Direct determination of neutrino mass parameters at future colliders

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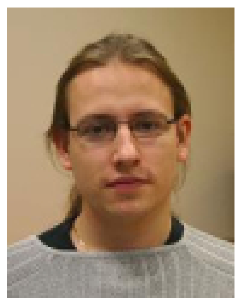

If the observed light neutrino masses are induced by their Yukawa couplings to singlet right-handed neutrinos, natural smallness of those renders direct collider tests of the electroweak scale neutrino mass mechanisms almost impossible both in the case of Dirac and Majorana (seesaw of type I) neutrinos. However, in the triplet Higgs seesaw scenario the smallness of light neutrino masses may come from the smallness of $B-L$ breaking parameters, allowing sizable Yukawa couplings even for a TeV scale triplet. We show that, in this scenario, measuring the branching fractions of doubly charged Higgs to different same-charged lepton flavours at LHC and/or ILC experiments will allow one to measure the neutrino mass parameters, which neutrino oscillation experiments are insensitive to, including the neutrino mass hierarchy, lightest neutrino mass and Majorana phases.

1 Introduction

Neutrino oscillation experiments have shown convincingly that at least two light neutrinos have non-zero masses and their mixing is characterized by two large mixing angles: θ_{12} and θ_{23}. Those facts are clear evidence of physics beyond the Standard Model [1]. However, despite intense experimental and theoretical efforts, the origin of neutrino masses is not yet understood. Also, our knowledge about neutrino masses and mixing angles is still quite limited – in particular current neutrino oscillation experiments are not sensitive to: Dirac or Majorana nature of light neutrinos, absolute values of neutrino masses and possible CP-violating Majorana phases.

One of the best motivated and best studied neutrino mass scenario is the triplet Higgs mechanism. [2,3,4,5,6] The $SU(2)_L$ triplet multiplet contains a doubly charged scalar that can be pair produced at colliders independently of their Yukawa couplings. Thus tests of this mechanism are limited only by the collision energy. The smallness of neutrino masses does not imply the smallness of triplet Yukawa couplings. As neutrino masses in this scenario are necessarily of Majorana type, they may be different from the Dirac fermion masses because of the smallness of $B-L$ breaking. This is natural by the 't Hooft criterion as $B-L$ is a conserved quantum number in the SM. Thus the neutrino Yukawa couplings to triplet may be sizable, constrained by unobserved lepton flavour violating interactions, and dominate over the triplet coupling to two gauge bosons. The triplet Yukawa couplings directly induce the neutrino mass matrix up to the small $B-L$ breaking triplet vacuum expectation value (VEV) which appears in neutrino masses as a common proportionality factor. Altogether those arguments imply that one can study the neutrino mass parameters at Large Hadron Collides (LHC) by just counting flavours of the same-charged lepton pairs originating from the doubly charged Higgs boson decays.

2 Phenomenological setup

In see-saw II model the SM particle spectrum is extended by a scalar multiplet Φ with the $SU(2)_L \times U(1)_Y$ quantum numbers $\Phi \sim (3,2)$. We also assume that its mass is below $\mathcal{O}(1)$ TeV and the pair production processes at colliders,

$$pp \to \Phi^{++}\Phi^{--} \quad \text{and} \quad e^+e^- \to \Phi^{++}\Phi^{--}, \tag{1}$$

are kinematically allowed. Such a scenario is realized, for example, in the little Higgs models [7,8,9,10].

The triplet couples to leptons via the Lagrangian

$$L = i\bar{\ell}^c_{Li}\tau_2 Y^{ij}_\Phi(\tau\cdot\Phi)\ell_{Lj} + h.c., \tag{2}$$

where $(Y_\Phi)_{ij}$ are the Majorana Yukawa couplings of the triplet to the lepton generations $i,j = e,\mu,\tau$. If the neutral component of triplet acquires a VEV v_Φ, the non-zero neutrino mass matrix is generated via

$$(m_\nu)_{ij} = 2(Y_\Phi)_{ij}v_\Phi. \tag{3}$$

The smallness of neutrino masses is explained by be smallness of v_Φ and the Yukawa couplings $(Y_\Phi)_{ij}$ can be of order SM Yukawa couplings. However, the precise values of $(Y_\Phi)_{ij}$ are not relevant for the collider physics we consider in this work. The relationship between neutrino parameters and doubly charged Higgs boson decays comes from the fact that the Yukawa coupling matrix of doubly charged Higgs to leptons is proportional to the Majorana mass matrix. Thus, to establish this connection experimentally, observable rates of the leptonic branching fractions must exist.

Starting from Eq. 3, we an find a direct relationship between the neutrino mixing matrix and a single leptonic decay channel:

$$\mathrm{Br}_{ij} = \begin{cases} \frac{|(m_\nu)_{ij}|^2}{\sum_{i\geq j}|(m_\nu)_{ij}|^2} & i=j, \\ \\ \frac{2|(m_\nu)_{ij}|^2}{\sum_{i\geq j}|(m_\nu)_{ij}|^2} & i\neq j, \end{cases} \tag{4}$$

where $(m_\nu)_{ij}$ is the neutrino mass matrix in flavor basis. The mass matrix contains six independent mixing parameters: three mixing angles (θ_{13}, θ_{23} and θ_{12}) and three phases (α_1, α_2 and δ), and three light neutrino masses. We expect all possible combinations of four leptons to occur in the final state.

3 Measuring the neutrino parameters

Doubly charged Higgs boson has 6 different leptonic decay channels. Branching ratios to these channels are directly related to $(m_\nu)_{ij}$. We can write an equation system that relates branching ratios of six different $\Phi^{\pm\pm}$ leptonic decay channels with unknown neutrino parameters,

$$\mathrm{BR}_{ij} = f_k(m, \mathrm{sgn}(\Delta m_{23}), \theta_{13}, \theta_{23}, \theta_{12}, \delta, \alpha_1, \alpha_2), \tag{5}$$

where m represents the mass of the lowest neutrino mass eigenstate (m_1 or m_3 for normal or inverted mass spectrum, respectively), $\mathrm{sgn}(\Delta m_{23})$ is the sign of the atmospheric mass splitting, that determines the neutrino mass hierarchy, $k = 1, ..., 6$ and $i, j = e, \mu, \tau$.

Now we fix the values of mixing angles to their tri-bimaximal values and concentrate on determining Majorana phases and absolute values of neutrino masses. The equation system can be solved analytically.

4 Results

4.1 Determination of mass hierarchy

Analytically a simple parameter C_1 can be found to uniquely determine the mass hierarchy:

$$C_1 \equiv \frac{2\mathrm{BR}_{\mu\mu} + \mathrm{BR}_{\mu\tau} - \mathrm{BR}_{ee}}{\mathrm{BR}_{ee} + \mathrm{BR}_{e\mu}} \tag{6}$$

- $C_1 > 1$ – normal mass hierarchy,
- $C_1 < 1$ – inverted mass hierarchy,
- $C_1 \approx 1$ – degenerate masses.

Figure 1 presents the dependency of doubly charged Higgs branching ratios on the lightest neutrino mass for the normal and inverted mass hierarchies. We have assumed a real mixing matrix i.e. fixed Majorana phases to zero. The $e\mu$ and $e\tau$ channels have only vanishingly small contributions for $\alpha_1 = \alpha_2 = 0$, but are increased for non-zero values of the Majorana phases. The branching ratio to ee channel is a especially good characteristic for mass hierarchy determination that varies greatly depending on the hierarchy and the neutrino mass. This branching ratio is negligible for the normal mass hierarchy with very small mass while it is the dominant decay channel for the inverted mass hierarchy. If the mass of the lightest state increases, both the normal and inverted hierarchies have almost the same distribution of branching ratios, $\Phi^{\pm\pm}$ decay to ee, $\mu\mu$ and $\tau\tau$ with nearly equal probabilities while the decays to other channels are negligible. This indicates the degenerate masses.

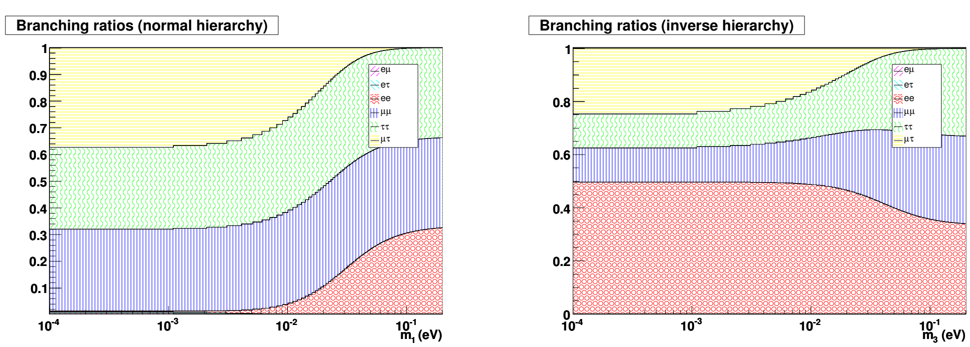

Figure 1: Distribution of the Φ^{++} leptonic branching ratios as a function of the lightest neutrino mass. The left (right) panel corresponds to the normal (inverted) mass hierarchy.

4.2 Majorana phases

Determination of Majorana phases depends on the previously measured neutrino mass values. Both for inverted spectrum or degenerate neutrino masses, Majorana phases strongly influence the decay rates, especially to $e\mu$ and $e\tau$ channels.

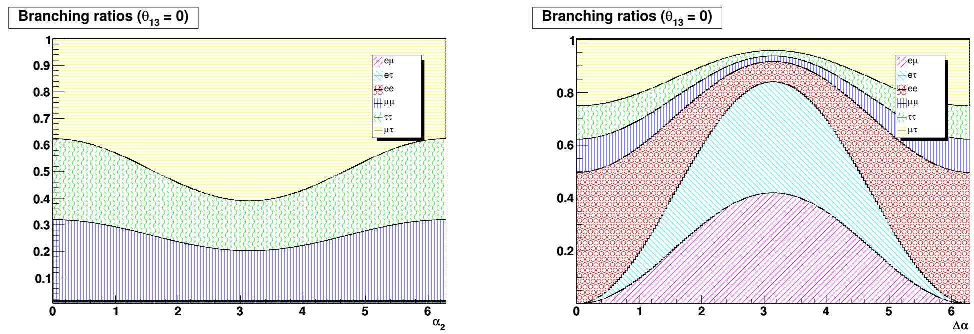

Figure 2: Distribution of the $\Phi^{\pm\pm}$ leptonic branching ratios for normal (left) and inverted hierarchy (right).

4.3 Measuring Higgs triplet VEV

In theory, Higgs triplet VEV can also be determined using the data of $\Phi^{\pm\pm}$ leptonic decays. However, an additional experimental measurement is needed for that, e.g. probing $\Phi^{++} \to W^+W^+$ decays or measuring $|(m_\nu)_{ee}|$ from the $0\nu\beta\beta$ experiments.

5 Conclusions

We have shown that the neutrino mass ordering, the lightest neutrino mass and the Majorana phases can be measured at colliders by just counting the lepton flavours. We emphasize that those are exactly these neutrino parameters which present neutrino oscillation experiments are not sensitive to. Therefore collider tests of neutrino mass mechanism may provide a major breakthrough in neutrino physics. One can actually fully determine the light neutrino mass matrix from collider experiments and/or from the measurement of neutrinoless double beta decay parameters. If the triplet Higgs turns out to be light enough to be produced at colliders, neutrino physics may get an unexpected contribution from collider experiments.

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