Neutrino masses and $0\nu\beta\beta$ decays in leptoquark models

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Motivation

❖ Neutrinos are massive and oscillate among different flavors :

⟹ Clear evidence of physics Beyond Standard Model (BSM).

❖ Weinberg operator: only d = 5 operator invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$\mathcal{L}^{d=5} = \frac{C^{(5)}_{ij}}{\Lambda}(\overline{L^C_i}\tilde{H}^*)(\tilde{H}^\dagger L_j) + \text{h.c.}$$

$$\Longrightarrow\ (m_\nu)_{ij} = \frac{C^{(5)}_{ij}\, v^2}{\Lambda} \qquad \text{(suppressed by } v^2/\Lambda)$$

⟹ Lepton Number (L) is broken (neutrinos are Majorana particles)

❖ Majorana masses induce neutrinoless double beta decay ($0\nu\beta\beta$) with half life

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|\mathcal{M}^{(3)}_\nu|^2|\textstyle\sum_i m_{\nu_i}U^2_{ei}|^2 \qquad \text{(chirality suppressed)}$$

⟹ Future experiments will improve significantly sensitivity (LEGEND – 1000).

❖ However, higher dimensional operators (d ≥ 7) can also appear in dynamical models for Majorana masses.

$$\mathcal{L}_{\text{SMEFT}} = \sum_{d\geq 5}\sum_a \frac{\mathcal{C}^{(d)}_a}{\Lambda^{d-4}}\mathcal{O}^{(d)}_a$$

Example: Scalar leptoquarks with Lepton Number Violating (LNV) from mixing

- m_{ν_i} at loop-level (d = 5)
- $0\nu\beta\beta$ from m_{ν_i} (d = 5) and additional tree-level contributions (d = 7)
- Other flavor effects testable in experiments (d = 6)

Our goal: to explore this interplay of m_{ν_i}, $0\nu\beta\beta$ and flavor observables.

Our framework

❖ Leptoquarks: colored particles that couple to quarks and leptons.

❖ Two models can break L:

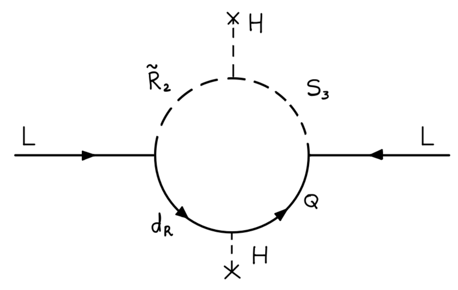
$S_3 \sim (\bar{\mathbf{3}},\mathbf{3},1/3)$ and $\widetilde{R}_2 \sim (\mathbf{3},\mathbf{2},1/6)$ or $S_1 \sim (\bar{\mathbf{3}},\mathbf{1},1/3)$ and $\widetilde{R}_2 \sim (\mathbf{3},\mathbf{2},1/6)$

⟹ We consider the $S_3 - \widetilde{R}_2$ model

$$\mathcal{L}_{\widetilde{R}_2\&S_3} \supset y^{ij}_{3L}\overline{Q^C_i}i\tau_2(\tau^a S^a_3)L_j - y^{ij}_{2L}\bar{d}_{Ri}\widetilde{R}_2 i\tau_2 L_j - \lambda_3 \widetilde{R}^\dagger_2(\tau^a S^a_3)^\dagger H + \text{h.c.}\,,$$

Mixing induces Lepton Number Violation

Neutrino masses are loop generated



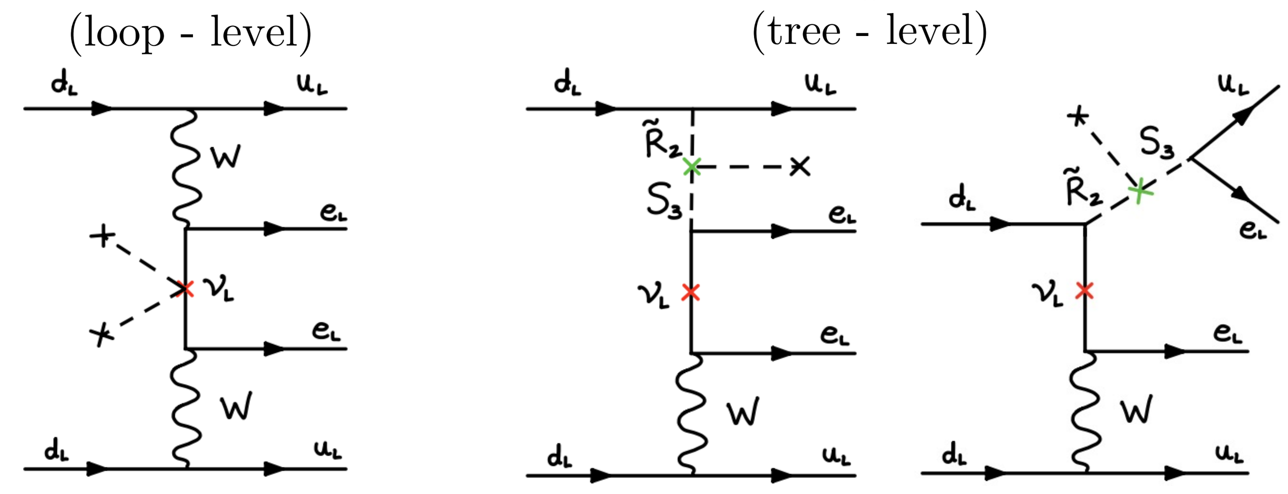
For $m_{\widetilde{R}_2} = m_{S_3} = M$

$$m_\nu \simeq -\frac{3\lambda_3}{32\pi^2}\frac{v^2}{M^2}\left(y^T_{2L}\cdot\hat{y}_d\cdot y_{3L} + y^T_{3L}\cdot\hat{y}_d\cdot y_{2L}\right)$$

$$m_\nu \simeq 0.1\ \text{eV}\left[\frac{|\lambda|}{M}\right]\left[\frac{m_q}{m_b}\right]\left[\frac{M}{10^8\ \text{TeV}}\right]\left[\frac{|y_{2L}y_{3L}|/M^2}{(10^8\ \text{TeV})^{-2}}\right]$$

Neutrinoless double beta decay

d = 5 contribution (loop - level) | d = 7 operators (tree - level)

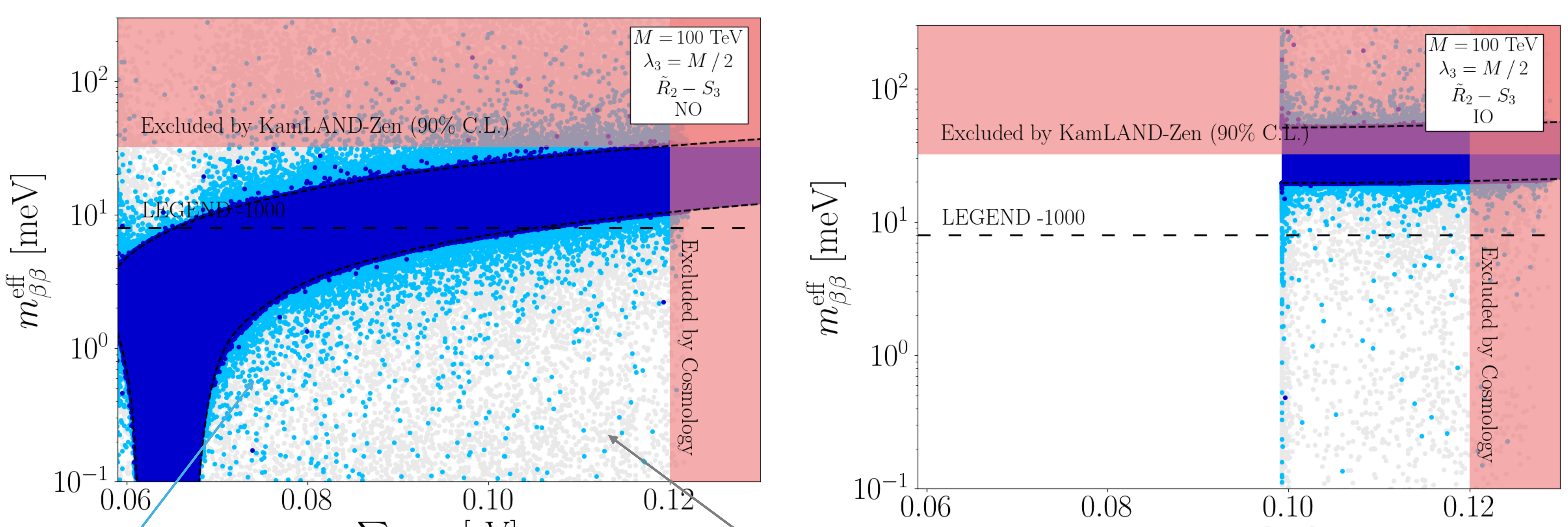


❖ The new contributions can be sizable as they are chirality enhanced ($\propto E/m_{\nu_i}$, $E \simeq 100$ MeV)

❖ Leptoquark masses as large as $\mathcal{O}(10^3\ \text{TeV})$ can be probed with current data .

Our predictions

❖ Predicition for parameters that reproduce viable neutrino masses



light blue : within reach of future experiments

gray : excluded by flavor

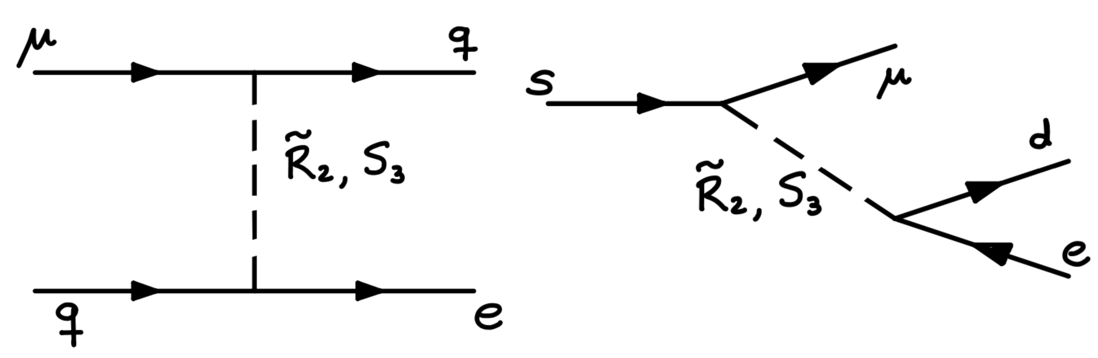
$$|m^{\text{eff}}_{\beta\beta}|^2 \equiv m^2_{\beta\beta} + \delta m^{2\,(\text{int})}_{\beta\beta} + \delta m^{2\,(\text{LQ})}_{\beta\beta}\ ;\ m_{\beta\beta} = \textstyle\sum_i U^2_{ei}m_{\nu_i}$$

❖ Ambiguity between normal and inverted ordering (destructive / constructive interactions)

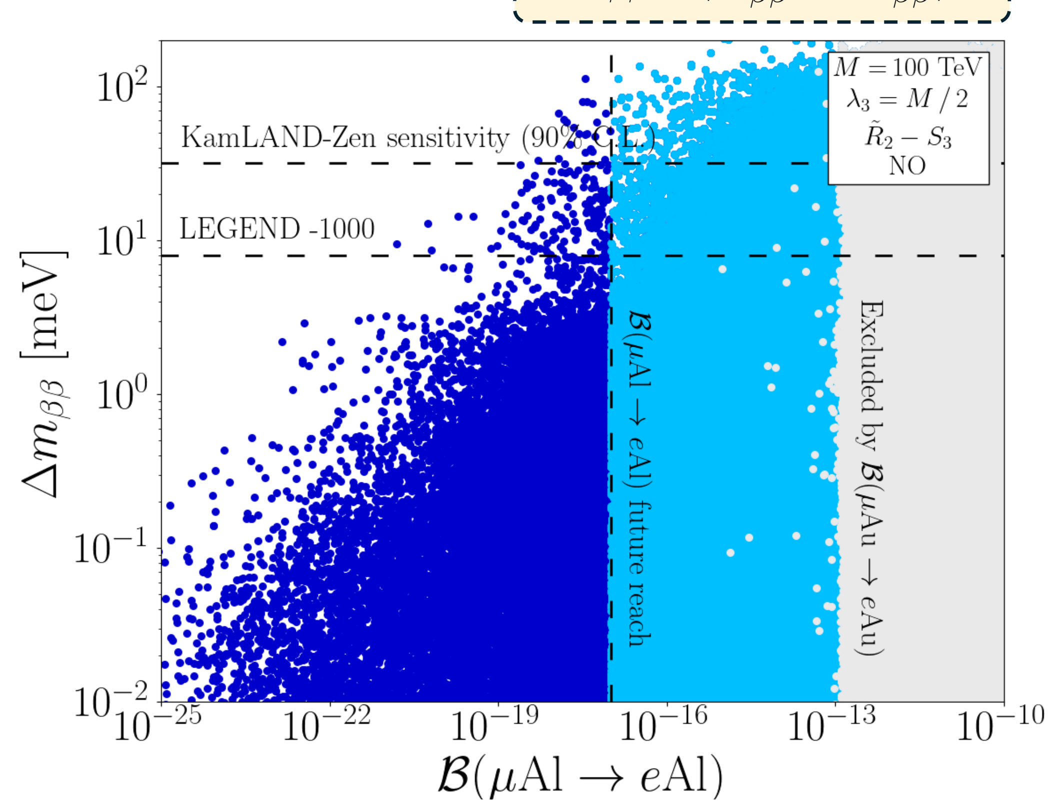
⟹ Further information needed to determine neutrino ordering (e.g., oscillations and cosmology)

$0\nu\beta\beta$ vs. $\mu N \to eN$

❖ LFV is a clean prediction of this setup – induced at tree-level (d = 6) :



$$\Delta m_{\beta\beta} \equiv |m^{\text{eff}\,2}_{\beta\beta} - m^2_{\beta\beta}|^{1/2}$$



❖ $\mu N \to eN$ can probe comparable mass scales to $0\nu\beta\beta$ ($\lesssim 10^3$ TeV)

❖ COMET (J-PARC) and Mu2E (Fermilab) will probe $\mathcal{B}(\mu\text{Al} \to e\text{Al}) \simeq 10^{-17}$

❖ Opportunity to test these scenarios.

❖ Complementarity to $0\nu\beta\beta$ future experiments (LEGEND – 1000).

Conclusions

❖ Scalar leptoquark models can loop generate neutrino masses through mixing.

❖ Aditional chiral-enhanced d = 7 contributions to $0\nu\beta\beta$ ⟹ breaking of naive power counting.

❖ Ambiguity between Normal Ordering and Inverted Ordering from $0\nu\beta\beta$ ⟹ further handle needed (oscillations, cosmology).

❖ Flavor physics and $0\nu\beta\beta$ can be used as complementary searches to probe new physics up to $\mathcal{O}(10^3\ \text{TeV})$!

⟹ Opportunity for Mu2E and COMET, as well as LEGEND – 1000.

[1] V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser and E. Mereghetti, JHEP 12, 097 (2018) [arXiv:1806.02780 [hep-ph]]

[2] S. Fajfer, L. P. S. Leal, O. Sumensari and R. Zukanovich Funchal, [arXiv:2406.XXXX [hep-ph]]