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Lepton Number Violation at Colliders in Linear Seesaw

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Large lepton number violation at colliders: predictions from the minimal linear seesaw mechanism

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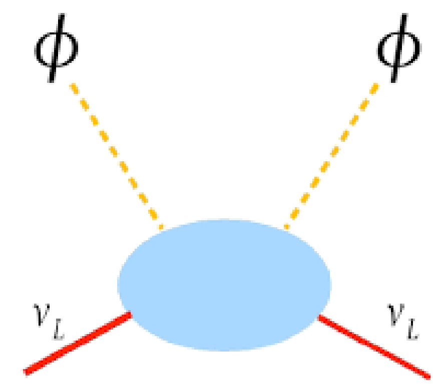
Lepton Number Violation (LNV)

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 Majorana masses for SM neutrinos via seesaw mechanisms.

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



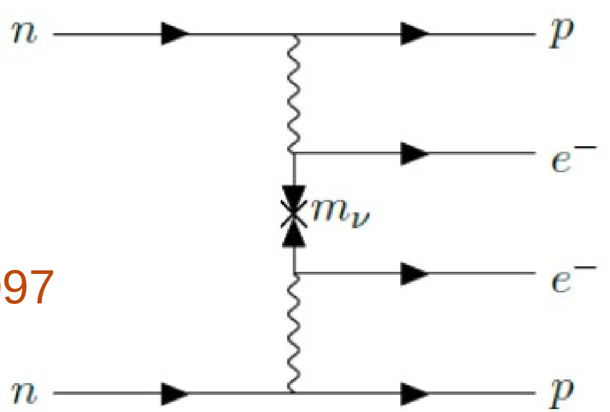
- Could explain the baryon asymmetry via leptogenesis.

Fukugita, Yanagida PLB 174 45

- Could provide a viable Dark Matter candidate.

Dodelson, Widrow PRL 72 17

Probing LNV



- Neutrinoless double beta decay ($0\nu\beta\beta$)

M.J. Dolinski et al, 1902.04097

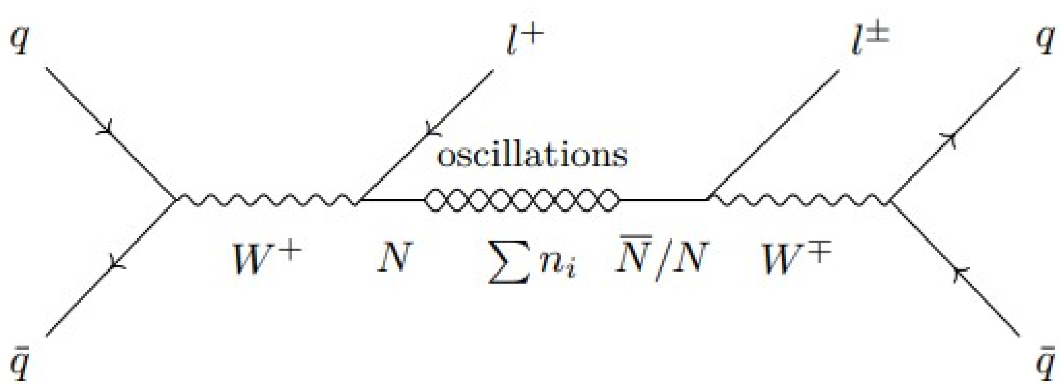
- Proton decay $p \to \pi^0 e^+$

Wilczek, Zee, PLB 88 (1979)

- Rare meson decay $M_1^- \to \ell_1^- \ell_2^- M_2^+$

E. J. Chun et al, 1908.09562

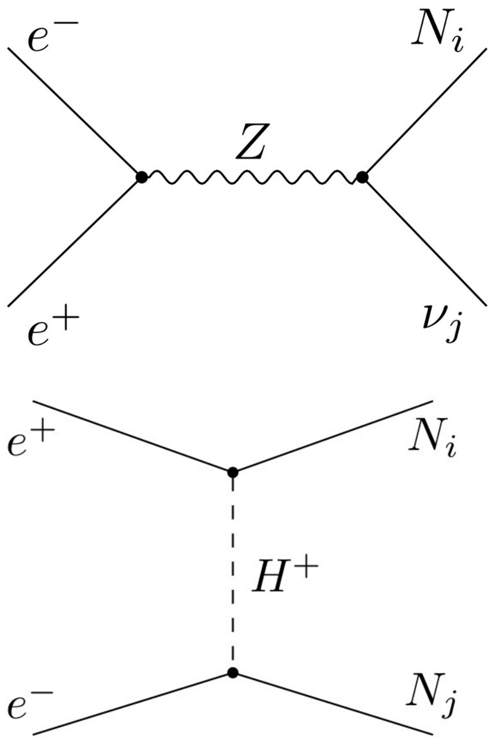
- Collider searches: same-sign dilepton production



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

Low Scale Seesaw

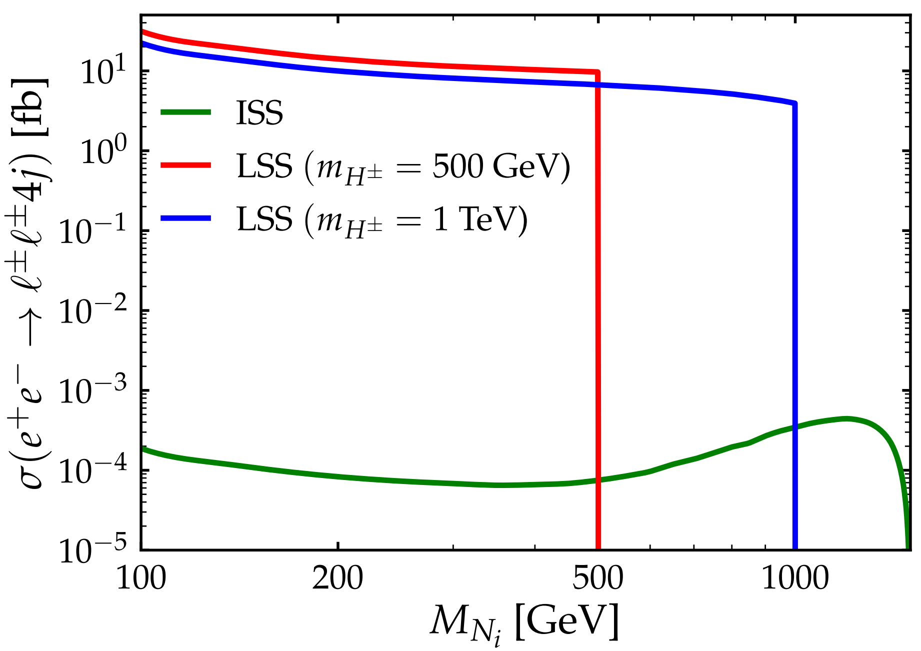
- In conventional "high-scale" seesaws, the mediators(RHN) are superheavy, and hence kinematically inaccessible at colliders.
- In low-scale seesaw models such as inverse or linear seesaw, the heavy mediators may be produced at high-energy collider setups.
- In inverse seesaw heavy neutrinos are produced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



Inverse

Linear

P.B. et al, 2304.06080



Minimal 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.

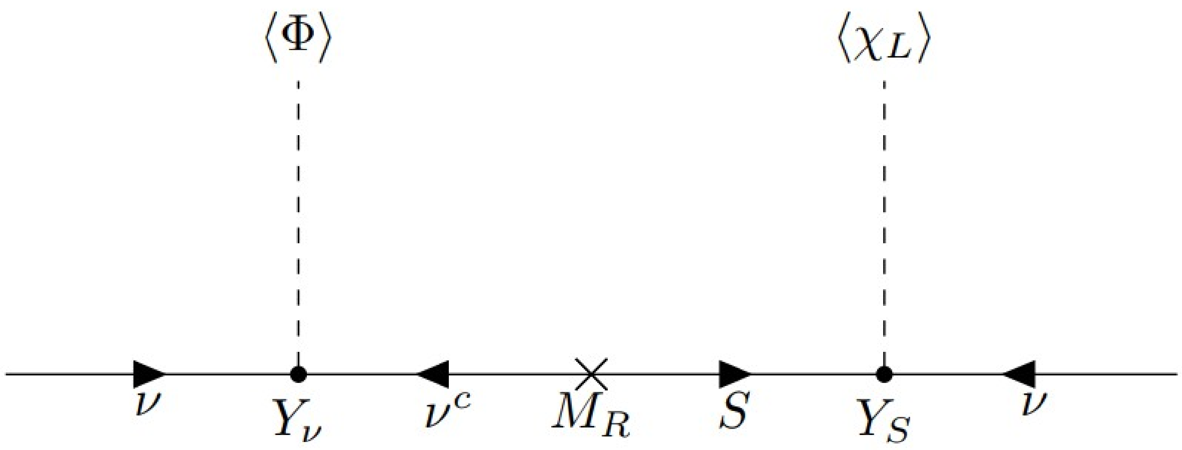
Akhmedov et al, hep-ph/9507275,
Malinsky et al, hep-ph/0506296

Here, the simplest version is realized within the SM gauge group itself:

P.B. et al, 2305.00994, 2304.06080

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

$$-\mathcal{L}_{\rm Yuk} = Y_\nu^\alpha L_\alpha^T C \nu^c \Phi + M_R \nu^c C S + Y_S^\alpha L_\alpha^T C S \chi_L + \text{h.c.}$$



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

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

$$m_\nu = \frac{\mathbf{m}_D \mathbf{M}_L^T + \mathbf{M}_L \mathbf{m}_D^T}{M_R}.$$

In contrast to type-I seesaw, m_ν scales linearly with m_D :
hence the name linear!

Neutrino mass diagonalization: $\mathcal{U}^\dagger \mathcal{M}_\nu \mathcal{U}^* = \mathcal{M}_\nu^{\text{diag}}$

$$\mathcal{U} \approx \begin{pmatrix} U & -\frac{i}{\sqrt{2}}\mathbf{S} & \frac{1}{\sqrt{2}}\mathbf{S} \\ 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\mathbf{S}^\dagger & -\frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

where $\mathbf{S} = \mathbf{m}_D / M_R$

Hence, mixing can be large.

Masses of heavy-neutrinos are

$$M_{N_{4,5}} = M_R\left(1+\frac{1}{2}|\mathbf{S}|^2\right) \mp \frac{1}{2M_R}\left(\mathbf{M}_L^\dagger \mathbf{m}_D + \mathbf{m}_D^\dagger \mathbf{M}_L\right)$$

The mass matrix m_ν has two nonzero eigenvalues

$$m_\nu^i = |\mathbf{M}_L||\mathbf{S}| \mp |\mathbf{M}_L^*\mathbf{S}|, \begin{cases} i = 2,\ 3 \text{ for } \mathbf{NO} \\ i = 1,\ 2 \text{ for } \mathbf{IO} \end{cases}$$

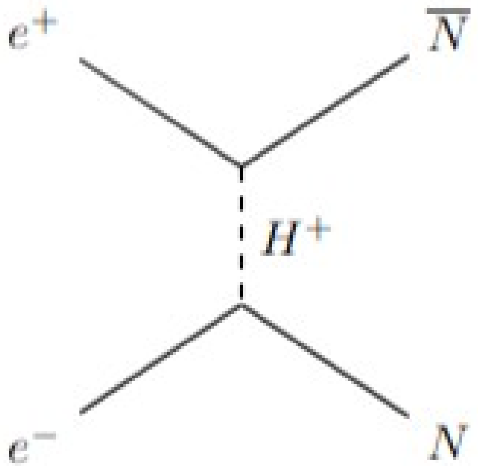
Heavy neutrino mass splitting can be written in terms of the measured mass square differences of light neutrinos:

$$\Delta M^{\mathbf{NO}} = \Delta m_{32}, \quad \Delta M^{\mathbf{IO}} = \Delta m_{21}.$$

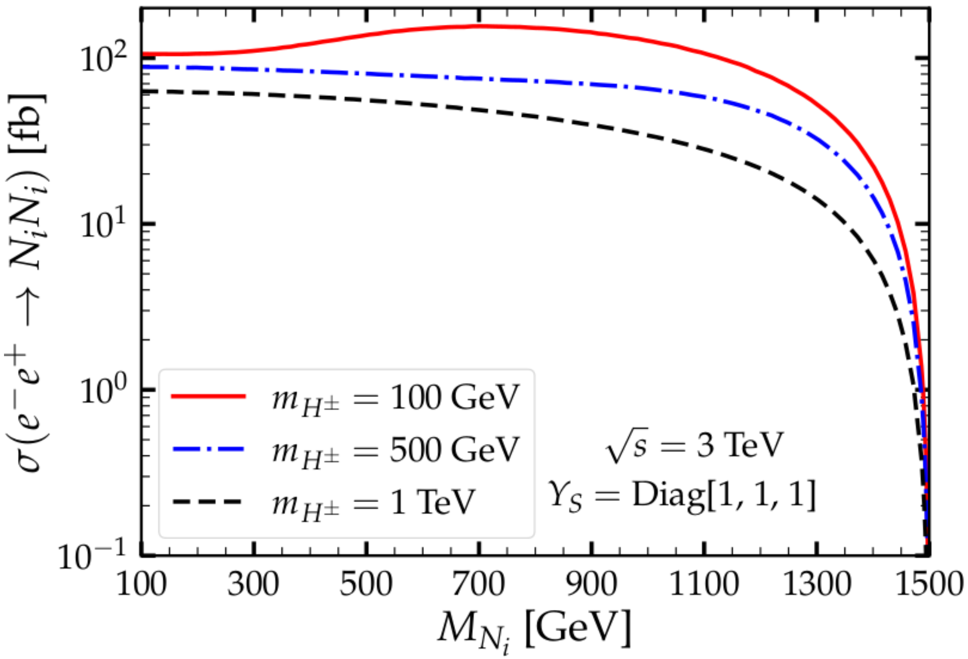
Heavy neutrino production channels

$\underline{e^+e^- \to NN:}$

ILC: 1506.07830, CLIC: 1812.06018, CEPC: 1811.10545

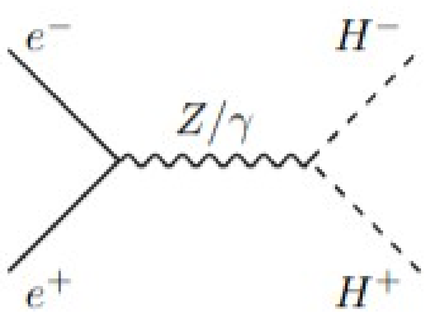


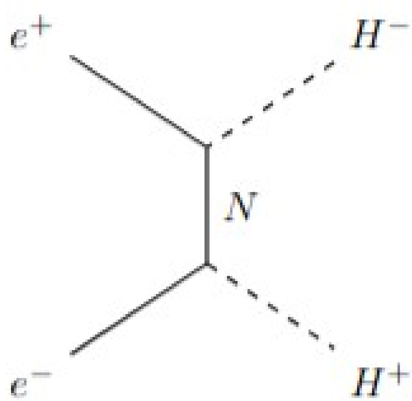
$\propto Y_S^2$



- From the decay of charged Higgs

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





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

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

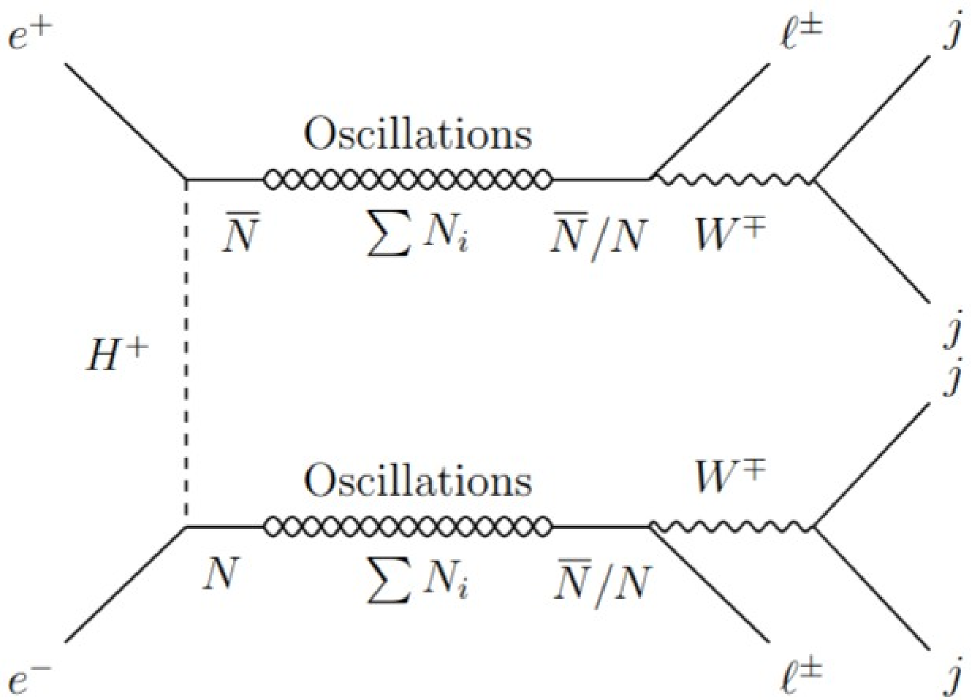
$$\Gamma(A \to \nu_\ell N_i) \approx \frac{|(Y_S)_{\ell i}|^2 \sin^2\beta}{32\pi} m_A\left(1 - \frac{M_{N_i}^2}{m_A^2}\right)^2.$$

Heavy neutrino-antineutrino ($N-\overline{N}$) oscillation

- N is produced together with an anti-lepton and $\overline{N}$ is produced together with a lepton.

S.Antusch. et al, 2012.05763

- Oscillations occur due to interference between the mass eigenstates $N_{4,5}$ during propagation.



$$e^+e^- \to N\overline{N} = \begin{cases} N \rightsquigarrow N, \overline{N} \rightsquigarrow \overline{N} \Rightarrow \ell^+\ell^- 4j \text{ (LNC)} \\ N \rightsquigarrow \overline{N}, \overline{N} \rightsquigarrow \overline{N} \Rightarrow \ell^+\ell^+ 4j \text{ (LNV)} \\ N \rightsquigarrow N, \overline{N} \rightsquigarrow N \Rightarrow \ell^-\ell^- 4j \text{ (LNV)} \\ N \rightsquigarrow \overline{N}, \overline{N} \rightsquigarrow N \Rightarrow \ell^+\ell^- 4j \text{ (LNC)} \end{cases}$$

Oscillation is necessary for LNV!

Heavy neutrino-antineutrino ($N-\overline{N}$) oscillation

- The oscillation probabilities in the lab frame

$$P_{\rm osc}^{N\to N(\bar N)}(x_1,x_2) = \frac{1}{L_N}\int_{x_1}^{x_2} \bar P_{\rm osc}^{N\to N(\bar N)}(x)dx.$$

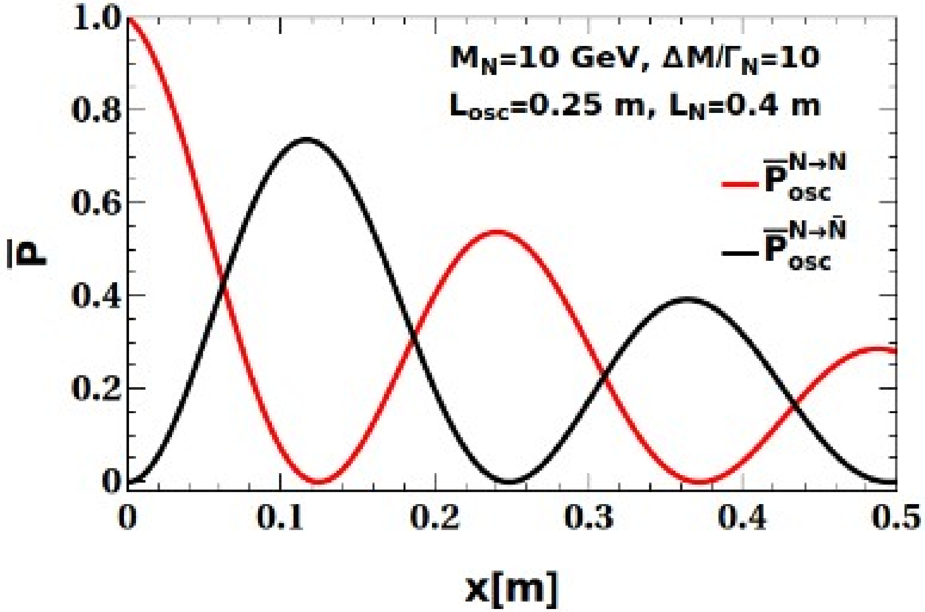
$$\bar P_{\rm osc}^{N\to N(\bar N)}(x) = \frac{1}{2}e^{-x/L_N}\left(1\pm\cos(2\pi x/L_{\rm osc})\right)$$

$$L_N = L_N^0\sqrt{\gamma^2-1}$$

$$L_{\rm osc} = L_{\rm osc}^0\sqrt{\gamma^2-1}$$

$$L_{\rm osc}^0 = c\tau_{\rm osc}$$

$$\tau_{\rm osc} = 2\pi/\Delta M$$



Oscillation length in the laboratory is large enough to be experimentally resolvable.

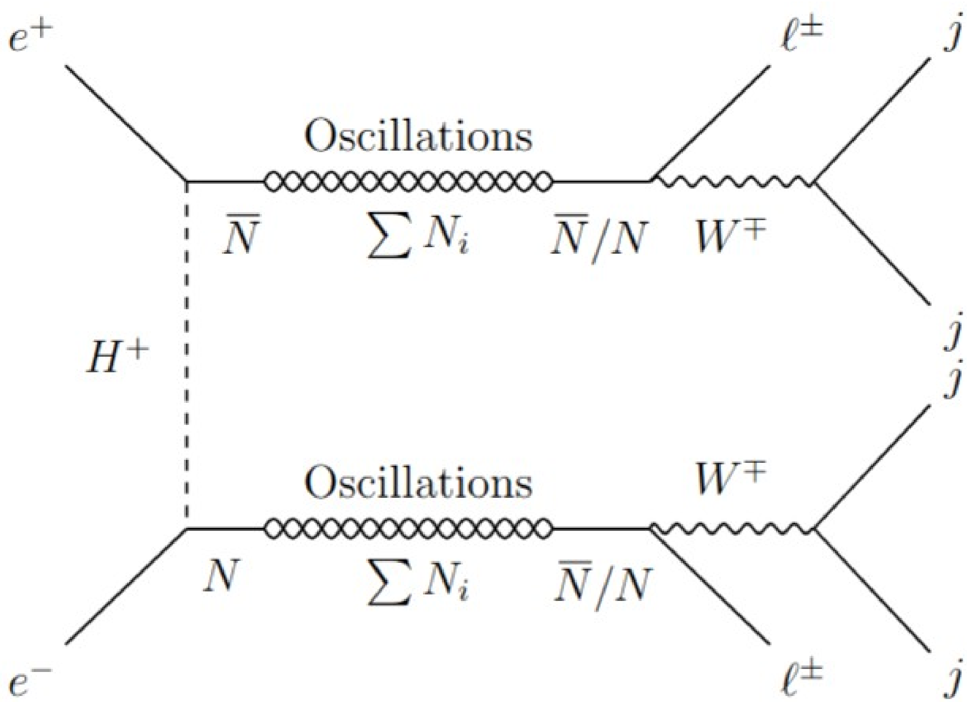
	ΔM [eV]	$L_{\rm osc}^0$ [m]	$M=10\,GeV$ $L_{\rm osc}$ [m] ($\gamma=150$)	$M=50\,GeV$ $L_{\rm osc}$ [m] ($\gamma=30$)
NO	41.51×10^{-3}	2.98×10^{-5}	4.5×10^{-3}	8.9×10^{-4}
IO	749.8×10^{-6}	1.65×10^{-3}	247×10^{-3}	49.5×10^{-3}

LNV at colliders

- Expected number of LNC and LNV events

$$N^{\mathrm{LNC}}(x_1, x_2, \sqrt{s}, \mathcal{L}) = \mathcal{L}\,\sigma\,\mathrm{BR}\left[\left(P_{\mathrm{osc}}^{N\to N}(x_1,x_2)\right)^2 + \left(P_{\mathrm{osc}}^{N\to \overline{N}}(x_1,x_2)\right)^2\right]$$

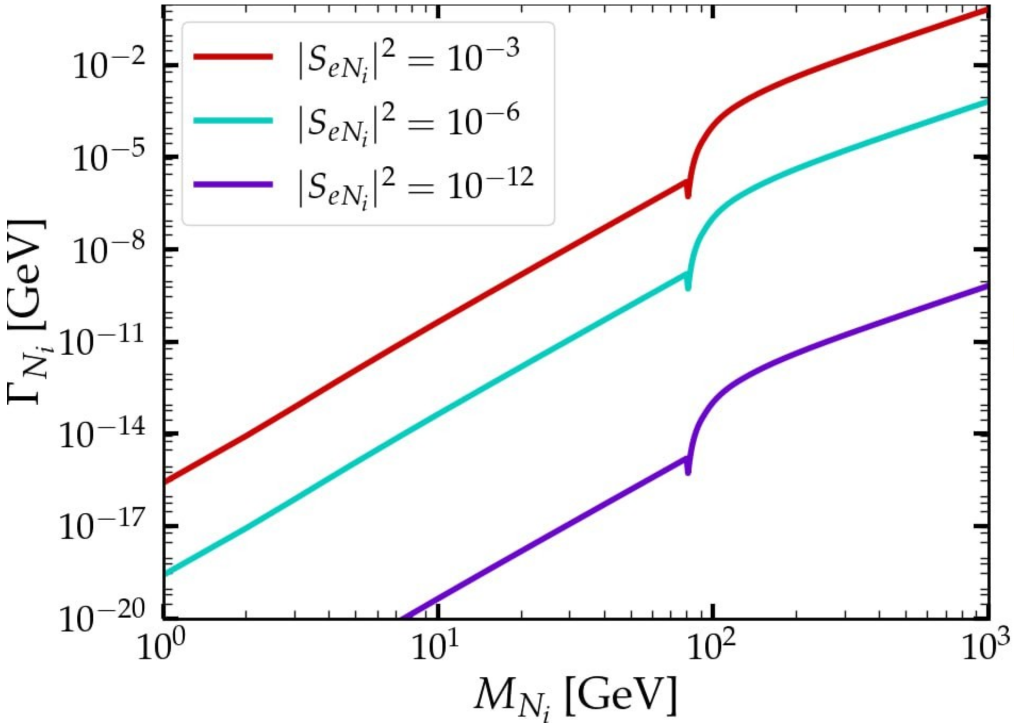
$$N^{\mathrm{LNV}}(x_1, x_2, \sqrt{s}, \mathcal{L}) = 2\mathcal{L}\,\sigma\,\mathrm{BR}\,P_{\mathrm{osc}}^{N\to N}(x_1,x_2)P_{\mathrm{osc}}^{N\to \overline{N}}(x_1,x_2),$$

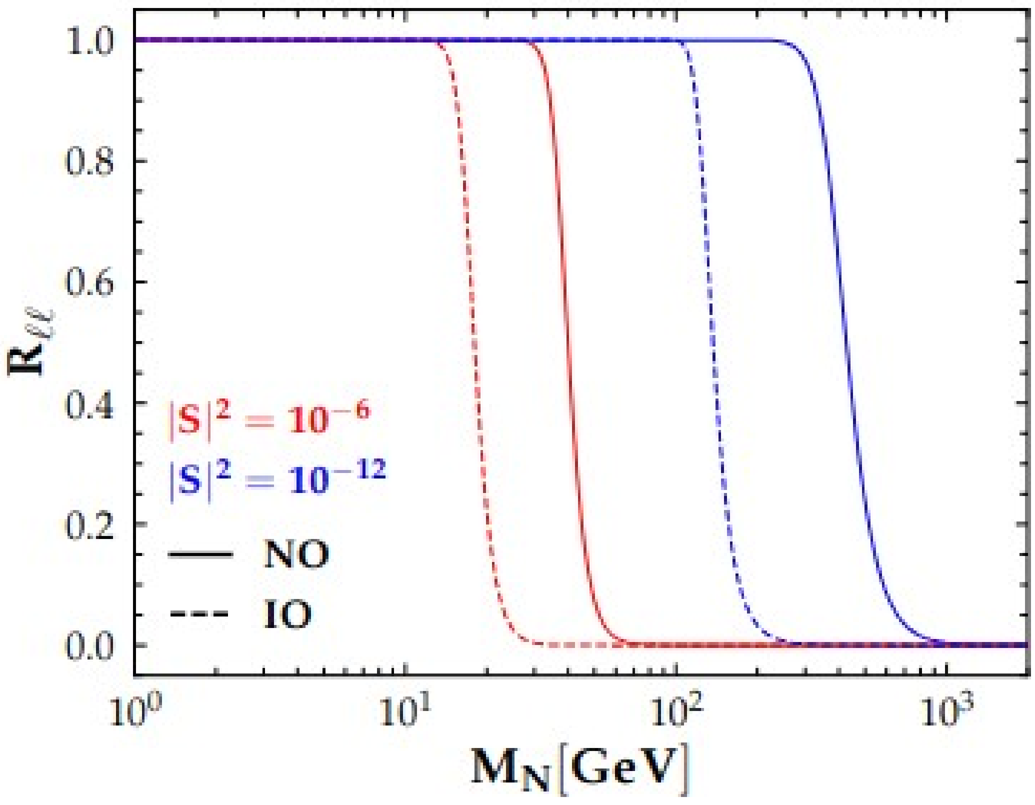


LNV at colliders

- The ratio between LNC and LNV events (for an ideal detector)

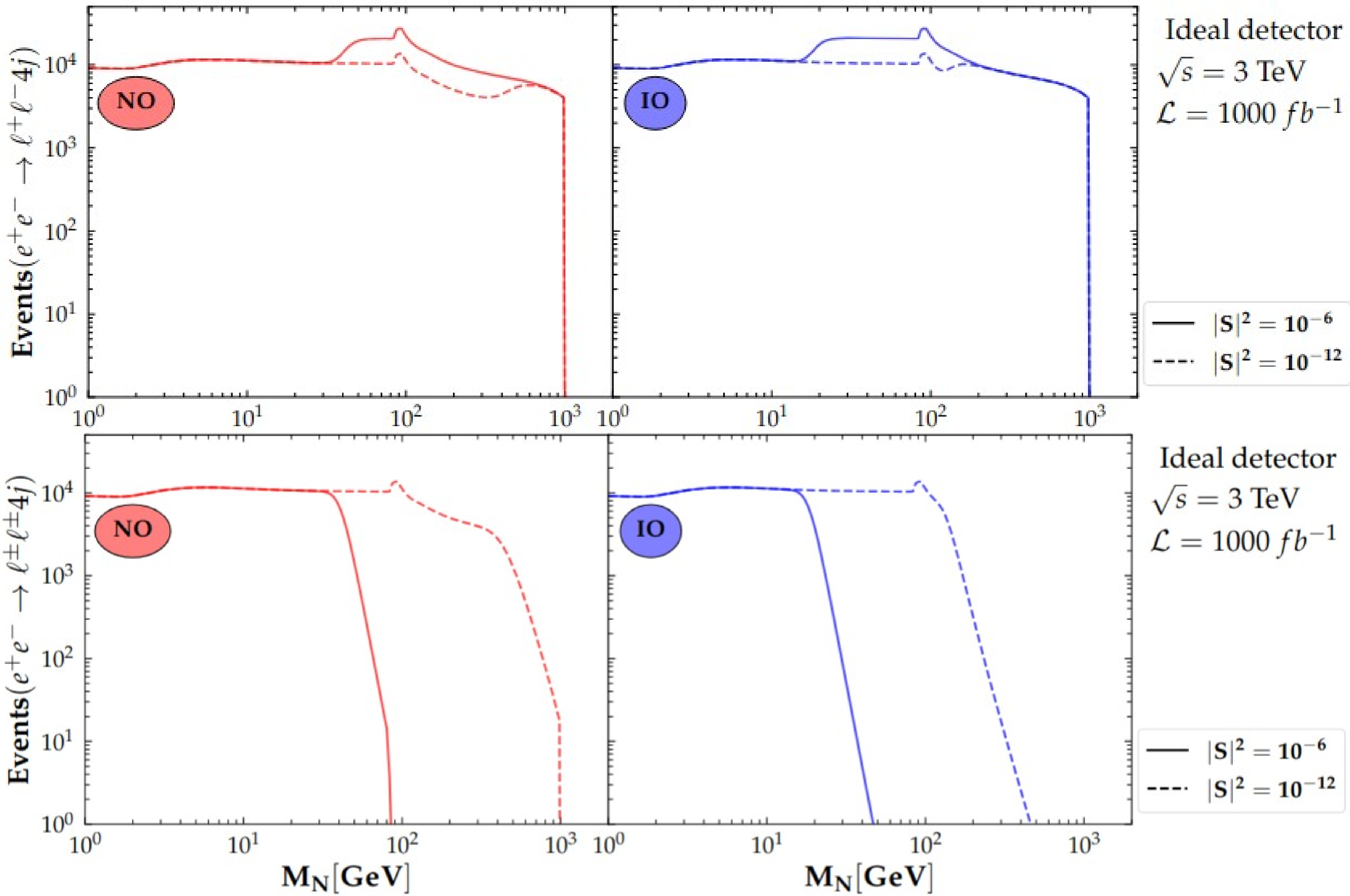
$$R_{\ell\ell} = \frac{N^{\mathrm{LNV}}}{N^{\mathrm{LNC}}} = \frac{y^2(2+y^2)}{2+y^2(2+y^2)} \text{ with } y = \frac{\Delta M}{\Gamma_N}$$



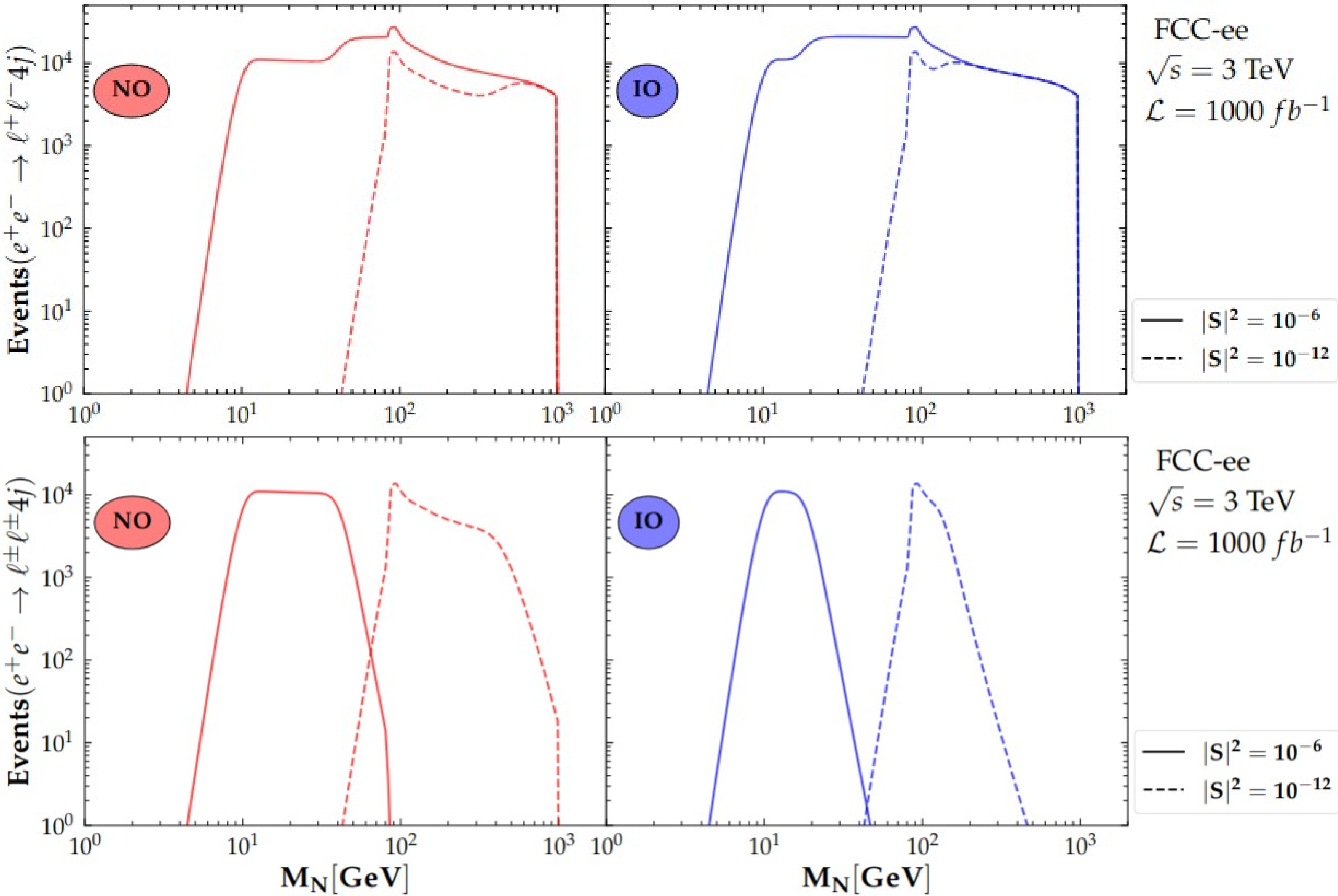


Above a certain M_N $R_{\ell\ell}$ drops to zero as $\frac{\Delta M}{\Gamma_N}$ becomes small

Ideal Detector



FCC-ee



NO
IO
FCC-ee
$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1000\ fb^{-1}$
$|S|^2 = 10^{-6}$
$|S|^2 = 10^{-12}$
Events$(e^+e^- \to \ell^+\ell^- 4j)$
Events$(e^+e^- \to \ell^\pm\ell^\pm 4j)$
M_N[GeV]

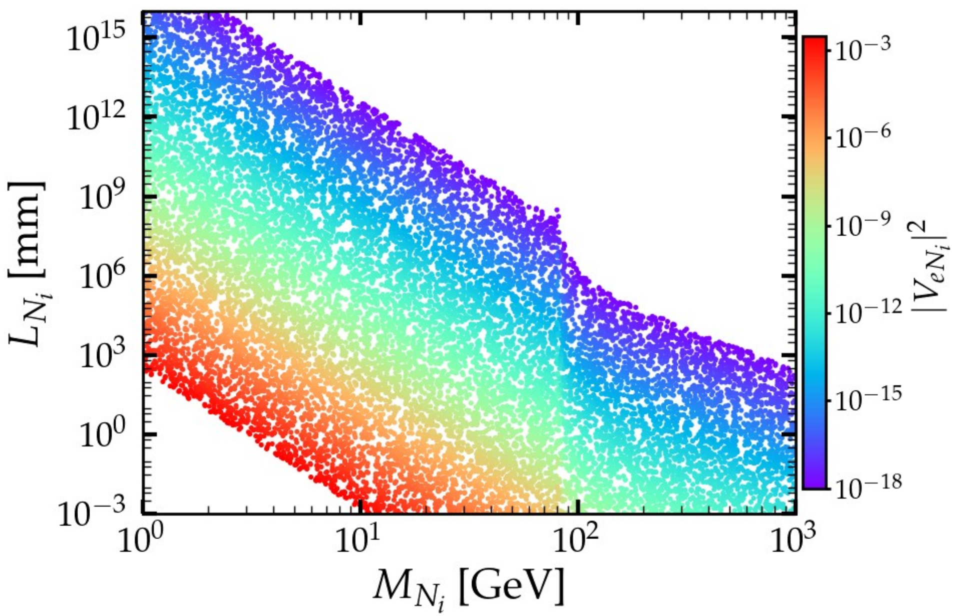
Conclusion

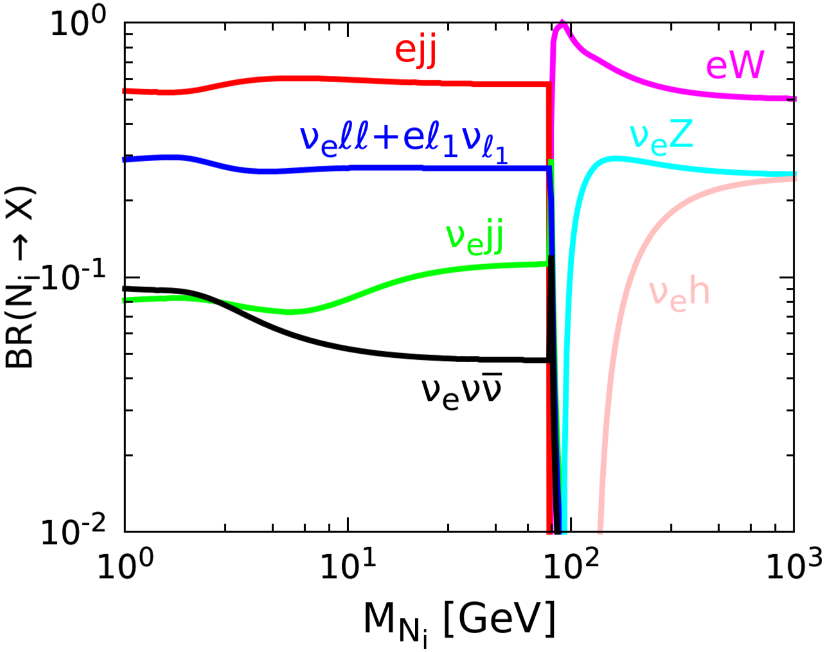
- Lepton number violating same-sign dilepton events are rare in SM, making them a distinctive signature for new physics.
- In contrast to other low-scale seesaw schemes, in linear seesaw mechanism, LNV can be large at high energies.
- The Yukawa coupling Y_S detemines the heavy-neutrino production instead of the small light-heavy neutrino mixing.
- Heavy neutrino-antineutrino oscillations are necessary for the LNV signal.
- A relatively large number of LNV events are expected at colliders.

Thank You

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

RHN decay modes





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