The seesaw portal at FCC-ee

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w/ Bertuzzo, Caputo, Hernandez- 2003.08391

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INFN

- ν masses and oscillations implies that physics beyond the SM does exist!
- ν masses can be add as in the SM quark sector $-\mathcal{L} = y_\nu \tilde{H} L N + h.c.$
- Dirac neutrinos and $y_\nu \simeq 10^{-13}$

SM gauge singlet

- N is in a real SM representation and admits a Majorana mass

$$-\delta\mathcal{L} = \frac{1}{2} M_N N N + h.c.$$

$m_N \simeq M_N$

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

Connections with baryogenesis via ν oscillation

~ 100 GeV

y_ν $\sim 10^{-7}$

M_N

$\sim 10^{15}$ GeV

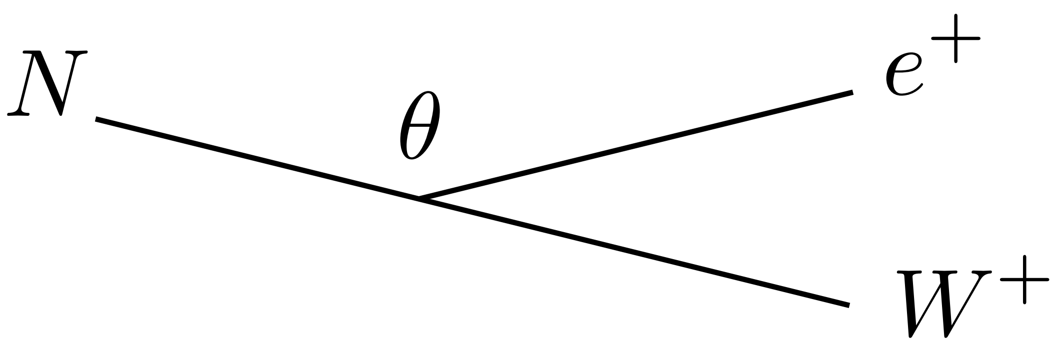
~ 1

Connections with GUT theories

- The new sterile states interact with the SM via $\nu - N$ mixing

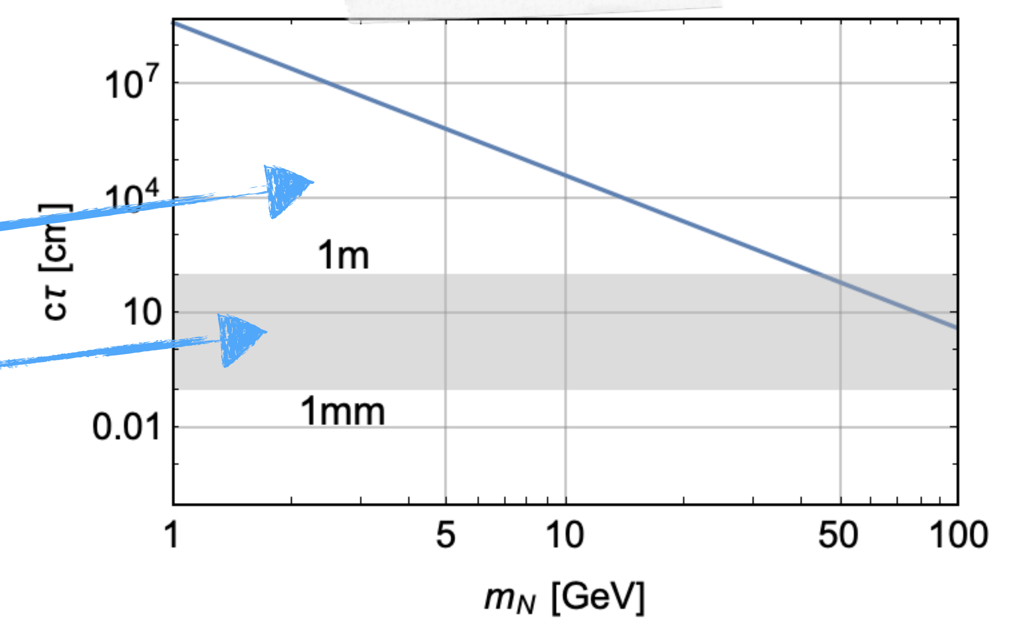
$$\begin{cases} \nu_{mass} = \cos\theta\ \nu + \sin\theta\ N \\ N_{mass} = -\sin\theta\ \nu + \cos\theta\ N \end{cases} \qquad \theta \simeq \frac{y_\nu v}{M_N} \simeq \sqrt{\frac{m_\nu}{m_N}}$$

- Heavy neutrino decay via charged / neutral currents



$$\Gamma_N \simeq 10^{-2}\ \text{GeV} \left(\frac{m_N}{100\ \text{GeV}}\right) \frac{m_\nu}{m_N}$$

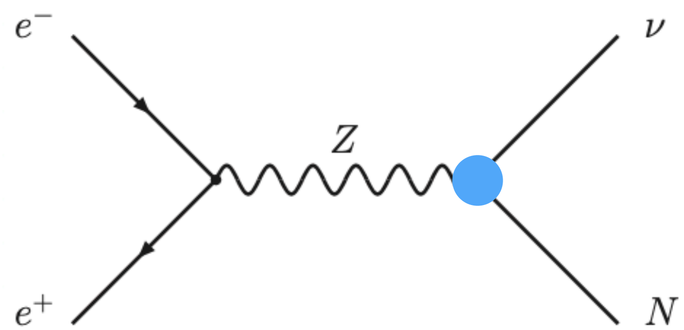
- They decay after macroscopic distances



Detector stable

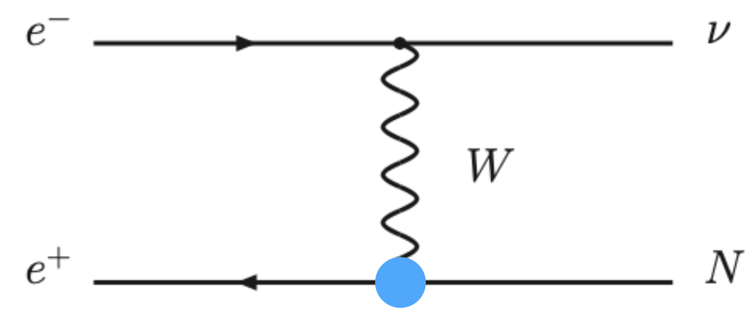
Displaced decay

$\sqrt{s} = m_Z$



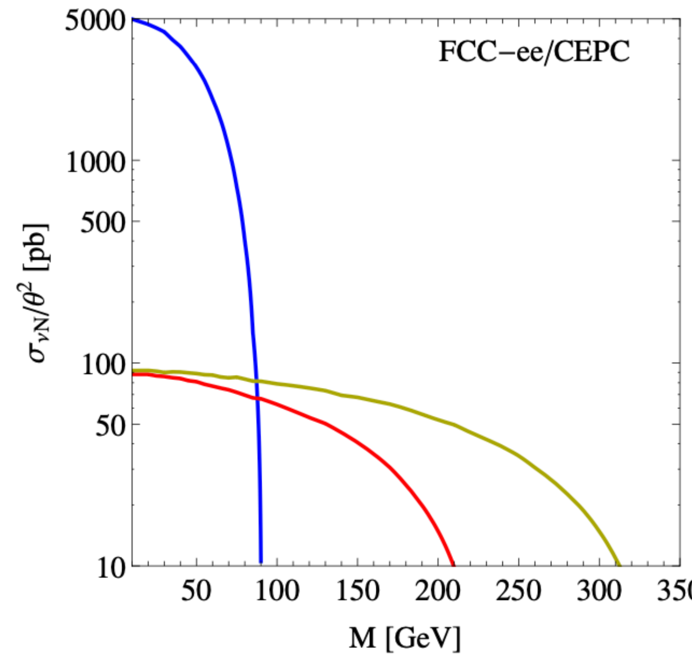
$\mathcal{O}(10^{12} - 10^{13})$ Z bosons

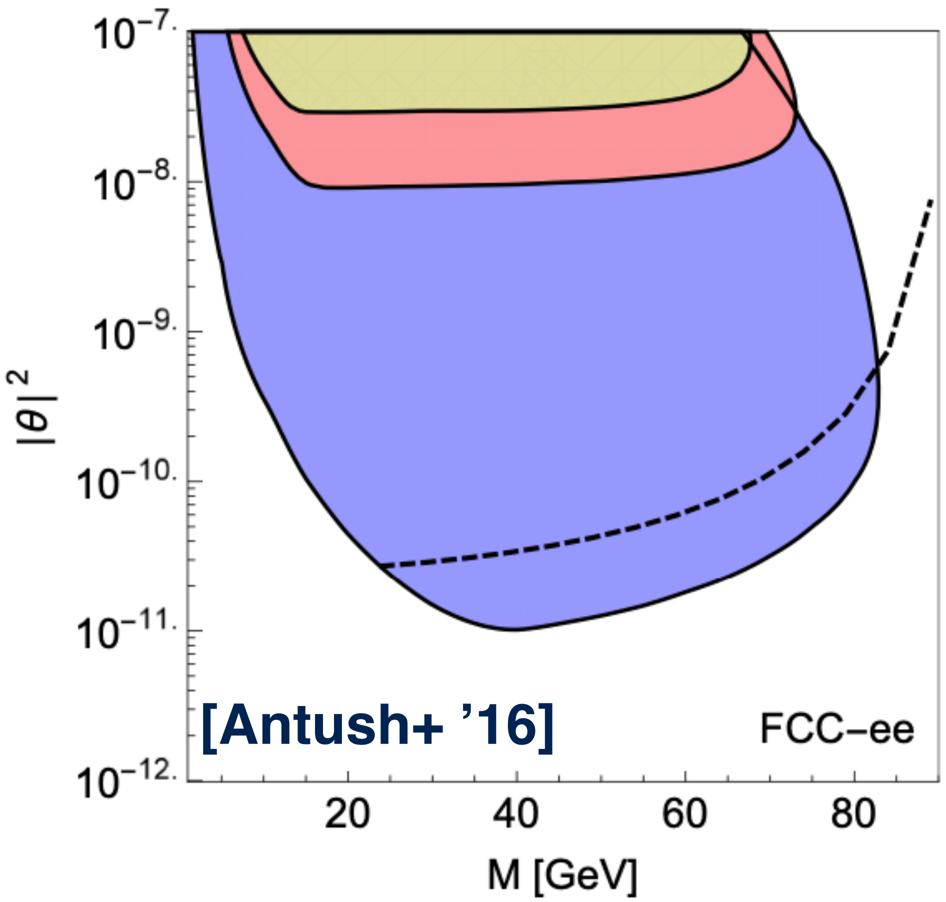
$\sqrt{s} > m_Z$

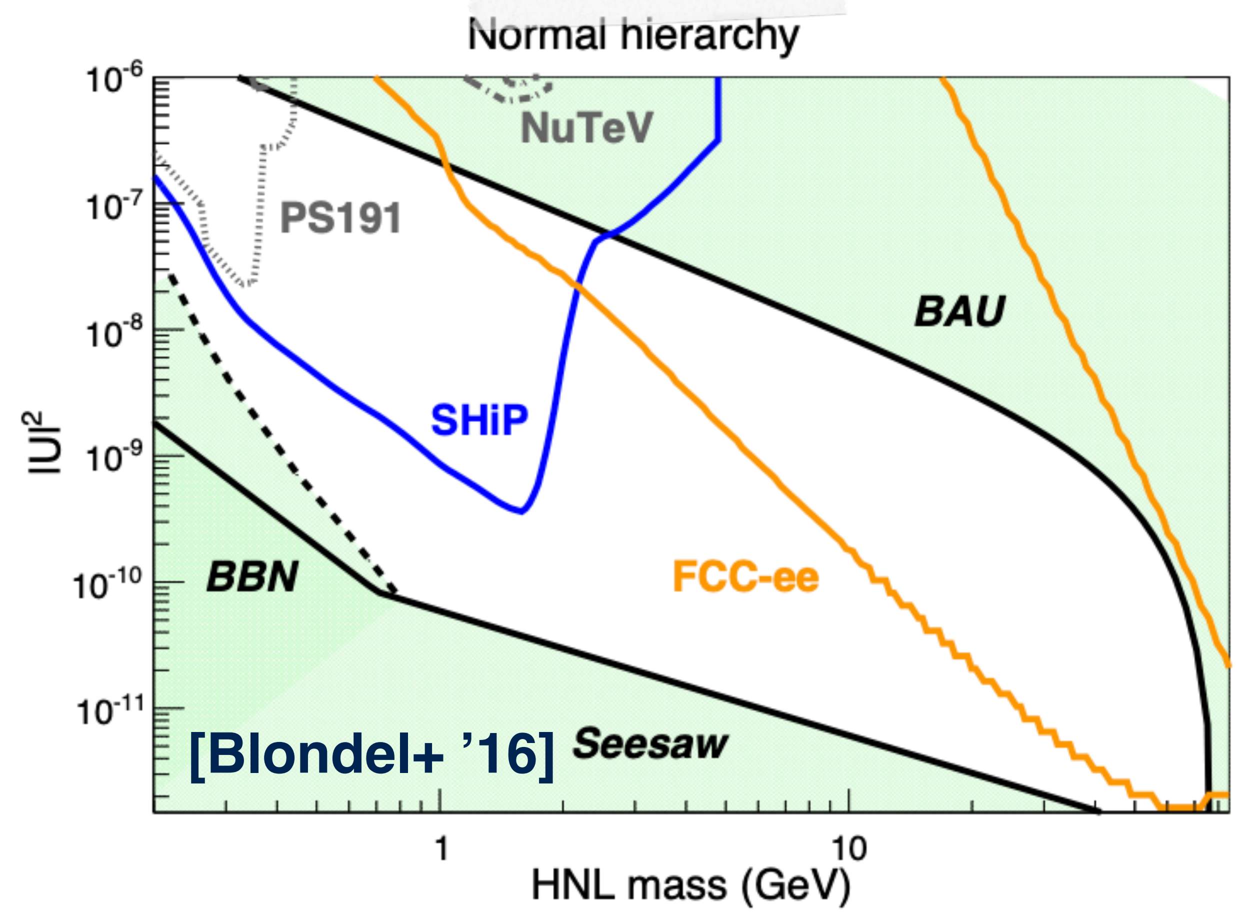


Tiny σ in the seesaw limit

$$\sigma_{\text{mix}} \simeq 2 \times 10^{-5} \left(\frac{1\ \text{GeV}}{m_N} \right)\ \text{fb}$$







- The naive seesaw scaling can be challenged with $n_N \geq 2$

$$\mathcal{M}_{mass} = \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M_N \end{pmatrix}$$

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

- One can express the Yukawa matrix as

physical masses

$$Y_\nu \simeq \frac{1}{v} U^* \sqrt{\mu} \sqrt{M_N}$$

with

$$\sqrt{\mu_{\rm NH}} = \begin{pmatrix} 0 & 0 \\ -\sin z \sqrt{m_2} & \pm\cos z \sqrt{m_2} \\ \cos z \sqrt{m_3} & \pm \sin z \sqrt{m_3} \end{pmatrix}$$

- Which can then be written as

$$Y_\nu \simeq \frac{1}{v} U^* \sqrt{m} \mathcal{R} \sqrt{M_N}$$

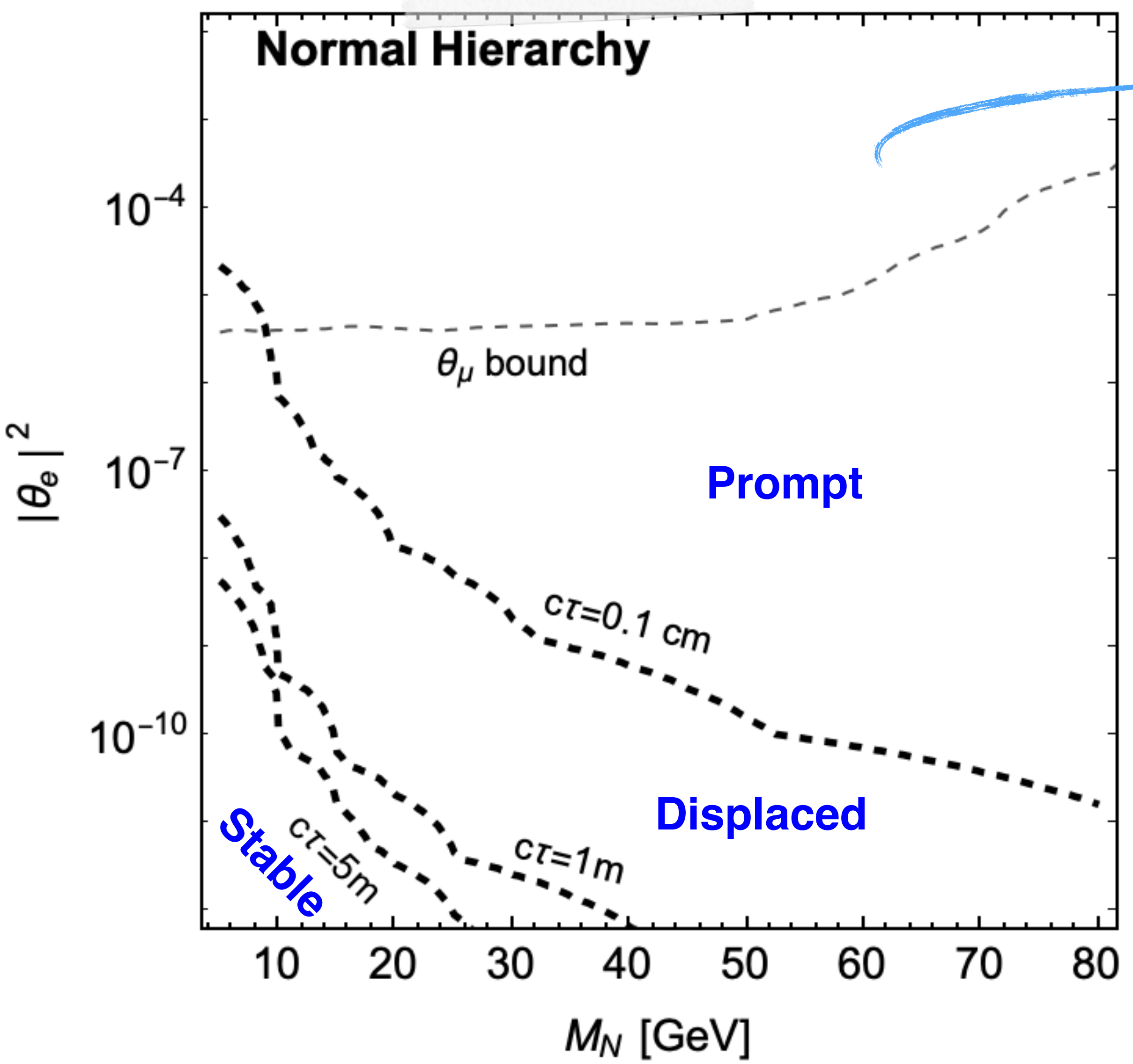
$$\mathcal{R} = \begin{pmatrix} \cos z & \pm \sin z \\ -\sin z & \pm\cos z \end{pmatrix}$$

- The angle z can take complex values! $z = \alpha + i\gamma$

- This allows θ to departure from the seesaw limit

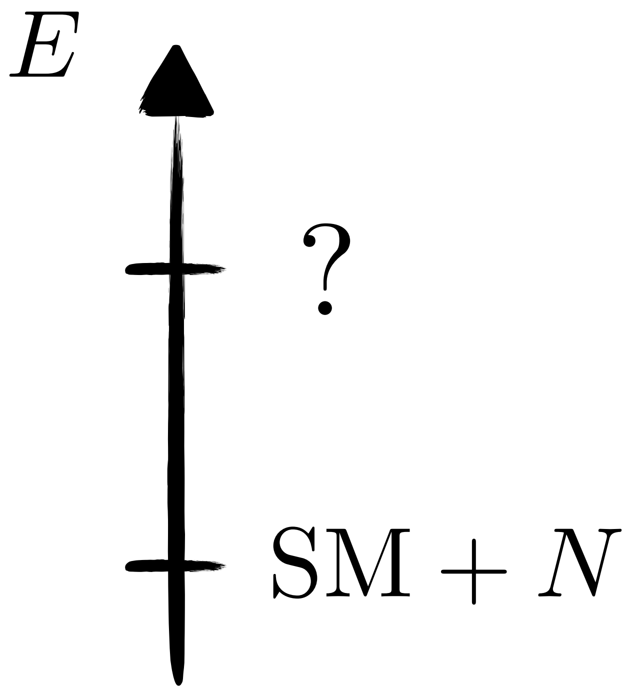
$$\theta \simeq 7.2 \times 10^{-6} e^{\gamma - i\alpha} \left(\frac{1 \text{ GeV}}{M_{N_{1,2}}} \right)^{1/2}$$

Exponential enhancement of the mixing angle



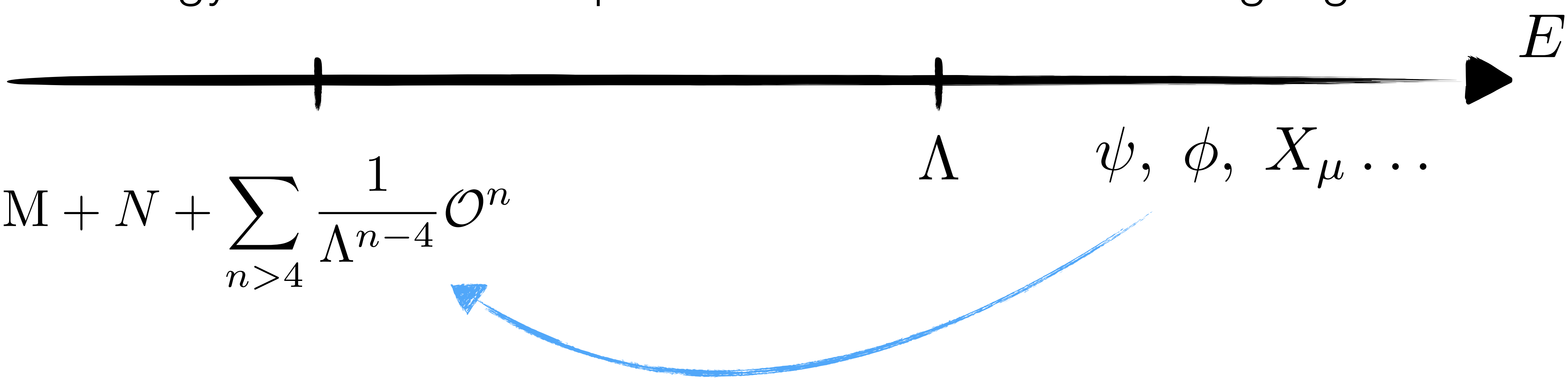
Direct searches contraints

- All three regimes possible
- Motivates searches for prompt N



- Are GeV scale RH neutrinos the only BSM states?
- Assume extra NP at a scale $\Lambda \gg v, M_N$

- At low energy their effects are parametrized with the EFT language



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

- Higher dimensional operators are built out from SM and N fields: $\nu\mathrm{SMEFT}$

- At dimension-5 only three operators are present

$$\mathcal{O}_W = (LH)(LH)$$ Weinberg operator $$m_\nu \simeq \frac{v^2}{\Lambda}$$

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

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

Genuine $\nu\mathrm{SMEFT}$ operators

- Many more at dimension-six…. **[Yi Liao+ ’16]**

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

	Operator
$\mathcal{O}^6_{Ne}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{e}_R\gamma_\mu e_R)$
$\mathcal{O}^6_{Nu}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{u}_R\gamma_\mu u_R)$
$\mathcal{O}^6_{Nd}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{d}_R\gamma_\mu d_R)$
$\mathcal{O}^6_{Nq}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{q}_L\gamma_\mu q_L)$
$\mathcal{O}^6_{NL}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{L}_L\gamma_\mu L_L)$
$\mathcal{O}^6_{NN}$	$(\bar{N}_R\gamma^\mu N_R)(\bar{N}_R\gamma_\mu N_R)$
$\mathcal{O}^6_{uddN}$	$(\bar{u}^c_R d_R \bar{d}^c_R)N_R + h.c.$
$\mathcal{O}^6_{qqdN}$	$(\bar{q}^c_L \varepsilon q_L \bar{d}^c_R)N_R + h.c.$

- Interestingly, these operator can change the prompt/displaced behavior **[DB+ ’20]**

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

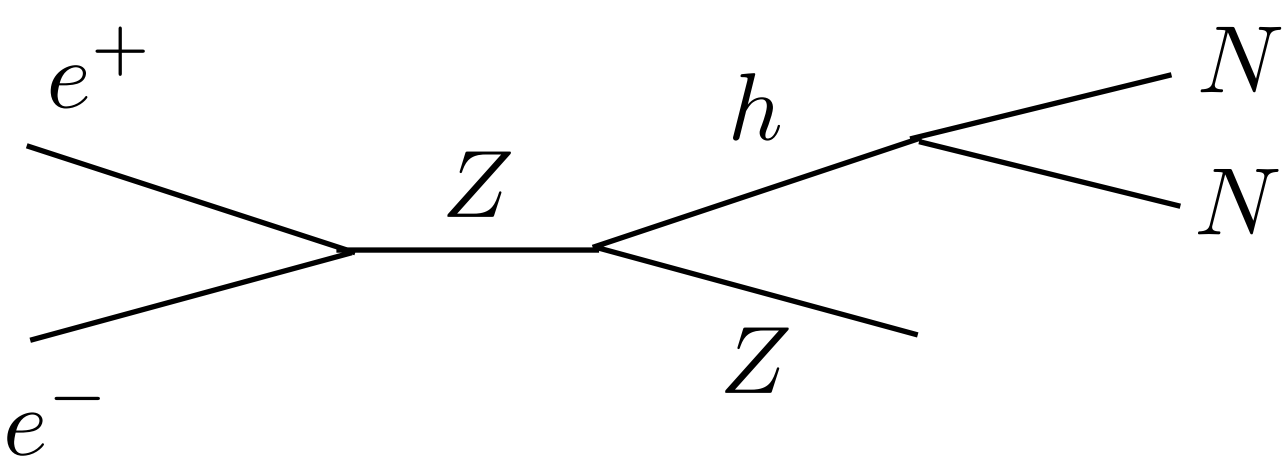
EWSB

NN — Contribution to N Majorana mass

hNN, $hhNN$ — New interactions

- New Higgs decay mode $$\Gamma(h \to NN) \simeq \frac{1}{2\pi}\frac{v^2}{\Lambda^2} m_h \sqrt{1 - 4\frac{m_N^2}{m_h^2}}$$

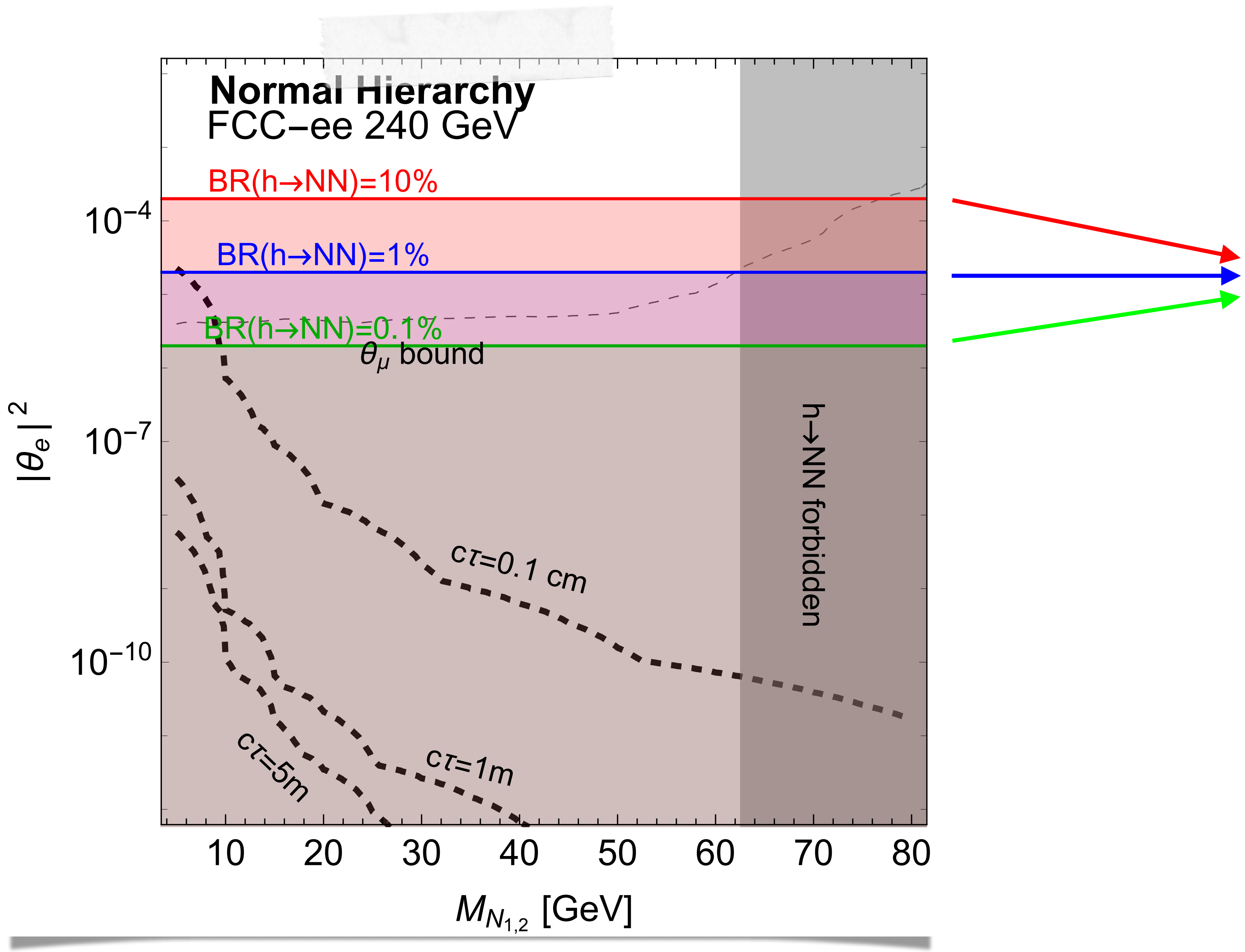
- And additional production channel relevant for FCC-ee



$$\sigma_{Zh}^{\mathrm{FCC-240}} \simeq 180 \text{ fb}$$

Independent of the mixing angle

- It could also be the main production mode for RH neutrinos at FCC-ee



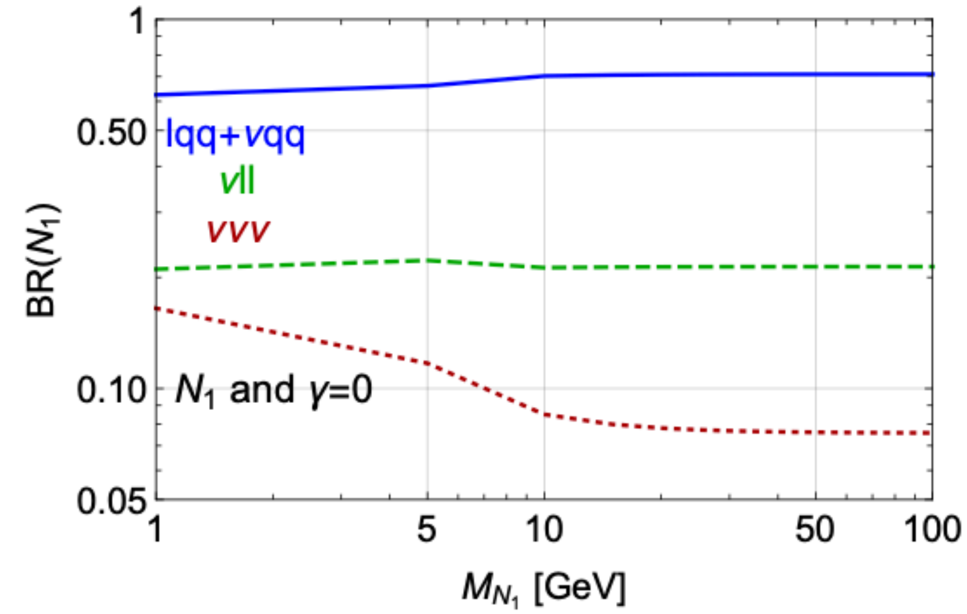
$$\sigma_{NH} > \sigma_{mix}$$

- It offers a complementary way to search for RH neutrinos

Provided Λ is not too large…

- The RH neutrino decays via mixing through neutral and charged-currents

Final state	Channel	Mediator
$\ell q\bar{q}$	$\ell_\alpha q_i \bar{q}_j$	$W^{(*)}$
$\nu q\bar{q}$	$\nu_\alpha q_i \bar{q}_j$	$Z^{(*)}$
$\nu\ell\ell$	$\ell_\alpha \ell_\beta \nu_\beta,\ \alpha \neq \beta$	$W^{(*)}$
	$\nu_\alpha \ell_\beta \ell_\beta,\ \alpha \neq \beta$	$Z^{(*)}$
	$\nu_\alpha \ell_\beta \ell_\beta,\ \alpha = \beta$	$W^{(*)}$ and $Z^{(*)}$
$\nu\nu\nu$	$\nu_\alpha \nu_\beta \nu_\beta$	$Z^{(*)}$



- And produced in pairs give rise to a plethora of final states

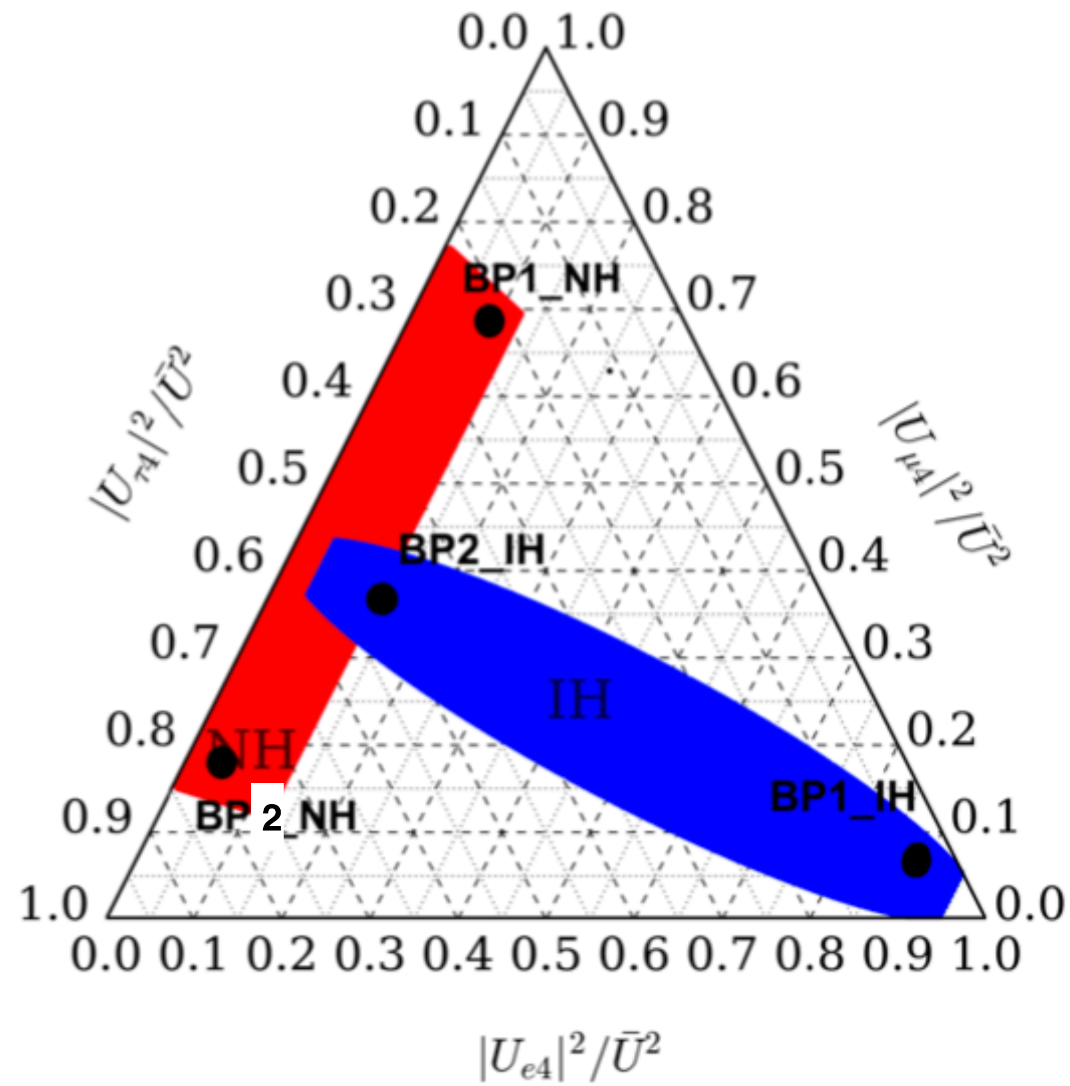
	Channel	SS
Fully-leptonic	$4\ell\ \not{E}_T$	✓
	$2\ell\ \not{E}_T$	
Semi-leptonic	$3\ell\ 2q\ \not{E}_T$	✓
	$2\ell\ 4q$	✓
	$2\ell\ 2q\ \not{E}_T$	
	$\ell\ 4q\ \not{E}_T$	
	$\ell\ 2q\ \not{E}_T$	
Fully-hadronic	$4q\ \not{E}_T$	
	$2q\ \not{E}_T$	
Invisible	$\not{E}_T$	

	Channel	SS
Fully-leptonic	$3\ell\ \tau\ \not{E}_T$	✓
	$2\ell\ 2\tau\ \not{E}_T$	
	$\ell\ \tau\ \not{E}_T$	
	$\ell\ 3\tau\ \not{E}_T$	
	$4\tau\ \not{E}_T$	
	$2\tau\ \not{E}_T$	
Semi-leptonic	$2\ell\ \tau\ 2q\ \not{E}_T$	
	$\ell\ 2\tau\ 2q\ \not{E}_T$	
	$\ell\ \tau\ 4q$	
	$\ell\ \tau\ 2q\ \not{E}_T$	

	Channel	SS
Semi-leptonic	$3\tau\ 2q\ \not{E}_T$	
	$2\tau\ 4q$	
	$2\tau\ 2q\ \not{E}_T$	
	$\tau\ 2q\ \not{E}_T$	
	$\tau\ 4q\ \not{E}_T$	

- Final states with Same-Sign leptons can be particularly clean

- The BRs in the final state depend on the choice of the CP phases of the PMNS



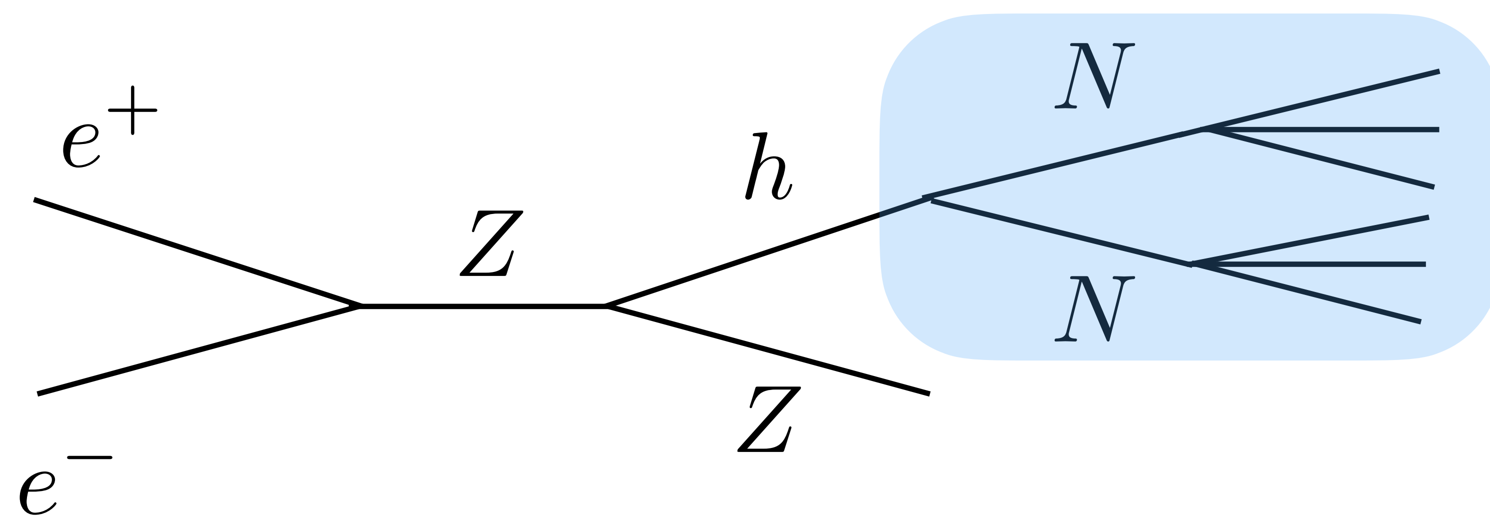
[Caputo+ '17]

- We can choose benchmark points that maximizes/minimizes the mixing with 1st+2nd generation leptons

$$\mathbf{BP1_{NH}}: \quad r_{e4}^2 : r_{\mu 4}^2 : r_{\tau 4}^2 = 0.10 : 0.68 : 0.22 \qquad \mathrm{BR}(NN \to 2\ell 4q) \simeq 0.16$$

$$\mathbf{BP2_{NH}}: \quad r_{e4}^2 : r_{\mu 4}^2 : r_{\tau 4}^2 = 0.05 : 0.15 : 0.80 \qquad \mathrm{BR}(NN \to 2\tau 4q) \simeq 0.12$$

PROMPT DECAYS



$\lambda_{\rm lab} < 0.1$ cm

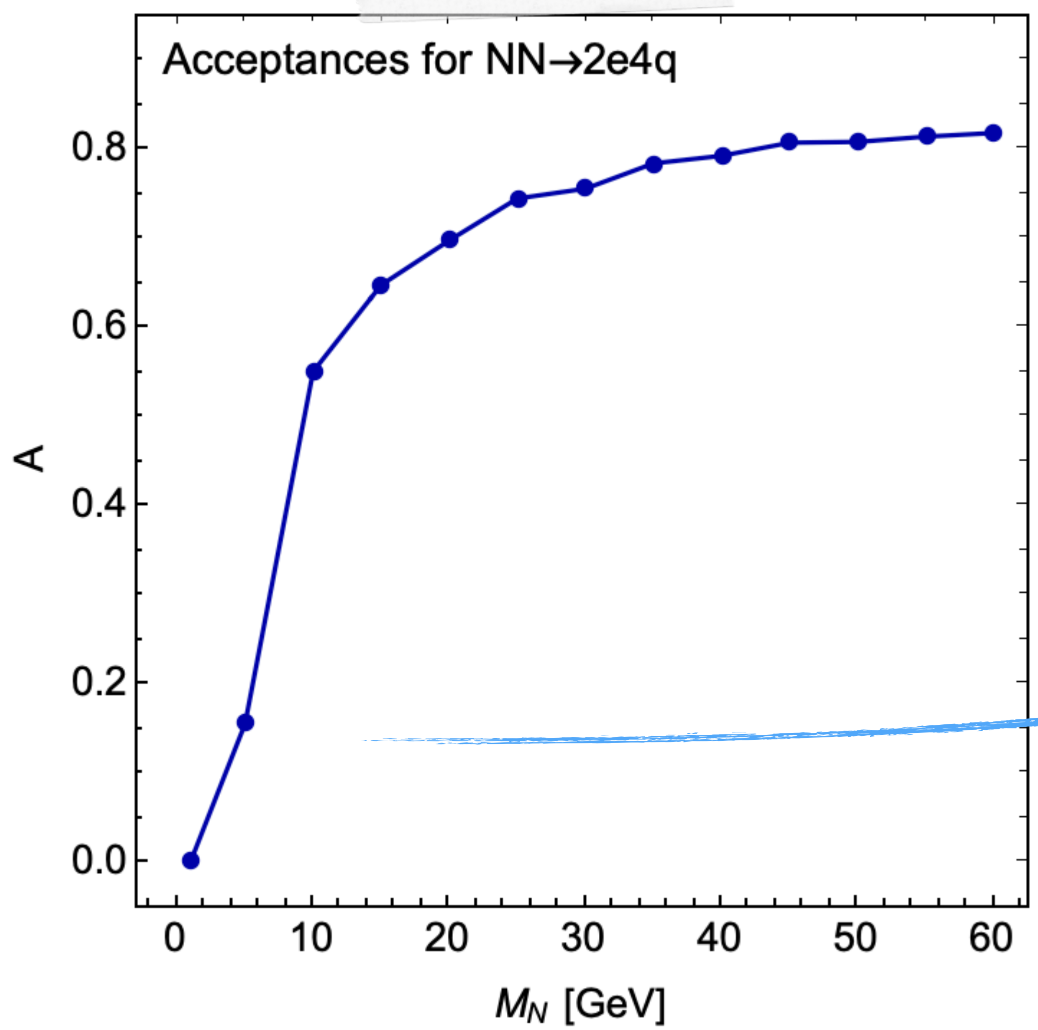
- First and second generation mixing

- Ask for $Z \to \ell^+\ell^-$
- Ask for $m_{\ell^+\ell^-}^{rec} = m_h$

Select Higgs-Strahlung process

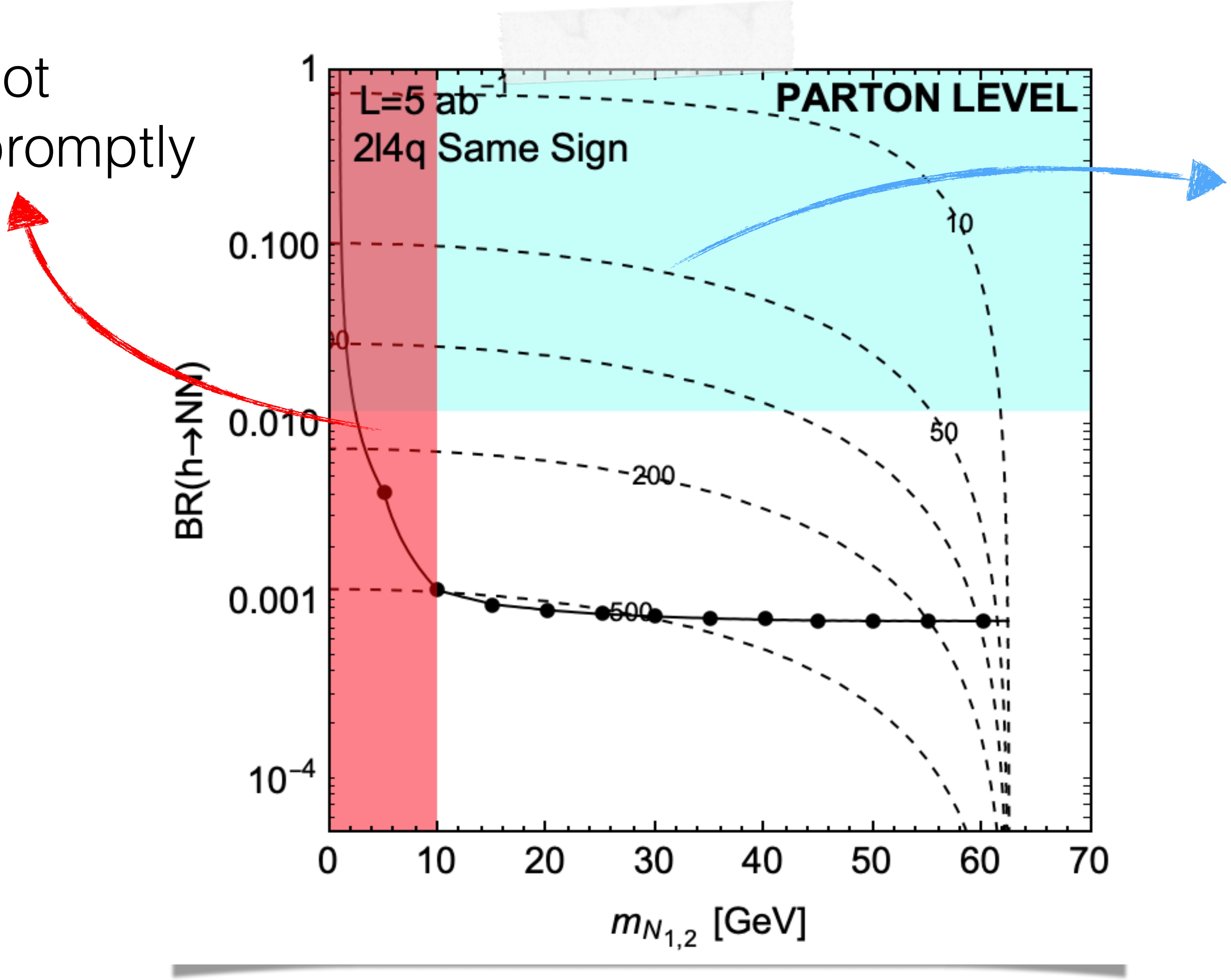
- Require an extra pair of SS leptons

Suppress SM backgrounds



Low acceptance at low mass due to isolation requirements

N cannot decay promptly



Limits from untagged H decays **[De Blas+ '19]**

- Sensitivity down to per-mill exotic Higgs branching ratios can be achieved!!
- Corresponds to $\Lambda \simeq 500\ \mathrm{TeV}$
- Can the flavor structure be determined once N is detected? Work in progress

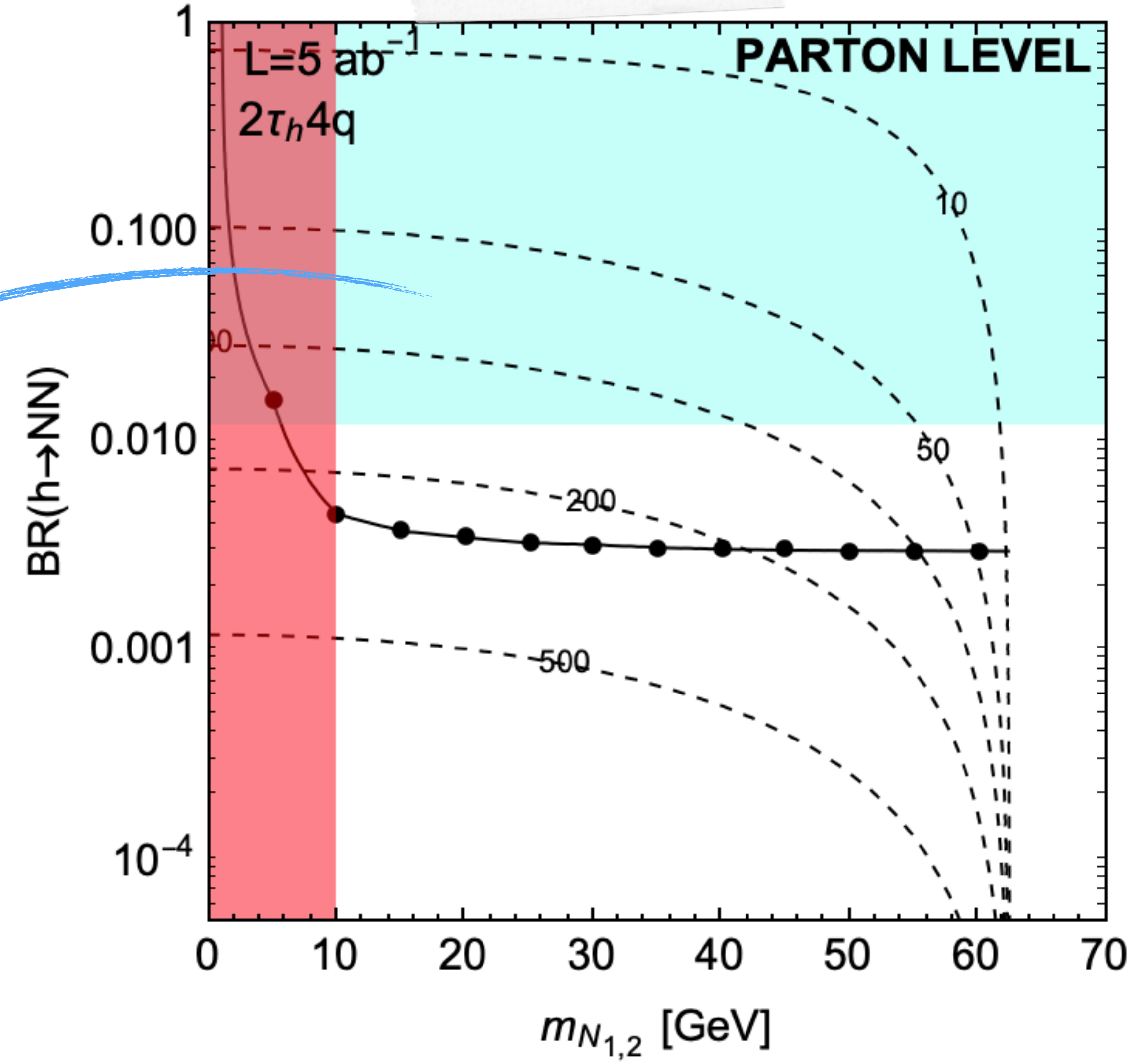
- Third generation mixing

- Ask for $Z \to \ell^+\ell^-$
- Ask for $m^{rec}_{\ell^+\ell^-} = m_h$

- Ask for
$\tau^- \to \pi^-\pi^0\nu_\tau$
$\tau^- \to \pi^-\nu_\tau$
$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$

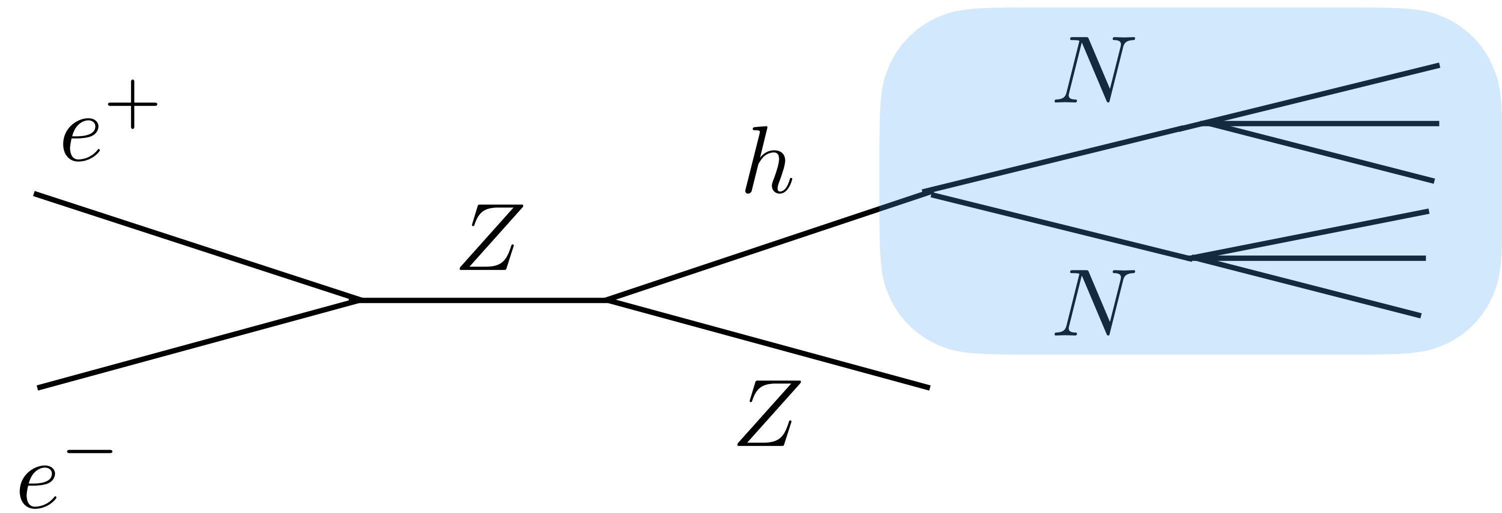
Select Higgs-Strahlung process

~46% of BR $\epsilon_{\tau_h} \simeq 90\%$ **[Tran+ '15]**



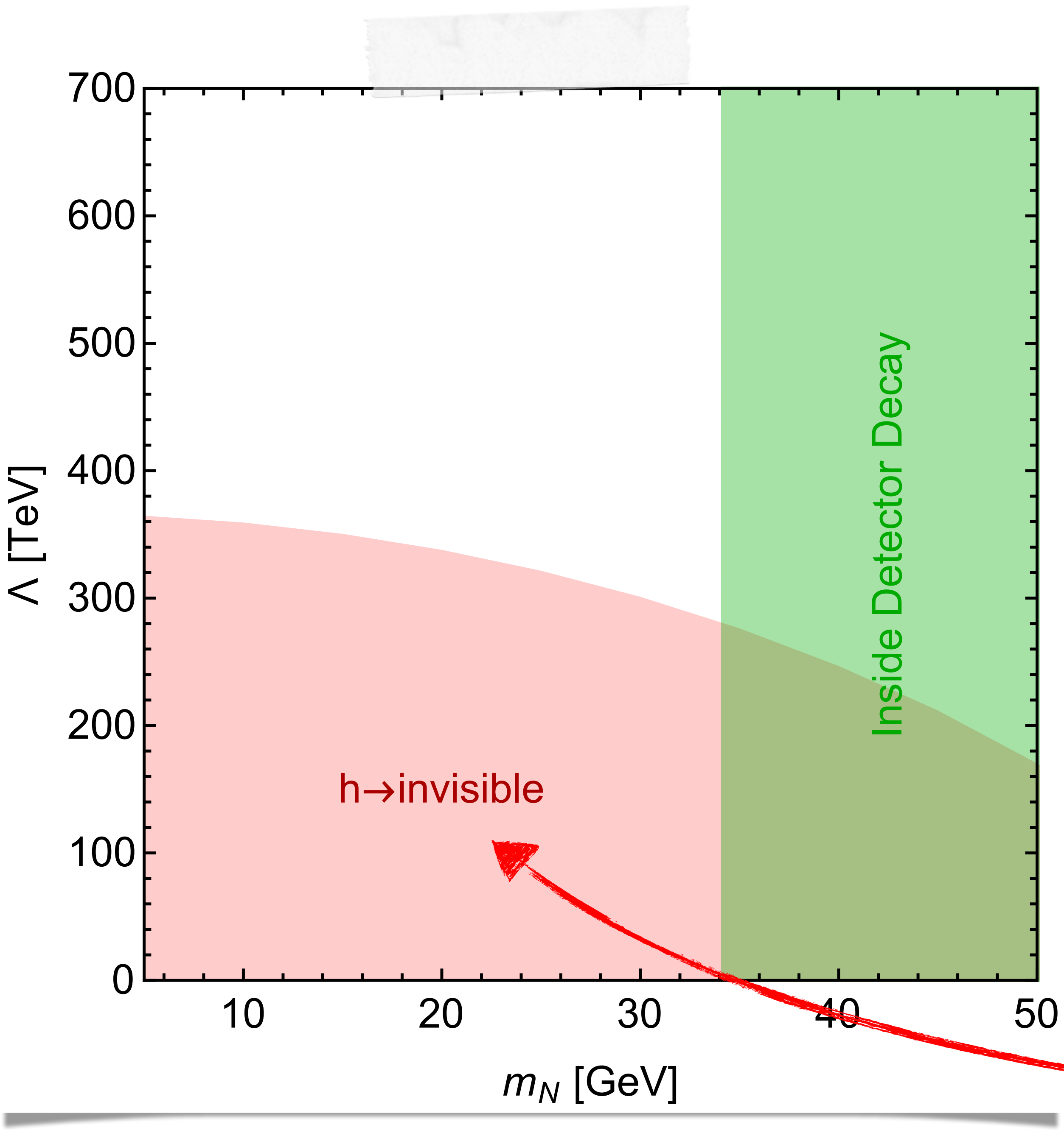
Parameter space not covered by indirect searches can be tested

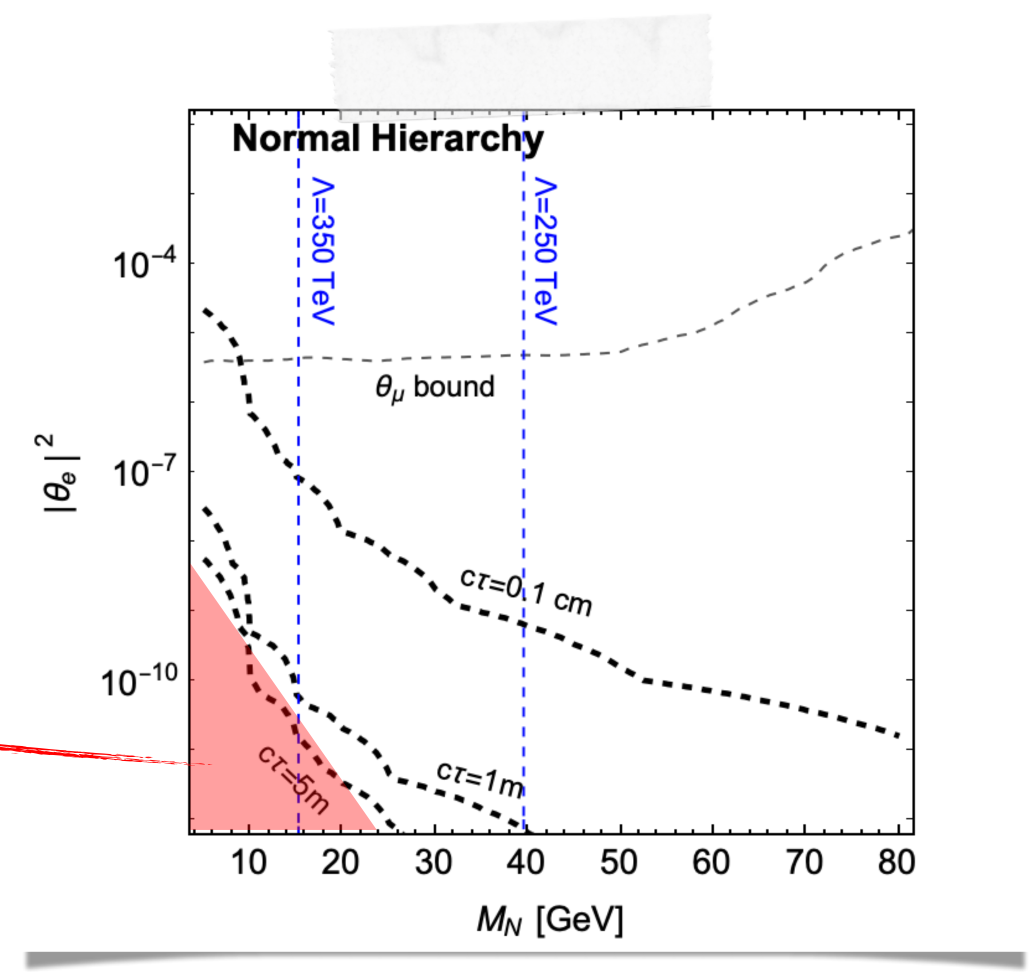
DETECTOR STABLE



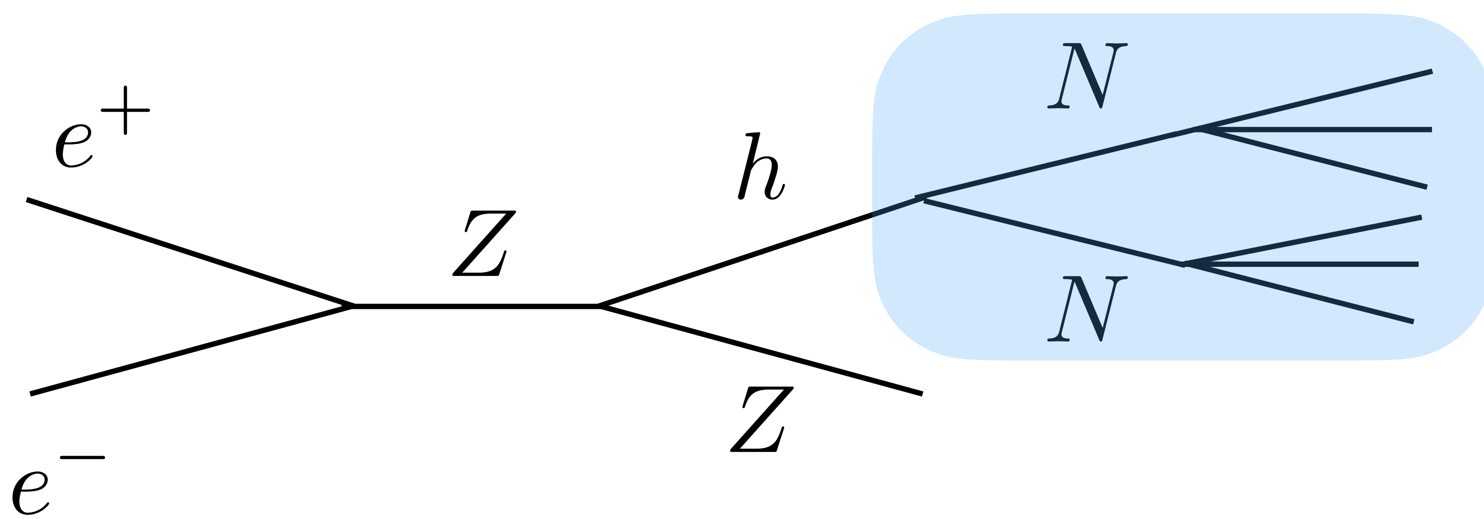
$\lambda_{\rm lab} > 5$ m

- Limits from Higgs invisible decays $\mathrm{BR}(h \to inv) \lesssim 0.22\%$ **[De Blas+ '19]**





DISPLACED DECAY



$$0.1 \text{ cm} < \lambda_{\text{lab}} < 1 \text{ m}$$

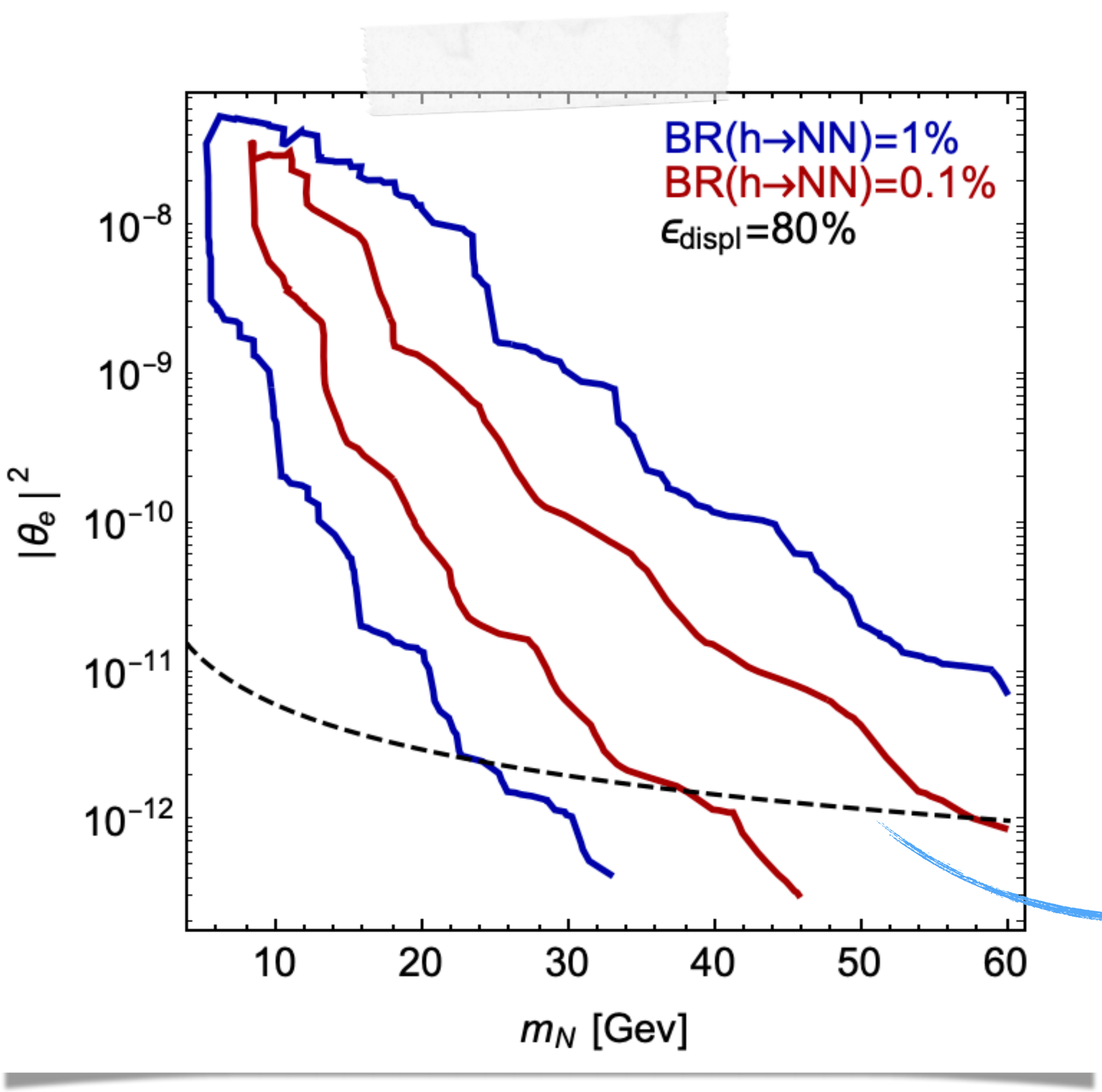
- First and second generation mixing

- Ask for $Z \to \ell^+\ell^-$
- Ask for $m^{rec}_{\ell^+\ell^-} = m_h$

Select Higgs-Strahlung process

Prompt!

- From the exponential decay law compute the probability to have two RH neutrinos decaying with a selected Δl



Seesaw limit $|\theta_e|^2 \simeq \dfrac{0.06\ \text{eV}}{m_N}$

- FCC-ee offers a great handle to search for long-lived RH neutrinos
  [Antush+ ’16, Blondel+ ’16]

- The naive seesaw scaling can be challenged when more than one RH neutrino is present in the spectrum

- RH neutrinos can decay promptly, displaced or be detector stable

- D>4 operators in the $\nu\mathrm{SMEFT}$ add new production and decay channels for RH neutrinos

- These extra production modes can be efficiently tested at future lepton colliders as FCC-ee both in at the Z-pole and at the Higgs threshold

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Thank you!