Precision Measurement of the EW Mixing Angle at the Z Pole

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PHENO 2026 May 11, 2026, 5:30 PM. 15m
David Lawrence Hall 106, University of Pittsburgh

Weak mixing angle

- On shell weak mixing angle - $\sin^2\theta_W$
  - A fundamental parameter in the Standard model
  - Related to the unification of the electromagnetic and weak forces

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \left(\frac{m_W}{m_Z}\right)^2 = \frac{1}{4|Q_f|}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

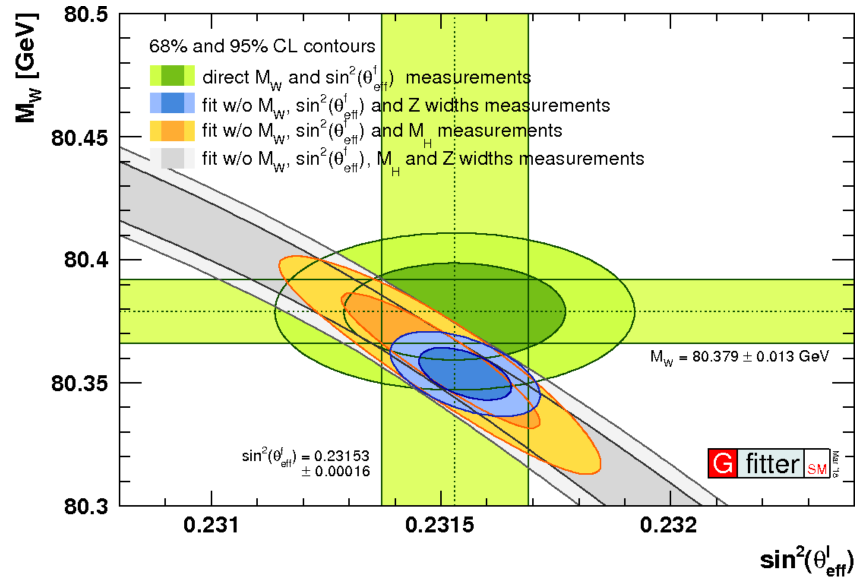
- Effective leptonic mixing angle – $\sin^2\theta_{\text{eff}}^l$

$$\sin^2\theta_{\text{eff}}^l = \frac{1}{4}\left(1 - \frac{g_V^l}{g_A^l}\right)$$

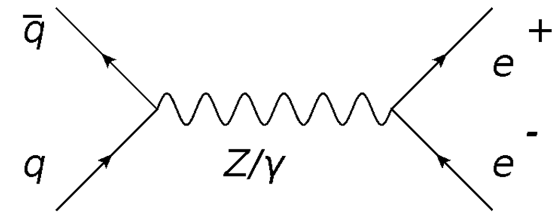
  - Includes loop corrections
  - Reflects the effective couplings of the Z boson to leptons

- Measurement of $\sin^2\theta_{\text{eff}}^l$
  - Provides a consistency check of the Standard Model
  - Serves as a powerful tool for searching for new phenomena

Gfitter (Aug 2024)



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

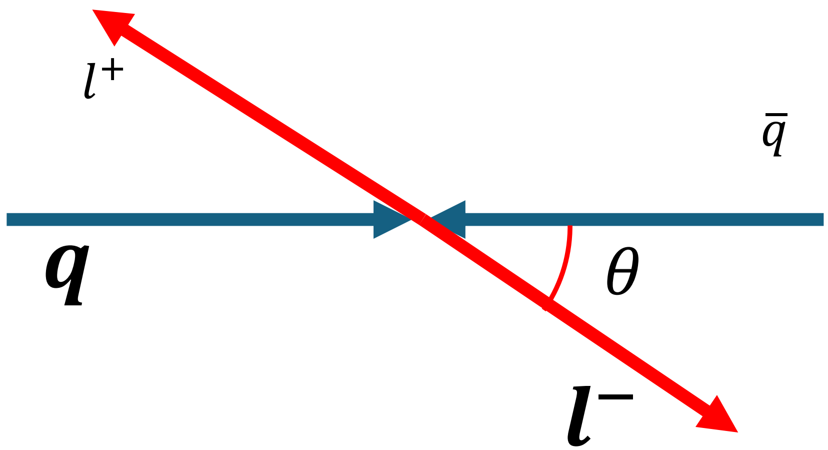


- **Key observable for mixing angle extraction**
  Asymmetry at the Z pole is sensitive to $sin^2\,\theta^l_{\rm eff}$

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

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

CM frame



The direction of the quark is defined as the direction of the rapidity of the dilepton. The dilution from events for which this is incorrect is derived from Parton Distribution Functions (PDFs)

Profiling with mass dependence of the Forward-backward asymmetry (A_{FB}) to constrain PDFs

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

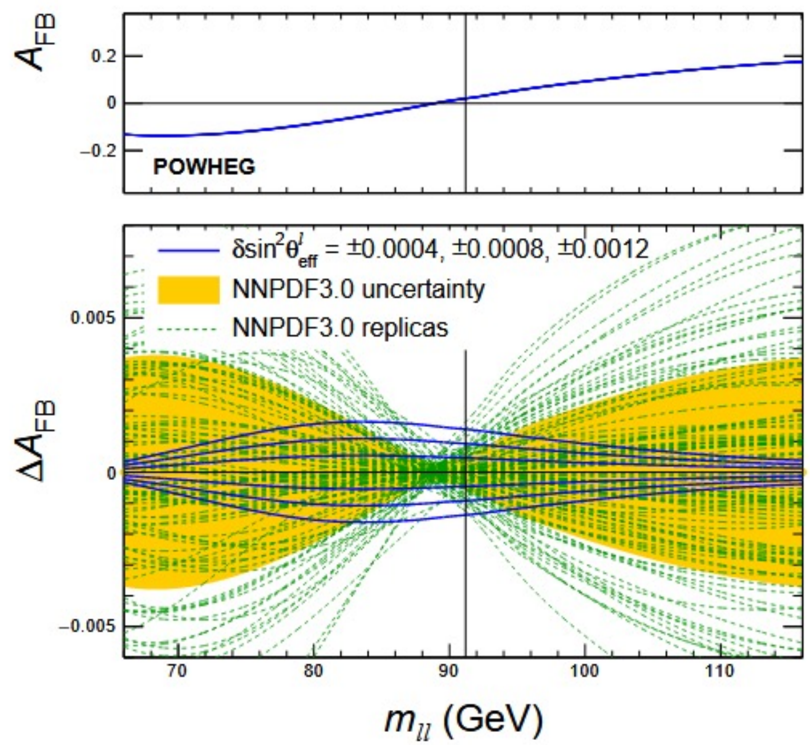
$$\frac{d\,\sigma_{DY}}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_4\cos\theta$$

- $A_{FB} = \frac{3}{8}A_4$, directly related to the mixing of $\mathrm{U(1)}$ and $\mathrm{SU(2)_L}$

- A_{FB} at Z peak
  - Sensitive to weak mixing angle and PDFs

- **A_{FB} in sideband region**
  - **Small sensitivity to mixing angle**
  - **Large sensitive to PDFs**

  → Can be used to constrain PDFs

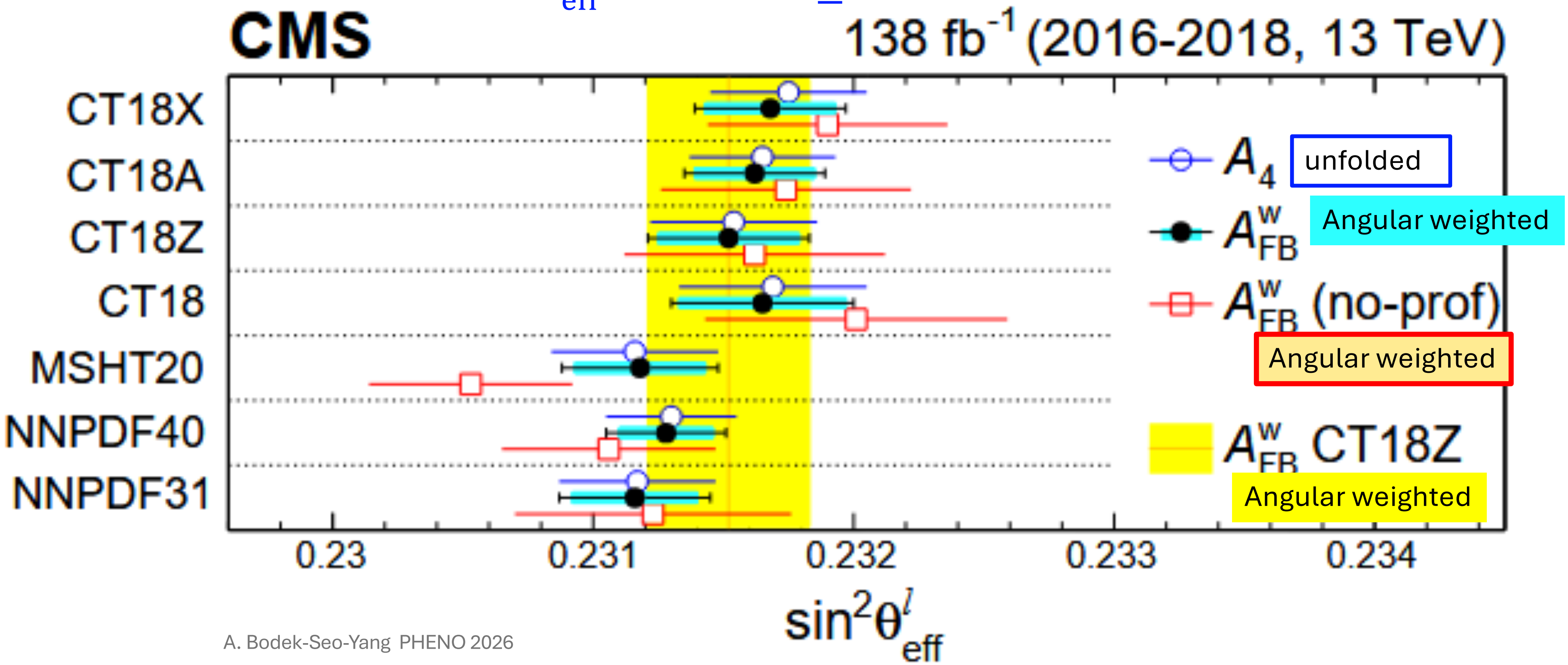


$$\sin^2\theta^l_{\mathrm{eff}} = 0.23152 \pm 0.00031$$

Issue: Residual PDF-set dependance of published $sin^2\,\theta^l_{\rm eff}$ after Afb profiling (though much better than before Afb profiling)

7 PDF sets were investigated

$$\sin^2\theta^l_{\rm eff} = 0.23152 \pm 0.00031$$



A. Bodek-Seo-Yang PHENO 2026

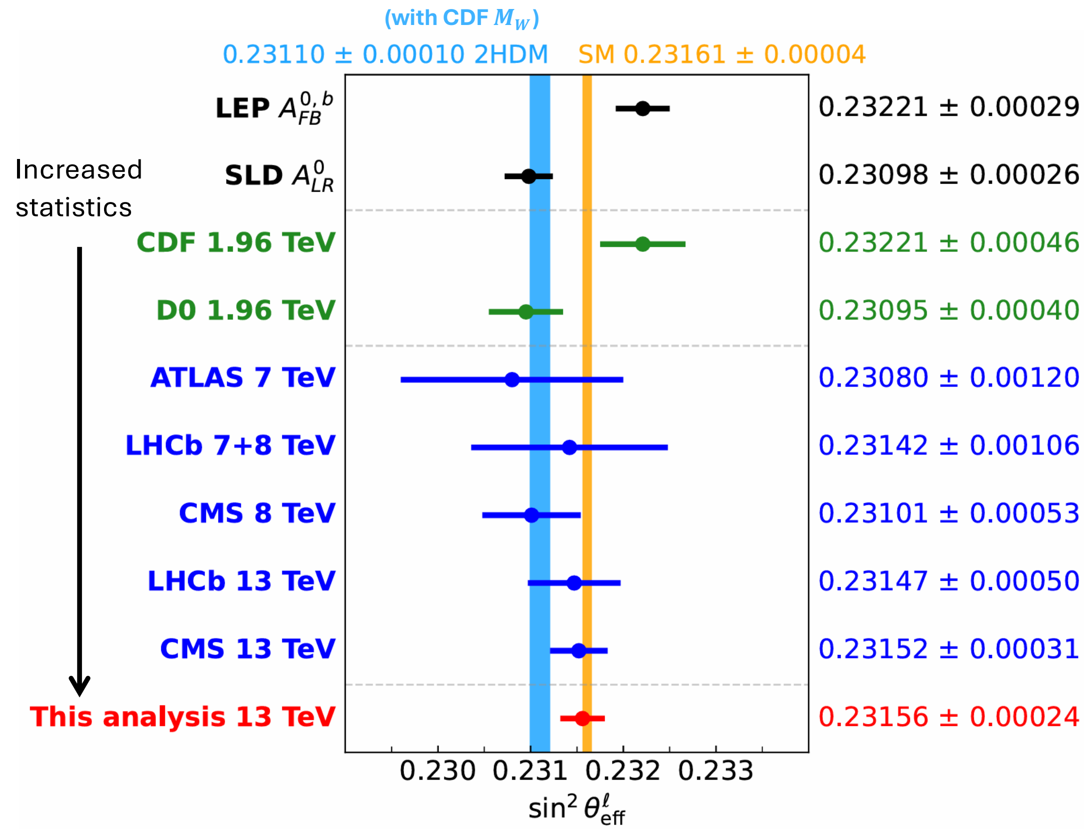
Measurements of $sin^2\,\theta^l_{\rm eff}$ at the Z pole

- Electron-positron collision
  - LEP: 0.23221 ± 0.00029
  - SLD: 0.23098 ± 0.00026

- CMS 13 TeV Phys. Lett. B 866 (2025) 139526
  - $\sin^2\theta^l_{\rm eff} = 0.23152 \pm 0.00031$

This talk

- Improved analysis of CMS 13 TeV arXiv:2508.18022
  - $\mathbf{\sin^2\theta^l_{\rm eff} = 0.23156 \pm 0.00024}$
  - **Vs SM** $\mathbf{0.23161 \pm 0.00004}$



Updated Analysis of $sin^2\,\theta^{l}_{\mathrm{eff}}$ with unfolded CMS 13 TeV Afb

arXiv:2508.18022

- Start with published CMS unfolded A4 (M) at 13 TeV profiled with A4 (mostly constrains u quarks)
- Add (now available) published CMS W asymmetry data at 13 TeV- (constrains d quarks)
- Add (now available) published CMS W/Z cross section ratios at 5 and 13 TeV (constrains s quarks)
- **Perform a combined profiling analysis of all three data sets with additional (total of 19) modern PDF sets.**
- **Use open-source fit platform xFitter.**

Updated analysis: Investigated 19 PDF sets

NNPDF40 (8)

Neural network base
Asymmetric strange

NNPDF40_nnlo
NNPDF40_nnlo_qed
NNPDF40_nnlo_mhou
NNPDF40_nnlo_qed_mhou
NNPDF40_an3lo
NNPDF40_an3lo_qed
NNPDF40_an3lo_mhou
NNPDF40_an3lo_qed_mhou

MSHT20 (4)

Polynomial parameterization
Asymmetric strange

MSHT20nnlo_as118
MSHT20qed_nnlo
MSHT20an3lo_as118
MSHT20qed_an3lo

CT18 (6)

Polynomial parameterization
Symmetric strange

CT18XNNLO: alternative scale choice
CT18ANNLO: including ATLAS 7 TeV W/Z measurement
CT18ZNNLO: A+X (Nominal PDF)
CT18qed_proton
CT18As_LatNNLO: asymmetric strange

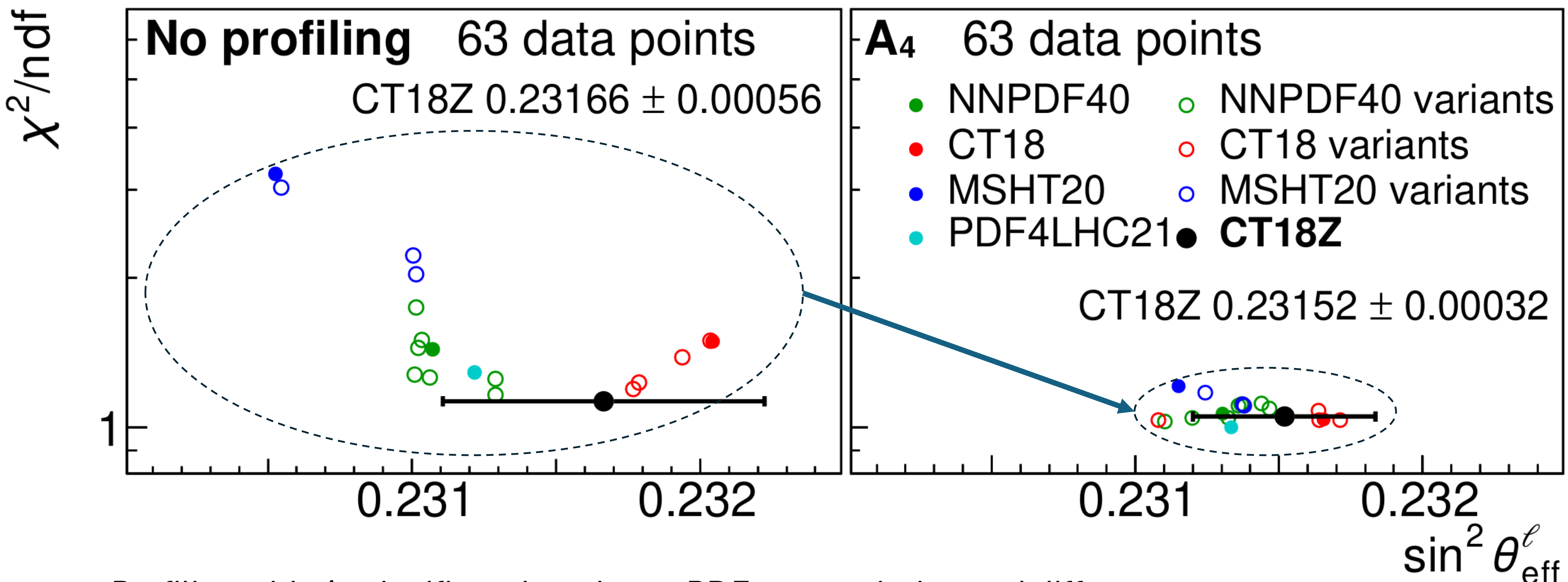
PDF4LHC21 (1)

Combination of CT18+MSHT20+NNPDF31
Asymmetric strange

PDF4LHC21_40

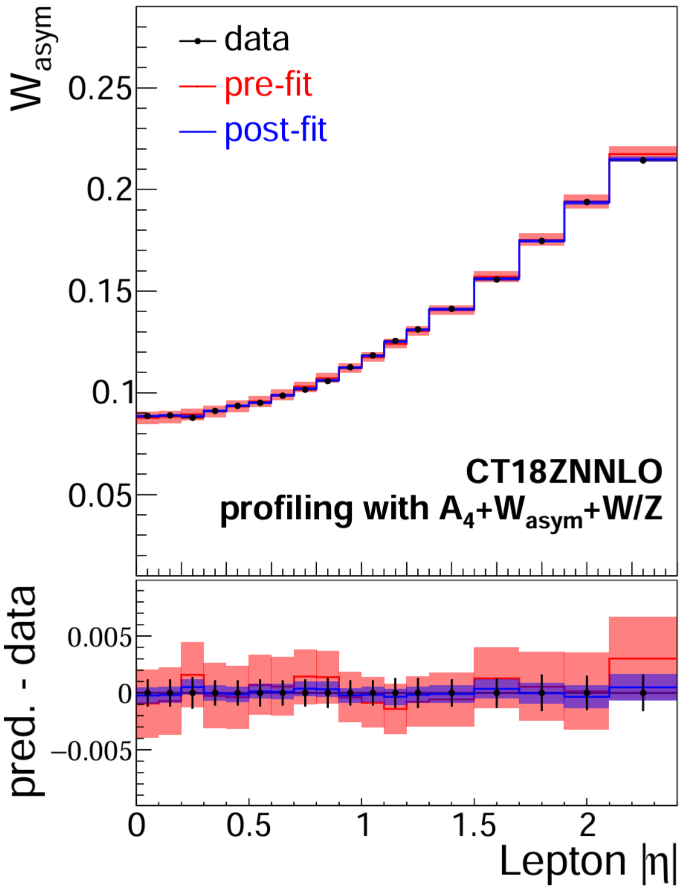
"qed": photon PDF and QED evolution
"an3lo": approximate N3LO QCD
"mhou": missing higher order uncertainty

$\sin^2\theta^l_{\rm eff}$ results with A_4(M,y) profiling



- Profiling with A_4 significantly reduces PDF uncertainties and differences across sets
- CT18 family tends to yield a bit larger $\sin^2\theta^l_{\rm eff}$ (consistent with the original CMS paper)

W-decay lepton charge asymmetry (W_{asym})



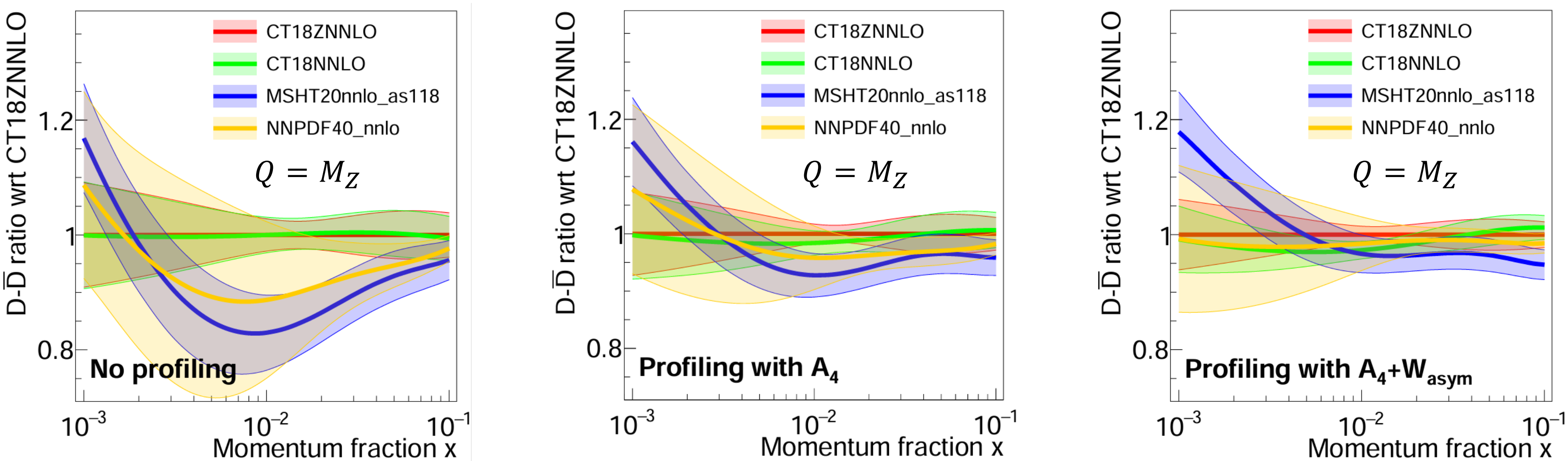
- W asymmetry can help constrain d/u PDF and reduce uncertainty of $\sin^2\theta^l_{\mathrm{eff}}$ (as investigated in Eur. Phy. J. C76 (2016) 115)

- CMS W charge asymmetry measurements at 13 TeV
  - Phys. Rev. D 102 (2020) 092012
  - 18 data points in bins of lepton pseudorapidity $|\eta_l|$

$$W_{\mathrm{asym}}(|\eta_l|) = \frac{\sigma_{W^+}(|\eta_l|) - \sigma_{W^-}(|\eta_l|)}{\sigma_{W^+}(|\eta_l|) + \sigma_{W^-}(|\eta_l|)}$$

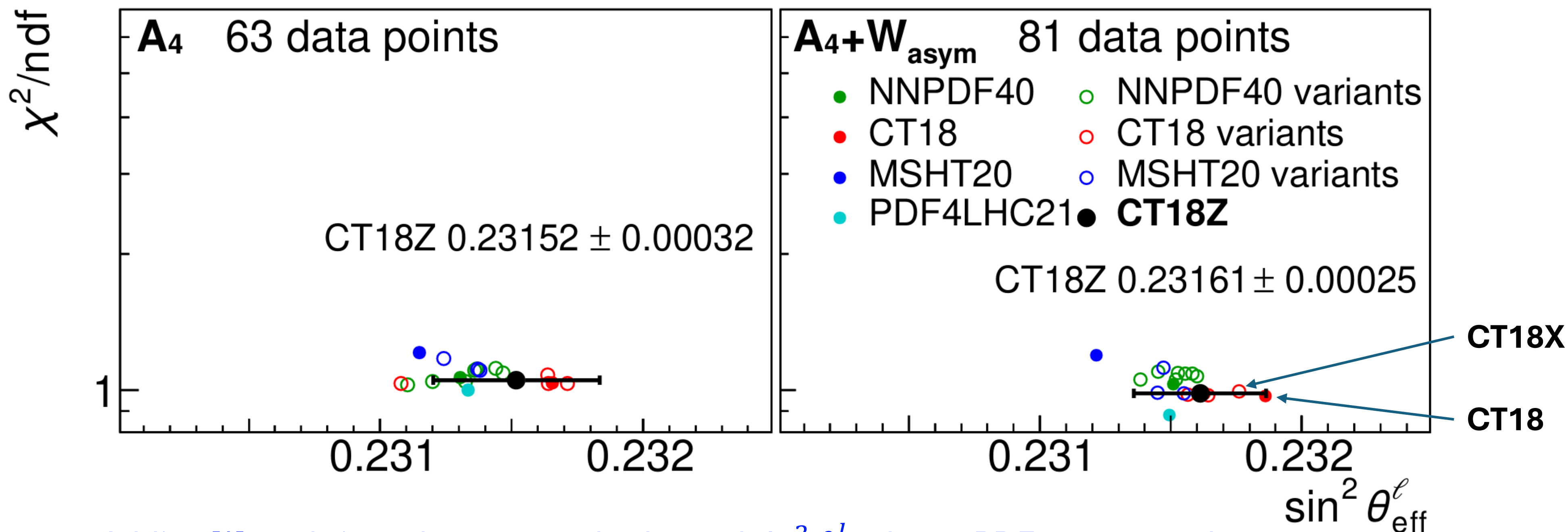
- Prediction from MCFM (NNLO)

Impact on down-type quarks



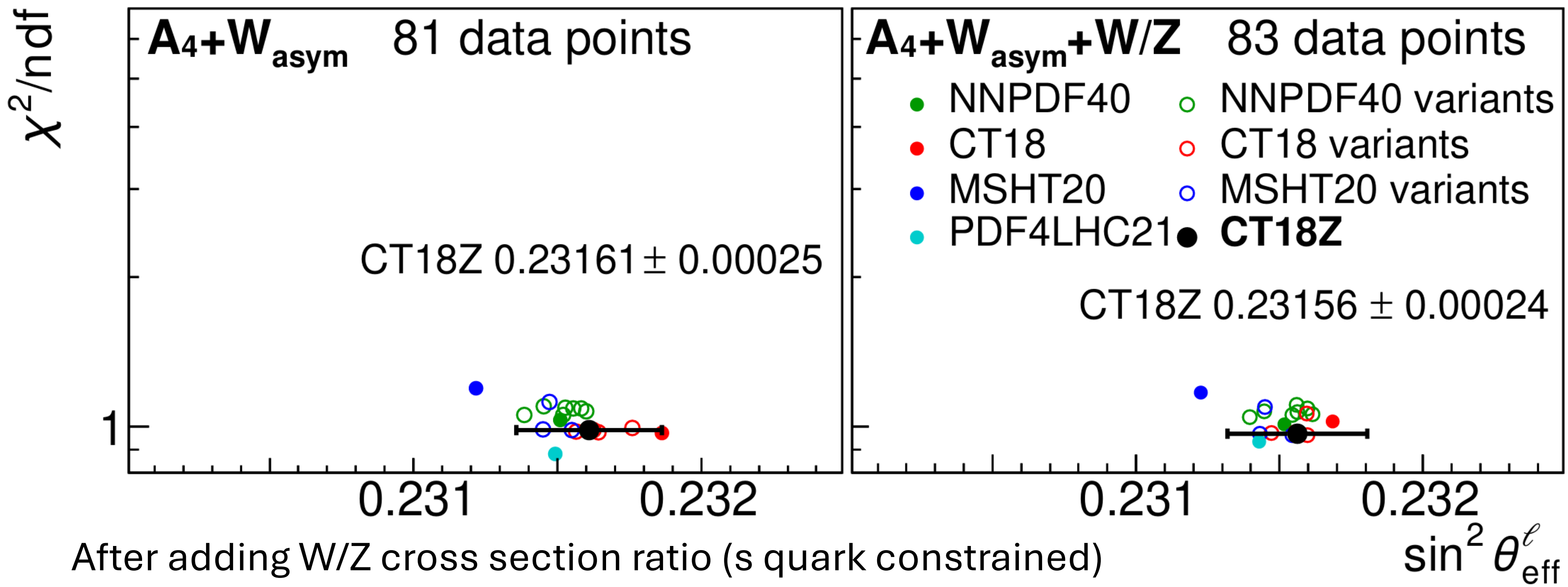
- Examine $D - \bar{D} \equiv (d + s + b) - (\bar{d} + \bar{s} + \bar{b})$, rather than $d_v = d - \bar{d}$
  - For fair comparison across PDFs with different assumptions on (a)symmetric sea-quark momentum distributions
- Adding W_{asym} further constrains the down-type quarks

$\sin^2\theta^l_{\text{eff}}$ results with A_4+W_{asym} profiling



- Adding W_{asym} brings the extracted values of $\sin^2\theta^l_{\text{eff}}$ for 19 PDF sets even closer
  - MSHT20 shows a lower $\sin^2\theta^l_{\text{eff}}$ than the others
  - Two of CT18 family (CT18 and CT18X) are within 1σ band, but gives slightly higher values
- CT18 and CT18X PDFs have smaller strange-quark distributions → higher $\sin\theta^l_{\text{eff}}$

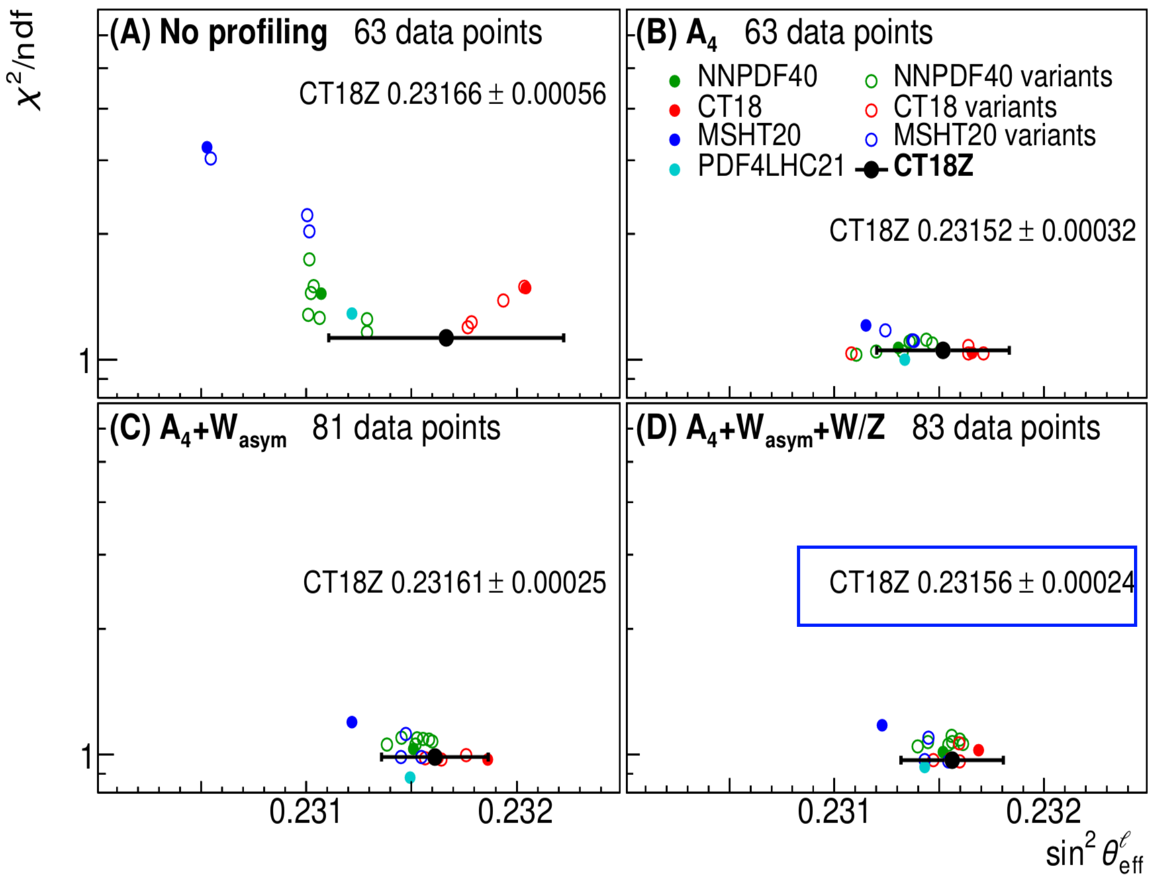
$\sin^2 \theta^l_{\mathrm{eff}}$ results with W/Z profiling



After adding W/Z cross section ratio (s quark constrained)

- CT18 and CT18X get closer to others
- Only one MSHT20 PDF remains outside 1σ band

Summary results with: No profiling vs A_4, A_4+W_{asym} vs A_4+W_{asym}+W/Z profiling



$$\sin^2\theta^l_{\mathrm{eff}} = \mathbf{0.23156 \pm 0.00024\ (CT18Z)}$$

- Most extracted $\sin\theta^l_{\mathrm{eff}}$ values lie within CT18Z uncertainty after profiling with A_4, W_{asym}, and the W/Z cross section ratio
  - Robust against 19 different PDF parameterizations and assumptions
- MSHT20 alone remains outside the CT18Z uncertainty band
  - a higher χ^2 may imply limited flexibility

Comparison to theory and other measurements

$$\sin^2\theta^l_{\text{eff}} = 0.23156 \pm 0.00024$$

- Improved extraction of $\sin^2\theta^l_{\text{eff}}$ from CMS unfolded A_4 measurements at 13 TeV
  - with additional PDF constraints from W_{asym} and W/Z cross section ratio
  - Uncertainty improved

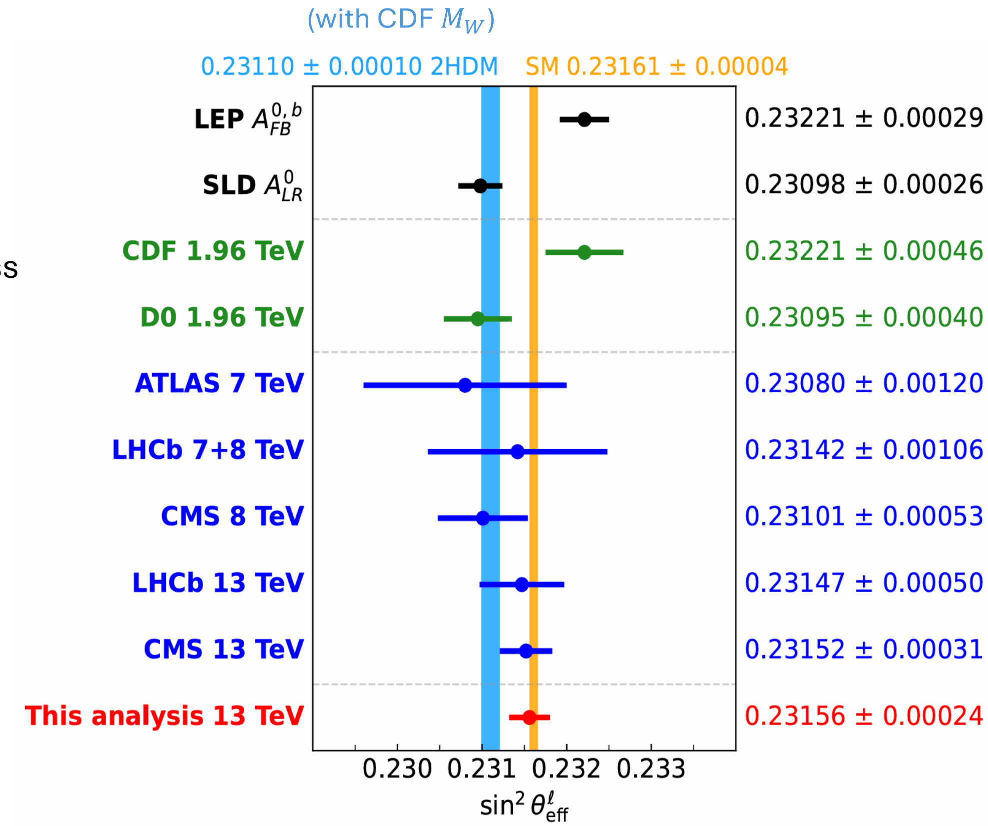
    0.00031 (CMS 13 TeV) → 0.00024 (This analysis)

- **World's best single measurement** of $\sin^2\theta^l_{\text{eff}}$
  - Surpasses the SLD result (2001) after 24 years

- arXiv:2508.18022 (to be published to *Physics Reports*)

$\sin^2\theta^l_{\text{eff}} = 0.23156 \pm 0.00024$

Vs SM 0.23161 ± 0.00004



Backup Slides

Comment on profiled PDF and Tolerance- I

Global PDF fits

- Covers a wide range of Q (GeV~TeV) and x $(0.0001 \sim 1)$
- **Tolerance factor T**($\geq$1) accounts for **limited flexibility** of parameterization and **data inconsistencies** $\Delta\chi^2 = T^2$

Both mix mixing angle and W mass analysis use profiling with $\Delta\chi^2 = 1$.

Mixing angle analysis uses :

- Angular weighted Afb, (2) Wasym (3) W/Z ratio at 13 TeV. **Systematic errors mostly cancel in these values , and the error is statistically dominated.**

- Therefore, for these measurements increasing the error by factor of T^2 is not appropriate. The PDF errors are given at 68% confidence level. **Precise measurements can be used as candles** to make sure that the parameterizations are able to accommodate these new precise data.

Comment on profiled PDF and Tolerance - II

Note Mixing angle measurements focus on specific Q $(\approx M_Z)$ and x $(0.001 - 0.1)$

- PDF constraints from these new measurements (A_4 or W_{asym} ,W/Z at 13 TeV) are evaluated with $T^2 = 1$ (i.e. $\Delta\chi^2 = 1$).
- We find that the flexibility of 18 modern PDF parameterization is sufficient within this specific region of Q ≈ M_Z and x = 0.001–0.1 to describe the data with good χ^2.

Shifts on the parameters are less than one sigma.

Index	Shift	Uncertainty
1	-0.3504	0.8694
2	0.2717	0.8387
3	0.7898	0.9109
4	0.1787	0.9624
5	0.3444	0.9351
6	-0.0301	0.9040
7	-0.0916	0.8728
8	-0.1417	0.8604
9	-0.1590	0.9051
10	0.3279	0.8996
11	0.0472	0.8138
12	-0.2362	0.8963
13	0.3884	0.8925
14	0.2833	0.8632
15	-0.3415	0.9174

Index	Shift	Uncertainty
16	0.0565	0.8568
17	0.3874	0.8994
18	-0.6933	0.9113
19	-0.1395	0.7319
20	-0.0184	0.9101
21	0.0383	0.9345
22	0.2112	0.9422
23	-0.4278	0.8088
24	-0.0668	0.8180
25	0.0209	0.8844
26	-0.0654	0.8620
27	-0.3304	0.9557
28	-0.1982	0.8950
29	-0.4636	0.8626
-	-	-

Table A.2. Shifts and uncertainties of the 29 nuisance parameters corresponding to the CT18Z set after profiling with A_4, W_{asym}, and W/Z fiducial cross-section ratio. The prior uncertainties are defined to be 1.0, and before profiling the shifts are zero and the errors are 1.0 by definition.

The tolerance parameters are about 5, 3 and 1, for the CTEQ, MSHT and NNPDF PDF sets respectively\cite{Fu:2023rrs,Harland-Lang:2024kvt,Hou:2019efy}. The latest CTEQ PDF sets were released in 2019, the latest MSHT PDF sets were released in 2020, and the latest NNPDF sets were released in 2021.

PDF	A_4 without profiling (63 data points)			A_4 profiling (63 data points)			A_4 + W_{asym} + W/Z profiling (83 data points)		
	$\sin^2\theta^{\ell}_{\rm eff}$	Diff. from CT18Z	χ^2	$\sin^2\theta^{\ell}_{\rm eff}$	Diff. from CT18Z	χ^2	$\sin^2\theta^{\ell}_{\rm eff}$	Diff. from CT18Z	χ^2
NNPDF40									
nnlo_as_01180_hessian [18]	23107 ± 49	-59	89	23130 ± 24	-22	66	23152 ± 23	-4	83
nnlo_as_01180_qed [19]	23102 ± 46	-64	108	23144 ± 23	-8	69	23161 ± 22	5	87
nnlo_as_01180_mhou [20]	23101 ± 45	-65	79	23110 ± 27	-42	64	23145 ± 24	-11	88
nnlo_as_01180_qed_mhou [19]	23103 ± 46	-63	93	23136 ± 24	-16	69	23156 ± 23	0	88
an3lo_as_01180 [21]	23129 ± 46	-37	72	23132 ± 25	-20	65	23154 ± 23	-2	87
an3lo_as_01180_qed [21]	23129 ± 49	-37	78	23147 ± 23	-5	68	23160 ± 22	4	89
an3lo_as_01180_mhou [21]	23106 ± 47	-60	78	23120 ± 26	-32	65	23140 ± 25	-16	86
an3lo_as_01180_qed_mhou [21]	23102 ± 44	-64	90	23137 ± 23	-15	69	23156 ± 23	0	91
CTEQ									
CT18NNLO [14]	23204 ± 64	38	92	23166 ± 36	14	64	23169 ± 24	13	84
CT18ZNNLO [14]	23166 ± 56	0	70	23152 ± 32	0	65	**23156 ± 24**	0	79
CT18ANNLO [14]	23179 ± 54	13	76	23164 ± 28	12	67	23160 ± 23	4	79
CT18XNNLO [14]	23194 ± 53	28	86	23171 ± 30	19	64	23160 ± 24	4	87
CT18QED-PROTON [15]	23204 ± 64	38	93	23164 ± 36	12	64	23155 ± 24	-1	80
CT18As_LatNNLO [16]	23177 ± 75	11	74	23108 ± 43	-44	64	23147 ± 35	-9	80
MSHT20									
MSHT20nnlo_as118 [23]	23053 ± 46	-113	200	23115 ± 30	-37	75	23123 ± 26	-33	96
MSHT20qed_nnlo [24]	23055 ± 59	-111	188	23124 ± 31	-28	73	23145 ± 27	-11	90
MSHT20an3lo_as118 [25]	23101 ± 47	-65	138	23138 ± 29	-14	69	23154 ± 26	-2	79
MSHT20qed_an3lo [26]	23101 ± 52	-65	126	23137 ± 31	-15	69	23143 ± 28	-13	80
PDF4LHC21_40 [45]	23122 ± 83	-44	80	23133 ± 33	-19	62	23143 ± 27	-13	77

NNPDF40, T=1
Lowest χ^2

CT18Z, T=5
Lowest χ^2

MRST20an3lo, T=3
Lowest χ^2

Precision Measurement of the Electroweak Mixing Angle in the Region of the Z pole

May 11, 2026, 5:30 PM
15m
David Lawrence Hall 106, University of Pittsburgh

Speaker

Arie Bodek (University of Rochester (US))

This contribution presents an overview of an improved extraction of the effective leptonic weak mixing angle, , based on the published CMS measurement of the forward-backward asymmetry in Drell-Yan events at 13 TeV. While the original CMS analysis achieved a significant reduction in experimental uncertainties, its overall precision remains limited by residual uncertainties in the parton distribution functions (PDFs). This talk highlights the impact of incorporating complementary CMS measurements (W asymmetry and W/Z cross section ratio) that probe different combinations of parton densities, thereby providing additional PDF constraints beyond those obtained from the asymmetry measurement alone. The improved analysis leads to a substantially reduced total uncertainty,

Much of what I present is from

Precision Measurements of the Electroweak Mixing Angle in the Region of the Z pole

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https://arxiv.org/abs/2508.18022

To be published in 2026:

Physics Reports collection of papers on Electroweak Precision Measurements,

edited by Costas Vellidis, Franco Bedeschi, Michael Ramsey-Musolf, Doreen Wackeroth, and Ashutosh Kotwal

Precision measurement of $sin^2\,\theta^l_{eff}$ at CMS are possible by using three techniques

Angular event weighting method for A_{FB} analyses: A. Bodek. Eur. Phys. J. C67 **(2010)** 321
Systematic errors in acceptance & efficiency cancel: The method yields the full acceptance experimental A_{FB} or A4, but includes the effects final state photon radiation (FSR) and detector resolution smearing.

Precise lepton momentum/energy scale (and modeling resolution) A. Bodek et al. , Eur. Phys. J. C72 **(2012)** 2194. → called Rochester corrections used in CDF (Tevatron) and CMS (LHC) (first used for muons and then used for both muons and electrons and HF in A_{FB} Run 2 analysis)

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

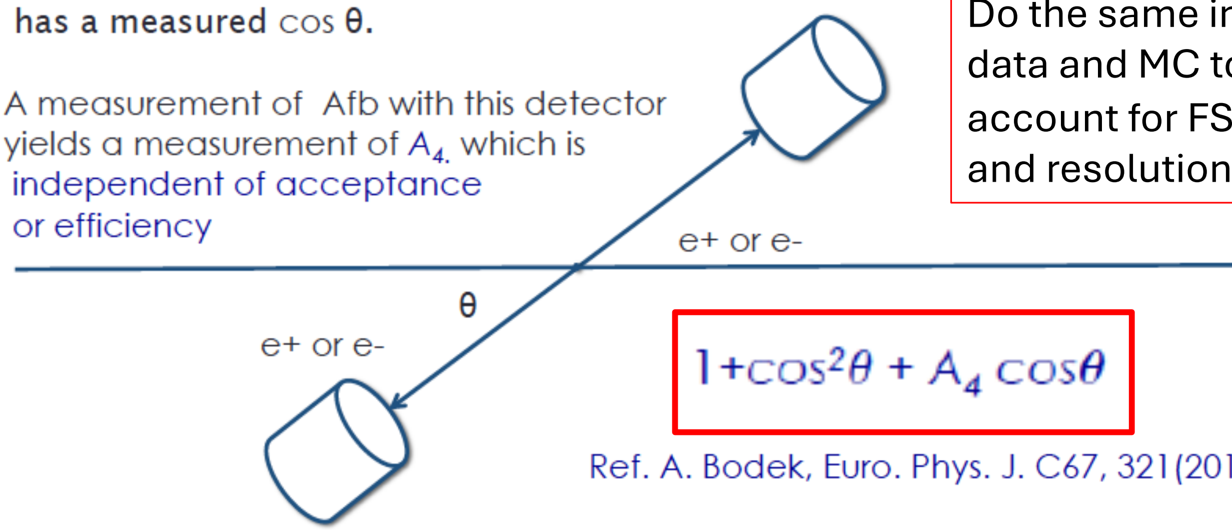
In situ cancellation of experimental systematic errors

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

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

Do the same in data and MC to account for FSR and resolution.



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

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.**

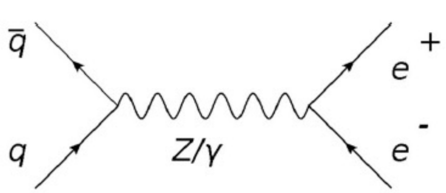
In situ reduction of PDF errors by PDF reweighting/profiling

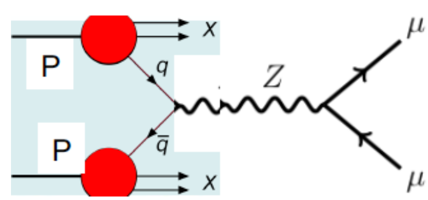
A.Bodek et al , Eur. Phys. H. **(2016)** C76 (Add constraints on parton distribution functions using mass dependence of Afb and W asymmetry (when available)

Use A_{FB} measured in the same detector at the same time.

- **Mass dependence of Afb** (constrains mostly u-ubar and some d-dbar)
  (used in mixing angle analyses CDF 2026, CMS 8 TeV 2018, CMS 13 TeV 2024)

- (when available) **W+/W- asymmetry.** (constrains u-dbar and d-ubar
  W produced via u-dbar, d-ubar, s-cbar, c-sbar. Used in our updated CMS 13 TeV 2025
- (when available) **Add: W/Z cross section ratio** (constrains strange quarks Z produced via u-ubar, d-dbar, s-sbar, c-cbar. Used in our updated CMS 13 TeV 2025





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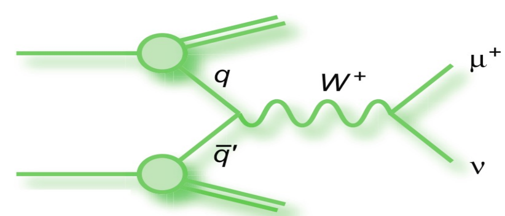
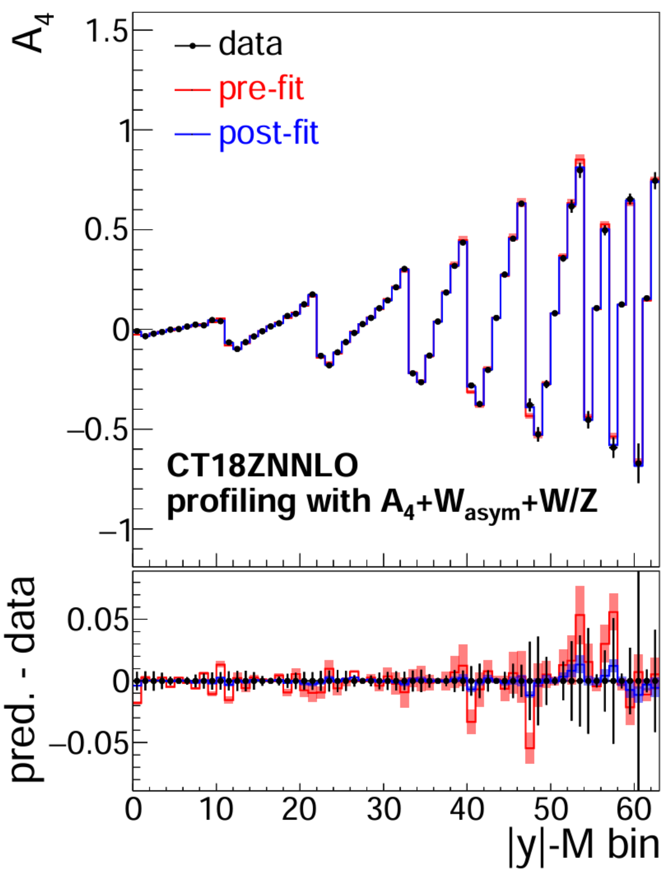


Reproducing original CMS result using published unfolded A_4(M,y)



- CMS A_4(M,y) measurements at 13 TeV
  - 63 data points in bins of mass and rapidity
  - Mass from 54 to 150 GeV
  - Rapidity < 3.4
- Prediction from POHWEG+Pythia8 (NNLO+PS)

Extraction of $\sin^2\theta_{\mathrm{eff}}^{l}$

- Minimizing χ^2

$$\chi^2(s,\beta_{\mathrm{exp}},\beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}}\beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}}(s) - \sum_k \Gamma_{ik}^{\mathrm{th}}\beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2$$

- $\boldsymbol{s}$: $\sin^2\theta_{\mathrm{eff}}^{l}$
- $\boldsymbol{\sigma_i^{\mathrm{exp}}}$ and $\boldsymbol{\sigma_i^{\mathrm{th}}}(\boldsymbol{s})$: measurement and prediction of i-th data point
- $\boldsymbol{\Delta_i}$: uncorrelated uncertainty of i-th data point
- $\boldsymbol{\beta_{j,\mathrm{exp}}}$ and $\boldsymbol{\Gamma_{ij}^{\mathrm{exp}}}$: experimental nuisance parameters and their impact matrixes
  - decomposition of A_4 covariance matrix
- $\boldsymbol{\beta_{j,\mathrm{th}}}$ and $\boldsymbol{\Gamma_{ij}^{\mathrm{th}}}$: theory nuisance parameters and their impact matrixes
  - PDF hessian error
  - electroweak theory uncertainty

- QCD scale uncertainty is evaluated outside the fit using the standard 7-point variation
  - Repeat the fit for each scale choice and take the envelope