Lepton Number Breaking from the Electroweak Scale

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(Work in progress)

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Motivation

- Neutrinos are not massless.
  - Origin of neutrino mass? Smallness? Dirac or Majorana?
- Seesaw Mechanism and Majorana neutrino
  - Type-1 seesaw, Heavy Neural Leptons (right-handed neutrinos) N are introduced.
  - HNL mass term violates lepton number L by 2 units and could be high mass scale, e.g. $M_N \gtrsim 10^9\ GeV$ for thermal Leptogenesis (challenging to probe experimentally).
  - If M_N is lower-scale, e.g. the electroweak scale, the physics can be probed by our current experiments.

Can lepton number symmetry be broken at the weak scale?

Lepton Number Breaking from the Weak Scale

- In SM, the Higgs doublet Φ does not carry lepton number:

$$\overset{0}{(\Phi^\dagger}\overset{0}{\Phi)}\overset{-1}{N}\overset{-1}{N} \xrightarrow[\text{EWSB}]{} \frac{1}{2}v^2\overset{-1}{N}\overset{-1}{N}$$, but $(\Phi^\dagger\Phi)NN$ does not preserve lepton number.

- To preserve global $U(1)_L$ symmetry above the weak scale, need an additional Higgs doublet Φ_1 which carries Lepton number beside the one Φ_2 that does not carry lepton number:

$$\underline{\overset{+2}{(\Phi_1^\dagger}\overset{0}{\Phi_2)}\overset{-1}{N}\overset{-1}{N}} \xrightarrow[\text{EWSB}]{} \frac{1}{2}v_1v_2\overset{-1}{N}\overset{-1}{N}$$ and breaks lepton number from the weak scale.

↑ dim=5, effective operator of some higher-scale physics. Hence, $\frac{C}{\Lambda_{NP}}\Phi_1^\dagger\Phi_2 NN$

Effective Field Theory (2HDML)

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_{i=1,2} (D^\mu \Phi_i)^\dagger (D_\mu \Phi_i) - V(\Phi_1, \Phi_2) + iN^\dagger \bar{\sigma}^\mu \partial_\mu N - \frac{C}{\Lambda} \Phi_1^\dagger \Phi_2 NN - Y_\nu \ell \Phi_2 N + h.c$$

SM Yukawa sectors all coupled to Φ_2

Two-Higgs Doublet Model (2HDM) Lagrangian

HNL Lagrangian, responsible for neutrino mass generation

- The tree-level two-Higgs doublet potential:

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$-(m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.)$$

Softly break lepton number symmetry

  - CP conserving, flavor limit
  - Lepton number symmetry prevents the term $\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + h.c.$

Neutrino Mass Generation via Type-1 Seesaw

Consider $\mathscr{L}_\nu \supset -\frac{C}{\Lambda}\Phi_1^\dagger\Phi_2 NN - Y_\nu \ell \Phi_2 N + h.c$

$$v_1^2 + v_2^2 \equiv v^2 \simeq (246\ GeV)^2,$$
$$v_1 = v\cos\beta,\ v_2 = v\sin\beta,\ \tan\beta = \frac{v_2}{v_1}$$

- For simplified single-generation model, $\langle \Phi_i \rangle = v_i/\sqrt{2}$.

$$(\frac{1}{2}\frac{C}{\Lambda}v^2\sin\beta\cos\beta)NN + \frac{Y_\nu v\cos\beta}{\sqrt{2}}\nu N \equiv \frac{1}{2}(\nu \quad N)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

with $m_D = \frac{Y_\nu v\cos\beta}{\sqrt{2}}$; $M = \frac{C}{\Lambda}v^2\cos\beta\sin\beta = \frac{C}{\Lambda}v^2\frac{1+\tan^2\beta}{\tan\beta}$

$$M \lesssim v$$

In the mass basis, $\nu \to i\cos\theta\ \nu + \sin\theta\ N$
$N \to -i\sin\theta\ \nu + \cos\theta\ N$

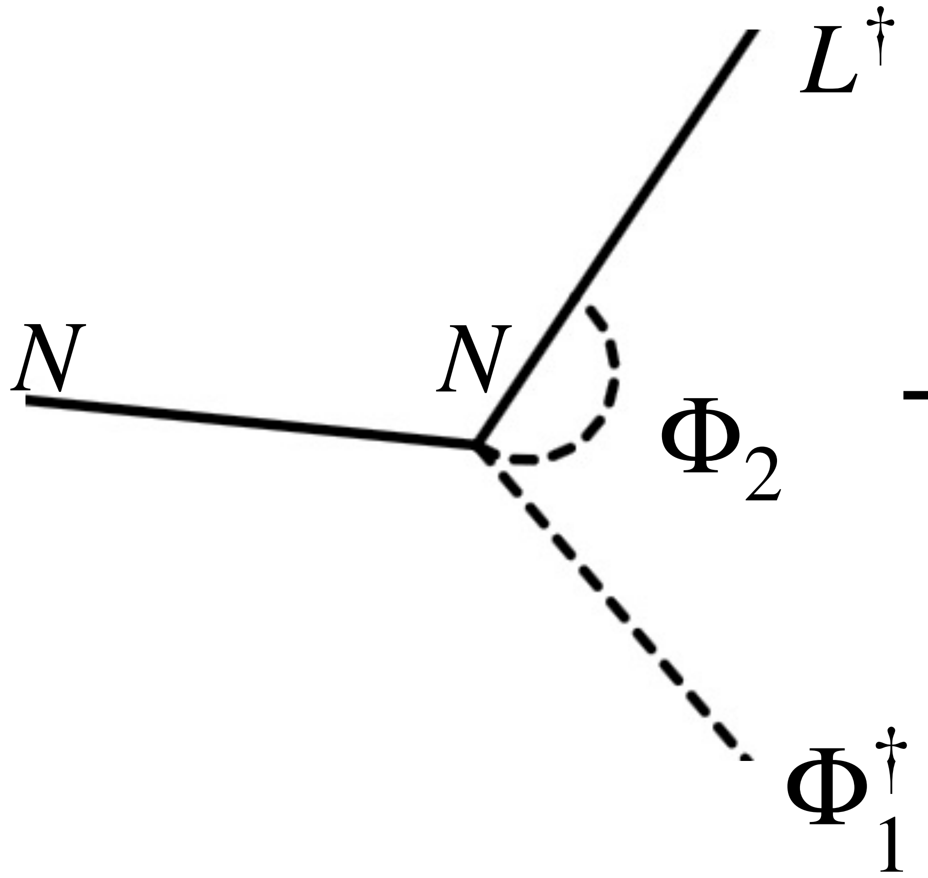
In the limit $m_D \ll M$, $m_\nu \simeq \frac{m_D^2}{M}$, $m_N \simeq M$ and $\cos\theta \simeq 1, \sin\theta \simeq m_D/M$

- For $n \geq 2$, the generation is done by Casas-Ibarra Parametrization and fitting to the neutrino oscillation data

Quantum Correction to HNL Mass

One-loop contribution

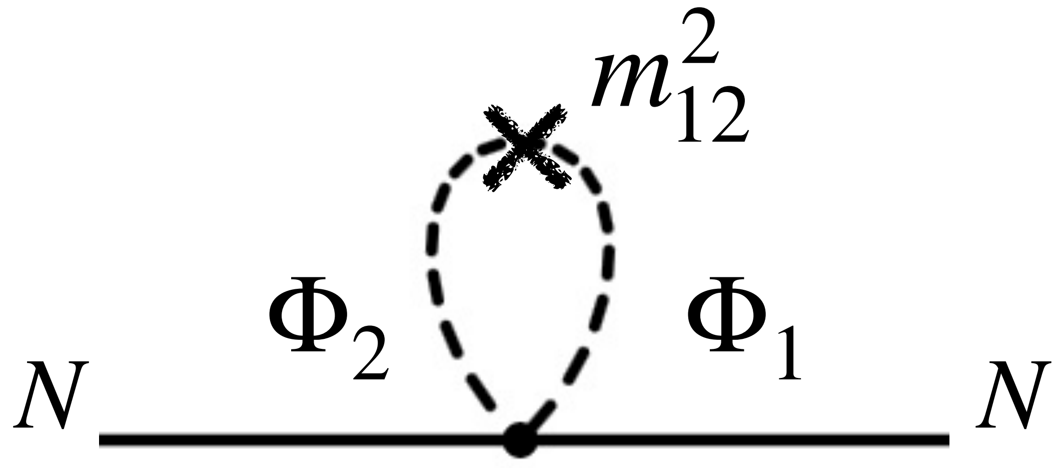
1. Dynamically generated Weinberg-type operator $(L\Phi_1)(L\Phi_2)$



$+$ field redefinition of N by EOM $\Longrightarrow \sim \dfrac{Y_\nu^2 C}{16\pi^2\Lambda}(L\Phi_1)(L\Phi_2)$

$$\frac{Y_\nu^2 C}{16\pi^2\Lambda} \ll \frac{C}{\Lambda}$$

2. Correction to N mass from $\dfrac{C}{\Lambda}\Phi_1^\dagger\Phi_2 NN + m_{12}^2\Phi_2^\dagger\Phi_1$



$$\Longrightarrow \quad \frac{C}{\Lambda}\frac{m_{12}^2}{16\pi^2} \ll \frac{1}{2}\frac{C}{\Lambda}v^2\sin\beta\cos\beta \quad \Longrightarrow \quad m_{12}^2 \ll 4\pi v^2$$

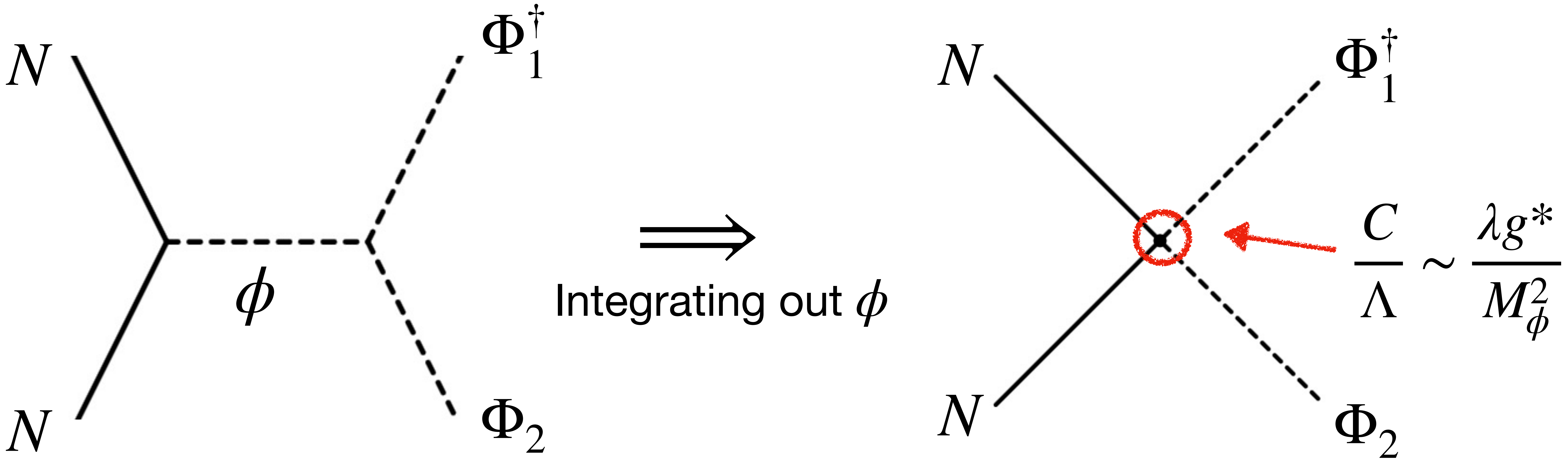
The correction to HNL mass term is small.

UV Completion

Scalar Singlet Example

Consider a heavy complex scalar singlet ϕ carrying lepton number $L = +2$

$$\mathscr{L} \supset \partial_\mu \phi^\dagger \partial^\mu \phi - M_\phi^2 \phi^\dagger \phi - \lambda \phi N N - g \phi \Phi_2^\dagger \Phi_1 + h.c.$$



Two-Higgs Doublet Model (2HDM)

- Expansion of the Higgs fields around the vev's:

$$\Phi_i = \begin{pmatrix} \Phi_i^+ \\ (v_i + \rho_i + i\eta_i)/\sqrt{2} \end{pmatrix}, \quad i = 1,2$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} \qquad \begin{aligned} A &= -\eta_1 \sin\beta + \eta_2 \cos\beta \\ H^\pm &= -\Phi_1^\pm \sin\beta + \Phi_2^\pm \cos\beta \end{aligned}$$

$$h_{SM} = H\cos(\beta - \alpha) + h\sin(\beta - \alpha)$$ (In the Higgs basis)

	Φ_2	Φ_1
Type-1	u, d, l	
Type-2	u	d, l
Lepton-specific	u, d	l
Flipped	u, l	d

Our model (2HDML) is Type-1.

- Parameters

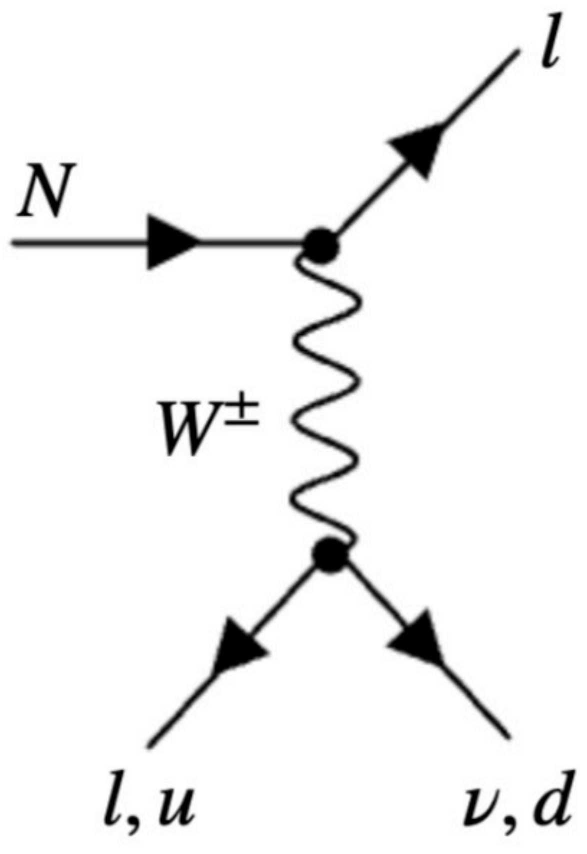
$$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, m_{12}^2 \;\rightarrow\; v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

v → 246 GeV; m_h → ~125 GeV

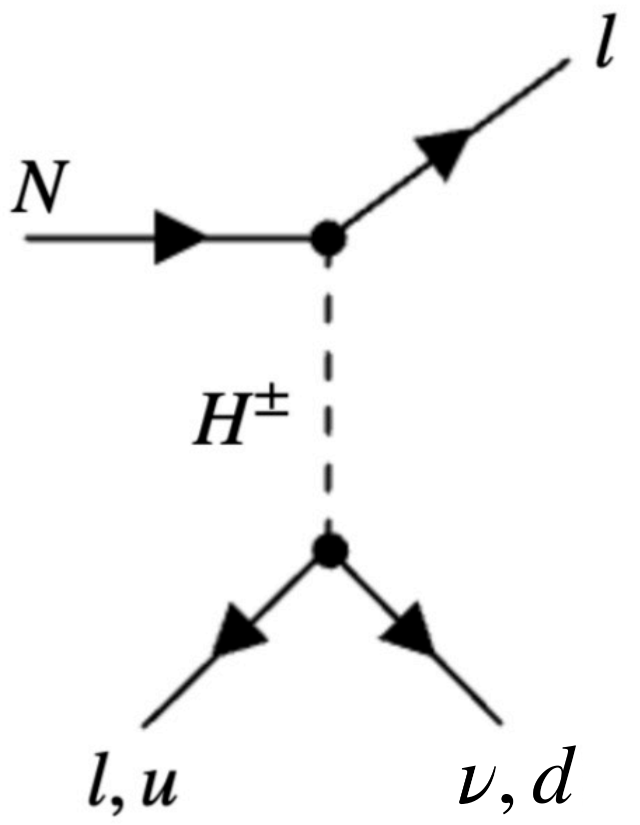
Heavy Neutral Lepton N

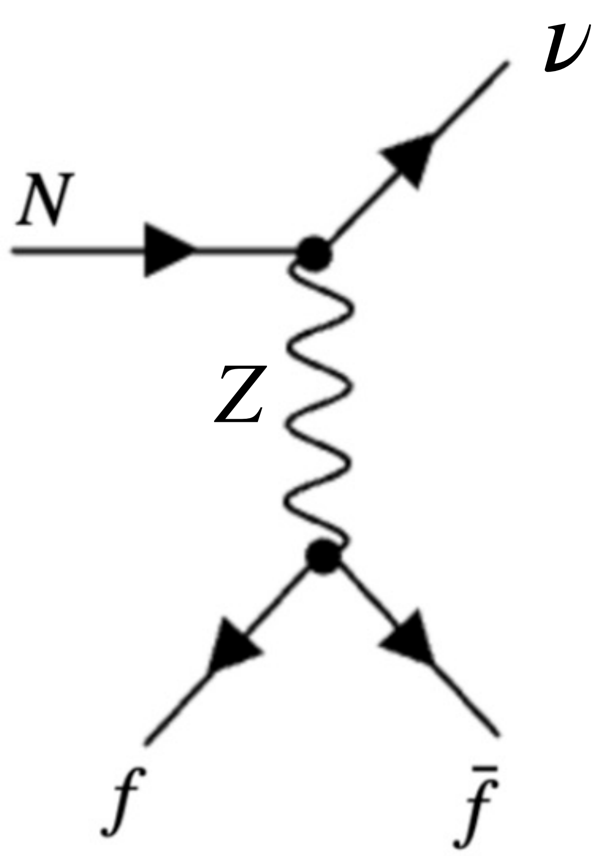
Examples of New decay channels

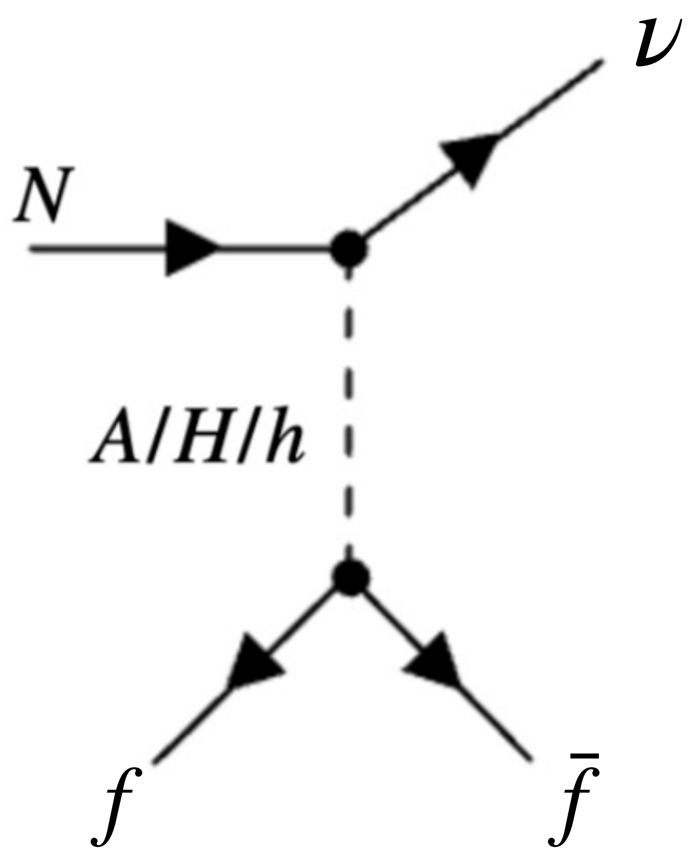
usual HNL:



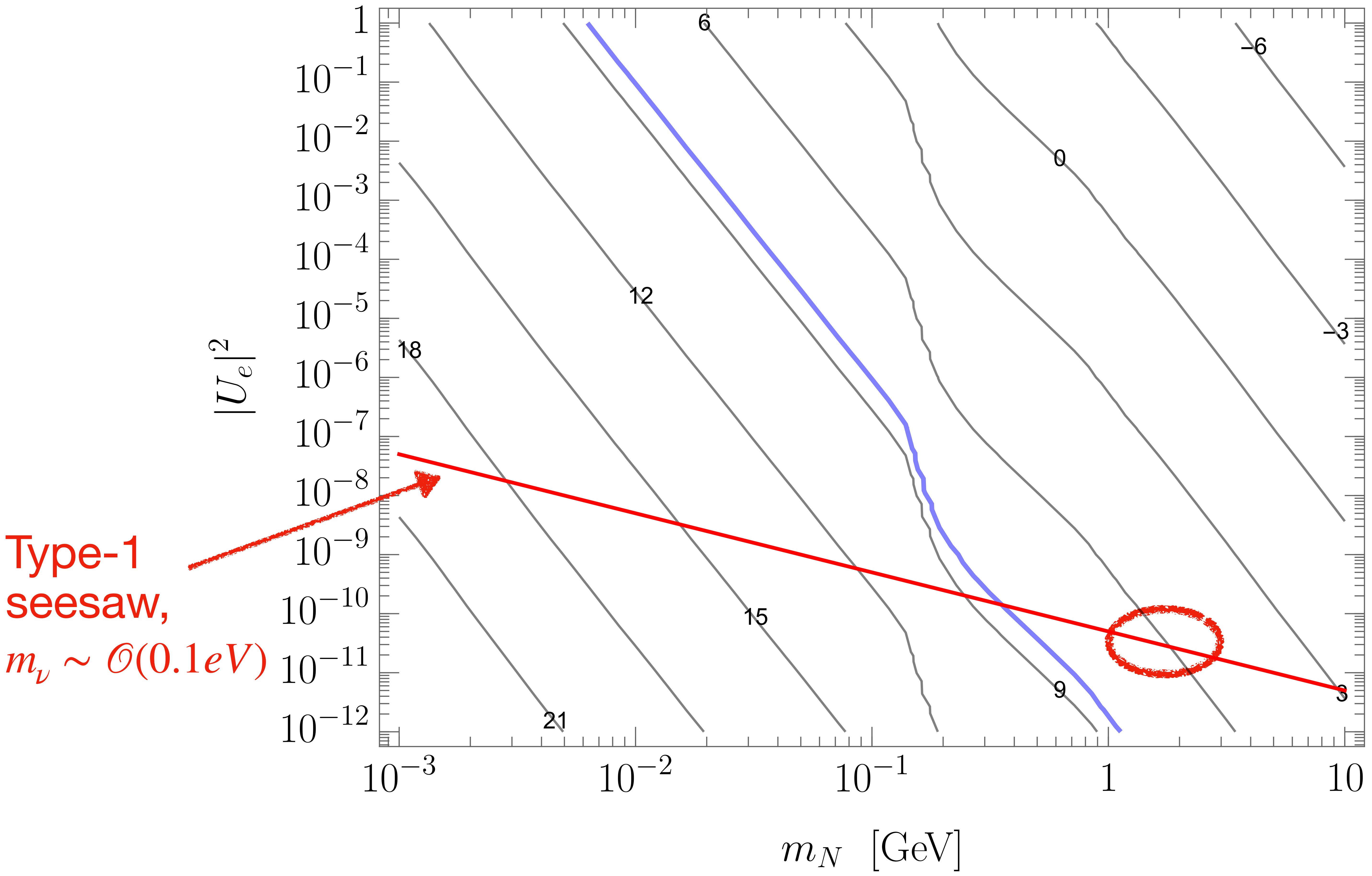
New in 2HDML:







GeV-scale HNL, which satisfies the seesaw relation, is long-lived.
$c\tau_N$ ($\gtrsim 10^6 m$) $\gg$ size of LHC detectors.



Light CP-Even Higgs h

$$\kappa_f \sum_{f=q,l} \frac{m_f}{v} h f \bar{f} + \kappa_N \frac{M}{v} hNN$$

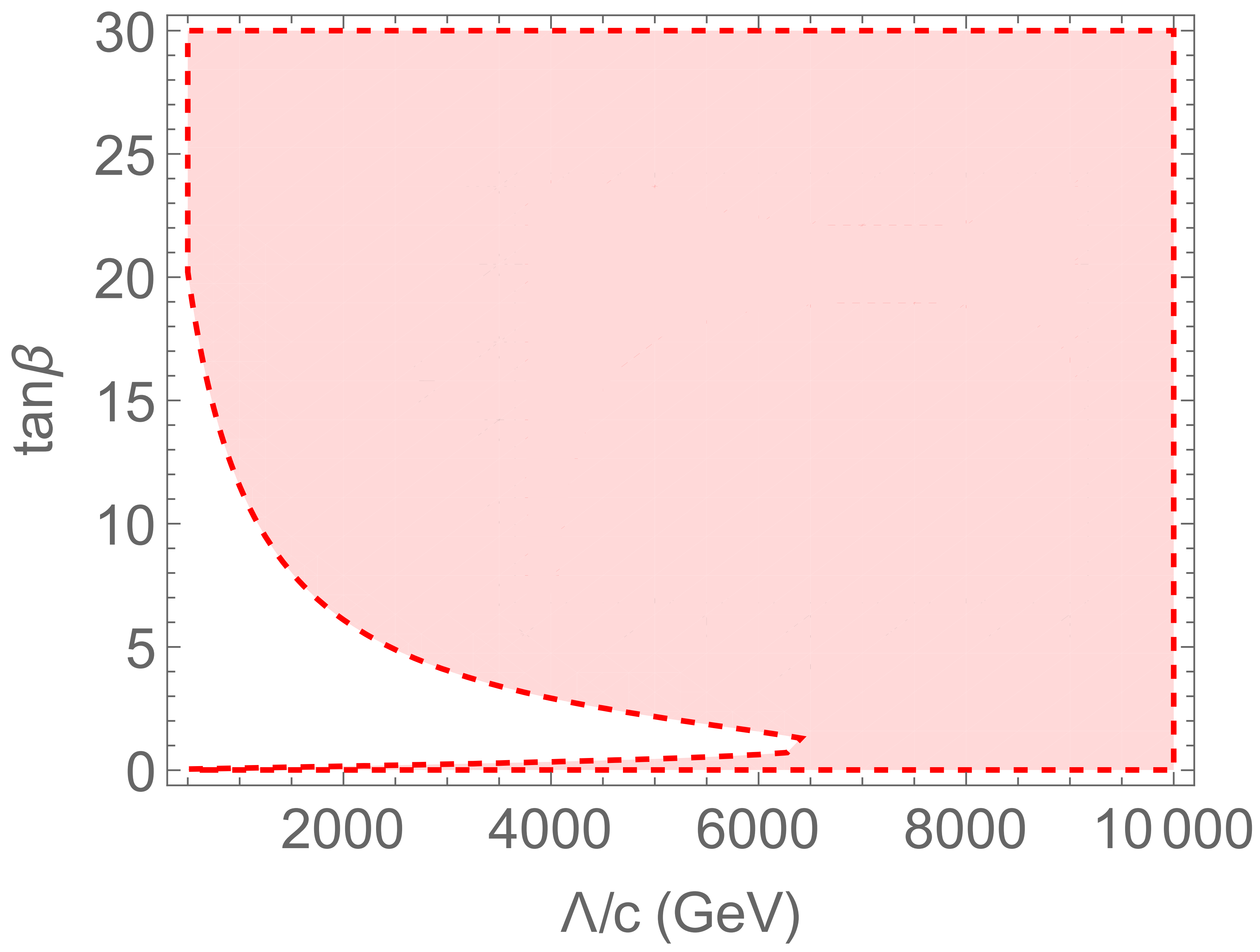
$$\kappa_f = \sin(\beta-\alpha) + \cos(\beta-\alpha)/\tan\beta$$

$$\kappa_N = \cos^2\theta \, [\frac{\cos(\beta-\alpha)}{2}(\frac{1}{\tan\beta} - \tan\beta) + \sin(\beta-\alpha)]$$

Measurements of the SM Higgs couplings place constraint on $\cos(\beta-\alpha)$: $\cos(\beta-\alpha)$ close to 0.

Higgs invisible decay: $h \to NN$

- Observed BR(h->inv) < 0.107 at the 95% CL (combined Run1+Run2 data at LHC; VBF, ggF, Zh, tth production modes are considered) [ATLAS, 2023, arXiv: 2301.10731]
- Derive an upper bound on N mass, ~3 GeV

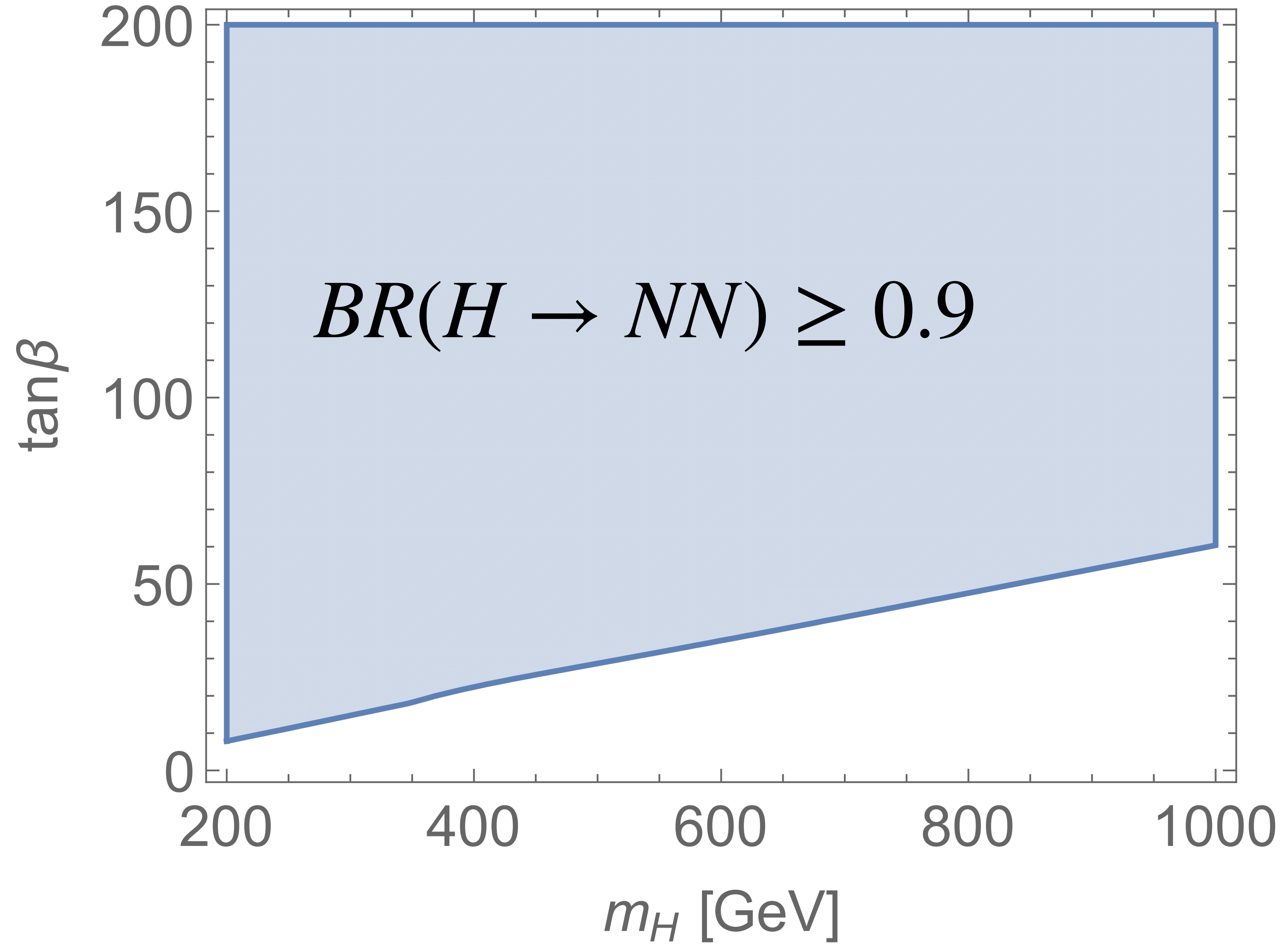


Heavy CP-Even Higgs H

$$\kappa_f \sum_{f=q,l} \frac{m_f}{v} H f \bar{f} + \kappa_N \frac{M}{v} HNN$$

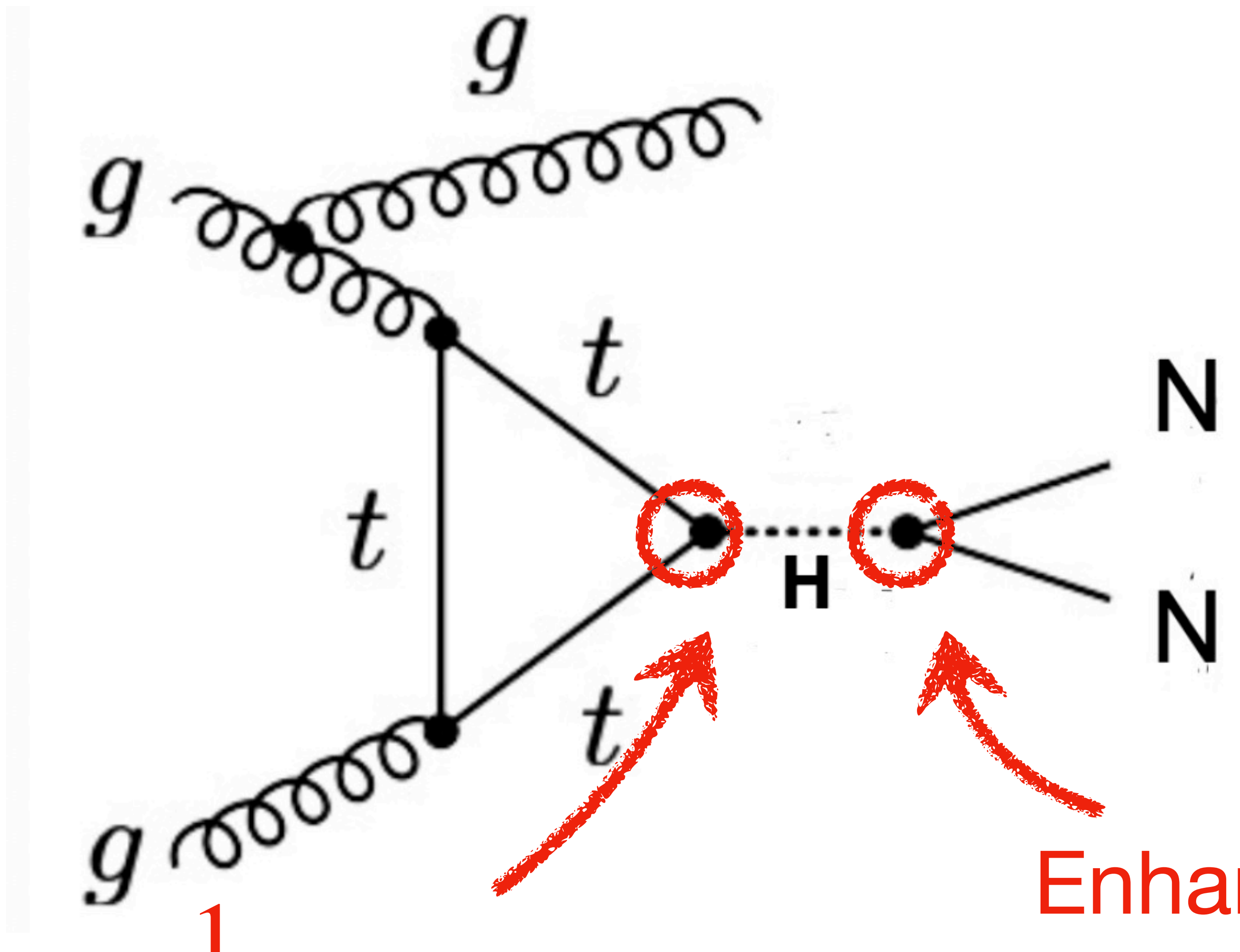
$$\kappa_f = \cos(\beta - \alpha) - \sin(\beta - \alpha)/\tan\beta$$

$$\kappa_N = \cos^2\theta\ [\cos(\beta - \alpha) - \frac{1}{2}\sin(\beta - \alpha)(\tan\beta - \frac{1}{\tan\beta})]$$



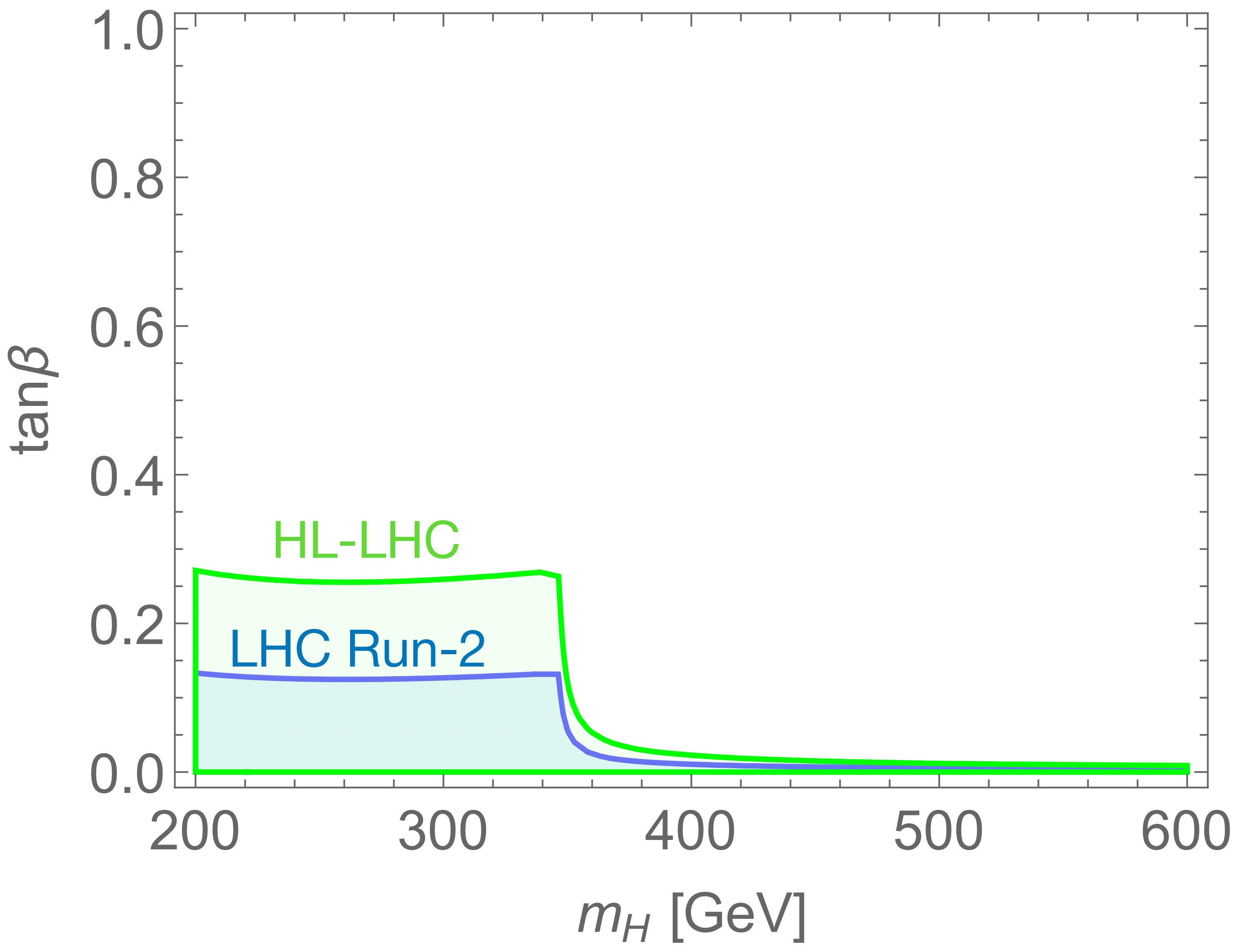
Mono-jet+ $\not{E}_T$

[ATLAS, 2021, arXiv: 2102.10874]



suppressed by $\frac{1}{\tan\beta}$ for $\tan\beta > 1$

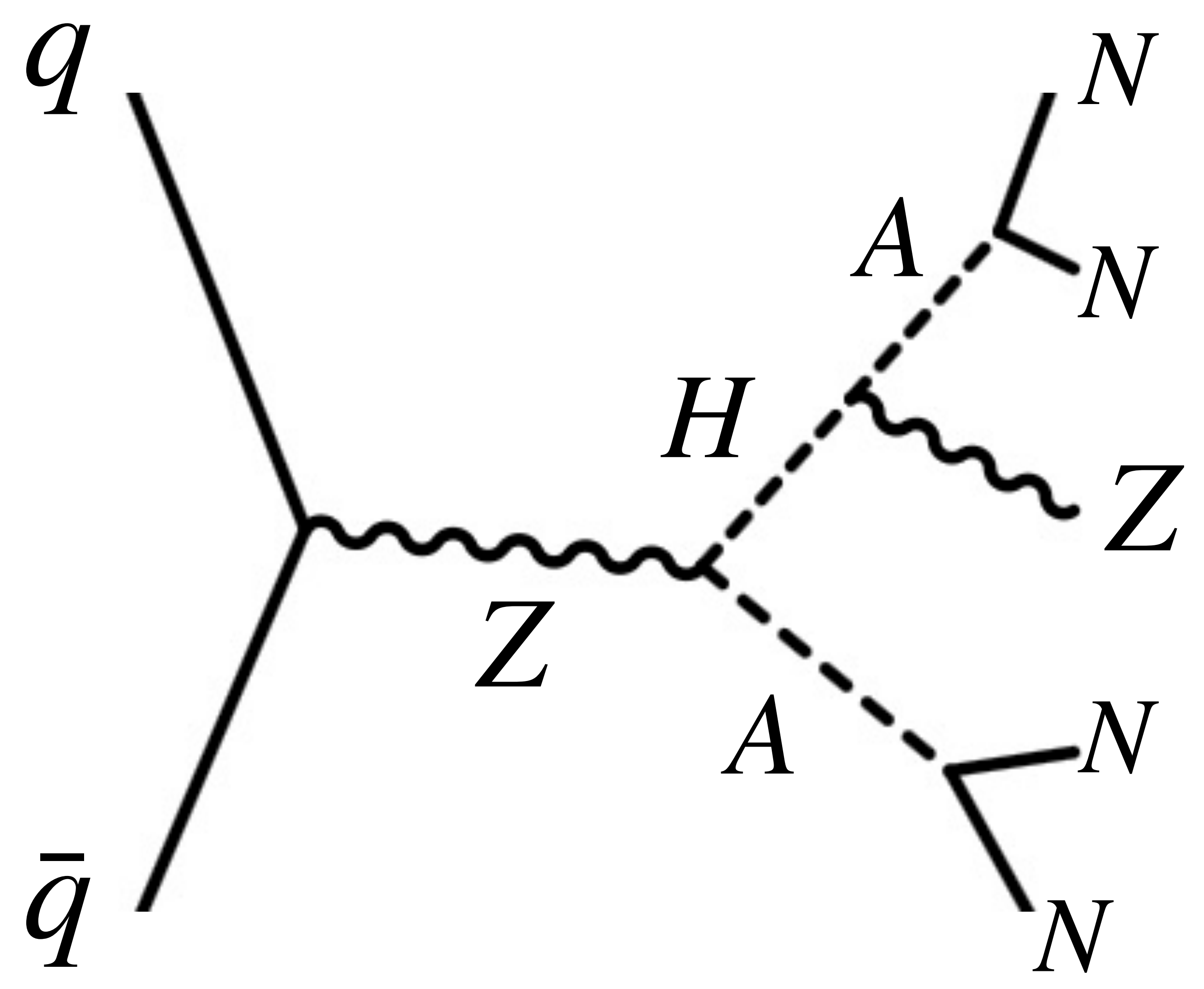
Enhanced by $\tan\beta$ for large $\tan\beta$



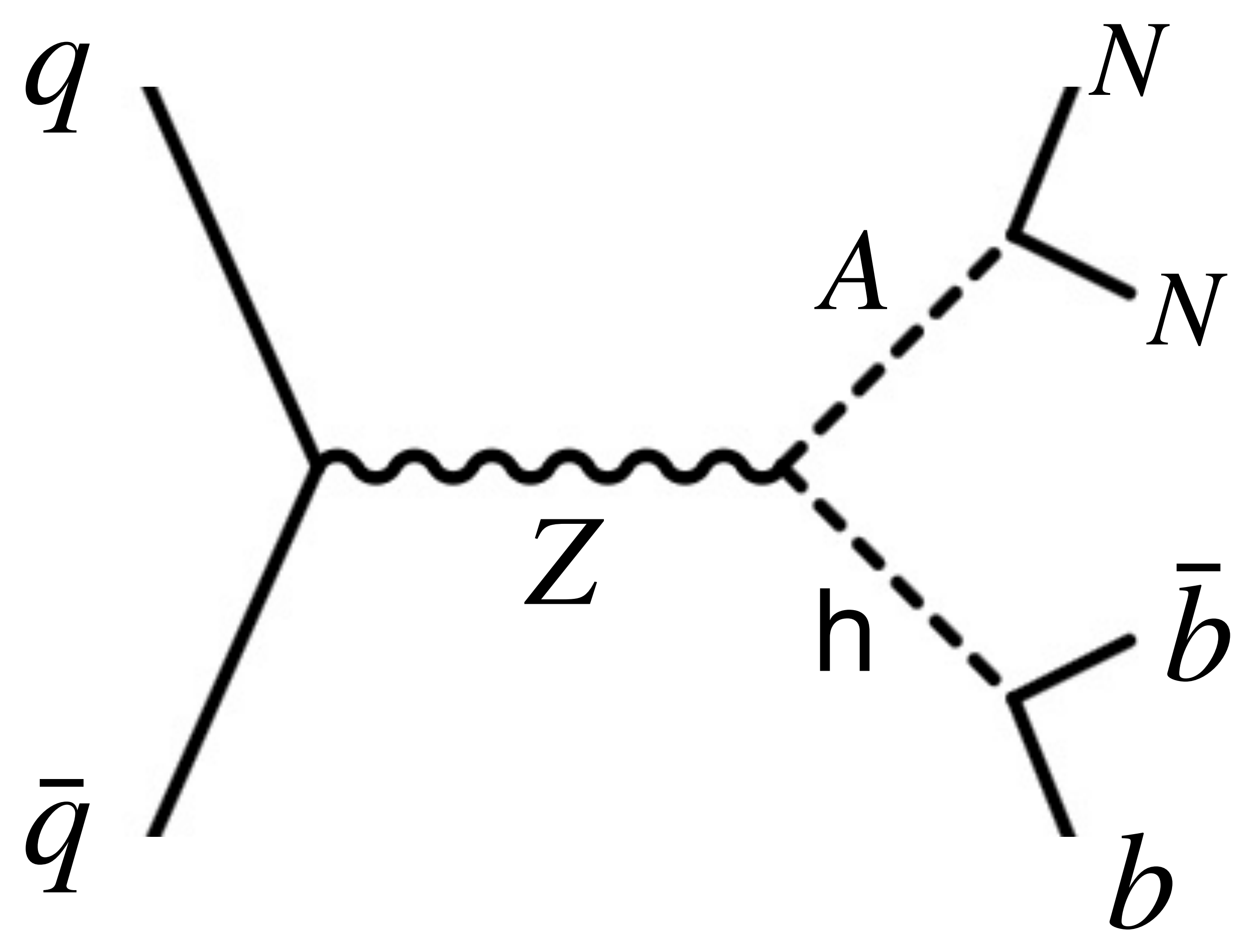
Potentially More Optimal Searches

associated production (analysis in progress)

mono-$Z + \not{E}_T$



mono-higgs + $\not{E}_T$

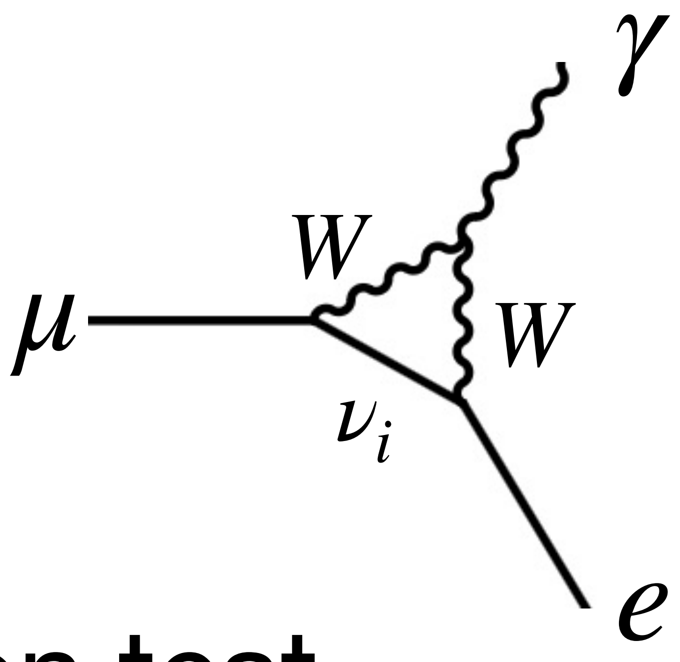


can consider A->NN decay without $1/\tan\beta$ suppression in large $\tan\beta$ region

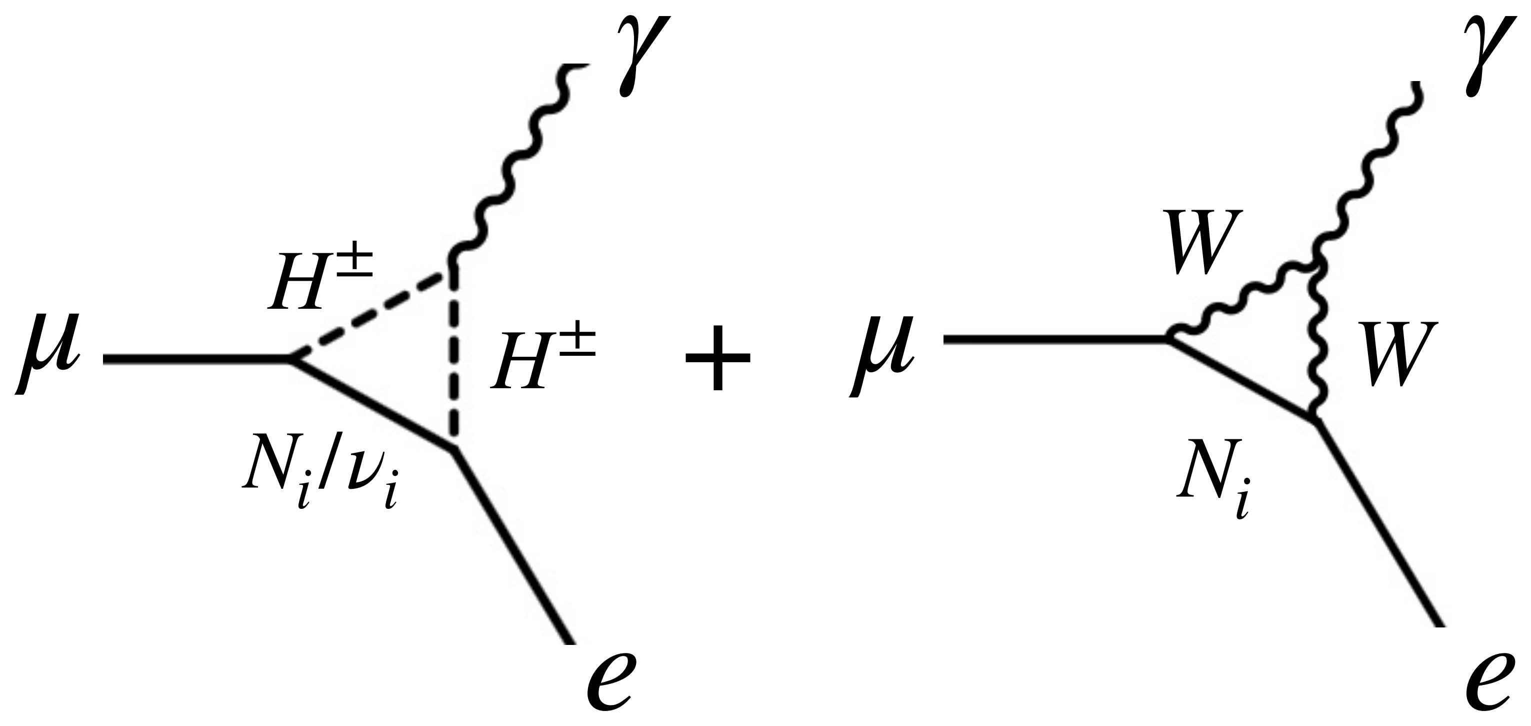
Outlook and Work in Progress

- Lepton flavor violation:

In SM:

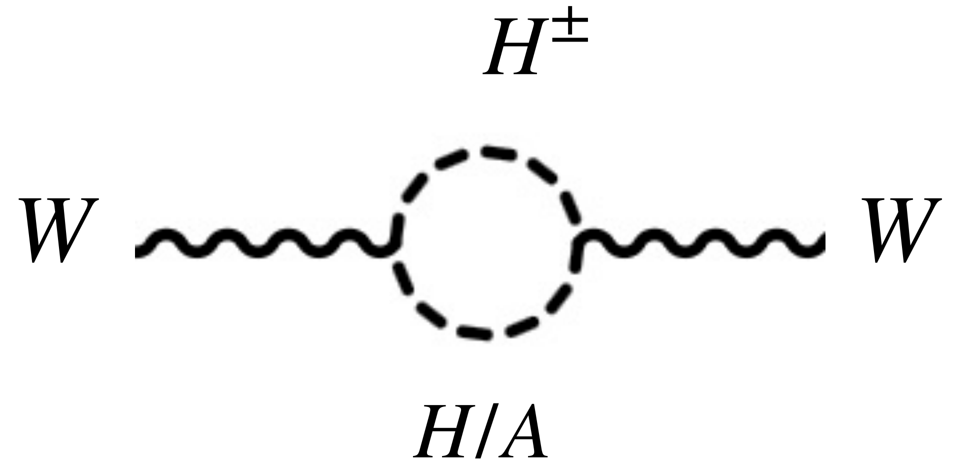


In 2HDML:



- EW precision test

e.g. correction to W,Z masses



- Other probes of HNLs (fix-target experiments, meson decay, etc)
- What if $L(N) = +1$? How does this lepton number assignment change the story?

Summary of our work by far

- 2HDML is a simple extension of SM. In this model, lepton number symmetry is broken from the weak scale and the HNL mass is predicted to be lighter than the weak scale.
- Correction to HNL mass at 1-loop level is small, which avoids spoiling the Type-1 seesaw mechanism.
- GeV-scale HNL, which satisfies the seesaw relation, is a long-lived particle, and thus $h \to NN$ is invisible at the LHC. We have shown that an upper bound $\sim \mathcal{O}(1)$ GeV on the HNL mass can be derived from analysis of this decay.
- $A/H \to NN$ becomes the dominant decay channel of A/H for large $\tan\beta$ in 2HDML. Yet the Yukawa couplings of A/H to fermions pairs in 2HDML are proportional to $1/\tan\beta$, which suppresses the production of A/H at LHC.

(Our work is ongoing with various potential directions to explore due to the rich phenomenology in 2HDML.)

Backup Slides

Extension to the Standard Model (SM)

- Type-1 seesaw: Introduce Right-Handed Neutrinos (RHN) $\bar{\nu}$
- To preserve global $U(1)_L$ symmetry above the weak scale, need an extra Higgs doublet carrying Lepton number while the SM Higgs doublet doesn't

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
Φ_1	1	2	$\frac{1}{2}$	-2
Φ_2	1	2	$\frac{1}{2}$	0
L	1	2	-$\frac{1}{2}$	1
Q	3	2	$\frac{1}{6}$	0
N	1	1	0	-1 (+1)
$\bar{l}$	1	1	1	1
$\bar{u}$	3	1	-$\frac{2}{3}$	0
$\bar{d}$	3	1	$\frac{1}{3}$	0

TABLE I. Quantum number assignments for fields.

Lepton number carrying doublet

SM-like Higgs doublet

Right-handed neutrino/
Heavy neutral lepton

2HDM Physics Spectrum (in Physical Basis)

$$\mathscr{L} \supset -\begin{pmatrix}\Phi_1^- & \Phi_2^-\end{pmatrix}\mathscr{M}_\pm^2\begin{pmatrix}\Phi_1^+ \\ \Phi_2^+\end{pmatrix} - \frac{1}{2}\begin{pmatrix}\eta_1 & \eta_2\end{pmatrix}\mathscr{M}_A^2\begin{pmatrix}\eta_1 \\ \eta_2\end{pmatrix} - \frac{1}{2}\begin{pmatrix}\rho_1 & \rho_2\end{pmatrix}\mathscr{M}_h^2\begin{pmatrix}\rho_1 \\ \rho_2\end{pmatrix} + \mathscr{L}_{int}$$

- $\mathscr{M}_\pm^2 = m_\pm^2\begin{pmatrix} s_\beta^2 & -c_\beta s_\beta \\ -c_\beta s_\beta & c_\beta^2\end{pmatrix};\ \ \mathscr{M}_A^2 = m_A^2\begin{pmatrix} s_\beta^2 & -c_\beta s_\beta \\ -c_\beta s_\beta & c_\beta^2\end{pmatrix};\ \ \mathscr{M}_h^2 = \begin{pmatrix} m_{h11}^2 & m_{h12}^2 \\ m_{h12}^2 & m_{h22}^2\end{pmatrix}$
- $m_\pm^2 = \frac{1}{2}\frac{m_{12}^2 + m_{12}^{2*}}{c_\beta s_\beta} - \frac{1}{2}\lambda_4 v_0^2;\ \ m_A^2 = \frac{1}{2}\frac{m_{12}^2 + m_{12}^{2*}}{c_\beta s_\beta}$

  $m_{h11}^2 = \frac{1}{2}(m_{12}^2 + m_{12}^{2*})\tan\beta + \lambda_1 v_0^2\cos\beta^2;\ \ m_{h22}^2 = \frac{1}{2}(m_{12}^2 + m_{12}^{2*})\cot\beta + \lambda_2 v_0^2\sin\beta^2;$

  $m_{h12}^2 = -\frac{1}{2}(m_{12}^2 + m_{12}^{2*}) + (\lambda_3 + \lambda_4)v_0^2\sin\beta\cos\beta$
- $\begin{pmatrix}G^\pm \\ H^\pm\end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta\end{pmatrix}\begin{pmatrix}\Phi_1^\pm \\ \Phi_2^\pm\end{pmatrix};\ \ \begin{pmatrix}G^0 \\ A\end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta\end{pmatrix}\begin{pmatrix}\eta_1 \\ \eta_2\end{pmatrix};\ \ \begin{pmatrix}H \\ h\end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha\end{pmatrix}\begin{pmatrix}\rho_1 \\ \rho_2\end{pmatrix}$