Searching for heavy neutrinos with WWH production

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Extensions of the Standard Model are required to give mass to the light neutrinos and explain neutrino oscillations. 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 production of the Higgs bosons in association with a pair of W bosons at future lepton colliders. Working in the inverse seesaw model and taking into account all possible experimental constraints, we find that sizable deviations, as large as 66% are possible. This makes the $W^+W^-H$ production cross-section a new, promising observable to constrain neutrino mass models. The effects are generic and expected to be present in other low-scale seesaw models.

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1 Introduction

The observation of neutrino oscillations implies that at least two neutrinos have a non-zero mass and that neutral lepton flavor is not conserved \cite{1}, thus requiring an extension of the Standard Model (SM). Among the many ideas put forward to generate the neutrino masses and mixing, one of the simplest is the addition of right-handed neutrinos, which are fermionic gauge singlets. Including all renormalizable terms allowed by the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ then naturally leads to the type I seesaw \cite{2,3,4,5,6,7}. However in this model, the size of light neutrino masses and the size of the new, heavy neutrinos couplings to SM particles essentially depends on the same parameter, suppressing them both and thus making hard to probe experimentally this model. An appealing alternative is to consider low-scale seesaw models, such as the inverse seesaw model \cite{9,10,11}, where a nearly conserved symmetry is introduced. This symmetry, which has to be lepton number \cite{12,13}, allows large couplings between heavy neutrinos and SM particles, which leads to a rich phenomenology. In this talk, we discuss how the Higgs sector can be used to probe these neutrino mass models, focusing on $W^+W^-H$ production at lepton colliders. While we present the results of a study in the inverse seesaw (ISS), we expect our results to hold for other low-scale seesaw models. The full details of this work can be found in the original study \cite{14}.

2 The inverse seesaw model: description and constraints

In the realization of the inverse seesaw that we consider, each generation is supplemented with a pair of right-handed gauge singlets, $\nu_R$ and $X$, with opposite lepton number. The additional mass terms to the SM Lagrangian are given by

$$L_{\text{ISS}} = -Y_\nu^i j \overline{\nu}_Li \tilde{\Phi} \nu_Rj - \frac{1}{2} \mu_{X} X_i^C X_j + \text{h.c.},$$

(1)

with $\Phi$ the SM Higgs field and $\tilde{\Phi} = i\sigma_2 \Phi^*$, $i,j = 1 \ldots 3$, $Y_\nu$ and $M_R$ complex matrices and $\mu_X$ a complex symmetric matrix. All terms are lepton number conserving, with the exception of the naturally small $\mu_X$ to which the light neutrino masses are proportional. Indeed for one generation and in the seesaw limit $\mu_X \ll m_D, M_R$, the neutrino mass matrix admits as singular values

$$m_\nu \simeq \frac{m_D^2}{m_D^2 + M_R^2} \mu_X,$$

(2)

$$m_{N_1, N_2} \simeq \sqrt{M_R^2 + m_D^2} \pm \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)},$$

(3)

where $m_D = Y_\nu \langle \Phi \rangle$. This corresponds to one light neutrino and two heavy, nearly degenerate heavy neutrinos with opposite CP parities forming a pseudo-Dirac pair. The smallness of $\mu_X$ allows to suppress the light neutrino mass while keeping the mixing between active and sterile neutrinos (that is proportional to $m_D M_R^{-1}$) large. As a consequence, it is possible to have large Yukawa couplings even when the seesaw scale is close to the electroweak scale.

Since a major motivation of these models is to explain neutrino oscillations, we reproduce data from the global fit NuFIT 3.0 \cite{15} by using the $\mu_X$-parametrization with next-order terms in the seesaw expansion that are relevant for large active-sterile mixing \cite{16}:

$$\mu_X \simeq \left( 1 - \frac{1}{2} M_R^{-1} m_D^T m_D M_R^{-1} \right)^{-1} M_R^{-1} m_D^T U_{\text{PMNS}}^* m_U U_{\text{PMNS}} m_D^T m_D^{-1} M_R^{-1},$$

(4)

Here, $m_\nu$ is the diagonal light neutrino mass matrix and $U_{\text{PMNS}}$ is the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) \cite{17,18}. This parametrization uses $Y_\nu$ and $M_R$ as input parameters.
will consider a scenario where both of them are diagonal, suppressing the rates of lepton-flavor-violating processes. Similarly constraints from the electron electric dipole moment measurements are avoided by choosing all mass matrices and couplings in the lepton sector to be real. As a consequence, the strongest experimental constraints come from a global fit \cite{19} to electroweak precision observables, tests of CKM unitarity and tests of lepton universality. Additionally, we require that the Yukawa couplings $Y_\nu$ remain perturbative, namely

$$\frac{|Y_{ij}|^2}{4\pi} < 1.5.$$ \hfill (5)

### 3 Heavy neutrinos and $W^+W^-H$ production at lepton colliders

With large neutrino Yukawa couplings and heavy neutrinos whose mass is close to the electroweak scale, the Higgs sector appears as a prime candidate to look for the imprint of the new particles present in the inverse seesaw model. Off-diagonal couplings could give rise to striking lepton-flavor-violating Higgs decays \cite{20} for example. If we restrict ourselves to seesaw scales above the Higgs mass, heavy neutrinos can also induce large deviations in the Higgs trilinear coupling \cite{16,21}. These can be as large as 10% at an energy scale of 500 GeV, which would be within reach of future lepton colliders such as the International Linear Collider at 1 TeV or CLIC 1.5 GeV, and even reach 30% at an energy scale of 2.5 TeV, which would be testable at collider energies of 3 TeV and above. It is in particular worth noting that these deviations are maximal for diagonal neutrino Yukawa coupling and heavy neutrinos of masses around 10 TeV, thus providing a new observable to test a regime very difficult to probe otherwise.

Inspired by the observation that $t$--channel fermions coupled to a Higgs boson can give sizable contributions to a cross-section, as is the case of $b\bar{b} \to W^+W^-H$ at the LHC for example \cite{22}, we turned our attention to the impact of heavy neutrinos on the production of a Higgs boson in association with a pair of $W$ bosons at a lepton collider, $e^+e^- \to W^+W^-H$. Sensitivity studies in the SM reported good detection prospects \cite{23}. In the ISS, the additional contributions due to the $t$--channel exchange of massive neutrinos, with respect to SM contributions, are given by the diagrams of fig. 1. Details of the calculation as well as values for the SM and neutrino inputs can be found in our original study \cite{14}.

In the fig. 2 (left), we present our numerical results for a benchmark scenario with $Y_\nu = 1$ and a hierarchical heavy neutrino spectrum where the masses of the pseudo-Dirac pairs are respectively 2.4 TeV, 3.6 TeV (this is the pseudo-Dirac pair that couples to the electron) and 8.6 TeV. We present results up to center-of-mass energies of 30 TeV. Since the process is very sensitive to the chirality of the incoming electron and positron, favoring left-handed electrons and right-handed positrons, we compare the polarized and unpolarized cross-sections, choosing the Compact Linear Collider (CLIC) baseline \cite{25}. It has an unpolarized positron beam, $P_{e^+} = 0$, and a polarized electron beam with $P_{e^-} = -80\%$. First, we observe that the polarized cross-section is nearly twice the unpolarized one, demonstrating the dependence on the electron chirality mentioned above. Second, we can see below 4 TeV that the presence of additional, heavy neutrinos reduces the cross-section. This is due to a
destructive interference between the $s$-channel and $t$-channel diagrams which is already present in the SM and is exacerbated in the ISS. In this regime, the deviation is maximal close 3 TeV and reaches $-38\%$. Third, if we keep increasing the center-of-mass energy, the intermediate heavy neutrino gets closer and closer to being on-shell, leading the heavy neutrino diagrams to dominate the amplitude and to a subsequent increase and large enhancement of the cross-section. This regime could typically be probed at very-high-energy lepton colliders based on different accelerator technologies, using muon beams like LEMMA [26] or high gradient acceleration concepts such as ALIC [27].

Fig. 2 (right) shows a contour map of the deviation of the ISS cross-section with respect to that of the SM, $\Delta_{\text{BSM}} = (\sigma_{\text{ISS}} - \sigma_{\text{SM}})/\sigma_{\text{SM}}$, as a function of the seesaw scale $M_R$ and of the neutrino Yukawa coupling $|Y_\nu|$, at the 3 TeV CLIC with a $-80\%$ polarized electron beam. We are working with a hierarchical spectrum for the heavy neutrinos that preserves the ratios used for the benchmark of fig. 2 (left), $M_{R_1} = 1.51 M_R$, $M_{R_2} = 3.59 M_R$ and $M_{R_3} = M_R$. The gray area excluded by the constraints mostly originates from the global fit [19]. The largest deviation in the ISS reaches $-38\%$ for $|Y_\nu| \sim 1$ and a seesaw scale of a few TeV. These results can be approximated within $1\%$ for $M_R > 3$ TeV by using the formula

$$A_{\text{approx}}^{\text{ISS}} = \frac{(1 \text{ TeV})^2}{M_R^2} \text{Tr}(Y_\nu Y_\nu^\dagger) \left( 17.07 - \frac{19.79 \text{ TeV}^2}{M_R^2} \right),$$

$$\Delta_{\text{BSM}} = \frac{A_{\text{approx}}^{\text{ISS}}}{A_{\text{approx}}^{\text{SM}}} - 11.94 A_{\text{approx}}^{\text{ISS}}.$$  \hfill (6)

We can see here that the process $e^+ e^- \rightarrow W^+ W^- H$ exhibits sizable deviations of at least $-20\%$ for a large fraction of the parameter space. It is worth comparing this result to the one we obtained for the trilinear Higgs coupling in [16]. When doing so, it is possible to see that sizable deviations can be obtained for $W^+ W^- H$ production in a much larger part of the parameter space than for the trilinear Higgs coupling.

Fig. 3 presents the kinematic distribution in pseudo-rapidity and energy of the $W$ and Higgs bosons at a center-of-mass energy of 3 TeV. We can clearly see that the shape of the SM and ISS distributions are easily distinguishable, with a noticeable difference in the central region and for boosted Higgs bosons. As a consequence, the deviation $\Delta_{\text{BSM}}$ can be enhanced with a simple choice of cuts. It was
found that choosing $|\eta_{H/W\pm}| < 1$ and $E_H > 1$ TeV pushes the corrections down to $-66\%$ without decreasing the cross-section by more than an order of magnitude. Indeed the ISS cross-section after cuts was found to be $0.14$ fb, which has to be compared to $1.23$ fb before cuts.

4 Conclusion

Low-scale seesaw models provide appealing extensions of the SM that can generate neutrino masses and mixing and which are potentially testable at the colliders and in low-energy experiments. Having new particles with a mass close to the Higgs mass and large Yukawa coupling, the can naturally leave a wide imprint on the Higgs sector. We have presented here the results of our study\cite{14} where we considered the effect of heavy neutrinos in the inverse seesaw on the production cross-section of $\ell^+\ell^- \to W^+W^-H$. We found that at tree-level corrections as large as $-38\%$ to the total cross-section can be obtained at CLIC, which can be enhanced to $-66\%$ after applying very basic cuts. Besides the deviations are found to be sizable in a significant fraction of the parameter and we expect our results to hold for other low-scale seesaw models. This makes this process a new probe of neutrino mass model, allowing to test regimes with diagonal and real Yukawa couplings which are difficult to access otherwise. This is highly complementary to other existing probes such as lepton-flavor-violating processes in the $O(10)$ TeV range.

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