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

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Motivation

Some mysteries of the Standard Model:

- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
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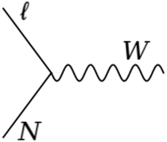
can be addressed by introducing new species of neutrinos.

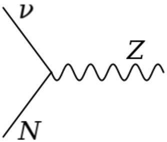
Bottom-Up Approach: The SM with Heavy Neutrinos

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

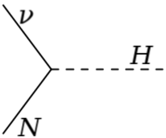
$\mathcal{L}_{W-N-l}$



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



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



Minimal scenario – without additional gauge bosons,
any form of (additional) CP violation in the neutrino sector ignored

HeavyN model: The Standard Model + Heavy Neutrinos

- effective extension of the Standard Model

  [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*
- 12 free parameters:
  - 3 masses ($\sim 10^2 - 10^3$ GeV)
  - 9 mixing parameters (3x3 mixing matrix for e, μ, τ and *N1, N2, N3*)

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Considered running scenarios

ILC:

- 250 GeV – total luminosity of 2000 fb^{-1}:
  - 900 fb^{-1} for LR beam polarisation (-80%, $+30\%$)
- 500 GeV – total luminosity of 4000 fb^{-1}:
  - 1600 fb^{-1} for LR beam polarisation (-80%, $+30\%$)
- 1 TeV – total luminosity of 8000 fb^{-1}:
  - 3200 fb^{-1} for LR beam polarisation (-80%, $+20\%$)

CLIC:

- 3 TeV – total luminosity of 5000 fb^{-1}:
  - 4000 fb^{-1} for negative electron beam polarisation (-80%, 0%)

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).

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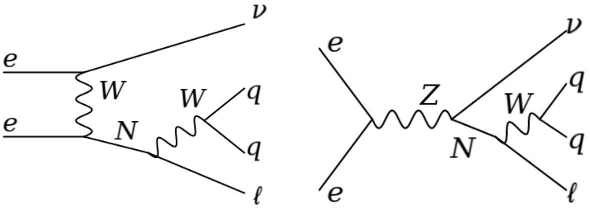
We probed the signature $qql\nu$, as it allows for direct reconstruction of N.



Our setup

- Dirac and Majorana neutrinos
- masses:

$$m_{N1} = 100\text{-}3200 \text{ GeV}$$
$$m_{N2} = m_{N3} = 10 \text{ TeV}$$

- couplings:

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

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

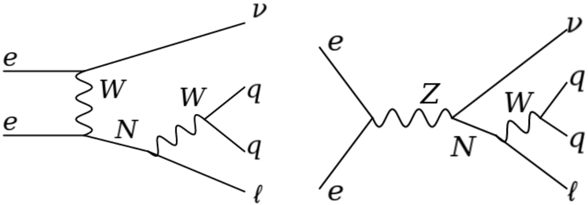
All the $N2$ and $N3$ couplings are set to zero.

- widths:

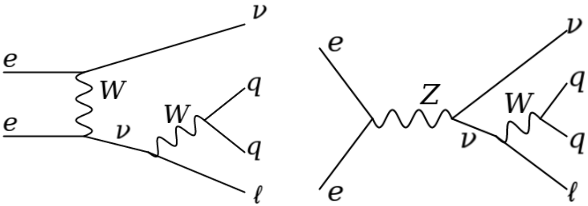
above $\mathcal{O}(1 \text{ keV}) \rightarrow$ prompt decays only (no LLP signature),
displaced vertices possible for masses $\mathcal{O}(10 \text{ GeV})$ and below

Signal vs. background

Signal:



Background:



+ many other more important background channels...

Analysis procedure

1. Generating physical events with WHIZARD
   - without N propagators ("background")
   - $e^+e^- \to N\nu \to qql\nu$ ("signal")
2. Simulating detector response with DELPHES
3. Preselection of events matching the required signal topology
4. BDT training for each considered signal scenario
5. CLs method applied to the BDT response distributions to extract expected exclusion limits

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)
  - S/B $\sim 10^{-3}$, e.g. 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* (incl. in Delphes)

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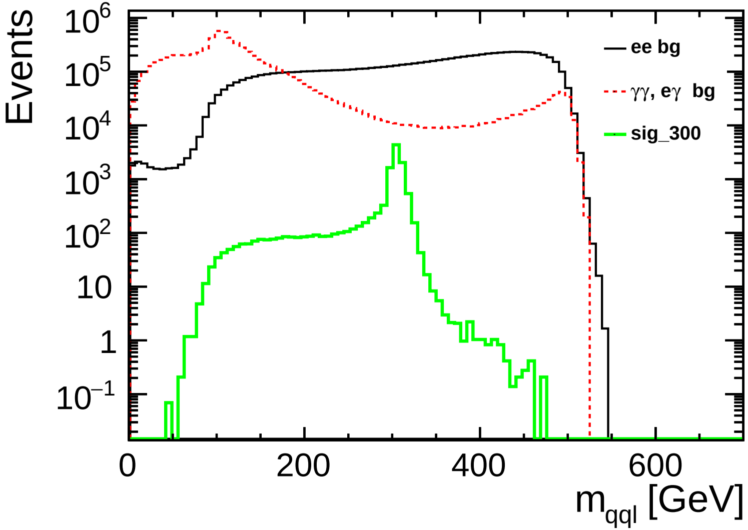
- Preselection:
  - cuts optimised to search for N: exactly 1 lepton and 2 jets in the final state

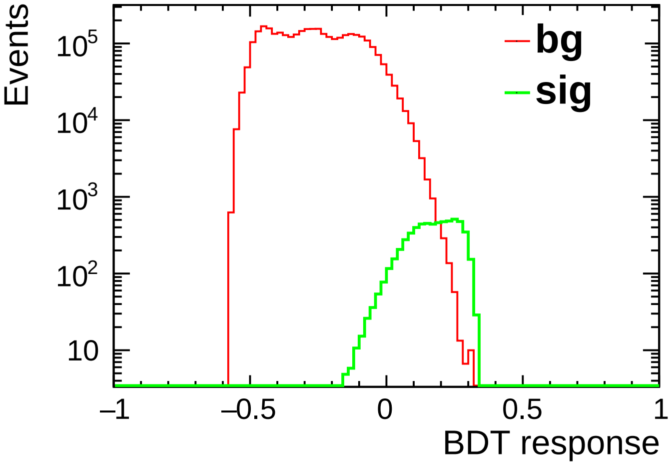
qql invariant mass



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

Boosted Decision Trees

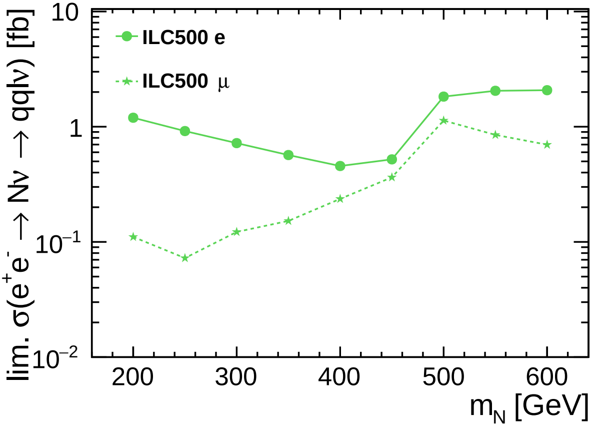
BDT trained with 8 input variables (see backup slides)



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

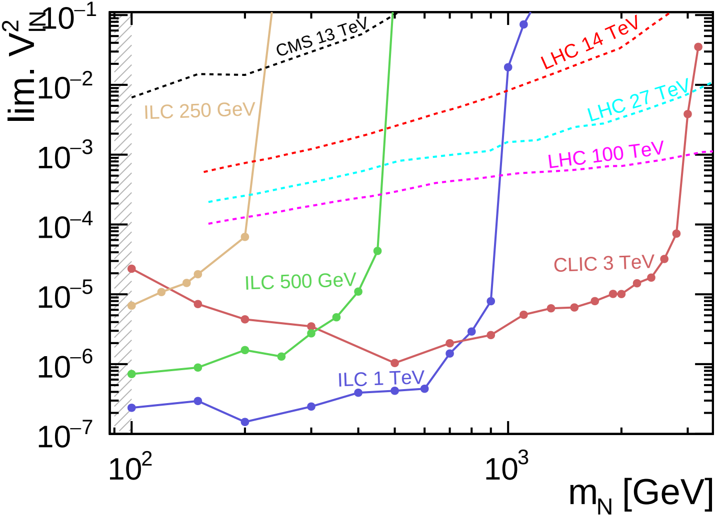
CLs method

BDT response is used to build a model in RooStats to use the CL_s method (combining both channels, systematic uncertainties).



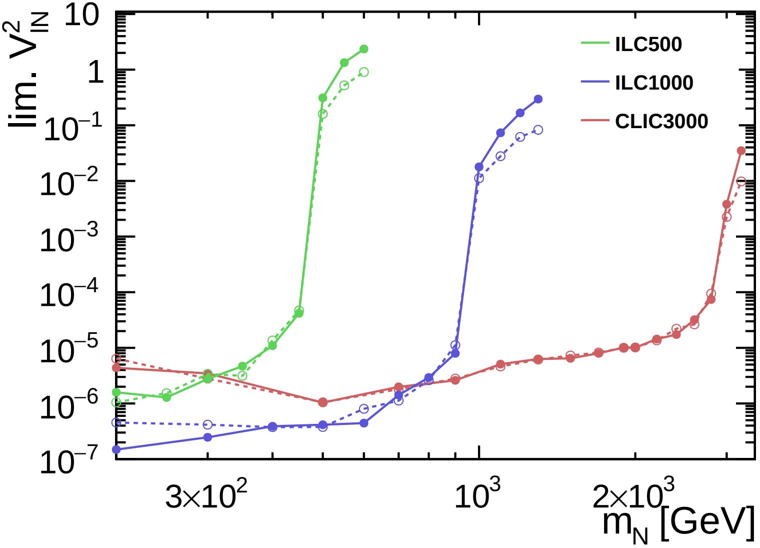
Final results

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

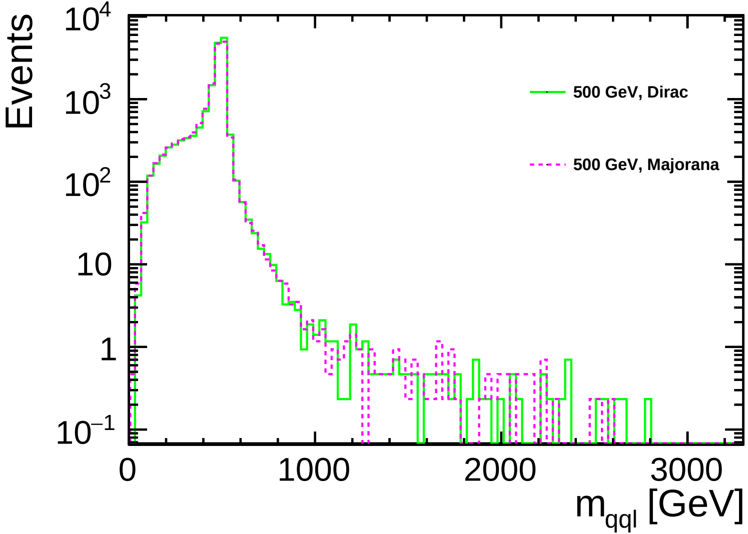


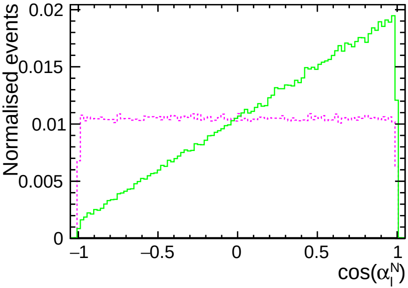
LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

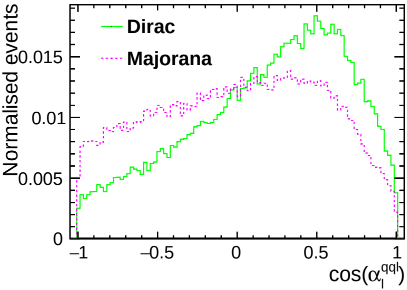
What about Majorana...?



Dirac vs. Majorana – *qql* invariant mass







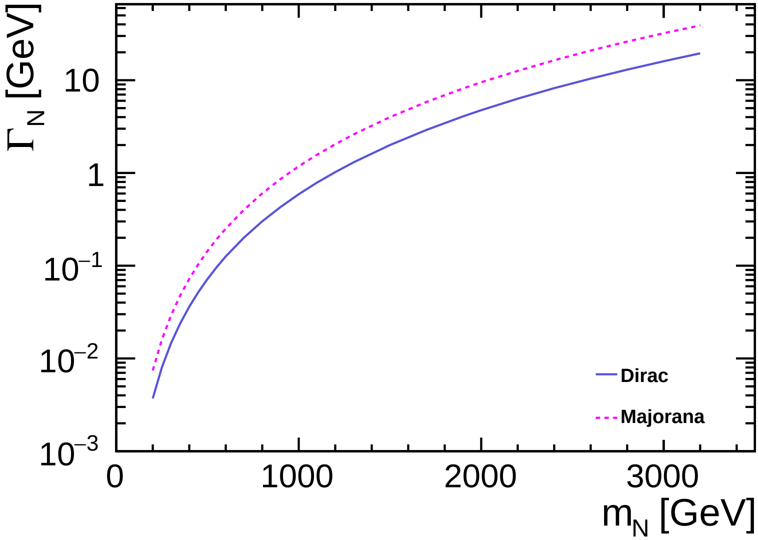
generator vs. detector

→ dedicated study in progress

Conclusions

1. At future e^+e^- colliders, heavy neutrino production could be observed almost up to the kinematic limit.
2. The expected coupling limits are much stronger than those at LHC/FCC-hh.
3. Discrimination between the Majorana and Dirac natures of the heavy neutrino requires further studies.

BACKUP: Neutrino width



BACKUP: Background channels

channel	σ_{500} [fb]	N_{500}	σ_{1000} [fb]	N_{1000}	σ_{3000} [fb]	N_{3000}
$e^+e^- \to qql\nu$	10,400	7,500,000	7,660	7,580,000	8,760	2,280,000
$e^+e^- \to llll$	3,010	60,100	4,190	73,100	5,810	838,000
$e^+e^- \to qqll$	2,020	158,000	2,510	188,000	3,210	204,000
$e^+e^- \to qqqqll$	21.9	5,700	102	22,900	701	5,500
$e^+e^- \to qqqql\nu$	416	301,000	209	265,000	155	12,800
$e^+e^- \to qql\nu l\nu$	82.7	52,400	49.0	53,700	62.6	22,900
$\gamma^E e^+ \to qql$	4,510	807,000	5,130	1,240,000	4,520	1,230,000
$\gamma^E e^- \to qql$	4,540	842,000	5,300	1,350,000	4,660	1,280,000
$\gamma^E\gamma^E \to qql\nu$	10.2	5,260	43.8	44,300	153	143,000
$\gamma^E\gamma^E \to qqll$	3.19	867	7.60	3,760	14.8	8,440
$\gamma^B e^+ \to qql$	8,740	2,550,000	8,290	4,200,000	4,330	2,110,000
$\gamma^B e^- \to qql$	8,860	2,610,000	8,660	4,600,000	4,940	2,530,000
$\gamma^B\gamma^B \to qql\nu$	–	–	35.6	35,600	13,500	13,400,000
$\gamma^B\gamma^B \to qqll$	20.4	5,380	94.1	64,700	1,460	1,070,000
$\gamma^E\gamma^B \to qql\nu$	7.70	2,950	123	104,600	2,880	2,720,000
$\gamma^E\gamma^B \to qqll$	21.7	5,610	70.7	39,200	380	291,000

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