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Neutrino mass as a signal of TeV scale physics

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Abstract

If the origin of neutrino masses is due to physics at the TeV scale, it would be of tremendous interest since it can be probed using ongoing collider as well as low energy rare process searches. So, a key question is: could the new physics behind neutrino masses be near the TeV scale? In this brief overview, I present arguments in favor of this possibility by presenting the example of TeV scale left–right symmetric models (LRSM) for neutrino mass based on type I seesaw paradigm. A particular issue with understanding the small neutrino masses in TeV scale LRSM is to understand the suppression of type II seesaw contribution to neutrino masses, which a priori could be much larger than desired. I discuss how using either D-parity breaking or by using supersymmetry, one can suppress these contributions to the desired level in a natural way. Experimental probes of this hypothesis are briefly touched upon. Constraints of supersymmetry and that of successful leptogenesis on the left–right scale are also emphasized. The former provides an upper limit and the latter, a lower limit on m_{W_R}.

1. Introduction

The neutrino oscillation experiments, celebrated by this year's Nobel prize, have unambiguously established over the past decade and half that neutrinos have tiny but non-zero masses as well as nontrivial mixings between different flavors. They have provided the first unambiguous evidence for physics beyond the standard model (SM) which predicts that neutrino masses van-

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ish. Since the origin of mass for all charged fermions of the standard model appears now to have been clarified by the discovery of the Higgs boson, an important question is whether there are new Higgs bosons and new fermions (and new forces) associated with understanding the origin of neutrino masses. As a starting point of this discussion, note that if we simply add three right handed neutrinos to the SM, one can write a Yukawa coupling of the form $\mathcal{L}_{\nu,Y} = h_\nu \bar{L}\tilde{H}\nu_R$ which via the SM Higgs vev can give a mass to neutrinos of magnitude $m_\nu = h_\nu < H^0 >$. However, since $< H^0 > \simeq 173$ GeV, to get sub-eV neutrino masses, we need to have $h_\nu \simeq 10^{-12}$, an "unnaturally" small number. So the strong suspicion among theorists is that there is some new physics beyond the standard model and new Higgs fields beyond the 125 GeV SM Higgs that are responsible for neutrino masses. The question then is at what scale this new physics manifests itself and can we test it experimentally. The goal of this article is to make a case that the origin of neutrino masses could be due to new physics at the multi-TeV scale and that there exists a natural class of TeV scale models for neutrino masses which can be probed at the LHC, the planned proton–proton collider at 100 TeV as well as low energy rare process search experiments such as $\mu \to e + \gamma$ and neutrinoless double beta decay.

The class of models, we focus on, is based on the simple paradigm of (type-I) seesaw mechanism [1] where the right handed neutrinos alluded to above have a heavy Majorana mass in addition to having a Yukawa coupling like all charged fermions. Neutrinos being electrically neutral allows for this possibility and it is not unreasonable to suspect that this also might be at the root of such diverse mass and mixing patterns for leptons compared to quarks. The crux of this physics is the seesaw mass matrix with the generic form in the (ν_L, N_R) space:

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \tag{1}$$

where m_D mixes the ν and N states and is generated by the SM Higgs vev and M_N is the Majorana mass for N which embodies the new neutrino mass physics. For three generations of fermions, both m_D and M_N are 3×3 matrices. The mass of the light neutrinos is then given by the symbolic seesaw formula:

$$M_\nu \simeq -m_D M_N^{-1} m_D^{\mathsf{T}}, \tag{2}$$

which also generates a mixing between the heavy (N) and the light neutrino (ν) again given by $\sim m_D/M_N \equiv V_{\ell N}$. The "unnaturalness" of the Yukawa couplings alluded to above are now considerably ameliorated due to two features of the formula above: first, it is the square of the Yukawa coupling h_ν that is present in the formula and secondly there is a heavy mass M_N in the denominator.

Clearly for a more fundamental understanding of the seesaw formula, one may ask the question: "Are the RH neutrinos N and their Majorana mass M_N, the seesaw scale put in by hand or is there a compelling theory that explains their origin in a natural manner?" Recall that these are the two key new ingredients in seesaw beyond the SM physics and their fundamental understanding would be a key step forward into the domain of Beyond the Standard Model (BSM) physics. Two immediate theories that present themselves and were discussed before the seesaw mechanism was suggested, are: (i) an SO(10) grand unified theory that has a **16** dimensional spinor representation that, in addition to containing the fifteen standard model fermions, has room for just one more neutral fermion which can be identified with the right handed neutrino; and (ii) the left–right symmetric (LRSM) extension of the standard model which was proposed to explain the parity violation observed in weak processes to be truly a low energy phenomenon that will disappear at higher energies [2]. In the LRSM, the right handed neutrino appears as the parity