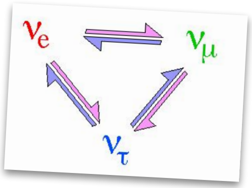
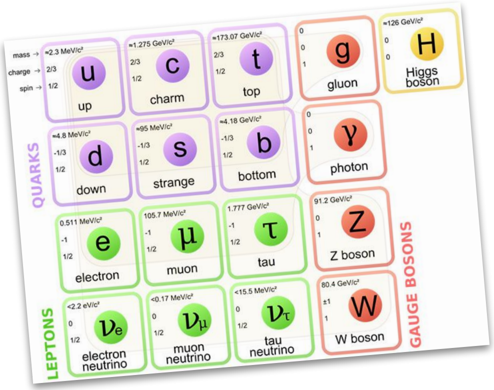
Long-Lived Sterile Neutrinos and Minimal Left-Right Symmetry

Based on arXiv:2406.15091

Jelle Groot, Jordy de Vries, Herbi Dreiner, Zeren Simon Wang, Julian Günther

Motivation: Neutrinos are massive!





The **Standard Model** is not a complete theory!

Neutrino oscillations imply massive neutrinos:

$$P(\nu_\mu \to \nu_e) \propto \sin\left(\frac{\Delta m^2 L}{2E}\right) \qquad \sum_{i=e,\mu,\tau} m_{\nu_i} \leq 0.12 \text{ eV}$$

Can we use the usual **Higgs mechanism**?

$$-y_e \overline{L}_L H e_R \xrightarrow{\text{EWSB}} -y_e v \overline{e}_L e_R$$
$$-y_\nu \overline{L}_L H \nu_R \xrightarrow{\text{EWSB}} -y_\nu v \overline{\nu}_L \nu_R$$

Add field ν_R , a **singlet** under the SM gauge group:

This requires $y_\nu \sim 10^{-12}$ to ensure $m_\nu \sim 0.1 \text{ eV}$ ...

Nothing fundamentally wrong; and nothing forbids **Majorana mass terms**!

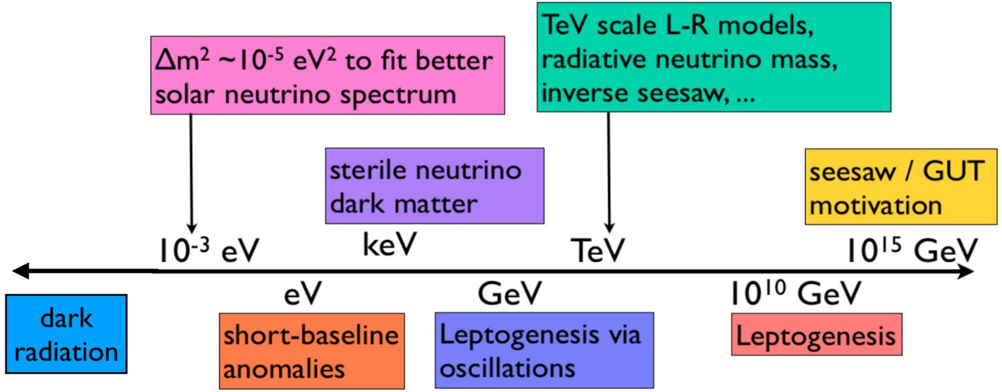
Motivation: What do we gain?

Majorana mass term doesn't break any **fundamental** symmetries:

$$\mathcal{L} \supset -y_\nu \overline{\nu_L} \varphi \nu_R - \nu_R^T C M_R \nu_R$$

M_R in principle unrelated to the EWSB scale...

What is the scale of M_R? $\rightarrow$ $y_v \simeq 1$ requires $M_R \simeq 10^{15}$ GeV



Our focus: Production of sterile neutrinos in colliders $\rightarrow M_R = \mathcal{O}(\text{GeV})$

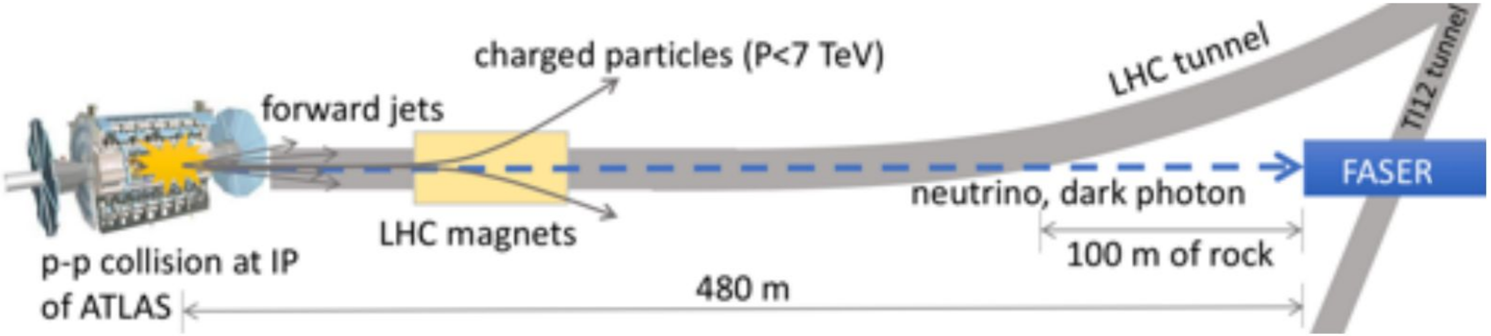
How do we look for these sterile neutrinos?

Long-lived enough to be detectable in **displaced-vertex (DV)** searches

Focus: Production via meson decays (copiously produced at LHC!)

Multiple (proposed) future DV experiments!

AL3X, ANUBIS, CODEX-b, DUNE, FACET,
FASER(2), MATHUSLA, MoEDAL-MAPP1(2), SHiP



The Standard Model as an Effective Field Theory

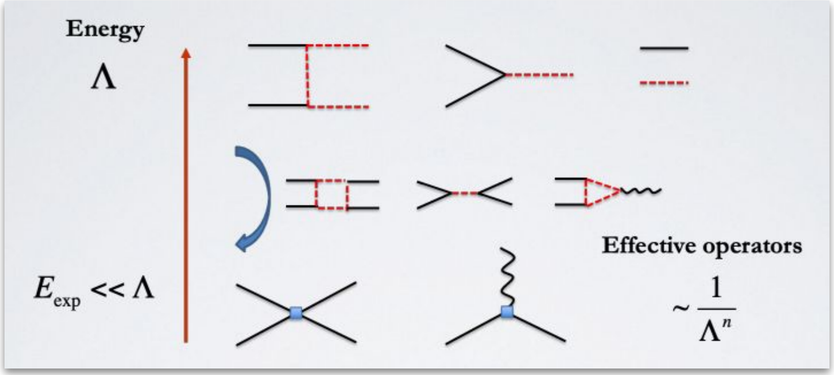
If sterile neutrinos exist, they need to arise from somewhere.

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{SM} + \sum_{d\geq 5}\sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

Agnostic approach: Attempt to make minimal assumptions regarding BSM

Assume BSM physics lives at a high energy scale $\gg v = 246\ \text{GeV}$

Separation of scales suggests using **EFT techniques**!



νSMEFT Framework

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

Focus in our work:

- Dim-6 operators with single sterile neutrino.
- Processes at tree level (generalization is possible)

Back of the envelope:

$$C_P^{(6)} = 10^{-5}$$

$$C_P^{(6)} \sim \frac{v^2}{\Lambda^2}$$

$$\Lambda \sim 80 \text{ TeV}$$

Customary in previous works:

- Express decay rates of N $\leftrightarrow$ SM in terms of νSMEFT Wilson Coefficients.
- **Benchmark Scenarios:** Estimate BSM scale sensitivity of experiments
- Turn on one Wilson coefficient for production, and one for decay.

Potential downsides: Oversimplification

- Unrealistic w.r.t. possible BSM scenarios
- Avoiding stringent limits set by other experiments ($0\nu\beta\beta$) (!)

Minimal Left-Right Symmetric Model

The salient details

Reminder:

$G_{SM} \in SU(2)_L \times U(1)_Y$

Required: SM symmetry group extension.

Elegant solution: $G_{LR} \in SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

What do we gain: Right-handed fermion doublets and gauge bosons W_R, Z'

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

ONLY FOR THE EXPERTS:

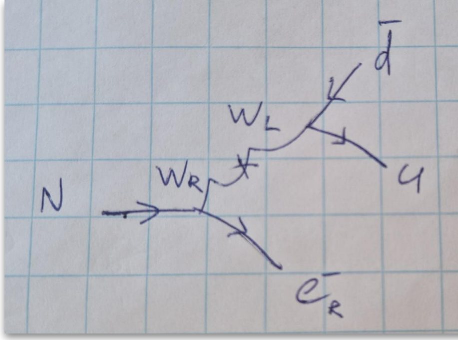
Extension of scalar section: Higgs bi-doublet and two scalar triplets

At scale $v_R \gg v$ these scalar field acquire vevs.

Choose a generalized discrete symmetry that establishes the seesaw relations

Plan of Attack

What benchmark scenarios should we consider?



> Remember: $M_N \equiv \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$

Simplest case is the **Type-II seesaw scenario:**

$M_D \to 0$. No mixing between SM neutrinos and sterile neutrinos.

Free parameters: RH gauge boson mass M_{W_R} and **mixing parameter** ξ :

Mixing matrix: $\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$

Small mixing angle: $\alpha = f(\xi) \left(\frac{M_{W_L}}{M_{W_R}} \right)^2$ with $0 < f(\xi) < 0.24$

Displaced vertex calculations

Now we have set our scene, let's do some calculations!

Sterile neutrino production:

Branching ratios of B-, D-, K- and π-mesons into sterile neutrinos.

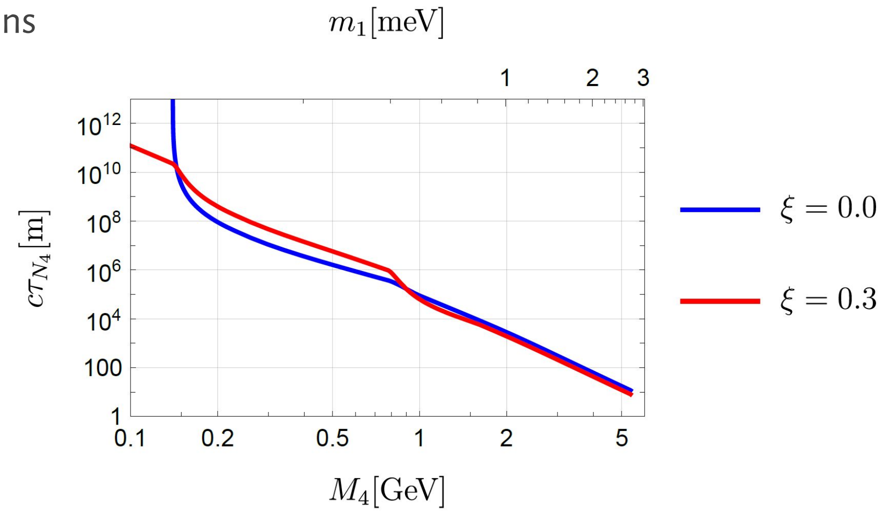
Sterile neutrino decay rates:

Possible final-state particle contents:

- Quarks: final-state mesons
- SM leptons
- SM neutrinos (invisible)

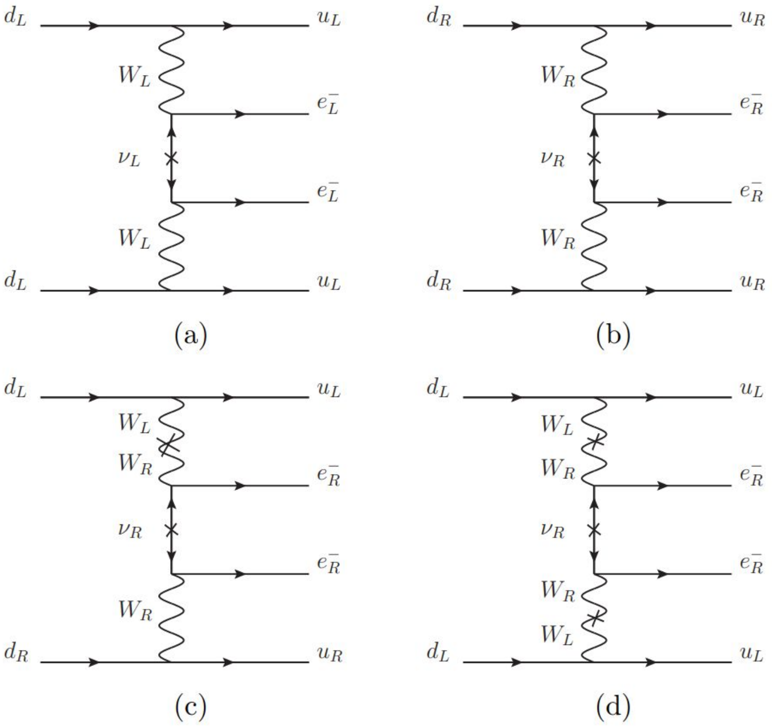
Sterile neutrino decay lengths:

Are DV searches viable?



$0\nu\beta\beta$ lifetime determination of Xenon-136

We can calculate $0\nu\beta\beta$ rates, these include some new-physics topologies:

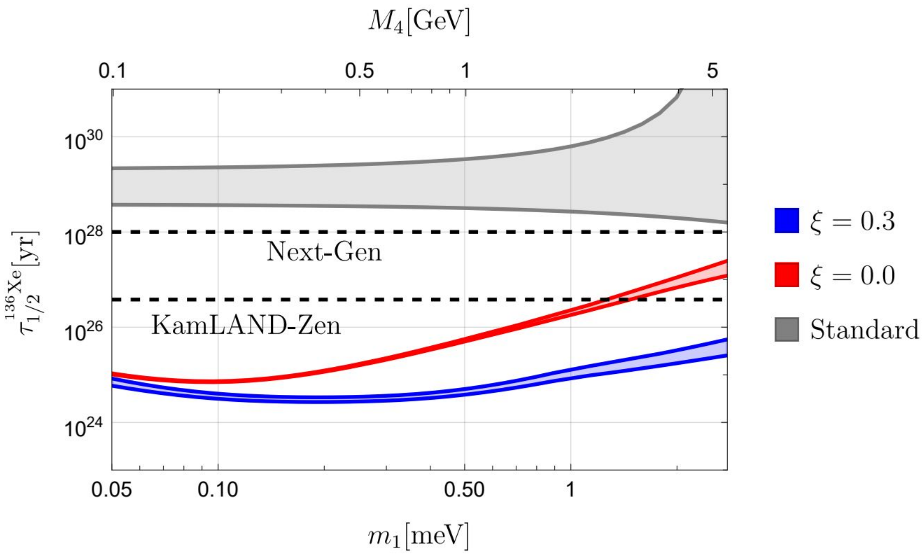


Lifetime determination of Xenon-136

$M_{W_R} = 15$ TeV
Normal Hierarchy

mLRSM can also used calculating $0\nu\beta\beta$ and other LNV processes.

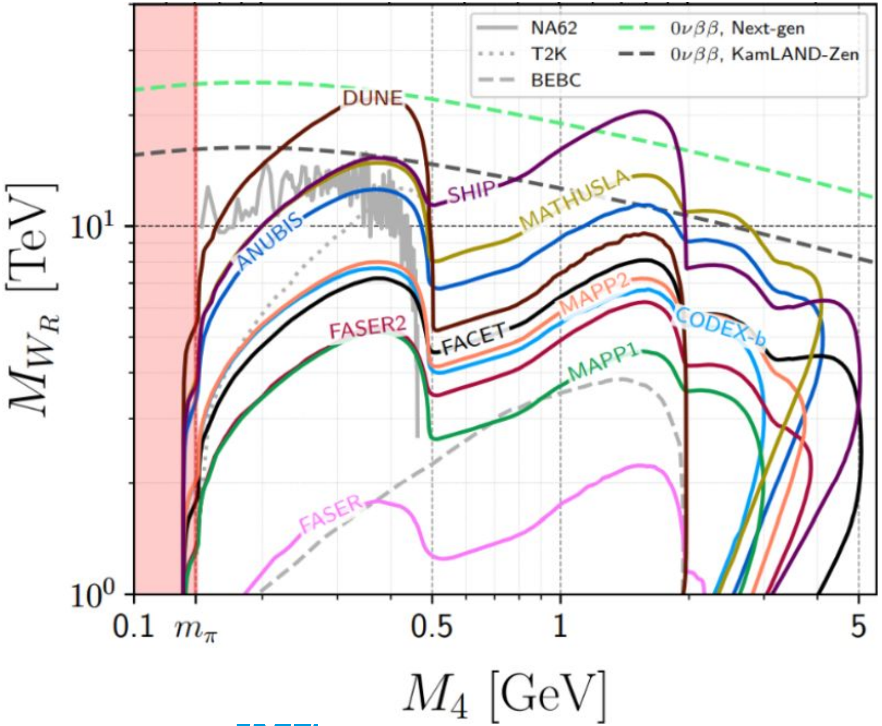
Additional decay topologies imply $0\nu\beta\beta$ signals could be found in next-gen experiments!



Compare sensitivity reaches:

Recast lifetimes, branching ratios and decay lengths.

Future $0\nu\beta\beta$ and DV experiments have comparable sensitivity reaches!



$\xi = 0.3$

Conclusions:

- mLRSM sterile neutrinos could elegantly explain multiple SM puzzles.
- DV and $0\nu\beta\beta$ searches are excellent, complementary probes of RH currents.
- Exciting future experimental bounds with sensitivities up to $M_{W_R} = \mathcal{O}(25\ \text{TeV})$
- The customary approach for DV searches could indeed be oversimplified if $0\nu\beta\beta$ limits are not included.
- Include Big Bang Nucleosynthesis bounds in a more general framework.

Thanks for your attention!

Backup slides: interference through non-zero mixing

Constructive/destructive interference is based on the Lorentz structure of the processes:

$$\langle h_{\mathrm{PS}}|\,\bar{q}_1\gamma^\mu P_{L,R}q_2\,|B,D\rangle = +\frac{1}{2}\,\langle h_{\mathrm{PS}}|\,\bar{q}_1\gamma^\mu q_2\,|B,D\rangle\,,$$
$$\langle h_{\mathrm{V}}|\,\bar{q}_1\gamma^\mu P_{L,R}q_2\,|B,D\rangle = \mp\frac{1}{2}\,\langle h_{\mathrm{V}}|\,\bar{q}_1\gamma^\mu\gamma^5 q_2\,|B,D\rangle\,,$$

Decay rates are proportional to $|C^{(6)}_{\mathrm{VRR}} \mp C^{(6)}_{\mathrm{VLR1}}|^2$

Backup slides: active-sterile neutrino-mass relation

Irrespective of choice of generalized P or C symmetry, the type-II seesaw scenario gives the relation

$$\widehat{M_N} = \frac{v_R}{v_L}\widehat{m}_\nu .$$

This leads to

$$\mathrm{NH}: M_{4,5} = \frac{m_{1,2}}{m_3} M_6, \qquad \mathrm{IH}: M_{4,5} = \frac{m_{3,1}}{m_2} M_6\,,$$

Backup slides: Neglecting 0νbb

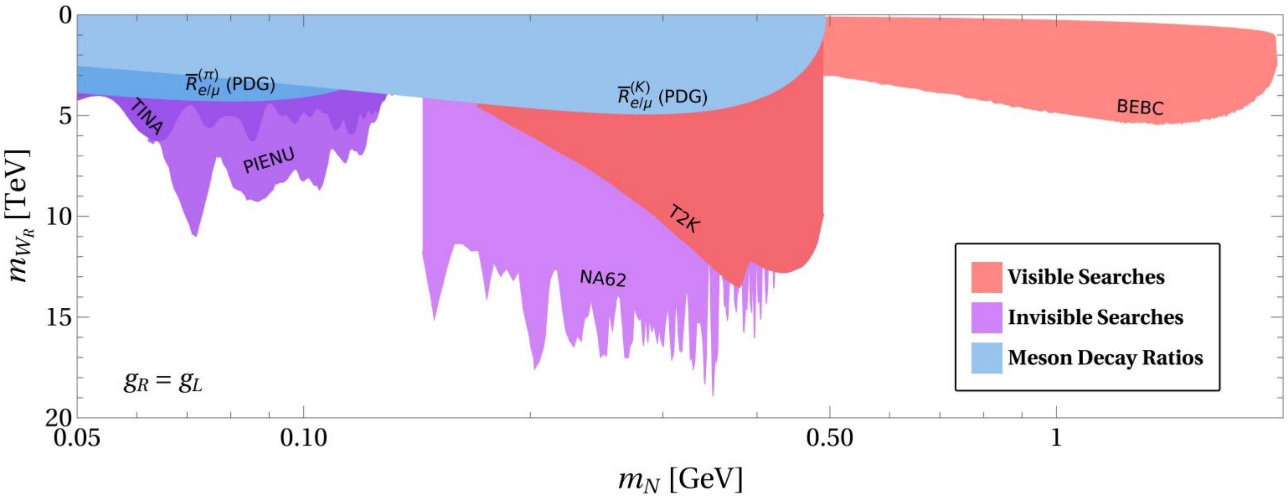


FIG. 2. Bounds on m_W as a function of m_N from visible searches (red) at T2K [27] and BEBC [31], from invisible peak searches (purple) at PIENU [53], TINA [54] and NA62 [30], as well as from π and K leptonic decay ratios (blue) [59] at 90% CL. We assume $\kappa = g_R/g_L = 1$.

$$\mathcal{L}_{\nu,\text{mass}} = -\frac{1}{2}\left(\overline{\nu_L}\ \overline{\nu_R{}^c}\right)\begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L{}^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

Backup slides: vev structure of G_LR

$$G_{\text{LR}} \equiv SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L},$$

$$\Delta_{L,R} \equiv \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix} \qquad \Delta_L \in (\mathbf{3},\mathbf{1},2) \text{ and } \Delta_R \in (\mathbf{1},\mathbf{3},2)$$

$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \Phi \in (\mathbf{2},\mathbf{2}^*,0)$$

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

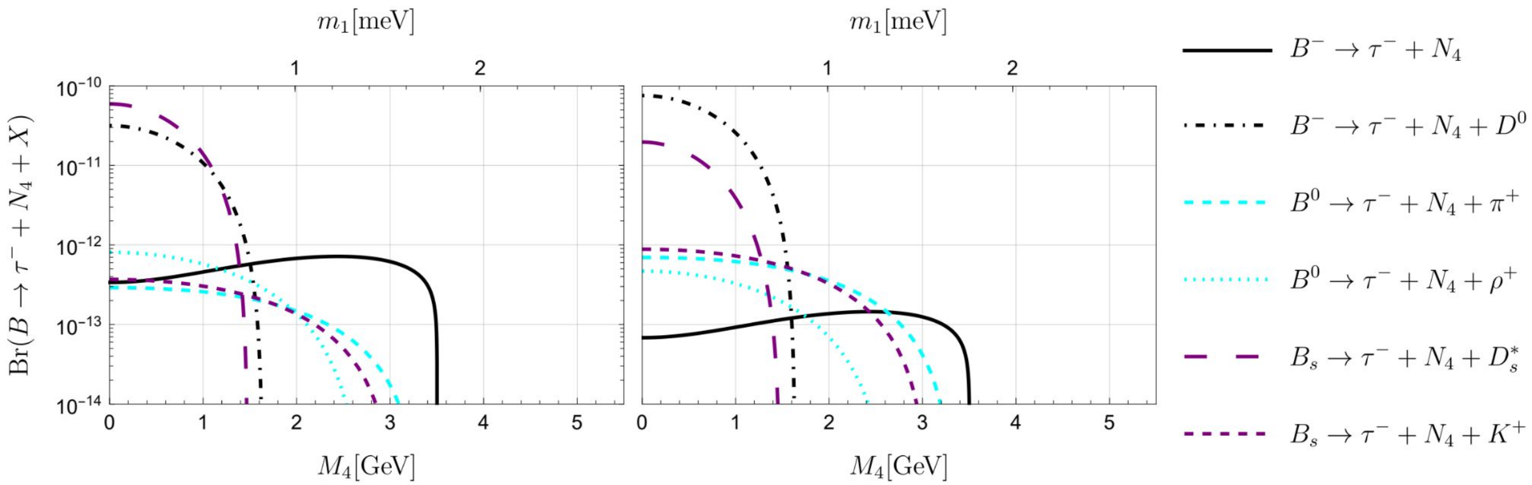
$$\sqrt{\kappa^2 + \kappa'^2} = v \qquad v_R \gg v \gg v_L$$

Sterile neutrino production rates

Determine branching ratios of B-, D-,K- and π-mesons into sterile neutrinos.

$M_{W_R} = 7$ TeV and in the left (right) panel $\xi = 0$ $(\xi = 0.3)$.

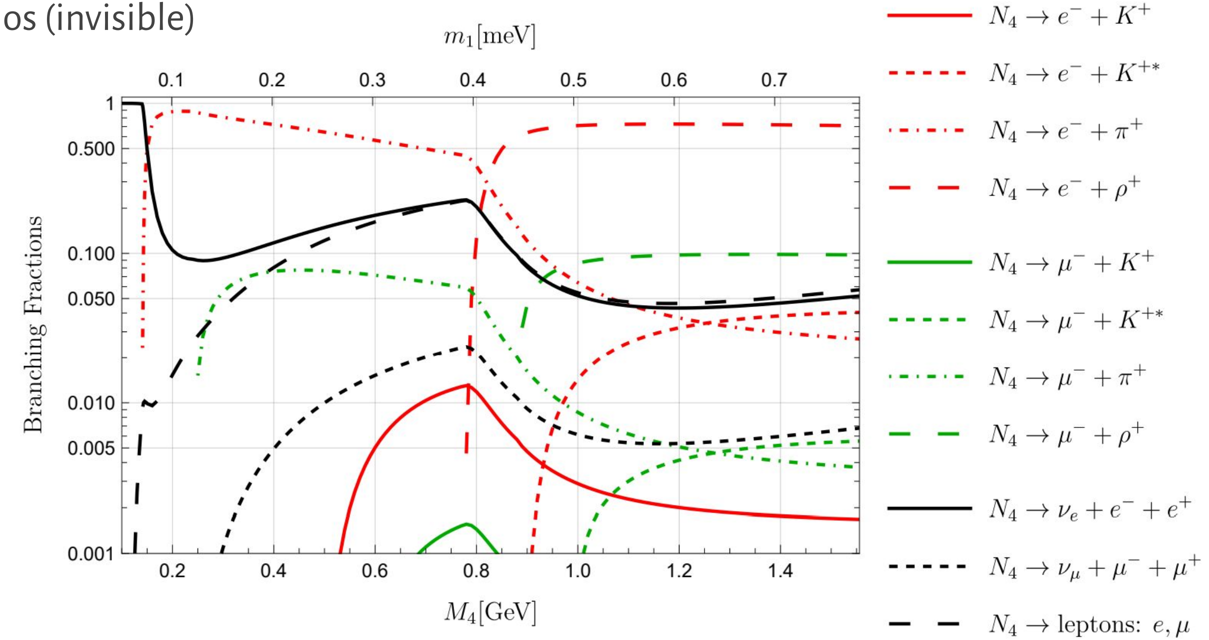
Significant constructive/destructive interference for non-zero mixing!



Sterile neutrino decay rates

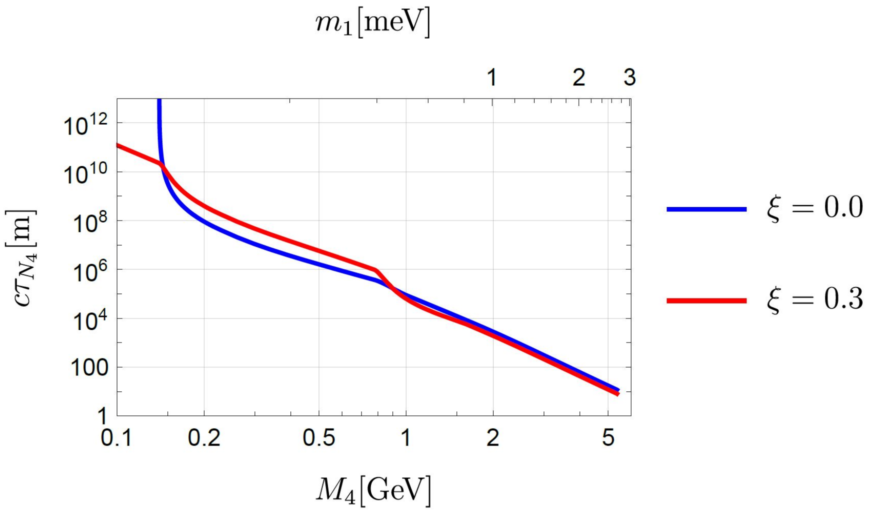
Possible final-state particle contents:

- Quarks: final-state mesons (Pseudo-scalar or Vector)
- SM leptons
- SM neutrinos (invisible)



Decay Lengths

Important in checking viability of displaced-vertex searches!



Multi-meson corrections:

For $M_4 \gtrsim 1$ GeV, assume quark currents + QCD corrections and no hadronic structure → customary in inclusive hadronic tau-lepton decay

Compare sensitivity reaches:

Left (right) panel
$\xi = 0$ ($\xi = 0.3$)

Recast lifetimes, branching ratios and decay lengths

Future $0\nu\beta\beta$ and DV experiments have comparable sensitivity reaches!