Constraining CP violating operators in charged and neutral triple gauge couplings

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Abstract

We constrain CP-violating charged and neutral anomalous triple gauge couplings using LHC measurements and projections of diboson and VBF $Zjj$ production, both with subsequent leptonic decays. For triple gauge couplings involving $W$ bosons we analyse asymmetries and interpret our results in the SMEFT at dimension-six. For neutral triple gauge couplings, which are dominantly constrained by high transverse-momentum bins, we present the resulting bounds in terms of a general anomalous couplings framework.

1 Introduction

The observation of the Higgs boson in 2012 \cite{1,2} has been a milestone in the confirmation of electroweak symmetry breaking (EWSB). Since, apart from fixing the Higgs couplings, the mechanism of EWSB also predicts the interactions of the electroweak gauge bosons, precise measurements of the triple gauge couplings (TGCs) play a crucial role in experimentally testing the SM. CP-violating interactions of the gauge bosons are of particular relevance in this regard, since they provide additional sources of CP violation, necessary to describe, for example, electroweak baryogenesis \cite{3–7}.

In our work, we study CP-odd anomalous triple gauge couplings involving two (charged) $W$ bosons, $WWZ$ and $WW\gamma$, as well as interactions of neutral gauge bosons, $ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$, which are completely absent in the SM. For charged anomalous triple gauge couplings, we consider constraints from the measurement of $WW \rightarrow \ell\ell\nu\nu$ \cite{8}, $WZ \rightarrow \ell^+\ell^-\ell^\pm\nu$ \cite{9}, $W\gamma \rightarrow \ell^\pm\nu\gamma$ \cite{10} and $Zjj \rightarrow \ell^+\ell^-jj$ production \cite{11}. To describe small deviations from the Standard Model (SM) values of the charged TGCs in a model-independent fashion, we will use the language of Standard Model Effective Field Theory (SMEFT) \cite{12–16}, where CP-odd SMEFT operators influencing the charged TGCs appear at dimension six. Constraints on these operators have been studied and constrained in Higgs boson \cite{17} and diboson production processes \cite{23,26} as well as vector boson scattering \cite{27}. Recently, CP violation in diboson production has also been studied in Ref. \cite{28}. We consider the same experimental inputs, but our analysis differs in the selection of observables sensitive to CP violation, using asymmetries rather than complete differential distributions, reducing both experimental and theoretical systematic uncertainties. Our study provides an independent confirmation of the results found in Ref. \cite{28} using SHERPA for the generation of both the SM as well as the beyond SM events, and they also serve as independent validation of the implementation of this sector in SHERPA.

For neutral anomalous triple gauge couplings we consider constraints from the $ZZ \rightarrow 4\ell$ and $2\ell2\nu$ final states \cite{29,30} as well as $Z\gamma \rightarrow 2\ell\gamma$ and $2\nu\gamma$ production channels \cite{31,32}. Due to the dominance of squared neutral triple gauge coupling (nTGC) contributions compared to the polarization-suppressed (linear) interference with the SM \cite{24,33,34}, we investigate their effects on the cross section in the high-$p_T$ regime, rather than studying asymmetries.

2 Charged aTGC

SMEFT \cite{12–16} provides a versatile framework to describe small deviations from the SM, such as those induced by anomalous triple gauge couplings. In the Warsaw basis \cite{14}, there are two dimension-six
operators leading to CP violation in diboson production through a modification of the $\gamma WW$ and $ZW$ interactions. We can describe them through the effective Lagrangian

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_{W}}{\Lambda^{2}} \mathcal{O}_{W} + \frac{c_{HWB}}{\Lambda^{2}} \mathcal{O}_{HWB},
$$

(1)

where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, $\Lambda$ denotes the new physics scale and the $c_i$ are the Wilson coefficients of the operators

$$
\mathcal{O}_{W} = \epsilon^{IJK} W_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} \mu, \quad \mathcal{O}_{HWB} = H^{I} \tau^{I} H^{J} \tau_{\mu} W_{\mu}^{I}. \quad (2)
$$

The operator $\mathcal{O}_{HWB}$ also affects Higgs-gauge couplings and its Wilson coefficient can thus be constrained independently through Higgs sector observables. In the following, we calculate and combine the constraints on the Wilson coefficients $c_{HWB}$ and $c_{W}$ from $WW$, $WZ$, $W\gamma$ and $Z\ell\ell$ production at the LHC. For each channel, we construct a single observable, an asymmetry $A_i$ in the number $N$ of events with a positive or negative value of an angle $\zeta_i$:

$$
A_i = \frac{N(\zeta_i > 0) - N(\zeta_i \leq 0)}{N(\zeta_i > 0) + N(\zeta_i \leq 0)} \quad i = WW, WZ, W\gamma, Z\ell\ell. \quad (3)
$$

For each considered channel $i$, a different angle $\zeta_i$ is defined from the triple products or, equivalently, the difference in azimuthal angle of the rapidity-ordered final-state (pseudo-)particles $k$ and $l$, e.g. $\sin \Delta \phi_{kl} \propto (p_{k} - p_{l}) \cdot (p_{k} \times p_{l})$. The asymmetries are defined such that they vanish exactly for the SM and SM backgrounds, where no CP violation is present. The study of asymmetries has the advantage that systematic uncertainties largely cancel in the ratio and the limits are therefore entirely determined by the statistical uncertainties.

We generate events at leading order (LO) with SHERPA-2.2.10 [35,36] with the default NNPDF30_nlnlo_as0118 parton distribution function [37] from LHAPDF 6.2.1 [38]; matrix elements are calculated with COMIX [39] and parton showered with CSSHOWER [40]. QED corrections are effected through a YFS soft-photon resummation [41,42]. For multi-parton interactions, hadronisation, and subsequent hadron decays we use the SHERPA default settings. EFT contributions are generated using the SMEFTsim model [43] in SHERPA through its UFO [44] interface [45]. We consider the interference of the SM with the dimension-six operator only and neglect contributions from the squares of dimension-six terms.

In each channel, we normalize the SM cross section to the experimentally observed cross section and assume identical normalization factors for the SM and the EFT contributions. To take into account detector effects, we include a flat detector efficiency which we deduce from the ratio of the predicted cross section and the predicted number of events provided by the experimental collaborations $\epsilon_{\text{det}} = N_{\text{events, pred}}/(\sigma_{\text{pred}} \mathcal{L}_{\text{int}})$.

**WW production.** For $WW$ production, we consider an asymmetry in the sine of the difference of the azimuthal angles $\phi$ of the two final state leptons ordered by their pseudorapidity, $\zeta_{WW} = \sin \Delta \phi_{\ell \ell}$. We make use of the existing RIVET [10] analysis to reproduce the experimental cuts and normalize the SHERPA cross section to the measured value of $\sigma_{\text{fid, EW}} = 379.1 \pm 27.1 \text{ fb} [8]$. The detector efficiency is deduced from the difference between the predicted cross section and the predicted number of events $\epsilon_{\text{det}} = 0.61$.

**WZ production.** For $WZ$ production, the CP-sensitive observable is $\zeta_{WZ} = \sin \Delta \phi_{Z\ell}$, where $\ell'$ denotes the lepton from the decay of the $W$ boson and $Z$ denotes the reconstructed $Z$ boson from the same-flavor-opposite-sign lepton pair. We normalize the SHERPA cross section to the measured value of $\sigma_{\text{fid, EW}} = 254.7 \pm 11.5 \text{ fb} [0]$ and assume a detector efficiency of $\epsilon_{\text{det}} = 0.52$.

**$W\gamma$ production** For $W\gamma$ production in the $\ell \nu \gamma$ final state we define the CP sensitive observable $\zeta_{W\gamma} = \sin \Delta \phi_{\ell \gamma}$, where $\ell$ and $\gamma$ denote the lepton from the $W$ boson decay and of the photon, respectively. CMS has performed an analysis for $W\gamma$ production at 13 TeV for an integrated luminosity of $\mathcal{L} = 127.1 \text{ fb}^{-1} [10]$. Including the decay of the $W$ boson, the analysis has measured a cross section of $\sigma_{\text{fid}} = (3.32 \pm 0.16) \text{ pb}$. We implemented the experimental cuts in RIVET and normalized the cross section after cuts to this value. From the expected number of signal events and the expected cross section, we deduce a detector efficiency of $\epsilon_{\text{det}} = 0.59$.

*The CP violation present in the SM have been checked to be negligible for the range of observables and coefficients considered in this letter.*
**Zjj production** In vector boson fusion Zjj production, CP violation in the ZWW and γWW couplings causes modulations in the ∆φjj distribution of the η-ordered jets, see Fig. 1. The shape of the modulation in ∆φjj is different for the $c_{\bar{W}B}$ and $O_{H\bar{W}B}$ operators. While the usual definition of the asymmetry, $\zeta_{\text{jj},1} = \sin \Delta \phi_{jj}$, maximizes the sensitivity to $c_{\bar{W}B}$, there is a partial cancellation of the modulation for $c_{\text{Q}}$. For the Zjj process we therefore define a second asymmetry in the $\Delta \phi_{jj}$ distribution, $\zeta_{\text{jj},2} = \sin(2\Delta \phi_{jj})$. We normalize the SHERPA cross section to the measured value of $\sigma_{\text{det,EW}} = 37.4 \pm 6.5$ fb \cite{28} and take into account a factor of $\epsilon_{\text{det}} = 0.85$ for detector effects.

**Combination.** We combine the constraints on the Wilson coefficients from measurements of the WW, WZ, Wγ and Zjj channels in a $\chi^2$ analysis. Since systematic uncertainties cancel out in our observables, we do not need to consider correlations between uncertainties of the different channels and directly calculate the $\chi^2$ via

$$
\chi^2 = \sum_i \frac{(A_i - 0.)^2}{\sigma^2_{A_i}}, \quad i = \text{WW, WZ, Wγ, Zjj},
$$

where $\sigma_{A_i}$ denotes the statistical uncertainty on the asymmetry in channel $i$. For the Zjj channel, where two asymmetries have been defined, we include a factor $\frac{1}{2}$ for the $\chi^2$ contribution of each asymmetry to avoid incorrectly overconstraining the operators by using the same information/events twice.

We present the expected results for LHC Run II with an integrated luminosity of $\mathcal{L}_{\text{int}} = 139$ fb$^{-1}$ as well as prospects for the high luminosity LHC with an integrated luminosity $\mathcal{L}_{\text{int}} = 3000$ fb$^{-1}$ in Fig. 2. The strongest constraints result from the Wγ and Zjj channels. Our bounds are slightly weaker than those presented in Ref. \cite{28}. This is mainly due to the inclusion of detector inefficiencies. For the Wγ channel, we benefit from being able to recast an existing 13 TeV analysis rather than relying on assumptions for the cuts. Therefore, the cross section used for this channel is a factor 10 smaller in our analysis than assumed in Ref. \cite{28}.

Our limit on $c_{H\bar{W}B}$ is much stronger than the bound resulting from Higgs observables. At 3000 fb$^{-1}$ luminosity the expected limits are $|c_{H\bar{W}B}|/\Lambda^2 < 3.1$ TeV$^{-2}$ from Higgs WBF+γ production \cite{22} and $|c_{H\bar{W}B}|/\Lambda^2 < 1.5$ TeV$^{-2}$ from standard Higgs production processes \cite{19} respectively compared to $|c_{H\bar{W}B}|/\Lambda^2 < 0.09$ TeV$^{-2}$ for this analysis of diboson observables. A fit combination of Higgs and diboson observables could in turn further improve the limits on other Wilson coefficients currently constrained from Higgs observables, $c_{H\bar{W}}$, $c_{\bar{W}B}$ and $c_{\bar{W}\bar{B}}$. The Wilson coefficient of the operator $O_{\bar{W}}$ is constrained to $|c_{\bar{W}}|/\Lambda^2 < 0.04$ TeV$^{-2}$ in our fit. High-luminosity LHC projections for diboson plus vector boson scattering data using distributions up to high-$p_T$ instead of actual CP-sensitive observables find competitive constraints of $|c_{H\bar{W}B}|/\Lambda^2 < 0.14$ TeV$^{-2}$ and $|c_{\bar{W}}|/\Lambda^2 < 0.02$ TeV$^{-2}$ \cite{27}, further highlighting the necessity to combine fits of all available LHC data sets.

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1Notice that our paper has a sign difference for the operator $c_{H\bar{W}B}$ with respect to Ref. \cite{28} and Ref. \cite{11}. We have validated our results by detailed comparison with MadGraph, with identical results. The one-parameter limits presented are not affected by the sign change.
Neutral triple gauge couplings are absent in the SM at LO. Therefore, the observation of these couplings would be a clear hint for physics beyond the SM [47]. The most general parametrization of nTGCs in ZZ and Zγ production is given by \[ \mathcal{L}_{\text{SM}} + \frac{c}{M_Z^2} \left[ -[f_Y^1 (\partial_\mu F_{\mu\beta}) + f_Y^2 (\partial_\mu Z_{\mu\beta})] Z_\alpha (\partial^\alpha Z_\beta) + [f_Y^3 (\partial^\alpha F_{\mu\beta}) + f_Y^4 (\partial^\alpha Z_{\mu\beta})] \tilde{Z}^{\mu\alpha} Z_{\beta} - [h_1^1 (\partial^2 F_{\mu\beta}) + h_1^2 (\partial^2 Z_{\mu\beta})] Z_\beta F^{\mu\alpha} - [h_3^1 (\partial^2 F_{\mu\beta}) + h_3^2 (\partial^2 Z_{\mu\beta})] Z_{\beta} F^{\mu\alpha} - [h_4^1 (\partial^2 Z_{\mu\beta}) + h_4^2 (\partial^2 Z_{\mu\beta})] Z_{\beta} F^{\mu\alpha} - [h_5^1 (\partial^2 Z_{\mu\beta}) + h_5^2 (\partial^2 Z_{\mu\beta})] Z_{\beta} F^{\mu\alpha} \right] \].

Non-zero coefficients \( f_Y^1, h_1^1 \) and \( h_1^2 \) lead to CP-violating interactions, while the coefficients \( f_Y^2, h_3^1 \) and \( h_3^2 \) parametrize CP-conserving \( ZZZ, ZZ\gamma \) and \( Z\gamma\gamma \) interactions. In the SM, all \( h_i \) and \( f_i \) are zero at tree level. At the one-loop level, however, the CP-conserving couplings \( f_5, h_3 \) and \( h_4 \), receive non-zero contributions with relative sizes at the order of \( \mathcal{O}(10^{-4}) \) [51].

In contrast to charged TGCs, neutral TGCs can currently only be constrained to a regime where the quadratic terms clearly dominate over the linear interference terms with the SM, which are suppressed by the allowed polarizations of the gauge bosons. As a result, bounds on CP-violating neutral triple gauge couplings (uTGCs) stem primarily from their effect on the cross section in the high-\( p_T \) regime and they do not come from CP asymmetries. In particular, we will study the high-\( p_T \) regime of the distributions of \( p_T^2 \) in ZZ production as well as \( E_T, \gamma \) in Zγ production. Bounds on nTGCs have previously been discussed for the LHC [24,33,44,52] as well as for future lepton [53,54] and proton colliders [55,57]. Since both the bounds on the coefficients of CP-violating interactions and their CP-conserving counterparts \( f_4^1 \leftrightarrow f_5^1, h_Y^1 \leftrightarrow h_Y^1, h_Y^2 \leftrightarrow h_Y^2 \) result from their quadratic effect on the cross section in the high-\( p_T \) regime, their limits are typically very similar.

Neutral triple gauge couplings do not appear at the dimension-six level in the SMEFT. They are, however, induced at dimension-eight [52] \( (f_Y^1, f_Y^2, h_Y^1, h_Y^2) \) or even higher dimension. While an interpretation of nTGCs in SMEFT at dimension-eight is therefore possible, the clear dominance of the quadratic terms over the dimension-eight interference terms renders the interpretation cumbersome and possibly flawed. Consequently, we will rely on the parametrization given in Eq. (5).

Events for the analysis of neutral anomalous gauge couplings are generated at leading order using the native SM+AGC model in SHERPA-2.1.1 [55] as well as an implementation in a UFO model [50,45,58]. Event generation includes both the suppressed and mostly negligible interference with the SM model as well as the squared nTGC contributions.
ZZ production. We study ZZ production in its leptonic 4ℓ [29] and 2ℓ2ν [30] final states. The measured cross sections in the fiducial regions of these channels are \( \sigma_{4\ell} = (46.2 \pm 2.4) \text{ fb} \) [29] and \( \sigma_{2\ell2\nu} = (25.4 \pm 1.7) \text{ fb} \) [30] respectively. In both cases, we use the \( p_T^f \) distributions to constrain the nTGC; in the 4ℓ final state we use the two leptons of the leading reconstructed Z boson. To facilitate direct comparison with published data, we employ the binning used by the experimental collaborations for their luminosity projections.

In our event generation, we include the LO \( gg \) and \( qq \) initial state contributions for ZZ production. The effect of nTGCs is, however, only included for the \( qq \) initial state which makes up for about 90% of the total number of events. NNLO QCD and NLO EW corrections for the events are included through bin-by-bin \( k \) factors, assuming the same values for SM and BSM contributions. These are deduced from the ratio of the LO results with respect to the most precise SHERPA prediction available. The total number of events in each bin \( i \) is given by \( N_{i}^{\mathrm{SHERPA}} = N_i^{\mathrm{qq}} + N_i^{gg} = \epsilon_i^{\mathrm{det}} L_{\mathrm{int}} (\sigma_i^{\mathrm{qq,NLO}} + 1.67 \sigma_i^{\mathrm{gg}}) \), where the \( gg \) contribution is corrected by a relative \( k \) factor of 1.67. Detector effects are accounted for through bin-by-bin detector efficiency factors \( \epsilon_i^{\mathrm{det}} \) for the 4ℓ final state (ranging between 0.57 and 0.69) while we use a global detector efficiency of \( \epsilon^{\mathrm{det}} = 0.57 \) for the 2ℓ2ν analysis.

| luminosity [ fb\(^{-1}\) ] | \( |f_1^Z| \times 10^4 \) | \( |f_2^Z| \times 10^4 \) |
|-----------------------------|-----------------|-----------------|
| 139                         | 11.             | 9.1             |
| 300                         | 9.1             | 7.7             |
| 3000                        | 7.2             | 6.1             |
| 3000 (half syst)            | 8.2             | 7.0             |
| 3000 (half syst)            | 5.3             | 4.5             |

Table 1: Expected limits on nTGCs for the combination of the ZZ → 4ℓ and ZZ → 2ℓ2ν analyses at different luminosities. The limits on the parameters \( f_1^Z \) which lead to CP-conserving interactions are equivalent to those on their CP-violating counterparts. In the two bottom rows, we present the limits assuming that the relative systematic uncertainties in each bin have been halved with respect to the value quoted by the experimental collaborations at 36.1 fb\(^{-1}\).

To set limits on the nTGCs, we perform a \( \chi^2 \) analysis for each bin in the two available \( p_T^f \) distributions,

\[
\chi^2 = \sum_{i \in \text{bins}} \frac{(N_i^{\text{data}} - N_i^{\text{pred}})^2}{N_i^{\text{data}} + (\sigma_i^{\text{syst}})^2},
\]

where \( N_i^{\text{data}} \) and \( N_i^{\text{pred}} \) denote the number of observed and predicted events in each bin and \( \sigma_i^{\text{syst}} \) is their systematic uncertainty. For both analysis channels, the constraints on nTGCs stem almost entirely from the last bin, i.e. \( p_T^f \in [555, 3000] \) GeV in 4ℓ final state and \( p_T^f \in [350, 1000] \) GeV in the 2ℓ2ν final state.

To validate our analysis, we have explicitly checked that we can reproduce the limits on \( f_1^Z \) presented by the experimental collaborations [29, 30] for a luminosity of 36.1 fb\(^{-1}\) at the 15% level. Deviations from those limits can be fully explained by the use of different Monte Carlo generators and the fact that we only know the global detector acceptance rather than a bin-by-bin value for the 2ℓ2ν final state.

Combining the limits from the 4ℓ and 2ℓ2ν final states for a luminosity of 3000 fb\(^{-1}\), we find 95% CL bounds of

\[
|f_1^Z| < 7.2 \times 10^{-4}, \quad |f_2^Z| < 6.1 \times 10^{-4},
\]

for the parameters inducing CP-violating interactions. Since the linear interference contributions are not statistically relevant, we display the limit on the absolute values of the parameters instead of presenting separated upper and lower 95% CL limits. We collect projected limits at different luminosities in Tab. 1.

As expected, the limits on the parameters \( f_1^Z \) which lead to CP-conserving interactions are equivalent to those of its CP-violating counterparts \( f_1^V \). Our combined 139 fb\(^{-1}\) limits approximately agree with those found by CMS for LHC Run-II in the 4ℓ final state [59], which however draws most of its sensitivity from an overflow bin, \( m_{ZZ} > 1300 \) GeV.

Had we included the overflow in the last bin instead of keeping to the binning used by the experimental collaborations, the obtained limits would have tightened by \( \lesssim 20\% \). We generally avoid including the overflow in our last bins, however, to make sure that all considered events lie in a kinematic regime for which the detector is well understood. In addition, using a constrained last bins circumvents potential issues when translating the limits to other frameworks such as EFTs.
Zγ production. We study Zγ production in the leptonic 2ℓγ [31] and 2νγ final states [32] to constrain the CP-odd interactions induced by \( h_1^Y \) and \( h_2^Y \), compare Eq. (4). The measured inclusive cross section for 2ℓγ final state is \( σ_{2\ellγ} = (1065.4 \pm 23.5) \text{ fb} \) [31]. For the analysis of the 2νγ final state which vetoes additional jets, the measured cross section is \( σ_{2\nuγ} = (524.4 \pm 4.8) \text{ fb} \) [32]. We assume a detector efficiency of \( ε_{2\ellγ}^{\text{det}} = 0.54 \) for the 2ℓγ channel and \( ε_{2\nuγ}^{\text{det}} = 0.89 \) for the 2νγ channel. NNLO QCD and NLO EW corrections are again included through bin-by-bin \( k \) factors by rescaling to the predictions in Refs. [31,32].

To calculate and combine the limits from Zγ, we again add up \( χ^2 \) for each bin in the \( E_{T,γ} \) distribution, see Eq. (5), using the binning given in the corresponding experimental references excluding overflow bins. Our last bins, which have the greatest sensitivity to the nTGCs, range from \( E_{T,γ} \in [500, 1200] \) GeV for 2ℓγ and \( E_{T,γ} \in [600, 1100] \) GeV for the 2νγ analysis. As we will point out below, including the overflow in the last bin has a severe impact on the limits on \( h_2^Y \). To validate our analysis, we have explicitly checked that we can reproduce the expected limits of the analysis of the 2νγ final state at a luminosity of 36.1 fb\(^{-1} \) [32] when including the overflow in the last bin.

Combining the limits from the 2ℓγ and 2νγ final states for a luminosity of 3000 fb\(^{-1} \), we find 95% CL bounds of

\[
|h_1^Y| < 2.7 \times 10^{-4}, \quad |h_2^Y| < 2.4 \times 10^{-4}, \quad |h_2^Z| < 6.1 \times 10^{-7}, \quad |h_2^Z| < 6.1 \times 10^{-7}, \quad (8)
\]

for the CP-odd nTGCs. These values assume the same relative systematic uncertainties as in the experimental references at 36.1 fb\(^{-1} \) and 139 fb\(^{-1} \). Including the overflow in the last bin, the limits on \( h_1^Y \) tighten by \( \sim 20\% \). On the other hand, the limits on \( h_2^Y \) are much more severely affected; they are approximately halved when including the overflow in the last bin. This implies that care has to be taken when translating limits based on an analysis including the overflow bin such as Ref. [32] into, for instance, an EFT framework. We collect the limits for other luminosities in Tab. 2. Since for higher luminosities and a fixed binning the uncertainty on the last bin quickly becomes dominated by systematic effects, we also present limits assuming systematic uncertainties are reduced by a factor of two. Because the limits on CP-even nTGCs are roughly equivalent to those on their CP-odd counterparts we do not present them explicitly here.

| luminosity [ fb\(^{-1} \)] | \( |h_1^Y| \times 10^4 \) | \( |h_2^Y| \times 10^4 \) | \( |h_2^Z| \times 10^7 \) | \( |h_2^Z| \times 10^7 \) |
|---------------------------|-----------------|-----------------|-----------------|-----------------|
| 139                       | 3.6             | 3.2             | 8.1             | 8.1             |
| 300                       | 3.2             | 2.9             | 7.3             | 7.2             |
| 3000                      | 2.7             | 2.4             | 6.1             | 6.1             |
| 3000 (half syst)          | 2.7             | 2.4             | 6.1             | 6.1             |
| 3000 (half syst)          | 2.0             | 1.8             | 4.5             | 4.4             |

Table 2: Expected limits on nTGCs for the combination of the \( Z\gamma \rightarrow 2\ell\gamma \) and \( Z\gamma \rightarrow 2\nu\gamma \) analyses at different luminosities. In the two bottom rows, we present the limits assuming that the relative systematic uncertainties in each bin have been halved with respect to the value quoted by the experimental collaborations.

4 Conclusions and Outlook

We have studied the constraints on CP-odd anomalous triple gauge couplings from diboson production. For the TGCs involving W bosons, we have analysed asymmetries in CP-sensitive observables based on \( Δφ \) and present our results in the SMEFT framework at dimension-six. Marginalizing over the second Wilson coefficient, we can constrain the coefficients to \( |c_{H\tilde{W}B}|/A^2 < 0.09 \text{ TeV}^{-2} \) and \( |c_{\tilde{W}}|/A^2 < 0.04 \text{ TeV}^{-2} \) at 3000 fb\(^{-1} \). The strongest limits stem from the analysis of \( Wγ \) and \( Zjj \) production. The improved limits on the coefficient \( c_{H\tilde{W}B} \) with respect to limits resulting from Higgs observables, motivates a combination of Higgs, vector boson scattering and diboson data for a combined fit of CP-violating operators.

To constrain neutral triple gauge couplings, we combined the bounds from the leptonic decay channels of ZZ and Zγ production. The most severe limits are obtained from the high-pr\( t \) regimes of differential distributions instead of CP-sensitive observables due to vanishingly small SM New Physics interference terms. The resulting combined limits on CP-odd interactions at 3000 fb\(^{-1} \) are \( |f_{\bar{Z}}| < 7.2 \times 10^{-4} \), \( |f_{\bar{Z}}| < 6.1 \times 10^{-4} \) from ZZ production and \( |h_1^Y| < 2.7 \times 10^{-4} \), \( |h_2^Y| < 2.4 \times 10^{-4} \), \( |h_2^Z| < 6.1 \times 10^{-7} \), \( |h_2^Z| < 6.1 \times 10^{-7} \).
from $Z\gamma$ production. Limits on $hV^2$ are significantly tighter when including the overflow above $\sim 1$ TeV in the last bin. This should be taken into account when translating these limits to an EFT framework.

In summary, we presented expected limits on $CP$-odd anomalous triple gauge couplings for future runs of the LHC and thereby provided bounds on additional sources of $CP$-violation in the SM.

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References

[1] G. Aad et al., ATLAS, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B716 (2012), 1–29, \texttt{arXiv:1207.7214 [hep-ex]}.

[2] S. Chatrchyan et al., CMS, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B716 (2012), 30–61 \texttt{arXiv:1207.7235 [hep-ex]}.

[3] A. D. Sakharov, Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, Pisma Zh. Eksp. Teor. Fiz. 5 (1967), 32–35, \texttt{[JETP Lett.5,24(1967); Sov. Phys. Usp.34,no.5,392(1991); Usp. Fiz. Nauk161,no.5,61(1991)]}.

[4] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe, Phys. Lett. 155B (1985), 36, IC/85/8.

[5] M. E. Shaposhnikov, Baryon Asymmetry of the Universe in Standard Electroweak Theory, Nucl. Phys. B287 (1987), 757–775.

[6] A. E. Nelson, D. B. Kaplan and A. G. Cohen, Why there is something rather than nothing: Matter from weak interactions, Nucl. Phys. B373 (1992), 453–478, UCSD-PTH-91-20, BUHEP-91-15.

[7] D. E. Morrissey and M. J. Ramsey-Musolf, Electroweak baryogenesis, New J. Phys. 14 (2012), 125003 \texttt{arXiv:1206.2942 [hep-ph]}.

[8] M. Aaboud et al., ATLAS, Measurement of fiducial and differential $W^+W^-$ production cross-sections at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C79 (2019), no. 10, 884 \texttt{[arXiv:1905.04242 [hep-ex]]}.

[9] M. Aaboud et al., ATLAS, Search for resonant $WW$ production in the fully leptonic final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B787 (2018), 68–88 \texttt{[arXiv:1806.01532 [hep-ex]]}.

[10] CMS, Measurement of the inclusive $W\gamma$ production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on effective field theory coefficients, CMS-PAS-SMP-19-002.

[11] G. Aad et al., ATLAS, Differential cross-section measurements for the electroweak production of dijets in association with a $Z$ boson in proton-proton collisions at ATLAS, \texttt{arXiv:2006.15458 [hep-ex]}.

[12] W. Buchmuller and D. Wyler, Effective Lagrangian Analysis of New Interactions and Flavor Conservation, Nucl. Phys. B268 (1986), 621–653, CERN-TH-4254/85.

[13] H. Georgi, Effective field theory, Ann. Rev. Nucl. Part. Sci. 43 (1993), 209–252.

[14] B. Grzadkowska, M. Iskrzynski, M. Misiak and J. Rosiek, Dimension-Six Terms in the Standard Model Lagrangian, JHEP 10 (2010), 085 \texttt{arXiv:1008.4884 [hep-ph]}.
[15] R. Alonso, E. E. Jenkins, A. V. Manohar and M. Trott, Renormalization Group Evolution of the Standard Model Dimension Six Operators III: Gauge Coupling Dependence and Phenomenology, JHEP 04 (2014), [159] arXiv:1312.2014 [hep-ph].

[16] I. Brivio and M. Trott, The Standard Model as an Effective Field Theory, Phys. Rept. 793 (2019), 1–98 arXiv:1706.08945 [hep-ph].

[17] F. Ferreira, B. Fuks, V. Sanz and D. Sengupta, Probing CP-violating Higgs and gauge-boson couplings in the Standard Model effective field theory, Eur. Phys. J. C77 (2017), no. 10, 675 arXiv:1612.01808 [hep-ph].

[18] J. Brehmer, F. Kling, T. Plehn and T. M. P. Tait, Better Higgs-CP Tests Through Information Geometry, Phys. Rev. D97 (2018), no. 9, 095017 arXiv:1712.02350 [hep-ph].

[19] F. U. Bernlochner, C. Englert, C. Hays, K. Lohwasser, H. Mildner, A. Pilkington, D. D. Price and M. Spannowsky, Angles on CP-violation in Higgs boson interactions, Phys. Lett. B790 (2019), 372–379 arXiv:1808.06577 [hep-ph].

[20] C. Englert, P. Galler, A. Pilkington and M. Spannowsky, Approaching robust EFT limits for CP-violation in the Higgs sector, Phys. Rev. D99 (2019), no. 9, 095007 arXiv:1901.05982 [hep-ph].

[21] V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter and E. Mereghetti, CP Violation in Higgs-Gauge Interactions: From Tabletop Experiments to the LHC, Phys. Rev. Lett. 123 (2019), no. 5, 051801 arXiv:1903.03625 [hep-ph].

[22] A. Biekötter, R. Gomez-Ambrosio, P. Gregg, F. Krauss and M. Schönherr, Constraining SMEFT operators with associated hγ production in Weak Boson Fusion, Physics Letters B 814 (2021), 136079 arXiv:2003.06379 [hep-ph].

[23] J. Kumar, A. Rajaraman and J. D. Wells, Probing CP-violation at colliders through interference effects in diboson production and decay, Phys. Rev. D78 (2008), 035014 arXiv:0801.2891 [hep-ph].

[24] S. Dawson, S. K. Gupta and G. Valencia, CP violating anomalous couplings in Wγ and Zγ production at the LHC, Phys. Rev. D88 (2013), no. 3, 035008 arXiv:1304.3514 [hep-ph].

[25] M. B. Gavela, J. Gonzalez-Fraile, M. C. Gonzalez-Garcia, L. Merlo, S. Rigolin and J. Yepes, CP violation with a dynamical Higgs, JHEP 10 (2014), 044 arXiv:1406.6367 [hep-ph].

[26] A. Azatov, D. Barducci and E. Venturini, Precision diboson measurements at hadron colliders, JHEP 04 (2019), 075 arXiv:1901.04821 [hep-ph].

[27] J. J. Ethier, R. Gomez-Ambrosio, G. Magni and J. Rojo, SMEFT analysis of vector boson scattering and diboson data from the LHC Run II, arXiv:2101.03180 [hep-ph].

[28] S. Das Bakshi, J. Chakrabortty, C. Englert, M. Spannowsky and P. Stylianou, ATLAS Violating CP Effectively, arXiv:2009.13394 [hep-ph].

[29] M. Aaboud et al., ATLAS, ZZ → ℓ⁺ℓ⁻ℓ⁺ℓ⁻ cross-section measurements and search for anomalous triple gauge couplings in 13 TeV pp collisions with the ATLAS detector, Phys. Rev. D 97 (2018), no. 3, 032005 arXiv:1709.07703 [hep-ex]].

[30] M. Aaboud et al., ATLAS, Measurement of ZZ production in the ℓ⁺ℓ⁻νν final state with the ATLAS detector in pp collisions at √s = 13 TeV, JHEP 10 (2019), 127 arXiv:1905.07163 [hep-ex]].

[31] G. Aad et al., ATLAS, Measurement of the Z(→ ℓ⁺ℓ⁻)γ production cross-section in pp collisions at √s = 13 TeV with the ATLAS detector, JHEP 03 (2020), 054 arXiv:1911.04813 [hep-ex]].

[32] M. Aaboud et al., ATLAS, Measurement of the Zγ → γγ production cross section in pp collisions at √s = 13 TeV with the ATLAS detector and limits on anomalous triple gauge-boson couplings, JHEP 12 (2018), 010 arXiv:1810.04995 [hep-ex]].

[33] U. Baur and E. L. Berger, Probing the weak boson sector in Zγ production at hadron colliders, Phys. Rev. D 47 (1993), 4889–4904 FSU-HEP-921030, ANL-HEP-PR-92-91, CERN-TH-6680-92.
[34] R. Rahaman and R. K. Singh, Anomalous triple gauge boson couplings in ZZ production at the LHC and the role of Z boson polarizations, Nucl. Phys. B 948 (2019), 114754 [arXiv:1810.11657 [hep-ph]].

[35] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert and J. Winter, Event generation with SHERPA 1.1, JHEP 02 (2009), 007 [arXiv:0811.4622 [hep-ph]].

[36] E. Bothmann et al., Sherpa, Event generation with SHERPA 1.1, JHEP 02 (2009), 007, [arXiv:0811.4622 [hep-ph]].

[37] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert and J. Winter, Event generation with SHERPA 1.1, JHEP 02 (2009), 007, [arXiv:0811.4622 [hep-ph]].

[38] E. Bothmann et al., Sherpa2, Event generation with Sherpa 2.2, SciPost Phys. 7 (2019), no. 3, 034, [arXiv:1905.09127 [hep-ph]].

[39] R. D. Ball et al., NNPDF, Parton distributions for the LHC Run II, JHEP 04 (2015), 040, [arXiv:1412.7420 [hep-ph]].

[40] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr and G. Watt, LHAPDF6: parton density access in the LHC precision era, Eur. Phys. J. C75 (2015), 132, [arXiv:1412.7420 [hep-ph]].

[41] D. R. Yennie, S. C. Frautschi and H. Suura, The infrared divergence phenomena and high-energy processes, Annals Phys. 13 (1961), 379–452.

[42] M. Schönherr and F. Krauss, Soft Photon Radiation in Particle Decays in SHERPA, JHEP 12 (2008), 018, [arXiv:0810.5071 [hep-ph]].

[43] I. Brivio, Y. Jiang and M. Trott, The SMEFTsim package, theory and tools, JHEP 12 (2017), 070, [arXiv:1709.06492 [hep-ph]].

[44] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer and T. Reiter, UFO – The Universal FeynRules Output, Comput. Phys. Commun. 183 (2012), 1201–1214, [arXiv:1108.2040 [hep-ph]].

[45] S. Höche, S. Kuttimalai, S. Schumann and F. Siegert, Beyond Standard Model calculations with Sherpa, Eur. Phys. J. C75 (2015), no. 3, 135, [arXiv:1412.6478 [hep-ph]].

[46] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth, J. Monk, H. Schulz and F. Siegert, Rivet user manual, Comput. Phys. Commun. 184 (2013), 2803–2819 [arXiv:1003.0694 [hep-ph]].
[55] A. Yilmaz, A. Senol, H. Denizli, I. Turk Cakir and O. Cakir, *Sensitivity on Anomalous Neutral Triple Gauge Couplings via ZZ Production at FCC-hh*, Eur. Phys. J. C 80 (2020), no. 2, 173, [arXiv:1906.03911][hep-ph].

[56] A. Senol, H. Denizli, A. Yilmaz, I. Turk Cakir and O. Cakir, *Study on Anomalous Neutral Triple Gauge Boson Couplings from Dimension-eight Operators at the HL-LHC*, [arXiv:1906.04589][hep-ph].

[57] J. Ellis, H.-J. He and R.-Q. Xiao, *Probing new physics in dimension-8 neutral gauge couplings at e+e- colliders*, Sci. China Phys. Mech. Astron. 64 (2021), no. 2, 221062, [arXiv:2008.04298][hep-ph].

[58] S. Banerjee, *private communication*.

[59] A. M. Sirunyan et al, CMS, *Measurements of pp → ZZ production cross sections and constraints on anomalous triple gauge couplings at √s = 13 TeV*, [arXiv:2009.01186][hep-ex].