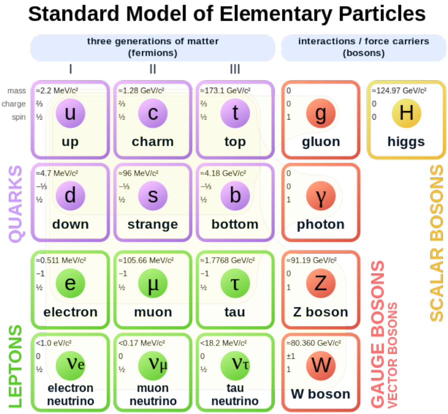
Quasi-Dirac HNLs in the Left-Right Symmetric Model

BLV 2024

Oleksii Mikulenko

Leiden University,
the Netherlands

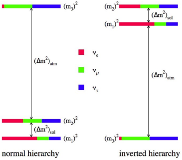
Beyond the Standard Model



Still missing:

Dark matter

Baryon asymmetry



Neutrino masses

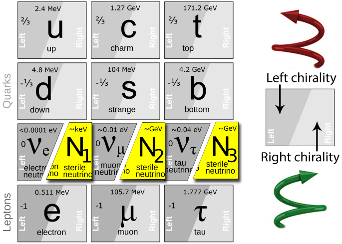
Heavy Neutral Leptons (HNL)

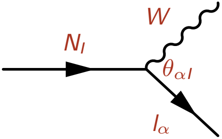
- Minimal solution – right-handed neutrinos with Majorana mass:

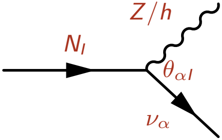
$$\mathcal{L}_N \supset -F_{\alpha I}\bar{L}_\alpha \tilde{H} N_I + \frac{M_I}{2}\bar{N}_I^c N_I + \text{h.c.},$$

- Mixing angles after spontaneous symmetry breaking

$$\theta_{\alpha I} = \frac{F_{\alpha I} v}{\sqrt{2} M_I}, \qquad U_{\alpha I} = |\theta_{\alpha I}| \ll 1$$







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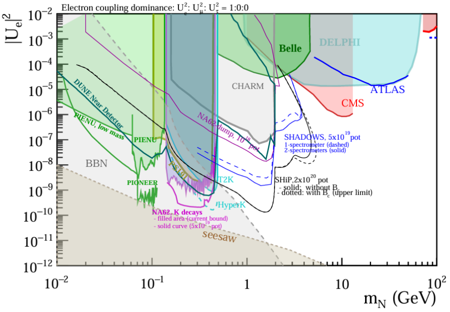
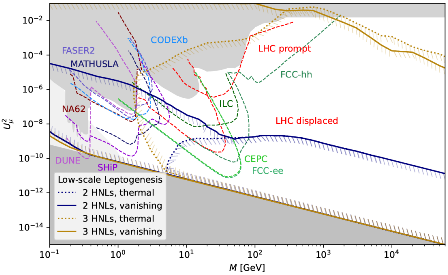
- The same two HNLs generate baryon asymmetry via leptogenesis.
  Bonus: HNLs can be as light as GeV if mass degenerate
- One HNL N_1 - keV dark matter.
  Negligible contribution to neutrino masses from stability considerations

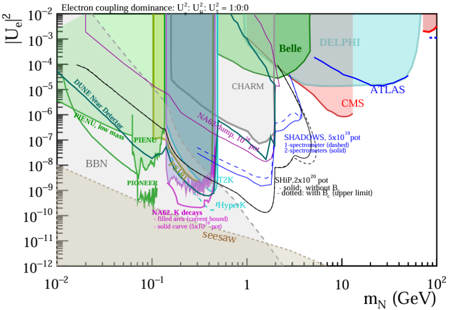
Experimental constraints

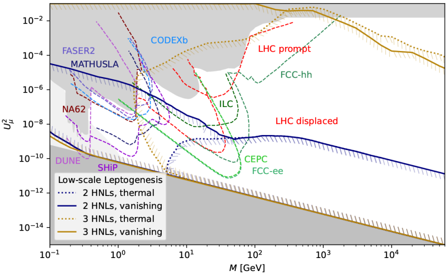




[2204.08039]

Experimental constraints





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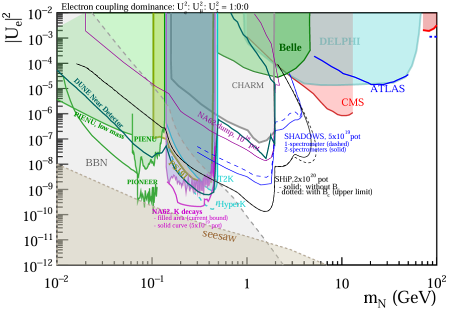
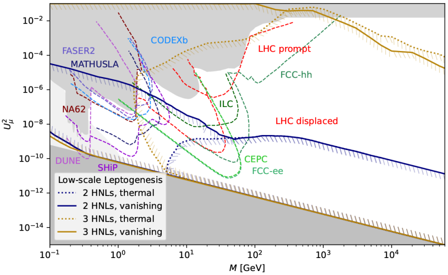
- Future experiments have the potential to observe **millions of events** $\Longrightarrow$ precision physics

Experimental constraints





[2204.08039]

- Future experiments have the potential to observe **millions of events**
  $\Longrightarrow$ precision physics
- (If we can have $U^2 \gg U^2_{\text{seesaw}}$)

Quasi-Dirac limit

- *Approximate lepton symmetry*: cancellation of seesaw contributions
- The mixing angles for two degenerate HNLs converge to the same value

$$\Delta m_N \ll m_N, \qquad U^2_{\alpha 2} = U^2_{\alpha 3}\left[1 + O\left(\frac{U^2_{\text{seesaw}}}{U^2}, \frac{\Delta m_N}{m_N}\right)\right] \equiv U^2_\alpha$$

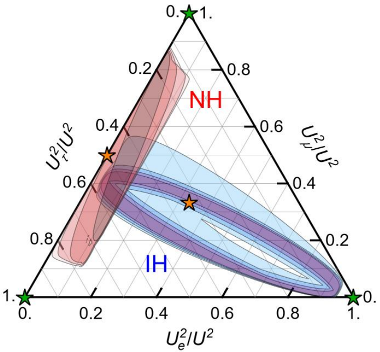
- Casas-Ibarra parametrization:

$$\theta = iU^{\text{PMNS}}(m_\nu^{\text{diag}})^{1/2} R (m_N^{\text{diag}})^{-1/2}$$

$$R_{\text{NH}} \sim \begin{pmatrix} 0 & 0 \\ 1 & \pm i \\ \mp i & 1 \end{pmatrix}, \quad R_{\text{IH}} \sim \begin{pmatrix} 0 & 0 \\ 1 & \pm i \\ \mp i & 1 \end{pmatrix}$$

— restricts flavor structure $x_\alpha \equiv U^2_\alpha / U^2$

as a function of a single Majorana phase η in the PMNS matrix



If a signal has been observed, what can we tell about the underlying physics of what has been found?

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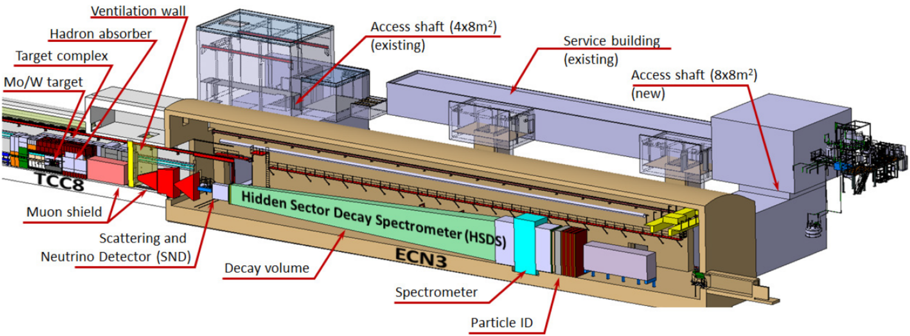
Have we solved any problem, or just added more?

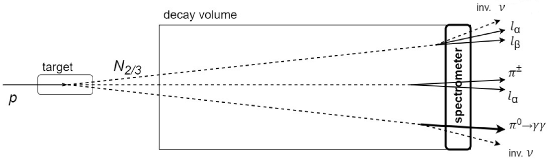
The SHiP experiment



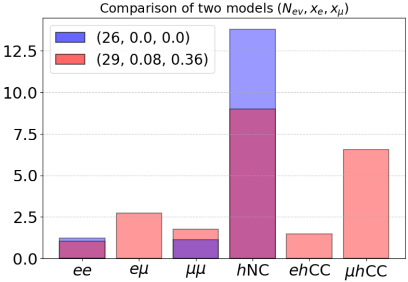
Requirement	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

Background source	Expected events
Neutrino DIS	< 0.1 (fully) / < 0.3 (partially)
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon combinatorial	1.2×10^{-2}

[2112.01487]



	Physics model	Final state
HSDS	HNL, SUSY neutralino	$\ell^\pm\pi^\mp$, $\ell^\pm K^\mp$, $\ell^\pm\rho^\mp(\rho^\mp \to \pi^\mp\pi^0)$
	DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^+\ell^-$
	DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
	HNL, SUSY neutralino, axino	$\ell^+\ell^-\nu$
	ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
	SUSY sgoldstino	$\pi^0\pi^0$
	LDM	Electron, proton, hadronic shower
SND	ν_τ, $\bar{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm, D^\pm, D^0, \overline{D^0}, \Lambda_c^+, \overline{\Lambda_c}^-$

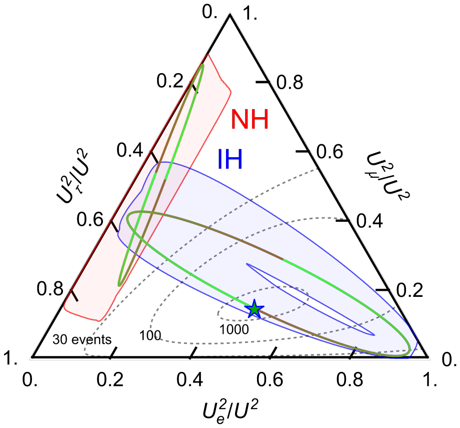


$$m_N = 1.5\,\mathrm{GeV}$$

	decay mode	mixing	$\Gamma_\alpha \times 10^{13}$, GeV
0)	$N \to 3\nu$	$U^2_{e,\mu,\tau}$	1.7
1)	$N \to \nu ee$	$(U^2_e, U^2_{\mu,\tau})$	(1.0, 0.2)
2)	$N \to \nu e\mu$	$U^2_{e,\mu}$	1.7
3)	$N \to \nu\mu\mu$	$(U^2_\mu, U^2_{e,\tau})$	(1.0, 0.2)
4)	$N \to \nu h^0$ (NC)	$U^2_{e,\mu,\tau}$	2.5
5)	$N \to eh^+$ (CC)	U^2_e	5.0
6)	$N \to \mu h^+$ (CC)	U^2_μ	5.0

$$\mathrm{Br}_i \sim x_e\Gamma_e + x_\mu\Gamma_\mu + x_\tau\Gamma_\tau$$

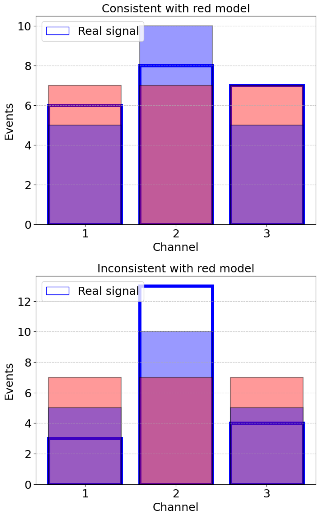
Probe two-HNL seesaw



→

Measure flavor couplings
U_α^2/U^2
↓
Test two HNLs hypothesis

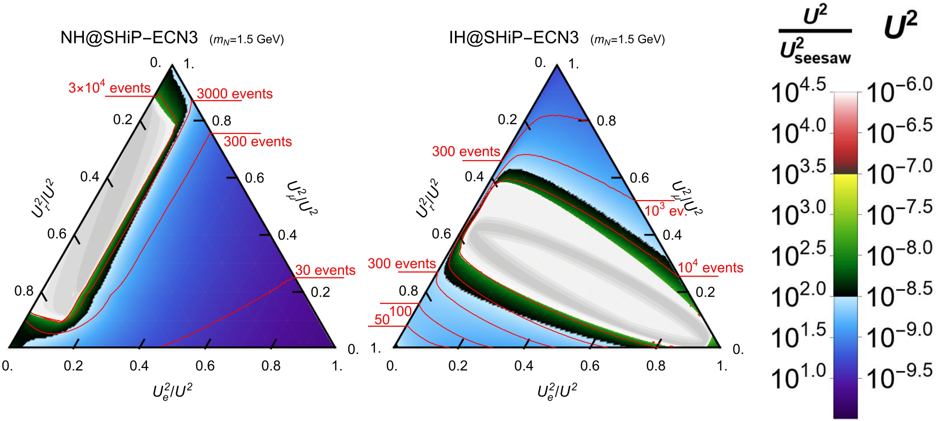
$$\underbrace{\lambda_i}_{\text{count in channel } i} = N_{ev} \cdot \overbrace{\epsilon_i}^{\text{efficiency}} \cdot \underbrace{\text{Br}_i}_{\text{th. branching}} + \overbrace{b_i}^{\text{background}}$$



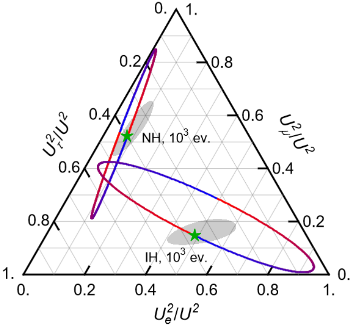
Sensitivity definition

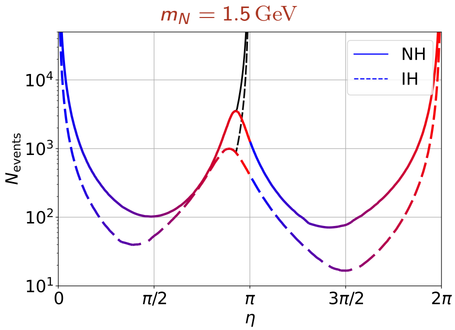
For a real model B, N_{ev} — **number of events, needed to exclude at CL all models A with probability P**

[2312.05163]
[2312.00659]


NH@SHiP−ECN3 (m_N=1.5 GeV)
IH@SHiP−ECN3 (m_N=1.5 GeV)
3×10^4 events
3000 events
300 events
30 events
300 events
10^3 ev.
10^4 events
300 events
100
50
U_e^2/U^2
U_μ^2/U^2
U_τ^2/U^2
U^2/U^2_{seesaw}
U^2
$10^{4.5}$ $10^{4.0}$ $10^{3.5}$ $10^{3.0}$ $10^{2.5}$ $10^{2.0}$ $10^{1.5}$ $10^{1.0}$
$10^{-6.0}$ $10^{-6.5}$ $10^{-7.0}$ $10^{-7.5}$ $10^{-8.0}$ $10^{-8.5}$ $10^{-9.0}$ $10^{-9.5}$

Measuring PMNS Majorana phase





With such a tool, what can we say about **nonminimal interactions** of HNLs?

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For example:

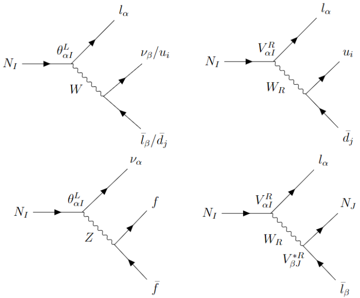
- Dipole portal [1803.03262]
- Axion-HNL coupling [1911.12394] [2212.11290]
- ...?

Add right-handed interactions: Left-Right Symmetric Model

$$
\begin{aligned}
SU_C(3) \times SU_L(2) \times SU_R(2) \times U_{B-L}(1) \to& \\
&\to SU_C(3) \times SU_L(2) \times U_Y(1) \\
&\to SU_C(3) \times U_{EM}(1)
\end{aligned}
$$

- Effective (below EW) left

$$
\begin{aligned}
\mathcal{L} \supset \quad & \theta^L_{\alpha I} \frac{G_F}{\sqrt{2}} \bar{l}_\alpha N^c_I \times [\bar{\nu}_\beta l_\beta + V^{\text{CKM}}_{ij} \bar{u}_{i,L} d_{j,L}] \\
& + \theta^L_{\alpha I} \frac{G_F}{\sqrt{2}} \bar{\nu}_\alpha N^c_I J_Z
\end{aligned}
$$



Add right-handed interactions: Left-Right Symmetric Model

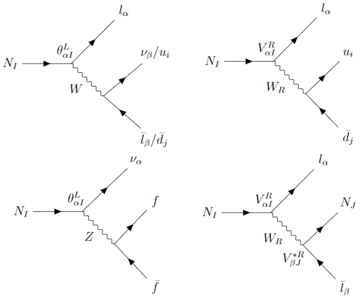
$$SU_C(3) \times SU_L(2) \times SU_R(2) \times U_{B-L}(1) \to$$
$$\to SU_C(3) \times SU_L(2) \times U_Y(1)$$
$$\to SU_C(3) \times U_{EM}(1)$$

- Effective (below EW) left

$$\mathcal{L} \supset \quad \theta^L_{\alpha I} \frac{G_F}{\sqrt{2}} \bar{l}_\alpha N_I^c \times [\bar{\nu}_\beta l_\beta + V^{\text{CKM}}_{ij} \bar{u}_{i,L} d_{j,L}] + \theta^L_{\alpha I} \frac{G_F}{\sqrt{2}} \bar{\nu}_\alpha N_I^c J_Z$$

- ...and right-handed interactions

$$+\theta^R_{\alpha I} \frac{G_F}{\sqrt{2}} \bar{l}_\alpha N_I \times \left[\tilde{V}^R_{J\beta} \bar{N}_J l_\beta + V^{R,\text{CKM}}_{ij} u_{i,R} d_{i,R} \right]$$



Two sets of couplings $|\theta| \ll 1$

$$\text{(LH):} \quad \theta^L_{\alpha I}, \qquad \text{(RH):} \quad \theta^R_{\alpha I} \sim \frac{m_W^2}{m_{W_R}^2}$$

Two sets of couplings $|\theta| \ll 1$

$$\text{(LH):} \quad \theta^L_{\alpha I}, \qquad \text{(RH):} \quad \theta^R_{\alpha I} \sim \frac{m_W^2}{m_{W_R}^2}$$

to be constrained by the seesaw relation:

$$m_\nu = -\underbrace{\theta^L M \theta^L}_{\text{type-I seesaw}} + \underbrace{\frac{v_L}{v_R} M}_{\text{type-II seesaw}}$$

— complicated 3×3 matrix equation.

has closed analytic solution for θ_L, if θ_R, m_N fixed [2403.07756]

$$\mathcal{L} \supset \bar{L}_\alpha([Y_e]_{\alpha\beta}\Phi - [Y_\nu]_{\alpha\beta}\sigma_2\Phi^*\sigma_2)R_\beta + \\ + \bar{L}^c_\alpha[Y_1]_{\alpha\beta} i\sigma_2\Delta_L L_\beta + \bar{R}^c_\alpha[Y_2]_{\alpha\beta} i\sigma_2\Delta_R R_\beta + \text{h.c.}$$

$$\Phi \to v\,\text{diag}(\cos b, -\sin b\, e^{-ia}) \qquad \Delta_{L,R} \to \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$$

Generalized parity: $Y_e^\dagger = Y_e, \quad Y_\nu^\dagger = Y_\nu, \quad Y_1 = Y_2$

After spontaneous symmetry breaking and diagonalization of l, N masses:

$$U^*_{\text{PMNS}} m_\nu^{\text{diag}} U^\dagger_{\text{PMNS}} = \\ -(vV_R Y - m_l^{\text{diag}} b e^{ia} V_R)[m_N^{\text{diag}}]^{-1}(vY^T V_R^T - V_R^T m_l^{\text{diag}} b e^{ia}) \\ + \frac{v_L}{v_R} V_R^* m_N^{\text{diag}} V_R^\dagger$$

with $Y = V_R^\dagger Y_\nu V_R$, $Y^\dagger = Y$, $V_R^\dagger = V_R$

$$U^*_{\text{PMNS}} m_\nu^{\text{diag}} U^\dagger_{\text{PMNS}} = - (v V_R Y - m_l^{\text{diag}} b e^{ia} V_R)[m_N^{\text{diag}}]^{-1}(v Y^T V_R^T - V_R^T m_l^{\text{diag}} b e^{ia}) + \frac{v_L}{v_R} V_R^* m_N^{\text{diag}} V_R^\dagger$$

$$\boxed{\theta^R_{\alpha I} = \frac{m^2_{W_L}}{m^2_{W_R}} [V_R]_{\alpha I}, \qquad \theta^L_{\alpha I} = \frac{i}{m_{N_I}} \left[v V_R Y - b e^{ia} m_l^{\text{diag}} V_R \right]_{\alpha I}}$$

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- Assume 2 quasi-Dirac pair N_2, N_3 ($|\theta_{L,2/3}|^2 \gg U^2_{\text{seesaw}}$) and a decoupled DM candidate ($|\theta_{L,1}|^2 \ll U^2_{\text{seesaw}}$)

$$m_N^{\text{diag}} = m_N \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad Y = y \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -i \\ 0 & i & 1 \end{pmatrix}, \quad y \gg 1$$

- and perturb this exact lepton symmetry

Type-I only: analytic solution

Neutrino masses: 0, m_2, m_3

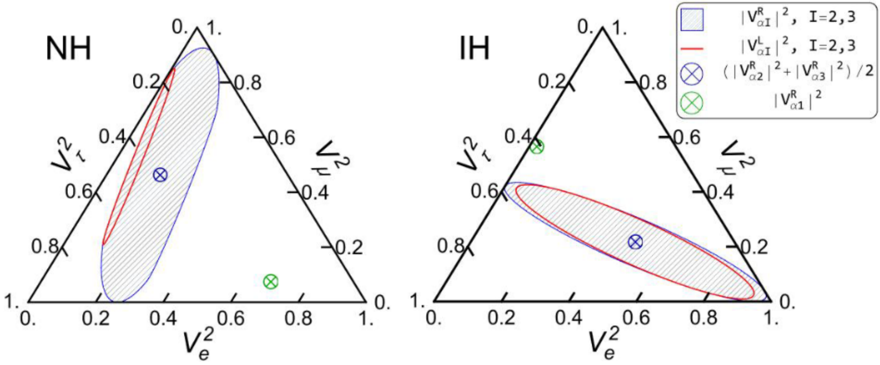
$$V^R = iU^*_{\text{PMNS}}O$$

$$V^L_{\alpha 2} = -iV^L_{\alpha 3} = \frac{e^{i\beta}}{\sqrt{m_2+m_3}}\tilde{U}^*_{\text{PMNS}}P \times \begin{pmatrix} 0 \\ \mp e^{-i\eta}\sqrt{m_2} \\ \sqrt{m_3} \end{pmatrix}, \quad \frac{|\theta^L_\alpha|^2}{\sum_\alpha |\theta^L_\alpha|^2} = |V^L_\alpha|^2$$

with

$$O = \frac{1}{\sqrt{2(m_2+m_3)}}\times$$
$$\times \begin{pmatrix} \sqrt{2(m_2+m_3)} & 0 & 0 \\ 0 & -i(\sqrt{m_3}e^{-i\beta} \pm \sqrt{m_2}e^{i\beta}) & \sqrt{m_3}e^{-i\beta} \mp \sqrt{m_2}e^{i\beta} \\ 0 & -(\sqrt{m_3}e^{i\beta} \mp \sqrt{m_2}e^{-i\beta}) & i(\sqrt{m_3}e^{i\beta} \pm \sqrt{m_2}e^{-i\beta}) \end{pmatrix}$$

— two free parameters: Majorana phase η and angle β



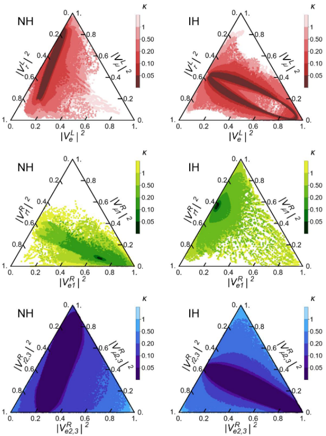
[2406.13850]

- V^L_α remain **the same** as in the minimal case — only depend on η
- $V^R_{\alpha 2}$, $V^R_{\alpha 3}$ depend on both η, β
- $|V^R_{\alpha 1}|^2$, $|V^R_{\alpha 1}|^2 + |V^L_{\alpha 1}|^2$ are fixed
- HNL mass splitting $|m_{N_2} - m_{N_3}|$ is arbitrary

Corrections

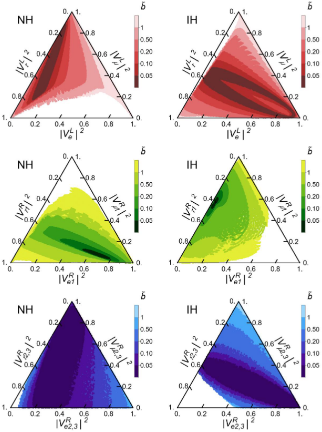
Type-II corrections

$$\kappa = \frac{v_L m_N}{v_R(m_2 + m_3)}$$



CP corrections

$$\tilde{b} = b\frac{\sqrt{2}yvm_\tau}{m_2 + m_3}$$



lightest neutrino mass becomes nonzero

Interesting signatures?

(De)coherence

- Decoherent pair:

$$\text{number of ev. } (X \to l_\alpha N \to l_\alpha l_\beta) \propto |V_{\alpha 2}|^2 |V_{\beta 3}|^2 + |V_{\alpha 3}|^2 |V_{\beta 2}|^2$$

- Coherent pair:

$$\text{number of ev. } (X \to l_\alpha N \to l_\alpha l_\beta^\pm) \propto |V_{\alpha 2} V_{\beta 3}^{(*)} + V_{\alpha 3} V_{\beta 2}^{(*)}|^2$$

Summing up over one lepton flavor (α) — everything reduces to $\propto |V_{\beta 2}|^2 + |V_{\beta 3}|^2$

Probing decoherence at SHiP

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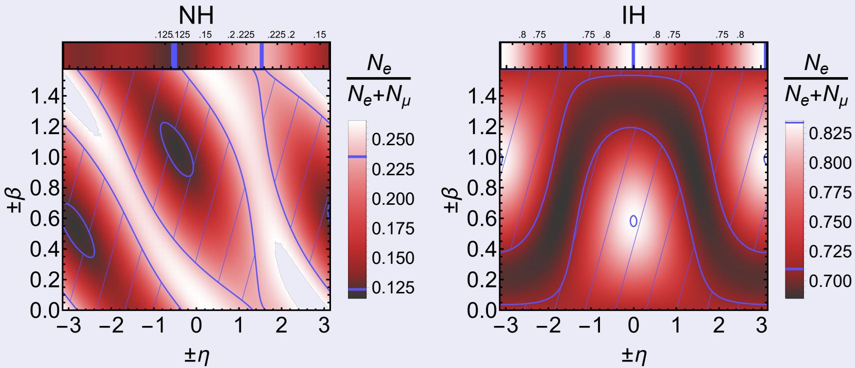
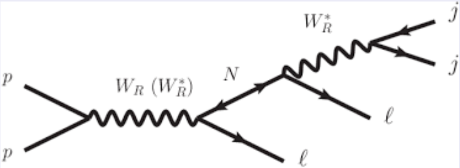
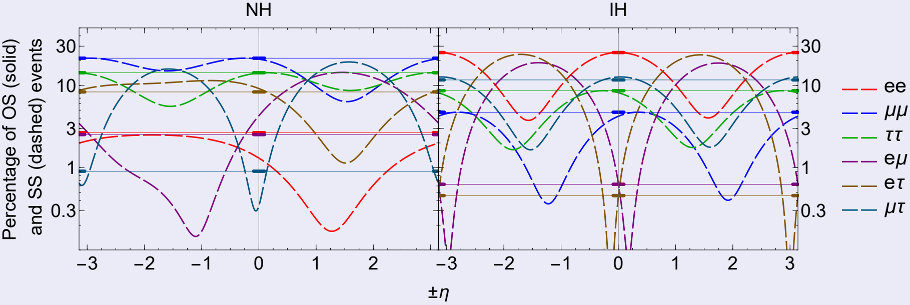


Coherent (blue) vs decoherent (red) case predictions

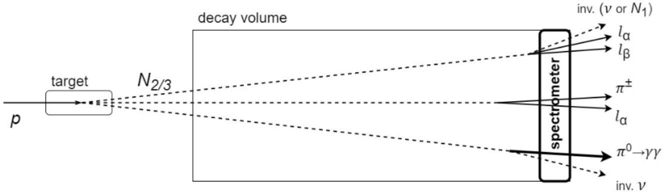
Probing decoherence with Keung-Senjanović process

- Full reconstruction of event matrix $X \to l_\alpha^- N \to l_\alpha^- l_\beta^\pm$
- In the coherent case, LNV can dominate LNC decays

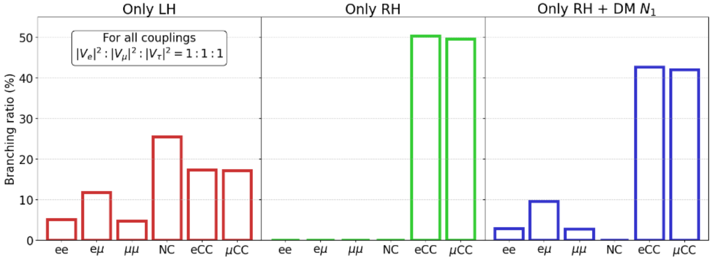




DM at SHiP



No $N_{2,3} \to N_1$ decay in the minimal LH case



DM at SHiP

- Benchmark model:

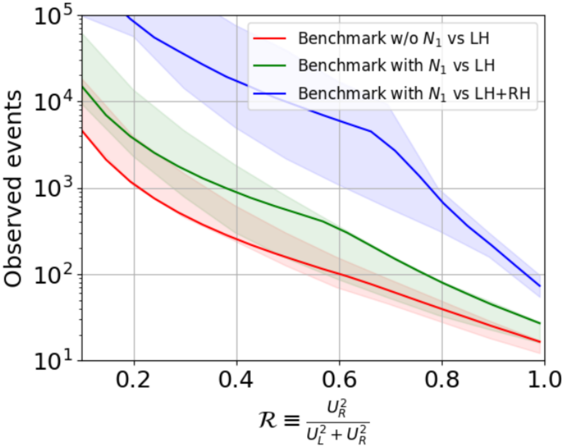
$$|V_e^L|^2 : |V_\mu^L|^2 : |V_\tau^L|^2 = 0.11 : 0.22 : 0.67$$
$$|V_{e2}^R|^2 : |V_{\mu 2}^R|^2 : |V_{\tau 2}^R|^2 = 0.16 : 0.46 : 0.38$$
$$|V_{e3}^R|^2 : |V_{\mu 3}^R|^2 : |V_{\tau 3}^R|^2 = 0.16 : 0.46 : 0.38$$
$$|V_{e1}^R|^2 : |V_{\mu 3}^R|^2 : |V_{\tau 3}^R|^2 = 0.49 : 0.22 : 0.30$$

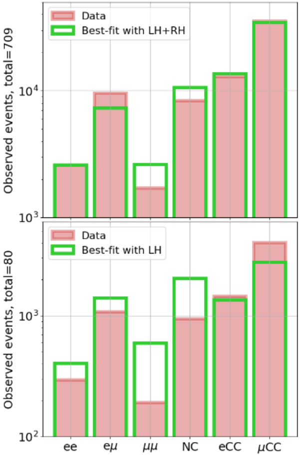
Fraction of RH interactions:

$$\mathcal{R} \equiv \frac{U_R^2}{U_L^2 + U_R^2}$$

For a given $\mathcal{R} < 1$, we want to distinguish

1. no light N_1 **versus** LH-only HNL with *arbitrary* V^L
2. with light N_1 **versus** LH-only HNL with *arbitrary* V^L,
3. with light N_1 **versus** HNL with both LH, RH-interactions, *arbitrary* couplings V^L, V^R, $\mathcal{R}$, but no N_1.


Benchmark w/o N_1 vs LH
Benchmark with N_1 vs LH
Benchmark with N_1 vs LH+RH
Observed events
$\mathcal{R} \equiv \frac{U_R^2}{U_L^2 + U_R^2}$

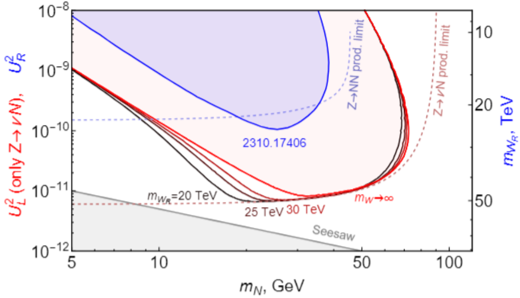

Data
Best-fit with LH+RH
Observed events, total=709
Data
Best-fit with LH
Observed events, total=80
ee
eμ
μμ
NC
eCC
μCC

Summary

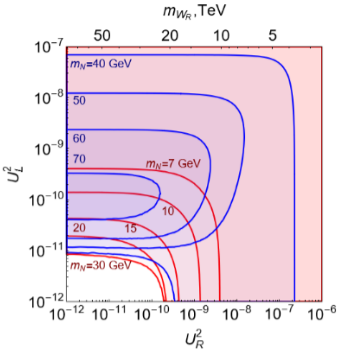
- Precision physics at Intensity Frontier is possible
- We need to know what results to expect and how to interpret them

Back-up

FCC-ee



U_R^2
U_L^2 (only $Z\to\nu N$),
m_{W_R}, TeV
m_N, GeV
2310.17406
$Z\to NN$ prod. limit
$Z\to\nu N$ prod. limit
m_{W_R}=20 TeV
25 TeV
30 TeV
$m_W\to\infty$
Seesaw



m_{W_R},TeV
U_L^2
U_R^2
m_N=40 GeV
50
60
70
m_N=7 GeV
10
15
20
m_N=30 GeV