Approaching the neutrino mass problem
with the DUNE Near Detector

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Neutrino mass: the problem

- ν-fit 4.0 [2018]

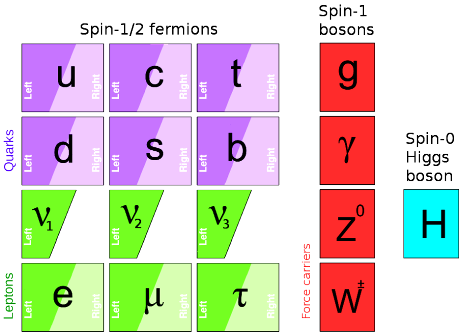
$$\Delta m^2_{21} = 7.39^{+0.21}_{-0.20} \times 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{31}| = 2.525^{+0.033}_{-0.031} \times 10^{-5}\ \text{eV}^2$$

- Planck [2018]

$$\sum m_\nu < 0.12\ \text{eV}$$

- Troitsk [2011] with ^{3}H β decay

$$\sum |U_{e\nu}|^2 m_\nu < 2.05\ \text{eV}$$



Issues?

- No ν_R in the SM, so no Yukawa coupling
- A neutrino ($\sim$eV) is $< 2 \times 10^{-6} m_e$
- Dirac vs Majorana? **LNV**

Easy!

Add "right-handed" neutrinos!

Approach: Inverse seesaw model, ISS(a,b)

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

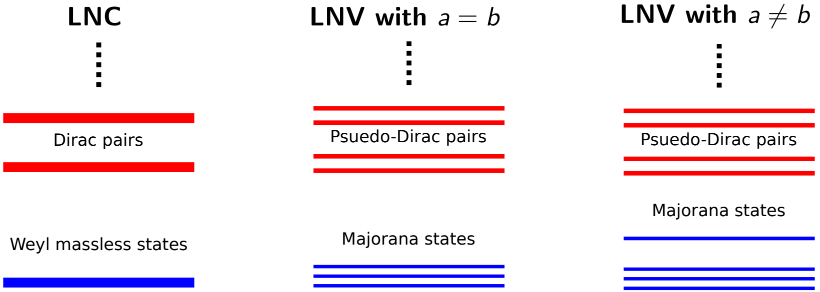
$$Y^D_{\alpha i}\overline{L_\alpha}\tilde{H}N^c_i + Y^R_{\alpha i}\overline{L_\alpha}HS_i + \frac{1}{2}(M_R)_{ij}\overline{N^c_i}N_j + \frac{1}{2}(\mu_R)_{ij}\overline{N^c_i}N_j + \frac{1}{2}(\mu_S)_{ij}\overline{S^c_i}S_j \text{ .h.c.}$$

$$\mathcal{M} = \overset{\text{LNC}}{\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R \\ 0 & M_R^T & 0 \end{pmatrix}} + \overset{\text{LNV}}{\begin{pmatrix} 0 & 0 & 0 \\ 0 & \mu_R & 0 \\ 0 & 0 & \mu_S \end{pmatrix}}$$

$m_D(3\times a)$ and $M_R(b\times a)$

Minimal realisation
$(a,b) = (2,2)$ or $(2,3)$

[Abada, Lucente, 2014]



Building observables: Majorana vs Dirac

- **Decay**: For a **charged current** process

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

For a **neutral current** process

$$d\Gamma(N \to \nu Y) = d\Gamma(N_D \to \nu Y) + d\Gamma(\overline{N}_D \to \overline{\nu} Y)$$

$$\Downarrow$$

$$\Gamma(N \to \nu Y) = 2\Gamma(N_D \to \nu Y)$$

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

factor of two enhancement is absent for light neutrinos, due to **polarisation** which suppresses $\Delta L = 2$ contributions

However, if mass effect is not negligible, regardless of polarisation

Dirac and Majorana neutrinos have **distinct** total decay rates

- **Production**: only CC processes involved $\Rightarrow$ no difference between Dirac and Majorana decay widths

Building observables: effect of helicity

- **Decays**: are affected by helicity at the distribution level, different behaviour for Majorana or Dirac Total decays are not: **arbitrariness** of polarisation direction

  NC decay to pseudo-scalar meson, for Majorana $\Rightarrow$ **isotropic**

$$\frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega_P}\left(N \to \nu P^0\right) \quad \propto \left(\sum_{\alpha=e}^{\tau} |U_{\alpha N}|^2\right)(1-x_P)^2$$

  NC decay to pseudo-scalar meson, for Dirac $\Rightarrow$ **angular dependence**

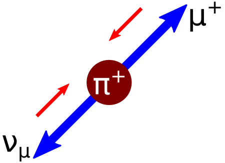
$$\frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega_P}\left(N_D \to \nu P^0\right) \propto \left(\sum_{\alpha=e}^{\tau} |U_{\alpha N}|^2\right)(1-x_P)[1-x_P \mp (1-x_P)\cos\theta]$$

- **Production**: processes are sensitive to helicity

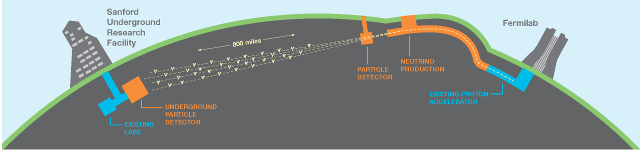
  Using scale factor to model flux of HNL from flux of light neutrino to fix phase space and helicity

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

unsuppression

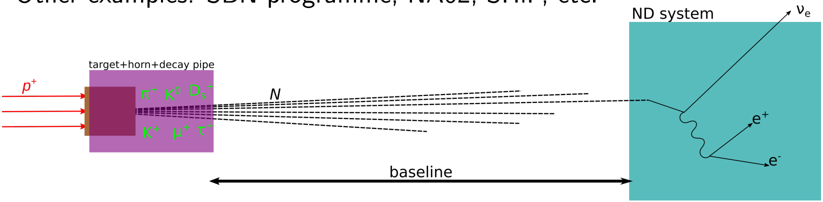


Beam dump experiment: DUNE

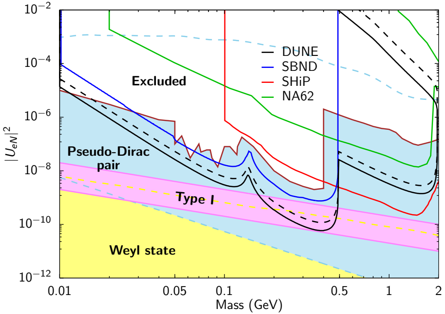


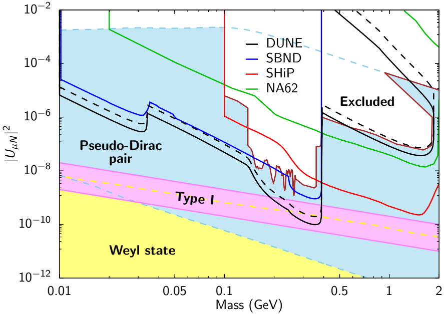
80 GeV protons beam on graphite target, total of 1.32×10^{22} POT, for each FHC and RHC modes

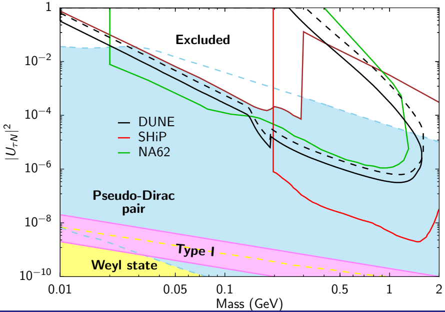
- ND placed **at 574 m** vs FD at 1300 km: ν flux 5×10^6 times more intense!
- LArTPC is $(3{\times}3{\times}4)\,\mathrm{m}^3$ by 50 t + HPArFGT $(3.5{\times}3.5{\times}6.4)\,\mathrm{m}^3$ by 8 t (?)
- Other examples: SBN programme, NA62, SHiP, etc.



GENIE (background = SM neutrino interactions) + **custom MC** (signal = HLN decays) ⇒ **fast MC** of DUNE ND Reconstruction ⇒ particle identification + kinematic distribution ⇒ reduce background







Sensitivity for channels with best prospect discovery:

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

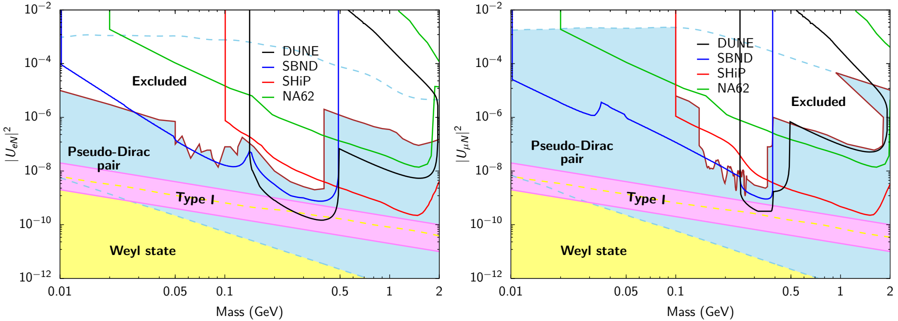
Focus on $N \to \ell^\mp \pi^\pm$ channels: best sensitivity!

If HNL is Dirac (and if there is charge-ID in ND):

- FHC mode $\Rightarrow$ more $\ell^-\pi^+$ (factor ~ 10)
- RHC mode $\Rightarrow$ more $\ell^+\pi^-$ (factor ~ 3 to 5)

If HNL is Majorana $\Rightarrow$ same rate of $\ell^-\pi^+$ and $\ell^+\pi^-$

- need to detect HNL first!
- need some statistics



Conclusions

- Varieties of model can **address** the neutrino problem
- **Inverse seesaw mechanism** provides also testable observables
- Helicity/polarisation are important!
- DUNE ND is **very sensitive** and can "close the gap"
- If we see a HNL, this can be explained by a low scale mass models
- With good statistics, we can determine if it is **majorana or Dirac**

If we don't see anything

- more powerful experiment?
- new techniques?
- better theory?

Efforts from all sides needed!

Thank you.