PROCEEDINGS OF SCIENCE

Probing Z Boson Couplings with Forward-Backward Asymmetry

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We examine the production of neutral current Drell-Yan (DY) lepton pairs within the framework of the Standard Model Effective Field Theory (SMEFT). Utilizing the open-source fit platform xFitter, we explore the impact of high-statistics measurements of the neutral current DY (NCDY) forward-backward asymmetry A_{FB} near the weak boson mass scale in both the present and upcoming stages of the Large Hadron Collider (LHC). Our analysis not only confirms previous findings regarding the sensitivity of A_{FB} to parton distribution functions (PDFs) but also delves into the precise determination of Z-boson couplings to left-handed and right-handed u-quarks and d-quarks. Additionally, we investigate contributions beyond the Standard Model using the SMEFT framework. We provide insights into the significance of the A_{FB} asymmetry for the electroweak SMEFT fit and the precision study of Z-boson physics at both the LHC and the high-luminosity HL-LHC.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

https://pos.sissa.it/

PoS(EPS-HEP2023)264

1. Introduction

To systematically investigate the role of the asymmetry in precision electroweak (EW) measurements, searches for BSM phenomena, and determinations of PDFs, a well-established framework is provided by the Standard Model Effective Field Theory (SMEFT) [1]. In this paper [2], we will concentrate on A_{FB} asymmetry measurements in NCDY production in the region near the Z-boson mass scale. The analysis will be performed in the framework of the SMEFT Lagrangian, including operators up to dimension $D = 6$ [1],

$$\mathcal{L} = \mathcal{L}^{(\mathrm{SM})} + \frac{1}{\Lambda^2} \sum_{j=1}^{N_6} C_j^{(6)} \, O_j^{(6)} \,, \tag{1}$$

where the first term on the right-hand side is the SM lagrangian, consisting of operators of mass dimension $D = 4$, while the next term is the EFT contribution containing N_6 operators O_j of mass dimension $D = 6$, each weighted by the dimensionless Wilson coefficient C_j divided by Λ^2, where Λ is the ultraviolet mass scale of the EFT.

In the di-lepton mass region near the Z-boson peak, four-fermion operators and dipole operators coupling fermions and vector bosons can be neglected in Eq. (1), and the whole effect of the $D = 6$ SMEFT Lagrangian is a modification of the vector boson couplings to fermions. Using LEP constraints, corrections to Z-boson couplings to leptons can also be neglected [3]. We will thus focus on the SMEFT corrections to Z-boson couplings to u- and d-quarks, that are least constrained by LEP and have not comprehensively been studied for the LHC.

To explore these SMEFT couplings, we will extend the implementation of the A_{FB} asymmetry provided in Ref. [4], using the quantum chromodynamics (QCD) fit platform `xFitter` (formerly known as `HERAFitter`) [5]. Firstly, we will recover the results of [4] on PDF extracted from A_{FB} pseudodata, and in addition obtain new constraints on Z-boson vector and axial couplings. We will examine the projected luminosity scenario of 3000 fb^{-1} for the High-Luminosity LHC (HL-LHC).

2. A_{FB} within SMEFT in `xFitter`

The left-handed and right-handed quark SM couplings are expressed in terms of the weak mixing angle θ_W as follows,

$$\begin{aligned} g^{Zu}_{R(\mathrm{SM})} &= 1/2 - 2/3 \sin^2\theta_W \,, \quad & g^{Zu}_{L(\mathrm{SM})} &= -2/3 \sin^2\theta_W \,, \\ g^{Zd}_{R(\mathrm{SM})} &= -1/2 + 1/3 \sin^2\theta_W \,, \quad & g^{Zd}_{L(\mathrm{SM})} &= 1/3 \sin^2\theta_W \,. \end{aligned} \tag{2}$$

The SMEFT couplings are obtained from the SM couplings via the corrections δg, i.e., $g_{(\mathrm{SMEFT})} \equiv g_{(\mathrm{SM})} + \delta g$:

$$\begin{aligned} g^{Zu}_L &\equiv g^{Zu}_{L(\mathrm{SMEFT})} = g^{Zu}_{L(\mathrm{SM})} + \delta g^{Zu}_L \,, \quad & g^{Zu}_R &\equiv g^{Zu}_{R(\mathrm{SMEFT})} = g^{Zu}_{R(\mathrm{SM})} + \delta g^{Zu}_R \,, \\ g^{Zd}_L &\equiv g^{Zd}_{L(\mathrm{SMEFT})} = g^{Zd}_{L(\mathrm{SM})} + \delta g^{Zd}_L \,, \quad & g^{Zd}_R &\equiv g^{Zd}_{R(\mathrm{SMEFT})} = g^{Zd}_{R(\mathrm{SM})} + \delta g^{Zd}_R \,. \end{aligned} \tag{3}$$

The forward-backward asymmetry A^*_{FB} is defined as

$$A^*_{\mathrm{FB}} = \frac{d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* > 0] - d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* < 0]}{d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* > 0] + d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* < 0]}. \tag{4}$$

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where θ^* is the decay angle between the outgoing lepton and the incoming quark. We will consider the measurement of the $A^*_{\rm FB}$ asymmetry differentially in $M_{\ell\ell}$ and $y_{\ell\ell}$ according to Eqs. (1), (4).

To perform this study, we extend the implementation [4] of the $A^*_{\rm FB}$ asymmetry in the `xFitter` platform [5] to i) include the SMEFT couplings described above in Eqs. (3), and ii) upgrade the calculations to double-differential distributions in both invariant mass $M_{\ell\ell}$ and rapidity $y_{\ell\ell}$ of the di-lepton final-state system. The collider energy, acceptance cuts and bin boundaries in $M_{\ell\ell}$ and $y_{\ell\ell}$ are adjustable parameters in the present computation. The mass effects of charm and bottom quarks in the matrix element are neglected and the calculation is performed in the $n_f = 5$ flavour scheme. The input theoretical parameters are chosen to be the ones from the EW G_μ scheme, which minimizes the impact of NLO EW corrections. The explicit values for the relevant parameters in our analysis can be found in Ref. [2]. Suitable data files which mimic future measurements at the HL-LHC have been generated for the analysis. We use the number of events with electron pairs from Z decays as predicted at LO with the acceptance cuts $|\eta_\ell| < 5$ and $p_T^\ell > 20$ GeV and introduce a further correction factor of 20% to model a realistic detector response.

The pseudodata have been generated for the collider center-of-mass energy of 13 TeV and integrated luminosity of 3000 fb^{-1}, the designed integrated luminosity at the end of the HL-LHC stage. To explore different proton PDF sets, several data files have been generated adopting the recent NNLO variants of the PDF sets CT18 [6], NNPDF4.0 [7], ABMP16 [8], HERAPDF2.0 [9] and MSHT20 [10].

We have optimized the bin widths based on the precision of the fitted couplings which we extract from the pseudodata. As a figure of merit, we have used the geometrical average error of the couplings. Based on this study, we chose the bin width of 5 GeV in the invariant mass and 0.6 in the rapidity of the dilepton system, since a further reduction of the bin width does not improve the sensitivity to the couplings significantly. The largest sensitivity to the couplings is expected in the region $55 \lesssim M_{ll} \lesssim 110$ GeV, and in our analysis we have adapted a slightly wider range $45 < M_{ll} < 145$ GeV. Here the upper boundary is well below the mass of the WW diboson system, so possible contributions from four-fermion operators can be neglected. We have limited the rapidity region $|y_{ll}| < 3.6$ assuming the extension of the detector acceptance up to pseudorapidity $|\eta_l| < 5$.

3. Results

The pseudodata sets are fitted with the four modifications to the couplings δ_{Lu}, δ_{Ru}, δ_{Ld}, δ_{Rd} being free parameters. The fit is performed by minimizing a χ^2 expression, which includes the uncertainties of pseudodata and PDFs. The latter are incorporated using the profiling technique [11]. As the tolerance criterion we use $\Delta\chi^2 = 1$. The results of the fit are presented in Figs. 1–3 as allowed regions for different pairs of corrections to the Z couplings to u- and d-type quarks at confidence level (CL) of 68%. The resulting uncertainties on the couplings to the d-type quarks are roughly a factor of two larger than the corresponding uncertainties for the u-type quarks.

In Figs. 1 the allowed regions are shown as obtained using different PDF sets.[1] Both the size and the shape of the allowed regions (i.e. the correlations between the fitted parameters) are similar, independent of the PDF set. The impact of the PDF uncertainties is sizable. Namely, after including

[1]The PDF uncertainties of the CT18 set were rescaled to CL=68%.

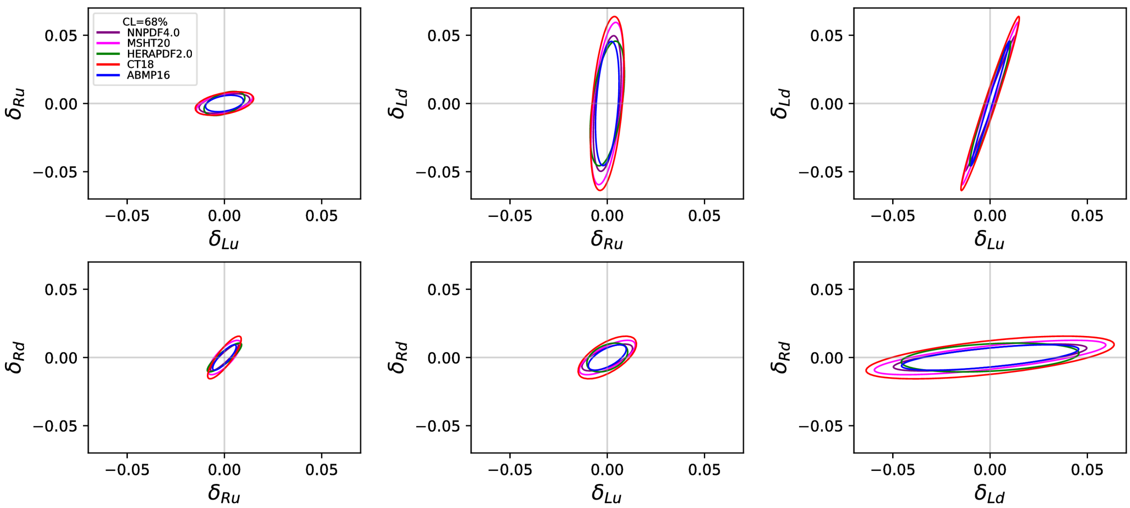

Figure 1: Allowed regions for all pairs of corrections to the Z couplings to u- and d-type quarks obtained using different PDF sets.

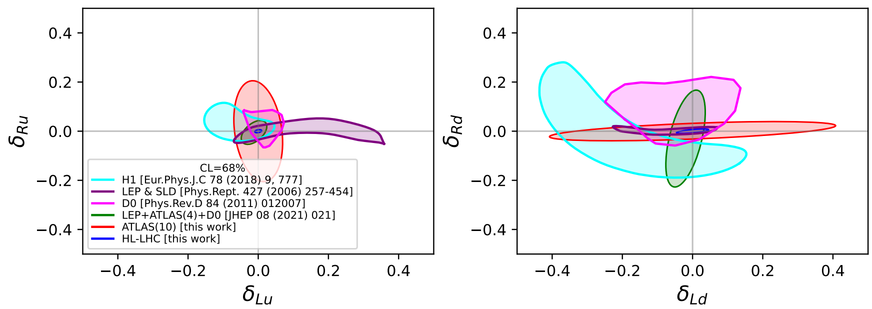

Figure 2: Allowed regions for all pairs of corrections to the Z couplings to u- and d-type quarks obtained using HL-LHC pseudodata as well as different existing data sets.

them into the fit the uncertainties on the couplings increase by a factor of ~ 3, i.e. the resulting uncertainties on the couplings are dominated by the PDF uncertainties. When using different PDF sets, the size of the average uncertainty does not change by more than a factor of 1.5 indicating a reasonable consistency between the size of the PDF uncertainties for the modern PDF sets.

In Figs. 2 we compare our results obtained for the HL-LHC with the other analyses of exisitng data from LEP, Tevatron, HERA and LHC. Namely, we compare with the analysis of the H1 Collaboration at HERA [12], the LEP+SLD combination [13], the analysis of D0 Collaboration at Tevatron [14] and the analysis of LEP, ATLAS and D0 data from Ref. [3]. In addition to the HL-LHC results, we present our results of analysing all available 10 bins from the ATLAS measurement of $A_{\rm FB}$ [15], while only 4 bins at the Z peak were used in the analysis of Ref. [3]. For the analysis of ATLAS data, we set the central data points to the theoretical predictions obtained at LO, while we use the data statistical and systematic uncertainties, as well as the PDF uncertainties. The level of precision expected at the HL-LHC outperforms any existing data sets.

In Figs. 3 we compare the results obtained for the HL-LHC with the results expected at the future colliders currently under discussion, LHeC [16] and FCC-eh [17]. For the LHeC, two

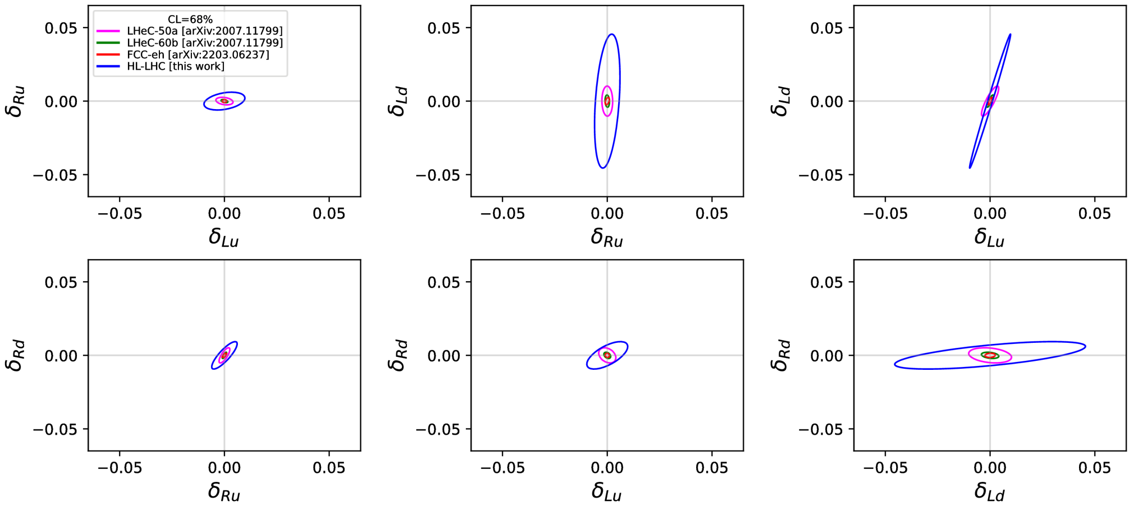

Figure 3: Allowed regions for all pairs of corrections to the Z couplings to u- and d-type quarks obtained using HL-LHC pseudodata compared to the ones for different future experiments.

electron beam energies of 50 or 60 GeV are considered, and two assumptions on the uncertainties. A sub-percent level of precision is expected at the LHeC, FCC-eh and HL-LHC, which is one order of magnitude better than what can be obtained using existing data sets from LEP, Tevatron, HERA and LHC.

4. Conclusions

We have studied the possibility to improve constraints on the Z couplings to the u- and d-type quarks using the future measurements of A_{FB} at the HL-LHC with 3000 fb^{-1}. We suggest double-differential measurements of the A_{FB} as a function of both the invariant mass and rapidity of the lepton pairs. Our quantitative analysis of the impact of the binning scheme on the precision of the extracted couplings suggests the choice of a specific binning scheme which ensures a substantial sensitivity to the couplings in such a measurement.

The resulting uncertainties on the couplings to the d-type quarks are found to be approximately a factor of two larger than the corresponding uncertainties for the u-type quarks. The uncertainties on the Z couplings to the u- and d-type quarks at the HL-LHC are expected at a percent level, thus outperforming by an order of magnitude any determinations of these couplings using existing data sets. This level of precision is similar but slightly less than expected at the LHeC and FCC-eh.

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