Lepton Nmber Violation at Colliders

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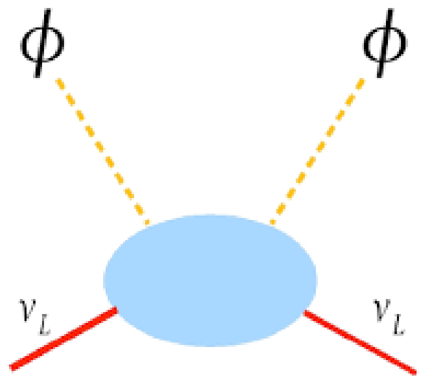
Lepton Number Violation (LNV)

Right-handed neutrinos (RHN) appear in many BSM scenarios and violate Lepton Number Symmetry due to the Majorana mass term:

$$\bar{N}_R^c M_N N_R$$

- Can generate small masses for SM neutrinos via seesaw mechanisms.



Minkowski, PLB 67 421
Mohapatra, Senjanovic, PRL 44 912
Schechter, Valle, PRD 22 2227

- Could explain the baryon asymmetry via leptogenesis.

Fukugita, Yanagida PLB 174 45

- Could provide a viable Dark Matter candidate.

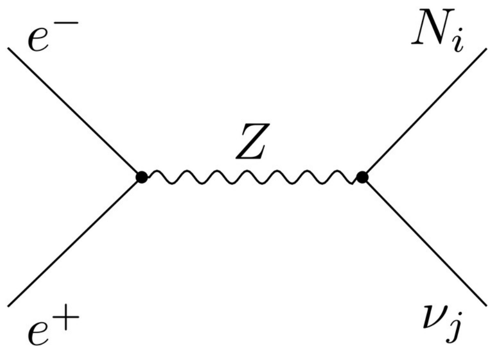
Dodelson, Widrow PRL 72 17

Challanges in probing LNV

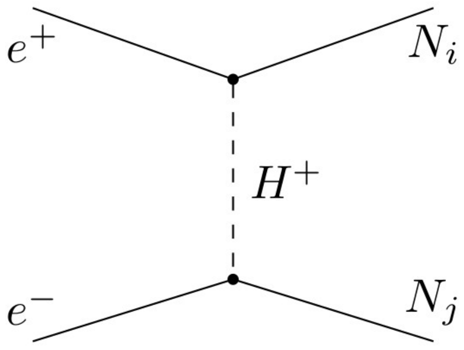
- The Majorana mass term violate lepton number and can lead to LNV decays of the heavy neutrinos.
- LNV decay channels have low SM backgrounds making them experimentally very appealing.
- An alternative to $0\nu\beta\beta$ decay experiments which can help us probe the Majorana nature of neutrinos.
- Branching ratios of LNV processes at colliders can be parametrically suppressed in the pure type-I seesaw model due to small mixing angle, which could potentially limit the discovery potential of such searches.

Low Scale Seesaw

- In conventional "high-scale" seesaws, the mediators(RHN) are superheavy, and hence kinematically inaccessible at colliders.
- In low-scale seesaw models such as inverse or linear seesaw, the heavy mediators may be produced at high-energy collider setups.
- In inverse seesaw heavy neutrinos are produced via the mixing and due to small mixing value the cross-section is small.

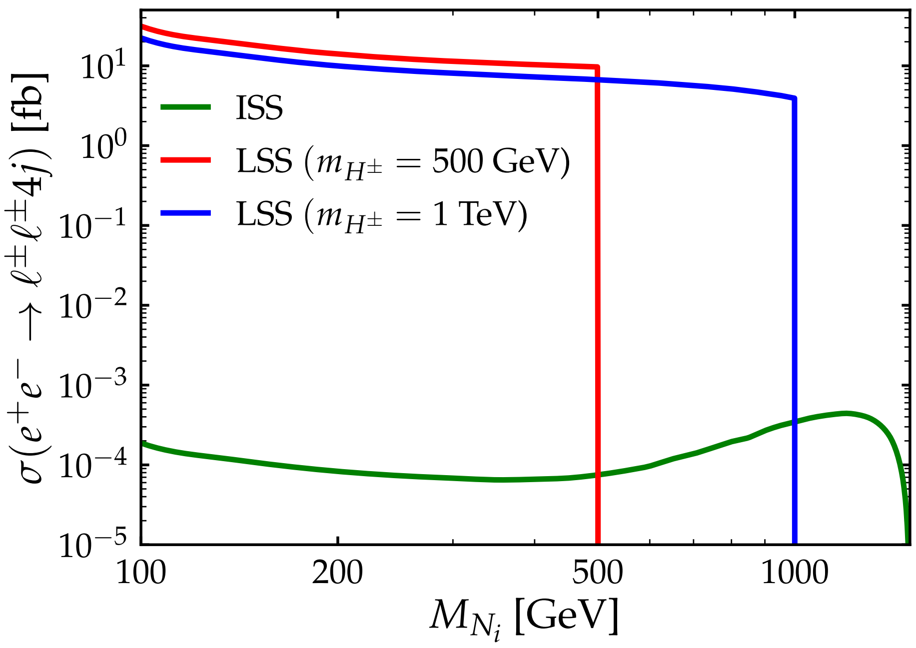


Inverse



Linear

P.B. et al, 2304.06080



Linear Seesaw Model

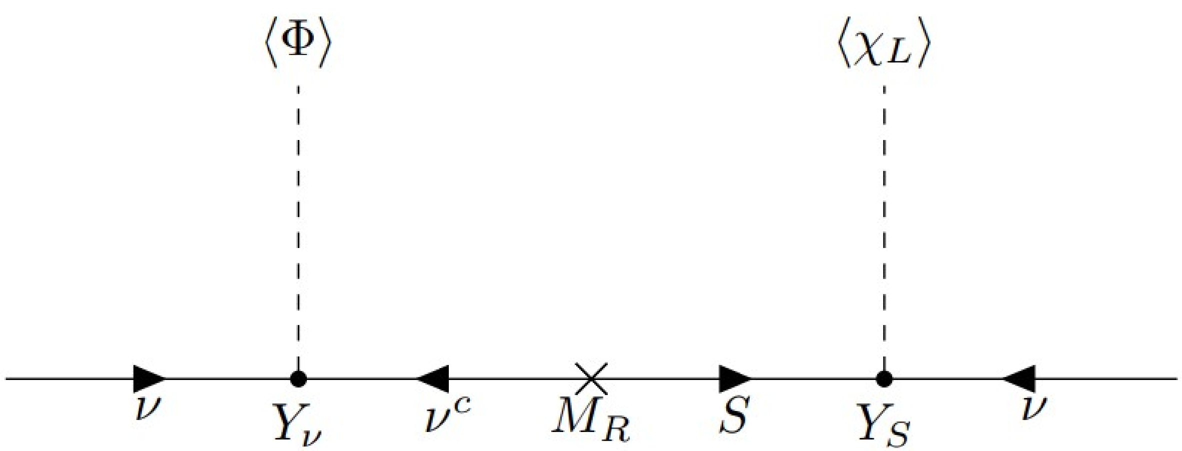
First proposed in the context of $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

and in the context of SO(10) framework. Akhmedov et al, hep-ph/9507275, Malinsky et al, hep-ph/0506296

Here, the simplest version is realized within the SM gauge group itself: P.B. et al, 2305.00994, 2304.06080

Add pair of 3 singlets with $L[\nu^c]=-1, L[S]=1$ and a scalar doublet $L[\chi_L]=-2$:

$$-\mathcal{L}_{\rm Yuk} = Y_\nu^{ij} L_i^T C \nu_j^c \Phi + M_R^{ij} \nu_i^c C S_j + Y_S^{ij} L_i^T C S_j \chi_L + \text{h.c.}$$



$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix} \quad \text{with} \quad m_D = \frac{Y_\nu v_\phi}{\sqrt{2}} \quad \text{and} \quad M_L = \frac{Y_S v_\chi}{\sqrt{2}}$$

Light neutrino masses in the limit $M_R \gg m_D \gg M_L$:

$$m_{\text{light}} = m_D (M_L M_R^{-1})^T + (M_L M_R^{-1}) m_D{}^T$$

In contrast to type-I seesaw, m_{light} scales linearly with m_D : hence the name linear!

Neutrino mass diagonalization:

$$\mathcal{U}^\dagger \mathcal{M}_\nu \mathcal{U}^* = \mathcal{M}_\nu^{\text{diag}}$$

$$\mathcal{U} \approx \begin{pmatrix} U_{\text{lep}} & -\frac{i}{\sqrt{2}} V & \frac{1}{\sqrt{2}} V \\ 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -V^\dagger & -\frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

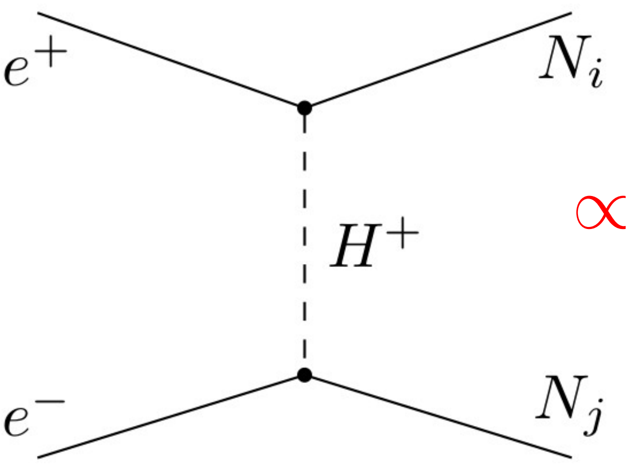
$$V = m_D \, (M_R^T)^{-1}$$

Hence, mixing can be large.

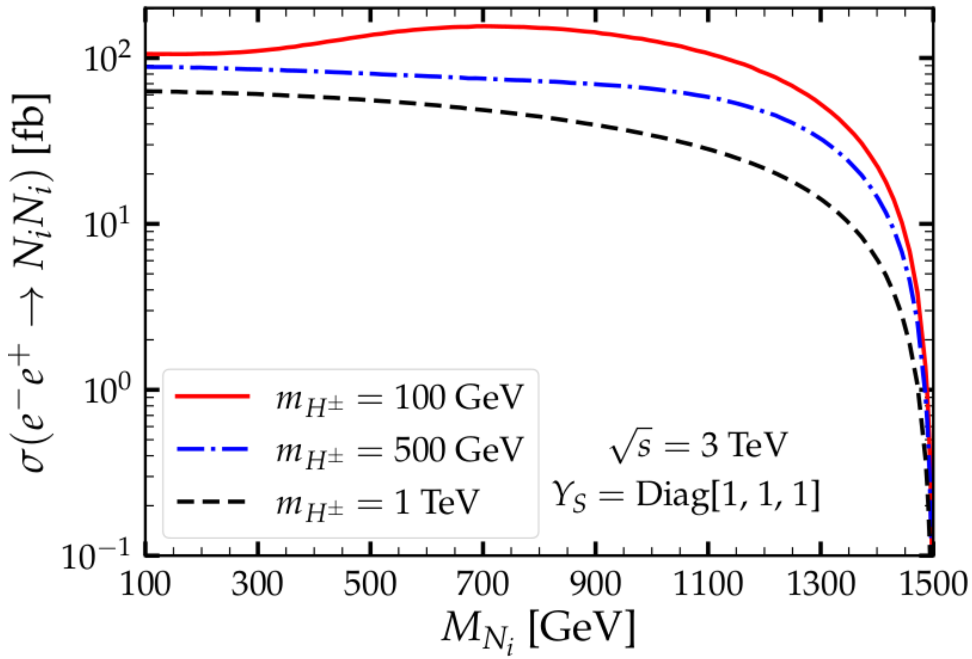
New heavy neutrino production channels

ILC: 1506.07830, CLIC: 1812.06018, CEPC: 1811.10545

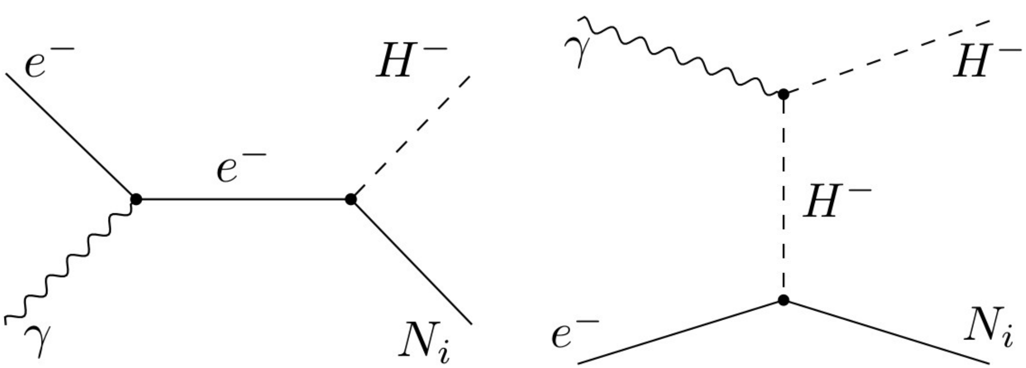
$e^+e^- \to NN$:



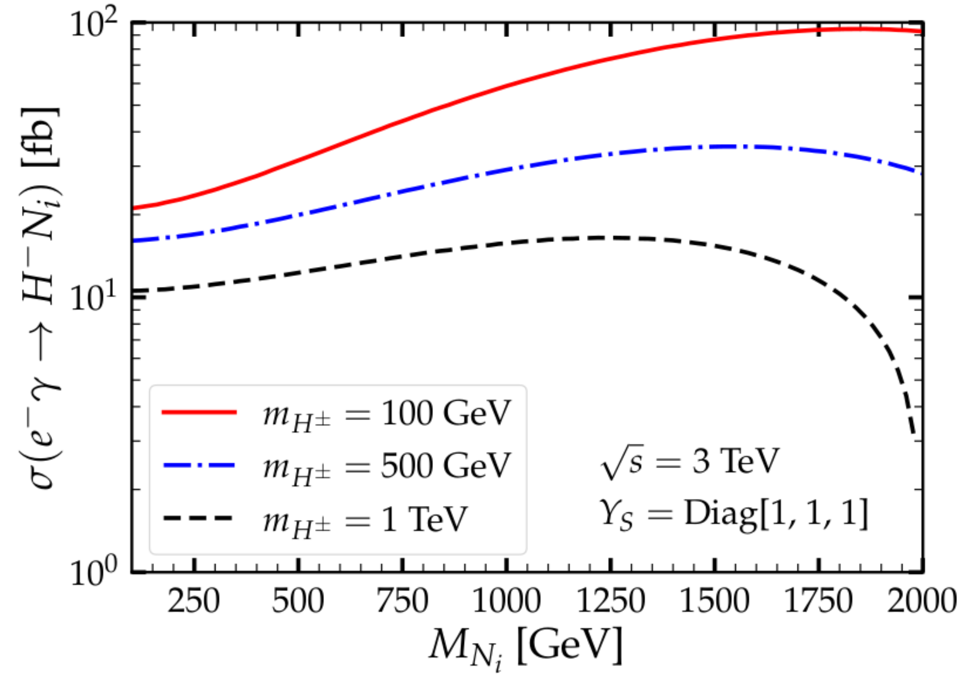
$\propto Y_S^2$



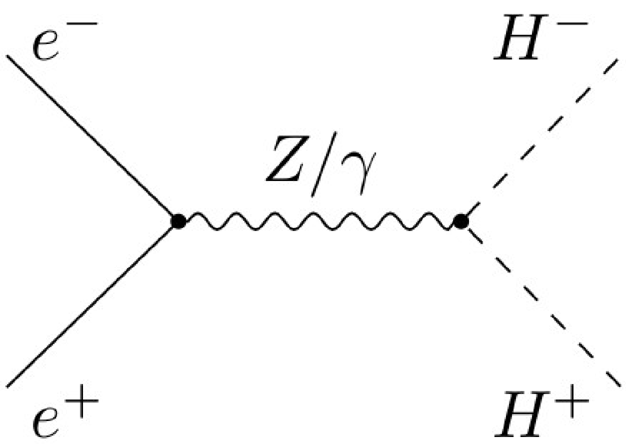
$e^-\gamma \to NH^-$:

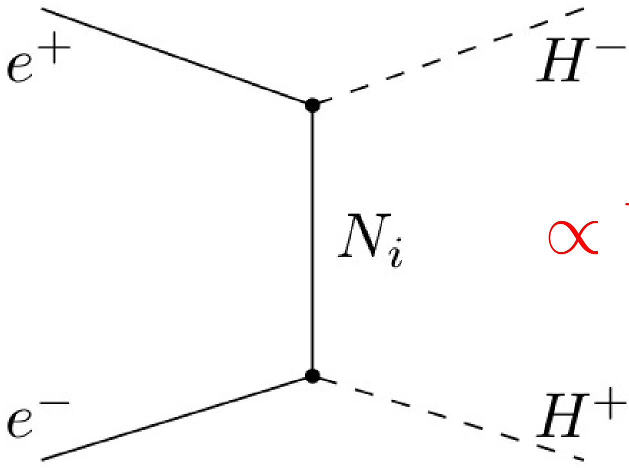


$\propto Y_S$

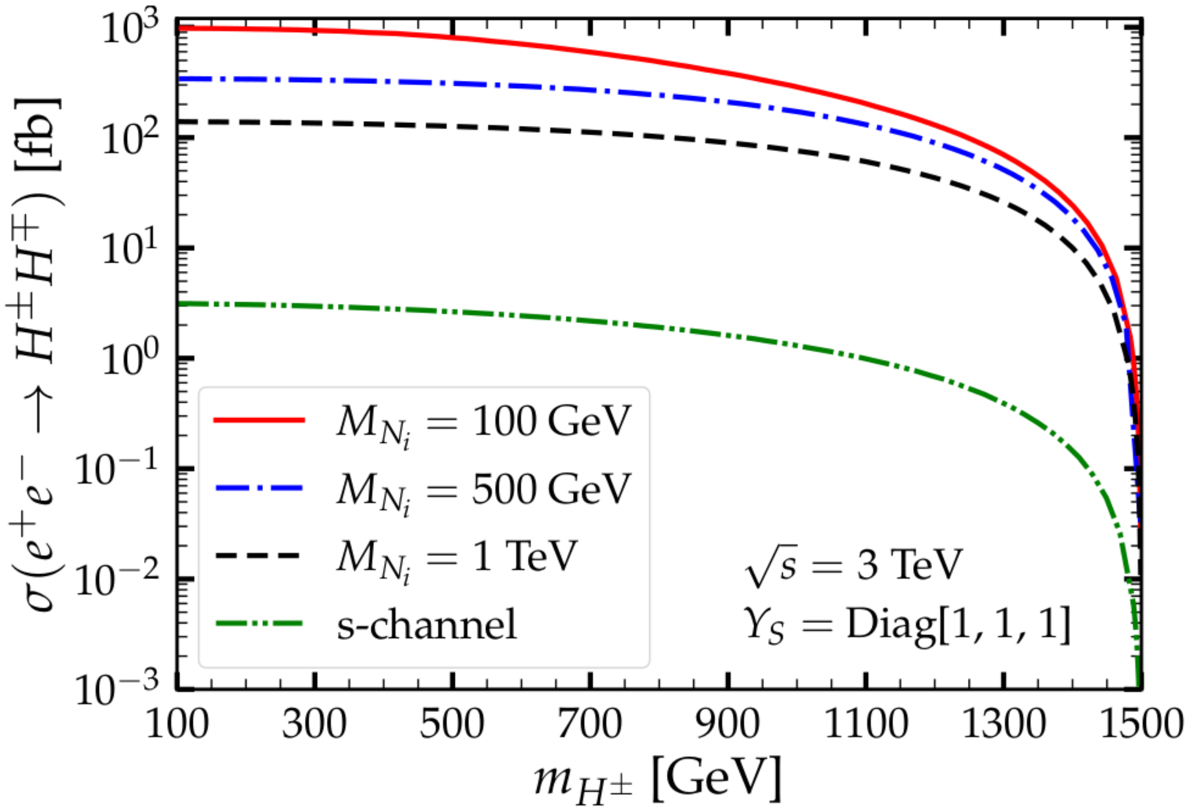


More possibilities...





$\propto Y_S^2$



H/A and $H^\pm$ decay modes

The decays of new scalars are controlled by the $U(1)_L$ symmetry

- Case 1: $m_{H^\pm}, m_{H/A} < M_{N_i}$

$$\Gamma(H^\pm \to \ell^\pm \nu_i) \approx \frac{|(Y_S M_N^{-1} Y_\nu^\dagger)_{\ell i}|^2 v^2 \sin^4\beta}{32\pi} m_{H^\pm}$$

$$\Gamma(H \to \nu_i \nu_j) \approx \frac{|(Y_S M_N^{-1} Y_\nu^\dagger)_{ij}|^2 v^2 \cos^2\alpha \sin^2\beta}{64\pi} m_H$$

$$\Gamma(A \to \nu_i \nu_j) \approx \frac{|(Y_S M_N^{-1} Y_\nu^\dagger)_{ij}|^2 v^2 \sin^4\beta}{64\pi} m_A.$$

H/A, $H^\pm$ are mostly composed of χ

$(H/A)WW$, $(H/A)ZZ$, $(H/A)\ell\ell$, $(H/A)qq$, AhZ, $H^\pm qq'$, $H^\pm W^\mp h \sim \mathcal{O}(v_\chi/v)$

Collider phenomenology is different from 2HDM.

- Case 2: $m_{H^\pm}, m_{H/A} > M_{N_i}$

$$\Gamma(H^\pm \to \ell^\pm N_i) \approx \frac{|(Y_S)_{\ell i}|^2 \sin^2\beta}{16\pi} m_{H^\pm} \left(1 - \frac{M_{N_i}^2}{m_{H^\pm}^2}\right)^2$$

$$\Gamma(H \to \nu_\ell N_i) \approx \frac{|(Y_S)_{\ell i}|^2 \cos^2\alpha}{32\pi} m_H \left(1 - \frac{M_{N_i}^2}{m_H^2}\right)^2$$

$$\Gamma(A \to \nu_\ell N_i) \approx \frac{|(Y_S)_{\ell i}|^2 \sin^2\beta}{32\pi} m_A \left(1 - \frac{M_{N_i}^2}{m_A^2}\right)^2.$$

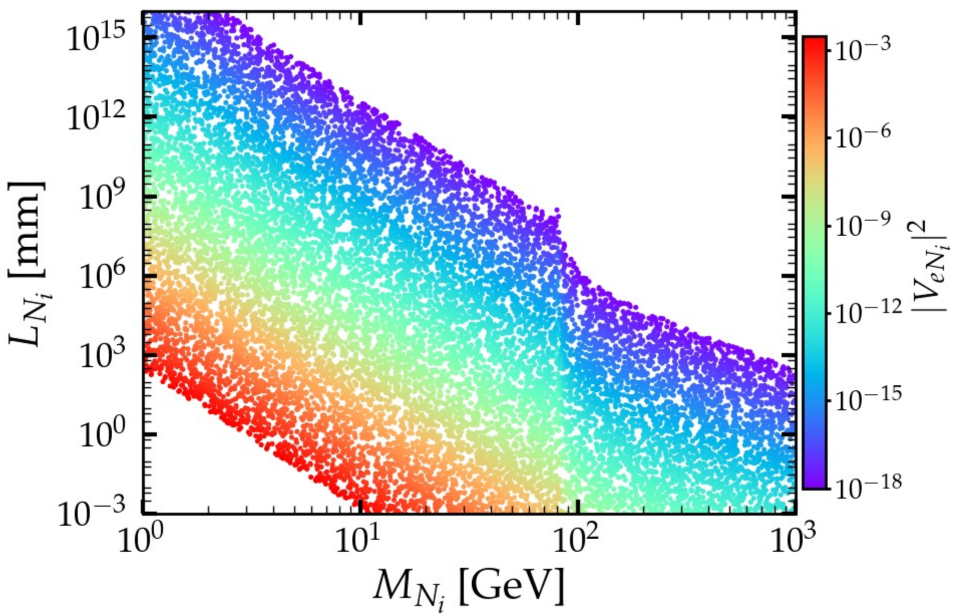
More interesting as

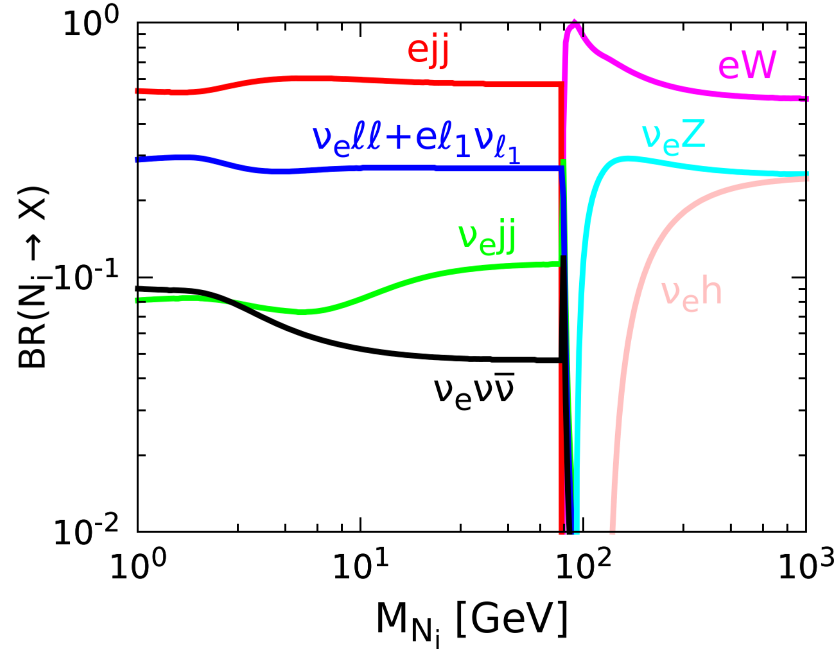
$N_i \to \ell W^*$

leads to interesting signatures

When $m_{H^\pm}, m_{H/A} > M_{N_i}$

RHN decay modes





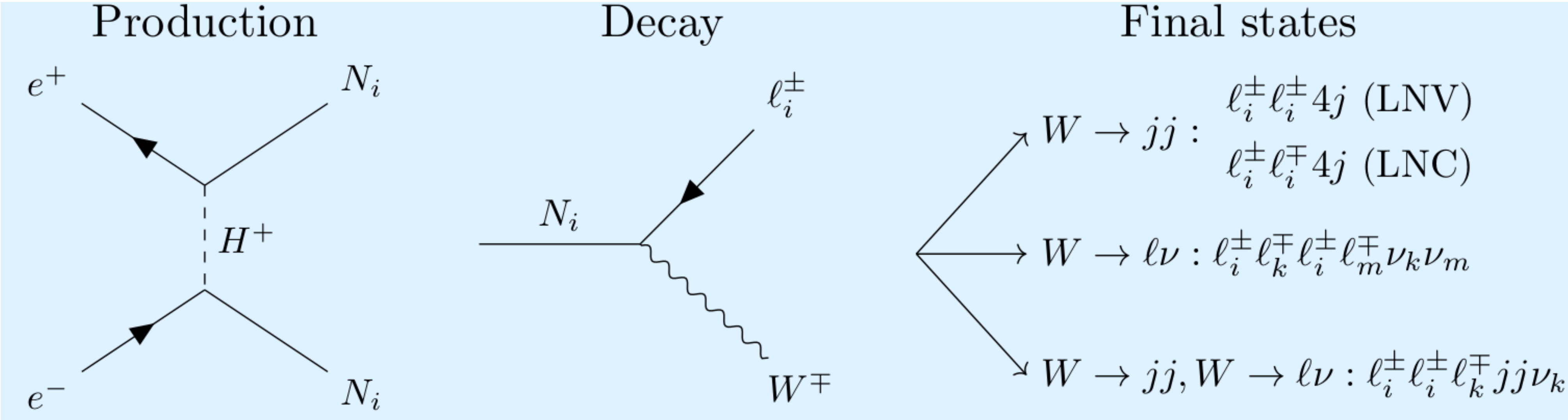
$CC: N_i \to \ell W^*$ $\quad NC: N_i \to \nu_\ell Z^*$ $\quad$ Yukawa: $N_i \to \nu_\ell h^*$

Small M_N and small $V_{\ell N}$ implies small decay width:

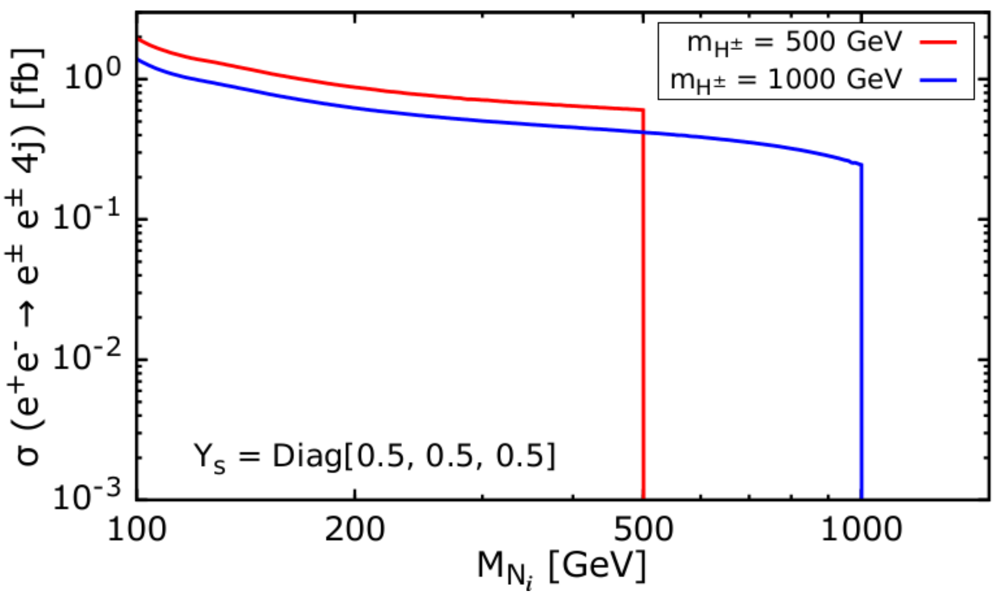
Long-lived RHN → Displaced vetrex

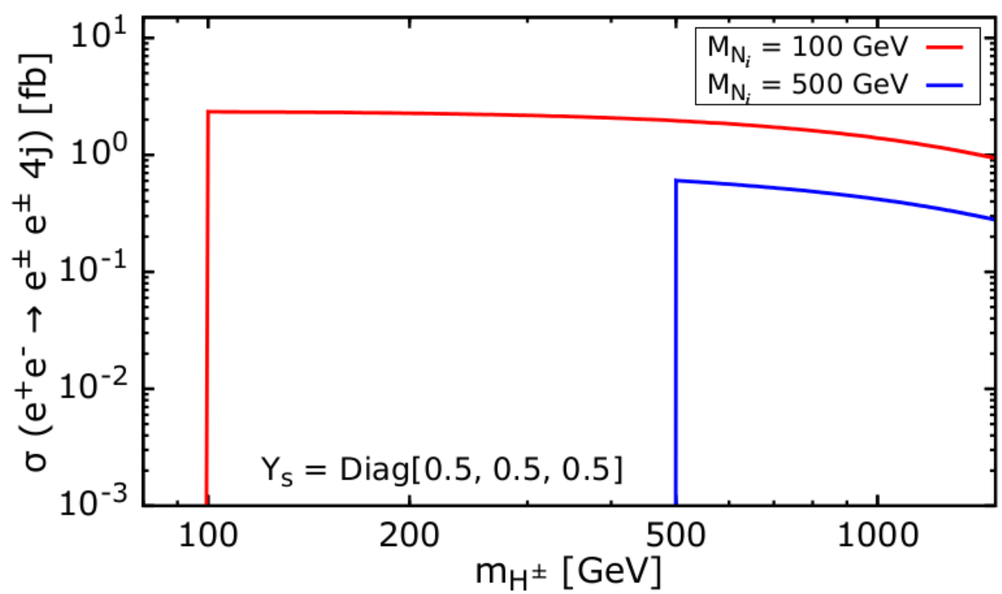
S. Antusch, O. Fischer, JHEP 12 (2016) 007
C.W. Chiang et al, 1908.09893

Collider signatures from $e^+e^- \to NN$:

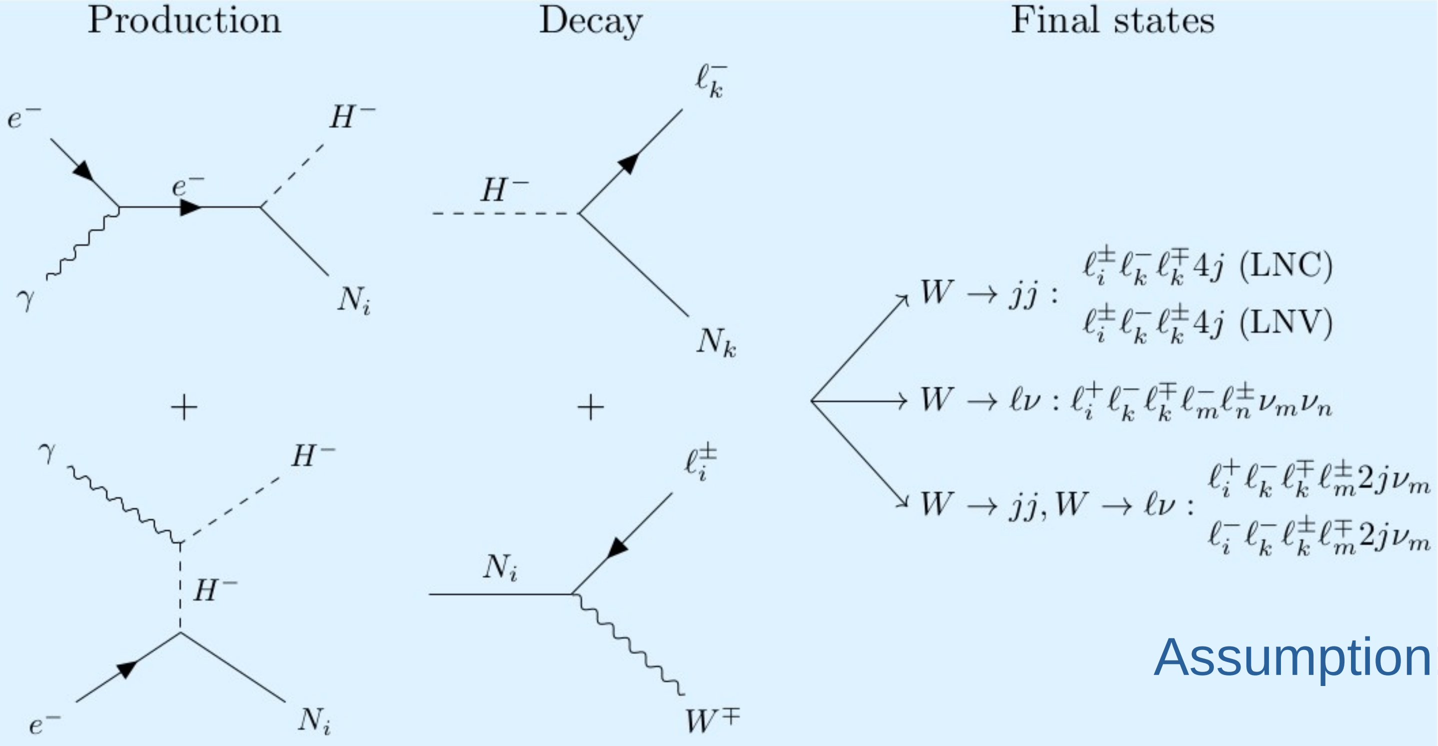


Assumption: $m_{H^\pm}, m_{H/A} > M_{N_i}$

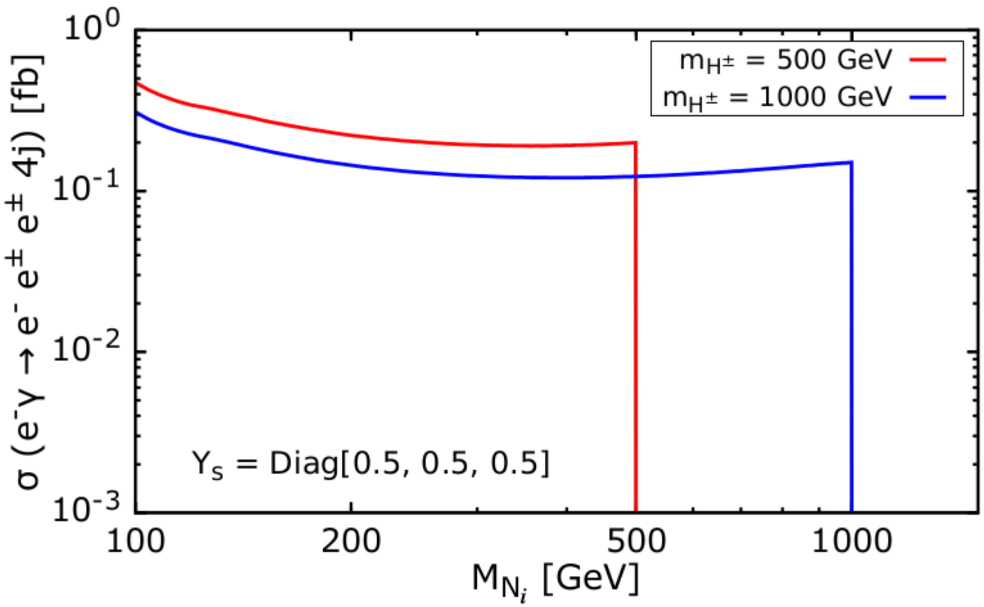


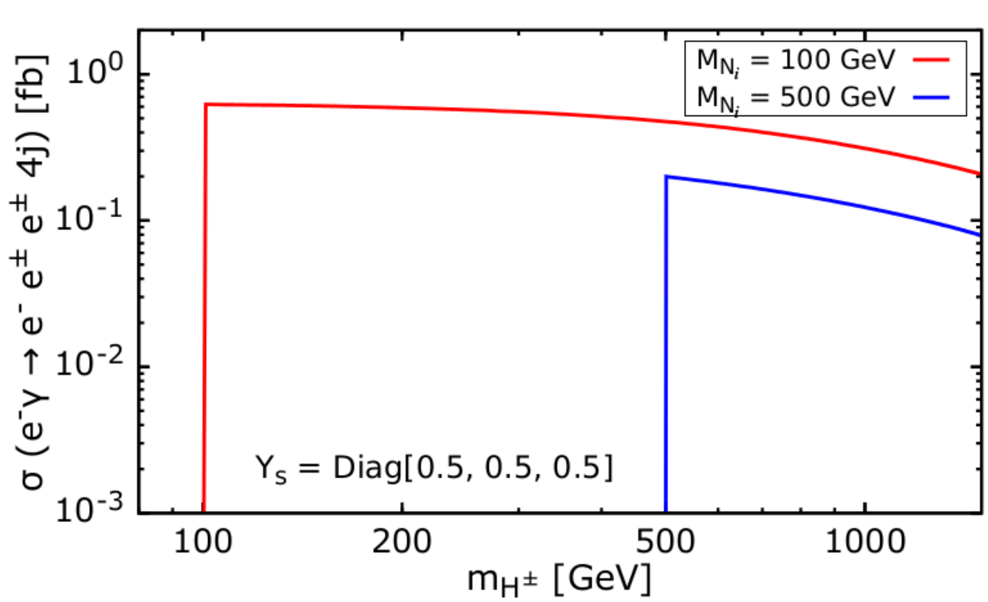


Collider signatures from $e^-\gamma \to NH^-$:

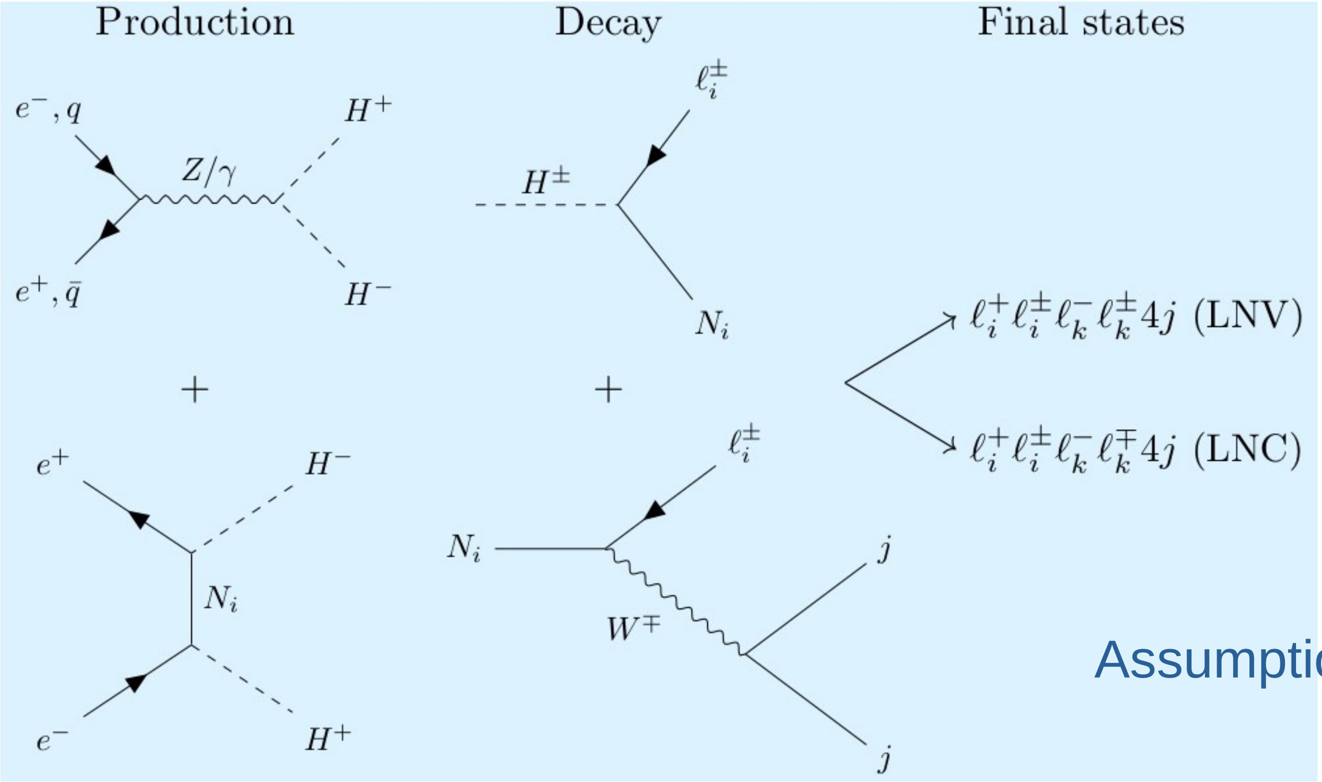


Assumption: $m_{H^\pm}, m_{H/A} > M_{N_i}$

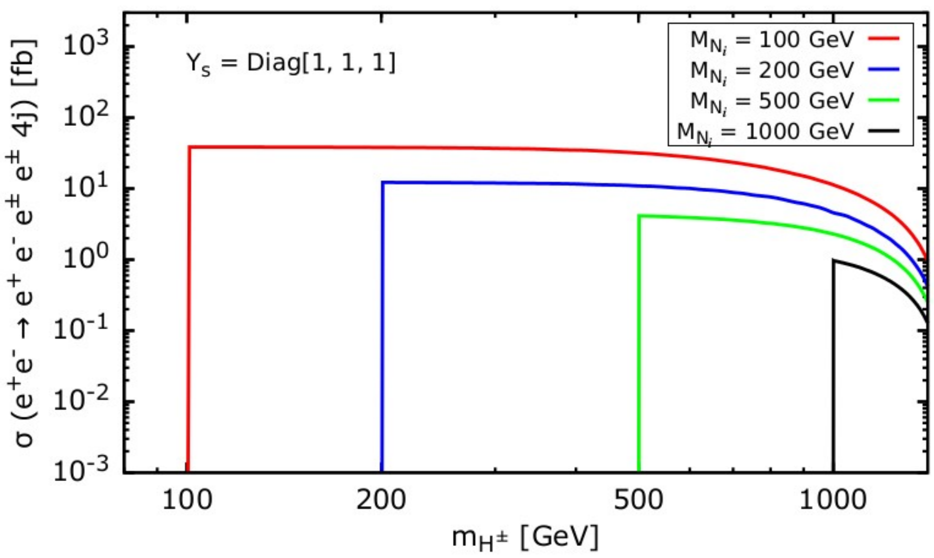


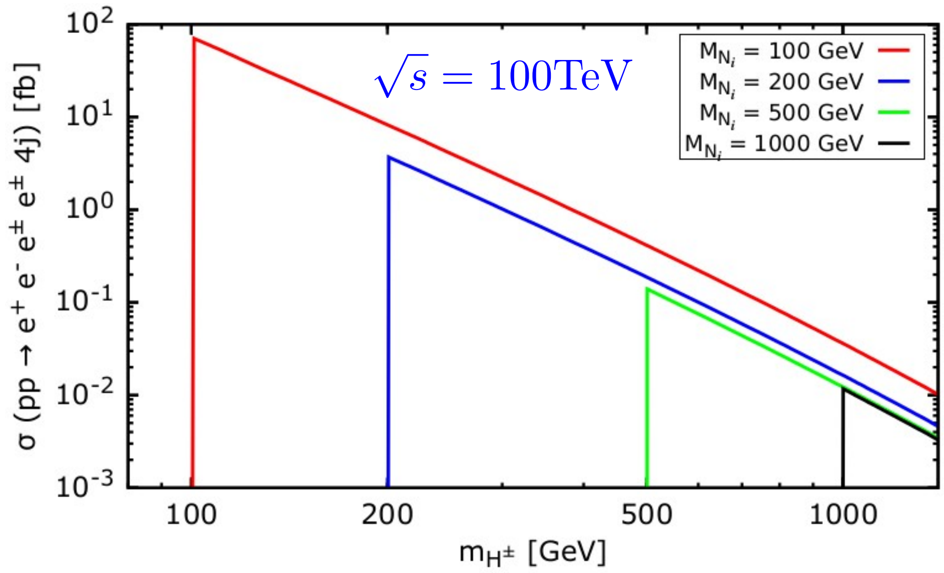


Collider signatures from $pp/e^-e^+ \to H^-H^+$:

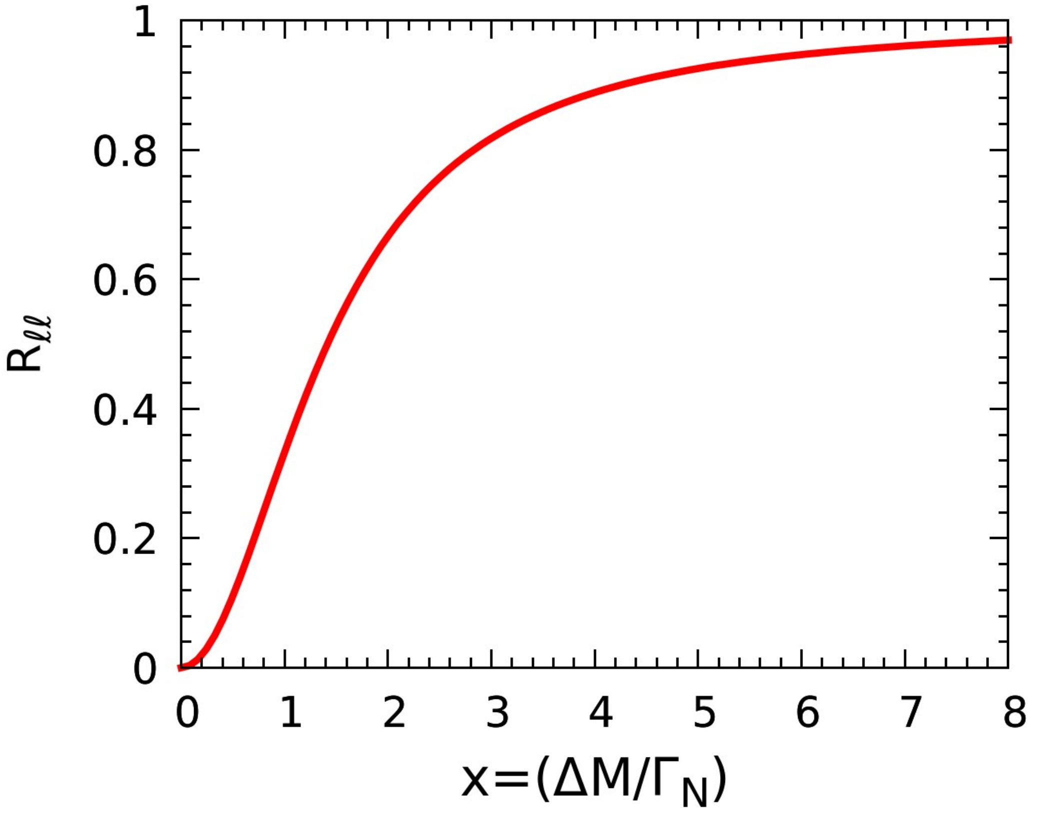


Assumption: $m_{H^\pm}, m_{H/A} > M_{N_i}$





LNV at colliders



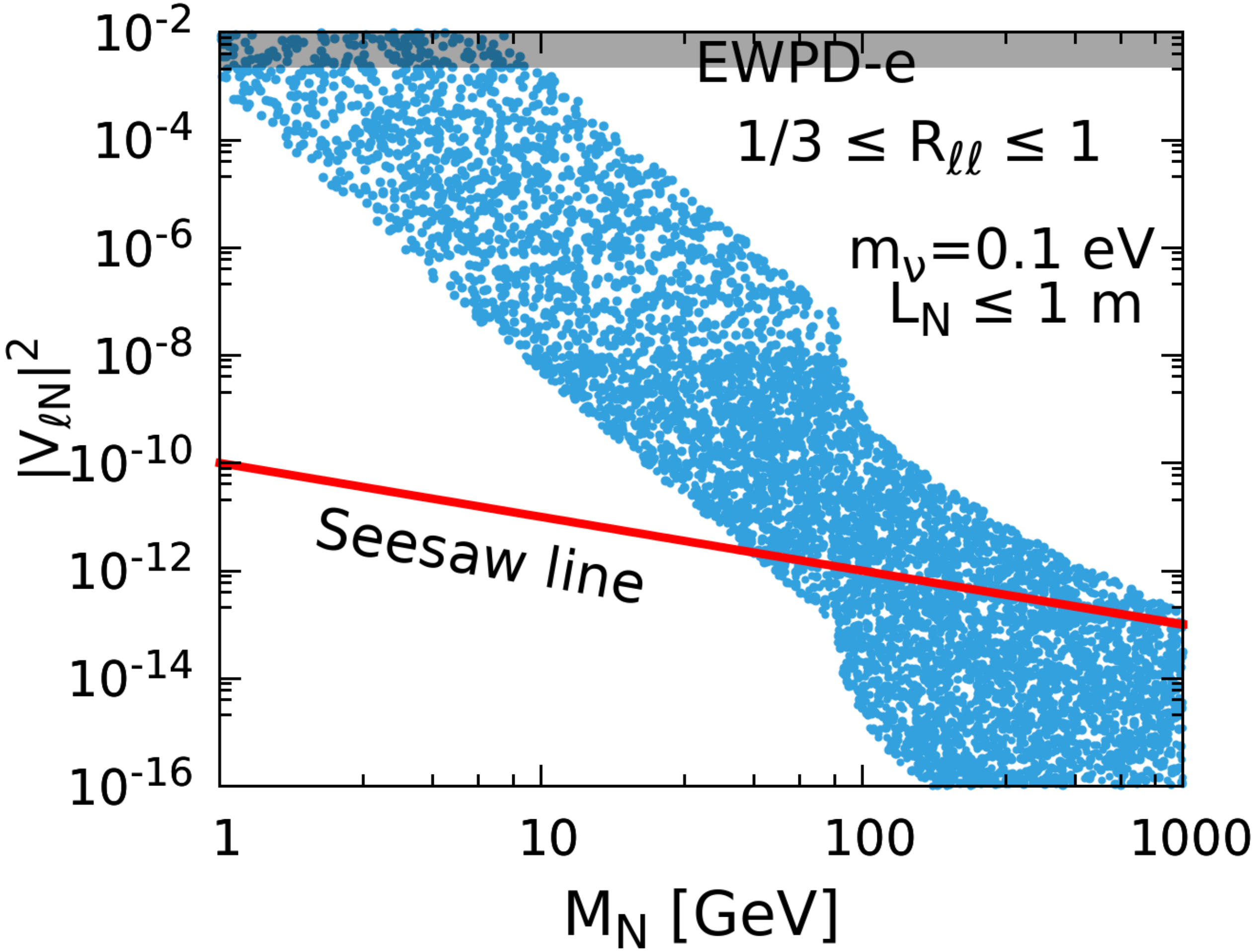
$$R_{\ell\ell} = \frac{\mathrm{LNV}}{\mathrm{LNC}} = \frac{\Delta M^2}{\Delta M^2 + 2\Gamma^2}$$

$$R_{\ell\ell} = \begin{cases} [0,1], & \text{quasi-Dirac} \\ 1, & \text{limiting Majorana} \\ 0, & \text{limiting Dirac} \end{cases}$$

G. Anamiati, M. Hirsch, 1607.05641
S. Antusch et al, 2210.10738

Measurement of $R_{\ell\ell}$ can provide valuable information on the neutrino mass generation mechanism.

LNV at colliders



So we expect a large number of LNV events at colliders with large cross-section.

Thank You