DPF-PHENO 2024

Exploring $0\nu\beta\beta$ decay and leptogenesis in low-scale seesaw model

University of Pittsburgh / Carnegie Mellon University
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Collaborators : Gang Li, Michael J. Ramsey-Musolf, Sebastian Urrutia Quiroga

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Plan of the talk

- Introduction
- The low-scale seesaw model
- Phenomenology of extended seesaw :

  — charged Lepton Flavor Violation (cLFV)
  — Neutrinoless double beta $(0\nu\beta\beta)$ decay
  — Leptogenesis
- Summary

Beyond the Standard Model Physics (BSM)

ν

- The nature of the neutrinos : Dirac or Majorana ???
- Is there lepton number violation (LNV) in the theory? If so, at what energy scale does it occur?

$$\Downarrow$$

Existence of the BSM frameworks.

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Aim :

- General consideration of Effective Field theory (EFT) approach : if there are experimentally observable signatures in $0\nu\beta\beta$ decay and the lepton asymmetry generated only by the right-handed neutrinos, the thermal leptogenesis is likely to be unviable.

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Aim :

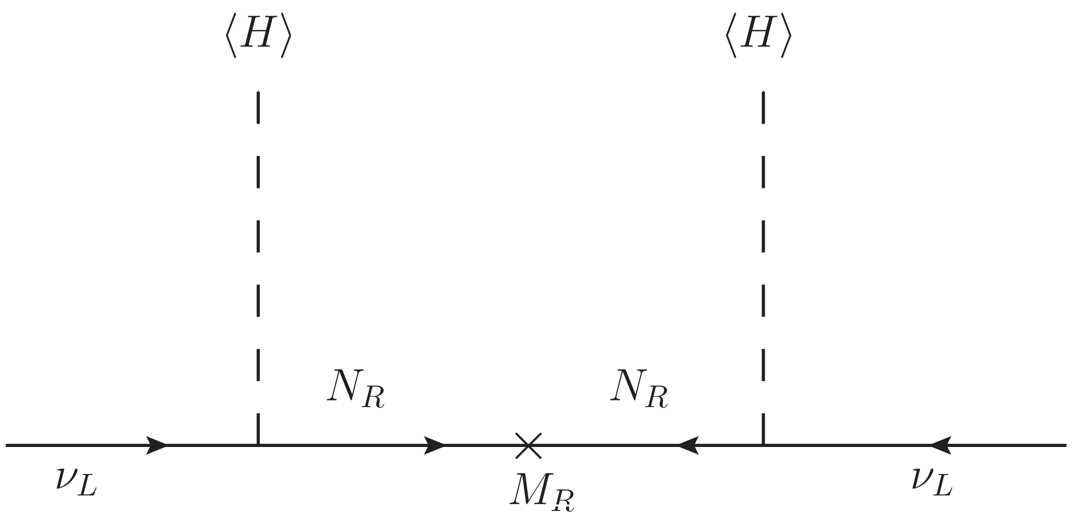
- General consideration of Effective Field theory (EFT) approach : if there are experimentally observable signatures in neutrino less double beta ($0\nu\beta\beta$) decay and the lepton asymmetry generated only by the right-handed neutrinos, the thermal leptogenesis is likely to be unviable.

- However, in the context of low-scale resonant leptogenesis, one can obtain the observed baryon asymmetry and observable signatures of $0\nu\beta\beta$ decay in the presence of additional sterile neutrinos.

The Seesaw Mechanism

$$\mathscr{L} = y\bar{L}N_R\tilde{H} + \frac{1}{2}M_R\overline{N_R^c}N_R + h.c.$$

N_R : Fermion Singlet



Type-I Seesaw

$$M_D = yv$$

$$\mathscr{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

$\downarrow$ $M_D \ll M_R$

$$m_\nu = -M_D M_R^{-1} M_D^T \sim \frac{v^2}{M_R}$$

Naturally suppressed by large scale !!!

High Scale Seesaw !!!

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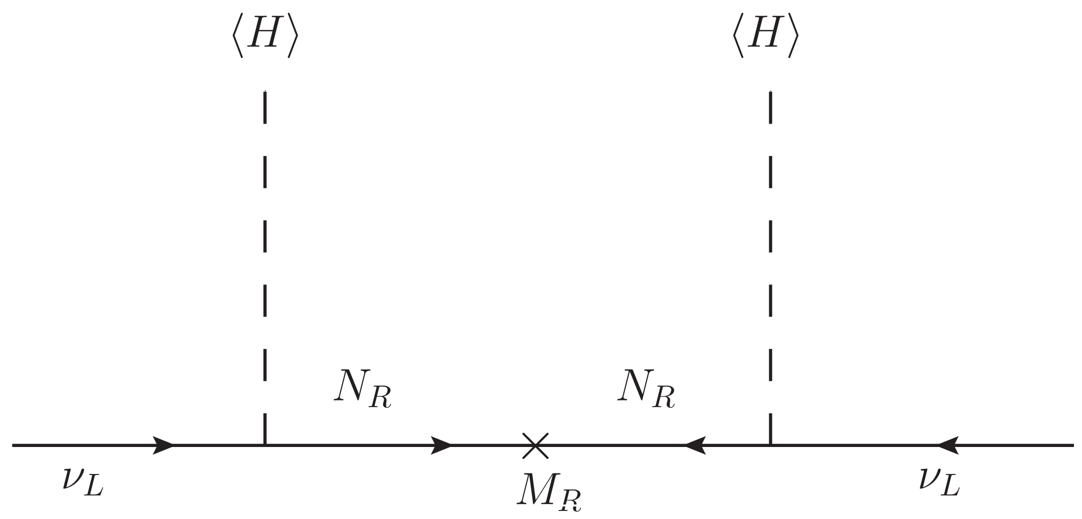

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Other types of Seesaw : Type-II and III.

SM + scalar triplet

SM + fermion triplet

Naturally suppressed by large scale !!!

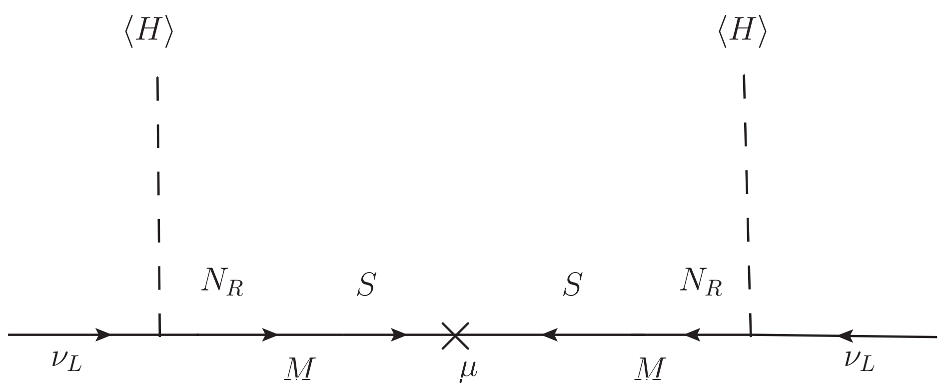
High Scale Seesaw !!!

The Low-scale Seesaw

Inverse Seesaw

Mohapatra, Valle, 1986

$$\mathscr{L} = M_D \bar{\nu}_L N_R + M \overline{N}_R S + \frac{1}{2} \mu \overline{S^c} S + h.c.$$



$$\mathscr{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$\downarrow \quad \mu \ll M_D \ll M$$

$$m_\nu = -M_D (M^{-1})^T \mu M^{-1} M_D^T \sim \frac{v^2}{M^2} \mu$$

Naturally suppressed by small scale $\mu \Rightarrow$ accessible at colliders.

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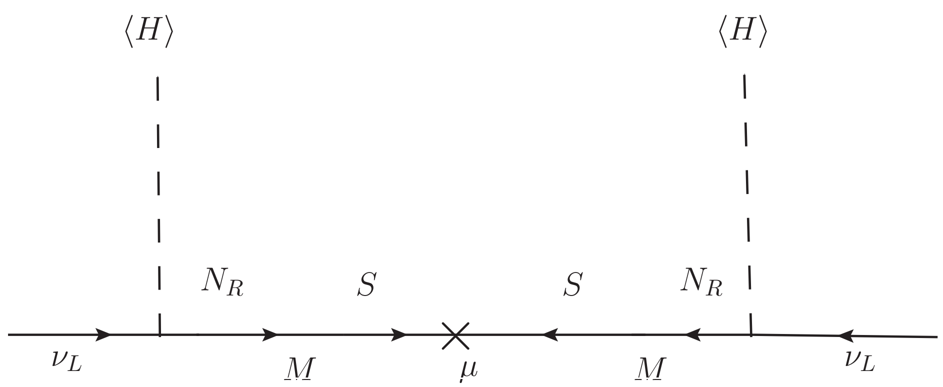

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Extended Seesaw

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$$\mu \ll M_D < M_S < M_R$$

$$\mu < M_S M_R^{-1} M_S^T$$

$$m_\nu = M_D M_S^{-1} \mu (M_D M_S^{-1})^T$$

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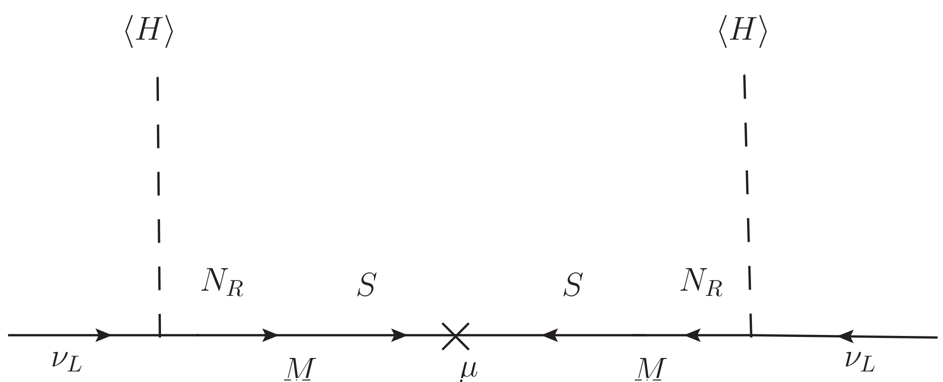

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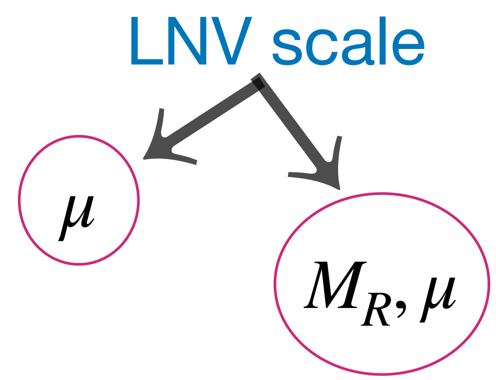

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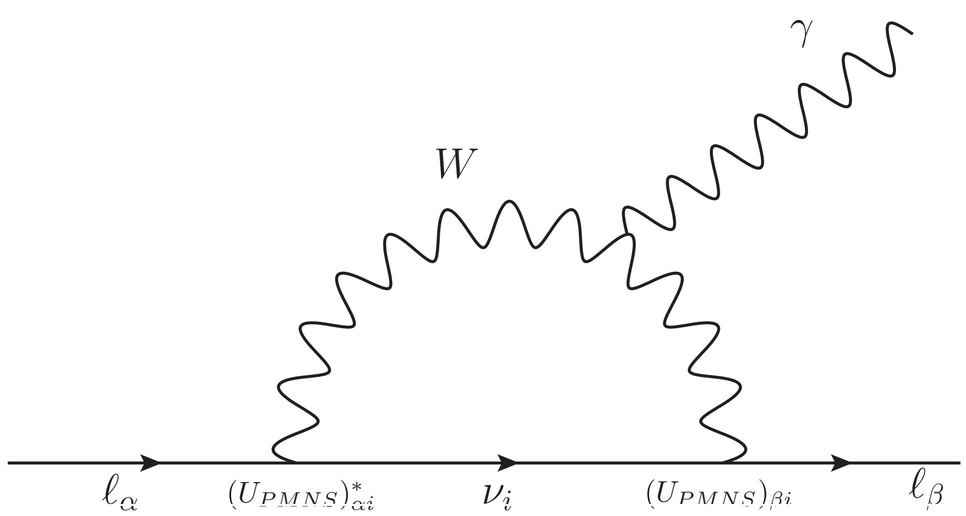
Lepton flavour violation (LFV)

- The observation of charged LFV would be a clear signal of BSM Physics.

SM+Dirac ν mass :



GIM suppression !!!

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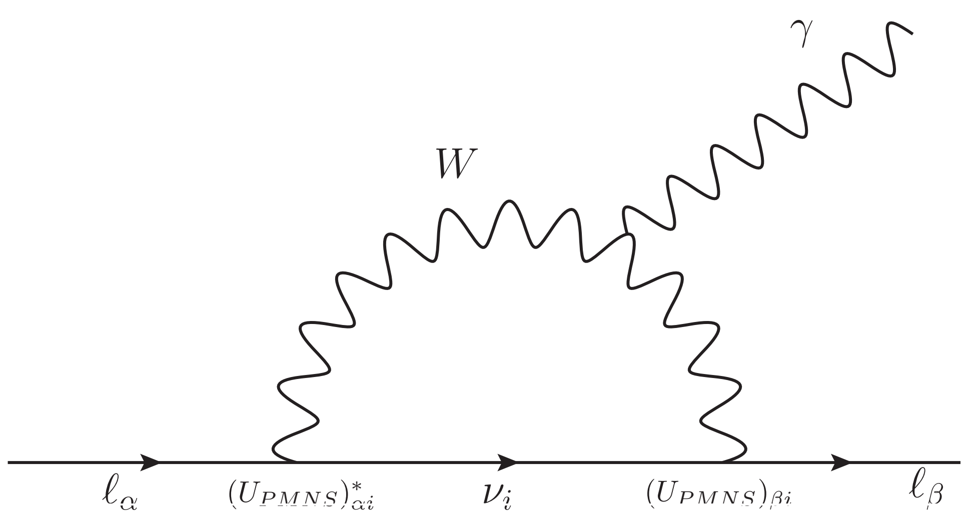
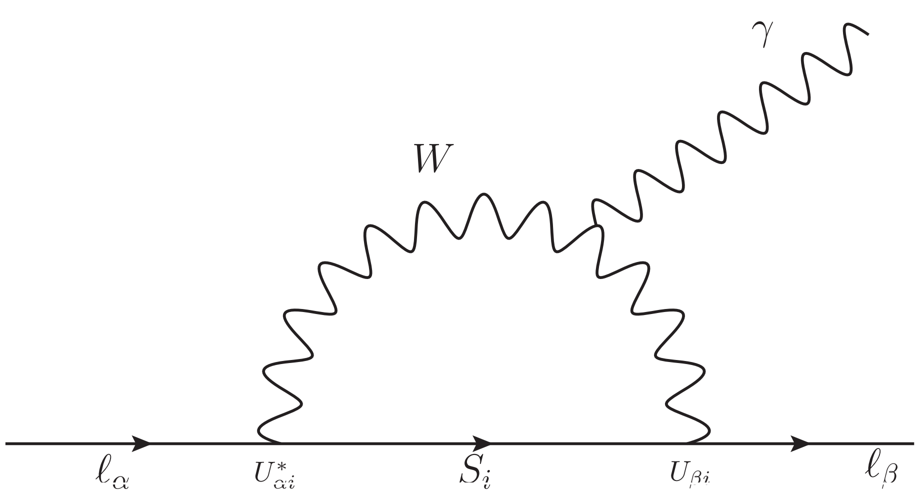


GIM suppression !!!

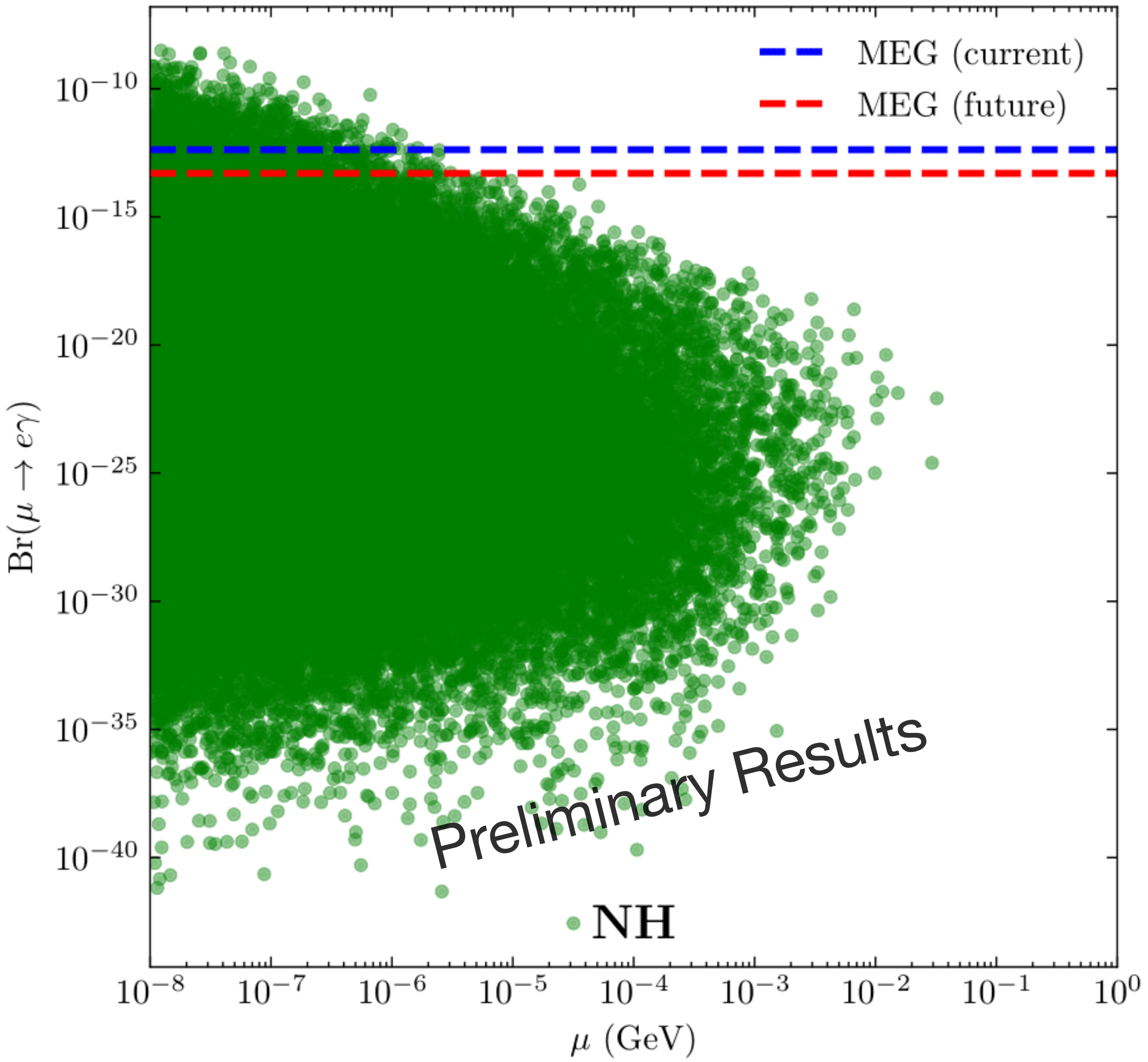
Extended seesaw model :

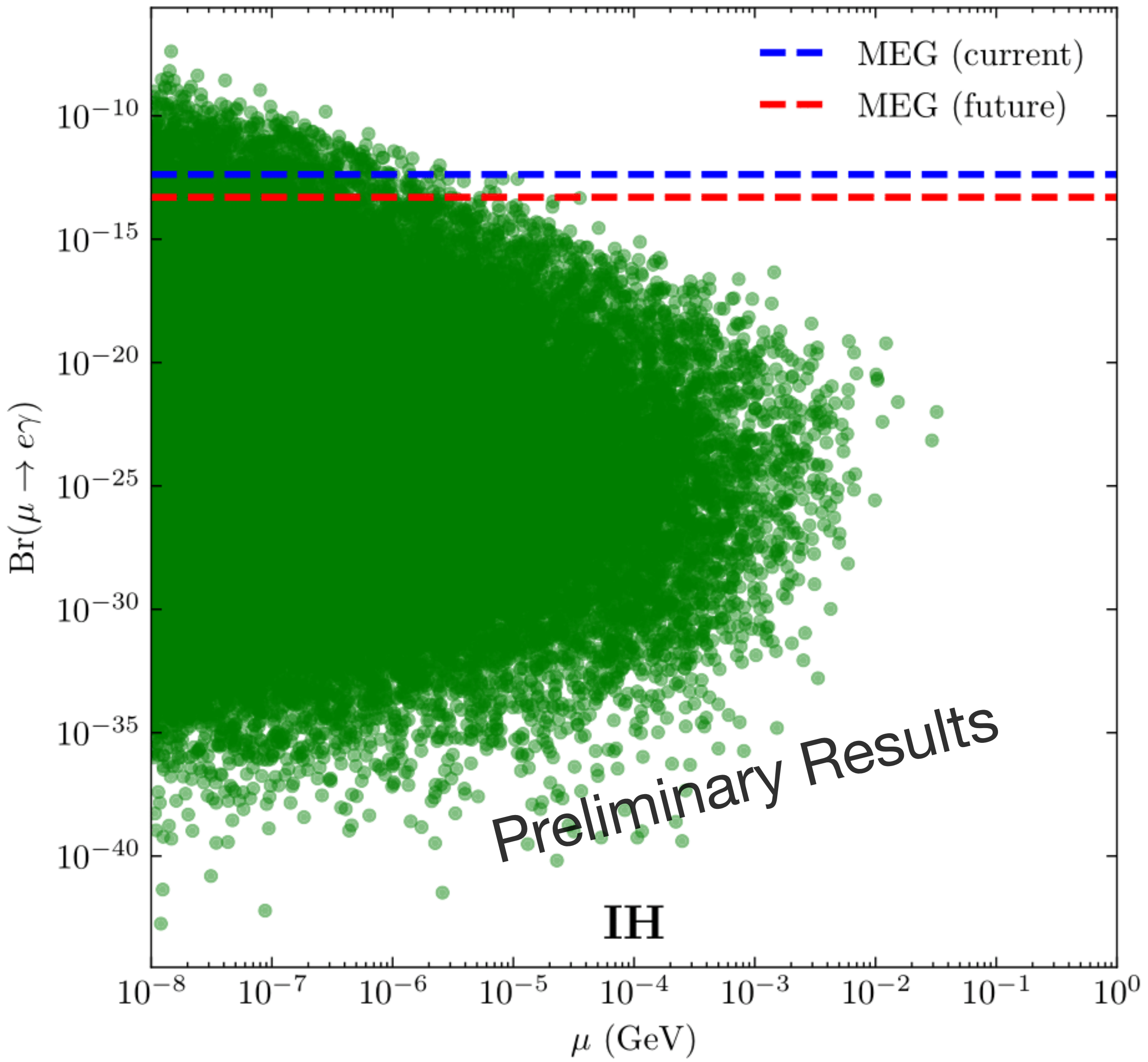


GIM suppression spoiled by the sterile neutrinos .

$$Br(\mu \to e\gamma) \simeq \frac{3}{2\pi}\alpha \left| \sum_{i=1}^{6} U^*_{\mu i} U_{ei} G_\gamma \left(\frac{m_i^2}{m_W^2} \right) \right|^2$$

$$U_{\alpha i} \propto M_D M_S^{-1}$$

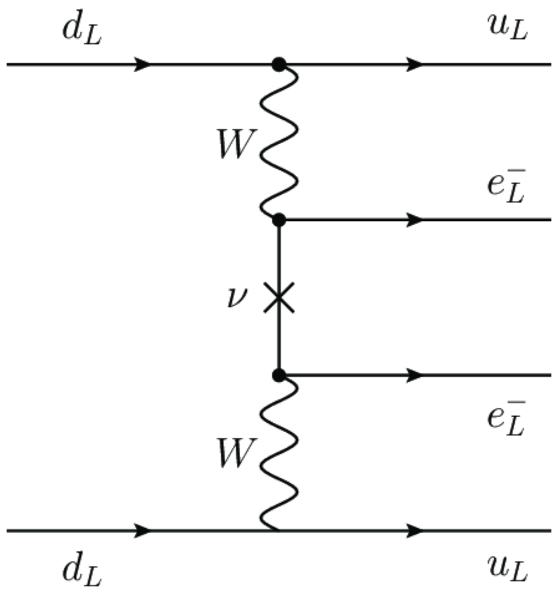




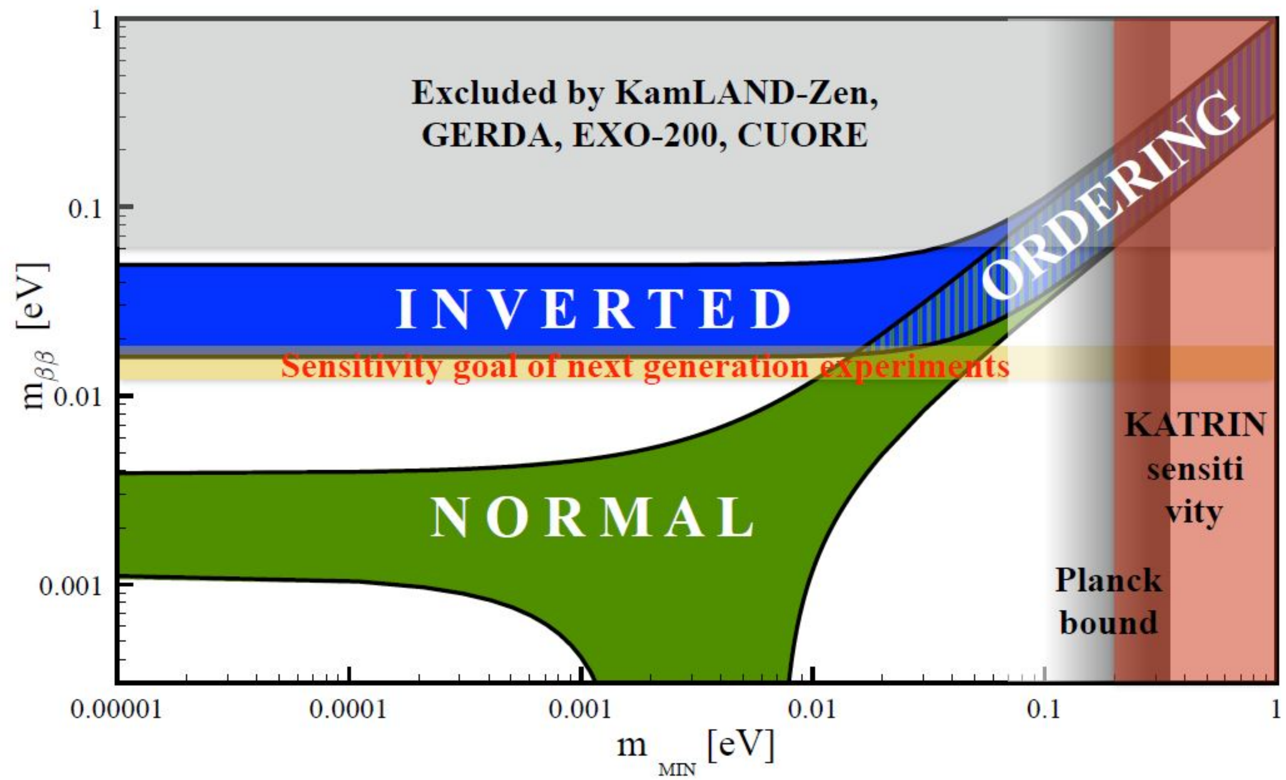
- We find that for 2 keV $\lesssim \mu \lesssim$ 10 MeV, the predicted branching ratio of $\mu \to e\gamma$ is within the reach of future experimental searches.

Neutrinoless double beta $(0\nu\beta\beta)$ decay

- In order to probe Majorana nature of massive neutrinos and LNV signatures, we need to study $0\nu\beta\beta$ decay : $(A, Z) \rightarrow (A, Z+2) + 2e^-$.



Standard Mechanism



https://tinyurl.com/2796wj2c

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$\downarrow$

NME

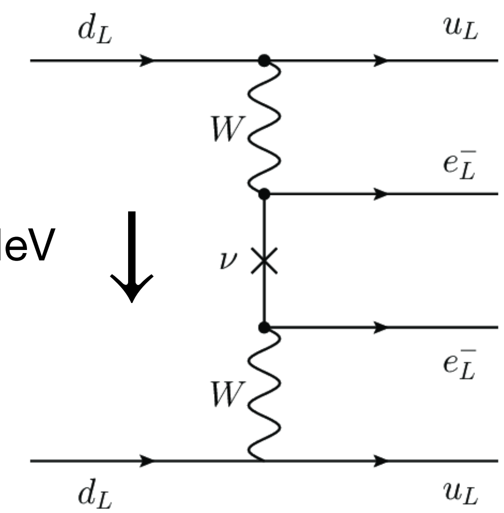
$$\langle m_{\beta\beta} \rangle = \left| \sum m_i U_{ei}^2 \right|$$

KamLAND-Zen (^{136}Xe) : $\langle m_{\beta\beta} \rangle < 61 - 165$ MeV

GERDA (^{76}Ge) : $\langle m_{\beta\beta} \rangle < 79 - 180$ MeV

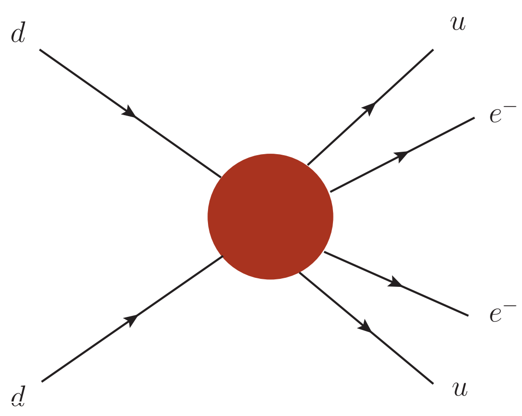
Standard Mechanism

$p \sim 200$ MeV



$$\sim G_F^2 m_\nu / p^2$$

Heavy BSM mechanism

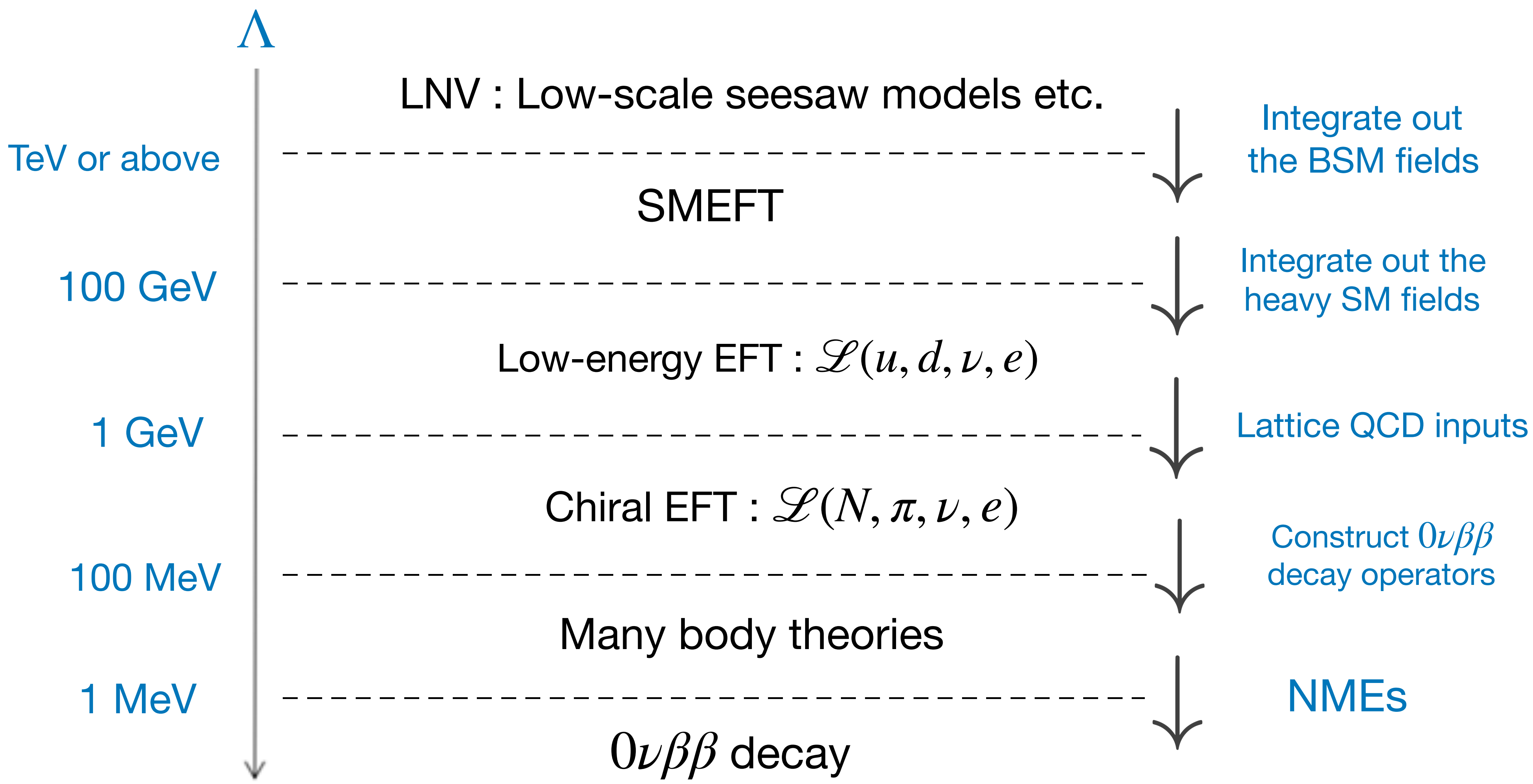


$$\sim c/\Lambda^5$$

$$\frac{c/\Lambda^5}{G_F^2 m_\nu / p^2} = c \left(\frac{3.3\ TeV}{\Lambda}\right)^5 \left(\frac{0.1\ eV}{m_\nu}\right) \Rightarrow$$

Contributions from heavy BSM mechanism could be comparable if $c \sim \mathcal{O}(1)$, $\Lambda \sim$ TeV.

EFT approach to $0\nu\beta\beta$ decay



EFT approach to $0\nu\beta\beta$ decay

Λ

LNV : Low-scale seesaw models etc.

TeV or above — Integrate out the BSM fields

SMEFT

100 GeV — Integrate out the heavy SM fields

Low-energy EFT : $\mathscr{L}(u, d, \nu, e)$

1 GeV — Lattice QCD inputs

Chiral EFT : $\mathscr{L}(N, \pi, \nu, e)$

100 MeV — Construct $0\nu\beta\beta$ decay operators

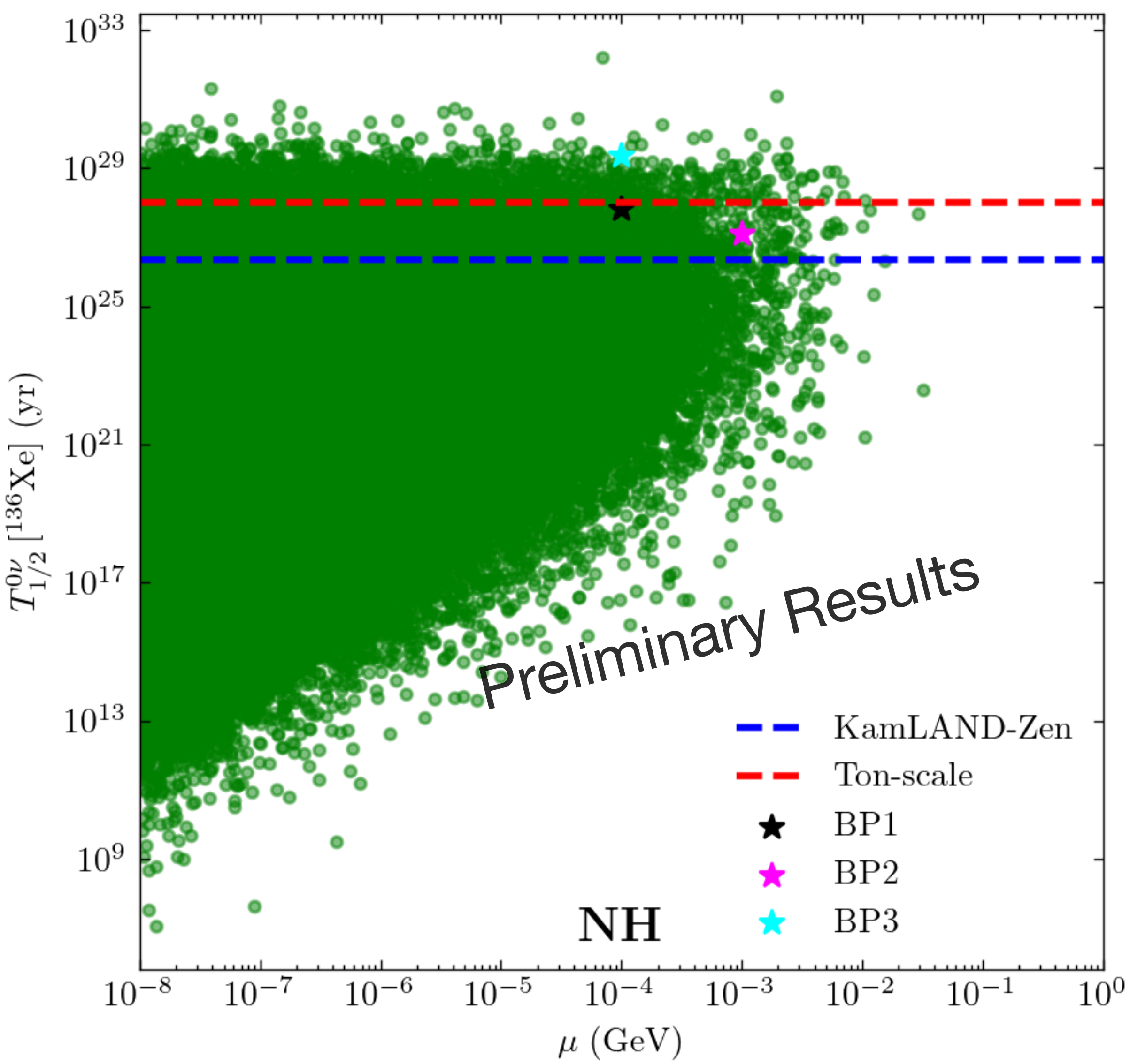
Many body theories

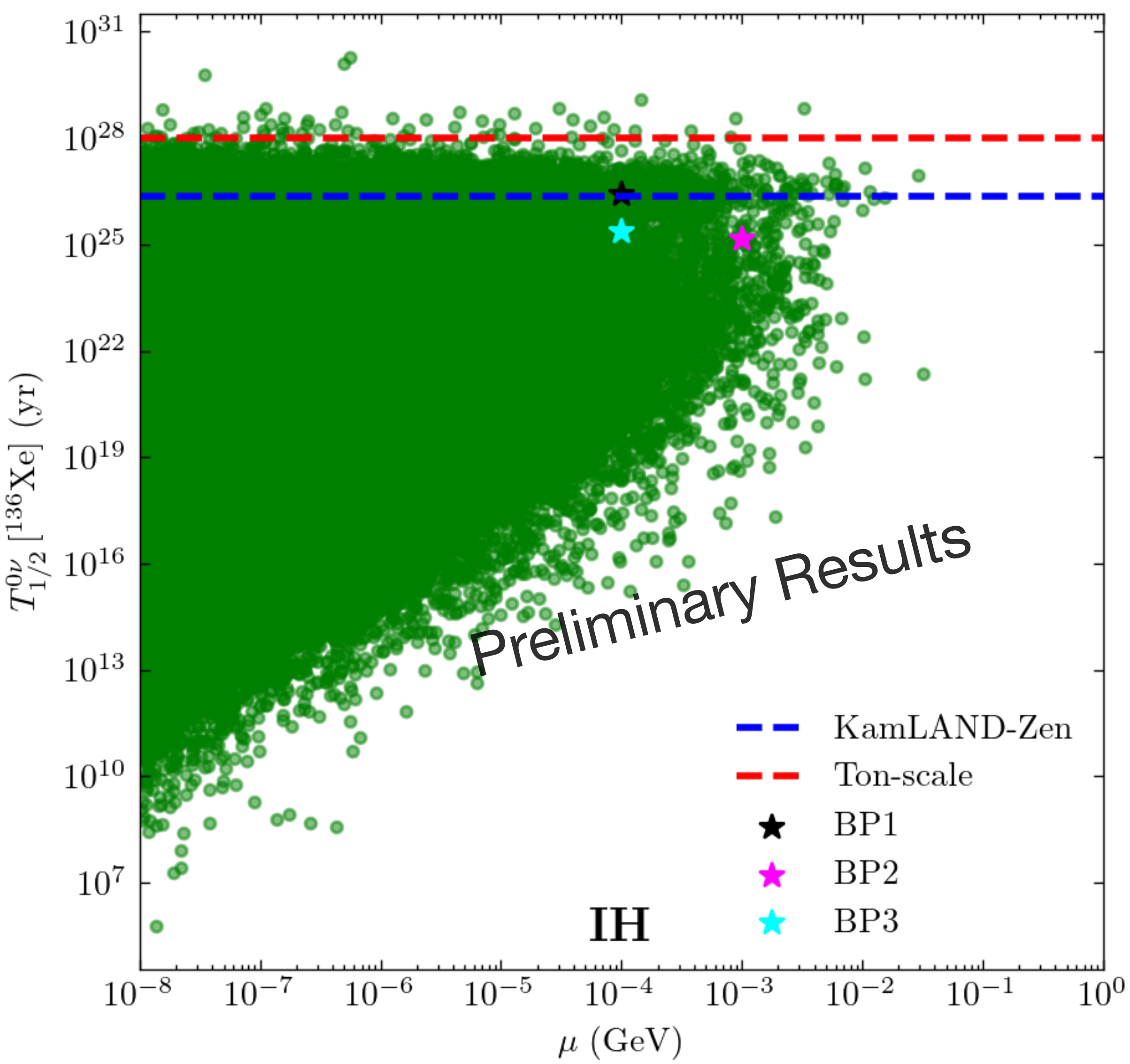
1 MeV — NMEs

$0\nu\beta\beta$ decay

Half-life :

$$\left(T^{o\nu}_{1/2}\right)^{-1} = g_A^4 G_{01} \left| \sum_{i=1}^{6} -\frac{m_i}{4m_e} \left(C^{(6)}_{\mathrm{VLL}}\right)^2_{ei} \left[\mathcal{M}_V + \mathcal{M}_A + \frac{2m_\pi^2}{g_A^2} g_\nu^{NN}\left(m_i\right) \mathcal{M}_{F,sd}\right] \right|^2$$





- We find that for $\mu \lesssim 10$ MeV, the predicted $0\nu\beta\beta$ decay is within the reach of experimental searches.

Leptogenesis

- The Majorana nature of neutrinos allows us to explore the possibility of leptogenesis in the model.

Thermal Leptogenesis

$M_{N_R} > 10^9$ GeV !!!

Gravitino Problem !!!

Not testable !!!

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Resonant Leptogenesis

Accessible at collider

No Gravitino Problem

Almost degenerate masses for two lightest RHNs $\sim$ few TeV

A. Pilaftsis & T.E.Underwood, 2004

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- Presence of the new particles in the model results in an additional contributions to CP asymmetry as well as washout.

- For the three benchmarks BP1, BP2 and BP3, with the right handed neutrino masses around 10 TeV, we get the correct baryon asymmetry of the universe, $\eta_B = (6.12 \pm 0.04) \times 10^{-10}$.

Summary

- The extended seesaw is very simple yet a powerful mechanism for neutrino masses.
- In this framework, the neutrino masses are suppressed by the extended seesaw parameter, μ, rather than introducing fine-tuned Yukawa couplings in other neutrino mass generation mechanisms.
- In the context of low-scale resonant leptogenesis, one can obtain the observed baryon asymmetry and observable signatures of $0\nu\beta\beta$ decay in the presence of additional sterile neutrinos.
- We have shown that the MeV- scale sterile neutrinos is sensitive to KamLAND-Zen experiment, and future ton-scale experiments offer potential signals while maintaining viable resonant leptogenesis.

Thank you!

Comments, questions, Suggestions!!!

Back-up Slide 1 :

LFV :

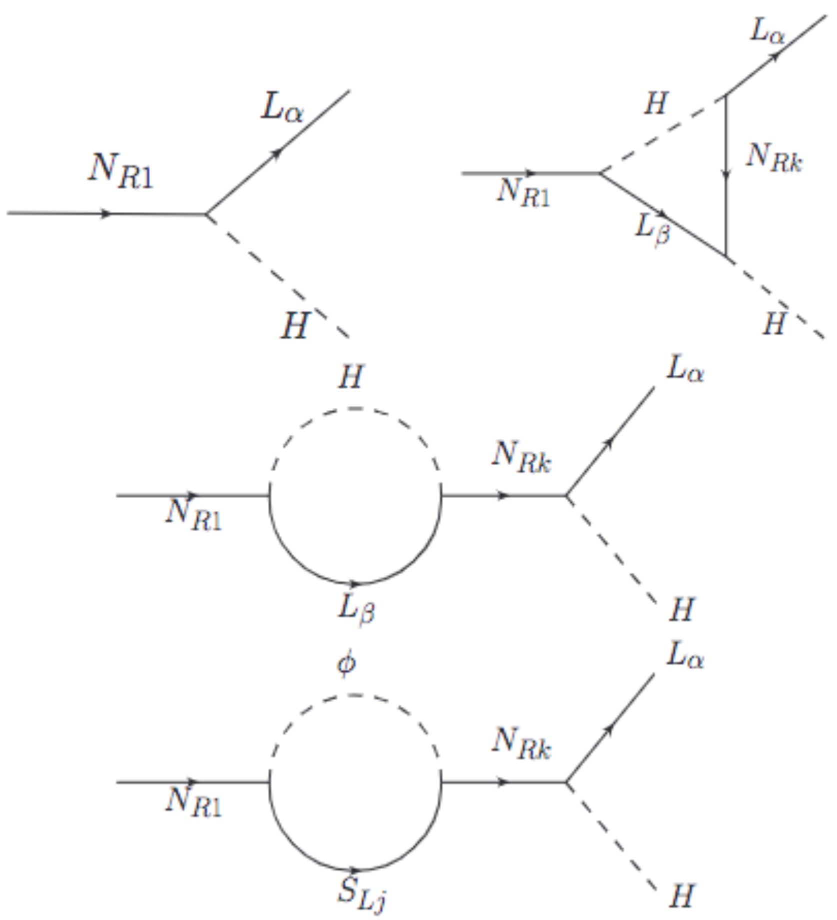
$$\frac{\mathrm{CR}(\mu N \to eN)}{\mathrm{BR}(\mu \to e\gamma)} = \frac{3 \cdot 10^{12} G_F^2 m_\mu^4}{96\pi^3\alpha} B(A,Z)$$

$$\frac{\mathrm{BR}(\mu \to eee)}{\mathrm{BR}(\mu \to e\gamma)} = \frac{\alpha}{3\pi}\left(\ln\frac{m_\mu^2}{m_e^2} - \frac{11}{4}\right)$$

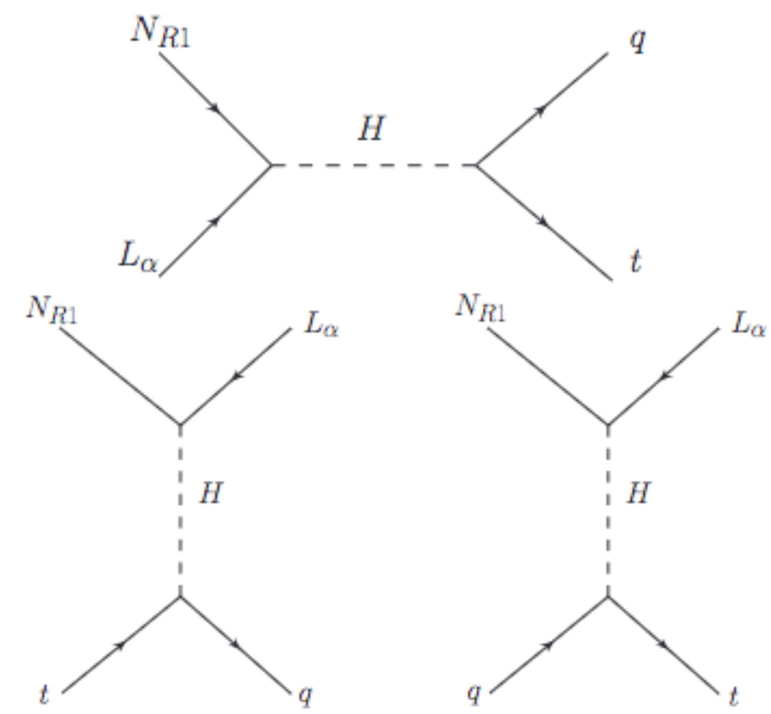
CP Asymmetry :

$$\epsilon_1 \simeq \frac{1}{8\pi}\sum_{k\neq 1}\left\{\frac{\mathrm{Im}\left[(\mathrm{Y_D^\dagger Y_D})_{k1}^2 + (\mathrm{Y_D^\dagger Y_D} + \mathrm{Y_S^\dagger Y_S})_{1k}\right]}{(Y_D^\dagger Y_D + Y_S^\dagger Y_S)_{11}}\left(\frac{1}{1-x_k}\right)\right\}$$

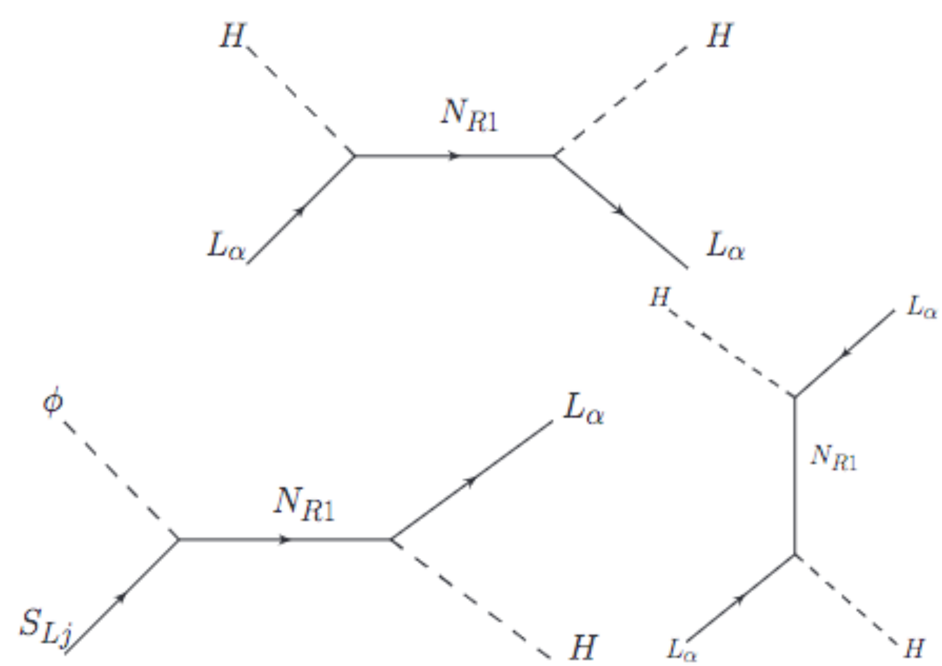
Back-up Slide 2 :



Decay



$\Delta L = 1$: Scattering process via Higgs exchange



$\Delta L = 2$: Scattering process via N_{R1} exchange