Constraints and tests of the TeV scale see-saw mechanism

Alejandro Ibarra

Physik-Department T30d, Technische Universität München,
James-Franck-Straße, 85748 Garching, Germany

E-mail: `alejandro.ibarra@ph.tum.de`

Abstract. The type I see-saw mechanism requires the existence of right-handed neutrinos with a Majorana mass much larger than the Dirac neutrino mass. Nevertheless, the right-handed neutrino mass scale is completely unknown and can range between 0 and the Planck mass. In this talk we discuss the constraints on the scenario where the right-handed neutrino mass lies at the TeV scale, motivated by the possibility of testing the mechanism of neutrino mass generation at the Large Hadron Collider.

1. Introduction

One of the simplest extensions of the Standard Model consists on introducing right-handed neutrinos [1]. Being singlets under the Standard Model gauge group, the most general Lagrangian contains two new terms: a Dirac mass term, coupling left- and right-handed neutrinos, and a Majorana mass term for the right-handed neutrinos:

$$-\mathcal{L} \supset \overline{\nu_L} M_D \nu_R + \frac{1}{2}\overline{\nu_R^C} M_M \nu_R + \text{h.c.} \tag{1}$$

In terms of the mass eigenstates ν_i and N_i this Lagrangian reads:

$$-\mathcal{L} \supset \frac{1}{2}\overline{\nu_i^C}\mathcal{M}_{\nu ij}\nu_j + \frac{1}{2}\overline{N_i^C}\mathcal{M}_{Nij}N_j + \text{h.c.} \tag{2}$$

If $M_M \gg M_D$, the light neutrino mass is related to the parameters of Eq. (1) through $\mathcal{M}_\nu \simeq -M_D M_M^{-1} M_D^T$, while the heavy neutrino mass through $\mathcal{M}_N \simeq M_M$.

Low energy experiments restrict the eigenvalues of $\mathcal{M}_\nu$ to be $\lesssim \mathcal{O}(0.1 \text{ eV})$, but not the size of the entries of M_D or M_M. In this talk, we will analyze the constraints on the scenario where the right-handed neutrino masses lie at the TeV scale, motivated by the exciting possibility of testing the mechanism of neutrino mass generation at collider experiments (see, *e.g.* [2]).

2. Scenarios with TeV mass right-handed neutrinos and large Yukawa couplings

From $\mathcal{M}_\nu \simeq -M_D M_M^{-1} M_D^T$, it follows that, naively, when $M_M = 1$ TeV then $m_D \approx 10^{-4}$ GeV in order to generate neutrino masses not larger than $\mathcal{O}(0.1 \text{ eV})$. This translates into a Yukawa coupling $\mathcal{O}(10^{-6})$ which induces low energy effects too suppressed to be observed, unless the right-handed neutrino has additional interactions, for instance when it is charged

under $U(1)_{B-L}$. There is, however, a class of see-saw scenarios where the Yukawa couplings can be sizable while being the right-handed neutrinos at the TeV scale. To identify this class of scenarios we first note that there is a continuous family of Dirac neutrino masses which solves the equation $\mathcal{M}_\nu = -M_D M_M^{-1} M_D^T$, given by $M_D = iU^*\sqrt{D_m}\Omega\sqrt{D_M}V^\dagger$ [3], where U is the unitary matrix which diagonalizes $\mathcal{M}_\nu$, $\mathcal{M}_\nu = U^* D_m U^\dagger$, V the matrix which diagonalizes M_M, $M_M = V^* D_M V^\dagger$, and Ω is an arbitrary complex orthogonal matrix: $\Omega\Omega^T = 1$. In the case of two right-handed neutrinos, the matrix Ω reads [4]:

$$\Omega_{\text{NH}} \equiv \begin{pmatrix} 0 & 0 \\ \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \end{pmatrix}, \qquad \Omega_{\text{IH}} \equiv \begin{pmatrix} \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \\ 0 & 0 \end{pmatrix}, \tag{3}$$

for normal hierarchy (NH) and inverted hierarchy (IH), respectively. It is possible to exploit the freedom in the choice of Ω to generate a sizable m_D with entries in U of $\mathcal{O}(0.1)$, in D_m of $\mathcal{O}(10^{-10}$ eV) and in D_M of $\mathcal{O}(10^3$ GeV). Decomposing $\hat{\theta} = \omega - i\xi$ and taking $\xi \gg 1$ one finds:

$$\Omega_{\text{NH}} \simeq \frac{e^{i\omega}e^\xi}{2}\begin{pmatrix} 0 & 0 \\ 1 & \mp i \\ i & \pm 1 \end{pmatrix}, \qquad \Omega_{\text{IH}} \simeq \frac{e^{i\omega}e^\xi}{2}\begin{pmatrix} 1 & \mp i \\ i & \pm 1 \\ 0 & 0 \end{pmatrix}. \tag{4}$$

Thus, by adjusting ξ it is possible to construct a viable see-saw scenario with TeV mass right-handed neutrinos and arbitrarily large Dirac masses. It is also important to note that the matrix Ω introduces in general new sources of flavour structure in M_D which are unrelated to the flavour mixing observed in neutrino oscillation experiments. However, in the limit $\xi \gg 1$ the extra flavour structure is fixed, thus rendering a fairly predictive scenario.

A large Dirac neutrino mass can significantly modify the charged current (CC) and neutral current (NC) leptonic interactions, due to the large mixing between left- and right-handed neutrinos. The CC and NC interactions involving the light Majorana neutrinos have the form:

$$\mathcal{L}_{CC}^\nu = -\frac{g}{\sqrt{2}}\bar{\ell}\gamma_\rho[U_{\text{lep}}]_{\ell i}\nu_i W^\rho + \text{h.c.} \simeq -\frac{g}{\sqrt{2}}\bar{\ell}\gamma_\rho\left[\left(1 - \frac{1}{2}(RV)(RV)^\dagger\right)U\right]_{\ell i}\nu_i W^\rho + \text{h.c.}, \tag{5}$$

$$\mathcal{L}_{NC}^\nu = -\frac{g}{2c_w}\bar{\nu}_i\gamma_\rho\left[U_{\text{lep}}^\dagger U_{\text{lep}}\right]_{ij}\nu_j Z^\rho + \text{h.c.} \simeq -\frac{g}{2c_w}\bar{\nu}_i\gamma_\rho\left[U^\dagger\left(1 - (RV)(RV)^\dagger\right)U\right]_{ij}\nu_j Z^\rho + \text{h.c.} \tag{6}$$

with $R^* \simeq M_D M_M^{-1}$. Furthermore, the left-right neutrino mixing gives rise to sizable CC and NC couplings of the heavy Majorana neutrinos N_j to the W and Z bosons:

$$\mathcal{L}_{CC}^N \simeq -\frac{g}{2\sqrt{2}}\bar{\ell}\gamma_\rho(RV)_{\ell i}(1-\gamma_5)N_i W^\rho + \text{h.c.}, \tag{7}$$

$$\mathcal{L}_{NC}^N \simeq -\frac{g}{2c_w}\overline{\nu_{\ell L}}\gamma_\rho(RV)_{\ell i}N_i Z^\rho + \text{h.c.}. \tag{8}$$

Thus, the combination RV parametrizes the effects of the heavy neutrinos in low energy phenomenology. Using the parametrization discussed above, this matrix can be cast as $RV \simeq -iU_{\text{lep}}\sqrt{D_m}\Omega^*\sqrt{D_M^{-1}}$ [5], which allows to express it in terms of the measurable neutrino parameters, the neutrino Yukawa eigenvalue and the heavy neutrino masses. Explicitly [6]:

$$(RV)_{\alpha 1} \simeq -e^{i\omega}yv\sqrt{\frac{M_2}{(M_1+M_2)}}\sqrt{\frac{m_3}{m_2+m_3}}(U_{\alpha 3} + i\sqrt{\frac{m_2}{m_3}}U_{\alpha 2}), \tag{9}$$

while $(RV)_{\alpha 2} \simeq \pm i\sqrt{M_1/M_2}(RV)_{\alpha 1}$. The corresponding expressions for the inverted hierarchy can be easily obtained upon the substitution $m_{2,3} \to m_{1,2}$, $U_{\alpha 2,\alpha 3} \to U_{\alpha 1,\alpha 2}$ ($\alpha = e, \mu, \tau$).

A series of measurements restrict the couplings of the charged and neutral current interactions of the light and heavy neutrinos, namely the elements of the matrix RV. Alternatively, these constraints can be translated into constraints on the parameters of the full theory, which in this scenario are just the neutrino Yukawa eigenvalue and the right-handed neutrino masses.

3. Constraints on the parameters of the TeV scale see-saw mechanism

The most important constraint on this scenario comes from measurements of neutrinoless double beta decay $((\beta\beta)_{0\nu})$. In the presence of additional CC interactions, the effective Majorana mass $|(m_\nu)_{ee}|$, which controls the $(\beta\beta)_{0\nu}$ rate, reads [7]:

$$|(m_\nu)_{ee}| \simeq \left| \sum_{i=1}^{3} U_{ei}^2 \, m_i - \sum_{k=1}^{2} \frac{M_a^2}{M_k} f(A) \, (RV)_{ek}^2 \right|, \qquad (10)$$

where $M_a \approx 0.9$ GeV and $f(A) = 0.079$ for ^{76}Ge. Thus, assuming $M_2 \sim 1000$ GeV and $|(RV)_{e2}| \sim 10^{-2}$, the experimental constraint $|(m_\nu)_{ee}| < 0.35$ eV [8] requires $(M_2 - M_1)/M_1 \lesssim 10^{-2}$. Thus, in this scenario the constraints from $(\beta\beta)_{0\nu}$ require the right-handed neutrinos to form a pseudo-Dirac pair in order to suppress the otherwise large lepton number violating effects.

Furthermore, the heavy neutrinos have lepton flavour violating CC interactions, which can contribute via quantum effects to the rare lepton decays. In contrast to the standard contribution to the process $\mu \to e\gamma$ from the light neutrinos, which is very suppressed by the tiny factor $\Delta m^2/M_W^2$ due to the GIM mechanism, the contribution from the heavy neutrinos is not GIM suppressed and could lead to large rates, unless the couplings are small. More concretely, if the rare muon decay is dominated by the effects of the heavy neutrinos [9]:

$$\mathrm{B}(\mu \to e\gamma) \simeq \frac{3\alpha}{8\pi} |(RV)_{\mu 1}(RV)_{e1}|^2 \left| G\left(\frac{M_1^2}{M_W^2}\right) - G(0) \right|^2, \qquad (11)$$
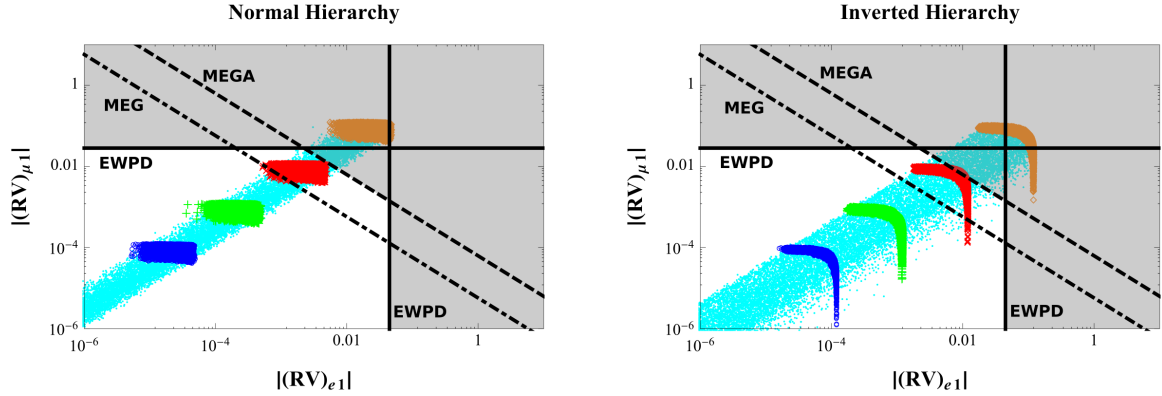
where $G(x)$ is a monotonic function which takes values in the interval $[4/3, 10/3]$, with $G(x) \cong \frac{10}{3} - x$ for $x \ll 1$. Then, in order to satisfy the experimental upper bound from MEGA [10], $\mathrm{B}(\mu \to e\gamma) \le 1.2 \times 10^{-11}$, the couplings must satisfy $|(RV)_{\mu 1}(RV)_{e1}| \lesssim 1.8 \times 10^{-4} \, (0.6 \times 10^{-4})$ for $M_1 = 100 \, (1000)$ GeV [6].

Lastly, the sizable left-right neutrino mixing implies a 3×3 leptonic mixing matrix which is non-unitary. From present neutrino oscillation data and different measurements of electroweak processes (e.g., on $W^\pm$ decays, invisible Z decays, universality tests of EW interactions) it follows that $|(RV)_{e1}|^2 \lesssim 2 \times 10^{-3}$, $|(RV)_{\mu 1}|^2 \lesssim 0.8 \times 10^{-3}$, $|(RV)_{\tau 1}|^2 \lesssim 2.6 \times 10^{-3}$ for $M_1 \gtrsim 100$ GeV [11].

We show in Fig. 1 the summary of constraints on the parameter space of the TeV see-saw scenario when the light neutrino spectrum has NH (left panel) and IH (right panel) for $M_1 = 1000$ GeV and different Yukawa couplings [6]. From the plot it follows that the most stringent constraint on the parameter space comes from neutrino oscillation experiments and the non-observation of the process $\mu \to e\gamma$, which restricts the Yukawa coupling to be $\lesssim 0.1$. Furthermore, our analysis indicates that the present bound on the $\mu \to e\gamma$ decay rate will make very difficult the observation of heavy right-handed neutrinos at the LHC or the observation of deviations from the Standard Model predictions in the electroweak precision measurements.

4. Conclusions

We have studied the constraints on a see-saw scenario where the right-handed neutrino mass lies at the TeV scale. In this scenario the flavour structure of the neutrino Yukawa couplings is essentially determined by the low energy neutrino parameters, leading to fairly strong correlations among the new phenomena. We have shown that the constraints from neutrino oscillation experiments and the non-observation of the process $\mu \to e\gamma$ makes very difficult the observation of the heavy right-handed neutrinos at the LHC or the observation of deviations from the Standard Model predictions in the electroweak precision measurements. However, the experimental constraints on this scenario still allow i) for an enhancement of the rate of neutrinoless double beta decay, which thus can be in the range of sensitivity of the GERDA

Figure 1. Constraints on the parameter space of the TeV see-saw scenario, spanned by $|(RV)_{e1}|$ and $|(RV)_{\mu1}|$ when the light neutrino spectrum has normal hierarchy (left panel) and inverted hierarchy (right panel), for $M_1 = 1$ TeV and neutrino Yukawa eigenvalue $y = 0.001$ (blue $\circ$), $y = 0.01$ (green $+$), $y = 0.1$ (red $\times$) and $y = 1$ (orange $\diamondsuit$). The cyan points correspond to random values of $y \leq 1$. The grey areas are excluded by the present measurements of electroweak precision observables (solid lines) or by the constraint $B(\mu \rightarrow e\gamma) \leq 1.2 \times 10^{-11}$ from MEGA (dashed line). The dot-dashed line corresponds to $B(\mu \rightarrow e\gamma) = 10^{-13}$, which is the projected sensitivity of the MEG experiment.

experiment [12] even when the light Majorana neutrinos possess a normal hierarchical mass spectrum, and ii) for the predicted $\mu \rightarrow e\gamma$ decay rate to be within the sensitivity range of the MEG experiment [13].

References
[1] For a review see, for example, Gonzalez-Garcia M C and Maltoni M 2008 *Phys. Rept.* **460** 1-129
[2] del Aguila F, Aguilar-Saavedra J A and Pittau R 2007 *JHEP* **0710** 047
[3] Casas J A and Ibarra A 2001 *Nucl. Phys.* B **618** 171-204
[4] Ibarra A and Ross G G 2004 *Phys. Lett.* B **591** 285; Ibarra A and Ross G G 2003 *Phys. Lett.* B **575** 279
[5] Ibarra A, Molinaro E and Petcov S T 2010 *JHEP* **1009** 108
[6] Ibarra A, Molinaro E and Petcov S T 2011 *Phys. Rev.* D **84** 013005
[7] Vergados J 1983 *Nucl. Phys.* B 218 109; Haxton W C and Stephenson J 1984 *Prog. Part. Nucl. Phys.* **12** 409; Blennow M *et al.* 2010 *JHEP* **1007** 096
[8] Klapdor-Kleingrothaus H V *et al.* 2001 *Eur. Phys. J.* A **12** 147-154
[9] Petcov S T 1977 *Sov. J. Nucl. Phys.* **25** 340 [Yad. Fiz. **25** (1977) 641]; Bilenky S M , Petcov S T and Pontecorvo B 1977 *Phys. Lett.* B **67** 309; Cheng T P and Li L F 1980 *Phys. Rev. Lett.* **45** 1908
[10] Brooks M L *et al.* [MEGA Collaboration] 1999 *Phys. Rev. Lett.* **83** 1521
[11] Antusch A, Baumann J P and Fernandez-Martinez E 2009 *Nucl. Phys.* B**810** 369
[12] Abt I *et al. Preprint* hep-ex/0404039; Smolnikov A A *Preprint* arXiv:0812.4194 [nucl-ex]
[13] Maki A 2008 *AIP Conf. Proc.* **981** 363-365