Probing new physics in the Higgs sector with effective field theories at the Large Hadron Collider

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Abstract. With the discovery of a particle consistent with a Higgs boson a new window of opportunity for searches for new physics opens up. These can be performed via precision physics or direct searches. The ATLAS and CMS experiments at the Large Hadron Collider study the Higgs boson couplings to other particles assuming that their structure is the same as that predicted in the Standard Model. With the addition of new physics via higher dimensional operators, in the framework of an effective field theory, the structure of these couplings changes. The implications on the Higgs boson production rates and the differential cross-sections are discussed. Prospects for the sensitivity of the ATLAS and CMS experiments to these higher dimensional operators are also discussed. This includes measurements both at the level of decay and production.

1. Introduction

At present, all the data obtained from the many experiments in particle physics are in agreement with the Standard Model (SM). In the SM there is one particle, the Higgs boson, that is responsible for giving masses to all the elementary particles [1, 2, 3, 4]. In July 2012 the ATLAS and CMS experiments at the Large Hadron Collider (LHC) reported the discovery of a boson, a Higgs-like particle with a mass $m_H \approx 125$ GeV based on the data accumulated during 2011 and a part of 2012 period [5, 6].

The experiments at the LHC have not revealed any definitive direct signature of new physics so far.[4] However, one is led to suspect that such physics should affect the interaction Lagrangian of the Higgs boson. This generates, for example, effective operators of dimension-6 contributing to interactions of the Higgs and the electro-weak boson fields, HVV , with $V = W, Z, \gamma$. Probing such effective couplings for the recently discovered scalar is therefore tantamount to opening a gateway to fundamental physics just beyond our present reach.

Such 'effective' interaction terms need to be $SU(2) \times U(1)$ invariant if they arise from physics above the electroweak scale. Constraints on such terms have already been studied, using precision electroweak data as well as global fits of the current Higgs boson data (see Ref. [7] and references therein). Many studies have also considered anomalous Higgs boson couplings in the context of future e^+e^- and ep colliders.

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[4] It is important to note that a number of anomalies in the Higgs boson data collected so far are seen. These will be summarized by other speakers. Whether these anomalies are statistical fluctuations or are connected with new physics beyond the SM becomes a very interest prospect for the Run II data taking.

The general conclusion, based on analyses of the 8 TeV data at the LHC, is that several (though not all) of the gauge invariant, dimension-6 HVV terms can at most have coefficients $\sim$ 5 TeV^{-2}. It still remains to be seen whether such small coefficients can be discerned with some ingeniously constructed kinematic distributions. Some work has nonetheless been done to study such distributions, in terms of either the gauge invariant operators themselves or the structures finally ensuing from them [8, 9]. At the same time, it is of interest to see if meaningful constraints do arise from the study of total rates at the LHC.

This paper is organized as follows: Section 2 briefly summarizes the effective field theory approach, Section 3 defines convenient observables based on ratios and Section 4 discusses the results. The paper is concluded with a summary in Section 5.

2. Effective field theory: Higher dimensional operators

In order to see any possible deviations from the SM in the Higgs boson sector, we will follow an effective field theory (EFT) framework. We consider $SU(2)_L \times U(1)_Y$ invariant operators of dimension up to 6, which affect Higgs boson couplings to itself and/or a pair of electroweak vector bosons. We have concentrated here on dimension-6 (D6) CP-conserving operators which affect Higgs boson phenomenology. They include [7]:

- Operators which contain the Higgs doublet Φ and its derivatives:

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi); \quad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi); \quad \mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3 \tag{1}$$

- Those containing Φ (or its derivatives) and the bosonic field strengths:

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi G^a_{\mu\nu}G^{a\,\mu\nu}; \quad \mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi; \quad \mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi;$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi); \quad \mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi; \quad \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi), \tag{2}$$

where

$$\hat{W}^{\mu\nu} = i\,\frac{g}{2}\sigma_a W^{a\,\mu\nu}; \quad \hat{B}^{\mu\nu} = i\,\frac{g'}{2}B^{\mu\nu}$$

and g, g' are, respectively, the $SU(2)_L$ and $U(1)_Y$ gauge couplings. $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\epsilon^{abc}W^b_\mu W^c_\nu$, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc}G^b_\mu G^c_\nu$. The covariant derivative of Φ is given as $D_\mu\Phi = (\partial_\mu + \frac{i}{2}g'B_\mu + ig\frac{\sigma_a}{2}W^a_\mu)\Phi$. The Lagrangian, in the presence, of the above operators can be generally expressed as:

$$\mathcal{L} \supset \kappa\left(\frac{2m_W^2}{v}HW^+_\mu W^{\mu-} + \frac{m_Z^2}{v}HZ_\mu Z^\mu\right) + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i, \tag{3}$$

where, in addition to the D6 operators, we also allow the SM-like HWW and HZZ couplings to be scaled by a factor κ. While $\kappa \neq 1$ is indicative of certain kinds of new physics, we are especially interested in the new observable features associated with the higher dimension operators (HDOs). Therefore, we have set $\kappa = 1$ for simplicity.

No operator of the form $\mathcal{O}_{GG}$ is assumed to exist since we are presently concerned with Higgs boson interactions with a pair of electroweak vector bosons only. The operator $\mathcal{O}_{\Phi,1}$ is severely constrained by the T-parameter (or equivalently the ρ parameter), as it alters the HZZ and HWW couplings by unequal multiplicative factors. As far as HZZ and HWW interactions are concerned, $\mathcal{O}_{\Phi,2}$ only scales the SM couplings, without bringing in any new Lorentz structure. It also alters the Higgs boson self-coupling, something that is the sole consequence of $\mathcal{O}_{\Phi,3}$ as well.

In view of the above, we focus on the four operators $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_W$ and $\mathcal{O}_B$. We do not include the operator $\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$ in the present analysis, because it mixes the Z and γ fields at tree level, violates custodial symmetry (by contributing only to the Z-boson mass) and is, therefore, highly constrained by the S and T-parameters at the tree level.

The already existing limits on the various operators discussed above are found in numerous references. Even within their current limits, some of the operators are found to modify the efficiencies of the various kinematic cuts. The question we address in the rest of the paper is: can these limits be improved in the next run(s) of the LHC through careful measurement of the ratios of total rates in different channels? As we shall see below, the answer is in the affirmative.

3. Ratios of cross-sections as chosen observables

The four HDOs under consideration affect Higgs boson production as well as its decays, albeit to various degress. For example, HDO-dependent single Higgs boson production processes are in association with vector bosons (VH) *i.e.* $pp \to VH$ (where $V = \{W, Z\}$) and vector-boson fusion (VBF). We show the production cross-sections in these channels at 14 TeV in Fig. 1, as functions of the four operator coefficients (f_i) taken one at a time.[5] The relevant decay channels which are dependent on such operators are $H \to WW^*, ZZ^*, \gamma\gamma, Z\gamma$. Figure 2 contains these branching ratios (BR) as functions of the four coefficients under consideration.

The VBF and VH rates are sensitive to f_{WW} and f_W, but depend very weakly on f_{BB} and f_B, while the cross-section $\sigma(pp \to WH)$, is completely independent of f_{BB} and f_B. The HDO effects in $H \to \gamma\gamma$ and $H \to Z\gamma$ for $f_i \sim \mathcal{O}(1)$ is of the same order as the loop-induced SM contribution, unlike in the case of the HWW and HZZ couplings. Therefore, $\mathrm{BR}_{H\to\gamma\gamma}$ becomes highly sensitive to f_{WW} and f_{BB}. Consequently, the 7+8 TeV data already restrict their magnitudes to small values of the order of $\lesssim 5$ TeV^{-2}. The limits on f_W and f_B, however, are relatively weaker, even after simultaneous imposition of constraints from electroweak precision data and LHC results.

Based on the above information, we set out to find observables which are sensitive to $f_i \lesssim 5$ TeV^{-2} in the high luminosity runs at the LHC. It is not completely clear yet how much statistics is required to probe such small values with various event shape variables. On the other hand, the more straightforward observables, namely, total rates in various channels, are also fraught with statistical, systematic and theoretical uncertainties which must be reduced as far as possible when precision is at a premium.

An approach that is helpful is looking at ratios of cross-sections in different channels. In this paper, we invoke two kinds of ratios. First, we take ratios of events in two different final states arising from a Higgs boson produced via the same channel (in our case, gluon fusion). Such a ratio enables one to get rid of correlated theoretical uncertainties such as those in PDF and renormalization/factorization scales. They also cancel the uncertainty in total width, which is correlated in the calculation of BRs into the two final states. Secondly, we consider the ratio of rates for the same final state for two different production channels (such as VBF and VH). Although the uncertainty in the BR cancels here, the theoretical uncertainties at the production level do not. Moreover, since the final state is the same in this case, some systematic uncertainties which are correlated (related to identification, isolation, trigger etc.) will also cancel. However, this is helpful in another manner. For some of the operators, the f_i-dependent shifts with respect to the SM are in the opposite direction for the numerator and the denominator in such ratios. We shall see that the use of both these kinds of ratios, including those involving the channel $Z\gamma$, can capture the HDO coefficients at a level unprecedented, going down to values where new physics can show up.

[5] We have used CTEQ6L1 parton distribution functions (PDFs) by setting the factorization (μ_F) and renormalization scales (μ_R) at the Higgs boson mass ($m_H = 125$ GeV).

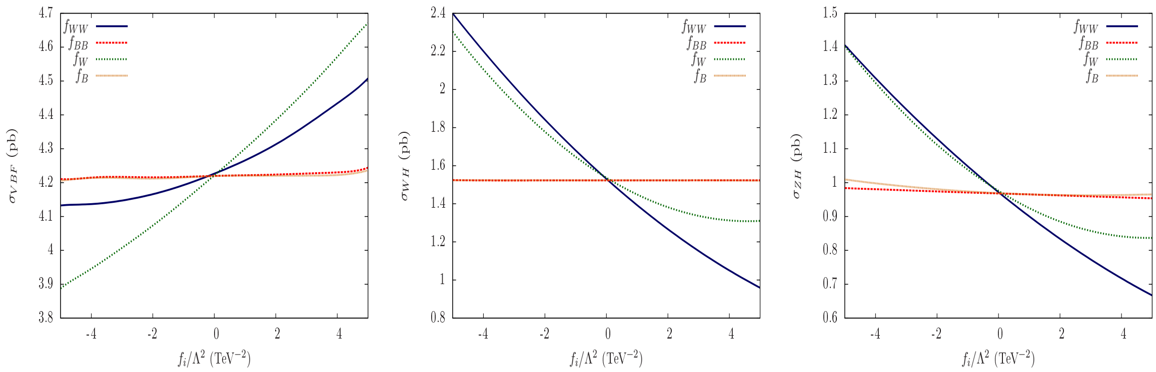

Figure 1. Higgs boson production cross-sections for the VBF and VH channels in the presence of HDOs at 14 TeV. Here the operators are varied one at a time.

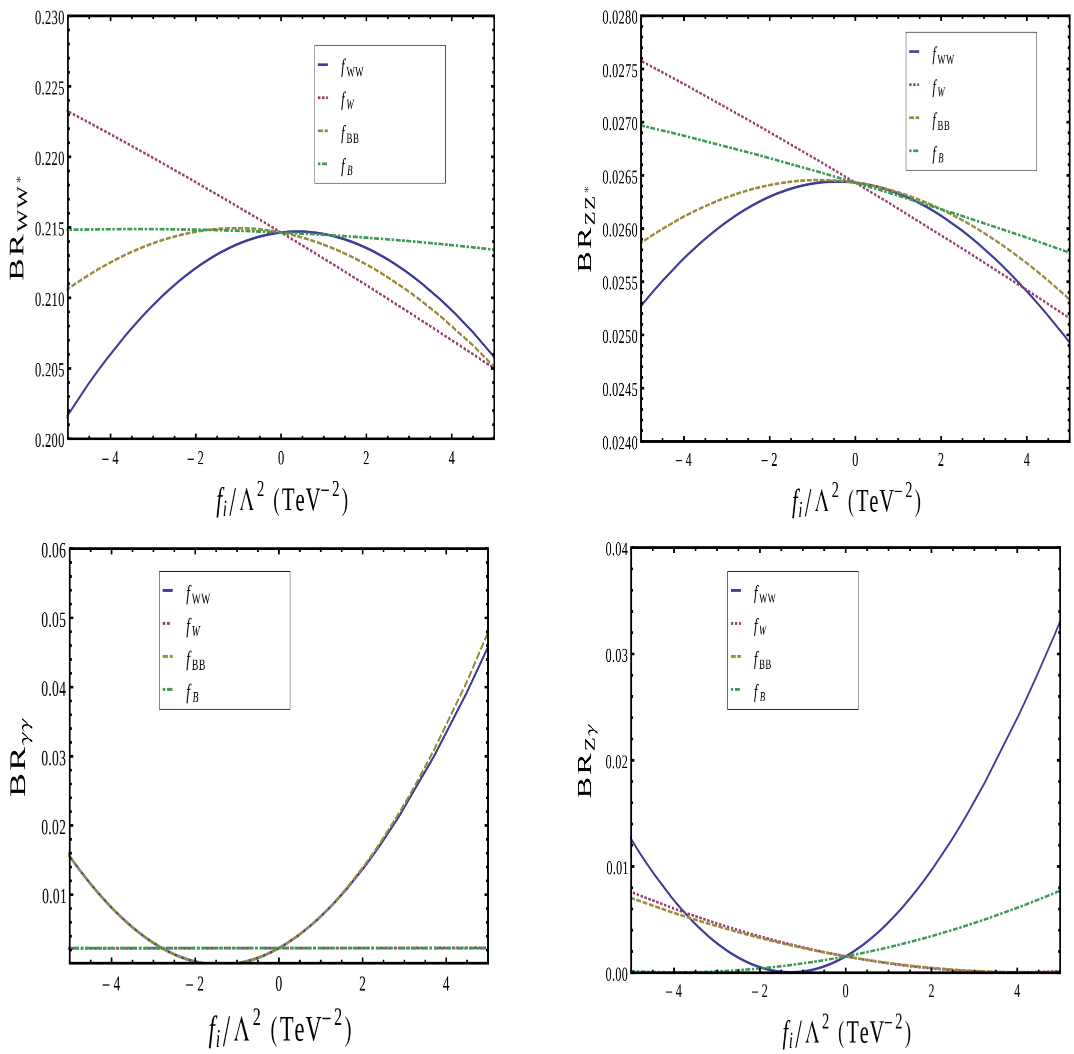

Figure 2. Branching ratios of $H \to WW^*, ZZ^*, \gamma\gamma, Z\gamma$ in presence of HDOs. The operators are varied one at a time.

Observables	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_W$	$\mathcal{O}_B$
$\mathcal{R}_1$ @ 7+8 TeV	$[-3.32, -2.91]$ $\cup$ $[+0.12, +0.57]$	$[-3.32, -2.91]$ $\cup$ $[+0.12, +0.57]$	Not bounded	Not bounded
$\mathcal{R}_1$ @ 14 TeV	$[-2.75, -2.66]$ $\cup$ $[-0.06, +0.03]$	$[-2.75, -2.66]$ $\cup$ $[-0.06, +0.03]$	Not bounded	Not bounded
$\mathcal{R}_2$ @ 14 TeV	$[-1.32, +1.21]$	Not bounded	$[-1.51, +1.72]$	Not bounded
$\mathcal{R}_3$ @ 14 TeV	Not used	Not used	Not used	$[-8.04, -7.63]$ $\cup$ $[-0.21, +0.17]$

Table 1. We summarize our obtained allowed region of the coefficients of HDOs using the three observables.

In the light of what is discussed above, we construct the following observables based on ratios [7]:

$$\mathcal{R}_1(f_i) = \frac{\sigma_{ggF} \times BR_{H\to\gamma\gamma}(f_i)}{\sigma_{ggF} \times BR_{H\to WW^*\to 2\ell 2\nu}(f_i)}, \tag{4}$$

where $\ell = e, \mu$ and f_i's are the operator coefficients;

$$\mathcal{R}_2(f_i) = \frac{\sigma_{VBF}(f_i) \times BR_{H\to\gamma\gamma}(f_i)}{\sigma_{WH}(f_i) \times BR_{H\to\gamma\gamma}(f_i) \times BR_{W\to\ell\nu}}, \tag{5}$$

and

$$\mathcal{R}_3(f_i) = \frac{\sigma_{ggF} \times BR_{H\to Z\gamma\to 2\ell\gamma}(f_i)}{\sigma_{ggF} \times BR_{H\to WW^*\to 2\ell 2\nu}(f_i)}. \tag{6}$$

Equations 4, 5 and 6 are sensitive to the operators, $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ and $\mathcal{O}_W$, and $\mathcal{O}_B$, respectively.

4. Results of the analysis

For our subsequent collider analysis, the chain we have used is as follows - first we have implemented the relevant dimension-6 interaction terms, as shown in Section 2, in FeynRules, and generated the Universal FeynRules Output (UFO) model files. These UFO model files have been used in the Monte-Carlo (MC) event generator MadGraph [10] to generate event samples. Next, the parton-showering and hadronization are performed using Pythia6 [11], and finally detector level analysis is carried using Delphes [12].

In Table 1 we summarize our obtained region of the parameter space allowed using three ratios, $\mathcal{R}_1$, $\mathcal{R}_2$ and $\mathcal{R}_3$. We present $\mathcal{R}_1$ using combined ATLAS+CMS data for 7+8 TeV runs. We also present a projected study for all three observables at 14 TeV with an integrated luminosity of 3000 fb^{-1}. The allowed regions on f_{WW} and f_{BB} are reduced at the 14 TeV 3000 fb^{-1} run as compared to the current data. Using the ratio $\mathcal{R}_2$ one can also put bounds on f_{WW} and f_W. There is a 'special' region of parameter space where the $\mathcal{R}_1$ mimics the SM expectation, therefore, $\mathcal{R}_2$ can also be used to infer the presence of $\mathcal{O}_{WW}$ with 'special' values of coefficient f_{WW}. The operator $\mathcal{O}_B$ does not show any aprreciable sensitivity in any production of the Higgs boson or its decay except in the $BR_{H\to Z\gamma}$. Therefore, the ratio $\mathcal{R}_3$ is constructed to constrain f_B by a significant amount, as evident from Table 1.

5. Summary and Conclusions

We have investigated how well one can constrain dimension-6 gauge-invariant operators inducing anomalous HVV interactions. Probing the gauge invariant operators individually, we feel, are important, since they can point at any new physics above the electroweak symmetry breaking scale. While the operators contributing to $H \to \gamma\gamma$ are subjected to the hitherto strongest limits using the (7+8) TeV data, the remaining ones are relatively loosely constrained, in spite of the bounds coming from precision electroweak observables. At any rate, it is necessary to reduce uncertainties as much as possible, since any realistically conceived new physics is likely to generate such operators with coefficients no greater than $\approx \mathcal{O}(1)$ TeV^{-2}. We show that a good opportunity to probe them at this level, and improve spectacularly over the existing constraints, arises if event ratios in various channels are carefully studied. These include both ratios of events in different final states with the same Higgs boson production channel and those where a Higgs boson produced by different production modes ends up decaying into the same final state. While a majority of the theoretical uncertainties cancel in the former category, the latter allows us to probe those cases where some dimension-6 operators shift the rates in the numerator and the denominator in opposite directions. We find that, after a thorough consideration of all uncertainties, all the couplings can be pinned down to intervals of width $\approx \mathcal{O}(1)$ TeV^{-2} using 3000 fb^{-1} of integrated luminosity at 14 TeV. Even with 300 fb^{-1}, the improvement over existing constraints is clearly expected, and the results are more uncertainty-free than in any other hitherto applied method. However, we must mention here that this approach should be complemented with the study of differential distributions, which is not within the scope of this paper.

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