Long-lived neutral fermions at the DUNE near detector

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based on 2310.12392

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Motivation - Heavy Neutral Leptons

The issue: massless neutrinos ν_L

- Neutrino oscillations necessitate massive neutrinos
- SM neutrinos ν_L are massless
  $\hookrightarrow$ Right-handed neutrino fields absent in SM

Solution: Introduce N_ν SM gauge singlet ν_R

- Interacts with SM fields via a Higgs Yukawa coupling
- Possible Majorana mass term for ν_R

$$\mathcal{L}_{\min} = \mathcal{L}_{SM} - \left[\frac{1}{2}\bar{\nu}_R^c \bar{M}_R \nu_R + \bar{L}\tilde{H}Y_\nu \nu_R + \text{h.c.}\right], \qquad \text{where } H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

- After EWSB, neutrino masses can be written as

$$\mathcal{L}_{m_\nu} = -\frac{1}{2}\bar{N}^C M_\nu N + \text{h.c.}\,, \qquad \text{with } N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \text{ and } M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y_\nu^* \\ \frac{v}{\sqrt{2}}Y_\nu^\dagger & \bar{M}_R^\dagger \end{pmatrix}$$

- ν_R are predicted in various other extensions of the SM

νSMEFT

At energy-scale Λ, introduce effective operators involving ν_R

$$\mathcal{L}_{\nu\text{SMEFT}} = \mathcal{L}_{\text{min}} + \sum_{d>4} \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}$$

Dimension-5 Operators, N_ν=1

Two dimension-5 operators possible

$$\mathcal{L}_{\nu_L}^{(5)} = \epsilon_{kl}\epsilon_{mn}(L_k^T\, C_L^{(5)}\, CL_m)H_l H_n\,, \qquad \mathcal{L}_{\nu_R}^{(5)} = -\bar{\nu}_R^c\, C_R^{(5)} \nu_R H^\dagger H\,.$$

After EWSB, these operators contribute to Majorana masses of ν_L and ν_R.

$$M_\nu = \begin{pmatrix} -v^2 C_L^{(5)} & \frac{v}{\sqrt{2}} Y_\nu^* \\ \frac{v}{\sqrt{2}} Y_\nu^\dagger & \bar{M}_R^\dagger + v^2 C_R^{(5),\dagger} \end{pmatrix}$$

νSMEFT

Dimension-6 Operators, $N_\nu = 1$

Class 1	$\psi^2 H^3$
$\mathcal{O}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$
Class 2	$\psi^2 H^2 D$
$\mathcal{O}_{H\nu e}$	$(\bar{\nu}_R\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$
Class 3	$\psi^2 HF$
$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$

Class 4	ψ^4
$\mathcal{O}_{du\nu e}$	$(\bar{d}_R\gamma^\mu u_R)(\bar{\nu}_R\gamma_\mu e)$
$\mathcal{O}_{Qu\nu L}$	$(\bar{Q}u_R)(\bar{\nu}_R L)$
$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d_R)$
$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d_R)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e_R)$

[Yi Liao , Xiao-Dong Ma, 2016 arXiv:1612.04527]

From νSMEFT to νLEFT

- Evolve operators from Λ to v (using one-loop QCD anomalous dimensions)
- At v, integrate out heavy SM fields, rotate to neutrino mass basis, and match to νLEFT

$$\mathcal{L}_{\nu\text{LEFT}} = \mathcal{L}_{SM} + \mathcal{L}_{m_\nu} + \underbrace{\sum_i c_i^{(6)} \mathcal{O}_i'^{(6)}}_{\mathcal{L}_{CC}^{(6)} + \mathcal{L}_{NC}^{(6)}}$$

- Evolve operators from v to Λ_{QCD}

Theoretical Scenarios - Minimal Scenario

Assume all $c_i^{(6)} = 0$, only active-sterile mixing

$$\nu_{L,k} = U_{kl}\nu_l$$

Focus on U_{e4} as a free parameter, treat $\nu_4 \approx \nu_R$:

$$L_{CC}^{(6)} \supset \sqrt{2}G_F c_{VLL,ij}^{(6)} (\bar{u}_L^i \gamma^\mu d_L^j)(\bar{e}_L \gamma_\mu \nu_R),$$

where $c_{VLL,ij}^{(6)} = -2V_{ij}U_{e4}$.

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HNL production

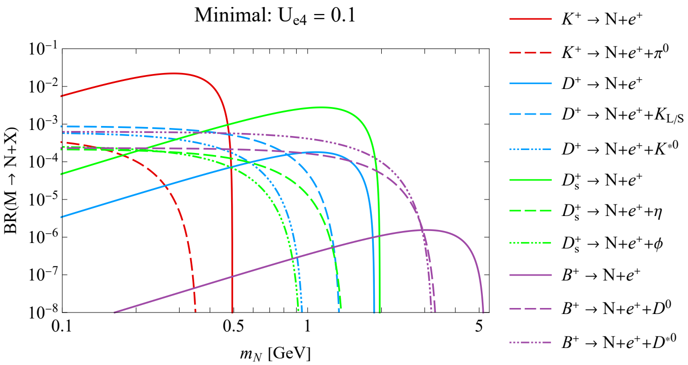
$$M^{\pm} \to N + e^{\pm}$$
$$M \to N + e^{\pm} + M'$$

HNL decay

$$N \to (e/\nu_e) + \text{mesons}$$
$$N \to \text{Leptons}$$

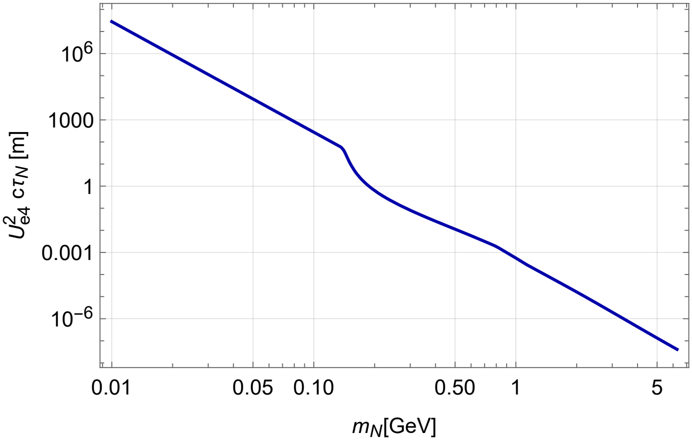
Theoretical Scenarios - Minimal Scenario - Production

$$M^{\pm} \to N + e^{\pm}$$
$$M \to N + e^{\pm} + M'$$

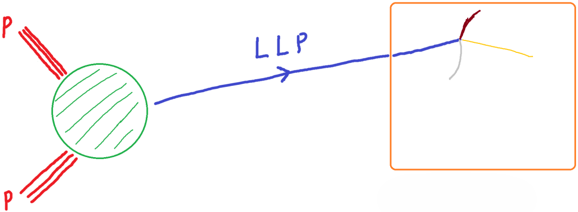


Theoretical Scenarios - Minimal Scenario - Decay

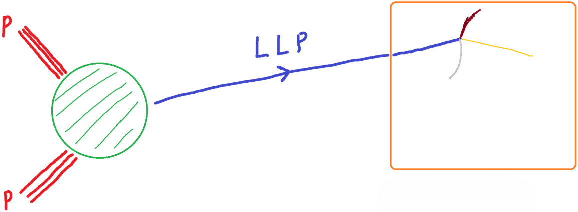
$$\Gamma_{N,\text{min}} = \Gamma_{N\to\text{leptons}} + \Theta\big(1\,\text{GeV} - m_N\big)\,\Gamma_{N\to\text{single meson}} + \Theta\big(m_N - 1\,\text{GeV}\big)\,\big[1 + \Delta_{\text{QCD}}(m_N)\big]\,\Gamma_{N\to\bar{q}q}\,.$$



Displaced-vertex Signatures



Displaced-vertex Signatures



Dedicated LLP detectors

MAPP

FASER

MoEDAL

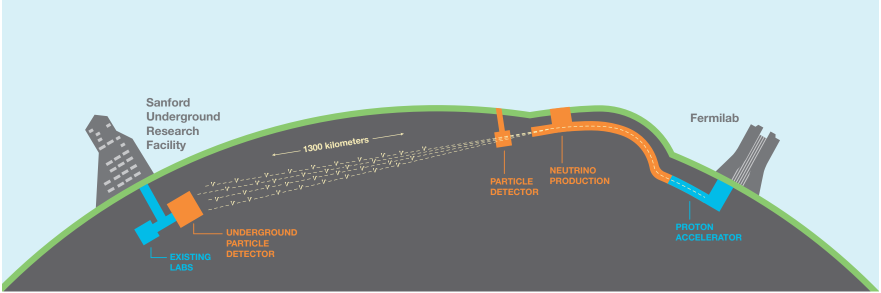
MATHUSLA

CODEX-b

ANUBIS

DUNE - Investigating Neutrino Oscillations

Deep **U**nderground **N**eutrino **E**xperiment



[LBNF and DUNE: Conceptual Design Report, Vol. 1 arXiv:1601.05471]

Fermilab

- proton beam (60 – 120 GeV) colliding with a graphite target
  $\hookrightarrow 1.1 \times 10^{21}$ POT per year
- secondary beam of charged particles focused with **magnetic horns**
- subsequent decays in decay pipe provide a focused neutrino beam

SURF

- 1300 km distance to Fermilab
- four 10 kt liquid argon TPCs
- large distance prohibits LLP detection

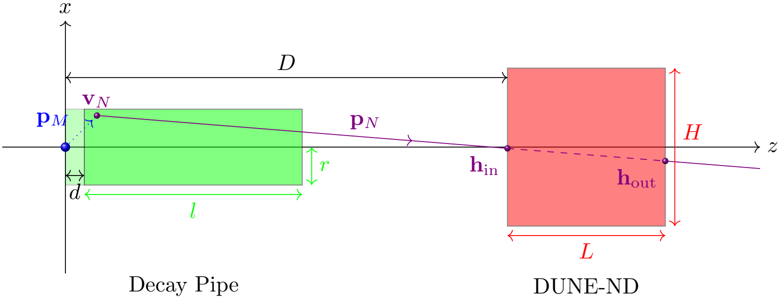
DUNE Near Detector (DUNE-ND)

Near detection system (NDS)

Monitor spectrum and flavor composition of neutrino beam

- Beamline measurement system
- Data aquisition system
- Fine-grained tracker

decay pipe length l	194 m
decay pipe radius r	2 m
distance: target - decay pipe d	27 m
near detector length L	6.4 m
near detector width H	3.5 m
distance: target - near detector D	574 m



Simulation Procedure

Expected number of LLP events

- Number of produced LLPs

$$N_{M,\,N}^{\text{prod}} = N_M \cdot \text{Br}\big(M \to N + X\big)$$

- Probability of LLP decaying inside the detector

$$P_{M,i}\left[N \text{ in f.v.}\right] = \exp\left[-\frac{L_{T,i}}{\lambda_i}\right] \cdot \left(1 - \exp\left[-\frac{L_{I,i}}{\lambda_i}\right]\right)$$

$\hookrightarrow$, $L_{T,i}$ and $L_{I,i}$ calculated based of production vertex and momenta.

- Monte-Carlo Simulation using `PYTHIA8` generating N_{MC} proton on target events

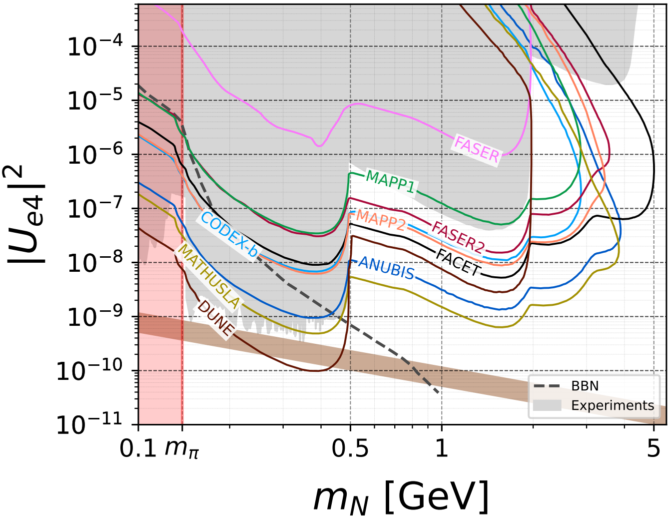
$$\left\langle P_M\left[N \text{ in f.v.}\right]\right\rangle = \frac{1}{N_{\text{MC}}} \sum_i^{N_{\text{MC}}} P_{M,i}\left[N \text{ in f.v.}\right]. \tag{1}$$

- Observed LLP events

$$N_N^{\text{obs}} = \text{Br}\big(N \to \text{visible}\big) \cdot \sum_M N_{M,\,N}^{\text{prod}} \left\langle P_M\left[N \text{ in f.v.}\right]\right\rangle$$

Results - Minimal Scenario

Free Parameters: U_{e4}, m_N
Display three-event isocurves (95% C.L.)
Brown-band: see-saw target region $|U_{e4}|^2 = m_\nu / m_N$ for $0.05\,\text{eV} < m_\nu < 0.12\,\text{eV}$.



Theoretical Scenarios - Leptoquarks

Focus on leptoquark representation $\tilde{R}_2$ with SM gauge representation $(\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\rm LQ} = -y_{jk}^{RL}\,\bar{d}_{Rj}\tilde{R}_2^a\epsilon^{ab}L_{Lk}^b + y_i^{\overline{LR}}\bar{Q}_{Li}^a\tilde{R}_2^a\nu_R + \text{h.c.}$$

Integrating out leptoquark, we get

$$C_{LdQ\nu,kji} = \frac{1}{m_{LQ}^2}\,y_i^{\overline{LR}}\,y_{jk}^{RL*}\,.$$

In νLEFT

$$L_{CC}^{(6)} \supset \sqrt{2}G_F\left(c_{SRR,ije}^{(6),CC}(\bar{u}_L^i d_R^j)(\bar{e}_L\nu_R) + c_{T,ije}^{(6),CC}(\bar{u}_L^i\sigma^{\mu\nu}d_R^j)(\bar{e}_L\sigma_{\mu\nu}\nu_R)\right),$$

$$L_{NC}^{(6)} \supset \sqrt{2}G_F\left(c_{SRR,ije}^{(6),NC}(\bar{d}_L^i d_R^j)(\bar{e}_L\nu_R) + c_{T,ije}^{(6),NC}(\bar{d}_L^i\sigma^{\mu\nu}d_R^j)(\bar{e}_L\sigma_{\mu\nu}\nu_R)\right),$$

where

$$c_{\text{SRR},ije}^{(6),CC} = 4c_{\text{T},ije}^{(6),CC} = \frac{v^2}{2}\frac{1}{m_{LQ}^2}y_i^{\overline{LR}}(y_{je}^{RL})^*\,,$$

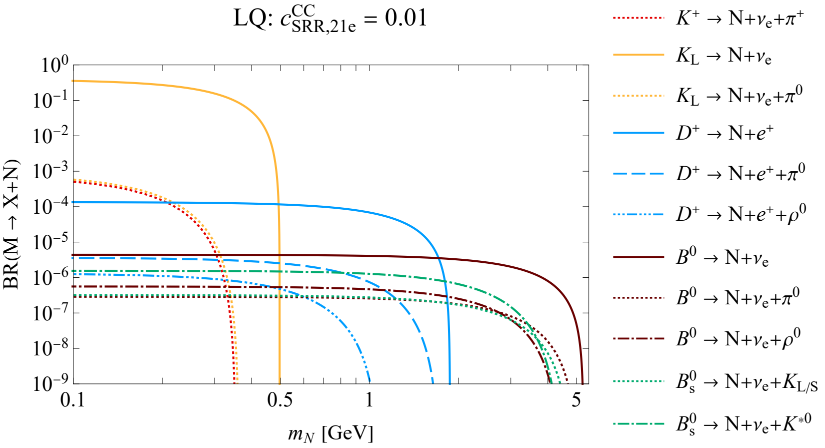
$$c_{\text{SRR},ije}^{(6),NC} = 4c_{\text{T},ije}^{(6),NC} = -V_{li}^* c_{\text{SRR},lje}^{CC}\,.$$

Additionally, consider non-zero U_{e4}.

Theoretical Scenarios - Leptoquarks - Production

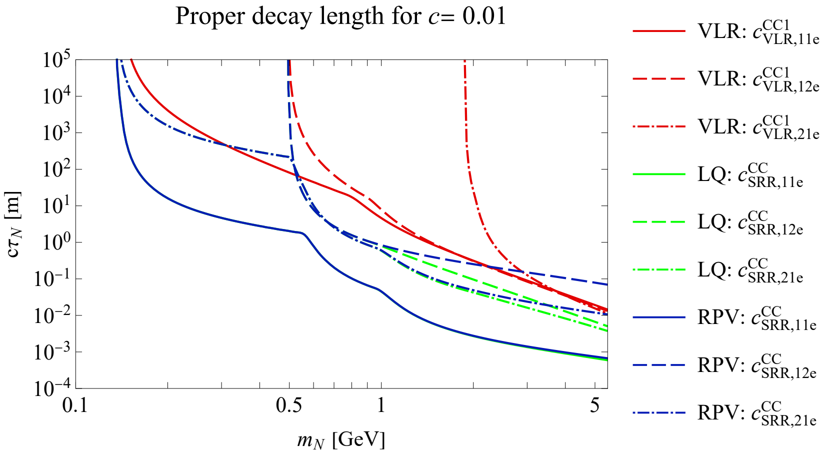
$$M^{\pm} \to N + e^{\pm} \qquad M^0 \to N + \nu_e$$

$$M \to N + e^{\pm} + M' \qquad M \to N + \nu_e + M'$$



Theoretical Scenarios - Leptoquark - Decay

$$\Gamma_{N,\mathrm{LQ}} = \Gamma_{N,\mathrm{min}} + \Gamma_{N\to\text{single meson},\mathrm{LQ}}$$



Theoretical Scenarios - RPV-SUSY

νSMEFT is **not** restricted to neutrinos, only SM gauge singlet fermions

- If lightest neutralino $\tilde{\chi}_1^0$ is very light, it is dominantly bino-like
- $\tilde{\chi}_1^0$ couples to fermion-sfermions pairs
- sfermions $\tilde{f}$ couple to SM quarks and leptons via RPV-operator

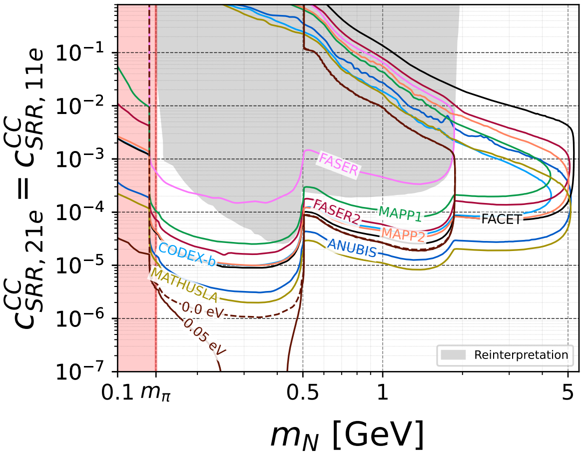
$$\lambda'_{ijk} L_i Q_j \bar{D}_k$$

Integrating out heavy sfermion fields, we obtain effective interactions similar to the leptoquark case

$$c^{(6),CC}_{\mathrm{SRR},ije} = -\,36 c^{(6),CC}_{\mathrm{T},ije} = \frac{3}{4}\frac{g'}{G_F}\frac{(\lambda'_{eij})^*}{m^2_{SUSY}}\,,$$
$$c^{(6),NC}_{\mathrm{SRR},ije} = -\,36 c^{(6),NC}_{\mathrm{T},ije} = -V^*_{li} c^{CC}_{\mathrm{SRR},lje}\,.$$

Results - Leptoquark Scenario

Free parameters: $c^{(6),CC}_{SRR,21e}$, $c^{(6),CC}_{SRR,11e}$, m_N
Fixed U via see-saw relation $U_{e4} = \sqrt{m_\nu / m_N}$ with $m_\nu = 0.05\,\text{eV}$ and $m_\nu = 0.0\,\text{eV}$.
Display three-event isocurves (95% C.L.)



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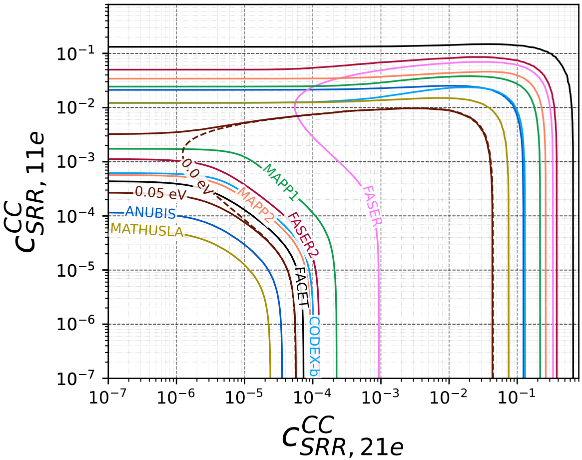

Conclusion

- Studied long-lived neutral fermions in an effective field theory approach.
  ↪ Heavy neutral leptons ν_R.
  ↪ Light neutralinos $\tilde{\chi}_1^0$ in RPV-SUSY.
- Performed Monte-Carlo simulations to obtain signal-event rates of rare decays
- Obtained DUNEs capability to detectd LLNFs
  ↪ compared it to LLP detector proposals at the LHC.
  ↪ DUNEs sensitivity complements LHC proposals

Thank you!