Probing the Nature of HNLs in Direct Searches and Neutrinoless Double Beta Decay

Patrick Bolton*, SISSA & INFN Trieste

Based on [2212.14690] with F. Deppisch, M. Rai and Z. Zhang

CERN Neutrino Platform Pheno Week 2023
14th March 2023

*patrick.bolton@ts.infn.it

Motivation

[Credit: E. Lisi]

Heavy neutral leptons (HNLs) are a well-motivated extension to the SM

- SM: Only left-handed fields $\nu_L \quad \Leftrightarrow \quad m_\nu = 0,\ \Delta L = 0$ to all orders

- In analogy to e_R, u_R, d_R, introduce ν_R:

$$\begin{aligned}\mathcal{L} &\supset -Y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.}\\ &\supset -\frac{Y_\nu}{\sqrt{2}}(v+h)\bar{\nu}_L\nu_R + \text{h.c.}\,, \quad m_\nu = \frac{Y_\nu v}{\sqrt{2}}\end{aligned}$$

$\Rightarrow Y_\nu \ll Y_e, Y_u, Y_d$?

- Lepton number (an accidental global symmetry of the SM) forbids

$$\mathcal{L} \supset -\frac{1}{2}M_R\bar{\nu}_R^c\nu_R + \text{h.c.}$$

$\Rightarrow$ This symmetry need not hold in the UV (dim-5 SMEFT operator)

$\Rightarrow$ *A priori*, M_R of arbitrary value (high-scale/low-scale seesaw mechanisms)

$\Rightarrow$ Motivation to consider an extended neutrino sector

Extended Neutrino Sector

Adding singlet fermion N_R to the SM (respecting $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$)

$$\mathcal{L}_{\mathrm{SMEFT}+N} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}_R \partial\!\!\!/ N_R - \left[\frac{1}{2} M_R \bar{N}_R^c N_R + Y_\nu \bar{L}\tilde{H} N_R + \text{h.c.}\right] + \sum_{d>5} \mathcal{L}^{(d)}$$

With n_S singlet states:

$$\mathcal{L} \supset -\frac{1}{2}\bar{n}_L \mathcal{M}_\nu n_L^c + \text{h.c.}\,, \quad \mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_\nu \\ \frac{v}{\sqrt{2}} Y_\nu^T & M_R \end{pmatrix}, \quad n_L = \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

Now block-diagonalise $\mathcal{M}_\nu$ as ($\frac{v}{\sqrt{2}} Y_\nu \ll M_R$)

$$U^\dagger \mathcal{M}_\nu U^* = \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} = \mathrm{diag}(m_1, m_2, m_3, \underbrace{m_{N_1}, m_{N_2}, \ldots}_{\text{HNLs}})$$

Mixing matrix : $$U = \begin{pmatrix} U_\nu & U_{\nu N} \\ U_{N\nu} & U_N \end{pmatrix} = \begin{pmatrix} (1 - \frac{1}{2}\Theta\Theta^\dagger) U_{\mathrm{PMNS}} & \Theta \\ -\Theta^\dagger U_{\mathrm{PMNS}} & 1 - \frac{1}{2}\Theta^\dagger\Theta^* \end{pmatrix} + \mathcal{O}(\Theta^3)$$

Parametrisation

We want to be compatible with the neutrino oscillation data

- $n_S = 2$ HNLs needed reproduce light neutrino data ($m_{\text{light}} = 0$)
- Casas-Ibarra approach:

$$U_\nu m_\nu U_\nu^T + U_{\nu N} m_N U_{\nu N}^T = 0 \quad \Rightarrow \quad \underbrace{\left(i m_N^{-1/2} U_{\nu N}^\dagger U_\nu m_\nu^{1/2}\right)}_{\mathcal{R}^T} \underbrace{\left(i m_\nu^{1/2} U_\nu^T U_{\nu N}^* m_N^{-1/2}\right)}_{\mathcal{R}} = 1$$

$$\Rightarrow \quad U_{\nu N} = i U_\nu m_\nu^{1/2} \mathcal{R}(x, y) m_N^{-1/2}$$

- Phenomenological approach: Consider one neutrino flavour (1+2 model)

$$U_\nu m_\nu U_\nu^T + U_{\nu N} m_N U_{\nu N}^T \approx m_\nu + m_N \Theta_{e1}^2 + m_N (1 + r_\Delta) \Theta_{e2}^2 = 0$$

Solve for the mixing ratio, where $\Theta_{ei} = |\Theta_{ei}| e^{i\phi_{ei}/2}$ and $r_\Delta \equiv (m_{N_2} - m_{N_1})/m_{N_1}$

$$\frac{\Theta_{e2}}{\Theta_{e1}} = i\sqrt{\frac{1 + x_\nu}{1 + r_\Delta}}\,; \quad x_\nu(|\Theta_{e1}|, \phi_{e1}) = \frac{m_\nu}{m_N \Theta_{e1}^2}$$

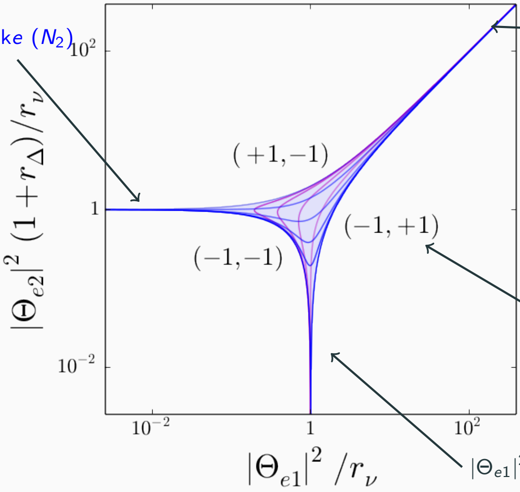
$$\Rightarrow \quad \frac{|\Theta_{e2}|^2}{|\Theta_{e1}|^2} = \frac{|1 + x_\nu|}{1 + r_\Delta}\,; \quad \cos\Delta\phi_e = -\frac{\text{Re}[1 + x_\nu]}{|1 + x_\nu|}$$

Phenomenological Parametrisation (1+2)

$$|\Theta_{e2}|^2 = \frac{m_\nu}{m_N(1+r_\Delta)}$$

$$\phi_{e2} = \pi$$

Standard Seesaw-like (N_2)



$$|\Theta_{e2}|^2 = \frac{|\Theta_{e1}|^2}{1+r_\Delta}$$

$$\Delta\phi_e = \pi$$

ISS-like

Pseudo-Dirac pair

$(\cos\phi_{e1}, \cos\phi_{e2})$

$$|\Theta_{e1}|^2 = r_\nu \equiv \frac{m_\nu}{m_N}$$

$$\phi_{e1} = \pi$$

Standard Seesaw-like (N_1)

Phenomenological Parametrisation (3+2)

Phenomenological approach can also include three light neutrino flavours (3+2 model):

$$\left[U_\nu m_\nu U_\nu^T + U_{\nu N} m_N U_{\nu N}^T\right]_{\alpha\beta} \approx m^\nu_{\alpha\beta} + m_N \Theta_{\alpha 1}\Theta_{\beta 1} + m_N(1+r_\Delta)\Theta_{\alpha 2}\Theta_{\beta 2} = 0$$

where $m^\nu_{\alpha\beta} \equiv [U_\nu m_\nu U_\nu^T]_{\alpha\beta}$

Now solve as:

$$\alpha = \beta \quad \Rightarrow \quad \frac{\Theta_{\alpha 2}}{\Theta_{\alpha 1}} = i\sqrt{\frac{1 + x^\alpha_{\alpha\alpha}}{1 + r_\Delta}}$$

$$\alpha \neq \beta \quad \Rightarrow \quad \frac{\Theta_{\beta 1}}{\Theta_{\alpha 1}} = y^\alpha_{\alpha\beta} \equiv \frac{x^\alpha_{\alpha\beta} + \sqrt{(x^\alpha_{\alpha\beta})^2 - x^\alpha_{\alpha\alpha}x^\alpha_{\beta\beta}}\sqrt{1 + x^\alpha_{\alpha\alpha}}}{x^\alpha_{\alpha\alpha}}$$

$$x^\rho_{\alpha\beta} = \frac{m^\nu_{\alpha\beta}}{m_N \Theta^2_{\rho 1}}$$

$$\#_{\text{elim}} = n_A(n_A - 1) + 2\min(n_A, n_S) = \begin{cases} 2\,, & n_A = 1, n_S = 2 \\ 10\,, & n_A = 3, n_S = 2 \\ 12\,, & n_A = 3, n_S = 3 \end{cases}$$

$n_A = 1, n_S = 2 \rightarrow$ $$U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \end{pmatrix}$$

$n_A = 3, n_S = 2 \rightarrow$ $$U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \\ \Theta_{\mu 1} & \Theta_{\mu 2} \\ \Theta_{\tau 1} & \Theta_{\tau 2} \end{pmatrix}$$

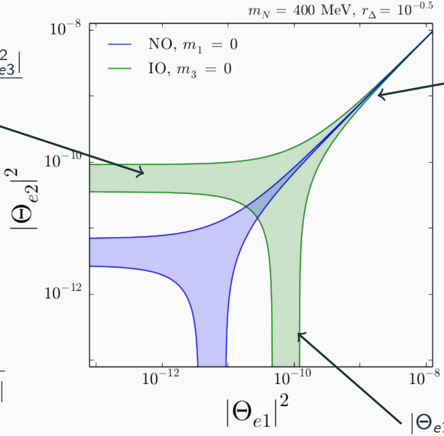
$$U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \\ \Theta_{\mu 1} & \Theta_{\mu 2} \\ \Theta_{\tau 1} & \Theta_{\tau 2} \end{pmatrix}$$

→ $m^{\nu}_{\alpha\beta}$: $m_{2(1)}, m_{3(2)}, \theta_{12}, \theta_{23}, \theta_{13}, \delta$ (NuFIT v5.2), α_{21}

→ $m_N, r_\Delta, |\Theta_{e1}|^2, \phi_{e1}$

$$|\Theta_{e2}|^2 = \frac{|m_2 U_{e2}^2 + m_3 U_{e3}^2|}{m_N(1+r_\Delta)}$$

$$|\Theta_{e2}|^2 = \frac{|\Theta_{e1}|^2}{1+r_\Delta}$$



$$|\Theta_{e1}|^2 = \frac{|m_2 U_{e2}^2 + m_3 U_{e3}^2|}{m_N}$$

NO:

$$m_2 = \sqrt{\Delta m^2_{\text{sol}}}$$

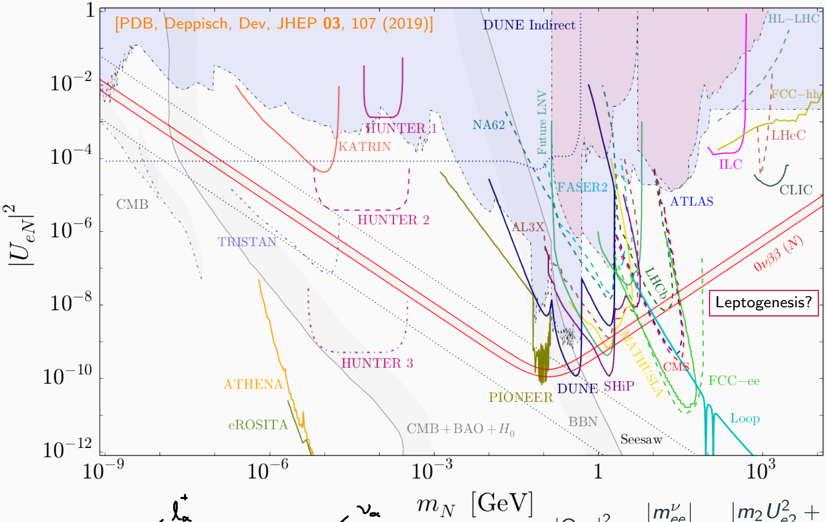
$$m_3 = \sqrt{\Delta m^2_{\text{sol}} + \Delta m^2_{\text{atm}}}$$

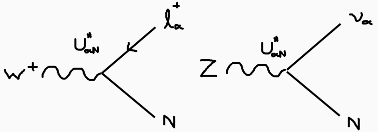
IO:

$$m_1 = \sqrt{|\Delta m^2_{\text{sol}} + \Delta m^2_{\text{atm}}|}$$

$$m_2 = \sqrt{|\Delta m^2_{\text{atm}}|}$$

Future Sensitivities on $|U_{eN}|^2$



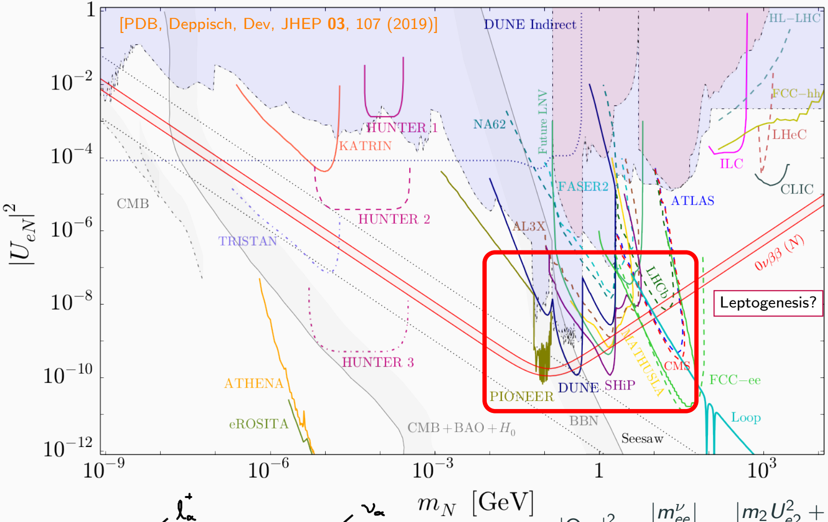


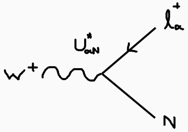
$$|\Theta_{e1}|^2 = \frac{|m^\nu_{ee}|}{m_N} = \frac{|m_2 U^2_{e2} + m_3 U^3_{e3}|}{m_N}$$

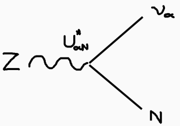
$$1.4 \text{ meV} < |m^\nu_{ee}| < 3.7 \text{ meV} \quad \text{(NO)}$$

$$19 \text{ meV} < |m^\nu_{ee}| < 48 \text{ meV} \quad \text{(IO)}$$

An Interesting Region?







$$|\Theta_{e1}|^2 = \frac{|m_{ee}^\nu|}{m_N} = \frac{|m_2 U_{e2}^2 + m_3 U_{e3}^3|}{m_N}$$

$1.4 \text{ meV} < |m_{ee}^\nu| < 3.7 \text{ meV}$ (NO)

$19 \text{ meV} < |m_{ee}^\nu| < 48 \text{ meV}$ (IO)

Neutrinoless Double Beta ($0\nu\beta\beta$) Decay

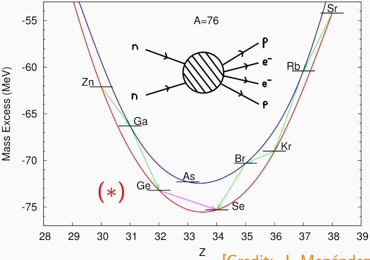
$0\nu\beta\beta$ Decay Process

When β decay is not kinematically accessable $(*)$,

$$^{A}_{Z}X \rightarrow {}_{Z+2}^{\;\;A}X + 2e^{-} + 2\bar{\nu} \quad (\Delta L = 0)$$

If lepton number is not conserved,

$$^{A}_{Z}X \rightarrow {}_{Z+2}^{\;\;A}X + 2e^{-} \quad (\Delta L = 2)$$

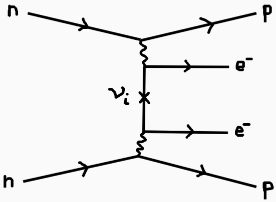


[Credit: J. Menéndez]

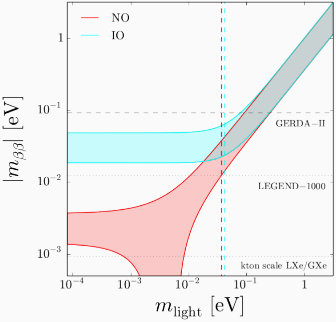
Contribution of light Majorana neutrinos:

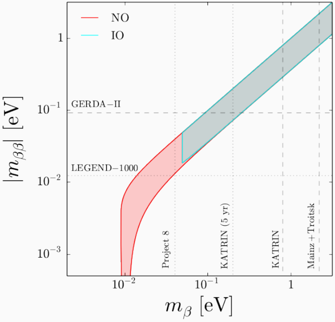
$$\frac{1}{T_{1/2}^{0\nu}} = \frac{G_{0\nu} g_A^4 |\mathcal{M}_\nu|^2}{m_e^2} |m_{\beta\beta}|^2$$

$$\begin{aligned} m_{\beta\beta} &= \sum_i U_{ei}^2 m_i \\ &= m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13} e^{i(\alpha_{31} - 2\delta)} \end{aligned}$$



Light Neutrino Contribution

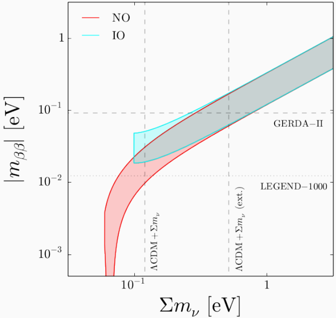




$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

$$\Sigma m_\nu = \sum_i m_i$$



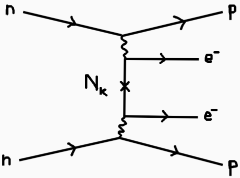
GERDA-II (^{76}Ge):

$T_{1/2}^{0\nu} > 1.8 \times 10^{26}$ yr
$|m_{\beta\beta}| < 92$ meV

LEGEND-1000 (*proposal*):

$T_{1/2}^{0\nu} \gtrsim 10^{28}$ yr
$|m_{\beta\beta}| \lesssim 12$ meV

Light Neutrino + HNL Contribution (3+2)



Including HNL exchange:

$$|m_{\beta\beta}^{\rm eff}| = \left| m_{\beta\beta}^{\nu} + \sum_i U_{eN_i}^2 m_{N_i} \frac{\mathcal{M}^{0\nu}(m_{N_i})}{\mathcal{M}_\nu} \right|$$

where *heavy* NME follows

$$\lim_{m_{N_i}\to 0} \mathcal{M}^{0\nu}(m_{N_i}) = \mathcal{M}_\nu \,, \qquad \lim_{m_{N_i}\to \infty} \mathcal{M}^{0\nu}(m_{N_i}) = \frac{m_e m_p}{m_{N_i}^2} \mathcal{M}_{\nu,{\rm sd}}$$

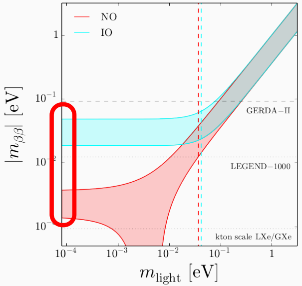
So we use interpolating formula

$$\mathcal{M}^{0\nu}(m_{N_i}) = \mathcal{M}_{\nu,{\rm sd}} \frac{\langle \mathbf{p}^2 \rangle \mathcal{F}(m_{N_i})}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \; ; \quad \langle \mathbf{p}^2 \rangle \equiv m_e m_p \left| \frac{\mathcal{M}_{X,{\rm sd}}}{\mathcal{M}_X} \right|$$

Light neutrino exchange ($m_{\beta\beta}^\nu \equiv m_{ee}^\nu$):

$$1.4 \text{ meV} < |m_{\beta\beta}^\nu| < 3.7 \text{ meV} \quad (\text{NO})$$

$$19 \text{ meV} < |m_{\beta\beta}^\nu| < 48 \text{ meV} \quad (\text{IO})$$



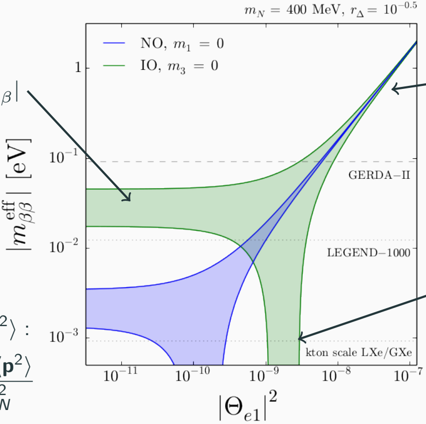
Light Neutrino + HNL Contribution (3+2)

$$|m_{\beta\beta}^{\text{eff}}| = \left| m_{\beta\beta}^{\nu} + m_N \Theta_{e1}^2 \frac{\langle \mathbf{p}^2 \rangle}{\langle \mathbf{p}^2 \rangle + m_N^2} + m_N (1 + r_\Delta) \Theta_{e2}^2 \frac{\langle \mathbf{p}^2 \rangle}{\langle \mathbf{p}^2 \rangle + m_N^2 (1 + r_\Delta)^2} \right|$$

$$= \left| \alpha m_{\beta\beta}^{\nu} + \beta m_N \Theta_{e1}^2 \right|$$

where

$$\alpha \equiv 1 - \frac{\langle \mathbf{p}^2 \rangle}{\langle \mathbf{p}^2 \rangle + m_N^2 (1 + r_\Delta)^2}, \quad \beta \equiv \frac{\langle \mathbf{p}^2 \rangle}{\langle \mathbf{p}^2 \rangle + m_N^2} - \frac{\langle \mathbf{p}^2 \rangle}{\langle \mathbf{p}^2 \rangle + m_N^2 (1 + r_\Delta)^2}$$



$|m_{\beta\beta}^{\text{eff}}| = \alpha |m_{\beta\beta}^{\nu}|$

$|m_{\beta\beta}^{\text{eff}}| = \beta m_N |\Theta_{e1}|^2$

$$|\Theta_{e1}|^2 = \frac{\alpha |m_{\beta\beta}^{\nu}|}{\beta m_N}$$

$r_\Delta \ll 1, \; m_N \gg \langle \mathbf{p}^2 \rangle$:

$$\alpha \approx 1, \quad \beta = \frac{2 r_\Delta \langle \mathbf{p}^2 \rangle}{m_N^2}$$

Direct Searches

HNL Production at Fixed-Target Experiments

Decays of pseudoscalar mesons $P = \{\pi, K, D, D_s\}$ produced in proton beam target

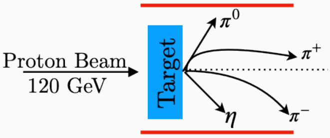
1) Two-body leptonic decays:

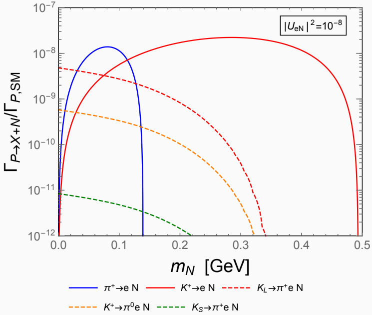
$$\mathrm{Br}(P^+ \to \ell_\alpha^+ N) \propto G_F^2 |U_{\alpha N}|^2 f_2\left(\frac{m_{\ell_\alpha}^2}{m_P^2}, \frac{m_N^2}{m_P^2}\right)$$

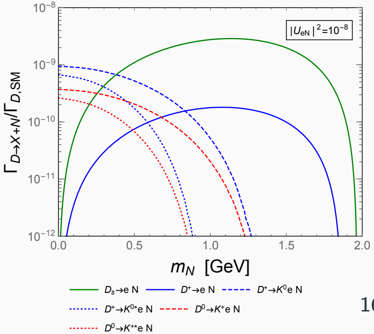
$$f_2\left(\frac{m_{\ell_\alpha}^2}{m_P^2}, \frac{m_N^2}{m_P^2}\right) \propto \frac{m_N^2}{m_P^2}\left(1 - \frac{m_N^2}{m_P^2}\right)^2$$

2) Three-body semi-leptonic decays:

$$\mathrm{Br}(P^+ \to P'^0 \ell_\alpha^+ N) \propto G_F^2 |U_{\alpha N}|^2 \underbrace{f_3\left(\frac{m_{\ell_\alpha}^2}{m_P^2}, \frac{m_N^2}{m_P^2}\right)}_{f_+(q^2),\, f_-(q^2)}$$





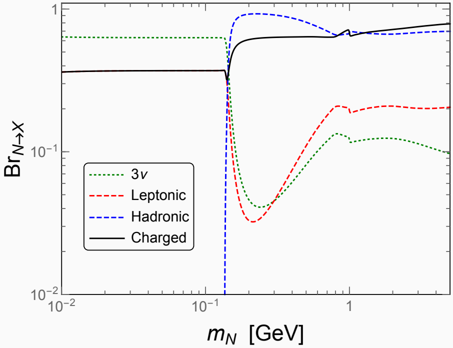


[Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf, JHEP 02 (2020) 174]

HNL Decay

Long-lived HNLs can decay inside the fiducial volume, e.g. Argon-based detector

- Invisible ($N \to 3\nu$) and neutral semi-leptonic ($N \to \nu\pi^0$) decays not detected
- Decays with charged final states (e.g., $N \to \nu\ell_\alpha^+\ell_\beta^-$, $N \to \ell_\alpha^+\pi^-$, $N \to \ell_\alpha^+\rho^-$) detected above KE threshold
  - $\Rightarrow$ For two-body decays, invariant mass reconstruction can suppress SM background
  - $\Rightarrow$ For $N \to \nu\ell_\alpha^+\ell_\beta^-$ ($\alpha, \beta = e, \mu$), backgrounds are low (mis-ID of $\pi^\pm$)



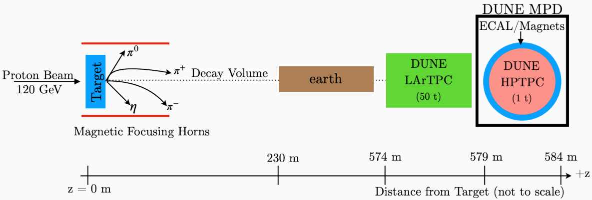
DUNE: Detector Modelling and Simulation

Using PYTHIAv8 (considering DUNE with 6.6×10^{21} PoT at 120 GeV):

- Simulated meson production (prod. fractions N_P and momentum profiles)
- Rest-frame decays of mesons to HNLs, boosted to lab frame
- HNLs required to decay to charged tracks inside the DUNE ND (for simplicity, assuming a conical cross section)

$$\epsilon_{\text{geo}} = \frac{1}{N_{\text{tot}}} \sum_{\text{cut}} e^{-\frac{m_N \Gamma_N}{p_{N_z}} L} \left(1 - e^{-\frac{m_N \Gamma_N}{p_{N_z}} \Delta\ell_{\text{det}}} \right), \quad L = 574 \text{ m}, \; \Delta\ell_{\text{det}} = 5 \text{ m}$$

$$\frac{p_{N_T}}{p_{N_z}} < \theta_{\text{det}} \sim 7 \times 10^{-3}$$



[Berryman, de Gouvêa, Fox, Kayser, Kelly, Raaf, JHEP 02 (2020) 174]

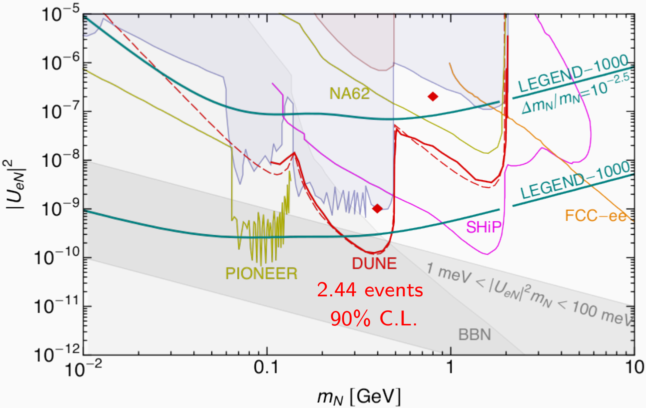
DUNE Sensitivity

Putting this all together obtain the DUNE sensitivity

$$\mathcal{N}_{\text{sig}}^{\text{DUNE}} = \sum_{P,\,\text{charged}} N_P \cdot \text{Br}(P \to N) \cdot \text{Br}(N \to \text{charged}) \cdot \epsilon_{\text{geo}}$$

In the phenomenological model:

$$N_{\text{sig}}^{\text{DUNE}} = \mathcal{N}_{\text{sig}}^{\text{DUNE}}(m_N, |\Theta_{e1}|^2) + \mathcal{N}_{\text{sig}}^{\text{DUNE}}\left(m_N(1+r_\Delta), |\Theta_{e2}|^2\right)$$



$0\nu\beta\beta$ Decay vs. Direct Searches

Analytical Comparison

For simplicity, we consider the 1+2 model

$\Rightarrow$ Only $|U_{eN}|^2$, electron channels (e.g. $N \to e^{\pm}\pi^{\mp}$) in DUNE

We can get an analytical estimate of r_Δ probed by LEGEND-1000 and DUNE

$\Rightarrow$ For $m_N < m_K$ ($m_N > m_K$), $K^+ \to e^+ N$ ($D_s^+ \to e^+ N$) dominates

$\Rightarrow$ For $m_N \lesssim 1$ GeV, $N \to e^{\pm}\pi^{\mp}$ dominates

LEGEND-1000 and DUNE rate in the $|\Theta_{e1}|^2 \gg m_\nu / m_N$ limit

$$N_{\rm sig}^{\rm DUNE} \propto \mathcal{A}(m_N)|\Theta_{e1}|^4 + \mathcal{A}\big(m_N(1+r_\Delta)\big)\frac{|\Theta_{e1}|^4}{(1+r_\Delta)^2} \quad \underset{r_\Delta \ll 1}{\Rightarrow} \quad |\Theta_{e1}|^2 \propto \sqrt{\frac{N_{\rm sig}^{\rm DUNE}}{\mathcal{A}(m_N)}}$$

$$|m_{\beta\beta}| \approx \beta m_N |\Theta_{e1}|^2 \quad \Rightarrow \quad |\Theta_{e1}|^2 \propto \frac{m_N}{r_\Delta (T_{1/2}^{0\nu})^{1/2}}$$

Giving,

$$r_\Delta \sim 1.5 \times 10^{-3} \left(\frac{m_N}{800 \text{ MeV}}\right) \left(\frac{300}{N_{\rm sig}^{\rm DUNE}}\right)^{1/2} \left(\frac{10^{28}\text{ yr}}{T_{1/2}^{0\nu}}\right)^{1/2}$$

Statistical Analysis – Likelihoods

Assume that LEGEND-1000 and DUNE are simple counting experiments following

$$\text{Pois}\left(n_{\text{obs}} \mid \lambda_{\text{sig}} + \lambda_{\text{bkg}}\right) \propto \frac{\left(\lambda_{\text{sig}} + \lambda_{\text{bkg}}\right)^{n_{\text{obs}}} e^{-\left(\lambda_{\text{sig}}+\lambda_{\text{bkg}}\right)}}{\Gamma\left(n_{\text{obs}} + 1\right)}$$

i.e. continious interpolation of Poission distribution

Given the model hypothesis $\boldsymbol{\theta} = \{m_\nu, m_N, r_\Delta, |\Theta_{e1}|^2, \phi_{e1}\}$, *expected* number of events:

$$\lambda_{\text{sig}}^{\text{LEGEND}} = \frac{\ln 2 \cdot N_A \cdot \mathcal{E}}{m_A \cdot T_{1/2}^{0\nu}(\boldsymbol{\theta})}, \quad \lambda_{\text{bkg}}^{\text{LEGEND}} = \mathcal{E} \cdot \mathcal{B} = 0.4 \text{ cts}$$

$$\lambda_{\text{sig}}^{\text{DUNE}} = N_{\text{sig}}^{\text{DUNE}}(\boldsymbol{\theta}), \quad \lambda_{\text{bkg}}^{\text{DUNE}} \approx 0$$

$$\mathcal{E} = 6632 \text{ kg} \cdot \text{yr}$$

$$\mathcal{B} = 6.4 \times 10^{-5}/(\text{kg} \cdot \text{yr})$$

Given data **D** and model parameters $\boldsymbol{\theta}$, global likelihood is

$$\mathcal{L}(\mathbf{D}|\boldsymbol{\theta}) = \text{Pois}\left(n_{\text{obs}}^{\text{LEGEND}} \mid \lambda_{\text{sig}}^{\text{LEGEND}} + \lambda_{\text{bkg}}^{\text{LEGEND}}\right) \cdot \text{Pois}\left(n_{\text{obs}}^{\text{DUNE}} \mid \lambda_{\text{sig}}^{\text{DUNE}}\right)$$

MCMC Likelihood Scan with Benchmark Points

We would like to estimate the posterior probability of the HNL hypothesis $\boldsymbol{\theta}$ given data $\mathbf{D}$

$$p(\boldsymbol{\theta}|\mathbf{D}) \propto \mathcal{L}(\mathbf{D}|\boldsymbol{\theta}) \cdot \pi(\boldsymbol{\theta})$$

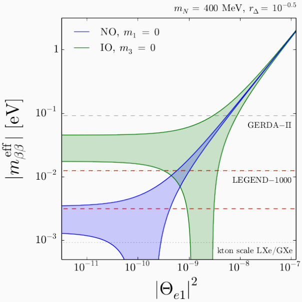
Perform MCMC scan (Metropolis-Hastings) of parameter space with flat priors:

- Consider 4 benchmark scenarios b: $\boldsymbol{\theta}_0 = \boldsymbol{\theta}_b$
- $\mathbf{D}$: Signals at LEGEND-1000 (✓/✗) and DUNE (✓/✗)

$$✓ : n_{\text{obs}} = \lambda_{\text{sig}}(\boldsymbol{\theta}_b) + \lambda_{\text{bkg}}$$

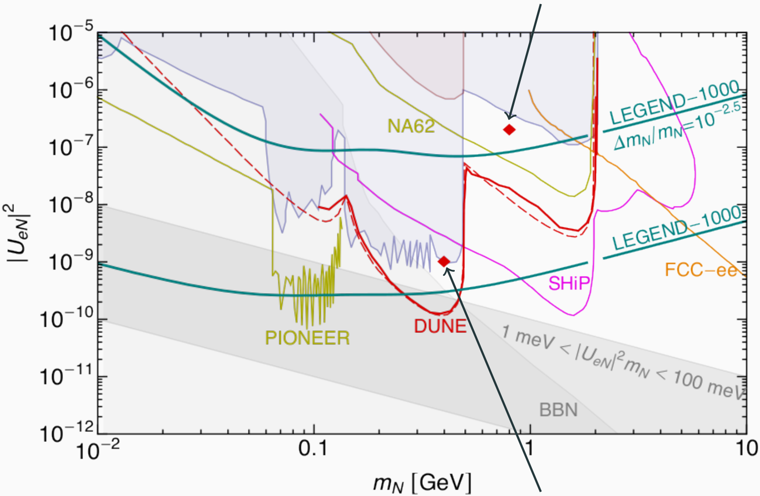
$$✗ : n_{\text{obs}} = \lambda_{\text{bkg}}$$

- Markov chain $[\boldsymbol{\theta}_0, \boldsymbol{\theta}_1, \ldots]$ to approximate $p(\boldsymbol{\theta}|\mathbf{D})$



Scenario b	m_ν [eV]	m_N [MeV]	$\lvert\Theta_{e1}\rvert^2$	r_Δ	$\lambda_{\text{sig}}^{\text{DUNE}}$	$\lambda_{\text{sig}}^{\text{LEGEND}}$	$T_{1/2}^{0\nu}$ [yr]
1	$10^{-1.9}$	400	$10^{-9.0}$	$10^{-0.5}$	76.7	5.94	$10^{27.8}$
2	$10^{-2.5}$	400	$10^{-9.0}$	$10^{-0.5}$	76.7	2.73	$10^{28.1}$
3	$10^{-1.9}$	800	$10^{-6.7}$	$10^{-2.5}$	325	15.5	$10^{27.4}$
4	$10^{-2.5}$	800	$10^{-6.7}$	$10^{-2.5}$	325	12.3	$10^{27.5}$

Benchmarks 3 and 4



Benchmarks 1 and 2

LEGEND-1000 (✓) and DUNE (✓)

Benchmark 1:

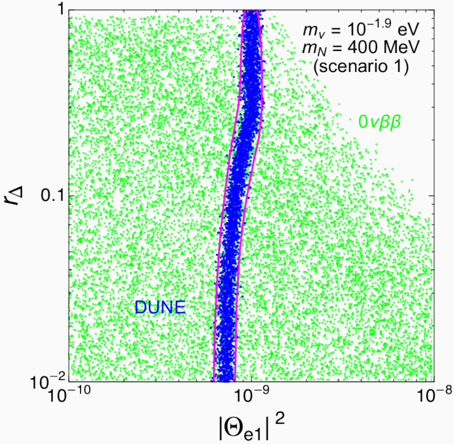
- $|\Theta_{e1}|^2 \approx 10^{-9}$ from DUNE
- m_ν saturates $T^{0\nu}_{1/2}$ half-life

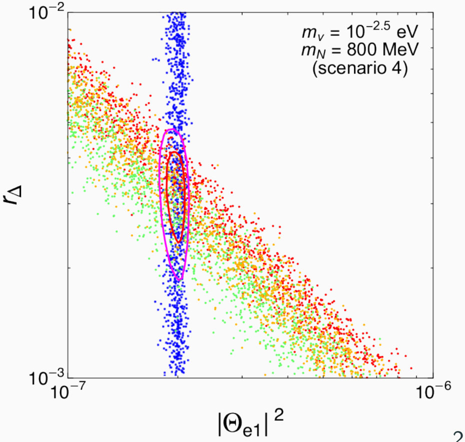
$\Rightarrow r_\Delta$ upper limit

Benchmark 4:

- $|\Theta_{e1}|^2 \approx 2 \times 10^{-7}$ from DUNE
- HNL pair dominates $T^{0\nu}_{1/2}$ half-life

$\Rightarrow 2 \times 10^{-3} \lesssim r_\Delta \lesssim 5 \times 10^{-3}$



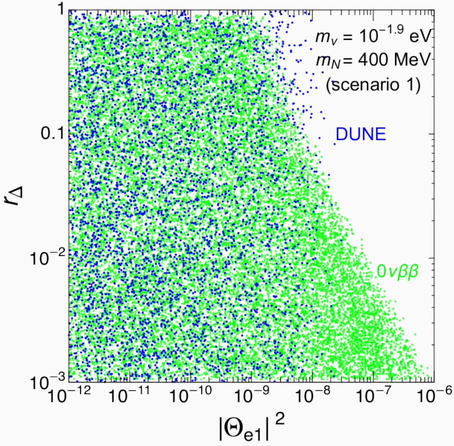


LEGEND-1000 (✓) and DUNE (✗)

Benchmark 1:

- $|\Theta_{e1}|^2 \lesssim 10^{-8}$ from DUNE
- m_ν saturates $T_{1/2}^{0\nu}$ half-life

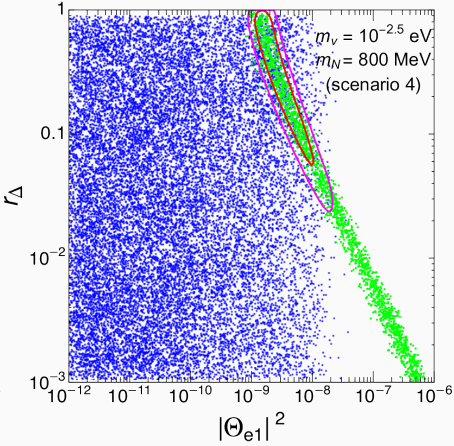
$\Rightarrow$ $|\Theta_{e1}|^2$ and r_Δ upper limits



Benchmark 4:

- $|\Theta_{e1}|^2 \lesssim 10^{-8}$ from DUNE
- HNL pair dominates $T_{1/2}^{0\nu}$ half-life

$\Rightarrow$ $r_\Delta \gtrsim 2 \times 10^{-2}$



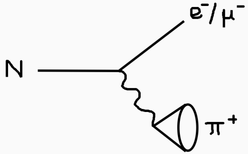
Adding Muon Channels

In the 3+2 model, we also consider muon channels at DUNE

- Additional N decays, e.g. $N \to \mu^{\pm}\pi^{\mp}$

$$N_{\text{sig}}^{\text{DUNE}}(\boldsymbol{\theta}) = \mathcal{N}_{\text{sig}}^{\text{DUNE}}(m_N, |\Theta_{e1}|^2, |\Theta_{\mu 1}|^2) + \mathcal{N}_{\text{sig}}^{\text{DUNE}}\left(m_N(1+r_\Delta), |\Theta_{e2}|^2, |\Theta_{\mu 2}|^2\right)$$

$$\Rightarrow \boldsymbol{\theta} = \{\alpha_{21}, m_N, r_\Delta, |\Theta_{e1}|^2, \phi_{e1}\}_{\text{NO/IO}}$$

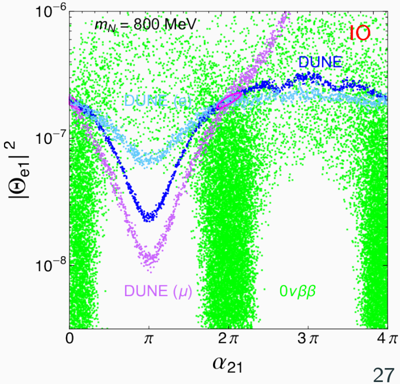


- New observables: Events with single flavour in final state

$$\mathcal{L}' = \mathcal{L} \cdot \prod_{\alpha=e,\mu} \text{Pois}\left(n_{\text{obs}}^{\text{DUNE}(\alpha)} \mid \lambda_{\text{sig}}^{\text{DUNE}(\alpha)}\right)$$

- Repeat MCMC scan with $\mathcal{L}'$

$\Rightarrow$ 3+2 model parameter space further constrained

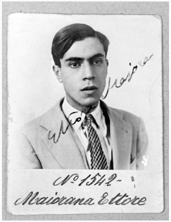


Conclusions

Conclusions

Can we probe the nature of HNLs with direct searches and $0\nu\beta\beta$ decay?

- Phenomenological parametrisation describing HNL pair contribution to m_ν
  - ⇒ Simple 1+2 model or more realistic 3+2 model
  - ⇒ $\boldsymbol{\theta} = (m_\nu, m_N, r_\Delta, |\Theta_{e1}|^2, \phi_{e1})$
  - ⇒ Majorana and pseudo-Dirac limits of HNL pair



- Probes:
  - ⇒ Constructive/destructive interference of HNL pair with ν in $0\nu\beta\beta$ decay
  - ⇒ Production and decay of HNL pair in fixed-target experiments

- Constraining HNL parameter space:
  - ⇒ MCMC scan of $p(\boldsymbol{\theta}|\mathbf{D})$ given a signal (✓) or no signal (✗) at LEGEND-1000 + DUNE
  - ⇒ Single flavour (this talk) + two flavour analyses
  - ⇒ **More work to be done!**

Thank you for listening

This project has received funding/support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881-HIDDeN

Backup

Phenomenological Parametrisation (General)

In the 3+2 set-up:

$$\underbrace{M_\nu}_{\text{rank}(M_\nu)=\min(n_A,n_S)+n_S} = \begin{pmatrix} 0\big|_{n_A\times n_A} & M_D\big|_{n_A\times n_S} \\ M_D^T\big|_{n_A\times n_A} & M_R\big|_{n_S\times n_S} \end{pmatrix} = U \cdot M_\nu^{\text{diag}} \cdot U^T$$

$$\#_{\text{params}} = \underbrace{\min(n_A, n_S)}_{\nu\text{ masses}} + \underbrace{\left[\min(n_A, n_S) + n_A(n_A-2)\right]}_{U_\nu} + \underbrace{n_S}_{N\text{ masses}} + \underbrace{\left[2n_A n_S - n_A(n_A-1) - 2\min(n_A, n_S)\right]}_{U_{\nu N}}$$

$$\#_{\text{elim}} = n_A(n_A-1) + 2\min(n_A, n_S) = \begin{cases} 2\,, & n_A = 1, n_S = 2 \\ 10\,, & n_A = 3, n_S = 2 \\ 12\,, & n_A = 3, n_S = 3 \end{cases}$$

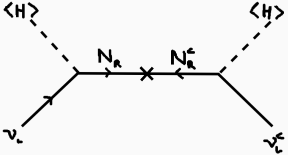
$n_A = 1, n_S = 2 \longrightarrow U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \end{pmatrix}$

$n_A = 3, n_S = 2 \longrightarrow U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \\ \Theta_{\mu 1} & \Theta_{\mu 2} \\ \Theta_{\tau 1} & \Theta_{\tau 2} \end{pmatrix}$

Seesaw Type

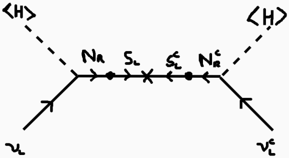
Type-I Seesaw:

$$M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_1^T & 0 \\ \frac{v}{\sqrt{2}} Y_1^T & M & 0 \\ 0 & 0 & M \end{pmatrix} \Rightarrow \begin{array}{l} \Theta = \left(\frac{v Y_1}{\sqrt{2} M}, 0 \right) \\ m_\nu = -\frac{v^2}{2M} Y_1 Y_1^T \end{array}$$



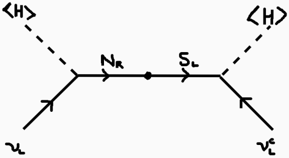
Inverse Seesaw (ISS):

$$M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_1 & 0 \\ \frac{v}{\sqrt{2}} Y_1^T & 0 & M \\ 0 & M & \mu \end{pmatrix} \Rightarrow \begin{array}{l} \Theta = \left(\frac{v Y_1}{2M}, \frac{v Y_1}{2M} \right) \\ m_\nu = \frac{v^2 \mu}{2M^2} Y_1 Y_1^T \\ \Delta m_N = \mu \end{array}$$



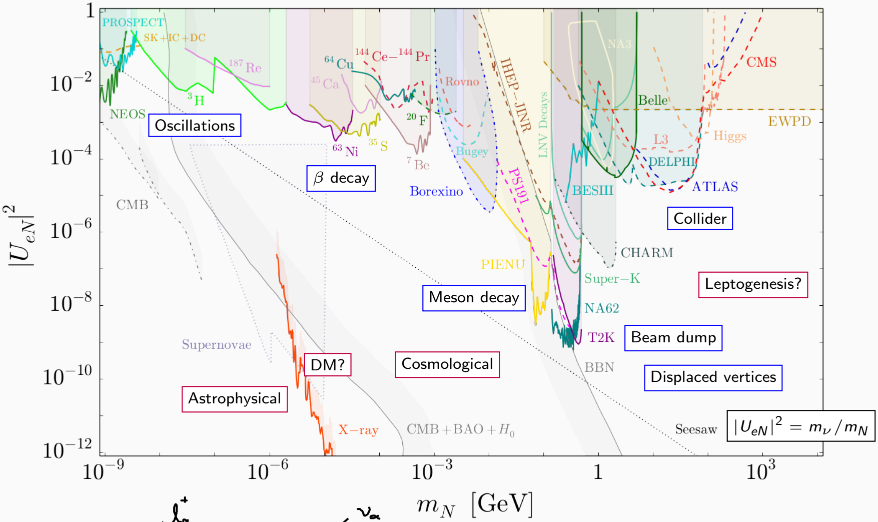
Linear Seesaw (LSS):

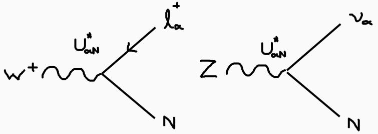
$$M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_1 & \frac{v}{\sqrt{2}} Y_2 \\ \frac{v}{\sqrt{2}} Y_1^T & 0 & M \\ \frac{v}{\sqrt{2}} Y_2^T & M & 0 \end{pmatrix} \Rightarrow \begin{array}{l} \Theta = \left(\frac{v(Y_1 - Y_2)}{2M}, \frac{v(Y_1 + Y_2)}{2M} \right) \\ m_\nu = -\frac{v^2}{2M} (Y_1 Y_2^T + Y_2 Y_1^T) \\ \Delta m_N = \Delta m_\nu = \frac{v^2}{M} Y_1^T Y_2 \end{array}$$



$$\Delta m_N \big|_{\text{LSS}} < \Delta m_N \big|_{\text{ISS}} < \Delta m_N \big|_{\text{ISS,1-loop}}$$

Current $|U_{eN}|^2$ Constraints





[PDB, Deppisch, Dev, JHEP **03**, 107 (2019)]

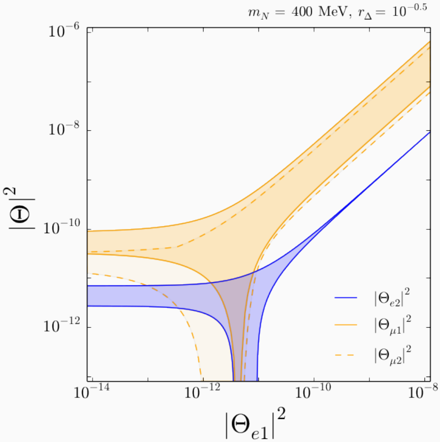
www.sterile-neutrino.org

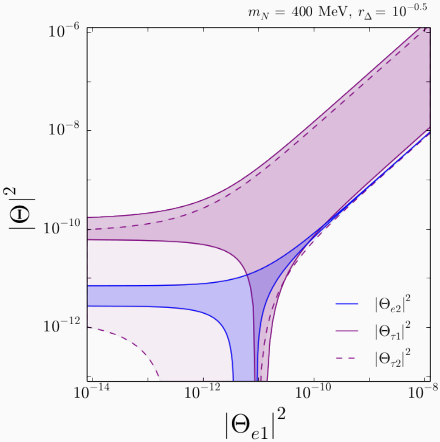
Phenomenological Parametrisation (3+2)

$$U_{\nu N} = \begin{pmatrix} \Theta_{e1} & \Theta_{e2} \\ \color{red}{\Theta_{\mu 1}} & \color{red}{\Theta_{\mu 2}} \\ \color{red}{\Theta_{\tau 1}} & \color{red}{\Theta_{\tau 2}} \end{pmatrix}$$

→ $m_{2(1)}, m_{3(2)}, \theta_{12}, \theta_{23}, \theta_{13}, \delta$ (NuFIT v5.2), $\color{blue}{\alpha_{21}}$

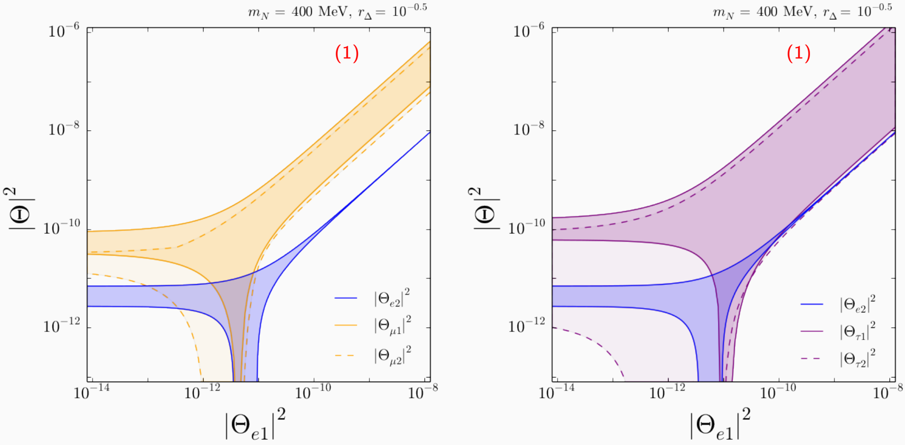
→ $m_N, r_\Delta, |\Theta_{e1}|^2, \color{blue}{\phi_{e1}}$





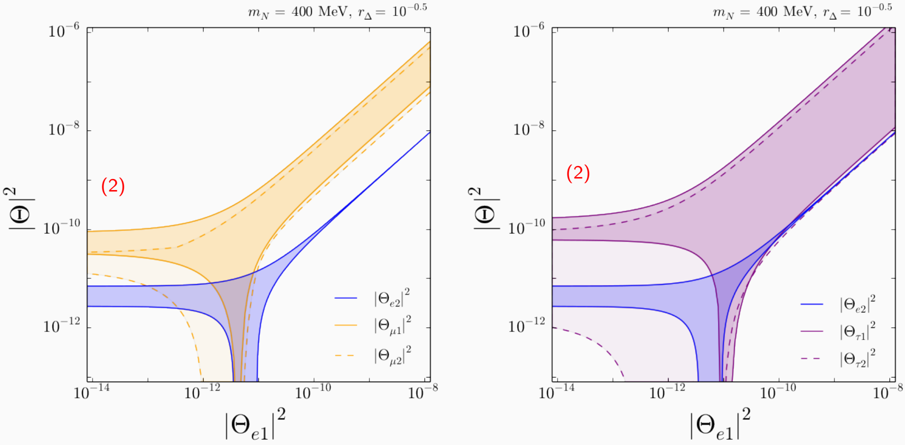
Phenomenological Parametrisation (3+2)

(1) $$|\Theta_{\beta 1}|^2 = |\Theta_{e1}|^2 \left| \frac{\sqrt{m_2}U_{\beta 2} + i\sqrt{m_3}U_{\beta 3}}{\sqrt{m_2}U_{e2} + i\sqrt{m_3}U_{e3}} \right|^2, \quad |\Theta_{\beta 2}|^2 = \frac{|\Theta_{\beta 1}|^2}{1 + r_\Delta} \quad \text{(NO)}$$



Phenomenological Parametrisation (3+2)

$$(2) \quad |\Theta_{\beta 1}|^2 = \left| \frac{m_2 m_3 (U_{e2} U_{\beta 3} - U_{e3} U_{\beta 2})^2}{m_N (m_2 U_{e2}^2 + m_2 U_{e3}^2)} \right|, \quad |\Theta_{\beta 2}|^2 = \left| \frac{(m_2 U_{e2} U_{\beta 2} + m_3 U_{e3} U_{\beta 3})^2}{m_N (1 + r_\Delta)(m_2 U_{e2}^2 + m_2 U_{e3}^2)} \right| \quad \text{(NO)}$$



Phenomenological Parametrisation (3+2)

$$(3) \quad |\Theta_{e1}|^2 = \left| \frac{m_2 m_3 (U_{e2} U_{\beta 3} - U_{e3} U_{\beta 2})^2}{m_N (m_2 U_{\beta 2}^2 + m_2 U_{\beta 3}^2)} \right|, \quad |\Theta_{e1}|^2 = \left| \frac{(m_2 U_{e2} U_{\beta 2} + m_3 U_{e3} U_{\beta 3})^2}{m_N (m_2 U_{\beta 2}^2 + m_2 U_{\beta 3}^2)} \right| \quad \text{(NO)}$$