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

arXiv:2508.18022

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DIS2026

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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

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

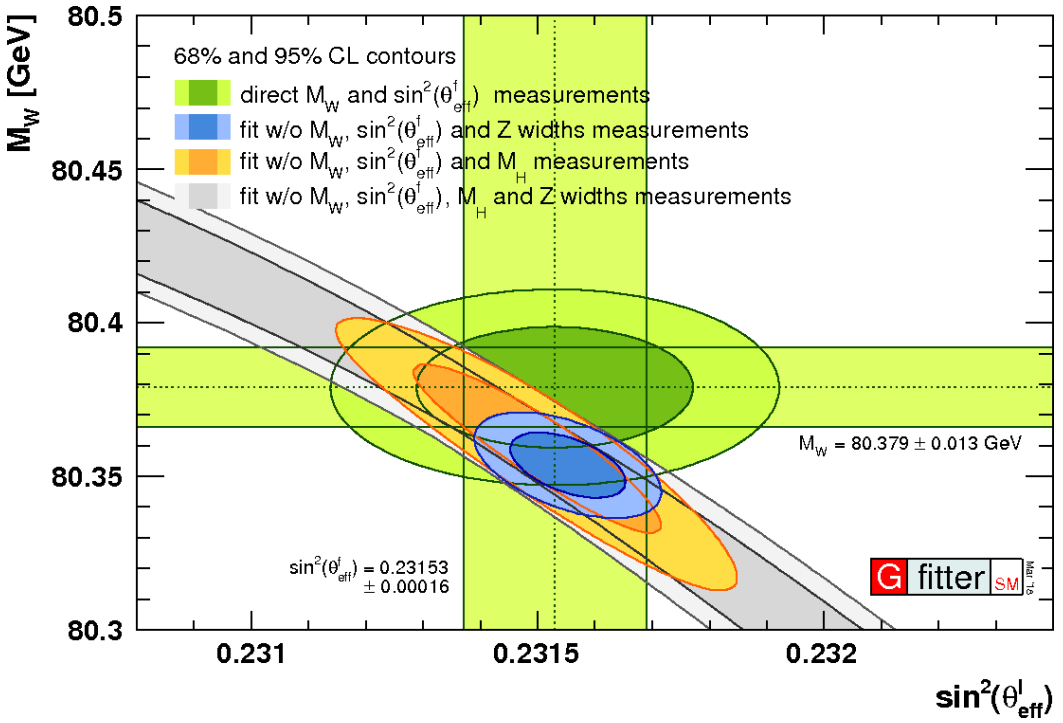
- Effective leptonic mixing angle

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

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

- Measurement of 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)

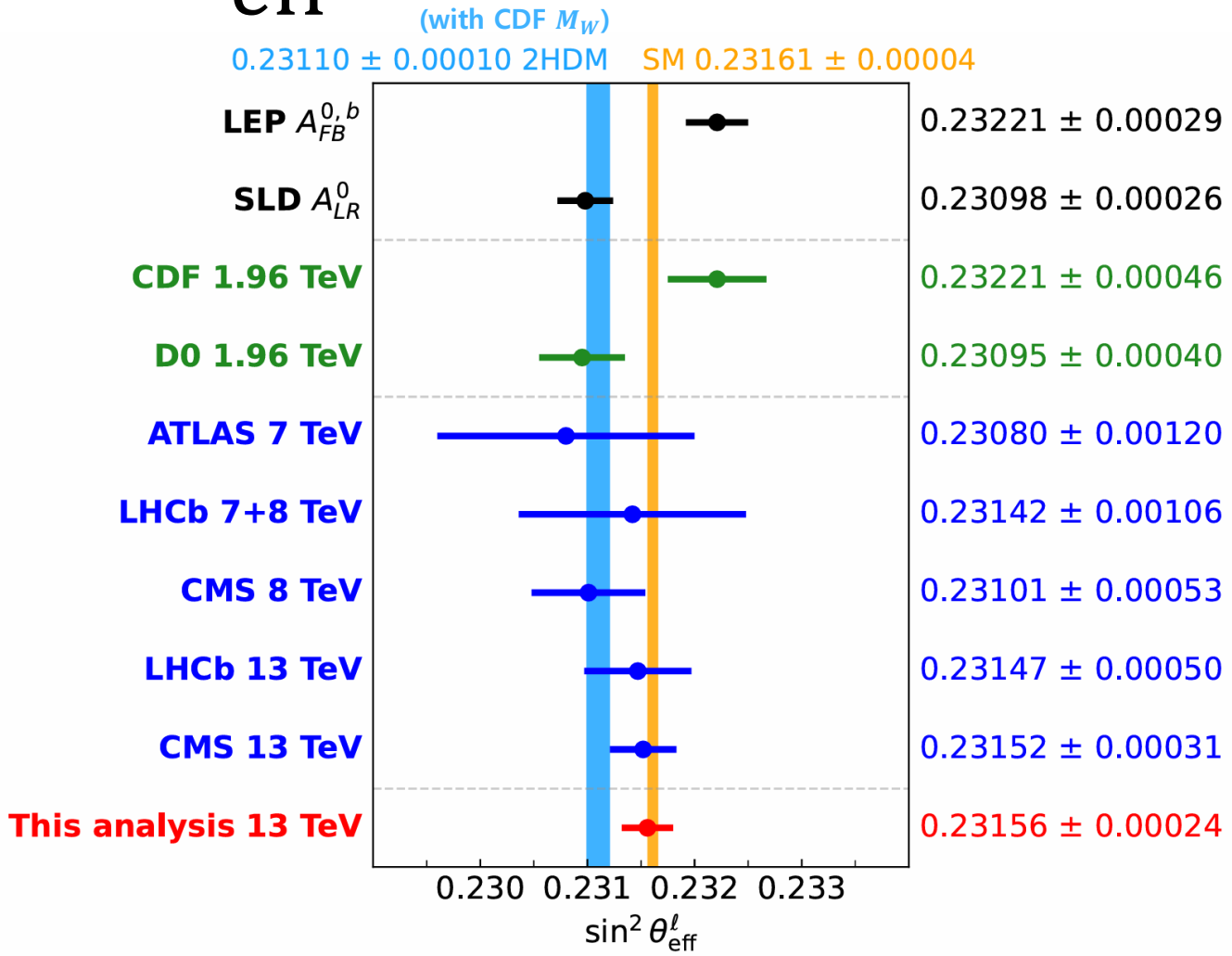


Measurements of $\sin^2\theta^l_{\text{eff}}$

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

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

- Improved analysis of CMS 13 TeV (**THIS TALK**) arXiv:2508.18022
  - $\boldsymbol{\sin^2\theta^l_{\text{eff}} = 0.23156 \pm 0.00024}$
  - Additional PDF constraint from W charge asymmetry and W/Z xsec ratio



CMS 13 TeV Analysis

arXiv:2408.07622

$$\sin^2\theta^l_{\text{eff}} = 0.23152 \pm 0.00031\ (\text{CT18Z})$$

- Precision comparable to that of electron collider

CERN Press Release, April 2024

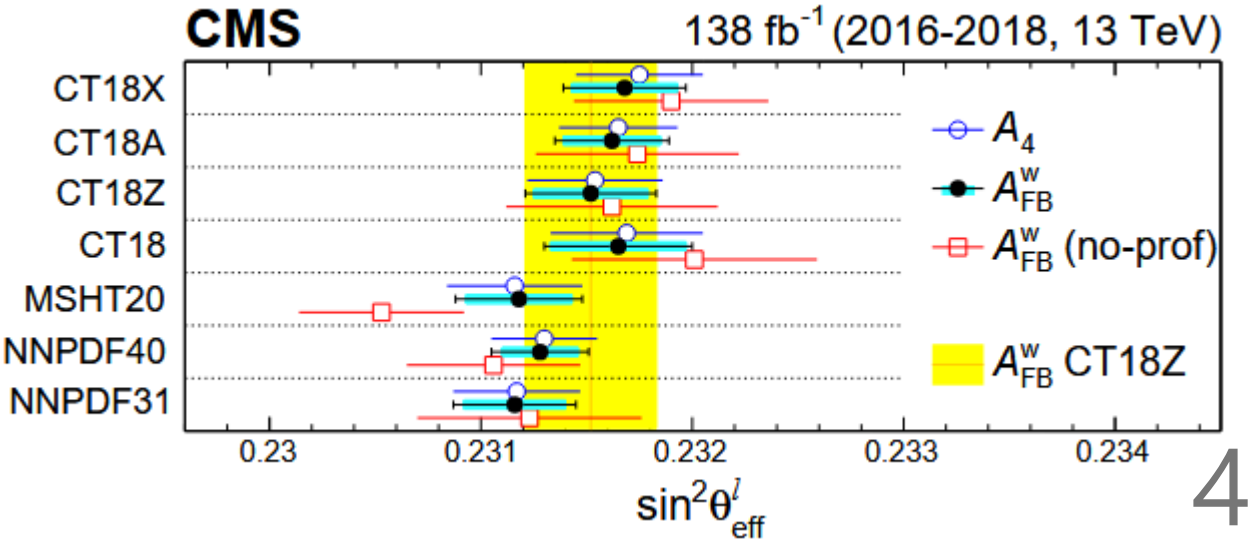
- PDF profiling to constrain PDF uncertainty
  - Still, PDF gives the largest uncertainty (0.00027)
  - Without the PDF tolerance factor ($\Delta\chi^2 = 1$)
- A_4 (=$8/3\ A_{FB}$) measurements are also published
  - For future reinterpretation with better understanding on PDF

- However, **possible systematic difference between PDFs remained an open question**
  - Both NNPDF and MSHT are lower than CT18
  - **CT18Z** is chosen as nominal PDF

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



New analysis

- Investigation on the source of the difference between PDFs
  - With 19 PDF sets: NNPDF40 (8), CT18 (6), MSHT20 (4) and PDF4LHC21 (1)
  - **CT18Z** is chosen as nominal PDF, following the original CMS paper

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

CT18NNLO
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)

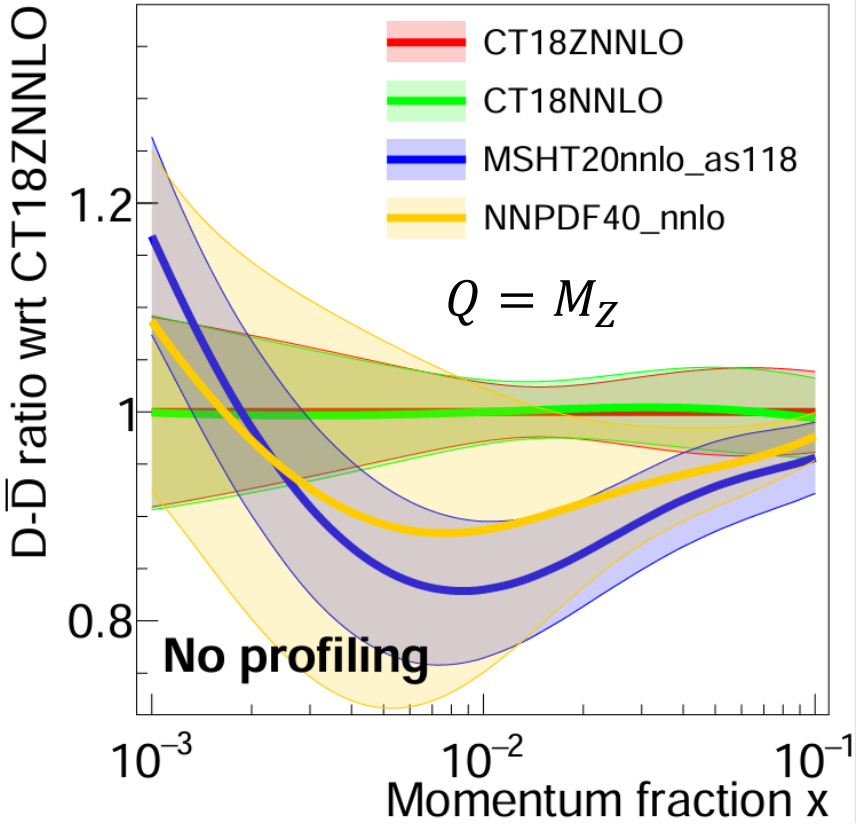
Combination of CT18+MSHT20+NNPDF31
Asymmetric strange

PDF4LHC21_40

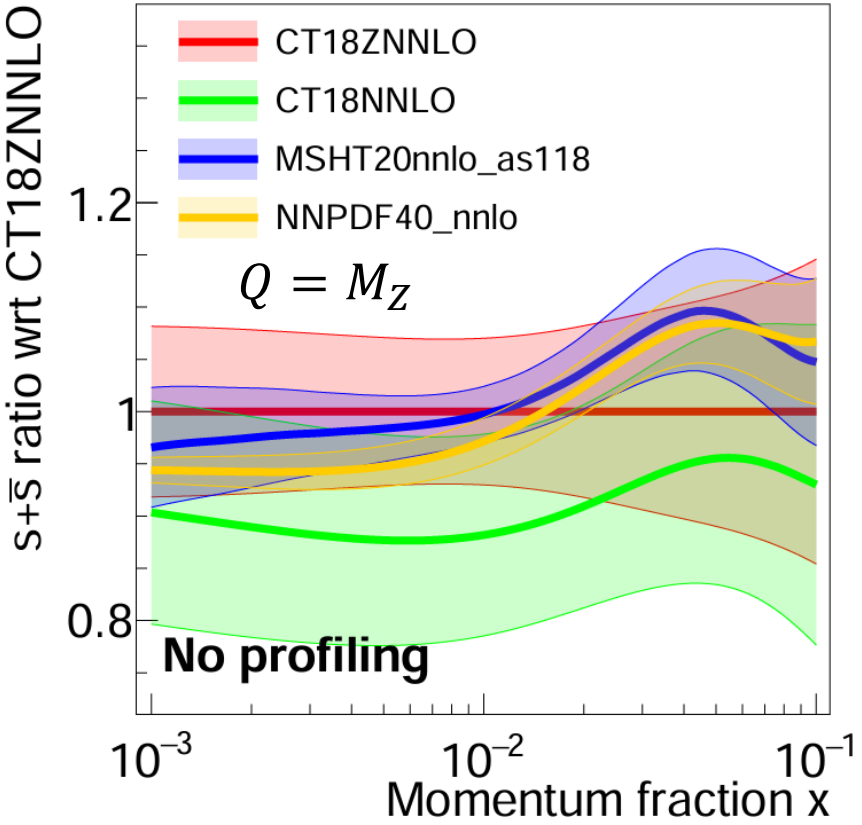
"qed": photon PDF and QED evolution
"an3lo": approximate N3LO QCD
"mhou": missing higher order uncertainty

New analysis

- We found that the difference comes from
  - Down-type valence quark distribution



  - Size of the strange quark content



- Use $D - \bar{D} \equiv (d + s + b) - (\bar{d} + \bar{s} + \bar{b})$, instead of $d_v = d - \bar{d}$
  - For a fair comparison across different assumptions on the sea-quark asymmetry
- MSHT<NNPDF<CT18 gives same ordering in the extracted $\sin^2 \theta_{\text{eff}}^l$

Some of CT18 family don't have data constraining strange at high Q^2

➔ Lower strange

➔ Higher $\sin^2 \theta_{\text{eff}}^l$

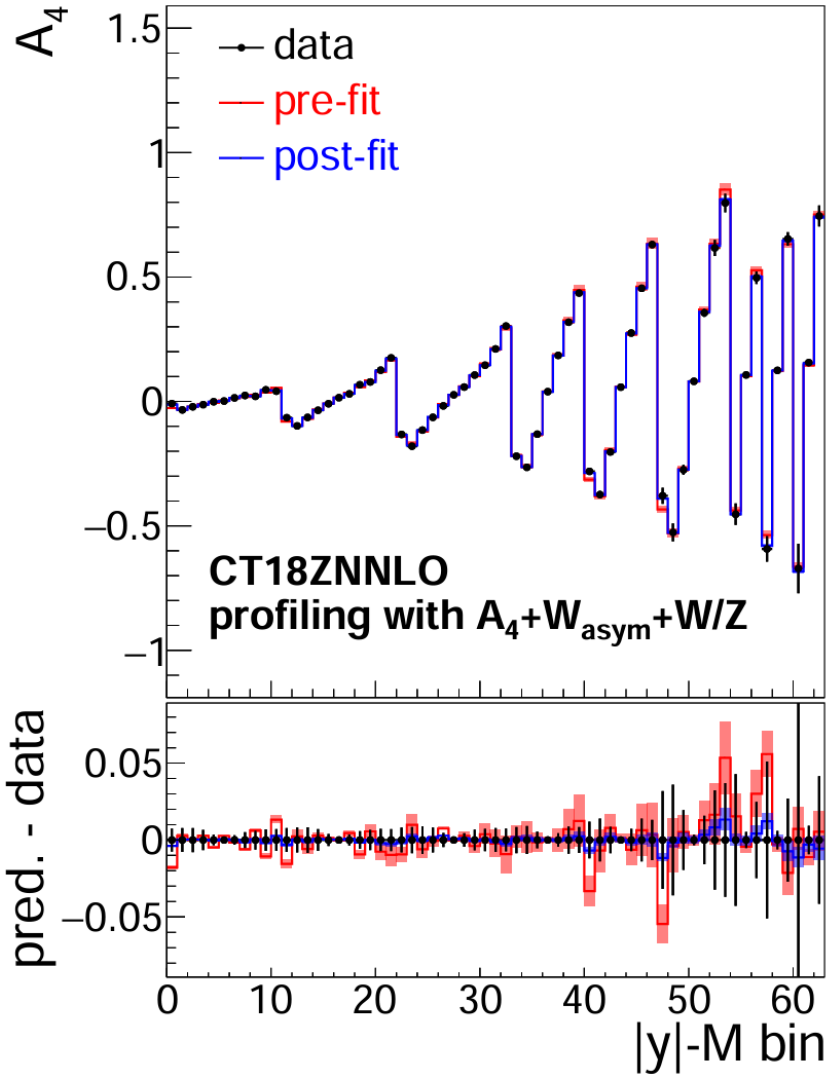
New analysis

- 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 from
  - CMS W charge asymmetry ($\boldsymbol{W_{\mathrm{asym}}}$) Phys. Rev. D 102 (2020) 092012 for down quark
  - CMS W/Z cross section ratio ($\boldsymbol{W/Z}$) JHEP 04 (2025) 162 for strange quark
  - With xFitter framework

- All measurements are ratios → Many systematic uncertainties are cancelled

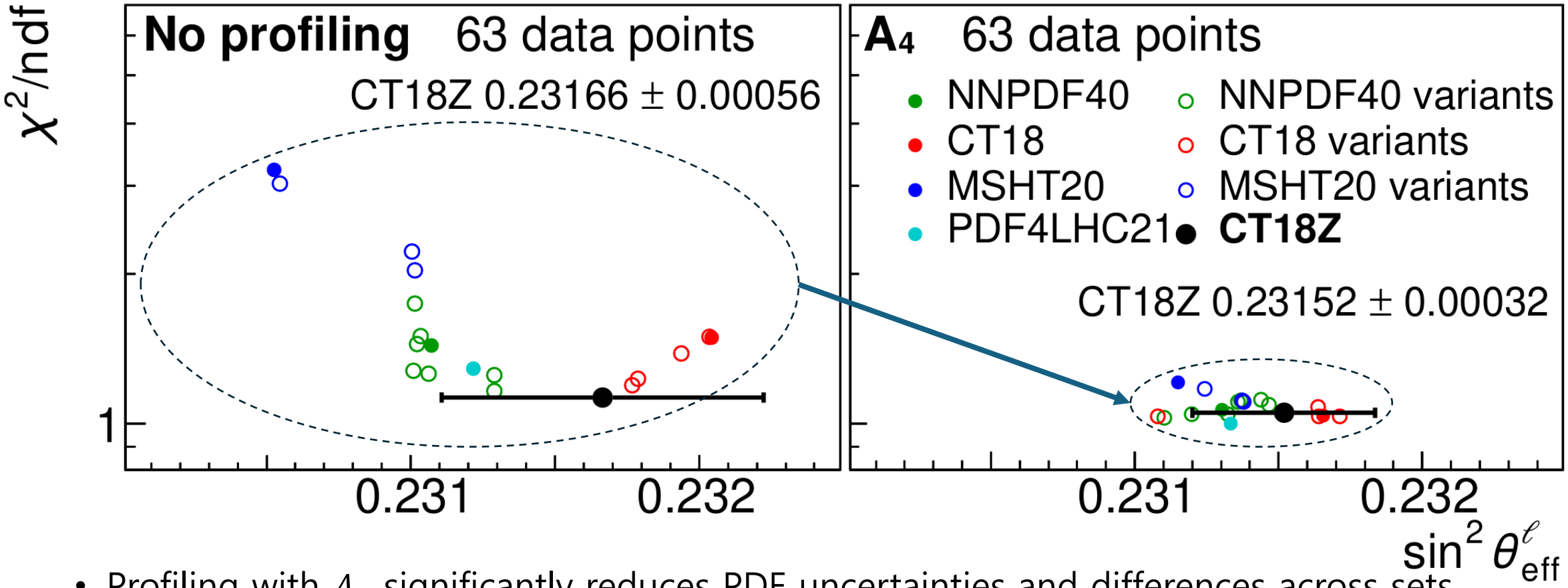
- Correlation between measurements
  - PDF: correlated (~0.00050)
  - Missing higher order uncertainties: uncorrelated
    - A_4 (0.00008), W_{asym} (0.00004), W/Z (0.00002)
  - Experimental uncertainties: uncorrelated
    - A_4 and W_{asym} have partial overlap in data-taking periods
    - But uncertainties that could have correlation are relatively small than other uncertainties
    - Correlation $\rho < 0.01$

Reproducing original CMS result using published A_4



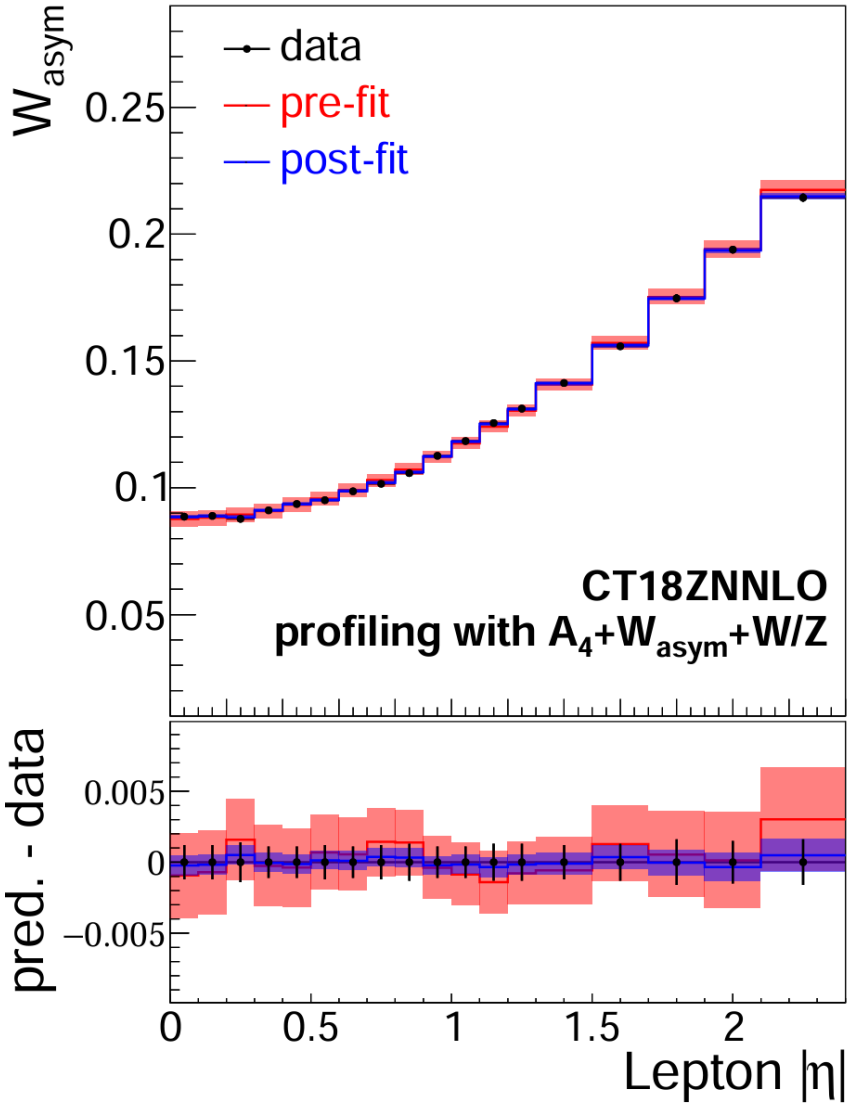
- CMS A_4 measurements at 13 TeV
  - 63 data points in bins of mass and rapidity
  - Mass from 54 to 150 GeV
  - Rapidity < 3.4
- Prediction from MiNNLO+Pythia8
  - PHOTOS for QED FSR
  - POWHEG Z_ew for weak NLO correction

$\sin^2\theta^l_{\mathrm{eff}}$ results with A_4 profiling



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

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

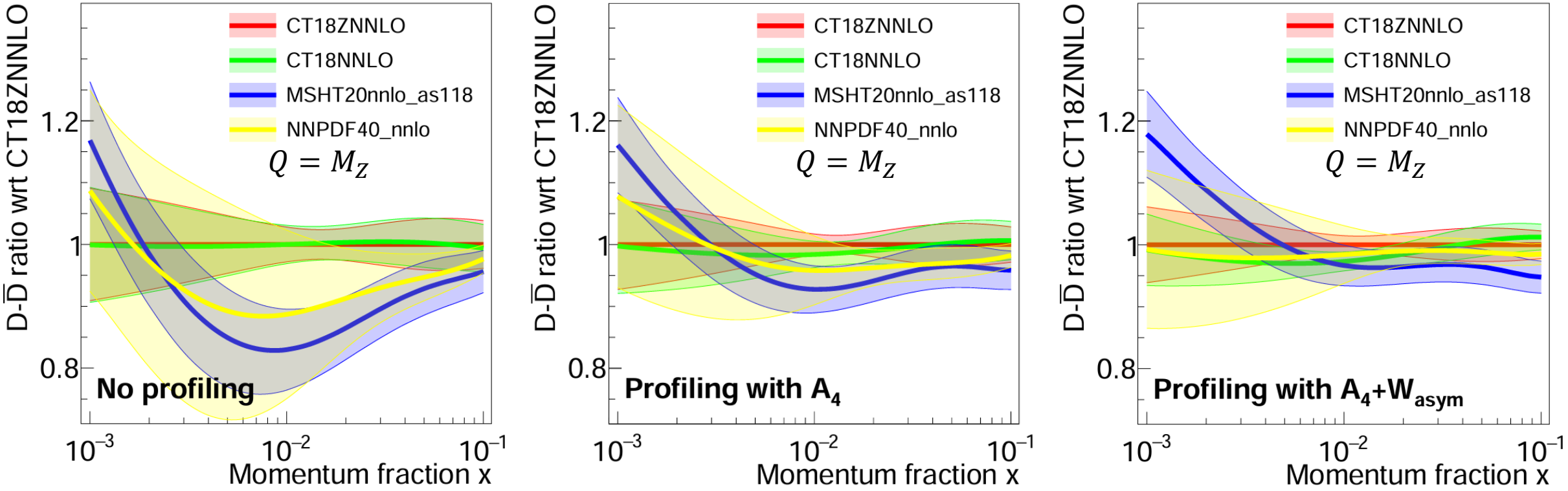


- W asymmetry can help constrain d/u PDF and reduce uncertainty of $\sin^2\theta^l_{\mathrm{eff}}$
  - Eur. Phy. J. C76 (2016) 115
- CMS W charge asymmetry measurements at 13 TeV
  - Phys. Rev. D 102 (2020) 092012
  - 18 data points in bins of lepton pseudorapidity $|\eta_l|$

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

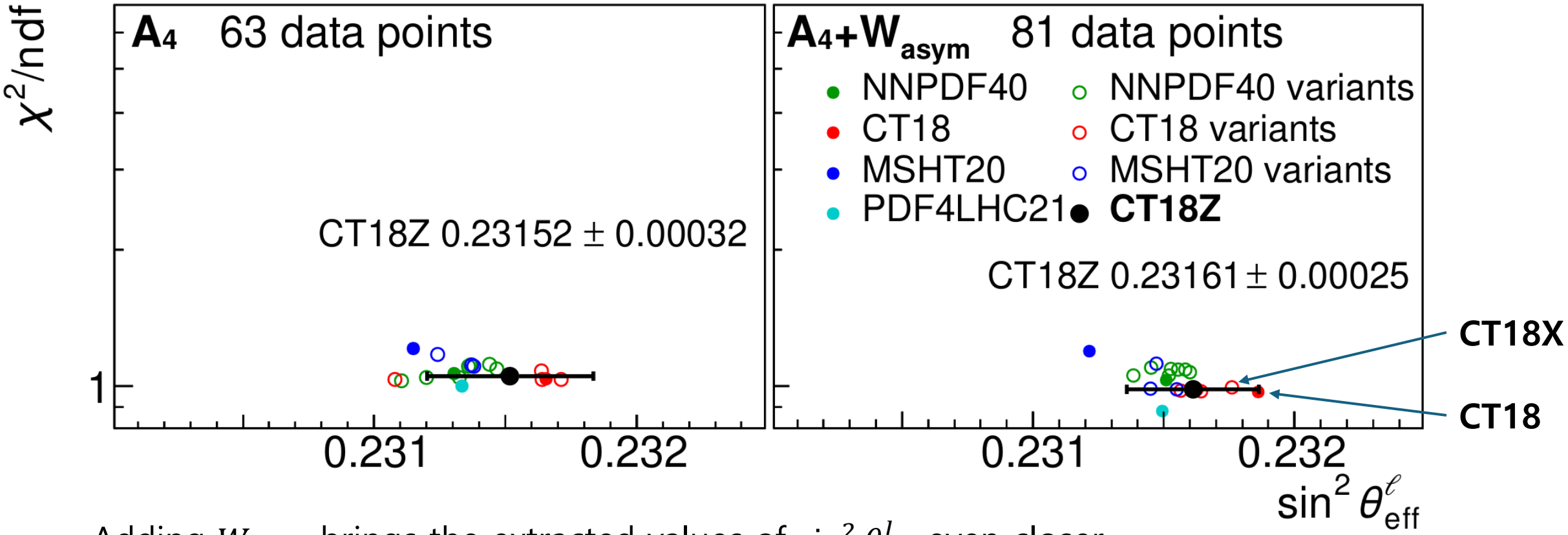
- Prediction from MCFM (NNLO)

Impact on down-type valence quarks



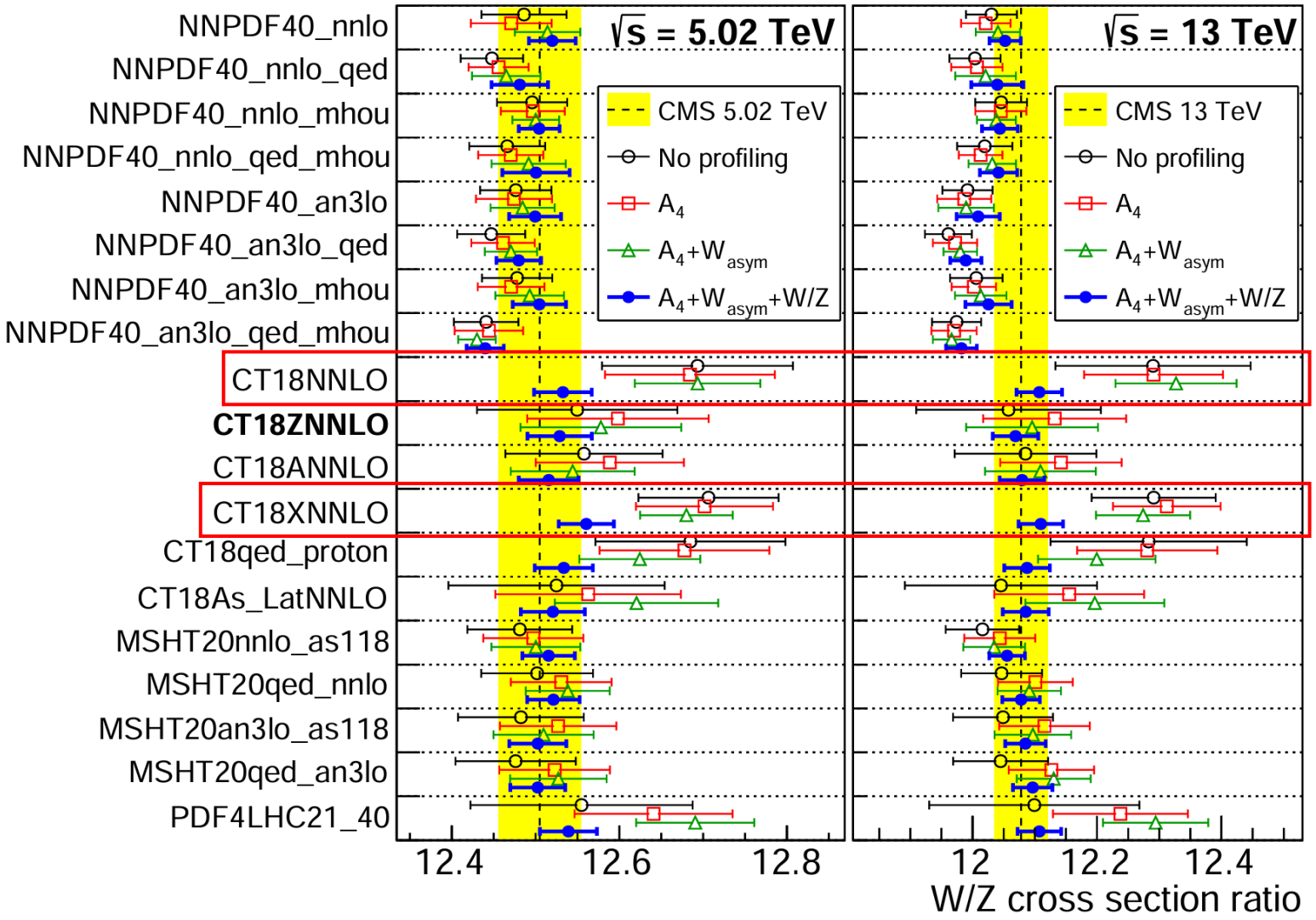
- Adding A_4 mitigates the difference across the PDFs
- Adding W_{asym} further constrains the down-type quarks

$\sin^2\theta^l_{\mathrm{eff}}$ results with W_{asym} profiling



- Adding W_{asym} brings the extracted values of $\sin^2\theta^l_{\mathrm{eff}}$ even closer
  - MSHT20 shows a lower $\sin^2\theta^l_{\mathrm{eff}}$ 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 $\sin\theta^l_{\mathrm{eff}}$

W/Z cross section ratio



- The W/Z ratio is strongly anti-correlated with the strange-quark content

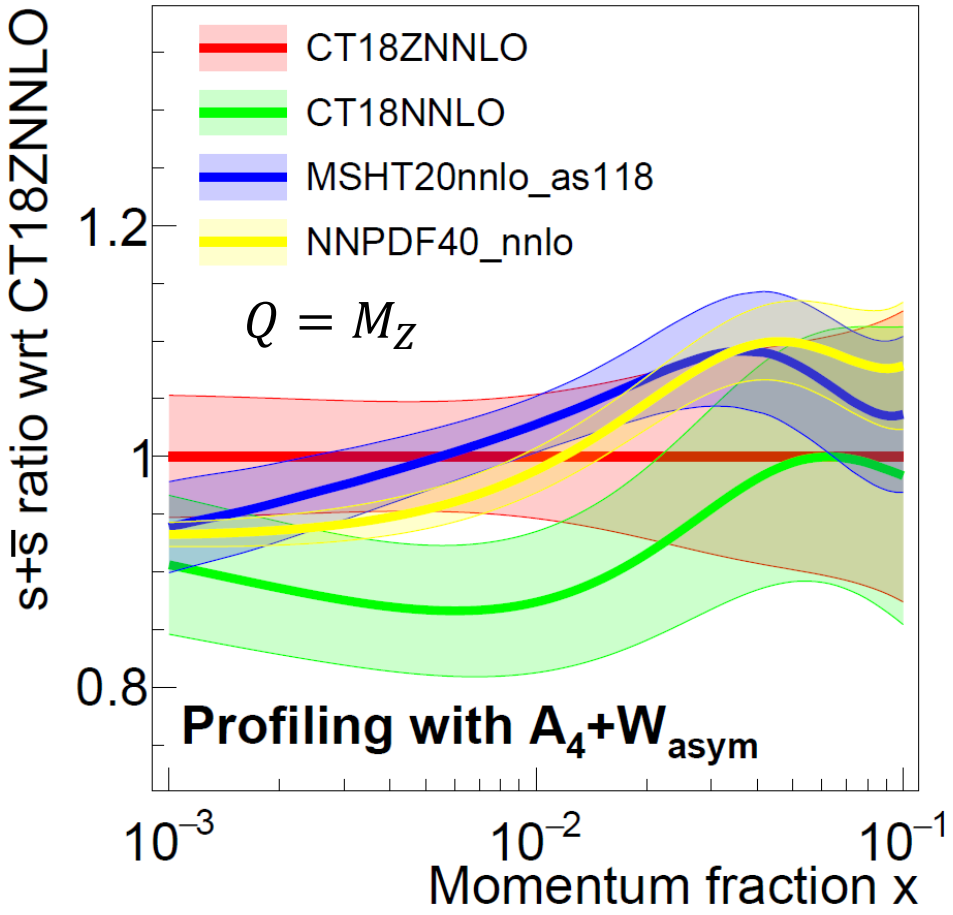
- CMS W/Z ratio (2 data points)
  - JHEP 04 (2025) 162

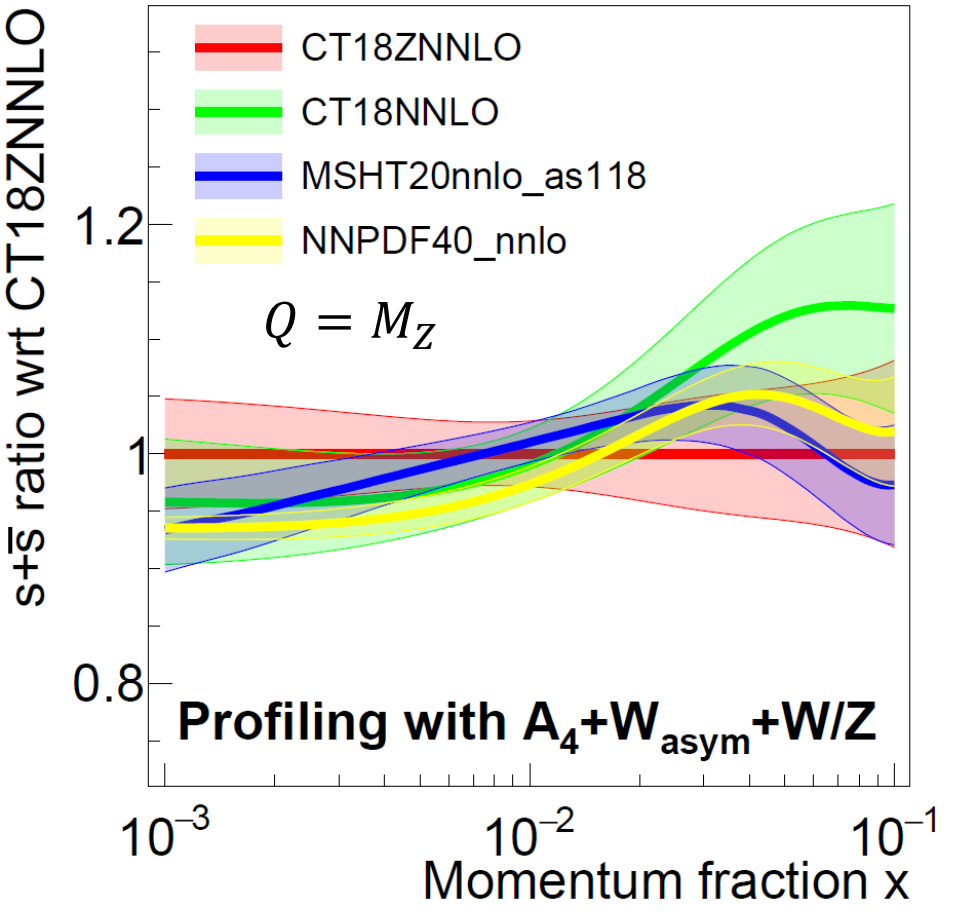
$12.505 \pm 0.037_{\text{stat}} \pm 0.032_{\text{syst}}$ (5.02 TeV)

$12.078 \pm 0.028_{\text{stat}} \pm 0.032_{\text{syst}}$ (13 TeV)

- Prediction from DYTurbo (NNLO+NNLL)

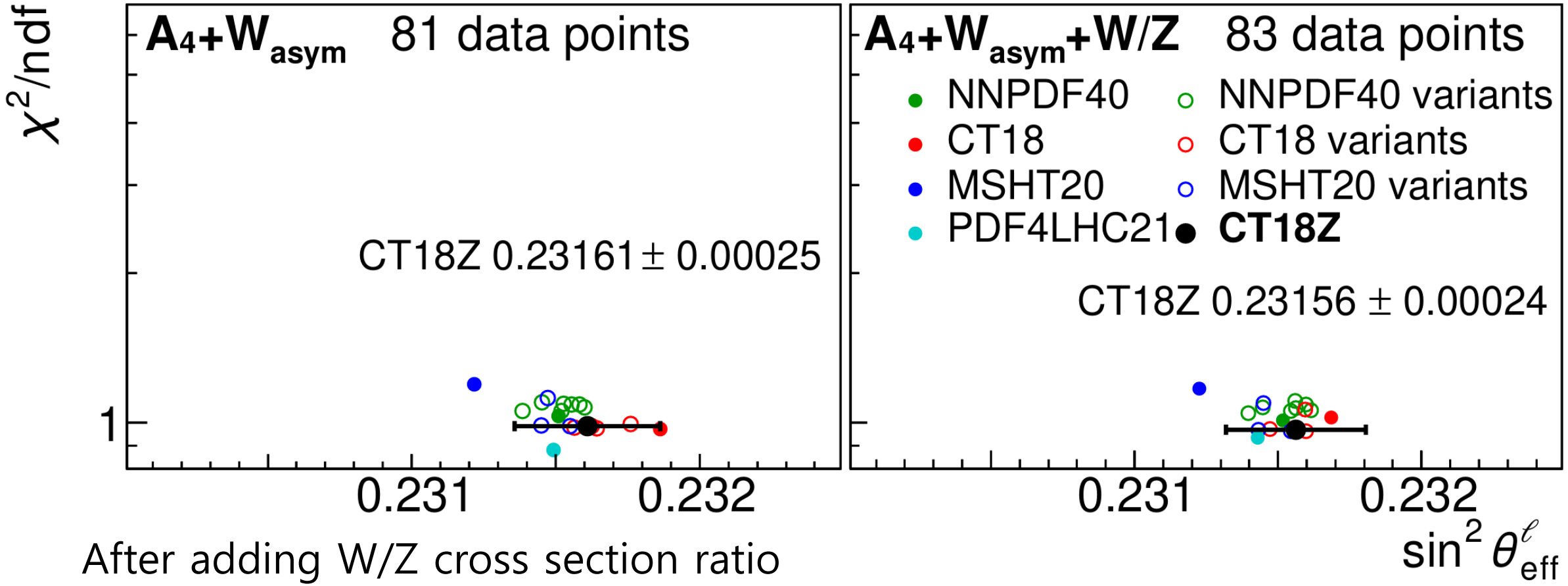
Impact on strange quark





Adding W/Z increase strange of CT18

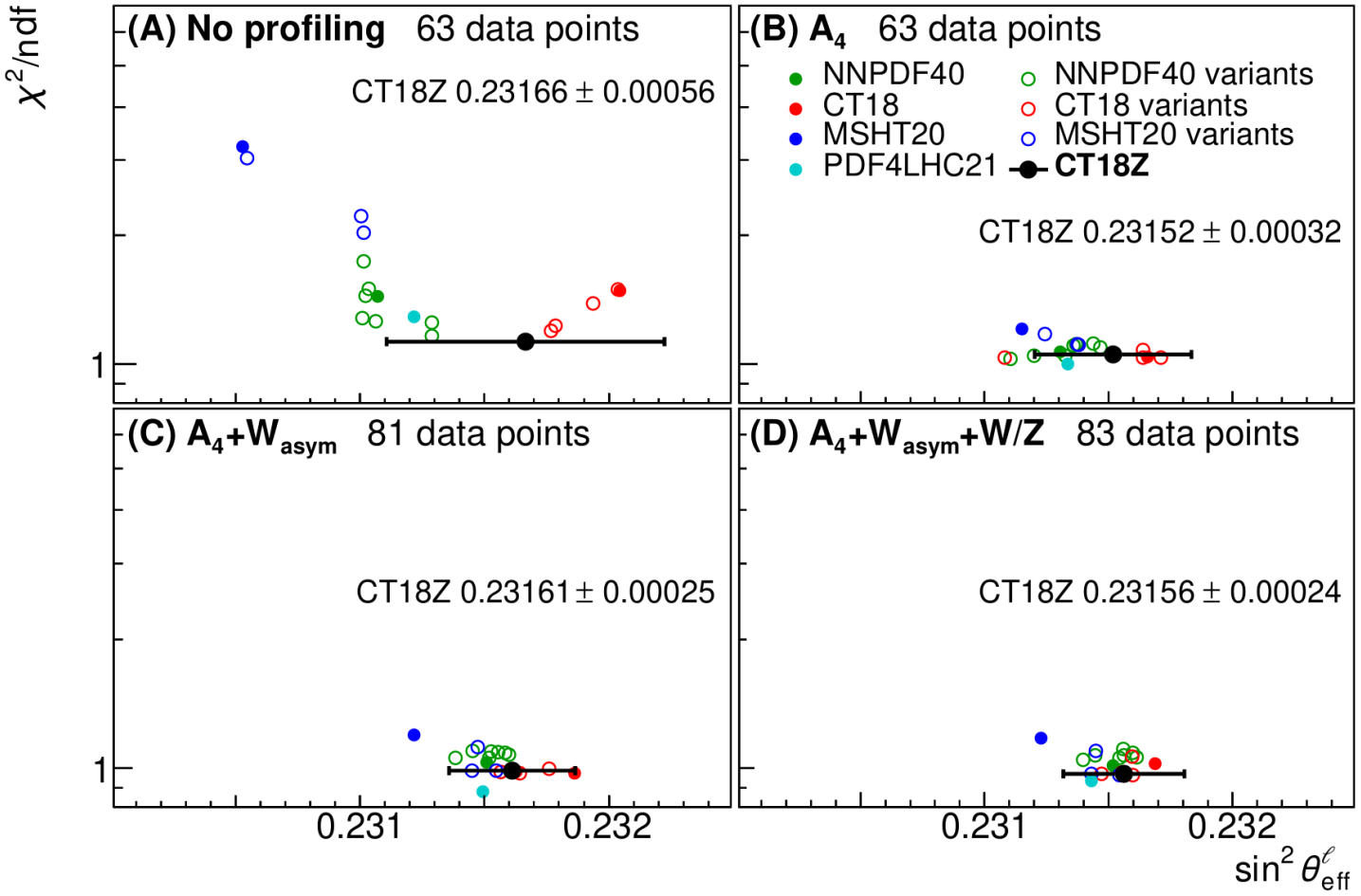
$\sin^2\theta^l_{\mathrm{eff}}$ results with W/Z profiling



After adding W/Z cross section ratio

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

Result



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

- 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 different PDF parameterizations and assumptions
- MSHT20 alone remains outside the CT18Z uncertainty band
  - a slightly higher χ^2 may imply limited flexibility

Conclusion

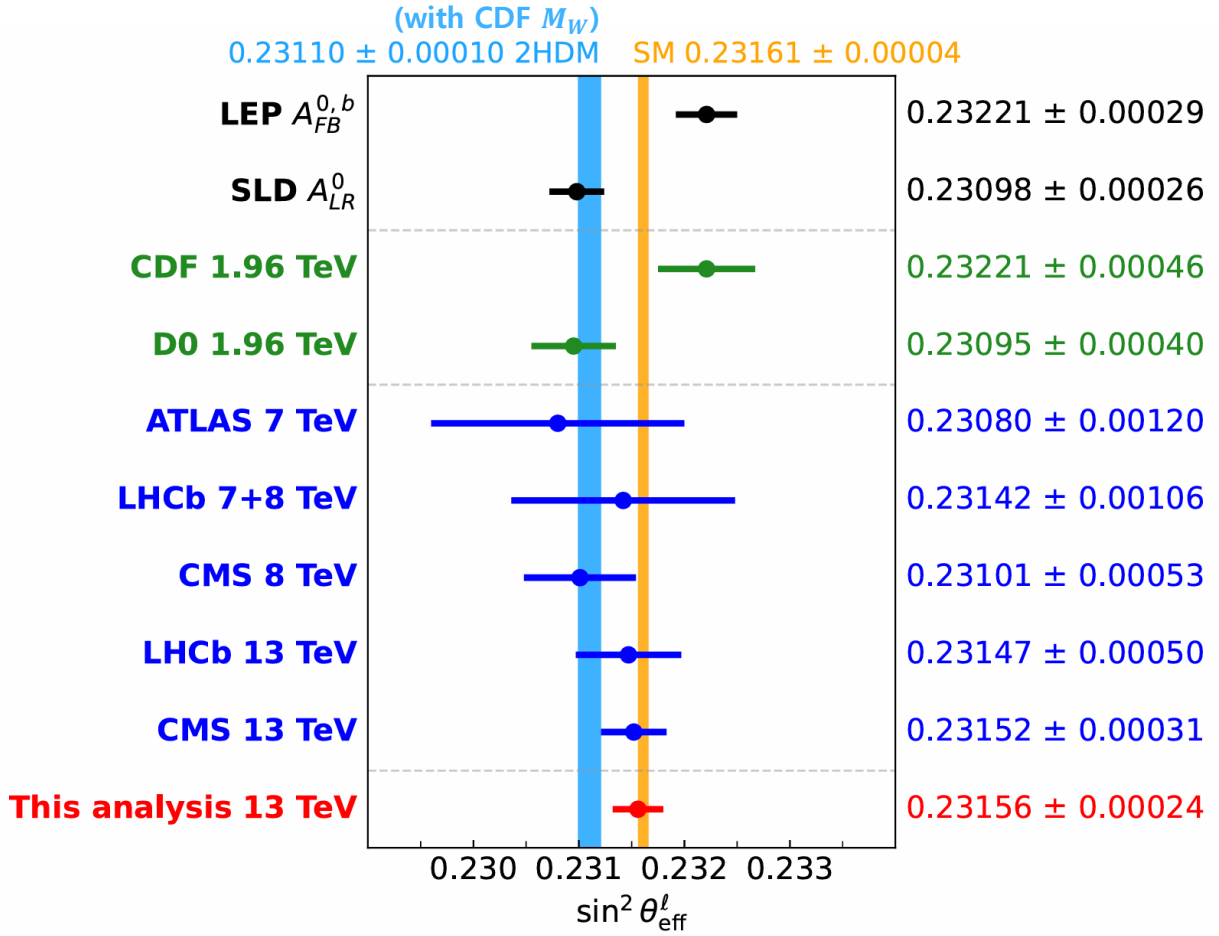
$$\sin^2\theta^l_{\text{eff}} = 0.23156 \pm 0.00024$$

- 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

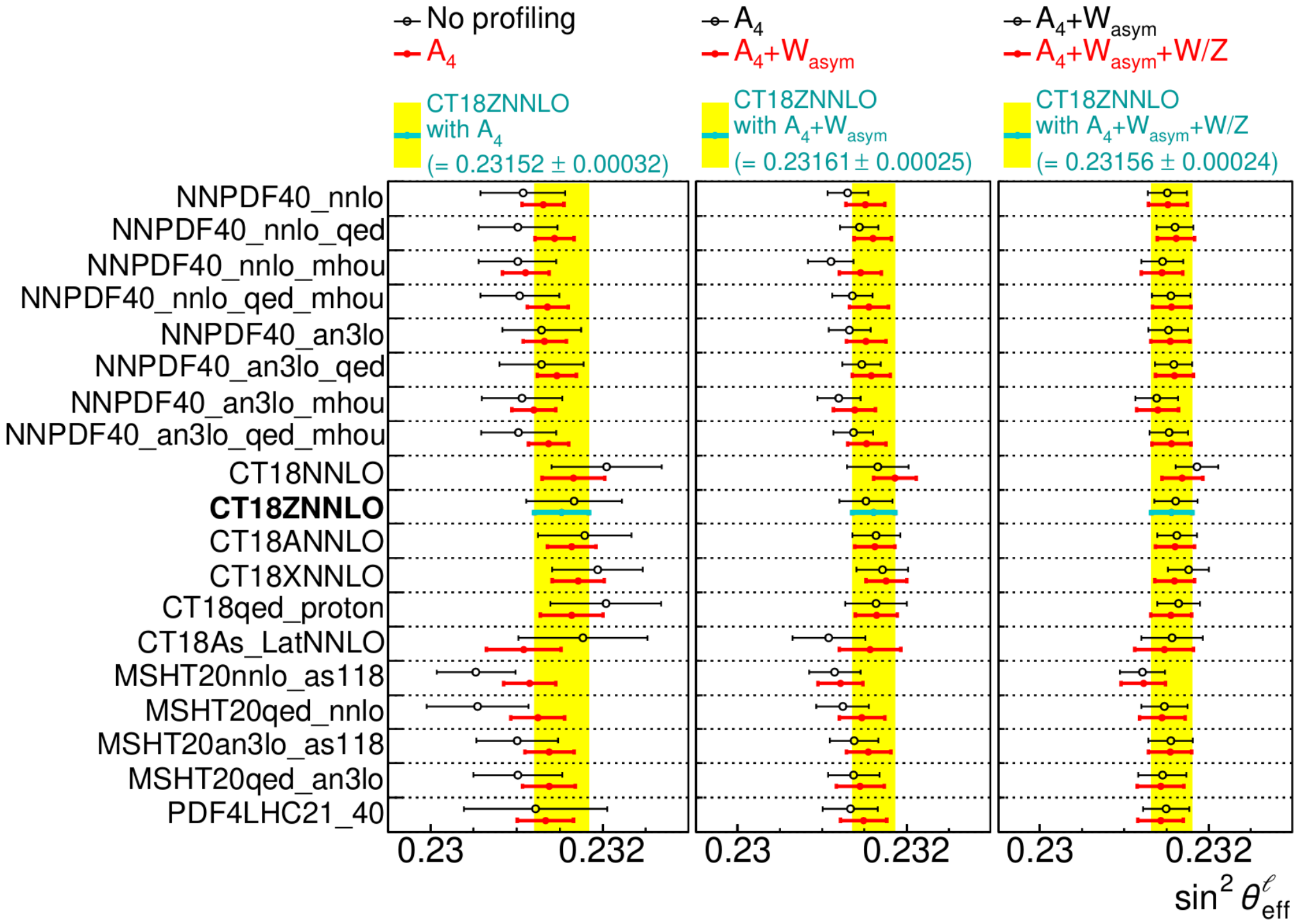
    0.00031 (CMS 13 TeV) → 0.00024 (This analysis)
  - More consistent results across various PDFs

- **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*)

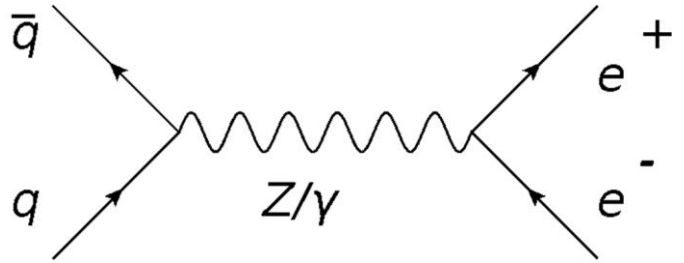


backup


No profiling
A4
A4+Wasym
A4+Wasym+W/Z
CT18ZNNLO with A4 (= 0.23152 ± 0.00032)
CT18ZNNLO with A4+Wasym (= 0.23161 ± 0.00025)
CT18ZNNLO with A4+Wasym+W/Z (= 0.23156 ± 0.00024)
NNPDF40_nnlo
NNPDF40_nnlo_qed
NNPDF40_nnlo_mhou
NNPDF40_nnlo_qed_mhou
NNPDF40_an3lo
NNPDF40_an3lo_qed
NNPDF40_an3lo_mhou
NNPDF40_an3lo_qed_mhou
CT18NNLO
CT18ZNNLO
CT18ANNLO
CT18XNNLO
CT18qed_proton
CT18As_LatNNLO
MSHT20nnlo_as118
MSHT20qed_nnlo
MSHT20an3lo_as118
MSHT20qed_an3lo
PDF4LHC21_40
0.23
0.232
sin2 θeff ℓ

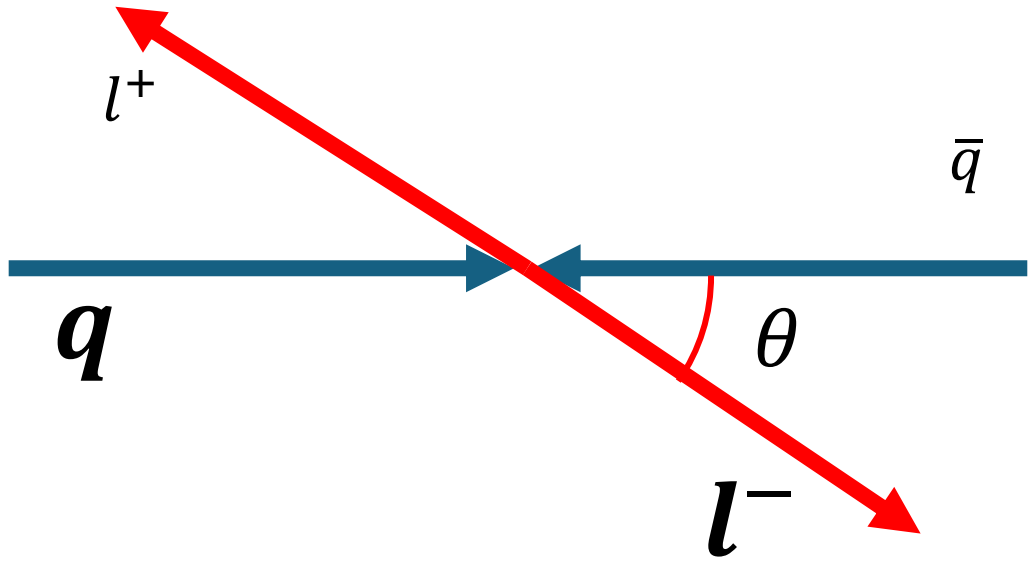
PDF	A_4 without profiling (63 data points)			A_4 profiling (63 data points)			$A_4 + W_{asym} + W/Z$ profiling (83 data points)		
	$\sin^2\theta^\ell_{eff}$	Diff. from CT18Z	χ^2	$\sin^2\theta^\ell_{eff}$	Diff. from CT18Z	χ^2	$\sin^2\theta^\ell_{eff}$	Diff. from CT18Z	χ^2
NNPDF40									
nnlo_as_01180_hessian [18]	23107 ± 49	-59	89	23130 ± 24	-22	66	23152 ± 23	-4	83
nnlo_as_01180_qcd [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_qcd_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_qcd [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_qcd_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
MSHT20qcd_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
MSHT20qcd_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

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)

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

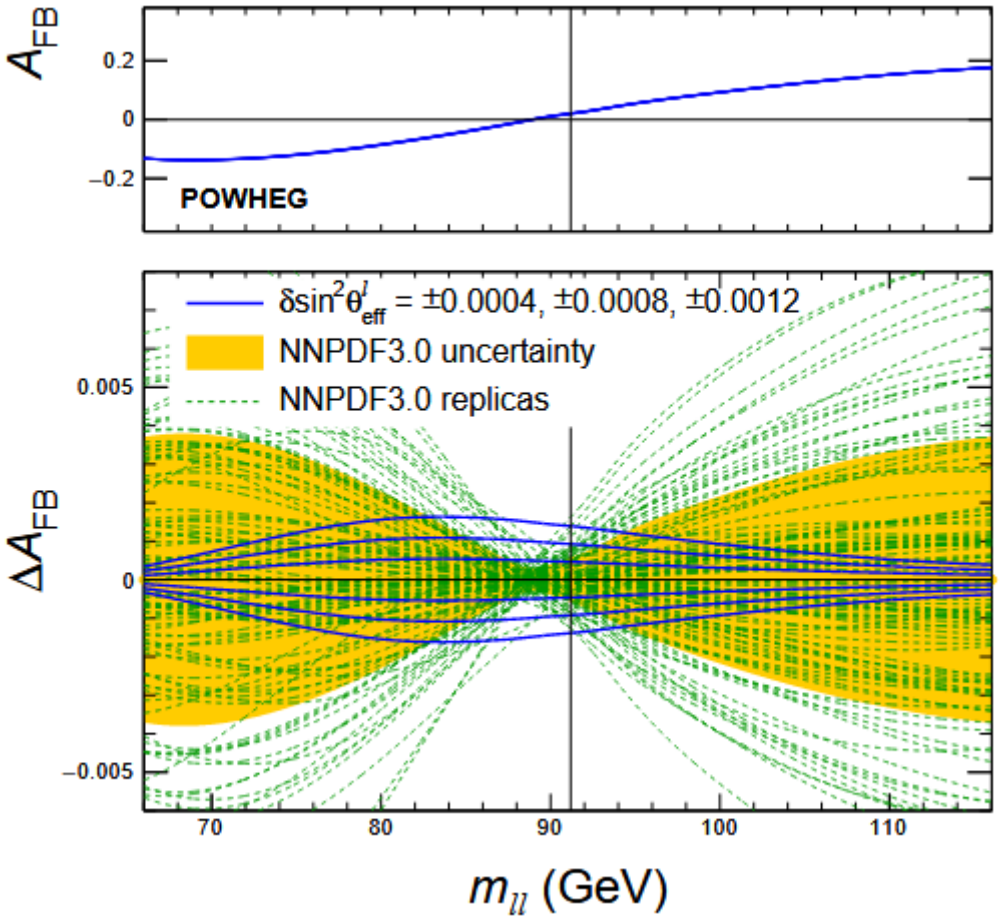
Forward-backward asymmetry (A_{FB})

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

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

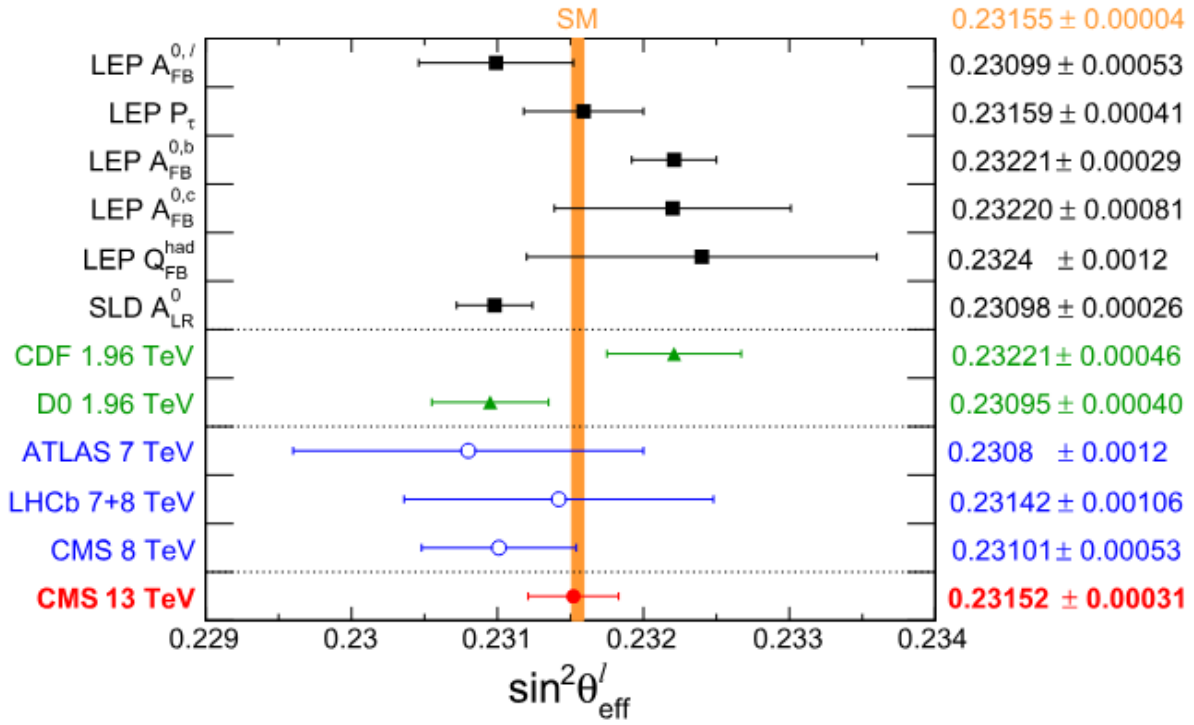
- A_{FB} at Z peak
  - Sensitive to weak mixing angle and PDFs
- A_{FB} in sideband region
  - Small sensitivity to mixing angle
  - Large sensitive to PDFs

  → 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

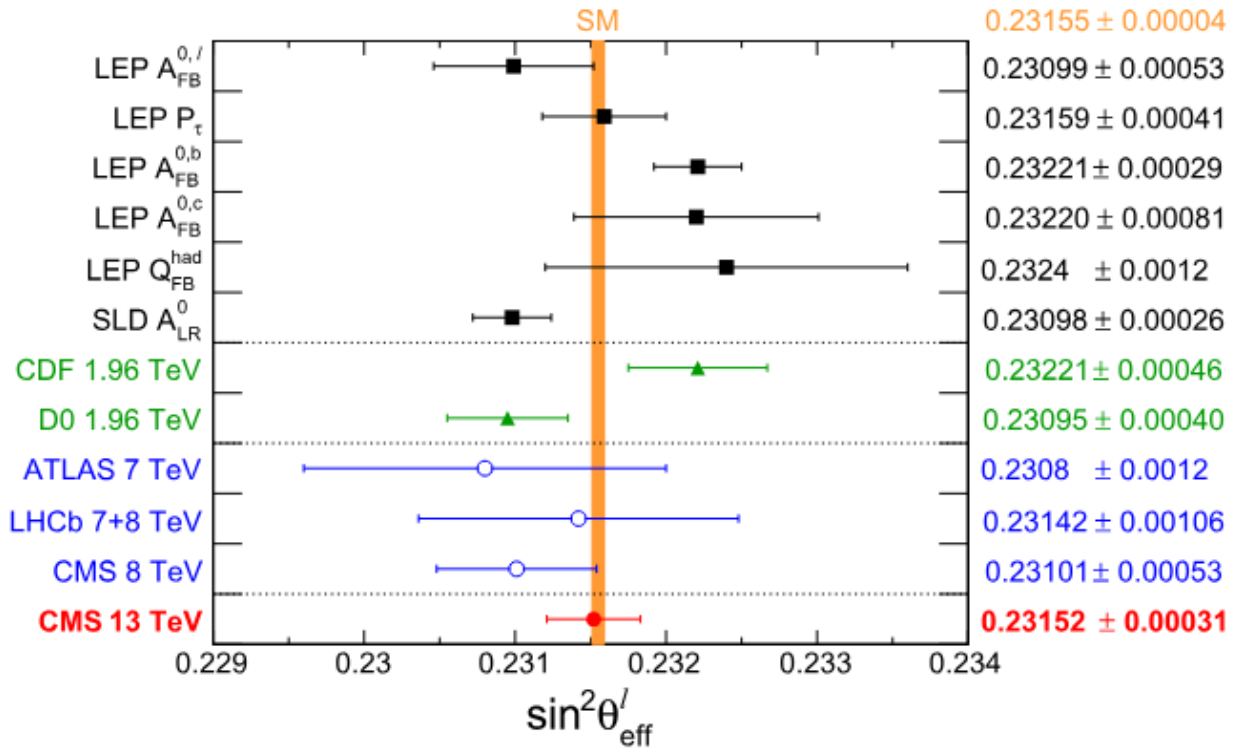


$\sin^2\theta^l_{\mathrm{eff}}$ measurement of CMS 13 TeV

- **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

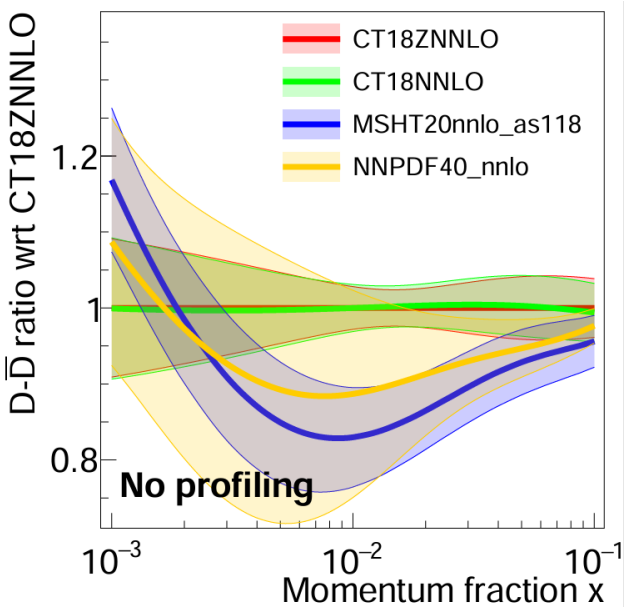
New analysis

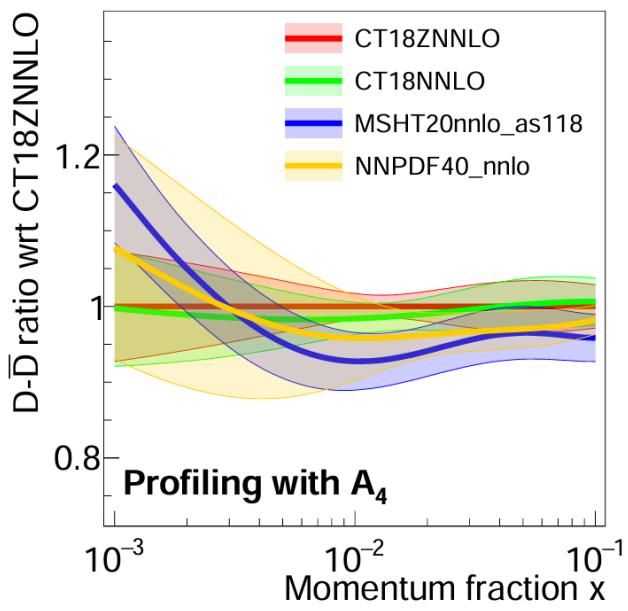
- Investigation on the source of the difference between PDFs
  - With 19 PDF sets: NNPDF40 (8), CT18 (6), MSHT20 (4) and PDF4LHC21 (1)
  - **CT18Z** is chosen as nominal PDF, following the original CMS paper

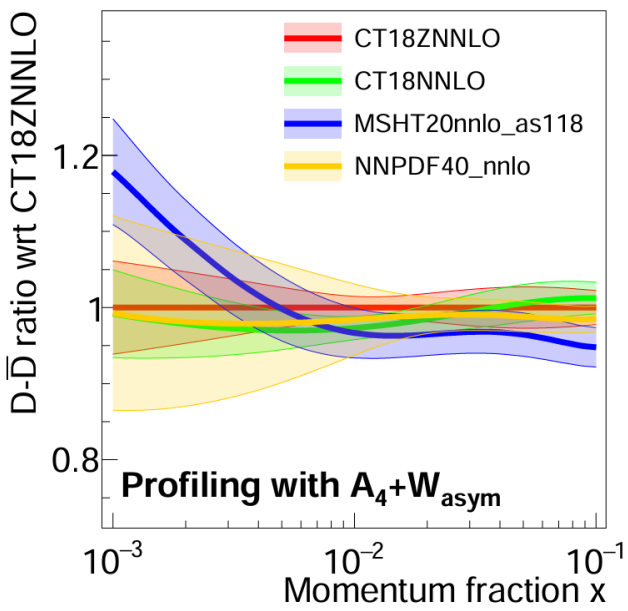
- We found that the difference comes from
  - Down-type valence quark distribution
  - Size of the strange quark content

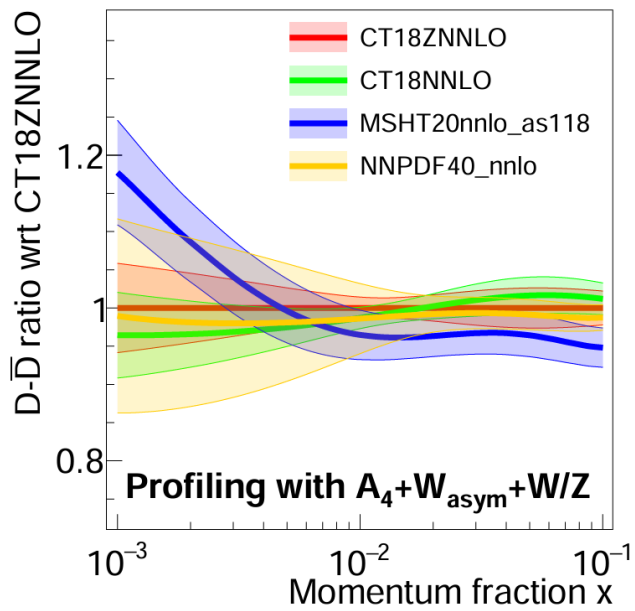
- We extracted new value of $\sin^2\theta^l_{\mathrm{eff}}$ based on $\boldsymbol{A_4}$ measurements of CMS 13 TeV
  - But with additional constraint on PDF using published CMS $\boldsymbol{W_{asym}}$ and $\boldsymbol{W/Z}$ cross section ratio
  - With xFitter framework

down-type quarks

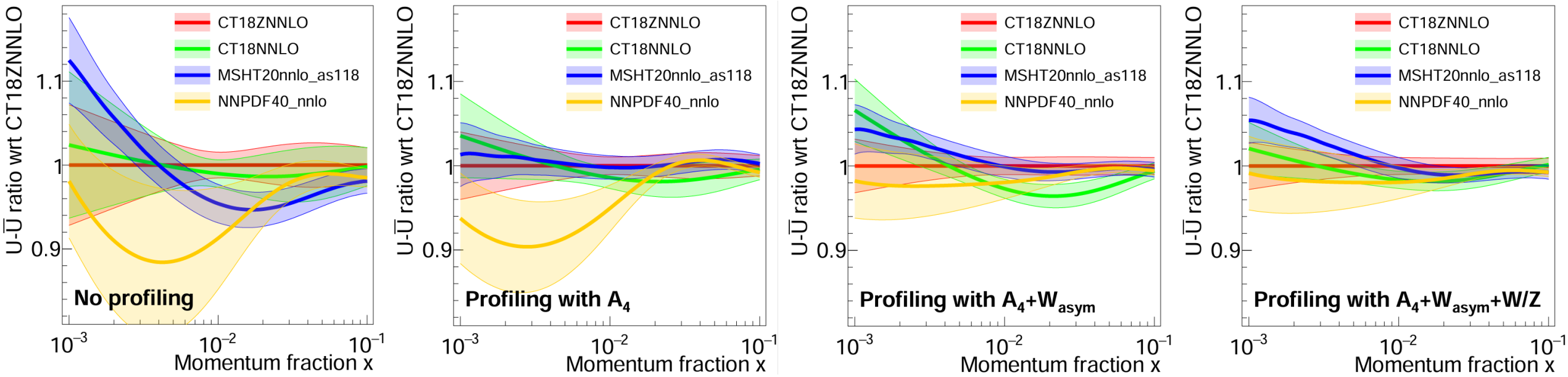




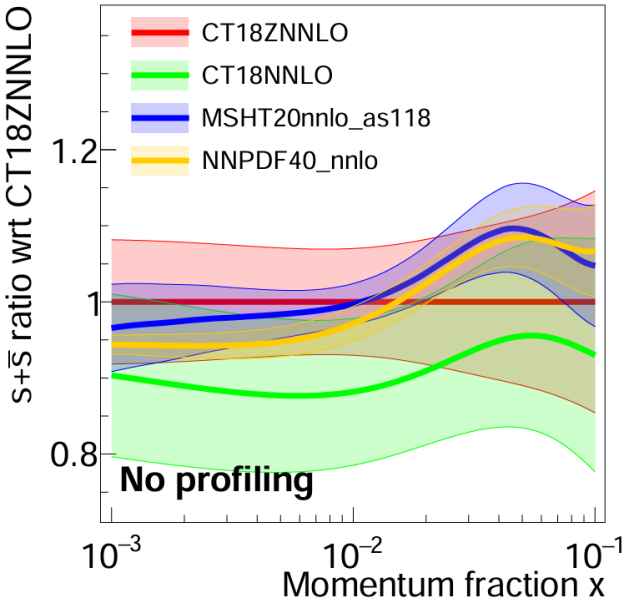


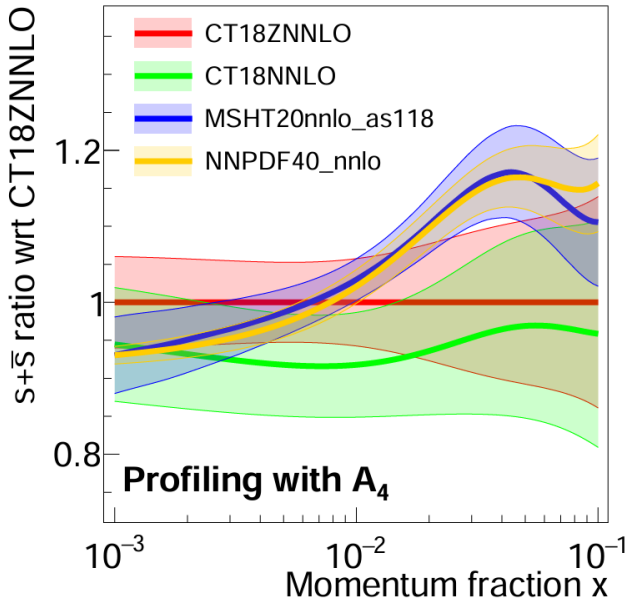


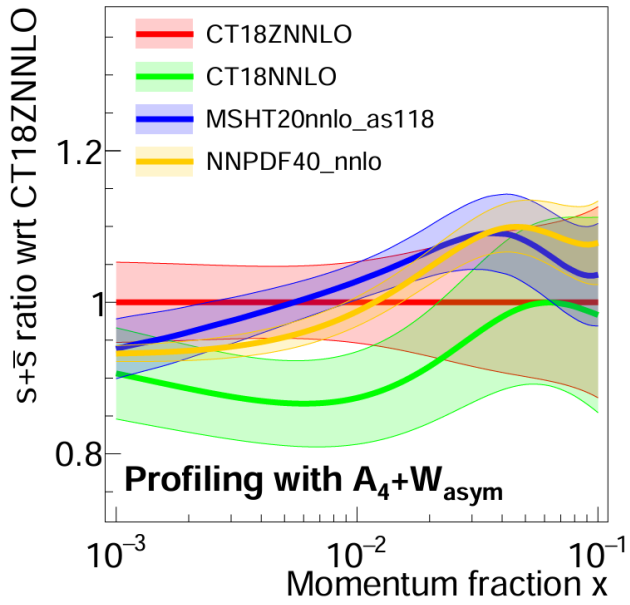
up-type quarks

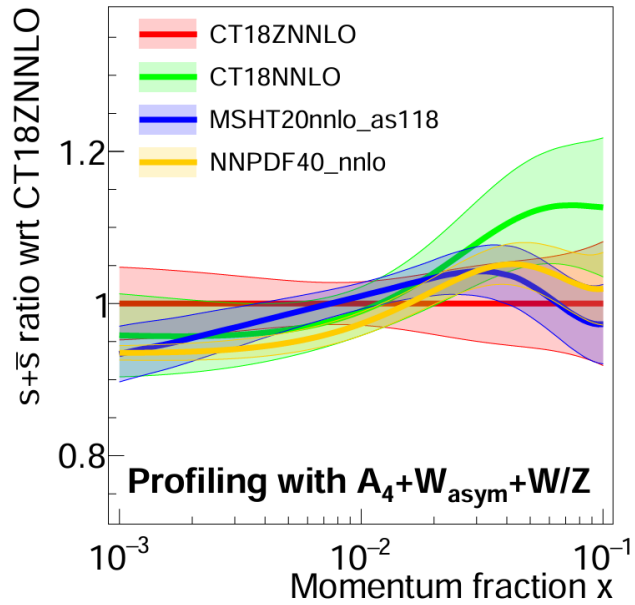


strange quarks

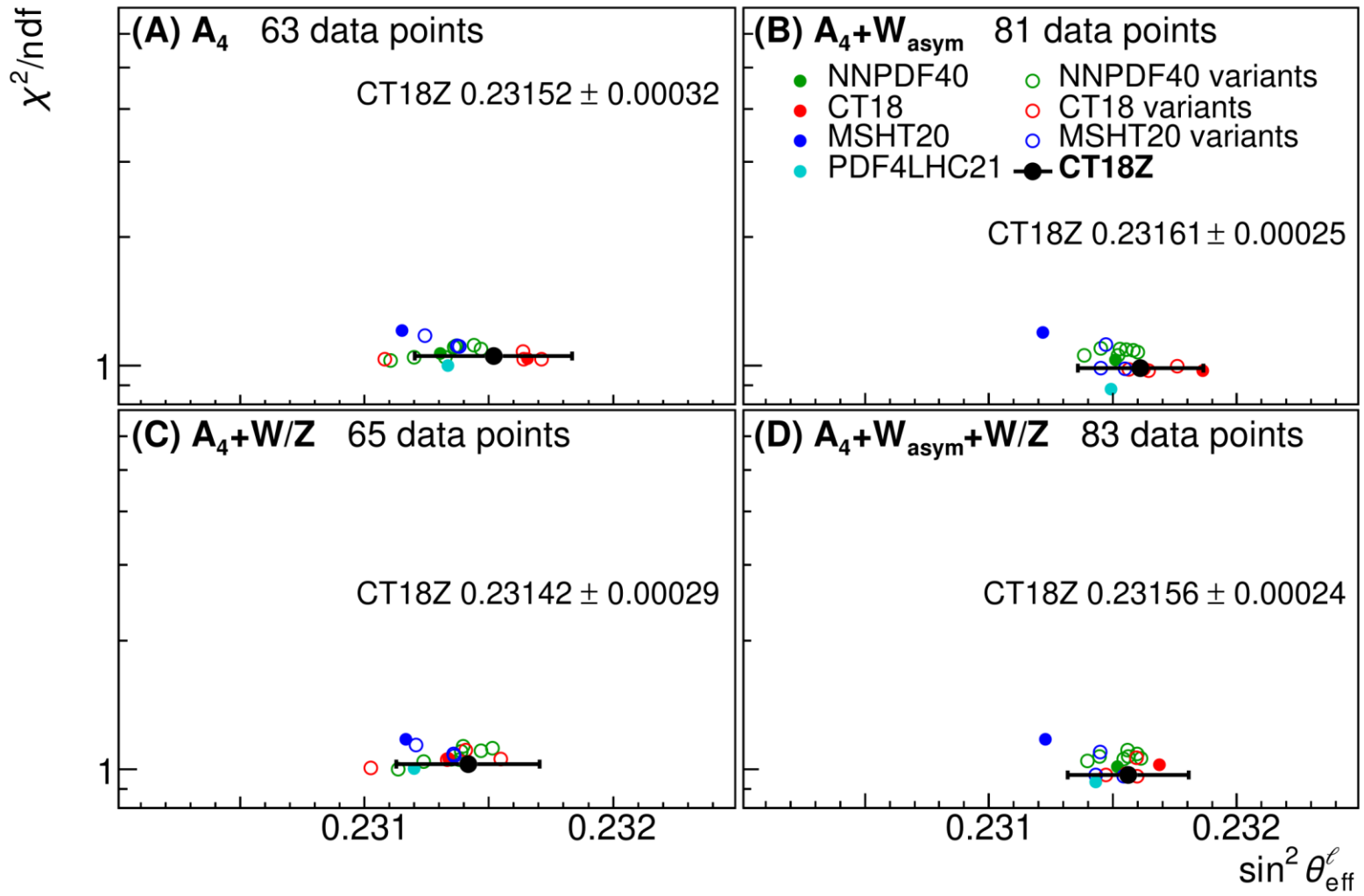








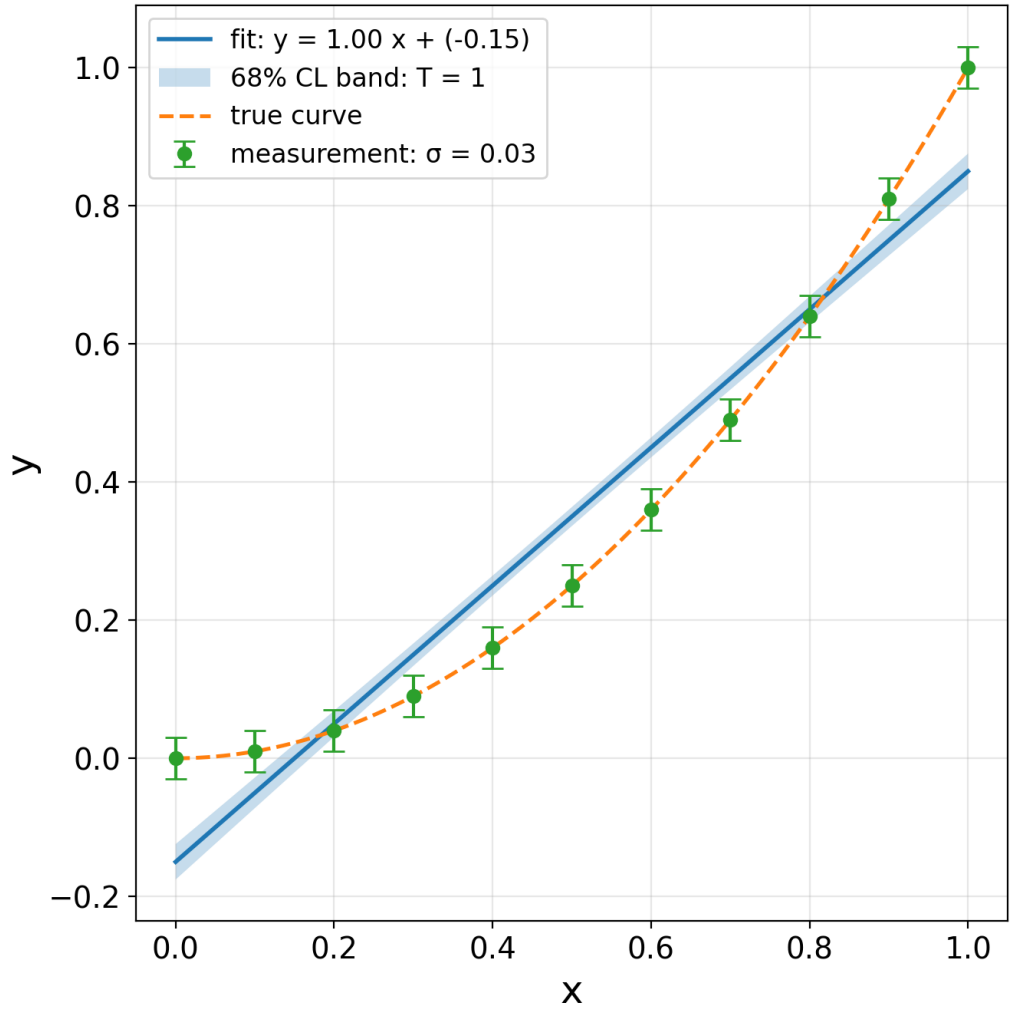
A4+W/Z


(A) A4 63 data points
CT18Z 0.23152 ± 0.00032
(B) A4+Wasym 81 data points
NNPDF40
CT18
MSHT20
PDF4LHC21
NNPDF40 variants
CT18 variants
MSHT20 variants
CT18Z
CT18Z 0.23161 ± 0.00025
(C) A4+W/Z 65 data points
CT18Z 0.23142 ± 0.00029
(D) A4+Wasym+W/Z 83 data points
CT18Z 0.23156 ± 0.00024
χ2/ndf
1
0.231
0.232
sin2 θeff

Tolerance example

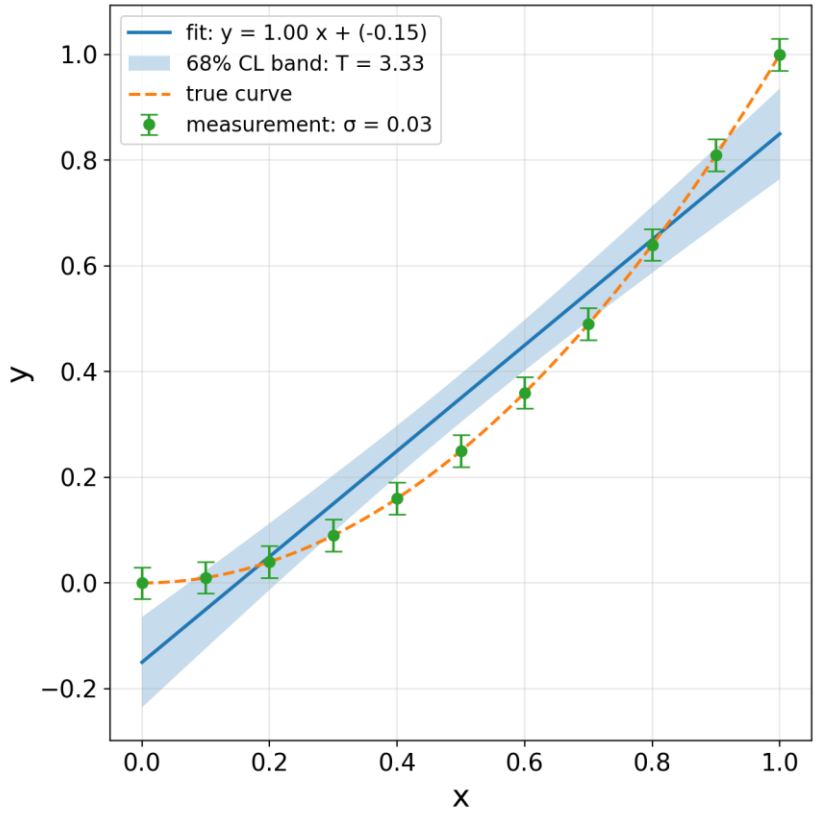
- Bad chi2
  - Limited parameterization
  - Data inconsistency
- Tolerance factor
  - Define 68% CL as $\Delta\chi^2 = 1 \rightarrow T^2$
  - Modification of χ^2 statistics
- Alternative interpretation
  - Inflation of data uncertainty

$$\Delta\chi^2_{new} = \frac{\Delta\chi^2}{T^2} = 1$$

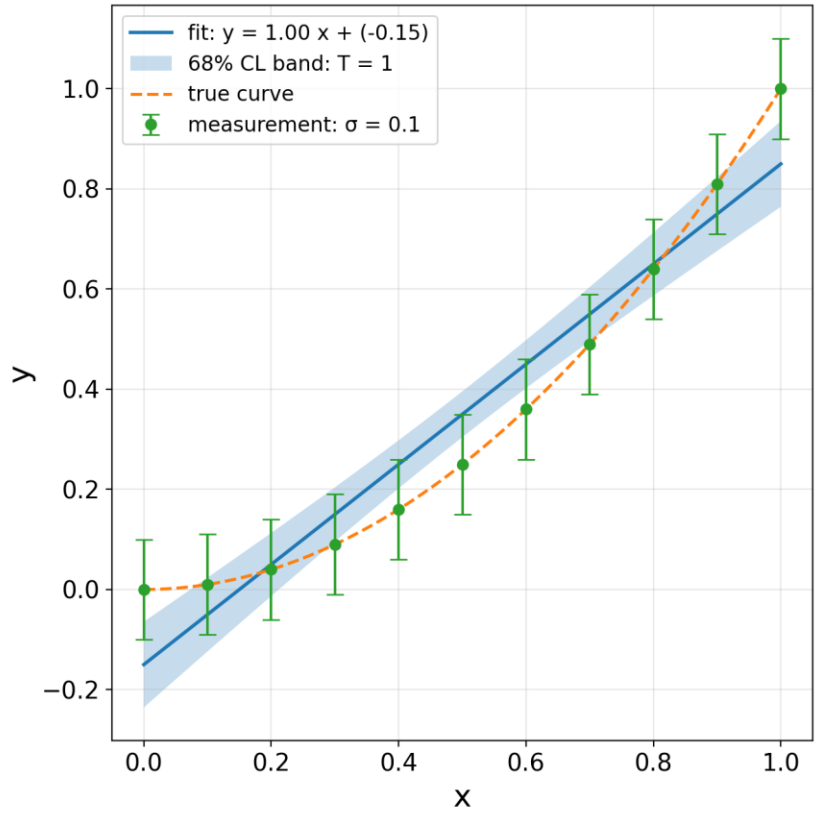


Tolerance example

Modification of χ^2 statistics



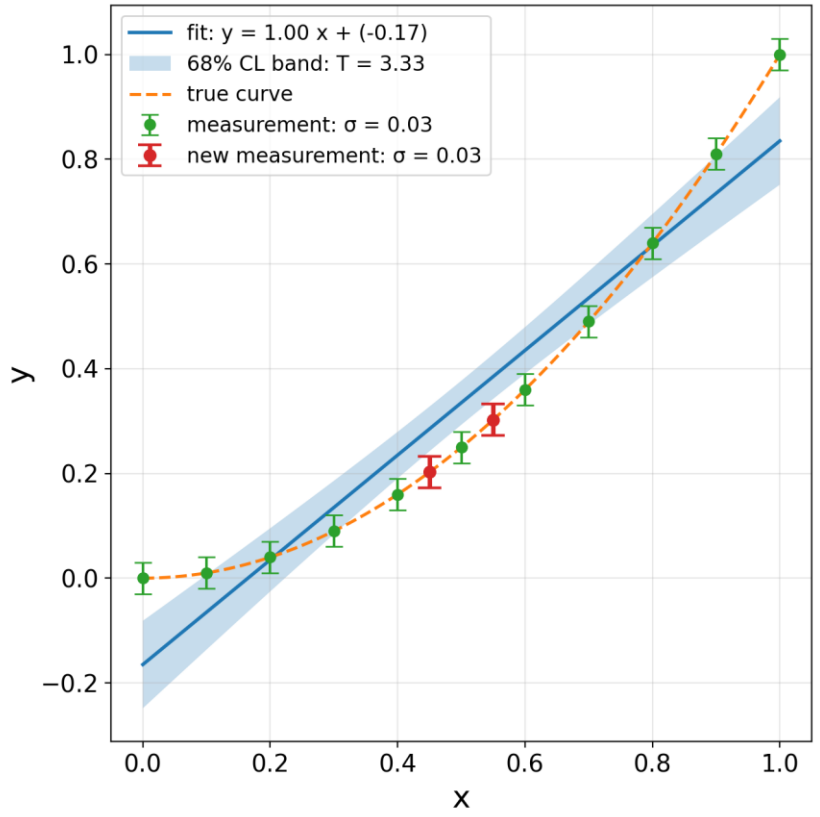
Inflation of data uncertainties



- They are just different interpretations
- Resulting in same fit result

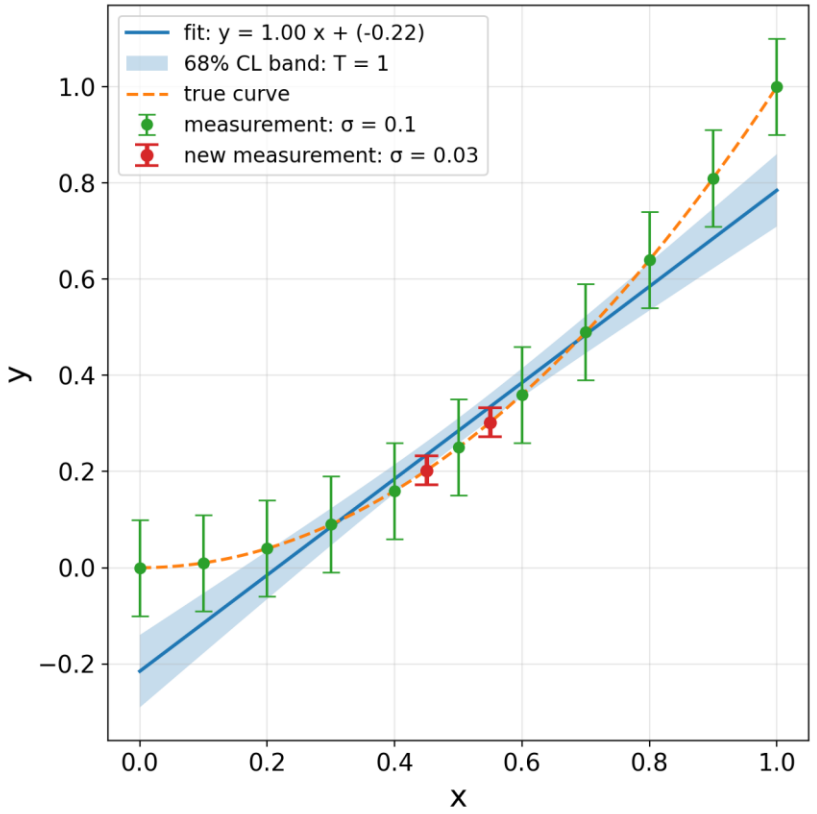
Tolerance example: adding new data

Modification of χ^2 statistics



- Old and new measurements with same power
- Less deviation at high and low x

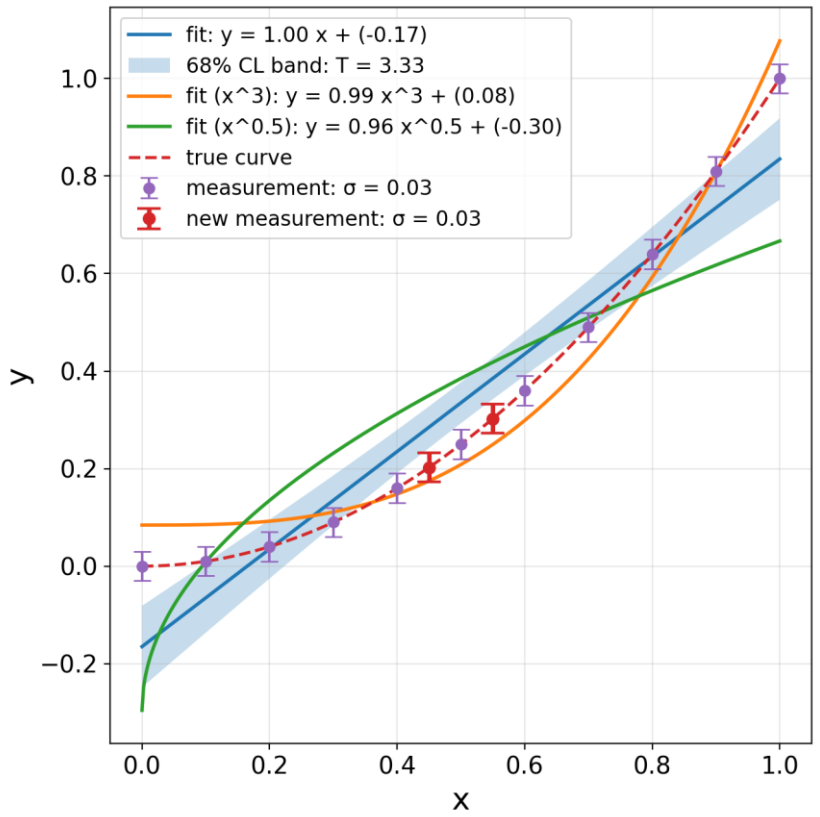
Inflation of data uncertainties



- Stronger constraint from new measurements
- More close to true curve at the region of interest (0.4-0.6)

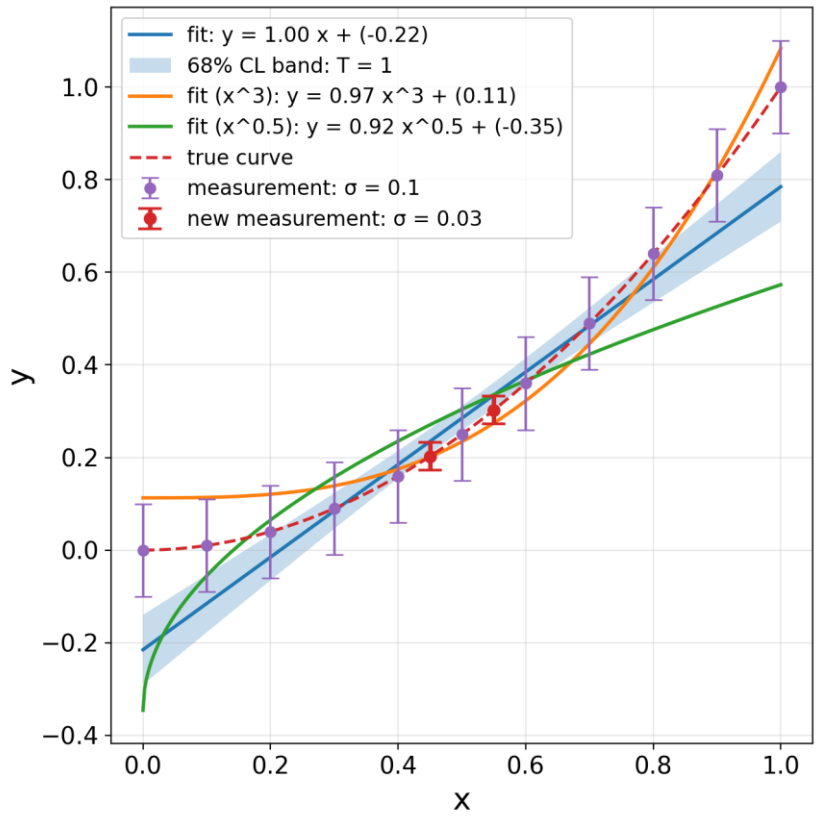
Tolerance example

Modification of χ^2 statistics



- Less parameterization dependence at high and low x

Inflation of data uncertainties



- Less parameterization dependence at the region of interest