Probing the nature of heavy neutrinos at future 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

LCWS’23
16.05.2023

*based on:*
[2202.06703]
[2301.02602]
and further development
Motivation

Some mysteries of the Standard Model:
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana
Some mysteries of the Standard Model:
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana

Can be addressed by introducing new species of neutrinos.
Let us assume that HNL couple only to the SM gauge bosons and Higgs:

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{W-N-\ell} + \mathcal{L}_{Z-N-\nu} + \mathcal{L}_{H-N-\nu} \]
Heavy Neutral Leptons at lepton colliders

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

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

At lepton colliders, single production with subsequent decay into \( q\ell q\ell \) is particularly interesting, as it allows for direct reconstruction of \( N \).
Analysis setup

- **HeavyN** model with 3 Dirac and Majorana neutrinos

- couplings:
  \[
  |V_{eN1}|^2 = |V_{\mu N1}|^2 = |V_{\tau N1}| \equiv V_{iN}^2
  \]
  \[V_{iN}^2 = 0.0003\] is used for generation of reference sig. samples
  
  All the \(N2\) and \(N3\) couplings are set to zero.

- masses:
  \[m_N \geq 100\text{ GeV}\]

- widths:
  
  above \(\Gamma \sim \mathcal{O}(1\text{ keV})\) → prompt decays only (no LLP signature),
  
  displaced vertices possible for masses \(\mathcal{O}(10\text{ GeV})\) and below
1. Generating physical events with WHIZARD
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow q\bar{q}\ell\nu$ ("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: $q\bar{q}\ell\nu$ background $\sim 10$ pb, signal $\sim 10$ fb
Generating physical events with Whizard

1. Generating physical events with Whizard
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qql\nu$ ("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

Simulating detector response with Delphes
Analysis procedure

1. Generating physical events with **Whizard**
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qql\nu$ ("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
Analysis procedure

1. Generating physical events with Whizard
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qql\nu$ ("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
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
   - S/B $\sim 10^{-3}$, e.g. ILC500: $qq\ell\nu$ 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. CLs method to get final results
Probing the nature of heavy neutrinos

ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV
Boosted Decision Trees

BDT trained with 8 input variables

ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV, $\mu$ in the final state
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 $V_{iN}^2$ 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: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$
Exclusion limits are very similar for the Dirac and Majorana neutrino hypothesis, except for off-shell production.
Are there any discriminant variables?
Are there any discriminant variables?

Lepton emission angle in the $N$ rest frame:

![Graph showing lepton emission angle](image)

Normalised events vs. $\cos(\alpha_N)$

Generator vs. detector

CLIC 3 TeV
Are there any discriminant variables?

Lepton emission angle in the $N$ rest frame:

![Graphs showing lepton emission angle in the $N$ rest frame.](image)

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:
   - LNV vs. \((\alpha_{BDT} \cdot \text{LNC} + \text{Background})\)
   - LNC vs. \((\alpha_{BDT} \cdot \text{LNV} + \text{Background})\)

\[\chi^2\text{-like statistic: } T' = \sum_{\text{bins}} \left[ (B + D) - (B + M) \right]^2 / (B + D + M)^2 \]

\[T = T' + \text{DOF} \quad (1)\]

Statistical test:

\[T \propto \chi^2_{\text{crit}}(\text{DOF}) \Rightarrow \text{hypotheses distinguishable} \]
How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - LNV vs. \((\alpha_{BDT} \cdot \text{LNC} + \text{Background})\)
   - LNC vs. \((\alpha_{BDT} \cdot \text{LNV} + \text{Background})\)

2. 2D histograms: \(\text{BDT}_{\text{LNV}} + \text{BDT}_{\text{LNC}}\), \(\text{BDT}_{\text{LNV}} - \text{BDT}_{\text{LNC}}\)
How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - LNV vs. \((\alpha_{BDT} \cdot \text{LNC} + \text{Background})\)
   - LNC vs. \((\alpha_{BDT} \cdot \text{LNV} + \text{Background})\)

2. 2D histograms: \(\text{BDT}_\text{LNV} + \text{BDT}_\text{LNC}, \text{BDT}_\text{LNV} - \text{BDT}_\text{LNC}\)

3. \(\chi^2\)-like statistic:
   \[
   T' = \sum_{bins} \frac{\left[(B + D) - (B + M)\right]^2}{\frac{1}{2}[(B + D) + (B + M)]} = \sum_{bins} \frac{(D - M)^2}{B + \frac{D + M}{2}}
   \]
   \[
   T = T' + \text{DOF}
   \]
How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - LNV vs. \((\alpha_{\text{BDT}} \cdot \text{LNC} + \text{Background})\)
   - LNC vs. \((\alpha_{\text{BDT}} \cdot \text{LNV} + \text{Background})\)

2. 2D histograms: \(\text{BDT}_{\text{LNV}} + \text{BDT}_{\text{LNC}}, \text{BDT}_{\text{LNV}} - \text{BDT}_{\text{LNC}}\)

3. \(\chi^2\)-like statistic:
   - \(T' = \sum_{\text{bins}} \frac{[(B + D) - (B + M)]^2}{\frac{1}{2}[(B + D) + (B + M)]} = \sum_{\text{bins}} \frac{(D - M)^2}{B + \frac{D + M}{2}}\) (1)
   - \(T = T' + \text{DOF}\) (2)

4. Statistical test:
   - \(T \geq \chi^2_{\text{crit}}(\text{DOF}) \Rightarrow \text{hypotheses distinguishable}\)
How to set limits?

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

and we search for \( \alpha_{\text{lim}} \), for which:

\[ T \rightarrow T(\alpha_{\text{lim}}) \equiv \chi^2_{\text{crit}}(\text{DOF}). \]
How to set limits?

\[ T' \rightarrow T'(\alpha_{\text{lim}}) = \sum_{\text{bins}} \frac{\alpha^2_{\text{lim}}(D - M)^2}{B + \alpha_{\text{lim}} \cdot \frac{D + M}{2}} \]

and we search for \( \alpha_{\text{lim}} \), for which:

\[ T \rightarrow T(\alpha_{\text{lim}}) \equiv \chi^2_{\text{crit}}(\text{DOF}) \]

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

1. Train BDT for different values of \( \alpha_{\text{BDT}} \)
2. For each \( \alpha_{\text{BDT}} \), calculate 95% CL limit \( \alpha_{\text{lim}} \) corresponding to \( T(\alpha_{\text{lim}}) = \chi^2_{\text{crit}}(\text{DOF}) \)
3. Select the best limit \( \alpha_{\text{min}} = \min(\alpha_{\text{lim}}) \)
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

Krzysztof Mękała (FUW/DESY)
Probing the nature of heavy neutrinos
16.05.2023 16 / 17
At future lepton colliders, heavy neutrino production could be observed almost up to the kinematic limit.

The expected coupling limits are much stronger than those for hadron colliders, including FCC-hh.

Future lepton colliders could also efficiently probe the nature of the heavy neutrinos.

Work in progress!
• effective extension of the Standard Model
  [HeavyN FeynRules]
• widely analysed for searches at hadron colliders
• 3 new heavy neutrinos – Majorana or Dirac particles: $N_1$, $N_2$, $N_3$
• 12 free parameters:
  • 3 masses ($\sim 10^2 – 10^3$ GeV)
  • 9 mixing parameters (3x3 mixing matrix for $e, \mu, \tau$ and $N_1, N_2, N_3$)
**BACKUP: Running scenarios**

**ILC:**
- 500 GeV: total luminosity of $4000 \text{ fb}^{-1}$
  - $2 \times 1600 \text{ fb}^{-1}$ for LR and RL beam polarisations
  - $2 \times 400 \text{ fb}^{-1}$ for LL and RR beam polarisations
  - assuming polarisation of $\pm 80\%$ for electrons and $\pm 30\%$ for positrons
- 1 TeV: total luminosity of $8000 \text{ fb}^{-1}$
  - $2 \times 3200 \text{ fb}^{-1}$ for LR and RL beam polarisations
  - $2 \times 800 \text{ fb}^{-1}$ for LL and RR beam polarisations
  - assuming polarisation of $\pm 80\%$ for electrons and $\pm 20\%$ for positrons

**CLIC:**
- 3 TeV: total luminosity of $5000 \text{ fb}^{-1}$
  - $4000 \text{ fb}^{-1}$ for negative electron beam polarisation
  - $1000 \text{ fb}^{-1}$ for positive electron beam polarisation
  - assuming polarisation of $\pm 80\%$ for electrons

**Muon Collider:**
- 3 TeV: total luminosity of $1000 \text{ fb}^{-1}$
- 10 TeV: total luminosity of $10,000 \text{ fb}^{-1}$
Probing the nature of heavy neutrinos
BACKUP: BDT variables

- $qq\ell$ invariant mass
- angle between jets
- angle between dijet and lepton
- lepton energy
- $qq\ell$ energy
- lepton transverse momentum
- dijet transverse momentum
- $qq\ell$ transverse momentum