# Heavy Neutrinos and Displaced Vertices in Higgs Decays

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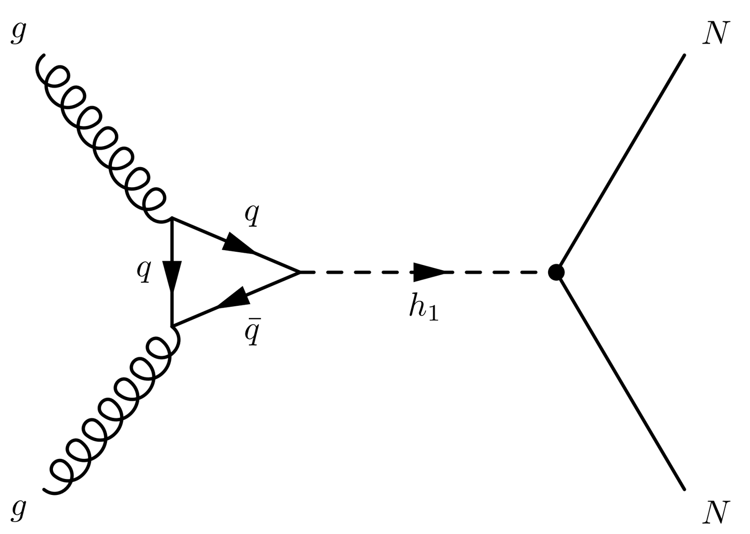
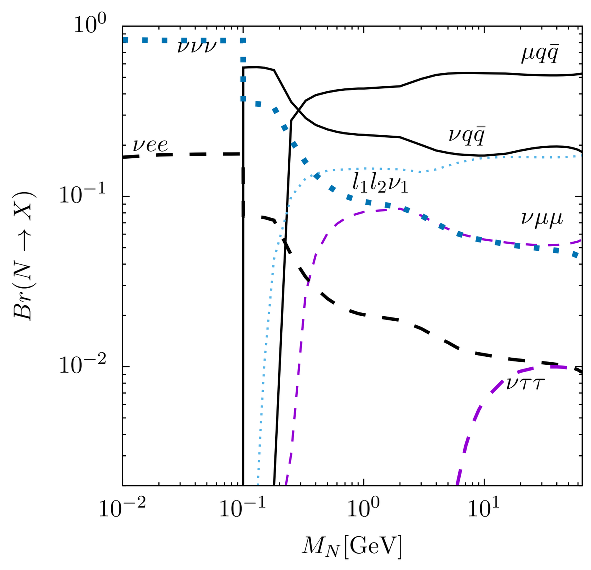
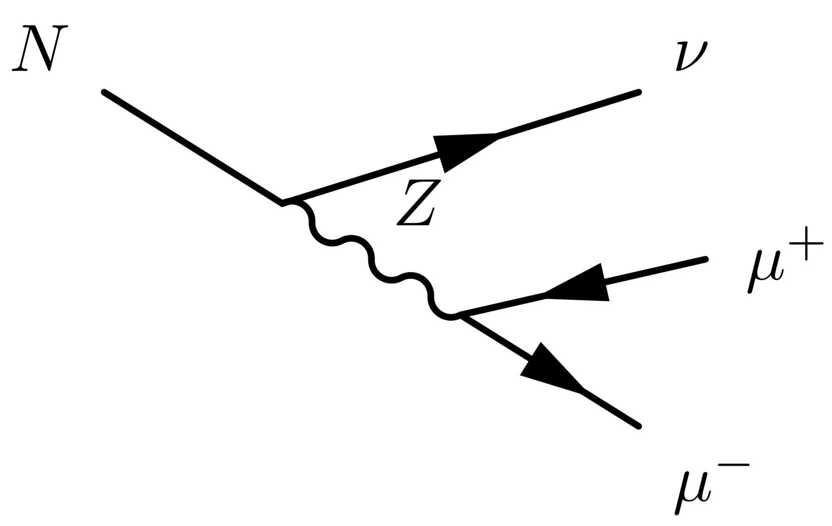
## Introduction

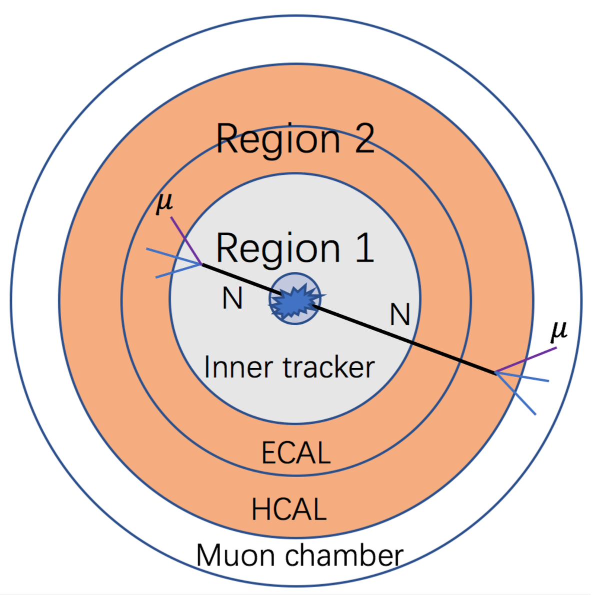
The observation of light neutrino masses and mixings serves as unambiguous experimental evidence for the existence of Physics Beyond the Standard Model (BSM). One of the simplest scenarios to explain the light neutrino masses is the $U(1)_{B-L}$ model, with an additional scalar field $\chi$ and right-handed(RH) neutrinos $N_i$. The vacuum expectation value of $\chi$ breaks the $B-L$ symmetry and generates Majorana masses for $N_i$, which in turn lead to light neutrino masses.

We explore the possibility to detect a low mass RH neutrino in the mass range $M_N \sim 5-60$ GeV. We consider the pair-production of RH neutrinos from SM Higgs decay and study its detectability into leptonic final states. This particular production mode is not limited by the active-sterile mixing $V_{lN}$. The decay length, however, crucially depends upon the mixing and for very low values, the RH neutrino will be long-lived. We focus on the ongoing LHC run-II, the future prospects for HL-LHC, including the detector option MATHUSLA, and $e^+e^-$ colliders such as ILC and CEPC, in probing the active-sterile mixing.




## Gauged $B-L$ Model

The gauge group of the $B-L$ model is $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. Compared to the Standard Model, it adds a Higgs singlet scalar field $\chi$, a neutral gauge boson $Z'$ and three RH neutrinos $N_i$.

- The vev of $\chi$ generates heavy Majorana masses, inducing the seesaw mechanism

$$m_\nu = \frac{m_D^2}{M_N} = V_{lN}^2 M_N = 0.1 \text{ eV} \cdot \left(\frac{V_{lN}}{10^{-6}}\right)^2 \frac{M_N}{100 \text{ GeV}}$$

- There are two Higgs mass eigenstates $h_1 \approx h_{SM}$ and $h_2$ which mix with an angle $\sin\alpha \leqslant 0.3$ (Roughly the current exp. limit).
- In the natural regime, the RH neutrinos have a decay breaking length $\sim$ 1m:

$$L = 0.047 \text{ m} \cdot \left(\frac{10^{-6}}{V_{lN}}\right)^2 \cdot \left(\frac{100 \text{ GeV}}{M_N}\right)^5$$

For simplicity we consider a single RH neutrino coupling only to muons. The main model parameters are:

- $Active-sterile\ mixing\ V_{\mu N}$
- $RH\ neutrino\ mass\ M_N$
- $Higgs\ mixing\ angle\ \sin\alpha$ = 0.3
- $B-L\ Higgs\ vev\ \langle\chi\rangle = 3.75\ TeV (m_{z'} = 6\ TeV,\ g' = 0.8)$

## Displaced Vertices

At the LHC and $e^+e^-$ colliders, we consider pair-production of RH neutrino's from SM Higgs decay. The RH neutrinos are long-lived and we consider decays to two muons as required to trigger such as displaced event.

In the case of the LHC, we use the following CMS kinematic acceptance and displaced vertex cuts [1]:

- Kinematical Acceptance (dimuon trigger)

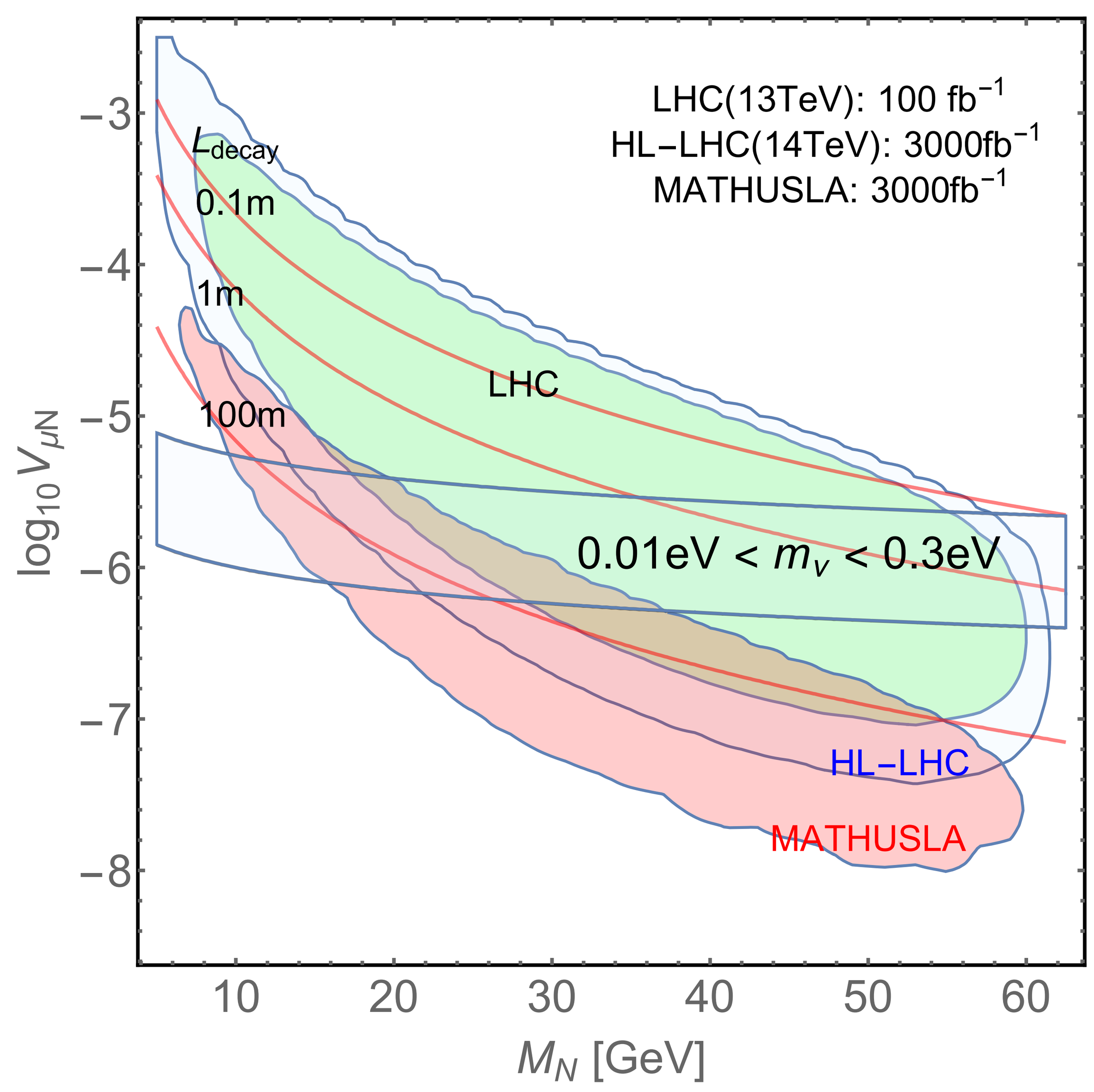
$$p_T(\mu) > 26 \text{ GeV},\ |\eta| < 2.0,\ (\triangle R > 0.2,\ \cos\theta_{\mu\mu} > -0.75)$$

- Inner Tracker

$$10 \text{ cm} < |L_{xy}| < 50 \text{ cm},\ |L_z| < 1.4 \text{ m},\ d_0/\sigma_d^t > 12,\ \sigma_d^t = 20\ \mu\text{m}$$

- Muon Chamber

$$0.5 \text{ m} < |L_{xy}| < 5 \text{ m},\ |L_z| < 8 \text{ m},\ d_0/\sigma_d^t > 4,\ \sigma_d^t = 2 \text{ cm}$$




We use analogous criteria for the other colliders/detectors. we pessimistically assume maximal background rates at the LHC [2], and the shaded regions in the plot denote the parameter space with more than two sigma significance in Chi-square analysis.

## Results

With the above simplifications, both the LHC and the lepton colliders (not shown in the figure) yield a similar sensitivity. The HL-LHC has the strongest sensitivity down to $V_{\mu N} \approx 10^{-7}$, while the MATHUSLA option can extend it with one more magnitude.

While this is much stronger than the analogous sensitivity of $W$ boson mediated searches, $V_{\mu N} \approx 10^{-4}$, it crucially depends on the Higgs mixing $\sin\alpha$ which we have assumed to be close to its experimental limit.

## References

[1] E. Accomando, L. Delle Rose, S. Moretti, E. Olaiya, and C. H. Shepherd-Themistocleous, *Novel SM-like Higgs decay into displaced heavy neutrino pairs in $U(1)'$ models*, *JHEP* **04 081**(2017)

[2] The CMS collaboration, *Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s}$ = 8 TeV*, *Phys. Rev.* **D91 052012**(2015)