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Impact of heavy sterile neutrinos on the triple Higgs coupling

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New physics beyond the Standard Model is required to give mass to the light neutrinos. One of the simplest ideas is to introduce new heavy, gauge singlet fermions that play the role of right-handed neutrinos in a seesaw mechanism. They could have large Yukawa couplings to the Higgs boson, affecting the Higgs couplings and in particular the triple Higgs coupling λ_{HHH}, the measure of which is one of the major goals of the LHC and of future colliders. We present a study of the impact of these heavy neutrinos on λ_{HHH} at the one-loop level, first in a simplified 3+1 model with one heavy Dirac neutrino and then in the inverse seesaw model. Taking into account all possible experimental constraints, we find that sizeable deviations of the order of 35% are possible, large enough to be detected at future colliders, making the triple Higgs coupling a new, viable observable to constrain neutrino mass models. The effects are generic and are expected in any new physics model including TeV-scale fermions with large Yukawa couplings to the Higgs boson, such as those using the neutrino portal.

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1. Introduction

The Super-Kamiokande experiment firmly established in 1998 that neutrinos oscillate [1], which calls for an extension of the Standard Model (SM) that generates neutrino masses and mixing. One of the simplest possibilities to explain neutrino masses is to add new fermionic gauge singlets that play the role of right-handed neutrinos. These new fermionic states could have large Yukawa couplings to the Higgs boson, having a sizeable impact on the Higgs couplings and opening new search strategies.

The Higgs self-couplings, and in particular the triple Higgs coupling λ_{HHH}, play a central role in probing electroweak symmetry breaking (EWSB) induced by the Higgs mechanism [2–6]. The measure of λ_{HHH} is one of the major goals of the LHC and of the future planned colliders such as the electron-positron International Linear Collider (ILC) or the Future Circular Collider in hadron mode (FCC-hh), a potential 100 TeV follow-up of the LHC. Investigating possible beyond-the-SM (BSM) effects on this coupling is thus very much needed and the effects induced by the heavy neutrinos present in seesaw mechanisms have been overlooked so far.

We present a study of the impact of these heavy neutrinos on λ_{HHH}, first by considering a simplified 3+1 model where the SM is minimally modified to account for three light massive Dirac neutrinos and one heavy sterile Dirac neutrino; then by considering the inverse seesaw mechanism [7–9] which is a realistic, renormalisable mass model with 9 Majorana neutrinos. Taking into account all theoretical and experimental constraints, we find in both studies [10, 11] sizeable effects, of the order of 35% for large off-shell Higgs momentum q_H^* and of the order of 10% for $q_H^* = 500$ GeV. This is clearly detectable at the FCC-hh and may be probed at the ILC, making the triple Higgs coupling λ_{HHH} a new, viable observable for the neutrino sector in order to constraint mass models.

2. The triple Higgs coupling

The Higgs field Φ of the SM can be written as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ \mathrm{v} + H + \imath G^0 \end{pmatrix}, \tag{2.1}$$

where H is the Higgs boson, G^0 is the neutral Goldstone boson, $G^\pm$ are the charged Goldstone bosons, and $\mathrm{v} \simeq 246$ GeV is the Higgs vacuum expectation value. After EWSB, the scalar potential of the SM contains the following terms involving the Higgs boson H,

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!} \lambda_{HHH} H^3 + \frac{1}{4!} \lambda_{HHHH} H^4, \tag{2.2}$$

where M_H is the Higgs boson mass and the tree-level values for the triple and quartic Higgs couplings are $\lambda^0_{HHH} = -3M_H^2/\mathrm{v}$ and $\lambda^0_{HHHH} = -3M_H^2/\mathrm{v}^2$ respectively.

Our one-loop calculation is performed in the on-shell renormalisation scheme. Our Higgs and electroweak inputs are the Higgs mass M_H, the W and Z boson masses M_W and M_Z, and the electric charge e. Details of the calculation and analytical formulas can be found in our articles [10, 11].

Our results will be presented in terms of deviations with respect to the tree-level value λ^0_{HHH} and to the renormalised one-loop value in the SM $\lambda^{1r,\mathrm{SM}}_{HHH}$ of the triple Higgs coupling,

$$\begin{aligned}\Delta^{(1)}\lambda_{HHH} &= \frac{1}{\lambda^0}\left(\lambda^{1r,\mathrm{full}}_{HHH} - \lambda^0\right),\\ \Delta^{\mathrm{BSM}} &= \frac{1}{\lambda^{1r,\mathrm{SM}}_{HHH}}\left(\lambda^{1r,\mathrm{full}}_{HHH} - \lambda^{1r,\mathrm{SM}}_{HHH}\right).\end{aligned} \tag{2.3}$$

with $\lambda^{1r,\mathrm{full}}_{HHH}$ being the one-loop renormalised triple Higgs coupling in the model considered. We will compare our results with the experimental sensitivities to the SM triple Higgs coupling at the LHC, the ILC and the FCC-hh. We use a sensitivity of $\sim 35\%$ at the high-luminosity run of the LHC (HL-LHC) according to Ref. [12] (see also Ref. [13]), with a scaling of $1/\sqrt{2}$ to combine ATLAS and CMS results. Using Ref. [14] and again a rescaling we take a sensitivity of $\sim 5\%$ at the FCC-hh with 3 ab^{-1}, and finally we take a sensitivity of 10% [15] at the 1 TeV ILC with 5 ab^{-1}.

3. Simplified 3+1 model

In a first study [10], we considered a simplified model that includes 3 light neutrinos and an extra heavy neutrino. All of them are Dirac fermions and the heavy neutrino couples to the SM particles through its mixing with SM fields. This leads to the following couplings between neutrinos and SM bosons, defined in the mass basis,

$$\begin{aligned}\mathscr{L} \ni &-\left(\frac{g_2}{\sqrt{2}}\bar{\ell}_i \not{W}^- B_{ij} P_L n_j + \frac{g_2}{\sqrt{2}M_W}\bar{\ell}_i G^- B_{ij}(m_{\ell_i}P_L - m_{n_j}P_R)n_j\right) + \mathrm{H.c.}\\ &- \frac{g_2}{2\cos\theta_W}\bar{n}_i \not{Z}(B^\dagger B)_{ij}P_L n_j + \frac{\imath g_2}{2M_W}\bar{n}_i(B^\dagger B)_{ij}G^0(-m_{n_i}P_L + m_{n_j}P_R)n_j\\ &- \frac{g_2}{2M_W}\bar{n}_i(B^\dagger B)_{ij}H(m_{n_i}P_L + m_{n_j}P_R)n_j,\end{aligned} \tag{3.1}$$

where ℓ_i are the charged leptons, n_i are the Dirac neutrinos of mass $m_{1\ldots4}$, g_2 is the SU(2) coupling constant, and B is a 3×4 mixing matrix.

The most relevant experimental constraints on our model come from electroweak precision observables (EWPO) and in particular from the global fit performed in [16, 17]. We have also taken into account constraints on the mixing matrix B coming from neutrino oscillations [18] with $\delta_{CP} = 0$. We also require two theoretical constraints. The loop expansion has to remain perturbative, and we apply either a loose (tight) bound of

$$\left(\frac{\max|C_{i4}|\,g_2\,m_{n_4}}{2M_W}\right)^3 < 16\pi\,(2\pi). \tag{3.2}$$

Since for fixed mixing the heavy neutrino width grows with its mass, we require as well $\Gamma_{n_4} \leq 0.6\,m_{n_4}$ for the quantum state to be a definite particle.

For our numerical study, SM parameter values were taken from the Particle Data Group [19] (with the exception of the SM Higgs boson mass fixed to $M_H = 125$ GeV). Taking $B_{\tau4} = 0.087$, $B_{e4} = B_{\mu4} = 0$, Fig. 1 displays the one-loop induced deviation of λ_{HHH} from its tree-level value while the insert presents the size of the corrections coming from the heavy neutrino. With these

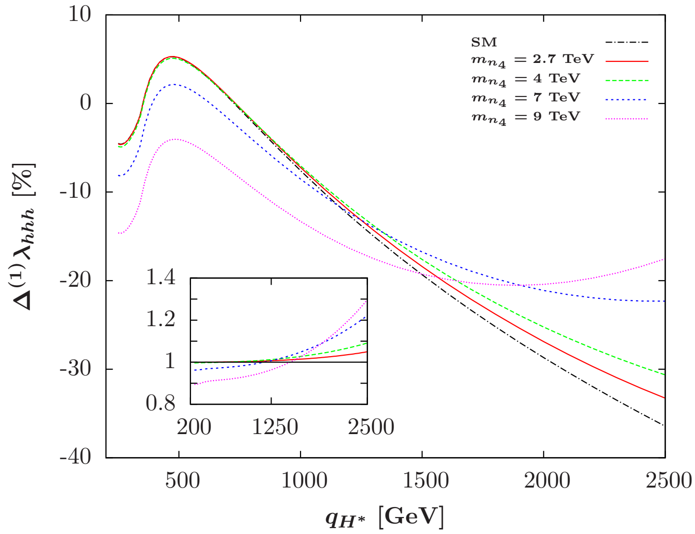

Figure 1: One-loop corrections to the triple Higgs coupling λ_{HHH} (in %) as a function of the momentum q_{H^*} of the splitting $H^*(q_{H^*}) \to HH$ (in GeV). The ratio of the genuine BSM contribution to λ_{HHH} with respect to the one-loop SM contribution is shown in the insert.

mixing parameters, a heavy neutrino mass of $m_{n_4} = 2.7$ TeV corresponds to an effective coupling to the Higgs equal to the one of the top quark while $m_{n_4} = 7$ TeV leads to the saturation of the tight perturbativity bound and $m_{n_4} = 9$ TeV saturates the width constraint. We observe that in the SM, the largest positive correction is at $q_{H^*} \simeq 500$ GeV, where the BSM contribution decreases it to -9% at $m_{n_4} = 9$ TeV. The largest negative correction comes at larger momentum where the deviation from the SM increases with larger m_{n_4}, reaching $+30\%$ for $m_{n_4} = 9$ TeV at $q_{H^*} = 2500$ GeV.

This behaviour leads us to chose $q_{H^*} \simeq 500/2500$ GeV as two most interesting off-shell momenta and to study the size of the BSM corrections induced by the heavy neutrino as a function of its mass and couplings. This is presented in Fig. 2 for $q_{H^*} = 500$ GeV (left) and $q_{H^*} = 2.5$ TeV (right). The largest effects are present in the high mixing / high heavy neutrino mass region, reaching slightly less that 10% negative deviation at $q_{H^*} = 500$ GeV (less that -5% with the tight perturbative bound displayed in red) and around $+30\%$ increase at $q_{H^*} = 2.5$ TeV (slightly less that $+25\%$ with the tight perturbative bound). This is always below the HL-LHC sensitivity (35%), but clearly visible at the FCC-hh (5%) and potentially visible at the ILC (10%).

4. Inverse seesaw model

In order to confirm the results obtained in the simplified 3+1 model, we performed in our next study [11] the analysis of the one-loop corrections to λ_{HHH} in a renormalisable, low-scale seesaw model, namely the inverse seesaw (ISS) [7–9]. We add to the SM Lagrangian 6 fermionic gauge singlets, 3 states with positive lepton number $L = +1$ (ν_R) and 3 states with negative lepton number $L = -1$ (X) with the following Yukawa couplings and mass terms,

$$\mathscr{L}_{\rm ISS} = -Y_\nu^{ij}\overline{\ell_i}\widetilde{\Phi}\nu_{Rj} - M_R^{ij}\overline{\nu_{Ri}^C}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^C}X_j + \text{H.c.}\,, \tag{4.1}$$

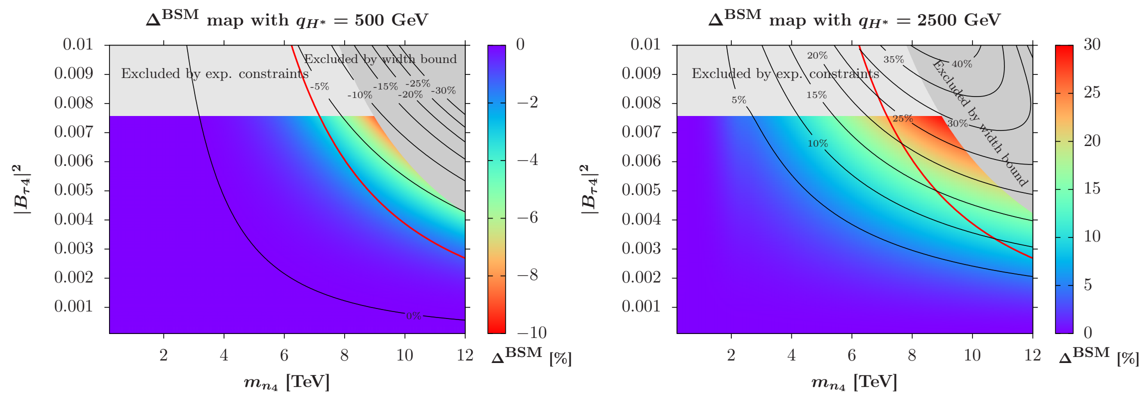

Figure 2: Contour maps of the neutrino corrections $\Delta^{\rm BSM}$ to the triple Higgs coupling λ_{HHH} (in %) as a function of the two neutrino parameters $|B_{\tau 4}|^2$ and m_{n_4} (in TeV), at a fixed off-shell Higgs momentum $q_{H^*} = 500$ GeV (left) and $q_{H^*} = 2500$ GeV (right). The other heavy neutrino mixing parameters are set to zero. The light grey area is excluded by the experimental constraints and the darker grey area is excluded from having $\Gamma_{n_4} > 0.6 m_{n_4}$ while the red line corresponds to the tight perturbativity bound.

leading after EWSB to 9 Majorana neutrinos N_i. Thanks to the two scale parameters μ_X and M_R it is possible to decouple the neutrino mass generation from the mixing between the active neutrinos and the fermionic gauge singlets. The light neutrino masses are suppressed by the small lepton-number breaking parameter μ_X. It is then possible to have at the same time Yukawa couplings Y_ν of order 1 and $M_R \sim 1$ TeV, which is within reach of the LHC and low energy experiments.

The calculation of the one-loop corrections to λ_{HHH} in the ISS is very similar to the calculation in the 3+1 model, but with Majorana neutrinos instead of Dirac neutrinos. All formulae are available in the appendix B of our article [11]. The set of constraints changes, though. The constraints from low-energy neutrino data are implemented via the μ_X-parametrisation [20],

$$\mu_X = M_R^T m_D^{-1} U_{\rm PMNS}^* m_\nu U_{\rm PMNS}^\dagger m_D^{T^{-1}} M_R, \tag{4.2}$$

at the lowest order in the seesaw expansion parameter $m_D M_R^{-1}$. Terms beyond this order are also included in our analysis and are given in the appendix A of our article [11]. Charged lepton flavour violation bounds are taken into account (see e.g. Ref. [21]) as well as the global fit to EWPO and the lepton universality tests [22]. Theoretical constraint on the heavy neutrino widths $\Gamma_{N_i} \leq 0.6 m_{N_i}$ and the Yukawa perturbativity constraint $|Y_\nu^2| < 1.5 \times 4\pi$ are also included.

Representative numerical results of our study of the size of the BSM corrections induced by the heavy neutrinos are displayed in Fig. 3. We have used a diagonal Yukawa texture $Y_\nu = |Y_\nu| I_3$ and a hierarchical heavy neutrino mass matrix with $M_R = {\rm diag}(1.51 M_R, 3.59 M_R, M_R)$, where M_R corresponds to the seesaw scale. This choice of textures for the two matrices leads to the largest effects in the ISS, reaching the $+30\%$ deviation for a large momentum $q_{H^*} = 2.5$ TeV and the -8% deviation for $q_{H^*} = 500$ GeV, for M_R around 9 TeV and large Yukawa couplings. These results can be approximated by the following formula that is used for the green lines in Fig. 3,

$$\Delta^{\rm BSM}_{\rm approx} = 0.51 \frac{(1~{\rm TeV})^2}{M_R^2} \left(8.45\,{\rm Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger) - 0.145\,{\rm Tr}(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)\right). \tag{4.3}$$

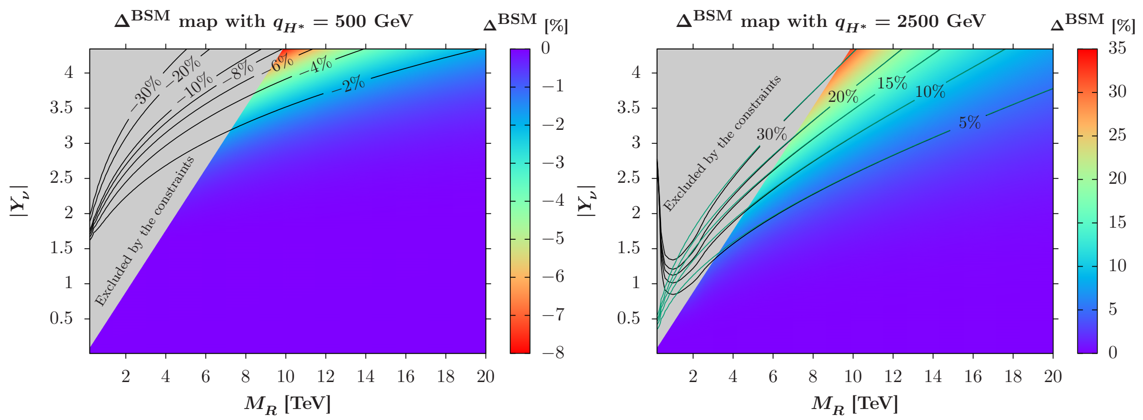

Figure 3: Contour maps of the heavy neutrino correction $\Delta^{\rm BSM}$ to the triple Higgs coupling λ_{HHH} (in %) as a function of the neutrino parameters M_R (in TeV) and $|Y_\nu|$ in the μ_X–parametrisation, at a fixed off-shell Higgs momentum $q_{H^*} = 500$ GeV and $q_{H^*} = 2.5$ TeV (right). We have used a diagonal Yukawa texture Y_ν with parameter $|Y_\nu|$ and a hierarchical heavy neutrino mass matrix, varying the seesaw scale M_R. The grey area is excluded by the constraints on the model and the green lines on the right figure are the approximated contour lines using eq.(4.3), while the black lines correspond to the full calculation.

The larger number of heavy neutrinos compared to the simplified 3+1 model would naively induce larger corrections in the ISS. However, the experimental constraints are stronger in this case, which leads to results similar to the simplified 3+1 analysis of the previous section. This confirms our previous conclusion that the triple Higgs coupling λ_{HHH} is a new, viable observable to constrain neutrino mass models.

5. Conclusion

The indubitable observation of neutrino oscillations requires the addition of BSM physics to generate neutrino masses and mixing and one of the simplest and well-motivated ideas adds new right-handed sterile neutrinos to the SM, leading to seesaw models. We have introduced the triple Higgs coupling as a new observable to constraint these neutrino mass models and we have found, first in a simplified 3+1 model and then in the inverse seesaw, that the one-loop effects induced by these heavy neutrinos can be as large as 30% with respect to the SM one-loop prediction. This is measurable at future colliders and it provides a new, complementary probe in the $\mathcal{O}(10)$ TeV range of the heavy neutrino masses. We stress that these effects are generic and would be expected in any model containing TeV scale fermions with large Higgs couplings, such as those using the neutrino portal.

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