# Probing the nature of heavy neutrinos at future lepton colliders

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LCWS'23
16.05.2023

*based on:*
[2202.06703]
[2301.02602]
and further development

# Motivation

Some mysteries of the Standard Model:

- dark matter density
- baryon asymmetry
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can be addressed by introducing new species of neutrinos.

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

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

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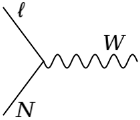
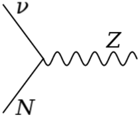



$\mathcal{L}_{Z-N-\nu}$

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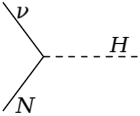

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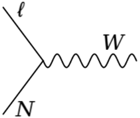


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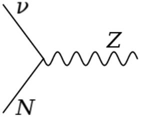


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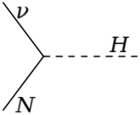
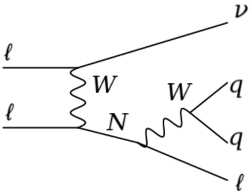
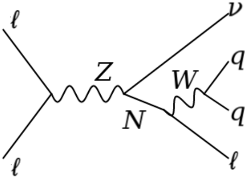



At lepton colliders, single production with subsequent decay into $qql$ is particularly interesting, as it allows for direct reconstruction of $N$.



# Analysis setup

- *HeavyN* model with 3 Dirac and Majorana neutrinos
- couplings:

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

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

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

- masses:

$$m_N \geqslant 100 \text{ GeV}$$

- 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
   - without $N$ propagators ("background")
   - $\ell^+\ell^- \to N\nu \to qq\ell\nu$ ("signal")
   - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
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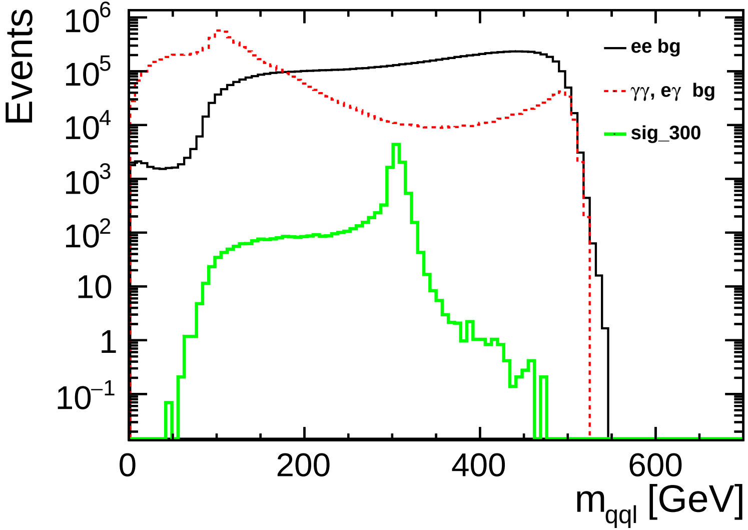
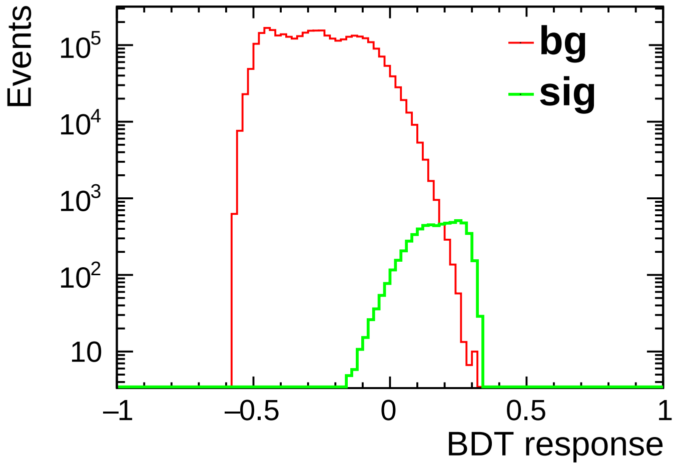
4. BDT training
5. CLs method to get final results

# *qql* invariant mass




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

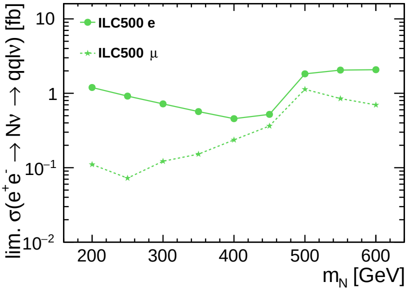
BDT trained with 8 input variables

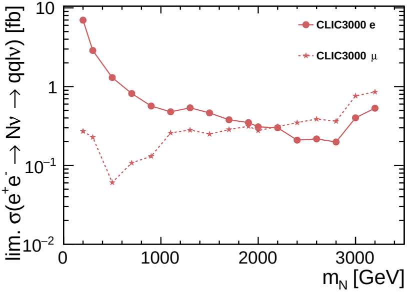



ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV, $\mu$ in the final state

# CLs method

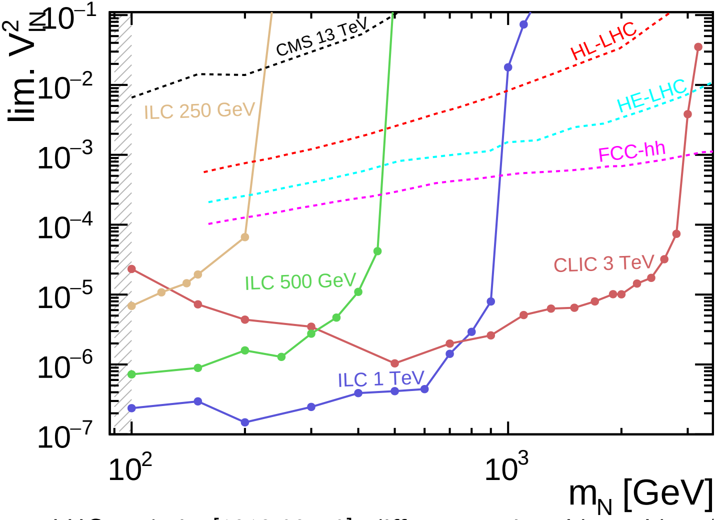
BDT response is used to build a model in RooStats to use the $CL_s$ method (combining both channels, $e^+e^-$: normalisation uncertainties).



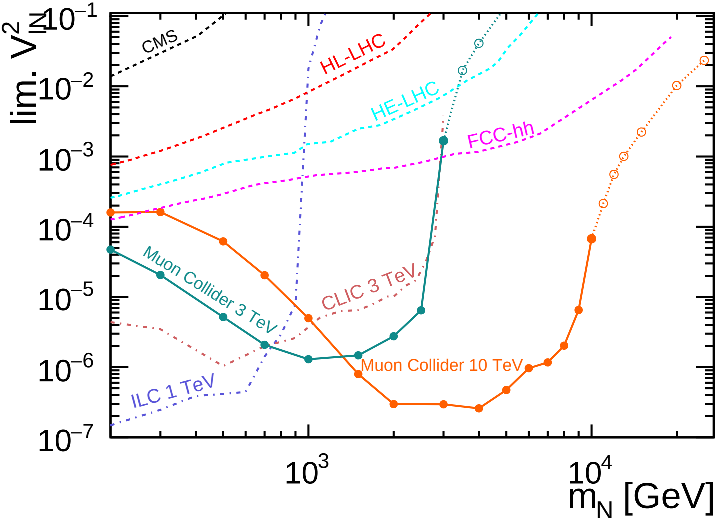
# Results for $e^+e^-$ colliders

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




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

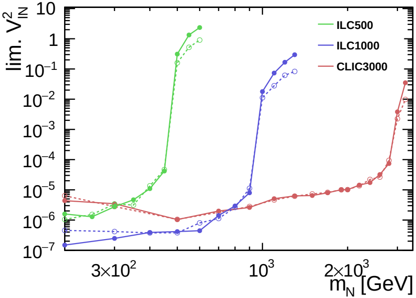
# Results for the Muon Collider

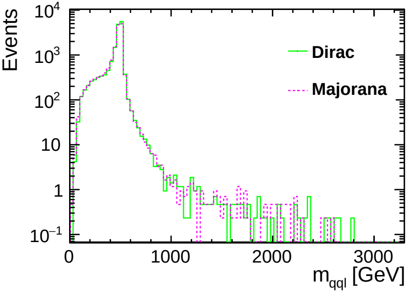



LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

# Dirac vs. Majorana

Exclusion limits are very similar for the Dirac and Majorana neutrino hypothesis, except for off-shell production.




CLIC 3 TeV

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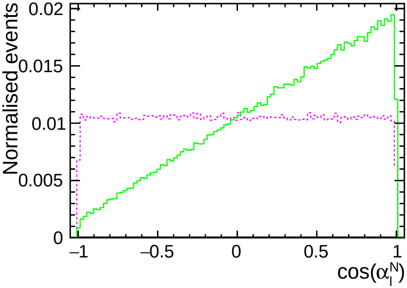
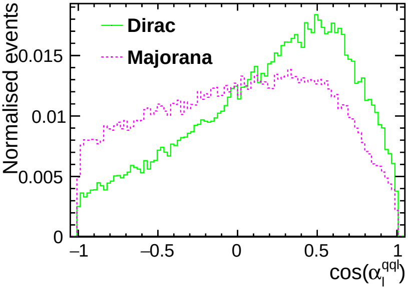
Lepton emission angle in the $N$ rest frame:




generator vs. detector

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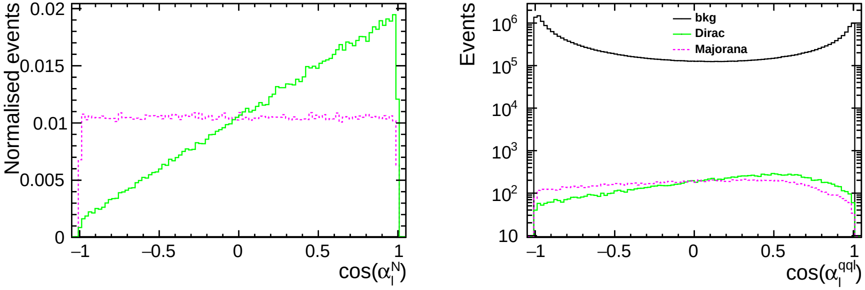


generator vs. detector

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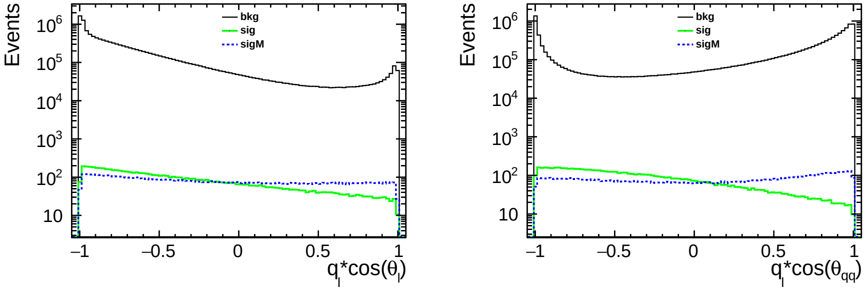
# More sophisticated variables...

Lepton and dijet directions relative to the electron (positron) beam for positive (negative) 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. ($\alpha_{BDT} \cdot$ LNC + Background)
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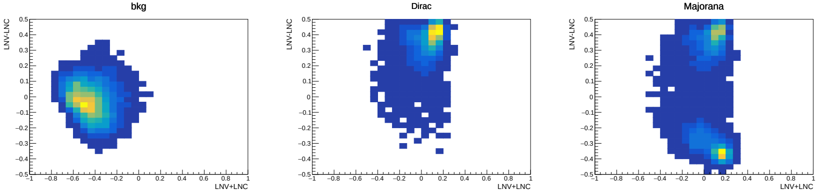
2. 2D histograms: $\mathrm{BDT_{LNV}}$+$\mathrm{BDT_{LNC}}$, $\mathrm{BDT_{LNV}}$-$\mathrm{BDT_{LNC}}$



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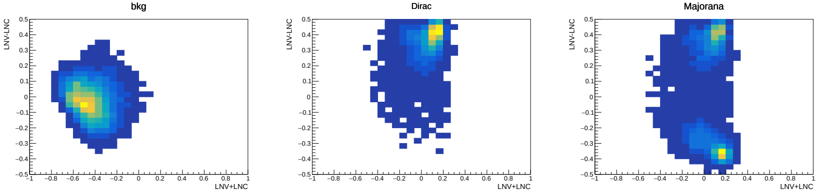


3. $\chi^2$-like statistic:

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

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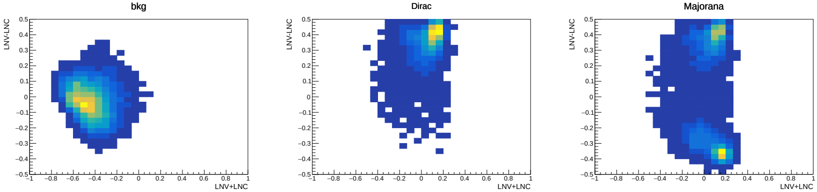


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4. Statistical test:

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

# How to set limits?

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

and we search for $\alpha_{lim}$, for which:

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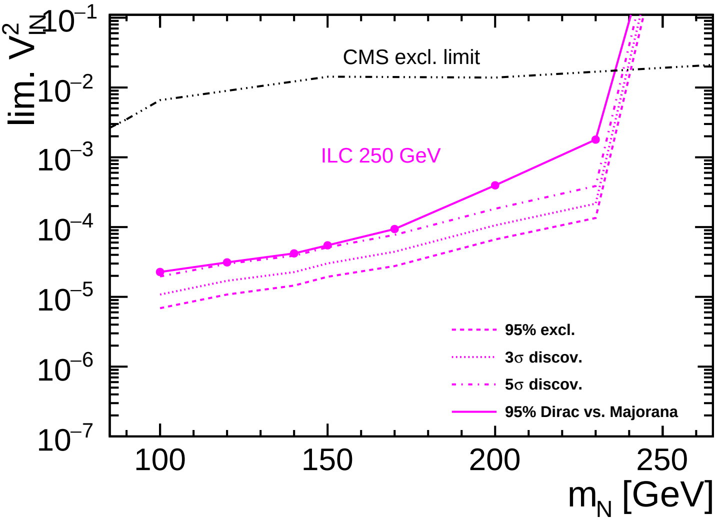
Technical realisation: signal scaling factor used in the BDT training $\alpha_{BDT}$ is varied to obtain the best limit for each $m_N$.

1. Train BDT for different values of $\alpha_{BDT}$
2. For each $\alpha_{BDT}$, calculate 95% CL limit $\alpha_{lim}$ corresponding to $T(\alpha_{lim}) = \chi^2_{crit}(DOF)$
3. Select the best limit $\alpha_{min} = min(\alpha_{lim})$
4. Set the final limit as $V_{\ell N}^{\text{lim}} = \alpha_{\text{min}} \cdot V_{\ell N}^{\text{ref}}$

# Dirac vs. Majorana – preliminary results for ILC250



# Conclusions

1. At future lepton colliders, heavy neutrino production could be observed almost up to the kinematic limit.
2. The expected coupling limits are much stronger than those for hadron colliders, including FCC-hh.
3. Future lepton colliders could also efficiently probe the nature of the heavy neutrinos.
4. Work in progress!

# 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 $e, \mu, \tau$ 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:**

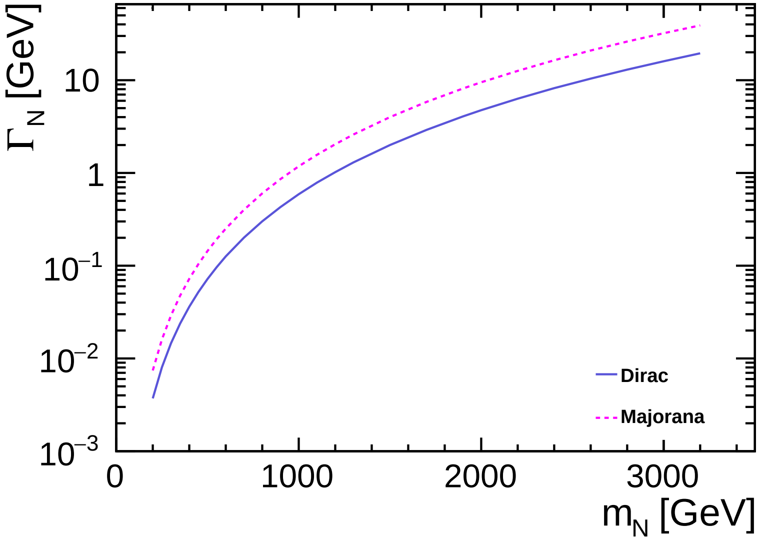
- 3 TeV: total luminosity of 5000 $fb^{-1}$
  - 4000 $fb^{-1}$ for negative electron beam polarisation
  - 1000 $fb^{-1}$ for positive electron beam polarisation

  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: 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