PROCEEDINGS OF SCIENCE

Trilinear Higgs coupling determination via single Higgs measurements at the LHC

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I will discuss an alternative method of probing the trilinear coupling of the Higgs boson at the LHC. The method relies on the fact that single Higgs production and decay processes are sensitive to trilinear Higgs coupling at one loop through electroweak corrections. We have studied one-loop electroweak effects induced by an anomalous Higgs trilinear coupling on total and differential rates in single Higgs processes with non-trivial final state kinematics. The results are based on a public Monte Carlo code that we have developed withing the framework of MadGraph5_aMC@NLO. The sensitivity of future LHC runs to determine the trilinear coupling via inclusive and differential measurements is also reported.

13th International Symposium on Radiative Corrections
24-29 September, 2017
St. Gilden, Austria

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PoS(RADCOR2017)064

1. Introduction

With the discovery of the 125 GeV Higgs boson, it is important that we measure all its properties to confirm if this particle is indeed the SM Higgs boson. In the SM, the Higgs sector is completely governed by the following Lagrangian,

$$\mathscr{L}_{\rm Higgs} = |D_\mu \Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi) \tag{1.1}$$

$$\begin{aligned} \text{where,}\ \ \Phi^\dagger &= (\phi^- \phi^0) \\ D_\mu &\equiv \partial_\mu - i g_2 W^a_\mu T^a - i g_1 B_\mu \\ V(\Phi) &= -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2. \end{aligned} \tag{1.2}$$

As a result of the electroweak symmetry breaking (EWSB), the first term gives rise to the couplings of Higgs with gauge bosons, the second term to the couplings of Higgs with fermions, and the third term to the self-couplings of the Higgs boson, namely trilinear and quartic Higgs self-couplings. The SM couplings of the Higgs boson with gauge bosons and fermions are known with an accuracy of 10-20 % at the LHC. However, the Higgs self-couplings are practically unconstrained at the LHC.

After the EWSB, the Higgs potential becomes,

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4, \tag{1.3}$$

with $\lambda_3 = \lambda_4 = \lambda$. Since the SM Higgs potential depends only on two free parameters, knowing the values of the Higgs mass ($m_H = 125$ GeV) and the vacuum expectation value ($v \approx 246$ GeV) fixes the self-couplings of the Higgs boson completely,

$$m_H^2 = 2\lambda v^2 \Rightarrow \lambda \simeq 0.13. \tag{1.4}$$

Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self couplings. Therefore, independent determinations of λ_3 and λ_4 are crucial. Since the discovery of a SM-like Higgs boson no new resonance at the LHC has been confirmed. This provides a good motivation for a model independent parametrization of modified Higgs self-couplings,

$$\lambda_3 = \kappa_3 \lambda_3^{\rm SM},\ \lambda_4 = \kappa_4 \lambda_4^{\rm SM}. \tag{1.5}$$

The Higgs self-couplings can be measured directly in multi-Higgs production processes. For example, information on trilinear can be extracted by studying Higgs pair production processes at the LHC. Higgs pair production via gluon fusion is the standard channel to probe trilinear directly. However, due to a very small production cross section (~ 33 fb at 13 TeV), its observation at the LHC is very challenging. Current experimental bounds on trilinear are obtained by placing an upper bound on the cross section in various Higgs decay modes. The most recent CMS analysis at 13 TeV with 36 fb^{-1} data in $2b2\gamma$ final state has excluded $\kappa_3 < -9$ and $\kappa_3 > 15$ [2]. On the other hand, the ATLAS analysis at 13 TeV in $4b$ final state and with 13.3 fb^{-1} excludes $\kappa_3 < -8$ and $\kappa_3 > 12$ [3]. The future prospects to measure trilinear at HL-LHC are also not very promising.

There is no hope to get any meaningful information on quartic coupling at the LHC. Are there alternate methods to measure Higgs self-couplings at the LHC ?

There has been a proposal of measuring trilinear at e^+e^- collider in ZH production via electroweak corrections [4]. This idea has been recently extended to the study of trilinear in single Higgs processes at the LHC [5, 6, 7, 8]. These studies have already confirmed that indirect bounds on κ_3 can be competitive with the direct ones. For example, a one parameter fit using 8 TeV LHC data implies [6],

$$-9.4 < \kappa_3 < 17. \tag{1.6}$$

2. $\mathscr{O}(\lambda)$ corrections in single Higgs processes

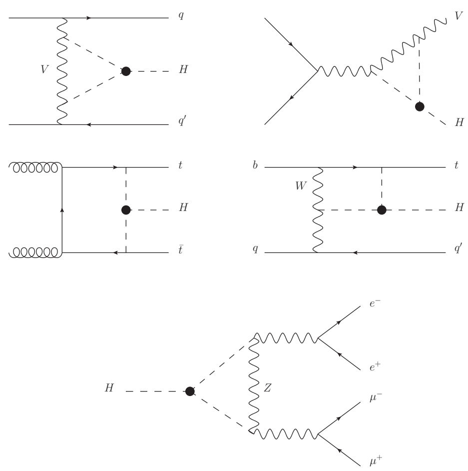

Figure 1: Representative one-loop diagrams in single Higgs processes with anomalous trilinear coupling and with non-trivial final state kinematics.

The BSM prediction for cross section/ decay width at NLO EW in presence of anomalous trilinear coupling is given by,

$$\Sigma_{\rm NLO}^{\rm BSM} = Z_H^{\rm BSM}[\Sigma_{\rm LO}(1+\kappa_3 C_1+\delta Z_H)+\Delta_{\rm NLO}^{\rm SM}], \tag{2.1}$$

$$Z_H^{\rm BSM} = \frac{1}{1-(\kappa_3^2-1)\delta Z_H}, \tag{2.2}$$

$$\delta Z_H = -\frac{9}{16\sqrt{2}\pi^2}\left(\frac{2\pi}{3\sqrt{3}}-1\right)G_\mu m_H^2 \tag{2.3}$$

$$= -1.536\times 10^{-3}. \tag{2.4}$$

The SM prediction can be obtained by setting $\kappa_3 = 1$. In the above, $Z_H^{\rm BSM}$ which depends on κ_3 quadratically, arises from the wave function renormalization and it is universal to all single Higgs processes. We have resummed the new physics contribution to get reliable prediction for large κ_3. $\Sigma_{\rm LO}$ includes any factorizable higher order correction. The term linear in κ_3 *i.e.* C_1 arises due to the interference of LO and λ_3 dependent one loop amplitudes. C_1 is UV finite and gauge invariant, and it is process dependent. $\Delta_{\rm NLO}^{\rm SM}$ includes contribution from virtual W, Z and γ as well as real emissions.

Channels	ggF	VBF	ZH	WH	$t\bar{t}H$	tHj	$H \to 4\ell$
$C_1(\%)$	0.66	0.63	1.19	1.03	3.52	0.91	0.82

Table 1: C_1 for different Higgs production processes at 13 TeV LHC and the $H \to 4\ell$ decay.

$C_1^{\Gamma}[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

Table 2: C_1 for the most relevant decay modes of the Higgs boson [6].

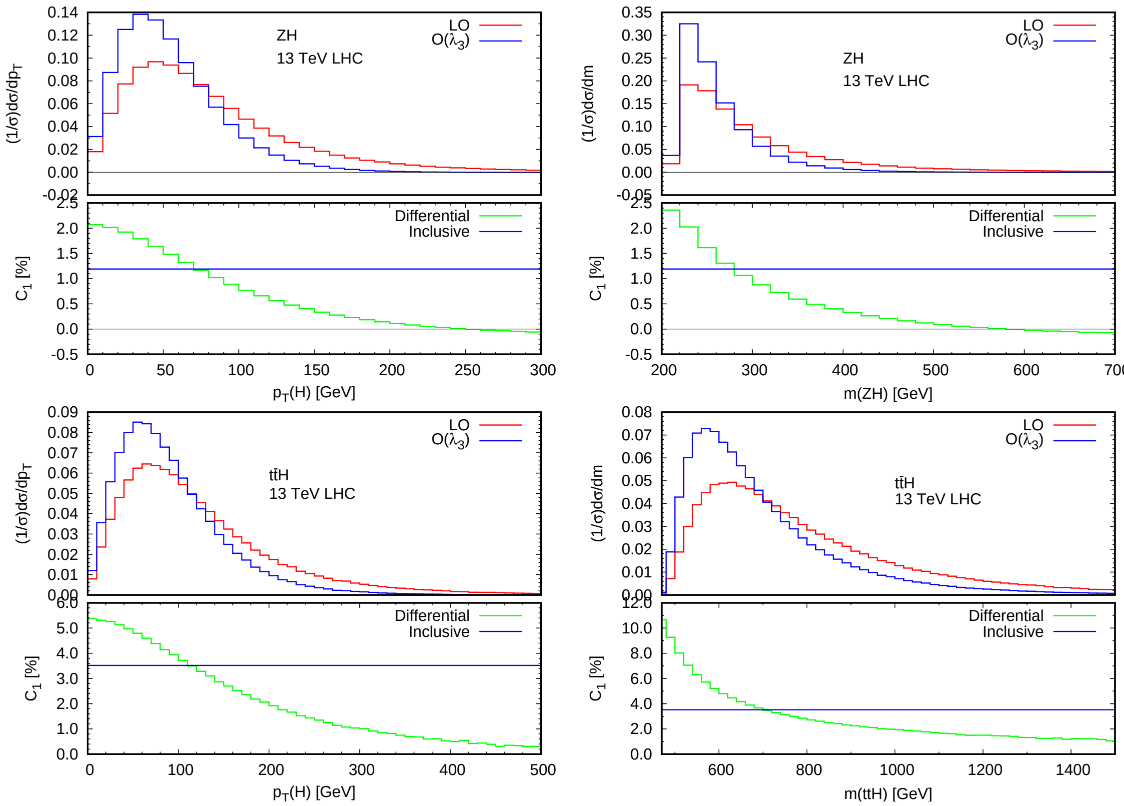

Figure 2: Effect of $\mathscr{O}(\lambda_3)$ correction at 13 TeV LHC in ZH and $t\bar{t}H$. Upper panel: normalized distributions at LO (red) and at $\mathscr{O}(\lambda_3)$ (blue). Lower panel: C_1 at the differential (green) and inclusive (blue) level.

In our calculation following input parameters are used,

$$
\begin{aligned}
G_\mu &= 1.1663787 \times 10^{-5}\ \text{GeV}^{-2},\ m_W = 80.385\ \text{GeV}, \\
m_Z &= 91.1876\ \text{GeV},\ m_H = 125\ \text{GeV},\ m_t = 172.5\ \text{GeV}.
\end{aligned} \tag{2.5}
$$

In Tables 1 and 2, we have listed C_1 at the inclusive level in various single Higgs production and decay channels [6, 1]. Among all the production channels C_1 is largest in the $t\bar{t}H$ channel. In Fig. 2, we study the effect of $\mathscr{O}(\lambda_3)$ correction on certain kinematic distributions. We find that the events due to the $\mathscr{O}(\lambda_3)$ correction are softer than those due to the LO effect. Due to this, C_1 at the differential level is larger in lower bins. Thus, in the lower bins of these distributions we are

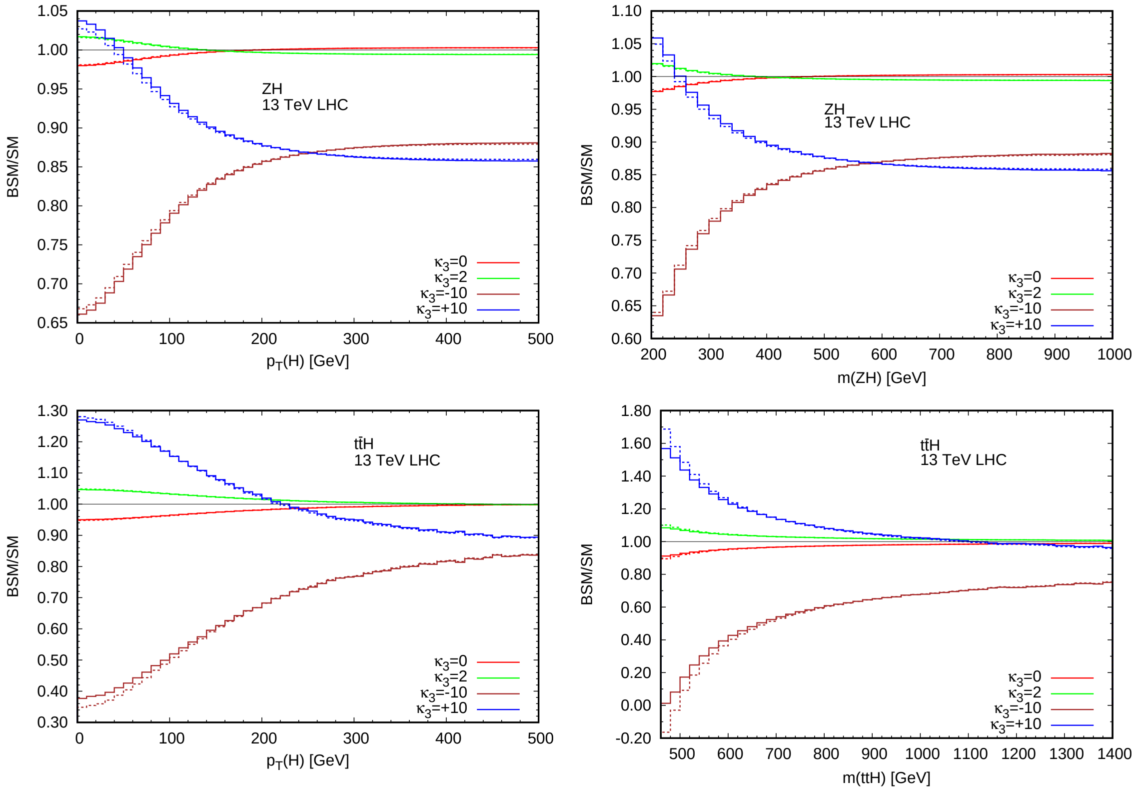

Figure 3: Comparison of BSM/SM ratio at differential level including (solid) or not (dashed) NLO EW corrections for different values of κ_3 at 13 TeV LHC.

expected to be more sensitive to the κ_3. However, due to a limited phase space the number of events are less in these kinematic regions. These results are obtained using a code based on reweighting of the LO events which we have developed within the framework of `MadGraph5_aMC@NLO` [9][1].

We find that at the inclusive level the numerical effects of full NLO EW corrections in the ratio $\sigma_{\text{BSM}}/\sigma_{\text{SM}}$ for all the production channels are negligible. In Fig. 3, we compare the ratio of BSM and SM cross sections at the differential level for different values of κ_3. The solid and dashed lines refer to the calculation with and without full NLO EW corrections respectively.

3. Global fit

The global fit performed in [6], used only total cross section information and included only κ_3 as a variable. We would like to utilize the different information on C_1 in the fit and generalize it in presence of other anomalous couplings of the Higgs boson like κ_t and κ_V. Since no differential information is available in the measured data at the moment, we focus on the future projections given by ATLAS for the high Luminosity run of the LHC with 3000 fb^{-1} data [10, 11].

The quantity of our interest to perform the fit for κ_3 is the signal strength $\mu = \mu_i \times \mu_f$, where

$$\mu_i = \frac{\sigma_i^{\text{BSM}}}{\sigma_i^{\text{SM}}} = (k_i^2 - 1) + Z_H^{\text{NP}}\left[1 + \frac{1}{K(i)_{\text{NLO}}^{\text{SM}}}(\kappa_3 - 1)C_1\right] \tag{3.1}$$

[1] https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsSelfCoupling

$$\mu_f = \frac{\mathrm{BR}^{\mathrm{BSM}}(f)}{\mathrm{BR}^{\mathrm{SM}}(f)} \approx \frac{k_f^2 + (\kappa_3 - 1)C_1^f}{\sum_j \mathrm{BR}^{\mathrm{SM}}(j)[k_j^2 + (\kappa_3 - 1)C_1^j]}, \tag{3.2}$$

and, the fit is obtained by maximizing a log-likelihood function [1].

We consider two scenarios for the treatment of uncertainties in the fit: S1, where we consider only statistical uncertainty and, S2 in which along with statistical, theory and experimental systematic uncertainties are also taken into account. As we expect, in S1 the fit is dominated by the gluon fusion channel, while in S2 $t\bar{t}H$ production channel provides the best constraint for $\kappa_3 < 1$. Improvements in bounds due to the use of differential information in $t\bar{t}H$ channel are more visible in S2. As we can see in Fig. 5, inclusion of more parameters to the fit relaxes the constraints especially in the region $\kappa_3 < 1$. Due to κ_3 dependence of the gluon fusion channel, the constraints in presence of κ_t are stronger than those in presence of κ_V.

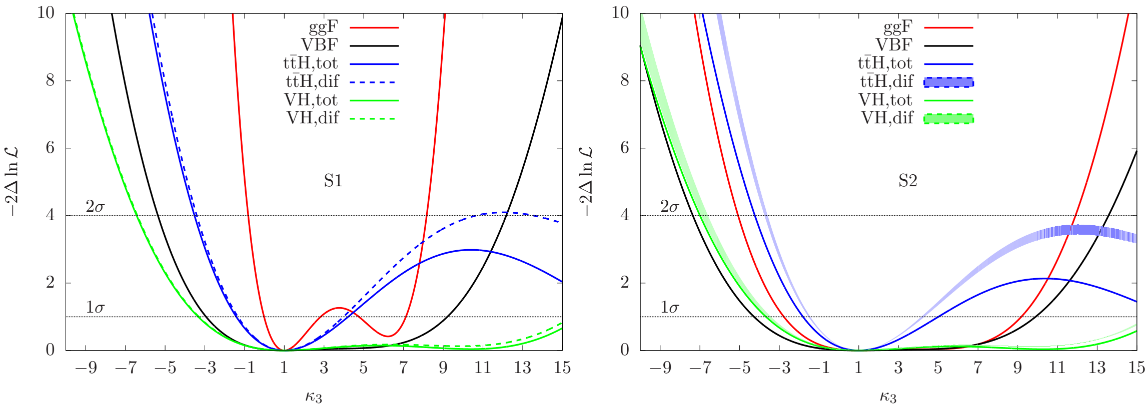

Figure 4: 1σ and 2σ bounds on κ_3 from single production processes, based on future projections for ATLAS-HL at 14 TeV. Left: only statistical uncertainty (S1). Right: experimental systematic uncertainty and theory uncertainty included (S2).

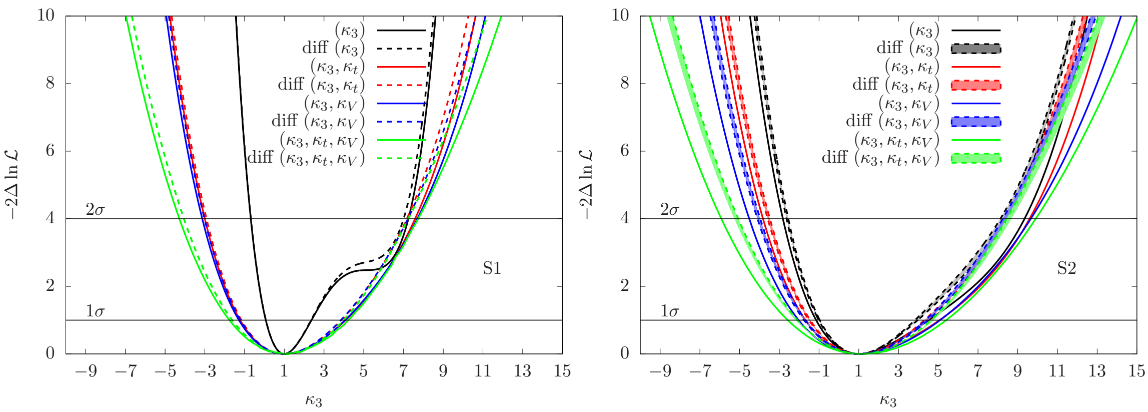

Figure 5: 1σ and 2σ bounds on κ_3 including all production processes, based on future projections for ATLAS-HL at 14 TeV. Left: only statistical uncertainty (S1). Right: experimental systematic uncertainty and theory uncertainty included (S2).

4. Summary and conclusions

Measuring the properties of 125 GeV Higgs boson is important to find hints of the physics beyond the SM in the LHC data. Among all the couplings of the Higgs boson, the Higgs self couplings are poorly known. Alternative and complementary approaches are being actively sought-for to constrain them using precisely measured observables at the LHC. We have globally considered the effects of loops which depend on the trilinear self coupling on to observables with just one Higgs boson in the final state. We have completed and organised in a public code the computation of one loop amplitudes relevant for the main Higgs production and decay channels at the LHC. Our results on global fit illustrate the complementarity of double Higgs production with precision measurements in single Higgs and motivate a more detailed experimental analyses.

Acknowledgments

I would like to thank the organizers of RADCOR 2017 for giving me the opportunity to present my work. I would like to acknowledge the financial support from MOVE-IN Louvain Cofund grant and the IISN "Fundamental interaction" convention 4.4517.08.

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