Prospects for Heavy Majorana Neutrino searches at future lepton colliders

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Outline

- **Processes $e^+e^- \to N\nu$ and $\mu^+\mu^- \to N\nu$**

  K. Mekala, J. Reuter, and A.F. Zarnecki, JHEP 06 (2022) 010, arXiv:2202.06703

  K. Mekala, J. Reuter, and A.F. Zarnecki, Phys. Lett. B 841 (2023) 137945, arXiv:2301.02602

  P. Li, Z. Liu, K.F. Lyu, arXiv:2301.07117.

- **Processes $e^+e^- \to N W^- e^+$ and $\mu^+\mu^- \to N W^- \mu^+$**

  E. Antonov, A. Drutskoy, M. Dubinin, arXiv:2308.02240.

- **Processes $e^-e^- \to W^-W^-$ and $\mu^+\mu^+ \to W^+W^+$**

  T. Asaka, T. Tsuyuki, Phys. Rev. D 92, 9, 094012 (2015), arXiv:1508.04937.

  R. Jiang, T. Yang, S. Qian, Y. Ban, J. Li, Z. You and Q. Li, arXiv:2304.04483.

Seesaw Type I model

Main task of experimental particle physics is search for Beyond the Standard Model effects.

Seesaw Type I model: widely discussed in literature

Details about seesaw model are in Mikhail Dubinin talk.

Model includes Heavy Neutral Leptons (Majorana), maybe 3 HNL: N_1, N_2, N_3

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu}$$

Neutrino mass matrix with Dirac and Majorana mass terms ($\boldsymbol{y}_\mathrm{D}$ – Yukawa coupling matrix)

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \qquad M_D = \boldsymbol{y}_\mathrm{D}\, v/\sqrt{2} \qquad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

Seesaw mechanism: small masses of active neutrinos are defined by large M_N parameter of Majorana term (after diagonalizing mass matrix).

If $M_N \approx 100$ GeV (within collider energy reach), then $M_\nu \approx 0.1$ eV if $\boldsymbol{y}_\mathrm{D} \approx 10^{-6}$.

"Classical" seesaw mixing parameter $|V_{\ell N}|^2 \approx M_\nu/M_N \leq 10^{-12}$, specific models ➔ $\times 10^3$-10^8
Example: arXiv: 1101.1382 (T. Asaka, S. Eijima, H. Ishida, JHEP 1104:011,2011)

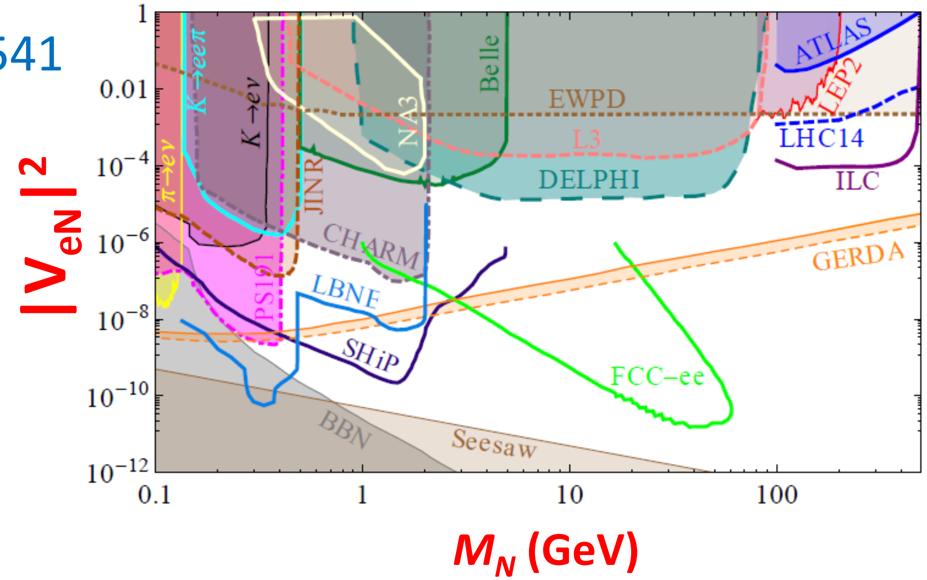
Experimental limits on mixing parameters

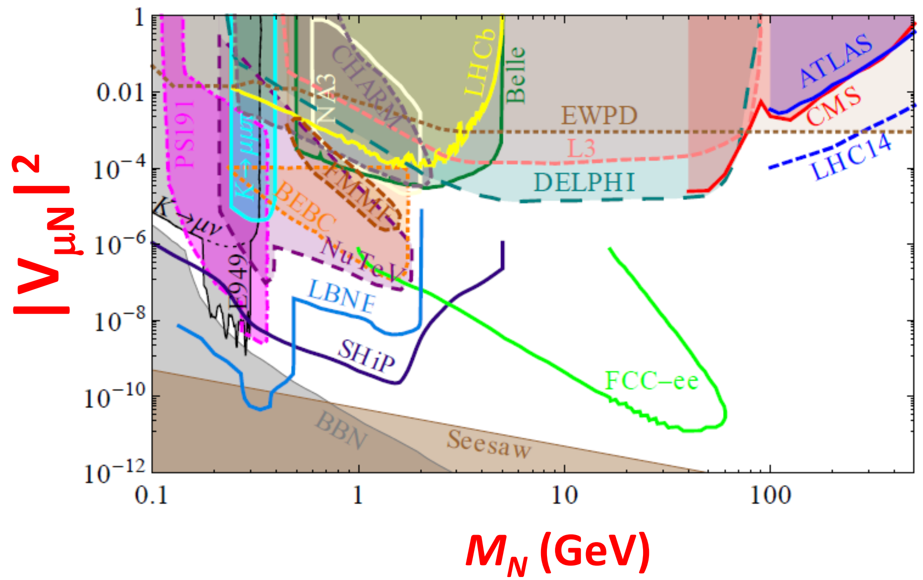
arXiv:1502.06541

Below 90 GeV ⟶ decays of
K mesons, B mesons, Z bosons

Mostly LHC current upper limits
and future estimates after 90 GeV,
weak upper limits

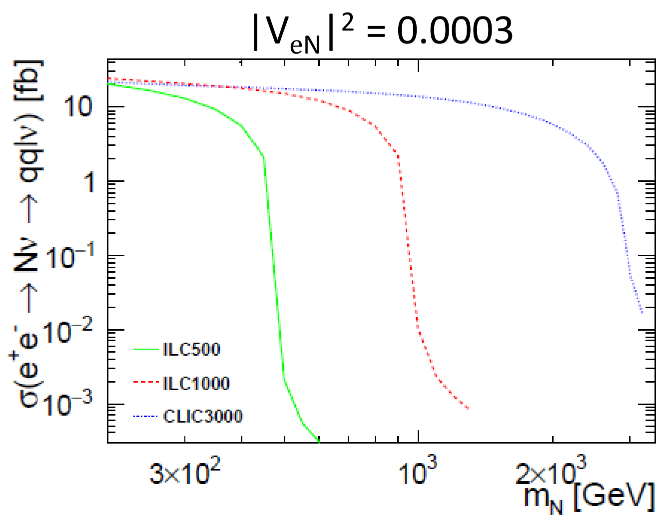
GERDA experiment:
neutrinoless double beta
(0νββ) decay.
In some models this limit at high
M_N mass can be circumvented

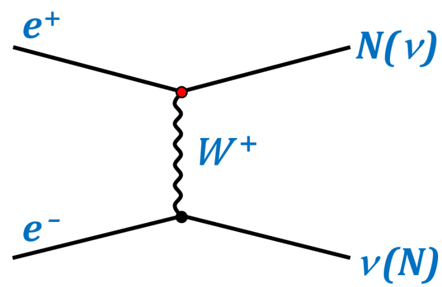


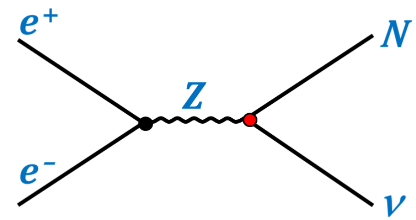


Process $e^+e^- \to N\nu$

arXiv:2202.06703







ILC, e^+e^-, 500 GeV, 1.6 ab^{-1}, P=(e^-:-80%, e^+:+30%)

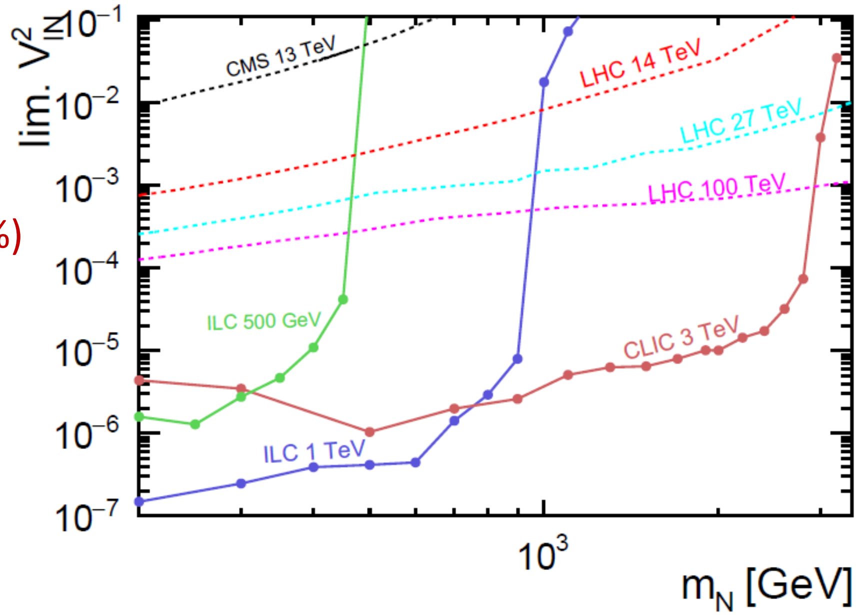
ILC, e^+e^-, 1000 GeV, 3.2 ab^{-1}, P=(e^-:-80%, e^+:+20%)

CLIC, e^+e^-, 3000 GeV, 4.0 ab^{-1}, P=(e^-:-80%)

Whizard, Delphes 3, BDT (TMVA, 8 variables)

➔ Very strong upper limits can be obtained

Upper limits on mixing parameter $|V_{eN}|^2$



For simplicity only one HNL with M(N) ≥ 100 GeV is assumed in calculations.

Process $\mu^+\mu^- \to N\nu$

arXiv:2301.02602

Upper limits on mixing parameter $|V_{\mu N}|^2$

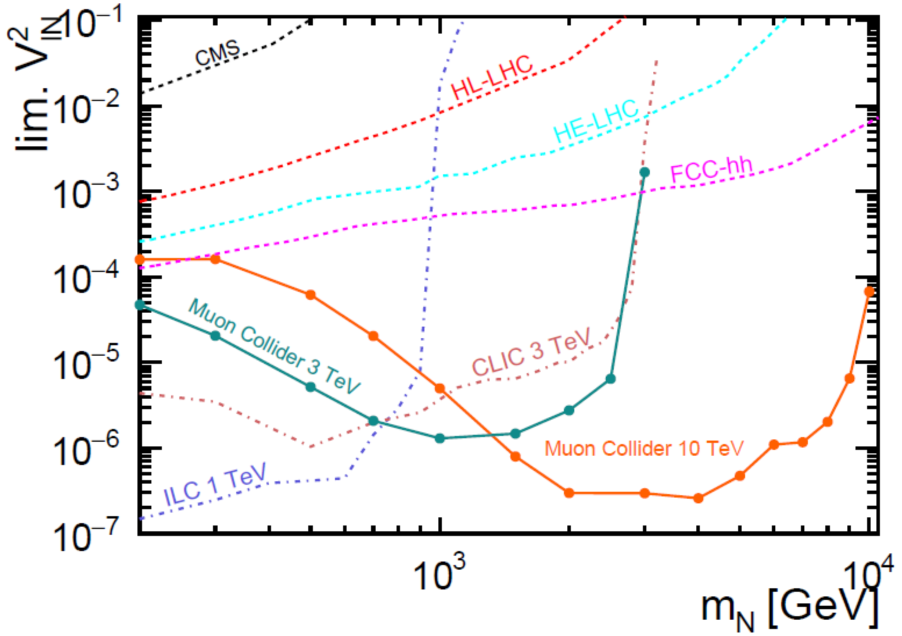


FIG. 3: Limits on the coupling $V^2_{\ell N}$ for different Muon Collider setups (solid lines: 3 TeV – turquoise, 10 TeV – orange). Dashed lines indicate limits from current and future hadron [1, 5] machines, dashed-dotted for e^+e^- colliders [16]. See text for details.

MuC, $\mu^+\mu^-$, 3000 GeV, 1.0 ab^{-1} ; $\mu^+\mu^-$, 10000 GeV, 10.0 ab^{-1}

Whizard 3, Delphes 3, BDT (TMVA, 8 variables)

➔ Very strong upper limits can be obtained for HNL masses almost up to CM energy.

Process $\mu^+\mu^- \to N\nu$

arXiv:2301.07117

Upper limits on mixing parameter $|V_{\mu N}|^2$

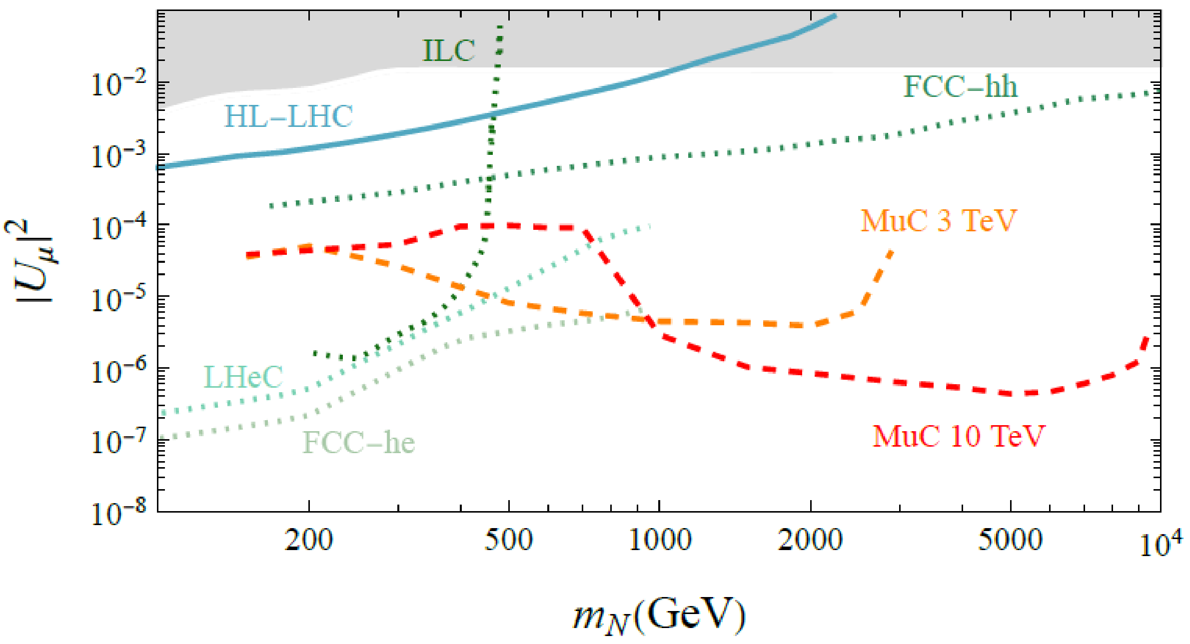


FIG. 10. The 95% exclusion limits on the $|U_\mu|^2$-m_N plane at different experimental facilities including LHC [32, 50, 79] and proposed future colliders (LHeC and FCC-he [80], FCC-hh [50, 81],ILC [28, 52]). MadGraph5, FeynRules

MuC, $\mu^+\mu^-$, 3000 GeV, 1.0 ab^{-1} ; $\mu^+\mu^-$, 10000 GeV, 10.0 ab^{-1}

Upper limits are similar to ones shown in previous slide

Processes $e^+e^- \to N W^- e^+$ and $\mu^+\mu^- \to N W^- \mu^+$

arXiv:2308.02240

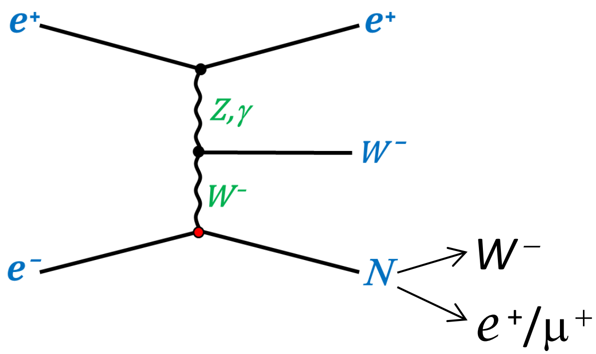
Processes with lepton number violation by 2 units:

$e^+e^- \to N W^- e^+ \to W^- W^- e^+ e^+ (/\mu^+)$

$\mu^+\mu^- \to N W^- \mu^+ \to W^- W^- \mu^+ \mu^+ (/e^+)$

$e^- e^- \to N W^- e^- \to W^- W^- e^+ e^- (/\mu^-)$

$\mu^+\mu^+ \to N W^+ \mu^+ \to W^+ W^+ \mu^+ \mu^- (/e^-)$

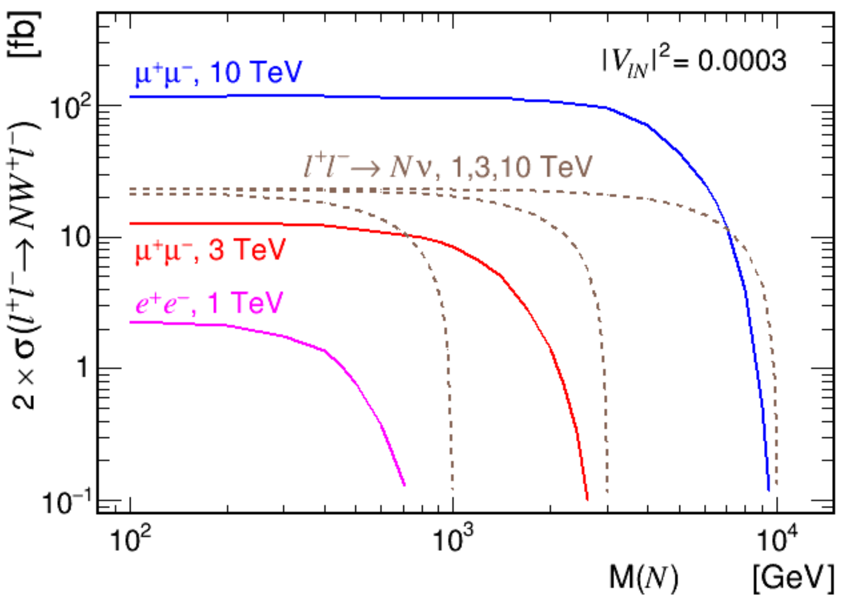


$\sigma(\mu^+\mu^+ \to N W^+ \mu^+) = 2 \times \sigma(\mu^+\mu^- \to N W^- \mu^+)$

Cross sections of these processes are enhanced by soft photon exchange in *t*-channel (infrared effect).

Positron is going close to beam positron direction and cannot be detected.

Other particles (W^-,W^-,e^+) can be reconstructed with high efficiency.



Processes $e^+e^- \to N W^- e^+$ and $\mu^+\mu^- \to N W^- \mu^+$

arXiv:2308.02240

ILC, e^+e^-, 1 TeV, 1 ab^{-1}

MuC, $\mu^+\mu^-$, 3 TeV, 1 ab^{-1}

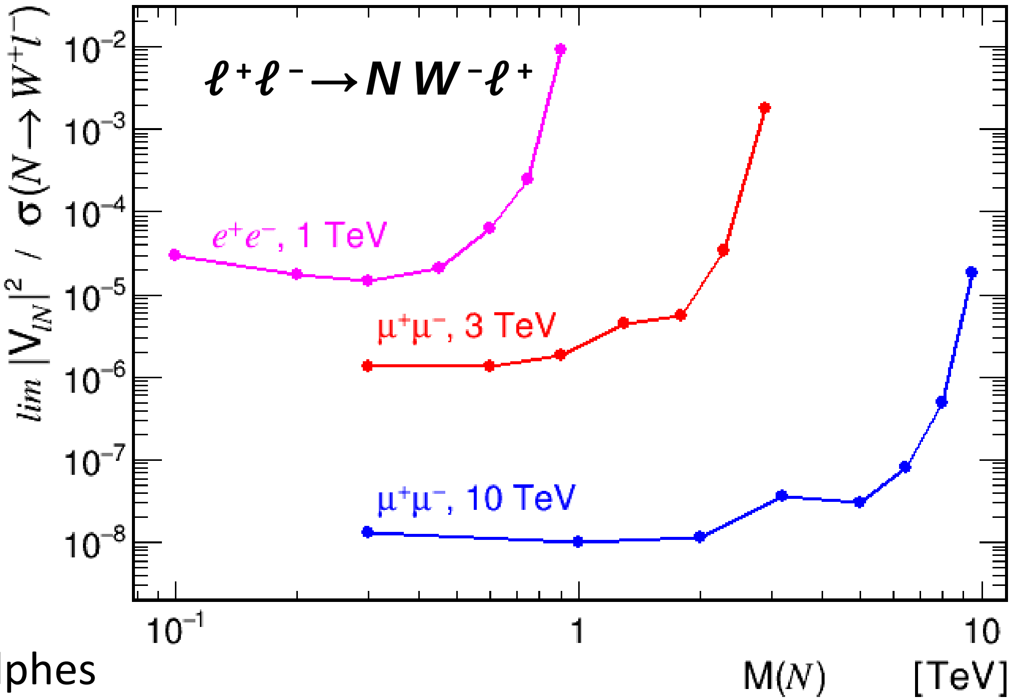
MuC, $\mu^+\mu^-$, 10 TeV, 10 ab^{-1}

Background can be effectively suppressed.

Signal: CompHEP, Pythia6, Delphes

Background: Whizard2 (Pythia6), Delphes

Upper limits on mixing parameter $|V_{\ell N}|^2$

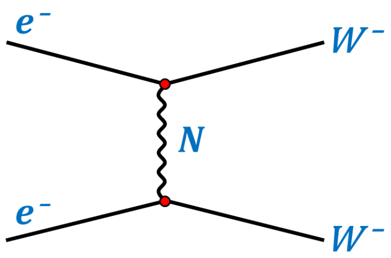


Upper limits obtained for $\ell^+\ell^- \to N W^- \ell^+$ process comparing with $\ell^+\ell^- \to N \nu$ process are slighly worse at $\sqrt{s}$ = 1 TeV, about the same at 3 TeV, and better at 10 TeV.

➔ It is possible to search for HNL using $\ell^+\ell^+ \to N W^+ \ell^+$ with same-sign beams.

Processes $e^- e^- \to W^- W^-$ and $\mu^+ \mu^+ \to W^+ W^+$

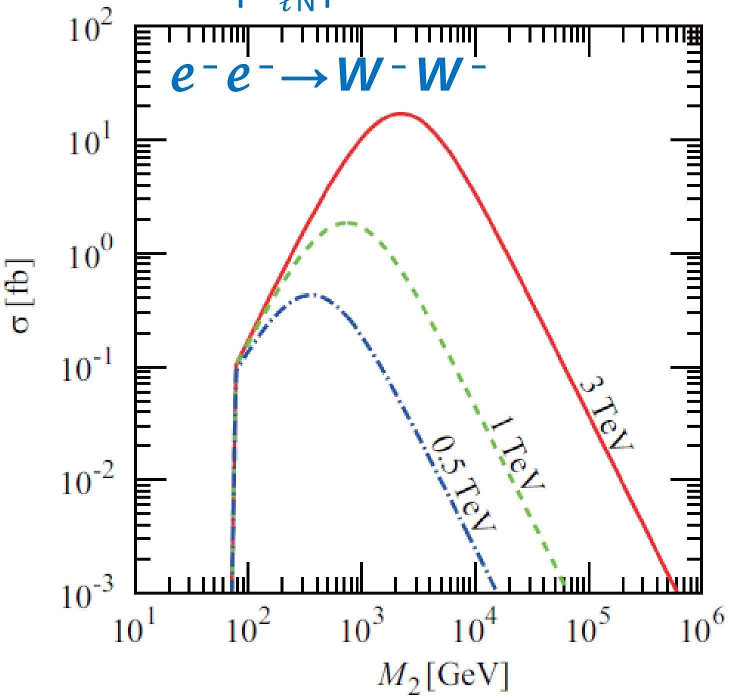
arXiv:1508.04937

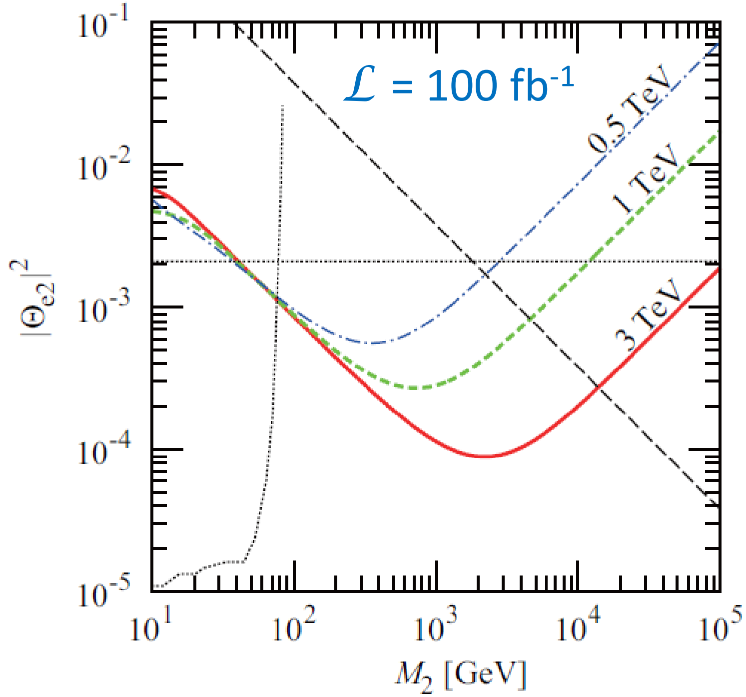


Model includes 3 HNL, only one with large mixing parameter.

Clean hadronic final state W(jj) W(jj) with 4 jets.
Energy E(4j) peaks at $\sqrt{s}$. No backgrounds under signal.

$|V_{\ell N}|^2 = 0.0021$



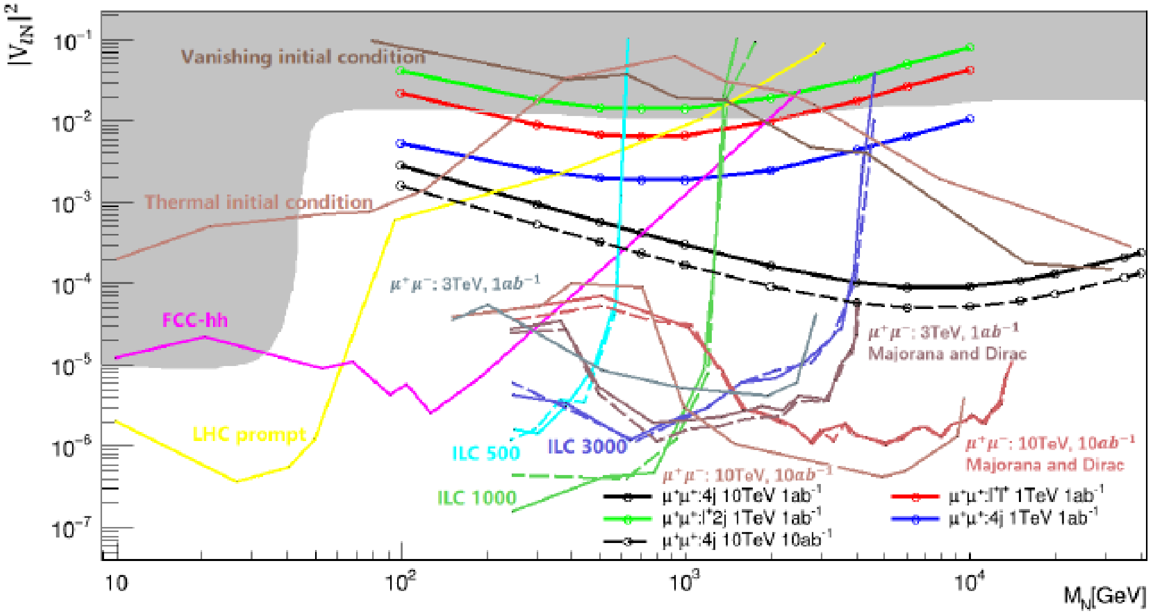


➡ Although upper limits are not strong, sensitivity to very large M(N) ~ 10^5-10^6 GeV

Processes $e^- e^- \to W^- W^-$ and $\mu^+\mu^+ \to W^+ W^+$

arXiv:2304.04483

$\mu^+\mu^+ \to W^+ W^+$



MadGraph5, Pythia8, Delphes

BDT background suppression

Figure 8: 2σ exclusion limit of $|V_{\mu N_1}|^2$ as a function of varying Majorana neutrino mass M_N. The green solid line corresponds to the semi-leptonic processes at a muon collider with $\sqrt{s} = 1\text{TeV}, \mathcal{L} = 1\ \text{ab}^{-1}$. The red solid line corresponds to the pure-leptonic processes at a muon collider with $\sqrt{s} = 1\text{TeV}, \mathcal{L} = 1\ \text{ab}^{-1}$. The dark-blue line corresponds to the hadronic processes at a muon collider with $\sqrt{s} = 1\text{TeV}, \mathcal{L} = 1\ \text{ab}^{-1}$. The black line corresponds to the hadronic processes at a muon collider with $\sqrt{s} = 10\text{TeV}, \mathcal{L} = 1\ \text{ab}^{-1}$. The black dotted line corresponds to the hadronic processes at a muon collider with $\sqrt{s} = 10\text{TeV}, \mathcal{L} = 10\ \text{ab}^{-1}$. The experimental result from LHC and other simulation results are also added for comparison.

Conclusions

- Future lepton colliders at high CM collision energies can provide very strong upper limits on mixing parameters $|V_{\ell N}|^2$ as function of M(N).

- Much stronger upper limits on $|V_{\ell N}|^2$ can be obtained for HNL masses M(N) > 100 GeV in future lepton colliders experiments comparing with upper limits expected in $(0\nu\beta\beta)$ experiments and at LHC.

- Expected upper limits could provide strict tests of specific Seesaw Type-I models with not constrained mixing parameter.

MC event simulation

Signal events : CompHEP generator ➔ Pythia 6 ➔ Delphes (detector modelling)

Background events : Whizard 2 generator (Pythia 6) ➔ Delphes

Generators: no beam polarization, ISR included

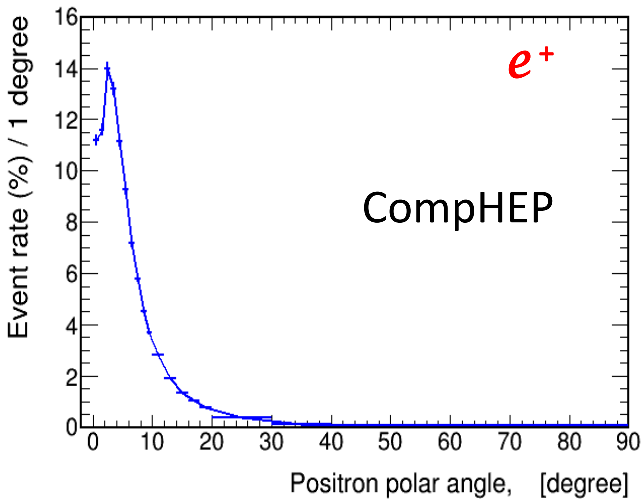
Delphes: ILD card at 1 TeV e^+e^- collisions, MuC card at 3 TeV and 10 TeV $\mu^+\mu^-$ collisions

Jet reconstruction: Valencia algorithm, reasonable shapes comparing with full simulation. Algorithm is forced to reconstruct 4 jets. At high W and Z energies we observe jet overlapping ➔ we have to treat two jets as one object (W or Z boson).

Preselections:

$\lvert\eta\,(\text{jet})\rvert < 0.9$	$\lvert\eta\,(\text{lepton})\rvert < 0.9$
E(jet) > 30 GeV	E(lepton) > 30 GeV

Event kinematics ($\sqrt{s}$ = 3 TeV, M(N) = 1 TeV)



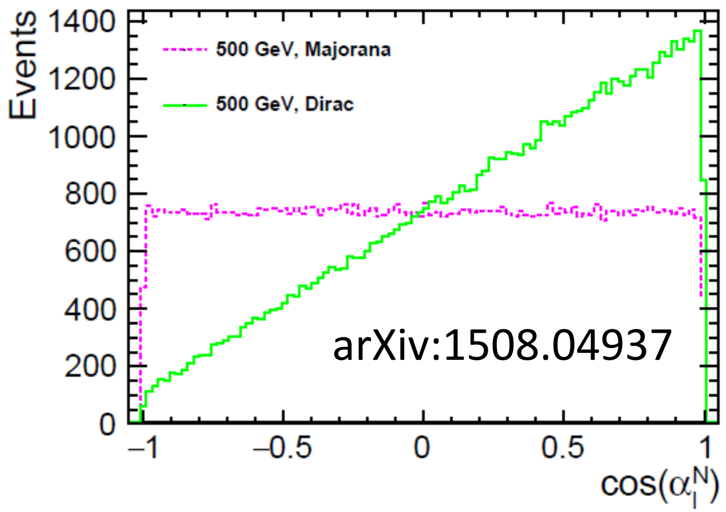
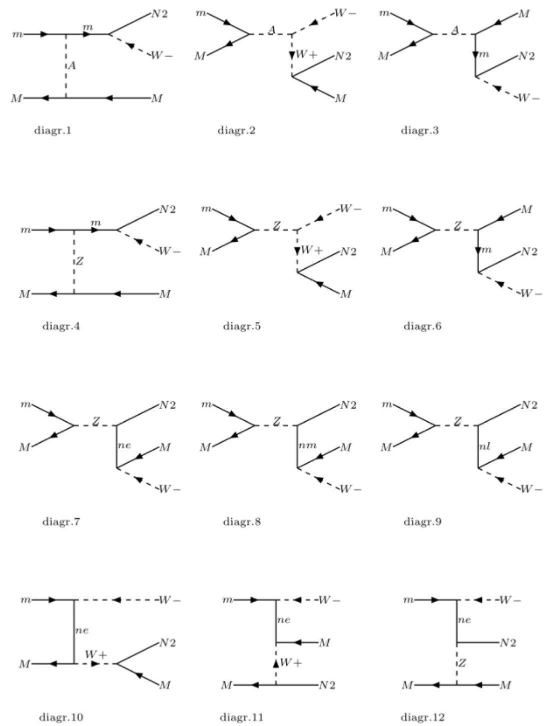


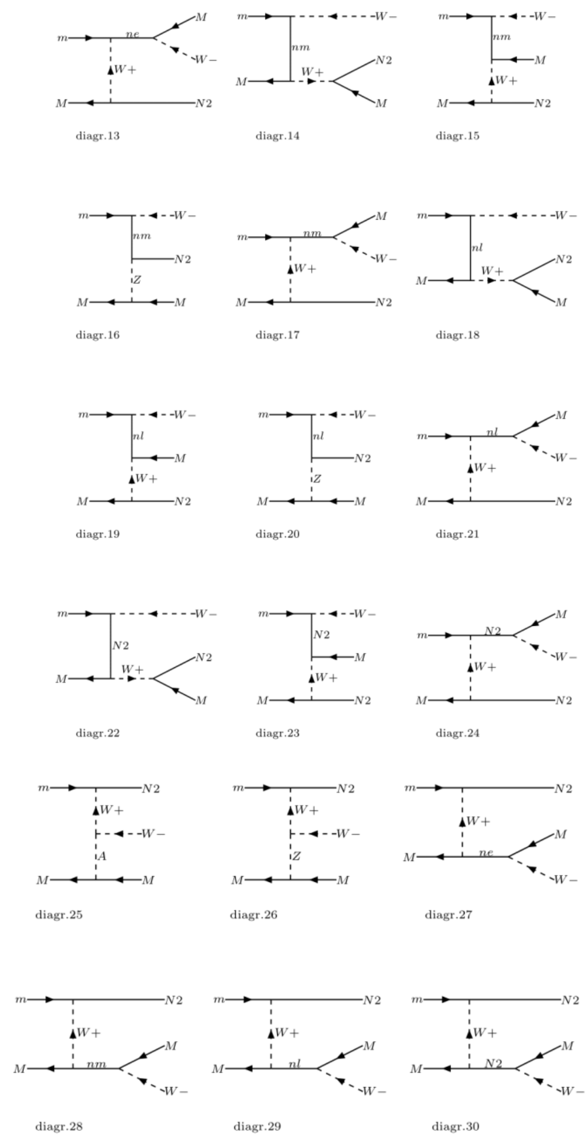
Figure 10: Distribution of the cosine of the lepton emission angle in the N rest-frame for the Majorana (pink dashed line) and the Dirac (green solid line) neutrinos with a mass of 500 GeV at CLIC3000 (generator level)

Majorana function (pink line) includes term f = N(1+cos(theta)) with lepton number conservation and term f = N(1-cos(theta)) with nonconservation.

Angular distributions for jets and lepton depend on CM energy and HNL mass.

Diagrams for $\mu^+\mu^- \to N W^- \mu^+$ process





$\gamma \to$ A

N $\to$ N2

$\mu^- \to$ m

1

$\mu^+ \to$ M

$\nu_e, \nu_\mu, \nu_\tau \to$ ne, nm, nl

Inverse Seesaw model

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

A. G. Dias, C. A. de S. Pires, P. S. Rodrigues da Silva, and A. Sampieri, "A Simple Realization of the Inverse Seesaw Mechanism," *Phys. Rev. D* **86** (2012) 035007, arXiv:1206.2590 [hep-ph].

S. S. C. Law and K. L. McDonald, "Generalized inverse seesaw mechanisms," *Phys. Rev. D* **87** (2013) no. 11, 113003, arXiv:1303.4887 [hep-ph].

R. N. Mohapatra and J. W. F. Valle, "Neutrino Mass and Baryon Number Nonconservation in Superstring Models," *Phys. Rev. D* **34** (1986) 1642.

E. Ma, "Lepton Number Nonconservation in $E(6)$ Superstring Models," *Phys. Lett. B* **191** (1987) 287.

E. Ma, "Radiative inverse seesaw mechanism for nonzero neutrino mass," *Phys. Rev. D* **80** (2009) 013013, arXiv:0904.4450 [hep-ph].

F. Bazzocchi, "Minimal Dynamical Inverse See Saw," *Phys. Rev. D* **83** (2011) 093009, arXiv:1011.6299 [hep-ph].

$$m_D = \boldsymbol{y}_D / \sqrt{2}$$

$$m_\nu \approx \frac{m_D^2}{M}\frac{\mu}{M} \qquad M_{1,2} \approx M \pm \frac{1}{2}\mu$$

$$|U_\ell|^2 = \sin^2\theta = \left(\frac{m_D}{M}\right)^2 = \frac{m_\nu}{\mu}$$

μ is a free parameter and mixing parameter may be sizable.

Theoretical model

Seesaw Type I model

Seesaw type-I model with unitarity is installed in generator CompHEP as proposed in arXiv: 1101.1382 (Takehiko Asaka, Shintaro Eijima, Hiroyuki Ishida, JHEP 1104:011,2011).

Model: 3 Heavy Neutral Leptons (Majorana), N1, N2, N3. For simplicity we include in calculations only one HNL with M(N) ≥ 100 GeV.

It can be realized in two scenarios: 1) huge masses of N2 and N3,
2) very small mixing parameter $|V_{\ell N1}|^2$ for “small” mass N1, that could be resulted from specific *CP*-violating phases in PMNS matrix (arXiv:1508.04937) .

To compare our results with recent results obtained in studies of $e^+e^- \to N\nu$ process (arXiv:2202.06703), we also assume:

$$|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}|^2 = |V_{\ell N}|^2 = 0.0003$$

Final limits on $|V_{\ell N}|^2$ will not depend on this assumption of mixing parameters.

HNL width is included in calculations (same as in arXiv:2202.06703) ➔ negligible effect.