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Probing the Higgs trilinear self-coupling via single Higgs processes and precision physics

Giuseppe Degrassi
Dipartimento di Matematica e Fisica, Università di Roma Tre and INFN, sezione di Roma Tre, I-00146 Rome, Italy
E-mail: degrassi@fis.uniroma3.it

I discuss the possibility of probing an anomalous Higgs trilinear coupling indirectly, through its effects in the single Higgs production and decay processes at the LHC and in the precision observables. Indeed, although these processes do not depend on this coupling at the tree level, they are sensitive to the trilinear Higgs self-coupling via loop effect. The constraints on the trilinear Higgs self-coupling that can be obtained from various observables, like the signal strength of the different channels, the cross-section of the associate Higgs production with top quarks and the measurement of the W mass, are presented.

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1. Introduction

One of the main goal of the present experimental research program at the Large Hadron Collider (LHC) is the study of the properties of the scalar resonance discovered in 2012 [1, 2]. This study provides strong evidence that this resonance is the Higgs boson of the Standard Model (SM). Indeed, the mass of this particle, $m_H = 125.09 \pm 0.24$ GeV, fits perfectly inside the range allowed by the Electroweak (EW) fit of precision observables, its couplings with the vector bosons are found to be compatible with those expected from the SM within a $\sim 10\%$ uncertainty, while in the case of the heaviest SM fermions (the top, the bottom quarks and the τ lepton) the compatibility is achieved with an uncertainty of $\sim 15-20\%$. Concerning the future, present estimates [3] indicate that at the end of the High Luminosity (HL) LHC Run with 3000 fb^{-1} luminosity the couplings of the Higgs boson to the vector bosons are expected to reach a few per-cent precision while the corresponding ones for the fermions, with the exception of the μ lepton, can reach $\sim 8-12\%$ precision.

The knowledge of the Higgs self interactions, i.e. of the shape of the scalar potential in the Lagrangian, is in a completely different status. In the SM, the Higgs potential in the unitary gauge reads

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 \tag{1.1}$$

where the Higgs mass (m_H) and the trilinear (λ_3) and quartic (λ_4) interactions are linked by the relations $\lambda_4^{\rm SM} = \lambda_3^{\rm SM} = \lambda = m_H^2/(2v^2)$, where $v = (\sqrt{2}G_\mu)^{-1/2}$ is the vacuum expectation value, and λ is the coefficient of the $(\Phi^\dagger\Phi)^2$ interaction, Φ being the Higgs doublet field.

The experimental verification of these relations, that fully characterize the SM as a renormalizable Quantum Field Theory, relies on the measurements of processes featuring at least two Higgs bosons in the final state. However, since the cross sections for this kind of processes are quite small, constraining the Higgs self interaction couplings is extremely challenging. At present the best result on Higgs pair production comes from CMS in the channel $HH \to bb\gamma\gamma$ were a limit at 95% C.L. on the production cross-section 19 times the SM one was obtained [4]. This result is translated into a range of excluded values for the trilinear self-coupling, namely $\lambda_3 < -8\ \lambda_3^{\rm SM}$ and $\lambda_3 > 15\ \lambda_3^{\rm SM}$. Concerning the future, a ATLAS study suggests, assuming an integrated luminosity of 3000 fb^{-1}, that it will be possible to exclude at the LHC only values in the range $\lambda_3 < -0.8\ \lambda_3^{\rm SM}$ and $\lambda_3 > 7.7\ \lambda_3^{\rm SM}$ via the $b\bar{b}\gamma\gamma$ signatures [5]. The translation from cross section results to bounds on λ_3 actually contains one assumption that can be specified as follows: "The only effect induced by (unspecified) New Physics (NP) beyond the SM is just a modification of the Higgs trilinear self-coupling and nothing else". This assumption is very restrictive and probably quite unrealistic. However, given the present experimental status and also the future perspective, one is somewhat forced to adopt it in order to obtain a limit on λ_3. Concerning the quartic Higgs self-coupling λ_4, its measurement via triple Higgs production seems beyond the reach of the LHC [6].

Given the present perspective on Higgs Physics one expects that at the end of the HL-LHC program while the coupling of the Higgs to gauge fields and fermions will be known $\mathcal{O}(3-10\%)$, λ_3 will be still poorly known, $\mathcal{O}(1)$. This situation suggest the idea of trying to constrain the trilinear Higgs self coupling, obviously under some assumptions, using the information coming from the precise measurements of single Higgs production and decay processes. This strategy, that has to be seen as complementary to Higgs pair production studies, relies on exploiting the dependence

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of single Higgs processes upon λ_3 via loop effects. It was first applied to ZH production at an e^+e^- collider in Ref. [7] and later to Higgs production and decay modes at the LHC [8–10]. Recently it was also applied to the case of precision observables, where the dependence upon λ_3 arises at the two-loop level in the vector boson self-energies [11, 12].

2. Working framework and assumptions

In order to implement this strategy one considers a Beyond-the-Standard-Model (BSM) scenario, described at low energy by the SM Lagrangian with a modified scalar potential. Furthermore it is assumed that only Higgs self couplings are affected by this modified potential while the strength of the couplings of the Higgs to fermions and vector bosons is not going to change with respect to its SM value. This scenario can be described by a Lagrangian of the form

$$\mathscr{L}_{\lambda_3} \equiv \mathscr{L}_{SM} - \sum_{n=3}^{N} c_{2n} (\Phi^\dagger \Phi)^n \,, \qquad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H + i\phi_2) \end{pmatrix}, \tag{2.1}$$

where N is an unspecified integer and the coefficients c_{2n} are arbitrary, namely no constraint on the size of c_{2n} is assumed. The Lagrangian $\mathscr{L}_{\lambda_3}$ actually differs from a standard SM Effective Field Theory (EFT) Lagrangian

$$\mathscr{L}_{EFT} \equiv \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\mathscr{L}^{D=6} + \dots \tag{2.2}$$

with Λ the scale of NP, in two aspects: i) it does not contain all possible D=6, D=8 etc. operators; ii) the coefficients c_{2n} do not exhibit an EFT scaling, i.e. $c_{2n+2} \sim c_{2n}/\Lambda^2$, that is instead present in the coefficients of the operators of different dimensionality in eq.(2.2). The latter point is important in order to assess the range of values of λ_3 that the Lagrangians in eq.(2.1) and eq.(2.2) can probe. Defining $\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$ one obtains from the two Lagrangians

$$\mathscr{L}_{\lambda_3}: \kappa_\lambda = 1 + \frac{2v^2}{2m_H^2} \sum_{n=1}^{N} c_{2n}\, n(n-1)(n-2) \left(\frac{v^2}{2}\right)^{n-2}, \qquad \mathscr{L}_{EFT}: \kappa_\lambda = 1 + c_6 \frac{2v^2}{m_H^2}\frac{v^2}{\Lambda^2} + \dots . \tag{2.3}$$

where the dots in the right part of eq.(2.3) represents terms suppressed by $1/\Lambda^4$. Eq.(2.3) tells us that while κ_λ obtained from $\mathscr{L}_{\lambda_3}$ has no restriction in size, κ_λ obtained from $\mathscr{L}_{EFT}$ can be at most $\mathscr{O}(\pm 5)$. Values of $\kappa_\lambda \sim \pm 5$ are not going to be experimentally probed in the near future. In this situation a more pragmatic and less ambitious approach can be taken: use $\mathscr{L}_{\lambda_3}$ instead of $\mathscr{L}_{EFT}$ in order to obtain a bound on λ_3.

Let me state what are the "boundaries" of a similar approach. We want to probe "large" values of κ_λ via perturbative calculations based on $\mathscr{L}_{\lambda_3}$. This implies that κ_λ cannot be "too" large otherwise perturbativity can be lost. In our set of observables we are just considering the loop contributions in which the modified Higgs self-couplings appear for the first time. Then these contributions are finite and gauge-invariant and moreover depend only upon λ_3. However $\mathscr{L}_{\lambda_3}$ is a not-renormalizable Lagrangian. Therefore we expect that higher-order contributions are going to depend on Λ as well as on quartic, quintic etc. Higgs self-interactions. We must assume that these contributions are under control, i.e. they are subdominant with respect to the effects we compute. This implies that these higher-order contributions should not contain any large amplifying factor

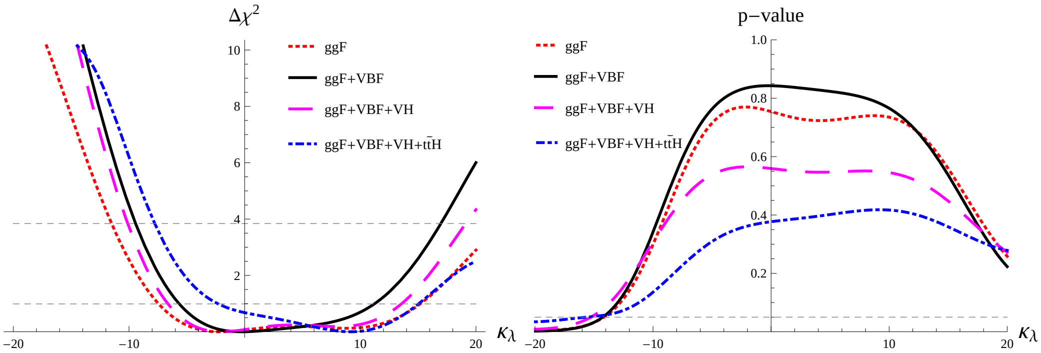

Figure 1: Left: χ^2 for different sets of observables in single Higgs processes. The two horizontal lines represent $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 3.84$. Right: corresponding p-value. The horizontal line is $p = 0.05$.

related to the scale Λ, or that Λ cannot be too far from the Electroweak scale. An estimate on Λ can be obtained looking at perturbative unitarity in the scattering of longitudinally polarized vector bosons and Higgses indicating that a scale of Λ of few TeV and values of $|\kappa_\lambda| \sim 10$ are allowed [13].

3. Results

The details of the computation of the contribution to the various observables of an anomalous Higgs trilinear coupling, and the experimental inputs used in the analysis presented below can be found in Ref. [8] for the for Higgs production cross sections and decay modes, and in Ref. [11] for W mass and the effective sine, m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$.

An anomalous Higgs trilinear coupling affecting the loop corrections to an observable O will modified the SM result according to:

$$O = O^{\rm SM}\left[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2\right], \tag{3.1}$$

where C_1 and C_2 are numerical coefficients. In single Higgs processes the coefficient C_2 is universal, coming from a diagram contributing to the wave function renormalization of the external Higgs field, so that while partial decay widths according to eq.(3.1) have a quadratic dependence on κ_λ, in branching ratios this dependence is cancelled. Instead the coefficient C_1 depends on the process considered and also on the kinematic assumed.

In order to set limits on κ_λ a simplified χ^2 fit can be performed. The best value of κ_λ is taken as the one that minimizes the $\chi^2(\kappa_\lambda)$ function defined as

$$\chi^2(\kappa_\lambda) \equiv \sum \frac{(O_{\rm exp} - O_{\rm the})^2}{(\delta)^2}, \tag{3.2}$$

where $O_{\rm exp}$ refers to the experimental measurement of the observable O, $O_{\rm the}$ is its theoretical value obtained from eq. (3.1) and δ is the total uncertainty, that we take as the sum in quadrature of the experimental and theory errors. In order to ascertain the goodness of our fit, the p-value as a function of κ_λ can be computed:

$$p\text{-value}(\kappa_\lambda) = 1 - F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda)), \tag{3.3}$$

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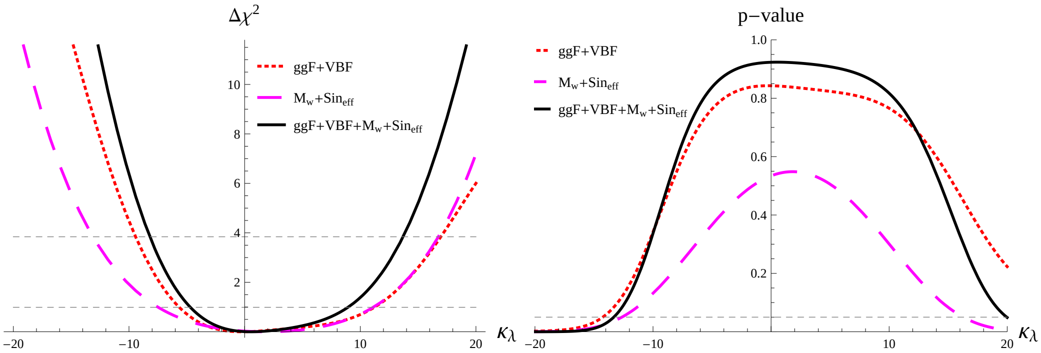

Figure 2: Left: χ^2 obtained combining information from single Higgs processes and precision physics. The meaning of the horizontal lines is as in fig.1.

where $F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda))$ is the cumulative distribution function for a χ^2 distribution with n degrees of freedom, computed at $\chi^2(\kappa_\lambda)$.

Limits on κ_λ from inclusive single Higgs processes[1] are obtained using the signal strength parameters μ_i^f. These parameters are defined combining observables as:

$$\mu_i^f \equiv \mu_i \times \mu^f = \frac{\sigma(i)}{\sigma(i)^{\rm SM}} \times \frac{{\rm BR}(f)}{{\rm BR}^{\rm SM}(f)}\,, \tag{3.4}$$

where the quantities μ_i are the Higgs production cross section, $\sigma(i)$, of the i type and μ^f are the branching ratio in the f channel, BR(f), normalized to their SM values, respectively. In the fit we taken for i the gluon fusion (ggF) and vector boson fusion (VBF) productions, the associated production with W and Z bosons (WH, ZH) and $t\bar{t}H$ production, while for f the $\gamma\gamma, ZZ, WW, b\bar{b}, \tau\tau$ decay channels.

In fig.1 the result of a χ^2 fit to the signal strength parameters obtained using an increasing number of production channels is presented. The most stringent bound on κ_λ comes from gluon-fusion and VBF data or

$$\kappa_\lambda^{\rm best} = -0.24\,, \qquad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.4, 17.0] \tag{3.5}$$

where the $\kappa_\lambda^{\rm best}$ is the best value and $\kappa_\lambda^{1\sigma}$, $\kappa_\lambda^{2\sigma}$ are respectively the 1σ and 2σ intervals. The 1σ and 2σ intervals are identified assuming a χ^2 distribution.

The information on κ_λ from single Higgs processes can be combined with that coming from precision physics. In fig.2 the result of the fit obtained considering the signal strength parameter for single Higgs production in ggF and VBF together with the two precision observables m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$ is presented. One finds

$$\kappa_\lambda^{\rm best} = 0.5\,, \qquad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-8.2, 13.7]\,, \tag{3.6}$$

The comparison between the numbers in eq. (3.6) and the corresponding ones for the ggF+VBF case, eq.(3.5), shows that the inclusion of the precision observables reduces the allowed range for

[1] Limits on κ_λ from differential distributions are presented in Refs. [10, 14].

κ_λ. Similarly, looking at the solid black line in the p-value part of fig. 2, we can exclude at more than 2σ the regions $\kappa_\lambda < -13.3$ and $\kappa_\lambda > 20.0$.

We conclude remarking that this range of κ_λ obtained using information coming from loop effects in single Higgs processes and precision physics is actually very competitive with the present bounds obtained from the direct searches of Higgs pair production.

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