Determining neutrino mass hierarchy from new physics

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Left-Right Symmetric Model as new physics

- gauge symmetry:

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

- symmetry breaking: LRSM $\xrightarrow{\text{scalar triplet}}$ SM $\xrightarrow{\text{scalar bidoublet}}$ $U(1)_{em}$
- neutrino mass generation: Light neutrino mass is generated by both type-I and type-II seesaw contributions:

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

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

- NP contributions to LNV ($0\nu\beta\beta$ decay) and LFV mainly involves left-right mixing which depends on Dirac neutrino mass M_D.
- 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.
- **advantages:** allows large value for $M_D \longrightarrow$ large left-right mixing $\longrightarrow$ new physics contributions to $0\nu\beta\beta$ decay and LFV decays
- **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 (under review in EPJC)**
  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 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 $\langle H_L \rangle \to 0$, $\mu_S \to 0$)**

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

$$m_\nu = M_L \text{ (type-II seesaw)}, \;\; m_S \simeq M M_R^{-1} M^T \,, \;\; m_N = M_R$$

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 :

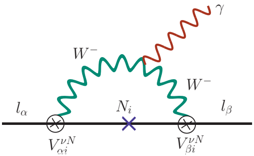
$$\begin{aligned}
\mathbb{M}' &= \begin{pmatrix} M_L & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} M_D \\ M \end{pmatrix} M_R^{-1} \begin{pmatrix} M_D^T & M^T \end{pmatrix} \\
&= \begin{pmatrix} M_L - M_D M_R^{-1} M_D^T & -M_D M_R^{-1} M^T \\ M M_R^{-1} M_D^T & -M M_R^{-1} M^T \end{pmatrix}
\end{aligned}$$

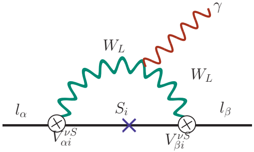
- Applying seesaw approx., $|-M M_R^{-1} M^T| > |-M_D M_R^{-1} M^T|$

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

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 $\Delta_{L,R}^{\pm\pm}$ 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; $M_{W_R} \gg M_{W_L}, \;\; M_{\Delta_{L,R}} \gg M_{N,S}$

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, $s_W \equiv sin\theta_W$ (θ_W is weak mixing angle),
$\Gamma_\mu = 2.996 \times 10^{-19}$ GeV (total decay width of muon),

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

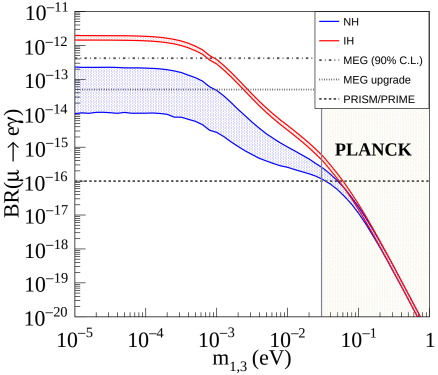
Experimental bounds on LFV decays

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

LFV Decays	Present Bound	Future Sensitivity
$\mathrm{Br}\,(\mu \to e\gamma)$	$\leq 4.2 \times 10^{-13}$ (MEG)	$\leq 1.0 \times 10^{-16}$ (PRIME..)
$\mathrm{Br}\,(\mu \to 3e)$	$\leq 1.0 \times 10^{-12}$ (SINDRUM)	10^{-16} (Mu3e)

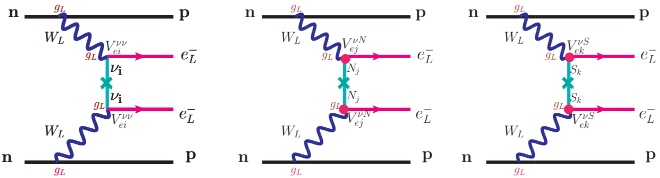
Table: Branching ratios for different LFV processes and their present experimental bound and future sensitivity values taken from various refs.

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



New contributions to $0\nu\beta\beta$ decay

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



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

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

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

Experimental constraints on $0\nu\beta\beta$ decay

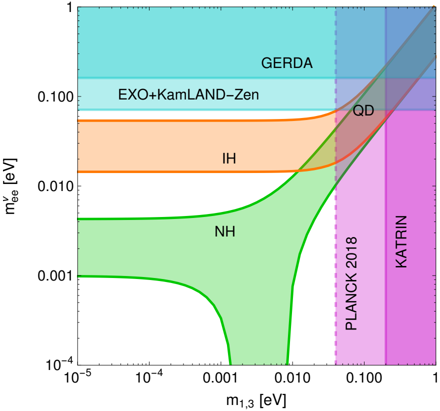
Isotope	$G_{01}^{0\nu}$ $[yrs^{-1}]$	$\mathcal{M}_{\nu}^{0\nu}$	$\mathcal{M}_{N}^{0\nu}$
^{76}Ge	5.77×10^{-15}	2.58–6.64	233–412
^{136}Xe	3.56×10^{-14}	1.57–3.85	164–172

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

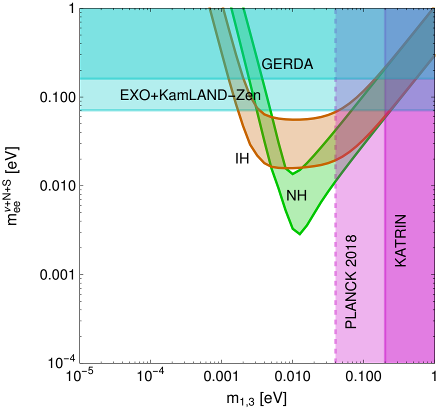
Experiment	Limit
GERDA	2.1×10^{25} yrs
GERDA Phase II	5.2×10^{25} yrs
EXO	1.6×10^{25} yrs
KamLAND-Zen	1.9×10^{25} yrs
Combined ^{136}Xe	3.4×10^{25} yrs

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

Constraints on lightest ν mass from $0\nu\beta\beta$ decay

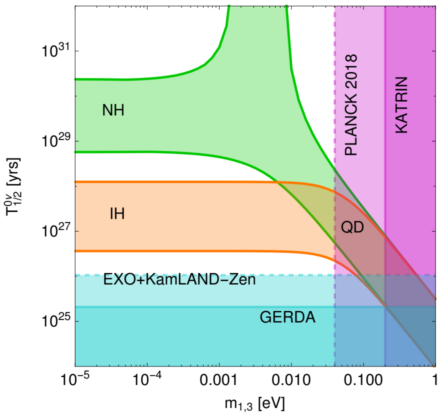


(Standard Mechanism)

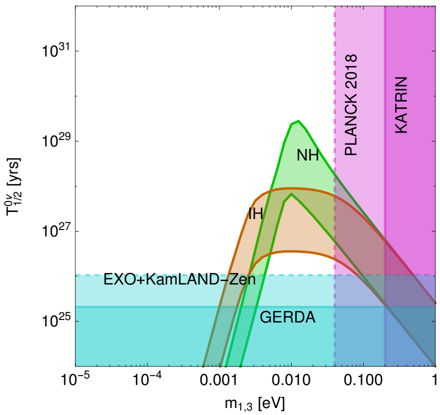


(NP contribution; $\nu + N_R + S$)

Constraints on lightest ν mass from $0\nu\beta\beta$ decay

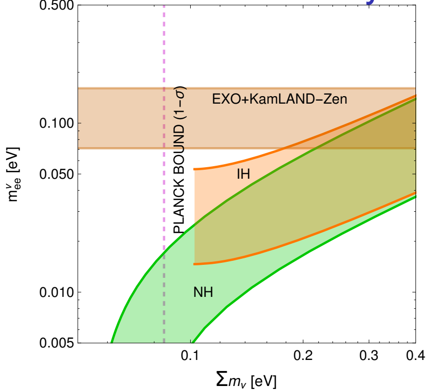


(Standard Mechanism)



(NP contribution; $\nu + N_R + S$)

result on mass hierarchy



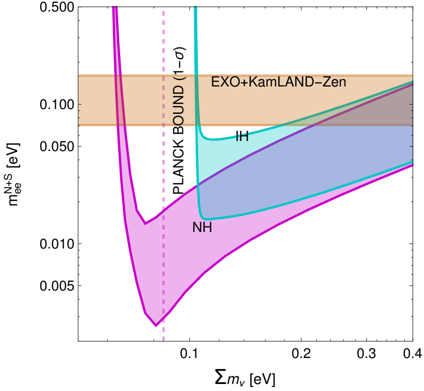


Figure: Allowed region of effective Majorana mass parameter ($|m_{ee}|$) as a function of sum of light neutrino masses (Σm_i) for std mechanism (left-panel) and N_R, S mediated diagrams (right-panel).

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

Summary and Conclusion

In the model;

- natural type-II seesaw dominance allows large light-heavy neutrino mixing and generates new physics contributions to LNV and LFV decays.
- light and heavy neutrino masses are expressed in terms of oscillation parameters.
- thus, LFV contributions can also be expressed in terms of oscillation parameters.
- bound on absolute scale of light neutrino masses and information on mass hierarchy are derived by studying new contributions to LFV decays and $0\nu\beta\beta$ decay.

Thank You!

Backup slides

In the model; The leptonic PMNS mixing matrix is parametrized in terms of neutrino mixing angles and phases as,

$$U_{\rm PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \mathrm{P},$$

mixing angles; $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, diagonal phase matrix carrying Majorana phases α and β is denoted by $\mathrm{P} = \mathrm{diag}\left(1, e^{i\alpha}, e^{i\beta}\right)$.
The light neutrino masses are in general diagonalised in terms of unitary mixing matrix $U \equiv U_{\rm PMNS}$ in a basis where charged lepton are already diagonal.

$$m_\nu^{\rm diag} = U_{\rm PMNS}^\dagger m_\nu U_{\rm PMNS}^* = \mathrm{diag}\left(m_1, m_2, m_3\right) ,$$

and the physical masses are related to the mass matrix in flavour basis as,

$$m_\nu = U_{\rm PMNS} m_\nu^{\rm diag} U_{\rm PMNS}^T .$$

Backup slides

Oscillation Parameters	Within 3σ range (*Schwetz et al.*)	within 3σ range (Gonzalez-Garcia et al.)
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	7.00-8.09	7.02 - 8.09
$\|\Delta m^2_{31}(\text{NH})\|[10^{-3}\text{eV}^2]$	2.27-2.69	2.317 - 2.607
$\|\Delta m^2_{31}(\text{IH})\|[10^{-3}\text{eV}^2]$	2.24-2.65	2.307 - 2.590
$\sin^2\theta_s$	0.27-0.34	0.270 - 0.344
$\sin^2\theta_a$	0.34-0.67	0.382 - 0.643
$\sin^2\theta_r$	0.016-0.030	0.0186 - 0.0250

Table: Neutrino oscillation parameters in 3σ range.

Backup slides

- light and heavy neutrino masses can be written as $m_\nu = f\langle\Delta_L\rangle$, $M_N = f\langle\Delta_R\rangle = (v_R/v_L)m_\nu$ with $f_L = f_R = f$.
- Since v_L and v_R are constants, the light left-handed and heavy right-handed neutrino masses are diagonalized by the same unitary mixing matrix, $U_{\rm PMNS}$.
- Thus the physical masses for right-handed neutrinos M_i are related to light neutrino mass eigenvalues m_i as $M_i \propto m_i \Rightarrow$ if the light neutrinos are normal hierarchical then the heavy right-handed neutrinos would also be hierarchical in the same manner, i.e. if $m_1 < m_2 << m_3$ then $M_{N_1} < M_{N_2} << M_{N_3}$.
- Thus, if we fix the largest mass eigenvalue of heavy right-handed neutrino as $M_N = M_{N_3}$, then M_{N_1}, M_{N_2} can be expressed in terms of NH pattern of light neutrino masses as,

$$\begin{aligned} M_{N_1} &= \frac{m_1}{m_3} M_N, \text{ NH}, \\ M_{N_2} &= \frac{m_2}{m_3} M_N, \text{ NH}. \end{aligned}$$

Backup slides

The individual mixing matrices are expressed in terms of Dirac neutrino mass matrix M_D, mixing term M and right-handed Majorana mass term M_R as,

$$\mathrm{V}^{\nu\nu} = U_{\rm PMNS}\,, \quad \mathrm{V}^{\nu S} = \frac{1}{m_S} M_D U^*_{\rm PMNS}\,, \quad \mathrm{V}^{\nu N} = \frac{v_L}{v_R} M_D U^{-1}_{\rm PMNS} \widehat{m}_\nu^{-1}\,,$$
$$\mathrm{V}^{S\nu} = \frac{1}{m_S} M_D^\dagger U_{\rm PMNS}\,, \quad \mathrm{V}^{SS} = U^*_{\rm PMNS}\,, \quad \mathrm{V}^{SN} = \frac{v_L}{v_R} m_S U^{-1}_{\rm PMNS} \widehat{m}_\nu^{-1}\,,$$
$$\mathrm{V}^{N\nu} = \mathcal{O}\,, \quad \mathrm{V}^{NS} = \frac{v_L}{v_R} m_S U^{-1}_{\rm PMNS} \widehat{m}_\nu^{-1}\,, \quad \mathrm{V}^{NN} = U_{\rm PMNS}\,.$$

For simplification, we have considered M to be diagonal and degenerate.

Backup slides

In general the Dirac neutrino mass matrix M_D is either of up-type quark mass matrix or charged lepton mass matrix. However we have considered an $SO(10)$ GUT motivated structure for M_D as,

$$M_D = \begin{pmatrix} 0.0111 & 0.0384 - 0.0103\,i & 0.038 - 0.4433\,i \\ 0.0384 + 0.0103\,i & 0.29281 & 0.8623 + 0.0002\,i \\ 0.038 + 0.4433\,i & 0.8623 - 0.0002\,i & 77.7573 \end{pmatrix}$$

Other model parameters:-

$$v_R \geq 15\,\text{TeV}\,, \quad M_{W_R} \geq 10\,\text{TeV}\,, \quad M_{\Delta^{++}} \simeq 10\,\text{TeV}\,, \quad M_N \simeq 1\,\text{TeV}\,.$$