

Limits on Higgs boson couplings in Effective field theory

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Abstract. We review the Effective Field Theory (EFT) to make projections on physics beyond the Standard Model in the Higgs sector. We provide relations between the non-Standard Model couplings of the Strongly-Interacting Light Higgs (SILH) effective Lagrangian implemented in the eHDecay package and the corresponding terms of the spin-0 Higgs Characterisation model's effective Lagrangian used with the aMC@NLO Monte Carlo generator. Constraints on BSM couplings are determined on the basis of existing experimental limits on Higgs boson width and branching ratios.

1. Introduction

In the summer of 2012, the CMS and ATLAS Collaborations at the LHC reported the discovery of a new resonance in searches for the Standard Model Higgs boson. To study this discovery in greater detail, both collaborations conducted analyses of the full LHC Run-I data [1-2]. It was shown that the new particle has a mass around 125 GeV and that the dominant production mechanism is gluon fusion. The decay of the new resonance into pairs of two gauge bosons ($\gamma\gamma$, ZZ , and WW) was observed. These production and decay modes identified the discovered particle as a neutral boson. The subsequent measurements of its couplings to fermions and bosons have shown the compatibility of these results with the expectations of the Standard Model related to the Higgs boson [3-4].

In the Standard Model, the electroweak symmetry breaking through the Higgs mechanism requires the presence of a neutral Higgs boson with spin 0 and positive CP-parity. Many theories beyond the Standard Model require an extended Higgs sector which also contains CP-odd physical eigenstates of Higgs boson as far as CP-even. In this case, mixing between CP-even and CP-odd eigenstates would be permissible and the Higgs boson observed experimentally may thus have mixed CP-parity. This is a very important possibility because the CP-violation effects in the Standard Model are too small to explain the baryon asymmetry of the Universe.

Detailed studies of Higgs boson candidate spin and parity performed by ATLAS and CMS collaborations have shown that the dominant hypothesis of spin and parity is $J^{CP} = 0^{++}$ [5-6]. These studies were performed with 25 fb^{-1} datasets obtained by each major experiment of the LHC and allow us to obtain the upper limit on a possible CP-odd contribution.

In this paper, we review the framework of the Effective field theory implemented in the eHDecay package in order to obtain limits on Higgs boson couplings by using the experimental limits on Higgs boson partial and total decay widths.



2. Effective field theory basis

The Effective field theory (EFT) is an approximate model for a physical phenomenon designed without the intention to describe the causal mechanism of the phenomenon. It includes the appropriate degrees of freedom to describe physical phenomena occurring at a chosen length scale or energy scale, while ignoring substructure and degrees of freedom at shorter distances. For the purpose of making projections about the characteristics of non-SM Higgs bosons, EFTs are very useful, as they can provide a framework for simulation that isn't strictly bound to a physical reality.

In this paper, we analyzed the Higgs effective Lagrangian implemented in a widely used Higgs Characterization model [7] for the aMC@NLO Monte Carlo generator. Such Lagrangians can be written for all reasonable spins (0, 1 and 2) of the Higgs boson. We review spin 0 effective Lagrangian describing the interaction of the Higgs boson with the gauge bosons of the Standard Model. The structure of this Lagrangian is described at (1), (2), and (3).

$$\begin{aligned}
 L_0^V = & \left\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\
 & - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
 & - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
 & - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{A\gamma gg} g_{A\gamma g} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] \\
 & - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
 & - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \\
 & - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} \right. \\
 & \left. + \left(\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c. \right) \right] \Big\} X,
 \end{aligned} \tag{1}$$

where Λ is the cutoff scale and $c_\alpha (\equiv \cos \alpha)$ is cosine of the mixing angle between 0^+ and 0^- . The (reduced) field strength tensors are defined as follows:

$$\begin{aligned}
 V_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V=A, Z, W^\pm), \\
 G_{\mu\nu}^a &= \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c,
 \end{aligned} \tag{2}$$

and the dual tensor is:

$$\tilde{V}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}. \tag{3}$$

Lagrangian (1) contains CP-even and CP-odd Higgs boson eigenstates which could be mixed by setting the α parameter to, alternately, zero and one. Case $c_\alpha = 1$ corresponds to a pure Standard Model CP-even Higgs boson state while $c_\alpha = 0$ corresponds to a pure BSM CP-odd Higgs boson state.

3. Limits on the Higgs couplings

In order to obtain limits on the Higgs boson couplings the eHDecay package was used [8]. This tool allows us to calculate the Higgs boson decay width and branching ratios with the given Lagrangian parameters. For example, figure 1 and figure 2 show how the Higgs boson partial decay width and branching ratio depend on a $C_{\gamma\gamma}$ coupling (assuming $C_{Z\gamma} = C_{ZZ} = C_{WW} = C_{gg} = 1$).

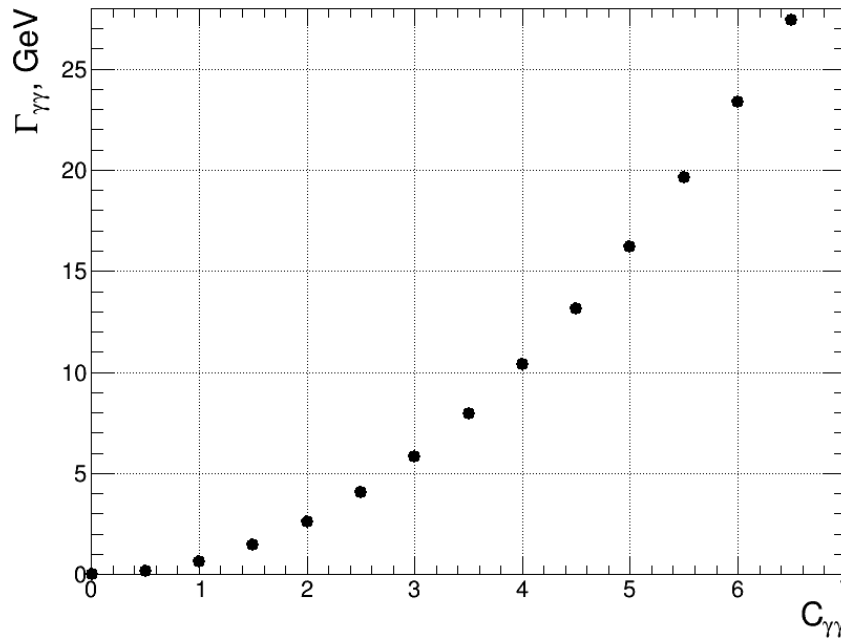


Figure 1. Higgs boson decay widths calculated via eHDecay as function of $C_{\gamma\gamma}$ coupling.

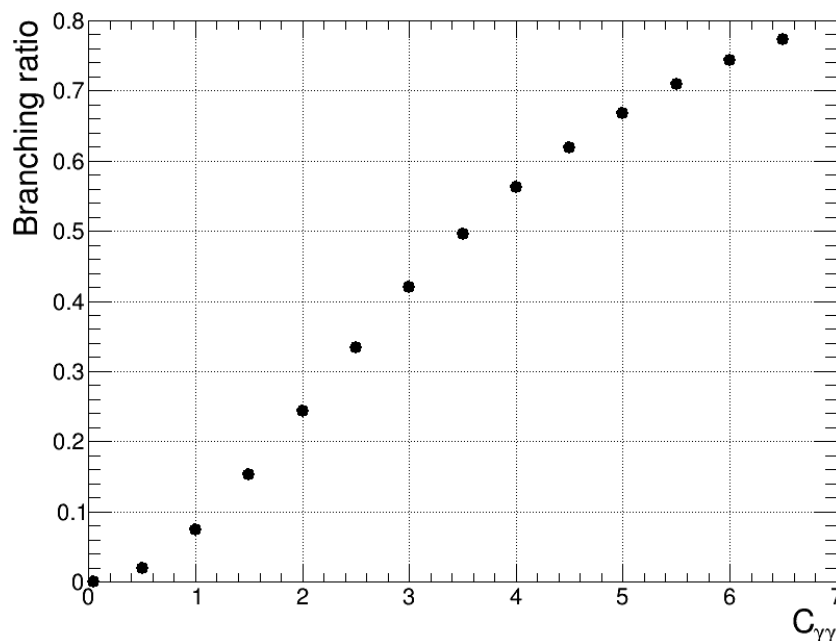


Figure 2. Higgs boson branching ratios calculated via eHDecay as function of $C_{\gamma\gamma}$ coupling.

During this study the following couplings were reviewed: $C_{\gamma\gamma}$, $C_{Z\gamma}$, C_{ZZ} , C_{WW} , C_{gg} , C_{ZdZ} and C_{WdW} . These couplings can be transformed to couplings used in Lagrangian (1) by the mapping formulas indicated at table 1 and table 2, where α_{EM} and α_s are the electromagnetic and strong

interaction constants respectively, v is the Higgs vacuum expectation value, θ_W is the Weinberg angle and $c = \sqrt{\frac{\alpha_{EM} G_F m_Z^2}{8\sqrt{2}\pi}}$.

Table 1. Mapping formulas for C_Z, C_W, C_{ZZ}, C_{WW} and $C_{\gamma\gamma}$ couplings.

C-coupling	C_Z	C_W	C_{ZZ}	C_{WW}	$C_{\gamma\gamma}$
k-coupling	$c_\alpha k_{SM}$	$c_\alpha k_{SM}$	$-\frac{v}{2\Lambda} c_\alpha k_{HZZ}$	$-\frac{v}{2\Lambda} c_\alpha k_{HWW}$	$-\frac{47\alpha_{EM}}{36\pi} c_\alpha k_{H\gamma\gamma}$

Table 2. Mapping formulas for $C_{gg}, C_{ZdZ}, C_{WdW}, C_{Zd\gamma}$ and $C_{Z\gamma}$ couplings.

C-coupling	C_{gg}	C_{ZdZ}	C_{WdW}	$C_{Zd\gamma}$	$C_{Z\gamma}$
k-coupling	$\frac{\alpha_S c_\alpha k_{Hgg}}{6\pi}$	$-\frac{v}{\Lambda} c_\alpha k_{HdZ}$	$-\frac{v}{\Lambda} c_\alpha k_{HdW}$	$-\frac{v}{\Lambda} c_\alpha k_{Hd\gamma}$	$-c_\alpha k_{HZ\gamma} \frac{c(94\cos^2\theta_W - 13)}{18\pi}$

Currently, LHC data exhibits an upper limit on the total Higgs boson decay width of 22 MeV [9]. Upcoming limits on partial decay widths are much more loose ($\Gamma_{ZZ} < 46 \text{ MeV}$ and $\Gamma_{WW} < 52 \text{ MeV}$). Obtained limits on coupling regions corresponding to experimental restrictions are indicated in table 3 (for C_{ZZ}, C_{WW}, C_{ZdZ} and C_{WdW} , the condition of positivity of the branching ratio was also involved).

Table 3. Coupling regions corresponding to the tightest experimental limits on a Higgs boson decay width.

Coupling	C_{ZZ}	C_{WW}	C_{gg}	$C_{\gamma\gamma}$	$C_{Z\gamma}$	C_{ZdZ}	C_{WdW}
Maximum	1.97	1.32	1.6593	5.827	12.687	1.01	0.90
Minimum	$-3.85 \cdot 10^5$	$-3.27 \cdot 10^4$	-1.6715	-5.820	-12.673	$-1.99 \cdot 10^5$	$-2.20 \cdot 10^4$

4. Conclusion

In this paper, the Effective field theory approach was used in order to calculate the limits for Higgs boson couplings from the experimental restrictions on the Higgs boson decay width. Mapping formulas which establish a connection between eHDecay and Higgs Characterization EFT bases were also obtained and can be used to recalculate obtained limits in terms of k-couplings of a widely used Higgs Characterisation model.

Acknowledgements

For his guidance and insight, we would like to thank Dr. R. Konoplich. The work of N. Belyaev was performed within the framework of the Center for Fundamental Research and Particle Physics supported by MEPhI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013). The work of T. Reid is partially supported by the US National Science Foundation under Grant No. PHY-1402964.

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