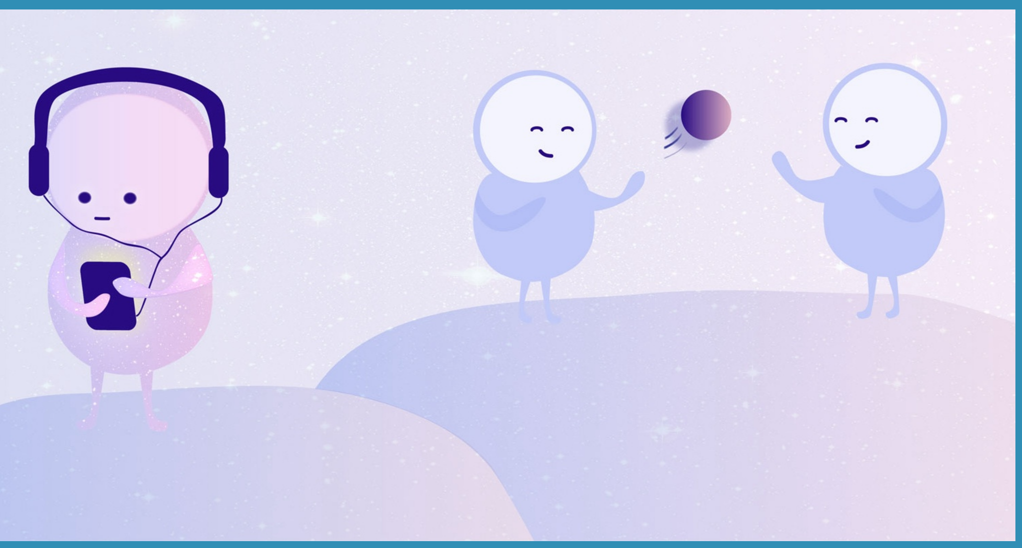

Probing the Nature of Heavy Neutral Leptons in Direct Searches & $0\nu\beta\beta$

based on arXiv:2212.14690

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Introduction

Heavy Neutral Leptons (HNLs) are a popular extension of the Standard Model to explain the lightness of neutrino masses and the matter-antimatter asymmetry through leptogenesis. Future direct searches, such as fixed target setups like DUNE, and neutrinoless double beta decay are both expected to probe the regime of active-sterile neutrino mixing in a standard Seesaw scenario of neutrino mass generation for HNL masses around $m_N \lesssim 1$ GeV. Motivated by this, we analyse the complementarity between future direct searches and neutrinoless double beta decay to probe the nature of HNLs, i.e., whether they are Majorana or quasi-Dirac states, and CP-violating phases in the sterile neutrino sector. Following an analytic discussion of the complementarity, we implement a generic fixed target experiment modelling DUNE. We perform a statistical study in how a combined search for HNLs in direct searches and neutrinoless double beta decay, using DUNE and LEGEND-1000 as representative examples, can probe the nature of sterile neutrinos.

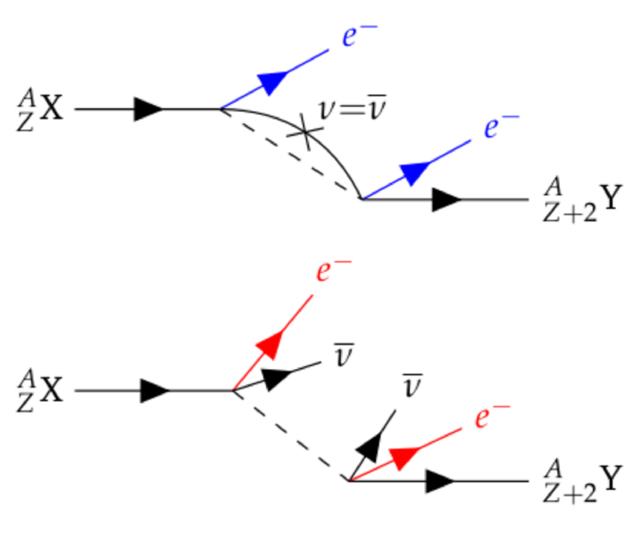
Models & Parameterisation

- For one neutrino and two HNLs simplified model, the mass matrix and mixing matrix are parameterised by[1]

$$\mathcal{M}_\nu = U_{1+2} \cdot diag(m_\nu, m_N, m_N(1 + r_\Delta)) \cdot U^T_{1+2}, \quad (1)$$

$$U_{1+2} \approx \begin{pmatrix} 1 & s_{e1} & s_{e2}e^{-i\delta} \\ -s_{e1}c_{12} - s_{e2}s_{12}e^{i\delta} & c_{12} & s_{12} \\ s_{e1}s_{12} - s_{e2}c_{12}e^{i\delta} & -s_{12} & c_{12} \end{pmatrix} \cdot D_\phi. \quad (2)$$

Here, $D_\phi = diag(1, e^{i\phi_1}, e^{i\phi_2})$ contains two majorana CP phase for the two HNL states.



$2\nu\beta\beta$ and $0\nu\beta\beta$ decay.

m_ν is the active neutrino mass scale, m_N is the HNL mass scale and r_Δ is the mass splitting between the two HNL states.

- The general half-life formula can be expressed as

$$\frac{\Gamma_{0\nu}}{\ln 2} = \frac{1}{T^{0\nu}_{1/2}} = \frac{G_{0\nu} g_A^4}{m_e^2} \left| \sum_i^{\mathcal{N}_A} U^2_{ei} m_i \mathcal{M}^{0\nu}(m_i) + \sum_\kappa^{\mathcal{N}_S} U^2_{eN_\kappa} m_{N_\kappa} \mathcal{M}^{0\nu}(m_{N_\kappa}) \right|^2, \quad (3)$$

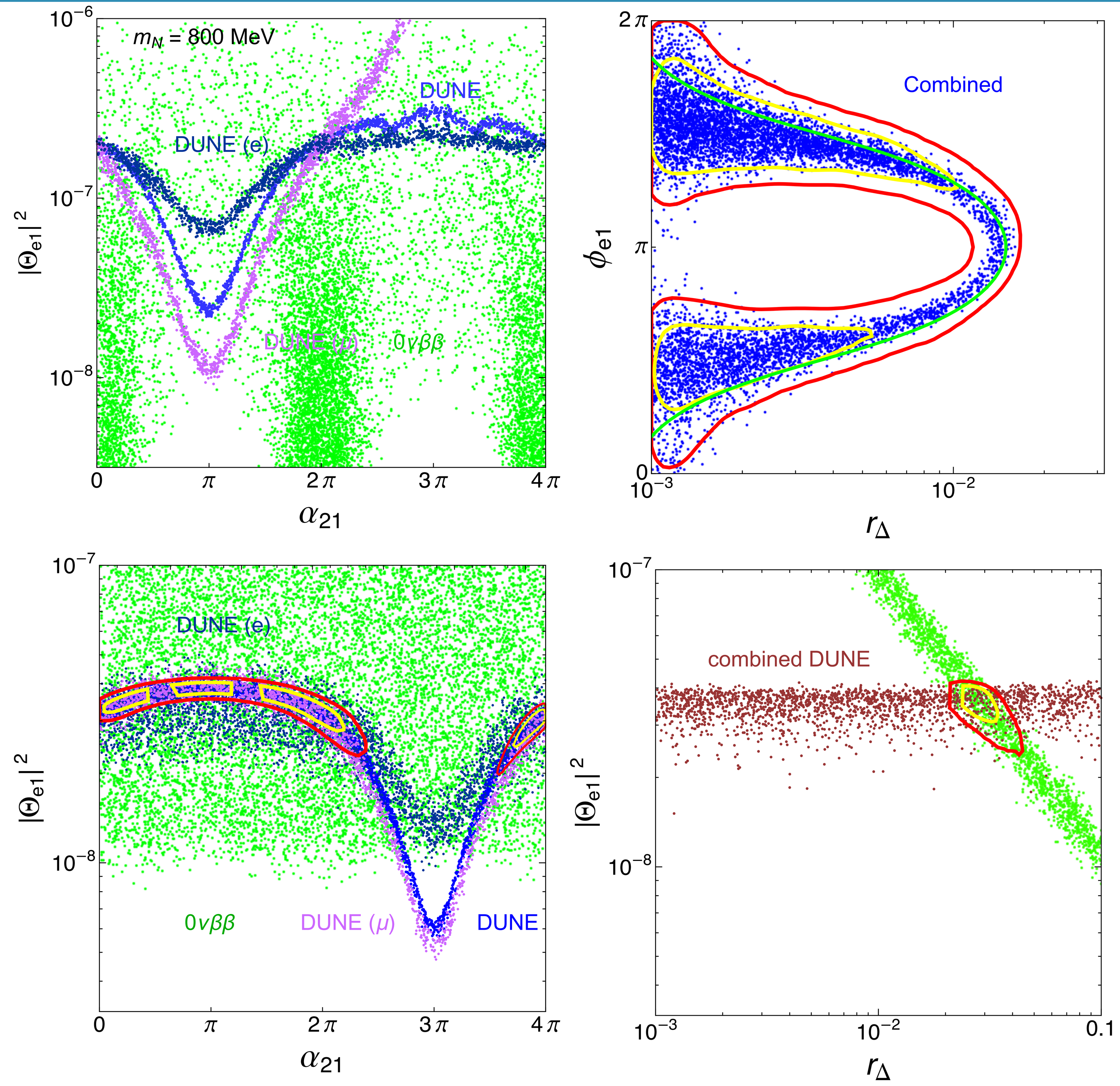
where $\mathcal{M}^{0\nu}$ is the nuclear matrix elements for $0\nu\beta\beta$ for different mass states.

- Since HNL can interact with SM particles via neutrino-HNL mixing, it can be produced by meson decay in fixed target experiment like DUNE. HNL can then be detected from it decay products (i.e. electrons, quarks and mesons)
- The Majorana or Dirac nature can be measured by the R parameter, which is defined as[2]

$$R_{ll} = \frac{m_N^2 r_\Delta^2}{2\Gamma_N^2 + m_N^2 r_\Delta^2}, \quad (4)$$

this parameter is valued between 0 for completely Dirac and 1 for Majorana.

Results and Discussion



Diagrams showing combined events of observing signals in both DUNE and LEGEND-1000 in IO (top) and NO (bottom). Benchmark is chosen for $m_N = 800$MeV, $|U_{e1}|^2 = 2 \times 10^{-7}$ and $r_\Delta = 10^{-2.5}$

- The measurements from $0\nu\beta\beta$ decay will us the effective mass in Eq.(3),

$$\left|m^{\rm exp}_{\beta\beta}\right| = 1.24 \times 10^{-2}{\rm eV} \left(\frac{2.36 \times 10^{-15}{\rm yr}^{-1}}{G_{0\nu}}\right)^{1/2} \left(\frac{5.28}{|\mathcal{M}^{0\nu}_\nu|}\right) \left(\frac{10^{28}{\rm yr}}{T^{0\nu}_{1/2}}\right)^{1/2} \quad (5)$$

- 3+2 model is used for the full analysis with massless lightest neutrino. Majorana CP phase $\alpha_{21} = 0$ for the saturated active effective masses in IO (m_{ee} = 50meV) and NO (m_{ee} = 3meV) .
- With the definitions of $\alpha \equiv 1 - \frac{\langle \mathbf{p}^2 \rangle \mathcal{F}(m_N(1+r_\Delta))}{\langle \mathbf{p}^2 \rangle + m_N^2(1+r_\Delta)^2}$ and $\beta \equiv \frac{\langle \mathbf{p}^2 \rangle \mathcal{F}(m_N)}{\langle \mathbf{p}^2 \rangle + m_N^2} - \frac{\langle \mathbf{p}^2 \rangle \mathcal{F}(m_N(1+r_\Delta))}{\langle \mathbf{p}^2 \rangle + m_N^2(1+r_\Delta)^2}$, an approximate relation in 1+2 model between the HNL mass (m_N), neutrino-HNL mixing ($|\Theta_{e1}|^2$), CP phase (ϕ_{e1}), HNL mass splitting (r_Δ)and neutrino mass m_ν is found to be

$$\cos\phi_{e1} = \frac{\left|m^{\rm exp}_{\beta\beta}\right|^2 - \alpha^2 m_\nu^2 - \beta^2 m_N^2 |\Theta_{e1}|^4}{2\alpha\beta m_\nu m_N |\Theta_{e1}|^2}, \quad (6)$$

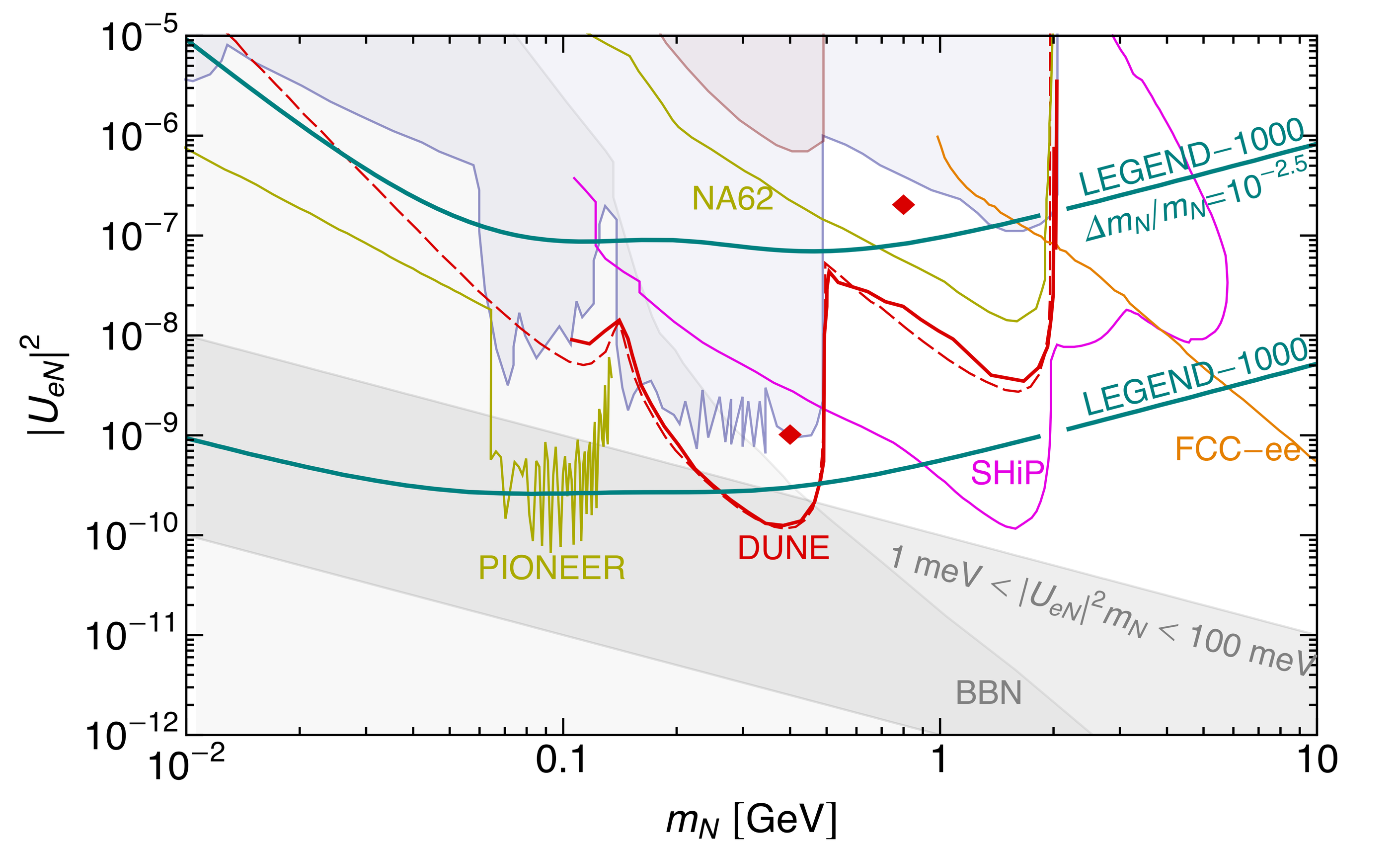
- D meson decays will be the dominant near GeV- HNL production channel and charged track and hadronic decay will be the main decay channels for HNL[3]. With all decay and production channels contained in $\mathcal{A}_{PP'}$, the mixing measured by DUNE will be

$$|\Theta_{e1}|^2 \approx 2 \times 10^{-7} \left(\frac{N^{\rm exp}_{\rm DUNE}}{300}\right)^{1/2} \left(\frac{6.6 \times 10^{21}}{N_{\rm POT}}\right)^{1/2} \left(\frac{5\ {\rm m}}{\Delta\ell_{\rm det}}\right)^{1/2} \left(\frac{7.3 \times 10^3{\rm MeV}^2}{\mathcal{A}_{PP'}(m_N)}\right)^{1/2} \quad (7)$$

- A combined analysis with signals in both experiments with a red contour of 2σ and yellow ones of 1σ. DUNE is also analysed for three neutrino flavours.

Conclusions and Outlook

- If a non-standard $0\nu\beta\beta$ The work has shown how $0\nu\beta\beta$ LENGEND-1000 and direct searches DUNE (ND) can constrain HNL mass and its mixing with neutrinos.
- The equivalence of using 1+2 simplified model and 3+2 minimal inverse-seesaw model has been illustrated with quasi-Dirac(R_{ll} nearly 0) limits.
- The relation between 5 parameters ($m_N, m_\nu, r_\Delta, |\Theta_{e1}|^2, \phi_{e1}$) has been studied in a great details in 1+2 model, and it is also extended into 3+2 model with only α_{21} and the mass ordering being the free active neutrino parameters.
- All the production and decay channels for 100 MeV to 1 GeV mass HNL has been reviewed in details.
- A modified continuous version of Poisson distribution has been applied for all the Monte Carlo simulations to give a more better match to the experiments.
- The work demonstrated Both LENGEND-1000 and DUNE can probe the region just above the seesaw line for near GeV mass HNL. The work also showed the fixed target experiments are more sensitive to the neutrino-HNL mixing, whereas the $0\nu\beta\beta$ experiments are sensitive to the HNL mass splitting.



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