PROCEEDINGS OF SCIENCE

Theoretical implications of the 125 GeV Higgs boson

Eleni Vryonidou[*†]
CERN, Theoretical Physics Department, Geneva 23 CH-1211, Switzerland
E-mail: eleni.vryonidou@cern.ch

I discuss theoretical implications and prospects of LHC Higgs measurements in determining the Higgs couplings and the form of the Higgs potential, as well as exploring beyond the Standard Model scenarios predicting new states.

Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)
4-9 June 2018
Bologna, Italy

[*]Speaker.

[†]Supported by a Marie Skłodowska-Curie Individual Fellowship of the European Commission's Horizon 2020 Programme under contract numbers 704187.

PoS(LHCP2018)098

1. Introduction

Since the Higgs boson discovery in 2012, LHC experiments have been searching for its production and decay in various channels. The findings of these searches so far show a good agreement with the Standard Model expectations. The search for new physics continues both by accurately measuring the couplings of the Higgs to fermions and gauge bosons, but also by looking for signs of new states in the scalar sector. In these proceedings I discuss recent experimental results and their implications for new physics scenarios, as well as prospects of determining unconstrained Higgs (self-)couplings at future LHC runs.

2. Higgs Couplings

A first direct evidence of the coupling of the Higgs to the top quark is given by the recent observation of the Higgs production in association with a top quark pair by CMS and ATLAS [1, 2]. Whilst gluon fusion production is also sensitive to the top Yukawa coupling, it is clear that any heavy particle running in the gluon fusion loop will lead to a contact ggh interaction and also contribute to this process. Therefore a degeneracy exists.

Within the Standard Model Effective Field Theory (SMEFT), deviations from the SM are parametrised via higher-dimension operators which modify the SM Lagrangian as follows:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathscr{O}(\Lambda^{-4}). \tag{2.1}$$

For gluon fusion and top-quark associated Higgs production the relevant operators are:

$$\begin{aligned} O_{t\phi} = \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}\,,\; O_{\phi G} = \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,, \\ O_{tG} = g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}\,. \end{aligned} \tag{2.2}$$

The measurement of $t\bar{t}H$ production is crucial as it can break the degeneracy between the top Yukawa coupling and the $O_{\phi G}$ operator [3], as shown in Figure 1. At the high-luminosity LHC (HL-LHC), the Higgs transverse momentum distribution can also provide information to distinguish between the two couplings, as also discussed in [4].

Global EFT fits results using LHC Higgs measurements are already available in the literature. Ref. [5] performs a 20-parameter fit of Higgs and gauge operators, using LEP results and also LHC Run I and II Higgs and gauge boson measurements. Similarly Ref. [6] performs a fit using Run I results, and provides a projection for the HL-LHC which demonstrates the importance of using differential information to constrain the operators.

In addition to the couplings of the Higgs to the gauge bosons and the 3rd generation fermions, a more challenging effort is underway to determine the couplings of the Higgs to the 2nd and 1st generation, for which very little is known. Various proposals exist in the literature, including the use of the radiative decays of the Higgs to vector bosons to extract the light quark Yukawa couplings [7]. These are very rare decays and the corresponding LHC measurements set bounds which lie at least one order of magnitude above the SM expectations [8, 9]. Another proposal [10] is to use the Higgs transverse momentum distribution at relatively low values of the p_T to extract bounds on the charm Yukawa coupling. This study finds promising results, in particular for the HL-LHC

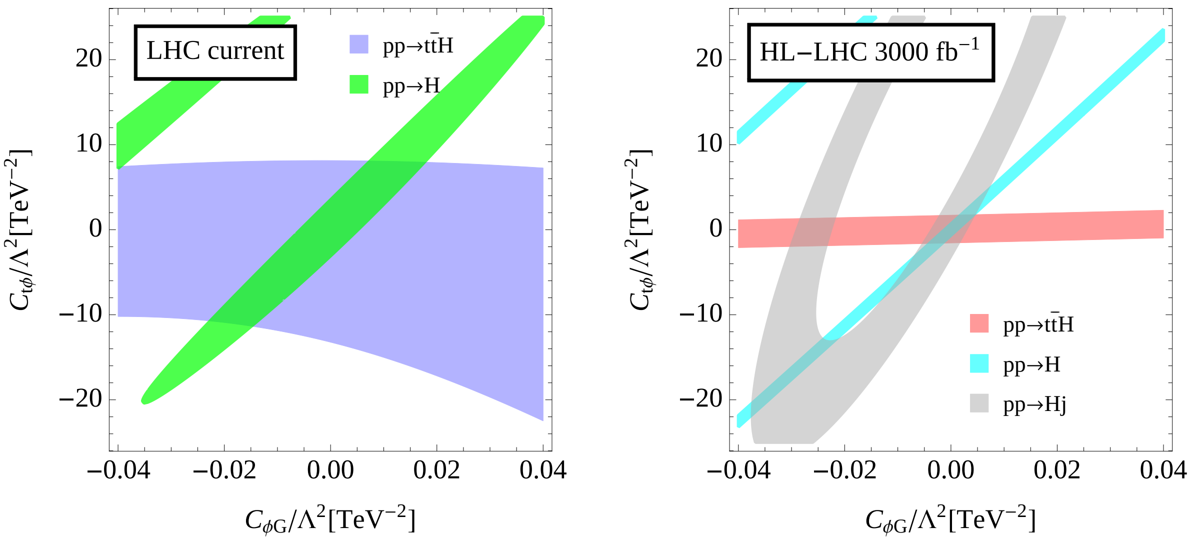

Figure 1: Two-operator fit using Higgs Run-I results and HL-LHC projections, taken from [3]. The recent observation of $t\bar{t}H$ will significantly reduce the width of the blue band in the left-hand-side plot.

where the bound on the charm Yukawa can reach [-0.6,3.0] the SM value. Extending this method to the 1st generation quarks has also been proposed in Ref. [11]. The charm Yukawa can also be probed by flavour tagging in Higgs production in association with a vector boson [12], with a limit currently at 110 times the SM expectation.

3. Searches for new scalars

Whilst the determination of the Higgs couplings is crucial in probing new physics, direct searches for new states in the scalar sector can also have profound implications. These searches consist of both searches for heavy scalars but also light states to which the SM-like 125 GeV Higgs can decay to. Any new particle with mass below $m_H/2$ and coupling to the Higgs will contribute to the Higgs invisible width. Limits on the invisible Higgs width [13] can be directly translated into limits on Higgs portal models with a scalar or fermion Dark Matter candidates [14]. The impact of the invisible width limit, used in combination with astrophysical Dark Matter constraints, is to significantly reduce the allowed parameter space of the Higgs portal model, which is the simplest extension of the SM.

Experimental searches for new scalars typically look for resonances in various decay channels such as $VV, ZH, HH, t\bar{t}, b\bar{b}, \tau\tau$. An example of a well-motivated model predicting such resonances is the 2HDM, and LHC results are widely used to constrain the 2HDM parameter space. The impact of LHC Run I results is shown in Figure 2 [15]. Both the measurements of Higgs couplings and searches for new states contribute. Higgs coupling measurements which show that the 125 GeV Higgs boson is SM-like, imply that the viable space of the 2HDM is the one of alignment, i.e. the region where $|\cos(\beta-\alpha)| \ll 1$. Global 2HDM limits can be set by combining Higgs signal strengths, resonant searches as well as theoretical constraints on the 2HDM input parameters as discussed in Ref. [16].

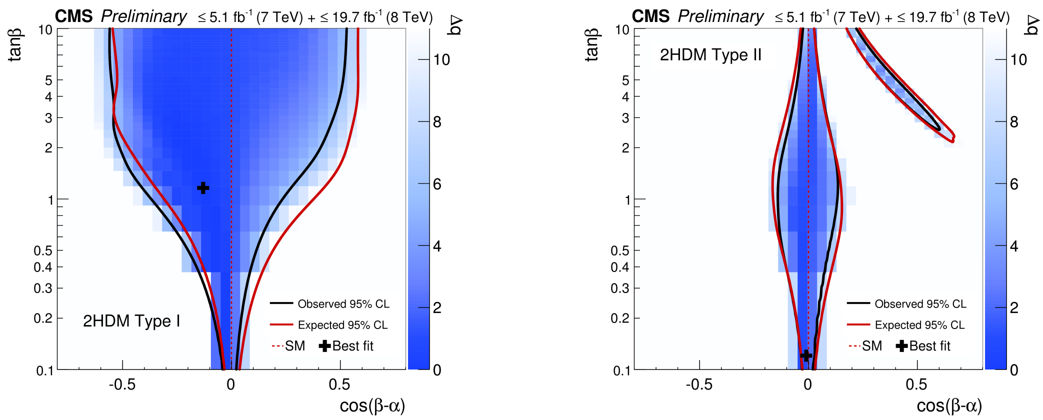

Figure 2: Constraints on the 2HDM parameter space for type I and type II scenarios using Run I results. Taken from [15].

4. Higgs potential

Beyond-the-SM physics can manifest itself by modifications of the Higgs potential. The form of the potential and the value of the Higgs self-coupling in the SM is fully determined by the Higgs mass and vev. Experimentally verifying this prediction is a crucial test for the SM. Moreover, the value of triple Higgs coupling can have implications on models of electroweak baryogenesis as it determines the type of the electroweak phase transition. As discussed in [17], for a range of modifications in the Higgs potential, a measurement of the triple Higgs coupling below 1.5 times the SM prediction disfavours electroweak baryogenesis.

Various theoretical constraints have been set on the triple Higgs coupling, by considering partial-wave unitarity and perturbativity [18]. This study excludes values of the triple Higgs coupling above 6 times the SM prediction. In the case of UV complete models with additional scalars, the allowed range of the Higgs self-coupling depends on how weakly or strongly coupled the theory is, with the maximum allowed value being around 8 times the SM prediction for the strongly coupled regime.

Experimental constraints on the Higgs self-coupling can be set by measuring double Higgs production. The most accurate cross-section (NNLO FT_approx) for double Higgs production in gluon fusion, the dominant production channel, is around 37 fb at the LHC at 14 TeV [19]. Current LHC measurements set an upper bound on the double Higgs production cross section of about 7 times the SM prediction [20].

The dependence of the various double Higgs production channels on the triple Higgs coupling (λ) is shown in Figure 3, as computed in [21]. Extracting the value of the triple Higgs coupling requires also the use of differential distributions to break the degeneracy between values of λ which lead to the same inclusive cross-section [22]. Projections for the HL-LHC show that a bound of a few can be set on $\kappa_\lambda = \lambda/\lambda_{SM}$, with the determination of the triple Higgs coupling remaining a challenge even for the HL-LHC.

In the context of the SMEFT, extracting the triple Higgs coupling from the measurement of the Higgs pair production cross section is not trivial, as the following 5 dimension-6 operators will

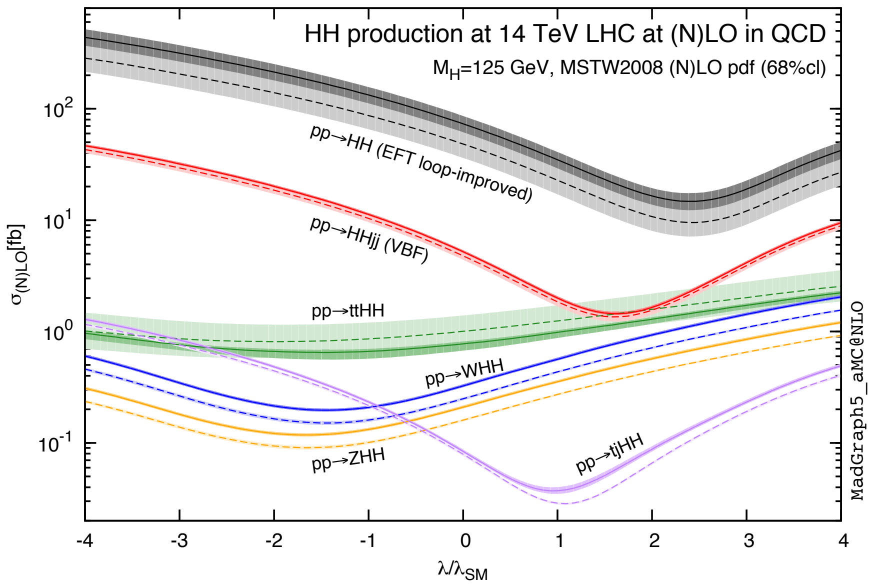

Figure 3: Dependence of double Higgs production cross-section on the triple Higgs coupling. Taken from [21].

enter in the production cross-section:

$$O_{t\phi} = \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi},\ \ O_{\phi G} = \left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu},$$
$$O_{tG} = g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu},\ \ O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$$
$$\text{and } O_6 = -\lambda(\phi^\dagger\phi)^3.$$

The dependence of the total HH cross-section on the Wilson coefficients of these operators is shown in Figure 4, along with operator constraints obtained from Run I Higgs and top-quark measurements. Given the current experimental bounds on other operators, only O_6 can lead to large deviations of the HH cross section from the SM predictions. As the experimental bound on the double Higgs production cross section closes in towards the SM prediction, a precise knowledge of all other Wilson coefficients will be needed in order to constrain c_6, and demands a global SMEFT interpretation.

As the determination of the triple Higgs coupling from double Higgs production is challenging, additional indirect constraints on λ can play a crucial role. Such indirect constraints can be obtained by considering the 1-loop weak corrections to Higgs production and decay [23, 24, 25, 26]. These studies have shown that competitive constraints on κ_λ can be set by considering LHC single Higgs results, in particular when differential information is exploited. Two-loop corrections to EWPO also feature a dependence on the triple Higgs coupling and can provide complementary information [27, 28].

At the HL-LHC a synergy between double and single Higgs production and the use of differential distributions can be used to constrain the triple Higgs coupling in a global EFT fit, as demonstrated in [29]. The impact of inclusive and differential single and double Higgs measurements is shown in Figure 5 for the HL-LHC. Only combining differential single and double Higgs measurements can break the degeneracy between different values of λ.

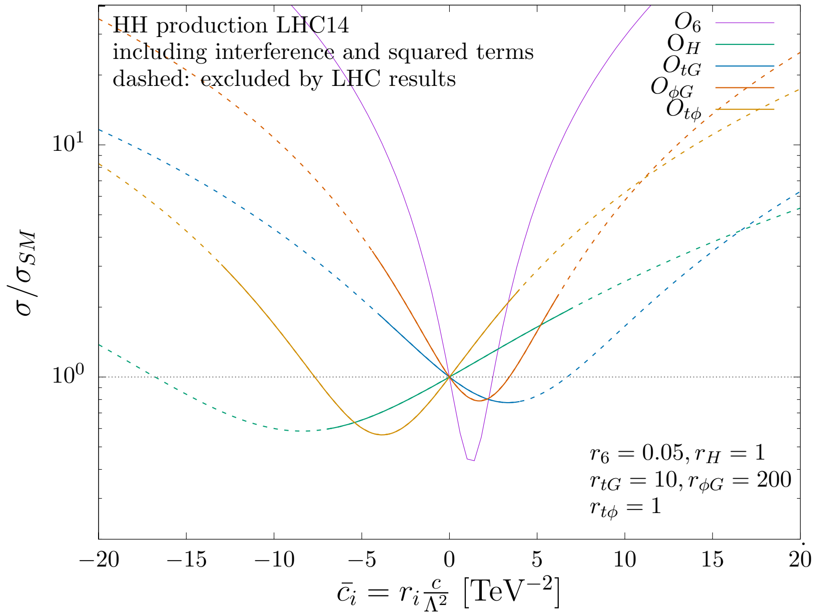

Figure 4: Dependence of double Higgs production cross-section on the Wilson coefficients of the relevant dimension-6 operators.

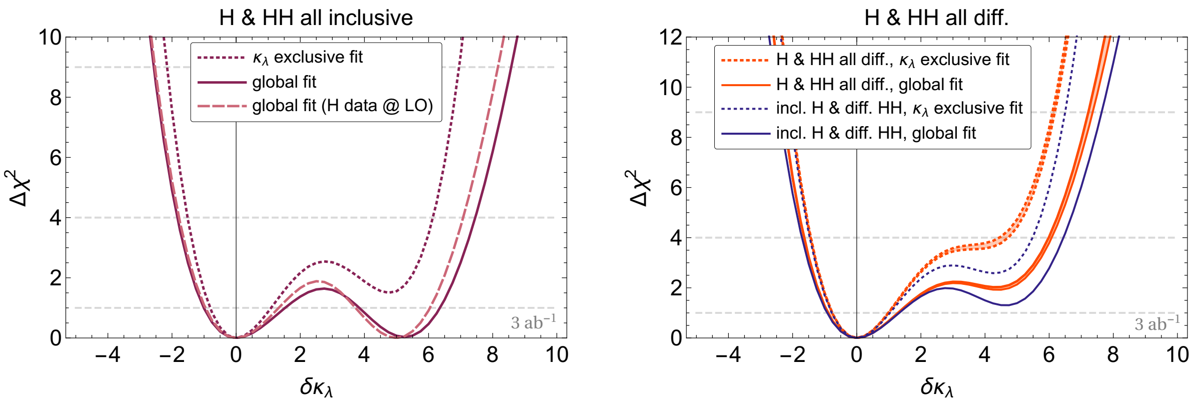

Figure 5: Impact of inclusive and differential single and double Higgs measurements in constraining the triple Higgs coupling at the HL-LHC. Taken from [29].

5. Conclusions

Measurements of Higgs couplings are so far in agreement with the SM predictions. Moderate deviations from the SM expectations are still allowed in the couplings of the Higgs to the fermions and the vector bosons and these can be parametrised in the SMEFT framework. Determining the couplings of the SM Lagrangian at dimension-6 is a major goal of the LHC and the first work towards global EFT fits is underway. Another challenge which remains is the determination of the Yukawa couplings of the first and second generations, with various proposals discussed in the literature. Searches for new states in the scalar sector are also important in constraining UV complete models which predict new light particles. Finally the form of the Higgs potential has yet to be experimentally verified. The combination of constraints from double Higgs production and indirect constraints from single Higgs production will be crucial in pinning down the value of the Higgs self-coupling. The LHC will explore and answer these crucial questions over the coming years.

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