High-energy colliders as a probe of neutrino properties

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The mediators of neutrino mass generation can provide a probe of neutrino properties at the next round of high-energy hadron (FCC-hh) and lepton colliders (FCC-ee/ILC/CEPC/CLIC). We show how the decays of the Higgs triplet scalars mediating the simplest seesaw mechanism can shed light on the neutrino mass scale and mass-ordering, as well as the atmospheric octant. Four-lepton signatures at the high-energy frontier may provide the discovery-site for charged lepton flavour non-conservation in nature, rather than low-energy intensity frontier experiments.

I. INTRODUCTION

Solar and atmospheric neutrino studies provided the discovery site for neutrino oscillations [1, 2]. These experiments were followed by reactor [3] and accelerator-based [4] studies that have confirmed the oscillation phenomenon and also substantially improved parameter determination. The discovery of neutrino oscillations has brought neutrino physics to the center of particle physics, giving the first clear evidence for new physics. Their existence also suggests the possibility of charged lepton flavour violating effects including rare processes, such as $\mu \to e\gamma$ decays [5].

Although current neutrino data are well-described by the three-neutrino paradigm, there are still loose ends to sort out, such as the neutrino mass-ordering, the atmospheric octant and the precise value of the CP phase [6, 7]. Back in the LEP days it was suggested that the mediators of neutrino mass generation could be produced at collider experiments [8] in such a way that high-energy studies could be used to probe neutrino oscillation parameters, such as the atmospheric angle. This is a characteristic feature, e.g., of models where supersymmetry is the origin of neutrino mass [9–12], which allow for such independent probes of neutrino mixing [13–15].

In this letter we propose the use of high-energy frontier hadron (FCC-hh [16]) and lepton colliders (FCC-ee/ILC/CEPC/CLIC), as an independent probe of neutrino properties, capable of shedding light on the neutrino mass scale and the neutrino mass-ordering through the rates for four lepton final-state events, as well as the atmospheric octant can be probed through the triplet Higgs decay pattern. Moreover, such high-energy experiments can also provide the first evidence for charged lepton flavour violation in nature.

II. ORIGIN OF NEUTRINO MASS

Despite efforts to underpin the ultimate mechanism responsible for neutrino mass generation, the challenge remains wide open. An attractive possibility is provided by the seesaw mechanism. Its most general formulation employs the Standard Model (SM) picture, i.e. the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge group [21, 22]. This leads to small active neutrino masses induced through
the exchange of heavy lepton or scalar mediators. The simplest seesaw mechanism is the type II seesaw with explicit breaking of lepton number, where neutrino masses are mediated by a triplet scalar,

\[ \Delta = \frac{1}{\sqrt{2}} \left( v_\Delta + \frac{\Delta^+}{\sqrt{\Delta^{++}}} \right), \]

so that only one complex symmetric Yukawa matrix \( Y_{\Delta \alpha \beta} \) describes the full flavour structure of the lepton sector [21, 22] through the Yukawa Lagrangian term

\[ \mathcal{L}_{\text{type II}} = [vY_{\Delta \alpha \beta} \bar{L}_\alpha C^{-1} t_2 \Delta L_\beta + \text{h.c.}] \]

where \( L_\alpha \) are the lepton doublets, \( C \) is the charge conjugation operator. The scalar potential \( V(\Phi, \Delta) \) is given as,

\[ V(\Phi, \Delta) = -m_\Phi^2 c^4 + \frac{\lambda}{4} \Phi^2 (\Phi^4) + \tilde{M}_\Delta^2 \text{Tr} [\Delta^4] \]

\[ + \lambda_2 [\text{Tr} \Delta^4]^2 + \lambda_3 [\Delta^4]^2 + [\mu \Phi^T (i\sigma_2 \Delta)^4 \Phi + \text{h.c.}] \]

\[ + \lambda_1 (\Phi^4) \text{Tr} [\Delta^4] + \lambda_4 \Phi^4 \Delta^4 \Phi. \]

where \( \Phi \) is the SM Higgs doublet. Its minimization generates a non-zero vacuum expectation value (VEV) for the neutral component of the triplet. Within the simplest approximation (\( \tilde{M}_\Delta \gg v_\Phi \)) the small induced triplet VEV \( v_\Delta \) is given as

\[ v_\Delta \approx \frac{\mu v_\Phi^2}{\sqrt{2} M_\Delta^2}. \]

where \( v_\Phi \) is the SM Higgs VEV. Eq. (4) shows how the smallness of \( v_\Delta \) requires either by a small \( \mu \), or a large value for \( \tilde{M}_\Delta \) characterizing the triplet scalar mass [23]. Note that in a more complete setup the parameter \( \mu \) can be given a full dynamical interpretation [22, 24]. Following t’Hooft’s naturalness argument, the small \( \mu \) parameter sources lepton number violation, so that in the limit \( \mu \to 0 \), lepton number symmetry is recovered. After electroweak symmetry breaking one obtains small neutrino masses

\[ m_{\nu_{\alpha \beta}}^0 = (Y_\Delta)_{\alpha \beta} \frac{v_\Delta}{\sqrt{2}} \]

For the simplest CP-conserving case the neutrino oscillation parameters will be determined by six elements of the real symmetric Yukawa matrix \( Y_{\Delta \alpha \beta} \). Four of these are well measured [6, 7], the remaining ones being the absolute neutrino mass and the atmospheric octant.

There are seven physical Higgs fields with definite masses namely, a doubly-charged (\( H^{\pm \pm} \)) and a singly-charged (\( H^{\pm} \)) scalar boson, plus two massive CP-even (\( h, H \)) and one massive CP-odd Higgs (\( A \)). The new scalars present in such simplest seesaw scheme may hold the key to electroweak vacuum stability and perturbative unitarity [24, 25]. The associated theoretical consistency restrictions, as well as the constraints from electroweak precision data and other experiments are discussed extensively in [23].

III. SIMPLEST SEESEAW AT COLLIDERS

There have been several experimental searches for signatures associated to the doubly-charged Higgs at high energy colliders [26–28]. Theoretical aspects of the type-II seesaw and triplet scalar models at different colliders have been discussed in [29–35] and reviewed in [36]. Depending on the magnitude of the triplet VEV \( v_\Delta \), the doubly-charged Higgs mainly decays to same-sign dileptons (\( v_\Delta \lesssim 10^{-4} \) GeV) or gauge bosons (\( v_\Delta > 10^{-4} \) GeV). Studying these leptonic or gauge boson decay modes at the LHC, one can constrain doubly charged Higgs properties. For small triplet VEV \( v_\Delta \lesssim 10^{-4} \) GeV, one obtains \( m_{H^{\pm \pm}} > 870 \) GeV [26, 27], whereas for \( v_\Delta > 10^{-4} \) GeV, the constraint is rather loose, \( m_{H^{\pm \pm}} > 220 \) GeV [28].

A key feature of the simplest seesaw mechanism is the presence of a doubly charged Higgs scalar \( H^{\pm \pm} \) which can be produced via the Drell-Yan process \( pp, e^+e^- \to \gamma^*/Z^* \to H^{\pm \pm}H^{\mp \mp} \), see Fig. 1. In Fig 2, we show this cross section at the proposed FCC-hh (\( \sqrt{s} = 100 \) TeV) pp-collider and a \( \sqrt{s} = 3 \) TeV \( e^+e^- \) ILC/CEPC/CLIC/FCC-ee collider. One sees that multi-TeV Higgs masses can be explored at such large center-of-mass energies and that for \( m_{H^{\pm \pm}} \sim 1 \) TeV, the production cross section is similar both for the 100 TeV pp and 3 TeV \( e^+e^- \) colliders. We will choose \( m_{H^{\pm \pm}} = 1 \) TeV as the benchmark for our study.

Once produced, the neutrino mass mediator \( H^{\pm \pm} \) can decay to two same-sign charged leptons (\( l^+l^\pm \)). The \( H^{\pm \pm} \) decay branching ratio to charged leptons depends on the
Yukawa coupling $Y_{\Delta\alpha\beta}$ and hence on the triplet VEV $v_\Delta$. For $v_\Delta < 10^{-4} \text{ GeV}$, $H^{\pm\pm} \to l^\pm l^\pm$ is the dominant decay mode. The flavor structure of $Y_{\Delta\alpha\beta}$ is of crucial importance here, as it determines both the neutrino properties as well as the branching ratio of $H^{\pm\pm}$ to charged leptons of different flavors at colliders.

The doubly-charged Higgs boson decays to leptonic final states are determined by the Yukawa coupling $Y_{\Delta}$. The decay widths are given by

$$\Gamma(H^{\pm\pm} \to l^i_{\pm} l^j_{\pm}) = \frac{m_{H^{\pm\pm}}}{(1 + \delta_{ij})16\pi} |Y_{\Delta}^i|^2,$$

with $Y_{\Delta} = \frac{\sqrt{2}}{v_\Delta} U \text{diag} \{m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\} U^T$, where $U$ is the lepton mixing matrix measured in oscillation experiments. The patterns of various leptonic channels will follow the profile of $Y_{\Delta}^i$. Current measurements of neutrino oscillation parameters [6, 7] restrict the diagonal and off-diagonal entries of the Yukawa coupling matrix $Y_{\Delta}$. Depending on the ordering of the light-neutrino mass spectrum we obtain the following decay branching ratio patterns:

- $\text{BR}(H^{++} \to \mu\mu) \gg \text{BR}(H^{++} \to e\mu) \text{ NO}$
- $\text{BR}(H^{++} \to e\mu) \gg \text{BR}(H^{++} \to \mu\mu) \text{ IO}$
- $\text{BR}(H^{++} \to \tau\tau) \gg \text{BR}(H^{++} \to e\tau)$

suggesting that, depending on the ordering of the light neutrino masses, $H^{++}$ can mainly decay to $\mu\mu$, $\tau\tau$ (for NO) or $e\mu$ (IO). Hence, it may be possible to probe the neutrino mass ordering normal ordering (NO) or inverted ordering (IO) just by looking into the decays of $H^{++}$ to same-flavour leptonic final states. In Fig. 3, we show the leptonic branching ratios (only those which are appreciable) both for NO (top panel) and IO (bottom panel).
The results are shown with respect to the $3\sigma$ allowed range of the “atmospheric” mixing angle $\theta_{23}$. Here the triplet vev is chosen as $v_\Delta \leq 10^{-4}$ GeV, $\delta_{CP}$ is varied in the range $[-\pi : \pi]$, and other oscillation parameters are fixed to their best fit values [6, 7]. The vertical line in each panel denotes $\theta_{23} = 45^\circ$. One sees that for NO, electron final-states are penalized with respect to those into muons and taus i.e. one can have sizeable branching ratios for $\mu\mu$ and $\mu\tau$ final states. One the other hand, for IO, $ee$ final states are dominant.

We now turn to the full 4-lepton signal cross-sections, starting from the lepton-flavour conserving ones. For large triplet VEV $v_\Delta > 10^{-4}$ GeV, the Yukawa coupling is small and $H^{\pm\pm}$ decays predominantly to $W^\pm W^\pm$. However, for small $v_\Delta$, the Yukawa coupling is large and $H^{\pm\pm}$ decays predominantly to dileptons, hence the four-lepton cross section can be experimentally detectable. In Fig. 4 we illustrate the correlation between $\sigma(e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to eee/\mu\mu\mu\mu)$ and the lightest neutrino mass both for NO and IO spectra. One sees that the tetramuon cross section is always larger in the case of NO, while the cross section into tetra-electron final states is always larger in the case of IO. Note that the difference becomes larger as the lightest neutrino mass gets smaller. This provides a way to probe the neutrino mass-ordering through the four-lepton final states coming from doubly-charged Higgs $H^{\pm\pm}H^{\mp\mp}$ pair-production.

**IV. LEPTON FLAVOUR VIOLATION**

The oscillation discovery has brought neutrino physics to the center of particle physics, giving the first clear evidence for new physics namely, lepton flavour non-conservation in neutrino propagation. This suggests also the possibility of charged lepton flavour violating effects including rare decays such as $\mu \to e\gamma$, so far never observed [5]. It is straightforward to determine the corresponding expressions for the $\mu \to e\gamma$ branching ratio [37, 38]:

$$\text{BR}(\mu \to e\gamma) \approx \frac{\alpha}{192\pi} \left|\langle Y_\Delta^c \rangle_{ee}\right|^2 \frac{1}{G_F^2} \frac{8}{m_{H^+_\Delta}^2 + m_{H^{++}}^2}.$$

In Fig. 5 we display some $\sigma(e^+e^- \to e\gamma)$ contours in the $m_{H^{\pm\pm}} - v_\Delta$ plane, obtained for normal ordered light neutrino spectrum and best-fit values for the neutrino oscillation parameters. One sees that the $\mu \to e\gamma$ branching ratio can easily exceed current sensitivities [5] for small values of the triplet VEV $v_\Delta$.

The idea that charged lepton flavour (and CP) violation could be first seen at high energies was first put forward in [39, 40] and revived in [41]. Here we demonstrate that the type II seesaw provides the simplest realization of this idea.
Figure 5. Contour of $\text{BR}(\mu \to e\gamma)$ in the $m_{H^\pm\mp} - v_\Delta$ plane. The oscillation parameters are fixed to their best fit values.

Indeed we see that, from Fig. 3, both for NO and IO one has quite large $\mu\tau$ branching fractions for $H^{++}$, similar to those for same-flavour ($\mu\mu$) final state. On the other hand, the branching ratio to the $e\mu$, $e\tau$ final states can exceed $O(10^{-2})$.

That charged lepton flavour violation may be first observed as a high-energy phenomenon can be seen neatly from Fig. 6. In the top panel we display $\sigma(e^+e^- \to H^{\pm\pm}H^{\mp\mp} \to eee\mu)$ versus $\text{BR}(\mu \to e\gamma)$ both for NO and IO with lightest neutrino mass $m_{\nu_1(3)} = 0$. One sees that the four-lepton signature cross-section can be sizeable, even when the low-energy $\text{BR}(\mu \to e\gamma)$ decay branching ratio lies well below detectability. As before, for small $v_\Delta$, the Yukawa coupling is large and $H^{\pm\pm}$ decays predominantly to dileptons, hence cLFV can be sizeable. In the top panel, one sees that the cross section to $eee\mu$ final states is larger in the case of IO, compared to NO and the difference becomes larger with a smaller mass of the lightest neutrino.

Similarly, in the bottom panel of Fig. 6 we show the charged lepton flavour violating 4-lepton cross section $\sigma(e^+e^- \to H^{\pm\mp}H^{\mp\pm} \to \mu^+\mu^-\mu^\mp\tau^\mp)$ in terms of $\text{BR}(\tau \to \mu\gamma)$. We again sees that the flavour-violating four-lepton final state cross-section can be sizeable even for tiny values of $\text{BR}(\tau \to \mu\gamma)$.

Notice that in Fig. 4 we have scanned over the full $3\sigma$ range of the oscillation parameters and found that the cross sections distinguish the mass orderings for most neutrino mass values. Likewise, in Fig. 6 the predicted ranges differ, except for tiny cLFV branching fractions.

Figure 6. Complementary cLFV probes: four-lepton cross-sections versus rare decay branching fractions $\text{BR}(\mu \to e\gamma)$ and $\text{BR}(\tau \to \mu\gamma)$. Red bands correspond to IO, while blue denote NO. The lightest neutrino mass is taken to be zero. Oscillation parameters are varied within their $3\sigma$ ranges [6, 7]. The doubly-charged Higgs mass is $m_{H^{\pm\pm}} = 1$ TeV and the triplet VEV lies in the range $10^{-7} \leq v_\Delta \leq 10^{-3}$ GeV. The gray bands are excluded by the MEG [5] (top panel) and BaBar limits [42] (bottom panel).

V. SUMMARY AND OUTLOOK

In the simplest seesaw mechanism one can probe neutrino oscillation physics at collider energies through the pattern of triplet Higgs boson decays. These can probe not only the lightest neutrino mass and the ordering of the neutrino masses, but also the flavour structure of the neutrino sector, paving the way to the reconstruction of neutrino oscillation parameters at collider experiments.
For example, Fig. 3 illustrates how the decay pattern of the triplet Higgs that mediates neutrino mass generation may probe the octant of the atmospheric mixing angle. This can be tested at a high energy hadron colliders such as the FCC, as well as future \( e^+e^- \) colliders such as ILC, CLIC or CEPC in China.

Likewise, Fig. 4 shows how the rates for four-lepton final-state events coming from pair-producing the doubly-charged Higgs may be used as a probe of the light neutrino mass ordering, illustrating how high-energy signatures clearly complement neutrino oscillation studies.

Last, but not least, Fig. 6 clearly suggests that charged lepton flavour violation could be observed first as a high-energy phenomenon, since the corresponding signal cross section can be sizeable even when low-energy rare processes, such as \( \mu \to e\gamma \), have negligible rates. In short, high-energy probes clearly complement low-energy searches for charged lepton flavour violation at high-intensity facilities.

The results found here illustrate the complementarity and interplay of the high-energy and high-intensity frontiers in particle physics, providing encouragement for dedicated simulation studies to evaluate the potential of these proposed facilities in probing the neutrino sector.

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