

## Global Constraints on Anomalous Triple Gauge Couplings in the Effective Field Theory Approach

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We present a combined analysis of LHC Higgs data (signal strengths) together with LEP-2  $WW$  production measurements. To characterize possible deviations from the standard model (SM) predictions, we employ the framework of an effective field theory (EFT) where the SM is extended by higher-dimensional operators suppressed by the mass scale of new physics  $\Lambda$ . The analysis is performed consistently at the order  $\Lambda^{-2}$  in the EFT expansion keeping all the relevant operators. While the two data sets suffer from flat directions, together they impose stringent model-independent constraints on the anomalous triple gauge couplings.

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The non-Abelian local symmetry of the standard model (SM) implies that cubic and quartic self-interactions of the gauge bosons must be present in the Lagrangian. An especially interesting example is the cubic interactions of  $W$  bosons with a photon or a  $Z$  boson because they can be directly probed in high-energy colliders such as LEP-2, Tevatron, and the LHC. The SM uniquely predicts the tensor structure of these interactions and fixes their strength in terms of the electromagnetic coupling  $e$  and the weak mixing angle  $\sin\theta_W \equiv s_\theta$ .

It has been recognized long ago that these predictions can be affected by new physics beyond the SM. This question can be addressed in a model-independent way in the linear effective field theory (EFT) framework, i.e., with the Higgs field embedded in an  $SU(2)$  doublet. In this approach, the SM is extended by nonrenormalizable gauge-invariant operators with mass dimensions  $D > 4$ , which encode the effects of new particles with the mass scale  $\Lambda$  much larger than the  $W$  boson mass  $m_W$ . The EFT approach organizes the new physics effects as an expansion in  $1/\Lambda$ , and the leading lepton-number-conserving corrections are  $\mathcal{O}(\Lambda^{-2})$  originating from  $D = 6$  operators. In the presence of  $D = 6$   $CP$ -conserving operators, the cubic couplings of electroweak gauge bosons take the form [1,2]

$$\begin{aligned} \mathcal{L}_{\text{TGC}} = & ie(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) A_\nu \\ & + ie \frac{c_\theta}{s_\theta} (1 + \delta g_{1,z}) (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) Z_\nu \\ & + ie(1 + \delta\kappa_\gamma) A_{\mu\nu} W_\mu^+ W_\nu^- + ie \frac{c_\theta}{s_\theta} (1 + \delta\kappa_z) Z_{\mu\nu} W_\mu^+ W_\nu^- \\ & + i \frac{\lambda_z e}{m_W^2} \left[ W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + \frac{c_\theta}{s_\theta} W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} \right], \end{aligned} \quad (1)$$

where  $\delta\kappa_z = \delta g_{1,z} - (s_\theta^2/c_\theta^2)\delta\kappa_\gamma$  and  $c_\theta = \sqrt{1 - s_\theta^2}$ . Therefore, as long as operators with  $D > 6$  are negligible, deformations of the cubic gauge interactions due to new physics can be parametrized by three anomalous triple gauge couplings (aTGCs):  $\delta g_{1,z}$ ,  $\delta\kappa_\gamma$ , and  $\lambda_z$ . In the SM limit,  $\delta g_{1,z} = \delta\kappa_\gamma = \lambda_z = 0$ . Nonzero aTGCs are effectively generated in models with new heavy particles, after the latter are integrated out at low energies. Starting from a minimally coupled renormalizable UV theory, only  $\delta g_{1,z}$  is generated at the tree level [3,4]; however, at a loop level all three aTGCs can be generated with arbitrary coefficients depending on the matter content of the theory. Given many possible forms that physics beyond the SM (BSM) could take, we think it is important to pursue a bottom-up approach in which as few assumptions as possible about the BSM sector are made. Consequently, in this Letter we will always allow all three aTGCs to be present simultaneously with arbitrary coefficients. We also note that with this model-independent approach our results can be readily translated to any different basis of  $D = 6$  operator, which is in general not true if arbitrary assumptions about the aTGCs are made.

Nonzero aTGCs affect experimental observables, such as the total and differential  $WW$  pair production cross section in high-energy colliders. Precision measurements of these quantities at the LEP-2  $e^+e^-$  collider allow one to constrain these coefficients [5] (see, e.g., Ref. [6] for future collider prospects). Reference [7] performed a simultaneous fit of the three aTGCs to the LEP-2 data at  $\mathcal{O}(\Lambda^{-2})$  in the EFT. That analysis revealed that robust limits on  $\delta g_{1,z}$  and  $\lambda_z$  are very weak, due to an accidental approximate flat direction of the fit for  $\delta g_{1,z} \approx -\lambda_z$ . Along this flat direction,  $\delta g_{1,z}$  and  $\lambda_z$  of order  $\sim 1$  are allowed by the LEP-2 data while the constraints on the orthogonal direction are at the  $\mathcal{O}(0.1)$  level.

In principle, the flat direction can be lifted by precision measurements of the  $WW$  and  $WZ$  differential production cross sections at the LHC. Unfortunately, a robust EFT analysis of these data has not yet been presented by the experimental collaborations and is difficult to perform with theorist-level tools using the publicly available information. Meanwhile, it has been pointed out that an independent set of observables—the LHC Higgs data—can also lead to strong constraints on the aTGCs [3,8–11]. However, these analyses are not completely general from the EFT point of view: the quadratic contributions in the aTGCs to the Higgs observables, formally of  $\mathcal{O}(\Lambda^{-4})$ , are included and/or not all possible  $D = 6$  operators affecting the Higgs observables are taken into account. We amend it in this Letter.

We derive constraints on the aTGCs from the combined LHC Higgs data and LEP-2  $WW$  data sets. In our analysis, all  $D = 6$  operators affecting Higgs couplings to matter and gauge boson self-couplings are allowed to be simultaneously present with arbitrary coefficients, assuming minimal flavor violation (MFV) [12]. In the Higgs basis [13], these parameters are [14]

$$\delta c_z, c_{zz}, c_{z\Box}, c_{\gamma\gamma}, c_{z\gamma}, c_{gg}, \delta y_u, \delta y_d, \delta y_e, \lambda_z. \quad (2)$$

Note that the dependence of the EFT cutoff  $\Lambda$  is included in the operator coefficients. The relation of these parameters to the interaction terms in the effective Lagrangian, as well as the relation to the aTGCs, can be found in Ref. [13]. Furthermore, we only take into account linear corrections in the Wilson coefficients, thus working consistently at the  $\mathcal{O}(\Lambda^{-2})$  in the EFT expansion. Note that, since different bases of  $D = 6$  operators in the literature differ by  $\mathcal{O}(\Lambda^{-4})$  terms corresponding to  $D > 6$  operators, only results obtained consistently at  $\mathcal{O}(\Lambda^{-2})$  are basis independent [15]. For the  $WW$  data, we use the measured total and differential  $e^+e^- \rightarrow W^+W^-$  cross sections of the different center-of-mass energies listed in Ref. [5]. These cross sections depend on a number of EFT parameters in addition to the aTGCs, in particular, on the ones inducing corrections to  $Z$  and  $W$  propagators and couplings to electrons. However, given the model-independent electroweak precision constraints [16], these measurements can effectively constrain three linear combinations of Wilson coefficients of  $D = 6$  operators that correspond to the aTGCs [7]. We use this dependence to construct the 3D likelihood function  $\chi_{WW}^2(\delta g_{1,z}, \delta\kappa_\gamma, \lambda_z)$ . For the LHC Higgs data, we use the signal-strength observables [17–32], that is, the ratio between the measured Higgs production cross section ( $\sigma$ ) times branching ratio (BR) and its SM prediction  $\mu \equiv (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ , listed in the Supplemental Material [33]. The effect of  $D = 6$  operators on  $\mu$  was calculated for each channel and production mode in Ref. [14] and independently cross-checked here. After imposing electroweak precision constraints, nine linear combinations of  $D = 6$  operators can affect  $\mu$  in an

observable way [3,34]. The crucial point is that two of these combinations correspond to the aTGCs  $\delta g_{1,z}, \delta\kappa_\gamma$ . Therefore, the likelihood function constructed from LHC Higgs data  $\chi_h^2(\delta g_{1,z}, \delta\kappa_\gamma, \dots)$  may lead to additional constraints on aTGCs. Indeed, combining the likelihoods  $\chi_{\text{comb}}^2 = \chi_h^2 + \chi_{WW}^2$ , we obtain strong constraints on the aTGCs at the level of  $\mathcal{O}(0.1)$ . Namely, we obtain the likelihood for the three variables only:  $\delta g_{1,z}, \delta\kappa_\gamma$ , and  $\lambda_z$ , after minimizing at each point the combined likelihood with respect to the remaining seven Wilson coefficients. We find the following central values,  $1\sigma$  errors, and the correlation matrix for the aTGCs:

$$\begin{pmatrix} \delta g_{1,z} \\ \delta\kappa_\gamma \\ \lambda_z \end{pmatrix} = \begin{pmatrix} 0.043 \pm 0.031 \\ 0.142 \pm 0.085 \\ -0.162 \pm 0.073 \end{pmatrix},$$

$$\rho = \begin{pmatrix} 1 & 0.74 & -0.85 \\ 0.74 & 1 & -0.88 \\ -0.85 & -0.88 & 1 \end{pmatrix}. \quad (3)$$

These constraints hold in any new physics scenario predicting approximately flavor blind coefficients of  $D = 6$  operators and in which  $D > 6$  operators are sub-leading. The constraints on all ten Wilson coefficients entering the analysis are reported in the Supplemental Material [33]. They are given in different bases for reader convenience [2,3,35–37].

Let us discuss here qualitatively the most important elements of our fit. Higgs data are sensitive to  $\delta g_{1,z}$  and  $\delta\kappa_\gamma$  primarily via their contribution to electroweak Higgs production channels. However, only one combination of these two aTGCs is strongly constrained, while the bound on the direction  $\delta\kappa_\gamma \approx 3.8\delta g_{1,z}$  is very weak. Analogously, as already discussed, also LEP-2 bounds present an approximate blind direction. This is illustrated in Fig. 1, where the  $WW$  and Higgs constraints in the  $\delta g_{1,z} - \delta\kappa_\gamma$  plane are shown separately [38]. Since the flat directions are nearly orthogonal, combining LHC Higgs and LEP-2  $WW$  data leads to the nontrivial constraints on aTGCs displayed in Eq. (3).

One could further strengthen the constraints on aTGCs by considering the process of single on-shell  $W$  boson production in association with an electron and a neutrino ( $e^+e^- \rightarrow WW^* \rightarrow We\nu$ ) [5], as in Ref. [7]. That process probes mostly  $\delta\kappa_\gamma$ , but it also affects limits on the remaining aTGCs due to the highly correlated nature of the constraints from  $WW$  and Higgs data. Indeed, we find that adding single  $W$  data to the combined likelihood roughly halves the confidence intervals for the aTGCs:  $\delta g_{1,z} = 0.017 \pm 0.023$ ,  $\delta\kappa_\gamma = 0.047 \pm 0.034$ ,  $\lambda_z = -0.089 \pm 0.042$ . However, we choose to highlight the more conservative result in Eq. (3) as we consider it more robust. The reason is that the experimental extraction of the single  $W$  cross section from fiducial measurements could be altered in a nontrivial way in the presence of the aTGC  $\delta\kappa_\gamma$ , which

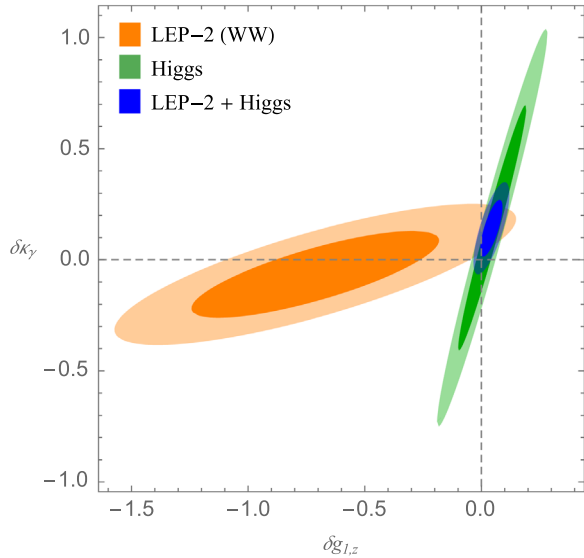


FIG. 1. Allowed 68% and 95% C.L. region in the  $\delta g_{1,z} - \delta\kappa_\gamma$  plane after considering LEP-2  $WW$  production data (TGC), Higgs data, and the combination of both data sets.

affects the photon  $t$ -channel contribution to the production amplitude. A more careful analysis is needed to render the single  $W$  constraint more robust.

In the following, we discuss whether the assumptions employed in our analysis can be relaxed without conflicting experimental data and, if yes, how this affects our results.

We begin by considering the possible impact of  $D = 8$  operators, contributing at  $\mathcal{O}(\Lambda^{-4})$ . In their presence, one obtains a more complicated structure of aTGCs going beyond the three-parameter characterization in Eq. (1). This is likely to open new flat directions in the fit, if the coefficients of the new aTGCs are allowed to be arbitrarily large. If the EFT expansion is valid, then the new contributions are suppressed by  $v^2/\Lambda^2$ , and therefore they are subleading with respect to the three aTGCs taken into account in our fit. However, since the experimental precision at the LHC is currently moderate,  $\mathcal{O}(20\%)$  at best, only higher-dimensional operators with  $\Lambda \lesssim$  few hundred GeV can be constrained by Higgs physics. For such a low  $\Lambda$ , it is not *a priori* obvious that the  $D = 8$  operators are subleading. One way to estimate their effect is to include in the analysis corrections to Higgs and  $WW$  observables that are *quadratic* in the Wilson coefficients of  $D = 6$  operators, as they are also of  $\mathcal{O}(\Lambda^{-4})$ . If the constraints on the aTGCs are severely affected by including the quadratic contributions, that would signal a potential sensitivity to  $D = 8$  operators [39]. In fact, constraints from Higgs or  $WW$  data alone are completely changed after including the quadratic terms. However, the *combined* data are only moderately sensitive. Once the quadratic contributions are included, we find the constraints  $\delta g_{1,z} = 0.032^{+0.043}_{-0.035}$ ,  $\delta\kappa_\gamma = 0.073^{+0.085}_{-0.075}$ ,  $\lambda_z = -0.098^{+0.058}_{-0.065}$ . The confidence intervals are shifted at the level of  $1\sigma$ ; however, qualitative

conclusions concerning the strength of the constraints on the aTGCs remain unchanged.

The sensitivity to  $D = 8$  operators is particularly relevant for the Higgs production in association with a  $W$  or  $Z$  boson ( $\sigma_{Vh}$ ), especially for large invariant mass of the  $Vh$  system  $m_{Vh}$  [4]. Although our results change very little with the inclusion of the quadratic contributions, we note that they can be significant around the best-fit point. This should be examined with care since the validity of our EFT expressions for  $\sigma_{Vh}$  is essential for lifting the flat direction of the LEP-2 data and obtaining strong constraints on aTGCs. We note that the EFT interpretation of Higgs searches could be made more robust if the  $m_{Vh}$  distributions were available. Indeed, we find that  $\sigma_{Vh}(m_{Vh} < 400 \text{ GeV})$  has a similar (reduced) sensitivity to linear (quadratic) terms. Therefore, assuming experimental measurements of  $\mu_{Vh}$  do not significantly alter with this cut, we find that the aTGC bounds remain unchanged, with a reduced sensitivity to higher-dimensional operators.

Furthermore, for low values of the EFT scale  $\Lambda$ , the presence of  $D > 6$  operators whose contribution is larger or comparable to that of  $D = 6$  operators could affect the  $Z$ -pole constraints on the latter (see also Ref. [40]). This in turn may affect the per-mille-level constraints on the  $Z$  and  $W$  couplings to fermions assumed in our analysis. However, since the constraints we obtained on the aTGC are at the  $\mathcal{O}(10\%)$  level, we do not expect this effect to qualitatively change our results unless the constraints on the  $Z$  and  $W$  coupling are relaxed to a similar level.

The question of the effect of the  $CP$  odd operators is closely related to the discussion above. Our constraints are based on Higgs signal-strength observables and on the total cross section and angular distribution of  $WW$  production. One can show that these are affected by  $CP$  odd operators only at  $\mathcal{O}(\Lambda^{-4})$ , as the  $CP$  violating contributions to the amplitude do not interfere with the SM contributions. Therefore, their effect on the aTGC bounds is of the same order as that of  $D = 8$  operators.

The next-to-leading-order (NLO) EFT corrections to Higgs observables can be divided into two groups. The QCD corrections  $\mathcal{O}(\alpha_s v^2/4\pi\Lambda^2)$  do not affect  $e^+e^- \rightarrow W^+W^-$ , but they can contribute corrections as large as  $\mathcal{O}(100\%)$  to Higgs processes. Fortunately, in the Higgs signal-strength observables, which involve a ratio of the observed to the predicted SM event rate, these large corrections are similar in the SM and new physics case, and therefore they largely cancel (see, e.g., Ref. [41] for the discussion in the context of the gluon fusion production process). The electroweak corrections  $\mathcal{O}(\alpha_{\text{ew}} v^2/4\pi\Lambda^2)$  are in general nonfactorizable. Some of these corrections correspond to a redefinition of the EFT parameters describing the Higgs couplings. For example, the effect of the recently calculated NLO EFT corrections to the  $h \rightarrow \gamma\gamma$  decay [42–44] is to replace the EFT parameter  $c_{\gamma\gamma}$  with a linear combination of the renormalized  $c_{\gamma\gamma}$  and other EFT

parameters. This has no impact whatsoever on our determination of the aTGCs. More generally, *logarithmically enhanced* NLO corrections respect the structure of the tree-level Lagrangian and do not affect the relations between different couplings in the effective Lagrangian that are assumed in the fit. On the other hand, *finite* NLO corrections may affect these relations. However, they are expected to be small, relative  $\mathcal{O}(10\%)$ , and given the current experimental precision of LHC Higgs observables they should not affect the analysis in any significant way. Finally, the NLO corrections to electroweak precision observables may affect bounds on certain operators; however, the resulting feedback on  $WW$  and Higgs observables should again be negligible.

Let us finally discuss the case in which no flavor symmetry is assumed. The main effects impacting the fit are (1) possible new operators affecting electroweak Higgs production and decay and (2) possible large values of the Yukawa couplings to light fermions.

As for the first point, in the EFT approach the coefficients of  $hZff$  and  $hWff'$  interactions are directly related to vertex corrections to the corresponding  $Zff$  and  $Wff'$  interactions. To estimate their possible effect, we use the results of a recent analysis of electroweak precision data in the flavor general EFT [16]. While most such terms are constrained with percent, or better, precision, vertex corrections to the couplings involving light quarks can be  $\mathcal{O}(10\%)$ . This would weaken (though not dramatically) the aTGC bounds obtained in the flavor blind case. However, the situation improves after taking into account also data from single  $Z$  and  $W$  Drell-Yan production at the LHC, where deviations from the SM are constrained at a few-percent level [45]. This is because the combination of  $Zqq$  and  $Wqq'$  couplings entering these processes is very similar to the one affecting the Higgs production cross section. Including the constraints from Ref. [45], we find that the aTGC limits in Eq. (3) hold with negligible modifications: the biggest effect is on  $\delta g_{1,z}$  where the constraints are 15% weaker.

Concerning the second point, the limits on the Higgs couplings in any current analysis crucially depend on assuming the MFV scenario, where the modifications of all Higgs Yukawa couplings can be related to just three parameters  $\delta y_{t,b,\tau}$  describing the Higgs couplings to the third generation fermions. Going beyond the MFV scenario, all Yukawa couplings become free parameters. Allowing the Higgs coupling to muons to be a free parameter has no appreciable consequences for aTGCs because the  $h \rightarrow \mu\mu$  data, which are included in our fit, constrain  $\delta y_\mu$ . On the other hand, data on tagged Higgs decays to quarks ( $c$ ,  $s$ ,  $d$ ,  $u$ ) are currently not available. Therefore, the only sensitivity of our set of observables to these couplings is via the modification of the total Higgs width and their one-loop contribution to the  $ggH$  coupling (see, however, Ref. [46]). Thus, our aTGC bounds remain unchanged if we allow for flavor-independent couplings, as

long as they are not much bigger than the SM value. The situation when they are allowed to be much bigger than their SM values is more complicated (see, e.g., Refs. [47–49]). Notice that large values are not incompatible with the EFT framework (as long as no flavor symmetry is assumed), which in principle predicts natural values of order  $v^2/\Lambda^2$  that easily exceed the small Yukawa couplings. Remarkably, even when light Yukawa couplings are as large as the bottom Yukawa coupling (which would almost double the total Higgs width), our aTGC bounds given in Eq. (3) qualitatively hold.

As discussed earlier, in this analysis we took into account only LEP-2 data on  $e^+e^- \rightarrow W^+W^-$  and ignored the Tevatron and LHC data on  $WW$  and  $WZ$  production in proton-(anti-)proton collisions. Including the latter could lead to better limits on the EFT parameters. However, to obtain robust constraints on aTGCs from a hadron collider, the current analysis strategies need to be improved. Unlike  $e^+e^-$  collisions at LEP, hadron collisions probe a wide range of energies, part of which may be beyond the validity regime of the EFT approach. The aTGC analyses should therefore restrict the range of center-of-mass energies of partonic collisions from which the constraints are derived to be below the EFT cutoff  $\Lambda$ . Since the cutoff is of course not known *a priori*, the results should be quoted in a function of  $\Lambda$  (as also proposed in Ref. [4] in the context of  $VH$  associated production). Next, the analyses should allow all three aTGCs to be present simultaneously, and a correlation matrix for the constraints on different parameters should be given. Finally, the analysis should be performed consistently at  $\mathcal{O}(\Lambda^{-2})$  in the EFT expansion, and the effects of neglecting or not  $\mathcal{O}(\Lambda^{-4})$  contributions should be quantified.

As a final comment, we note that the tight bounds we obtain via the combination of LEP-2  $WW$  and LHC Higgs data strongly constrain deviations in the  $h \rightarrow 4\ell$  distributions, which will be investigated in the LHC Run 2. These decays can be described experimentally through a set of pseudo-observables [50], which can then be matched to the  $D = 6$  operators in the EFT at tree level [51]. The strong bounds we obtain on the pseudo-observables from our fit are very similar to those presented in Ref. [51] using only LEP2 data with  $\lambda_z = 0$ . Therefore, to a good approximation, the analysis performed in that work for such a specific case holds now in full generality. In particular, the very strong bounds on the contact terms  $e_{Z\ell_{L,R}}$  imply small deviations in the  $h \rightarrow 4\ell$  spectrum [51].

To conclude, by working at  $\mathcal{O}(\Lambda^{-2})$  in the EFT and under the MFV assumption, we obtained strong and model-independent bounds on the aTGCs via the combination of LEP-2  $WW$  and LHC Higgs signal-strength data. The combination of the two data sets lifts the flat direction affecting each of them taken separately, thus showing the importance of performing global analysis in the EFT framework. Combined with the  $W$ - and  $Z$ -pole observables analysis of Ref. [16], the results of this work can be used to

set strong constraints on a wide class of possible new physics scenarios.

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- [38] The bounds from  $WW$  data alone slightly depend on the scale at which the SM couplings  $g$  and  $g'$  are evaluated. Working at leading order, these are higher-order effects, and thus any scale is equally valid. Differently than in Ref. [7], here we extract those couplings from  $G_F$ ,  $m_Z$  and  $\alpha_{em}(m_Z)$  and then run them up to the LEP-2 energy  $\sqrt{s} \approx 200$  GeV. The resulting values are  $g \approx 0.645$  and  $g' \approx 0.357$ . The dependence of the combined Higgs and  $WW$  fit on this choice is instead very small.
- [39] Keeping the quadratic terms while neglecting  $D = 8$  operators can be justified for certain classes of UV completions of the EFT [4].
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