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

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Motivation

Some problems of the Standard Model:

- existence and nature of dark matter
- baryon asymmetry
- neutrino oscillations and mass hierarchy
- nature of neutrinos: Dirac or Majorana

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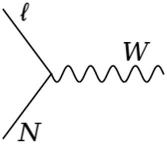
can be solved by introducing new species of neutrinos.

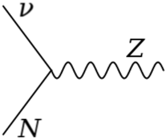
The Standard Model with heavy neutrinos

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

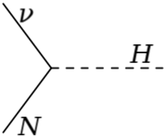
$\mathcal{L}_{W-N-l}$



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



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



Minimal scenario – without additional gauge bosons

HeavyN model: The Standard Model + Heavy Neutrinos

- UFO model developed by R. Ruiz, D. Alva, T. Han, C. Weiland...
  [HeavyN FeynRules]
- widely analysed for searching 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*
- 15 free parameters:
  - 3 masses ($\sim 10^2 - 10^3$ GeV)
  - 3 widths
  - 9 mixing parameters (3x3 mixing matrix for e, μ, τ and *N1, N2, N3*)

e^+e^- signal collider signature

There are many ways to search for heavy neutrinos: both direct ($qql\nu, qq\nu\nu, ll\nu\nu$) and indirect (EWPOs, Higgs branching ratios).

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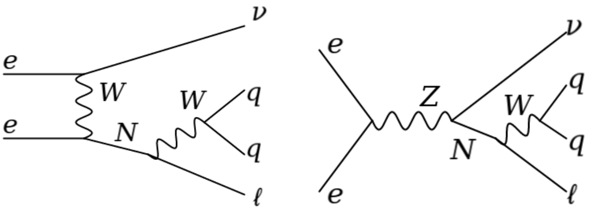
We chose the $qql\nu$ signature, as it allows for direct reconstruction of N.



Our setup

- Dirac and Majorana neutrinos
- masses:

$$m_{N1} = 200\text{-}3200 \text{ GeV}$$
$$m_{N2} = m_{N3} = 10 \text{ TeV}$$

- couplings:

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

$|V_{lN}|^2 = 0.0003$ is used for reference signal samples generation

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

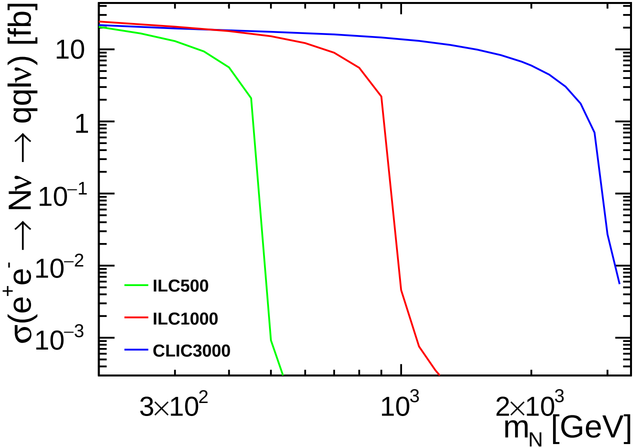
- considered collider scenario:

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

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

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

Signal cross section



Dirac neutrinos, including beam spectra,
left-handed electrons (and right-handed positrons for ILC)

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

- WHIZARD 2.8.5 (WHIZARD 3.0.0 for the Majorana case)
- ISR and beam spectra included
- $e\gamma$ and $\gamma\gamma$ backgrounds included (BS and EPA)
- ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb,
  CLIC3000: $qql\nu$ background $\sim$ 9 pb, signal $\sim$ 10 fb
- 10M events generated for main background channels
- 300k events generated for each signal scenario

Background processes considered

$e^+e^- \to qql\nu$	$\gamma^{EPA}e^{\pm} \to qql$	$\gamma^{BS}e^{\pm} \to qql$	$\gamma^{EPA}\gamma^{BS} \to qql\nu$
$e^+e^- \to qqll$	$\gamma^{EPA}\gamma^{EPA} \to qql\nu$	$\gamma^{BS}\gamma^{BS} \to qql\nu$	$\gamma^{EPA}\gamma^{BS} \to qqll$
$e^+e^- \to llll$	$\gamma^{EPA}\gamma^{EPA} \to qqll$	$\gamma^{BS}\gamma^{BS} \to qqll$	
$e^+e^- \to qqqql\nu$			
$e^+e^- \to qqqqll$			
$e^+e^- \to qql\nu l\nu$			

ILC1000 γ^{BS}-induced background generated using CIRCE files for ILC500 (scaled to the energy of 1 TeV)

Detector simulation and preselection

- Detector simulation:
  - DELPHES 3.4.2
  - simulating ILC detector using *delphes_card_ILCgen.tcl*, CLIC detector – *delphes_card_CLICdet_Stage3_fcal.tcl*

Detector simulation and preselection

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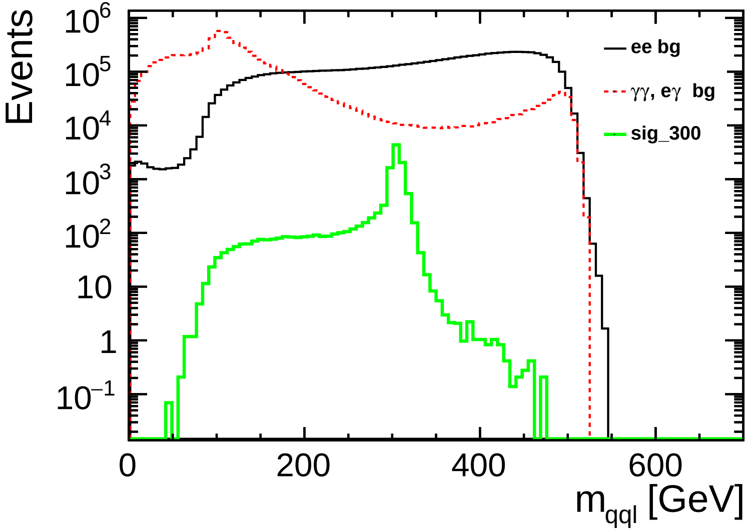
  - DELPHES 3.4.2
  - simulating ILC detector using *delphes_card_ILCgen.tcl*, CLIC detector – *delphes_card_CLICdet_Stage3_fcal.tcl*
- Preselection:
  - cuts optimised to search for N: exactly 1 lepton and 2 jets in the final state (hadronic energy outside two jets below 20 GeV)

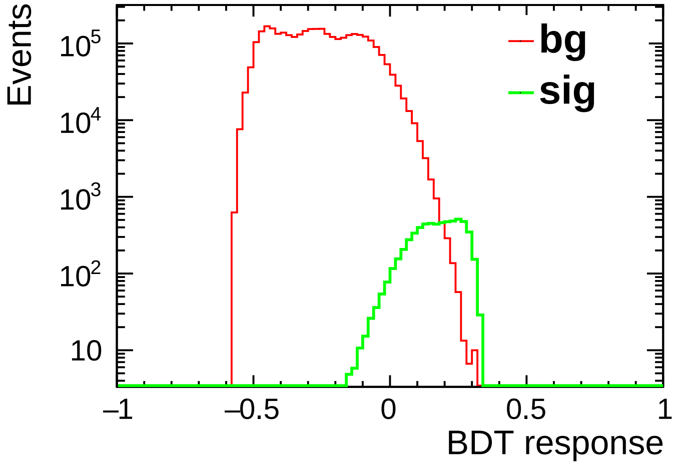
qql invariant mass



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

BDT response

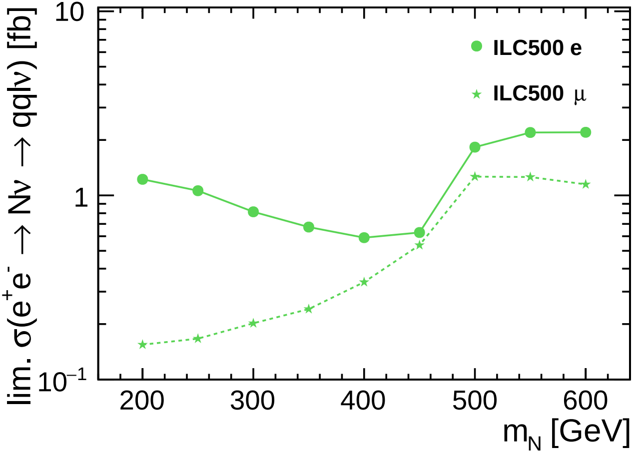
BDT trained with 8 input variables (see backup slides)



ILC 500 GeV, (-80%, +30%), m_N = 300 GeV, Dirac neutrino, μ in the final state

Limits – cross section

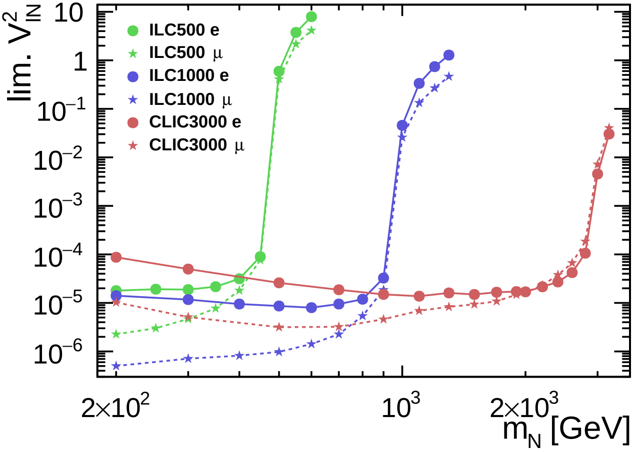
Cross section limit is calculated by scaling reference scenario to obtain significance of 1.64 (95% CL) for optimal BDT response cut.



Dirac neutrinos

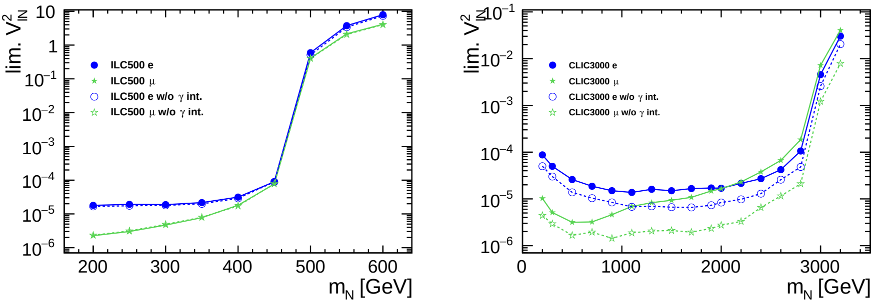
Limits – coupling

The expected cross section limits can be translated to the limits on the mixing parameter V_{lN}^2 in the considered HeavyN model.



Dirac neutrinos

Impact of $e\gamma$ and $\gamma\gamma$ interactions

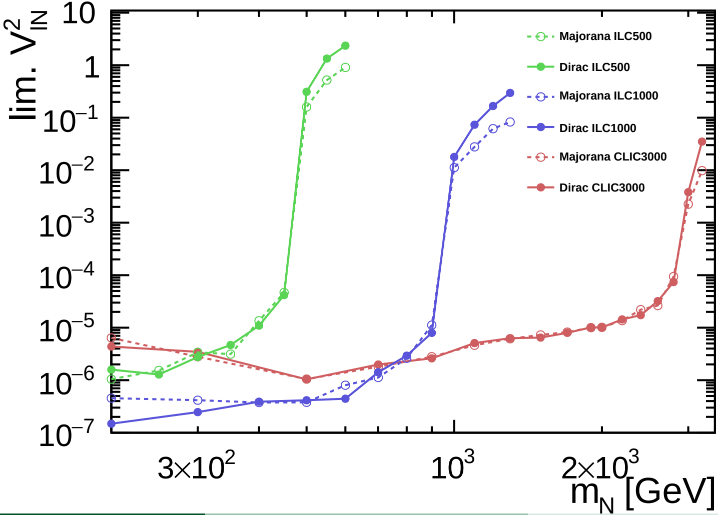


ILC500 vs. CLIC3000

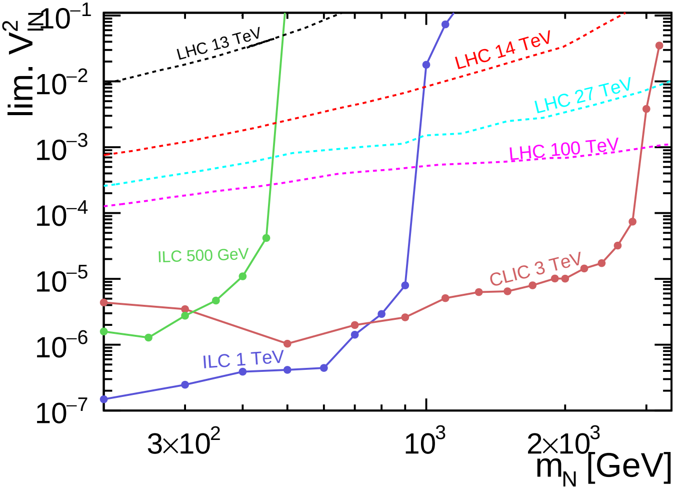
Difference caused by the spectra...

Dirac vs. Majorana neutrinos

Limits from electron and muon channels were combined using RooStats and CLs approach.



Final results



Dirac neutrinos

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

Conclusions

1. We studied the potential to observe 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. Expected coupling limits much stronger than those at LHC/FCC-hh.
4. Significant background contribution from the $e\gamma$ and $\gamma\gamma$ interactions (ISR and beamstrahlung).
5. Work in progress...

References

D. Alva, T. Han, and R. Ruiz.
Heavy Majorana neutrinos from Wγ fusion at hadron colliders.
Journal of High Energy Physics, 2015(2):72, Feb. 2015.

S. Pascoli, R. Ruiz, and C. Weiland.
Heavy Neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14$, 27, and 100 TeV.
Journal of High Energy Physics, 2019, Jun. 2019.

BACKUP: BDT variables

- *qql* invariant mass
- angle between jets
- angle between dijet and lepton
- lepton energy
- *qql* energy
- lepton transverse momentum
- dijet transverse momentum
- *qql* transverse momentum

BACKUP: Impact of $e\gamma$ and $\gamma\gamma$ interactions

channel	events aft. presel.	% events aft. presel. [%]
e^+e^- bg	4,750,054	18.60%
$e^\pm\gamma$, $\gamma\gamma$ bg	6,790,222	22.22%
sig_{300GeV}	5,705	27.44%

ILC500, e in final state

channel	events aft. presel.	% events aft. presel. [%]
e^+e^- bg	2,719,748	3.64%
$e^\pm\gamma$, $\gamma\gamma$ bg	15,546,863	13.14%
sig_{300GeV}	5,315	6.81%

CLIC3000, e in final state