- Charged lepton flavor violating processes can probe ultra heavy HNLs, but only as long as their Yukawa couplings is $|Y_{\text{tot.}}|^2 \leq 8\pi/\varphi$.
- Proposals for lepton colliders can probe scales of left-right symmetric models up to $\sim 70\,\text{TeV}$.

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Bounds on neutrino mass scale beyond the EW scale

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Introduction

We search for Heavy Neutral Leptons (HNLs) in two different models. First, in the type I seesaw, we re-examine the bounds from charged lepton flavor violating (cLFV) processes, now including non-decoupling loop diagrams. We then examine the validity of such bounds, by making an analysis of the unitarity of the S matrix. Finally, analyze the sensitivity that proposals for lepton colliders have for HNLs but now in the LRSM.

Type-I Seesaw

- SM extension, adds neutrally charged singlets, N called HNLs (Heavy Neutral Leptons). New Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\bar{N}_{i,R}\not{\partial}N_{i,R} - Y_{\alpha i}\,\bar{L}_{\alpha,L}\cdot\tilde{\phi}\,N_{i,R} - \frac{1}{2}\bar{N}^C_{i,R}(M_N)_{ii}\,N_{i,R} + \text{H.c.}\,.$$

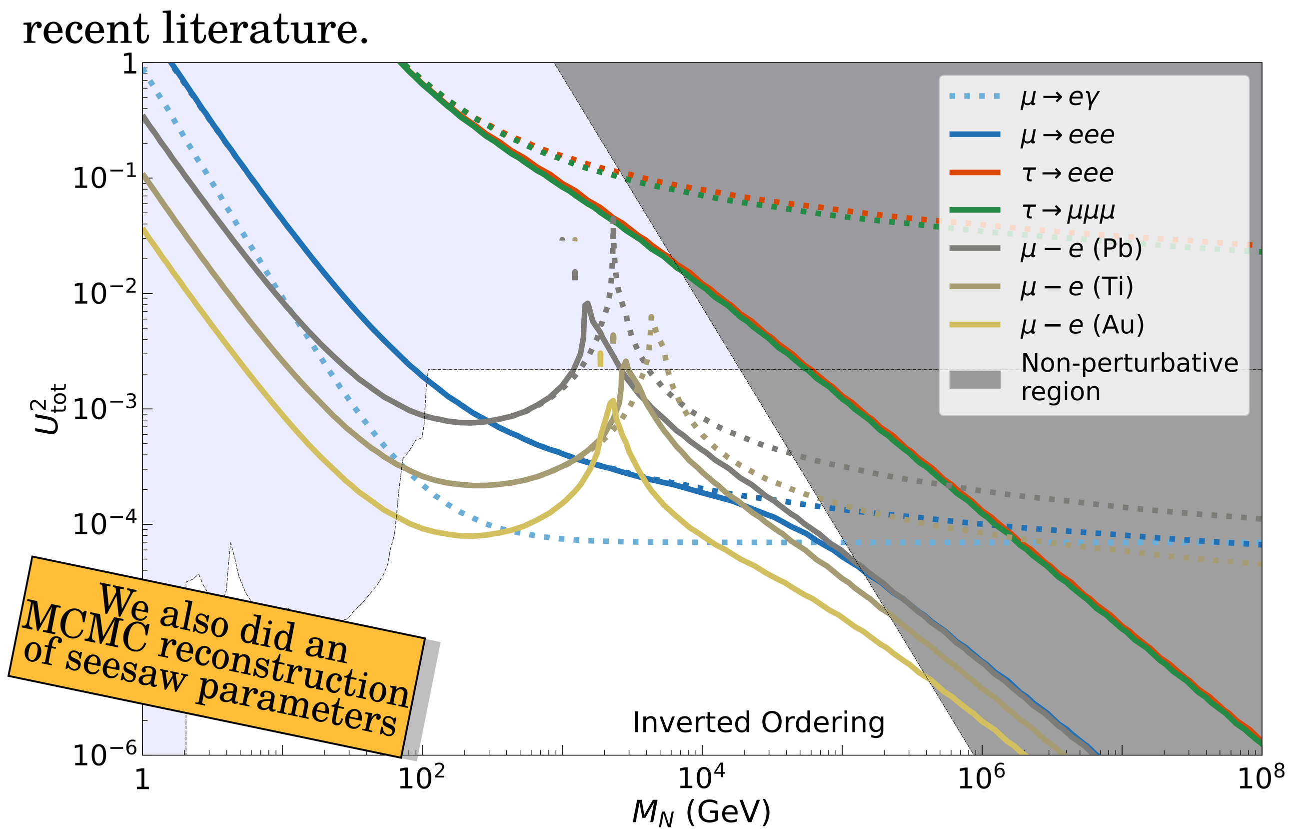
- Induces seesaw mechanism, and therefore small neutrino masses

$$M_\nu = -M_D^T\frac{1}{M_N}M_D$$

- A right parametrization of the Yukawa matrix allows you to have big mixing angles and small neutrino masses.
- You can directly search for the at experiments. For very heavy HNLs, above the EW scale, you can only probe them indirectly, for example through bounds on cLFV.

Bounds from cLFV

Bounds from cLFV processes grow with mass, which has been neglected in recent literature.



Can we trust these bounds?

- The shaded region on the right denotes where the "theory stops being perturbative"
- We performed a perturbative unitarity study to see where the shaded region should start
- S matrix demands that the partial waves, a^J, should follow $\text{Re}\{a^J\} \leq \frac{1}{2}$.
- The $J=1$ partial wave sets a bound on Yukawa couplings $|Y_{\text{tot.}}|^2 \leq 8\pi/\varphi$.

Left-Right Symmetric Model

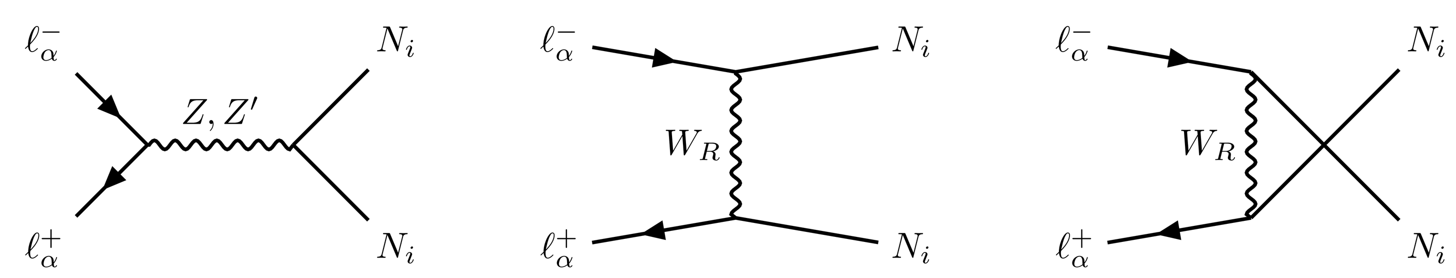
- Gauge extension of the SM. Restores parity at a higher energy

$$\text{SU}(2)_R\times\text{SU}(2)_L\times\text{U}(1)_{\text{B-L}} \xrightarrow{v_R} \text{SU}(2)_L\times\text{U}(1)_{\text{Y}} \xrightarrow{v} \text{U}(1)_Q$$

- Adds new zoo of particles, gauge bosons like W_R and Z'; as well a large scalar sector. The model also includes HNLs
- Includes also a seesaw mechanism, but mixing angle is too small to be probed easily. HNLs are produced through interactions with the new gauge bosons

Lepton colliders and LRSM

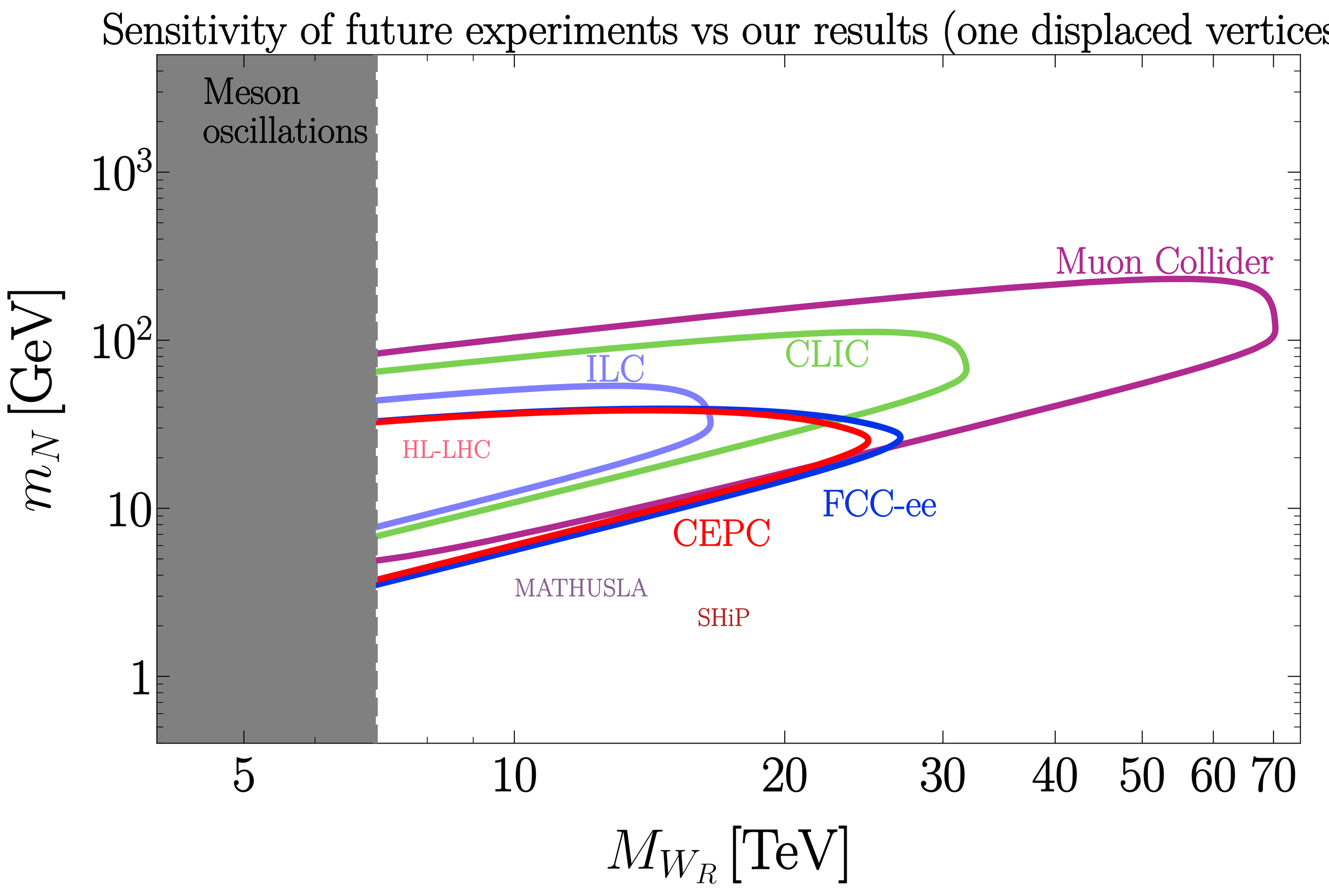
Several proposals for lepton colliders: FCC, CEPC, ILC, CLIC and muon colliders. The HNL production diagrams are



Decays are mostly semi-leptonic in LRSM, no missing energy. We estimate the sensitivity of lepton colliders of HNLs decaying at least $5\,\text{mm}$ from the IP.

Bounds from displaced vertices

Sensitivity of future experiments vs our results (one displaced vertices)



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