

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

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Some problems of the Standard Model:

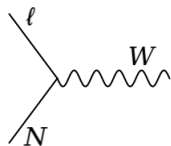
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana

can be solved by introducing new species of neutrinos.

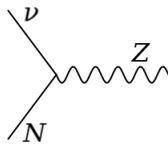
The Standard Model with heavy neutrinos

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

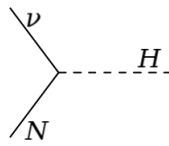
$$\mathcal{L}_{W-N-l}$$



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



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



Minimal scenario – without additional gauge bosons

HeavyN model: The Standard Model + Heavy Neutrinos

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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 $N1, N2, N3$)

Where to search for such neutrinos?

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Searches at the LHC very challenging...

What next...?

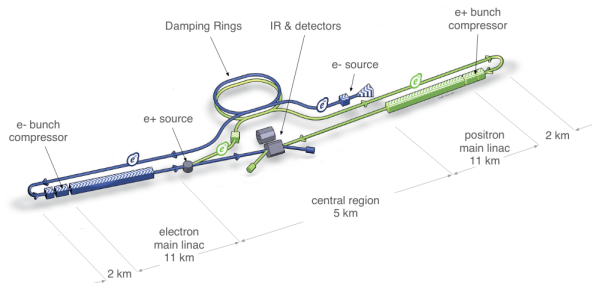
An electron-positron machine

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An electron-positron machine

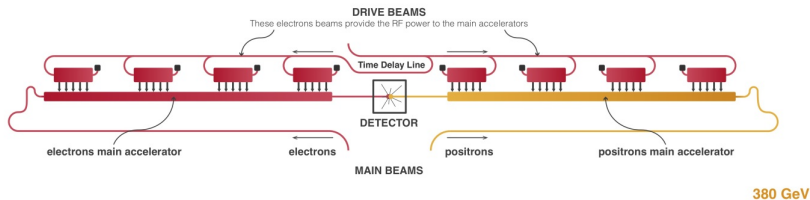


International Linear Collider (ILC)



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

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%

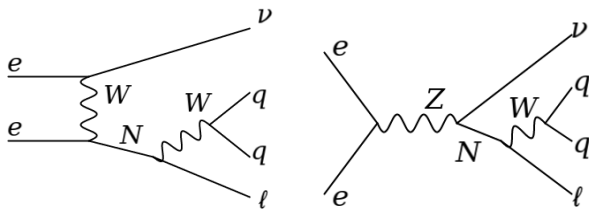
Heavy neutrino signature at e^+e^- colliders

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

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 ($qq\ell\nu$, $qq\nu\nu$, $ll\nu\nu$) and indirect (EWPOs, Higgs branching ratios).

We decided to use the $qq\ell\nu$ signature.



It allows for direct reconstruction of N .

- Dirac and Majorana neutrinos
- masses:

$$m_{N1} = 200\text{-}3200 \text{ GeV}$$

$$m_{N2} = m_{N3} = 10 \text{ TeV}$$

- couplings:

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

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

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

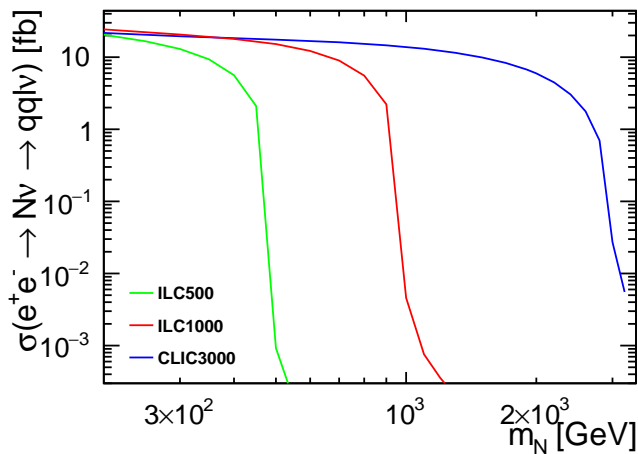
- considered collider scenario:

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

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

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

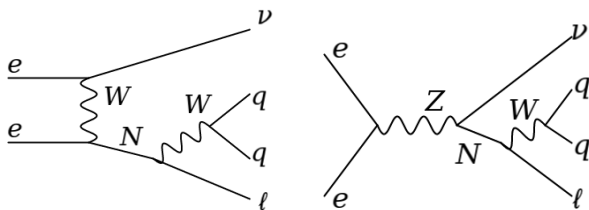
Signal cross section



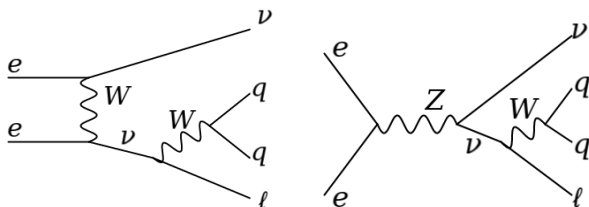
LR polarisation, including beam spectra

Signal vs. background

Signal:

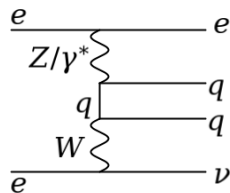
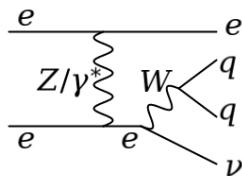
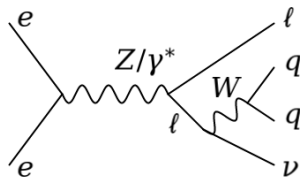
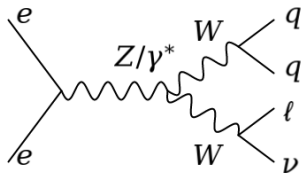
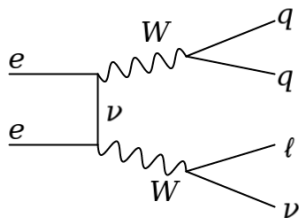


Background:



+ many other more important background channels...

Example of background channels



Analysis procedure

- 1 Generating physical events with WHIZARD
(Monte Carlo generator widely used in the e^+e^- community)
 - without N propagators ("background")
 - $e^+e^- \rightarrow N\nu \rightarrow qq\nu$ ("signal")

<https://whizard.hepforge.org>

- 2 Simulating detector response with DELPHES
(fast simulation framework)

<https://cp3.irmp.ucl.ac.be/projects/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 and 3.0.0
 - $e\gamma$ and $\gamma\gamma$ backgrounds included (BS and EPA)
 - ILC500: $q\bar{q}/\nu$ background ~ 10 pb, signal ~ 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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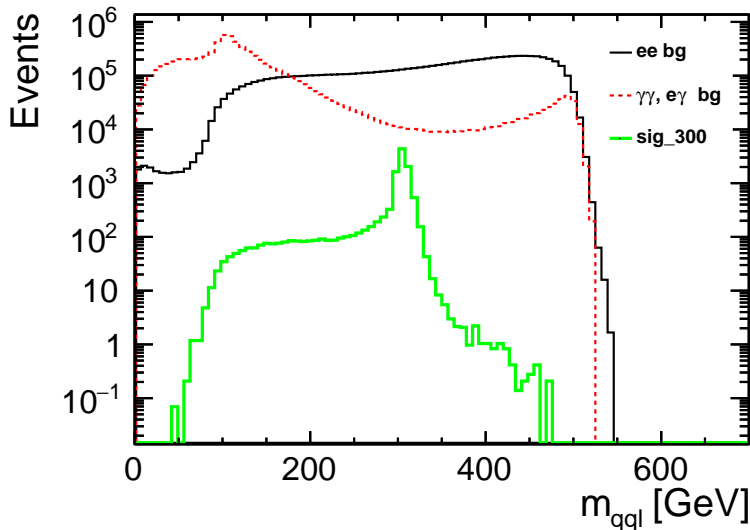
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- Preselection:

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

$qq\ell$ invariant mass



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

BDT method

Idea:

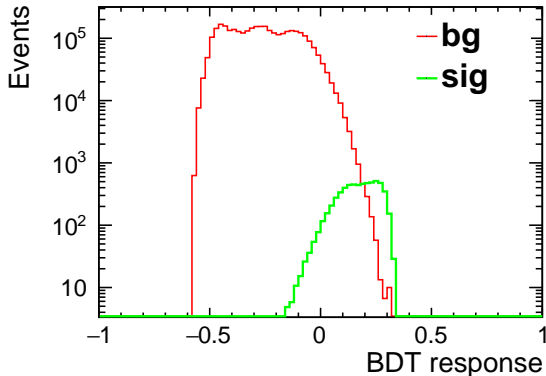
many input variables $\xrightarrow{\text{decision trees}}$ 1 output variable

BDT method

Idea:

many input variables $\xrightarrow{\text{decision trees}}$ 1 output variable

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 \rightarrow exclusion limits based on likelihood distributions

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

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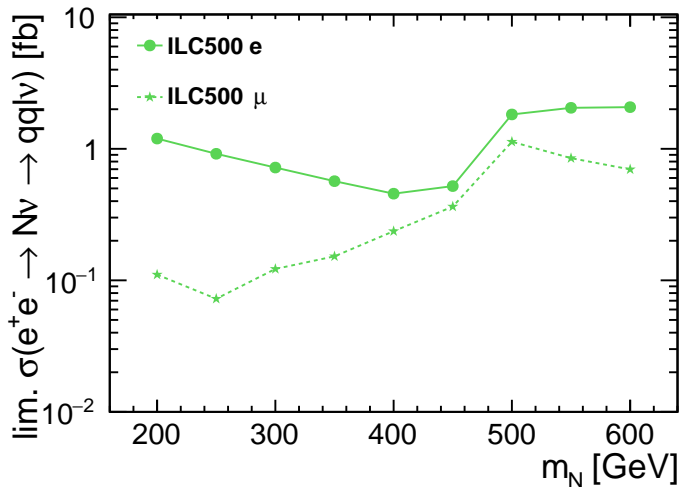
BDT response is used to build a model in ROOSTATS

Pros:

- combining electron and muon channels
- systematic uncertainties

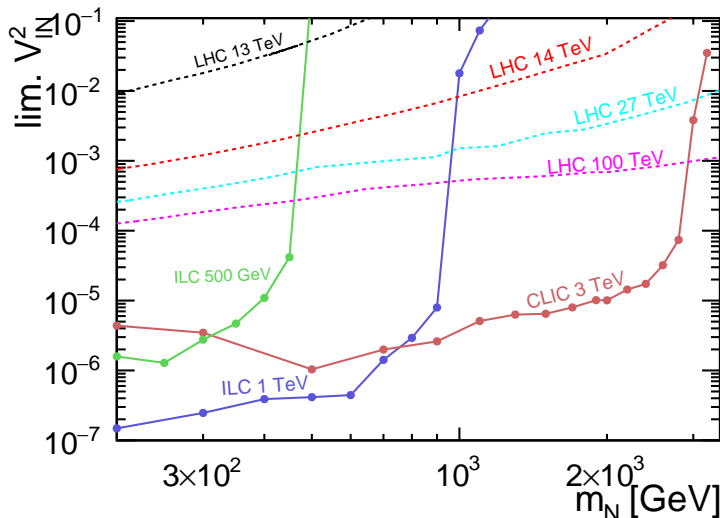
Limits – cross section

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



Final results



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



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

- 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 are much stronger than those at LHC/FCC-hh.
- 4 Paper in preparation...

References

-  M. Aicheler et al.
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-  D. Alva, T. Han, and R. Ruiz.
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Journal of High Energy Physics, 2015(2):72, Feb. 2015.
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-  S. Pascoli, R. Ruiz, and C. Weiland.
Heavy Neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14, 27, \text{ and } 100 \text{ TeV}$.
Journal of High Energy Physics, 2019, Jun. 2019.

BACKUP: Running scenarios

ILC:

- 500 GeV: total luminosity of 4000 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 polarisationsassuming polarisation of $\pm 80\%$ for electrons and $\pm 30\%$ for positrons
- 1 TeV: total luminosity of 8000 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 polarisationsassuming polarisation of $\pm 80\%$ for electrons and $\pm 20\%$ for positrons

CLIC:

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

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