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Prospects for measurement of the weak mixing angle at LHCb

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Abstract

We project the potential sensitivity to the weak mixing angle in future measurements by LHCb Upgrade II at the High Luminosity LHC. The LHCb experiment covers forward rapidities at the LHC, and expects to record at least 300 fb^{-1} of data. The studies presented here consider a measurement of the weak mixing angle by analysing the forward-backward asymmetry in Drell-Yan events. We present expectations for both the statistical sensitivity of such measurements with integrated luminosities up to 300 fb^{-1}, and the uncertainties due to knowledge of the parton distribution functions.

1 Introduction

This document considers measurements of the weak mixing angle at the LHCb Upgrade II experiment in the High Luminosity Large Hadron Collider (HL-LHC) era. The weak mixing angle is a key parameter in the Standard Model of particle physics, describing the vector and axial-vector components of the coupling of the Z boson. However, it is also related to other parameters in the theory, such as the W boson mass, through electroweak unification. Measuring the angle at the LHC is a crucial programme of research for several reasons: first, the two most precise measurements of the angle to date, made at LEP and SLD disagree at a level of about 3 standard deviations [1]. These measurements probe different processes, and, as such, this discrepancy may be driven by effects beyond the Standard Model [2]. LHC measurements probe interactions involving the collision of light quarks at higher precision than before. Secondly, the programme of precision measurements at the LHC is expected to yield a measurement of the W boson mass at the level of about 9 MeV or better [3]. This precision is roughly equivalent (when phrased as an indirect measurement of the weak mixing angle) to the current level of precision on the combination of the most precise weak mixing angle determinations. Ultimately, in order to test the electroweak sector of the Standard Model as precisely as possible, and to test the validity of our theories, we must seek to improve the precision of measurements of the weak mixing angle.

It is useful at this stage to consider the difference between the weak mixing angle and the effective leptonic weak mixing angle. These parameters are the same at leading order, but corrections at higher orders mean that these parameters take different values, with these corrections absorbed into the definition of the effective angle. The effective leptonic weak mixing angle is the parameter that is typically measured and probed in collider experiments.

At the LHC the effective leptonic weak mixing angle can be determined by measuring the angular distribution of Drell-Yan events: the Z boson and virtual photon production contributions and their interference are determined by the relative vector and axial-vector couplings of the gauge bosons (the full angular distribution for collisions of quarks is given in, for example, Ref. [4]). The presence of the vector and axial-vector couplings generates terms proportional to $\cos\theta^*$ (the azimuthal angle of the negatively charged lepton in the Collins-Soper frame [5]), and an asymmetry between the number of forward events (with $\cos\theta^* > 0$) and the number of backward events (with $\cos\theta^* < 0$); the forward-backward asymmetry is defined as $A_{fb} = (N_f - N_b)/(N_f + N_b)$. By measuring the asymmetry and comparing the data to templates generated with different values of the effective leptonic weak mixing angle, one can determine the value favoured by the data. Crucial to such measurements is the assignation of the z-axis (and through this the sign of $\cos\theta^*$). At parton-level this direction can be determined by the direction of the initial-state quark. However, the LHC collides protons, with the quark and anti-quark in each collision equally likely to be in either proton. Consequently, any asymmetry is removed at zero rapidity. At higher rapidities the parton direction is better known, since the quark is likely to carry more momentum than the anti-quark, and thus provide the longitudinal boost of any Z boson[1] produced; Fig. 1 shows the fraction of events where the Z boson travels in the same longitudinal direction as the initial-state quark. This significantly reduces the

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[1] Or virtual photon. From this point on in this note the label 'Z boson' shall refer to the 'mediator', covering also the virtual photon and interference effects.

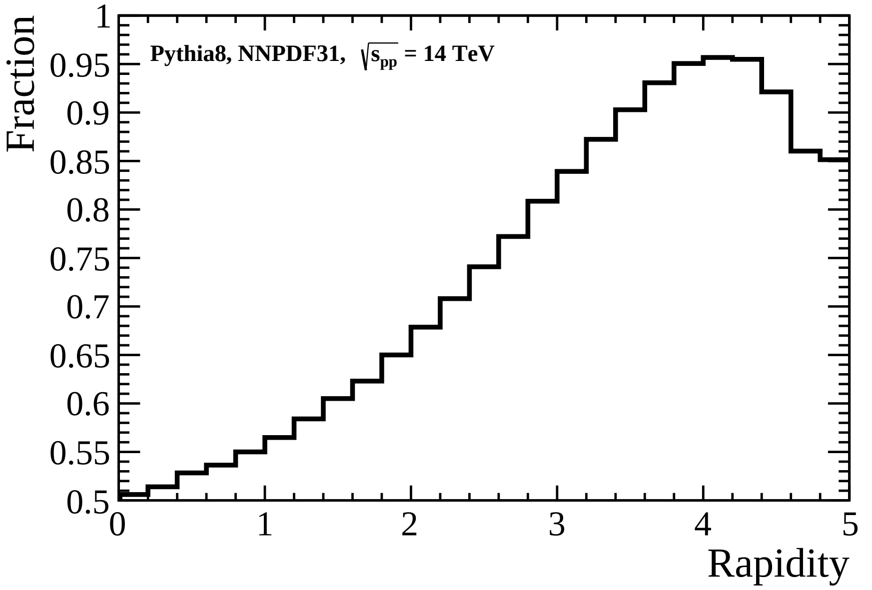

Figure 1: The fraction of events where the Z boson travels in the same direction along the z-axis as the colliding quark, in proton-proton collisions with $\sqrt{s} = 14\,\text{TeV}$. This increases as the event becomes more forward, reaching a maximum in the region probed by LHCb. The decrease once the rapidity is greater than 4 is explained by Fig. 3; the fraction of collisions involving valence quarks decreases, and collisions between a sea-quark and a sea-antiquark are equally likely to have the quark in either proton, no matter the rapidity. The predictions here are based on the central NNPDF31 PDF set, and are generated using Pythia8. No detector effects are simulated for this figure.

ambiguity in the choice of z-axis (at proton-level) at higher rapidities, and means that measurements at higher rapidities have larger forward-backward asymmetries (as shown in Fig. 2) and more sensitivity to the effective leptonic weak mixing angle than those at lower rapidities.

This is a significant advantage of measurements at LHCb, which probes high rapidities (roughly above 2.0), since the z-axis at proton level matches that at parton level more often. This boosts the statistical sensitivity of measurements at LHCb. In addition, there is less dilution between proton-level and parton-level collisions to consider so that the impact of PDFs lessened; knowledge of parton distribution functions (PDFs) is less critical at these high rapidities. Fig. 3 shows the partonic composition of collisions, with a notable increase in $u\bar{u}$ collisions at higher rapidities due to the increase in the up-quark PDF at high-x. In addition, measurements at LHCb are not just of forward Z bosons. The leptons themselves can be very forward, allowing extremal values of $\cos\theta^{*}$ to be probed. Since the sensitivity of measurements to the effective leptonic weak mixing angle increases with coverage of large $|\cos\theta^{*}|$, this favours measurements at LHCb.

2 The LHCb experiment and upgrades

The LHCb experiment probes high rapidities at the LHC. It was initially designed specifically to probe the physics of b-quarks, but has developed into a ‘general purpose

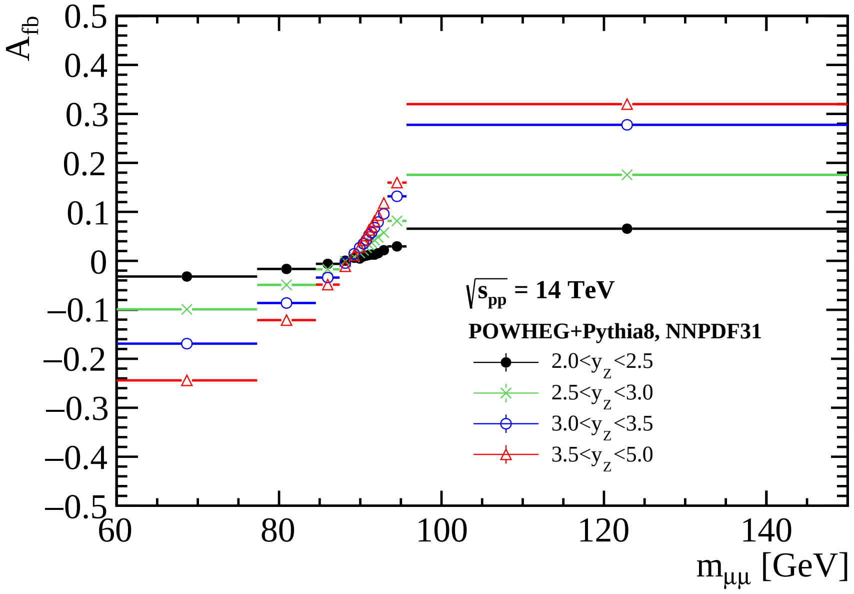

Figure 2: The forward-backward asymmetry in Z boson events, as a function of the dimuon invariant mass and rapidity. The predictions here are based on the central NNPDF31 PDF set, and are generated using POWHEG, with Pythia8 used for the parton shower. No detector effects are simulated for this figure. Uncertainties shown are statistical, associated with the size of the simulated sample.

detector' in the forward region, with a broad physics programme including high precision measurements of electroweak bosons. Indeed, LHCb has already made one measurement of the effective leptonic weak mixing angle [6], finding $\sin^2(\theta^{lept.}_{\rm eff.}) = 0.23142 \pm 0.00106$. ATLAS [7], CMS [4, 8], and the Tevatron experiments [9] have also made measurements. Projections of future performance have also been made [10–12].

In future LHCb measurements the larger dataset means that the statistical uncertainty on the effective leptonic weak mixing angle (the largest uncertainty in Run 1 LHCb analysis) will be significantly reduced. This reduction in the statistical uncertainty also motivates the use of additional techniques to reduce and control the other uncertainties in the measurement, for example, performing the analysis as a function of rapidity. In addition, the largest systematic uncertainties on the existing analysis were due to knowledge of the momentum scale. With additional data to determine these effects more precisely, such uncertainties will also reduce. Recent PDF sets have also improved knowledge of the parton distribution functions at the values of x probed by LHCb by up to a factor of 2 [13]. The profiling or reweighting of PDF replicas [14] will also allow the further reduction of PDF uncertainties.

Key to this programme of research are the two upgrades for the LHCb experiment. The first of these is due to be installed in 2019 and 2020, and will allow the experiment to record data with luminosities that are roughly five times larger. By the end of the fourth LHC run, a total integrated luminosity of $50\,\mathrm{fb}^{-1}$ will have been accumulated. A further upgrade [15] will then increase the proton collision rate by a further factor of 10, and allow the collection of at least $300\,\mathrm{fb}^{-1}$ of data.

A study of the sensitivity of the effective leptonic weak mixing angle from future measurements at LHCb is presented here. For the purpose of this study, the experiment is

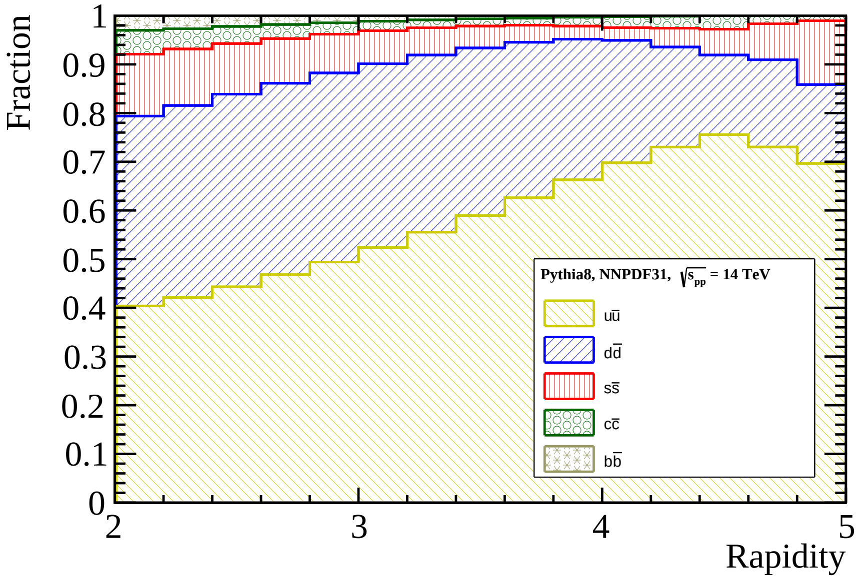

Figure 3: Leading order predictions for the fraction of Z bosons produced at LHCb that are produced from each initial state, in proton-proton collisions with $\sqrt{s} = 14\,\text{TeV}$. The predictions here are based on the central NNPDF31 PDF set, with the simulated events generated using Pythia8. The reduction in valence quark collisions for rapidities above 4 is due to the high-x values being probed: well above 0.3. Above such values of x the valence quark PDFs decrease. No detector effects are simulated for this figure.

assumed to have coverage in the region $2 < \eta < 5$ for muons. In addition, one muon must have $p_{\mathrm{T}} > 20\,\text{GeV}$; this muon is responsible for the event being accepted by the trigger. The second muon is required to have $p_{\mathrm{T}} > 5\,\text{GeV}$. These asymmetric requirements increase the acceptance at high $|\cos\theta^{*}|$. The muons are assumed to be detected, reconstructed and measured with resolution and efficiencies similar to the performance of the current LHCb detector [16, 17], though for simplicity, and given the plans for the LHCb upgrades [18], the efficiency for the LHCb trigger to select these events is taken as unity. Events are considered in the mass window from $60 < m_{\mu\mu} < 150\,\text{GeV}$.

3 Methodology, measurement strategies and estimating sensitivities

Simulated events are generated using POWHEG [19, 20] with PYTHIA8 [21, 22] for the parton shower, using NNPDF31 PDF sets [23]. Expected distributions (for generating toy datasets) are taken as the mean of distributions found from 100 equiprobable PDF sets. The samples are produced at leading order in Electroweak theory, and next-to-leading-order in perturbative QCD (pQCD). In addition, for the simple studies already presented in figures 1 and 3, the entire event is also generated using PYTHIA8, at leading order in pQCD. This sample is also used to cross-check the accuracy of the studies presented here.

The forward-backward asymmetry in Drell-Yan events is considered as a function of mass and rapidity. Templates of this asymmetry are generated for the 100 equiprobable PDF replicas from NNPDF31, and also for different values of the effective leptonic weak mixing angle. The effect of the variation of the effective leptonic weak mixing angle on the templates is found in three different ways: first, the events are directly reweighted within POWHEG for a different value of the angle; second, new samples are generated using a new central value of the angle; third, the angular distribution of events is reweighted to account for the effects of a variation of the angle. All three methods give consistent templates and results. The effect on the variation of the PDF replica considered within NNPDF31 is studied within POWHEG, and is cross-checked by directly generating events having changed the choice of initial PDF replica within the set.

For each toy dataset under consideration, the different effective leptonic weak mixing angle templates (associated with a given PDF replica) are fitted to the forward-backward asymmetry in the toy data. This lets the value of the effective leptonic weak mixing angle favoured by that particular PDF replica to be found. The mean value of the effective leptonic weak mixing angle extracted from the 100 equiprobable PDF replicas is considered the value favoured by that toy dataset. The spread (RMS) of the values favoured by the 100 PDF replica sets the PDF uncertainty associated with that dataset *from current PDF knowledge*. The Bayesian PDF reweighting technique [14] is also applied in order to use the data itself to constrain the PDF uncertainties, since some replicas describe the data better than others. This takes advantage of different dimuon invariant mass regions being more sensitive to PDF variations, and others being more sensitive to variations in the effective leptonic weak mixing angle, as shown in Fig. 4.

An ensemble of 2500 toys are run for each value of integrated luminosity considered. This allows the expected size of PDF uncertainties (both from current knowledge, and reweighted) to be determined from the mean uncertainties over the 2500 toys. The spread (RMS) of the extracted values of the effective leptonic weak mixing angle in the 2500 toys then sets the expected statistical precision for that integrated luminosity. This process is repeated for different integrated luminosities, to determine how the potential precision of a measurement at LHCb will change as more data is collected.

In addition, in any real analysis of data there will be systematic effects and additional uncertainties, both experimental and theoretical, to account for—*e.g.* the accuracy of the knowledge of the detector momentum scale. These are not considered further here in projecting potential sensitivities. This note simply sets out the potential for a ‘perfectly understood’ forward detector. A key task over the coming decade and beyond for analysts at LHCb will therefore be to ensure that such additional uncertainties are sufficiently small that the required precision is met.

4 Results

The expected uncertainties are shown in Fig. 5. Integrated luminosities up to $100\,\mathrm{fb}^{-1}$ are considered explicitly here; beyond this, the number of effective PDF replicas found after applying the reweighting technique becomes too small for meaningful and accurate results. However, the results at lower integrated luminosities can be used to extrapolate the uncertainties expected for the full $300\,\mathrm{fb}^{-1}$ dataset. Without the reweighting, the PDF uncertainty is expected to be about 20×10^{-5}; with sufficient data, this can be reduced to below 10×10^{-5} using the reweighting technique. Statistical uncertainties are also expected to be roughly 5×10^{-5} using the full LHCb dataset. This means that, with sufficient control of other sources of uncertainty, a measurement at LHCb using the full intended

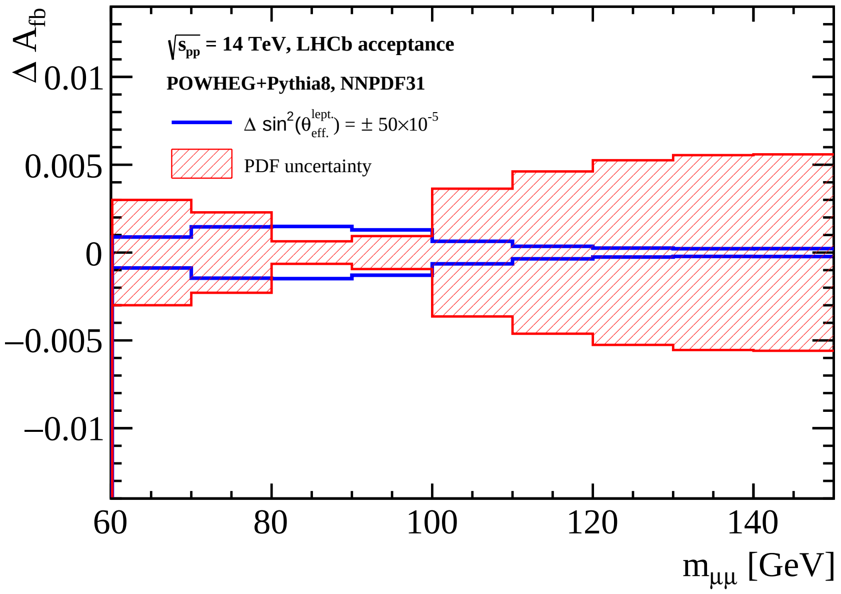

Figure 4: The relative change in the forward-backward asymmetry, integrated over the full LHCb acceptance, from a shift in the effective leptonic weak mixing angle by $\pm 50 \times 10^{-5}$. Also shown on the plot are the PDF uncertainties on the forward-backward asymmetry, found from 100 equiprobable PDF sets in NNPDF31. No detector effects are simulated for this figure.

dataset can be significantly more precise that the combination of measurements at LEP and SLD (16×10^{-5}), which is currently the most precise overall direct determination of the angle. This also means that LHCb will play a significant role in any overall LHC combination of measurements of the effective leptonic weak mixing angle.

5 Further improvements

Measurements of the full angular distribution can provide further sensitivity to the effective leptonic weak mixing angle than the forward-backward asymmetry. Alternatively the forward-backward asymmetry can be determined with events weighted as a function of $\cos\theta^*$ to improve sensitivity [24]. However, in both cases, the accuracy in determining the angular distribution becomes more crucial: in the studies presented here events must simply be correctly labeled as ‘forward’ or ‘backward’.

An additional improvement is also possible for LHCb at the HL-LHC. The ability to reconstruct electrons at LHCb is currently limited by the design of the electromagnetic calorimeter, where individual cells saturate for transverse energies of about 10 GeV, since the initial design of the experiment was optimised for the study of lower energy decays of heavy flavour particles. However, in the forthcoming upgrades, this limitation can be significantly relaxed or removed, allowing measurements using electronic final states at LHCb to contribute equally to measurements using final states containing muons, when considering precision electroweak observables. In this case, the statistical sensitivity can be expected to improve by up to a factor of $\sqrt{2}$, while also placing additional constraints on PDFs. By increasing the number of final states under study, additional systematic uncertainties will also be reduced, since the calorimeter energy scale and the

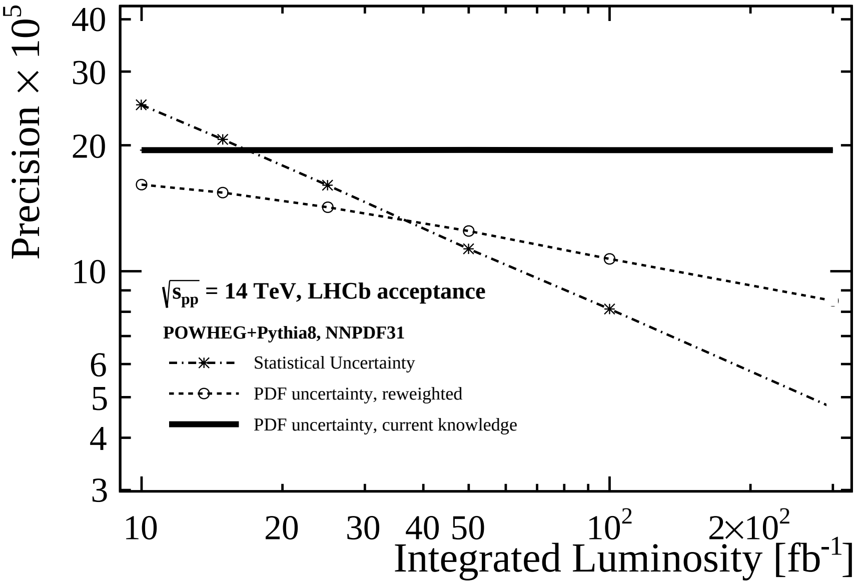

Figure 5: The expected statistical and PDF uncertainties arising from different sources in future measurements of the effective leptonic weak mixing angle at LHCb, as found from measuring the forward-backward asymmetry in Drell-Yan events. For the range 100–300 fb^{-1} the projections are obtained by extrapolation.

track momentum scale are not expected to exhibit significant correlations.

While we have considered here the potential statistical sensitivity of future measurements of the effective leptonic weak mixing angle at the LHCb experiment, as well as the expected PDF uncertainty, future work will be needed to understand systematic effects. It is clear that there are additional sources of uncertainty that must be controlled in any future measurement. These include both theoretical uncertainties (for example, higher order electroweak effects), as well as systematic effects associated with the LHCb detector (such as knowledge of the detector momentum scale). There are also additional PDF uncertainties to be considered, such as modeling uncertainties, exhibited by the spread of results between different PDF sets.

6 Conclusions

The forward coverage of the LHCb experiment at the LHC, coupled to the large dataset to be collected by the experiment (300 fb^{-1}) in the HL-LHC era, means that future measurements of the effective leptonic weak mixing angle using LHCb data can potentially rival the precision of the LEP and SLD combination. Such measurements are also expected to play an important role in future combinations of weak mixing angle measurements. Key to such performance is excellent understanding of both additional systematic effects at the detector, and additional theoretical uncertainties.

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