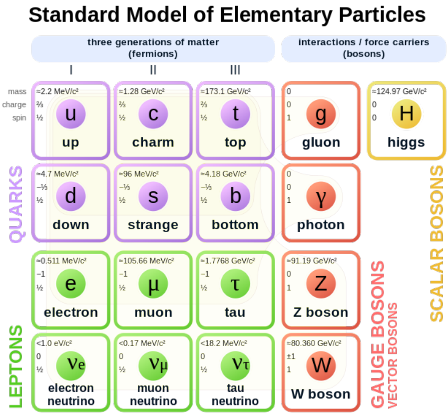
Precision searches for Heavy Neutral Leptons

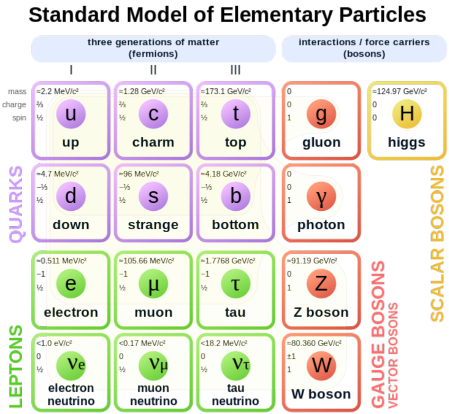
Nikhef Theory Seminar
05.12.2024

Alex Mikulenko
Leiden University

Beyond the Standard Model



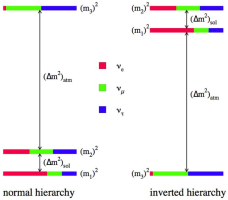
Beyond the Standard Model



Still missing:

Dark matter

Baryon asymmetry

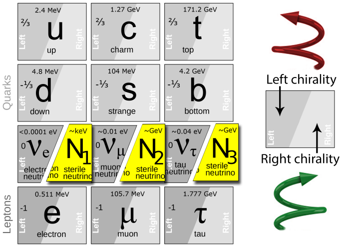


Neutrino masses

Heavy Neutral Leptons (HNL)

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

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



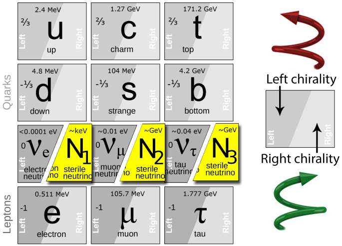
Heavy Neutral Leptons (HNL)

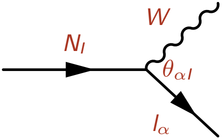
- Minimal case – right-handed neutrinos with Majorana mass:

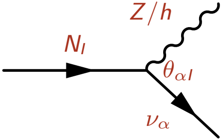
$$\mathcal{L}_N \supset -F_{\alpha I}\bar{L}_\alpha \tilde{H} N_I + \frac{M_I}{2}\bar{N}_I^c N_I + \text{h.c.},$$

- Mixing angles after spontaneous symmetry breaking

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



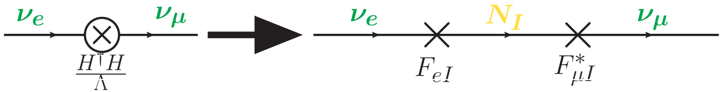




Neutrino masses

- Neutrino oscillation can be described by an effective dimension-5 operator (Weinberg operator):

$$\mathcal{L} \supset \frac{(\bar{L}\tilde{H})(\tilde{H}L)}{\Lambda}$$



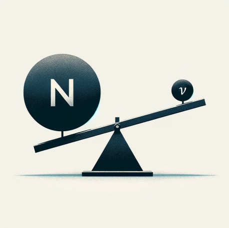
- Naturally small m_ν thanks to the *seesaw* mechanism:

$$\text{mass matrix} = \begin{pmatrix} 0 & m_{\text{Dirac}} \\ m_{\text{Dirac}}^T & M_I \end{pmatrix}$$

$$\downarrow$$

$$\text{light state mass } m_\nu = m_{\text{Dirac}} M^{-1} m_{\text{Dirac}}^T$$

— the heavier M_I, the smaller m_ν.



- **Two neutrinos** are confirmed to be massive — at least **two HNLs** needed
- Neutrino oscillation parameters are determined by HNL properties

$$m_{\alpha\beta} = \sum_I \theta_{\alpha I} M_I \theta_{\beta I}$$

- Couplings at least at the seesaw bound

$$\boxed{U_I^2 \gtrsim U_{\text{seesaw}}^2 \equiv \frac{\sqrt{\Delta m_{\text{atm}}^2}}{M_I} \sim 5 \cdot 10^{-11} \frac{1\,\text{GeV}}{M_I}}$$

Baryon asymmetry

HNLs satisfy Sakharov conditions

1. B-**violation:** L is violated by Majorana mass. Generated L is converted into B by $B-L$ conserving processes during electroweak transition
2. C, CP-**violation:** HNL Yukawa sector provides a new source for CP-violation
3. **Departure from equilibrium:** feebly-interacting HNL decouple easily from the plasma

Baryon asymmetry

HNLs satisfy Sakharov conditions

1. *B*-**violation:** *L* is violated by Majorana mass. Generated *L* is converted into *B* by $B - L$ conserving processes during electroweak transition
2. *C*, *CP*-**violation:** HNL Yukawa sector provides a new source for *CP*-violation
3. **Departure from equilibrium:** feebly-interacting HNL decouple easily from the plasma

- Naively, *CP*-violation is too small: typical mass scale for successful baryogenesis $M_1 \gtrsim 10^9\ \mathrm{GeV}$ [0802.2962]

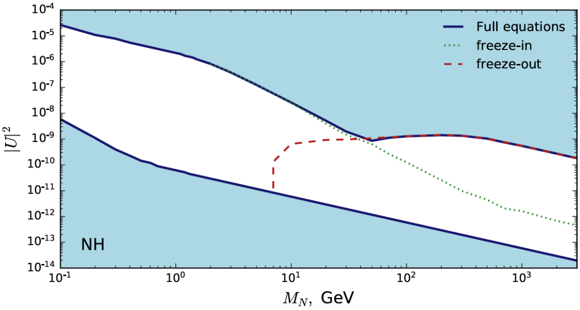
  — *beyond experimental detection*

Resonant leptogenesis

- *CP*-violation and asymmetry generation enhanced if HNLs are *degenerate*

$$\Delta M_N \sim \Gamma_N \quad \Longrightarrow \quad \epsilon_{CP} = \frac{\Gamma_{N\to X} - \Gamma_{N\to \bar{X}}}{\Gamma_{N\to X} + \Gamma_{N\to \bar{X}}} \sim O(1)$$

- Baryogenesis becomes possible at as low as the GeV scale

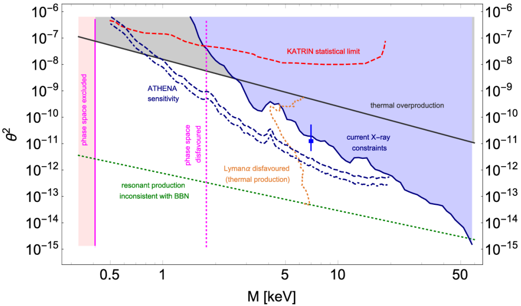


[2008.13771]

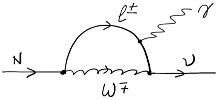
- **Two degenerate** HNLs with a **GeV** mass are *sufficient* to explain baryon asymmetry and ν masses
- Two degenerate HNLs can "naturally" have large couplings $U^2 \gg U^2_{\text{seesaw}}$ by forming a quasi-Dirac pair

Dark matter

- A light HNL is extremely long-lived: $\tau \sim G_F^{-2} m_N^{-5}$ — dark matter candidate
- Viable mass range is around keV



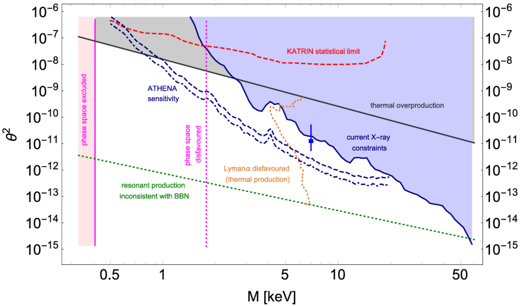
X-ray emission



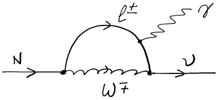
[1807.07938]

Dark matter

- A light HNL is extremely long-lived: $\tau \sim G_F^{-2} m_N^{-5}$ — dark matter candidate
- Viable mass range is around keV



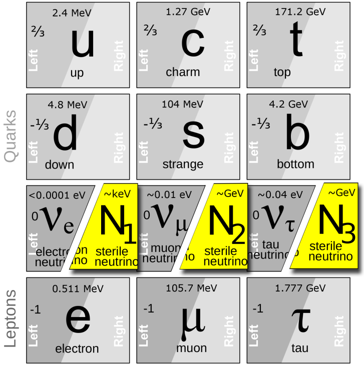
X-ray emission

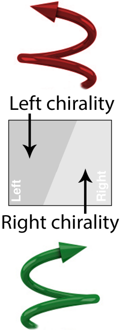


[1807.07938]

The DM candidate N_1 is much lighter than the degenerate pair N_2, N_3 and has negligible contribution to ν mass

νMSM

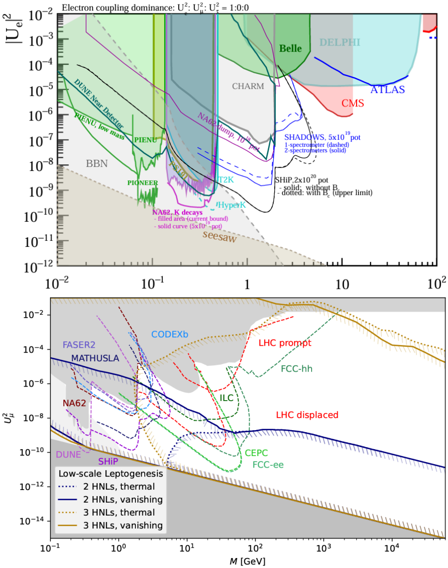




Neutrino minimal Standard Model

- (relatively) little ambiguity
- detectable and testable

Experimental constraints

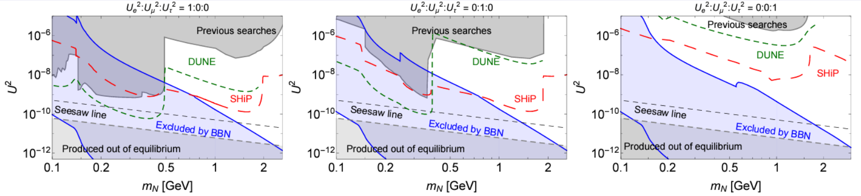


[2204.08039]

Lower bound

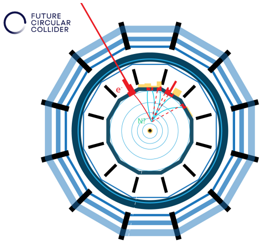
HNL mixing angles are bound from below — limit of 'how deep to search'

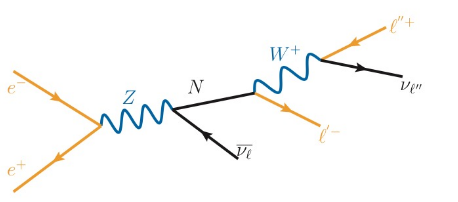
1. Above a few GeV – the seesaw bound
2. Below a few GeV – primordial nucleosynthesis constraints on HNL lifetime $\tau \lesssim 0.02\,\mathrm{s}$. Pions from $N \to l\pi$ decays catalyze $p \leftrightarrow n$ conversion and spoil the BBN predictions



[2008.00749]

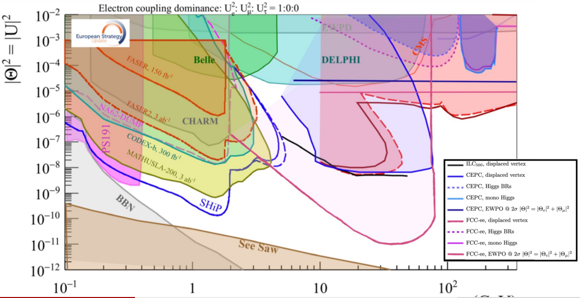
$5 - 90\,\mathrm{GeV}$ mass range: FCC-ee





$e^- e^+$ collider at the Z-resonance

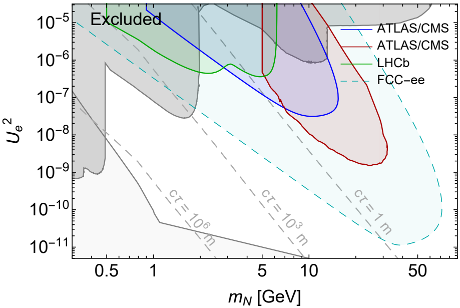
$5 \cdot 10^{12}$ Z-bosons

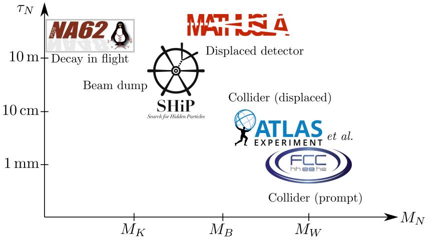


[2203.05502]

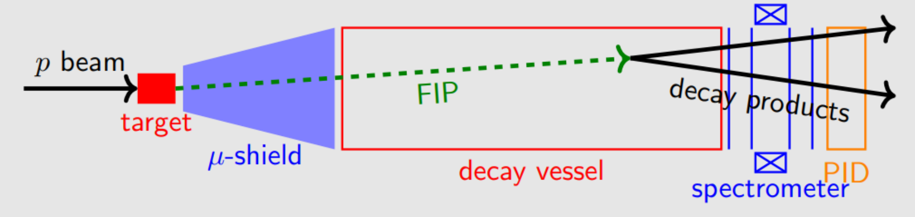
Below 5 GeV: a dedicated experiment

- Lifetime $\sim 1/m_N^5$ — light HNLs have macroscopic decay length and escape the detectors
- LHC/FCC are not suitable for probing new physics at GeV scale
- Need for a dedicated experiment

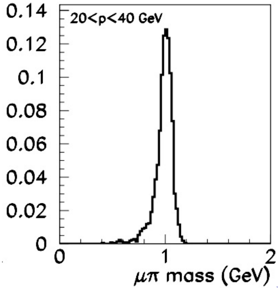




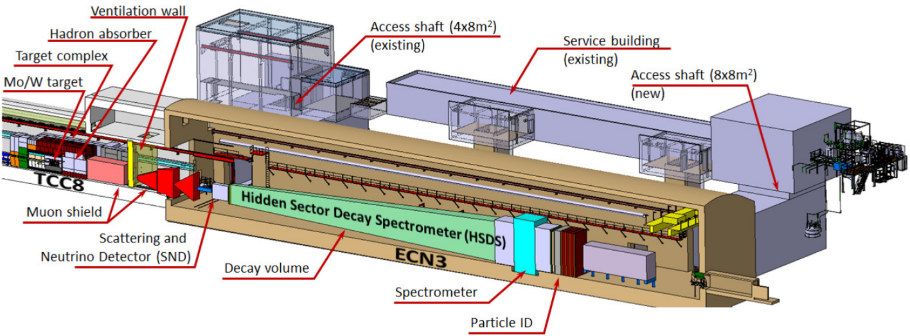
Beam-dump facility



1. BDF experiments may search for all new particles regardless of their nature
2. Clean environment: easy to measure the properties of new particles - mass, spin, their being portal particles or particles from more complicated models
3. → potentially we can not only find new particles, but also **probe their connection to BSM problems**!



The SHiP experiment

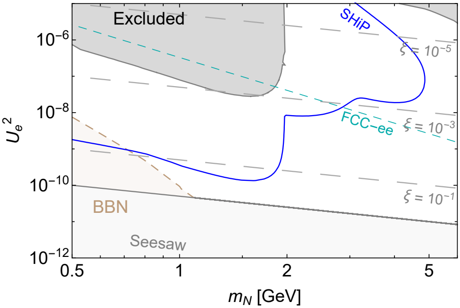


Requirement	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially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

SHiP sensitivity



- SHiP benefits from high intensity ($6 \cdot 10^{20}$ PoT) and large geometric coverage ($5 \times 10 \times 50\,\mathrm{m}^3$)
- For small couplings, the number of events scales as $N_{ev} \propto U^4$

- *SHiP might observe up to millions of events*

Above 100 GeV: muon collider

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

International
MUON Collider
Collaboration

D. Schulte   Muon Collider, March 23, 2021   14

Consistent analysis

- HNL couplings should follow from the seesaw relation $m_\nu = \theta M_N \theta^T$

Consistent analysis

- HNL couplings should follow from the seesaw relation $m_\nu = \theta M_N \theta^T$
- Casas-Ibarra parametrization:

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

with complex orthogonal matrix R : $R^T R = 1$

- For two HNLs:

$$R = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \\ 0 & 0 \end{pmatrix} \text{(NH)}, \qquad R = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix} \text{(IH)}$$

— R depends on single complex angle ω

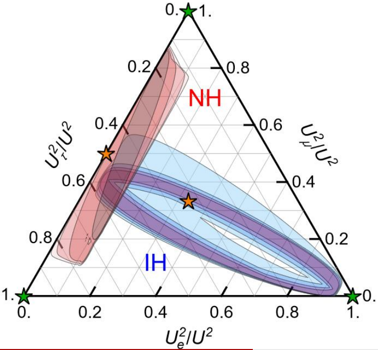
Quasi-Dirac limit

- Approximate symmetry limit: $\Delta m_N \ll m_N$, $e^{|\mathrm{Im}\ \omega|} \gg 1$.
- Two HNLs become identical

$$U^2_{\alpha 2} = U^2_{\alpha 3} \equiv U^2_\alpha, \qquad U^2 \equiv \sum U^2_\alpha \gg U^2_{\text{seesaw}}$$

up to $O(U^2_{\text{seesaw}})$, $O(\Delta m_N U^2/m_N)$ corrections

- **Parameter space highly reduced**



The flavor structure

$$x_\alpha \equiv U^2_\alpha / U^2$$

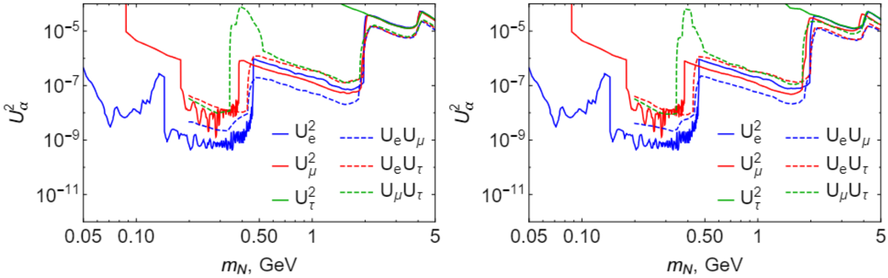
depends only on a single PMNS Majorana phase and measurable oscillation parameters

Consistent analysis

Combine all ingredients together

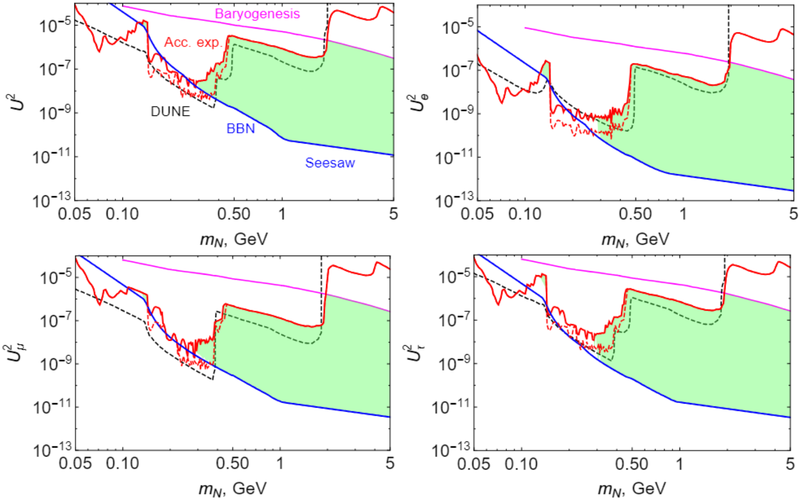
1. x_α consistent with neutrino oscillation data
2. Experimental limits
3. BBN limits
4. Leptogenesis

Experimental constraints: simple rescale



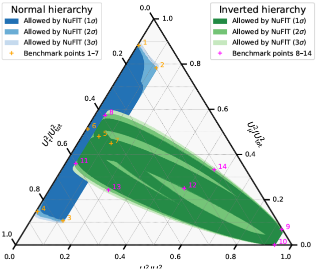
$$U^2_{\text{upper}}(x_\alpha) = \min\left(\frac{U^2_{e,\text{acc}}}{x_e}, \frac{(U_eU_\mu)_{\text{acc}}}{\sqrt{x_e x_\mu}}, \frac{U^2_{\mu,\text{acc}}}{x_\mu}, \dots\right)$$

Full constraints

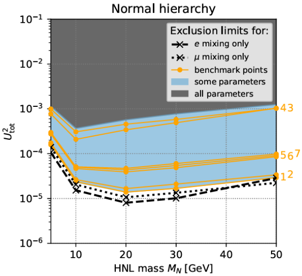


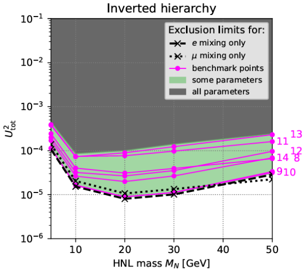
[2101.09255]

ATLAS reinterpretation



[2107.12980]





Proper interpretation of experimental sensitivity is needed for realistic models

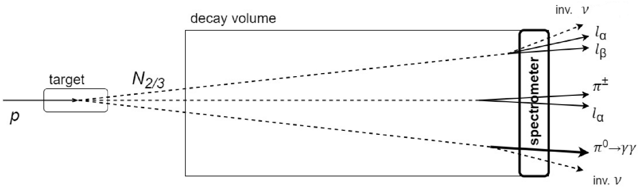
Extend the concept of sensitivity:

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

Have we solved any problem, or just added more?

[2312.05163]
[2312.00659]

Back to SHiP



	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	$\pi^0\pi^0$
SND	LDM	Electron, proton, hadronic shower
	ν_τ, $\overline{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production (ν_e, ν_μ, ν_τ)	$D_s^\pm$, $D^\pm$, D^0, $\overline{D^0}$, Λ_c^+, $\overline{\Lambda_c}^-$

SHiP

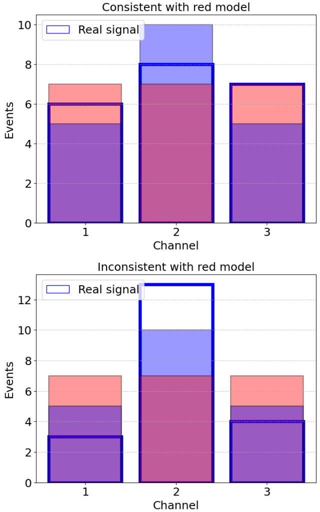
1. is approved
2. reconstructs many states with high precision and zero background
3. has the potential to observe a multitude of events

New physics probe: through decay modes

$$\underset{\text{count in channel } i}{\lambda_i} = N_{ev} \cdot \overset{\text{efficiency}}{\epsilon_i} \cdot \underset{\text{th. branching}}{\mathrm{Br}_i} + \overset{\text{background}}{b_i}$$

$$\mathrm{Br}_i = \mathrm{Br}_i(x_\alpha)$$

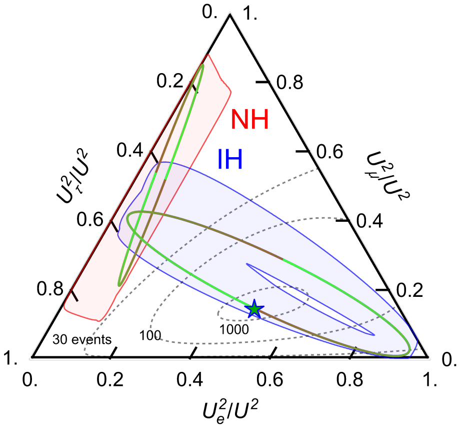
does not depend on the total U^2



Sensitivity definition

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

Probe two-HNL seesaw

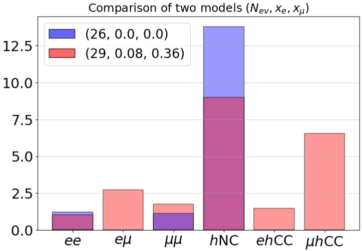


→

Measure flavor structure
↓
Test two HNLs hypothesis

Relevant decays

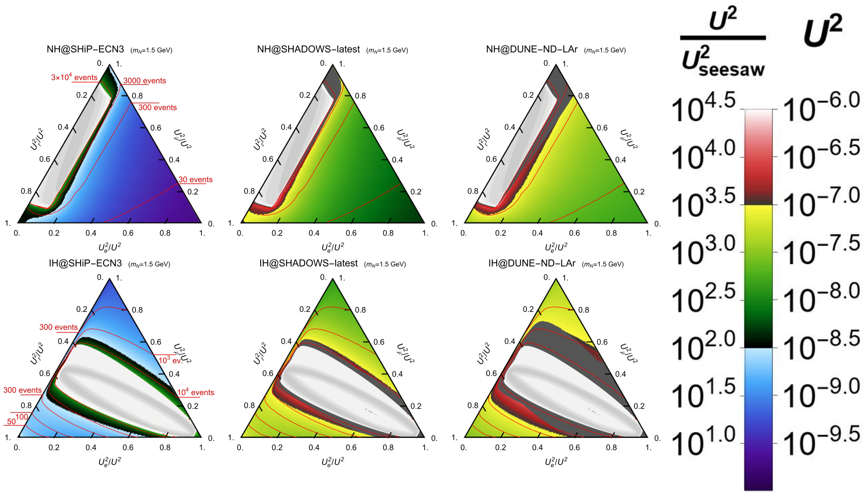
- Benchmark setup: $m_N = 1.5\,\mathrm{GeV}$
- Decays: $N \to \nu ee$, $\nu e\mu$, $\nu\mu\mu$, νqq, eqq, μqq

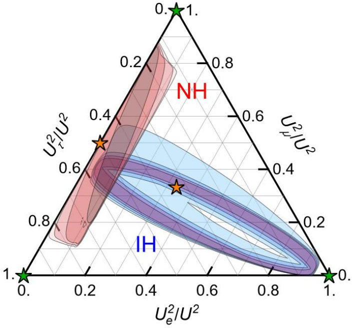


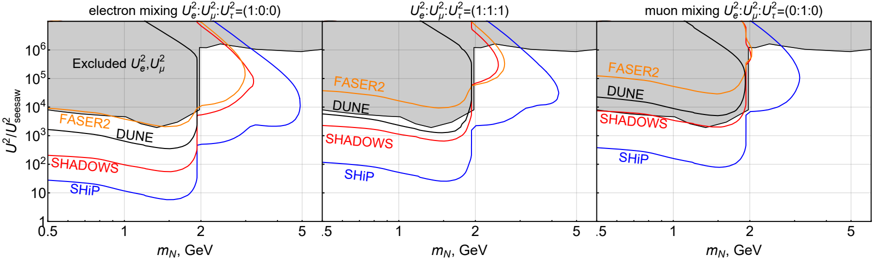
	decay mode	mixing	$\Gamma_\alpha \times 10^{13}$, GeV
0)	$N \to 3\nu$	$U^2_{e,\mu,\tau}$	1.7
1)	$N \to \nu ee$	$(U^2_e, U^2_{\mu,\tau})$	(1.0, 0.2)
2)	$N \to \nu e\mu$	$U^2_{e,\mu}$	1.7
3)	$N \to \nu\mu\mu$	$(U^2_\mu, U^2_{e,\tau})$	(1.0, 0.2)
4)	$N \to \nu h^0$ (NC)	$U^2_{e,\mu,\tau}$	2.5
5)	$N \to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

1. e/μ-coupling — probed directly by ee+eh/$\mu\mu$+μh
2. τ-coupling — is probed *indirectly* via total normalization ($e\mu$+h NC)

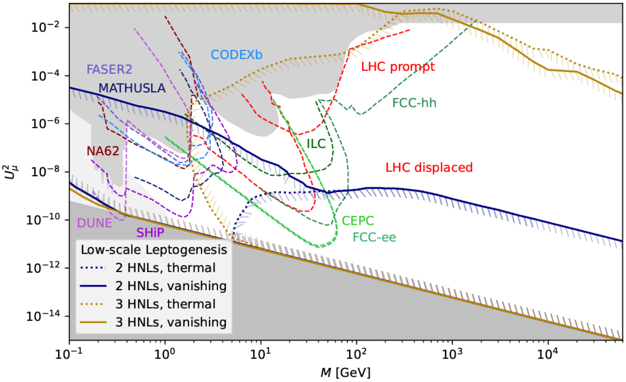
New sensitivity




NH
IH
U_e^2/U^2
U_μ^2/U^2
U_τ^2/U^2
0.
0.2
0.4
0.6
0.8
1.


electron mixing $U_e^2:U_\mu^2:U_\tau^2$=(1:0:0)
$U_e^2:U_\mu^2:U_\tau^2$=(1:1:1)
muon mixing $U_e^2:U_\mu^2:U_\tau^2$=(0:1:0)
Excluded U_e^2,U_μ^2
FASER2
DUNE
SHADOWS
SHiP
U^2/U^2_{seesaw}
m_N, GeV

HNLs at MuC: motivation



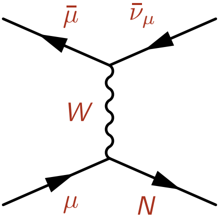
- Barely any experiment probes the region of very heavy $m_N \gtrsim 100\,\mathrm{GeV}$
- For three HNLs, successful baryogenesis is possible with large U^2

MuC — intensity & energy frontier

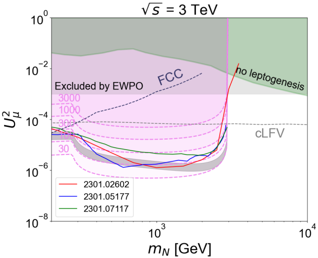
- Probing new physics with muons at scale s:

$$\sigma \sim \frac{g^4}{16\pi s} = 10^2\,\text{fb} \times g^4 \frac{(10\,\text{TeV})^2}{s}, \qquad \mathcal{L}\sigma \sim 10^6 \cdot g^4$$

- HNLs are **not penalized** by high mass:

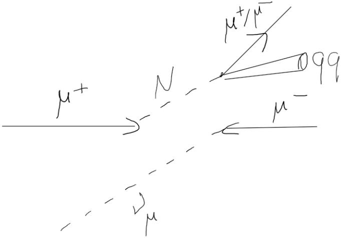


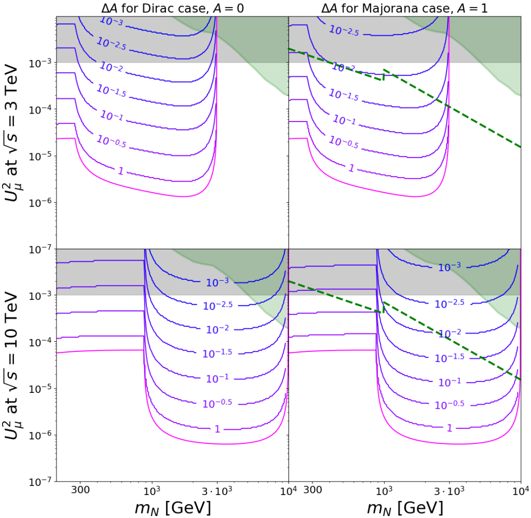
$$\sigma_{\text{weak}} = \underbrace{\frac{g^4}{16\pi m_W^2}}_{\approx 200\,\text{fb}} \approx \frac{10^3 - 10^4}{s}$$



LNV at muon collider I

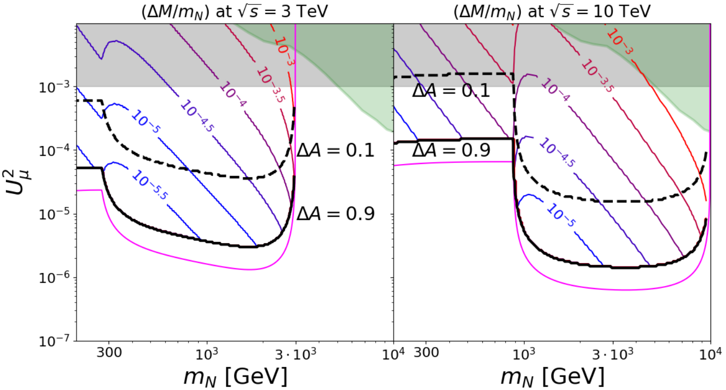
- Muon collider ($\sqrt{s} = 10\,\mathrm{TeV}$) — probe HNLs above the electroweak scale
- Leptogenesis is possible with 3 HNL species
- Simple measurement of $A = 2\mathrm{LNV}/(\mathrm{LNV} + \mathrm{LNC})$ — look at **forward-backward** asymmetry





LNV at muon collider II

- For three HNLs: two mass splitting
- No simple formula for mass splittings; order-of-magnitude $A \sim \Delta M^2/\Gamma^2$ for $A \ll 1$

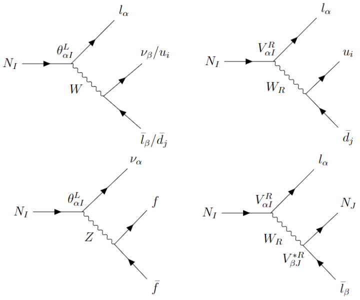


HNLs in Left-Right Symmetric Model [2406.13850]

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

- Effective (below EW) left

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

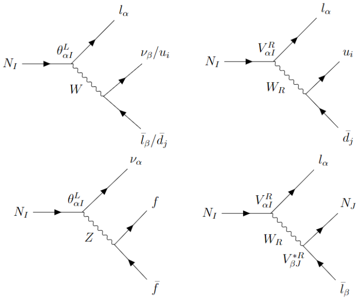


HNLs in Left-Right Symmetric Model [2406.13850]

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

- Effective (below EW) left

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



- ...and right-handed interactions

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

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

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

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

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

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

- 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

Simplest type-I seesaw

- Neutrino masses: 0, m_2, m_3

Simplest type-I seesaw

- Neutrino masses: 0, m_2, m_3

$$V^R = i\tilde{U}^*_{\rm PMNS} O, \qquad U^R_I = \frac{m^2_{W_L}}{m^2_{W_R}}$$

$$V^L_{\alpha 2} = -iV^L_{\alpha 3} = \frac{e^{i\beta}}{\sqrt{m_2+m_3}} \tilde{U}^*_{\rm PMNS} P \times \begin{pmatrix} 0 \\ \mp e^{-i\eta}\sqrt{m_2} \\ \sqrt{m_3} \end{pmatrix}, \qquad U^L_{2,3} = \frac{\sqrt{2}yv}{m_N}$$

$\tilde{U}_{\rm PMNS}$ — mass-ordered PMNS matrix

Simplest type-I seesaw

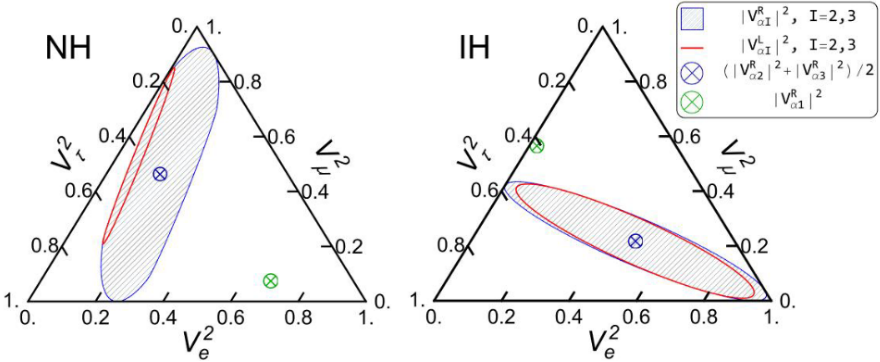
- Neutrino masses: $0,\ m_2,\ m_3$

$$V^R = i\tilde{U}^*_{\text{PMNS}} O, \qquad U_I^R = \frac{m^2_{W_L}}{m^2_{W_R}}$$

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

$\tilde{U}_{\text{PMNS}}$ — mass-ordered PMNS matrix

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

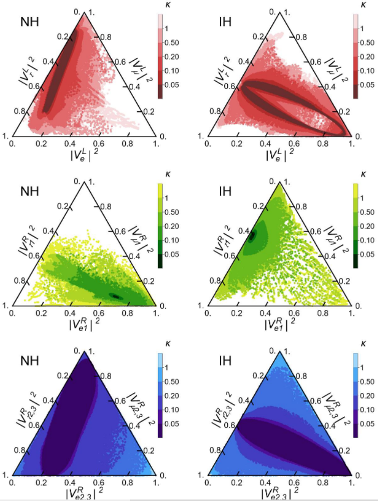

NH
IH
0.
1.
0.2
0.4
0.6
0.8
1.
0.
0.8
0.6
0.4
0.2
0.
0.2
0.4
0.6
0.8
1.
V_τ^2
V_μ^2
V_e^2
|V^R_αI|^2, I=2,3
|V^L_αI|^2, I=2,3
(|V^R_α2|^2+|V^R_α3|^2)/2
|V^R_α1|^2

Type-II corrections

$$U^*_{\rm PMNS} m_\nu^{\rm diag} U^\dagger_{\rm PMNS} = -v^2 V_R Y [m_N^{\rm diag}]^{-1} Y^T V_R^T + \boxed{\frac{v_L}{v_R}} V_R^* m_N^{\rm diag} V_R^\dagger$$

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

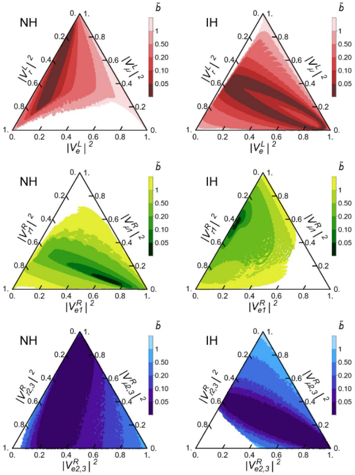
- Numerical "continuation" from $\kappa = 0$ to nonzero κ
- Take V_R, $m^\nu_{\rm diag}$ for given κ, increase κ and find corrections



CP-violating symmetry breaking

$$U^*_{\rm PMNS} m_\nu^{\rm diag} U^\dagger_{\rm PMNS} = -v^2 V_R \boxed{Y} [m_N^{\rm diag}]^{-1} \boxed{Y^T} V_R^T$$

$$vY \to vY - m_l^{\rm diag} b e^{ia}$$



(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

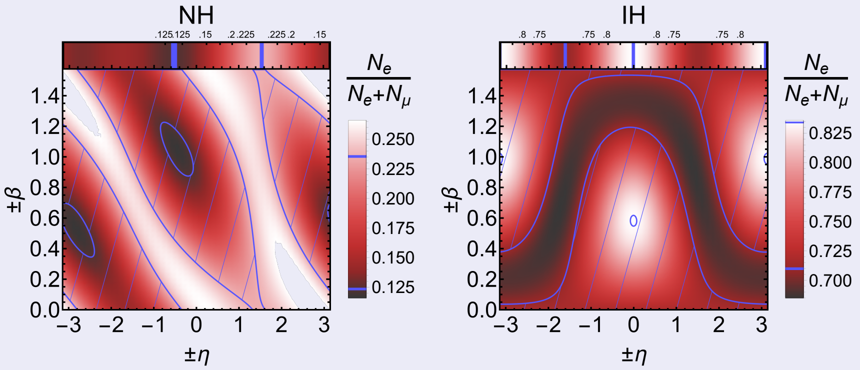
- The initial lepton is lost in the target — no information?

Probing decoherence at SHiP

- The initial lepton is lost in the target — no information?
- Not if kinematic constraints help us
- For example, $D \to l_\alpha N \to l_\alpha l_\beta$ cannot have τ-leptons for a GeV HNL

Probing decoherence at SHiP

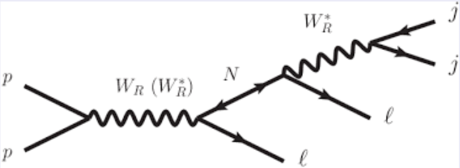
- The initial lepton is lost in the target — no information?
- Not if kinematic constraints help us
- For example, $D \to l_\alpha N \to l_\alpha l_\beta$ cannot have τ-leptons for a GeV HNL

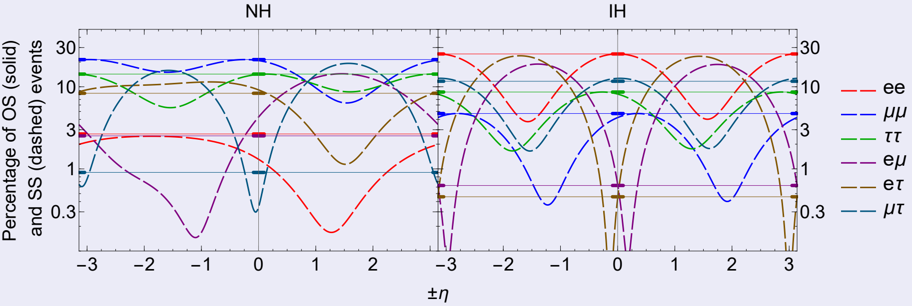


Coherent (blue) vs decoherent (red) case predictions

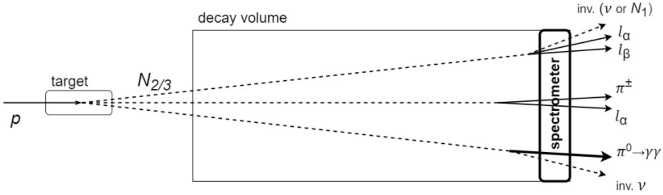
Probing decoherence with Keung-Senjanović process

- 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

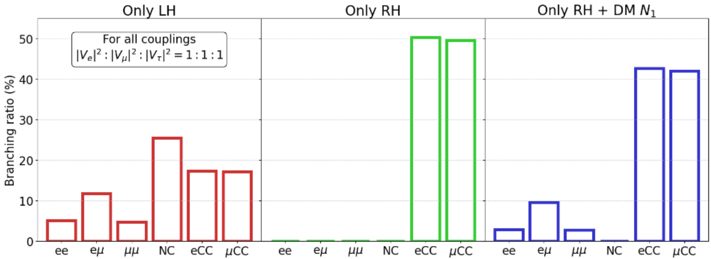




DM at SHiP



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



DM at SHiP

- Benchmark model:

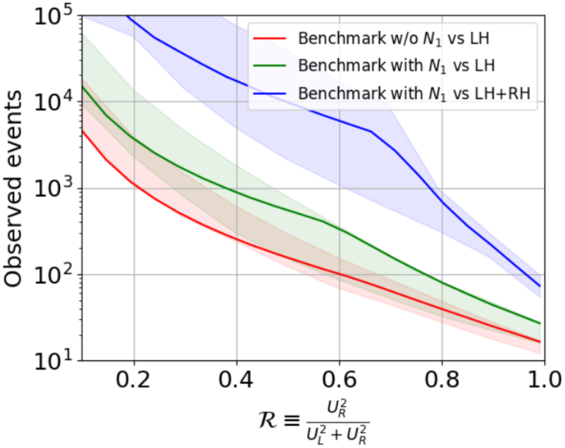
$$|V_e^L|^2 : |V_\mu^L|^2 : |V_\tau^L|^2 = 0.11 : 0.22 : 0.67$$
$$|V_{e2}^R|^2 : |V_{\mu 2}^R|^2 : |V_{\tau 2}^R|^2 = 0.16 : 0.46 : 0.38$$
$$|V_{e3}^R|^2 : |V_{\mu 3}^R|^2 : |V_{\tau 3}^R|^2 = 0.16 : 0.46 : 0.38$$
$$|V_{e1}^R|^2 : |V_{\mu 3}^R|^2 : |V_{\tau 3}^R|^2 = 0.49 : 0.22 : 0.30$$

Fraction of RH interactions:

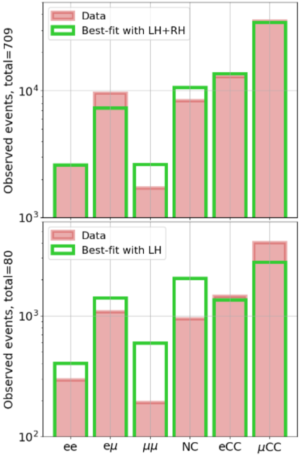
$$\mathcal{R} \equiv \frac{U_R^2}{U_L^2 + U_R^2}$$

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.



Observed events
10^5
10^4
10^3
10^2
10^1
0.2
0.4
0.6
0.8
1.0
Benchmark w/o N_1 vs LH
Benchmark with N_1 vs LH
Benchmark with N_1 vs LH+RH
$\mathcal{R} \equiv \frac{U_R^2}{U_L^2 + U_R^2}$



Data
Best-fit with LH+RH
Observed events, total=709
10^4
10^3
Data
Best-fit with LH
Observed events, total=80
10^3
10^2
ee
eμ
μμ
NC
eCC
μCC

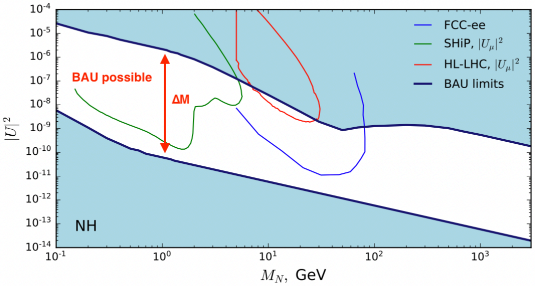
Summary

- HNLs offer a solution to multiple problems simultaneously
- HNLs are the search target for the near-future experiments
- A consistent approach is needed, combining experimental analysis with theoretical premises

Back-up

Degenerate HNLs

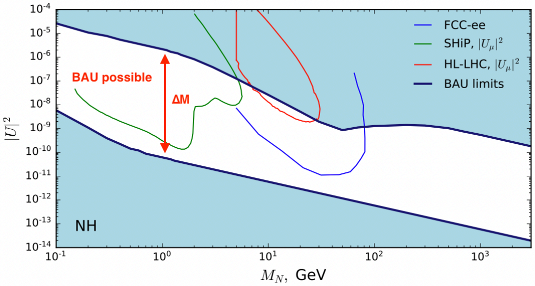
- Baryon asymmetry demands 2 HNLs with **almost degenerate masses** and **the same mixing angles**



Can we understand that we observed such HNLs?

Degenerate HNLs

- Baryon asymmetry demands 2 HNLs with **almost degenerate masses** and **the same mixing angles**



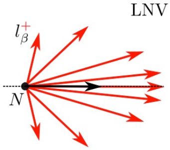
Can we understand that we observed such HNLs?

→ **Lepton number violation signature**

Degenerate HNLs at SHiP

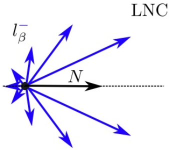
- Two HNLs with similar masses $\Rightarrow$ **HNL oscillations**
- Ratio of probability of lepton number violating (LNV) and conserving (LNC) processes:

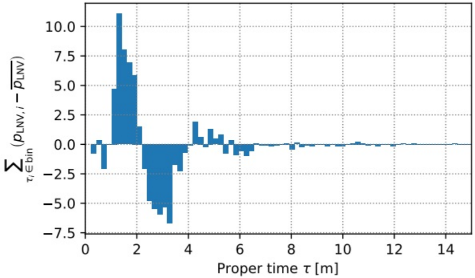
$$\frac{P_{\text{LNV}}}{P_{\text{LNC}}} \sim \frac{1-\cos\Delta M\tau}{1+\cos\Delta M\tau} \qquad \tau\text{– HNL proper time} \qquad (1)$$



$\langle E^{(H)}_{l_\beta,\text{LNV}}\rangle \gtrsim \langle E^{(H)}_{l_\beta,\text{LNC}}\rangle$

- Kinematics of LNV and LNC decays is statistically different





✓ SHiP can resolve HNL oscillations [1912.05520]

✓ Needs $\mathcal{O}(10^3)$ events – middle of the exploration region

✓ Oscillation period: $2\pi/\Delta M$