# Single HNL production at lepton colliders

**K. Mękała**[1,2], J. Reuter[2], A. F. Żarnecki[1]

[1]Faculty of Physics, University of Warsaw
[2]Theory Group, Deutsches Elektronen-Synchrotron DESY, Hamburg

Heavy Neutral Lepton search potential of future HET factories
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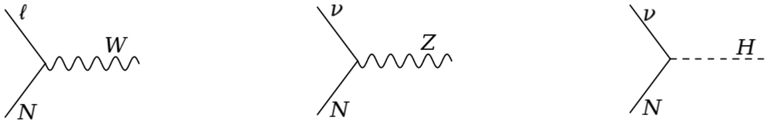
based on
*JHEP 06 (2022) 010* [arXiv: 2202.06703]
[arXiv: 2301.02602]

# HNL at lepton colliders

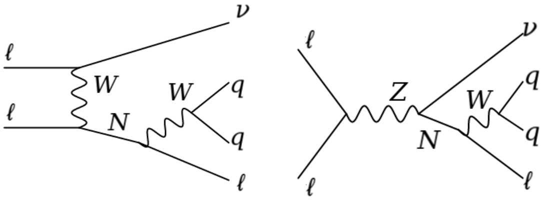
Let us assume that HNL couple only to the SM gauge bosons and Higgs:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{W-N-\ell} + \mathcal{L}_{Z-N-\nu} + \mathcal{L}_{H-N-\nu}$$

$\mathcal{L}_{W-N-\ell}$ $\mathcal{L}_{Z-N-\nu}$ $\mathcal{L}_{H-N-\nu}$




At lepton colliders, single production with subsequent decay into $qql$ could be efficiently probed, as it allows for direct reconstruction of $N$.



# Analysis setup

- Dirac and Majorana neutrinos
- masses:

$$\mathrm{m}_{N1} = 100\text{-}10{,}000\ \mathrm{GeV}$$
$$\mathrm{m}_{N2} = \mathrm{m}_{N3} = 10\ \mathrm{TeV}$$

- couplings:

$$|V_{eN1}|^2 = |V_{\mu N1}|^2 = |V^2_{\tau N1}| \equiv V^2_{lN}$$

$V^2_{lN} = 0.0003$ is used for generation of reference sig. samples

All the $N2$ and $N3$ couplings are set to zero.

- widths:

above $\mathcal{O}(1\ \mathrm{keV}) \rightarrow$ prompt decays only (no LLP signature),

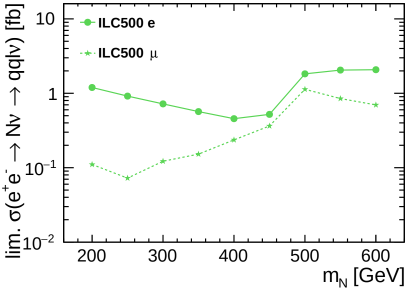
displaced vertices possible for masses $\mathcal{O}(10\ \mathrm{GeV})$ and below

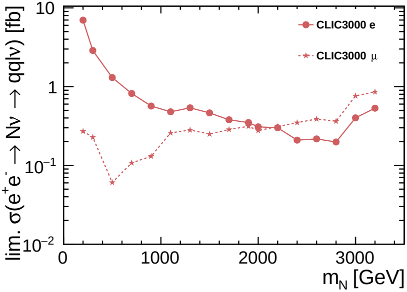
# Analysis procedure

1. Generating physical events with WHIZARD
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \to N\nu \to qq\ell\nu$ ("signal")
   - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
   - S/B $\sim 10^{-3}$, e.g. ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb
2. Simulating detector response with DELPHES
3. Preselection of events matching required signal topology
   - cuts opt. to search for $N$: exactly 1 lepton and 2 jets in the final state
4. BDT training
5. Using CLs method to get final results

# CLs method

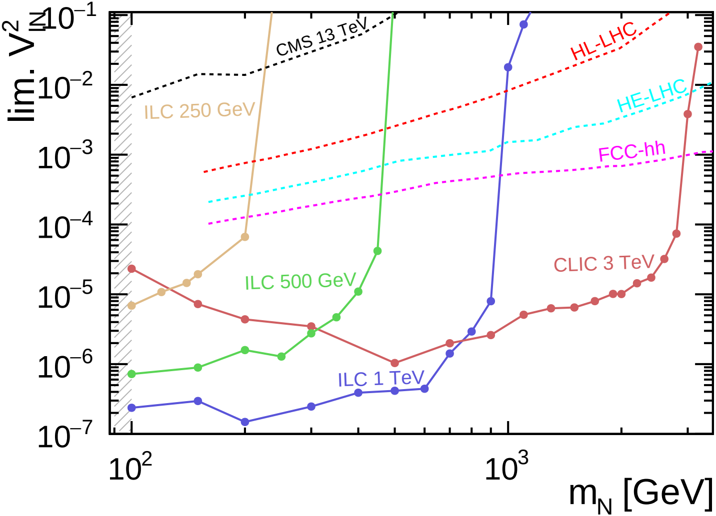
BDT response is used to build a model in RooStats to use the $CL_s$ method (combining both channels, $e^+e^-$: normalisation uncertainties).



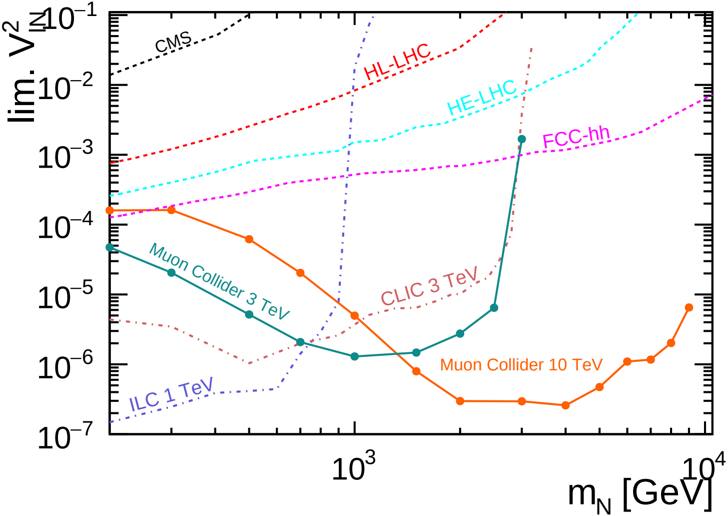
# Results for $e^+e^-$ colliders

The cross section limits can be translated into limits on the $V_{lN}^2$ parameter.



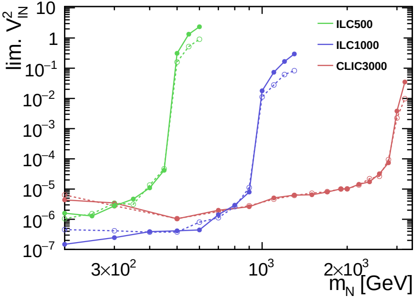

LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

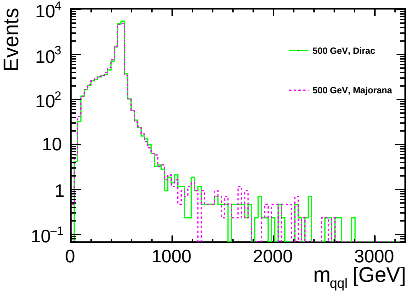
# Results for the Muon Collider




LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

# Dirac vs. Majorana

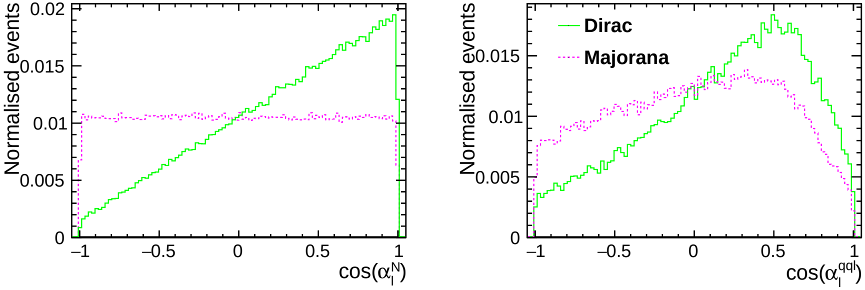



CLIC 3 TeV

# Are there any discriminant variables?

Lepton emission angle in the $N$ rest frame:

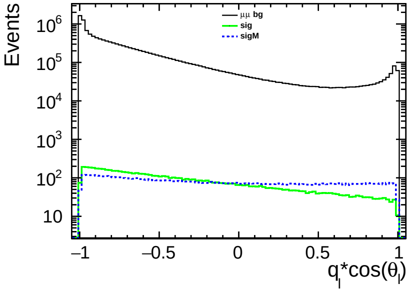


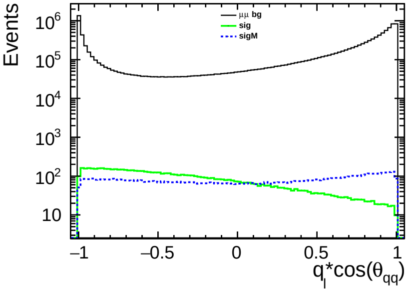

generator vs. detector

CLIC 3 TeV

# More sophisticated variables...

Lepton and dijet directions relative to the electron (positron) beam for positive (negative) lepton charge $q_l$:

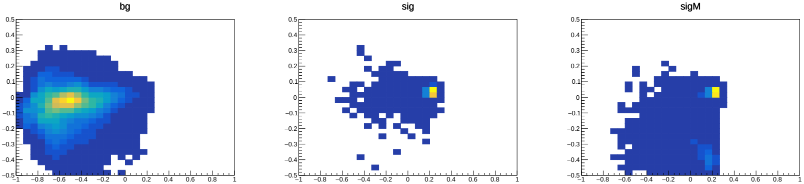



ILC 250 GeV, $m_N = 150$ GeV

# How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - Dirac vs. ($\alpha_{BDT}$ · Majorana + Background)
   - Majorana vs. ($\alpha_{BDT}$ · Dirac + Background)
2. 2D histograms: $BDT_D+BDT_M$, $BDT_D-BDT_M$




3. $\chi^2$-like statistic:

$$T' = \sum_{bins} \frac{[(B+D)-(B+M)]^2}{\frac{1}{2}[(B+D)+(B+M)]} = \sum_{bins} \frac{(D-M)^2}{B+\frac{D+M}{2}} \quad (1)$$

$$T = T' + \mathrm{DOF} \quad (2)$$

4. Statistical test:

$$T \geqslant \chi^2_{crit}(\mathrm{DOF}) \Rightarrow \text{hypotheses distinguishable}$$

# How to set limits?

$$T' \rightarrow T'(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D-M)^2}{B + \alpha_{lim} \cdot \frac{D+M}{2}}$$

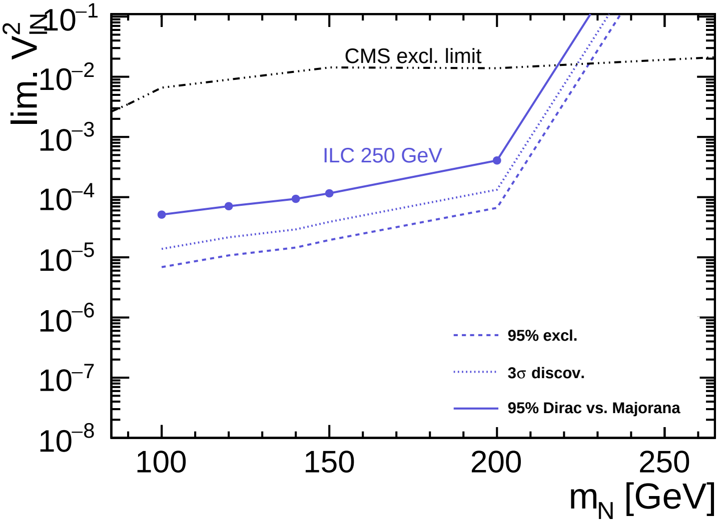
and we search for $\alpha_{lim}$, for which:

$$T \rightarrow T(\alpha_{lim}) \equiv \chi^2_{crit}(DOF).$$

Technical realisation: signal scaling factor used in the BDT training $\alpha_{BDT}$ is varied to obtain the best limit for each $m_N$.

1. Train BDT for different values of $\alpha_{BDT}$
2. For each $\alpha_{BDT}$, calculate 95% CL limit $\alpha_{lim}$ corresponding to $T(\alpha_{lim}) = \chi^2_{crit}(DOF)$
3. Select the best limit $\alpha_{min} = min(\alpha_{lim})$
4. Set the final limit as $V_{\ell N}^{\mathrm{lim}} = \alpha_{\mathrm{min}} \cdot V_{\ell N}^{\mathrm{ref}}$

# Dirac vs. Majorana - results



# Conclusions

1. At future lepton colliders, heavy neutrino production could be observed almost up to the kinematic limit.
2. The expected coupling limits are much stronger than those at LHC/FCC-hh.
3. Future lepton colliders could also efficiently probe the nature of the heavy neutrinos (work in progress!).

# BACKUP: HeavyN model

- effective extension of the Standard Model

  [HeavyN FeynRules]
- widely analysed for searches at hadron colliders

  e.g. [arXiv:1411.7305], [arXiv:2008.01092], [arXiv:2011.02547]
- 3 new heavy neutrinos – Majorana or Dirac particles: *N1, N2, N3*
- 12 free parameters:
  - 3 masses ($\sim 10^2 - 10^3$ GeV)
  - 9 mixing parameters (3x3 mixing matrix for $e, \mu, \tau$ and *N1, N2, N3*)

# BACKUP: Running scenarios

**ILC:**

- 500 GeV: total luminosity of 4000 $fb^{-1}$
  - 2 x 1600 $fb^{-1}$ for LR and RL beam polarisations
  - 2 x 400 $fb^{-1}$ for LL and RR beam polarisations

  assuming polarisation of $\pm$80% for electrons and $\pm$30% for positrons
- 1 TeV: total luminosity of 8000 $fb^{-1}$
  - 2 x 3200 $fb^{-1}$ for LR and RL beam polarisations
  - 2 x 800 $fb^{-1}$ for LL and RR beam polarisations

  assuming polarisation of $\pm$80% for electrons and $\pm$20% for positrons

**CLIC:**

- 3 TeV: total luminosity of 5000 $fb^{-1}$
  - 4000 $fb^{-1}$ for negative electron beam polarisation
  - 1000 $fb^{-1}$ for positive electron beam polarisation

  assuming polarisation of $\pm$80% for electrons

**Muon Collider:**

- 3 TeV: total luminosity of 1000 $fb^{-1}$
- 10 TeV: total luminosity of 10,000 $fb^{-1}$

# BACKUP: Neutrino width