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

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Motivation

Some problems of the Standard Model:

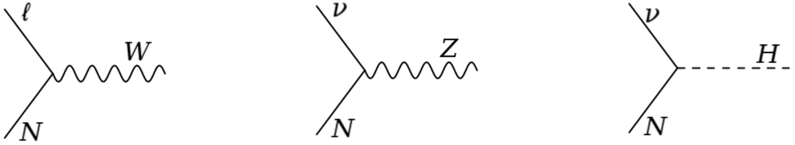
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana

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

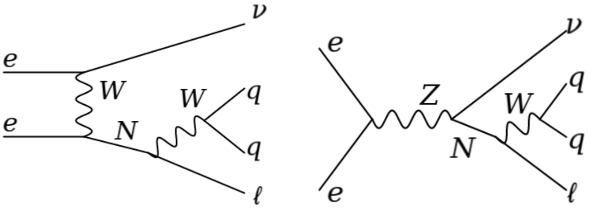
HeavyN model: The Standard Model + Heavy Neutrinos

- effective model developed by R. Ruiz, D. Alva, T. Han...
  [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*
- 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*)

Heavy neutrino signature at e^+e^- colliders

We focus on the single heavy neutrino production. There are many ways to search for such a process: both direct ($qql\nu, qq\nu\nu, ll\nu\nu$) and indirect (EWPOs, Higgs branching ratios).

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



Our setup

- Dirac and Majorana neutrinos
- masses:

$$\mathrm{m}_{N1} = 200\text{-}3200 \text{ GeV}$$
$$\mathrm{m}_{N2} = \mathrm{m}_{N3} = 10 \text{ TeV}$$

- couplings:

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

$V^2_{lN} = 0.0003$ is used for reference signal samples generation

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

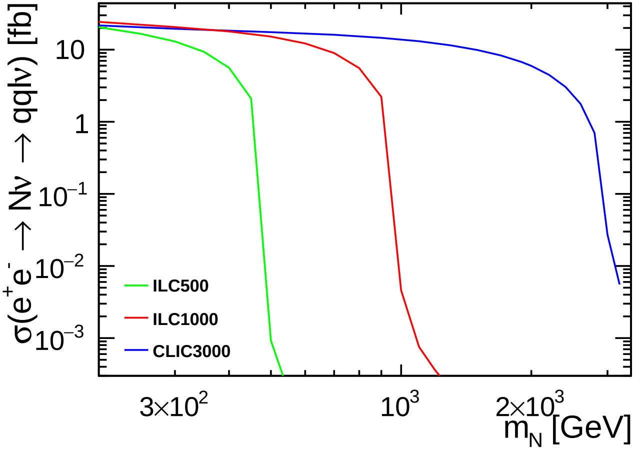
- considered collider scenarios:

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}, $(e^-, e^+) = (-80\%, 0\%)$

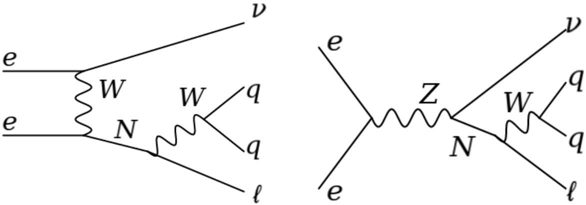
Signal cross section



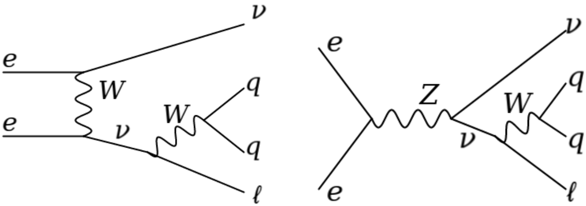
LR polarisation, including beam spectra

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: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb

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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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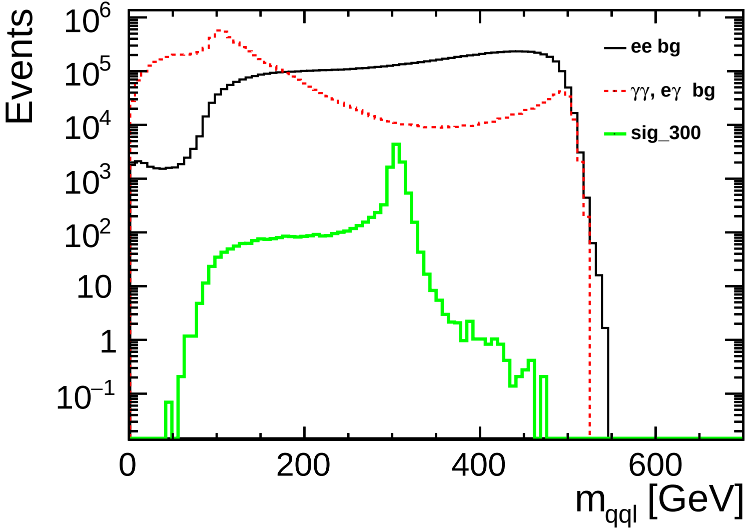
- Preselection:
  - cuts optimised to search for N: exactly 1 lepton and 2 jets in the final state

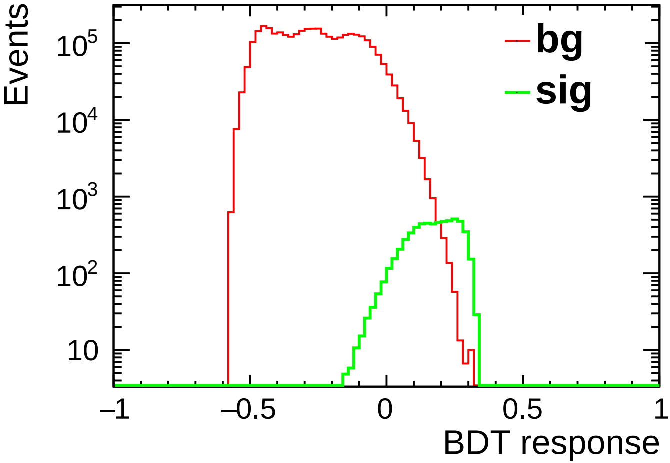
qql invariant mass



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

Boosted Decision Trees

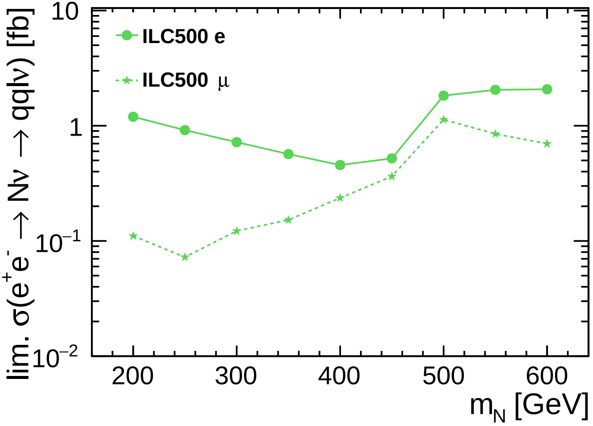
BDT trained with 8 input variables (see backup slides)



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

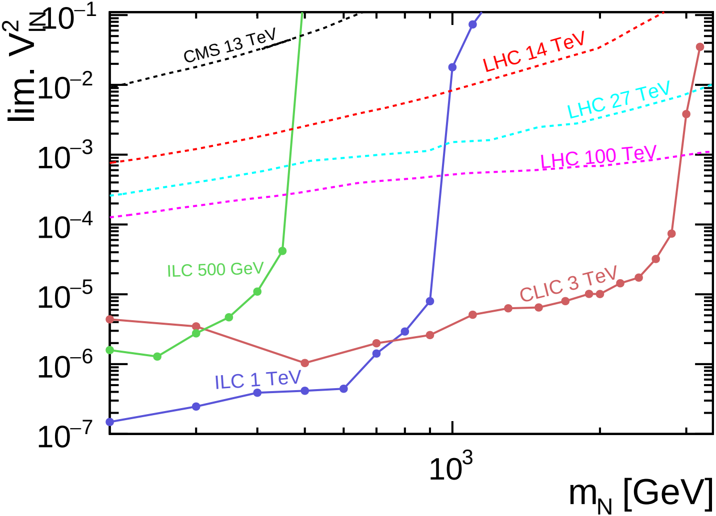
CLs method

BDT response is used to build a model in RooStats to use CL_s method (combining both channels, systematic uncertainties)
Cross section limit is calculated by scaling reference scenario to obtain a significance of 1.64 (95% CL) for optimal BDT response cut.



Final results

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



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

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. The expected coupling limits are much stronger than those at LHC/FCC-hh.
4. The paper already submitted to JHEP: [arXiv: 2202.06703]

References

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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