



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

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Abstract

We review the current status and techniques used in precision measurements of the effective leptonic weak mixing angle $\sin^2 \theta_{\text{eff}}^\ell$ (a fundamental parameter of the Standard Model (SM)) in the region of the Z pole with emphasis on hadron colliders. We also build on these techniques to extract the most precise single measurement to date of $\sin^2 \theta_{\text{eff}}^\ell$ from a new analysis of the published forward-backward asymmetry (A_{FB}) in Drell-Yan dilepton production in proton-proton collisions at a center of mass energy of 13 TeV measured by the CMS collaboration at the large hadron collider. The uncertainty in $\sin^2 \theta_{\text{eff}}^\ell$ published by CMS is dominated by uncertainties in Parton Distribution Functions (PDFs), which are reduced by PDF profiling using the dilepton mass dependence of A_{FB} . Our new extraction of $\sin^2 \theta_{\text{eff}}^\ell$ from the CMS values of A_{FB} includes profiling with additional new CMS measurements of the W-boson decay lepton asymmetry, and W/Z cross section ratios. We obtain the most precise single measurement of $\sin^2 \theta_{\text{eff}}^\ell$ to date of 0.23156 ± 0.00024 , which is in excellent agreement with the SM prediction of 0.23161 ± 0.00004 . We also discuss outlook for future measurements at the LHC including more precise measurements of $\sin^2 \theta_{\text{eff}}^\ell$, a measurement of $\sin^2 \theta_{\text{eff}}^\ell$ for b-quarks in the initial state, and a measurement of the running of $\sin^2 \theta^{\text{MS}}(\mu)$ up to 3 TeV.

© To be submitted for publication by Elsevier Ltd. (*In a Physics Reports collection of papers on Electroweak Precision Measurements, edited by Costas Vellidis, Franco Bedeschi, Michael Ramsey-Musolf, Doreen Wackeroth, and Ashutosh Kotwal*)

Keywords: Precision measurements of weak mixing angle, Standard Model.

1. Introduction

The weak mixing angle $\sin^2 \theta_W$ is a fundamental parameter of the Standard Model (SM) of particle physics. In the on-shell scheme, $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$, where M_W and M_Z are the masses of the W and Z bosons, respectively. The effective leptonic weak mixing angle $\sin^2 \theta_{\text{eff}}^\ell$ (which can be expressed in terms of $\sin^2 \theta_W$ with a radiative correction factor) is the quantity more directly extracted from experiment.

In the SM $\sin^2 \theta_W$, $\sin^2 \theta_{\text{eff}}^\ell$ and M_W are predicted to very high accuracy by using the experimental values of M_Z , the Fermi constant, the fine structure constant, the mass of Higgs boson, the quark masses, and the value of the Quantum Chromodynamics (QCD) strong coupling (α_s) at M_Z . The predictions of the 2025 SM fit[1, 2] are

$\sin^2 \theta_{\text{eff}}^{\ell} = 0.23161 \pm 0.00004$, and $M_W = 80.3560 \pm 0.0050$ GeV. The two most precise measurements of M_W are in disagreement with each other. The measurement by the CDF collaboration [3] of 80.4335 ± 0.0094 GeV is about 9 standard deviations higher than the SM value, and the measurement by the CMS collaboration [4] of 80.3602 ± 0.0099 GeV is in good agreement with the SM. The CDF measurement of M_W can be accommodated by introducing new physics processes beyond the SM. For example, using the CDF measurement of M_W as input a Two Higgs Doublet Model [5] (2HDM) predicts $\sin^2 \theta_{\text{eff}}^{\ell} = 0.23110 \pm 0.00010$.

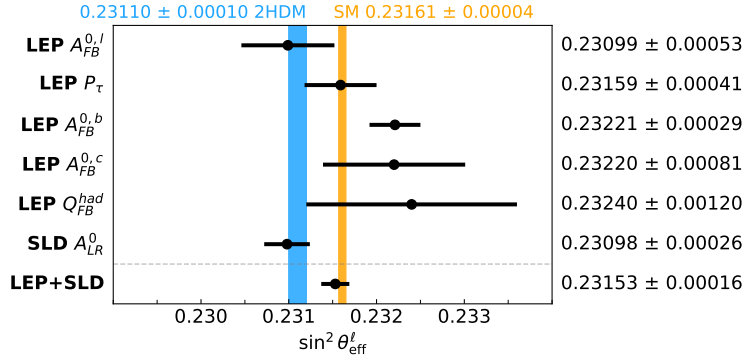


Figure 1. Measurements of $\sin^2 \theta_{\text{eff}}^{\ell}$ in electron colliders (LEP, SLD) [6] compared to the prediction of the 2025 SM global fit [1, 2]. Also shown is the prediction of the Two Higgs Doublet Model [5] corresponding to the CDF M_W value [3] (80.4335 ± 0.0094 GeV). The average of all six different LEP/SLD measurements is 0.23153 ± 0.00016 , which is in excellent agreement with the SM value. However, the χ^2 is 11.5/5(dof) which may be from systematic errors which are not accounted for.

CERN, and a value of 0.23098 ± 0.00026 from the measurement of the asymmetry of Z boson production cross sections for left-handed and right-handed electrons (A_{LR}) by the SLD experiment at SLAC. It is interesting to note that the SLD A_{LR} measurement of $\sin^2 \theta_{\text{eff}}^{\ell}$ is lower than the SM prediction and is more consistent with the predictions of 2HDM, while the LEP measurement from the b-quark forward-backward asymmetry ($A_{FB}^{0,b}$) is higher than the SM prediction. The average of all six different measurements of $\sin^2 \theta_{\text{eff}}^{\ell}$ at LEP and SLD (shown in Fig.1) is 0.23153 ± 0.00016 which is in excellent agreement with the SM value. However, the χ^2/ndf is 11.5/5 which may be from systematic errors which are not accounted for. In addition to A_{LR} and $A_{FB}^{0,b}$ the other four measurements shown in Fig.1 are extracted from: $A_{FB}^{0,l}$ (which is the average from $A_{FB}^{0,e}$, $A_{FB}^{0,\mu}$, and $A_{FB}^{0,\tau}$), P_{τ} (parity violation in τ decays), $A_{FB}^{0,c}$ and A_{FB}^{had} .

The measured asymmetry of b-quarks in the final state is a product of quark and electron asymmetries $A_{FB}^{0,b} = A_e A_b$. Here A_e is sensitive to $\sin^2 \theta_{\text{eff}}^{\ell}$ while A_b is rather insensitive (by a factor of 100) to SM parameters. The deviation of $A_{FB}^{0,b}$ from the SM prediction is either a fluctuation, or the consequence of new physics [6]. Therefore, new precision measurements $\sin^2 \theta_{\text{eff}}^{\ell}$ in processes involving both light and heavy quarks in the initial or final state are an important tool in searches for physics beyond the SM.

3. $\sin^2 \theta_{\text{eff}}^{\ell}$ measurements in hadron colliders

With recent advances in experimental and analysis techniques [9–11], measurements of $\sin^2 \theta_{\text{eff}}^{\ell}$ at hadron colliders extracted from the forward-backward asymmetry in Drell-Yan dilepton events have become competitive with the published measurements by e^+e^- collider experiments. In this paper we report on the extraction of the world's best measurements of $\sin^2 \theta_{\text{eff}}^{\ell}$ from an updated analysis of published asymmetries of Drell-Yan dilepton events at the Large Hadron Collider (LHC) as described below.

In Drell-Yan production of dilepton events in proton-proton collisions at the LHC the positive z direction is defined as the direction of the rapidity of the dilepton pair. The angular distribution of the negative lepton (integrated over all Z boson transverse momenta) in the Collins-Soper frame [12] is given by the following equation:

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

The weak mixing angle has been measured at low energy several fixed target experiment [7, 8] including atomic parity violation, polarized electron scattering, and neutrino experiments. However, the most precise extractions of $\sin^2 \theta_{\text{eff}}^{\ell}$ are from measurements of asymmetries in the region of the Z pole in e^+e^- and hadron colliders.

2. $\sin^2 \theta_{\text{eff}}^{\ell}$ measurements in e^+e^- colliders

The two most precise measurements [6] of $\sin^2 \theta_{\text{eff}}^{\ell}$ in e^+e^- colliders differ by 3.2 standard deviations. A value of 0.23221 ± 0.00029 from the measurements of the b-quark forward-backward asymmetry $A_{FB}^{0,b}$ at the LEP experiments at

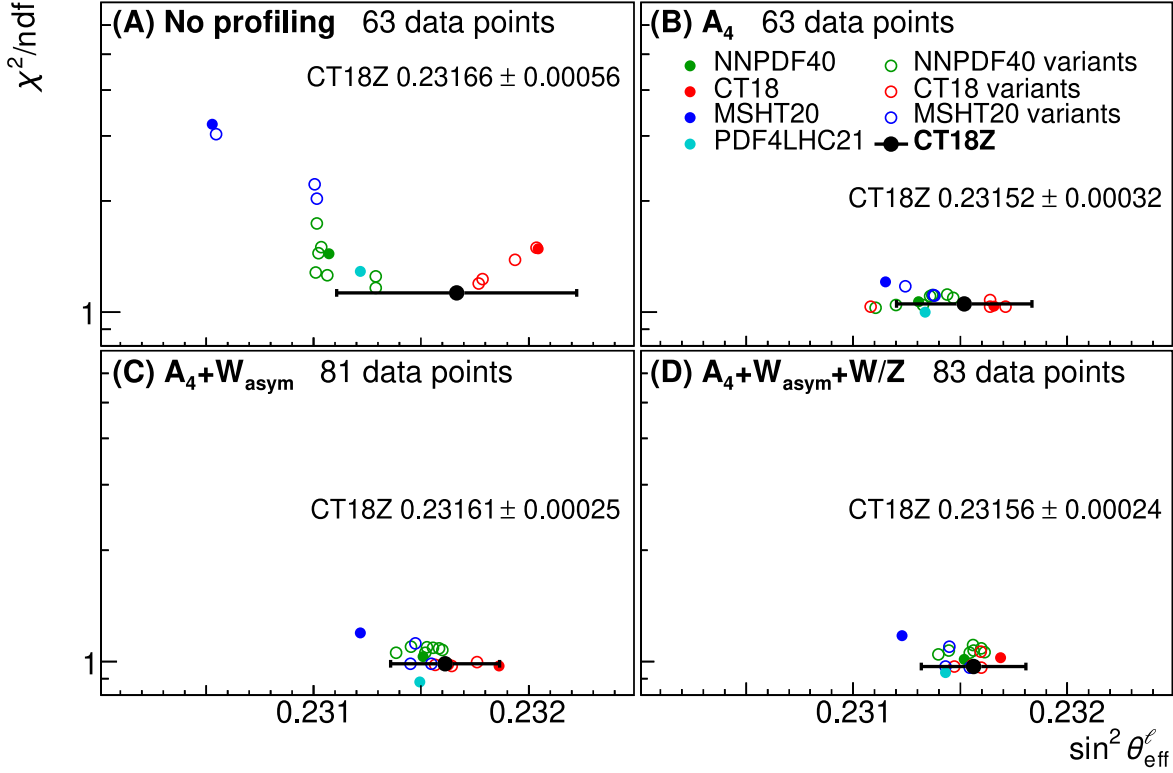


Figure 2. Extracted values of $\sin^2 \theta_{\text{eff}}^{\ell}$ from the 13 TeV CMS A_4 data for 19 different PDF sets on the horizontal axis. (A) Before profiling. (B) After profiling with A_4 . (C) After profiling with A_4 plus W decay lepton asymmetry. (D) After profiling with A_4 plus W decay lepton asymmetry plus W/Z cross section ratios. The vertical axis shows the χ^2 values of the fits divided by the number of degrees of freedom ($N_{\text{data}} - 1$), where one degree of freedom corresponds to the free parameter $\sin^2 \theta_{\text{eff}}^{\ell}$.

where A_0 and A_4 are functions of the rapidity (y) and mass (M) of the dilepton pair. When integrating over $\cos \theta$ (full acceptance) $A_{\text{FB}}^{\text{full}} = (3/8)A_4$.

4. The CMS measurement of $\sin^2 \theta_{\text{eff}}^{\ell}$ at 13 TeV

Recently, the CMS collaboration at the LHC reported[13] on a measurement of $\sin^2 \theta_{\text{eff}}^{\ell}$ (0.23152 ± 0.00031) extracted from the forward-backward asymmetry A_{FB} in Drell–Yan dilepton production in proton-proton collisions at a center of mass energy $\sqrt{s} = 13$ TeV with an integrated luminosity of 138 fb^{-1} . The statistical error in this measurement is ± 0.00010 . The experimental systematic error is small because of the precise lepton momentum calibration[9] and the use of the angular weighted[10] forward-backward asymmetry A_{FB}^w . The experimental systematic errors in acceptance and efficiencies mostly cancel in the angular weighted A_{FB}^w , which can be regarded as the detector-level equivalent of full-acceptance asymmetry.

The dominant source of error in the CMS measurements originates from uncertainties in the Parton Distribution Functions (PDFs) of the proton. The three major PDF sets are from the CTEQ [14–17] (Coordinated Theoretical-Experimental Project on QCD) collaboration, NNPDF [18–22] (Neural Network Parton Distribution Function) collaboration and MSHT [23–27] (Mass Scheme Hessian Tolerance) collaboration. The PDF uncertainties in each PDF set, as well as the differences between $\sin^2 \theta_{\text{eff}}^{\ell}$ values extracted using different PDF sets, are significantly reduced by using the A_4 PDF re-weighting/profiling technique (first proposed in [11]) to constrain PDFs as described below. In the CMS analysis the CT18Z_{NNLO} [14] PDF was chosen as the nominal PDF because the extracted value of $\sin^2 \theta_{\text{eff}}^{\ell}$ was in the middle of those obtained with the other PDF sets and provided the best coverage of their central values.

In addition to the extraction of $\sin^2 \theta_{\text{eff}}^{\ell}$ at 13 TeV, the CMS collaboration reported on the extraction of the mass and rapidity dependent angular coefficient A_4 ($= 8A_{\text{FB}}/3$). The extraction and unfolding of A_4 requires very good modeling

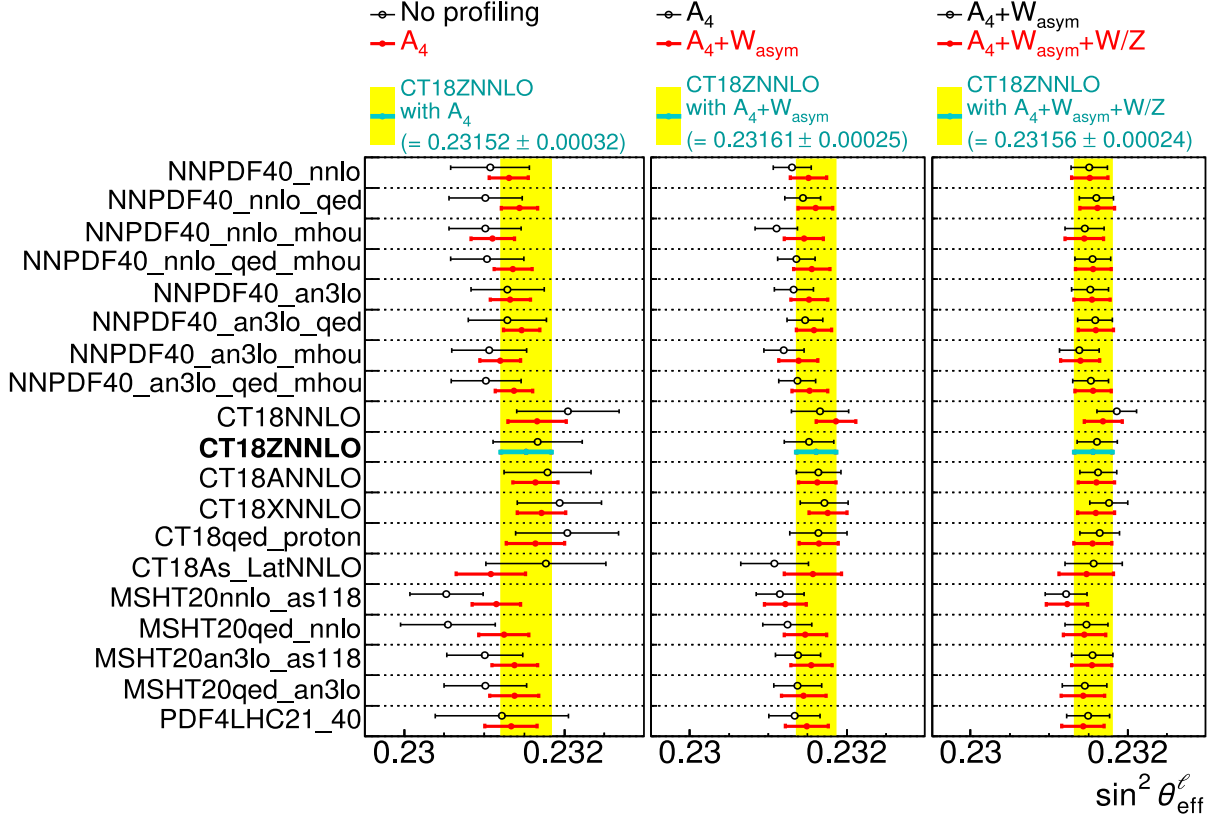


Figure 3. Values of $\sin^2 \theta_{\text{eff}}^l$ (extracted with 19 different PDF sets) before profiling compared to values after profiling with the CMS 13 TeV A_4 data (63 data points, left panel) and by also including the CMS W_{asym} measurement[28] at 13 TeV (18 additional data points, middle panel) and then by also including the CMS measurement of the W and Z cross section ratio[29] at 13 TeV (1 additional point, right panel).

of the detector acceptance, efficiencies and resolutions. If the modeling of efficiencies, acceptance and resolutions are correct, then the extracted value of $\sin^2 \theta_{\text{eff}}^l$ from the unfolded A_4 should be in agreement with the value extracted from the angular weighted A_{FB}^w . This consistency has been achieved in the CMS analysis. The unfolded values of A_4 can then be used in future extractions of more precise values of $\sin^2 \theta_{\text{eff}}^l$ by combination with future hadron collider measurements of A_4 , or by including additional PDF constraints from new measurements as is done in this paper.

5. PDF re-weighting/profiling

The PDF re-weighting/profiling technique to constrain PDFs[11] primarily relies on including the rapidity and dilepton mass dependence of A_4 to constrain PDFs in the analysis. This is because at the region of the Z pole, A_4 is sensitive to the vector couplings, which depend on $\sin^2 \theta_{\text{eff}}^l$, and also to PDFs. At higher and lower dilepton mass A_4 is sensitive to PDFs, but much less sensitive to $\sin^2 \theta_{\text{eff}}^l$. Consequently, A_4 measurements in the high and low mass regions provides additional constraints on PDFs.

When PDF replicas are used in the analysis, the PDF constraints are implemented by the re-weighting of a large number of PDF replicas. PDF replicas with predictions of A_4 which are in disagreements with the measurements in the high and low mass regions are assigned lower weights. The re-weighting implementation was first used to reduce PDF errors in the measurement of $\sin^2 \theta_{\text{eff}}^l$ by the CDF experiment at the Tevatron[30–32], and then by the CMS experiment at 8 TeV[33]. When Hessian PDFs are used, the technique is implemented by profiling the eigenvectors of the Hessian PDFs. The profiling implementation was used in the preliminary measurement of $\sin^2 \theta_{\text{eff}}^l$ by the ATLAS experiment at 8 TeV[34], and in the recent CMS measurement of $\sin^2 \theta_{\text{eff}}^l$ at 13 TeV[13]. The two implementations are equivalent and Hessian PDFs can readily be used to generate replica PDFs.

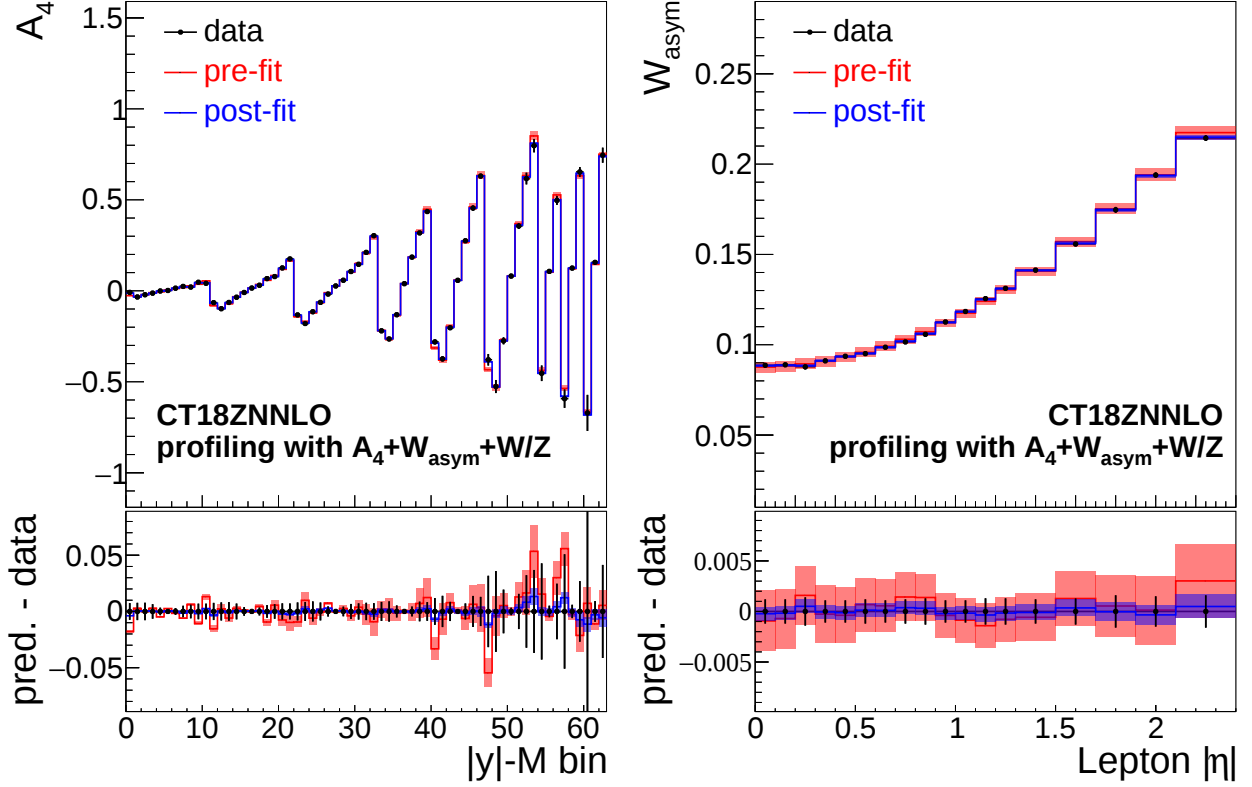


Figure 4. Comparison of the predictions of CT18ZNNLO for $A_4(|y|, m)$, and $W_{asym}(|\eta|)$ before (red) and after (blue) full profiling.

6. A new analysis of the published CMS 13 TeV measurements of A_4

In this section, we present a new analysis based on the published CMS measurements of A_4 at 13 TeV. As a starting point, we reproduce the original CMS analysis, where the dilepton rapidity and mass dependence of A_4 was used to profile PDFs and extract $\sin^2 \theta_{\text{eff}}^\ell$ with the open-source code xFITTER[35, 36], as done by CMS. Then, we extend this approach by including additional CMS measurements of W and Z boson production in the profiling. For this extended analysis, we adopt the CT18ZNNLO PDF set as the nominal PDF, consistent with the CMS analysis, and we increase the number of investigated PDF sets from 14 to 19.

6.1. Reproduction of the CMS 13 TeV analysis

As described in the CMS publication[13] the value of $\sin^2 \theta_{\text{eff}}^\ell$ is determined in a profiling analysis, by minimizing the χ^2 function

$$\chi^2(\beta_{\text{exp}}, \beta_{\text{th}}) = \frac{(\sigma_i^{\text{exp}} + \sum_j \Gamma_{ij}^{\text{exp}} \beta_{j,\text{exp}} - \sigma_i^{\text{th}} - \sum_k \Gamma_{ik}^{\text{th}} \beta_{k,\text{th}})^2}{\Delta_i^2} + \sum_j \beta_{j,\text{exp}}^2 + \sum_k \beta_{k,\text{th}}^2. \quad (2)$$

The correlated experimental (theoretical) uncertainties are included in the nuisance vector β_{exp} (β_{th}) and their impact on the measured distributions (theory predictions) is described by the matrix Γ^{exp} (Γ^{th}). The index i runs over all N_{data} data points (63 for A_4 profiling) of the $(|y|, M)$ double-differential A_4 measurement, whereas the j and k indices correspond to the experimental and theoretical uncertainty nuisance parameters, respectively. The measurements and the uncorrelated experimental uncertainties are represented by σ_i^{exp} and Δ_i , respectively, whereas the theoretical predictions are denoted by σ_i^{th} . The information in the experimental covariance matrix of the double-differential A_4 measurement is included in the Γ^{exp} matrix.

The theoretical prediction is obtained with the POWHEG 2.0 event generator at multi-scale improved next-to-next-to-leading order (MiNNLO_{PS}) accuracy in QCD [37], matched to PYTHIA 8.2 for parton showering. Photon

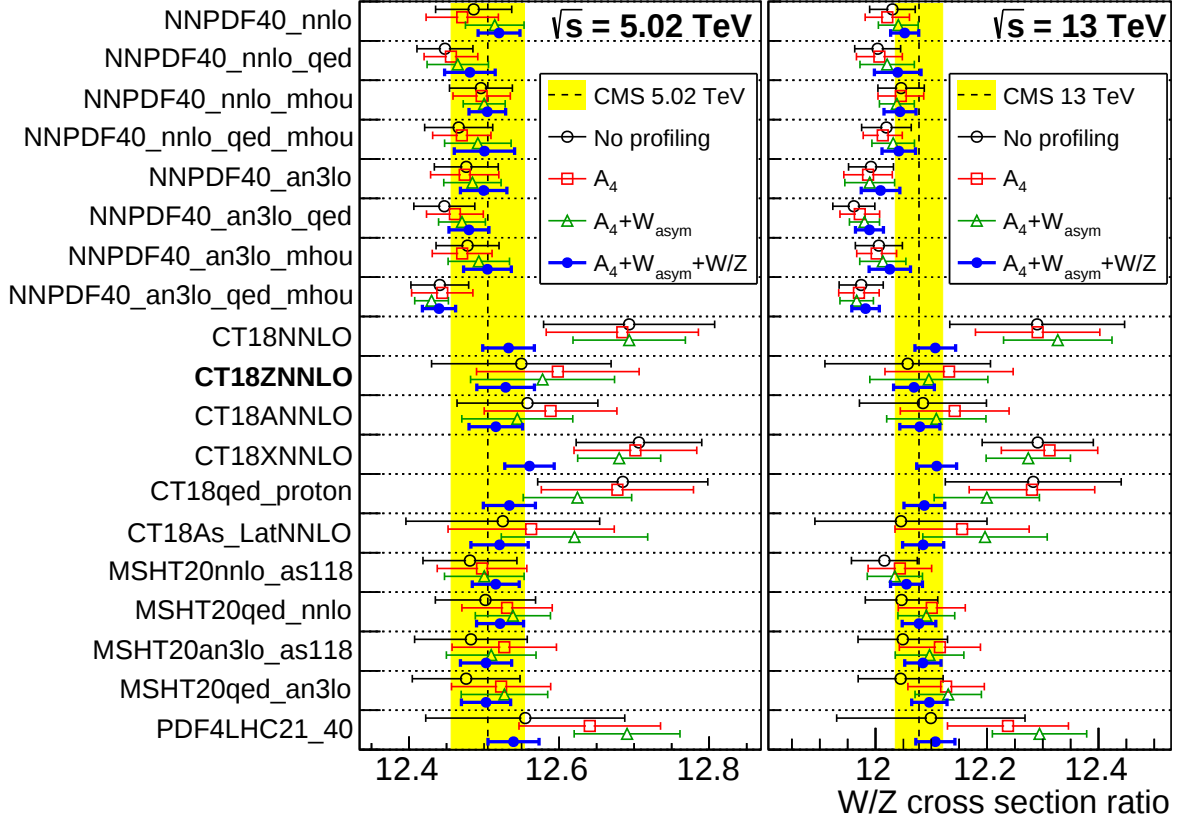


Figure 5. Comparison of the predictions of 19 PDFs sets with various levels of profiling to the W/Z cross section ratios measured by CMS at 5.02 TeV and 13 TeV

final-state radiation is simulated with the PHOTOS 2 package [38]. In addition, next-to-leading order virtual weak corrections are included using POWHEG-Z_{EW} [39–41], and the Z-boson transverse-momentum spectrum is reweighted to data, following the original CMS analysis.

The theoretical uncertainty includes contributions from the missing higher-order QCD and Electroweak (EW) corrections, as evaluated with POWHEG-Z_{EW} and PDF uncertainties by using grids generated at NLO with MADGRAPH5-AMC@NLO [42] and PINEAPPL [43, 44]. The matrix Γ^{th} includes nuisance parameters reflecting the missing higher-order EW corrections, the PDF Hessian uncertainties, and the $\sin^2 \theta_{\text{eff}}^{\ell}$ parameter itself, which is left free in the fit. The impact of missing higher-order QCD corrections is estimated by repeating the fit for each of the six scale variations, and the maximum deviation from the central result is taken as the uncertainty.

Values of $\sin^2 \theta_{\text{eff}}^{\ell}$ (in units of 10^{-5}) extracted *before and after profiling* with the 13 TeV A_4 distribution are shown in Table 1 for 19 PDF sets. Most of the PDFs are Next-to-Next-to-Leading-Order QCD (NNLO), and some are Approximate-Next-to-Next-to-Next-to LO (an3lo). PDF sets labeled “qed” account for QED (Quantum Electrodynamics) effects and include photon distributions. The NNP40 label “mhou” indicates that these PDFs sets include corrections for “missing higher-order uncertainties”. The MSHT and NNP40 PDF sets assume asymmetric sea strange quark densities. The CTEQ PDF sets (except for CT18As PDF) assume symmetric strange quark densities.

The total uncertainties in Table 1 include contributions from statistical, experimental systematic, theoretical, and PDF sources. The differences in the results obtained with the various PDF sets (*before profiling*) are mostly attributed to differences in the choices of experimental data, parameterizations and assumptions on the flavor decomposition. If there are sufficient parameters in the PDF sets, then the profiled PDFs should be able to describe all data that are used in the $\sin^2 \theta_{\text{eff}}^{\ell}$ profiling analysis with good χ^2 . The columns labeled marked “Diff. from CT18Z” show the difference between the value of $\sin^2 \theta_{\text{eff}}^{\ell}$ extracted with each of the 19 PDF sets and that obtained using the nominal CT18ZNNLO

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 θ _{eff} ^ℓ	Diff. from CT18Z	χ ²	sin ² θ _{eff} ^ℓ	Diff. from CT18Z	χ ²	sin ² θ _{eff} ^ℓ	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_as.118 [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_as.118 [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

Table 1. Values of sin² θ_{eff}^ℓ (in units of 10⁻⁵) before and after profiling with the CMS 13 TeV A₄ distribution (63 points) for 19 PDF sets. Also shown are the values extracted by including the CMS 13 TeV W-decay lepton asymmetry and the CMS W/Z cross section ratios (total of 83 points) in the profiling. The total uncertainties include contribution from statistical, experimental systematic, theoretical and PDF sources. The column marked "Diff. from CT18Z" is the difference from sin² θ_{eff}^ℓ extracted with the CT18ZNNLO PDF set. Note, the χ² values before profiling do not include PDF errors, while the χ² values after profiling include PDF errors.

PDF set.

6.2. Including W decay lepton asymmetry and W/Z cross section ratios in PDF profiling

The uncertainty in sin² θ_{eff}^ℓ is significantly reduced after profiling with A₄, but some differences between PDF sets remain. As shown in [11], including the W boson decay lepton asymmetry measurements (W_{asym}) in the profiling provides additional constraints on the d/u ratio, leading to a further reduction of the PDF uncertainty in sin² θ_{eff}^ℓ. Moreover, some CT18 PDF sets lack sufficient constraints on the strange-quark distribution at high energy scales, resulting in systematically lower strange-quark densities compared to other PDFs and thereby predicting a larger effective weak mixing angle. Incorporating the W/Z cross section ratios can provide further constraints on the strange-quark distribution, helping to reduce these discrepancies.

Therefore, we perform an updated analysis of the published CMS 13 TeV A₄ data (63 data points) and also include the recent CMS W_{asym} measurement[28] at 13 TeV (18 additional data points) as well as the CMS measurement of the W and Z fiducial cross section ratios[29] at 5.02 TeV (12.505 ± 0.037_{stat} ± 0.032_{syst}) and 13 TeV (12.078 ± 0.028_{stat} ± 0.032_{syst})(2 additional data points). The results are shown in the columns of Table 1 and in Figures 2, 3, 4, and 5.

Extracted values of sin² θ_{eff}^ℓ from the 13 TeV CMS A₄ data for different PDF sets are shown on the horizontal axis of each of the four panels in Fig. 2. The vertical axis show the values of χ² normalized to the number of degrees of freedom, ndf = N_{data} - 1, where the subtraction accounts for the single free parameter sin² θ_{eff}^ℓ. Shown are the values before profiling (panel A, 63 data points). After profiling with A₄ (panel B, 63 data points), after profiling with A₄ and also with W decay lepton asymmetry (panel C, 81 data points), and after profiling with A₄ and the W decay lepton asymmetry and also the W/Z cross section ratios (panel D, 83 data points).

As seen in Table 1 (and Figures 2 and 3) after A₄ profiling the error in the extracted value of sin² θ_{eff}^ℓ with the nominal CT18ZNNLO PDF set is reduced from 0.00056 to 0.00032. By also including the W decay lepton asymmetry and the W/Z cross section ratios the uncertainty for the nominal CT18ZNNLO is reduced to 0.00024.

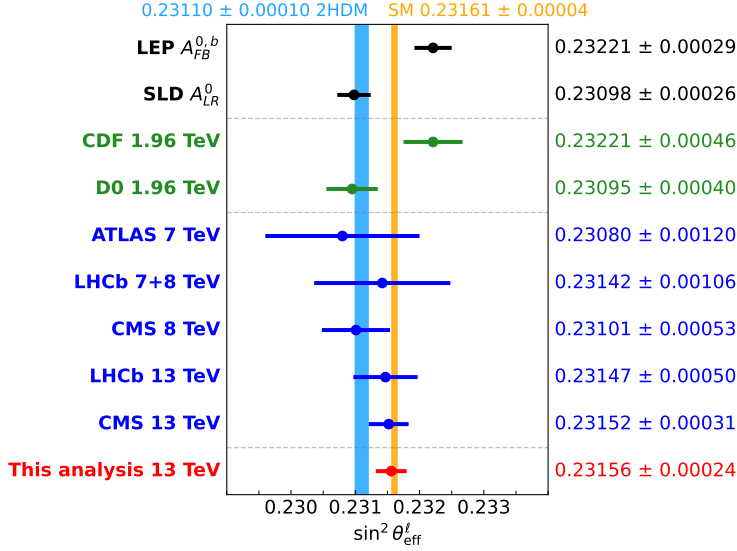


Figure 6. Comparison of $\sin^2 \theta_{\text{eff}}^l$ extracted this analysis (labeled "This analysis 13 TeV") with previous measurements [6, 13, 32, 33, 46–49] and the prediction of the 2025 SM global fit [1, 2]. Also shown is the prediction of the Two Higgs Doublet Model[5] corresponding to the CDF M_W value[3] (80.4335 ± 0.0094 GeV).

measurement[28] at 13 TeV (18 additional data points, middle panel) and then by also including the CMS measurement of the W and Z cross section ratios (2 additional points, right panel).

Comparisons of the predictions of CT18ZNNLO for $A_4(|\eta|, m)$, and $W_{\text{asym}}(|\eta|)$ before (red) and after (blue) full profiling are shown in Fig. 4. After profiling there is excellent agreement between the PDF predictions and the $A_4(|\eta|, m)$ and $W_{\text{asym}}(|\eta|)$ measurements. And comparisons of the predictions of 19 PDF sets with various levels of profiling to the CMS measured W/Z cross section ratios is shown in Fig. 5.

Fig. 6 shows a comparison of $\sin^2 \theta_{\text{eff}}^l$ extracted in this analysis with the nominal CT18ZNNLO PDF set (Labeled "This analysis 13 TeV") to previous measurements [6, 13, 32, 33, 46–49]. Also shown are the predictions of the 2025 SM global fit [1, 2] and the prediction of the Two Higgs Doublet Model[5] corresponding to the CDF M_W value[3] of 80.4335 ± 0.0094 GeV.

In conclusion, by including the new CMS 13 TeV W boson decay lepton asymmetry and the W/Z cross section ratios in the profiling analysis, we extract the best single measurement to date of $\sin^2 \theta_{\text{eff}}^l = 0.23156 \pm 0.00024$. After profiling with the CMS 13 TeV A_4 , W_{asym} and the W/Z cross section ratios, the extracted values of $\sin^2 \theta_{\text{eff}}^l$ for 18 other PDF sets are within one standard deviation of the nominal CT18ZNNLO value. The value is in excellent agreement with the Standard Model value of $\sin^2 \theta_{\text{eff}}^l = 0.23161 \pm 0.00004$ and is 1.8 standard deviations higher than prediction of 2HDM of $\sin^2 \theta_{\text{eff}}^l = 0.23110 \pm 0.00010$.

7. Outlook for the future

(1) As of Oct. 2025, the run II integrated luminosity delivered by the LHC at 13.6 TeV is 300 fb^{-1} . Consequently, with the addition of the 13.6 TeV data the statistical errors are expected to be reduced by a factor of $\sqrt{(140 + 300)/140}$. Using CMS data at 13 and 13.6 TeV, We estimate that the uncertainty in the extracted value of $\sin^2 \theta_{\text{eff}}^l$ with the combined 13 and 13.6 TeV can be reduced to between ± 0.00019 and ± 0.00021 . Better precision can be obtained by combining with future unfolded A_4 measurements from ATLAS and LHCb.

(2) A first measurement of the mixing angle at 13 TeV for b -quarks in the initial state sample[51, 52] (i.e the $bG \rightarrow bZ$ Compton process) is currently under way by the Seoul National University/Rochester group at CMS. The expected uncertainty with the 13 TeV data sample is ± 0.00332 . The analysis needs to be done in the recoil frame

After profiling with all three W and Z measurements, the central values of $\sin^2 \theta_{\text{eff}}^l$ for 18 PDF sets (including three of the four MSHT20 PDFs sets) are within one standard deviation of the CT18ZNNLO nominal PDF value. The single profiled MSHT20 PDF set with central value which is 1.38 standard deviation low (*MSHT20nnlo.as118*) has poor χ^2 . In contrast, as shown in Table 1, the profiled *MSHT20an3lo.as118* gives the same $\sin^2 \theta_{\text{eff}}^l$ as CT18ZNNLO with good χ^2 . By including the W decay lepton asymmetry and the W/Z cross section ratios, there is hardly any difference in the extracted values of $\sin^2 \theta_{\text{eff}}^l$ between PDFs with asymmetric or symmetric strange quark distributions.

Fig. 3 shows values of $\sin^2 \theta_{\text{eff}}^l$ (extracted with 19 different PDF sets) before profiling compared to values after profiling with the CMS 13 TeV A_4 data (63 data points, left panel) and by also including the CMS W_{asym}

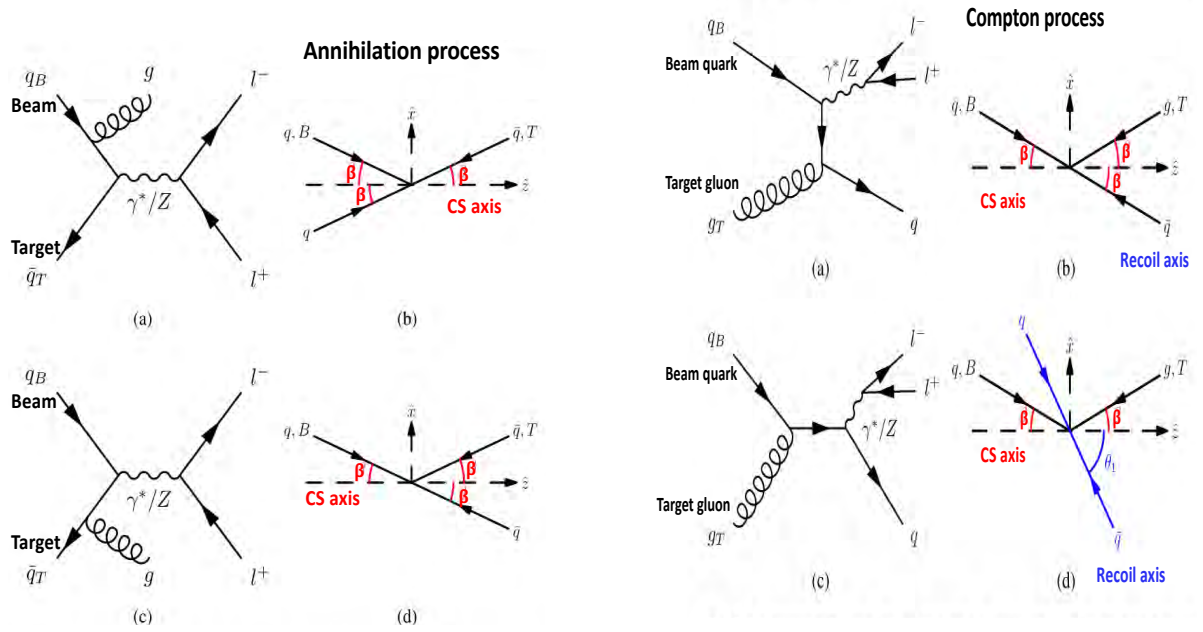


Figure 7. Left panel: The $q\bar{q}$ annihilation process. Right panel: the quark-gluon (qG) Compton process. These show that for qG process, the "recoil frame" has the correct quark direction for the z axis. (Figures from Ref. [50]).

which is illustrated in Fig.7. The expected asymmetry for dileptons in the "recoil frame" for $b\bar{g} \rightarrow bZ$ events (calculated in Ref.[53]) is shown in Fig.8. This measurement has been investigated theoretically in [53–58]. It is of interest because the two measurements of the $A_{FB}^{0,b}$ in e^+e^- colliders deviate from the SM predictions. The measurement of $A_{FB}^{0,b}$ at the Z pole at LEP of 0.0992 ± 0.0016 differs by 2.4 standard deviation from the SM prediction of 0.1030 ± 0.0002 [59]. The measurement of $A_{FB}^{0,b}$ at $\sqrt{s} = 57.8$ GeV by experiments at KEK-TRISTAN[60] of -0.57 ± 0.09 differs by 1.6 standard deviation from the SM value[61] (diluted by $b\bar{b}$ mixing[61]) of 0.43.

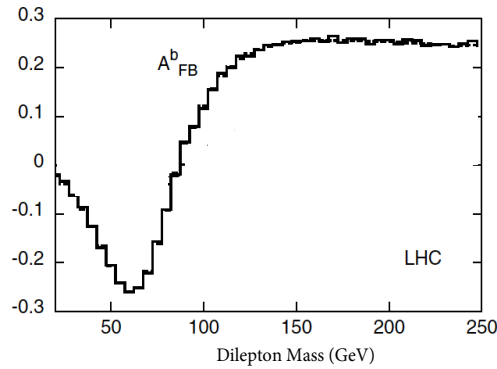


Figure 8. The expected forward-backward asymmetry of dileptons in the "recoil frame" for $b\bar{g} \rightarrow bZ$ Compton process. (figure from [53])

(3) A first measurement of the running of $\sin^2 \theta^{\overline{MS}}(\mu)$ above the Z mass (up to 3 TeV) can be extracted from the current 13 TeV run II and 13.6 TeV run III LHC data samples[62]. A Monte Carlo study[62] (shown in Fig.9) of the scale dependence of the EW mixing angle in the SM (blue line) is compared to the combined experimental measurement at $\mu = m_Z$ (violet point). The expected results are shown in black crosses (black squares) for the LHC Run3 (HL-LHC). For clarity, the Run3 and HL-LHC points are shifted to the left and right, respectively. The outer error bars represent the total expected uncertainty in $\sin^2 \theta^{\overline{MS}}(\mu)$, while the inner error bars include only statistical and experimental uncertainties (excluding PDFs, QCD and EW higher-order uncertainties). Figure taken from [62].

Further improvement in the above three measurements is expected at the high luminosity LHC (HL-LHC) for which the expected integrated luminosity is 3000 fb^{-1} .

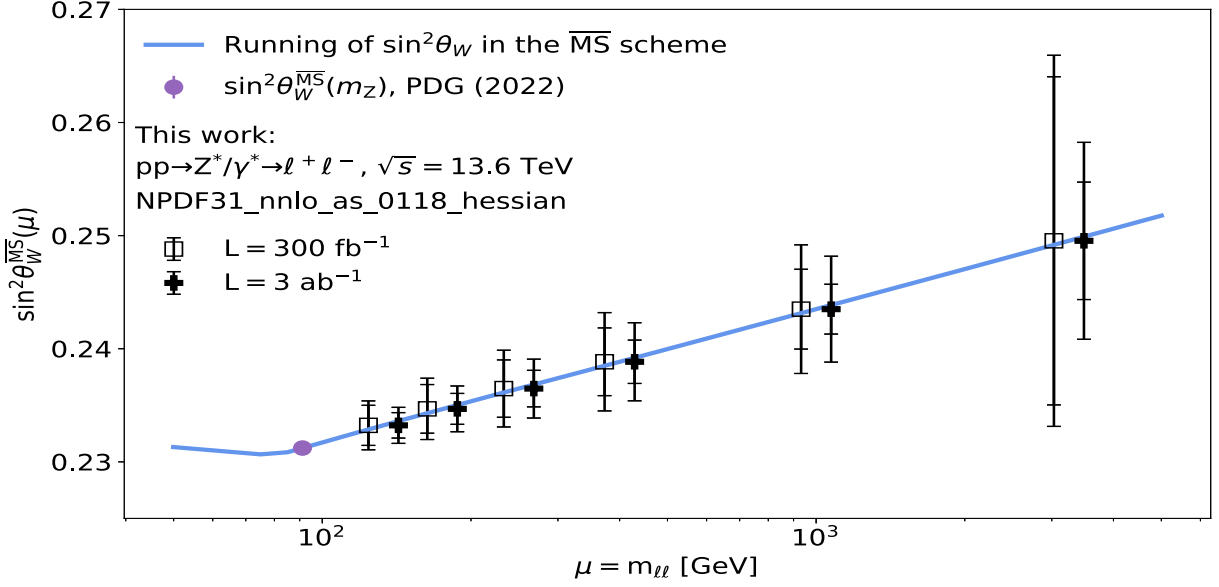


Figure 9. A Monte Carlo study of the energy scale dependence of the EW mixing angle in the SM (blue line), compared to the combined experimental measurement at $\mu = m_Z$ (violet point). The expected results are shown in black crosses (black squares) for the LHC Run3 (HL-LHC). For clarity, the Run3 and HL-LHC points are shifted to the left and right, respectively. The outer error bars represent the total expected uncertainty in $\sin^2 \theta_W^{\overline{\text{MS}}}(\mu)$, while the inner error bars include only statistical and experimental uncertainties (excluding PDFs, QCD and EW higher-order uncertainties). Figure taken from [62].

8. Acknowledgements

Research supported by the U.S. Department of Energy under University of Rochester grant number DE-SC0008475 and by MSIP and NRF (Republic of Korea).

Appendix A. Effects of PDF profiling with CMS A_4 , W_{asym} and W/Z ratio measurements

This appendix provides additional details supporting the improved extraction of the weak mixing angle presented in Section 6. The improved extraction is achieved by incorporating additional W and Z boson data, which constrain the parton distribution functions in the region around $Q \approx M_Z$ and $x = 0.001$ – 0.1 . This Appendix explains how profiling with CMS measurements influences the PDFs and complements the discussion in the main text.

The most relevant PDF quantities for the mixing angle extraction are the valence-quark distributions, defined as $d_v = d - \bar{d}$ and $u_v = u - \bar{u}$, as the mixing angle measurement in proton-proton collisions relies on the asymmetry in the momentum distributions between quarks and antiquarks. Although the momentum difference mainly arises from up and down quarks, some PDF collaborations allow asymmetric distribution for other flavors as well. Therefore, for consistent comparison across different PDFs, it is useful to examine the $D - \bar{D}$ and $U - \bar{U}$ distributions, where $D = d + s + b$ and $U = u + c$. Figures A.10 and A.11 show how the $D - \bar{D}$ and $U - \bar{U}$ PDFs are constrained before and after profiling, illustrating how different PDFs converge after profiling with additional W and Z boson measurements.

It is also informative to examine the $s + \bar{s}$ PDF, which is primarily constrained by the W/Z cross section ratio measurements, as shown in Figure A.12. The CT18 PDF exhibits a smaller $s + \bar{s}$ component than the other PDF sets because the global PDF fit does not include some LHC data that constrain the strange quark at high Q^2 . This results in a higher mixing angle extracted with CT18. The inclusion of the W/Z ratio measurement brings the $s + \bar{s}$ PDF in CT18 to better agreement with the other PDFs and results in a value of the mixing angle which is closer to that obtained with CT18Z. The PDF nuisance parameter shifts after profiling are shown in Table 2, 3 and 4 for CT18ZNNLO, NNPDF40 and PDF4LHC21, respectively.

Global PDFs are obtained by fitting a wide range of experimental data, covering Q values from roughly 1 GeV to several TeV and x values between 10^{-4} and 1, through χ^2 minimization. The uncertainties of the fitted parameters are

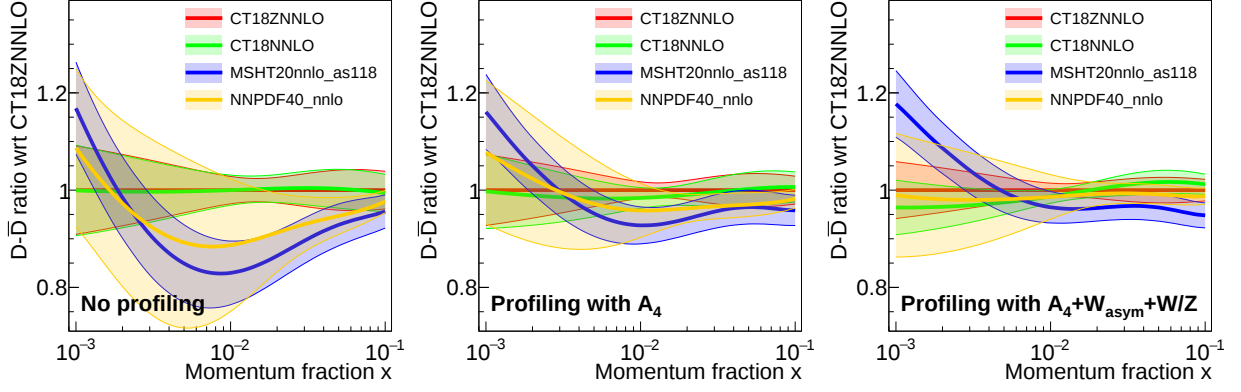


Figure A.10. Ratios of the $D - \bar{D}$ distributions with respect to CT18Z for several PDF sets at $Q = M_Z$. The left panel shows the results without profiling, the middle panel includes profiling with A_4 measurement, and the right panel includes profiling with A_4 , W_{asym} , and W/Z measurements.

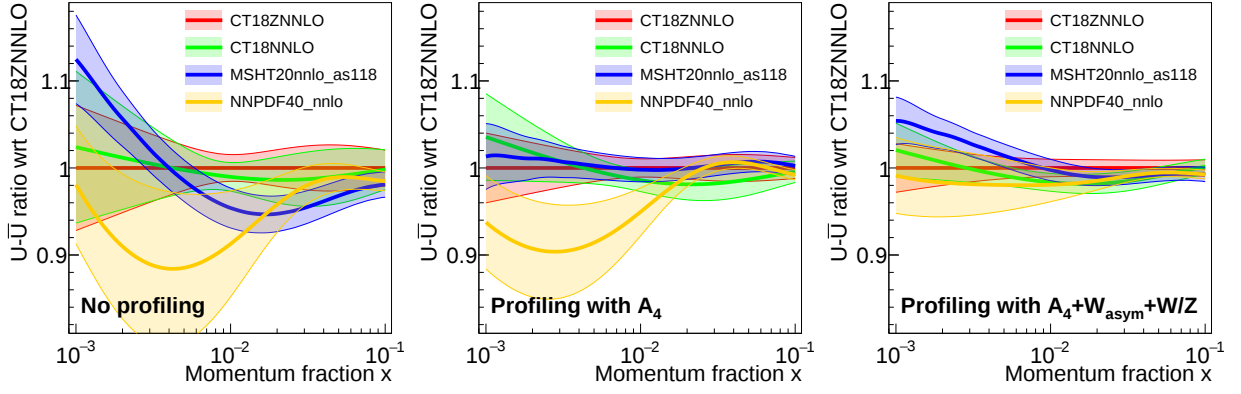


Figure A.11. Ratios of the $U - \bar{U}$ distributions with respect to CT18Z for several PDF sets at $Q = M_Z$. The left panel shows the results without profiling, the middle panel includes profiling with A_4 measurement, and the right panel includes profiling with A_4 , W_{asym} , and W/Z measurements.

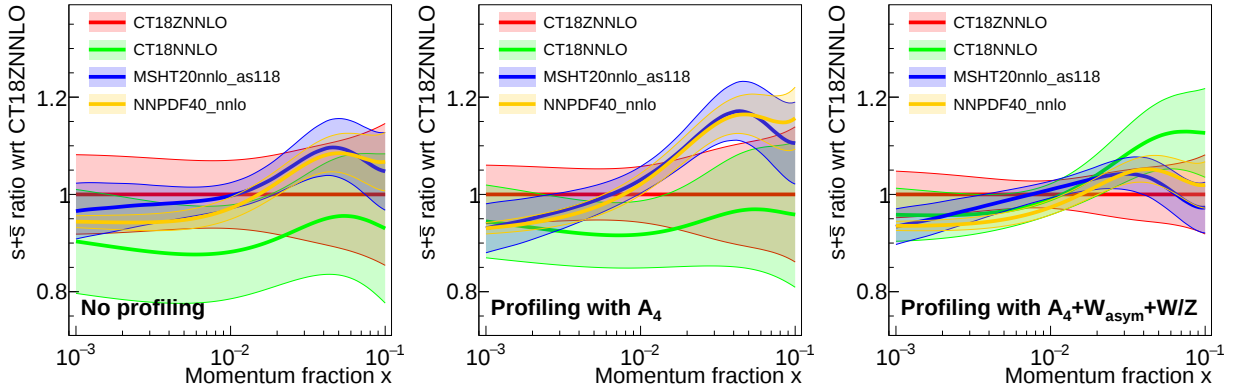


Figure A.12. Ratios of the $s + \bar{s}$ distributions with respect to CT18Z for several PDF sets at $Q = M_Z$. The left panel shows the results without profiling, the middle panel includes profiling with A_4 measurement, and the right panel includes profiling with A_4 , W_{asym} , and W/Z measurements.

Index	Shift	Uncertainty	Index	Shift	Uncertainty
1	-0.3504	0.8694	16	0.0565	0.8568
2	0.2717	0.8387	17	0.3874	0.8994
3	0.7898	0.9109	18	-0.6933	0.9113
4	0.1787	0.9624	19	-0.1395	0.7319
5	0.3444	0.9351	20	-0.0184	0.9101
6	-0.0301	0.9040	21	0.0383	0.9345
7	-0.0916	0.8728	22	0.2112	0.9422
8	-0.1417	0.8604	23	-0.4278	0.8088
9	-0.1590	0.9051	24	-0.0668	0.8180
10	0.3279	0.8996	25	0.0209	0.8844
11	0.0472	0.8138	26	-0.0654	0.8620
12	-0.2362	0.8963	27	-0.3304	0.9557
13	0.3884	0.8925	28	-0.1982	0.8950
14	0.2833	0.8632	29	-0.4636	0.8626
15	-0.3415	0.9174	-	-	-

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.

defined by $\Delta\chi^2 = T^2$, where T is a tolerance factor. Some PDF groups adopt $T > 1$ to account for the limited flexibility of their parameterizations, and inconsistencies among different experimental datasets due to possible underestimation of the uncertainties. In both the original CMS analysis and this updated study, a tolerance factor of 1 is used, assuming that the flexibility of the PDF parameterization is sufficient within the specific region of $Q \approx M_Z$ and $x = 0.001\text{--}0.1$, and the ratio measurements employed here minimize the possible underestimation of uncertainties. For global PDF fits covering much wider kinematic ranges, however, larger or dynamic tolerance values may be required.

References

- [1] S. Navas, et al., Review of particle physics, *Phys. Rev. D* 110 (3) (2024) 030001. doi:10.1103/PhysRevD.110.030001.
- [2] S. Navas, et al., Review of particle physics 2025 online update (2025).
URL <https://pdg.lbl.gov/2025/reviews/rpp2024-rev-standard-model.pdf>
- [3] T. Aaltonen, et al., High-precision measurement of the W boson mass with the CDF II detector, *Science* 376 (6589) (2022) 170–176. doi:10.1126/science.abk1781.
- [4] V. Chekhovsky, et al., High-precision measurement of the W boson mass with the CMS experiment at the LHC, arXiv:2412.13872.
- [5] T. Biekötter, S. Heinemeyer, G. Weiglein, Excesses in the low-mass Higgs-boson search and the W -boson mass measurement, *Eur. Phys. J. C* 83 (5) (2023) 450. arXiv:2204.05975, doi:10.1140/epjc/s10052-023-11635-3.
- [6] S. Schael, et al., Precision electroweak measurements on the Z resonance, *Phys. Rept.* 427 (2006) 257–454. arXiv:hep-ex/0509008, doi:10.1016/j.physrep.2005.12.006.
- [7] K. S. Kumar, S. Mantry, W. J. Marciano, P. A. Souder, Low Energy Measurements of the Weak Mixing Angle, *Ann. Rev. Nucl. Part. Sci.* 63 (2013) 237–267. arXiv:1302.6263, doi:10.1146/annurev-nucl-102212-170556.
- [8] J. Erler, K. S. Kumar, Low Energy Measurements of the Weak Mixing Angle, to be published in *Physics Reports*, Collection of papers on Electroweak Precision Measurements, edited by Costas Vellidis and others. (2025).
- [9] A. Bodek, A. van Dyne, J. Y. Han, W. Sakumoto, A. Strelnikov, Extracting Muon Momentum Scale Corrections for Hadron Collider Experiments, *Eur. Phys. J. C* 72 (2012) 2194. arXiv:1208.3710, doi:10.1140/epjc/s10052-012-2194-8.
- [10] A. Bodek, A simple event weighting technique for optimizing the measurement of the forward-backward asymmetry of Drell-Yan dilepton pairs at hadron colliders, *Eur. Phys. J. C* 67 (2010) 321–334. arXiv:0911.2850, doi:10.1140/epjc/s10052-010-1287-5.
- [11] A. Bodek, J. Han, A. Khukhunaishvili, W. Sakumoto, Using Drell-Yan forward-backward asymmetry to reduce PDF uncertainties in the measurement of electroweak parameters, *Eur. Phys. J. C* 76 (3) (2016) 115. arXiv:1507.02470, doi:10.1140/epjc/s10052-016-3958-3.
- [12] J. C. Collins, D. E. Soper, Angular Distribution of Dileptons in High-Energy Hadron Collisions, *Phys. Rev. D* 16 (1977) 2219. doi:10.1103/PhysRevD.16.2219.
- [13] A. Hayrapetyan, et al., Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle in proton-proton collisions at $\sqrt{s} = 13$ eV, *Phys. Lett. B* 866 (2025) 139526. arXiv:2408.07622, doi:10.1016/j.physletb.2025.139526.
- [14] T.-J. Hou, et al., New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC, *Phys. Rev. D* 103 (1) (2021) 014013. arXiv:1912.10053, doi:10.1103/PhysRevD.103.014013.
- [15] K. Xie, B. Zhou, T. J. Hobbs, The photon content of the neutron, *JHEP* 04 (2024) 022. arXiv:2305.10497, doi:10.1007/JHEP04(2024)022.

Index	Shift	Uncertainty	Index	Shift	Uncertainty
1	0.1702	0.8311	26	0.4421	0.8970
2	-0.3638	0.9166	27	0.1147	0.9267
3	-0.0252	0.8970	28	0.6423	0.9442
4	-0.0872	0.9093	29	0.1025	0.9038
5	-0.6236	0.7571	30	0.3838	0.9298
6	-0.2378	0.8382	31	0.0914	0.9048
7	-0.1834	0.9047	32	0.3759	0.9471
8	-0.9734	0.5963	33	0.1796	0.9052
9	-0.1429	0.9243	34	-0.1740	0.8979
10	-0.6822	0.9225	35	0.4388	0.8988
11	0.2039	0.8057	36	-0.2822	0.8771
12	-0.1852	0.8971	37	-0.0082	0.8757
13	0.2140	0.6241	38	0.0767	0.9185
14	-0.2108	0.8419	39	0.1393	0.8705
15	-0.3464	0.9008	40	0.5912	0.9277
16	-0.2316	0.8514	41	0.2028	0.9477
17	0.0642	0.9039	42	-0.1651	0.9247
18	0.1783	0.9480	43	-0.8559	0.9395
19	-0.7155	0.7832	44	0.7538	0.9190
20	0.3688	0.9101	45	0.1681	0.9445
21	-0.6457	0.8871	46	-0.1919	0.9023
22	0.3443	0.9302	47	0.2433	0.8918
23	0.3121	0.8653	48	-0.1794	0.9338
24	0.3442	0.8521	49	0.1257	0.8620
25	0.1940	0.8793	50	0.4701	0.9350

Table A.3. Shifts and uncertainties of the 50 nuisance parameters corresponding to the NNPDF40 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.

Index	Shift	Uncertainty	Index	Shift	Uncertainty
1	0.2883	0.7999	21	0.2996	0.7869
2	-0.3396	0.5063	22	0.1989	0.8614
3	-0.3407	0.8273	23	0.3345	0.8628
4	0.4421	0.6529	24	-0.0169	0.9059
5	-0.0596	0.8237	25	0.0363	0.7250
6	0.0464	0.8450	26	-0.2264	0.8403
7	-0.3998	0.8406	27	0.6605	0.8171
8	0.2427	0.7671	28	-0.3767	0.8359
9	0.7427	0.8438	29	0.1010	0.7748
10	-0.0194	0.9031	30	-0.2818	0.7922
11	0.5687	0.8004	31	-0.1927	0.8567
12	-0.3910	0.8307	32	-0.5815	0.8584
13	-0.4395	0.7776	33	0.2795	0.7215
14	0.0897	0.8790	34	0.5507	0.8566
15	0.1018	0.7773	35	0.6231	0.8519
16	-0.2810	0.7366	36	0.1936	0.8049
17	-0.4838	0.7187	37	0.1708	0.7104
18	-0.2134	0.7196	38	-0.5745	0.7558
19	0.3362	0.8235	39	0.0406	0.6484
20	0.4485	0.8393	40	1.0870	0.7168

Table A.4. Shifts and uncertainties of the 40 nuisance parameters corresponding to the PDF4LHC21 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.

- [16] T.-J. Hou, H.-W. Lin, M. Yan, C. P. Yuan, Impact of lattice strangeness asymmetry data in the CTEQ-TEA global analysis, Phys. Rev. D 107 (2023) 076018. arXiv:2211.11064, doi:10.1103/PhysRevD.107.076018.
- [17] T.-J. Hou, et al., New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC, <https://cteq-tea.gitlab.io/project/> (2025).
- [18] R. D. Ball, et al., The path to proton structure at 1% accuracy, Eur. Phys. J. C 82 (5) (2022) 428. arXiv:2109.02653, doi:10.1140/epjc/s10052-022-10328-7.
- [19] R. D. Ball, et al., Photons in the proton: implications for the LHC, Eur. Phys. J. C 84 (5) (2024) 540. arXiv:2401.08749, doi:10.1140/epjc/s10052-024-12731-8.
- [20] R. D. Ball, et al., Determination of the theory uncertainties from missing higher orders on NNLO parton distributions with percent accuracy, Eur. Phys. J. C 84 (2024) 517. arXiv:2401.10319, doi:10.1140/epjc/s10052-024-12772-z.
- [21] R. D. Ball, et al., The path to N³LO parton distributions, Eur. Phys. J. C 84 (7) (2024) 659. arXiv:2402.18635, doi:10.1140/epjc/s10052-024-12891-7.
- [22] R. D. Ball, et al., The path to N³LO parton distributions, <https://nnpdf.mi.infn.it/nnpdf4-0-qcd/> (2025).
- [23] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin, R. S. Thorne, Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs, Eur. Phys. J. C 81 (4) (2021) 341. arXiv:2012.04684, doi:10.1140/epjc/s10052-021-09057-0.
- [24] T. Cridge, L. A. Harland-Lang, A. D. Martin, R. S. Thorne, QED parton distribution functions in the MSHT20 fit, Eur. Phys. J. C 82 (1) (2022) 90. arXiv:2111.05357, doi:10.1140/epjc/s10052-022-10028-2.
- [25] J. McGowan, T. Cridge, L. A. Harland-Lang, R. S. Thorne, Approximate N³LO parton distribution functions with theoretical uncertainties: MSHT20aN³LO PDFs, Eur. Phys. J. C 83 (3) (2023) 185, [Erratum: Eur.Phys.J.C 83, 302 (2023)]. arXiv:2207.04739, doi:10.1140/epjc/s10052-023-11236-0.
- [26] T. Cridge, L. A. Harland-Lang, R. S. Thorne, Combining QED and approximate N³LO QCD corrections in a global PDF fit: MSHT20qed.an3lo PDFs, SciPost Phys. 17 (1) (2024) 026. arXiv:2312.07665, doi:10.21468/SciPostPhys.17.1.026.
- [27] T. Cridge, L. A. Harland-Lang, R. S. Thorne, Combining QED and approximate N³LO QCD corrections in a global PDF fit: MSHT20qed.an3lo PDFs, <https://www.hep.ucl.ac.uk/msht/grids.shtml> (2025).
- [28] A. M. Sirunyan, et al., Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry in $p\bar{p}$ collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D 102 (9) (2020) 092012. arXiv:2008.04174, doi:10.1103/PhysRevD.102.092012.
- [29] A. Hayrapetyan, et al., Measurement of the inclusive cross sections for W and Z boson production in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV, JHEP 04 (2025) 162. arXiv:2408.03744, doi:10.1007/JHEP04(2025)162.
- [30] T. Aaltonen, et al., Indirect Measurement of $\sin^2 \theta_W (M_W)$ Using e^+e^- Pairs in the Z -Boson Region with $p\bar{p}$ Collisions at a Center-of-Momentum Energy of 1.96 TeV, Phys. Rev. D 88 (7) (2013) 072002, [Erratum: Phys.Rev.D 88, 079905 (2013)]. arXiv:1307.0770, doi:10.1103/PhysRevD.88.072002.
- [31] T. A. Aaltonen, et al., Indirect Measurement of $\sin^2 \theta_W$ (or M_W) Using $\mu^+\mu^-$ Pairs from γ^*/Z Bosons Produced in $p\bar{p}$ Collisions at a Center-

- of-Momentum Energy of 1.96 TeV, Phys. Rev. D 89 (7) (2014) 072005. arXiv:1402.2239, doi:10.1103/PhysRevD.89.072005.
- [32] T. A. Aaltonen, et al., Measurement of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ using e^+e^- pairs from γ^*/Z bosons produced in $p\bar{p}$ collisions at a center-of-momentum energy of 1.96 TeV, Phys. Rev. D 93 (11) (2016) 112016, [Addendum: Phys.Rev.D 95, 119901 (2017)]. arXiv:1605.02719, doi:10.1103/PhysRevD.93.112016.
- [33] A. M. Sirunyan, et al., Measurement of the weak mixing angle using the forward-backward asymmetry of Drell-Yan events in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 78 (9) (2018) 701. arXiv:1806.00863, doi:10.1140/epjc/s10052-018-6148-7.
- [34] Measurement of the effective leptonic weak mixing angle using electron and muon pairs from Z-boson decay in the ATLAS experiment at $\sqrt{s} = 8$ TeV, ATLAS-CONF-2018-037 (unpublished) (7 2018).
- [35] S. Alekhin, et al., HERAFitter, Eur. Phys. J. C 75 (2015) 304. arXiv:1410.4412, doi:10.1140/epjc/s10052-015-3480-z.
- [36] S. Camarda, et al., QCD analysis of W- and Z-boson production at Tevatron, Eur. Phys. J. C 75 (2015) 458. arXiv:1503.05221, doi:10.1140/epjc/s10052-015-3655-7.
- [37] P. F. Monni, E. Re, M. Wiesemann, MiNNLO_{PS}: optimizing $2 \rightarrow 1$ hadronic processes, Eur. Phys. J. C 80 (11) (2020) 1075. arXiv:2006.04133, doi:10.1140/epjc/s10052-020-08658-5.
- [38] P. Golonka, Z. Was, PHOTOS Monte Carlo: A Precision tool for QED corrections in Z and W decays, Eur. Phys. J. C 45 (2006) 97–107. arXiv:hep-ph/0506026, doi:10.1140/epjc/s2005-02396-4.
- [39] M. Chiesa, F. Piccinini, A. Vicini, Direct determination of $\sin^2 \theta_{\text{eff}}^{\ell}$ at hadron colliders, Phys. Rev. D 100 (7) (2019) 071302. arXiv:1906.11569, doi:10.1103/PhysRevD.100.071302.
- [40] M. Chiesa, C. L. Del Pio, F. Piccinini, On electroweak corrections to neutral current Drell–Yan with the POWHEG BOX, Eur. Phys. J. C 84 (2024) 539. arXiv:2402.14659, doi:10.1140/epjc/s10052-024-12908-1.
- [41] L. Barze, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini, A. Vicini, Neutral current Drell-Yan with combined QCD and electroweak corrections in the POWHEG BOX, Eur. Phys. J. C 73 (6) (2013) 2474. arXiv:1302.4606, doi:10.1140/epjc/s10052-013-2474-y.
- [42] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07 (2014) 079. arXiv:1405.0301, doi:10.1007/JHEP07(2014)079.
- [43] C. Schwan, PineAPPL: NLO EW corrections for PDF processes, SciPost Phys. Proc. 8 (2022) 079. arXiv:2108.05816, doi:10.21468/SciPostPhysProc.8.079.
- [44] S. Carrazza, E. R. Nocera, C. Schwan, M. Zaro, PineAPPL: combining EW and QCD corrections for fast evaluation of LHC processes, JHEP 12 (2020) 108. arXiv:2008.12789, doi:10.1007/JHEP12(2020)108.
- [45] R. D. Ball, et al., The PDF4LHC21 combination of global PDF fits for the LHC Run III, J. Phys. G 49 (2022) 080501. arXiv:2203.05506, doi:10.1088/1361-6471/ac7216.
- [46] V. M. Abazov, et al., Measurement of the Effective Weak Mixing Angle in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$ Events, Phys. Rev. Lett. 120 (24) (2018) 241802. arXiv:1710.03951, doi:10.1103/PhysRevLett.120.241802.
- [47] G. Aad, et al., Measurement of the forward-backward asymmetry of electron and muon pair-production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, JHEP 09 (2015) 049. arXiv:1503.03709, doi:10.1007/JHEP09(2015)049.
- [48] R. Aaij, et al., Measurement of the forward-backward asymmetry in $Z/\gamma^* \rightarrow \mu^+ \mu^-$ decays and determination of the effective weak mixing angle, JHEP 11 (2015) 190. arXiv:1509.07645, doi:10.1007/JHEP11(2015)190.
- [49] R. Aaij, et al., Measurement of the effective leptonic weak mixing angle, JHEP 12 (2024) 026. arXiv:2410.02502, doi:10.1007/JHEP12(2024)026.
- [50] J.-C. Peng, W.-C. Chang, R. E. McClellan, O. Teryaev, Lepton angular distribution of Z boson production and jet discrimination, Phys. Lett. B 797 (2019) 134895. arXiv:1907.10483, doi:10.1016/j.physletb.2019.134895.
- [51] A. M. Sirunyan, et al., Measurement of the associated production of a Z boson with charm or bottom quark jets in proton-proton collisions at $\sqrt{s}=13$ TeV, Phys. Rev. D 102 (3) (2020) 032007. arXiv:2001.06899, doi:10.1103/PhysRevD.102.032007.
- [52] V. Khachatryan, et al., Measurements of the associated production of a Z boson and b jets in pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 77 (11) (2017) 751. arXiv:1611.06507, doi:10.1140/epjc/s10052-017-5140-y.
- [53] F. del Aguila, L. Ametller, P. Talavera, Forward backward asymmetries of lepton pairs in events with a large transverse momentum jet at hadron colliders, Phys. Rev. Lett. 89 (2002) 161802. arXiv:hep-ph/0206160, doi:10.1103/PhysRevLett.89.161802.
- [54] S. Forte, T. Giani, D. Napoletano, Fitting the b-quark PDF as a massive-b scheme: Higgs production in bottom fusion, Eur. Phys. J. C 79 (7) (2019) 609. arXiv:1905.02207, doi:10.1140/epjc/s10052-019-7119-3.
- [55] D. Figueroa, S. Honeywell, S. Quackenbush, L. Reina, C. Reuschle, D. Wackeroth, Electroweak and QCD corrections to Z-boson production with one b jet in a massive five-flavor scheme, Phys. Rev. D 98 (9) (2018) 093002. arXiv:1805.01353, doi:10.1103/PhysRevD.98.093002.
- [56] J. M. Campbell, R. K. Ellis, F. Maltoni, S. Willenbrock, Associated production of a Z Boson and a single heavy quark jet, Phys. Rev. D 69 (2004) 074021. arXiv:hep-ph/0312024, doi:10.1103/PhysRevD.69.074021.
- [57] M. Beccaria, G. Macorini, G. Panizzo, C. Verzegnassi, New Physics signals from measurable polarization asymmetries at LHC, Phys. Lett. B 730 (2014) 149–154. arXiv:1308.4331, doi:10.1016/j.physletb.2014.01.010.
- [58] D. Figueroa, S. Honeywell, S. Quackenbush, L. Reina, C. Reuschle, D. Wackeroth, Precision studies of vector-boson production with heavy quarks at the LHC: the case of $Z + b$ jet., PoS LL2018 (2018) 082. arXiv:1810.08241, doi:10.22323/1.303.0082.
- [59] M. Cobal, G. Guerrieri, H. Khanpour, G. Panizzo, M. Pinamonti, L. Pintucci, L. Toffolin, Bottom quark forward-backward asymmetry at the future electron-positron collider FCC-ee arXiv:2501.17677.
- [60] K. Ueno, et al., Measurement of the forward - backward asymmetry in $e^+e^- \rightarrow b\bar{b}$ and the b quark branching ratio to muons at TRISTAN using neural networks, Phys. Lett. B 381 (1996) 365–371. doi:10.1016/0370-2693(96)00543-6.
- [61] F. Liu, et al., Measurements of cross-section and asymmetry for $e^+e^- \rightarrow b$ anti-b and heavy quark fragmentation at KEK TRISTAN, Phys. Rev. D 49 (1994) 4339–4347. doi:10.1103/PhysRevD.49.4339.
- [62] S. Amoroso, M. Chiesa, C. L. Del Pio, K. Lipka, F. Piccinini, F. Vazzoler, A. Vicini, Probing the weak mixing angle at high energies at the LHC and HL-LHC, Phys. Lett. B 844 (2023) 138103. arXiv:2302.10782, doi:10.1016/j.physletb.2023.138103.