

LHC and the origin of neutrino mass

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Abstract. It is often said that neutrino mass is a window to a new physics beyond the standard model (SM). This is true if neutrinos are Majorana particles for the SM with Majorana neutrino mass is not a complete theory. The classical text-book test of neutrino Majorana mass, the neutrino-less double beta decay depends on the completion, and thus cannot probe neutrino mass. As pointed out already twenty five years ago, the colliders such as Tevatron or LHC offer a hope of probing directly the origin of neutrino (Majorana) mass through lepton number violating production of like sign lepton pairs. I make a case here for this in the context of all three types of seesaw mechanism.

1. Introduction

We know that neutrinos are massive [1] but light: $m_\nu \lesssim 1\text{eV}$ from beta decay. If we wish to account for tiny neutrino masses with only the degrees of freedom of the SM neutrino masses can be parametrized by Weinberg's [2] $d = 5$ effective operator

$$\mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}$$

where L_i stands for left-handed leptonic doublets and H for the usual Higgs doublet (with a vev v). This in turn produces neutrino Majorana mass matrix

$$\frac{v^2}{M} Y = U_{PMNS} m_\nu^{diag} U_{PMNS}^T$$

where U_{PMNS} stands for the leptonic mixing matrix.

The non-renormalizable nature of the above operator signals the appearance of new physics through the mass scale M . The main consequence is the $\Delta L = 2$ violation of lepton number through:

- a) neutrino-less double beta decay $\nu 0\beta\beta$
- b) same sign charged lepton pairs in colliders.

While the neutrino-less double beta decay is a text-book probe of Majorana neutrino mass, the like sign lepton pair production, although suggested already a quarter of century ago [3], has only recently been studied more seriously. In what follows I argue that this process may be our best bet in probing directly the origin of neutrino mass. Due to the lack of space I can cover only the essential points and I cannot do justice to the fast growing literature in the field. I apologize in advance for the omission of papers that merit quotation.

If M is huge, there is no hope of direct observation of new physics. It is often said that large M is more natural, for then Yukawas do not have to be small. For example, $M = 10^{13} \text{GeV} - 10^{14} \text{GeV}$ corresponds to Y of order one. However, small Yukawas are natural in a sense of being protected by chiral symmetries and anyway most of the SM Yukawas are small. Furthermore, large ratios of mass scales needs fine-tuning, so there is nothing more natural about large M . I adopt the strategy here of keeping M free and looking for theoretical predictions, in particular through grand unification.

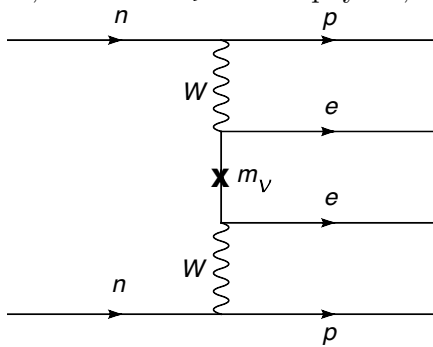
In order to get a window to new physics, we need a renormalizable theory of the above effective operator. It turns out that there are only three different of producing it through the exchange of heavy:

- I) fermion singlet (1C , 1W , $Y = 0$), called right-handed neutrino. This is type I seesaw [4]
- II) bosonic weak triplet (1C , 3W , $Y = 2$), the type II seesaw [5]
- III) fermion weak triplet (1C , 3W , $Y = 0$), called type III seesaw [8]

The types I and II have been studied at length, while type III almost ignored, except for recent past.

It is easy to see that all three types of seesaw lead to the one and the same $d=5$ operator above. By itself seesaw is not more useful than just Weinberg's operator unless we can reach the scale M or have a theory of these singlets and/or triplets. This is reminiscent of the Fermi effective theory of low energy weak interactions: saying that the four fermion interactions can be described by the exchange of a W boson is appropriate either at the scale M_W or if you have a theory of a W boson. This is precisely what the SM gauge theory had achieved by correlating a plethora of low energy ($E \ll M_W$) weak interaction processes. Until then one had more use from an effective language of Fermi than a language of an unknown W boson particle and its unknown couplings and that is why for more than two decades the Fermi theory was preferred.

It is often said that neutrino mass is a window to new physics . This is true if it is Majorana for the SM with Majorana neutrino mass is not complete, as manifest from the $d=5$ operator. In the Dirac case, the theory is complete. One just adds a right-handed neutrino whose Majorana mass is zero and gets the usual Dirac Yukawa couplings. In this case, except for neutrino oscillations there is no hope for new physics since all the interesting phenomena such as lepton flavor violation (LFV) are suppressed by tiny neutrino masses. Majorana case, on the other hand, connects m_ν to new physics, such as desperately searched for $\nu 0\beta\beta$ decay.



This probes neutrino Majorana mass in the range 0.1 - 1 eV.

However, in general m_ν not directly connected to $\nu 0\beta\beta$ decay. While it does produce it, the inverse is not true. $\nu 0\beta\beta$ decay does not imply the measure of neutrino mass, since it depends on the completion of the SM needed for the $d=5$ neutrino mass. An example is provided by the L-R symmetric theory with W_R in the TeV region and the right-handed neutrino mass m_N in the 100 GeV -TeV region. This contribution can easily dominate over the left-handed one since neutrino mass can even go to zero (small Dirac Yukawa) while keeping the W_R contribution finite. Neutrino-less double beta decay by itself cannot know what caused it and thus cannot probe directly neutrino mass or its origin. This is similar to the possible observation of proton

decay which cannot probe the cause of the decay itself. This is not to say that this important experimental probe of lepton number violation is not a priority, simply we need more. It is crucial that we trace seesaw in the colliders by studying lepton number violating production of like sign lepton pairs. I exemplify it on the original example of low scale left-right symmetry [3]

2. Left-right symmetry and the origin of neutrino mass

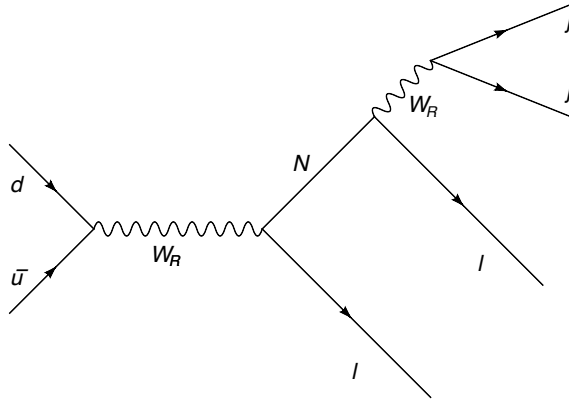
L-R symmetric theories [9] are based on the $SU(2)_L \times SU(2)_R \times U(1)$ gauge group augmented by parity or charge conjugation. Then:

W_L implies W_R

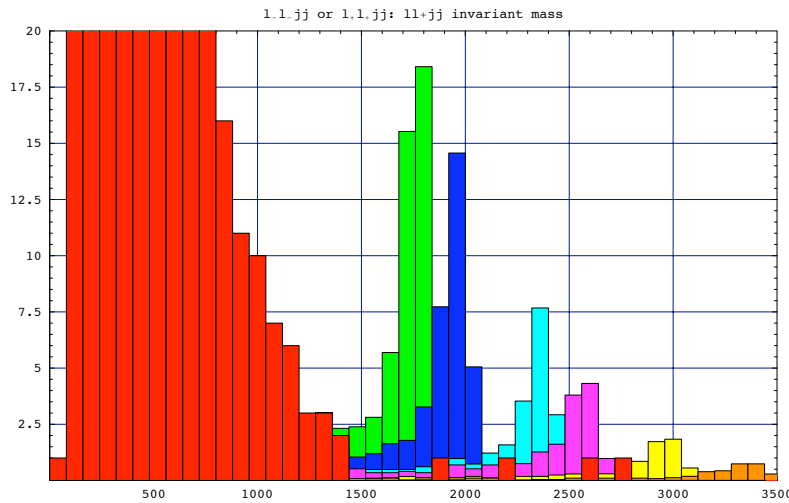
ν_L implies ν_R , with m_{ν_R} of order M_R through the breaking of L-R symmetry

Type I seesaw: connects neutrino mass to scale of parity restoration.

Colliders: produce W_R through Drell-Yan.



Once the right-handed gauge is produced, it will decay into a right-handed neutrino and a charged lepton. The right-handed neutrino, being Majorana particle, decays equally often into charged leptons or anti-leptons and jets. In turn one has exciting events of same sign lepton pairs and two jets, as a clear signature of lepton number violation. This is a collider analog of neutrino-less double beta decay, and it allows for the determination of W_R mass as shown in the figure below.



number of events for $L = 8fb^{-1}$ (courtesy of F. Nesti)

$M_R(TeV) = 1.8 \quad 2 \quad 2.4 \quad 2.6 \quad 3 \quad 3.4$

This offers

- a) direct test of parity restoration through a discovery of W_R
- b) direct test of lepton number violation through a Majorana nature of ν_R
- c) determination of W_R and N masses

A detailed study [10] concludes an easy probe of W_R up to 3.5 TeV and ν_R in 100 - 1000 GeV for integrated luminosity of 30 fb^{-1} . It needs a study of flavor dependence, i.e. connection with LFV [11].

It is worth noting that the same signatures can be studied in the SM with ν_R [12], but it requires miraculous cancellations of large Dirac Yukawa couplings in order to produce right-handed neutrinos. This is a long shot, not really worth pursuing in my opinion.

The L-R theory possesses naturally also type II seesaw [6]. The type II offers another spectacular signature: pair production of doubly charged Higgses which decay into same sign lepton (anti lepton) pairs [13]. This can serve as a determination of the neutrino mass matrix in the case when type I is not present or very small [15].

This is all very nice, but the question is whether a low L-R scale is expected or not. It is perfectly allowed, but not predicted. This theory can be embedded in SO(10) grand unified theory, where L-R symmetry becomes charge conjugation and is a finite gauge transformation. The scale of L-R breaking ends up being high though, either close to M_{GUT} in the supersymmetric version, or around 10^{10} GeV or so in the ordinary version.

We are faced then with a crucial question: is there a simple predictive grand unified theory with seesaw at LHC? The answer is yes, a minimal extension of the original Georgi-Glashow theory [16], with an addition of an adjoint fermion representation [17].

3. Minimal non supersymmetric SU(5)

The minimal SU(5) theory consists of: $24_H + 5_H$ Higgs multiplets, where 24_H is used to break the original symmetry to the SM one, and 5_H completes the breaking, and the three generation of quarks and leptons $3(10_F + \bar{5}_F)$. The theory fails for two important reasons:

- a) gauge couplings do not unify
 - 2 and 3 meet at 10^{16} GeV (as in susy),
 - but 1 meets 2 too early at $\approx 10^{13} \text{ GeV}$
- b) neutrinos massless (as in the SM)

possible higher dimensional operator not enough: neutrino mass too small ($\lesssim 10^{-4} \text{ eV}$).

A simple extension cures both problems: add just one extra fermionic 24_F [17].

Under $SU(3)_C \times SU(2)_W \times U(1)_Y$ decomposition gives: $24_F = (1, 1)_0 + (1, 3)_0 + (8, 1)_0 + (3, 2)_{5/6} + (\bar{3}, 2)_{-5/6}$. The unification works as follows: triplet fermion (like wino in MSSM) slows down $U(1)$ coupling as to make it meet the other two at the single point. Effectively, the theory behaves as light wino, gluino heavy (10^7 GeV), no Higgsino, no sfermions (they are irrelevant for unification being complete representations, as in split susy).

With the notation singlet $S = (1, 1)_0$, triplet $T = (1, 3)_0$, it is evident that we have mixed Type I and Type III seesaw

$$(M_\nu)^{ij} = v^2 \left(\frac{y_T^i y_T^j}{m_T} + \frac{y_S^i y_S^j}{m_S} \right)$$

An immediate consequence is one massless neutrino, i.e. the hierarchical spectrum.

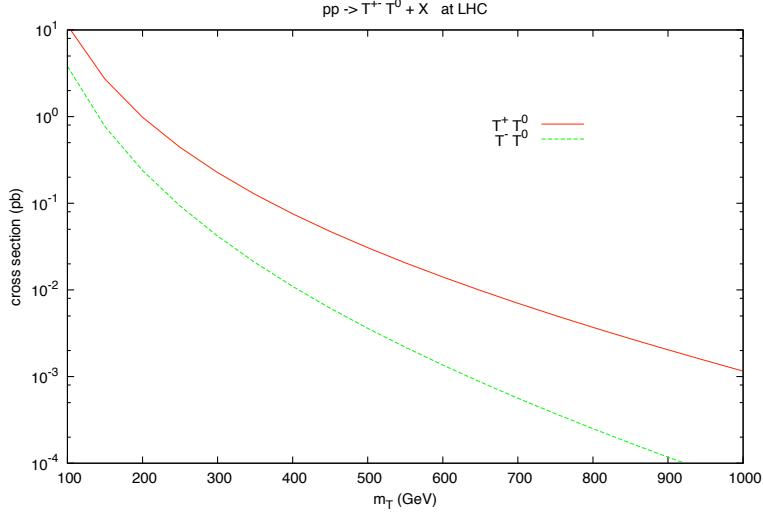
3.1. T at LHC

The fermion weak triplet can be produced through gauge interactions (Drell-Yan)

$$pp \rightarrow W^\pm + X \rightarrow T^\pm T^0 + X$$

$$pp \rightarrow (Z \text{ or } \gamma) + X \rightarrow T^+ T^- + X$$

with the cross section for the T pair production



The best channel is like-sign dileptons + jets

$$BR(T^\pm T^0 \rightarrow l_i^\pm l_j^\pm + 4 \text{ jets}) \approx \frac{1}{20} \times \frac{|y_T^i|^2 |y_T^j|^2}{(\sum_k |y_T^k|^2)^2}$$

Same couplings y_T^i contribute to ν mass matrix and T decays, so that T decays can serve probe the neutrino mass matrix [18].

Let me illustrate the signal with the cuts for $M_T = 200 \text{ GeV}$ [19]

$\sigma_{\text{signal}} = 119 \text{ fb}$ without any cuts

Cuts \Downarrow	$\sigma_{\text{sig.}}(\text{fb})$
$p_T(\ell) > 15(\text{GeV})$	115
$p_T(\text{jets}) > 20 (\text{GeV})$	64
$ \eta(\ell) < 2.5$	50
$ \eta(\text{jets}) < 3$	48
$\Delta R_{\ell\ell} > 0.3$	45
$\Delta R_{\ell j} > 0.5$	37
$\Delta R_{jj} > 0.5$	32
$\cancel{p}_T < 25 \text{ GeV}$	22

SM backgrounds appear under control: $\sigma_{\text{background}} \lesssim 1 \text{ fb}$ with cuts [20].

4. Summary and Outlook

I have argued here that the experimental probe of (Majorana) neutrino mass origin is lepton number violation at colliders (same sign dileptons), a high energy analogue of neutrino-less double beta decay. A classical example is provided by the L-R theory: possible discovery of W_R and ν_R . This offers a spectacular possibility of observing parity restoration and the Majorana nature of neutrinos, but the low M_R scale relevant for LHC not predicted.

I have provided then an explicit example of a predictive grand unified theory: ordinary minimal SU(5) with extra fermionic adjoint. A weak fermionic triplet is predicted in the TeV range (type III seesaw) whose decay is connected with neutrino mass.

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