

The Higgs Portal: Constraints on New Physics

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In view of no direct sign of new physics so far and the pending puzzles that cannot be solved within the Standard Model (SM) the Higgs sector plays an increasingly important role as a portal to physics beyond the SM. New physics can be parametrized in a rather model-independent way in the SM effective theory (SMEFT). In this contribution I will discuss what we can learn about new physics from Higgs fits to SMEFT higher-dimensional operators.

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1. Introduction

The Higgs boson discovered in 2012 by the LHC experiments ATLAS [1] and CMS [2] behaves very Standard Model (SM)-like [3, 4]. Due to open questions that cannot be answered within the SM, however, one of the main goals of the LHC is to search for new physics (NP). Since we lack any direct discovery of physics beyond the SM (BSM) so far the Higgs sector as a portal to NP plays an important role in setting indirect limits on NP. In this contribution I will discuss how we can use Higgs fits to access NP and what we can learn from them.

On the theory side, NP can be described either in a model-dependent way within specific UV complete models like *e.g.* supersymmetry and the 2-Higgs-Doublet Model (2HDM) or also composite Higgs models as an example for a strongly interacting Higgs boson. Or the manifestations of BSM physics are described through anomalous couplings in a rather model-independent approach either by a linear (SMEFT) [5–11] or non-linear (EWChL) effective Lagrangian [12–17].

The SMEFT smoothly departs from the SM by assuming the SM field content and gauge symmetries and that NP only enters at some high energy scale Λ . The SM deviations are then described by higher-dimensional operators built from the SM fields. In this linear realization of the Higgs sector the Higgs boson is part of a doublet and the leading NP effects are described by dimension-6 (dim-6) operators that are suppressed by the NP scale Λ^2 . The effective Lagrangian is hence given by¹

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4}) + h.c. , \quad (1)$$

where the sum extends on the possible dim-6 operators $O_i^{(6)}$ and their related Wilson coefficients $C_i^{(6)}$. In the non-linear realization on the other hand, the Higgs field can also be a singlet.

In the following sections I will discuss various aspects of SMEFT, starting with SMEFT at the top-Higgs interface in Sec. 2, followed by the status of a global SMEFT analysis in Sec. 3 and SMEFT in Higgs pair production in Sec. 4. I will finish in Sec. 5 with a brief discussion of NP aspects in specific UV-complete models, focussing on the Higgs pair production process.

2. The Top-Higgs Interface

The importance of the top quark in EFT fits derives from the fact that the top quark is the only fermion that couples with an order one Yukawa coupling to the Higgs boson so that it plays a privileged role in most BSM scenarios for electroweak symmetry breaking (EWSB) and the stabilisation of the weak scale. In weakly coupled models like supersymmetry (SUSY) this leads to the introduction of SUSY partners, the stops. Strongly coupled models on the other hand, where the Higgs boson is a composite object, come along with heavy top partners (in order to explain the fermion masses through partial compositeness [18–20]). Moreover, the precise knowledge of the top-Higgs interaction is crucial for the determination of the trilinear Higgs self-coupling from Higgs pair production.

The LHC processes at the top-Higgs interface that are particularly interesting for EFT analyses are besides top-quark pair production associated Higgs production with a top quark pair, inclusive

¹A possible dim-5 operator for the generation of the neutrino masses is not relevant for LHC phenomenology.

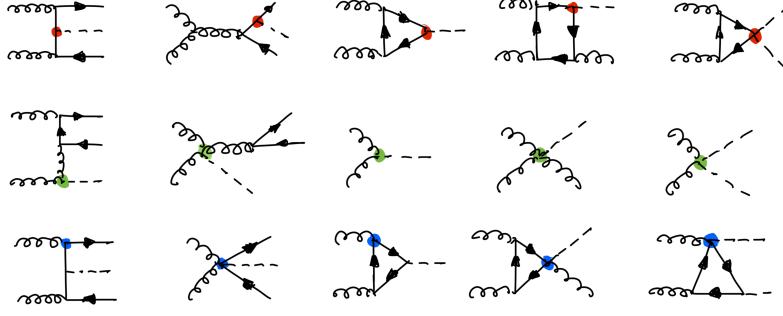


Figure 1: Sample diagrams contributing to associated top-Higgs production $t\bar{t}H$ (two left columns), single Higgs production H (third column), Higgs+jet production (fourth column) and Higgs pair production HH (last column) together with the dim-6 operators involving the Higgs boson and the top quark, $O_{t\phi}$ (red), $O_{\phi G}$ (green) and O_{tG} (blue).

Higgs production, Higgs+jet and Higgs pair production. The sample diagrams in Fig. 1 show which dim-6 operators involving the Higgs boson and the top quark affect these processes. We have the operator $O_{t\phi}$ that modifies the top-Higgs interaction, the $O_{\phi G}$ operator inducing a point-like Higgs-gluon interaction and the chromomagnetic operator O_{tG} modifying the interaction between tops and gluons,

$$O_{t\phi} = (\phi^\dagger \phi)(\bar{Q}_L \tilde{\phi} t_R) + h.c. \quad (2)$$

$$O_{\phi G} = (\phi^\dagger \phi) G_{\mu\nu}^a G^{a\mu\nu} \quad (3)$$

$$O_{tG} = (\bar{Q}_L \sigma^{\mu\nu} T^a t_R) \phi G_{\mu\nu}^a + h.c. , \quad (4)$$

where ϕ denotes the Higgs doublet, $\tilde{\phi} = i\sigma^2 H^*$ its charge conjugate, Q the $SU(2)_L$ quark doublet built from the top and bottom quarks t and b , $G_{\mu\nu}^a$ the gluon field strength tensor, T^a the $SU(3)$ generators ($a = 1, \dots, 8$), and $\sigma^{\mu\nu} = i/2[\gamma^\mu, \gamma^\nu]$.²

The description of inclusive Higgs production through effective operators [26–31] suffers from a two-fold degeneracy, namely in the operators $O_{t\phi} - O_{\phi G}$ and in $O_{tG} - O_{\phi G}$. The former degeneracy can be resolved by studying *e.g.* the transverse momentum distribution of single Higgs production [31–33]. As the operators O_{tG} and $O_{\phi G}$ contribute to associated production of a Higgs boson with a top-quark pair in a different way, the remaining degeneracy between these two operators can be resolved by performing fits to their Wilson coefficients using input from single Higgs production, Higgs plus jet production [34–42] and $t\bar{t}H$, *cf.* Fig. 2 [43].

3. Global Analysis

An important aspect of the SMEFT analysis is that all relevant operators that contribute to the various processes included in a fit have to be used in order to keep it model- and basis-independent.

²Associated Higgs production with a top quark pair is also affected by four-fermion operators, which can be constrained from top-quark pair production [21] so that we do not consider them here further. The gluonic dim-6 operator can be constrained from multijet-signatures [22] and is not discussed further here either. Finally, Higgs pair production is affected by the modification of the trilinear Higgs self-coupling [9, 23, 24] which will be investigated later in Sec. 4. CP-violating operators are neglected under the assumption of CP conservation [25].

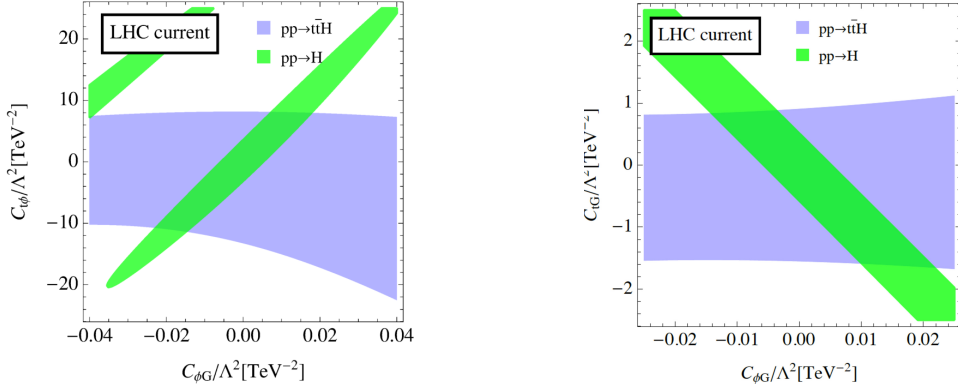


Figure 2: Allowed region in the $O_{t\phi} - O_{\phi G}$ plane (left) and the $O_{tG} - O_{\phi G}$ plane (right) at 95% confidence level. Plots taken from [43].

The problem is, however, that there is a large number of dim-6 operators. For three fermion generations we have 2499 non-redundant operators and 59 for one generation [10]. A global SMEFT fit hence has to deal with a huge parameter space with possibly a large number of flat directions and local minima. A practical approach that is pursued to reduce the number of operators in the fits is to apply symmetry assumptions like *e.g.* flavour and CP conservation and to focus on certain subsectors like *e.g.* Higgs, electroweak (EW), top, Higgs-EW, or Higgs-top. Then only the operators relevant for the considered particles and processes are included assuming that the remaining operators are well constrained from other processes. It has to be examined, however, to which extent this is justified in order not to draw wrong conclusions from the parameter fit.

Figure 3 shows an example of the 95% CL limits in a fit including 34 degrees of freedom in the analysis, taking into account also next-to-leading order QCD corrections to various SMEFT contributions. For details and recent developments, see [45, 46]. The marginalised (global) and the individual fit cases are compared to the bounds from the LHC Top WG EFT note [44]. As can be inferred from the plot for almost all degrees of freedom the bounds obtained from the individual fits are comparable to or more stringent than the marginalised results from the global fit since in the former cross-correlations between the different directions spanned by the fitted degrees of freedom

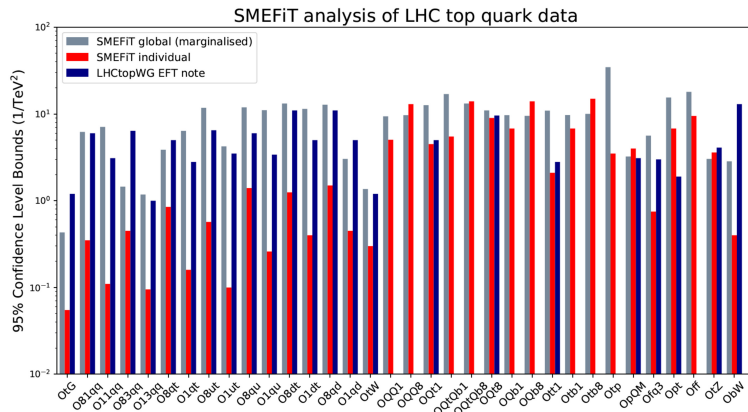


Figure 3: The 95% CL bounds on 34 degrees of freedom in the marginalised (global) and the individual fit cases compared with the bounds from the LHC Top WG EFT note [44]. Plot taken from [45].

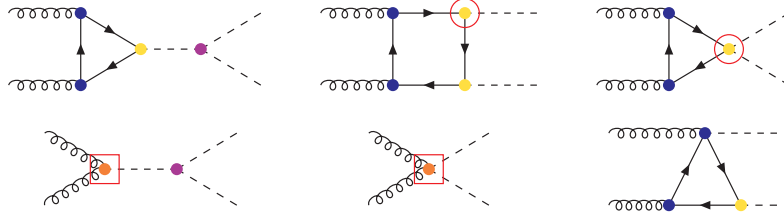


Figure 4: Dimension-6 operators affecting Higgs pair production: O_H (not shown), O_6 (violet), $O_{t\phi}$ (yellow), $O_{\phi G}$ (orange), and O_{tG} (blue). Boxes (circles) mark some examples of effective single- and double-Higgs couplings to gluons (fermions).

are neglected.

4. Higgs Pair Production

The measurement of the Higgs self-interactions provides the ultimate test of the Higgs mechanism [47]. The trilinear Higgs self-coupling is accessible in Higgs pair production with gluon fusion providing the dominant process at the LHC [48]. The dim-6 operators affecting Higgs pair production [9, 24, 49] are shown in Fig. 4. Besides an overall shift of the couplings due to O_H the operators affect the Higgs self-coupling (O_6) and the top Yukawa coupling ($O_{t\phi}$). They furthermore induce effective single Higgs and double Higgs couplings to the gluons through $O_{\phi G}$, an effective 2-Higgs-2-fermion coupling through $O_{t\phi}$ and novel diagrams due to the chromomagnetic dipole operator O_{tG} . In the non-linear EFT approach the couplings between one and two Higgs bosons to the gluons (marked by the boxes) are not related as well as the single- and two-Higgs couplings to the fermions (marked by the circles), in contrast to the SMEFT approach at up to dimension 6 so that Higgs pair production becomes sensitive to the way EWSB is realized. When all other SMEFT parameters are fixed to their SM values, ATLAS (CMS) finds that the observed limits on the trilinear Higgs self-coupling at the 95% CL lie between -5 and +12 (-11.8 and 18.8) times the SM value [50, 51]. With increasing precision on HH production, however, the precise knowledge of the other Wilson coefficients will be required to bound the trilinear Higgs self-coupling.

An alternative way to constrain its values is given indirectly by exploiting single Higgs production where the trilinear Higgs self-coupling enters through EW corrections.³ It has been shown in several papers [54–59] that a competitive or at least complementary bound as compared to HH production can be obtained. The challenge, however, is that several processes with different functional dependence on the coupling have to be considered which requires a global fit. Moreover, the dominant effect on single Higgs production comes from other leading-order operators (barring portal models where all SM couplings are unchanged but only the Higgs self-couplings are modified [56]). And finally, nine additional EFT coefficients have to be varied [58].

The potential of combining single and double Higgs fits to confine the trilinear coupling modifier κ_λ [60] is shown in Fig. 5. It shows the constraints including differential observables in single and double Higgs production as well as their combination (pink). When including non-negligible effects from all nine EFT parameters, double Higgs production leads to much stronger

³For limits on the trilinear Higgs self-coupling from two-loop effects in the EW observables, see [52, 53].

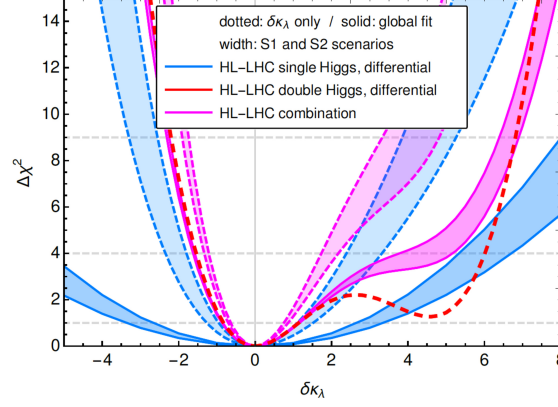


Figure 5: Constraints from differential single Higgs (blue), differential double Higgs (dashed red) production and their combination (pink) at the HL-LHC with $\sqrt{s} = 13$ TeV and $\int \mathcal{L} = 3 \text{ ab}^{-1}$. Taken from [60].

constraints. Single Higgs data are relevant, however, to lift the degenerate minima around $\delta\kappa_\lambda \sim 5$. The experiments have provided direct and indirect constraints on κ_λ mostly by considering κ_λ variations only. With increasing experimental sensitivity therefore the next steps to be performed are the simultaneous fit of both direct and indirect constraints and the inclusion of the relevant EFT operators in the analysis.

Distributions play a particularly important role in order to test NP and resolve degeneracies among the different EFT operators affecting the observable. The impact of the next-to-leading-order QCD corrections on the mass and p_T distributions of Higgs pair production in the framework of a non-linearly realised EFT including the full mass dependence has been investigated in [61]. It is found that the mass effects lead to significant non-uniform K -factors as compared to the heavy top-limit [62].

5. UV Complete Models

In order to be sensitive to light resonances EFT analyses have to be complemented by investigations of specific UV complete models which shall be exemplified here for the case of Higgs pair production through gluon fusion. Here new physics can enter at several levels, as can be inferred from Fig. 6 showing sample diagrams contributing to Higgs pair production in the Next-to-Minimal-Supersymmetric extension (NMSSM) (left) [63] and in the composite Higgs model (right) [64]. Thus the Higgs Yukawa couplings to the top and bottom quarks in the triangle and box diagrams as well as the trilinear Higgs self-coupling can be modified where in particular the deviation of the latter from its SM value can lead to larger cross sections [48]. Moreover, new particles can enter through the loops. Additional Higgs bosons H_k can lead to a resonant enhancement of the cross section [23, 47, 63, 65]. In composite Higgs models additionally a novel 2-Higgs-2-fermion coupling appears. All these effects can induce cross sections that are considerably larger than the SM prediction [66].

Models with extended Higgs sectors can also lead to an interesting single-double top-Higgs interplay. Figure 7 shows the comparison of the invariant mass distribution for $pp \rightarrow t\bar{t}$ (left) and $pp \rightarrow hh$ (right) where h denotes the SM-like among the three neutral CP-mixing Higgs bosons H_i ($i = 1, 2, 3$) of the CP-violating 2HDM (C2HDM) [67–70], comparing the signal and interference

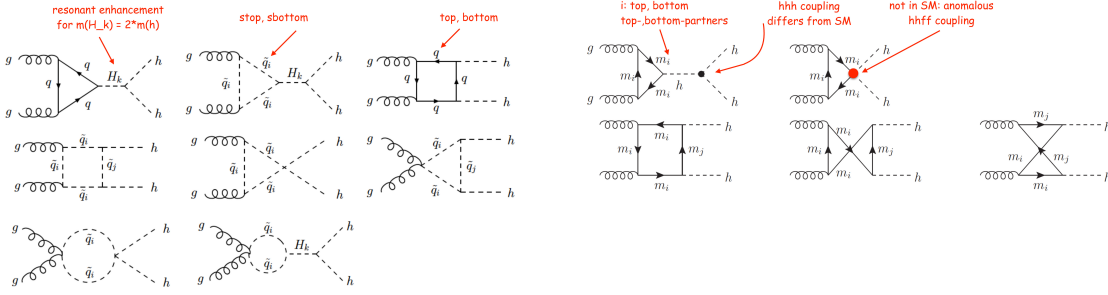


Figure 6: Sample diagrams contributing to Higgs pair production in the NMSSM (left) [63] and the composite Higgs model with top/bottom partners (right) [64].

cross sections. As can be inferred from these plots the destructive signal-background interference in the resonance search for heavy non-SM-like Higgs bosons renders single Higgs production in competition with the heavy Higgs discovery in Higgs pair production where constructive signal-background interferences can enhance the cross section [71].

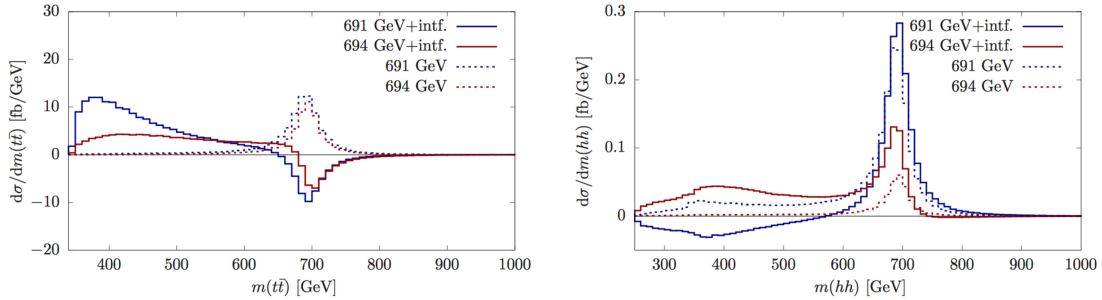


Figure 7: Invariant mass distribution for $pp \rightarrow t\bar{t}$ (left) and $pp \rightarrow hh$ (right) at 13 TeV at leading order for the different Higgs states $H_i \neq h$ (blue: $H_i = H_2$, red: $H_i = H_3$). For details, see [71].

6. Conclusions

In this contribution, I discussed the SMEFT as a powerful framework to parametrize and test BSM physics in a rather model-independent way. We have seen that distributions play a particularly important role as they allow to test several NP operators at the same time and can resolve potential degeneracies. Global analyses taking into account all relevant observables are important to keep the analysis model- and basis-independent and they receive increasing attention. In the context of Higgs pair production the increasing experimental precision requires as next steps the simultaneous fit of both single and double Higgs processes and the gradual inclusion of all relevant EFT operators in the fits. The reality check with specific UV-complete models shows that in particular in Higgs pair production significant new physics effects are still possible.

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