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Light Heavy Neutrinos

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Abstract

Heavy right-handed neutrinos are a natural addition to the particle content of the Standard Model. Within the high-scale seesaw mechanism they provide a natural explanation for the lightness of the active neutrinos. We here briefly discuss a few possible modifications of the standard seesaw scenario that permit relatively light heavy neutrinos at or below the electroweak scale. Such scenarios are experimentally testable and we touch upon the corresponding phenomenology at colliders and in meson decays.

1. Introduction

With the discovery of the Higgs boson and with the ongoing determination of its couplings to fermions at the LHC, we are tantalizingly close to verify the mechanism responsible for the charged fermion masses. What will remain missing though is an understanding of the light neutrino masses. The observation of neutrino oscillations [1] demonstrates that neutrinos have a finite mass and that individual lepton flavour is violated. Furthermore, light neutrinos are usually considered to be Majorana particles, an assumption that quite naturally allows us to understand the small masses in terms of a slightly broken lepton number symmetry. It is natural to expect that the violation of the individual lepton flavours (as verified by neutrino oscillations) and the total lepton number (only true for Majorana neutrinos) will show up in other contexts as well. This for example includes rare lepton flavour violating (LFV) decays of muons and taus, the total lepton number violating (LNV) neutrinoless double beta decay ($0\nu\beta\beta$) and similar decays and processes at low and high energies.

Neutrino oscillations also demonstrate that at least two of the three active neutrinos have a finite mass but they are not able to pinpoint the absolute neutrino masses. Upper limits on the effective neutrino mass scale are determined from (i) tritium beta-decay experiments, (ii) astronomical observations combined with cosmological models and (iii) searches for $0\nu\beta\beta$ decay. Current results point to an upper limit on the heaviest active neutrino mass of the order of 0.1 eV. Among the three probes, $0\nu\beta\beta$ takes a special role as its observation would prove the violation of total lepton number and thereby essentially confirm a Majorana nature of neutrinos [2].

Although it is difficult to probe the nature and absolute mass scale of neutrinos in other experimental contexts especially at high energies, the possible violation of lepton number should be searched for at all accessible energy regions. This is because the observation of such processes would equally allow us a direct insight into the mechanism of neutrino mass generation. Several such mechanisms have been put forward in the literature. The most popular example is the so-called seesaw mechanism (of type I) in which heavy right-handed Majorana neutrinos N with masses $\gtrsim 10^{11}$ GeV are added to the Standard Model (SM). Their interaction with the left-handed neutrinos induces the light Majorana masses of active neutrinos after electroweak (EW) symmetry breaking. The light Majorana-type neutrino masses are then naturally generated by the breaking of lepton number symmetry at a very high scale [3, 4, 5, 6, 7, 8] through the 5-dimensional Weinberg operator. Mechanisms of neutrino mass generation also quite generically

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provide an explanation of the baryon asymmetry of the Universe through the leptogenesis mechanism. The observation of LNV can have deep implications on the viability of baryogenesis models, cf. [9].

Despite its popularity, the default type-I seesaw mechanism has two phenomenological problems: (i) In the standard regime with $m_N \gtrsim 10^{11}$, the heavy neutrinos are far too heavy to be probed experimentally; (ii) The right-handed neutrinos are gauge singlets and even if their masses were low enough for experimental searches (the scenario we focus on in this short report), the heavy neutrinos only couple via their mixing with light neutrinos which is tightly constrained by the lightness of the latter. The relaxation of the correlation between the mixing and the small neutrino masses will be the second issue we focus on here. In addition, the mixing is also experimentally constrained by EW precision data and searches for lepton flavour violating processes [10, 11].

In the following we will briefly describe modifications of the standard seesaw mechanism with relatively light heavy neutrinos down to $m_N \approx 1$ GeV and with a testable mixing strength, and address their impact in meson decays.

2. Neutrino Seesaw Models

In the standard type-I seesaw model [3] with the mass matrix

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

for the left- and right-handed neutrino[1], the mass of the light neutrino ν and its mixing θ with the heavy neutrino N is given by $m_\nu = -m_D^2/m_N$ and $\theta = m_D/m_N = \sqrt{m_\nu/m_N}$, respectively. For the observed light neutrino mass scale $m_\nu \approx 0.1$ eV this yields

$$\theta \approx 10^{-5}\sqrt{\frac{\text{GeV}}{m_N}}, \tag{2}$$

and for a GeV scale heavy neutrino the mixing is rather small. This conclusion will be very different in the inverse seesaw scenario [12] described by the mass matrix

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & m_N \\ 0 & m_N & \mu \end{pmatrix}, \tag{3}$$

[1]We work with one generation per species throughout this report.

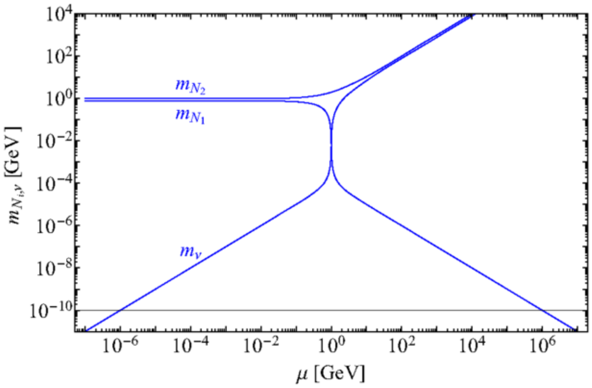

Figure 1: Neutrino masses in the modified seesaw model Eq. 5 as a function of the LNV mass term μ. The heavy neutrino mass is m_N = 1 GeV and the Dirac mass is $m_D = 10^{-2}$ GeV. The spectrum for small $\mu \ll 1$ GeV includes a pair of heavy Majorana neutrinos forming a quasi-Dirac state, whereas for large $\mu \gg 1$ GeV, it contains a pair of heavy quasi-degenerate Majorana neutrinos. Successful light neutrino mass generation occurs for $\mu \approx 10^{-6}$ GeV (inverse seesaw) and $\mu \approx 10^6$ GeV (standard seesaw).

similarly for the left-handed neutrino, the right-handed neutrino and an additional SM gauge singlet state S. With the freedom provided by the small lepton number violating mass parameter μ, the observed light neutrino masses can be generated for any $\theta = m_D/m_N$ [13]. In essence, the magnitude of the neutrino mass $m_\nu = \theta^2\mu$ becomes decoupled from the heavy neutrino mass [14],

$$\theta \approx 10^{-2}\sqrt{\frac{\text{keV}}{\mu}}. \tag{4}$$

This can be understood as the two heavy neutrinos have opposite CP parities and they form a quasi-Dirac state with relative mass splitting of the order $\kappa = \mu/m_N$. Lepton number violating processes and observables are suppressed by this small mass splitting, such as the light neutrino mass which can be conveniently expressed as $m_\nu = \theta\kappa m_D$. This means that in the inverse seesaw mechanism, the lightness of the active neutrinos is driven by both the small left-right mixing or the small splitting between the heavy neutrino masses.

In order to study the transition between the standard and inverse seesaw scheme, we now analyze the modified scenario

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu & m_N \\ 0 & m_N & \mu \end{pmatrix}, \tag{5}$$

again for the left-handed neutrino, the right-handed neutrino and the added singlet state. The mass spectrum of