



ATLAS PUB Note

ATL-PHYS-PUB-2018-037

28th November 2018



Prospect for a measurement of the Weak Mixing Angle in $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events with the ATLAS detector at the High Luminosity Large Hadron Collider

The ATLAS Collaboration

This document describes a sensitivity study for the determination of the weak mixing angle from the measurement of the Z boson forward-backward asymmetry using 3000 fb^{-1} of data to be collected by the ATLAS experiment with proton proton collisions at $\sqrt{s} = 14 \text{ TeV}$ at the High Luminosity Large Hadron Collider.

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1 Introduction

In the Standard Model (SM), the Z boson couplings differ for left- and right-handed fermions. The difference leads to an asymmetry in the angular distribution of positively and negatively charged leptons produced in Z boson decays. This asymmetry depends on the weak mixing angle ($\sin^2 \theta_W$) between the neutral states associated to the $U(1)$ and $SU(2)$ gauge groups, i.e. the relative coupling strengths between the photon and the Z boson. The differential cross section for the decay of the Z/γ^* to dilepton final state can be written at leading order as:

$$\frac{d\sigma}{d(\cos \theta)} = \frac{\alpha^2}{4s} \left[\frac{3}{8} A (1 + \cos^2 \theta) + B \cos \theta \right], \quad (1)$$

where $\sqrt{s}$ is the centre-of-mass energy of the quark and anti-quark, and θ is the angle between the negative lepton and the quark. The coefficients A and B depend on the charge of the fermions (Q_f) and are defined as [1]:

$$\begin{aligned} A &= Q_l^2 Q_q^2 - 2Q_l g_V^q g_V^l \chi_1 + (g_A^{q^2} + g_V^{q^2})(g_A^{l^2} + g_V^{l^2}) \chi_2, \\ B &= -4Q_l g_A^q g_A^l \chi_1 + 8g_A^q g_V^q g_A^l g_V^l \chi_2, \end{aligned} \quad (2)$$

where χ_1 is the interference between Z and γ^* contributions and χ_2 is the Z Breit-Wigner. The vector and axial-vector couplings of the fermions to the Z -boson are define respectively as $g_V^f = t_3^f - (2Q_f \times \sin^2 \theta_W)$ and $g_A^f = t_3^f$. The vector coupling depends on the charge and on the weak isospin (t_3^f) of the fermions and on the weak mixing angle (θ_W). The coefficient B introduces a forward-backward asymmetry in θ arising from the presence of both vector and axial-vector couplings.

Experimentally this asymmetry can be simply expressed as:

$$A_{FB} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N(\cos \theta^* < 0)} = \frac{3}{8} \frac{B}{A}, \quad (3)$$

where θ^* is the angle between the negative lepton and the quark in the Collins-Soper frame [2] of the dilepton system and N represents the number of forward decays ($\cos \theta^* > 0$) and the number of backward decays ($\cos \theta^* < 0$). This forward-backward asymmetry is enhanced by the Z/γ^* interference and exhibits significant dependence on the dilepton rapidity and invariant mass taking a different sign at high mass and at low mass. Since the asymmetry depends directly on the vector and axial-vector couplings, it is sensitive to the weak mixing angle which relates the two. In order to compare this studies with previous experimental determinations, a scheme is adopted in which the higher order corrections to the Z boson couplings are absorbed in effective couplings. The resulting effective parameter $\sin^2 \theta_{eff}$ is defined [3], and is proportional to $\sin^2 \theta_W$.

Several measurements of $\sin^2 \theta_{eff}$ have been made at previous and current colliders, and the current world average is dominated by the combination of measurements at LEP and at SLD, which gives $\sin^2 \theta_{eff} = 0.231530 \pm 16 \times 10^{-5}$. However, the two most precise measurements differ by over 3σ [3]. It is of great scientific interest the study of the weak mixing angle at the Large Hadron Collider (LHC) and at the High-Luminosity Large Hadron Collider (HL-LHC). Precision measurements may give insight into the tension between the previous precision measurements or may show signs of new physics.

Measurements of A_{FB} which at the LHC show the greatest sensitivity to $\sin^2 \theta_{eff}$ are at high Z rapidity when at least one lepton is present in the forward region [4]. At a rapidity of 0, the initial state is symmetric,

with equal probability for the initial-state quark to be originated from either proton. Therefore, in such a kinematic configuration no forward-backward asymmetry is present due to a complete dilution of the parton-level asymmetry in the proton-proton collisions. For increasing Z boson rapidities the momentum fraction of one parton reaches larger x where the valence quark Parton Density Function (PDF) dominate because the valence quarks typically carry more momentum than the antiquarks. Therefore, the Z boson is more likely to be boosted in the quark direction and the incoming quark direction can be determined. Consequently a forward-backward asymmetry is visible, providing sensitivity to $\sin^2 \theta_{eff}$, and it varies with the boson rapidity.

This note reports the projected sensitivity for the measurement of the Z boson forward-backward asymmetry as a function of the dilepton invariant mass and rapidity, assuming 3000 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$ to be collected with an upgraded ATLAS detector during the HL-LHC phase. Only Z bosons decaying to electrons pairs are considered in this analysis since this final state provides the best experimental precision within the largest acceptance of the upgraded ATLAS detector.

2 The HL-LHC and the ATLAS detector

During the HL-LHC phase an instantaneous luminosity of around $5 - 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an average number of collisions per bunch crossing (pile-up) of 200 are expected. To cope with the higher luminosity at the HL-LHC and its associated high pile-up and intense radiation environment several detector upgrades are foreseen for the ATLAS detector. A new inner tracking system (ITk) [5], extending the tracking region from $|\eta| \leq 2.5$ up to $|\eta| \leq 4.0$, will provide the ability to reconstruct forward charged particle tracks, which can be matched to calorimeter clusters for forward electron reconstruction, or associated to forward jets. A new detector, high granularity timing detector (HGTD) [6] designed to mitigate the pile-up is also foreseen. The other planned upgrades to the ATLAS detector are described in detail in Ref. [7].

3 Analysis

Monte Carlo (MC) simulated events with Powheg-BOX [8] generator interfaced to Pythia8 [9] are used to predict $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ signal at $\sqrt{s} = 14 \text{ TeV}$. The events are overlaid with additional inelastic pp collisions per bunch-crossing simulated with Pythia. Parameterisations of the expected ATLAS detector performances during the HL-LHC runs have been derived [7] and applied on particle-level objects to emulate the detector response. Lepton trigger and identification efficiencies are derived as a function of $|\eta|$ and p_T and used to estimate the likelihood of a given lepton to fulfil either the trigger or identification requirement, respectively. Electron energy resolutions and scale estimates are also parameterised as a function of $|\eta|$ and transverse energy for each electron.

Events are selected requiring at least one electron firing the single electron trigger except for events in which both electron candidates are in the forward region ($|\eta| > 2.5$) where a dielectron trigger is required. Only events with exactly two electron candidates of opposite charge and each having $p_T > 25 \text{ GeV}$ are further selected. Each electron candidate must satisfy a set of *tight* selection criteria, which have been optimised for the level of pile-up expected at the HL-LHC [10]. The invariant mass of the electron pair is required to be loosely consistent with the Z boson mass, $60 < m_{ee} < 200 \text{ GeV}$. The fiducial acceptance of $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events is split into three orthogonal analysis channels depending on the electron pseudorapidity. Considering an integrated luminosity of 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$, 540 million events are

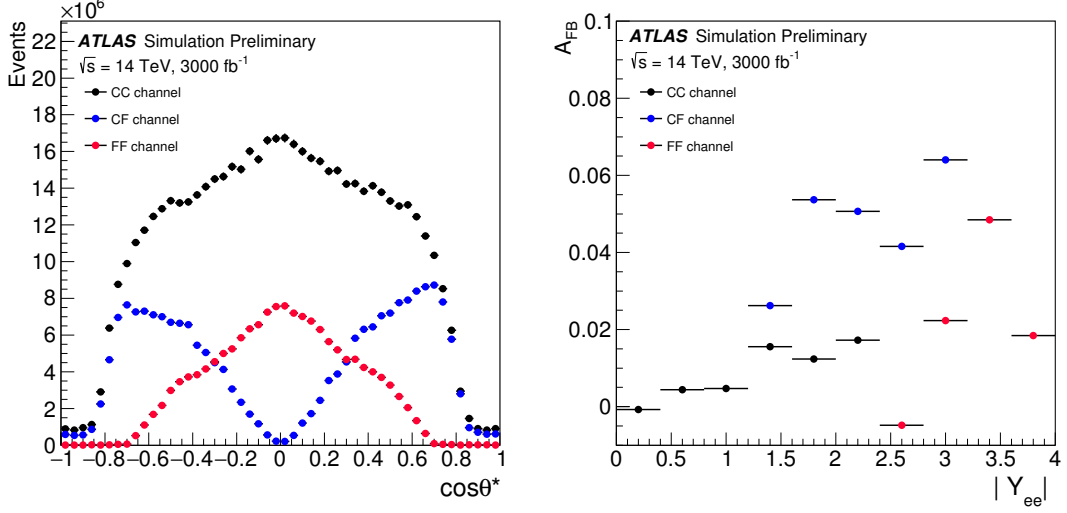


Figure 1: (left) The $\cos \theta^*$ distribution for CC, CF and FF channels for the selected $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events expected for 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$. (right) The A_{FB} distribution at particle level in the fiducial volume as a function of the absolute dielectron rapidity for CC, CF and FF channels for $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events expected for 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$.

expected with a pair of electrons in the central region of the detector, $|\eta| < 2.47$, (CC channel), 210 million events are expected with a pair of electrons, where one electron is in the forward region ($2.5 < |\eta| < 4.2$) of the detector (CF channel) and 150 million events are expected with a pair of electrons in the forward region of the detector (FF channel).

The events in each channel are further categorised in 10 equal-size bins in absolute dilepton rapidity up to $|Y_{ee}| = 4.0$. On the left of Figure 1 the $\cos \theta^*$ distribution for the $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$ candidate in the three different channels is shown for 3000 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$. The CF channel select event at high $\cos \theta^*$ value where the forward-backward asymmetry is more pronounced, therefore the sensitivity to the A_{FB} and consequently to $\sin^2 \theta_{eff}$ is higher in this channel.

The contribution of jets misidentified as electrons is suppressed using an additional track isolation requirement. In the forward region, the timing information provided by the HGTD is used to improve the electron isolation by rejecting additional tracks from interactions close in space, but separated in time from the hard-scatter vertex. The purity of the candidate sample is determined with simulation, and is found to be greater than 99% in the CC channel, between 90 and 98% in CF, and between 60 and 90% in the FF channel depending on the dilepton rapidity. The signal significance in the CF channel is improved up to 20% thanks to the enhance signal efficiency provided by the timing information of the HGTD.

The background-subtracted expected events in the three different channels are unfolded to forward and backward fiducial cross sections using the inverse of the response matrix to correct for detector effects and migrations between m_{ee} and $|Y_{ee}|$ bins. In the CF and FF channels, migrations from one bin to another bin in m_{ee} are up to 50 and 60% respectively.

Various sources of uncertainty are considered in the analysis and propagated via the unfolding procedure to the results. Significant uncertainties arise from the limited knowledge of the momentum scale and resolution of the electrons. Following the methodology in Ref. [11], in order to account for possible non-linearity in the energy scale of electrons reconstructed in the central (forward) region, a systematic

of 0.5% (0.7%) is considered for electrons with $E_T < 55$ GeV and up to 1.5% (2.1%) for $E_T > 100$ GeV. Uncertainties associated with background are mostly relevant in the CF and FF channels. Given the lack of knowledge of the composition and the modelling of the misidentified electrons and the limited statistic of the MC samples used for the background determination, an overall normalisation systematic of 10% is considered for the background shape modelling. Since it was verified that this uncertainty has a negligible effect on the measurement, an additional 5% uncertainty, uncorrelated across bins, is considered on the background yield for all bin of invariant mass and rapidity .

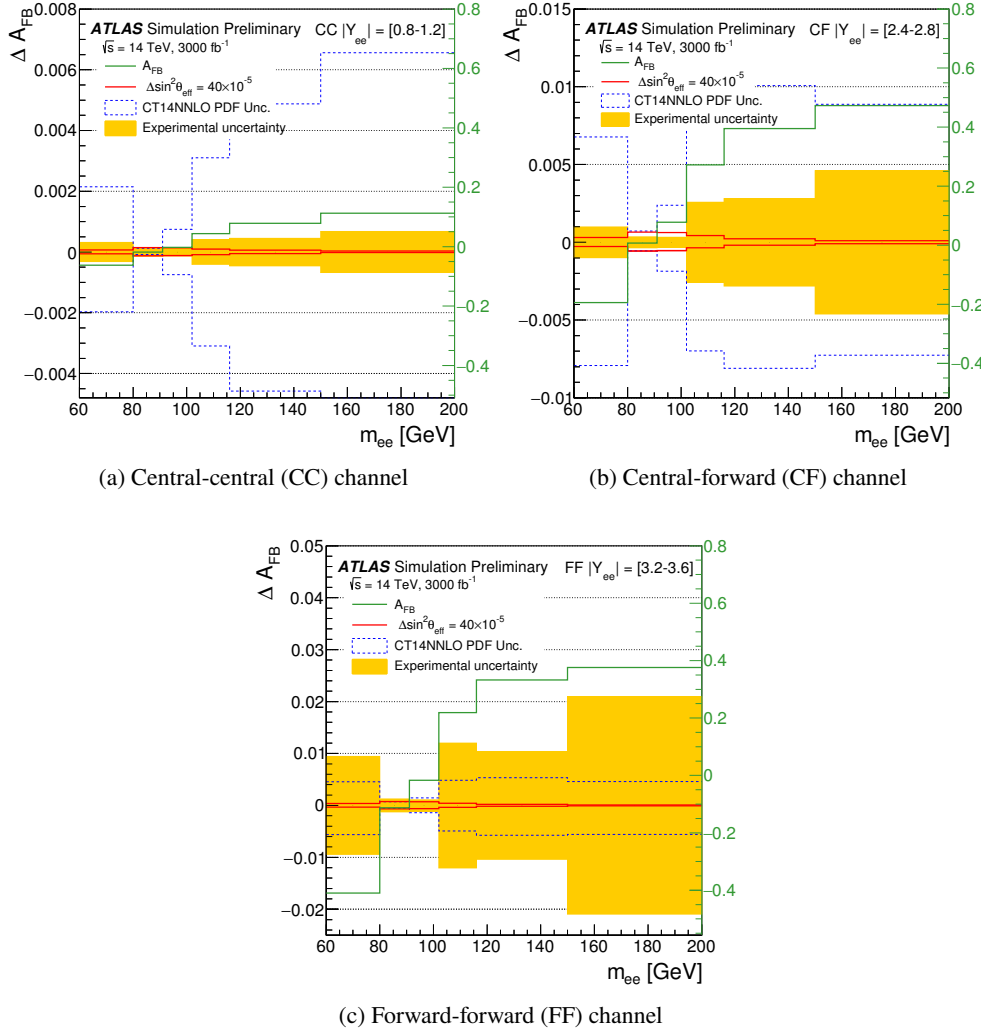


Figure 2: Distribution of the uncertainty on A_{FB} (ΔA_{FB}) as a function of dielectron mass for the CC, CF and FF channels. The filled bands correspond to the experimental uncertainty. The solid red lines correspond to a variations of $\sin^2 \theta_{eff}$ corresponding to 40×10^{-5} . The dashed blue lines illustrate the total uncertainty of CT14 NNLO PDF set before in-situ profiling. Overlaid green line shows the particle-level A_{FB} distribution.

The A_{FB} for the CC, CF and the FF channel is calculated as function of $|Y_{ee}|$ and m_{ee} following Equation 3 from projected measurements of particle level fiducial cross sections. On the right side of Figure 1 the expected amplitude of the A_{FB} as function of $|Y_{ee}|$ in the fiducial volume is shown for CC, CF and FF

channels separately. The expected sensitivity to particle level A_{FB} as a function of m_{ee} is also shown in Figure 2 for each channel for a chosen rapidity bin.

4 Results

The extraction of $\sin^2 \theta_{eff}$ is done by minimising the χ^2 value comparing particle-level A_{FB} distributions with different weak mixing angle hypotheses in invariant mass and rapidity bins combining CC, CF and FF channels. The default A_{FB} distributions are generated, at leading order (LO) in QCD, with DYTURBO an optimised version of DYRES/DYNNLO [12] with NNLO CT14 PDF [13] and the world average value for $\sin^2 \theta_{eff} = 0.23153$. The same LO calculation is used to compute A_{FB} variations for different values of $\sin^2 \theta_{eff}$ and PDFs. As shown in Figure 2, the imperfect knowledge of the PDF results in sizeable uncertainties in A_{FB} , in particular in regions where the absolute value of the asymmetry is large, i.e. at high and low m_{ee} . On the contrary, near the Z boson mass peak, the effect of varying $\sin^2 \theta_{eff}$ is maximal, while being significantly smaller at high and low masses. Thus, a global fit is performed where $\sin^2 \theta_{eff}$ is extracted while constraining at the same time the PDF uncertainties. The profiling procedure [14] used in this analysis to constraint the PDF uncertainties follows the one used in previous ATLAS publication [15] and is implemented in the *xFitter* package [16].

With this analysis, a significant reduction of the light quarks uncertainties at low x is seen and the expected uncertainty on the extraction of $\sin^2 \theta_{eff}$ are 25×10^{-5} , 21×10^{-5} and 40×10^{-5} for the CC, CF and FF channels respectively. Combining the three channels together, the measurement reaches a precision of $\Delta \sin^2 \theta_{eff} = 18 \times 10^{-5} (\pm 16 \times 10^{-5} \text{ (PDF)} \pm 9 \times 10^{-5} \text{ (exp.) })$. The uncertainty of the results remains dominated by the currently limited knowledge of the PDFs. In Table 1 the $\sin^2 \theta_{eff}$ sensitivity obtained with this analysis is compared with the latest published ATLAS measurement at $\sqrt{s} = 8$ TeV [17]. When comparing results at 14 and 8 TeV, it should be noted that the forward-backward asymmetry in Z -events at $\sqrt{s} = 14$ TeV is smaller than the asymmetry observed at $\sqrt{s} = 8$ TeV, in addition the PDFs at lower x , more important at $\sqrt{s} = 14$ TeV, are less known, resulting in an smaller overall sensitivity to extract $\sin^2 \theta_{eff}$. The loss of sensitivity is approximately compensated by the increased Z -boson production cross-section from 8 to 14 TeV (a factor of 1.8). Therefore, with the same integrated luminosity of 20 fb^{-1} , a simple extrapolation to $\sqrt{s} = 14$ TeV centre-of-mass energy of the $\sin^2 \theta_{eff}$ extracted at $\sqrt{s} = 8$ TeV by the ATLAS experiment would result into the same statistical uncertainty and a 45% increase of the PDF uncertainty.

In the context of the Yellow Report for the HL-LHC, prospect PDF fits including HL-LHC pseudo-data of future PDF-sensitive measurements from ATLAS and CMS were performed [19]. Three prospect PDF scenarios were considered and compared with the reference PDF set PDF4LHC15 [20]. The expected sensitivity of the $\sin^2 \theta_{eff}$ measurement with 3000 fb^{-1} at $\sqrt{s} = 14$ TeV is improved by 10–25% depending on the prospect PDFs scenario considered. In Table 1 the $\sin^2 \theta_{eff}$ precision obtained with the "ultimate" HL-LHC PDF set is compared with the one obtained with CT14NNLO PDF set.

Finally the sensitivity of the analysis to $\sin^2 \theta_{eff}$ extraction is also estimated with a prospect PDF set including expected data from LHeC collider [21]. In this case the PDF uncertainty is reduced by an additional factor of 5 with respect to the one obtained with the HL-LHC prospect PDFs.

Figure 3 compares the ATLAS sensitivity studies of $\sin^2 \theta_{eff}$ presented in this note to previous measurements from the LHC experiments [17, 22–24], the combined legacy measurement from the CDF and D0 experiments at the Tevatron [25], and the most precise individual legacy measurements from LEP

	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb $^{-1}$]	20	3000	3000
PDF set	MMHT14 [18]	CT14 [13]	PDF4LHC15 _{HL-LHC} [19]
$\sin^2 \theta_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

Table 1: The value of $\sin^2 \theta_{eff}$ with the breakdown of uncertainties from the ATLAS preliminary results at $\sqrt{s} = 8$ TeV with 20 fb $^{-1}$ [17] is compared to the projected $\sin^2 \theta_{eff}$ measurements with 3000 fb $^{-1}$ of data at $\sqrt{s} = 14$ TeV for two PDF sets considered in this note. All the numbers values are given in units of 10^{-5} . Note that other sources of systematic uncertainties, such as the impact of the MC statistical uncertainty, evaluated in Ref. [17] are not considered in this prospect analysis. For the HL-LHC prospect PDFs the "ultimate" scenario is chosen.

and SLD [26]. The accuracy of the measurement of the weak mixing angle obtained with an analysis of the A_{FB} in Z-events with 3000 fb $^{-1}$ at $\sqrt{s} = 14$ TeV with the ATLAS detector at HL-LHC exceeds the precision achieved in all previous single-experiment results to date and the measurement is dominated by PDF uncertainties. To explore the full potential of the HL-LHC data will be therefore essential to reduced PDF uncertainties. A moderate improvement of the sensitivity of this measurement is observed when using prospect PDF sets which include ancillary neutral current Drell-Yann measurements performed with the data collected during the high luminosity phase of the LHC, as included in PDF4LHC15_{HL-LHC} set. Further improvements may be achieved when using additional data on W charge asymmetry and with the structure function data from the LHeC collider.

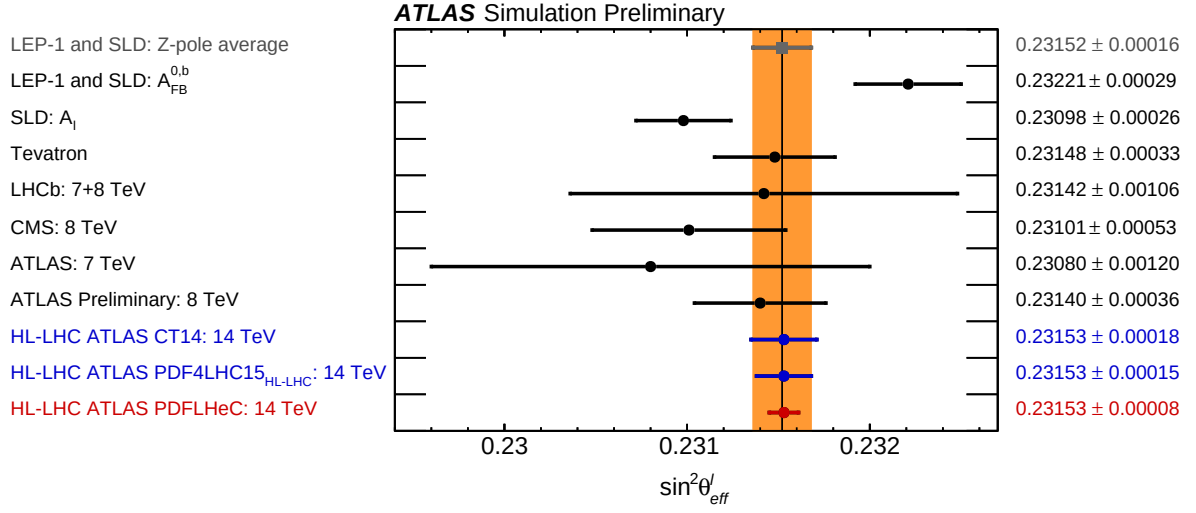


Figure 3: Comparison of the expected precision of the effective leptonic weak mixing angle presented in this note to previous measurements at LEP-1 and SLD [26], at the Tevatron [25], and at the LHC [17, 22–24]. The overall LEP-1 and SLD average [1] is represented together with its uncertainty as a vertical band. The ATLAS results from this analysis are shown with different PDF set scenarios.

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