Chapter E

Beyond the Standard Model (BSM)

1 (Triple) Higgs coupling imprints at future lepton colliders

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1.1 Triple Higgs coupling studies in an EFT framework

The measurement of the triple Higgs coupling is one of the major goals of the future colliders. The direct measurement at lepton colliders relies on the production of Higgs boson pairs in two main channels: $e^+e^- \to ZHH$, which is dominant at centre-of-mass energies below 1 TeV and maximal at around 500 GeV, and $e^+e^- \to HH\nu_e\bar{\nu}_e$, which becomes dominant for high-energy colliders. This direct measurement is required to be at least at a centre-of-mass energy of 500 GeV, and is hence only possible at future linear colliders, such as the International Linear Collider (ILC), operating at 500 GeV or 1 TeV [1], or the Compact Linear Collider (CLIC), operating at 1.4 TeV (stage 2) or 3 TeV (stage 3) [2]. The SM triple Higgs coupling sensitivity is estimated to be $\delta\kappa_\lambda = (\lambda_{HHH}/\lambda_{HHH}^{SM} - 1) \sim 28\%$ at the 500 GeV ILC, with a luminosity of 4 ab^{-1} [3,4], and $\delta\kappa_\lambda \sim 13\%$ at the CLIC, when combining the 1.4 TeV run, with 2.5 ab^{-1} of data, and the 3 TeV run, with 5 ab^{-1} of data [5].

Still, circular lepton collider projects, such as the Circular Electron–Positron Collider (CEPC) [6] or the FCC-ee [7,8], which run at energies below 500 GeV (not to mention the ILC or the CLIC running at lower energies), can provide a way to constrain the triple Higgs coupling [9]. Since Ref. [10], in which it was first proposed to use precision measurements to constrain the triple Higgs coupling, in particular, the measurements in single Higgs production at lepton colliders, there have been studies of the combination of single and double Higgs production observables, not only at lepton but also at hadron colliders [11–14]. The analyses use the framework of Standard Model effective field theory (SMEFT). According to the latest ECFA report [15], the combination of HL-LHC projections [16] with ILC exclusive single Higgs data gives $\delta\kappa_\lambda = 26\%$ at 68% CL, while with the FCC-ee (at 250 or 365 GeV) this goes down to $\delta\kappa_\lambda = 19\%$, and with CEPC we get $\delta\kappa_\lambda = 17\%$. We will present in more detail the results of Refs. [12,13], which demonstrate how important the combination of the LHC results with an analysis at lepton colliders is, and show the potential of the FCC-ee.[†]

Figure E.1.1 (left) displays the latest experimental results available at the 13 TeV LHC for the search of non-resonance Higgs pair production and the 95% CL limits on the triple Higgs coupling, which have been presented in Ref. [17]. The results constrain $\delta\kappa_\lambda$ in the range

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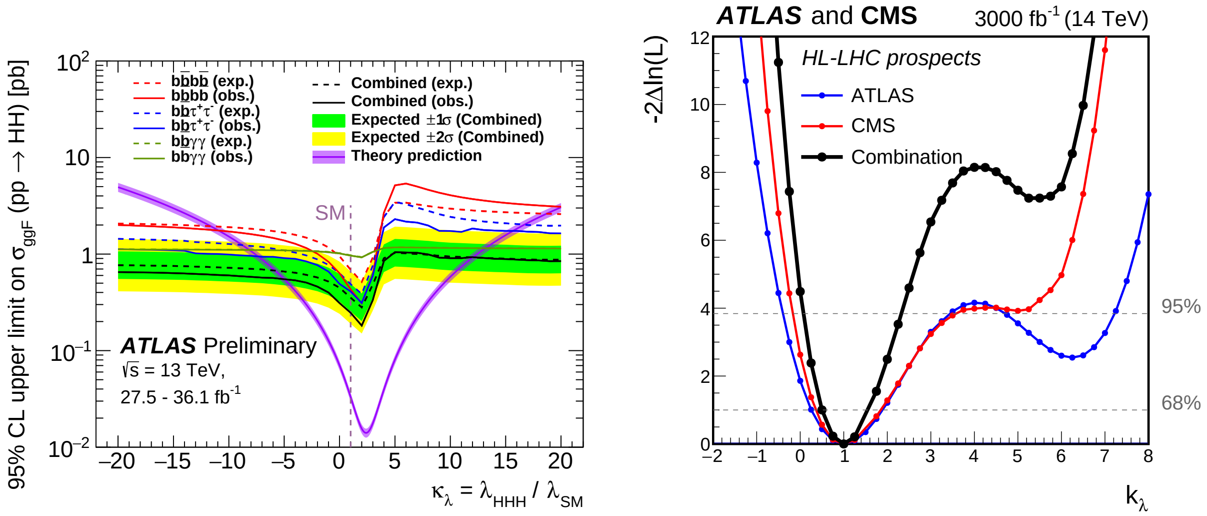

Fig. E.1.1: Left: Latest experimental bounds on the triple Higgs coupling from the ATLAS collaboration at the 13 TeV LHC, combining $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$ final states. Taken from Ref. [17]. Right: Minimum negative-log-likelihood distribution of κ_λ at the HL-LHC with 3 ab^{-1} of data, including differential observables in Higgs pair production, with ATLAS (blue), CMS (red), and ATLAS+CMS (black) projected results. Figure taken from Ref. [16].

$[-6.0 : 11.1]$. We can compare them with the projections at the HL-LHC with 3 ab^{-1} presented in the HL-HE LHC report [16] in an SMEFT framework, using a differential analysis in the channel $\mathrm{pp} \to \mathrm{HH}$. Compared with the projection in Ref. [12], which also included single Higgs data in the channels $\mathrm{pp} \to \mathrm{W}^\pm\mathrm{H}, \mathrm{ZH}, \mathrm{t\bar{t}H}$, there is a substantial improvement, thanks to the experimental differential analysis. We have $-0.5 \leq \delta\kappa_\lambda \leq 0.5$ at 68% CL and $-0.9 \leq \delta\kappa_\lambda \leq 1.3$ at 95% CL. The degeneracy observed in Ref. [12] with a second minimum at $\delta\kappa_\lambda \sim 5$ is now excluded at 4σ.

The combination with data from lepton colliders removes the second minimum even more drastically and only the SM minimum is left at $\delta\kappa_\lambda = 0$ [13], in particular when data from 250 GeV and 350–365 GeV centre-of-mass energies are combined [13]. This is shown in Fig. E.1.2, where two set-ups are compared, the combination of HL-LHC data with circular lepton colliders (FCC-ee or CEPC) data on the left-hand side, and the combination of HL-LHC data with the ILC data on the right-hand side. In both cases, the lepton collider data consist of measurements in the channels $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-, \mathrm{ZH}, \nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mathrm{H}$. The second minimum disappears completely even with a relatively low integrated luminosity of $\mathcal{L} = 200\ \mathrm{fb}^{-1}$ at 350 GeV, when combined with the data at 250 GeV. Note that the FCC-ee (or CEPC), thanks to its much higher luminosity in the 250 GeV run, is doing significantly better than the ILC.

1.2 Probing heavy neutral leptons via Higgs couplings

Since the confirmation of neutrino oscillations in 1998 by the Super-Kamiokande experiment [18], it has been established that at least two neutrinos have a non-zero mass [19]. This experimental fact cannot be accounted for in the SM and requires new physics. One of the simplest extensions is the addition of new heavy neutral leptons that are gauge singlets and mix with the active neutrinos to generate the light neutrino masses. An appealing model, allowing for these new fermionic states to be in the range of gigaelectronvolts to a few teraelectronvolts

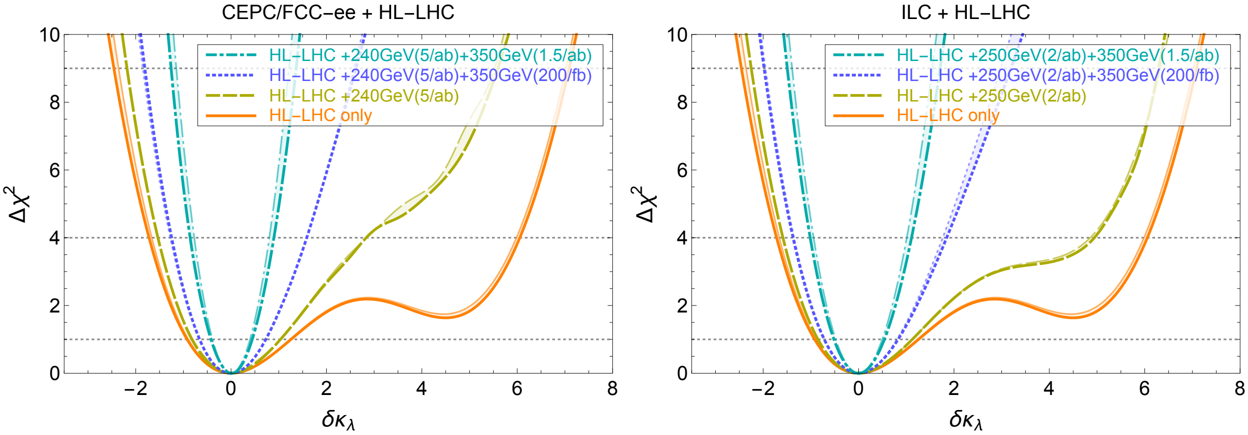

Fig. E.1.2: $\Delta\chi^2$ distributions for a global fit of the parameter $\delta\kappa_\lambda$ at circular lepton colliders (left) or at the ILC (right), combined with HL-LHC data. The different lines compare the different centre-of-mass energies and luminosity scenarios. Figures taken from Ref. [13].

while having Yukawa couplings of order one, is the inverse see-saw (ISS) model [20–22], in which a nearly conserved lepton-number symmetry [23, 24] is introduced, naturally explaining the smallness of the mass of the lightest neutrino states while allowing for large couplings between the heavy neutrinos and the Higgs boson, leading to a rich phenomenology. In this view, the very precise study of the Higgs sector at lepton colliders can offer a unique opportunity to test low-scale see-saw mechanisms, such as the ISS.

1.2.1 Heavy neutral leptons in the gigaelectronvolt regime

We begin with the gigaelectronvolt regime. In these low-scale see-saw models, the mixing between the active and the sterile neutrinos leads to modified couplings of neutrinos to the W, Z, and Higgs bosons. This naturally leads to the idea of using precision measurements of the Higgs boson branching fractions into gauge bosons in order to test the mass range $M_{\mathrm{N}} < M_{\mathrm{H}}$, where M_{N} is the mass of the heavy neutrino states and M_{H} is the mass of the Higgs boson. As H → NN is allowed, the invisible Higgs decay width is modified and hence the branching fraction $\mathrm{BR}(\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-)$ is modified via the modified total decay width Γ_{H}. According to an analysis of 2015 [25], the FCC-ee could be the most competitive lepton collider to test this option, as demonstrated in Fig. E.1.3. In particular, the experimental sensitivity to $\mathrm{BR}(\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-)$ is expected to be 0.9% at the FCC-ee, compared with 1.3% at the CEPC, operating at 240 GeV [26], and 6.4% at the ILC, operating at 250 GeV [1].[‡]

1.2.2 Probing heavy neutral leptons in the multi-teraelectronvolt regime

Since the coupling of the heavy neutral leptons to the Higgs boson can be quite large in low-scale see-saw models for masses M_{N} of a few teraelectronvolts, it is also very appealing to use, again, Higgs properties to probe a mass regime of $M_{\mathrm{N}} \sim \mathcal{O}(1-10\ \mathrm{TeV})$.

Off-diagonal couplings of the Higgs boson to heavy neutral leptons will induce charged-lepton-flavour-violating (cLFV) decays [28]. In particular, simplified formulae were provided in Ref. [29], showing that cLFV Higgs decays exhibit a different functional dependence on see-

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[‡] The latest analysis at the ILC, using a luminosity of 500 fb^{-1}, states that a precision of 4.1% can be achieved [27].

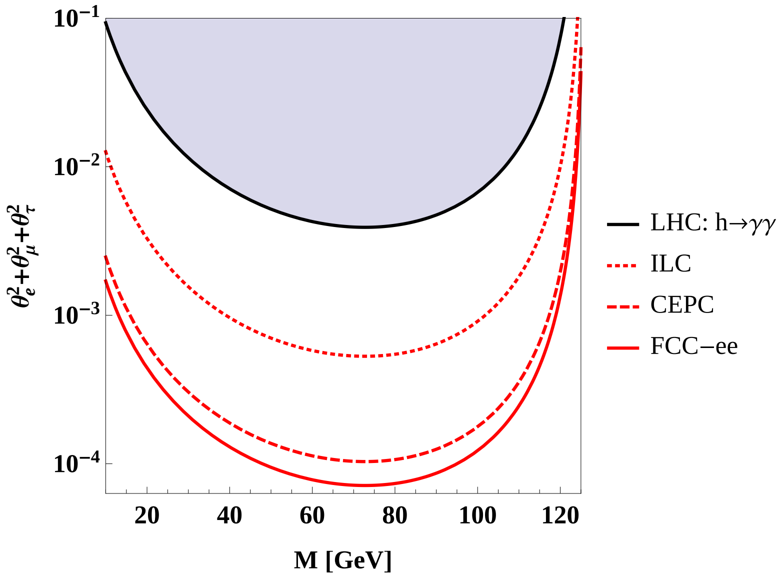

Fig. E.1.3: Estimated sensitivities on the heavy sterile neutrino properties from the decay $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$, assuming 10 years of data collection. The black line denotes the bound from the LHC coming from $\mathrm{H} \to \gamma\gamma$ with up to 2015 data. Taken from Ref. [25].

saw parameters than cLFV radiative decays. They thus provide complementary observables to search for heavy neutral leptons. In a typical low-scale see-saw model like the ISS, the predicted branching fraction can be as large as $\mathrm{BR}(\mathrm{H} \to \tau\mu) \sim 10^{-5}$ and could even reach $\mathrm{BR}(\mathrm{H} \to \tau\mu) \sim 10^{-2}$ in a supersymmetric model [30], thus being well within the reach of a Higgs factory like the FCC-ee. However, Higgs observables are also uniquely sensitive to diagonal couplings and this was discussed in particular in Refs. [31, 32], using the triple Higgs coupling, and in Ref. [33], using a direct physical observable, the production cross-section $\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-\mathrm{H})$. Taking into account all theoretical and experimental constraints that were available, the three studies have found sizeable effects.

In the triple Higgs coupling studies, the one-loop corrections to λ_{HHH}, defined as the physical triple Higgs coupling after electroweak symmetry breaking, are studied. The calculation is performed in the on-shell scheme and compares the SM prediction with the prediction in low-scale see-saw models (specifically the ISS presented in Ref. [32]). Representative one-loop diagrams involving the new heavy neutral leptons are given in Fig. E.1.4 and details of the calculation and analytical formulae can be found in the original articles. The results are given in terms of deviations with respect to the tree-level value λ^0_{HHH} and to the renormalised one-loop value in the SM $\lambda^{1,\mathrm{SM}}_{\mathrm{HHH}}$ of the triple Higgs coupling,

$$\begin{aligned}\Delta^{(1)}\lambda_{\mathrm{HHH}} &= \frac{1}{\lambda^0}\left(\lambda^1_{\mathrm{HHH}} - \lambda^0\right) ,\\ \Delta^{\mathrm{BSM}} &= \frac{1}{\lambda^{1,\mathrm{SM}}_{\mathrm{HHH}}}\left(\lambda^1_{\mathrm{HHH}} - \lambda^{1,\mathrm{SM}}_{\mathrm{HHH}}\right) ,\end{aligned} \tag{1.1}$$

with λ^1_{HHH} being the one-loop renormalised triple Higgs coupling in the low-scale see-saw model considered. The constraints from low-energy neutrino observables are implemented via the μ_X parametrization; see Ref. [29] for more details and Appendix A of Ref. [32] for terms beyond the lowest order in the see-saw expansion. All relevant theoretical and experimental bounds

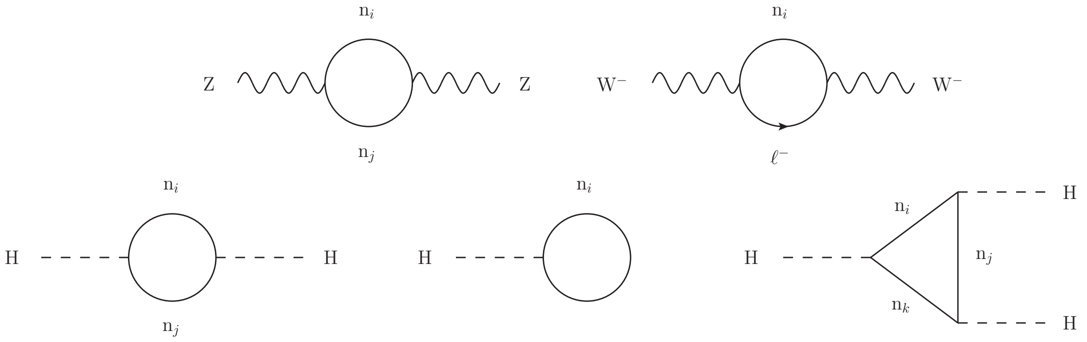

Fig. E.1.4: Representative Feynman diagrams for the one-loop corrections to λ_{HHH} involving the neutrinos in the ISS model.

are taken into account. The most stringent constraint comes from the global fit to electroweak precision observables and lepton universality tests [34].

Figure E.1.5 displays the results of the analysis in the plane $M_R - |Y_\nu|$ where M_R is the seesaw scale and $|Y_\nu|$ is the magnitude of the Yukawa coupling between the heavy neutral leptons and the Higgs boson. For an off-shell Higgs momentum of $q_{\mathrm{H}^*} = 500\,\mathrm{GeV}$ splitting into two on-shell Higgs bosons, sizeable deviations can be obtained, up to $\Delta^{\mathrm{BSM}} \simeq -8\%$. Compared with the expected sensitivity of $\sim$10% at the ILC at 1 TeV with $5\,\mathrm{ab}^{-1}$ [35] or the FCC-hh sensitivity of $\sim$5% when two experiments were to be combined [36], the deviation can be probed and hence test masses of order $\mathcal{O}(10\ \mathrm{TeV})$. In the case of the FCC-hh, as the hadronic centre-of-mass energy is large, the case $q_{\mathrm{H}^*} = 2500$ GeV is even more interesting, with a deviation up to $\Delta^{\mathrm{BSM}} \simeq +35\%$, leading to a larger coverage of the parameter space and the possibility of testing the model at the 3 TeV CLIC, where the sensitivity to λ_{HHH} is expected to be of the order of 13% [5]. The triple Higgs coupling λ_{HHH} is a viable new (pseudo-)observable for the neutrino sector in order to constrain mass models, and might also be used in the context of the FCC-ee in an indirect way in $\mathrm{e^+e^-} \to \mathrm{ZH}$ at the two-loop order, given the expected sensitivity the FCC-ee is supposed to reach in this channel. Studies remain to be done in this context.

The study presented in Ref. [33] considered a more direct observable, the production cross-section $\sigma(\mathrm{e^+e^-} \to \mathrm{W^+W^-H})$ at lepton colliders. The set-up is the same as in Ref. [32], albeit with an updated global fit using NuFIT 3.0 [37] to explain neutrino oscillations. The representative diagrams in the Feynman–'t Hooft gauge are displayed in Fig. E.1.6, with the contributions of the heavy neutral leptons in the t channel.

The deviation Δ^{BSM} now stands for the comparison between the total cross-section $\sigma(\mathrm{e^+e^-} \to \mathrm{W^+W^-H})$ calculated in the ISS model and in the SM, $\Delta^{\mathrm{BSM}} = (\sigma^{\mathrm{ISS}} - \sigma^{\mathrm{SM}})/\sigma^{\mathrm{SM}}$. Using the CLIC baseline for the polarisation of the beams [2] with an unpolarised positron beam, $P_{\mathrm{e}^+} = 0$, and a polarised electron beam, $P_{\mathrm{e}^-} = -80\%$, the contour map at 3 TeV in the same $M_R - |Y_\nu|$ plane is presented in the left-hand side of Fig. E.1.7. Again, the grey area is excluded by the constraints that mostly originate from the global fit [34]. The process $\mathrm{e^+e^-} \to \mathrm{W^+W^-H}$ exhibits sizeable negative deviations, of at least -20%. Note that the full results can be approximated within 1% for $M_R > 3$ TeV by the simple formulae presented in Ref. [33]. Compared with the left-hand side of Fig. E.1.5, the coverage of the parameter space is here much larger. optimised cuts can also be chosen to enhance the deviation, such as the cuts $|\eta_{\mathrm{H/W^\pm}}| < 1$ and $E_{\mathrm{H}} > 1$ TeV (see the right-hand side of Fig. E.1.7 for the η distributions),

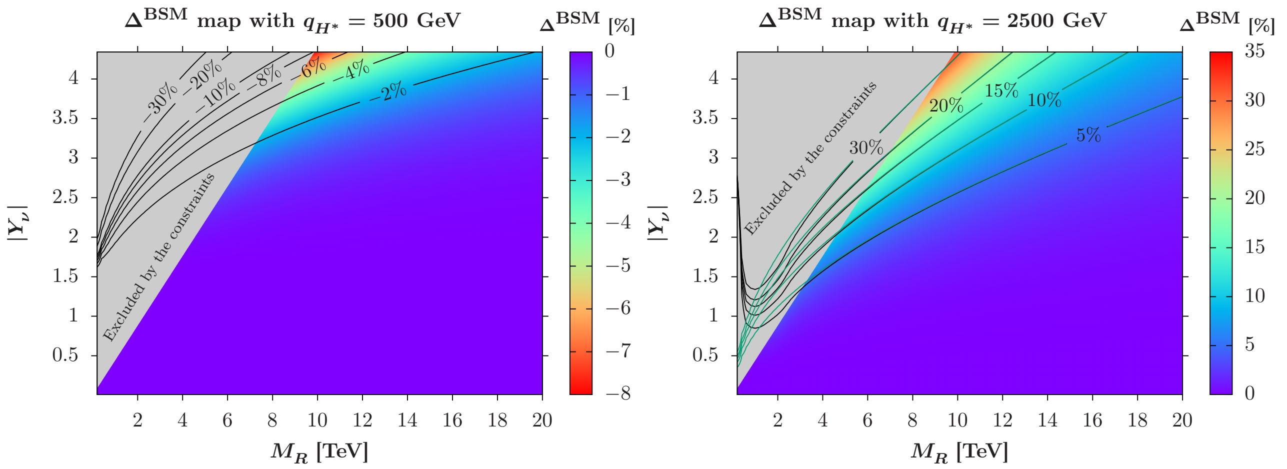

Fig. E.1.5: Contour maps of the heavy neutral lepton correction $\Delta^{\rm BSM}$ to the triple Higgs coupling $\lambda_{\rm HHH}$ (in %) as a function of the heavy neutral lepton parameters M_R (in teraelectronvolts) and $|Y_\nu|$ at a fixed off-shell Higgs momentum $q_{\rm H^*}$ = 500 GeV (left) and $q_{\rm H^*}$ = 2500 GeV (right). The details of the spectrum are given in Ref. [32]. The grey area is excluded by the constraints on the model and the green lines on the right figure are contour lines that correspond to our approximate formula, while the black lines correspond to the full calculation.

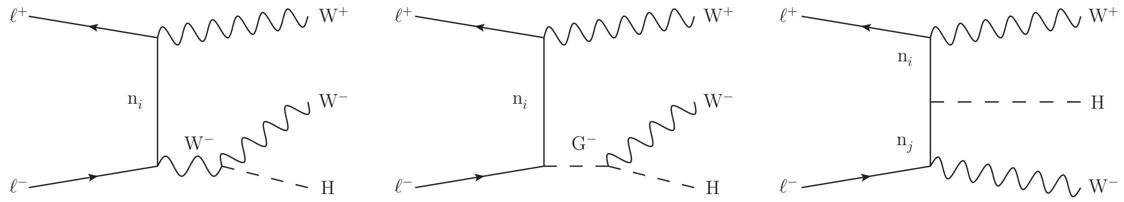

Fig. E.1.6: ISS neutrino contributions to the process $\ell^+\ell^- \to \mathrm{W}^+\mathrm{W}^-\mathrm{H}$ in the Feynman–'t Hooft gauge. Mirror diagrams can be obtained by flipping all the electric charges; the indices i, j run from 1 to 9.

which push the corrections down to -66% while keeping an ISS cross-section at a reasonable level: 0.14 fb, as compared with 1.23 fb before cuts. This has been studied for a benchmark scenario with $|Y_\nu| = 1$ and heavy neutrinos in the range 2.4–8.6 TeV. The results means that this observable has a great potential that needs to be checked in a detailed sensitivity analysis. In the context of the FCC-ee, a similar observable could be chosen to test the effects of heavy neutral leptons in the same mass range, albeit at the one-loop level, namely the production cross-section $\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZH})$.

1.3 Conclusions

This contribution has presented the current status of the triple Higgs coupling measurements at the LHC and the prospects for future lepton colliders. As combined studies in an EFT framework using precision measurements in single Higgs observables, as well as direct Higgs pair production, have shown, lepton colliders are able to completely remove the degeneracy in the measurement of the triple Higgs coupling beyond the 4σ level, and the combination of data collected at a centre-of-mass energy of 250 GeV with data collected at energies of at least 350 GeV is of crucial importance for very-high-precision measurements in single Higgs

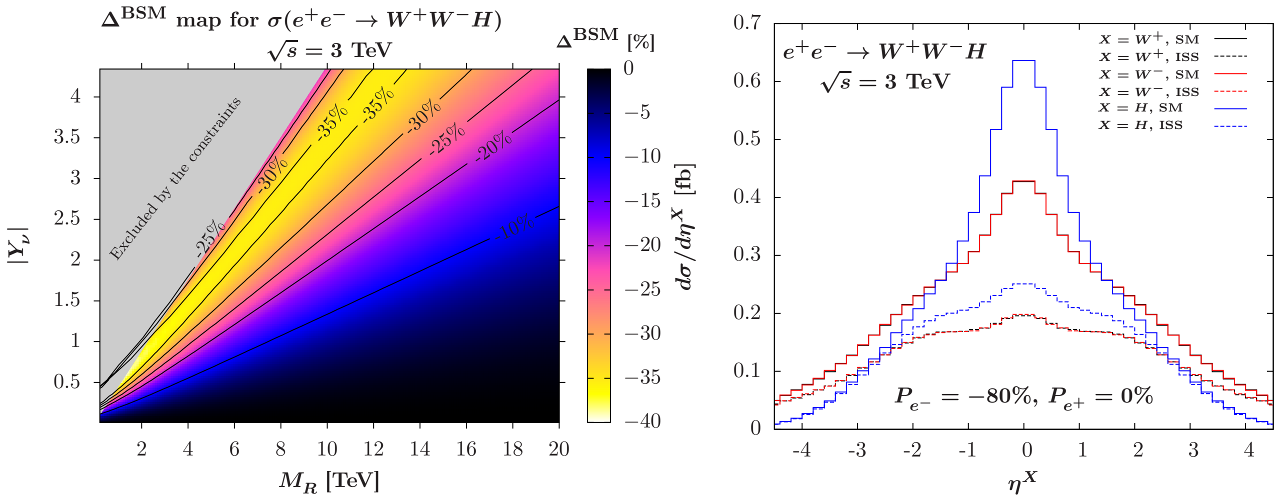

Fig. E.1.7: Left: Contour map of the neutrino corrections $\Delta^{\rm BSM}$ at the 3 TeV CLIC, using a -80% polarised electron beam, as a function of the see-saw scale M_R and $|Y_\nu|$. Right: Pseudo-rapidity distributions of the W^+ (black), W^- (red), and Higgs (blue) bosons. The solid curves stand for the SM predictions while the dashed curves stand for the ISS predictions, for the benchmark scenario described in the text. Figures taken from Ref. [33].

physics. Opportunities offered by the Higgs sector to test neutrino mass models at future lepton colliders have also been presented. The FCC-ee is very competitive to test the heavy sterile neutrino option in the gigaelectronvolt regime. As far as the teraelectronvolt regime for the heavy neutrino scale is concerned, studies reported in the literature have shown that the CLIC and ILC at high energies could offer new avenues in the Higgs sector via precision measurements of the triple Higgs coupling, as well as of the production cross-section of a pair of W bosons in association with a Higgs boson. In the same spirit, the FCC-ee may well offer new opportunities in the same mass regime via precision calculations at one and two loops for the ZH production cross-section, which remain to be studied.

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