# Long-Lived Sterile Neutrinos and Minimal Left-Right Symmetry

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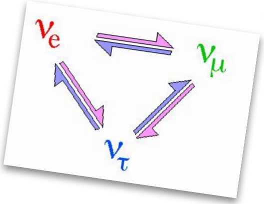
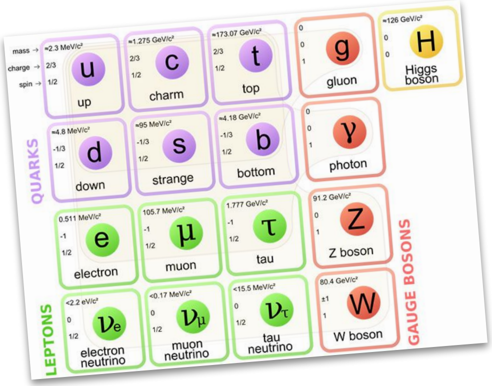
# **Motivation:** Neutrinos are massive!





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

Add field $\nu_R$ , a **singlet** under the SM gauge group: $-y_\nu\overline{\nu_L}\varphi\nu_R \xrightarrow{\text{EWSB}} -y_\nu v\overline{\nu_L}\nu_R$

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:** How to deal with Majorana terms?

*"Everything not forbidden is compulsory"*
- Murray Gell-Mann

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...

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

**Seesaw mechanism** instates relations between LH and RH sectors.

$$m_1 \simeq \left|\frac{y_\nu^2 v^2}{M_R}\right|, \quad m_2 \simeq M_R$$

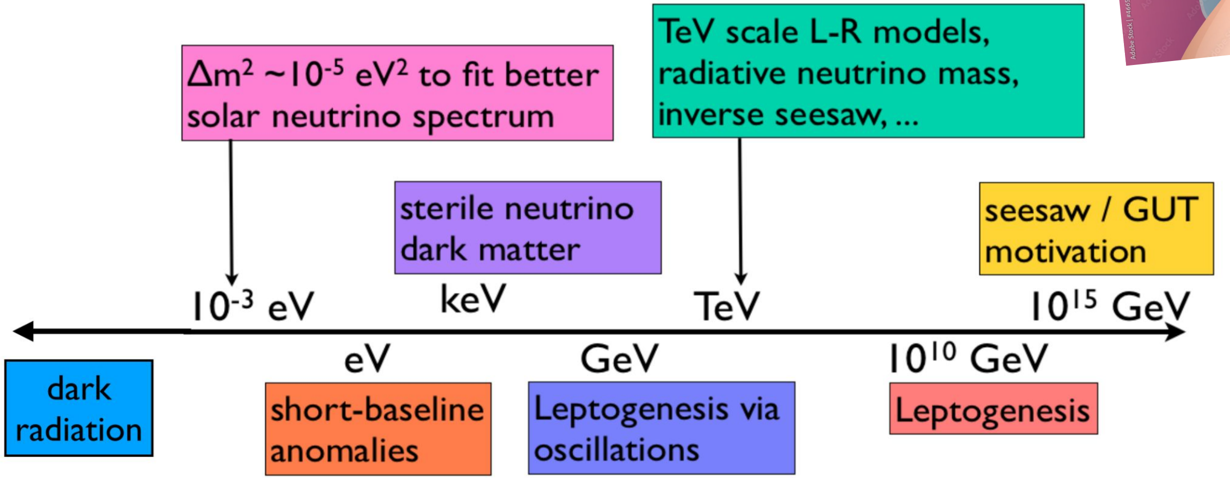
$$\nu_1 = \nu_L + \theta\nu_R{}^c$$
$$\nu_2 = \nu_R + \theta\nu_L{}^c$$

$$|\theta| \simeq \sqrt{\frac{m1}{m2}}$$

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

# **Motivation:** What is the right-handed mass scale?

Many mass scales could provide solutions to SM puzzles!


$\Delta m^2 \sim 10^{-5}$ eV$^2$ to fit better solar neutrino spectrum

TeV scale L-R models, radiative neutrino mass, inverse seesaw, ...

sterile neutrino dark matter

seesaw / GUT motivation

$10^{-3}$ eV
keV
TeV
$10^{15}$ GeV
eV
GeV
$10^{10}$ GeV

dark radiation

short-baseline anomalies

Leptogenesis via oscillations

Leptogenesis

I've blatantly stolen Thomas' graphic! Thank you Thomas.

**Conclusion:** Interesting to investigate a wide range of scales!

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

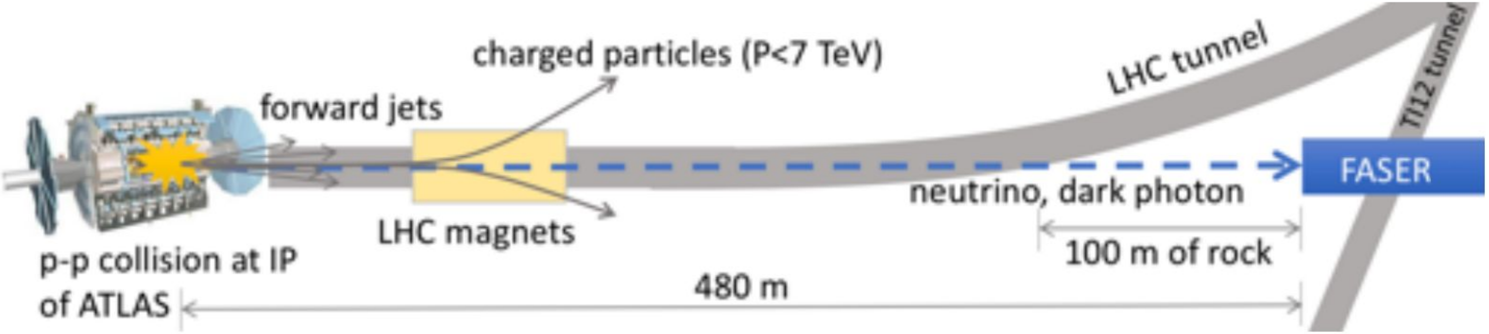
# How do we look for these sterile neutrinos?

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

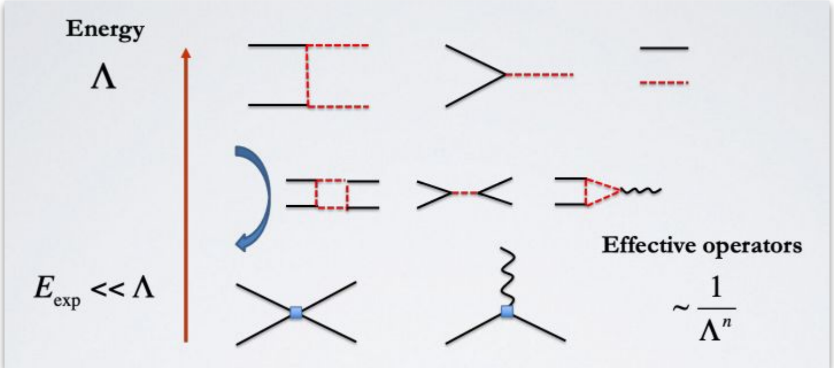
If sterile neutrinos exist, they need to arise from somewhere.

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

**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**!



# $\nu$SMEFT Framework

$\nu_R$-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)

**Customary in previous works:**

- Express decay rates of N $\leftrightarrow$ SM in terms of $\nu$SMEFT Wilson Coefficients.
- **Benchmark Scenarios:** 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 $G_{SM}$

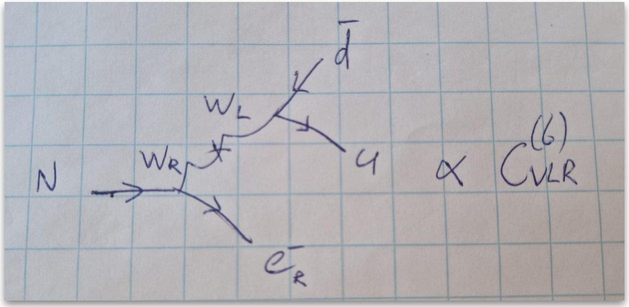
**Extension of scalar section:** Higgs bi-doublet and two scalar triplets

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?



**Simplest case:**

Type-II seesaw scenario; $M_D \to 0$, no active-sterile mixing.

**Important parameters:**

$M_{W_R}$ and mixing parameter $\xi$:

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix} \qquad \zeta = \frac{\xi}{2(\xi^2+1)} \left(\frac{M_{W_L}}{M_{W_R}}\right)^2, \text{ with } 0 < \xi < 0.8$$

Only vector gauge bosons → three Wilson coefficients: $C^{(6)}_{\text{VLL}},\ C^{(6)}_{\text{VLR}},\ C^{(6)}_{\text{VRR}}$

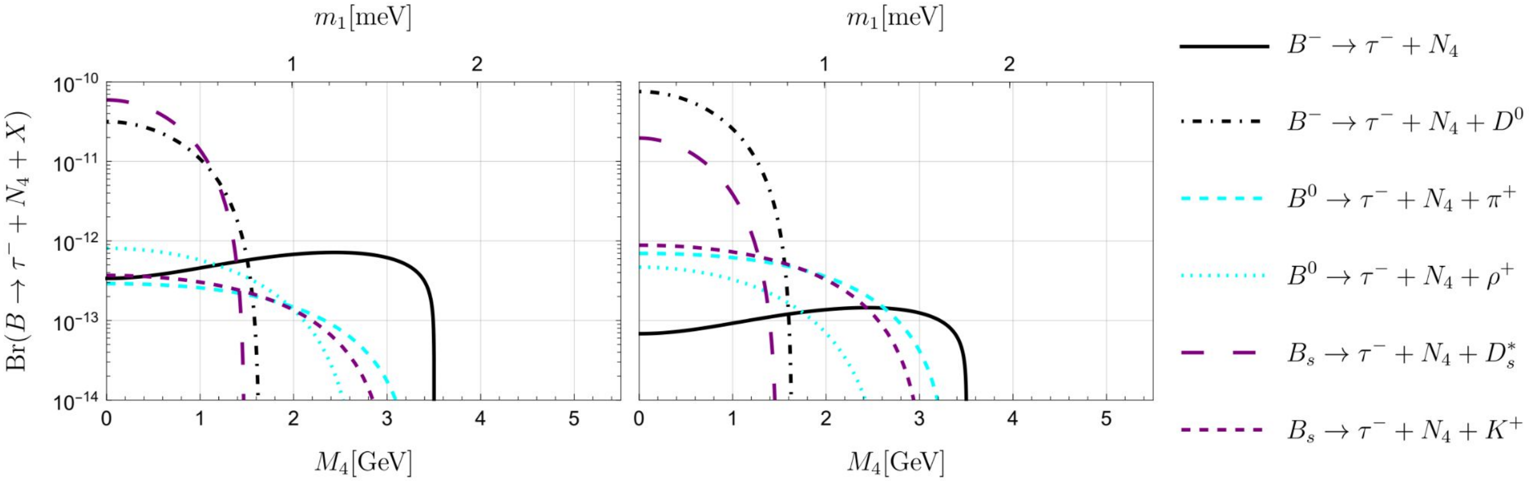
We can also consider different seesaw scenarios and different discrete symmetries!

# Meson decay rates

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

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

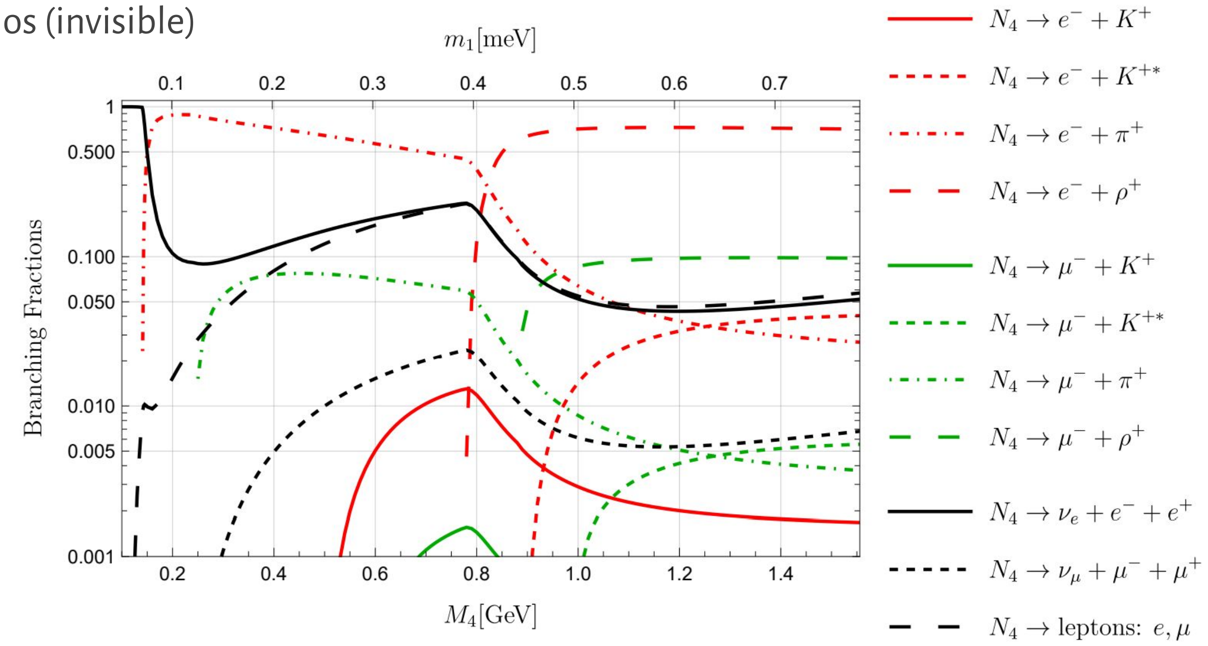
Significant constructive/destructive interference for non-zero mixing!



# Sterile neutrino decay rates

**Possible final-state particle contents:**

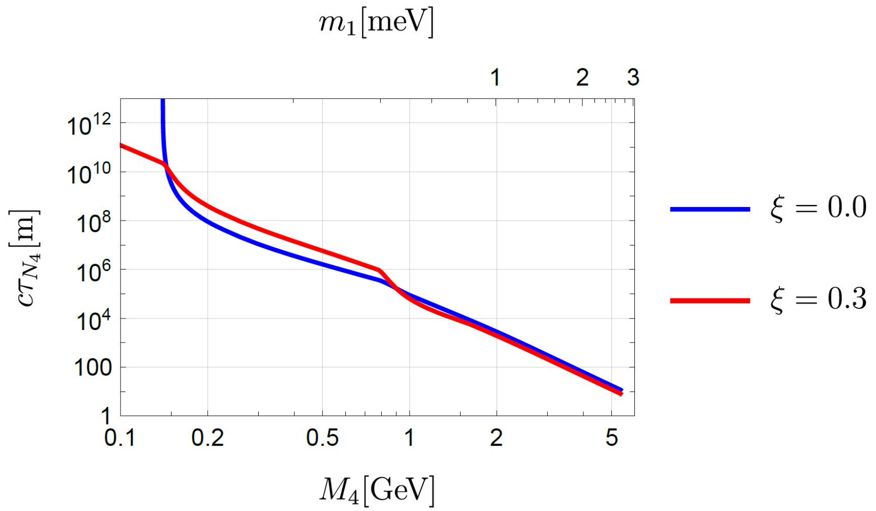
- Quarks: final-state mesons (Pseudo-scalar or Vector)
- SM leptons
- SM neutrinos (invisible)



# Decay Lengths

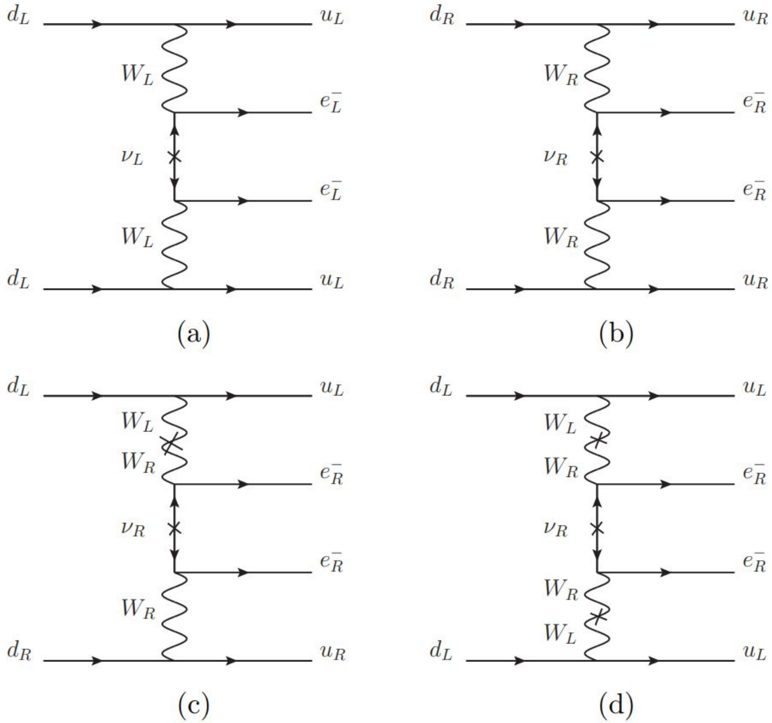
Important in checking viability of displaced-vertex searches!

**Multi-meson corrections:**
For $M_4 \gtrsim 1\ \mathrm{GeV}$, assume quark currents + QCD corrections and no hadronic structure → customary in inclusive hadronic tau-lepton decay



# Lifetime determination of Xenon-136

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

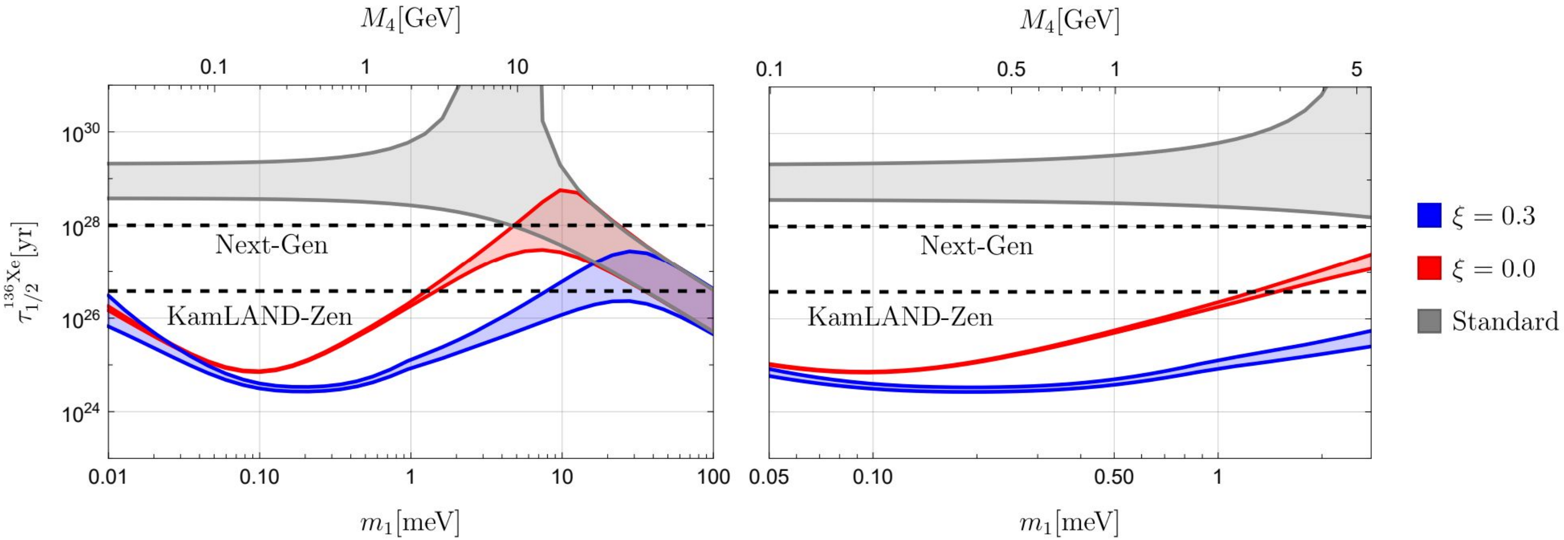


# Lifetime determination of Xenon-136

$M_{W_R} = 15$ TeV
Normal Hierarchy

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

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

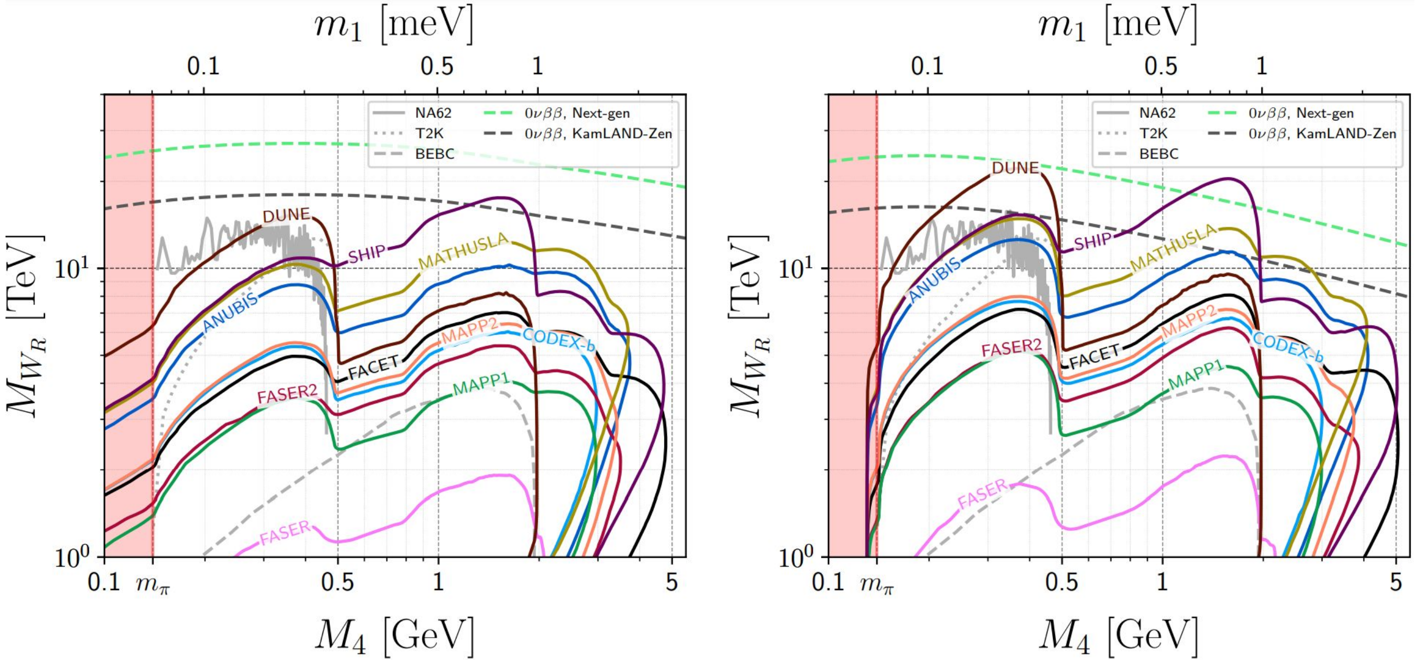


# Compare sensitivity reaches:

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!

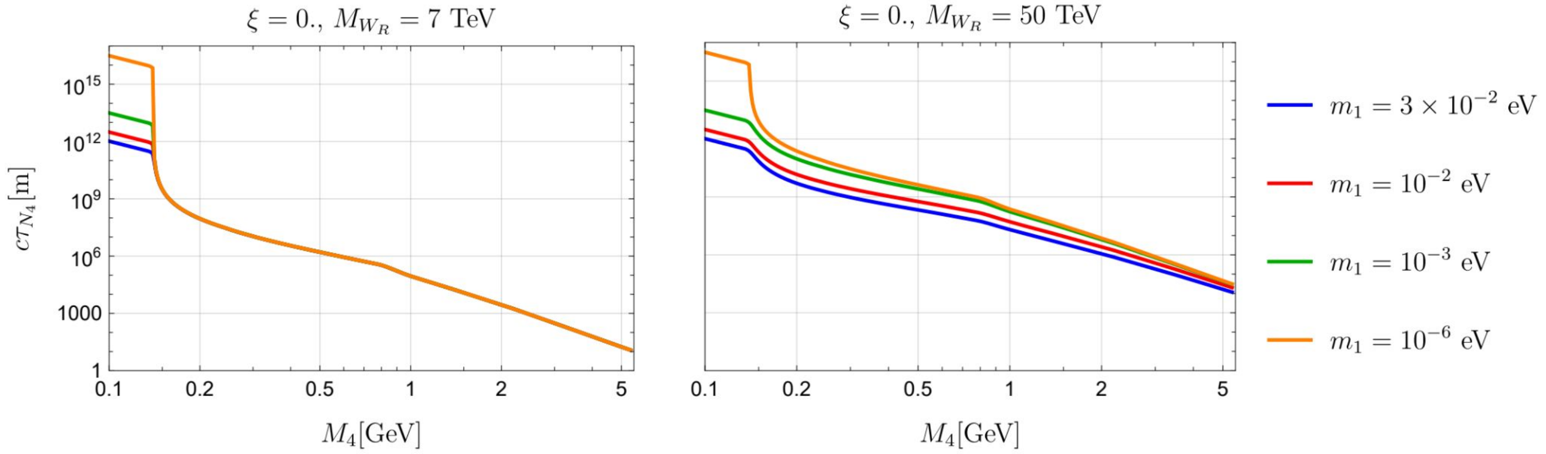


# Decay Lengths: Type-I seesaw

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

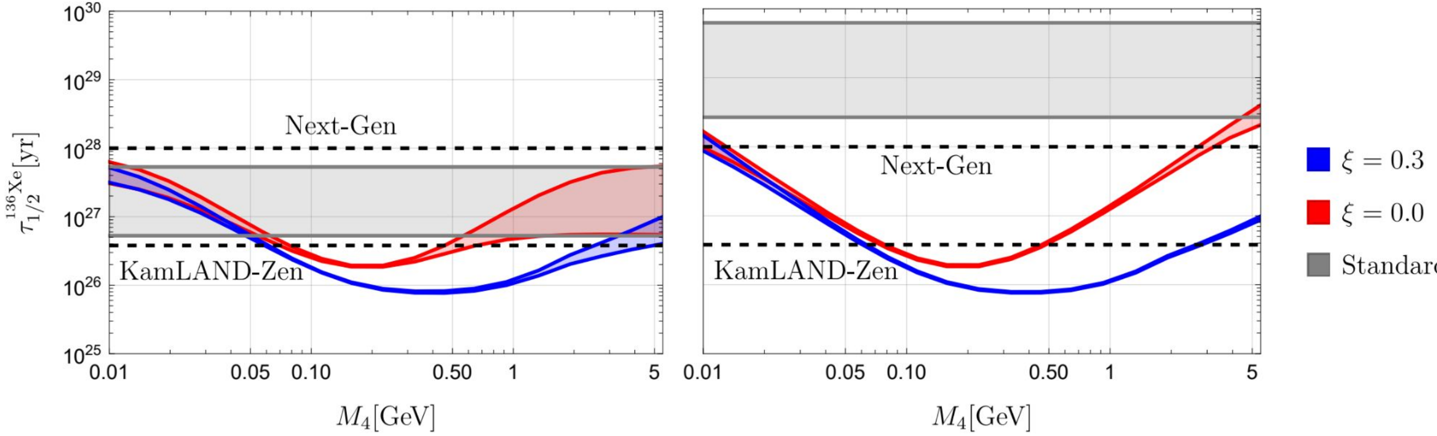
For large $M_{W_R}$ , lightest active neutrino mass has large impact.

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!

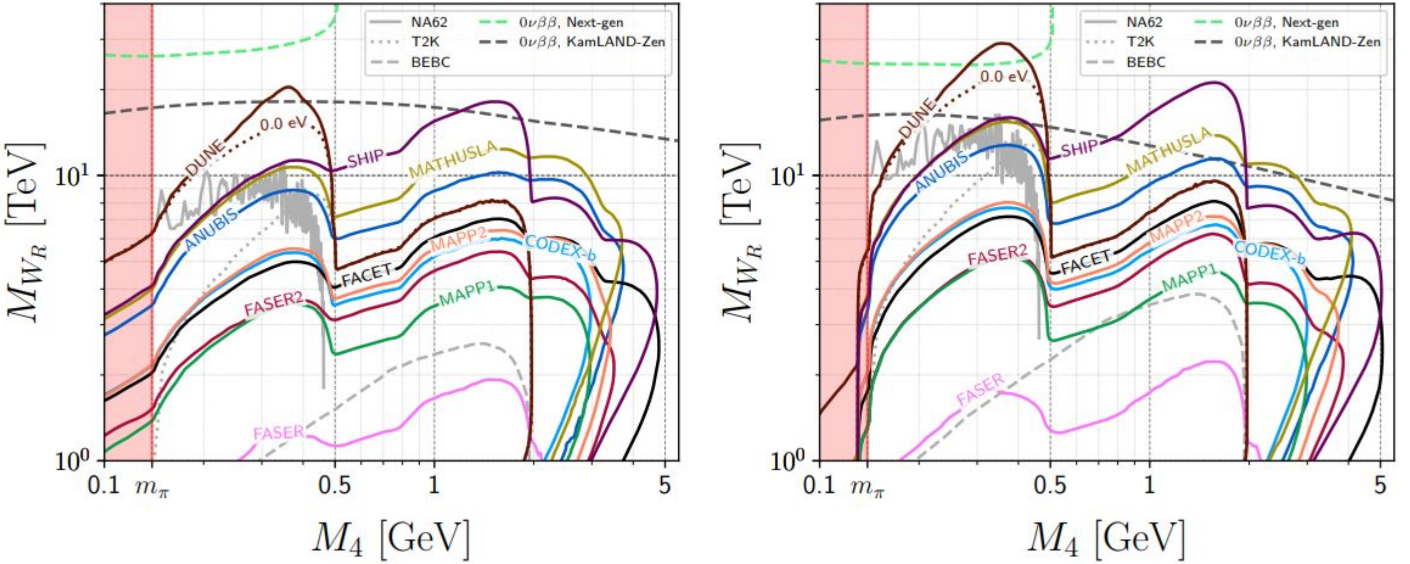


$M_{W_R} = 15$ TeV Normal Hierarchy, Left (right) panel $m_1 = 0.03$ eV ($m_1 = 0.001$ eV)

# Compare sensitivity reaches:

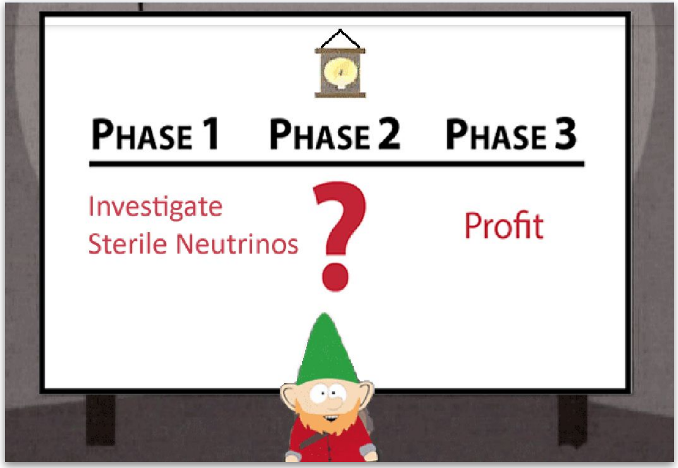
Left (right) panel
$\xi = 0.3 \; (\xi = 0.0)$

Recast lifetime, branching ratio and decay lengths



# What's next?

- Include BBN bounds
- Further investigate multi-meson corrections to the lifetime
- Investigate leptogenesis via oscillations



# Conclusions

- mLRSM sterile neutrinos could elegantly explain multiple SM puzzles
- DV and $0\nu\beta\beta$ searches are excellent, complementary probes of right-handed currents
- 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

# Thanks for your attention!

# **Backup slides:** interference through non-zero mixing

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

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

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

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

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

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

# **Backup slides:** vev structure of G_LR

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

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

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

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

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