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

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Motivation

Some problems of the Standard Model:

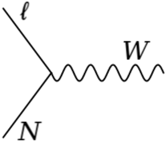
- neutrino mass hierarchy and oscillations
- nature of antineutrinos: Dirac or Majorana
- baryon asymmetry
- dark matter density

can be solved by introducing new species of neutrinos.

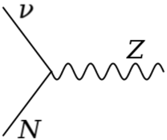
The Standard Model with heavy neutrinos

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

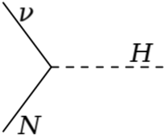
$\mathcal{L}_{W-N-l}$



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



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



Minimal scenario – without additional gauge bosons

HeavyN model: The Standard Model + Heavy Neutrinos

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

Our setup

- Dirac 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}, $(e^-, e^+) = (\text{-}80\%, +30\%)$

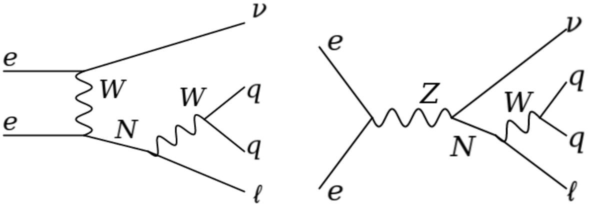
ILC 1 TeV, 3.2 ab^{-1}, $(e^-, e^+) = (\text{-}80\%, +20\%)$

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

e^+e^- signal collider signature

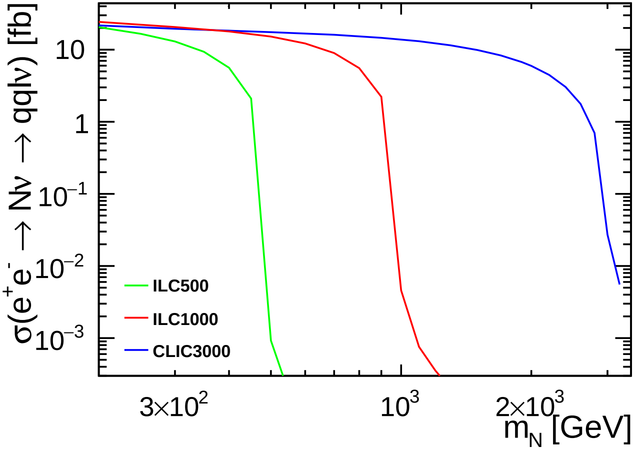
There are many ways to search for heavy neutrinos: both direct ($qql\nu, qq\nu\nu, ll\nu\nu$) and indirect (EWPOs, Higgs branching ratios).

We decided to use the $qql\nu$ signature.



It allows for direct reconstruction of N.

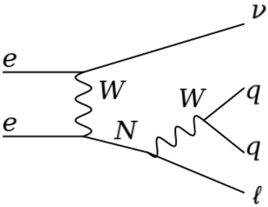
Signal cross section

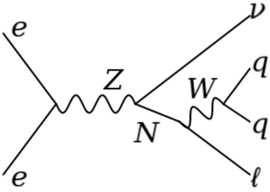


LR polarisation, including beam spectra

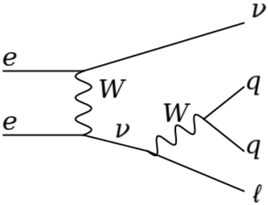
Signal vs. background

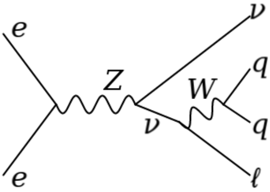
Signal:





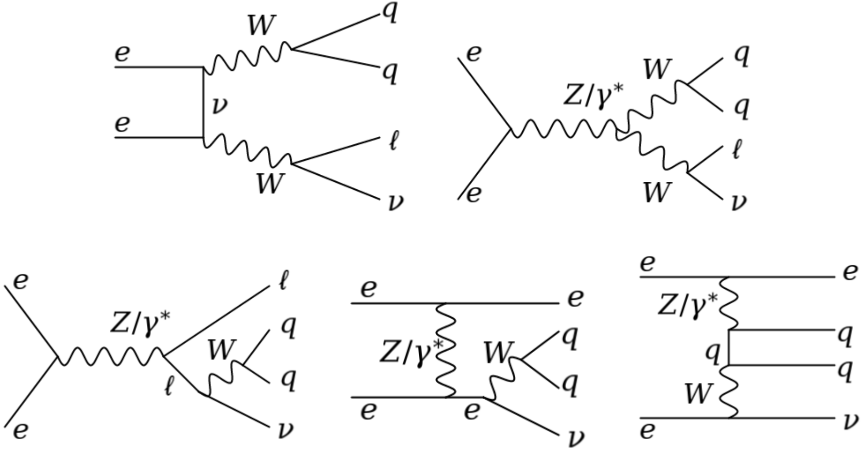
Background:





$+$ many other more important background channels...

Background



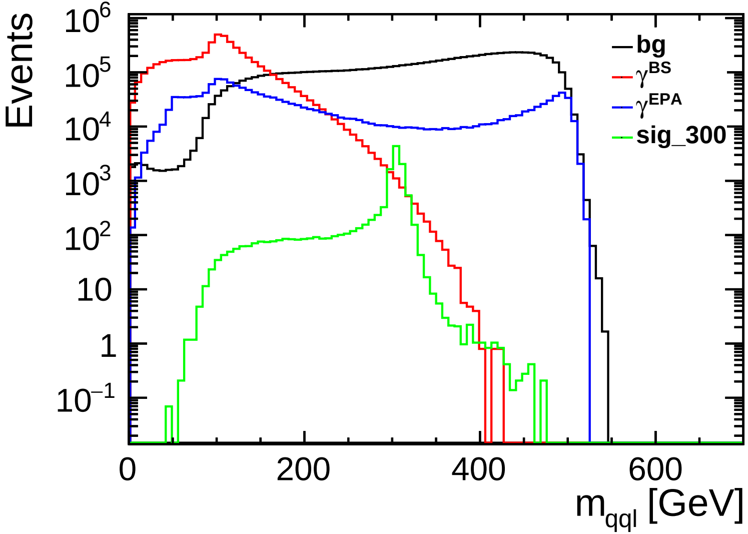
Analysis procedure

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. Using BDT method to get final results

Event generation and detector simulation

- Event generation:
  - WHIZARD 2.8.5
  - 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
- 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 (hadronic energy outside two jets below 20 GeV)

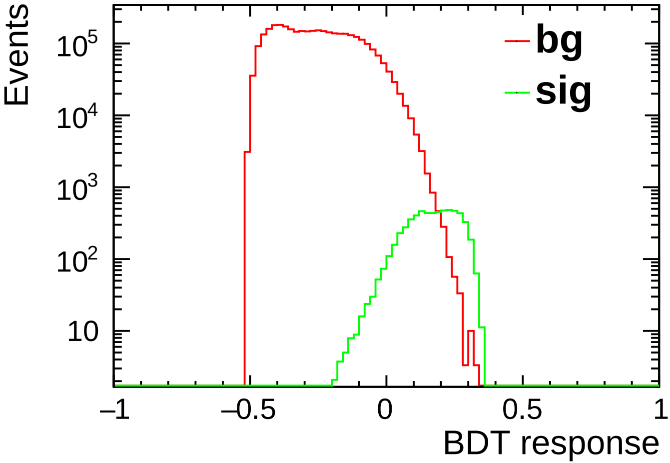
qql invariant mass



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

BDT response

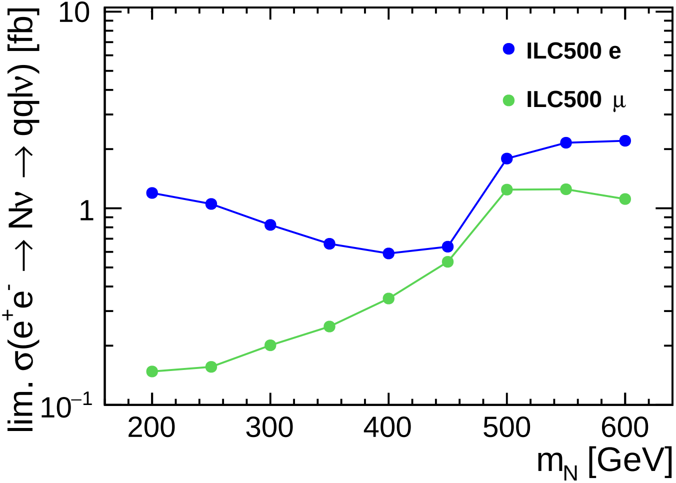
BDT trained with 8 input variables (see backup slides)



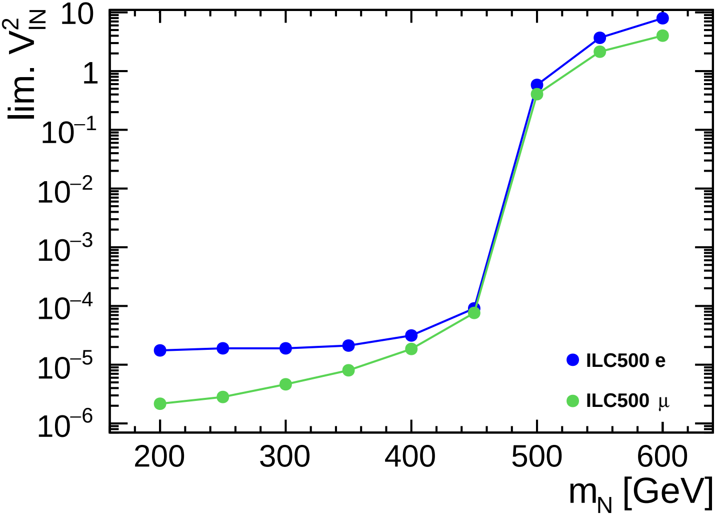
ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV, μ in the final state

Limits – cross section

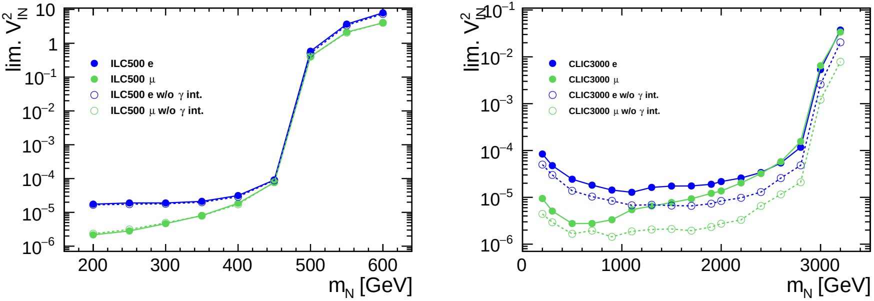
Cross section limit is calculated by scaling reference scenario to obtain significance of 1.64 (95% CL) for optimal BDT response cut.



Limits – coupling

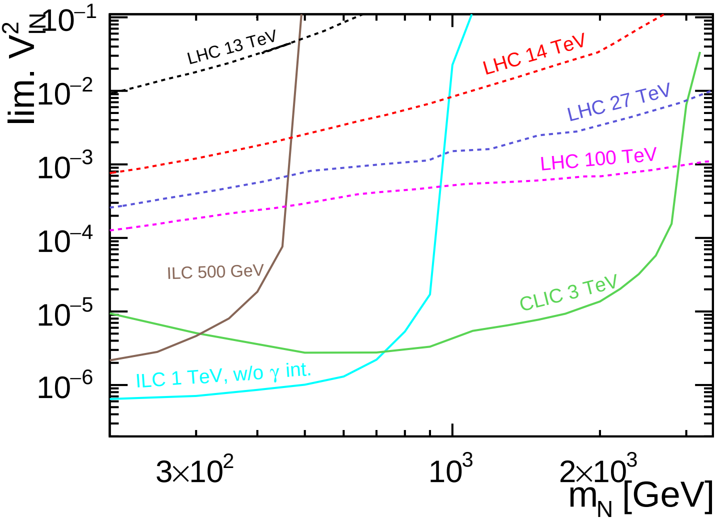


Impact of the γ interactions



ILC500 vs. CLIC3000

Final results



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. We developed a method to efficiently discriminate between the signal and the background.
3. We estimated the impact of gamma-induced background channels.
4. We showed that future linear colliders could be a good place to search for heavy neutrinos.

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: event generation – ILC500, (-80%, +30%)

channel	σ [fb]	generated events
$qql\nu$	1.04E+04	10M
$llll$	3.01E+03	10M
$qqll$	2.02E+03	10M
$qqqqll$	2.19E+01	100k
$qqqql\nu$	4.16E+02	100k
$qql\nu l\nu$	8.27E+01	100k
sig_300 ($qql\nu$)	1.30E+01	300k

BACKUP: event generation – ILC500, (-80%, +30%)

channel	σ [fb]	generated events
$\gamma^{EPA} e^- \to qql$	4.54E+03	1M
$\gamma^{EPA} e^+ \to qql$	4.51E+03	1M
$\gamma^{EPA} \gamma^{EPA} \to qql\nu$	1.02E+01	1M
$\gamma^{EPA} \gamma^{EPA} \to qqll$	3.19E+00	750k
$\gamma^{BS} e^- \to qql$	8.86E+03	10M
$\gamma^{BS} e^+ \to qql$	8.74E+03	10M
$\gamma^{BS} \gamma^{BS} \to qqll$	2.04E+01	1M
$\gamma^{BS} \gamma^{BS} \to qql\nu$	4.20E-02	10k

BACKUP: event generation – ILC1000, (-80%, +20%)

channel	σ [fb]	generated events
$qql\nu$	7.66E+03	10M
$llll$	4.19E+03	10M
$qqll$	2.51E+03	10M
$qqqql\nu$	2.09E+02	100k
$qqqqll$	1.02E+02	100k
$qql\nu l\nu$	4.90E+01	100k
sig_300 ($qql\nu$)	2.06E+01	300k

BACKUP: event generation – CLIC3000, (-80%, 0%)

channel	σ [fb]	generated events
$qql\nu$	8.76E+03	10M
$llll$	5.81E+03	10M
$qqll$	3.21E+03	10M
$qqqqll$	7.01E+02	100k
$qqqql\nu$	1.55E+02	100k
$qql\nu l\nu$	6.26E+01	100k
sig_700 ($qql\nu$)	1.61E+01	300k

BACKUP: event generation – CLIC3000, (-80%, 0%)

channel	σ [fb]	generated events
$\gamma^{EPA} e^- \rightarrow qql$	4.66E+03	1M
$\gamma^{EPA} e^+ \rightarrow qql$	4.52E+03	1M
$\gamma^{EPA}\gamma^{EPA} \rightarrow qql\nu$	1.53E+02	1M
$\gamma^{EPA}\gamma^{EPA} \rightarrow qqll$	1.48E+01	1M
$\gamma^{BS}\gamma^{BS} \rightarrow qql\nu$	1.35E+04	10M
$\gamma^{BS} e^- \rightarrow qql$	4.94E+03	10M
$\gamma^{BS} e^+ \rightarrow qql$	4.33E+03	10M
$\gamma^{BS}\gamma^{BS} \rightarrow qqll$	1.45E+03	10M

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