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Heavy Neutral Leptons from low-scale seesaws

with the DUNE Near Detector

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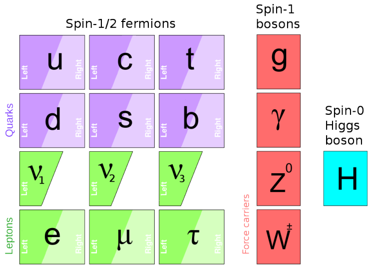
Based on
arXiv:1905.00284



$\Longleftrightarrow$

- Plank survey [2018]

$$\sum_i m_{\nu_i} < 0.12\,\text{eV at } 90\%\text{C.L.}$$

- Troitsk [2011] with ^{3}H β-decay

$$\sum_i |U_{ei}|^2 m_{\nu_i} < 2.05\,\text{eV}$$

- ν-fit 4.0 [2018]

$$\Delta m^2_{21} = 7.39^{+0.21}_{-0.20} \times 10^{-5}\,\text{eV}^2$$
$$|\Delta m^2_{31}| = 2.522^{+0.033}_{-0.031} \times 10^{-3}\,\text{eV}^2$$

Problems:

- No ν_R in SM, so no Yukawa ($d \leq 4$).
- $m_\nu \ll m_e$, six orders of magnitude!
- ν can be a Majorana particle.

Solutions:

theory: many models and also minimal.

e.g. add heavy neutrinos to SM + seesaw.

phenomenology: not so nice.

e.g. Type I seesaw typically requires new particles at GUT scale.

experiment: need something appealing...

Inverse seesaw

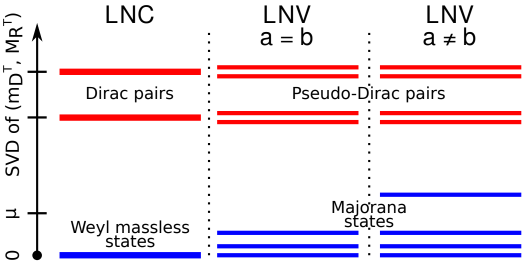
"Recipe" for a minimal inverse seesaw [A. Abada, M. Lucente, '14]

- Extend the SM by adding singlet fermions $N_{i=1..a}$ with LN $= +q_L$ and $S_{j=1..b}$ with LN $= -q_L$

  $\Rightarrow$ **symmetry-protection** lower the physics scale!
- Majorana mass terms, with "natural" LNV parameters and cancellations among high scale contributions.
- Light neutrinos described ✓, but also new heavier particles: **Heavy Neutral Leptons**.
- Forbidden mixing angles and masses accessible by current and future experiment $$$

$$\mathcal{L} = \frac{1}{2}\left(\overline{\nu},\, \overline{N},\, \overline{S^C}\right)\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & \mu_R & M_R^T \\ 0 & M_R & \mu_S \end{pmatrix}\begin{pmatrix} \nu^C \\ N^C \\ S \end{pmatrix}$$

Heavy Neutral Lepton can be either a (pseudo-)Dirac or a Majorana particle.



Testable signatures

Sterile neutrinos **mix** with light neutrinos into flavour neutrinos: new particles take part to **neutrino process** thanks to **mixing-suppressed couplings**.
Regardless of model realisation, there is an HNL with **mass** in experimental range.

- kink in Curie plots of β decay (keV$\sim$MeV)
- $0\nu\beta\beta$ decay (keV$\sim$TeV)
- searches of HNL decays in beam dump experiments (MeV$\sim$GeV)
- peak searches in pion and kaon decays (MeV$\sim$GeV)
- searches of LNV or cLFV events (MeV$\sim$GeV)
- collider searches of displaced vertices (TeV)

[A. Atre *et al.*, '09]

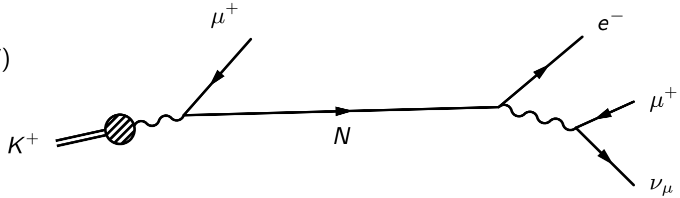
[M. Drewes, B. Garbrecht, '17]

$\Longrightarrow$

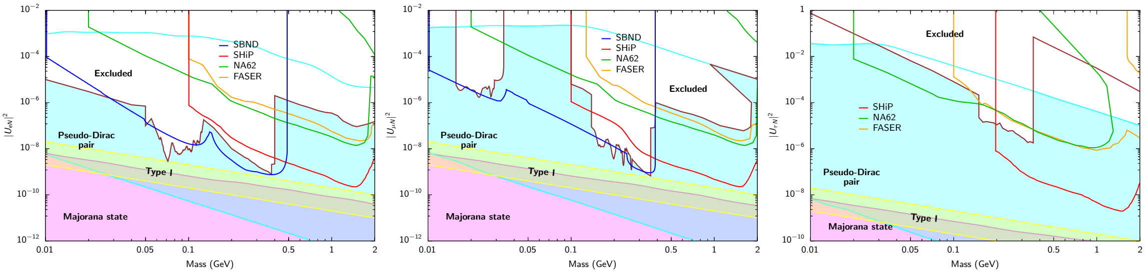
Signature HNL produced in a **neutrino beam** and then **decay-in-flight** inside the detector.

Production two- and three-body decays from pseudo-scalar meson ($\pi^\pm, K^\pm, K^0, D_S^\pm$), muon and tau decay.

Decay semi-leptonic two-body decays into charged and neutral **pseudo-scalar mesons** or vector mesons, leptonic three-body decay, radiative decay etc.



Current limits, predictions, and region of interest



Limits from

PS191, '86, '88

PIENU, '18

CHARM II, '95

NuTeV and E815, '95

DELPHI, '99

T2K, '19

Predictions for

SBN, '17

SHiP, '16

NA62, '18

FASER, '18

Regions of interest for neutrino mass models:

- Type I seesaw band ($20\,\text{meV} < m_\nu < 0.2\,\text{eV}$).
- ISS (2,2) and ISS (2,3) in which HNL is a pseudo-Dirac neutrino.
- ISS (2,3) in which HNL is a Majorana.

Majorana vs Dirac and role of helicity

Practical Dirac-Majorana confusion theorem [Kayser, Shrock, 82] :

factor of two enhancement is absent for (almost) massless neutrinos, due to polarisation which suppresses $\Delta L = 2$ contributions.

For a **charged current** process

$$\mathrm{d}\Gamma\left(N \to \ell_\alpha^- X^+\right) = \mathrm{d}\Gamma\left(N_D \to \ell_\alpha^- X^+\right) \quad \text{and} \quad \mathrm{d}\Gamma\left(N \to \ell_\alpha^+ X^-\right) = \mathrm{d}\Gamma\left(\overline{N}_D \to \ell_\alpha^+ X^-\right)$$

For a **neutral current** process

$$\mathrm{d}\Gamma\left(N \to \nu Y\right) = \mathrm{d}\Gamma\left(N_D \to \nu Y\right) + \mathrm{d}\Gamma\left(\overline{N}_D \to \overline{\nu} Y\right) \quad \Rightarrow \quad \Gamma(N \to \nu Y) = 2\,\Gamma\left(N_D \to \nu Y\right)$$

If mass effect is not negligible, Dirac and Majorana neutrinos have **distinct** total decay rates.
Neglecting charges of final states gives same result for CC processes.

HNL beam is **not polarised** as light neutrinos are: arbitrariness of the polarisation $\to$ total decay not affected by helicity, but **angular distribution** is!

$$\frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega} \approx A \;\text{ for Majorana} \quad \text{and} \quad \frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega} \approx A \mp B\cos\theta \;\text{ for Dirac}$$

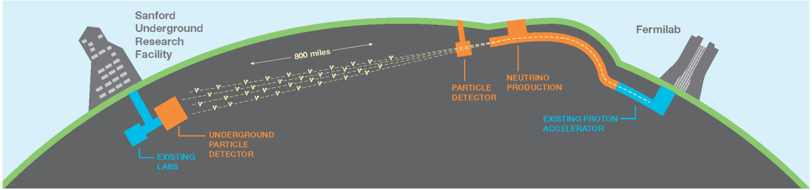
The angular dependence is lost after integration over the PS.

DUNE Near Detector

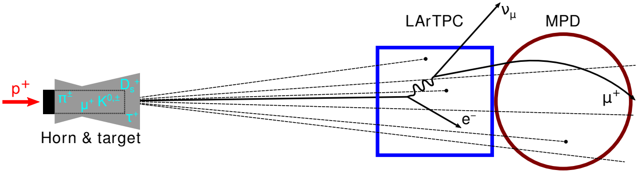
Main goal is precision **oscillation physics**, but also large variety of complementary studies.

80 GeV proton beam impinging on graphite target

1.32×10^{22} POT for 6 years in ν–mode (same POT in $\overline{\nu}$–mode).



Near Detector is required to **normalise flux** and remove **cross-section systematics**.
Placed at 574 m from target $\Rightarrow$ intense ν flux!
5×10^6 higher than at FD (1300 km), up to $E_\nu = 20$ GeV.



- LArTPC with fiducial volume $24\,m^3$ and mass 35 t.
- Multi Purpose Detector (MPD), gaseous TPC, fiducial volume $100\,m^3$ and mass 1 t.
- LArTPC and MPD are movable (DUNE-PRISM).
- 3D Scintillation Tracker, on-axis, for flux monitoring and neutron contamination.

Number of events

Number of events $\mathcal{N}_d$ to be compared with **background** $\mathcal{N}_b$ (SM neutrino–nucleon interactions)

$$\mathcal{N}_d = \int \mathrm{d}E \, e^{-\frac{\Gamma_{\mathrm{tot}} L}{\gamma\beta}} \left(1 - e^{-\frac{\Gamma_{\mathrm{tot}} \lambda}{\gamma\beta}}\right) \frac{\Gamma_d}{\Gamma_{\mathrm{tot}}} \frac{\mathrm{d}\phi_N}{\mathrm{d}E} W_d(E)$$

L = baseline
λ = length of detector

Parentage components of light neutrino beams are scaled by

$$\mathcal{K}^{\pm}_{X,\alpha}(m_N) \equiv \frac{\Gamma^{\pm}(X \to NY)}{\Gamma\,(X \to \nu_\alpha Y)} \,,$$

to fix phase space and helicity.
$\mathrm{d}\phi_N/\mathrm{d}E$ is the expected HNL beam at the ND site,

$$\frac{\mathrm{d}\phi_{N^\pm}}{\mathrm{d}E}(E_N) \approx \sum_{X,\alpha} \mathcal{K}^{\pm}_{X,\alpha}(m_N) \frac{\mathrm{d}\phi_{X\to\nu_\alpha}}{\mathrm{d}E}(E_N - m_N)$$

$W_d(E)$ is the **binned ratio** of E_{true} spectrum after and before the **background reduction**.
Particle ID reduces background by a 10–10^4 factor; to further reduce background:

- GENIE simulation of neutrino events in Ar
- Custom MC simulation of HNL decays

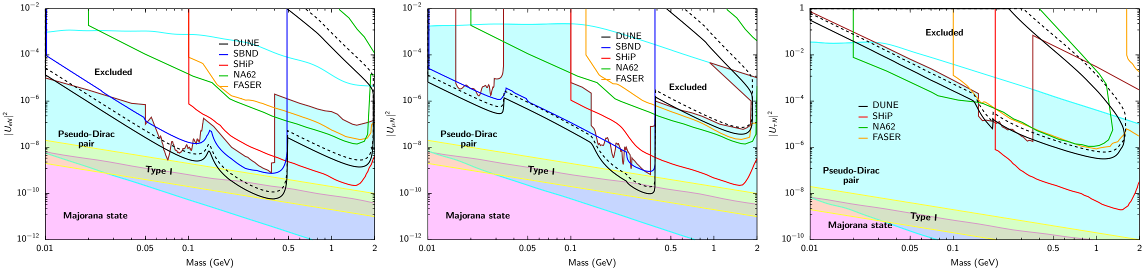
are input to fast MC of DUNE ND reconstruction and **kinematic distributions** are compared

For each channel, define **90% C.L. sensitivity** using Feldman & Cousins method [Feldman, Cousins, 98] in rejecting H_0, “only background is observed”.

Sensitivity to discovery

Combining regions of channels with **"good" detection sensitivity** (high branching ratio, controlled background):

$$N \to \nu e^+ e^-,\ \nu\mu^+\mu^-,\ \nu e^\mp \mu^\pm,\ e^\mp\pi^\pm(|U_{eN}|^2),\ \mu^\mp\pi^\pm(|U_{\mu N}|^2),\ \nu\pi^0.$$



- Backgroundless lines ($\mathcal{N}_d > 2.44$).
- Sensitivity above m_{K^0} thanks to production from D_s meson.
- Charge-ID washed out $\Rightarrow$ sensitivity to Majorana HNL is $2\times$ better than to Dirac.
- Sensitivities to other channels (also with background analysis) and to $|U^*_{\alpha N} U_{\beta N}|$ [P. Ballett, TB, Pascoli, '19].

solid line : Majorana HNL

dashed line : Dirac HNL

Sensitivity to LNV ...work in progress...

Focusing on channel with best sensitivity: $N \to \ell^{\mp}\pi^{\pm}$.
If we had beam in neutrino mode w/o contamination of $\overline{\nu}$, then

- if HNL is Dirac, only $\ell^{-}\pi^{+}$ expected at ND $\to$ **no events in the other channel**!
- if HNL is Majorana, both $\ell^{\mp}\pi^{\pm}$ expected at ND with equal probability.

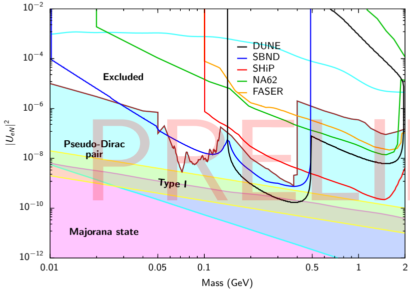
Contamination of $\overline{\nu}$ (unavoidable) requires **more events** in order to distinguish between the two hypotheses.

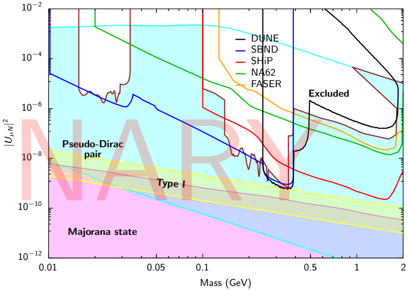
Dirac vs **Majorana**

$$\mathcal{N}_{N_D \to \ell^- \pi^+} \equiv \sigma_- > \sigma_+ \equiv \mathcal{N}_{\overline{N}_D \to \ell^+ \pi^-}$$

vs

$$\mathcal{N}_{N \to \ell^- \pi^+} = \mathcal{N}_{N \to \ell^+ \pi^-} = \sigma_- + \sigma_-$$





Conclusions

- The neutrino mass problem has numerous solutions, like the **Inverse seesaw**
- Different realisations of the model are reflected in different phenomenology (**Dirac vs Majorana**)
- Best experimental probe is **decay in-flight** of an HNL.
- It can be tested **current/future experiments**, like DUNE.
- The DUNE Near Detector has a vast **complementary physics program**.

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Take home message

- DUNE ND has exceptional **sensitivity to discovery** of HNL.
- In the region of $0.01\,\mathrm{GeV} < m_N < 2\,\mathrm{GeV}$, $|U_{\alpha N}|^2 < 10^{-10}$.
- Current limits extended and **regions of theoretical interest** reached.
- After discovery, **nature of HNL** could be determined.

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Thank you.