Effect of light-heavy neutrino mixing on LNV and LFV decays in LRSM

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Outline

- Generic Left-Right Symmetric Model
- LRSM with natural type-II seesaw
- Effect of light-heavy neutrino mixing on $0\nu\beta\beta$ decay
- Effect of light-heavy neutrino mixing on LFV decays
- Constraining lightest neutrino mass scale from results
- Summary and Conclusion

Left-Right Model as New Physics

- Gauge Symmetry:

$$\mathcal{G}_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

- The existence of right-handed (RH) neutrinos, as required for the type-I seesaw mechanism, or the triplet scalars, as required for the type-II seesaw mechanism can both be naturally motivated in a LRSM.
- neutrino mass generation: In conventional LRSM, where symmetry breaking is implemented with scalar bidoublet and triplets, light neutrino mass is governed by both type-I and type-II seesaw contributions:

$$M_\nu \;=\; -M_D M_R^{-1} M_D^T + M_L \;\equiv\; M_\nu^{\rm I} + M_\nu^{\rm II}\,.$$

M_D is the Dirac neutrino mass, M_R and M_L are the Majorana masses of right and left-handed neutrinos respectively.

Generic LRSM

- The scale of M_R is decided by the vev of right-handed scalar triplet (Δ_R) which spontaneously breaks LRSM to SM.
- The smallness of light neutrino mass is connected to high scale of parity restoration which can't be verified by current and planned collider experiments.
- **TeV scale LRSM:**

$$Left - right\ mixing\ \propto\ \frac{M_D^2}{M_R};$$

$$M_R \sim TeV,\ M_D^2 \sim 10^4 GeV,\ M_\nu \sim GeV(invalid)$$

- Thus M_D should be taken to be very small in order to get sub-eV scale light neutrino mass.

Type-I/Type-II dominance in LRSM

- For phenomenological purposes, it is usually assumed that only one of the contributions is dominant for the low-scale LRSM.
- New physics contributions to LNV ($0\nu\beta\beta$ decay) mainly involves left-right mixing which depends on Dirac neutrino mass M_D.
- Necessarily M_D should be large in order to expect LNV signatures.
- **Type-I dominance:** Assume $M_L \rightarrow 0$

  $$M_\nu \; = \; -M_D M_R^{-1} M_D^T$$

  light-heavy neutrino mixing effects are suppressed for TeV-scale parity restoration
- **Type-II dominance:** Assume $M_D \rightarrow$ very much suppressed

  $$M_\nu \; = \; M_L$$

  Studies that assume $M_D \rightarrow 0$ therefore miss to comment on LNV, LFV involving left-right mixing.

Natural type-II seesaw dominance

- **natural Type-II dominance:** In this case, type-I seesaw contribution is exactly cancelled out $\Rightarrow$ we get only type-II contribution without any assumption.
- **advantages:** allows large value for $M_D \longrightarrow$ large left-right mixing $\longrightarrow$ new physics contributions to $0\nu\beta\beta$ decay
- **Pritimita, Dash, Patra; JHEP: 10(2016) 147**
  We analyze all new physics contributions to $0\nu\beta\beta$ decay to derive bound on the absolute scale of lightest neutrino masses and mass hierarchy.
- **Dash, Pritimita, Patra, Yajnik; arxiv: 2105.11795**
  We ignore W_R, Δ_R contributions and focus only on those contributions which involve large active-sterile neutrino mixing.

LRSM with natural type-II seesaw dominance

Dash, Pritimita, Patra, Yajnik; arXiv: 2105.11795

- **Fermions**

  $q_L(2,1,1/3,3)$ $q_R(1,2,1/3,3)$

  $\ell_L(2,1,-1,1)$ $\ell_R(1,2,-1,1)$

  $\mathbf{S\,(1,1,0,1)}$

  Scalars

  $\Phi(2,2,0,1)$

  $\Delta_L(3,1,2,1)$ $\Delta_R(1,3,2,1)$

  $H_L(2,1,-1,1)$ $H_R(1,2,-1,1)$

- The neutral lepton sector of generic LRSM contains three active left-handed neutrinos ν and three right-handed neutrinos N_R.
- We add three sterile neutrinos S, for generating light neutrino mass through natural type-II seesaw term.
- Int. lagrangian for leptons,

$$
\begin{aligned}
-\mathcal{L}_{Yuk} \;&=\; \overline{\ell_L}\left[Y_3\Phi + Y_4\widetilde{\Phi}\right]\ell_R + f\,\left[\overline{(\ell_L)^c}\ell_L\Delta_L + \overline{(\ell_R)^c}\ell_R\Delta_R\right] \\
&\quad + F\,\overline{(\ell_R)}H_R S^c + F'\,\overline{(\ell_L)}H_L S + \mu_S\overline{S^c}S \;+\text{h.c.} \\
&\supset\; M_D\overline{\nu}N_R + M_L\overline{\nu^c}\nu + M_R\overline{N_R^c}N_R + M\overline{N_R}S + \mu_L\overline{\nu^c}S + \mu_S\overline{S^c}S
\end{aligned}
$$

LRSM with natural type-II seesaw dominance

Dash, Pritimita, Patra, Yajnik; arXiv:2105.11795

- We have taken the mass parameter $\mu_S \overline{S^c} S$ to be zero or very small so that the generic inverse seesaw contribution involving μ_S is very much suppressed.
- induced VEV for H_L is also taken to be zero ($\langle H_L \rangle \to 0$).
- **complete neutral lepton mass matrix (with $\langle H_L \rangle \to 0$, $\mu_S \to 0$)**

$$\mathbb{M} = \left(\begin{array}{c|ccc} & \nu & S & N_R^c \\ \hline \nu & M_L & 0 & M_D \\ S & 0 & 0 & M \\ N_R^c & M_D^T & M^T & M_R \end{array} \right), \; M_R > M > M_D \gg M_L,$$

$$m_\nu = M_L \quad \text{(type-II seesaw)},$$

$$m_S \simeq M M_R^{-1} M^T \,, \quad m_N = M_R$$

M is mixing matrix in N_R, S sector, $M_L(M_R)$ is Majorana mass matrix for left-handed (right-handed) neutrinos.

Diagonalization Procedure

- With seesaw approx.: $M_R > M > M_D \gg M_L$, after integrating out heavy neutrinos, the resulting neutrino mass matrix :

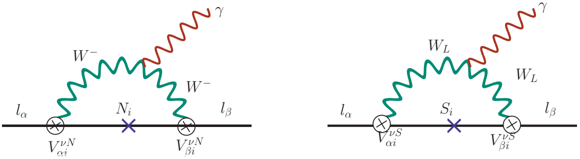
$$\begin{aligned} \mathbb{M}' &= \begin{pmatrix} M_L & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} M_D \\ M \end{pmatrix} M_R^{-1} \begin{pmatrix} M_D^T & M^T \end{pmatrix} \\ &= \begin{pmatrix} M_L - M_D M_R^{-1} M_D^T & -M_D M_R^{-1} M^T \\ M M_R^{-1} M_D^T & -M M_R^{-1} M^T \end{pmatrix} \end{aligned}$$

- Applying seesaw approx., $|-MM_R^{-1}M^T| > |-M_D M_R^{-1} M^T|$

$$\begin{aligned} m_\nu &= \left[M_L - M_D M_R^{-1} M_D^T \right] \\ &\quad - \left(-M_D M_R^{-1} M^T \right) \left(-M M_R^{-1} M^T \right)^{-1} \left(-M M_R^{-1} M_D^T \right) \\ &= M_L - M_D M_R^{-1} M_D^T + M_D M_R^{-1} M_D^T = M_L = m_\nu^{\mathrm{II}} \end{aligned}$$

LFV in LRSM

- In our model, LFV decays can be mediated by heavy right-handed neutrino N_R, extra sterile neutrino S, charged scalar triplets $\Delta^{\pm\pm}_{L,R}$ and gauge bosons $W_{L,R}$.
- We focus only on those contributions which involve large active-sterile neutrino mixing, i.e. due to the neutrinos N_R and S in order to constrain light neutrino masses from LFV decays.



- We ignore other possible contributions by imposing the limiting conditions; $M_{W_R} \gg M_{W_L}, \quad M_{\Delta_{L,R}} \gg M_{N,S}$

Model features

- One of the elegant features of this framework is that we have expressed model parameters like light neutrino mass, heavy and sterile neutrino masses in terms of oscillation parameters.
- For NH ($m_1 \sim m_2 << m_3$),

$$\begin{aligned} m_1 &= \text{lightest neutrino mass} \\ m_2 &= \sqrt{m_1^2 + \Delta m_{\rm sol}^2} \\ m_3 &= \sqrt{m_1^2 + \Delta m_{\rm atm}^2 + \Delta m_{\rm sol}^2} \end{aligned}$$

- For IH ($m_3 << m_1 \sim m_2$),

$$\begin{aligned} m_3 &= \text{lightest neutrino mass} \\ m_1 &= \sqrt{m_3^2 + \Delta m_{\rm atm}^2} \\ m_2 &= \sqrt{m_1^2 + \Delta m_{\rm sol}^2 + \Delta M_{\rm atm}^2} \, . \end{aligned}$$

Model features

- LFV decays mediated via heavy neutrino N_R and sterile neutrino S are proportional to masses and mixing of N_R, S.
- In the model, masses and mixing of heavy neutrinos are expressed in terms of oscillation parameters.
- Thus, LFV contributions can also be expressed in terms of oscillation parameters.
- For ex.,

$$\mathrm{Br}_{\mu\to e\gamma} = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_\mu^4}{M_{W_L}^4}\frac{m_\mu}{\Gamma_\mu}|\mathcal{G}_\gamma^{\mu e}|^2 \,,$$

where, $\Gamma_\mu = 2.996 \times 10^{-19}$ GeV (total decay width of muon),

$$G_\gamma^{\mu e} \;=\; \left|\sum_{i=1}^{3}\left\{\mathrm{V}_{\mu i}^{\nu N^*}\mathrm{V}_{ei}^{\nu N}\mathcal{G}_\gamma\left(x_{N_i}\right) + \mathrm{V}_{\mu i}^{\nu S^*}\mathrm{V}_{ei}^{\nu S}\mathcal{G}_\gamma\left(x_{S_i}\right)\right\}\right|^2$$

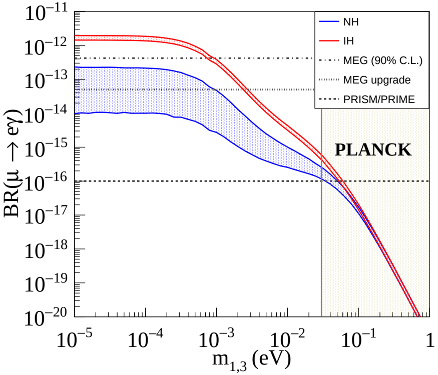
Experimental bounds on LFV decays

New physics models that discuss LFV are constrained by muon decay experiments since the current limits on τ observables are less stringent.

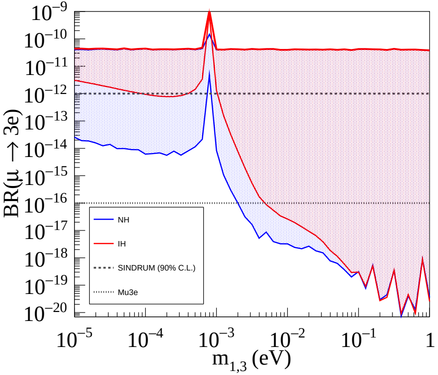
LFV Decays (with Branching Ratios)	Present Bound	Future Sensi
$\mathrm{Br}\,(\mu \to e\gamma)$	$\leq 4.2 \times 10^{-13}$ (MEG)	$\leq 1.0 \times 10^{-16}$ (P
$\mathrm{Br}\,(\mu \to 3e)$	$\leq 1.0 \times 10^{-12}$ (SINDRUM)	10^{-16} (Mu3

Table: Branching ratios for different LFV processes and their present experimental bound and future sensitivity values taken from various refs.

Constraints on light neutrino mass scale from $\mu \to e\gamma$ $[N_R + S$ contributions$]$

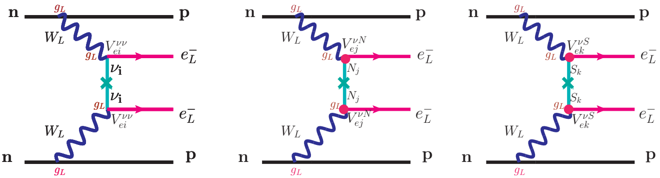


Constraints on light neutrino mass scale from $\mu \to 3e$ [$N_R + S$ contributions],



New contributions to $o\nu\beta\beta$ decay

We give emphasis on left-handed current effects due to the exchange of heavy neutrinos N_R and S_L.



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{01}^{0\nu}\left|\frac{\mathcal{M}_\nu^{0\nu}}{m_e}\right|^2\left[\left|m_{ee}^{\nu}\right|^2+\left|m_{ee}^{N}\right|^2+\left|m_{ee}^{S}\right|^2\right]$$

$$= G_{01}^{0\nu}\left(\frac{\mathcal{M}_\nu^{0\nu}}{m_e}\right)^2\cdot\left|m_{\beta\beta}^{\rm eff}\right|^2 .$$

where, $G^{0\nu}$ is phase-space factor, $\mathcal{M}_\nu^{0\nu}$ is NME, $m_{\beta\beta}^{\rm eff}$ is effective Majorana mass parameter.

Experimental constraints on $o\nu\beta\beta$ decay

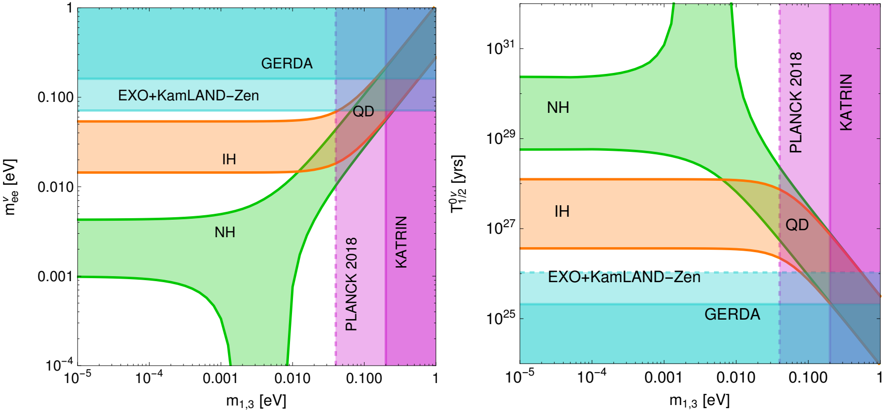
Isotope	$G_{01}^{0\nu}$ $[yrs^{-1}]$	$\mathcal{M}_{\nu}^{0\nu}$	$\mathcal{M}_{N}^{0\nu}$	
^{76}Ge	5.77×10^{-15}	2.58–6.64	233–412	
^{136}Xe	3.56×10^{-14}	1.57–3.85	164–172	

Table: phase space factor and NMEs taken from various refs.

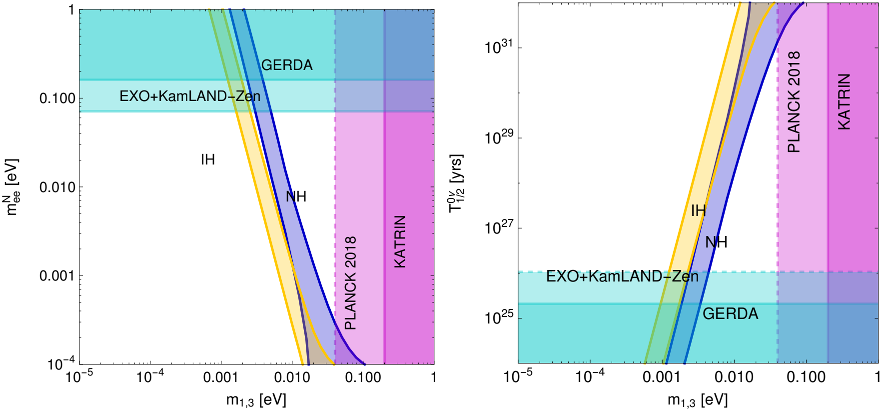
Experiment	Limit
GERDA	2.1×10^{25} yrs
GERDA Phase II	5.2×10^{25} yrs
EXO	1.6×10^{25} yrs
KamLAND-Zen	1.9×10^{25} yrs
Combined ^{136}Xe	3.4×10^{25} yrs

Table: Limits on the half-life of $0\nu\beta\beta$.

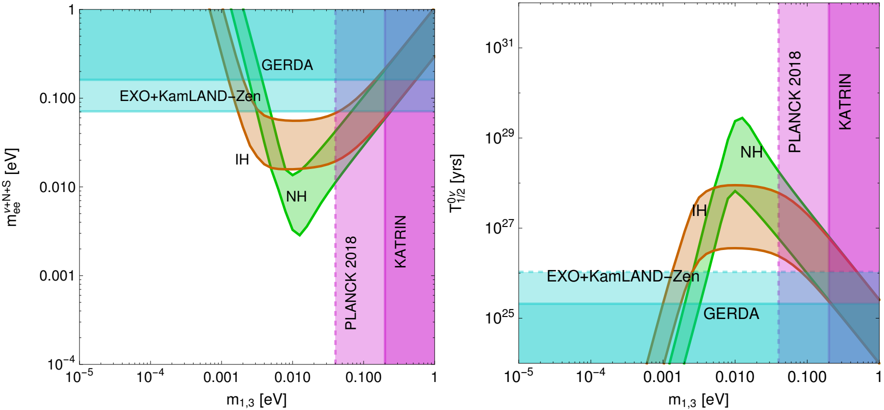
Standard mechanism contribution to $0\nu\beta\beta$ decay



Constraints on lightest nu mass from $o\nu\beta\beta$ decay ($N_R + S$ contributions)



Constraints on lightest nu mass from $o\nu\beta\beta$ decay ($\nu + N_R + S$ contributions)



imp. result on mass hierarchy

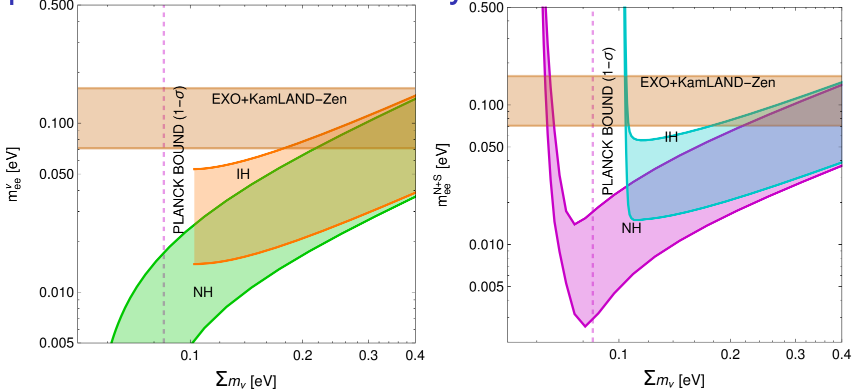
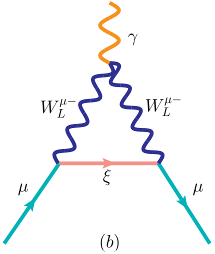


Figure: Allowed region of effective Majorana mass parameter ($|m_{ee}|$) as a function of sum of light neutrino masses (Σm_i) for std mechanism (left-panel) and N_R, S mediated diagrams (right-panel).

$$\Sigma_{m_\nu} < 84\,\text{meV}\ (1\sigma\ \text{C.L.}),\ < 146\,\text{meV}(2\sigma\ \text{C.L.}),\ < 208\,\text{meV}(3\sigma\ \text{C.L.})$$

Comments on muon (g-2) anomaly



(Majumdar, Patra, Pritimita, Senapati, Yajnik; JHEP 09 (2020) 010)

- In this framework new contributions to a_μ can arise with heavy and sterile neutrino N_R, S mediation.
- These contributions depend on heavy and sterile neutrino masses and their mixing with muons, which are related to light neutrino masses and oscillation parameters.
- Thus, this scenario opens the possibility of constraning light neutrino masses and mass hierarchy from FNAL results on a_μ.

Summary and Conclusion

- Seesaw Mechanism: a simple theoretical mechanism for origin of neutrino mass which predicts Majorana nature of neutrinos.
- Type-I and Type-II seesaw can be naturally motivated in a LRSM.
- Natural type-II seesaw dominance mechanism in an extended LRSM allows large light-heavy neutrino mixing and generates new physics contributions to LNV and LFV decays.
- One elegant feature of the model is that it connects heavy neutrinos with light neutrinos by expressing heavy neutrino masses in terms of oscillation parameters.
- Thus, LFV contributions can also be expressed in terms of oscillation parameters.
- Bound on Absolute scale of neutrino masses and information on mass hierarchy can be derived by studying new contributions to LFV decays and $0\nu\beta\beta$ decay in the model.


Thank you!