Probing the nature of HNL at lepton colliders

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3rd ECFA workshop on e+e- Higgs, Electroweak and Top Factories
10.10.2024

based on:
[2202.06703]
[2301.02602]
[2312.05223]

Motivation

Some mysteries of the Standard Model:

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

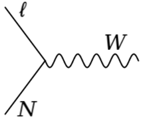
can be addressed by introducing new species of neutrinos.

Heavy Neutral Leptons at lepton colliders

Let us assume that HNLs couple only to the SM gauge bosons and Higgs:

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

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



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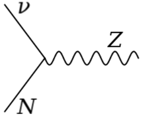

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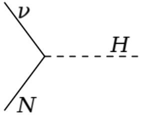

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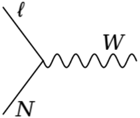

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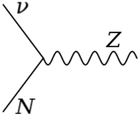

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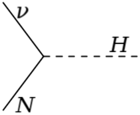
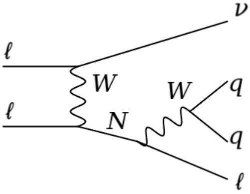
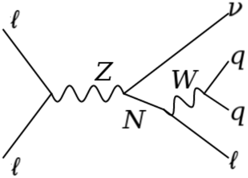


At lepton colliders, single production with subsequent decay into qql is particularly interesting, as it allows for direct reconstruction of N.





Lepton colliders

ilc

clic

International
MUON Collider
Collaboration

Analysis setup

- model with a single Dirac or Majorana neutrino
- couplings:

$$|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}^2| \equiv V_{lN}^2$$

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

- masses:

$$\mathrm{m}_N \geqslant 100 \text{ GeV}$$

- widths:

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

Analysis procedure

1. Generating physical events with WHIZARD
   - $\ell^+\ell^- \rightarrow N\nu \rightarrow qq\ell\nu$ and "background"
   - ILC at 250 GeV, 500 GeV and 1 TeV; CLIC at 3 TeV
   - parton shower and hadronisation with PYTHIA 6
   - beam spectra and polarisation included
   - S/B $\sim 10^{-3}$, e.g. ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb

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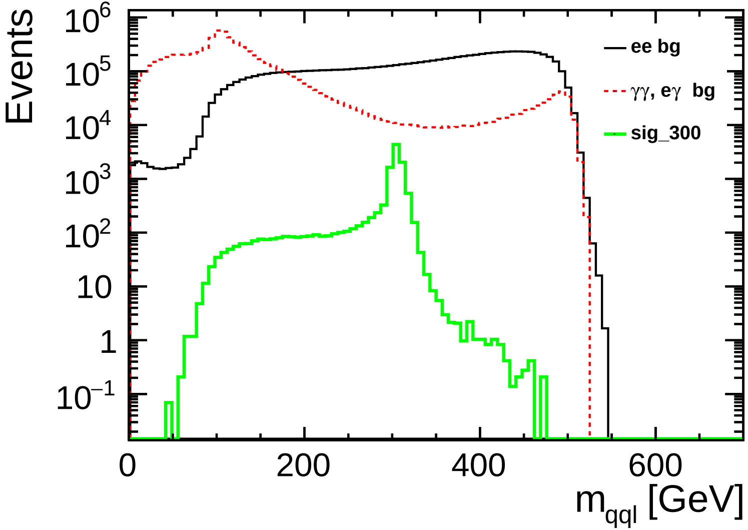
4. BDT training
5. CLs method to get final results

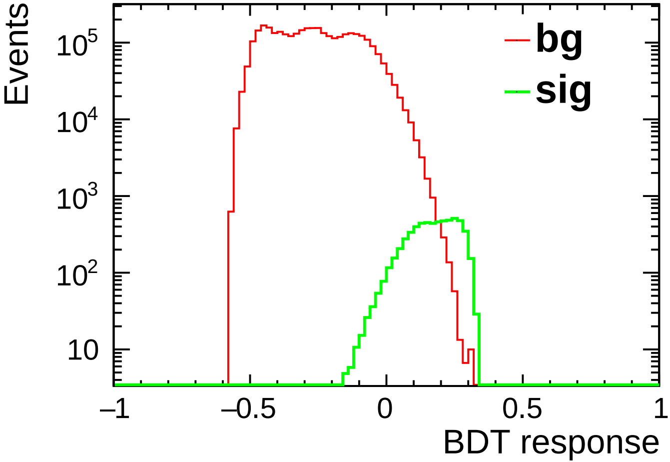
qql invariant mass



ILC 500 GeV, (-80%, +30%), m_N = 300 GeV

Boosted Decision Trees

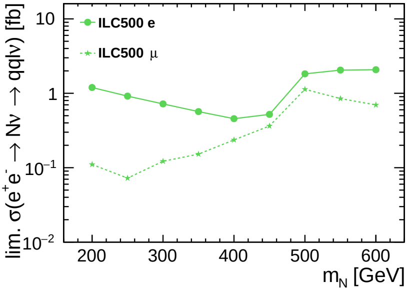
BDT trained with 8 input variables

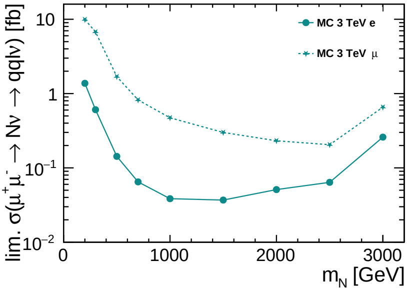


ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV, μ in the final state

CLs method

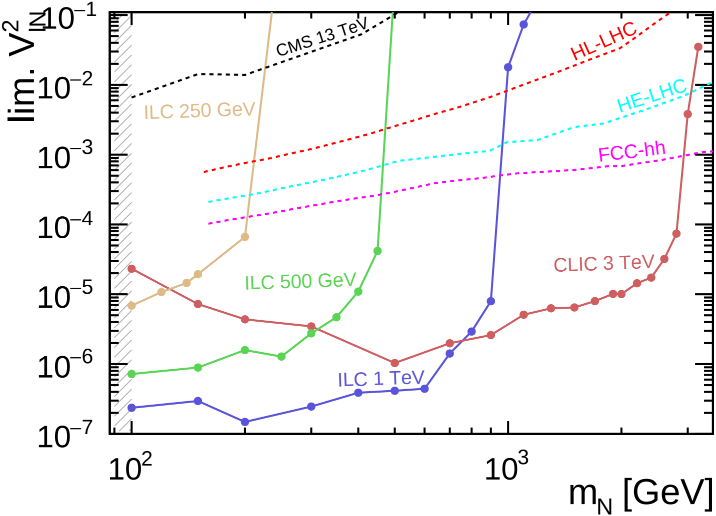
BDT response is used to build a model in RooStats to use the CL_s method (combining both channels, normalisation uncertainties).





Results for e^+e^- colliders

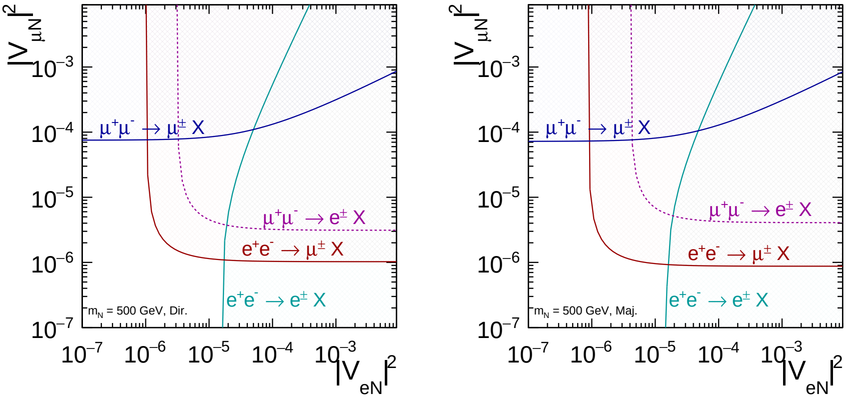
The cross-section limits can be translated into limits on the V_{lN}^2 parameter.



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

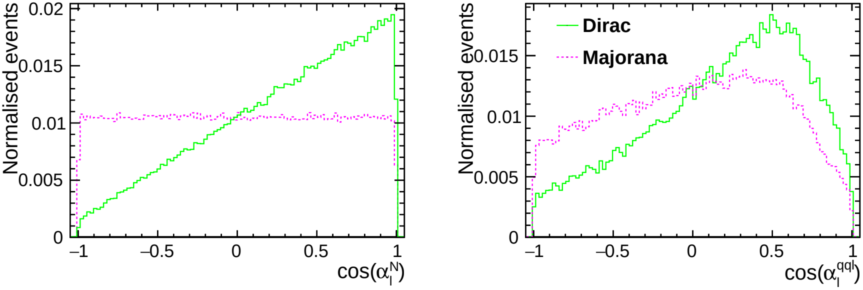
Dirac vs. Majorana

Exclusion limits are very similar for the Dirac- and Majorana-neutrino hypotheses



Are there any discriminant variables?

Lepton emission angle in the N rest frame:



generator vs. detector

CLIC 3 TeV

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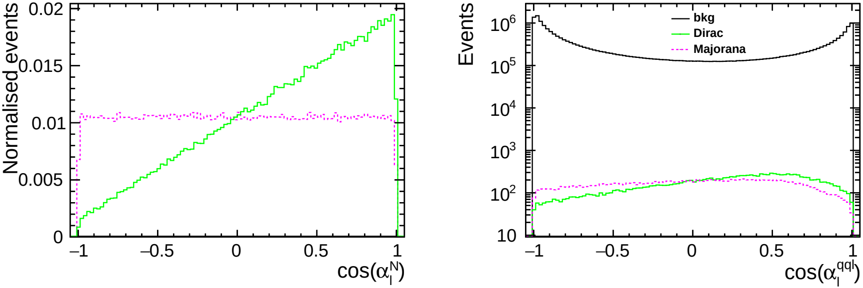

generator vs. detector

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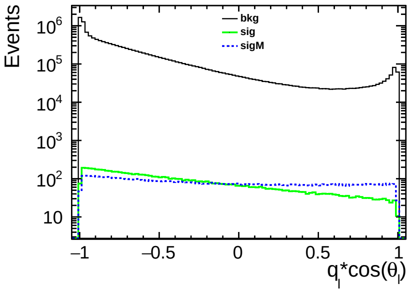
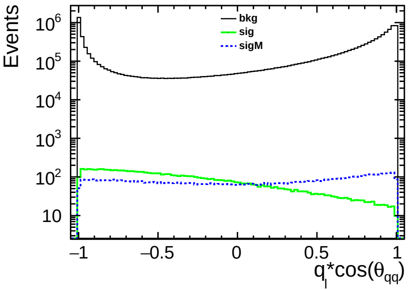
More sophisticated variables...

Lepton and dijet LAB angle relative to the electron (positron) beam multiplied by the lepton charge q_l:





ILC 250 GeV, $m_N = 150$ GeV

How to distinguish the two species of neutrinos?

1. 2 (independent) BDT trainings:
   - LNV vs. (α_{BDT} · LNC + Background)
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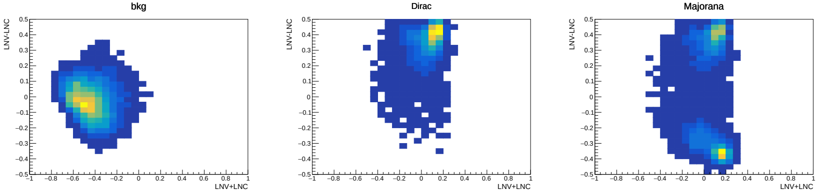
2. 2D histograms: $\mathrm{BDT_{LNV}}$+$\mathrm{BDT_{LNC}}$, $\mathrm{BDT_{LNV}}$-$\mathrm{BDT_{LNC}}$



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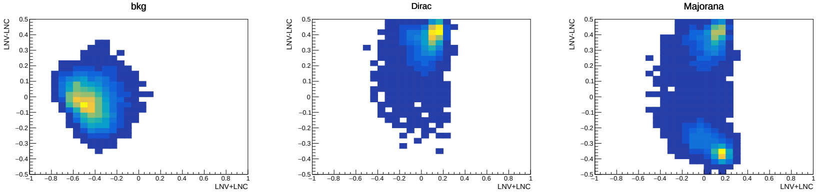

3. χ^2-like statistic:

$$T' = \sum_{bins} \frac{[(B+D)-(B+M)]^2}{\frac{1}{2}[(B+D)+(B+M)]} = \sum_{bins} \frac{(D-M)^2}{B+\frac{D+M}{2}} \quad (1)$$

$$T = T' + \text{DOF} \quad (2)$$

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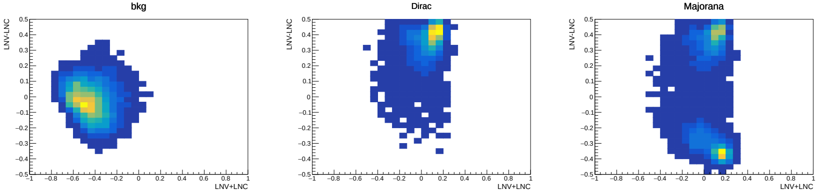

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$$T = T' + \mathrm{DOF} \quad (2)$$

4. Statistical test:

$$T \geqslant \chi^2_{crit}(\mathrm{DOF}) \Rightarrow \text{hypotheses distinguishable}$$

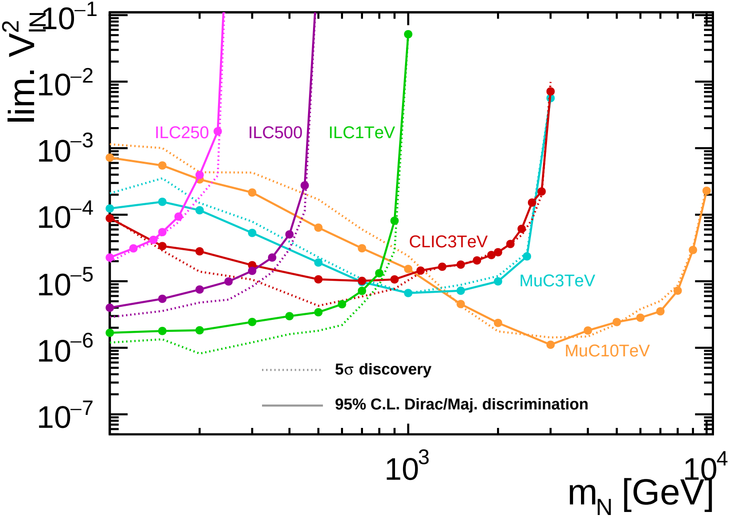
How to set limits?

$$T' \rightarrow T'(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D - M)^2}{B + \alpha_{lim} \cdot \frac{D+M}{2}}$$

and we search for α_{lim}, for which:

$$T \rightarrow T(\alpha_{lim}) \equiv \chi^2_{crit}(DOF).$$

Dirac vs. Majorana – results



Conclusions

1. Lepton colliders are an excellent tool for discovering and discriminating HNLs.
2. Hadron colliders reach high masses, but lepton colliders reach (much) lower couplings.
3. Combination of charge & angular information allows access on the Dirac vs. Majorana nature (discrimination almost always possible if HNLs discovered!).

BACKUP: HeavyN model

- 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*)

BACKUP: Running scenarios

ILC:

- 500 GeV: total luminosity of 4000 fb^{-1}
  - 2 x 1600 fb^{-1} for LR and RL beam polarisations
  - 2 x 400 fb^{-1} for LL and RR beam polarisations

  assuming polarisation of $\pm$80% for electrons and $\pm$30% for positrons
- 1 TeV: total luminosity of 8000 fb^{-1}
  - 2 x 3200 fb^{-1} for LR and RL beam polarisations
  - 2 x 800 fb^{-1} for LL and RR beam polarisations

  assuming polarisation of $\pm$80% for electrons and $\pm$20% for positrons

CLIC:

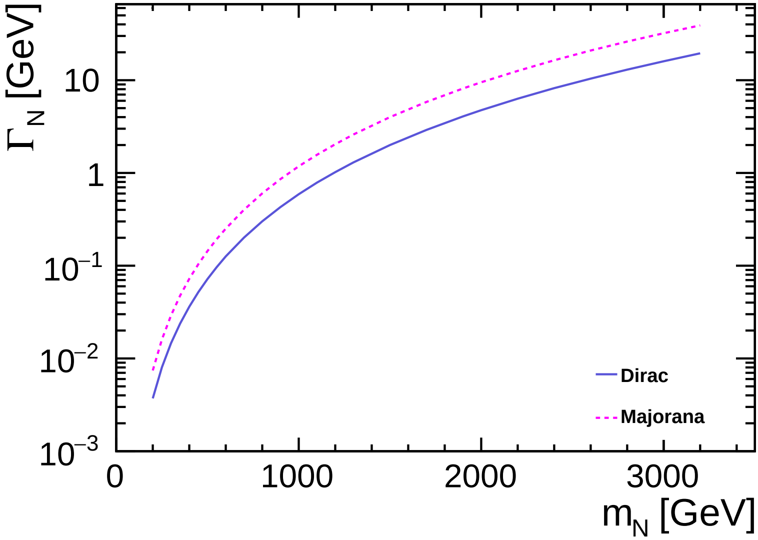
- 3 TeV: total luminosity of 5000 fb^{-1}
  - 4000 fb^{-1} for negative electron beam polarisation
  - 1000 fb^{-1} for positive electron beam polarisation

  assuming polarisation of $\pm$80% for electrons

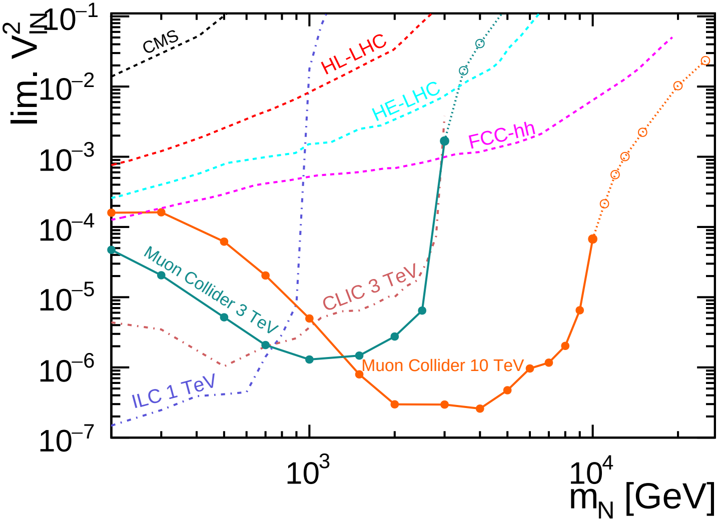
Muon Collider:

- 3 TeV: total luminosity of 1000 fb^{-1}
- 10 TeV: total luminosity of 10,000 fb^{-1}

BACKUP: Neutrino width



BACKUP: Results for the Muon Collider



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