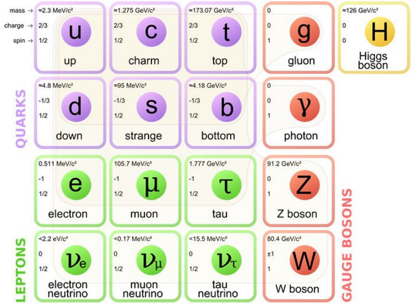
The Search for Long-Lived Sterile Neutrinos in Minimal Left-Right Symmetric EFT

Nikhef | Universiteit van Amsterdam

Jelle Groot | Presentation | 28-02-2023

Motivation



SM is great, but has its shortcomings!

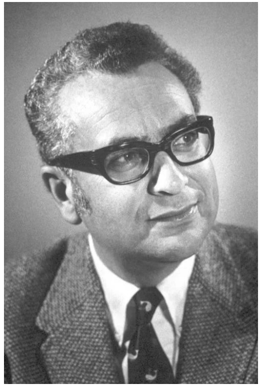
Neutrino Oscillations → SM Neutrinos have mass, but how?

Easiest solution → Add right-handed neutrino term to SM Lagrangian

$$\mathcal{L} \;=\; \mathcal{L}_{SM} - \left[\frac{1}{2}\bar{\nu}_R^c \bar{M}_R \nu_R + \bar{L}\tilde{H}Y_\nu \nu_R + \text{h.c.}\right]$$

Singlet under the SM gauge group → "Sterile neutrino"

Nothing forbids Majorana mass terms



"Everything not forbidden is compulsory"

- Murray Gell-Mann

Motivation

mLRSM

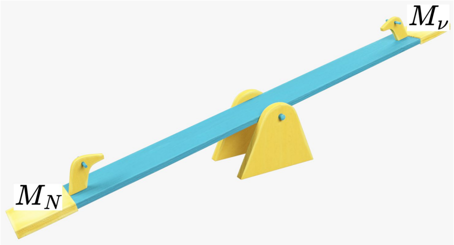
Long-Lived Sterile Neutrinos

νSMEFT

Previous Work

Current Work

Motivation



Both Dirac and Majorana mass terms → Majorana eigenstates

No clear guidelines to sterile neutrino masses

Type-I seesaw → $\begin{pmatrix} 0 & M \\ M & B \end{pmatrix}$ → active neutrino mass ~ $y_D^2 v^2 / M_N$

Naturalness argument → Extremely large M_N

Should be taken with a grain of salt!

Smaller Yukawa → Broad range of M_N

Possible Solution to other SM puzzles:

Dark matter candidate, Baryon asymmetry of the Universe

Minimal Left-Right Symmetric Model

Simple high-energy theory that adds sterile neutrinos

SM symmetry group extension:

$$G_{SM} \in SU(2)_L \times U(1)_Y \rightarrow G_{LR} \in SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Now with right-handed doublets in the fermion sector! $L_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R}$

Also: right-handed gauge bosons W_R, Z'

Important: G_{LR} needs to break down to G_{SM}

Necessary: Extend scalar sector compared to SM

Minimal Left-Right Symmetric Model

Important:
G_{LR} breaks down to G_{SM}

Necessary:
Extend scalar sector

Intuition: SM Higgs doublet → BSM Bi-doublet $\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$

$$\mathcal{L}_e = -g_e \left[\begin{pmatrix} \bar{\nu}_e & \bar{e} \end{pmatrix}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \bar{e}_R \begin{pmatrix} \phi^{+*} & \phi^{0*} \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right]$$

Not sufficient → Leads to $U(1) \times U(1)$ after EWSB

We need to introduce two extra scalar triplets: $\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix}$

Transformation rules: $\Delta_L \in (3,1,2)$, $\Delta_R \in (1,3,2)$, $\Phi \in (2,2^*,0)$

Minimal Left-Right Symmetric Model

Scalar Sector:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

When G_{LR} is spontaneously broken:

Scalar fields acquire vevs:

$$\langle\Phi\rangle = \begin{pmatrix} \kappa/\sqrt{2} & 0 \\ 0 & \kappa' e^{i\alpha}/\sqrt{2} \end{pmatrix}, \quad \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R/\sqrt{2} & 0 \end{pmatrix}, \quad \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L}/\sqrt{2} & 0 \end{pmatrix}$$

v_R : Breaks $SU(2)_R$ symmetry, sets mass scale for W_R, Z'

κ, κ' : Breaks $SU(2)_L \times U(1)_{B-L}$ to $U(1)_{EM}$, sets mass scale for $W^\pm, Z$

$$\sqrt{\kappa^2 + \kappa'^2} = v$$

Phases induce CP-violation

For consistency with experiment: $v_r > v > v_L$

Minimal Left-Right Symmetric Model

Construct all Yukawa terms:

$$\mathcal{L}_Y = -\bar{Q}_L(\Gamma\Phi + \tilde{\Gamma}\tilde{\Phi})Q_R - \bar{L}_L(\Gamma_l\Phi + \tilde{\Gamma}_l\tilde{\Phi})L_R - (\bar{L}_L^c i\tau_2\Delta_L Y_L L_L + \bar{L}_R^c i\tau_2\Delta_R Y_R L_R) + \text{h.c.}$$

After EWSB we retrieve our familiar mass matrix:

$$\mathcal{L}_\nu = -\frac{1}{2}(\bar{\nu}_L^c, \bar{\nu}_R)\begin{pmatrix} M_L^\dagger & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{h.c.}$$

Masses depend on scalar sector and Yukawa couplings:

$$M_D = (\kappa\Gamma_l + \kappa'\tilde{\Gamma}_l e^{-i\alpha})/\sqrt{2},$$
$$M_L = \sqrt{2}Y_L^\dagger v_L e^{-i\theta_L},$$
$$M_R = \sqrt{2}Y_R v_R.$$

We still have to impose a discrete symmetry:

Generalized P or Generalized C

$$\mathcal{P}: \quad \Gamma_l = \Gamma_l^\dagger, \quad \tilde{\Gamma}_l = \tilde{\Gamma}_l^\dagger, \quad Y_L = Y_R,$$
$$\mathcal{C}: \quad \Gamma_l = \Gamma_l^T, \quad \tilde{\Gamma}_l = \tilde{\Gamma}_l^T, \quad Y_L = Y_R^\dagger,$$

$$\mathcal{P}: \quad M_L = v_L/v_R M_R^\dagger e^{-i\theta_L},$$
$$\mathcal{C}: \quad M_L = v_L/v_R M_R e^{-i\theta_L}.$$

Scalar Sector after SSB:

$$\langle\Phi\rangle = \begin{pmatrix} \kappa/\sqrt{2} & 0 \\ 0 & \kappa' e^{i\alpha}/\sqrt{2} \end{pmatrix}$$

$$\langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L}/\sqrt{2} & 0 \end{pmatrix}$$

$$\langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R/\sqrt{2} & 0 \end{pmatrix}$$

Minimal Left-Right Symmetric Model

Relations between M_L and M_R:

$$\mathcal{P}: \quad M_L = v_L/v_R M_R^\dagger e^{-i\theta_L},$$
$$\mathcal{C}: \quad M_L = v_L/v_R M_R e^{-i\theta_L}.$$

Still in flavor basis → Diagonalize to go to mass basis

$$M_\nu = M_L - M_D M_R^{-1} M_D^T$$
$$M_N = M_R\,.$$

Quick Recap:

- motivated existence of sterile neutrinos
- in minimalist fashion, introduced high-energy extension to SM
- construct G_{LR} such that it leads to the usual SM *with* sterile neutrinos
- write down Lagrangian, break symmetry, retrieve mass matrix
- impose discrete symmetry, rotate to mass basis

Long-Lived Sterile Neutrinos

Long enough lifetime to be reconstructed in displaced-vertex searches

Focus:

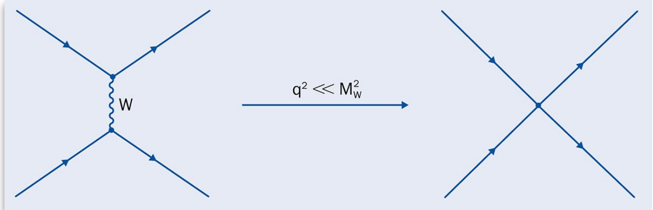
- Light sterile neutrinos (5 GeV)
- production via rare meson decays (copiously produced at LHC!)
- direct production via parton collisions neglected < 5 GeV

Separation of scales: $v_r \gg 5\ \mathrm{GeV}$

Use EFT framework with usual SM fields and n sterile neutrino fields.

Singlets in the EFT but not in mLRSM? → label 'sterile' still appropriate

νSMEFT



Renormalizable part of Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} - \left[\frac{1}{2}\bar{\nu}_R^c \bar{M}_R \nu_R + \bar{L}\tilde{H} Y_\nu \nu_R + \text{h.c.}\right]$$

Plan of attack:

- Evolve mLRSM operators down to EW scale
- match to EFT invariant under SM gauge group
- Lagrangian gives dim-4 (and lower) operators in the neutrino SM EFT → ***ν*****SMEFT**

Focus:

- higher-dimensional operators with single sterile neutrino
- hadronic processes at tree level

Generalization possible in a future work

νSMEFT

Focus:
- higher-dimensional operators with single sterile neutrino
- hadronic processes at tree level

Through matching related to G_{LR} parameters at M_{W_R}

Then:
- Evolve to EW scale
- Integrate out W-boson
- Match to $SU(3)_c \times U(1)_{\text{QED}}$ - invariant effective Lagrangian

$$\mathcal{L}^{(6,7)}_{\text{mass}} = \frac{2G_F}{\sqrt{2}} \Big\{ \bar{u}_L \gamma^\mu d_L \left[\bar{e}_L \gamma_\mu C^{(6)}_{\text{VLL}} \nu + \bar{e}_R \gamma_\mu C^{(6)}_{\text{VLR}} \nu \right] + \bar{u}_R \gamma^\mu d_R \, \bar{e}_R \, \gamma_\mu C^{(6)}_{\text{VRR}} \nu$$
$$\bar{u}_L d_R \, \bar{e}_L \, C^{(6)}_{\text{SRR}} \nu + \bar{u}_R d_L \, \bar{e}_L \, C^{(6)}_{\text{SLR}} \nu + \bar{u}_L \sigma^{\mu\nu} d_R \, \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\text{TRR}} \nu \; + \text{h.c.} \Big\}$$

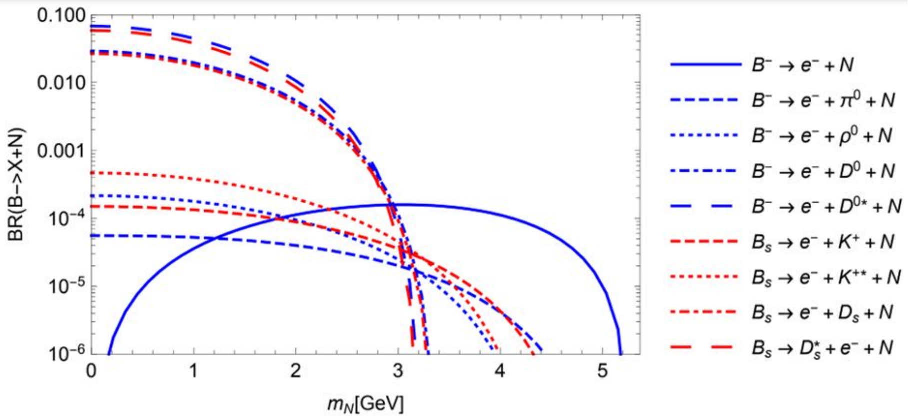
$$C^{(6)}_{\text{VLL}} = c^{(6)}_{\text{VL}} PU + \bar{C}^{(6)}_{\text{VL}} P_s U$$

with

$$c^{(6)}_{\text{VL}} = -2V\mathbb{1} - \frac{4\sqrt{2}v}{g} C^{(6)}_{\nu W} V M_D^\dagger$$

Previous Work

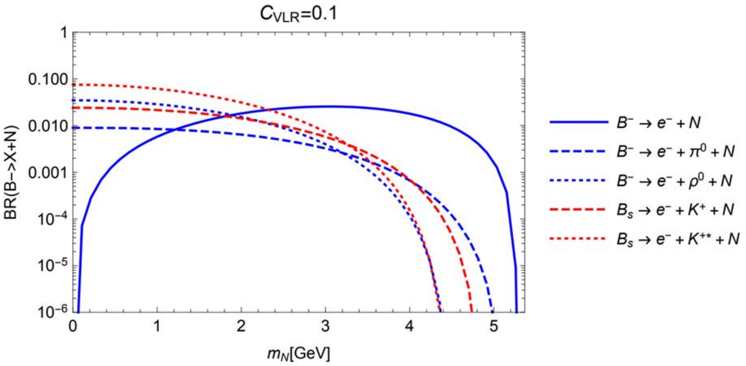
Calculated decay rates for rare mesons into sterile neutrinos:
Turn on Wilson coefficients to check dominant production channels
Only non-zero: $(C^{(6)}_{\mathrm{VLL}})_{ijk4} = -2V_{ij}U_{k4}$



Three-body decay dominate at lighter M_N

Previous Work

Turning on other Wilson coefficients



We can also calculate sterile neutrinos decaying into SM fermions:

$$N \to \nu + f + \bar{f}$$

Possibilities:

- quarks: final-state neutral mesons (PS or V)
- SM leptons
- SM neutrinos (invisible channel)

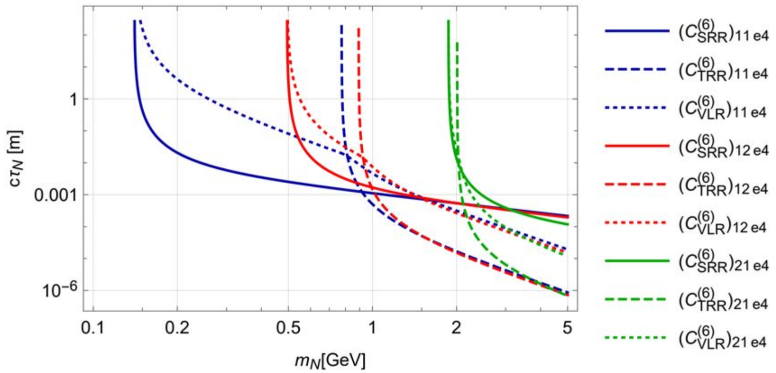
Subtleties: Multi-meson final states → Dominant at large M_N

Solution: Compare to sterile neutrino case to tau-lepton case

$$1 + \Delta_{QCD}(m_\tau) \equiv \frac{\Gamma(\tau \to \nu_e + \text{hadrons})}{\Gamma_{\text{tree}}(\tau \to \nu_\tau + \bar{u} + D))},$$ → $$1 + \Delta_{QCD}(m_N) \equiv \frac{\Gamma(N \to e^-/\nu_e + \text{hadrons})}{\Gamma_{\text{tree}}(N \to e^-/\nu_e + \bar{q}q)},$$

Previous Work

Calculate proper decay length:



Important for displaced-vertex searches!

Numerical simulations → viability of neutral long-lived particle searches

Current Work

What we've done:

- Explored high-energy model
- Constructed νSMEFT framework
- Branching ratio calculations

What's still left to do?

- Numerical simulations similar to 2021 paper
- Consider several configurations of the mLRSM parameters → flavor benchmarks
- Tying our results to their implications on $0\nu\beta\beta$ (and perhaps other LNV decays)

mLRSM Parameter Configurations:

- Vary mixing between left and right-handed gauge bosons
- Vary mass of right-handed gauge boson
- Gauge impact of CP-violating phases

Thanks for listening!