LOW ENERGY SIGNATURES OF THE TEV SCALE SEESAW MECHANISM

Emiliano Molinaro

Centro de Física Teórica de Partículas (CFTP)
Instituto Superior Técnico, Lisboa, Portugal

in collaboration with A. Ibarra and S.T. Petcov

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OUTLINE

SEESAW MECHANISMS

A Majorana mass term for $\nu_{\ell L}(x)$ can arise after EWSB from the (*unique*) d=5 operator:

$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{L^c_\ell}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_{\ell'}\right) + \mathrm{H.c.}$$

$$L_\ell(x) \;=\; (\nu_{\ell L}(x), \ell_L(x)) \;, \qquad \tilde{\phi}(x) \;=\; i\tau_2\phi(x)$$

$$\Downarrow$$

Three possible extensions of the SM. Tree-level exchange of new "heavy" particles:

1. Type I Seesaw scenario: *SM-singlet fermions*
2. Type II Seesaw scenario: *SU(2)-triplet scalars* with $Y = 2$
3. Type III Seesaw scenario: *SU(2)-triplet fermions* with $Y = 0$

TYPE I SEESAW SCENARIO

- Seesaw scenarios with *two mass scales* $(M_D,\ M_N)$:

$$\mathcal{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(M_D)_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^C_{aL}}\,(M_N)_{ab}\,\nu_{bR} \;+\; \mathrm{H.c.}$$

- Neutrino mass eigenstates (χ_i, N_j), $i = 1,2,3,$ $j = 1,\ldots,k$:

$$\Omega^T \begin{pmatrix} \mathbf{O}_{3\times 3} & M_D \\ M_D^T & M_N \end{pmatrix} \Omega \;=\; \begin{pmatrix} U^*_{\mathrm{PMNS}}\,\hat{m}\,U^\dagger_{\mathrm{PMNS}} & \mathbf{O}_{3\times k} \\ \mathbf{O}_{k\times 3} & V^*\hat{M}V^\dagger \end{pmatrix}$$

$$\hat{m} \;=\; \mathrm{diag}(m_1, m_2, m_3) \qquad \hat{M} \;=\; \mathrm{diag}(M_1, M_2, \ldots, M_k)$$

- *Hierarchy between Dirac and Majorana mass scales*: $R^* \equiv M_D\, M_N^{-1}$

$$\Omega \;\simeq\; \begin{pmatrix} \mathbf{1} - \frac{1}{2}RR^\dagger & R \\ -R^\dagger & \mathbf{1} - \frac{1}{2}R^\dagger R \end{pmatrix} \;+\; \mathcal{O}(R^3)$$

TYPE I SEESAW SCENARIO

$$
\begin{aligned}
m_\nu &\equiv U^*_{\rm PMNS}\,\hat{m}\,U^\dagger_{\rm PMNS} \simeq -M_D M_N^{-1} M_D^T \equiv -(RV)^*\,\hat{M}\,(RV)^\dagger \\
|(m_\nu)_{\ell\ell'}| &\cong \Big|\sum_k (RV)^*_{\ell' k}\, M_k\, (RV)^\dagger_{k\ell}\Big| \lesssim 1\ \text{eV}
\end{aligned}
$$

- *Standard type I see-saw scenario*:
  $M_D \approx 100$ GeV and $m_j \approx 0.05$ eV $\Longrightarrow$ $M_j \approx 10^{14}$ GeV
  any low energy effect of RH neutrinos decouples at least with their mass squared

- *Alternative see-saw scenarios*: $M_j = (100 \div 1000)$ GeV
  $\Longrightarrow$ approx. conserved lepton charge
  $\Longrightarrow$ sizable $(RV)_{\ell k}$ and heavy pseudo-Derac neutrinos
  Branco, Grimus, Lavoura, 1989; Gonzalez-Garcia, Valle, 1989; Kersten, Smirnov, 2007; Gavela, Hambye, Hernandez, Hernandez, 2009

Possibility of testing the see-saw mechanism at colliders

TYPE I SEE-SAW SCENARIO

- The mixing between RH Majorana neutrinos and LH flavour neutrinos constrained by low energy data (*neutrino oscillations, lepton universality tests, rare lepton decays, ...,and $(\beta\beta)_{0\nu}$-decay*)
- CC and NC weak interactions of *light* Majorana neutrinos χ_j:

$$\mathcal{L}^{\nu}_{CC} = -\frac{g}{\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,((1+\eta)U_{\rm PMNS})_{\ell j}\,\chi_{jL}\,W^\alpha + \text{H.c.}\,,$$

$$\mathcal{L}^{\nu}_{NC} = -\frac{g}{2c_w}\,\overline{\chi_{iL}}\,\gamma_\alpha\,\left(U^\dagger_{\rm PMNS}(1+\eta+\eta^\dagger)U_{\rm PMNS}\right)_{ij}\,\chi_{jL}\,Z^\alpha$$

$\eta = -\frac{1}{2}RR^\dagger,\ |\eta_{ij}| \lesssim \mathcal{O}(10^{-3})$ Antusch, Baumann, Fernandez-Martinez, 2009;
Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, 2006

- CC and NC interactions of *heavy* Majorana fermions N_k:

$$\mathcal{L}^{N}_{CC} = -\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha + \text{H.c.}\,,$$

$$\mathcal{L}^{N}_{NC} = -\frac{g}{4c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,Z^\alpha + \text{H.c.}$$

TYPE I SEE-SAW SCENARIO

Constraints on the neutrino Yukawa couplings in the pseudo-Dirac regime:
$|M_2 - M_1|/M_1 \ll 1$ and $M_3 \gg M_{1,2}$, $(RV)_{\ell 2} \simeq \pm i(RV)_{\ell 1}\sqrt{M_2/M_1}$

- Size of neutrino Yukawa couplings:

$$\begin{aligned} y^2 v^2 &\equiv \max\left\{\mathrm{eig}\left(M_D M_D^\dagger\right)\right\} \\ &\cong 2\, M_1^2 \left(\left|(RV)_{e1}\right|^2 + \left|(RV)_{\mu 1}\right|^2 + \left|(RV)_{\tau 1}\right|^2\right) \end{aligned}$$

- Constraints from perturbative unitarity, $\Gamma_{N_i}/M_i < 1/2$:

$$y < 4$$

- Constraints from EW precision observables, η_{ii}:

$$y \lesssim 0.06 \left(\frac{M_1}{100\ \mathrm{GeV}}\right)$$

$\mu \to e + \gamma$

- $$B(\mu \to e + \gamma) = \frac{\Gamma(\mu \to e + \gamma)}{\Gamma(\mu \to e + \nu_\mu + \overline{\nu}_e)} = \frac{3\alpha_{\rm em}}{32\pi} |T|^2$$

$$T = \sum_{j=1}^{3} [(1+\eta)\, U_{\rm PMNS}]^*_{\mu j}\, [(1+\eta)\, U_{\rm PMNS}]_{ej}\, G\left(\frac{m_j^2}{M_W^2}\right) + \sum_{k=1}^{2} (RV)^*_{\mu k}\, (RV)_{ek}\, G\left(\frac{M_k^2}{M_W^2}\right)$$

- Upper limit on the couplings from $B(\mu \to e + \gamma) < 1.2 \times 10^{-11}$:

$$\left|(RV)^*_{\mu 1}\, (RV)_{e1}\right| < 1.8\,(0.6) \times 10^{-4}\,, \quad \text{for } M_1 = 100\,(1000)\,\text{GeV}$$

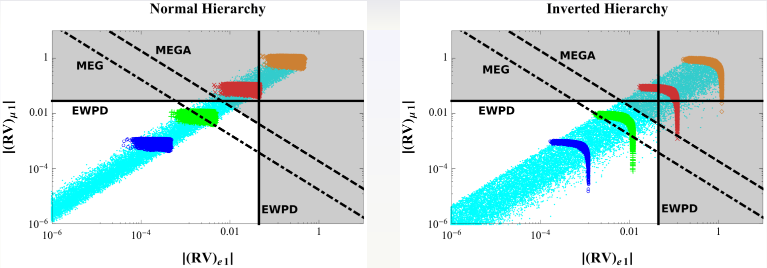

Figure: $M_1 = 100$ GeV and *i*) $y = 0.001$, *ii*) $y = 0.01$, *iii*) $y = 0.1$, *iv*) $y = 1$.

production and detection at the LHC with $L \sim 13\ \mathrm{fb}^{-1}$ *with a* 5σ *significance for* $M_1 \sim 100\,\mathrm{GeV}$*:*

del Aguila, Aguilar-Saavedra, 2009

$$q\bar{q}' \to \mu^+ N_{PD} \to \mu^+\mu^- W^+ \to \mu^+\mu^-\mu^+\nu_\mu$$

$$\Downarrow$$

$$y \gtrsim 0.04 \ \text{ for NH with } M_1 = 100\,\mathrm{GeV}$$
$$y \gtrsim 0.05 \ \text{ for IH with } M_1 = 100\,\mathrm{GeV}$$

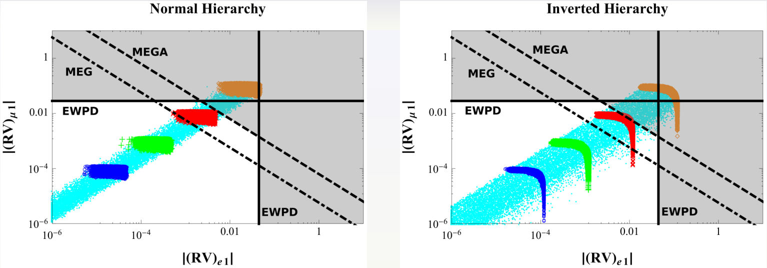

Figure: $M_1 = 1000$ GeV and *i*) $y = 0.001$, *ii*) $y = 0.01$, *iii*) $y = 0.1$, *iv*) $y = 1$.

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NEUTRINOLESS DOUBLE BETA DECAY

$$(A, Z) \implies (A, Z+2) + e^- + e^-$$

$$^{48}\mathrm{Ca},\ ^{76}\mathrm{Ge},\ ^{82}\mathrm{Se},\ ^{124}\mathrm{St},\ ^{130}\mathrm{Te},\ ^{136}\mathrm{Xe}$$

- The decay rate of the nucleus is: $\Gamma_{0\nu\beta\beta} \propto |{<}m{>}|^2$:

$$|{<}m{>}| \;\cong\; \left|\sum_i (U_{\rm PMNS})^2_{ei}\, m_i - \sum_k F(A, M_k)\,(RV)^2_{ek}\, M_k\right|$$

- From the see-saw mass relation:

$$|{<}m{>}| \;\cong\; \left|\sum_k (RV)^2_{ek}\, M_k\,(1 + F(A, M_k))\right| \propto |(RV)_{e1}|^2 |M_2 - M_1|/M_1$$

- The function $F(A, M_k)$ exhibits a rather weak dependance on A:

Haxton, Stephenson, 1984; Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez, 2010

$$F(A, M_k) \;\cong\; \left(\frac{M_a}{M_k}\right)^2 f(A)$$

$$M_a \cong 0.9\,\mathrm{GeV}, \qquad M_k \gtrsim 100\,\mathrm{GeV}, \qquad f(A) \approx 10^{-2} \div 10^{-1}$$

NEUTRINOLESS DOUBLE BETA DECAY

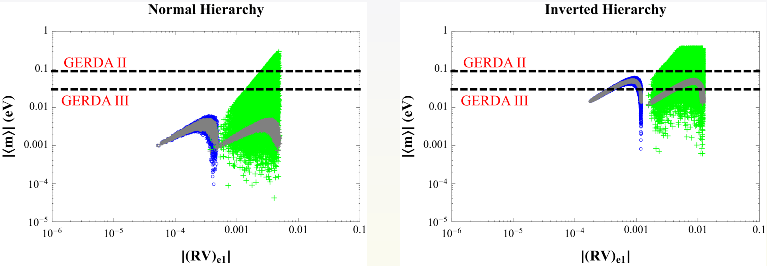

Figure: $|<m>|$ vs $|(RV)_{e1}|$ for ^{76}Ge, for $M_1 = 100$ GeV and $i)$ $y = 0.001$, $ii)$ $y = 0.01$. In gray $|<m>^{\rm std}|$.

INTERPLAY BETWEEN $B(\mu \to e + \gamma)$ AND $|< m >|$

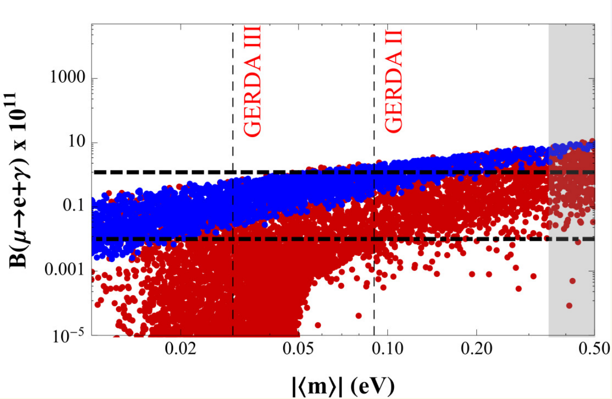

Figure: $M_1 = 100$ GeV, $|M_2 - M_1|/M_1 = 10^{-3}$ and *i*) NH neutrino mass spectrum, *ii*) IH neutrino mass spectrum.

SUMMARY

- $|(m_\nu)_{\ell\ell'}| \lesssim 1$ eV and non-observation of $(\beta\beta)_{0\nu}$-decay implies extremely suppressed CC and NC interactions of N_j with SM charged leptons and neutrinos, unless N_j form a pseudo-Dirac pair (softly broken L charge)
- The flavour structure of the NC and CC couplings of the heavy RH neutrinos is essentially determined by the low energy neutrino parameters, leading to strong correlations among different observables
- The present lower bound on $\mu \to e + \gamma$ decay rate makes very difficult the observation of the heavy RH neutrinos at LCH or the observation of deviations from the SM predictions in the EW precision data
- All present experimental constraints on this scenario still allow *i*) for an enhancement of the rate of $(\beta\beta)_{0\nu}$-decay, within the sensitivity of GERDA, even with NH light $\nu's$ mass spectrum and *ii*) for $\mu \to e + \gamma$ decay rate to be within the sensitivity range of the MEG experiment