Approaching the neutrino mass problem

with a beam dump experiment

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~~with a beam dump experiment~~ **with DUNE ND**

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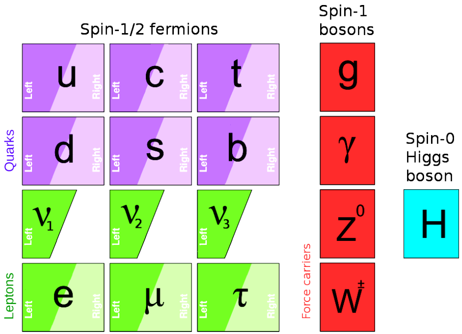
- yes, it is a **problem**: why is it so light?
- there **will be** a neutrino experiment with good capabilities!
- **If** we see new physics, **then** we will be able "**solve**" the puzzle

Neutrino mass: the problem



- NuFIT 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 2×10^{-6} lighter than e, 6×10^{-12} than a t quark
- Dirac vs Majorana $\Rightarrow$ **LNV**

Neutrino mass: a "simple" solution

Extend the SM by adding singlet fermions, N_i

$$\boxed{\mathcal{L}_{\mathrm{SM}+N} = \mathcal{L}_{\mathrm{SM}} + i\overline{N}_i \partial\!\!\!/ N_i + Y_{\alpha i}\overline{L}_\alpha \tilde{H} N_i^c + \frac{1}{2}(M_R)_{ij}\overline{N^c}_i N_j + \mathrm{h.c.}}$$

- **Type I seesaw**

  Neglecting matrix nature of $m_\nu = -m_D M_R^{-1} m_D^T + \ldots$, if $m_D \sim$ EW then $M_R \sim$ GUT; lower scale possible, but bounds on

  $$|U_{\alpha N}|^2 \simeq m_\nu / M_N \lesssim 10^{-7 \text{ to } -10}$$

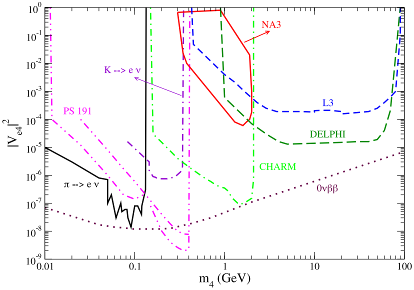
- **Symmetry-protected seesaw**

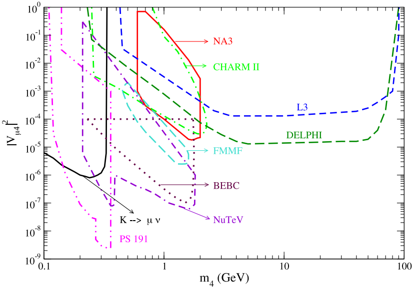
  Define $N_{i=1..a}$ with $L = 1$ and $S_j = N^c_{j=1..b}$ with $L = -1$

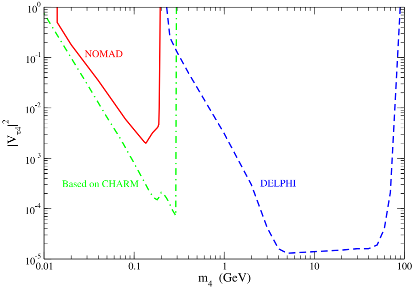
  Cancellations between pairs ensured by *'t Hooft natural* LNV parameters + symmetry to protect texture of $\mathcal{M}$ = **forbidden** mixing angles and **testable** neutrino masses

Light neutrino masses $\propto$ LNV parameters

- keV∼MeV: kinks in Curie plots, $0\nu\beta\beta$ decay
- MeV∼GeV: peak searches in pion and kaon decays
- MeV∼GeV: HNL decays in *beam dump experiments*
- ∼TeV: collider physics

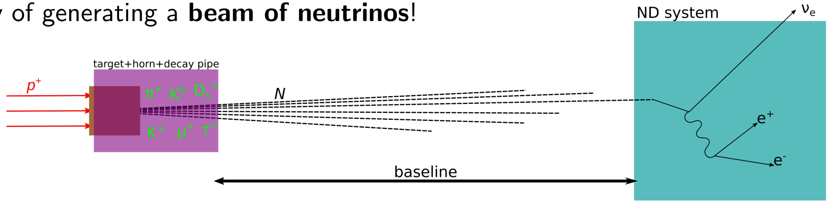






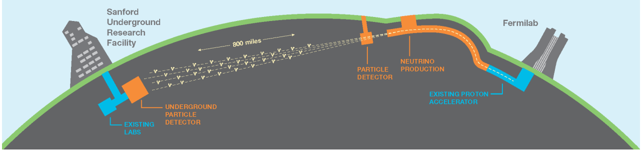
Dumping a beam of high energy **proton** on a fixed target (or other parts of the beam facility [MiniBooNE, 2017])

Producing pions and muons (and others) which decay ⇒ this is the conventional way of generating a **beam of neutrinos**!



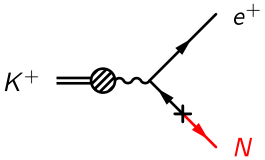
	Channel	BR (%)	m_N(MeV)
π^+	$\mu^+\nu_\mu$	99.98	33.91
	$e^+\nu_e$	0.01	139.06
K^+	$\mu^+\nu_\mu$	63.56	387.81
	$\pi^0 e^+\nu_e$	5.07	358.19
	$\pi^0\mu^+\nu_\mu$	3.35	253.04
	$e^+\nu_e$	0.16	493.17
K_L^0	$\pi^\pm e^\mp\nu_e$	40.55	357.12
	$\pi^\pm\mu^\mp\nu_\mu$	27.04	252.38
μ^+	$\overline{\nu_\mu} e^+\nu_e$	100.00	105.14

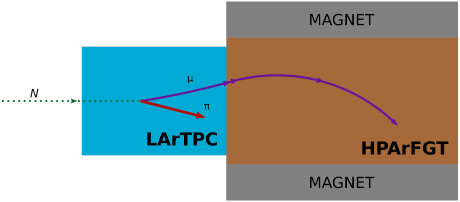
	Channel	BR (%)	m_N/MeV
D_s^+	$\tau^+\nu_\tau$	5.48	191.42
	$\mu^+\nu_\mu$	0.55	1862.63
	$e^+\nu_e$	0.008	1967.78
τ^+	$\pi^+\pi^0\overline{\nu_\tau}$	25.49	1502.31
	$\overline{\nu_\tau} e^+\nu_e$	17.82	1776.35
	$\overline{\nu_\tau}\mu^+\nu_\mu$	17.39	1671.20
	$\pi^+\overline{\nu_\tau}$	10.82	1637.29



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

- DUNE ND placed at 574 m! ν flux $\sim 5 \times 10^6$ times more intense than at the FD (at 1300 km)
- 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: PS191, SBN programme, NA62, SHiP, etc.





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

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R \\ 0 & M_R^T & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & \mu_R & 0 \\ 0 & 0 & \mu_S \end{pmatrix} \qquad m(3 \times a) \text{ and } M(b \times a)$$

In the LNC limit, $\min\{3+b, a\}$ Dirac pairs and $|3+b-a|$ massless Weyl states
The masses of the Dirac pairs are just the **SVD values** of (m_D^T, M_R^T)
For $a \neq b$, extra massless Weyl state, degenerate with the light neutrinos

Minimal realisation [Abada, Lucente, 2014] that gives: light neutrino masses **and** a mass MeV – GeV with strong couplings?

- ISS(2,2) in which the HNL belongs to the lightest pseudo-Dirac pair
- ISS(2,3) in which the HNL belongs to the lightest pseudo-Dirac pair
- ISS(2,3) with large LNV parameter and the Weyl state becomes a Majorana state with target mass

Approach: matrix scan

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & \mu_R & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix}$$

Random matrix scan of $7a + b + 2\,a\,b$ of ISS(a,b)
The combinations $(m_N, |U_{\alpha N}|^2)$ are clustered together in **regions** $\Rightarrow$ any point inside is explained by a **valid mass matrix**

Constraints:

- oscillation: Δm^2 and U_{PMNS} structure
- cLVF processes like $\mu \to e\gamma$, Br $< 4.2 \times 10^{-13}$ [MEG collaboration, 2016]
- $0\nu\beta\beta$ limits, $m_{\beta\beta} < 150\,\text{meV}$ [GERDA collaboration, 2017]
- non-unitarity from EW precision measurements [Fernandez-Martinez *et al.*, 2016]

$$\text{Br} = \frac{3\alpha}{32\pi} \left| \sum_i \hat{U}^*_{\mu i}\, \hat{U}_{ei}\, G\left(\frac{m_i^2}{M_W^2}\right) \right|$$

$$m_{\beta\beta} \simeq \left| \sum_i \hat{U}^2_{ei} \frac{p^2\, m_i}{p^2 - m_i^2} \right|$$

$$|\delta_{\alpha\beta} - (\underset{\text{PMNS}}{U\,U^\dagger})_{\alpha\beta}| = \left| \sum_{i=4}^{n} U_{\alpha i} U^*_{\beta i} \right|$$

Building observables: Majorana vs Dirac

For a **charged current** process

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

For a **neutral current** process

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

$$\Downarrow$$

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

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

Building observables: effect of helicity

Arbitrariness of the polarisation makes total decay not affected by helicity
Distribution **is** affected though!!

e.g. decay to pseudo-scalar meson: charged current, for both Dirac and Majorana

$$\frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega_{\ell_\alpha}}(N \to \ell_\alpha^- P^+) \propto |U_{\alpha N}|^2 \lambda^{\frac{1}{2}}(1, x_\ell, x_P) \times \left[(1-x_\ell)^2 - x_P(1+x_\ell) \pm (x_\ell - 1)\lambda^{\frac{1}{2}}(1, x_\ell, x_P)\cos\theta\right]$$

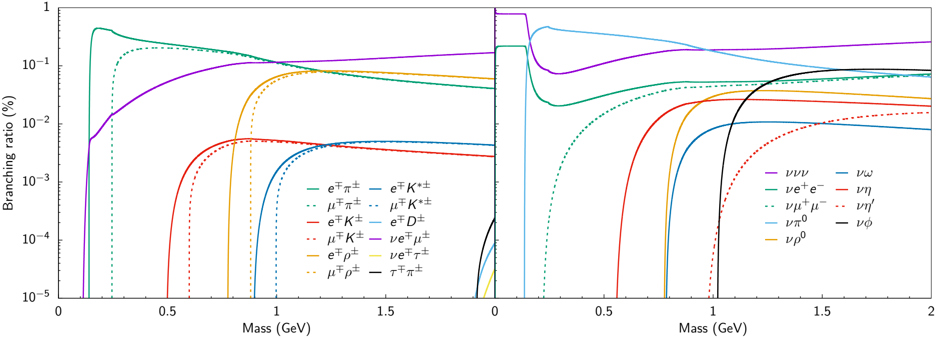
Neutral current, for Majorana $\Rightarrow$ **isotropic**

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

Neutral current, for Dirac $\Rightarrow$ **angular dependence**

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

Building observables: decay rates



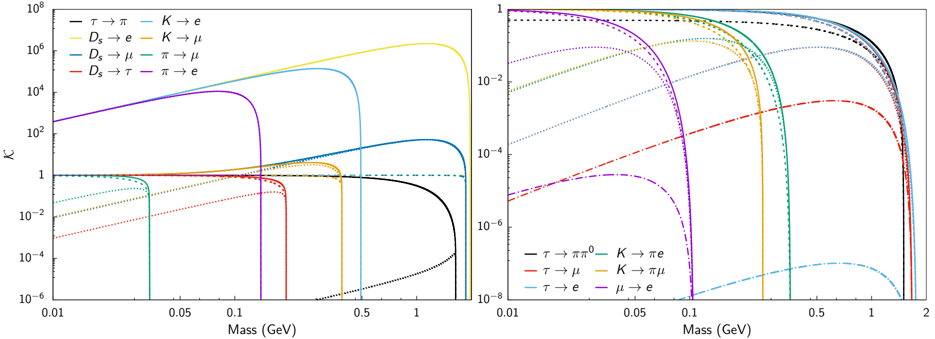
Channel	Threshold	Channel	Threshold	Channel	Threshold
$\nu\nu\nu$	10^{-9} MeV	$e^\mp K^\pm$	494 MeV	$\nu\eta'$	958 MeV
νe^+e^-	1.02 MeV	$\nu\eta$	548 MeV	$\mu^\mp K^{*\pm}$	997 MeV
$\nu e^\pm\mu^\mp$	105 MeV	$\mu^\mp K^\pm$	559 MeV	$\nu\phi$	1019 MeV
$\nu\pi^0$	135 MeV	$\nu\rho^0$	776 MeV	$\nu e^\pm\tau^\mp$	1776 MeV
$e^\mp\pi^\pm$	140 MeV	$e^\mp\rho^\pm$	776 MeV	$e^\mp D^\pm$	1870 MeV
$\nu\mu^+\mu^-$	210 MeV	$\nu\omega$	783 MeV	$\nu\mu^\pm\tau^\mp$	1880 MeV
$\mu^\mp\pi^\pm$	245 MeV	$\mu^\mp\rho^\pm$	882 MeV	$\tau^\mp\pi^\pm$	1870 MeV
		$e^\mp K^{*\pm}$	892 MeV		

Building observables: production scaling

Helicity is important! The flux of HNL is the flux of light neutrino **scaled** by

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

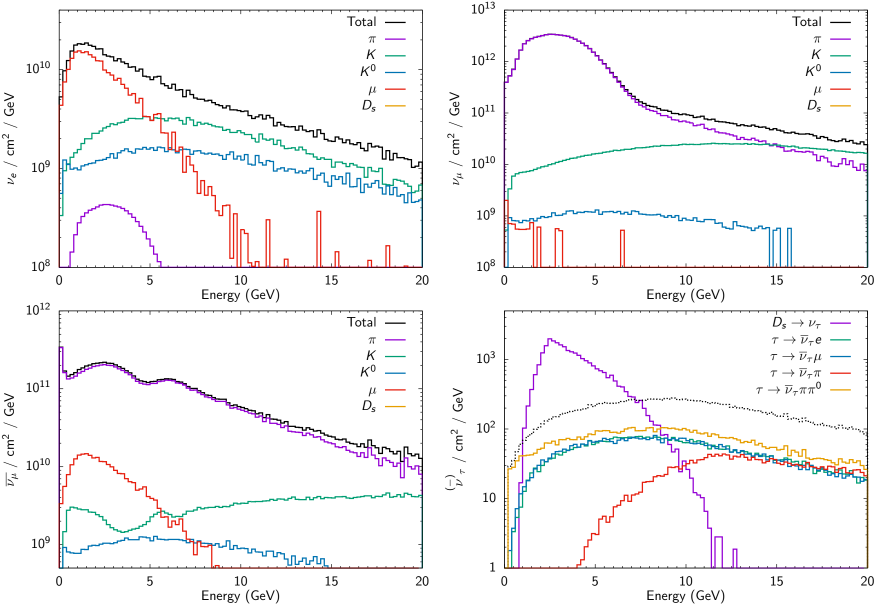
fixes phase space and helicity **unsuppression**



If we knew **all contributions** to the light neutrino flux:

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

Experiment: ν flux prediction (FHC mode)



Experiment: number of events

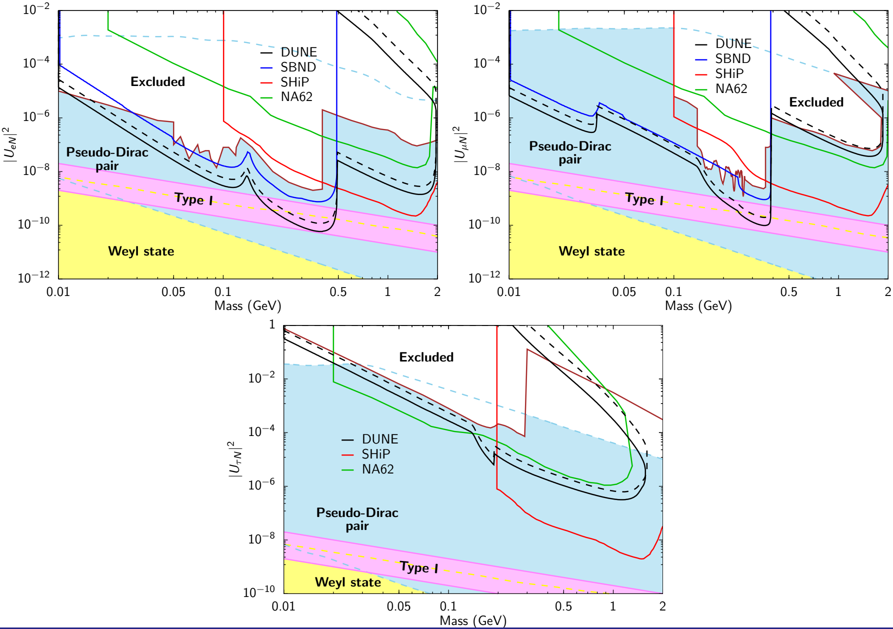
Number of events to be compared with **background** (= SM neutrino interactions)

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

- **GENIE simulation** of neutrino events in argon are input to **fast MC** of DUNE ND Reconstruction
- **Custom MC simulation** of HNL decays inside DUNE ND & reconstruction
- Particle identification **reduces** background by a factor from 10 and up to 10^4
- Comparison of **kinematic distributions** helps reduce background further
- $W_d(E)$ is a the **binned ratio** of the true N energy spectrum after and before the background reduction

For each channel, define 90 % C.L. sensitivity using Feldman & Cousins method [Feldman, Cousins, '98].

Results: sensitivity to discovery



Results: sensitivity to LNV

Focus on $N \to e\pi$ and $N \to \mu\pi$ channels: best sensitivity!

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

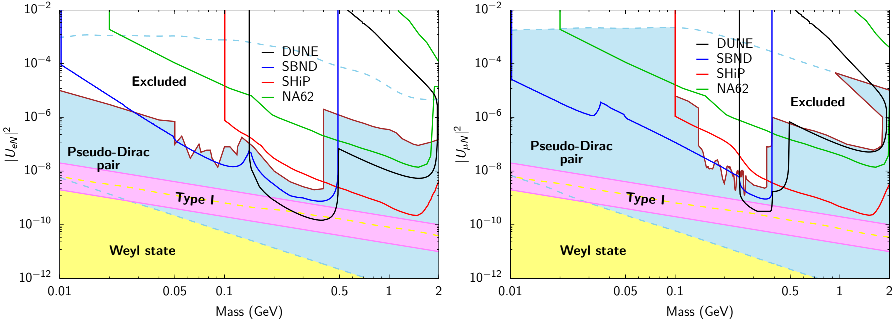
- FHC mode $\Rightarrow$ more $\ell^-\pi^+$ (factor $\sim$ 10)
- RHC mode $\Rightarrow$ more $\ell^+\pi^-$ (factor $\sim$ 3 to 5)

$$|N\rangle = |L\rangle + \left(\frac{m}{E}\right)|R\rangle$$

[de Gouvea, 2019]

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

need of 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.