Improved Extraction of $\sin^2\theta^l_{\text{eff}}$ from Recent CMS A_{FB} Measurements at 13 TeV with Additional PDF Constraints from W and Z measurements

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Weak mixing angle

- The weak mixing angle
  - A fundamental parameter in the Standard model
  - Related to the unification of the electromagnetic and weak forces

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

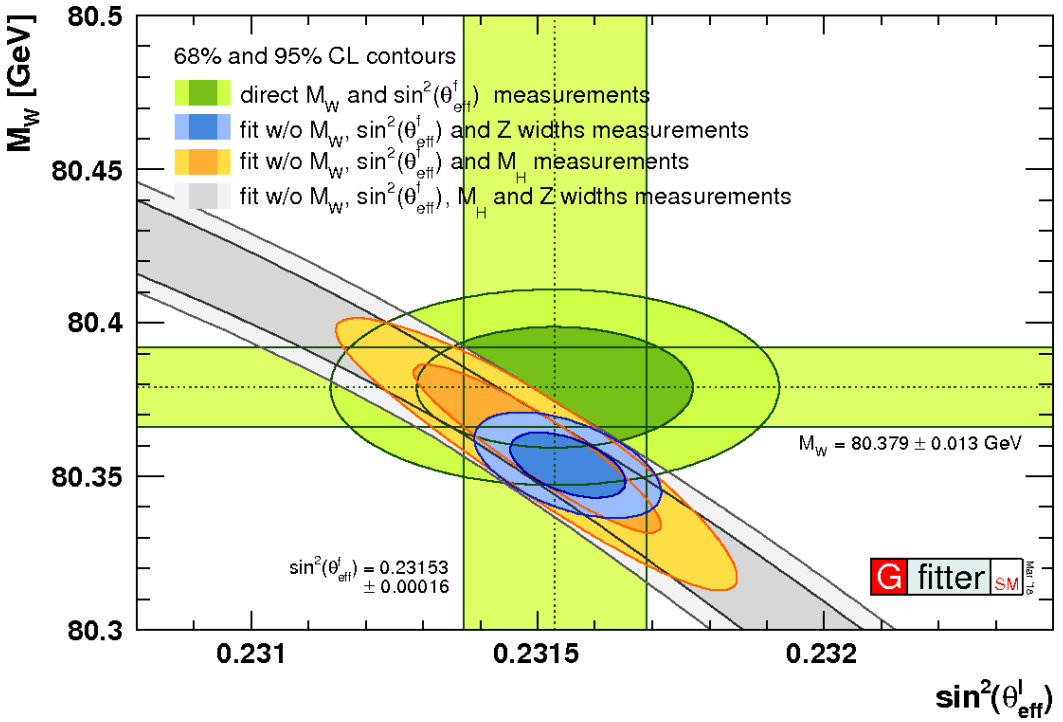
- Effective leptonic mixing angle

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

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

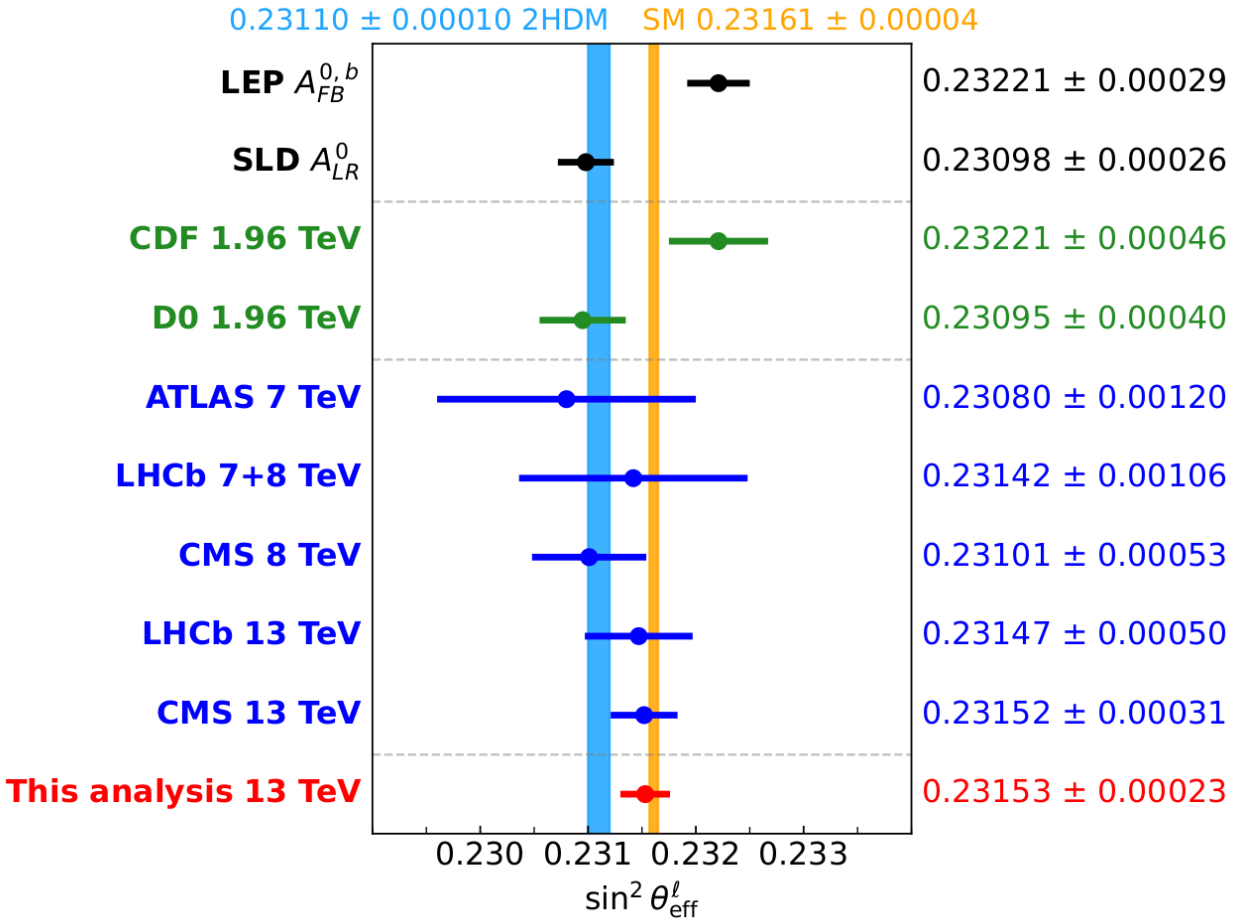
- Measurement of the weak mixing angle
  - Provides a consistency check of the Standard Model
  - Serves as a powerful tool for searching for new phenomena

Gfitter (Aug 2024)

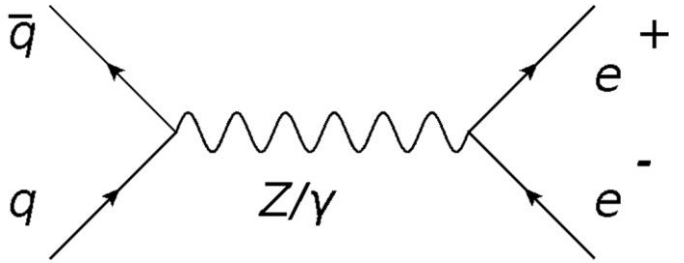


Measurements of $\sin^2\theta^l_{\mathrm{eff}}$

- Electron-positron collision
  - LEP: 0.23221 ± 0.00029
  - SLD: 0.23098 ± 0.00026
- CMS 13 TeV Phys. Lett. B 866 (2025) 139526
  - $\sin^2\theta^l_{\mathrm{eff}} = 0.23152 \pm 0.00031$
- Improved analysis of CMS 13 TeV (**THIS TALK**)
  - $\boldsymbol{\sin^2\theta^l_{\mathrm{eff}} = 0.23153 \pm 0.00023}$

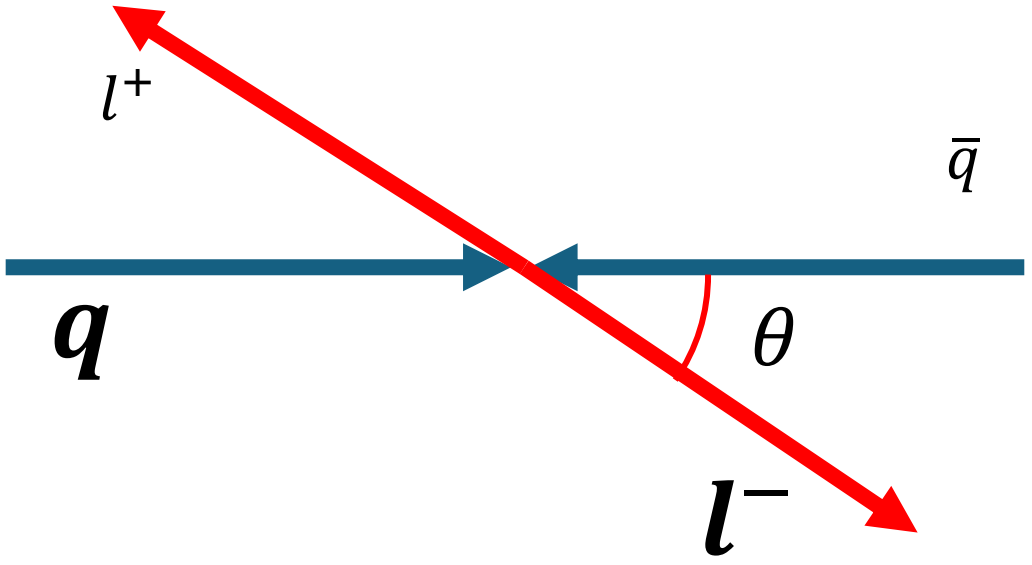


Forward-backward asymmetry (A_{FB})



- **Key observable for mixing angle extraction**

CM frame



θ: Angle btw incoming and outgoing particles

$\cos\theta > 0$, forward event (F)

$\cos\theta < 0$, backward event (B)

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

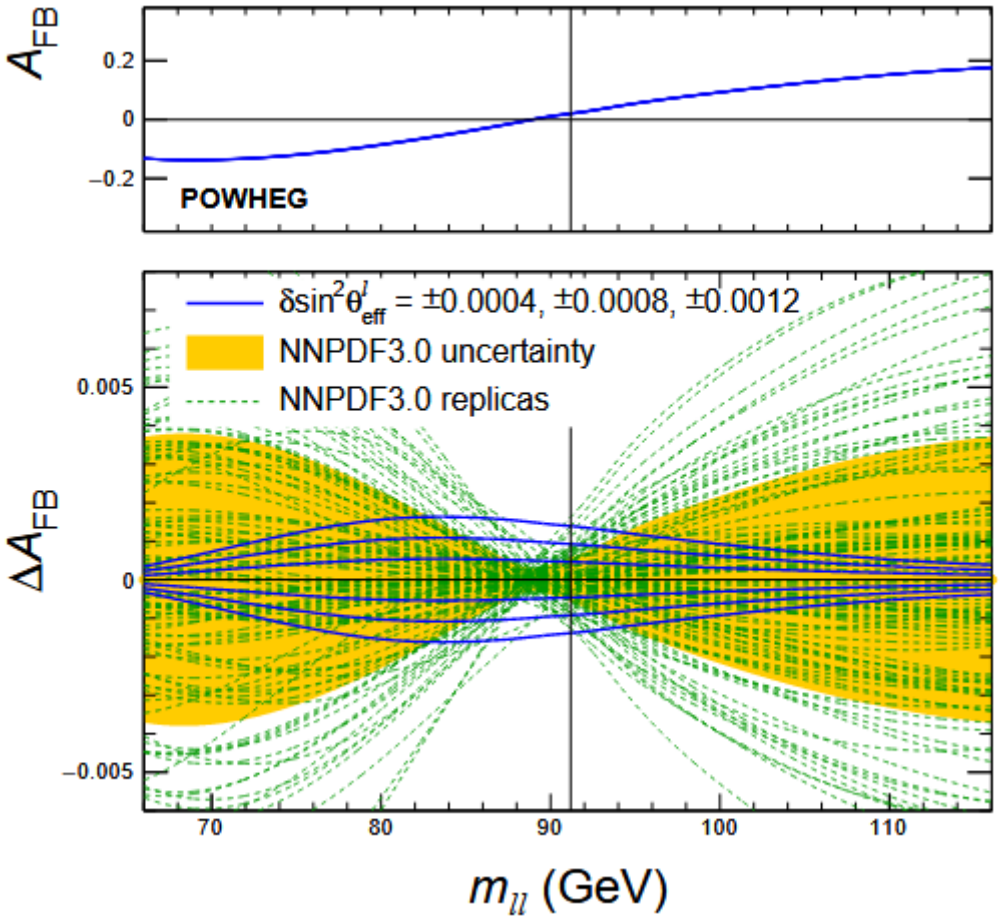
Forward-backward asymmetry (A_{FB})

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

- $A_{FB} = \frac{3}{8}A_4$, non-zero due to mixing of $U(1)$ and $SU(2)_L$

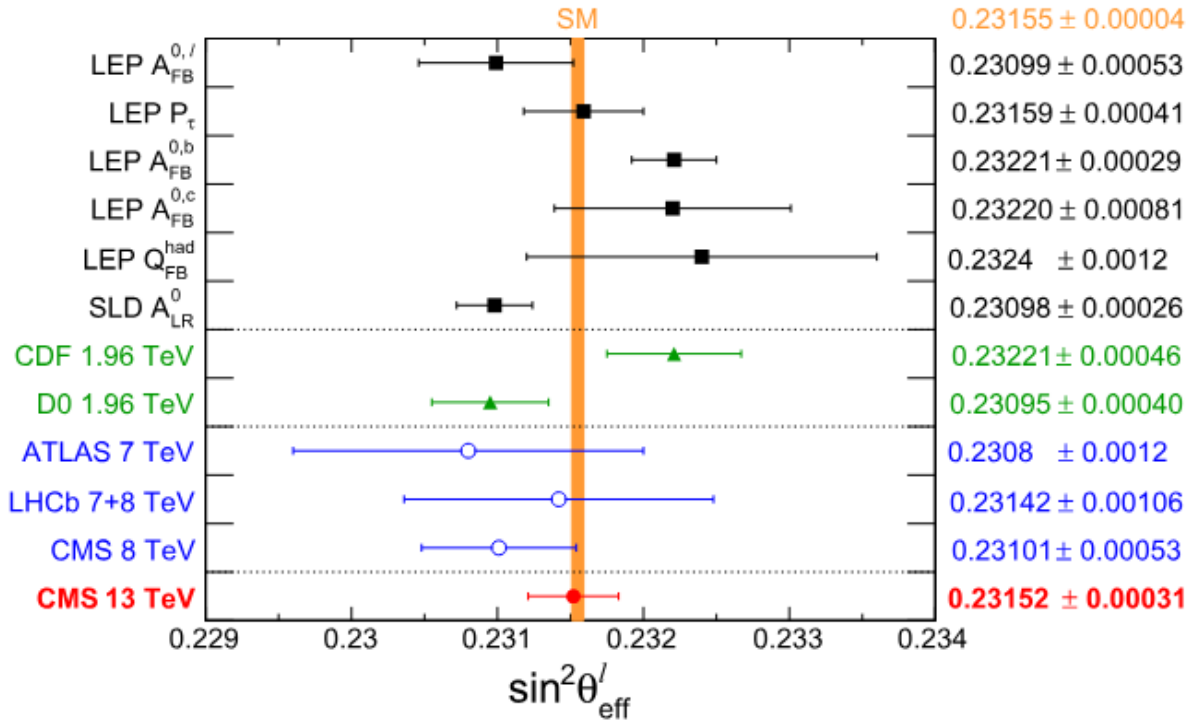
- A_{FB} at Z peak
  - Sensitive to weak mixing angle and PDFs
- A_{FB} in sideband region
  - Small sensitivity to mixing angle
  - Large sensitive to PDFs

  → Can be used to constrain PDFs



Challenge in hadron collision

- Electron-positron (LEP, SLD)
  - Forward axis = electron direction
- Proton-antiproton (Tevatron)
  - Forward axis ≈ proton direction
  - Dilution of A_{FB}
    → PDF uncertainty
- Proton-Proton (LHC):
  - Forward axis ~ dilepton rapidity direction
  - Stronger dilution of A_{FB}
    → Larger PDF uncertainty

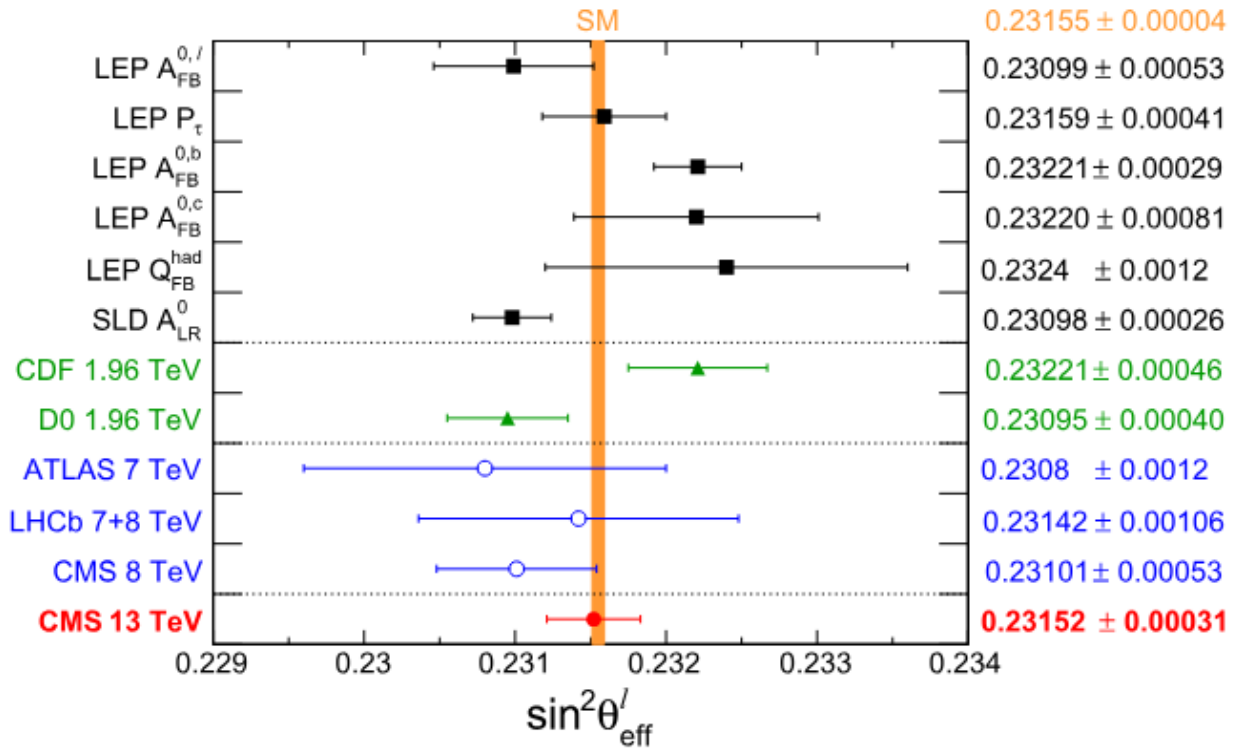


$\sin^2\theta^l_{\mathrm{eff}}$ measurement of CMS 13 TeV

- **Despite of the challenge in pp collision, CMS achieved a precision comparable to LEP and SLD**

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

  - PDF profiling Eur. Phy. J. C 76 (2016) 115
  - Angular event reweighting technique Eur. Phys. J. C 67 (2010) 321
  - Utilizing forward electrons
  - Large statistics



- The most precise measurement at hadron collider
- Published in Phys. Lett. B 866 (2025) 139526
- The uncertainty is dominated by PDF uncertainty (0.00027)
- A_4 measurements (rapidity & mass bins) are also published for future reinterpretation

Remaining question

- It was a great achievement to reach a precision at hadron collider comparable to that of electron collider

CERN Press Release, April 2024

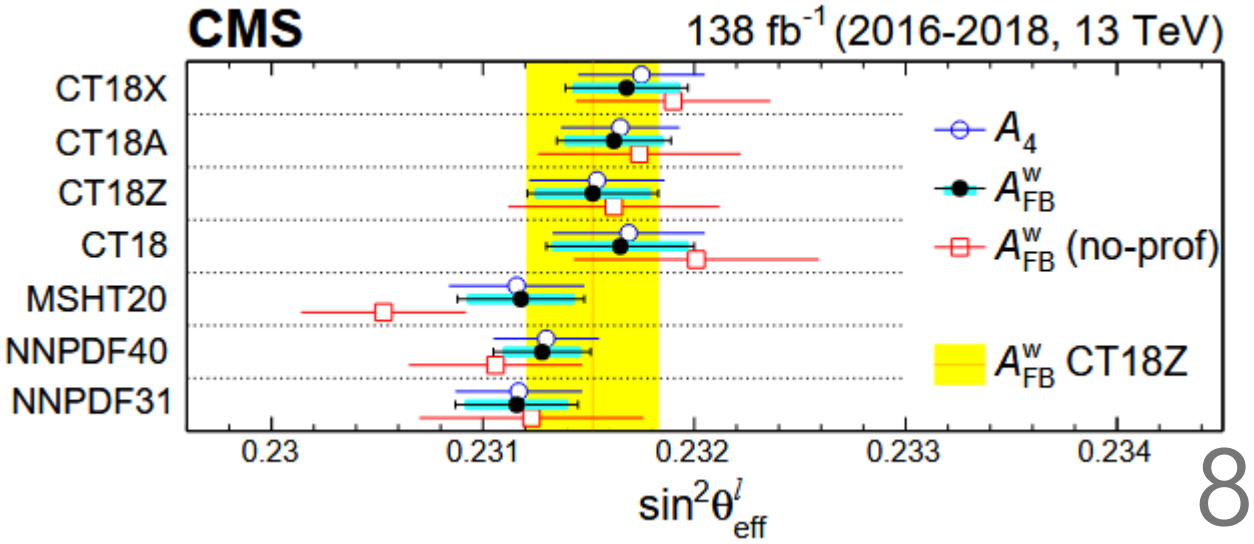
The CMS experiment at CERN measures a key parameter of the Standard Model

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

- However, possible systematic difference between PDFs remained an open question

Both NNPDF and MSHT are lower than CT18



New analysis

- Investigation on the source of the difference between PDFs
  - With 19 PDF sets: NNPDF40 (8), CT18 (6), MSHT20 (4) and PDF4LHC21 (1)

- We found that the difference comes from
  - Dilution from down quark
  - Size of the strange quark content

- We extracted new value of $\sin^2\theta^l_{\mathrm{eff}}$ based on $\boldsymbol{A_4}$ measurements of CMS 13 TeV
  - But with additional constraint on PDF using published CMS $\boldsymbol{W_{asym}}$ and $\boldsymbol{W/Z}$ cross section ratio at 13 TeV
  - With xFitter framework

Investigated 19 PDF sets

NNPDF40 (8)

Neural network base
Asymmetric strange

NNPDF40_nnlo: nominal
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 of original CMS 13 TeV paper)
CT18qed_proton
CT18As_LatNNLO: asymmetric strange

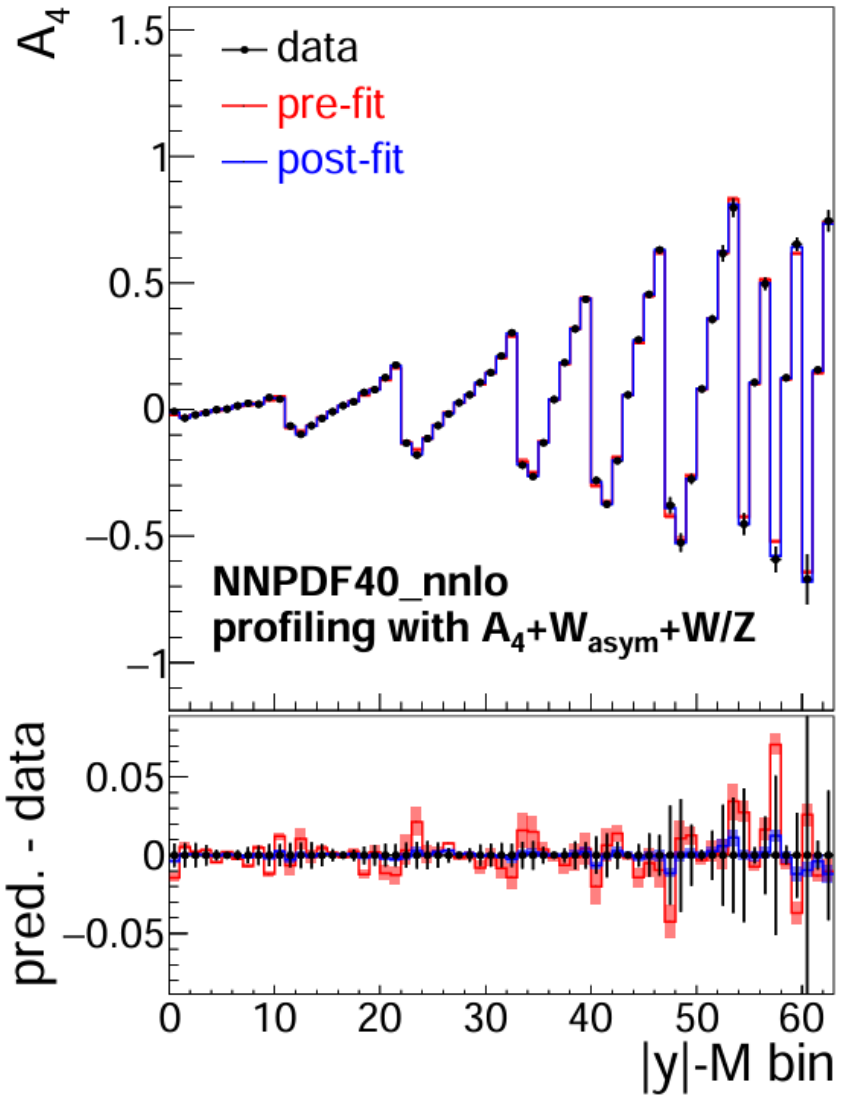
PDF4LHC21 (1)

Combination of CT18+MSHT20+NNPDF31
Asymmetric strange

PDF4LHC21_40

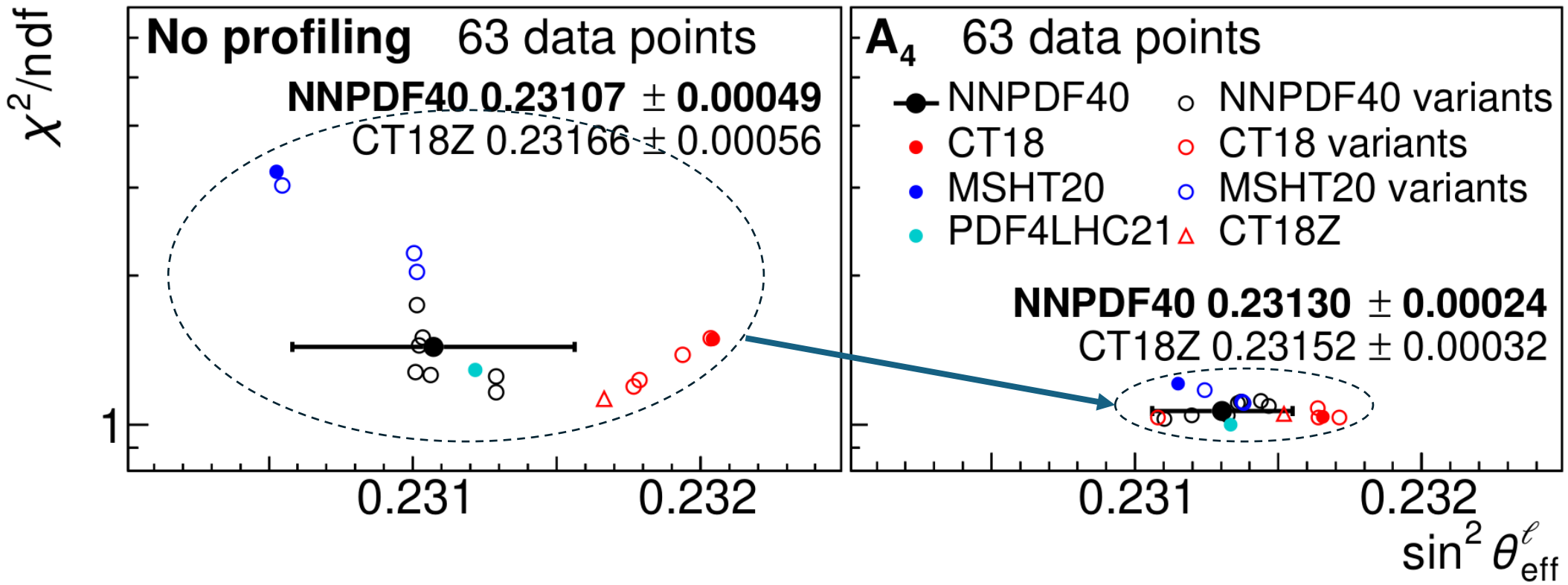
"qed": photon PDF and QED evolution
"an3lo": approximate N3LO QCD
"mhou": missing higher order uncertainty

A_4



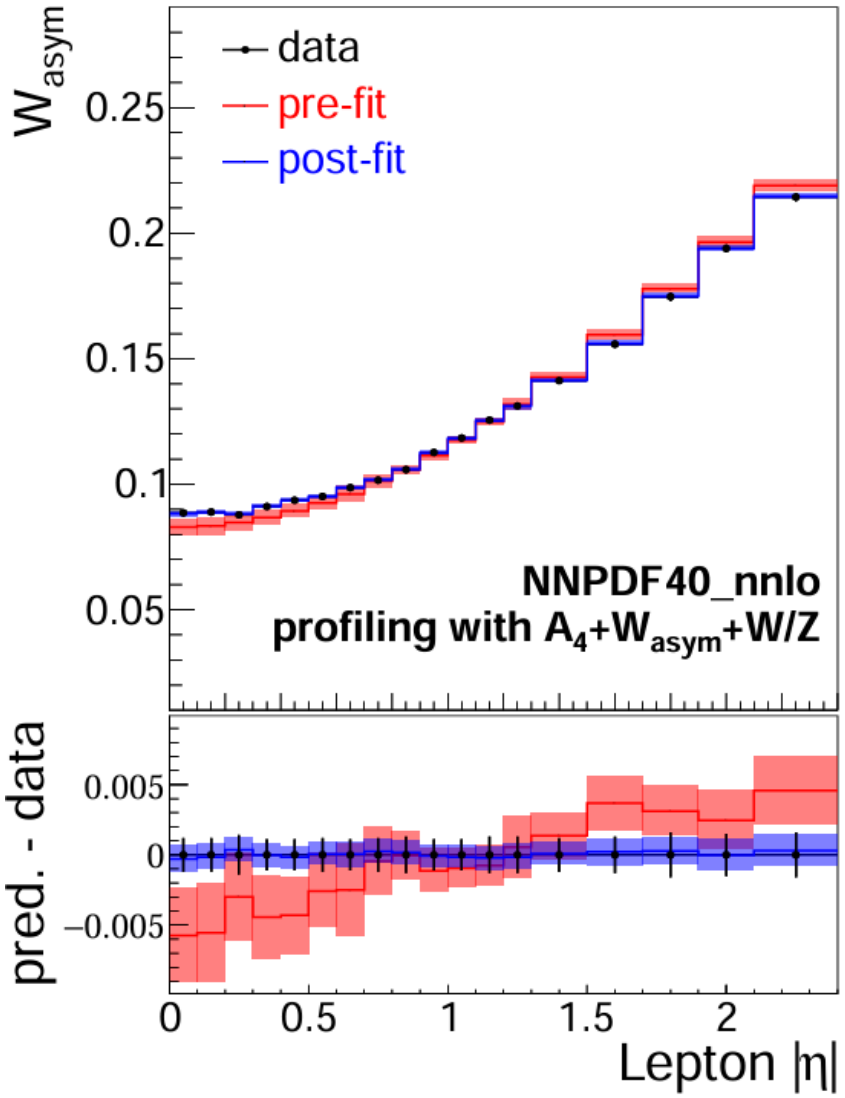
- CMS A_4 measurements at 13 TeV
  - 63 data points in bins of mass and rapidity
  - Mass from 54 to 150 GeV
  - Rapidity < 3.4
- Prediction from POHWEG+Pythia8 (NNLO+PS)

A_4



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

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

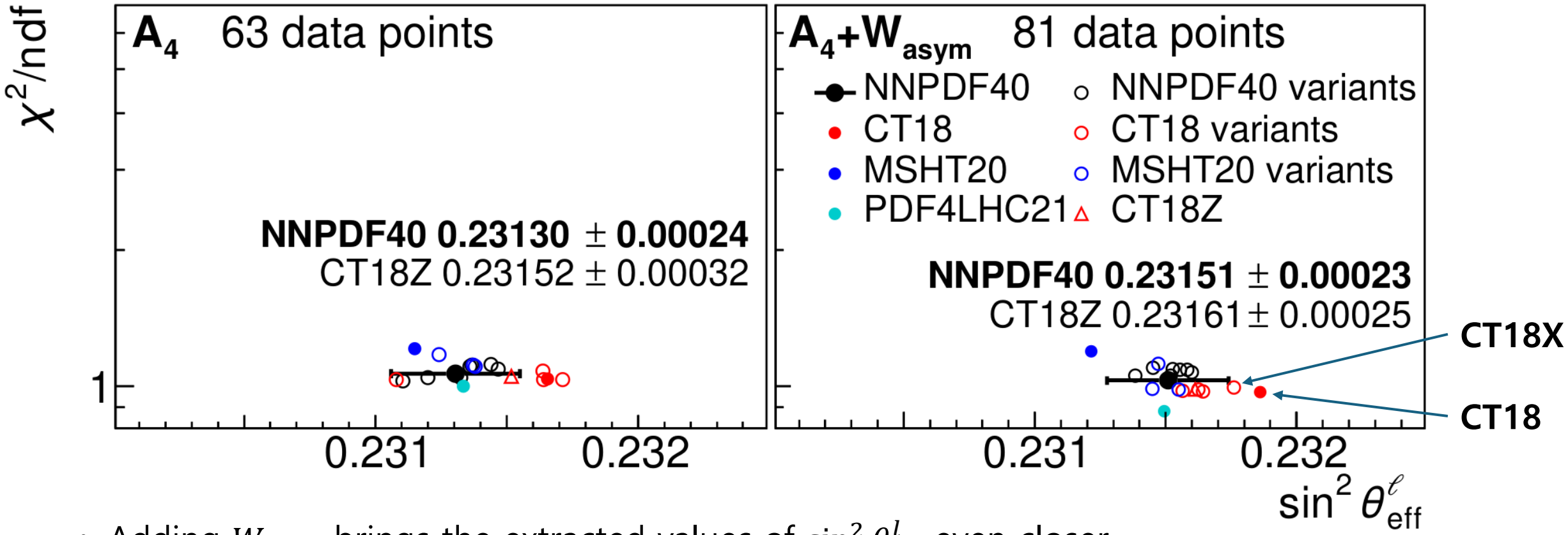


- W asymmetry can help constrain d/u PDF and reduce uncertainty of $\sin^2\theta^l_{\mathrm{eff}}$
  - Eur. Phy. J. C76 (2016) 115
- CMS W charge asymmetry measurements at 13 TeV
  - Phys. Rev. D 102 (2020) 092012
  - 18 data points in bins of lepton absolute pseudorapidity $|\eta_l|$

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

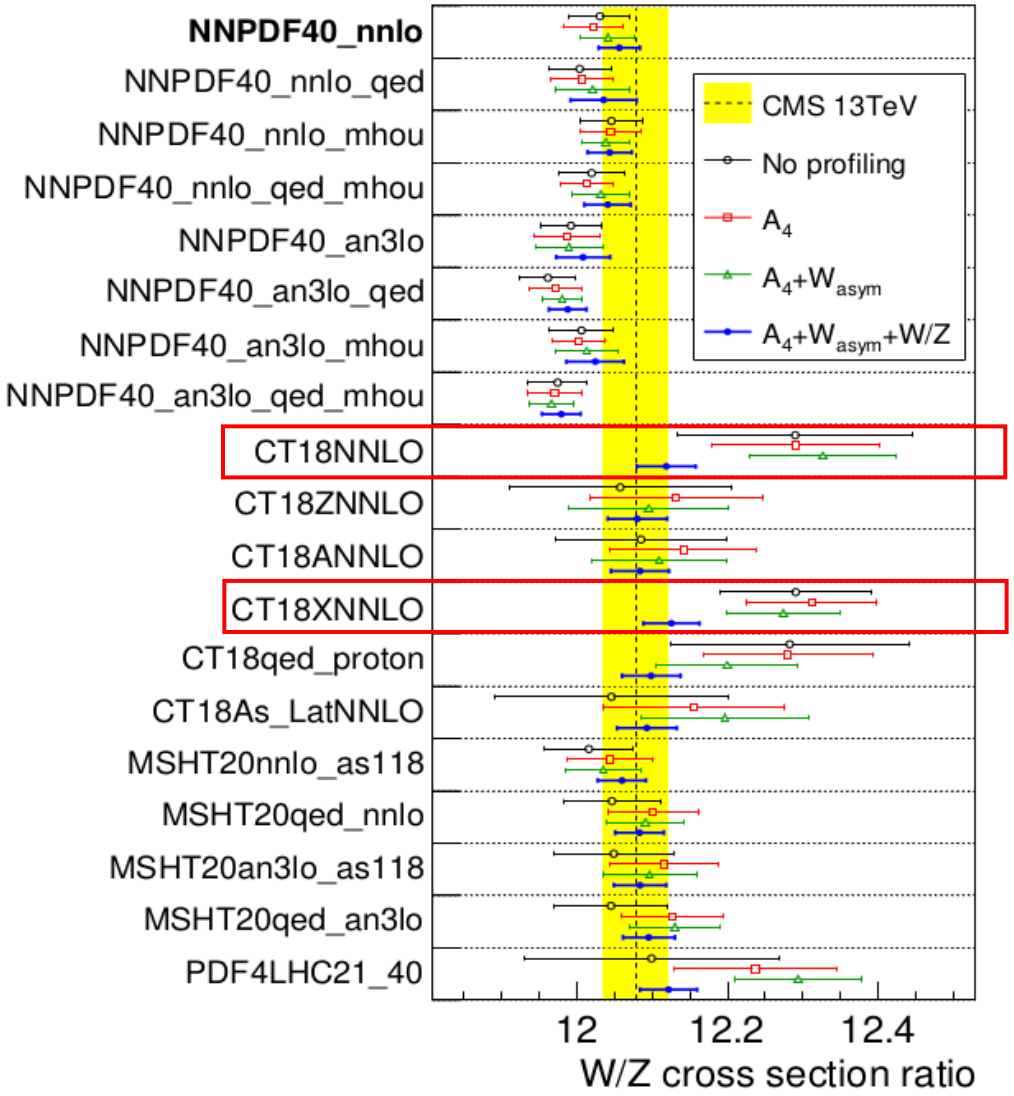
- Prediction from MCFM (NNLO)

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



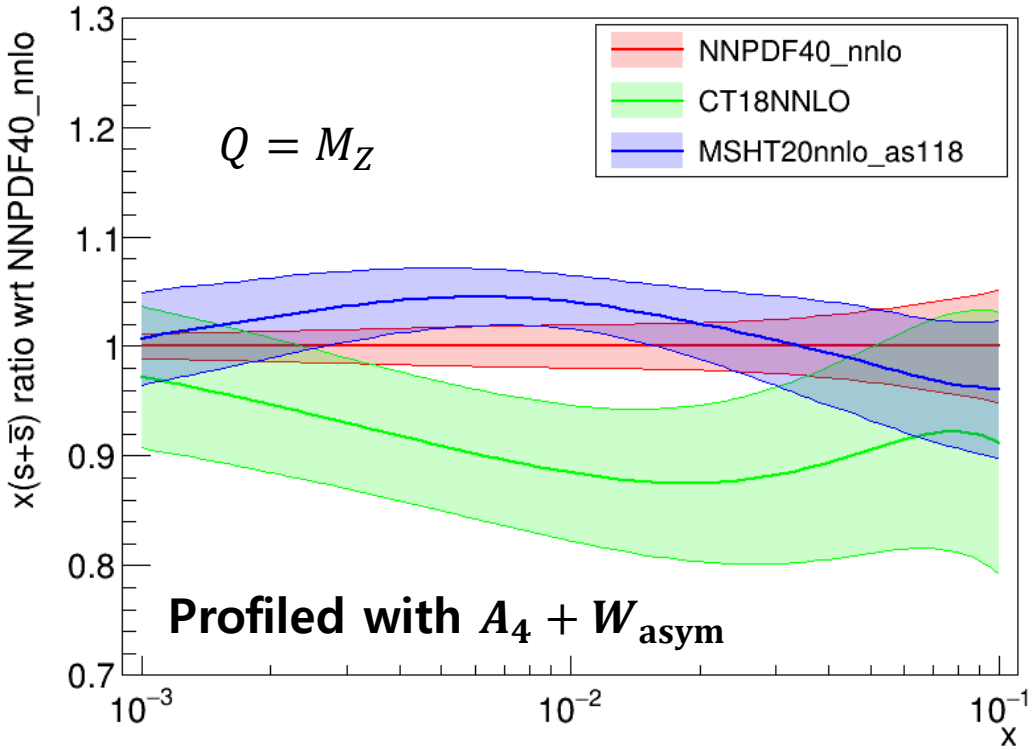
- Adding W_{asym} brings the extracted values of $\sin^2\theta^{l}_{\mathrm{eff}}$ even closer
- Now, only two of CT18 family (CT18 and CT18X) lie more than 1σ above the NNPDF40 uncertainty band
- These PDFs have smaller strange-quark distributions → higher $\sin\theta^{l}_{\mathrm{eff}}$

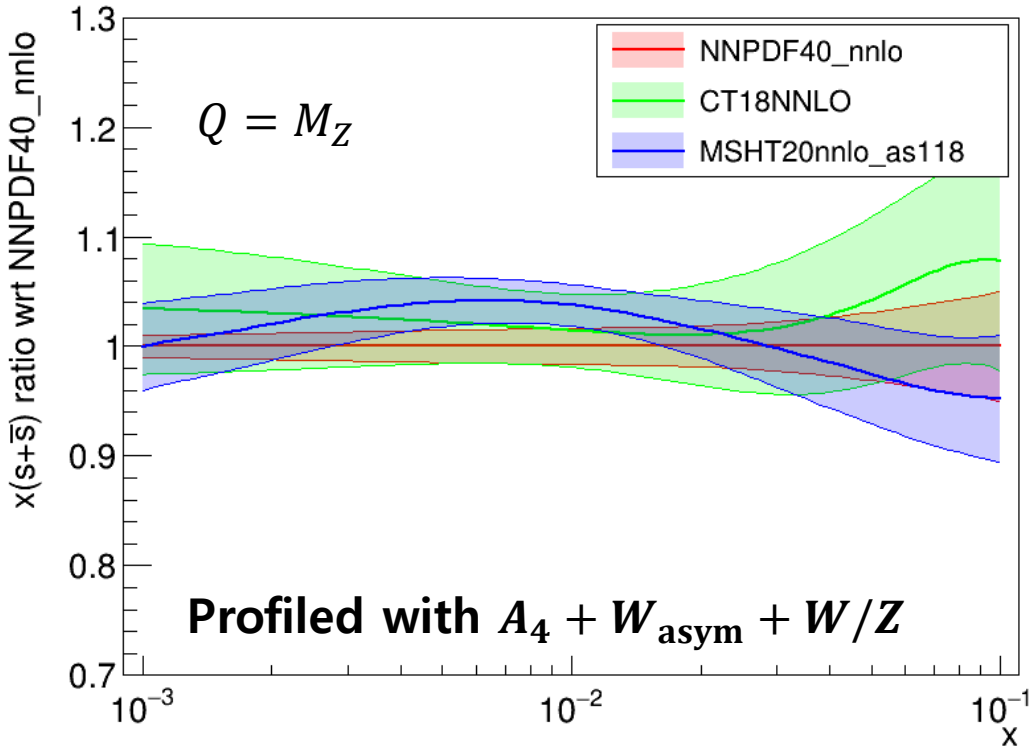
W/Z cross section ratio



- The W/Z ratio is strongly anti-correlated with the strange-quark content
- CMS W/Z ratio at 13 TeV (1 data point)
  $\sigma_W/\sigma_Z = 12.078 \pm 0.028_{\text{stat}} \pm 0.032_{\text{syst}}$
- Prediction from DYTurbo (NNLO+NNLL)

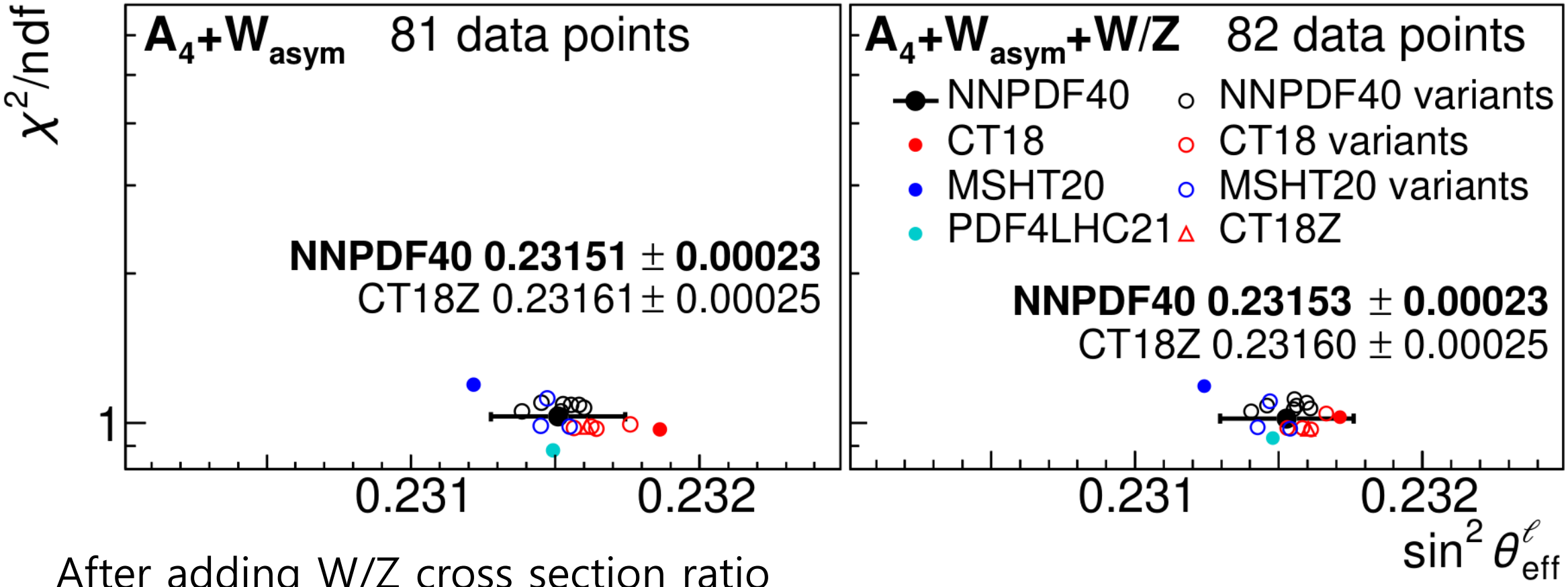
Impact on strange quark





Adding W/Z increase strange of CT18

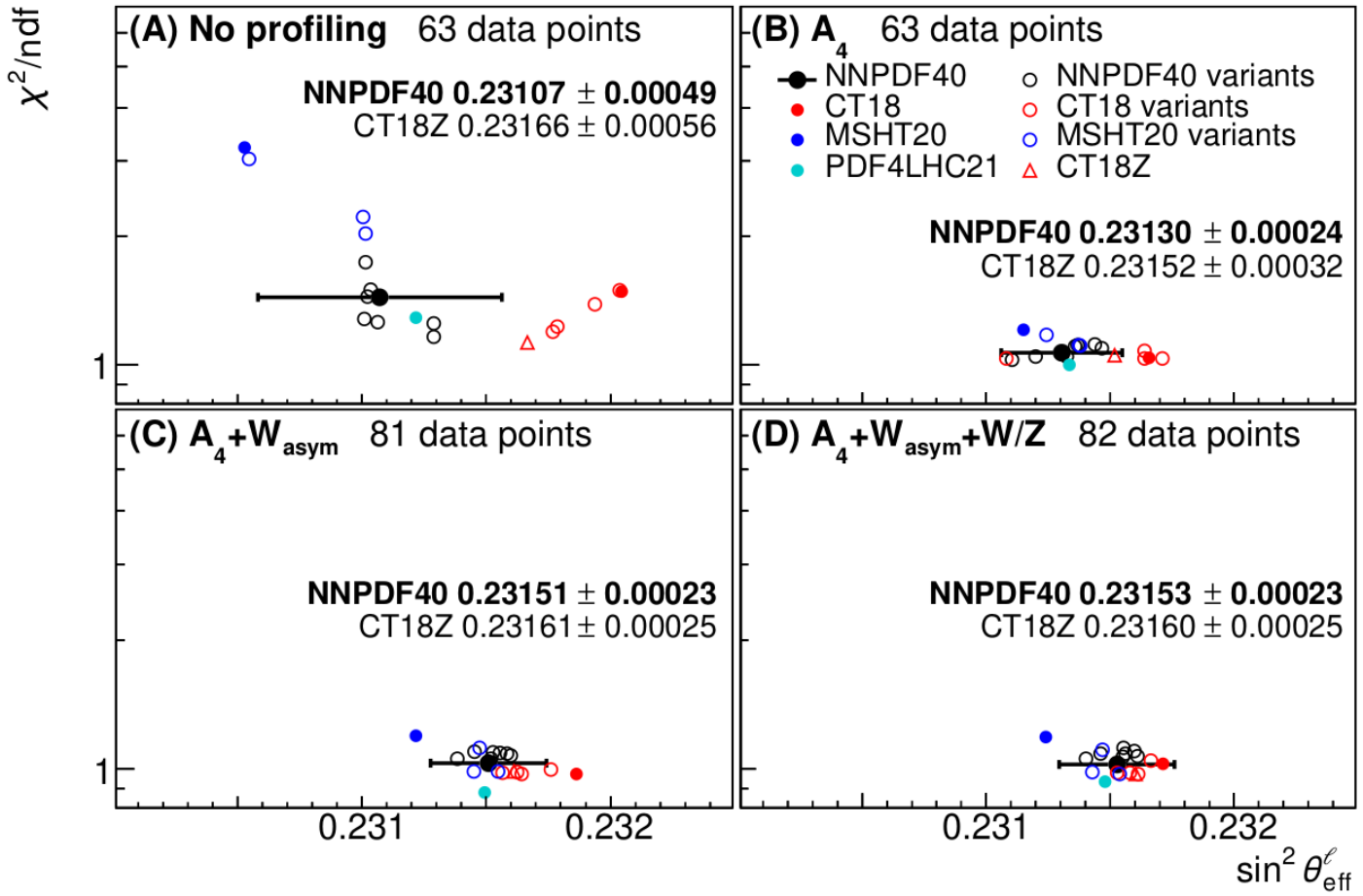
W/Z cross section ratio



After adding W/Z cross section ratio

- CT18 and CT18X also fall within the NNPDF40 uncertainty band
- Only one MSHT20 PDF remains outside 1σ band

Result



$\sin^2 \theta^l_{\text{eff}} = 0.23153 \pm 0.00023$ (NNPDF40)

- Most extracted $\sin \theta^l_{\text{eff}}$ values lie within NNPDF40 uncertainty after profiling with A_4, W_{asym}, and the W/Z cross section ratio
  - Robust against different PDF parameterizations and assumptions
- MSHT20 alone remains outside the NNPDF40 uncertainty band
  - a slightly higher χ^2 may imply limited flexibility

Conclusion

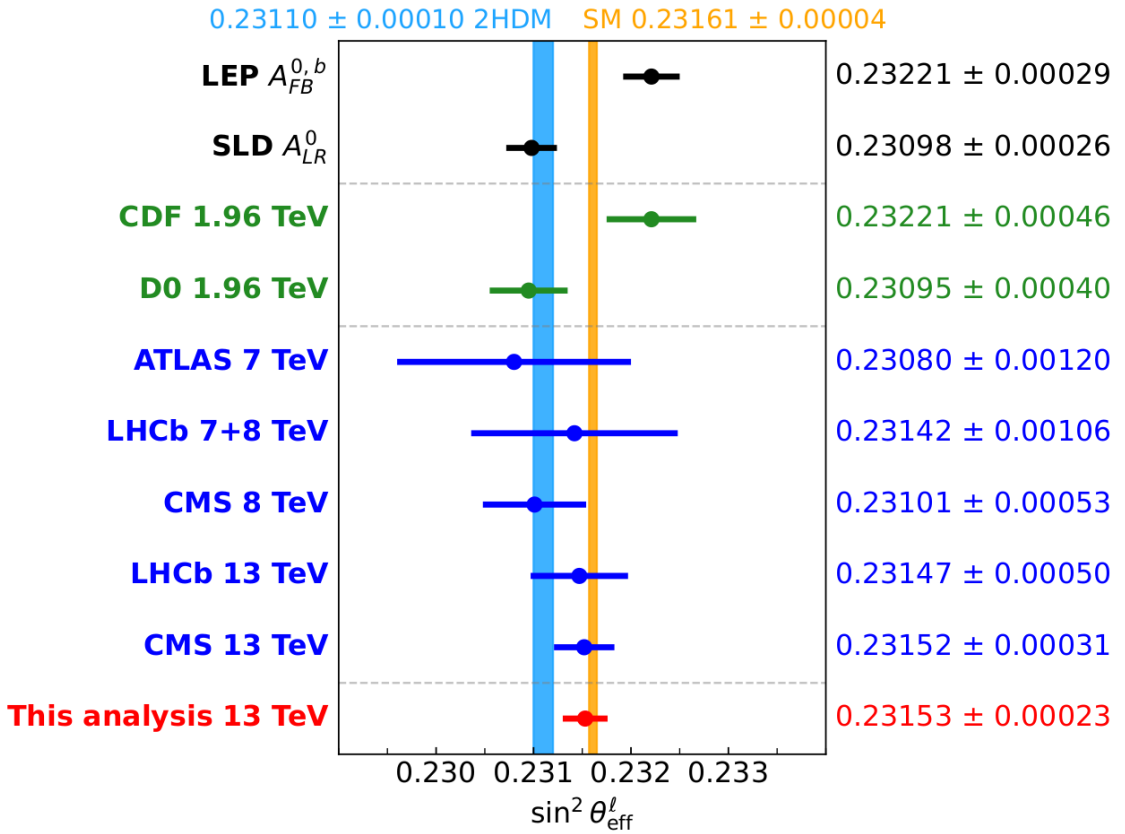
$$\sin^2\theta^l_{\text{eff}} = 0.23153 \pm 0.00023$$

- Improved extraction of $\sin^2\theta^l_{\text{eff}}$ from CMS 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) → 0.00023 (This analysis)

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

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



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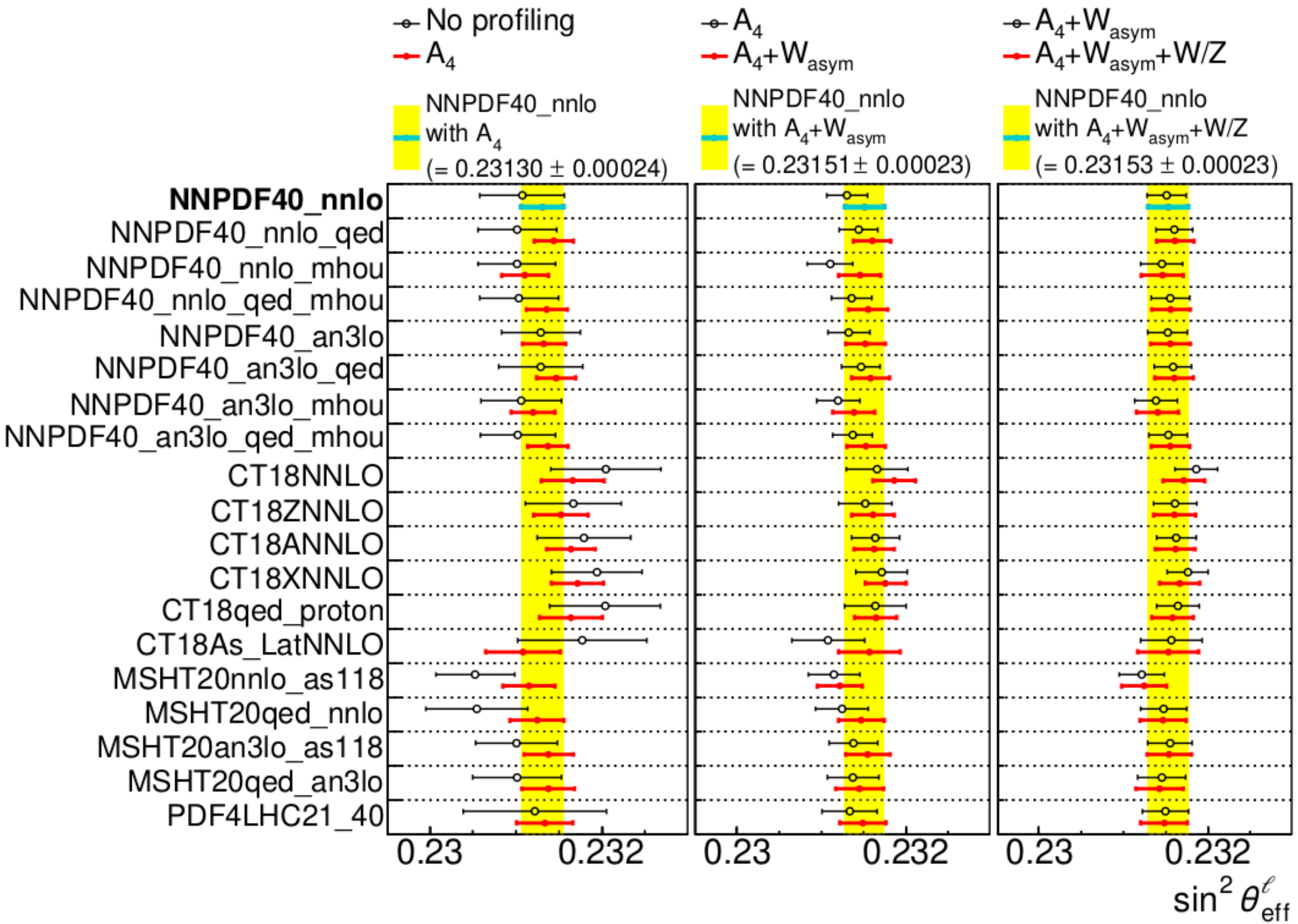
No profiling
A_4
NNPDF40_nnlo with A_4 (= 0.23130 ± 0.00024)
A_4
A_4+W_{asym}
NNPDF40_nnlo with A_4+W_{asym} (= 0.23151± 0.00023)
A_4+W_{asym}
$A_4+W_{asym}+W/Z$
NNPDF40_nnlo with $A_4+W_{asym}+W/Z$ (= 0.23153 ± 0.00023)
NNPDF40_nnlo
NNPDF40_nnlo_qed
NNPDF40_nnlo_mhou
NNPDF40_nnlo_qed_mhou
NNPDF40_an3lo
NNPDF40_an3lo_qed
NNPDF40_an3lo_mhou
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CT18ZNNLO
CT18ANNLO
CT18XNNLO
CT18qed_proton
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PDF4LHC21_40
0.23
0.232
$\sin^2\theta^{\ell}_{eff}$