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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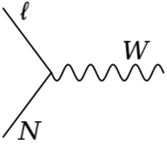
can be solved by introducing new species of neutrinos.

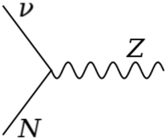
The Standard Model with heavy neutrinos

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

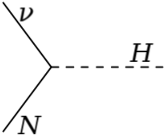
$\mathcal{L}_{W-N-l}$



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



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



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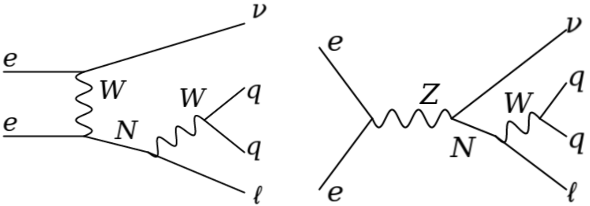
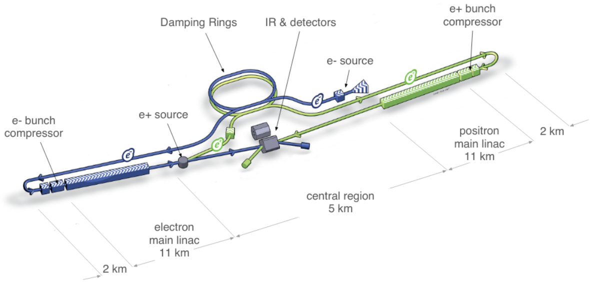
We chose the $qql\nu$ signature, as it allows for direct reconstruction of N.



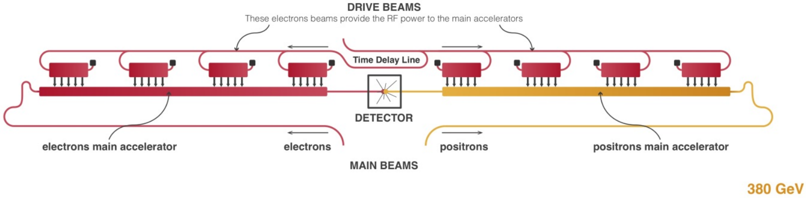
International Linear Collider (ILC)



- superconducting accelerating cavities
- length of 31 km
- energy of 250-500 GeV, possible upgrade to 1 TeV
- polarisation for both beams (80%/30%)

for details see: arXiv:1306.6327

Compact LInear Collider (CLIC)



- two-beam accelerating scheme
- length of 11-50 km
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- electron beam polarisation of 80%

for details see: arXiv:1812.07987

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.

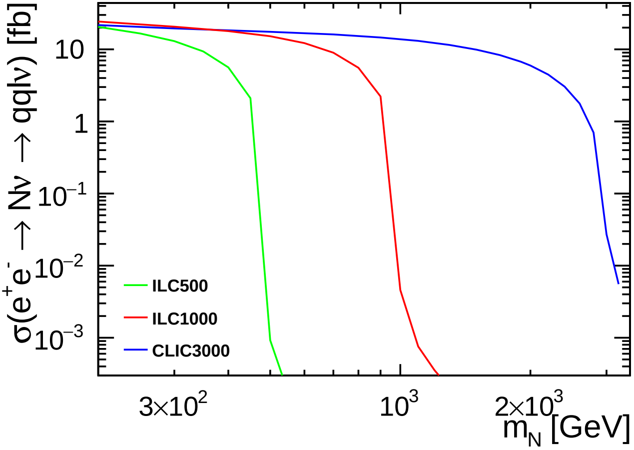
- considered collider scenario:

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")
    - $e^+e^- \to N\nu \to qql\nu$ ("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 (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

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

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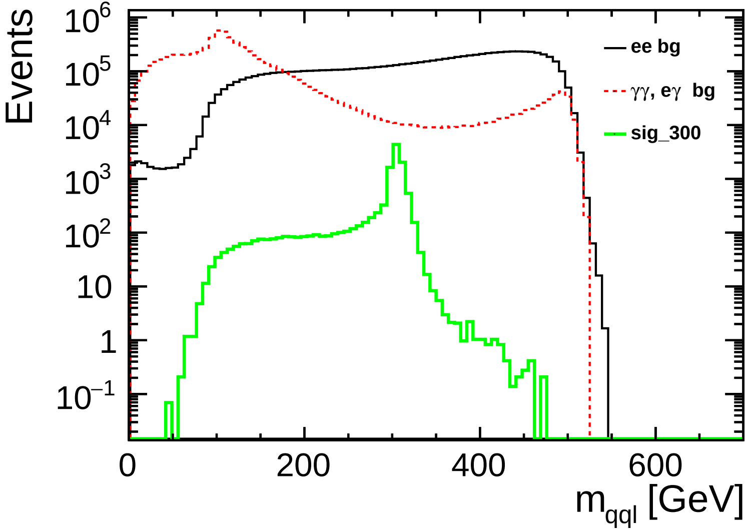
- Preselection:
  - cuts optimised to search for N: exactly 1 lepton and 2 jets in the final state (hadronic energy outside two jets below 20 GeV)

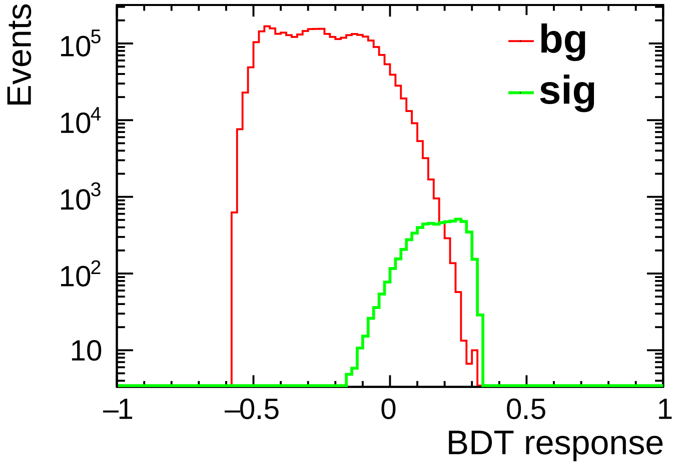
qql invariant mass



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

BDT response

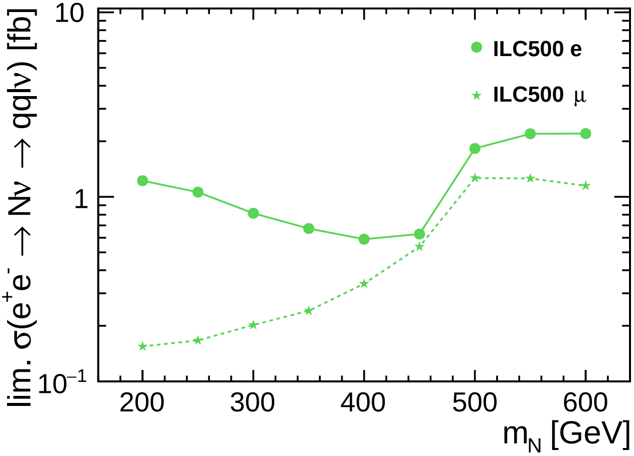
BDT trained with 8 input variables (see backup slides)



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

Limits – cross section

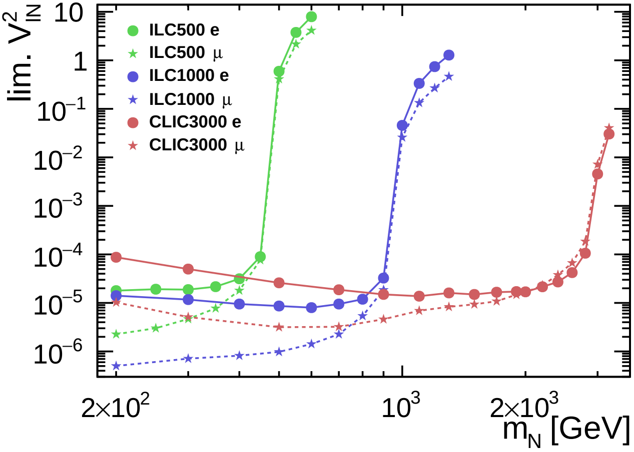
Cross section limit is calculated by scaling reference scenario to obtain significance of 1.64 (95% CL) for optimal BDT response cut.



Dirac neutrinos

Limits – coupling

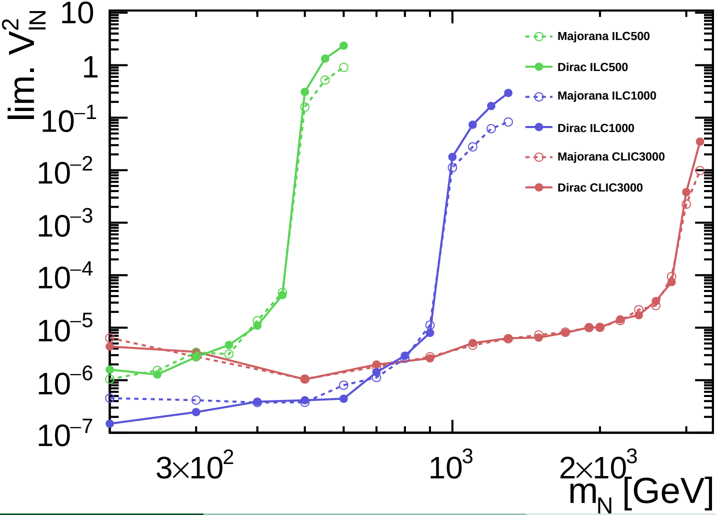
The expected cross section limits can be translated to the limits on the mixing parameter V_{lN}^2 in the considered HeavyN model.



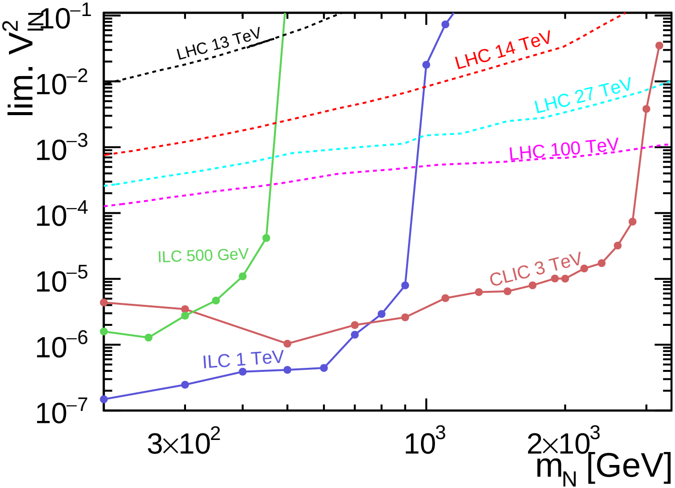
Dirac neutrinos

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 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. 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 $W\gamma$ 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

CLs method → exclusion limits based on likelihood distributions

"how probable is the signal+background scenario
in respect to the only-background scenario?"

BDT response is used to build a model in RooStats

Pros:

- combining electron and muon channels
- systematic uncertainties (*to be analysed...*)

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

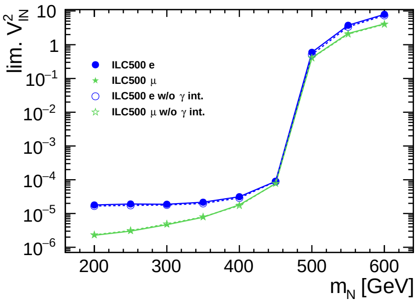
channel	events aft. presel.	% events aft. presel. [%]
e^+e^- bg	4,750,054	18.60%
$e^\pm\gamma$, $\gamma\gamma$ bg	6,790,222	22.22%
$\mathrm{sig}_{300\mathrm{GeV}}$	5,705	27.44%

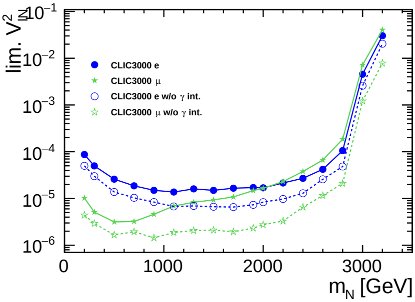
ILC500, e in final state

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%
$\mathrm{sig}_{300\mathrm{GeV}}$	5,315	6.81%

CLIC3000, e in final state

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





ILC500 vs. CLIC3000