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# Neutrino mass models at the TeV scale and their tests at the LHC

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Assuming that the new particles introduced by type-I, type-II, type-III see-saw in order to mediate neutrino masses are below a TeV, we describe their resulting manifestations at LHC.

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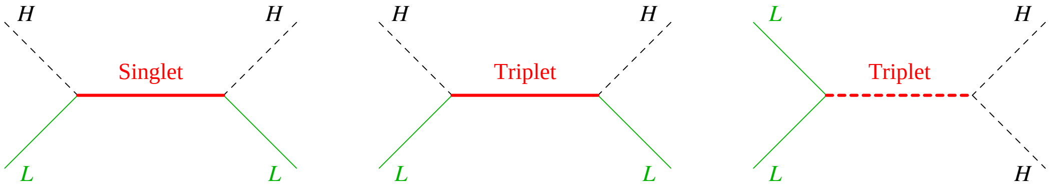

**Figure 1:** *The neutrino Majorana mass operator* $(LH)^2$ *can be mediated by tree level exchange of:* I) *a fermion singlet ('see-saw');* II) *a fermion triplet;* III) *a scalar triplet.*

## 1. See-saw models

In the past decade we observed violations of lepton flavor in neutrinos and understood that it is due to neutrino oscillations due to neutrino masses [1]. Neutrino masses can be of Majorana type (violating also lepton number) or of Dirac type (adding to the SM a light right-handed neutrino, such that lepton number is conserved).

We here stick to the most plausible scenario for neutrino masses: the see-saw models, all designed to give at tree level Majorana masses described by the unique dimension-5 effective operator $(LH)^2/2\Lambda_L$. as illustrated in fig. 1. Observed neutrino masses $m_\nu = v^2/\Lambda_L$ (where $v = 174\,\text{GeV}$ is the Higgs vev) are reproduced for $\Lambda_L \sim 10^{14}\,\text{GeV}$. The three see-saw models are described by the following lagrangians [1]. Type I see-saw employs extra right handed neutrinos $N_i$ $(i = \{1,2,3\})$ with Yukawa couplings:

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \bar{N}_i i\partial\!\!\!/ N_i + (\lambda_N^{ij}\, N^i L^j H + \frac{M^{ij}}{2} N_i N_j + \text{h.c.}) \tag{1.1}$$

Type II employs one triplet scalar $T^a$ with couplings:

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + |D_\mu T|^2 - M_T^2 |T^a|^2 + \frac{1}{2}(\lambda_T^{ij} L^i \varepsilon \tau^a L^j T^a + \lambda_H M\ H\varepsilon\tau^a H\ T^{a*} + \text{h.c.}) \tag{1.2}$$

Type III is similar to type I, with $N_i$ substituted by weak triplets $N_i^a$:

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \bar{N}_i i D\!\!\!\!/ N_i + \left[\lambda_N^{ij}\, N_i^a (L_j \tau^a \varepsilon H) + \frac{M^{ij}}{2} N_i^a N_j^a + \text{h.c.}\right]. \tag{1.3}$$

One important issue is how can we test if one of these models is right.

## 2. Virtual effects

The $(LH)^2$ operator also induces couplings of two left-handed leptons with the higgs or with heavy SM vectors, but all the resulting rates are uninterestingly small: e.g. the cross-section for the lepton-number-violating scattering $ee \to W^- W^-$ is $\sigma \sim 1/\Lambda_L^2$ above the kinematical threshold.

Going to higher dimension 6 order, see-saw models generate different operators [2]:

- Type-I see-saw generates the $(H^\dagger \bar{L}) i\partial\!\!\!/ (HL)$ operator that manifests as flavor violating neutrino interactions.

**Figure 2:** *Lepton-number-violating signals of type-II and type-III see-saw at the LHC pp collider.*

- Type-III see-saw gives the $(H^\dagger \tau^a \bar{L}) \not{D} (H \tau^a L)$, that also give flavor violating interactions for charged leptons.

- Type-II see-saw gives flavor violating $|L\tau^a L|^2$ four-fermion interactions, as well as operators involving the higgs doublet $H$.

- At loop level, see-saw models induce the lepton-number-violating operator $(\bar{\mu}\gamma_\mu P_L e)^2$: that gives muonium $M = e^-\mu^+$ oscillations into anti-muonium $\bar{M} = e^+\mu^-$.

The experimental bounds on the coefficients of these operators are at the level of $10^{-2-5}/v^2$. But the naive expectation is that all these effects are suppressed by $\sim 1/\Lambda_L M$. While more optimistic non minimal scenarios are possible, the most likely scenario seems that all such effects are many orders of magnitude too small to be observed, even if the see-saw particles have mass $M$ around the weak scale.

## 3. Real effects

There is no reason why $M$ should be close to the weak scale rather than to $\Lambda_L$. *However, if $M$ is within the energy range accessible at LHC, the best hope is that some of the particles that mediate neutrino masses might be light enough to be produced at the LHC.*

No detectable effect arises if they only have the small couplings needed to mediate the small neutrino masses. This is likely the case of the right-handed neutrinos of type-I see-saw, unless extra interactions exist, such as an extra $\mathrm{U}(1)_{B-L}$ vector [3].

On the contrary, the scalar or fermion $\mathrm{SU}(2)_L$ triplets of type-II [4] and type-III [5] see-saw models have weak gauge interactions, fully predicted by theory. Consequently, gauge interactions lead to pair production of the various components of the fermion $N = \{N^0, N^\pm\}$ or of the scalar $T = \{T^0, T^\pm, T^{\pm\pm}\}$ triplets. The production cross-sections decrease with increasing $M$: at LHC with $\sqrt{s} = 7\,\mathrm{TeV}$ one has $\sigma(pp \to NN) \sim 1\,\mathrm{fb}$ for $M \approx 600\,\mathrm{GeV}$, while $\sigma(pp \to TT^*)$ is smaller by a factor $\approx 10$ because scalars are not produced in $s$-wave.

Once these particles are produced, they sooner or later decay because of their small interactions that lead to neutrino masses: the smallness of these couplings can make life-times longer, but this is not a problem for detectability. Indeed the life-time of a fermion triplet with mass $M$ that gives a contribution $\tilde{m}_1$ to neutrino masses is

$$\tau_{N_0} = \tau_{N_\pm} = \frac{8\pi v^2}{\tilde{m}_1 M^2} = 1.5\,\mathrm{cm}\frac{\mathrm{meV}}{\tilde{m}_1}\left(\frac{100\,\mathrm{GeV}}{M}\right)^2 \tag{3.1}$$

up to corrections suppressed by $M_Z^2/M^2$: the smallness of neutrino masses can lead to decay vertices detectably displaced from the production point. The main decay modes are $N^\pm \to \ell^\pm Z, \overset{(-)}{\nu}_\ell W^\pm$ and $N^0 \to W^+\ell^-, W^-\ell^+$, all with comparable branching ratios. As a consequence the signals are of the type $\ell\ell VV$ where $\ell$ is a lepton (charged or neutral) and $V$ is a $Z, W^\pm$ or higgs boson.

The $\ell\ell VV$ signal is produced also in type-II see-saw, together with $VVVV$ and $\ell\ell\ell\ell$ signals. Indeed, in view of the type-II see-saw Lagrangian of eq. (1.2), scalar triplets have two decay modes: $\Gamma(T^{\pm\pm} \to \ell^\pm\ell^\pm) \sim \lambda_T^2 M/4\pi$ and $\Gamma(T^{\pm\pm} \to W^\pm W^\pm) \sim \lambda_H^2 M/4\pi$. If $\lambda_T \sim \lambda_H$ the triplet life-time is comparable to eq. (3.1), otherwise it can be much shorter. Lepton number is violated only when both couplings $\lambda_T$ and $\lambda_H$ are present, so that a lepton-number-violating $\ell\ell VV$ signal arises when both decays happen, as in the left diagram in fig. 2: given that the each of the heavy SM vectors dominantly decays into two quarks, the main signal is $pp \to \ell^\pm\ell^\pm 4j$.

The diagrams in fig. 2 shows how type-II and III see-saw can produce lepton-number violating signals: in the two models there are peaks in different combinations of invariant masses. Appropriate cuts can suppress the SM backgrounds to these processes: apparent violation of lepton number arises when two neutrinos carry away lepton number and undetectably small missing transverse energy.

The type-II signal $pp \to \ell^+\ell^+\ell^-\ell^-$ has been searched for by CMS [7] (with 0.98/fb statistics), setting the bound $M > 300\,\mathrm{GeV}$ for $\ell = \{e, \mu\}$ and 100% branching ratio of $T^{++} \to \ell^+\ell^+$. However, type-II or III triplets can produce baryogengesis via thermal leptogenesis only if heavier than 1.6 TeV [6], beyond the discovery reach of LHC.

Finally, we point out that type II and III see-saw belong to a more general class of models that gives well defined non trivial signatures at LHC and production cross sections predicted as function of the unknown mass $M$ of new particles [8]: the models where one new multiplet that only has small couplings to pairs of SM particles, broadly classified as H (Higgs doublet), L (leptons) or Q (quarks). The resulting signals are:

| coupled to | signals | models |
|---|---|---|
| LH | $pp \to \ell\ell VV$ | type-II and III see-saw, heavy lepton |
| LL | $pp \to \ell\ell\ell\ell$ | type-II see-saw, di-lepton |
| HH | $pp \to VVVV$ | type-II see-saw |
| QH | $pp \to jjVV$ | heavy quark |
| LQ | $pp \to \ell\ell jj$ | lepto-quark |
| QQ | $pp \to jjjj$ | di-quark |

In each case dedicated search strategies can and need to be devised. As far as I know very little experimental activity has been so far reported on these signals, while the interest is presently monopolized by easier signals (such as $pp \to \ell\ell$) and by scenarios motivated by the hierarchy problem (such as supersymmetry). If the hierarchy problem is instead due to anthropic selection and if the $g-2$ muon anomaly is real, specific models can explain the observed $g-2$ without using new scalars at the weak scales [9], and their experimental signals are similar to those of type-II and III see-saw.

## 4. Conclusions

Fig. 1 shows how type-II (a scalar triplet) and type-III (a fermion triplet) see-saw can produce lepton-number violating signals at LHC. Appropriate cuts can suppress the SM backgrounds to these processes: apparent violation of lepton number arises when two neutrinos carry away lepton number and undetectably small missing transverse energy. Appropriate combinations of invariant masses would allow to see other less spectacular signals, and reconstruct part of the physics behind neutrino masses. Type-I see-saw, by itself, does not lead to detectable signals.

However, type-II see-saw at the weak scale would lead to a hierarchy problem, and scalar or fermion triplets can produce baryogengesis via thermal leptogenesis only if heavier than 1.6 TeV, beyond the discovery reach of LHC.

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