Heavy Neutrinos at Future Linear $e^+e^-$ Colliders

K. Mękała$^1$, J. Reuter$^2$, A. F. Żarnecki$^1$

$^1$Faculty of Physics, University of Warsaw
$^2$Theory Group, Deutsches Elektronen-Synchrotron (DESY), Hamburg

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Some problems of the Standard Model:
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana
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can be solved by introducing new species of neutrinos.
The Standard Model with heavy neutrinos

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

Minimal scenario – without additional gauge bosons
HeavyN model: The Standard Model + Heavy Neutrinos

• effective model developed by R. Ruiz, D. Alva, T. Han... [HeavyN FeynRules]

• widely analysed for searches at hadron colliders

• 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 \(N1, N2, N3\))
Where to search for such neutrinos?

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International Linear Collider (ILC)

- superconducting accelerating cavities
- length of 31 km
- energy of 250-500 GeV, possible upgrade to 1 TeV
- polarisation for both beams (80%/30%)
- two-beam accelerating scheme
- length of 11-50 km
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- electron beam polarisation of 80%
We focus on the single heavy neutrino production. There are many ways to search for such a process: both direct ($qqlv$, $qqνν$, $llνν$) and indirect (EWPOs, Higgs branching ratios).

We probed the signature $qqlv$, as it allows for direct reconstruction of $N$. 

\[ \text{Diagram showing processes involving heavy neutrino production} \]
Our setup

- Dirac and Majorana neutrinos

- masses:

  \[ m_{N_1} = 200\text{--}3200 \text{ GeV} \]
  \[ m_{N_2} = m_{N_3} = 10 \text{ TeV} \]

- couplings:

  \[ |V_{eN_1}|^2 = |V_{\mu N_1}|^2 = |V_{\tau N_1}|^2 \equiv V_{\text{lN}}^2 \]

  \[ V_{\text{lN}}^2 = 0.0003 \] is used for the generation of reference signal samples

  All the \( N_2 \) and \( N_3 \) couplings are set to zero.

- considered collider scenario:

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

  ILC 1 TeV, 3.2 ab\(^{-1}\), \((e^-, e^+) = (\,-80\%, \, +20\%)\)

  CLIC 3 TeV, 4.0 ab\(^{-1}\), \((e^-, e^+) = (\,-80\%, \, 0\%)\)
Signal cross section

\[ \sigma(e^+e^\rightarrow \nu_N \rightarrow -e^+e^-) \text{ [fb]} \]

LR polarisation, including beam spectra
Signal vs. background

Signal:

Background:

+ many other more important background channels...
Analysis procedure

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

2. Simulating detector response with **Delphes**

3. Preselection of events matching the required signal topology

4. BDT training

5. Using CLs method to get final results
Event generation and detector simulation

- **Event generation:**
  - **WHIZARD** 2.8.5 and 3.0.0
  - $e\gamma$ and $\gamma\gamma$ backgrounds included (BS and EPA)
  - ILC500: $qq/\nu$ background $\sim 10$ pb, signal $\sim 10$ fb

- **Detector simulation:**
  - **Delphes 3.4.2** simulating ILC detector using **delphes card ILCgen.tcl**
  - CLIC detector – **delphes card CLICdet Stage3 fcal.tcl**

- Preselection:
  - cuts optimised to search for $N$: exactly 1 lepton and 2 jets in the final state
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$q\bar{q}/ \text{invariant mass}

Events

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^{-1}$

$0$

$200$

$400$

$600$

$m_{q\bar{q}}$ [GeV]

ILC 500 GeV, (-80%, +30%)

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Boosted Decision Trees

BDT trained with 8 input variables (see backup slides)

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, systematic uncertainties). The cross-section limit is calculated by scaling the reference scenario to obtain a significance of 1.64 (95% CL) for the optimal BDT response cut.

![Graph showing limit on the cross-section as a function of $m_N$]
The cross section limits can be translated into limits on the $V_{iN}^2$ parameter.
1. We searched for heavy neutrinos at future $e^+e^-$ linear colliders using events generated with Whizard and detector simulation from Delphes.

2. Heavy neutrino production can be observed almost up to the kinematic limit.

3. The expected coupling limits are much stronger than those at LHC/FCC-hh.

4. Accepted for JHEP (today!): [2202.06703]
References

M. Aicheler et al.

D. Alva, T. Han, and R. Ruiz.
Heavy Majorana neutrinos from $W\gamma$ fusion at hadron colliders.

H. Baer et al.

S. Pascoli, R. Ruiz, and C. Weiland.
Heavy Neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14, 27, \text{ and } 100 \text{ TeV}$. 
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
BACKUP: Neutrino width

\[ \Gamma_N \text{ [GeV]} \]

\[ m_N \text{ [GeV]} \]

- Dirac
- Majorana

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BACKUP: Cross section limits – ILC1000

\[ \lim \sigma(e^+e^- \rightarrow q\bar{q}N) \text{ [fb]} \]

\[ Nm^2 \]

\[
\nu qql \rightarrow \nu N \rightarrow -e^+ (e^\sigma \lim. ILC1000 e \nu) \mu \]

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BACKUP: Cross section limits – CLIC3000

\[ \text{lim. } \sigma(e^+e^- \rightarrow N \nu) \text{ [fb]} \]

\[ m_N \text{ [GeV]} \]
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