



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

Luighi P. S. Leal (University of São Paulo, University Paris-Saclay)

in collaboration with Svjetlana Fajfer, Olcyr Sumensari and Renata Zukanovich Funchal

[arXiv: 2406.20050 [hep-ph]]



Motivation

- ❖ Neutrinos are massive and oscillate
- ❖ Neutrino masses are described by the Weinberg operator:

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

Evidence of physics
Beyond Standard
Model (BSM)

Majorana
neutrino masses

Lepton Number
(L) is broken

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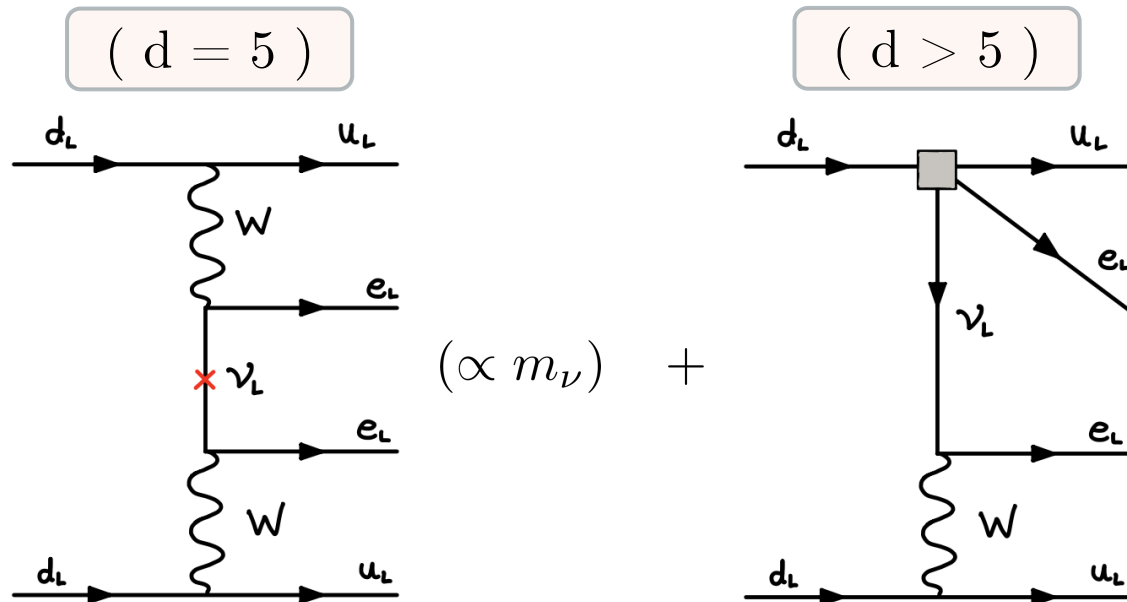
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❖ Neutrinoless double beta decays are a clean prediction :



⇒ However, concrete BSM models
for neutrino masses induce additional
contributions to $0\nu\beta\beta$

This Talk: We explore this effects in
a minimal leptoquark (LQ) model

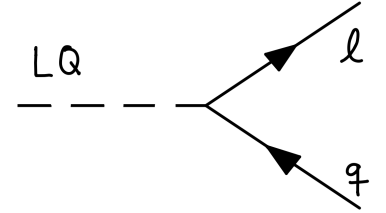
Our Framework

❖ Leptoquarks: colored particles that couple to quarks and leptons

❖ Example: $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ and $\tilde{R}_2 \sim (\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\tilde{R}_2 \& S_3} \supset \boxed{y_{3L}^{ij}} \overline{Q_i^C} i\tau_2 (\tau^a S_3^a) L_j - \boxed{y_{2L}^{ij}} \bar{d}_{Ri} \tilde{R}_2 i\tau_2 L_j - \boxed{\lambda_3} \tilde{R}_2^\dagger (\tau^a S_3^a)^\dagger H + \text{h.c.},$$

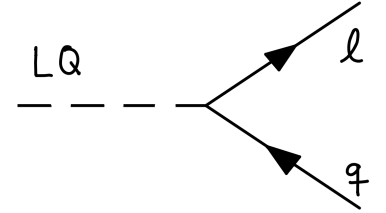
↑
Mixing induces
Lepton Number Violation



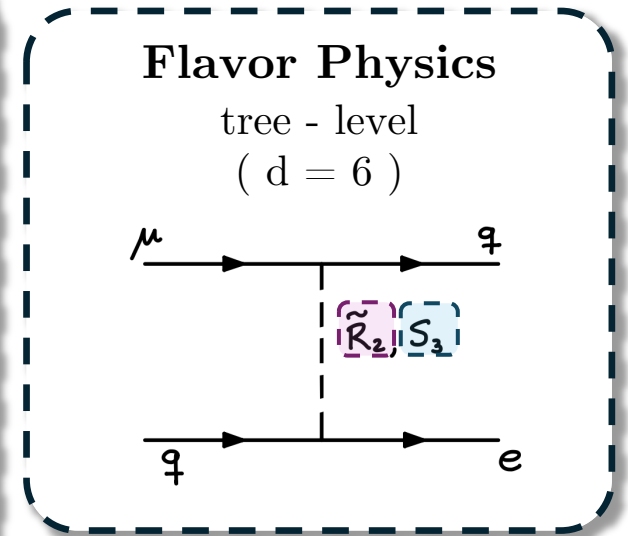
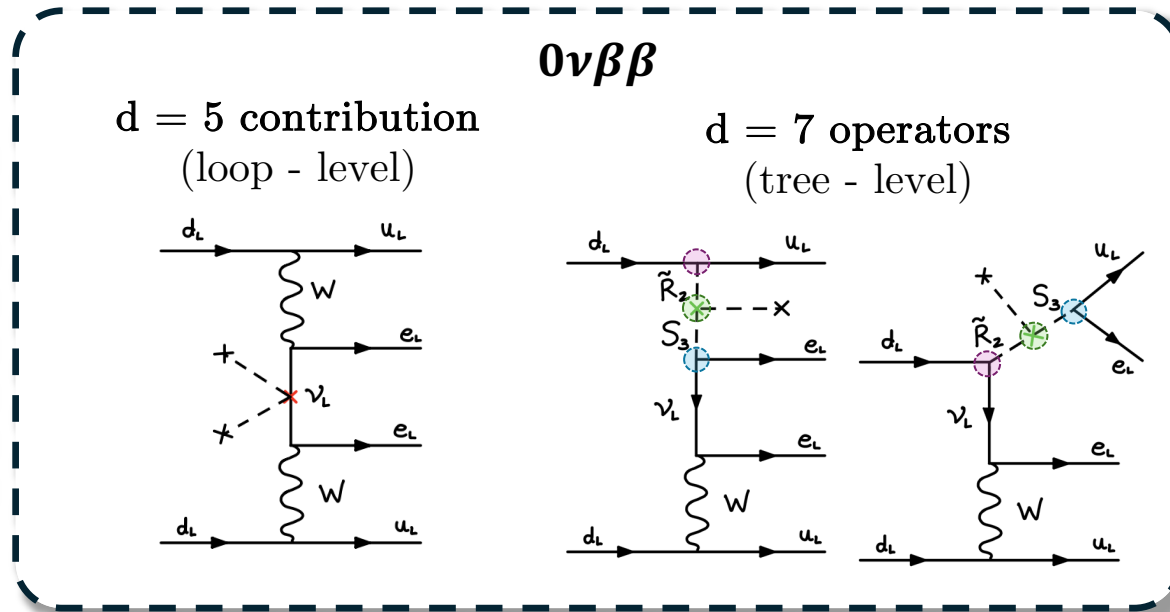
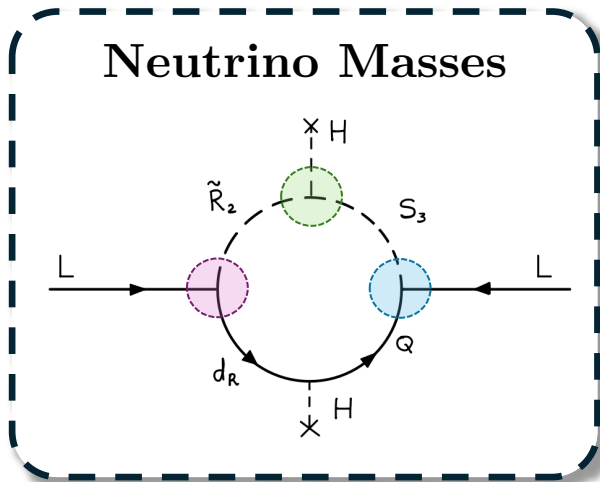
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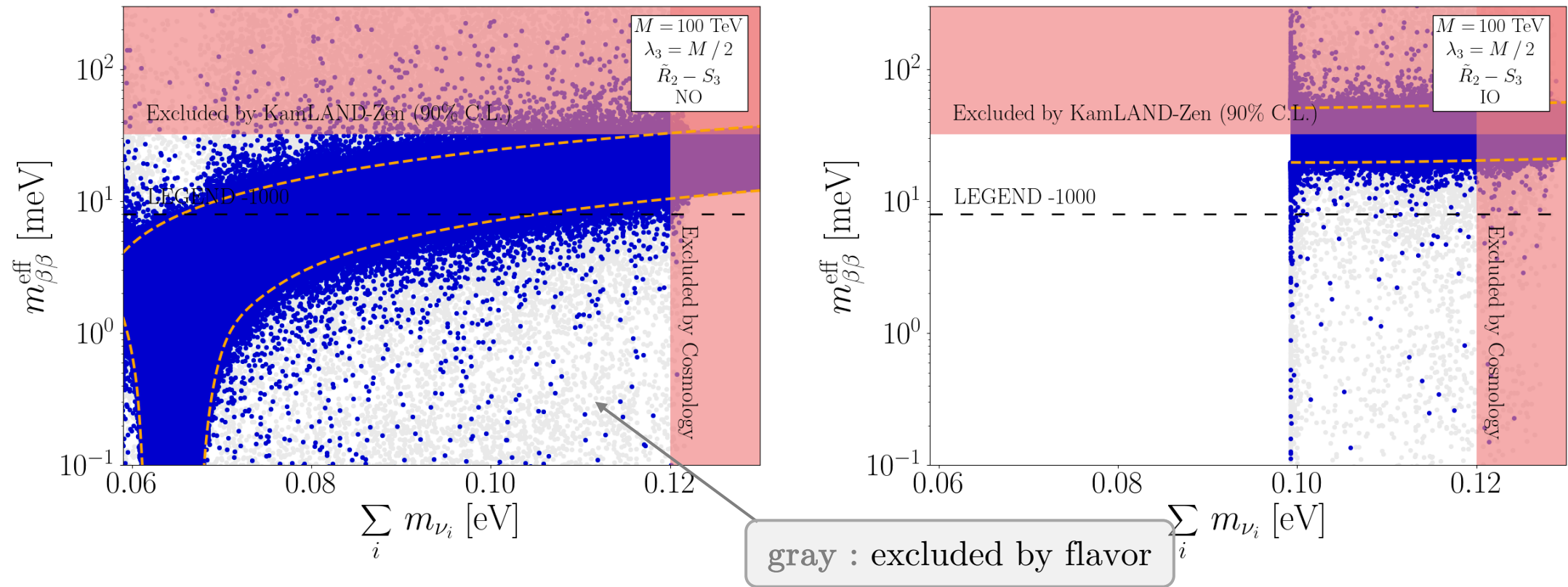


❖ LQ contributions to $0\nu\beta\beta$ are chirality enhanced ($\propto E/m_{\nu_i}$, $E \simeq 100 \text{ MeV}$)
 \Rightarrow breaking of naive power counting

Predictions

$$\left(m_{\beta\beta}^{\text{eff}}\right)^2 \equiv m_{\beta\beta}^2 + \delta m_{\beta\beta}^{2(\text{int})} + \delta m_{\beta\beta}^{2(\text{LQ})} ; m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$$

- ❖ Benchmark: $m_{\tilde{R}_2} = m_{S_3} = M = 100 \text{ TeV}$
- ❖ LQ Yukawas fixed to explain neutrino masses for both neutrino orderings

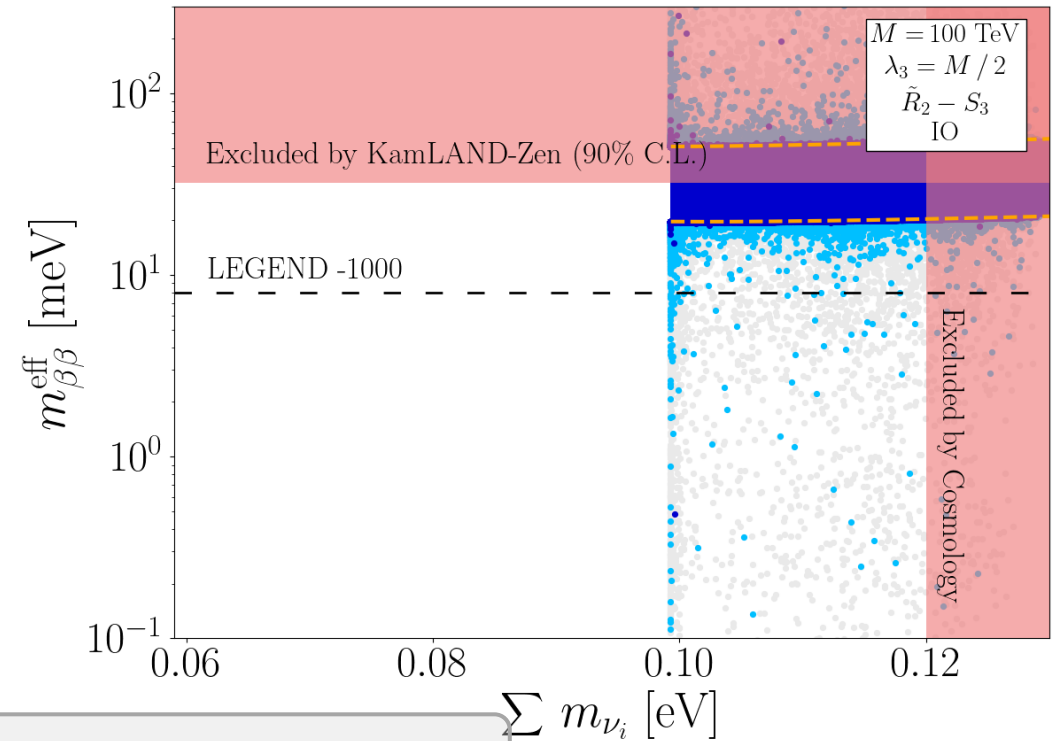
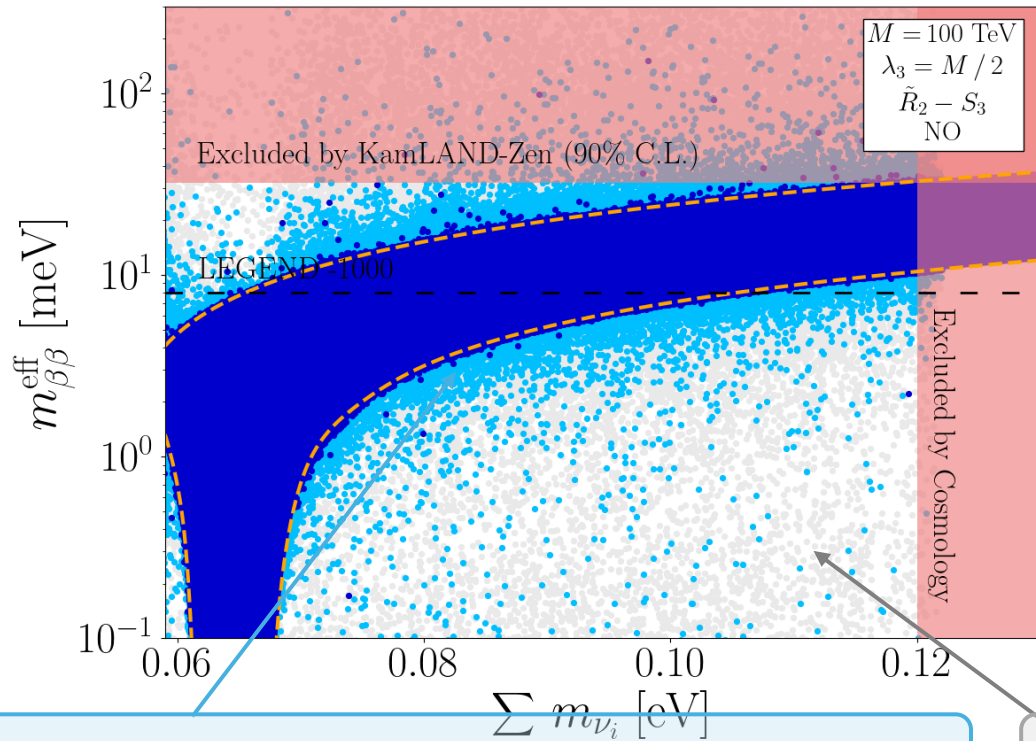


⇒ Ambiguity between normal and inverted ordering (more information needed)

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- ❖ Benchmark: $m_{\tilde{R}_2} = m_{S_3} = M$
- ❖ LQ Yukawas fixed to explain neutrino masses for both neutrino orderings





light blue : within reach of future experiments


gray : excluded by flavor

Flavor physics and $0\nu\beta\beta$ are complementary to probe new physics up to $\mathcal{O}(10^3 \text{ TeV})$

Thank you!

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



Srejanas Fajfer^a, Luighi P.S. Leal^{b,c}, Olegry Sumenari^a, Renata Zakasovič Funchal^a
^a Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91191 Gif-sur-Yvette, France
^b Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, 05314-970 São Paulo, Brazil

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 $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$\mathcal{O}_5^{lept} = \frac{C_{ij}^{lept}}{\Lambda} (\bar{L}_i^c \tilde{H})(\tilde{H}^T L_j) + h.c.$$

$$\Rightarrow (m_{\nu})_{ij} = \frac{C_{ij}^{lept}}{\Lambda} v^2 \quad (\text{suppressed by } v^2/\Lambda)$$
- ⇒ Lepton Number (L) is broken (neutrinos are Majorana particles)
- ◆ Majorana masses induce neutrinoless double beta decay ($0\nu\beta\beta$) with half life

$$\langle \bar{\nu}\nu \rangle = G^{eff} \mathcal{M}^{(d)} \sum_{ij} m_{\nu_{ij}} U_{ij}^2 P^{\pm} \quad (\text{chirality suppressed})$$
- ⇒ Future experiments will improve significantly sensitivity (LEGEND - 1000).
- ◆ However, higher dimensional operators ($d \geq 7$) can also appear in dynamical models for Majorana masses.

$$\mathcal{O}_{COMET} = \sum_{ijkl} C_{ijkl}^{(d)} \sum_{\alpha\beta\gamma\delta} \bar{L}_i^c \tilde{H} \gamma_{\alpha} L_j \tilde{H}^T \gamma_{\beta} L_k \tilde{H} \gamma_{\gamma} L_l \tilde{H}^T \gamma_{\delta} P^{\pm}$$

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

m_{ν} at loop-level ($d = 5$)

$0\nu\beta\beta$ from m_{ν} ($d = 5$) and additional tree-level contributions ($d = 7$)

Other flavor effects (stable in experiments) ($d = 6$)

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

Our framework

- ◆ Leptoquark: colored particles that couple to quarks and leptons.
- ◆ Two models can break L:
 $\{S_1 \sim (\bar{3}, 1, 1/3)\}$ and $\{\tilde{S}_2 \sim (\bar{3}, 2, 1/6)\}$ or $S_1 \sim (\bar{3}, 1, 1/3)$ and $\tilde{S}_2 \sim (\bar{3}, 2, 1/6)$
 ⇒ We consider the $S_1 - \tilde{S}_2$ model

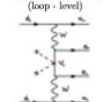
$$\mathcal{L}_{\tilde{S}_1, \tilde{S}_2} = \sum_{ij} \bar{L}_i \gamma_{\mu} S_1^{\mu} q_j + \sum_{ij} \bar{L}_i \gamma_{\mu} \tilde{S}_2^{\mu} q_j + \sum_{ij} \bar{L}_i \gamma_{\mu} S_1^{\mu} \tilde{S}_2^{\nu} q_j + h.c.$$
- Mixing induces Lepton Number Violation
- ◆ Neutrino masses are loop generated

$$m_{\nu} \simeq -\frac{g_{\tilde{S}_1}^2 g_{\tilde{S}_2}^2}{32\pi^2} \sum_{ij} \tilde{C}_{ij}^{(d)} \tilde{C}_{ij}^{(d)} \tilde{C}_{ij}^{(d)} \tilde{C}_{ij}^{(d)} \tilde{C}_{ij}^{(d)} \tilde{C}_{ij}^{(d)}$$
- For $m_{\tilde{S}_1} = m_{\tilde{S}_2} = M$

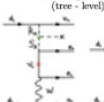
$$m_{\nu} \simeq 0.1 \text{ eV} \left[\frac{\Lambda}{M} \right] \left[\frac{M}{10^3 \text{ TeV}} \right] \left[\frac{10 \text{ eV}}{10^3 \text{ TeV}} \right]$$

Neutrinoless double beta decay

d = 5 contribution
(loop - level)



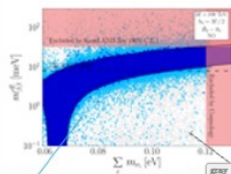
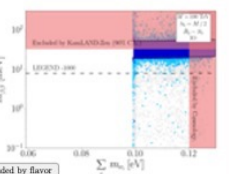
d = 7 operators
(tree - level)



- ◆ The new contributions can be similar as they are chirality enhanced.
- ◆ Leptoquark masses as large as $\mathcal{O}(10^3 \text{ TeV})$ can be probed with current data.

Our predictions

- ◆ Prediction for parameters that reproduce viable neutrino masses

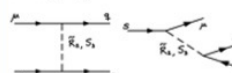
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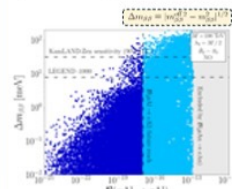
grey : excluded by flavor

- ◆ 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. $\mu N \rightarrow eN$

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





- ◆ $\mu N \rightarrow eN$ can probe comparable mass scales to $0\nu\beta\beta$ ($\leq 10^3 \text{ TeV}$)
- ◆ COMET (J-PARC) and Mu2E (Fermilab) will probe $R(\mu, \lambda) \rightarrow e, \lambda) \simeq 10^{-17}$
- ◆ 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.
- ◆ Additional 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. Meglitz, *JHEP* 12, 097 (2016) [arXiv:1606.02790 [hep-ph]]

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

Backup

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

Future sensitivity: $\mathcal{B}(\mu\text{Al} \rightarrow e\text{Al}) \simeq 10^{-17}$

