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:

\[ -L \supset -\nu_L M_D \nu_R + \frac{1}{2} \nu_R M M \nu_R + h.c. \]  

(1)

In terms of the mass eigenstates \( \nu_i \) and \( N_i \) this Lagrangian reads:

\[ -L \supset 1/2 \nu_i M_{\nu i j} \nu_j + 1/2 N_i c M_{N i j} N_j + h.c. \]  

(2)

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

Low energy experiments restrict the eigenvalues of \( M_\nu \) 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 \( M_\nu \simeq -M_D M_M^{-1} M_D^T \), it follows that, naively, when \( M_M = 1 \text{ TeV} \) then \( m_D \approx 10^{-4} \text{ GeV} \) 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 $M_\nu = -M_D M_M^{-1} M_D^t$, given by $M_D = i U^* \sqrt{D_m^{\Omega} V^T \sqrt{D_M V} \Omega}$ [3], where $U$ is the unitary matrix which diagonalizes $M_\nu$, $M_\nu = U^* D_m U$, $V$ the matrix which diagonalizes $M_M$, $M_M = V^* D_M V$, and $\Omega$ is an arbitrary complex orthogonal matrix: $\Omega \Omega^T = 1$. In the case of two right-handed neutrinos, the matrix $\Omega$ reads [4]:

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

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

$$\Omega_{NH} \approx \frac{e^{i \omega} e^\xi}{2} \begin{pmatrix} 0 & 0 & 0 \\ 1 & \mp i & i \\ i & \pm i & 0 \end{pmatrix}, \quad \Omega_{IH} \approx \frac{e^{i \omega} e^\xi}{2} \begin{pmatrix} 1 & \mp i & 0 \\ i & i & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$ (4)

Thus, by adjusting $\xi$ 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 $\Omega$ 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) lepton 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:

$$\mathcal{L}_{CC}^N = -\frac{g}{\sqrt{2}} \bar{\nu}_i U_{i \ell} \nu_\ell W^\rho + \text{h.c.} \simeq -\frac{g}{\sqrt{2}} \bar{\nu}_i \gamma_\rho \left[\left(1 - \frac{1}{2} (RV)(RV)^T\right) \nu_\ell \right]_{ij} \nu_\ell W^\rho + \text{h.c.},$$

$$\mathcal{L}_{NC}^N = -\frac{g}{2c_w} \bar{\nu}_i U_{i \ell} \nu_\ell \nu \gamma_\rho \left[U_{i \ell} U_{\ell j}\right] \nu_j Z^\rho + \text{h.c.} \simeq -\frac{g}{2c_w} \bar{\nu}_i \gamma_\rho \left[U^\dagger \left(1 - (RV)(RV)^T\right) U\right]_{ij} \nu_j Z^\rho + \text{h.c.},$$ (5)

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:

$$\mathcal{L}_{CC}^N \simeq -\frac{g}{2\sqrt{2}} \bar{\nu}_i \gamma_\rho (RV) \left(1 - \gamma_5\right) N_j \nu_\rho + \text{h.c.},$$

$$\mathcal{L}_{NC}^N \simeq -\frac{g}{2c_w} \bar{\nu}_i \gamma_\rho (RV) \left(1 - \gamma_5\right) N_j \nu_j Z^\rho + \text{h.c.}.$$ (7)

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 $RV \simeq -i U_{\nu \ell} \sqrt{D_m^{\Omega} V^T \sqrt{D_M V} \Omega}$ [5], which allows to express it in terms of the measurable neutrino parameters, the neutrino Yukawa eigenvalue and the heavy neutrino masses. Explicitly [6]:

$$(RV)_{a1} \simeq -e^{i \omega} y \nu \sqrt{\frac{M_2}{M_1 + M_2}} \sqrt{\frac{m_3}{m_2 + m_3}} (U_{a3} + i \sqrt{\frac{m_2}{m_3}} U_{a2}),$$ (9)

while $(RV)_{a2} \simeq \pm i \sqrt{M_1/M_2} (RV)_{a1}$. The corresponding expressions for the inverted hierarchy can be easily obtained upon the substitution $m_{2,3} \rightarrow m_{1,2}$, $U_{a2,3} \rightarrow U_{a1,2}$ ($\alpha = e, \mu, \tau$).

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.

---

The $U(1)_{B-L}$ is a spontaneous symmetry breaking mechanism that allows for the creation of a seesaw mechanism where the light neutrino mass can be generated by a small Dirac mass term $m_D$ compared to the heavy Majorana masses $M_M$. The seesaw formula $m_\nu = -M_D M_M^{-1} M_D^T$ is used to relate the light neutrino mass matrix to the heavy Majorana mass matrix. The matrix $\Omega$ is chosen to diagonalize $M_\nu$ and $M_M$, allowing for a continuous family of Dirac masses.

The CC and NC interactions are modified due to the large mixing between left- and right-handed neutrinos. The expressions for the CC and NC couplings involve the matrix $RV$, which parametrizes the effects of the heavy neutrinos in low energy phenomenology. The resulting expressions for $(RV)_{a1}$ and $(RV)_{a2}$ are given in terms of the measurable neutrino parameters and the neutrino Yukawa eigenvalue.
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]:

\[
|(m_\nu)_{ee}| \approx \sum_{i=1}^{3} U_{ei}^2 m_i - \sum_{k=1}^{2} \frac{M_k^2}{M_1} f(A) (RV)_{ek}^2,
\]

where \( M_a \approx 0.9 \) GeV and \( f(A) = 0.079 \) for \(^{76}\)Ge. Thus, assuming \( M_2 \approx 1000 \) 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 \( \mu \rightarrow e\gamma \) from the light neutrinos, which is very suppressed by the tiny factor \( \Delta m^2/M_3^2 \) 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]:

\[
B(\mu \rightarrow e\gamma) \approx \frac{3\alpha}{8\pi} |(RV)_{\mu1}(RV)_{e1}|^2 |G\left(\frac{M_1^2}{M_W^2}\right) - G(0)|^2,
\]

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], \( B(\mu \rightarrow e\gamma) \lesssim 1.2 \times 10^{-11}\), the couplings must satisfy \(|(RV)_{\mu1}(RV)_{e1}| \lesssim 1.8 \times 10^{-4}\) \((0.6 \times 10^{-4})\) for \( M_1 = 100 \) (1000) GeV [6].

Lastly, the sizable left-right neutrino mixing implies a \( 3 \times 3 \) 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 \(|(RV)_{e1}|^2 \lesssim 2 \times 10^{-3}\), \(|(RV)_{\mu1}|^2 \lesssim 0.8 \times 10^{-3}\), \(|(RV)_{\tau1}|^2 \lesssim 2.6 \times 10^{-3}\) 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 \( \mu \rightarrow e\gamma \), which restricts the Yukawa coupling to be \( \lesssim 0.1\). Furthermore, our analysis indicates that the present bound on the \( \mu \rightarrow e\gamma \) 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 \( \mu \rightarrow e\gamma \) 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 ◦), $y = 0.01$ (green +), $y = 0.1$ (red ×) and $y = 1$ (orange ◊). 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].

Acknowledgments
The author would like to thank Emiliano Molinaro and Serguey Petcov for a very pleasant and fruitful collaboration. This work was partially supported by the DFG cluster of excellence “Origin and Structure of the Universe.”

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. 2003 Eur. Phys. J. A 12 147-154
[9] Pontecorvo B 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. B810 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