Long-lived particles in the see-saw portal

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based on 2003.08391, 2011.04725, 2201.11754, 22xx:yyyyy
w/ Bertuzzo, Caputo, Hernandez, Mele, Taoso, Toni

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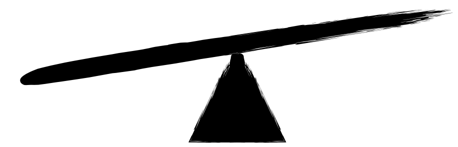
INFN

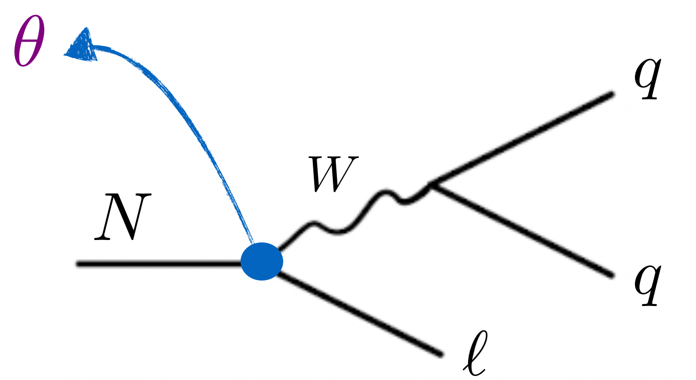
Neutrino masses require new physics beyond the Standard Model

$$-\delta\mathcal{L} = y_\nu LHN + \frac{1}{2} m_N NN + h.c.$$

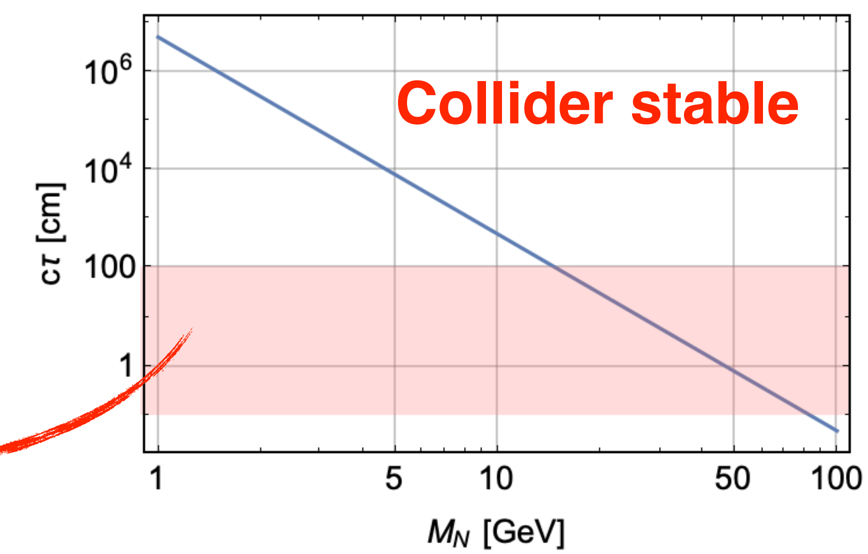
m_N  $m_\nu \simeq \frac{y_\nu^2 v^2}{m_N}$

RH neutrinos at the EW scale are a **target for collider searches**

Small active-sterile mixing $\theta \simeq \sqrt{m_\nu / m_N}$ implies long lifetime for RH neutrinos

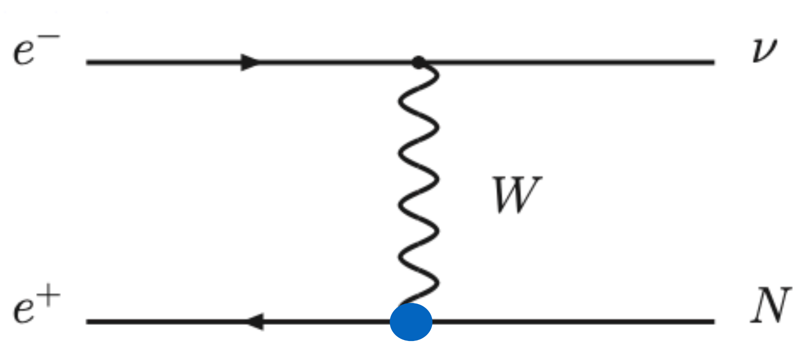


$$c\tau \simeq 5\ \mathrm{m} \left(\frac{10\ \mathrm{GeV}}{m_N} \right)^4$$

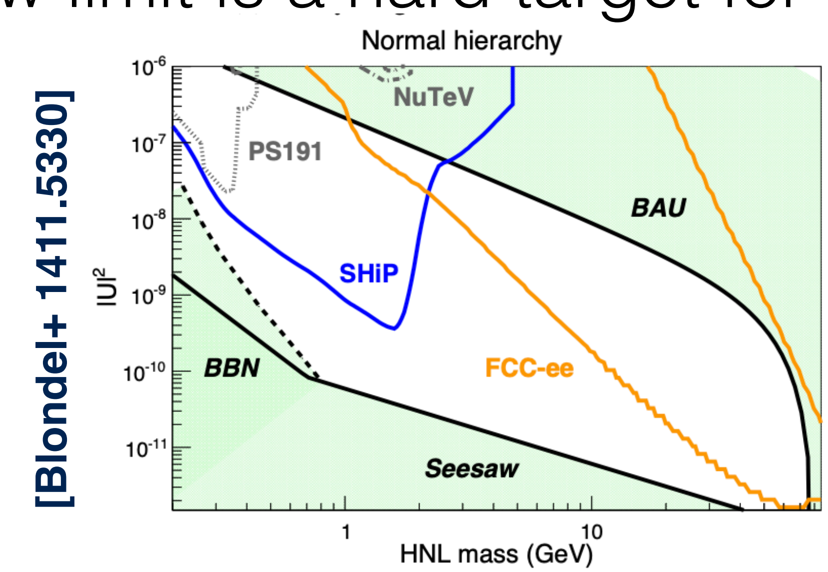


Collider displaced

$\sigma_{\rm prod}$ also mixing suppressed



See-saw limit is a hard target for collider



The naive see-saw scaling can be modified with $n \geq 2$ RH neutrinos

$$y_\nu \to Y_\nu \qquad m_N \to M_N \qquad m_\nu \simeq v^2 Y_\nu \frac{1}{M_N} Y_\nu^T = U^* m_\nu^{(d)} U^\dagger$$

Matrices

Solve for $Y_\nu \simeq \frac{1}{v} U^* \sqrt{m} \mathcal{R} \sqrt{M_N}$ and $\theta_{\nu N} \simeq -U^* \sqrt{m} \mathcal{R} \frac{1}{\sqrt{M_N}}$

$\mathcal{R}$ is an $n \times n$ complex orthogonal matrix and $\sqrt{m}\sqrt{m}^T = m_\nu^{(d)}$

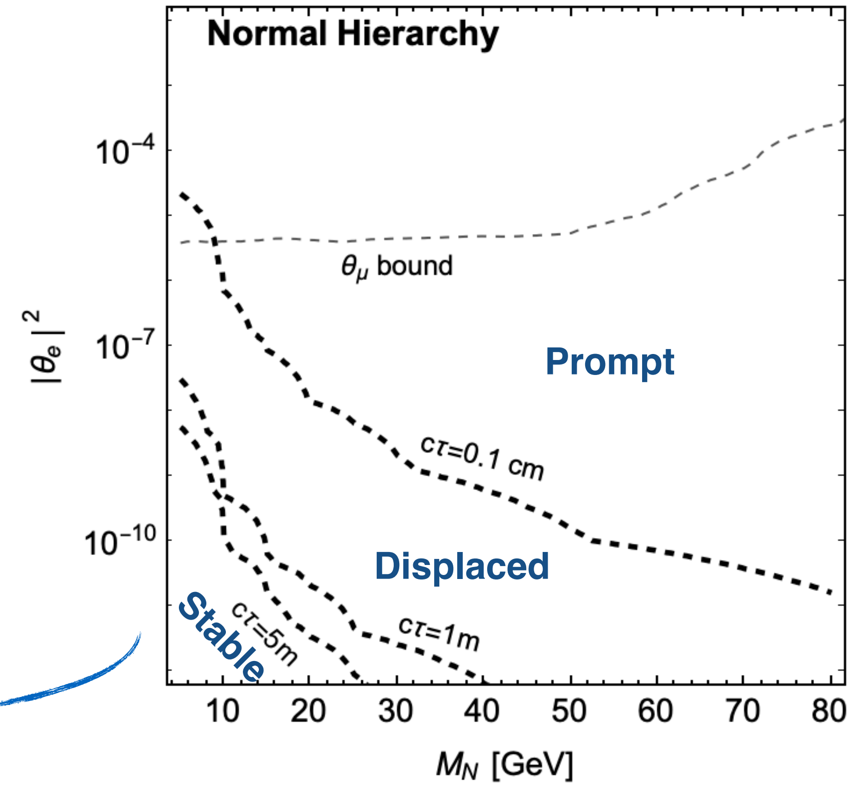
The imaginary entries of $\mathcal{R}$ cause an enhancement of the mixing **[Casas+ 0103065]**

With $n = 2$ $\quad \mathcal{R} = \begin{pmatrix} \cos z & \pm \sin z \\ -\sin z & \pm \cos z \end{pmatrix} \qquad z = \alpha + i\gamma$

$$\theta \simeq 7.2 \times 10^{-6}\, e^{\gamma - i\alpha} \left(\frac{1\ \text{GeV}}{M_N}\right)^{1/2} \neq \sqrt{\frac{m_\nu}{M_N}}$$

$$c\tau \sim 5\ \text{m} \left(\frac{10^{-10}}{\theta^2}\right) \left(\frac{10\ \text{GeV}}{m_N}\right)^5$$

Different lifetime regimes possible



The naive see-saw pheno can be modified by additional NP at a scale $\Lambda \gg m_N$

E

UV

$\psi,\ \phi,\ X_\mu \ldots$

Λ

Only two operators at $d = 5$

$$\mathcal{O}_{NH} = N N H^\dagger H$$

$$\mathcal{O}_{NB} = N \sigma^{\mu\nu} N B_{\mu\nu}$$

$$\mathrm{SM} + N + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \mathcal{O}^n = \nu\mathrm{SMEFT}$$

(a.k.a. see-saw portal)

$\mathcal{O}_{NH} = NNH^\dagger H$ and $\mathcal{O}_{NB} = N\sigma^{\mu\nu}NB_{\mu\nu}$ give new decay for h and Z

Primary target for future Higgs and Z factories!!!

$$\Gamma(h \to NN) \simeq \frac{1}{2\pi}\frac{v^2}{\Lambda^2}m_h \qquad \Gamma(Z \to N_1 N_2) \simeq \frac{1}{16\pi^2}\frac{1}{6\pi\Lambda^2}s_w^2 m_Z^3$$

Loop suppressed
[Craig+ 2001.00017]

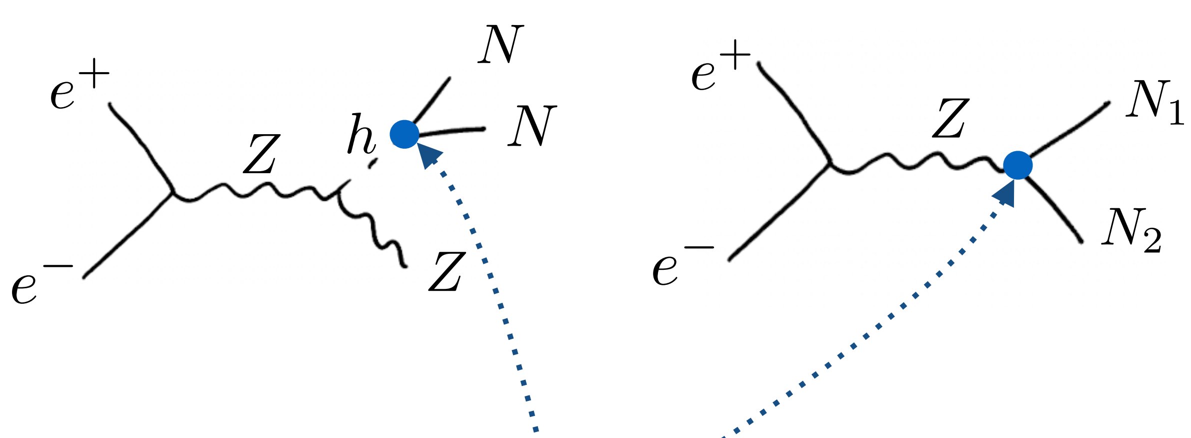
Higgs run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	σ_{Zh} [fb]
FCC-ee	240	5	193
ILC	250	2 (pol)	297
CLIC-380	380	1 (pol)	133
CEPC	240	5.6	193

Z pole run

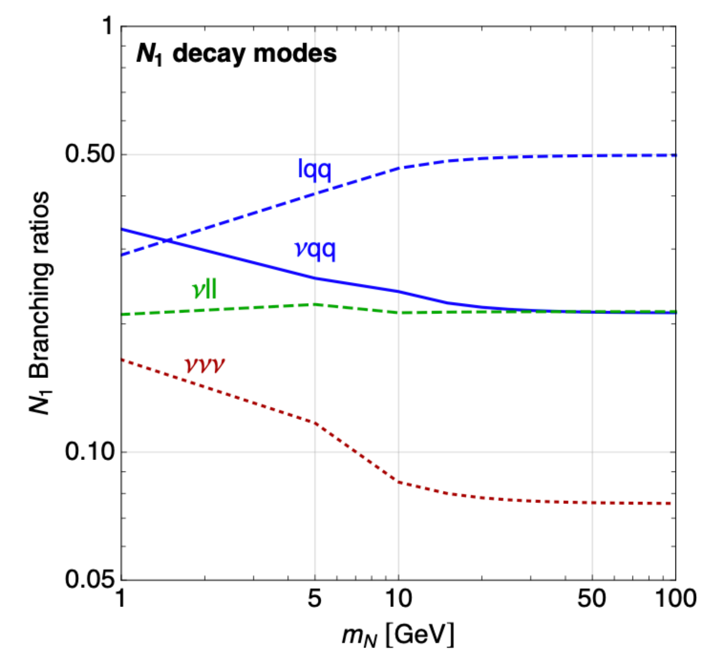
Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	N_Z
FCC-ee	m_Z	150	6.5×10^{12}
CEPC	m_Z	16	6.9×10^{11}

Production not suppressed by θ…



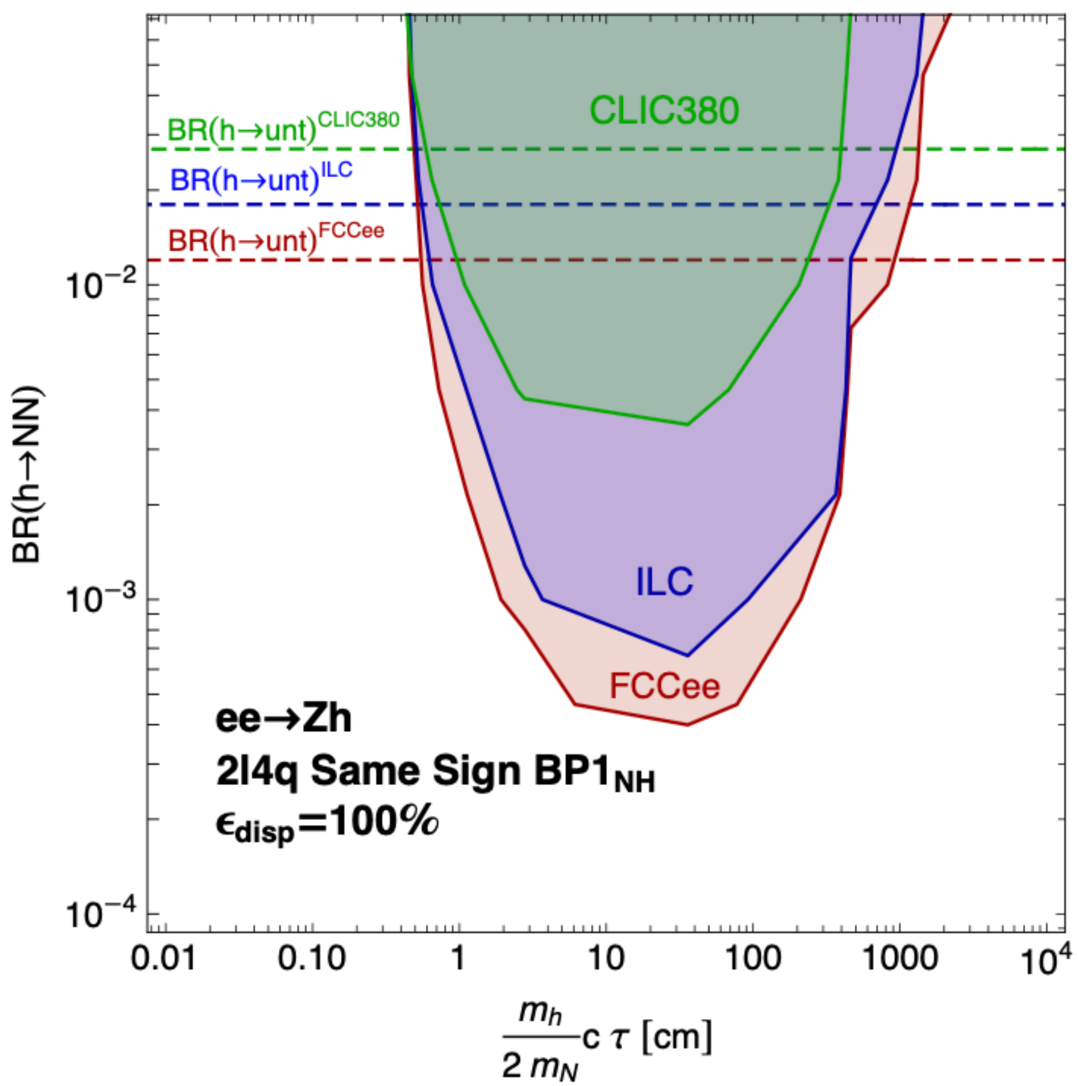
…but suppressed by Λ

Decay still induced by the mixing

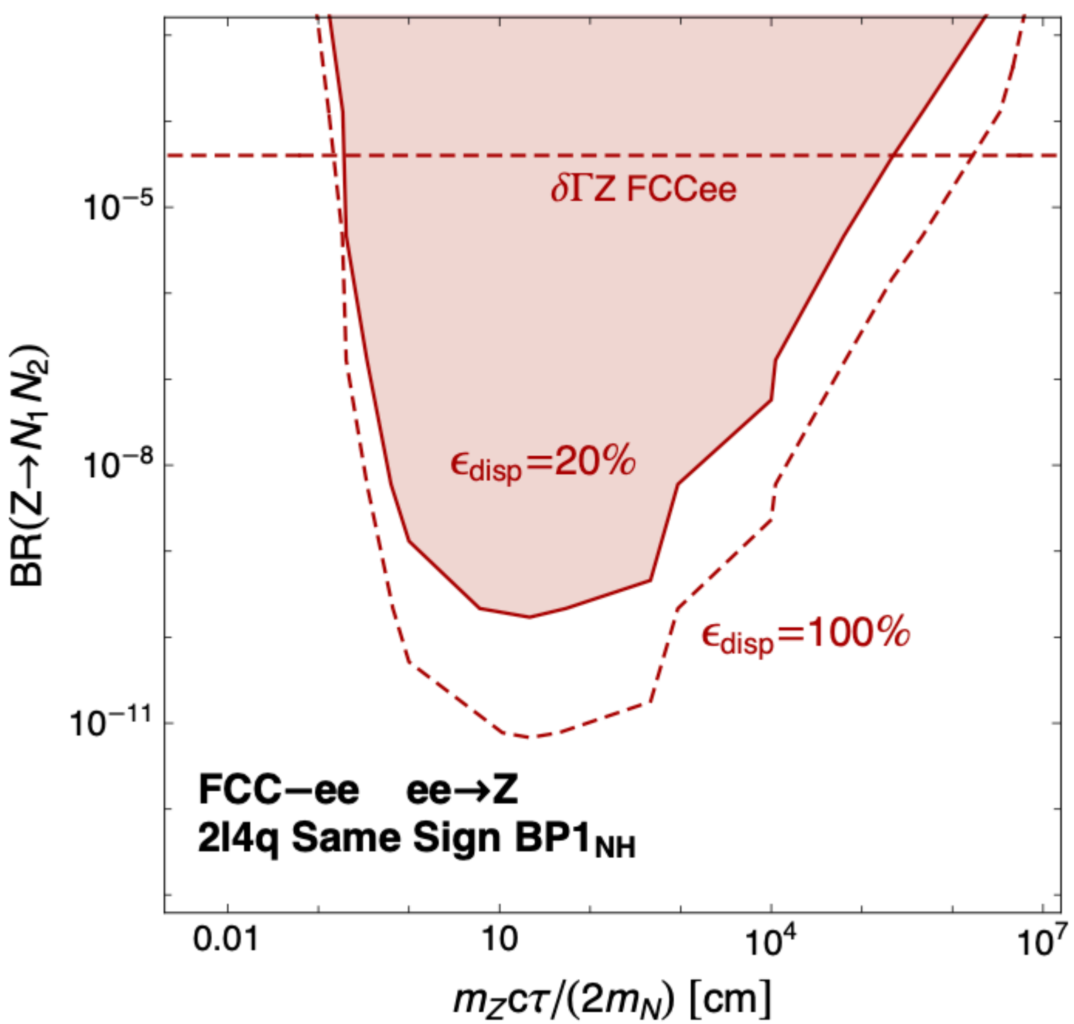


- Consider displaced decay within $L \in [0.1\ \mathrm{cm}, 1\ \mathrm{m}]$ with $\mathcal{P}(x_i, x_f) = e^{-\frac{x_i}{\beta\gamma c\tau}} - e^{-\frac{x_f}{\beta\gamma c\tau}}$
- Majorana nature allows for same-sign lepton from $NN \to \ell^+\ell^+ 4q$
- Negligible background due to lepton number conservation in the SM
- Clean channel with ~20% of decay rate

Higgs run $\sqrt{s} = 240\ \mathrm{GeV}$



Z-pole run $\sqrt{s} = m_Z$



- Direct limits well beyond attainable sensitivity from precision measurements
- Test of NP in the multi-TeV regime for Λ **[See Caputo+ 1704.08721 for related LHC analysis]**
- See 2011.04725 for the prompt and collider stable cases

At any $d=6$ many more operators…

[Liao+ 1612.04527]

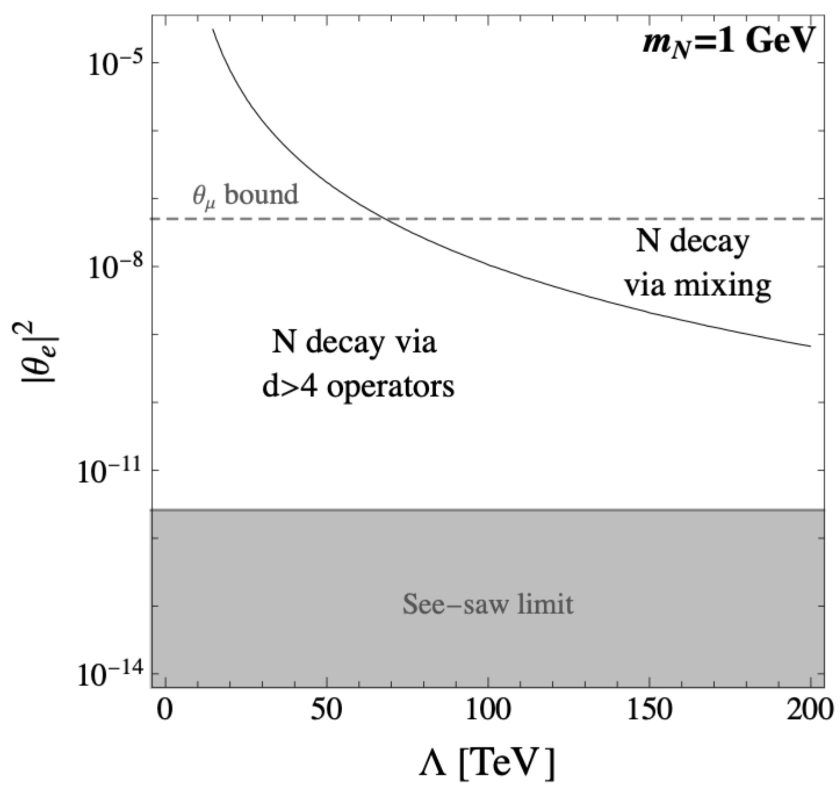
	Operator
$\mathcal{O}^6_{LNH}$	$(\bar{L}\tilde{H}N_R)(H^\dagger H) + h.c.$
$\mathcal{O}^6_{LNB}$	$(\bar{L}\sigma^{\mu\nu}N_R)B_{\mu\nu}\tilde{H} + h.c$
$\mathcal{O}^6_{LNW}$	$(\bar{L}\sigma^{\mu\nu}N_R)\sigma^a W^a_{\mu\nu}\tilde{H} + h.c$
$\mathcal{O}^6_{NH}$	$(\bar{N}_R\gamma^\mu N_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}^6_{NeH}$	$(\bar{N}_R\gamma^\mu e_R)(\tilde{H}^\dagger i\overleftrightarrow{D}_\mu H) + h.c.$
$\mathcal{O}^6_{4N}$	$(\bar{N}^c_R N_R)(\bar{N}^c_R N_R) + h.c.$
$\mathcal{O}^6_{Nedu}$	$(\bar{N}_R\gamma^\mu e_R)(\bar{d}_R\gamma_\mu u_R)$
$\mathcal{O}^6_{NLqu}$	$(\bar{N}_R L)(\bar{q}_L u_R) + h.c$
$\mathcal{O}^6_{LNqd}$	$(\bar{L}N_R)\varepsilon(\bar{q}_L d_R) + h.c$
$\mathcal{O}^6_{LdqN}$	$(\bar{L}d_R)\varepsilon(\bar{q}_L N_R) + h.c$
$\mathcal{O}^6_{LNLe}$	$(\bar{L}N_R)\varepsilon(\bar{L}e_R) + h.c$
$\mathcal{O}^6_{Ne}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{e}_R\gamma_\mu e_R)$
$\mathcal{O}^6_{Nu}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{u}_R\gamma_\mu u_R)$
$\mathcal{O}^6_{Nd}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{d}_R\gamma_\mu d_R)$
$\mathcal{O}^6_{Nq}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{q}_L\gamma_\mu q_L)$
$\mathcal{O}^6_{NL}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{L}_L\gamma_\mu L_L)$
$\mathcal{O}^6_{NN}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{N}_R\gamma_\mu N_R)$
$\mathcal{O}^6_{uddN}$	$(\bar{u}^c_R d_R \bar{d}^c_R)N_R + h.c.$
$\mathcal{O}^6_{qqdN}$	$(\bar{q}^c_L \varepsilon q_L \bar{d}^c_R)N_R + h.c.$

They induce additional decay modes…

Operator	Decay	Mixing	Loop
$\mathcal{O}^6_{LNB,W}$	$N\to\nu\gamma$	×	✓
	$N\to\nu Z^*$	×	✓
	$N\to\ell W^*$	×	✓
$\mathcal{O}^6_{LNH}$	$N\to\nu H^*$	×	×
$\mathcal{O}^6_{NH}$	$N\to\nu Z^*$	✓	×
$\mathcal{O}^6_{NeH}$	$N\to\ell W^*$	×	×
$\mathcal{O}^6_{4f}$ − *neutral*	$N\to 3f$	✓	×
$\mathcal{O}^6_{4f}$ − *charged*	$N\to 3f$	×	×

…that can dominate over the mixing

[DB+ 2003.08391, 2201.11754]

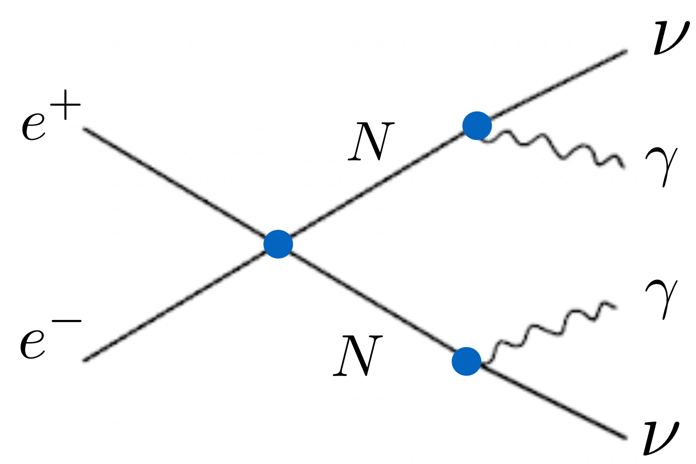


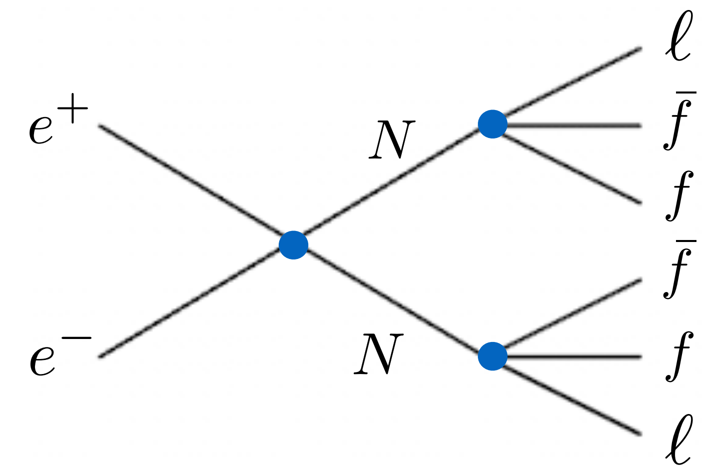
- Four-fermi operators give $\sigma \sim \dfrac{s}{\Lambda^4}$
- Interesting target for multi-TeV collider

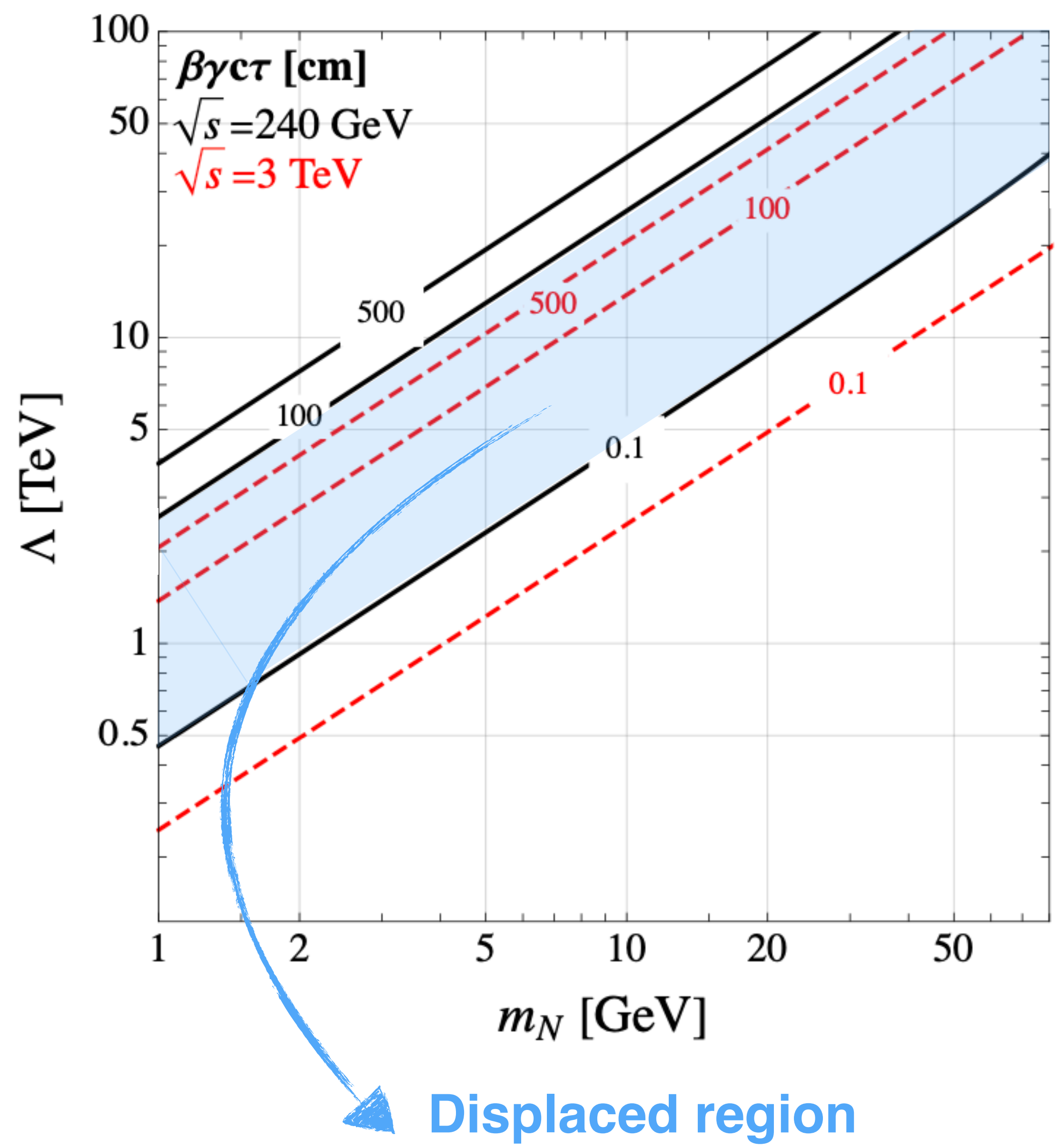
High-energy run

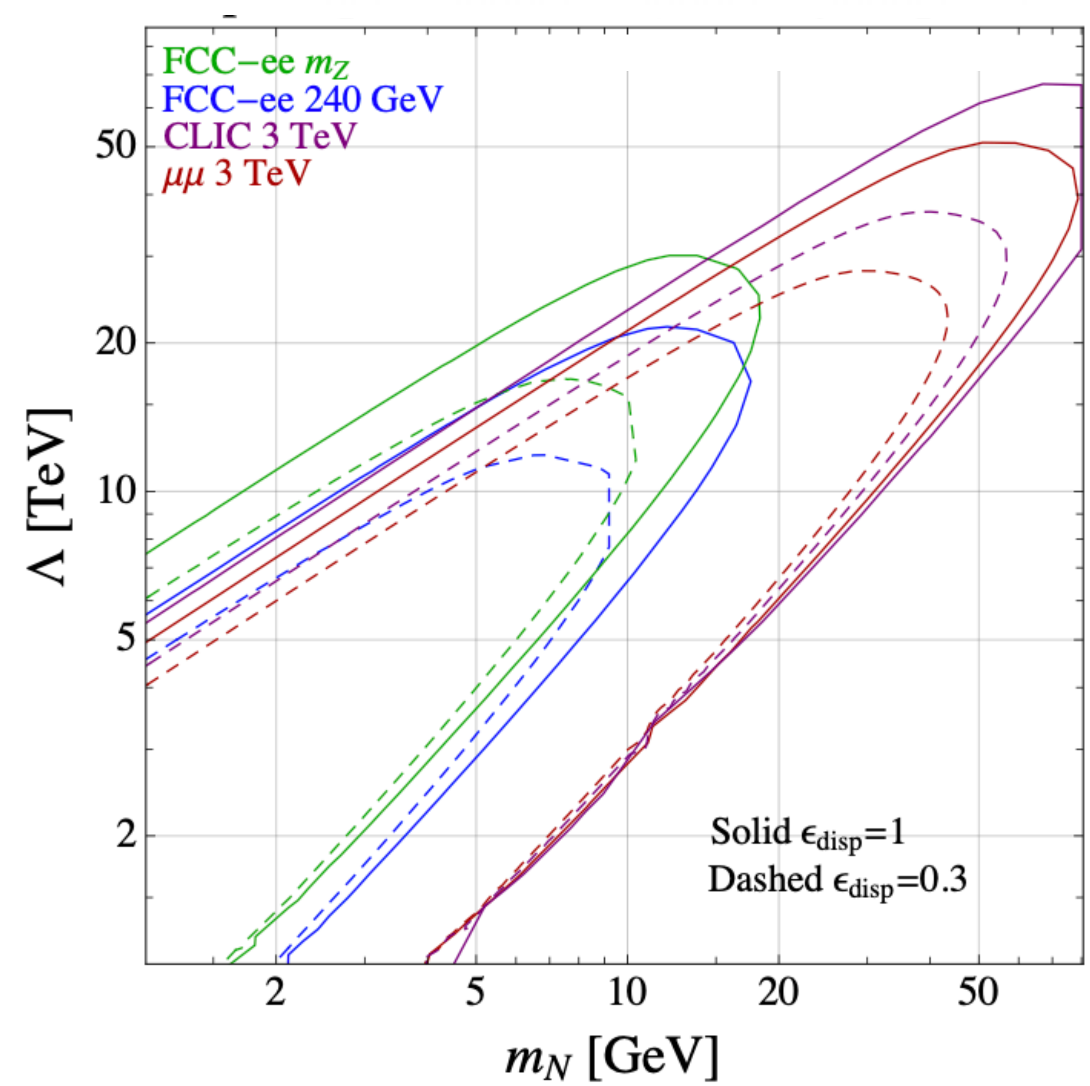
Collider	$\sqrt{s}$ [TeV]	$\int\mathcal{L}$ [ab^{-1}]
CLIC	3	3
$\mu\mu$	3	1

Two interesting channels: $N \to \nu\gamma$ and $N \to 3f$









Multi-TeV sensitivity!!!

- See 2201.11754 for the prompt and collider stable cases

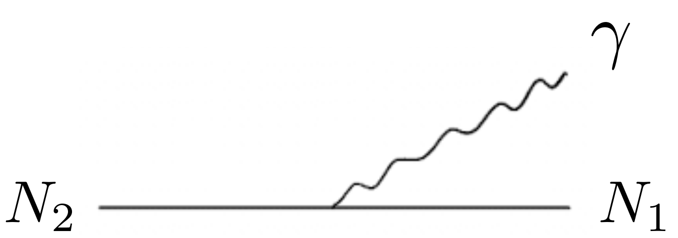
Many experiments are sensitive to $c\tau \sim \mathcal{O}(10-100)$ m

FASER, MATHUSLA, ANUBIS, CODEX-b, MoEDAL-MAPP, AL3X, FACET, SHiP, SND@LHC…

Can they test this scenario? Focus on the simplest case:no mixing and only $\mathcal{O}^5_{NB}$

$$\mathcal{O}^5_{NB} = N_1 \sigma^{\mu\nu} N_2 B_{\mu\nu}$$

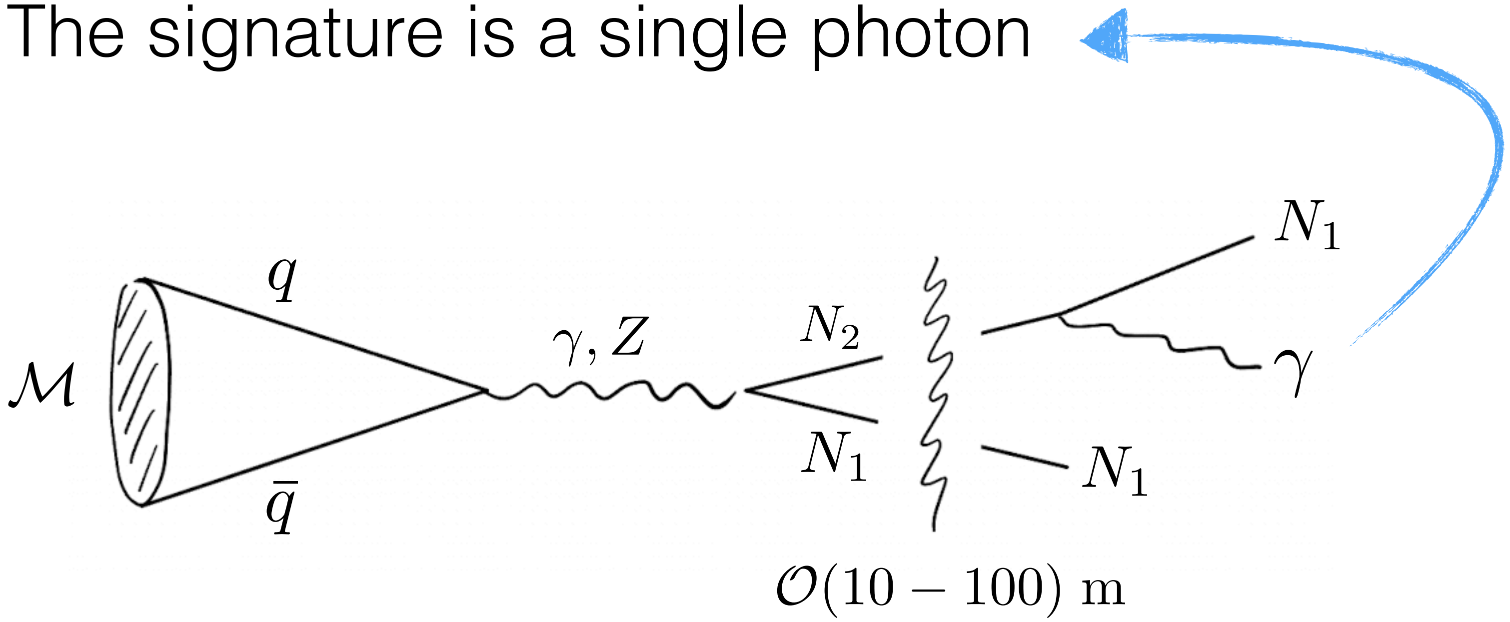
The decay length is controlled by the mass splitting

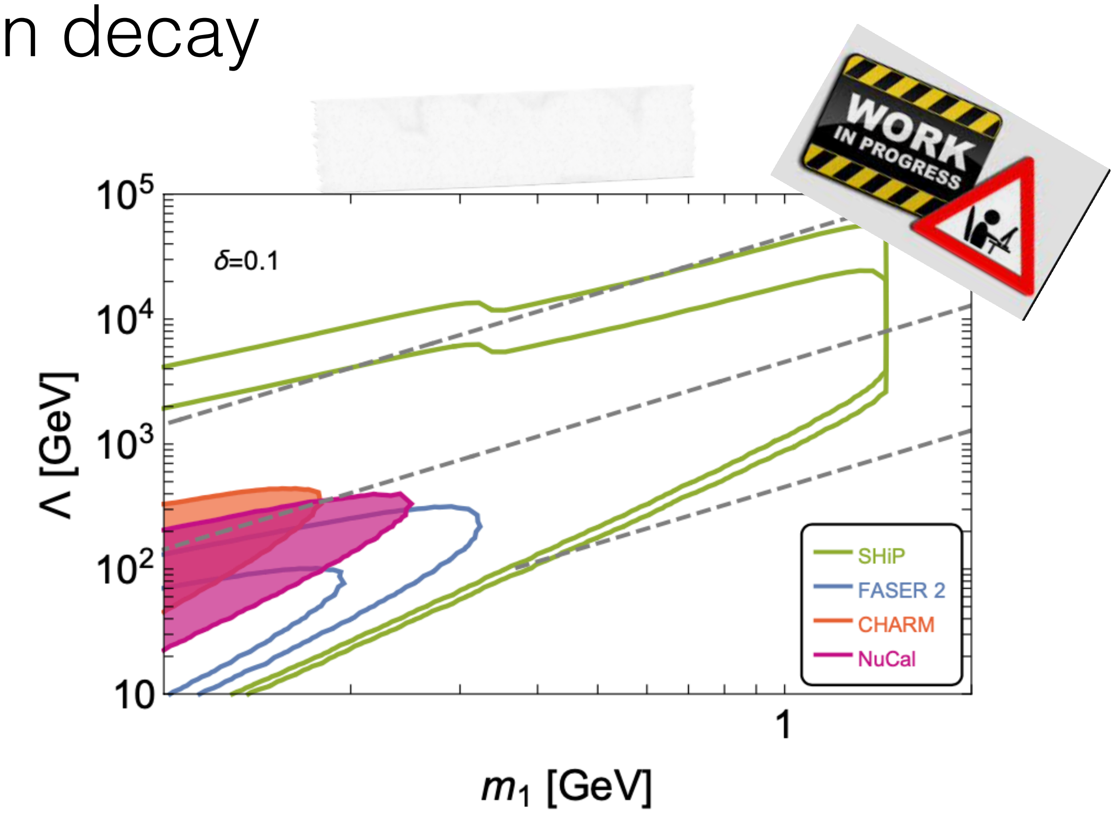


$$c\tau \simeq 0.5 \text{ m} \left(\frac{0.1}{\delta}\right)^3 \left(\frac{\Lambda}{100 \text{ GeV}}\right)^2 \left(\frac{0.1 \text{ GeV}}{m_{N_1}}\right)^3 \qquad \delta = \frac{m_{N_2} - m_{N_1}}{m_{N_1}}$$

For $m_N \lesssim 1$ GeV dominant production via meson decay

The signature is a single photon





FASER capable of tagging this final state. What's about other experiments?

Experimental input welcome!!!

Conclusions

- Beyond the minimal see-saw paradigm many more opportunities for LLPs
  - with $n \geq 2$ RHN lifetime can span many order of magnitude in $c\tau$
  - $d > 4$ operators in the $\nu\mathrm{SMEFT}$ induce extra production and decay modes

- For decay lengths $0.1\ \mathrm{cm} \lesssim L \lesssim 1\ \mathrm{m}$ collider searches are effective
  - Higgs and Z factories can test multi-TeV regimes in the $\nu\mathrm{SMEFT}$
  - Higher sensitivity with respect to indirect precision measurements

- Larger decay length can be tested by displace facilities
  - Simplest signature has a single photon. Challenging! is it feasible?
  - Many more channels to be explored including interplay with the mixing

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THANK YOU