Probing the nature of heavy neutrinos

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

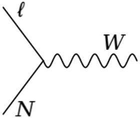
ILD Analysis/Software Meeting
12.04.2023

Heavy Neutral Leptons at lepton colliders

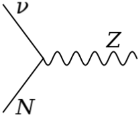
Let us assume that HNL couple only to the SM gauge bosons and Higgs:

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

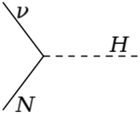
$\mathcal{L}_{W-N-\ell}$



$\mathcal{L}_{Z-N-\nu}$



$\mathcal{L}_{H-N-\nu}$

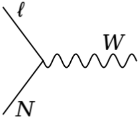


Heavy Neutral Leptons at lepton colliders

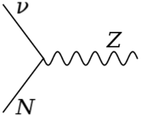
Let us assume that HNL couple only to the SM gauge bosons and Higgs:

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

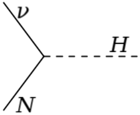
$\mathcal{L}_{W-N-\ell}$



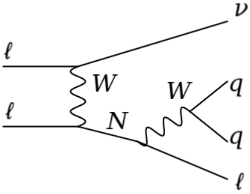
$\mathcal{L}_{Z-N-\nu}$

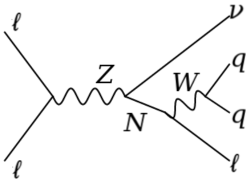


$\mathcal{L}_{H-N-\nu}$



At lepton colliders, single production with subsequent decay into *qql* is particularly interesting, as it allows for direct reconstruction of *N*.





Analysis setup

- Dirac and Majorana neutrinos
- 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.

- masses:

$$\mathrm{m}_N \geqslant 100 \text{ GeV}$$

- widths:

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

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

Analysis procedure

1. Generating physical events with WHIZARD
   - without N propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qq\ell\nu$ ("signal")
   - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included for ILC and CLIC
   - S/B $\sim 10^{-3}$, e.g. ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb

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
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included for ILC and CLIC
   - S/B $\sim 10^{-3}$, e.g. ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb
2. Simulating detector response with DELPHES

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
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included for ILC and CLIC
   - 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

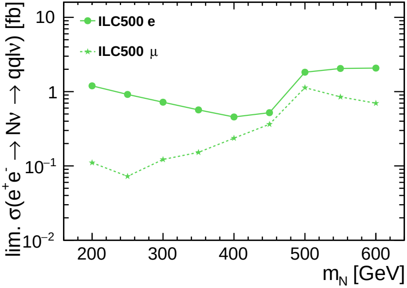
Analysis procedure

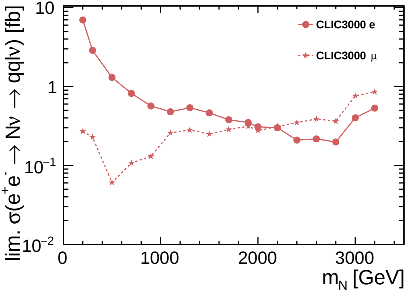
1. Generating physical events with WHIZARD
   - without N propagators ("background")
   - $\ell^+\ell^- \to N\nu \to qq\ell\nu$ ("signal")
   - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included for ILC and CLIC
   - 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

Analysis procedure

1. Generating physical events with WHIZARD
   - without N propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qq\ell\nu$ ("signal")
   - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included for ILC and CLIC
   - 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

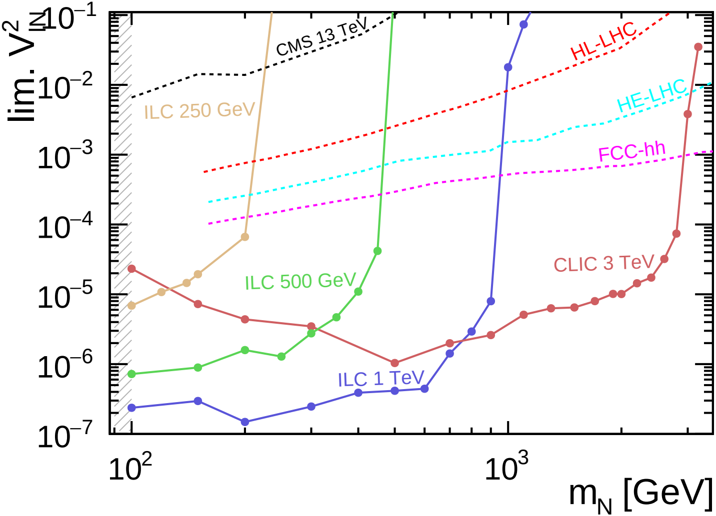
BDT response is used to build a model in RooStats to use the CL_s method (combining both channels, e^+e^-: normalisation uncertainties).





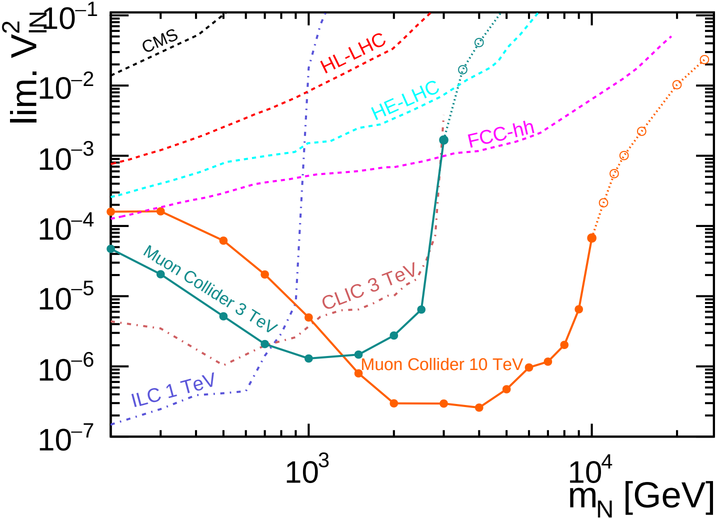
Results for e^+e^- colliders

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



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

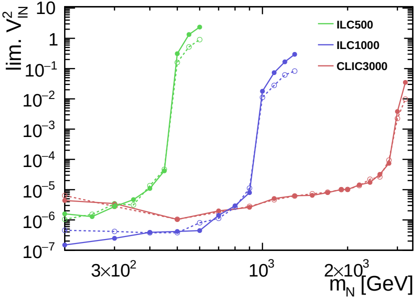
Results for the Muon Collider

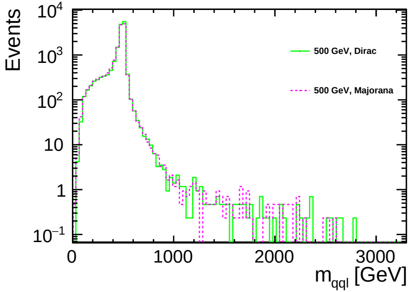


LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

Dirac vs. Majorana

Exclusion limits are very similar for the Dirac and Majorana neutrino hypothesis, except for off-shell production.



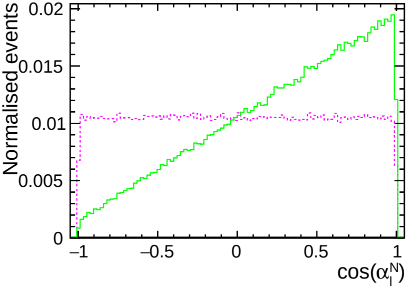


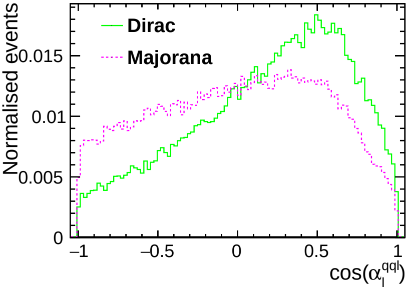
CLIC 3 TeV

Are there any discriminant variables?

Are there any discriminant variables?

Lepton emission angle in the N rest frame:



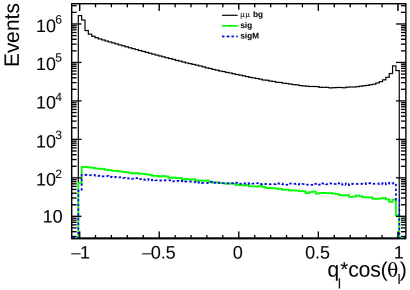


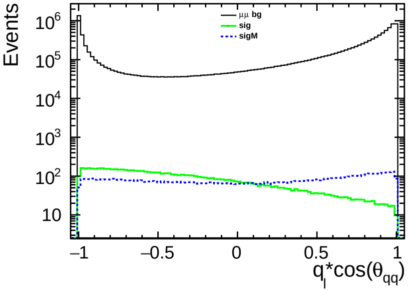
generator vs. detector

CLIC 3 TeV

More sophisticated variables...

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





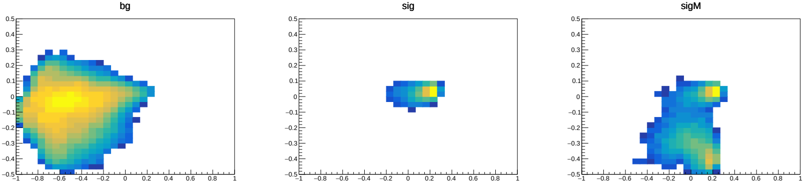
ILC 250 GeV, $m_N = 150$ GeV

How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - Dirac vs. ($\alpha_{BDT} \cdot$ Majorana + Background)
   - Majorana vs. ($\alpha_{BDT} \cdot$ Dirac + Background)

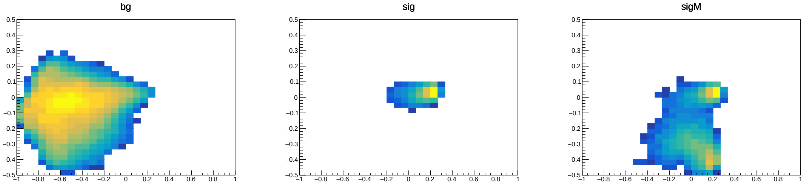
How to distinguish the two species of neutrinos?

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



How to distinguish the two species of neutrinos?

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



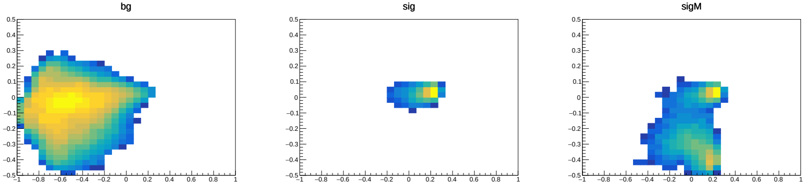
3. χ^2-like statistic:

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

$$T = T' + \mathrm{DOF} \tag{2}$$

How to distinguish the two species of neutrinos?

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



3. χ^2-like statistic:

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

$$T = T' + \mathrm{DOF} \tag{2}$$

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 α_{lim}, for which:

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

How to set limits?

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

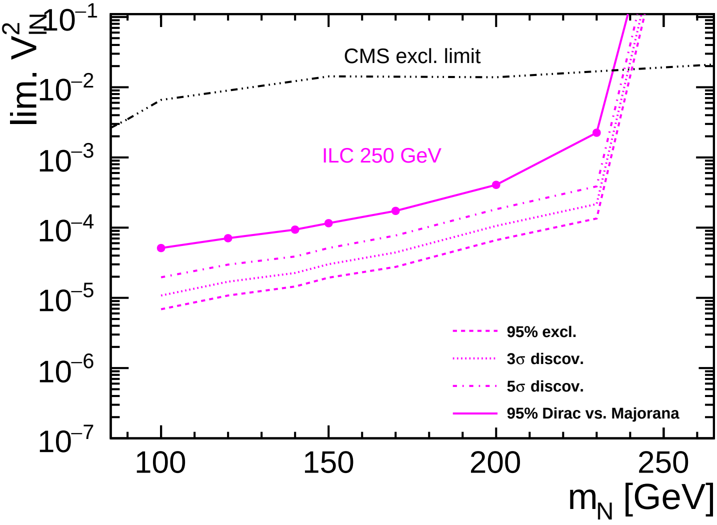
and we search for α_{lim}, for which:

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

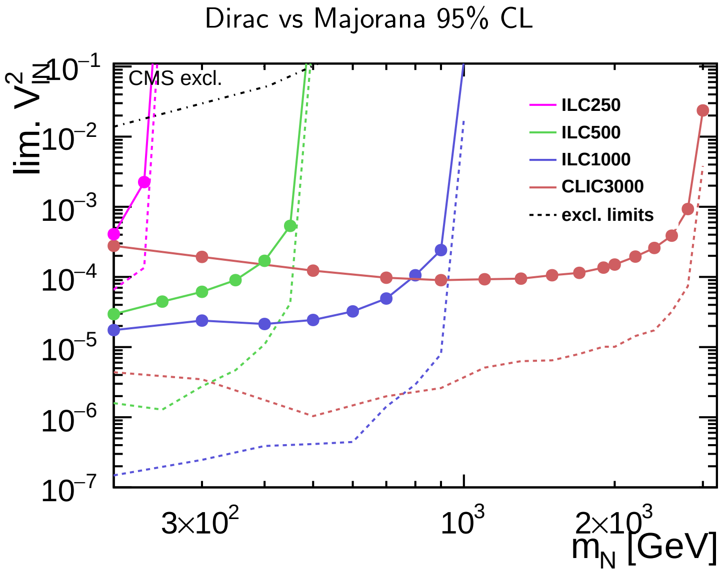
Technical realisation: signal scaling factor used in the BDT training α_{BDT} is varied to obtain the best limit for each m_N.

1. Train BDT for different values of α_{BDT}
2. For each α_{BDT}, calculate 95% CL limit α_{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 $V_{\ell N}^{\text{lim}} = \alpha_{\text{min}} \cdot V_{\ell N}^{\text{ref}}$

Dirac vs. Majorana – preliminary results for ILC250



Dirac vs. Majorana – preliminary 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.
4. Work in progress; planning to finalise for LCWS'23

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, μ, τ 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