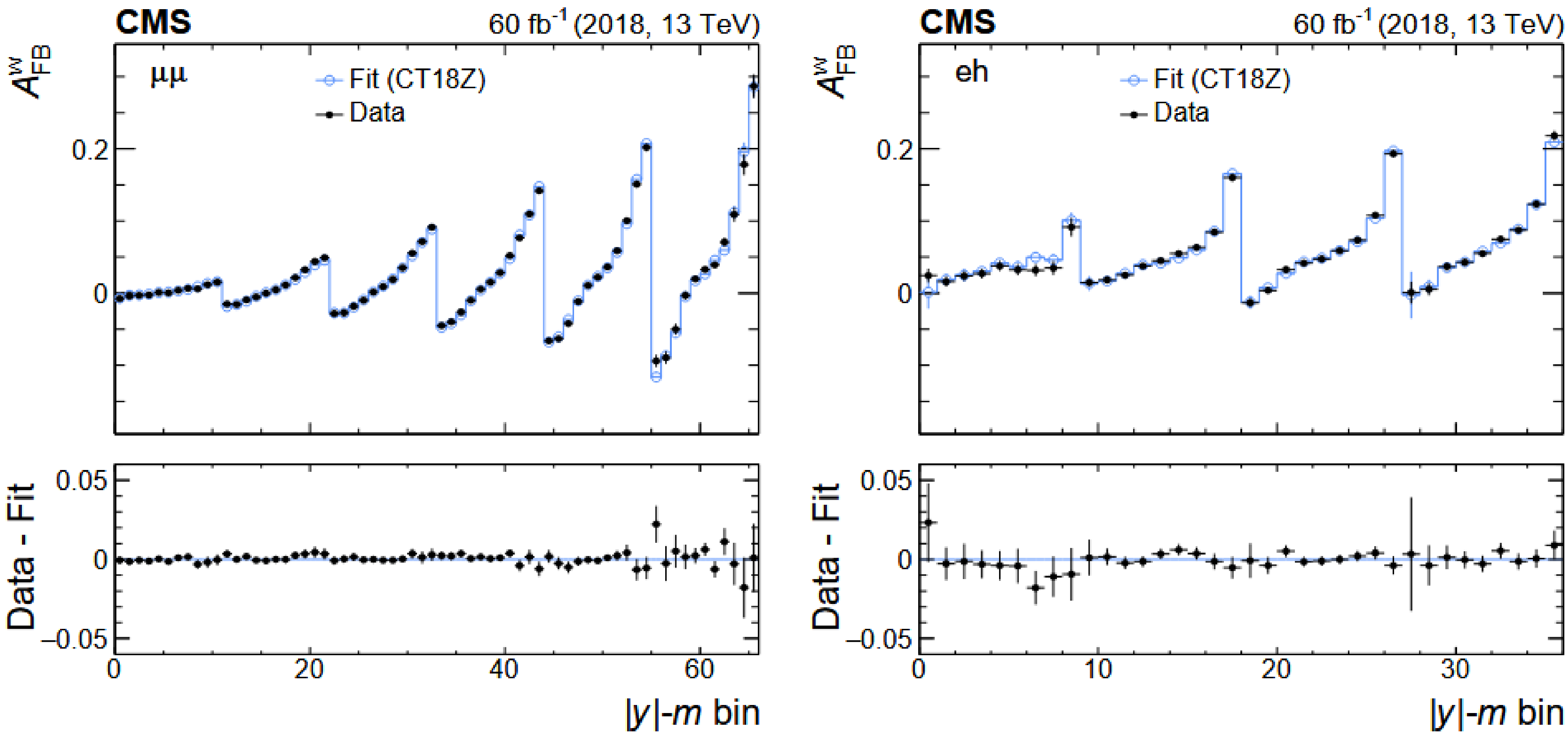
Extracting $\sin^2\theta^l_{eff}$ with A^w_{FB}

Channel	Absolute rapidity bin edges											$n_{\|y\|}$
μμ, ee	0.0	0.4	0.8	1.2	1.6	2.0	2.4					6
eg				1.2	1.6	2.0	2.4	2.7				4
eh						2.0	2.4	2.7	3.0	3.4		4

Channel	Reconstructed m bin edges (GeV)											n_m
μμ, ee	54	66	76	82	86	89.5	92.7	96	100	106	116	150	11
eg, eh		66	76	82	86	89.5	92.7	96	100	106	116		9

- A^w_{FB} is measured in bins of $|y_{ll}|$ and m_{ll}
  - $|y_{ll}| < 3.4$
  - $54 < m_{ll} < 150$ GeV

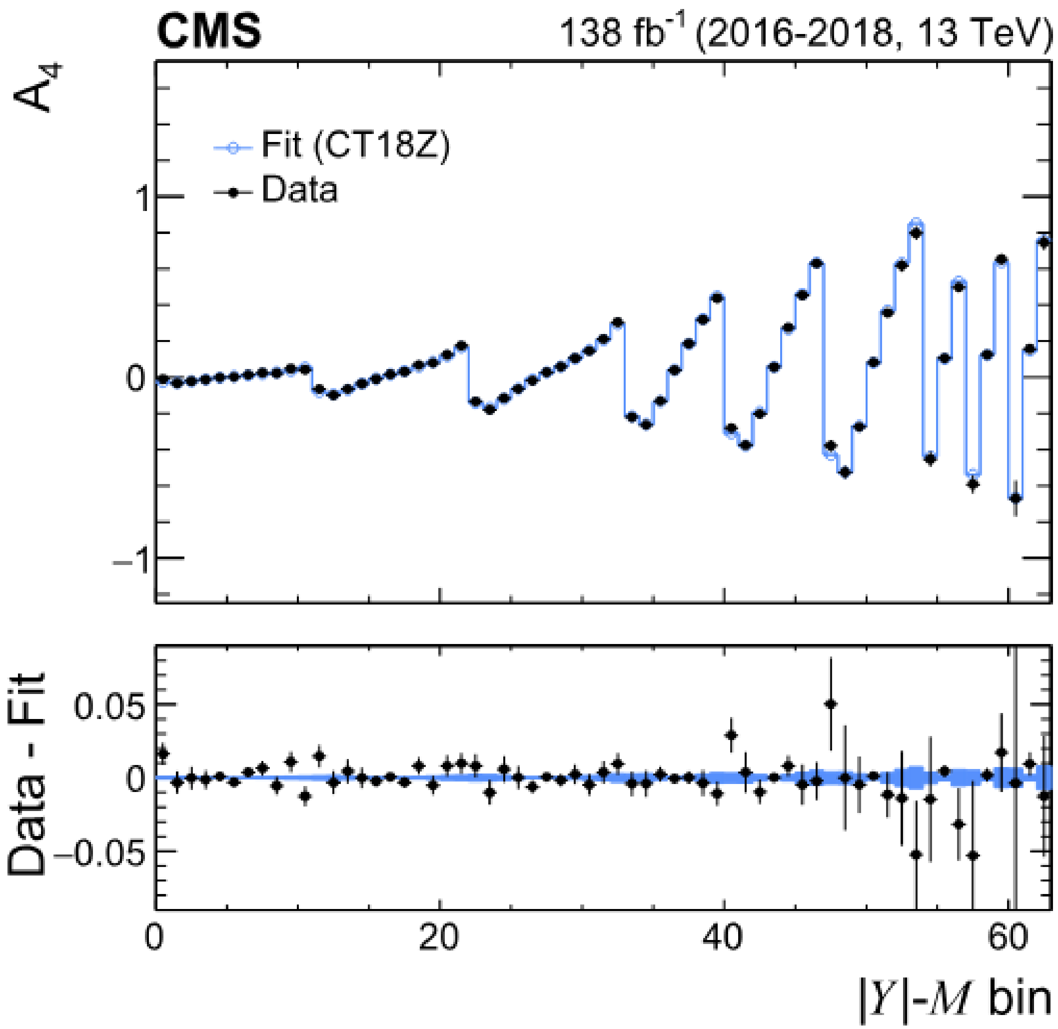
Extracting $\sin^2\theta^{l}_{eff}$ with A^{w}_{FB}



Extracting $\sin^2\theta_{eff}^{l}$ with A_{FB}^{w}

	$\chi^2_{\min}$	bins	p (%)	$\sin^2\theta^{\ell}_{\text{eff}}$	stat	exp	th	PDF	MC	bg	eff	calib	other
μμ	241	264	83	$23\,142 \pm 38$	17	17	6	30	13	3	2	5	4
ee	257	264	60	$23\,171 \pm 41$	22	18	5	30	14	4	5	3	7
eg	119	144	93	$23\,253 \pm 61$	30	40	3	44	23	11	12	20	8
eh	105	144	99	$23\,114 \pm 48$	18	33	9	37	14	10	16	18	6
$\ell\ell$	731	816	98	$23\,152 \pm 31$	10	15	8	27	8	4	6	6	3

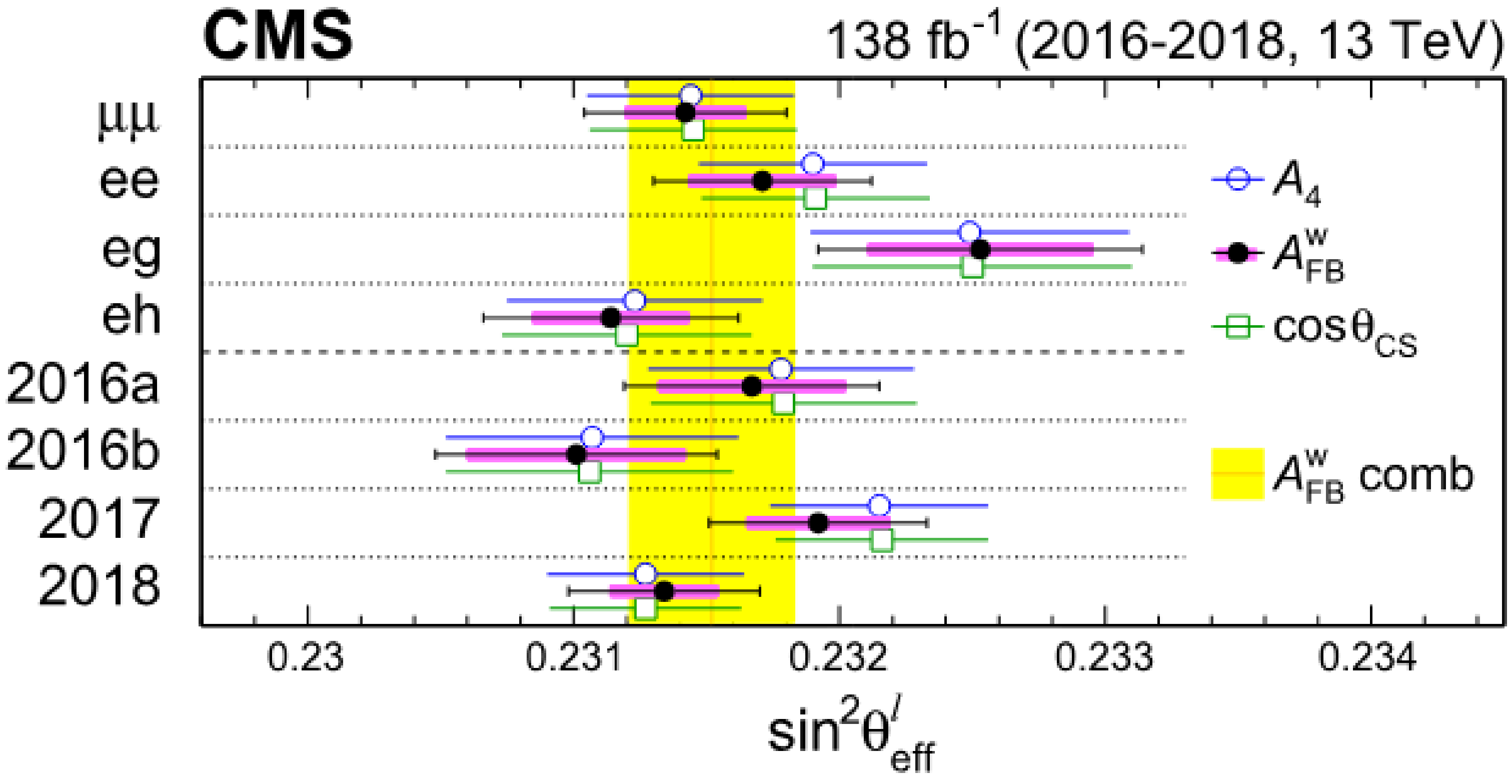
Extracting $\sin^2\theta_{eff}^{l}$ with unfolded A_4



Channel	χ^2_{min}	bins	p (%)	$\sin^2\theta^{\ell}_{eff}$
μμ	62	54	19	23 144 ± 39
ee	48	54	69	23 190 ± 43
eg	11	12	41	23 249 ± 60
eh	9	12	66	23 123 ± 48
$\ell\ell$	64	63	39	23 154 ± 32

Unlike A_{FB}^{w}, in which acceptance and efficiencies cancel, unfolding requires very good modeling of acceptance and efficiencies.

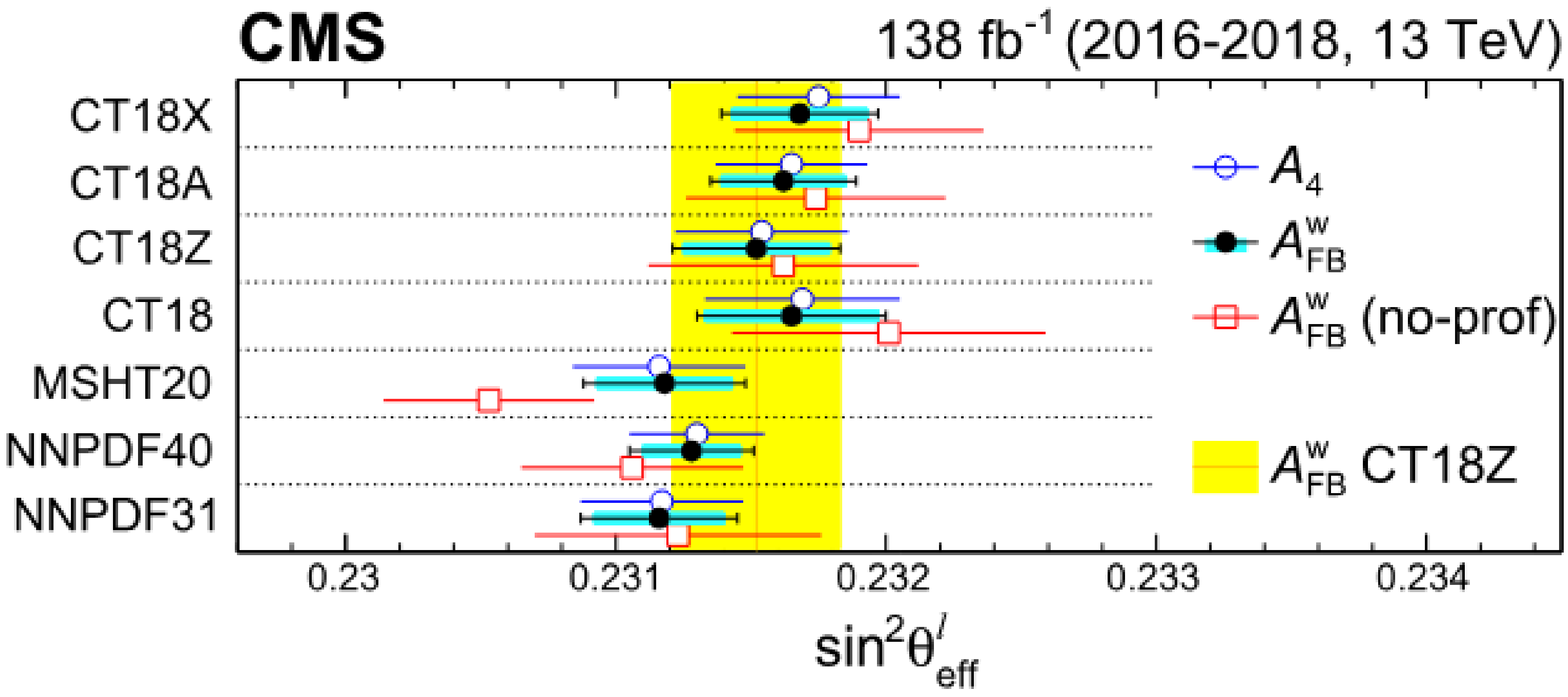
Comparison of three methods



- $\sin^2\theta^l_{eff}$ using unfolded A_4 is consistent with $\sin^2\theta^l_{eff}$ extracted from A^w_{FB}
- → Good modeling of acceptance and efficiencies

Results with various PDFs

- CT18Z result is reported as the nominal result



Conclusion

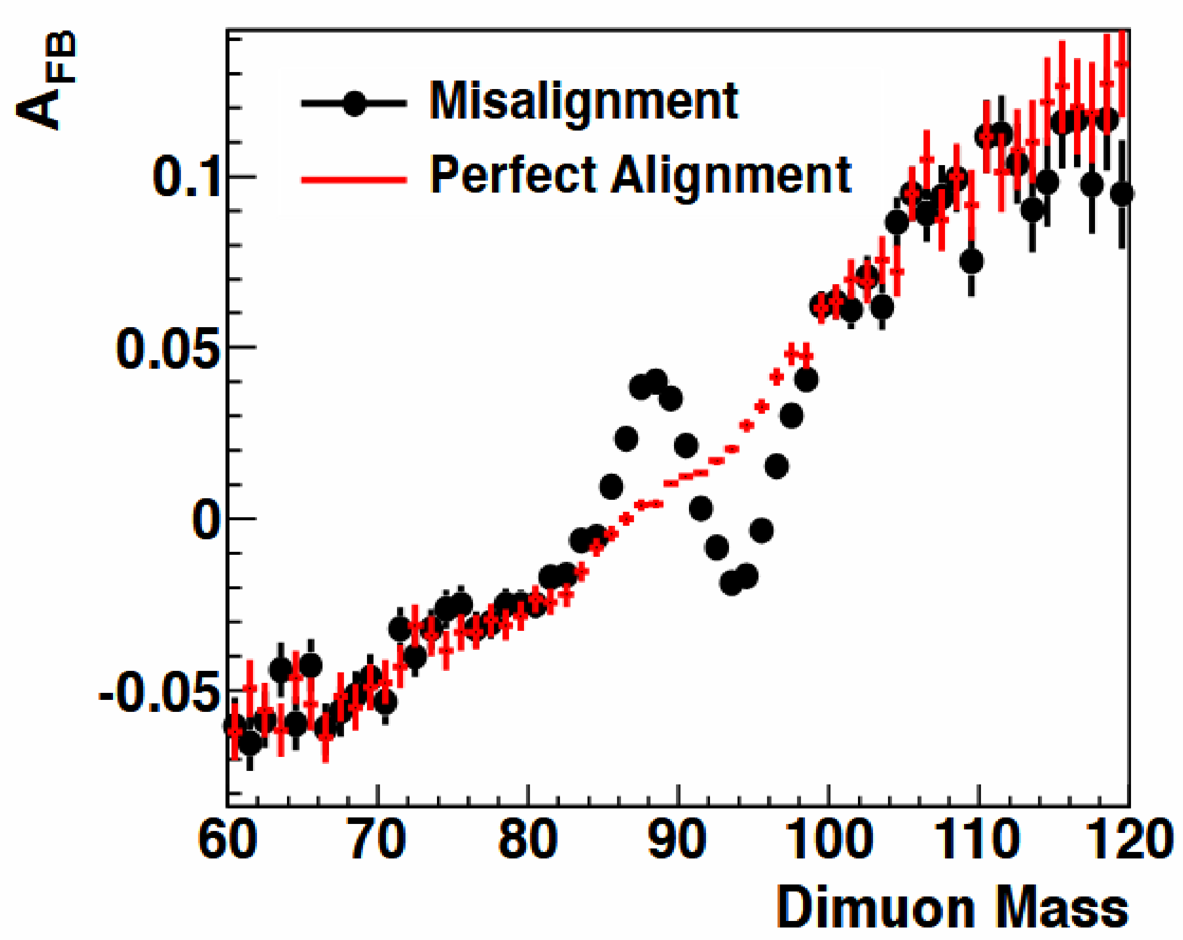
- Weak mixing angle measurement at 13 TeV using CMS Run 2 data ($138\ \mathrm{fb}^{-1}$)
  - $\sin^2\theta^{l}_{eff} = 0.23152 \pm 0.00031$ (CT18ZNNLO)
  - The most precise measurement at hadron collider
  - Unfolded A_4 is also measured for future reinterpretation
  - Published in PLB 10.1016/j.physletb.2025.139526

- We need better understanding on PDF to improve the measurement further

backup

Analysis strategy 7

Precise lepton momentum calibration



https://doi.org/10.1140/epjc/s10052-012-2194-8

- Miscalibration of lepton momentum can introduce unphysical wiggle in A_{FB}
- Lepton momentum is calibrated using Z peak