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Higgs Pair Production and Triple Higgs Couplings at the LHC in the 2HDM

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Gaining information about the shape of the Higgs potential is one of the main goals of particle physics for the coming years. The trilinear Higgs self-interactions can directly be probed via Higgs pair production, which at the LHC happens dominantly through gluon fusion. In models with extended Higgs sectors the trilinear self-coupling of the detected Higgs boson can strongly deviate from the prediction of the Standard Model (SM) due to large loop corrections even in scenarios where all couplings to gauge bosons and fermions are very close to their SM values. Furthermore, triple Higgs couplings involving additional Higgs bosons can have an important impact on the pair production process of the SM-like Higgs boson via the resonant contribution of the heavy Higgs. We study the phenomenological implications for Higgs pair production in the framework of the Two Higgs Doublet Model (THDM). We analyze the potential sensitivity to both, the SM-like trilinear Higgs self-coupling and the beyond-the-SM triple Higgs coupling involving a resonantly produced CP-even Higgs. In particular, we focus on the theoretical predictions of two observable quantities: the total Higgs pair production cross section and the invariant mass distribution of the two Higgs bosons in the final state. We show that the inclusion of loop corrections to the trilinear Higgs couplings as well as the resonant heavy Higgs contribution are crucial in this context.

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1. Introduction

The possibility of a strong first order phase transition, which is necessary for electroweak baryogenesis, is correlated with large deviations of the trilinear self-coupling of the observed Higgs boson, κ_λ, from the Standard Model (SM) prediction in many models of physics beyond the SM. The current experimental bounds on κ_λ are $-0.4 < \kappa_\lambda < 6.3$ at the 95% C.L. from ATLAS [1] and $-1.24 < \kappa_\lambda < 6.49$ from CMS [2], where $\kappa_\lambda \equiv \lambda_{hhh}/\lambda_{\rm SM}$, and $\lambda_{\rm SM}$ is the lowest-order prediction for the trilinear Higgs coupling in the SM. These bounds leave room for large deviations that can occur even in simple extensions of the SM field content like the Two Higgs Doublet Model (2HDM). Future experiments at the LHC and the High-Luminosity Large Hadron Collider (HL-LHC) are expected to provide greater sensitivity which will probe a large variety of Beyond-the-Standard-Model (BSM) scenarios. Therefore, accurate theoretical predictions of the phenomenology of BSM models giving rise to modifications in the Higgs self-coupling are crucial. Here, we review the impact of large corrections to the trilinear Higgs couplings on the 2HDM phenomenology in the context of double Higgs production at the HL-LHC as well as the role of the BSM Higgs self interactions that involve a resonant heavy Higgs boson and two SM-like Higgs bosons [3].

The 2HDM extends the field content of the SM by one additional complex doublet, introducing four extra degrees of freedom that mix and give rise to a total of five physical Higgs bosons. We consider the CP-conserving 2HDM with a Z_2 symmetry that prevents the appearance of flavour changing neutral currents at lowest order and that can be softly broken by a mass term m_{12}^2. The imposition of a discrete symmetry leads to four different types of the 2HDM depending on the Yukawa couplings to the fermions of the scalar sector. We analyze the 2HDM type I, in which all fermions and gauge bosons couple exclusively to one of the Higgs doublets. Performing the convenient rotations of the eigenstates to the mass basis, one can work with the set of free parameters:

$$\cos(\beta-\alpha)\,, \quad \tan\beta\,, \quad v\,, \quad m_h\,, \quad m_H\,, \quad m_A\,, \quad m_{H^\pm}\,, \quad m_{12}^2\,, \tag{1}$$

where $\cos(\beta-\alpha) \to 0$ in the so-called alignment limit, in which h has the same couplings to the fermions and gauge bosons as in the SM, and α (β) denotes the mixing angle of the CP even (CP odd and charged) sector. $\tan\beta$ is the ratio of the vacuum expectation values of the two doublets, v_2 and v_1, which obey the relation $v = \sqrt{v_1^2 + v_2^2} \approx 246$ GeV, and $m_h, m_H, m_A, m_{H^\pm}$ are the masses of the light CP even Higgs h (identified in the following with the one discovered at ≈ 125 GeV), the heavy CP even Higgs H, the CP odd Higgs A and the charged Higgses $H^\pm$, respectively.

It is known that the Higgs self-couplings and the derived observables in extended Higgs sectors may receive sizable contributions from the new heavy states in the model though radiative corrections [4]. To account for these effects we will use the effective potential approach:

$$V_{\rm eff} = V_{\rm tree} + V_{\rm CW} + V_{\rm CT}\,, \tag{2}$$

where $V_{\rm tree}$ is the tree-level scalar potential in the 2HDM, $V_{\rm CW}$ is the one-loop Coleman–Weinberg potential and $V_{\rm CT}$ is the counterterm contribution that is chosen such that the masses and mixing angles are kept at their tree-level values and therefore can conveniently be used as input parameters.

In this setup, the effective trilinear Higgs couplings can be computed as the third derivatives of the potential with respect to the Higgs fields, evaluated at the minimum, in particular:

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$$\lambda_{hhh} = \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{h=0,\, H=0}, \quad \lambda_{hhH} = \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^2 \partial H}\right|_{h=0,\, H=0}. \tag{3}$$

In our notation, we will use the dimensionless parameters, λ_{hhh_j} $(h_j = h, H)$, such that the Feynman rules are given by $-ivn!\lambda_{hhh_j}$, where v is the vacuum expectation value and n is the number of identical Higgses in the vertex, thus recovering the SM definition $-6iv\lambda_{SM}$ with $\lambda_{SM} = m_h^2/2v^2$.

The most direct access to the trilinear Higgs coupling λ_{hhh} is through Higgs pair production, where this parameter enters at the lowest order in the process. At a hadron collider, the dominant production channel is gluon fusion. In the SM there are two diagrams that contribute to the process at leading order, a triangle and a box diagram (Fig. 1), giving rise to a large destructive interference contribution that results in a small cross section. The size of the interference contribution can be modified very significantly if the trilinear Higgs coupling, present in the triangle diagram, acquires large loop corrections due to the contribution of heavy scalars in the loops [5]. The hh production cross section can furthermore be much enhanced if a large contribution is present from the resonant diagram involving the exchange of the heavy CP even state, H, in the s-channel.

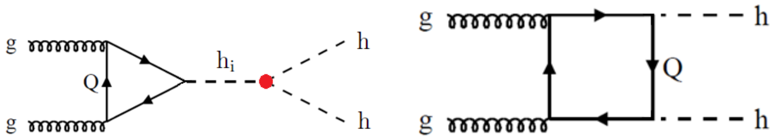

Figure 1: Leading order (SM-like) Higgs pair production diagrams in the 2HDM.

2. Numerical analysis and results

We have analyzed a series of benchmark planes of the allowed parameter space in the 2HDM by means of the python package `thdmTools`, see Ref. [6], where also a complete set of the applied constraints can be found. We have obtained the predictions of the loop-corrected trilinear Higgs couplings via the public code `BSMPT` [7, 8], which performs the derivatives of the one-loop effective potential at zero temperature as described above. Finally, we have used a modified version of the code `HPAIR` [9–12] that performs the calculation of the gluon fusion Higgs pair production cross section in the 2HDM and includes the corrections of the trilinear Higgs couplings.

2.1 Total cross section predictions

In Ref. [3] the impact of deviations in the trilinear Higgs couplings on double Higgs production at the HL-LHC has been investigated. In the present analysis we show that large corrections can arise from loop corrections to the trilinear Higgs couplings.

In Fig. 2 we show the predictions for the trilinear Higgs couplings (upper) and the Higgs pair production cross section normalised to the SM value (lower) for a benchmark scenario that features large deviations in κ_λ at tree level. In this scenario $m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$ and $m_H = m_A = m_{H^\pm} =$ 1000 GeV, yielding a cross section that essentially arises from the non-resonant contributions since the diagram involving H exchange is negligible. The allowed parameter space is located within the region of the solid black contour.

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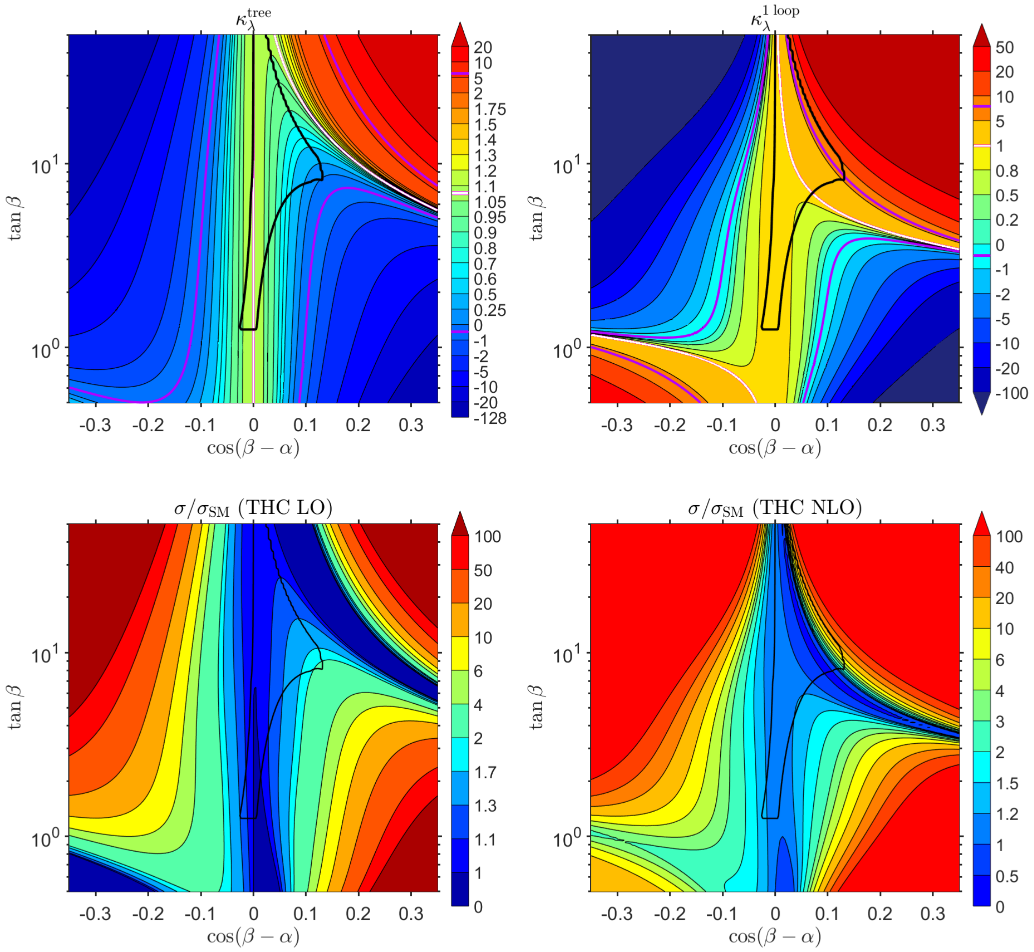

Figure 2: Predictions for the trilinear Higgs coupling κ_λ at tree level (upper left) and one-loop order (upper right) and for the total Higgs pair production cross section normalised to the SM prediction including the trilinear Higgs couplings at tree level (lower left) and at one-loop order (lower right). The parameter region allowed by the applied constraints is located inside the black countour.

In the lower left plot, with the trilinear Higgs couplings at tree level (THC LO) we observe that the maximum deviation from the SM prediction within the allowed area occurs precisely at the "tip" that is furthest away from the alignment limit. Here the enhancement factor in the cross section is ~ 3. This corresponds to the minimum size of $\kappa_\lambda \approx 0$ (see upper left plot).

Large loop corrections to the trilinear Higgs couplings are realised in the allowed region with $\cos(\beta-\alpha) > 0$ (see orange region in the upper right plot, where in purple the current experimental bound from ATLAS is shown). When including these corrections in the hh production prediction we observe deviations in the cross section of up to ~ 20 with respect to the SM within the allowed region, as can be observed in the lower right plot. We also observe regions where the cross section is smaller than the SM cross section due to a value of $\kappa_\lambda \approx 2.5$, for which it is known that the destructive interference between box and triangle diagrams is maximised. This wide range of possible effects arises solely due to the inclusion of loop corrections to the trilinear Higgs couplings.

Thus, in scenarios with large corrections to the trilinear Higgs couplings and negligible resonant contribution, the behaviour of κ_λ is directly reflected in the Higgs pair production cross section.

2.2 m_{hh} distributions in the 2HDM

We now explore the phenomenological impact of the loop corrections to the trilinear Higgs couplings on the invariant mass distribution of the two SM-like Higgs bosons in the final state. In particular, we select two benchmark scenarios for which we plot the invariant mass distributions with the trilinear Higgs couplings at leading order and including loop corrections.

In Fig. 3 (left) we show the invariant mass distribution for a benchmark point in the 2HDM-I with $\tan\beta = 10$, $c_{\beta-\alpha} \equiv \cos(\beta-\alpha) = 0.2$, $m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$, $m_H = 512.5$ GeV and $m_A = m_{H^\pm} = 545$ GeV. This point features large corrections to the Higgs self interactions, shifting $\kappa_\lambda = 0.99$ at tree level to $\kappa_\lambda = 3.61$ at one-loop order. The distribution with loop-corrected trilinear couplings (blue curve) shows at low m_{hh} a large enhancement with respect to the distribution at leading order (red) since the cancellation at low m_{hh} of the triangle and box contributions happening accidentally in the SM ($\kappa_\lambda = 1$) now takes place at larger values of m_{hh}. This yields a much smaller contribution than the bump observed in the red curve at the di-top production threshold, $m_{hh} \approx 400$ GeV. The loop corrections to λ_{hhH} play a minor role in this case, indicated by the fact that the green dashed curve (only corrections to λ_{hhH} included) lies almost on top of the tree-level prediction, while the yellow dashed curve (only corrections to κ_λ included) is very similar to the prediction with both couplings at loop level. The interference between the resonant diagram and the continuum creates a dip–peak structure at the resonance $m_{hh} = m_H$ involving the BSM trilinear coupling λ_{hhH}.

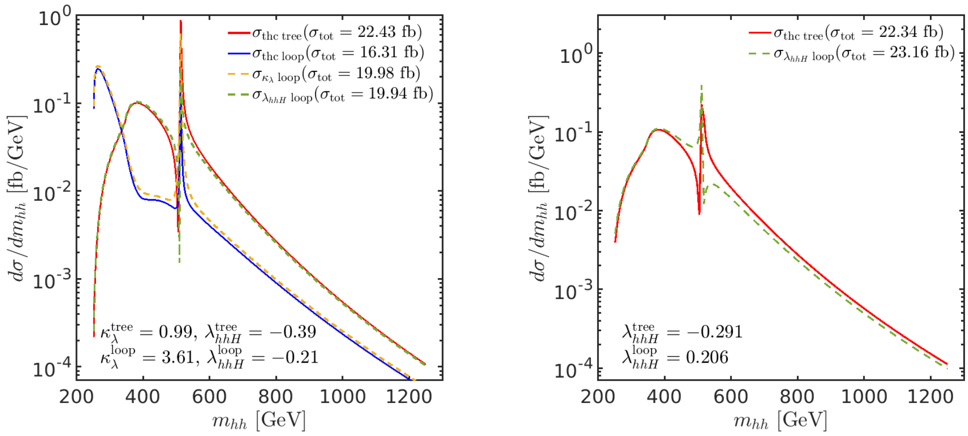

Figure 3: Left: Invariant mass distribution for a benchmark point in the 2HDM-I with $\tan\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = (m_H^2\cos^2\alpha)/\tan\beta$, $m_H = 512.5$ GeV and $m_A = m_{H^\pm} = 545$ GeV for tree-level and loop-level insertions of the trilinear Higgs couplings. Right: Impact of loop corrections to λ_{hhH} on the resonance shape for a benchmark point as in the left plot but with $m_H = 504$ GeV and $m_A = m_{H^\pm} = 650$ GeV.

In Fig. 3 (right) we show a case in which the loop corrections to λ_{hhH} play an important role. This happens in scenarios with mass splitting among the heavy scalars and the scale $M = \sqrt{m_{12}^2/(\sin\beta\cos\beta)}$. In those cases the coupling $\lambda_{h\phi\phi}$ ($\phi = H, A, H^\pm$) that is proportional to the difference $(M^2 - m_\phi^2)$ becomes sizeable and yields large corrections from the scalars $H, A, H^\pm$ that

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contribute in the loops of the λ_{hhH} coupling. For the chosen scenario this has the effect of flipping the sign of λ_{hhH} and therefore the product of the two couplings involved in the resonant diagram, $\lambda_{hhH} \times \xi_H^t$ (where ξ_H^t is the top Yukawa coupling of the heavy Higgs boson), changes its sign, which leads to a change in the structure of the resonance that can be observed in the plot [3]. The dip-peak structure that was present at leading order becomes a peak-dip structure if the loop corrections to λ_{hhH} are included, highlighting again the importance of the inclusion of loop corrections.

3. Summary and conclusions

In this contribution we have extended the work of Ref. [3] and shown that sizeable deviations in trilinear Higgs couplings, which are allowed by all current constraints, can arise from loop-induced effects of heavier BSM states in trilinear Higgs couplings. We have demonstrated their significant impact on Higgs pair production at the HL-LHC. Furthermore, we have shown that invariant mass distributions are drastically sensitive to deviations in trilinear Higgs couplings from the SM value. Thus, a precise theoretical framework is essential for the interpretation of the experimental results.

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