

# Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC

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**ABSTRACT:** Neutral current Drell-Yan (DY) lepton-pair production is considered in the framework of the Standard Model Effective Field Theory (SMEFT). Using the open-source fit platform `xFitter`, we investigate the impact of high-statistics measurements of the neutral current DY (NCDY) forward-backward asymmetry  $A_{\text{FB}}$  near the weak boson mass scale in the present and forthcoming stages of the Large Hadron Collider (LHC). Besides recovering earlier results on the  $A_{\text{FB}}$  sensitivity to parton distribution functions, we analyze the precision determination of  $Z$ -boson couplings to left-handed and right-handed  $u$ -quarks and  $d$ -quarks, and explore Beyond-Standard-Model contributions using the SMEFT framework. We comment on the role of the  $A_{\text{FB}}$  asymmetry for the electroweak SMEFT fit and precision  $Z$ -boson physics at the LHC and high-luminosity HL-LHC.

**KEYWORDS:** SMEFT, Electroweak interaction, Lepton production, proton-proton scattering, Parton Distribution Functions

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## 1 Introduction

The physics program centering on electroweak (EW) precision observables receives essential inputs from measurements of  $W$  and  $Z$  bosons at the LHC. Owing to the cancellation of many systematic uncertainties, the forward-backward asymmetry  $A_{\text{FB}}$  in NCDY lepton-pair production is a crucial component of this program. The  $A_{\text{FB}}$  asymmetry is employed for determinations of the weak mixing angle  $\theta_W$  from LHC measurements at the  $Z$ -pole [1–4], complementing LEP/SLD [5] and Tevatron [6] results.

Given that parton distribution functions (PDFs) constitute one of the dominant uncertainty sources in the precision EW physics program at the LHC, it is especially relevant that the  $A_{\text{FB}}$  asymmetry has been shown to provide us with new sensitivity to PDFs [7–11]. This sensitivity is currently not exploited in global PDF extractions [12–16], and could potentially lead to dramatic improvements in our knowledge of PDFs. This applies, in particular, in kinematic regions which are relevant for new physics searches in the multi-TeV region at the LHC, for instance in the context of Beyond-Standard-Model (BSM) heavy  $Z'$  [17, 18] and  $W'$  bosons [19], and photon-induced di-lepton production processes [20–22].

Furthermore, as in Ref. [11] the impact of the forward-backward  $A_{\text{FB}}$  asymmetry in the neutral current sector may be combined with that of the lepton-charge  $A_W$  asymmetry in the charged current sector. This points to strategies which are alternative to those taken in experimental analyses such as in Refs. [1, 3, 23], and aim at exploiting new measurements, capable of providing sensitivity to PDFs with low theoretical and experimental systematics while controlling correlations. Related investigations of the  $A_{\text{FB}}$  asymmetry in Ref. [24] focus on the behavior induced by the NNPDF4.0 set [14]. See also the studies [25–30] based on the package EPUMP [31, 32].

To systematically investigate the role of the asymmetry in precision EW measurements, searches for BSM phenomena, and determinations of PDFs, a well-established framework is provided by the Standard Model Effective Field Theory (SMEFT) [33]. Details can be found in recent reviews [34, 35] and SMEFT fitting packages [36–38]. Recent SMEFT

studies of precision electroweak observables in di-lepton channels at the LHC have been performed in Refs. [39–44] and analogous studies on the role of PDFs in BSM searches in Refs. [45, 46].

In this paper we will concentrate on  $A_{\text{FB}}$  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  $D = 6$  [33, 47],

$$\mathcal{L} = \mathcal{L}^{(\text{SM})} + \frac{1}{\Lambda^2} \sum_{j=1}^{N_6} C_j^{(6)} \mathcal{O}_j^{(6)}, \quad (1.1)$$

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  $\mathcal{O}_j$  of mass dimension  $D = 6$ , each weighted by the dimensionless Wilson coefficient  $C_j$  divided by  $\Lambda^2$ , where  $\Lambda$  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 [39, 43] in Eq. (1.1), and the whole effect of the  $D = 6$  SMEFT Lagrangian is a modification of the vector boson couplings to fermions. Using LEP constraints [5], corrections to  $Z$ -boson couplings to leptons can also be neglected [43]. We will thus focus on the SMEFT corrections to  $Z$ -boson couplings to  $u$ -type (including  $c$ ) and  $d$ -type (including  $s, b$ ) quarks, that are least constrained by LEP and have not comprehensively been studied at the LHC.

To explore these SMEFT couplings, we will extend the implementation of the  $A_{\text{FB}}$  asymmetry provided in Ref. [9], using the quantum chromodynamics (QCD) fit platform **xFitter** (formerly known as **HERAFitter**) [48–50]. As a check, we will recover the results of Ref. [9] on PDF extracted from  $A_{\text{FB}}$  pseudodata, and in addition we will obtain new constraints on  $Z$ -boson vector and axial couplings. We will examine the projected luminosity scenario of  $3000 \text{ fb}^{-1}$  for the High-Luminosity LHC (HL-LHC) [51–53].

The paper is organized as follows. In Sec. 2 we present the SMEFT treatment of the NCDY di-lepton production process in terms of EFT corrections to the SM couplings, and its implementation to make predictions for the  $A_{\text{FB}}$  asymmetry in **xFitter**. In Sec. 3 we describe the  $A_{\text{FB}}$  pseudodata generation. In Sec. 4 we carry out the main analysis within **xFitter**, leading to the determination of the SMEFT couplings. In Sec. 5 we give conclusions.

## 2 $A_{\text{FB}}$ within SMEFT in **xFitter**

In this section we start by describing the  $D = 6$  SMEFT Lagrangian for  $Z$ -boson interactions with fermions, and introduce the SMEFT couplings for left-handed and right-handed  $u$ -quarks and  $d$ -quarks. Next we define the SMEFT vector and axial couplings, and express the forward-backward asymmetry  $A_{\text{FB}}$  in terms of these couplings. We discuss the extension of the **xFitter** implementation [9] for  $A_{\text{FB}}$  to the SMEFT case.

The SMEFT lagrangian for the coupling of the  $Z$ -boson to fermions is given by

$$\begin{aligned} \mathcal{L}_Z^{(\text{SMEFT})} = 2M_Z \sqrt{G_\mu \sqrt{2}} Z^\alpha \Big\{ & \bar{q}_L \gamma_\alpha \left( g_{L(\text{SM})}^{Zq} + \delta g_L^{Zq} \right) q_L + \bar{u}_R \gamma_\alpha \left( g_{R(\text{SM})}^{Zu} + \delta g_R^{Zu} \right) u_R \\ & + \bar{d}_R \gamma_\alpha \left( g_{R(\text{SM})}^{Zd} + \delta g_R^{Zd} \right) d_R + \{\text{leptonic terms}\} \Big\} \end{aligned} \quad (2.1)$$

Here  $q_L$  is the left-handed quark  $\text{SU}(2)$  doublet, while  $u_R$  and  $d_R$  are the right-handed quark  $\text{SU}(2)$  singlets. The left-handed and right-handed quark SM couplings are expressed in terms of the weak mixing angle  $\theta_W$  as follows,

$$\begin{aligned} g_{R(\text{SM})}^{Zu} &= 1/2 - 2/3 \sin^2 \theta_W, & g_{L(\text{SM})}^{Zu} &= -2/3 \sin^2 \theta_W, \\ g_{R(\text{SM})}^{Zd} &= -1/2 + 1/3 \sin^2 \theta_W, & g_{L(\text{SM})}^{Zd} &= 1/3 \sin^2 \theta_W. \end{aligned} \quad (2.2)$$

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

$$\begin{aligned} g_L^{Zu} &\equiv g_{L(\text{SMEFT})}^{Zu} = g_{L(\text{SM})}^{Zu} + \delta g_L^{Zu}, & g_R^{Zu} &\equiv g_{R(\text{SMEFT})}^{Zu} = g_{R(\text{SM})}^{Zu} + \delta g_R^{Zu}, \\ g_L^{Zd} &\equiv g_{L(\text{SMEFT})}^{Zd} = g_{L(\text{SM})}^{Zd} + \delta g_L^{Zd}, & g_R^{Zd} &\equiv g_{R(\text{SMEFT})}^{Zd} = g_{R(\text{SM})}^{Zd} + \delta g_R^{Zd}. \end{aligned} \quad (2.3)$$

The vector and axial couplings of the  $Z$ -boson are defined by taking the combinations  $L \pm R$  of the left-handed and right-handed fermion couplings. So the SMEFT vector and axial couplings are given by

$$\begin{aligned} g_V^{Zu} &= g_R^{Zu} + g_L^{Zu}, & g_A^{Zu} &= g_R^{Zu} - g_L^{Zu}, \\ g_V^{Zd} &= g_R^{Zd} + g_L^{Zd}, & g_A^{Zd} &= g_R^{Zd} - g_L^{Zd}. \end{aligned} \quad (2.4)$$

In order to maximize the sensitivity, we consider the DY triple-differential cross section in the di-lepton invariant mass  $M_{\ell\ell}$ , di-lepton rapidity  $y_{\ell\ell}$  and angular variable  $\theta^*$  between the outgoing lepton and the incoming quark in the Collins-Soper (CS) reference frame [54]. In this frame, the decay angle is measured from an axis symmetric with respect to the two incoming partons. The expression for the angle  $\theta^*$  in the CS frame is given by

$$\cos \theta^* = \frac{p_{Z,\ell\ell}}{M_{\ell\ell} |p_{Z,\ell\ell}|} \frac{p_1^+ p_2^- - p_1^- p_2^+}{\sqrt{M_{\ell\ell}^2 + p_{T,\ell\ell}^2}}, \quad (2.5)$$

where  $p_i^\pm = E_i \pm p_{Z,i}$  and the index  $i = 1, 2$  corresponds to the positive and negative charged lepton respectively. Here  $E$  and  $p_Z$  are the energy and the  $z$ -components of the leptonic four-momentum, respectively;  $p_{Z,\ell\ell}$  is the di-lepton  $z$ -component of the momentum and  $p_{T,\ell\ell}$  is the di-lepton transverse momentum. At leading order (LO) in QCD and EW theory, this cross section can be written as

$$\frac{d^3 \sigma}{dM_{\ell\ell} dy_{\ell\ell} d\cos \theta^*} = \frac{\pi \alpha^2}{3M_{\ell\ell} s} \sum_q P_q [f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) + f_{\bar{q}}(x_1, Q^2) f_q(x_2, Q^2)], \quad (2.6)$$

where  $s$  is the square of the centre-of-mass energy of the collision,  $x_{1,2} = M_{\ell\ell} e^{\pm y_{\ell\ell}} / \sqrt{s}$  are the momentum fractions of the initial-state partons,  $f_{q,\bar{q}}(x_i, Q^2)$  are their PDFs,  $Q^2$  is the

squared factorization scale, and the factor  $P_q$  contains the propagators and couplings of the  $Z$ -boson, photon, and  $Z$ - $\gamma$  interference,

$$\begin{aligned}
P_q = & e_\ell^2 e_q^2 (1 + \cos^2 \theta^*) \\
& + \frac{M_{\ell\ell}^2 (M_{\ell\ell}^2 - M_Z^2)}{2 \sin^2 \theta_W \cos^2 \theta_W [(M_{\ell\ell}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} (e_\ell e_q) \left[ g_V^{Z\ell} g_V^{Zq} (1 + \cos^2 \theta^*) + 2 g_A^{Z\ell} g_A^{Zq} \cos \theta^* \right] \\
& + \frac{M_{\ell\ell}^4}{16 \sin^4 \theta_W \cos^4 \theta_W [(M_{\ell\ell}^2 - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \\
& \times \left\{ [(g_A^{Z\ell})^2 + (g_V^{Z\ell})^2][(g_A^{Zq})^2 + (g_V^{Zq})^2](1 + \cos^2 \theta^*) + 8 g_A^{Z\ell} g_V^{Z\ell} g_A^{Zq} g_V^{Zq} \cos \theta^* \right\}.
\end{aligned} \tag{2.7}$$

Here  $M_Z$  and  $\Gamma_Z$  are the mass and the width of the  $Z$  boson,  $e_\ell$  and  $e_q$  are the lepton and quark electric charges,  $g_V^{Z\ell} = -1/2 + 2 \sin^2 \theta_W$  and  $g_A^{Z\ell} = -1/2$  are the vector and axial couplings of leptons, and  $g_V^{Zq}$  and  $g_A^{Zq}$  are the SMEFT vector and axial couplings of quarks in Eqs. (2.3), (2.4). The first and third terms on the right hand side of Eq. (2.7) are the square of the  $s$ -channel diagrams with photon and  $Z$ -boson mediators respectively, while the second term is the interference between the two.

The forward-backward asymmetry  $A_{\text{FB}}^*$  is defined as

$$A_{\text{FB}}^* = \frac{d^2 \sigma / dM_{\ell\ell} dy_{\ell\ell} [\cos \theta^* > 0] - d^2 \sigma / dM_{\ell\ell} dy_{\ell\ell} [\cos \theta^* < 0]}{d^2 \sigma / dM_{\ell\ell} dy_{\ell\ell} [\cos \theta^* > 0] + d^2 \sigma / dM_{\ell\ell} dy_{\ell\ell} [\cos \theta^* < 0]}. \tag{2.8}$$

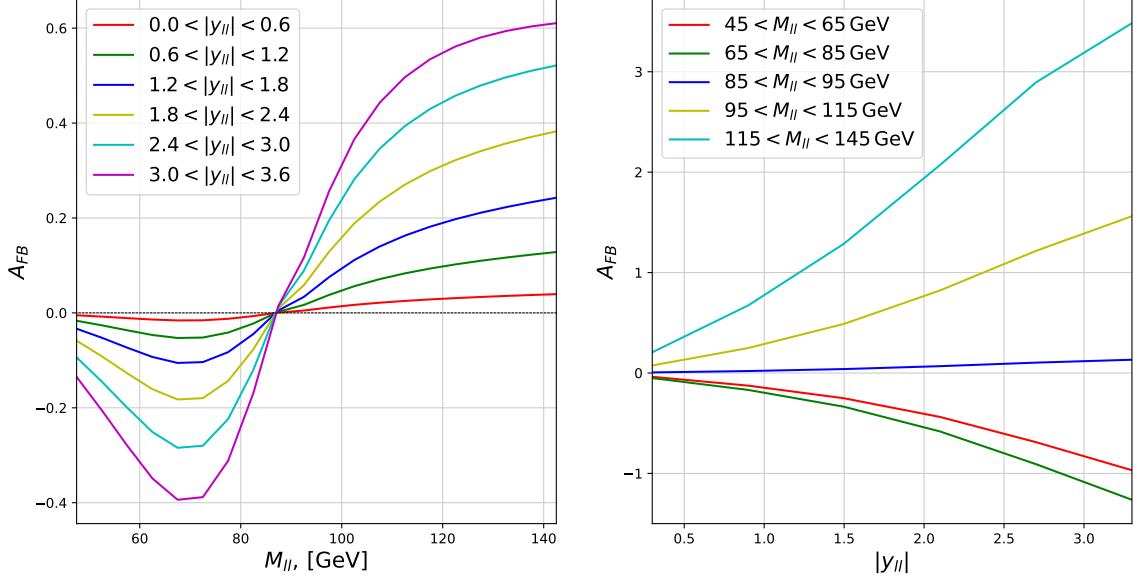
We will consider the measurement of the  $A_{\text{FB}}^*$  asymmetry differentially in  $M_{\ell\ell}$  and  $y_{\ell\ell}$  according to Eqs. (2.6), (2.8).

To perform this study, we extend the implementation [9] of the  $A_{\text{FB}}^*$  asymmetry in the **xFitter** platform [48, 49] to i) include the SMEFT couplings described above in Eqs. (2.3), (2.4), 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. Fiducial selections are applied to the leptons, by requiring them to have a transverse momentum  $p_T^\ell > 20$  GeV and pseudorapidity  $|\eta_\ell| < 5$ . The mass effects of charm and bottom quarks in the matrix element are neglected, as appropriate for a high-scale process, 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  $G_\mu$  scheme, which minimizes the impact of NLO EW corrections, see e.g. Ref. [55]. The explicit values for the relevant parameters in our analysis are the following:  $M_Z = 91.188$  GeV,  $\Gamma_Z = 2.441$  GeV,  $M_W = 80.149$  GeV,  $\alpha_{em} = 1/132.507$ .

The predicted  $A_{\text{FB}}$  as a function of the invariant mass and rapidity of the di-lepton system at LO in the SM is shown in Fig. 1. The  $A_{\text{FB}}$  crosses zero around  $M_{\ell\ell} \approx M_Z$ . Also, due to its definition using the longitudinal boost of the di-lepton system, it approaches zero at  $y_{\ell\ell} = 0$ . For this calculation, we used the HERAPDF2.0 [16] PDF set, however, its general features do not depend on the PDF set.<sup>1</sup>

We next investigate the dependence of the predicted  $A_{\text{FB}}$  on the couplings. In Figs. 2 and 3 we show the numerically-calculated partial derivatives of the  $A_{\text{FB}}$  with respect to

<sup>1</sup>Theoretical predictions for  $A_{\text{FB}}$  obtained using other PDF sets can be found e.g. in Ref. [3] or Ref. [7].



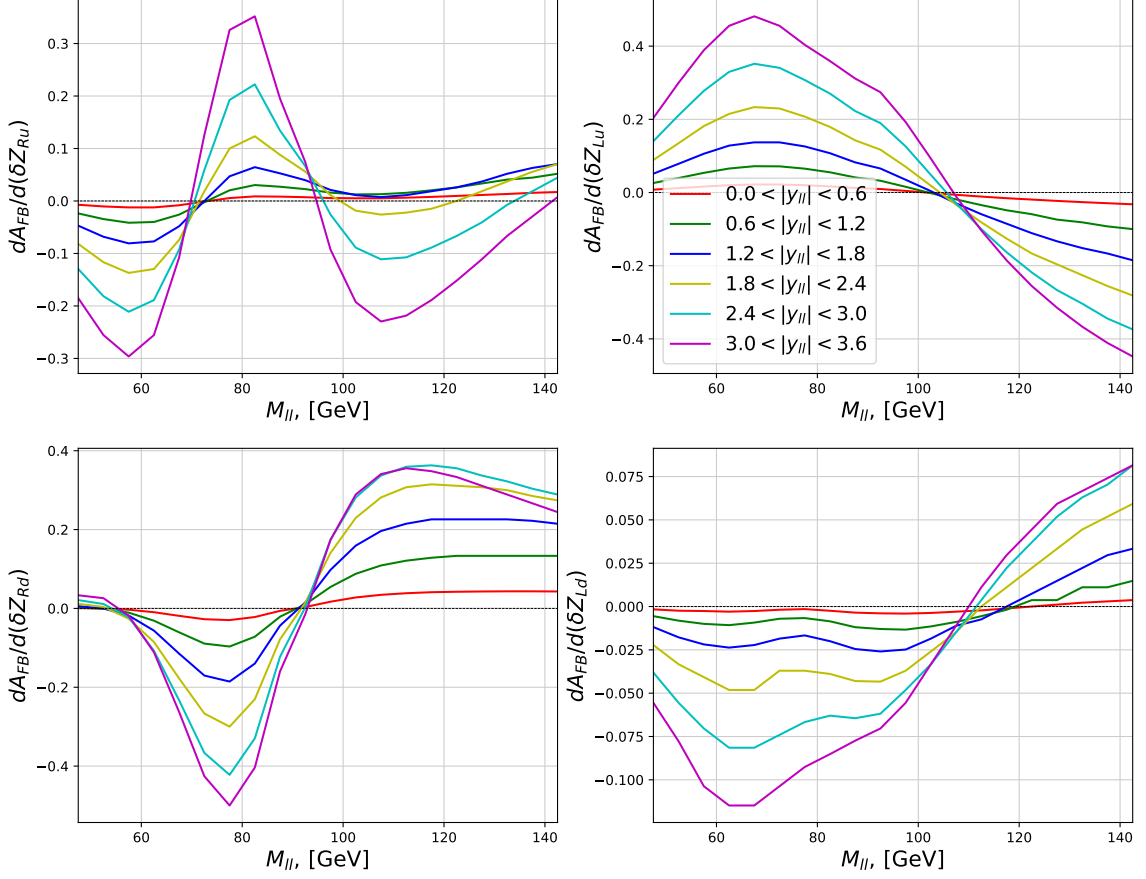
**Figure 1.** The predicted  $A_{FB}$  as a function of the invariant mass of the dilepton system in different rapidity intervals (left) and rapidity of the dilepton system in different invariant mass intervals (right) at LO in the SM.

each coupling as a function of the invariant mass and rapidity of the dilepton system. Furthermore, in Figs. 4 and 5 these derivatives are shown with respect to the axial and vector couplings. It is instructive to see from Fig. 2 that the partial derivatives as functions of  $M_{\ell\ell}$  cross zero at values of  $M_{\ell\ell}$  which are almost independent of  $y_{\ell\ell}$ . As a result, the partial derivatives as functions of  $y_{\ell\ell}$  vanish after integrating over the  $M_{\ell\ell}$  regions which contain such turnover points near their centers (e.g.,  $\partial A_{FB}/\partial \delta g_R^{Zd} \approx 0$  for  $85 < M_{\ell\ell} < 95$  GeV). This is an important observation for experimental analyses which aim to measure  $A_{FB}$  in bins of  $M_{\ell\ell}$  and  $y_{\ell\ell}$ : in particular, in order to retain sensitivity to the couplings, the binning scheme should be chosen carefully, preferably such that the points where the derivatives vanish are placed at the bin boundaries, rather than at their centers. Furthermore, the magnitudes of the derivatives give an idea of which phase-space regions are expected to be most sensitive to the couplings. However, one needs to take into account the expected statistical uncertainties also. Therefore, we will come back to this after introducing the pseudodata in the next section.

### 3 Generation of pseudodata sets

Suitable data files which mimic future measurements at the HL-LHC have been generated for the analysis. The central values of the pseudodata points are set to the SM theoretical predictions. An important piece of information contained in the data files is the statistical precision associated to the  $A_{FB}$  experimental measurements in each bin. It is given by:

$$\Delta A_{FB} = \sqrt{\frac{1 - A_{FB}^2}{N}}, \quad (3.1)$$

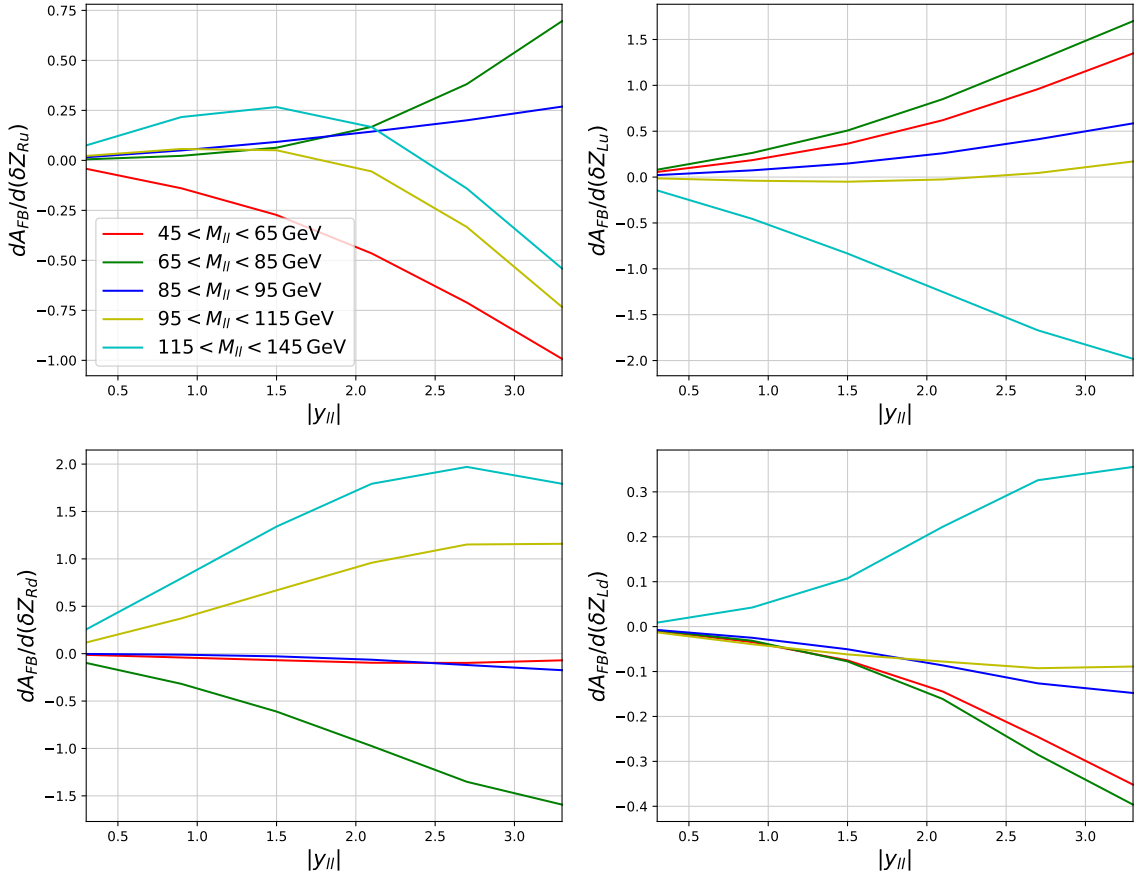


**Figure 2.** The partial derivatives of the predicted  $A_{\text{FB}}$  with respect to  $\delta_{Ru}$  (upper left),  $\delta_{Lu}$  (upper right),  $\delta_{Rd}$  (lower left) and  $\delta_{Ld}$  (lower right) couplings as a function of the invariant mass of the dilepton system in different rapidity intervals at LO.

where  $N$  is the expected total number of events in a specific invariant mass interval. 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 [56]. The choice of LO accuracy for the expected number of events provides a conservative estimation of the statistical uncertainty. The higher-order QCD corrections through next-to-next-to-leading order (NNLO) for the DY process are, generally, moderate and do not distort much differential distributions, see, e.g. Ref. [57]. We have checked that the usage of NNLO QCD predictions would increase the expected number of events by factor 1.1–1.4 depending on the phase space region, so the statistical uncertainties does not change by more than 20% [9]. Furthermore, we have tested our approach by comparing the statistical uncertainties from the ATLAS measurement of  $A_{\text{FB}}$  [3] with the ones produced using our pseudodata scenario, and found a reasonable agreement within a factor of two.<sup>2</sup>

<sup>2</sup>Since the results of the ATLAS measurement [3] are reported in the full phase space of the leptons, the statistical uncertainties depend also on the extrapolation factors which we did not include in this study.

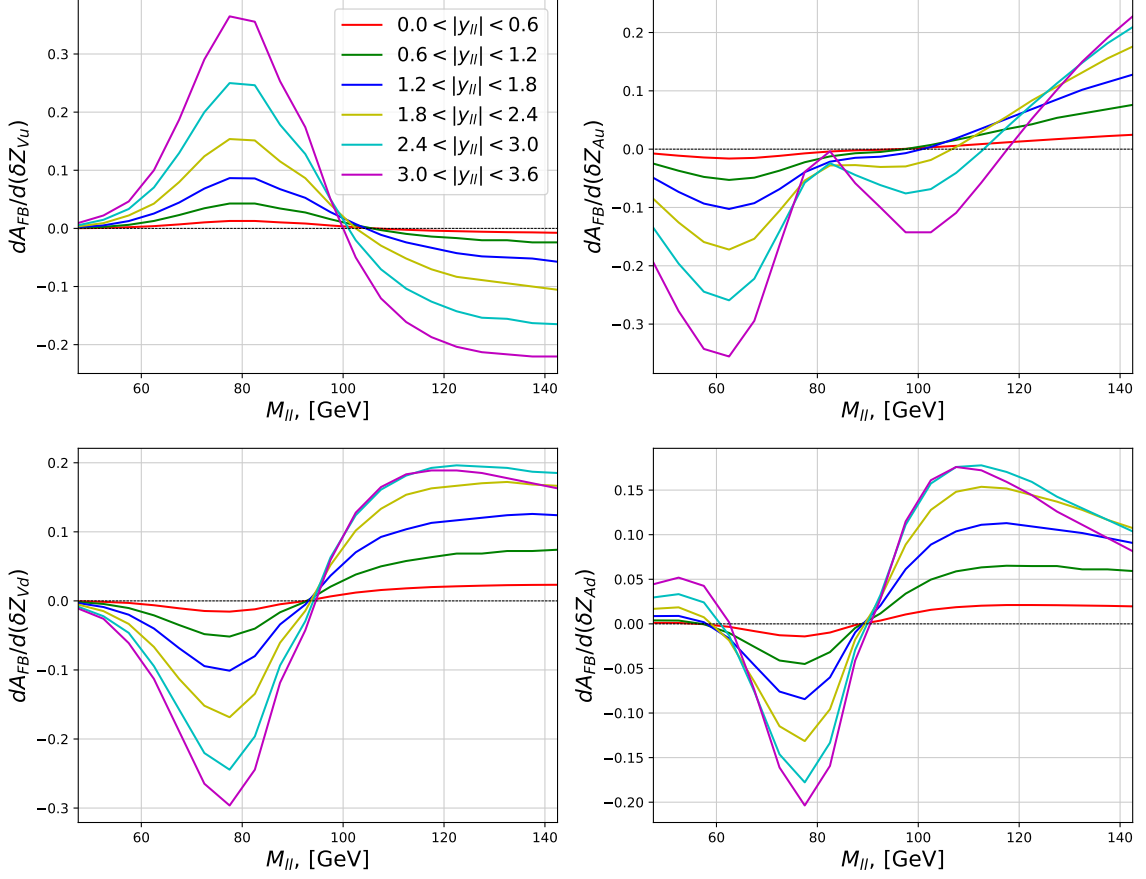




**Figure 3.** The partial derivatives of the predicted  $A_{\text{FB}}$  with respect to  $\delta_{Ru}$  (upper left),  $\delta_{Lu}$  (upper right),  $\delta_{Rd}$  (lower left) and  $\delta_{Ld}$  (lower right) couplings as a function of the rapidity of the dilepton system in different invariant mass intervals at LO.

The pseudodata have been generated for the collider centre-of-mass energy of 13 TeV and integrated luminosity of  $3000 \text{ fb}^{-1}$ , the designed integrated luminosity at the end of the HL-LHC stage [51]. To explore different proton PDF sets, several data files have been generated adopting the recent NNLO variants of the PDF sets CT18 [12], NNPDF4.0 [14], ABMP16 [15], HERAPDF2.0 [16] and MSHT20 [13] along with their respective uncertainties as provided by each fitting group.

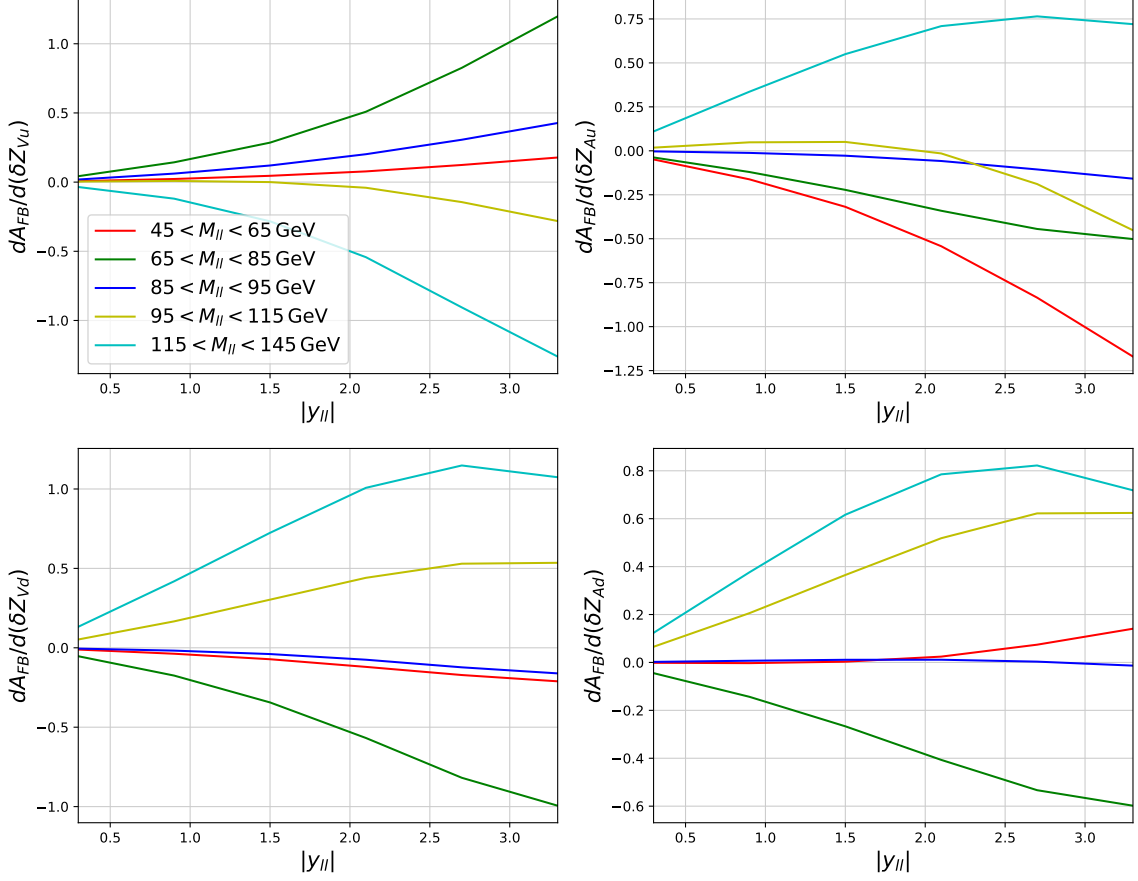
Theoretical uncertainties arising from the choice of factorization and renormalization scales have been assessed. For this purpose, we used theoretical predictions at NLO obtained using `MadGraph5_aMC@NLO` [58] interfaced to `APPLgrid` [59] through `aMCfast` [60]. We have found that the impact of scale variations by the conventional factor of two in the theoretical predictions at NLO is small compared to the statistical uncertainties of the pseudodata, and thus we do not include it in our analysis. A similar study (focused on the impact of the  $A_{\text{FB}}$  on PDFs) was performed in Ref. [9]. Also, it is worth mentioning that even smaller theoretical uncertainties could be expected at NNLO in QCD. Furthermore, while it would be important to include the NLO EW effects in an analysis of experimental



**Figure 4.** Same as in Fig. 2 for the axial and vector couplings.

data aiming to obtain accurate central values, they are not expected to bring significant modification to the uncertainties.

Another important ingredient of the pseudodata is the binning scheme. As discussed in Section 2, bins with the turnover points of the partial derivatives of  $A_{FB}$  with respect to the couplings should be avoided, because in such bins the sensitivity to the couplings is washed out after integrating over the bin. In general, one needs as fine as possible bins in order to maximize the sensitivity to the parameters of interest. However, due to limited detector resolution too fine bins cannot be used. 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, i.e. the fourth root of the product of the resulting uncertainties on each of the four determined couplings,  $\sqrt[4]{\Delta\delta g_R^{Zu}\Delta\delta g_R^{Zd}\Delta\delta g_L^{Zu}\Delta\delta g_L^{Zd}}$ . In Fig. 6 we show this quantity as a function of the invariant mass and rapidity bin widths. 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. These bin widths are feasible given the resolution of the existing detectors. The minimum expected number of events in a bin amounts to  $\sim 10000$ , thus the probability distribution function



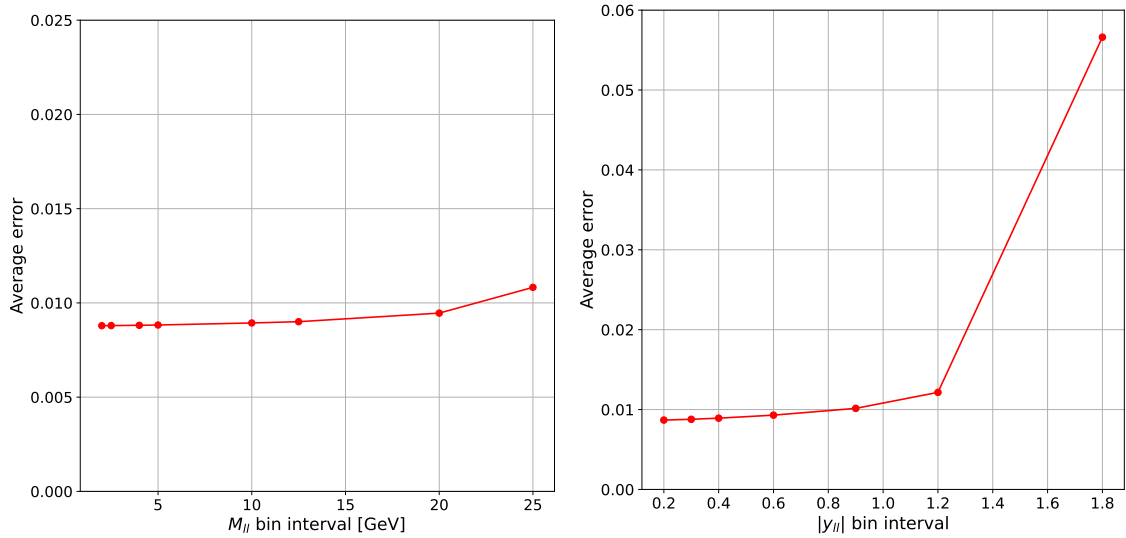
**Figure 5.** Same as in Fig. 3 for the axial and vector couplings.

of the statistical uncertainty is well approximated by a normal distribution.

It is illustrative to look at the magnitudes of the partial derivatives as a function of the invariant mass and rapidity of the dilepton system weighted by the inverse of the statistical uncertainty of pseudodata in the corresponding phase-space region, as shown in Figs. 7–10. This quantity is proportional to the sensitivity to the couplings which can be extracted from such a phase-space region. The largest sensitivity to the couplings is expected in the region  $55 \lesssim M_{ll} \lesssim 110$  GeV (see Figs. 7, 9), and in our analysis we have adopted a slightly wider range  $45 < M_{ll} < 145$  GeV. Here the upper boundary is well below the mass of the  $WW$  diboson system, such that 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  $|\eta| < 5$  (while potentially the region  $|y_{ll}| > 3.6$  could provide even further improvement for the sensitivity to the couplings).

## 4 Results

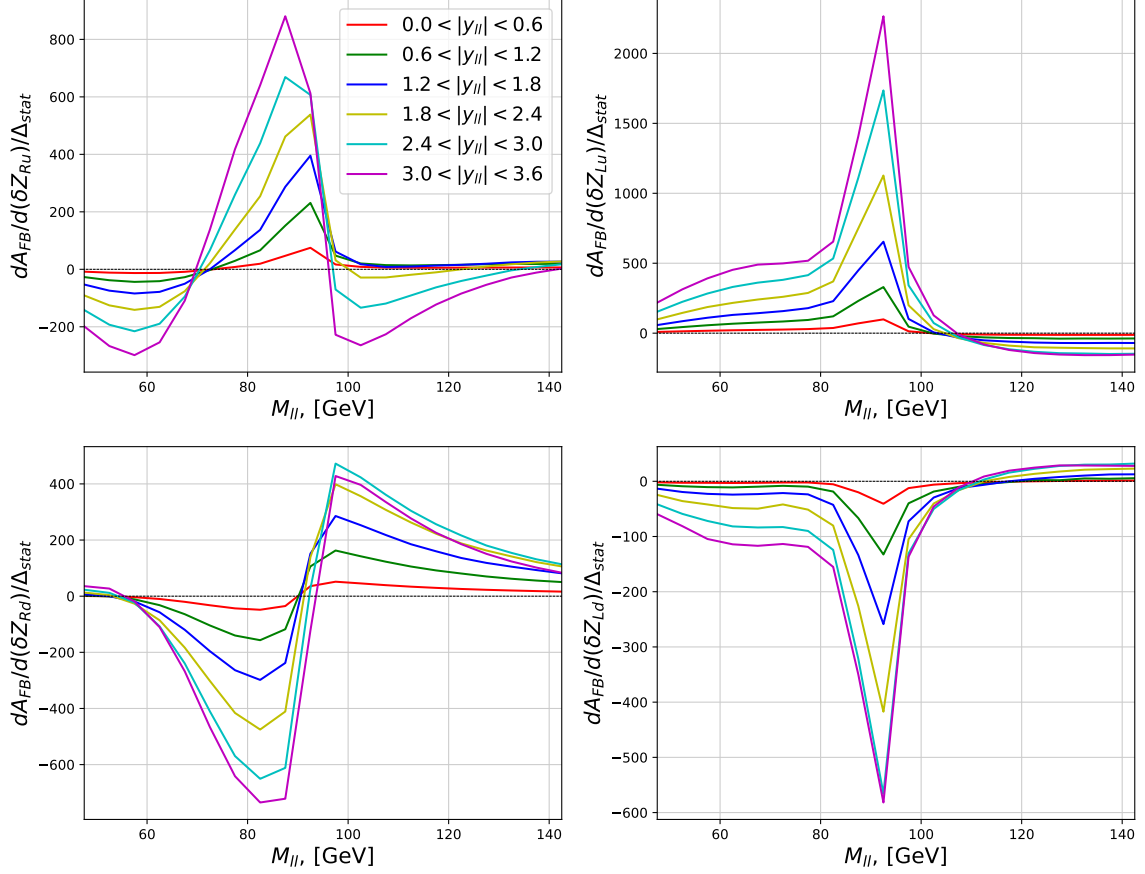
The pseudodata sets are fitted with the four modifications to the couplings  $\delta_{Lu}$ ,  $\delta_{Ru}$ ,  $\delta_{Ld}$ ,  $\delta_{Rd}$  being free parameters. The fit is performed using the MINUIT [61] library by minimizing



**Figure 6.** The average error in the fitted couplings as a function of the invariant mass (left) and rapidity (right) bin widths.

a  $\chi^2$  expression, which follows the one used in Ref. [16] and includes the uncertainties of pseudodata and PDFs. The latter are incorporated using the profiling technique [62]. In this method, the PDF uncertainties are included in the  $\chi^2$  using nuisance parameters which are further constrained according to the tolerance criterion of the fit. As the tolerance criterion we use  $\Delta\chi^2 = 1$ . In this approach, one assumes that the new data are compatible with the theoretical predictions using the existing PDF set. No further theoretical uncertainties beyond the PDF uncertainties are considered when calculating the  $\chi^2$ . The uncertainties on the fitted parameters are obtained using the **HESSE** method which computes numerically the second derivatives of the  $\chi^2$  with respect to the fitted parameters [48, 50]. This assumes that the dependence of the theoretical predictions on the parameters of interest is linear near the minimum of the  $\chi^2$ . We cross-checked the uncertainties using the **MINOS** algorithm which uses the profile likelihood method to compute asymmetric confidence intervals, as well as the **MNCONT** algorithm [61] which explicitly finds 2D contours where the  $\chi^2$  is minimal, and found a good agreement with the hessian uncertainties.

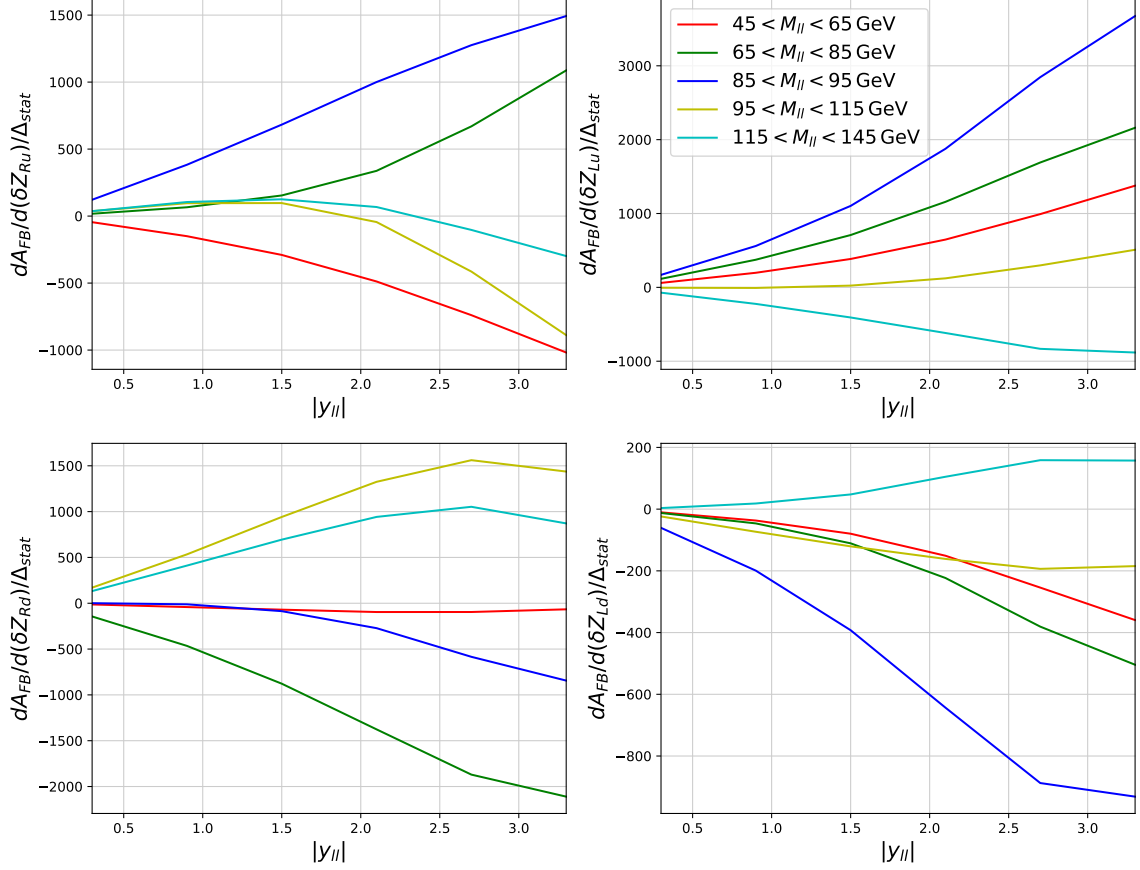
The results of the fit are presented in Figs. 11–19 as allowed regions for different pairs of corrections to the  $Z$  couplings to  $u$ - and  $d$ -type quarks at confidence level (CL) of 68%. The resulting uncertainties on the couplings to the  $d$ -type quarks are roughly a factor of two larger than the corresponding uncertainties for the  $u$ -type quarks. A similar impact of the  $A_{FB}$  measurements on the PDFs was found in Ref. [9]: it was shown that these measurements are most sensitive to the weighted sum  $(2/3)u_v + (1/3)d_v$  of the valence  $u$ - and  $d$ -quarks, and we report the same finding in the present study. This is related to the valence quark content of the proton and also to the fact that the  $d\bar{d}$  initiated process gets more suppressed at high rapidity (where the sensitivity to the couplings is largest) in comparison to the  $u\bar{u}$  initiated ones [8]. The exact details of this effect depend on the quark PDF behaviour at high values of the partonic momentum fraction  $x$  [17, 24, 25, 46, 63].



**Figure 7.** The partial derivatives of the predicted  $A_{FB}$  with respect to  $\delta_{Ru}$  (upper left),  $\delta_{Lu}$  (upper right),  $\delta_{Rd}$  (lower left) and  $\delta_{Ld}$  (lower right) couplings weighted by the inverse of the statistical uncertainty as a function of the invariant mass of the dilepton system in different rapidity intervals at LO.

In Figs. 11 and 12 the allowed regions are shown as obtained using different PDF sets.<sup>3</sup> These results are presented using either couplings to right- and left-handed quarks or axial-vector couplings. 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. To illustrate the impact of the PDF uncertainties on the results, in Figs. 13 and 14 we show the allowed regions obtained with and without including the PDF uncertainties into the fit. Furthermore, in Fig. 15 we show the average size of the uncertainties on the fitted couplings as obtained using different PDF sets. The impact of the PDF uncertainties is sizable. Namely, after including them into the fit the uncertainties on the couplings increase by a factor of  $\sim 3$ , 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. However, it is worth mentioning also that the PDF

<sup>3</sup>The PDF uncertainties of the CT18 set were rescaled to CL=68%.

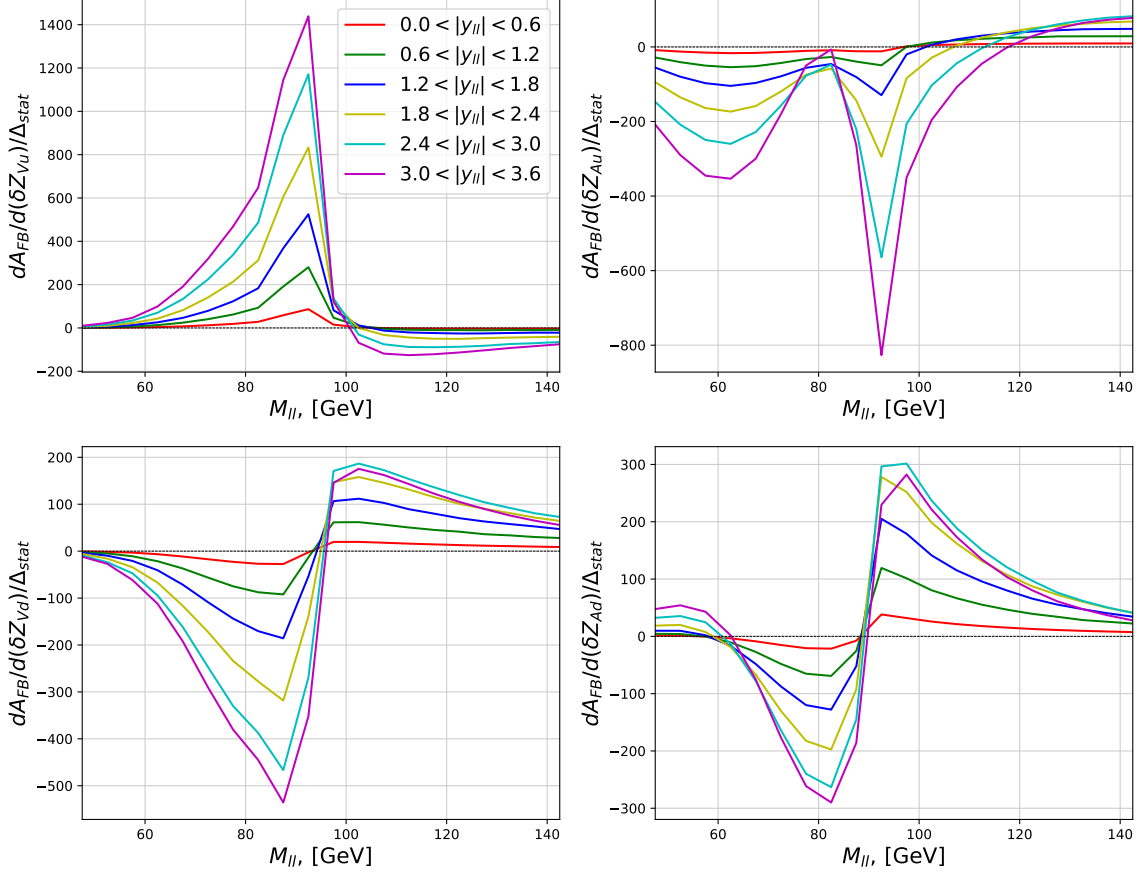


**Figure 8.** The partial derivatives of the predicted  $A_{\text{FB}}$  with respect to  $\delta_{Ru}$  (upper left),  $\delta_{Lu}$  (upper right),  $\delta_{Rd}$  (lower left) and  $\delta_{Ld}$  (lower right) couplings weighted by the inverse of the statistical uncertainty as a function of the rapidity of the dilepton system in different invariant mass intervals at LO.

uncertainties are constrained by the pseudodata when using the profiling technique. The behaviour of quark and antiquark densities at large Bjorken- $x$  varies significantly between different PDF sets [7, 8, 17] strongly affecting the theoretical predictions for the  $A_{\text{FB}}$  in the high rapidity bins. However the discrepancies between different PDF sets will foreseeably reduce after the inclusion of additional experimental data covering the large- $x$  regions [63]. The  $A_{\text{FB}}$  observable has proved particularly sensitive to quark and anti-quark densities in the large Bjorken- $x$  region [9, 11, 17], which can be accessed through measurements of the asymmetry at high rapidities [9, 11]. In order to provide consistent results, in the future such analyses should comprise a simultaneous fit of the proton PDFs and the couplings.

In Figs. 16 and 17 we compare our results obtained for the HL-LHC<sup>4</sup> with the other analyses of existing data from LEP, Tevatron, HERA and LHC. The results are presented using either couplings to right- and left-handed quarks or axial and vector couplings. Namely, we compare with the analysis of the H1 Collaboration at HERA [64],

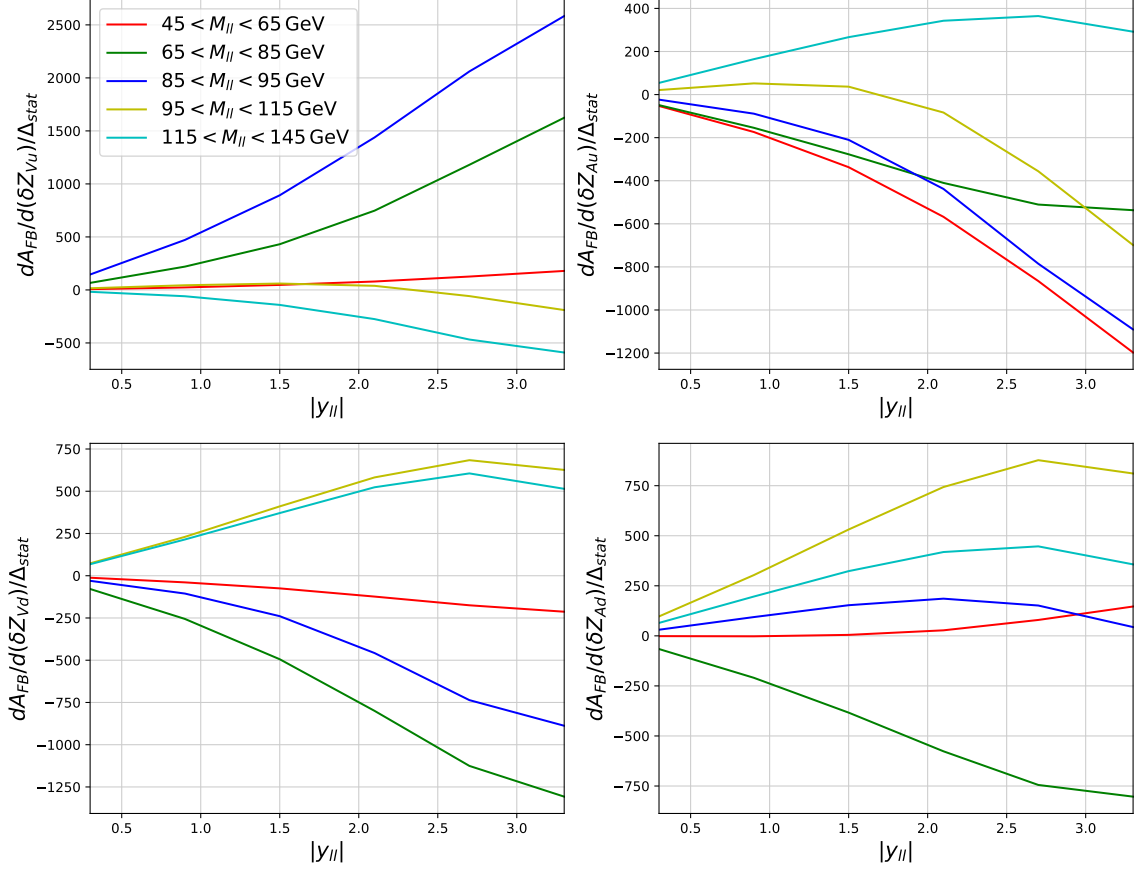
<sup>4</sup>We show the results obtained using the ABMP16 PDF set, since only this set provides symmetric PDF errors which are easier to include in the PDF profiling.



**Figure 9.** Same as in Fig. 7 for the axial and vector couplings.

the LEP+SLD combination [5], the analysis of D0 Collaboration at Tevatron [65] and the analysis of LEP, ATLAS and D0 data from Ref. [43]. In addition to the HL-LHC results, we present our results of analysing all available 10 bins from the ATLAS measurement of  $A_{\text{FB}}$  [3], while only 4 bins at the  $Z$  peak were used in the analysis of Ref. [43]. 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. Such a procedure provides credible uncertainties on the  $Z$  couplings, while in order to get meaningful central values one would need to use theoretical calculations with higher-order QCD corrections. The level of precision expected at the HL-LHC outperforms any existing data sets. Also, we note that using all the 10 data bins from the ATLAS measurement [3] provides more information on some of the couplings (e.g.  $\delta_{Rd}$ ) compared to the 4 bins at the  $Z$  peak which were used in the analysis of Ref. [43].

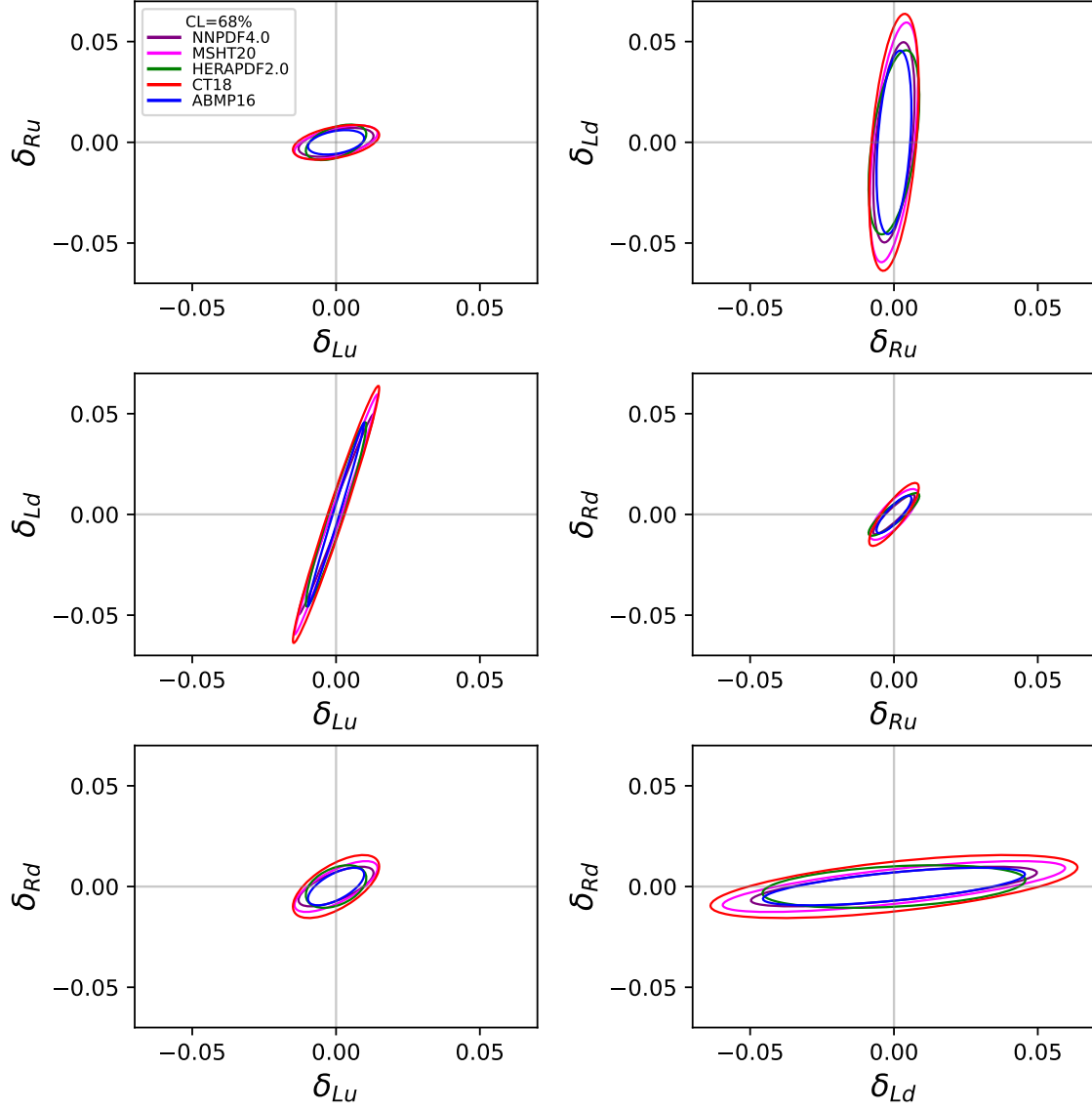
In Figs. 18 and 19 we compare the results obtained for the HL-LHC with the results expected at the future colliders currently under discussion, LHeC [66, 67] and FCC-eh [68, 69]. For the LHeC, two electron beam energies of 50 or 60 GeV are considered, and two assumptions on the uncertainties. The results are provided for the so-called aggressive uncertainty scenario for  $E_e = 60$  GeV, and the conservative one for  $E_e = 50$  GeV (further details



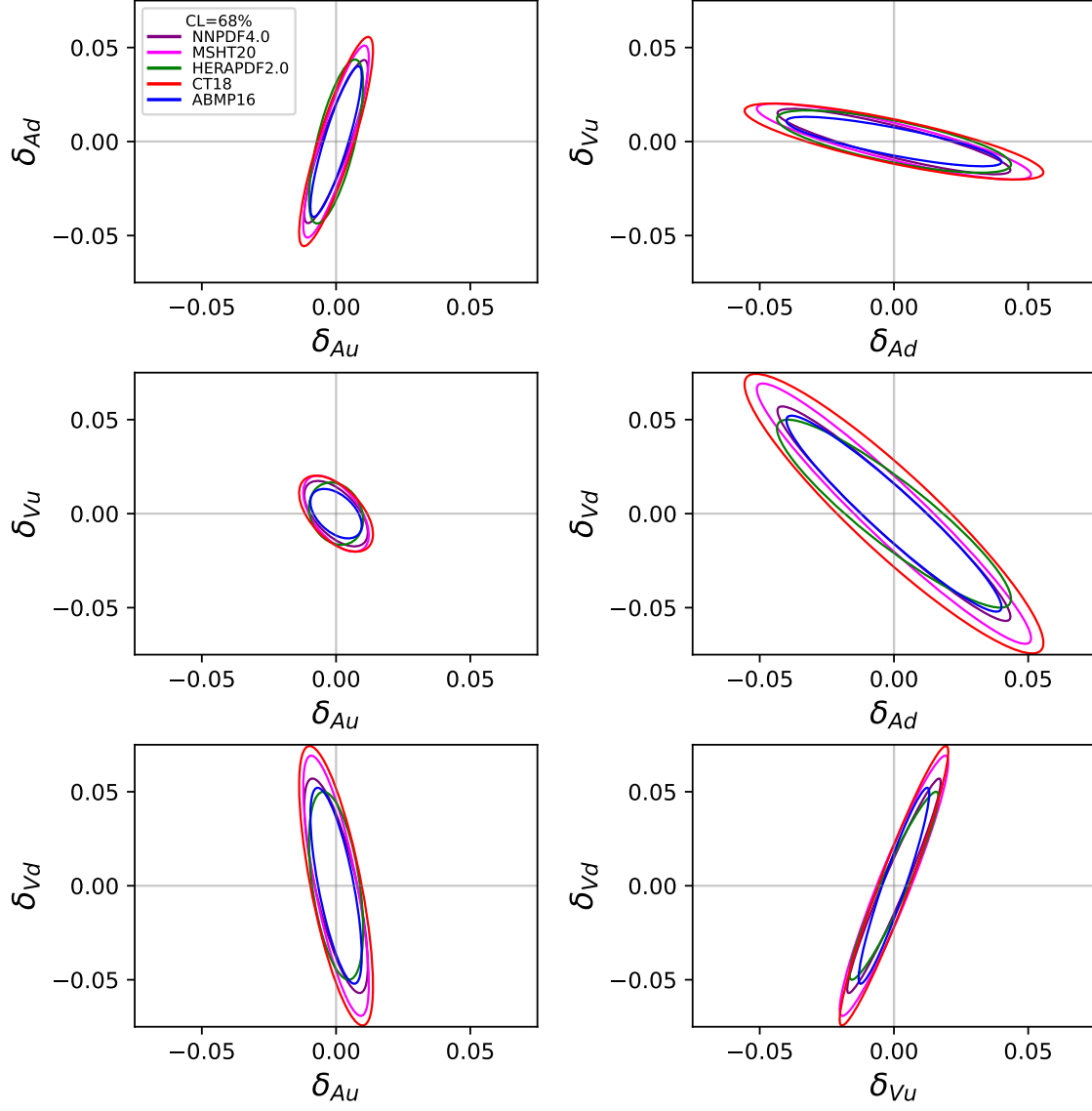
**Figure 10.** Same as in Fig. 8 for the axial and vector couplings.

can be found in Ref. [66]). Furthermore, in Fig. 20 the average size of the uncertainties which can be obtained using current and future data sets are compared. 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. More precisely, the average size of the uncertainties which are expected at the FCC-eh are a factor of 6 better than the one from our HL-LHC expectation, while the LHeC uncertainties are only 1.7–4 times smaller (depending on the scenario) than our HL-LHC results. Note that uncertainties may be also reduced at FCC-hh collider, due to increased cross section and luminosity compared to the HL-LHC. This could be studied using similar methods as those used for the HL-LHC in this paper. However, it requires a dedicated investigation of the detector acceptance and is beyond the scope of the current analysis.

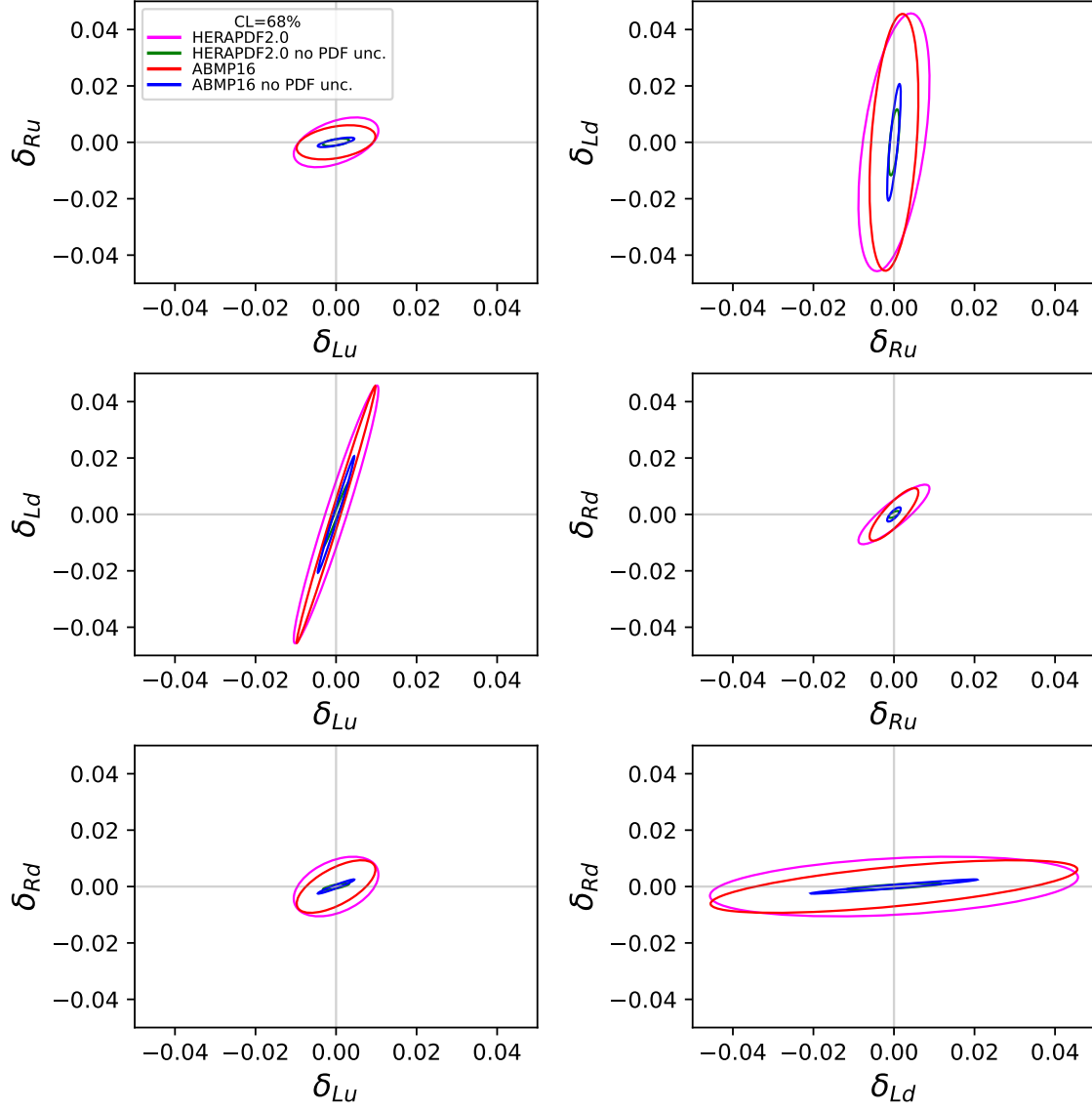




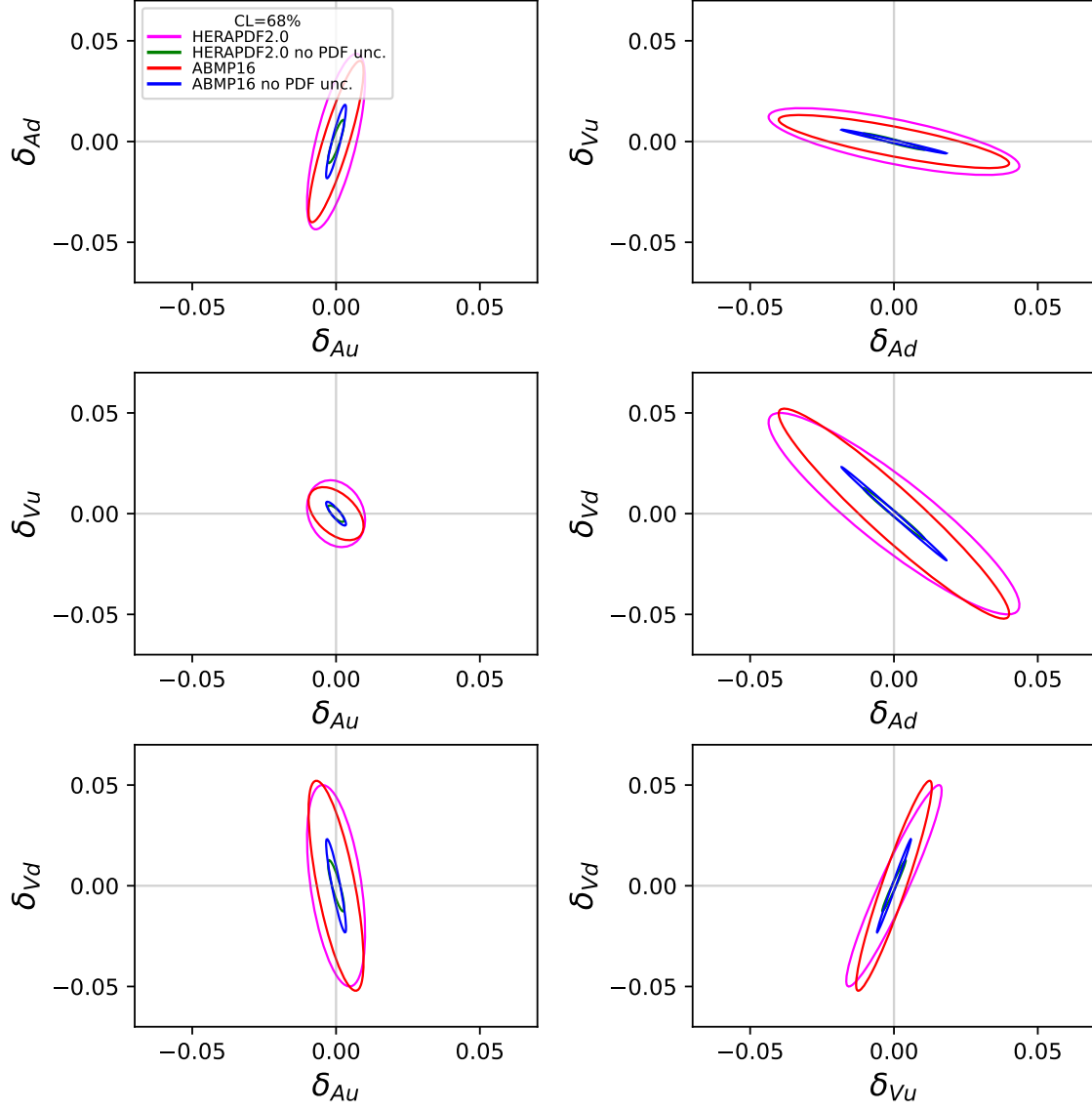
**Figure 11.** Allowed regions for all pairs of corrections to the  $Z$  couplings to  $u$ - and  $d$ -type quarks obtained using different PDF sets.



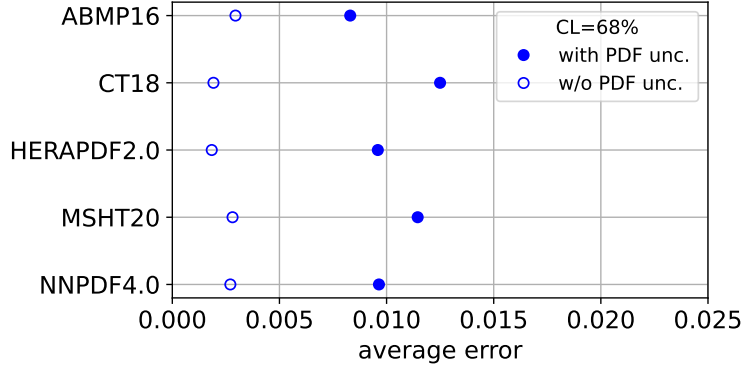
**Figure 12.** Same as in Fig. 11 for the axial and vector couplings.



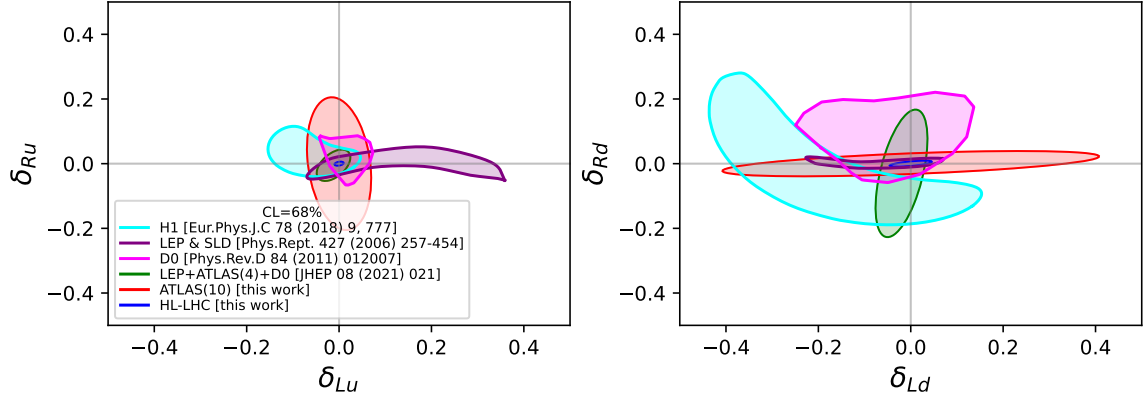
**Figure 13.** Allowed regions for all pairs of corrections to the  $Z$  couplings to  $u$ - and  $d$ -type quarks obtained using the ABMP16 and HERAPDF2.0 PDF sets with and without PDF uncertainties.



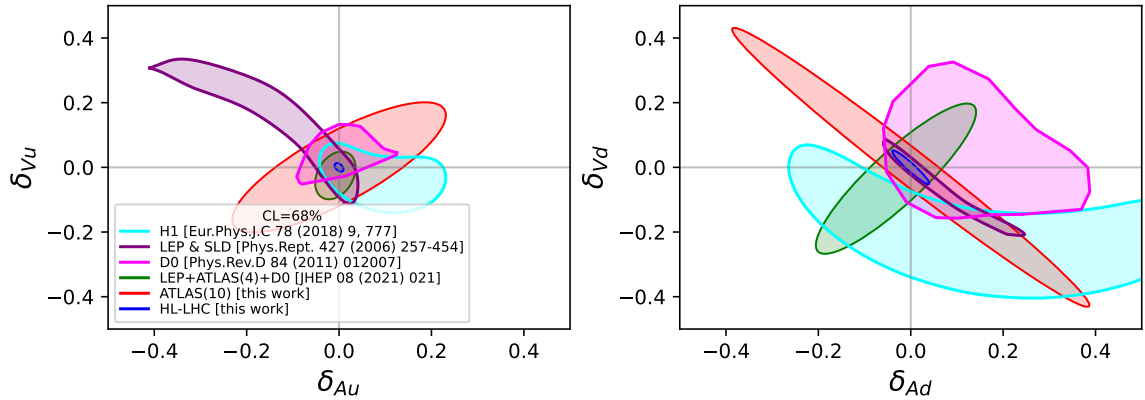
**Figure 14.** Same as in Fig. 13 for the axial and vector couplings.



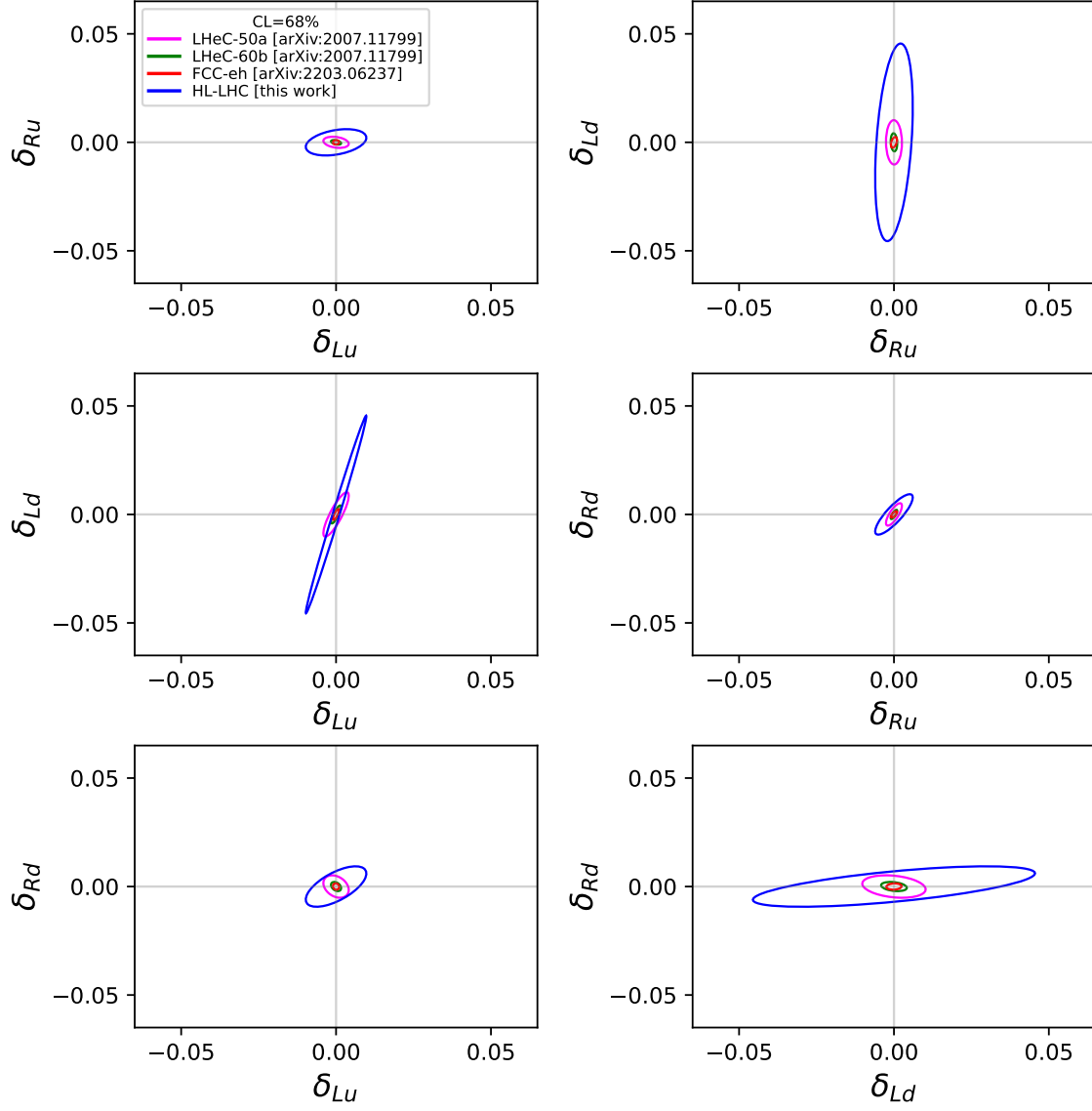
**Figure 15.** The average size of the uncertainties on the fitted corrections to the  $Z$  couplings to  $u$ - and  $d$ -type quarks obtained using different PDF sets.



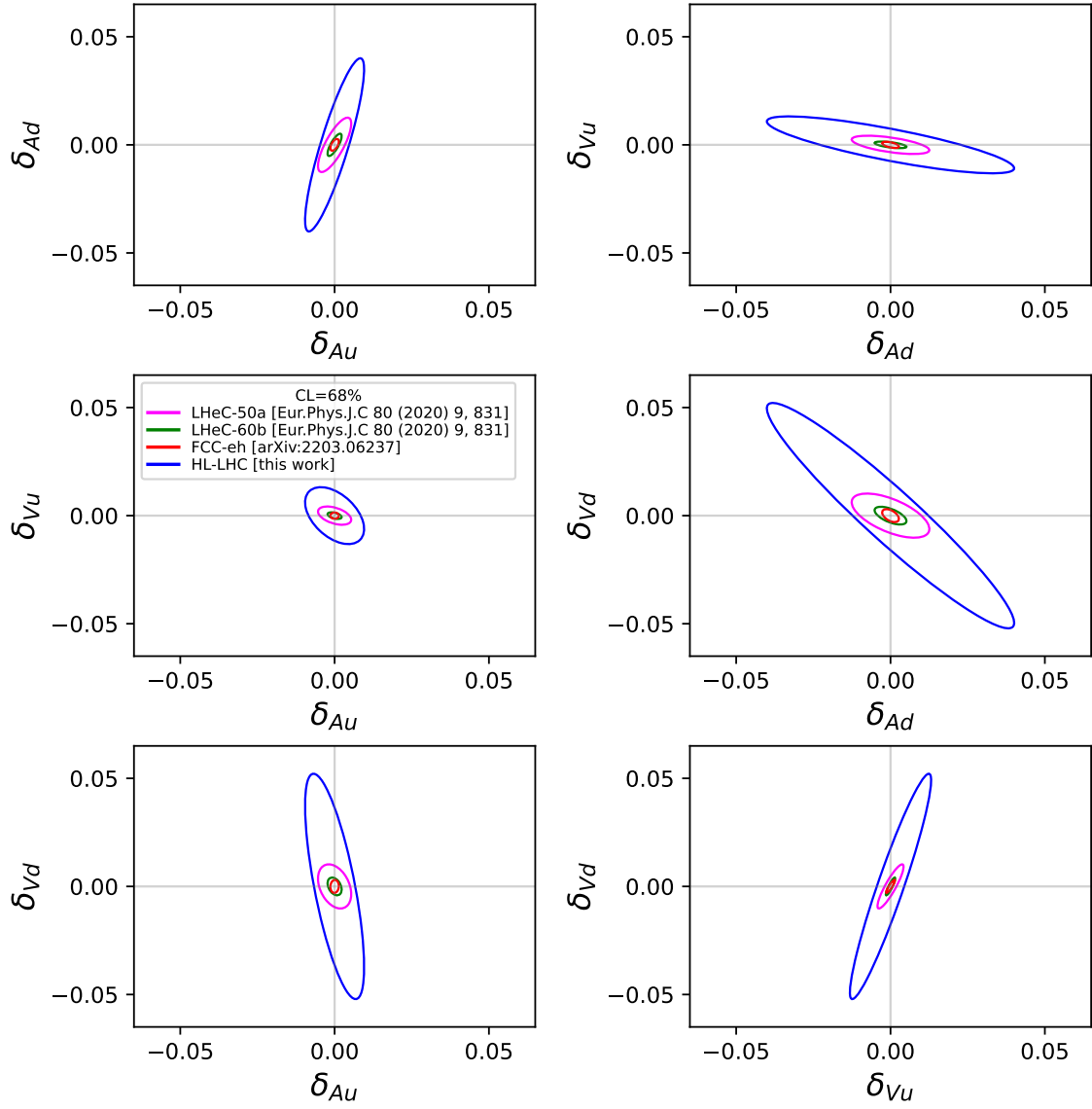
**Figure 16.** Allowed regions for all pairs of corrections to the  $Z$  couplings to  $u$ - and  $d$ -type quarks obtained using HL-LHC pseudodata as well as different existing data sets.



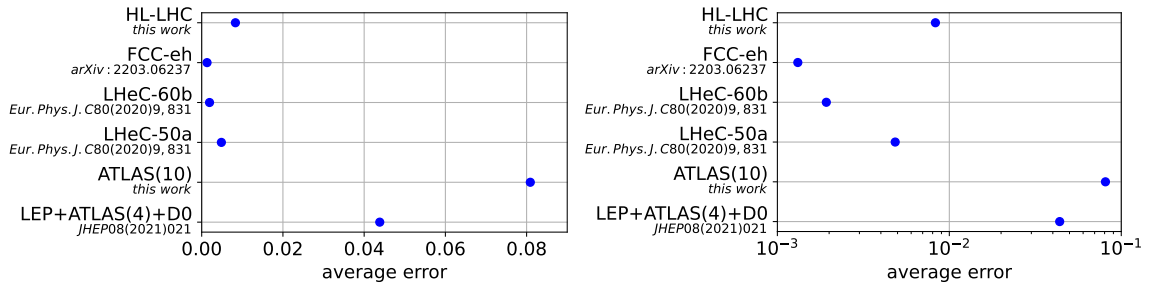
**Figure 17.** Same as in Fig. 16 for the axial and vector couplings.



**Figure 18.** 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.



**Figure 19.** Same as in Fig. 18 for the axial and vector couplings.



**Figure 20.** The average size of the uncertainties on the fitted corrections to the Z couplings to  $u$ - and  $d$ -type quarks for different future experiments using the linear (left) or logarithmic (right) scale.

## 5 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  $A_{\text{FB}}$  at the HL-LHC with  $3000 \text{ fb}^{-1}$ . We have investigated in detail the dependence of the  $A_{\text{FB}}$  on the various couplings in different regions of the invariant mass of the lepton pair, and we have shown that a wide range of  $45 < M(\ell\ell) < 145 \text{ GeV}$  is profitable to constrain the couplings. Furthermore, a measurement as function of the rapidity of the lepton pair provides a significant added value. Thus, we suggest double-differential measurements of the  $A_{\text{FB}}$  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. Since the  $A_{\text{FB}}$  observable is strongly sensitive to the proton PDFs, we find a significant dependence of the results on the PDF set used for such study, as was checked using the ABMP16, CT18, HERAPDF2.0, MSHT20 and NNPDF4.0 PDF sets. Preferably, in the future such analyses should comprise a simultaneous fit of the proton PDFs and the couplings.

The results were compared with the existing analyses of the LEP, HERA, Tevatron and LHC data, as well as with the results which are expected at the future colliders LHeC and FCC-eh. The uncertainties on the  $Z$  couplings to the  $u$ - and  $d$ -type quarks at the HL-LHC are expected at 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 a little inferior to the one which is expected at the LHeC and FCC-eh.

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