Long-Lived Sterile Neutrinos and Minimal Left-Right Symmetry

Based on arXiv:2406.15091

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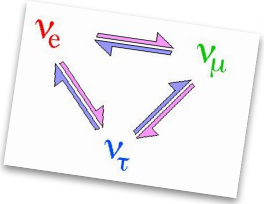
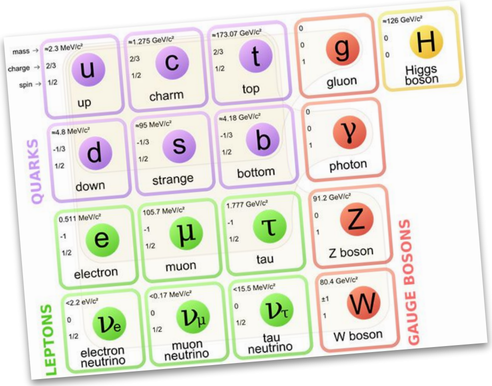
New-ν Physics: From Collider to Cosmology (Durham University)

10-04-2024

Motivation: Neutrinos are massive!





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

Neutrino oscillations imply massive neutrinos:

$$P(\nu_\mu \to \nu_e) \propto \sin\left(\frac{\Delta m^2 L}{2E}\right)$$

$$\sum_{i=e,\mu,\tau} m_{\nu_i} \leq 0.12\text{ eV} \simeq 10^{-37}\text{ kg}$$

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

$$-y_e \overline{e_L} \varphi e_R \xrightarrow{\text{EWSB}} -y_e v \overline{e_L} e_R$$

$$-y_\nu \overline{\nu_L} \varphi \nu_R \xrightarrow{\text{EWSB}} -y_\nu v \overline{\nu_L} \nu_R$$

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**!

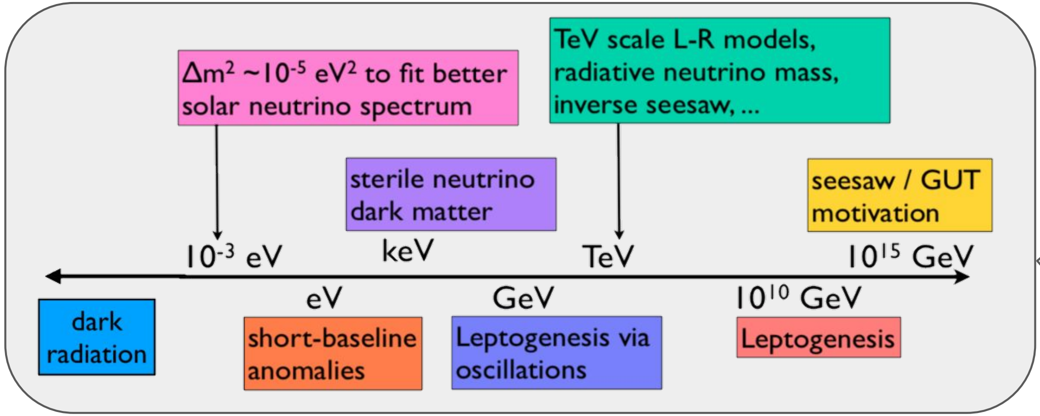
Motivation: Where do we look?

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

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

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



Graphic stolen from Thomas!

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

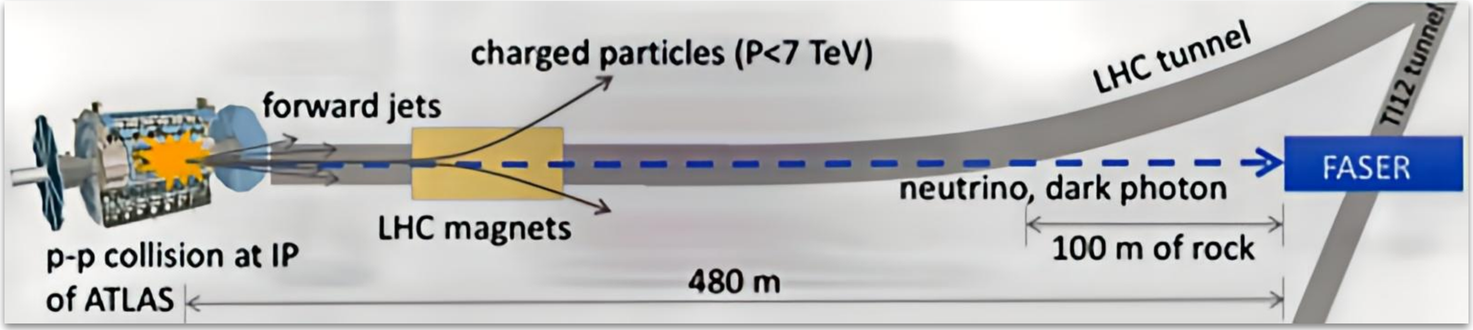
How do we look for these sterile neutrinos?

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

Make minimal assumptions regarding BSM structure.

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

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

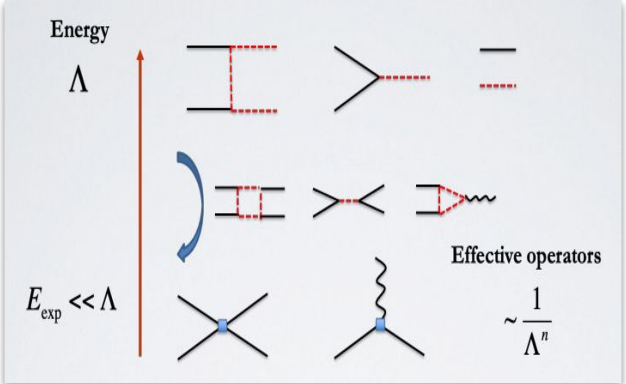
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d\geq 5}\sum_{i}\frac{C_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

At energy-scale Λ, introduce effective operators involving ν_R.

Focus in our work:

- Dim-6 operators with one sterile neutrino.
- Processes at tree level.

Generalization is possible.



νSMEFT Framework

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

Customary in previous works:

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

Back of the envelope:

$$C_P^{(6)} = 10^{-5}$$
$$C_P^{(6)} \sim \frac{v^2}{\Lambda^2}$$
$$\Lambda \sim 80 \text{ TeV}$$

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

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}

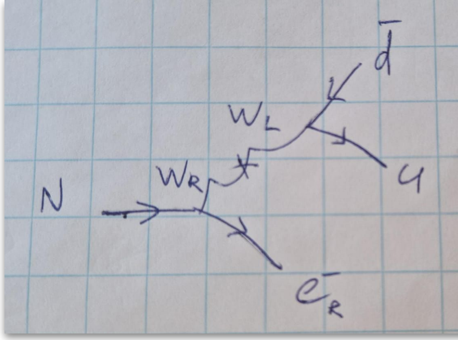
Extension of scalar section: Higgs bi-doublet and two scalar triplets

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.

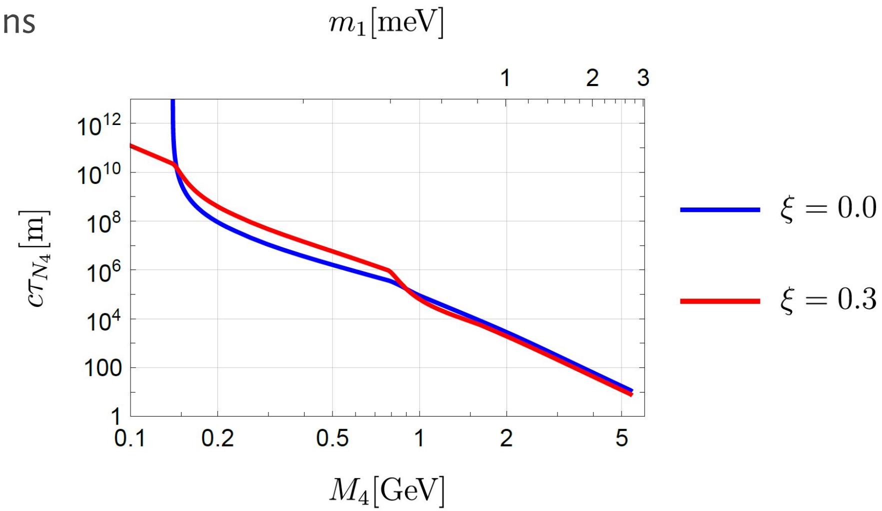
Sterile neutrino decay rates:

Possible final-state particle contents:

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

Sterile neutrino decay lengths:

Are DV searches viable?



Displaced-vertex experiment simulations

Calculate events using Monte Carlo methods in PYTHIA 8:

- Generate a number of sterile neutrinos from meson decays:

$$N^{\text{prod}}_{M,N} = N_M \cdot \text{Br}\big(M \to N + X\big)$$

- Calculate the probability of decaying inside the experiment:

$$P_{M,i}\big[N \text{ in f.v.}\big] = \exp\left[-\frac{L_{T,i}}{\lambda_i}\right] \cdot \left(1 - \exp\left[-\frac{L_{I,i}}{\lambda_i}\right]\right)$$

- Generate a bunch of events:

$$\big\langle P_M\big[N \text{ in f.v.}\big]\big\rangle = \frac{1}{N_{\text{MC}}} \sum_i^{N_{\text{MC}}} P_{M,i}\big[N \text{ in f.v.}\big]$$

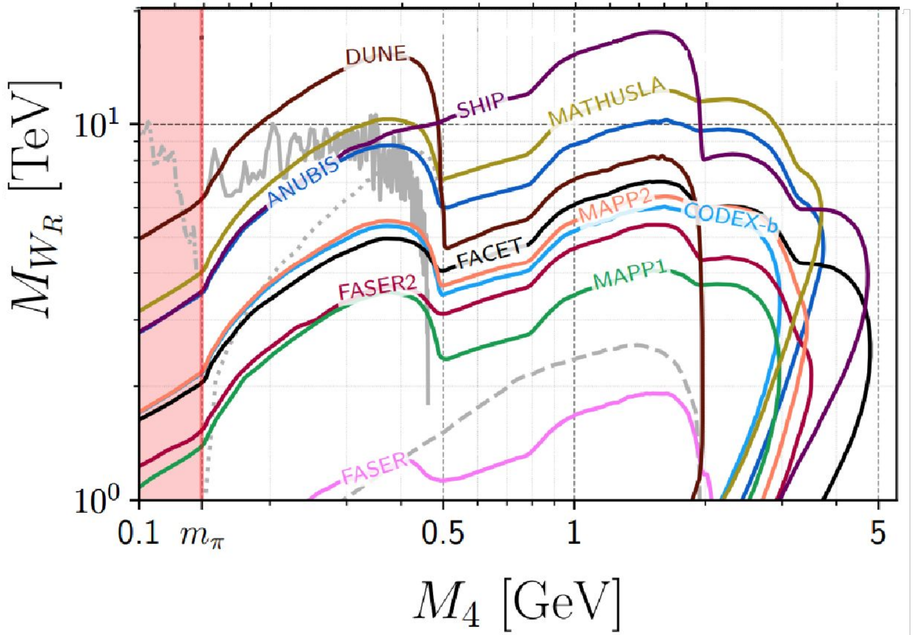
- Only consider sterile neutrinos decaying into visible final states:

$$N^{\text{obs}}_N = \text{Br}\big(N \to \text{visible}\big) \cdot \sum_M N^{\text{prod}}_{M,N} \cdot \big\langle P_M\big[N \text{ in f.v.}\big]\big\rangle$$

Sensitivity reaches of (future) experiments

Sensitivity reaches up to $\mathcal{O}(20\ \mathrm{TeV})$!

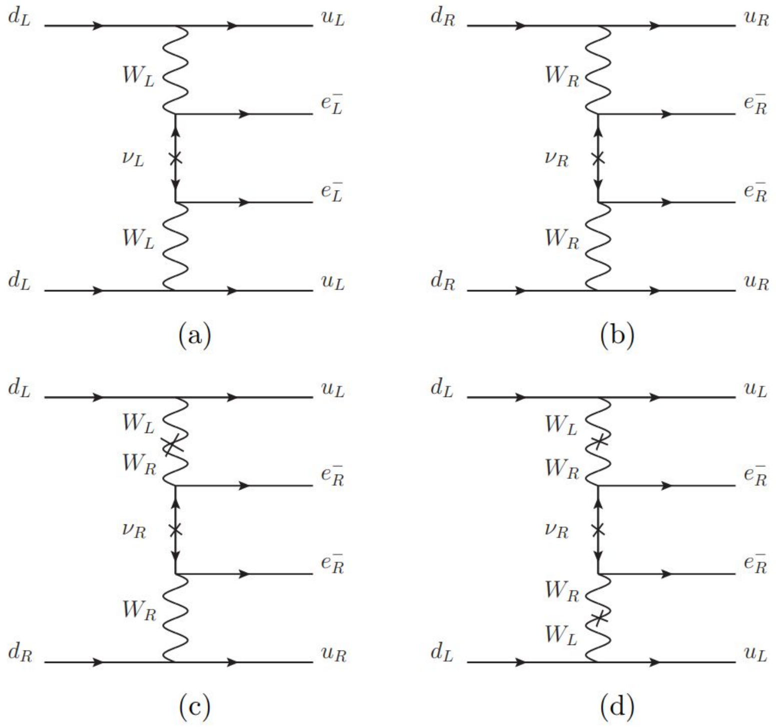
DUNE and SHiP have comparable sensitivity reaches.



$\xi = 0.3$

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

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

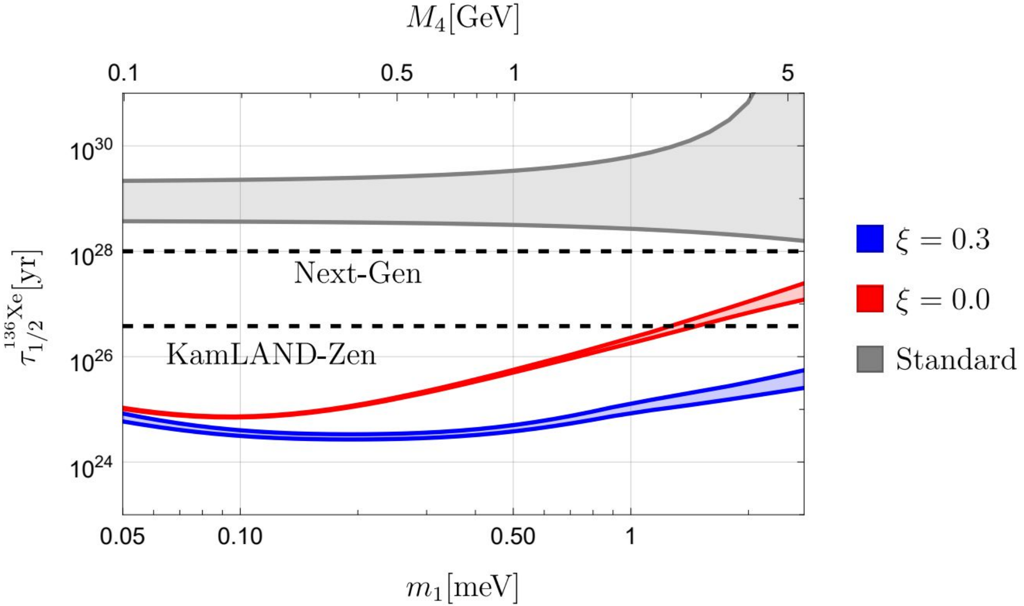


$0\nu\beta\beta$ lifetime determination of Xenon-136

$M_{W_R} = 15$ TeV
Normal Hierarchy

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

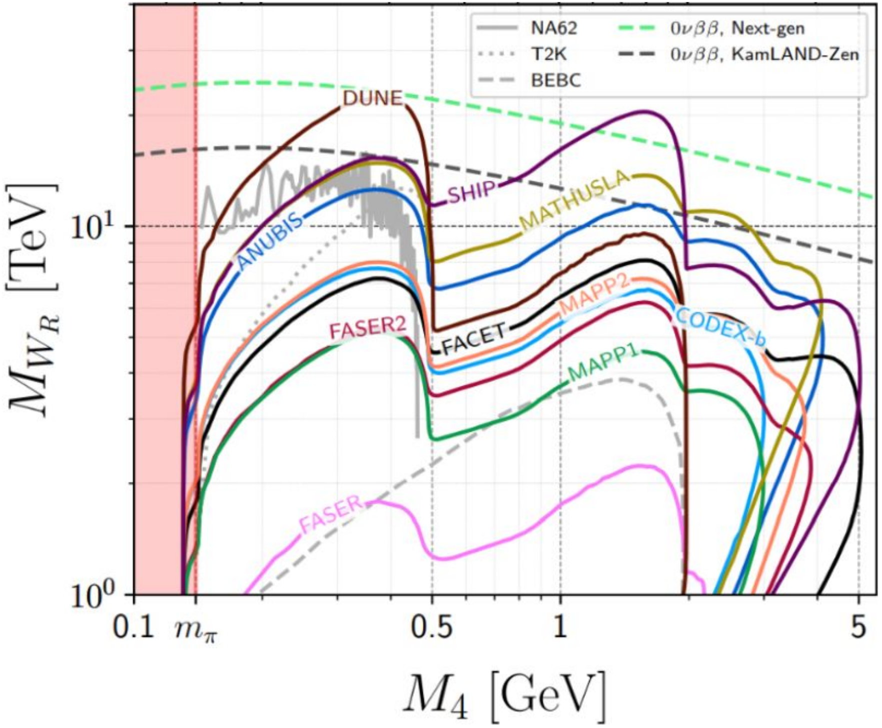
Additional decay topologies imply $0\nu\beta\beta$ signals could be found in next-gen experiments!



Compare sensitivity reaches:

Recast lifetimes, branching ratios and decay lengths.

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



$\xi = 0.3$

Motivation
Setting the scene
DV Calculations
$0\nu\beta\beta$ lifetime
Conclusions

Conclusions

- mLRSM sterile neutrinos could elegantly explain multiple SM puzzles.
- DV and $0\nu\beta\beta$ searches are excellent, complementary probes of RH currents
- Sensitivity of DUNE complements LHC proposals
- Exciting future experimental bounds with sensitivities up to $M_{W_R} = \mathcal{O}(25 \text{ TeV})$
- The customary approach for DV searches could be oversimplified if $0\nu\beta\beta$ limits are not included

Motivation
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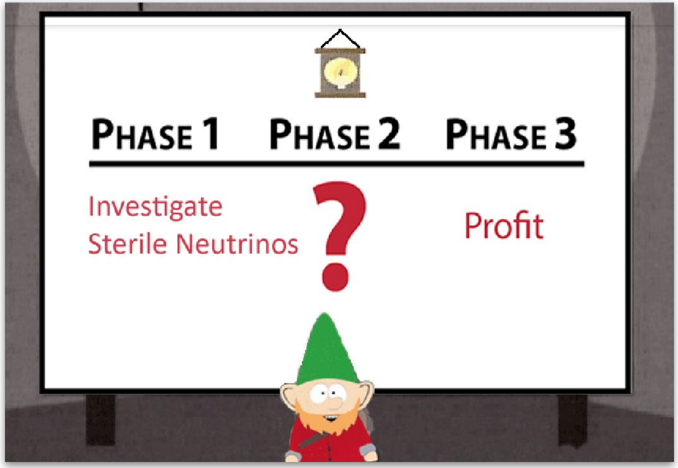
Thanks for your attention!

Also interesting to investigate:

- Big Bang Nucleosynthesis pheno
- Multi-meson corrections to the sterile neutrino lifetime
- Direct partonic production of GeV-scale sterile neutrinos



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Backup slides: interference through non-zero mixing

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

$$\langle h_{\rm PS}|\,\overline{q}_1\gamma^\mu P_{L,R}q_2\,|B,D\rangle = +\frac{1}{2}\,\langle h_{\rm PS}|\,\overline{q}_1\gamma^\mu q_2\,|B,D\rangle\,,$$

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

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

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

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

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

Backup slides: vev structure of G_LR

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

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

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

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

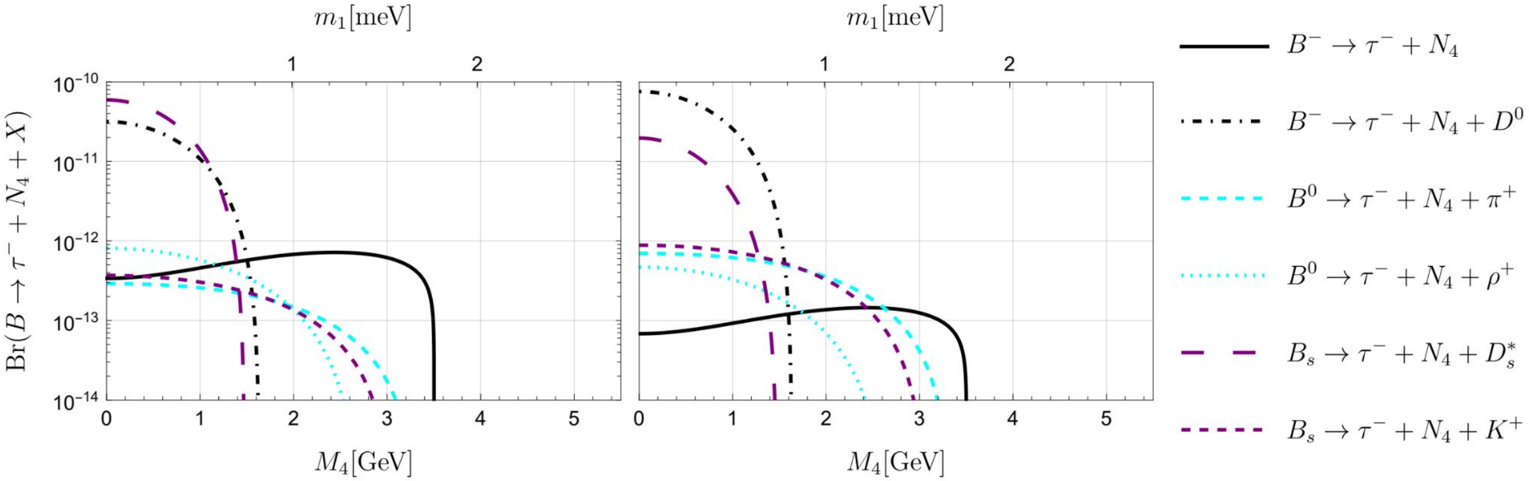
$$\sqrt{\kappa^2 + \kappa'^2} = v \qquad v_R \gg v \gg v_L$$

Meson decay rates

We can determine B-, D-,K- and π-meson branching ratios into sterile neutrinos.

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

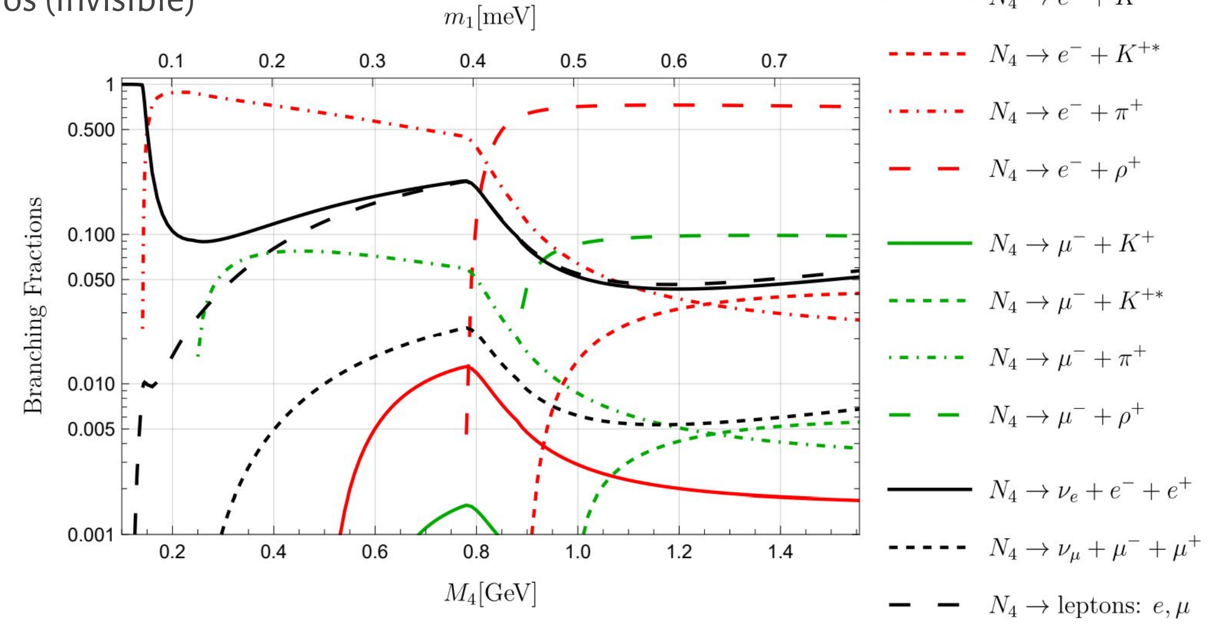
Significant constructive/destructive interference for non-zero mixing!



Sterile neutrino decay rates

Possible final-state particle contents:

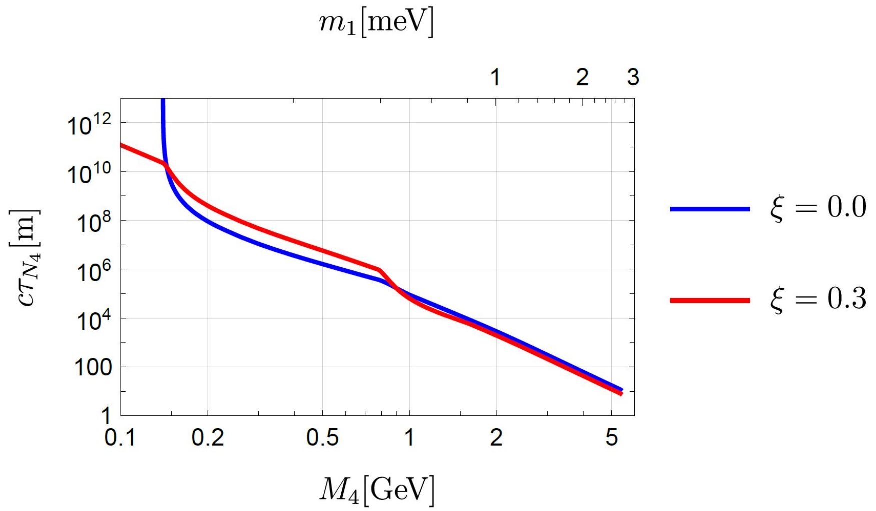
- Quarks: final-state mesons (Pseudo-scalar or Vector)
- SM leptons
- SM neutrinos (invisible)



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

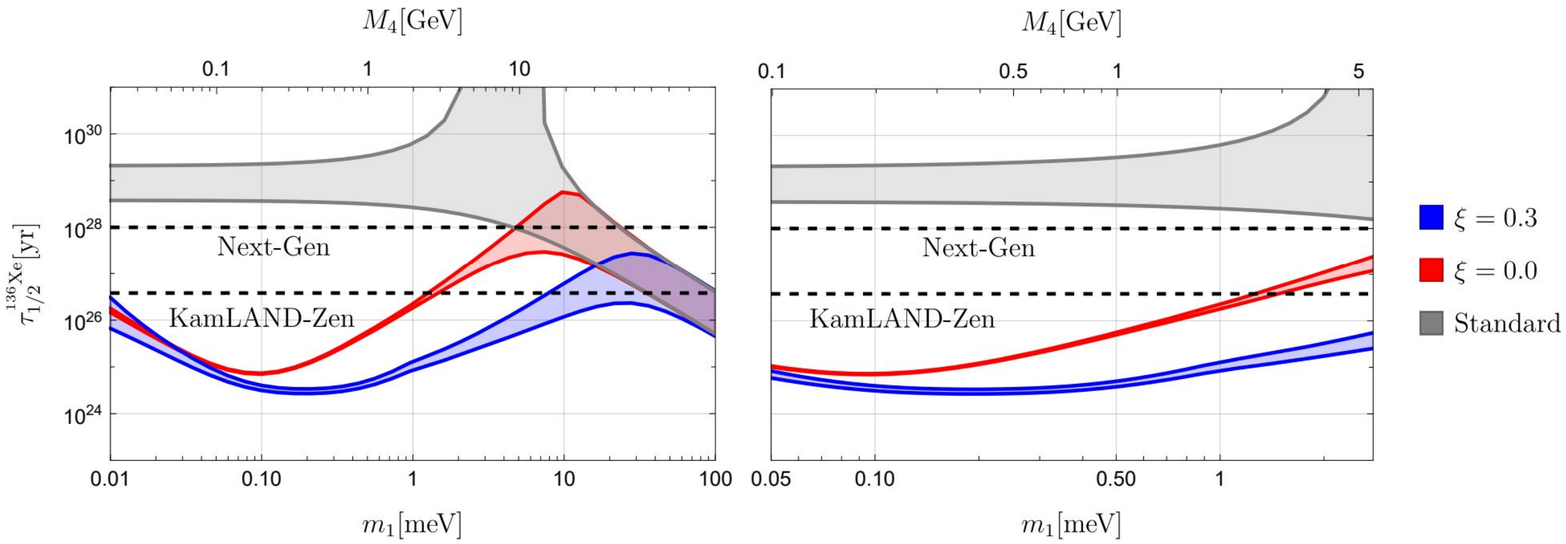


$M_{W_R} = 15$ TeV
Normal Hierarchy

Lifetime determination of Xenon-136

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

Stringent limits; $0\nu\beta\beta$ signals could be found in next-gen experiments!

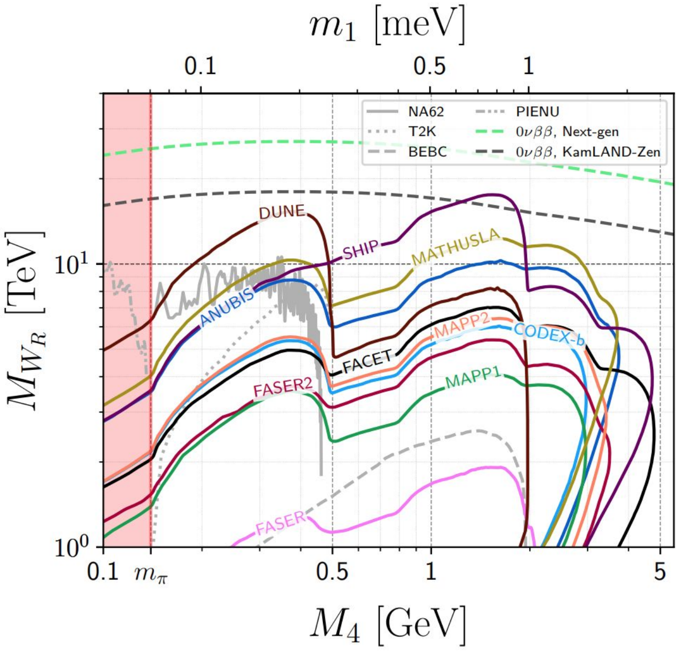


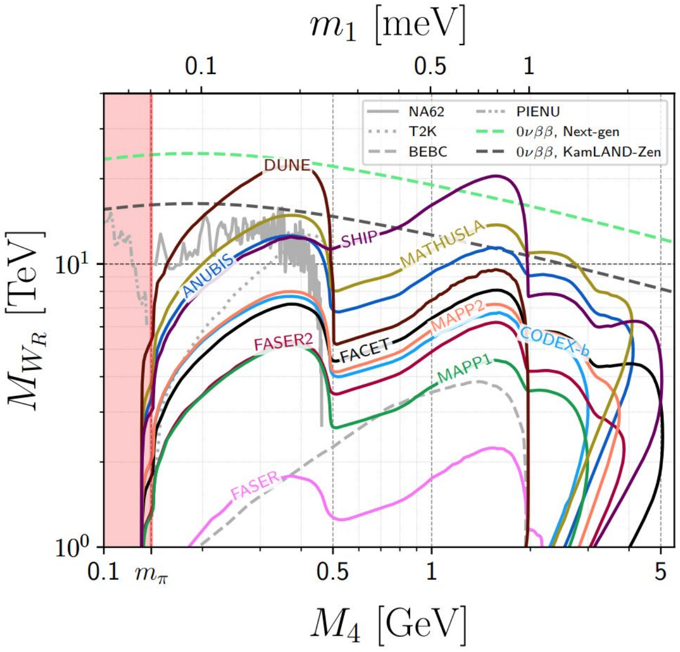
Compare sensitivity reaches:

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

Recast lifetime, branching ratio and decay lengths

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



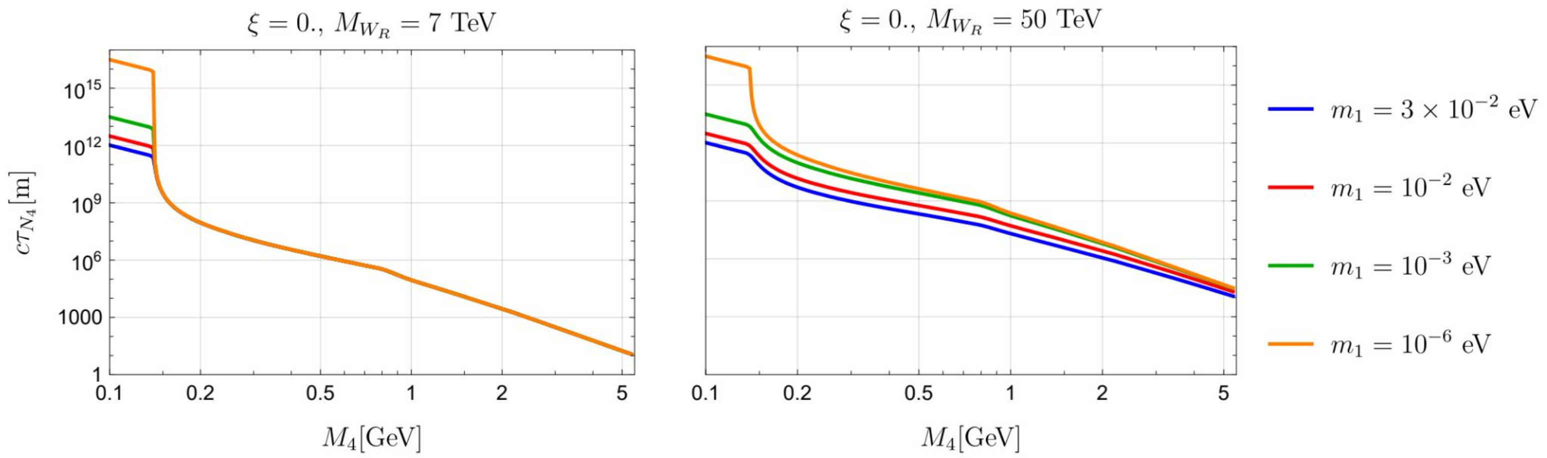


Decay Lengths: Type-I seesaw

Repeat analysis for type-I seesaw scenarios: $M_D \neq 0$, non-zero active-sterile mixing

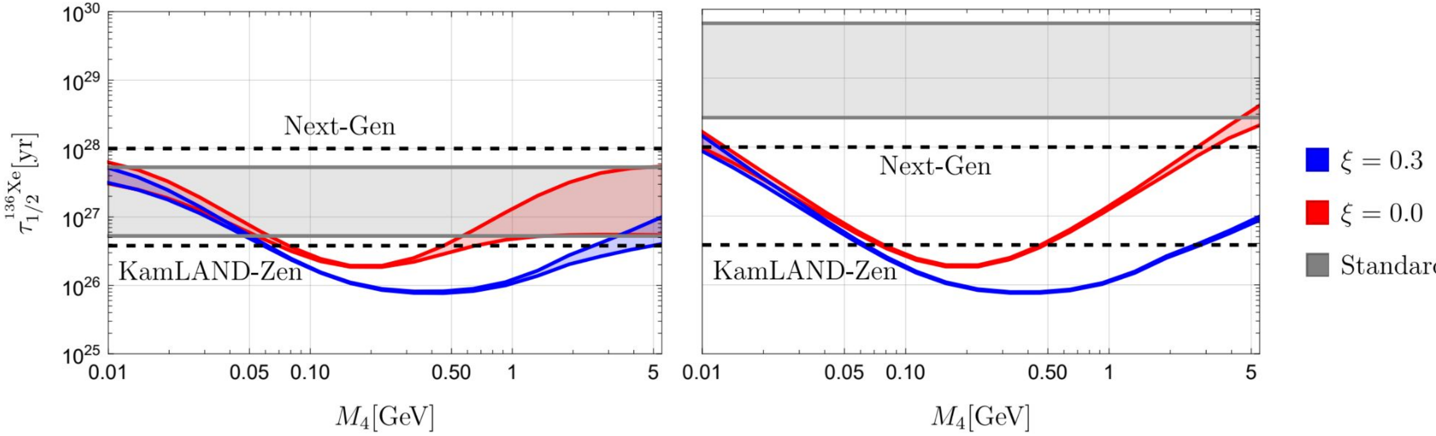
For large M_{W_R} , lightest active neutrino mass has large impact.

For small M_{W_R} and $M_4 > M_\pi$ right-handed contributions dominate.



Lifetime determination of Xenon-136: Type-I seesaw

$0\nu\beta\beta$ signals could be found in next-gen experiments!



$M_{W_R} = 15$ TeV Normal Hierarchy, Left (right) panel $m_1 = 0.03$ eV ($m_1 = 0.001$ eV)

Compare sensitivity reaches:

Left (right) panel
$\xi = 0.3\ (\xi = 0.0)$

Recast lifetime, branching ratio and decay lengths