TOWARDS NEUTRINO MASS ORIGIN*

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We discuss the possibility of probing the origin of neutrino mass at the LHC. To this end, we focus on processes mediated by the Higgs boson, in particular on its rare decay to a pair of heavy right-handed neutrinos. Probing the mass origin is possible when heavy neutrino mass is protected by an extended gauge symmetry, such as Left–Right symmetry. In this case, the Higgs triplet that provides the heavy neutrino mass mixes with the SM one. We discuss the collider features, relevant backgrounds and a set of selection criteria which enhance the sensitivity, including a cut on the heavy neutrino vertex displacement.

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1. Introduction

The recently discovered [1] scalar particle at the LHC exhibits all the features of a Higgs boson [2]. It agrees with the breaking of the electroweak symmetry and provides mass for charged fermions as uniquely predicted by the Standard Model (SM) [3]. Nevertheless, the origin of neutrino mass remains to be understood. In a recent article [4], we analysed the possibility of probing this origin by observation of rare decays of the SM Higgs boson to a pair of heavy RH neutrinos.

In contrast to charged fermions where only Dirac masses are allowed, neutral particles may produce a Majorana mass term [5]. An important phenomenological consequence then is the breaking of any U(1) symmetry carried by the neutrino, in particular that of lepton number. Searches for

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breaking of this fundamental symmetry started with neutrino-less beta decay [6] and have been going on ever since in meson decays, gauge mediated production of heavy neutrinos (N) at hadron colliders [7] and Higgs decays.

The preferred theoretical setting to provide neutrino mass is arguably the seesaw mechanism [8]. It is here that Majorana mass finds its natural setting and suppresses the light neutrino masses

$$M_\nu = -M_{\rm D}^T M_N^{-1} M_{\rm D} \tag{1}$$

with Dirac couplings similar in size to those of charged fermions. Although conceptually pleasing, this framework complicates the quest to determine the origin of neutrino mass.

For charged fermions, the relation between the decay rate of the SM Higgs and the final state particle's mass is unambiguous, due to a single Dirac–Yukawa coupling. With both Dirac and Majorana terms, this unique relation seemingly breaks down and requires more experimental input to reconstruct (1).

2. Left–Right symmetry

Left–Right (LR) symmetric theories give an understanding of the asymmetric form of weak interactions [9] through restoration of Left–Right parity [10]. The minimal LR symmetric model (LRSM) [11] accommodates seesaw and unambiguously relates Dirac and Majorana couplings within the seesaw formula [12], simplifying the search for neutrino mass origin.

Phenomenologically interesting is the possibility of observing the Majorana nature of N and the associated breaking of lepton number in the Keung–Senjanović (KS) channel [7] at the LHC [13, 14]. Such an observation would allow the measurement of the Majorana mass matrix M_N and predict low energy lepton number [15, 16] and flavour [17] violating processes, such as $0\nu 2\beta$ and *e.g.* $\mu \to e\gamma$. Moreover, the Dirac mass can be computed

$$M_{\rm D} = i M_N \sqrt{M_N^{-1} M_\nu}\,, \tag{2}$$

and tested with sub-dominant decays of N at the LHC, $0\nu 2\beta$ and the electron electric dipole moment [12]. With such observations, one could reconstruct the seesaw mechanism and understand the lightness of left-handed neutrinos.

2.1. Higgs portal to neutrino mass origin

An attractive feature of LR theories, going beyond the seesaw, is the spontaneous origin of N mass. Similar to the charged fermions in the SM, the mass of N is protected by a spontaneously broken gauge symmetry, in this case $\mathrm{SU}(2)_{\rm R} \times \mathrm{U}(1)_{B-L}$. This gauge symmetry is broken by $\Delta_{\rm R}$, a triplet under $SU(2)_R$ with $B - L = 2$. Such assignment allows for a Majorana–Yukawa term for N: $\mathcal{L}_N = \frac{M_N}{v_R} N^T C \Delta_R N + \text{h.c.}$, and provides a dynamical origin for its mass. In order to test this mechanism, one would like to observe the relation between the decay rate of δ, the real part of the neutral component of Δ_R, and the mass of N

$$\Gamma(\delta \to NN) \propto m_N^2 \,. \tag{3}$$

This may not be easy due to the limited production of δ at the LHC.

However, there is another possibility, allowed by the LRSM scalar potential. For more details on spontaneous breaking of parity and the associated indirect bounds from mesonic processes, see [18]. Here, we only recall that after the electroweak breaking is completed, a mixing θ between the SM Higgs (h) and δ will appear. Its size depends on the quartics ρ_1 and α_1 of the LRSM potential and is linearly suppressed with the LR scale v_R

$$\sin\theta \simeq \left(\frac{\alpha_1}{2\rho_1}\right)\left(\frac{v}{v_R}\right) < 0.44 \,, \tag{4}$$

where the latter 95% C.L. constraint results from the uncertainty of the Higgs production [19].

The presence of such mixing allows for the intriguing possibility of h decaying to a pair of N [20]. To estimate the relevant branching ratio, one can normalize to the dominant $b\bar{b}$ decay mode

$$\frac{\Gamma(h \to NN)}{\Gamma(h \to b\bar{b})} \simeq \frac{\tan\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2 . \tag{5}$$

Including NLO effects, we get a branching ratio of the order of 10^{-3}–10^{-4} in the relevant mass window for N between 60 and 15 GeV. Thus, we may expect $\mathcal{O}(10^3)$ events at the 13 TeV LHC run with 100 fb^{-1} of collected data in the dominant $h \to gg$ channel with a cross section of 45 pb, enough to warrant a detailed collider study.

2.2. LNV Higgs decays at the LHC

Pair production of N from Higgs decay would be a spectacular process, if observed at colliders. It violates lepton number, therefore, there is no significant background, at least not at parton level and infinite calorimetric precision. Physically, it may provide a way towards determination of neutrino mass origin, as discussed below.

After production through the Higgs portal, N typically decays through its gauge interactions, mediated predominantly by W_R: $N \to \ell q q'$. This gives a final state with 50% of the same, 50% opposite sign leptons due to the

Majorana character of N, together with four jets. In contrast to the KS process, where a high momentum charged lepton and a boosted N appear from the heavy $W_{\rm R}$ resonance, the Higgs is fairly light at 125 GeV. This implies that the ultimately six-body final state is relatively soft.

Another feature, useful in search for N, is the appreciable lifetime that can result in observable displacement in the detector. Similar to the muon, N with an electroweak scale mass well below the mass of $W_{\rm R}$ that mediates its decay, has a macroscopic lifetime in the Higgs frame [4]

$$\left(c\tau_N^0\right)^{-1} \simeq 0.06 \text{ mm} \left(\frac{m_N}{30 \text{ GeV}}\right)^5 \left(\frac{3 \text{ TeV}}{M_{W_{\rm R}}}\right)^4 , \tag{6}$$

resulting in a pair of vertices with a correlated displacement.

2.3. Signal simulation and vertex displacement

To simulate the $h \to NN$ process, we adapted the LRSM implementation [4] to include the ggh vertex and the mixing parameter θ in the Higgs sector. The signal was simulated using MadGraph5 with PYTHIA6 and, finally, Delphes3 was used to emulate the detector response. Here, the detector response parameters were designed as those of generic N searches (see [4]).

2.4. Backgrounds and significance estimates

There are three classes of backgrounds to be considered in such searches. First, there are lepton number conserving SM backgrounds with the same sign leptons and neutrinos that carry away lepton number. Since the missing energy resolution is imperfect, tails with small neutrino momentum come into the signal region. Such backgrounds come from di-boson and $t\bar{t}$ production. We studied the behaviour of the signal and backgrounds and devised a set of cuts to optimise the sensitivity [4]. The corresponding number of events after imposition is shown in Table I.

TABLE I

Expected events at the 13 TeV LHC with $\mathcal{L} = 100$ fb^{-1} after cuts. The signal is generated with $m_N = 40$ GeV, $\sin\theta = 10\%$, $M_{W_{\rm R}} = 3$ TeV and $n_j = 1, 2, 3$.

Process	No cuts	$\mu^\pm\mu^\pm + n_j$	$\not{E}_{\rm T}$	$p_{\rm T}$	$m_{\rm T}$	$m_{\rm inv}$
$WZ + ZZ$	3 M	599	172	94	52	28
$W^\pm W^\pm 2j$	389	115	16	5	3	1
$t\bar{t}$	10 M	509	97	40	22	14
Signal (40)	543	44	43	41	38	37

The second type of background comes from detector effects, *e.g.* secondary conversion, and affects the electron channel. For this reason, we concentrate here on the muon final state, where this is not an issue. Finally, the dominant source of background should come from misidentified QCD jets. Such estimates are data-driven and behave similarly to di-boson production. As a conservative estimate, we estimate this contribution by adding $2.5 \times (VV)$ events to the total background.

Finally, we use the information on decay length (6) to set up a cut on transverse vertex displacement $d_{\rm T}$ (see Fig. 1, left). For each point in the m_N–$M_{W_{\rm R}}$ plane, an optimized L is chosen with a window cut $L/10 < d_{\rm T} < 5L$, resulting in the significance contours displayed in Fig. 1, right.

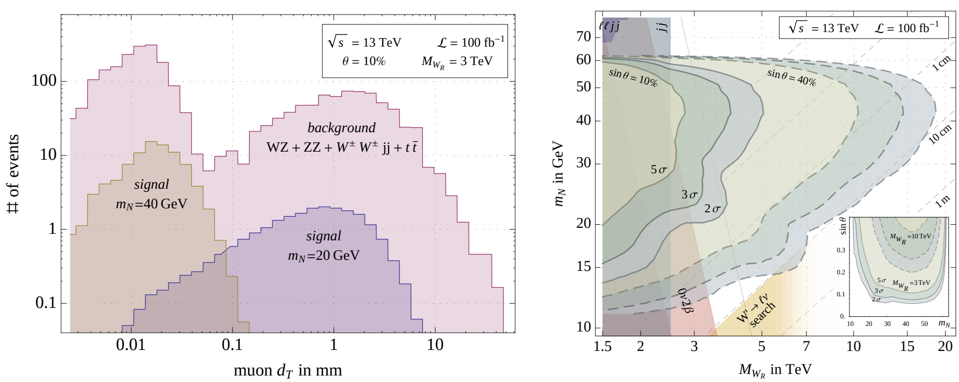

Fig. 1. Left: Transverse displacement of the muon vertex. Right: Contours of signal significance in σs for $\theta = 10\%$ (40%) in solid (dashed) lines. Searches for the KS and di-jet channels (blue) and $W_{\rm R} \to \ell + \not{E}$ (yellow) are shown. Color on-line.

3. Conclusions

In contrast to gauge mediated LNV searches at colliders, the Higgs portal has been relatively less explored. In [4], we carried out a collider study showing that processes, such as the exotic decay of the SM Higgs boson to a pair of N, can provide a complementary channel, potentially able to probe indirectly high scales, beyond the direct reach of the LHC.

Moreover, one could obtain sufficient information to test Eq. (3) and thereby establish the origin of N mass. This can be done by counting the number of events, measuring the mass of N from the $m_{\ell jj}^{\rm inv}$ peak and its decay length, while having an independent determination of θ from a global fit to the Higgs data.

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