

# Heavy Neutral Leptons at $e^+e^-$ colliders

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*based on:*

[2202.06703]

[2301.02602]

[2312.05223]

Some mysteries of the Standard Model:

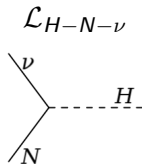
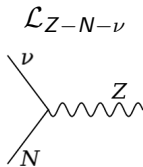
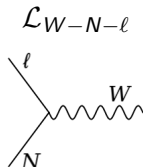
- dark matter density
- baryon asymmetry
- neutrino masses, mass hierarchy and oscillations
- nature of neutrinos: Dirac or Majorana

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:

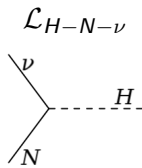
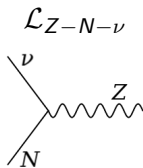
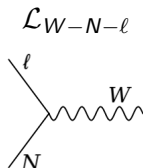
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{W-N-\ell} + \mathcal{L}_{Z-N-\nu} + \mathcal{L}_{H-N-\nu}$$



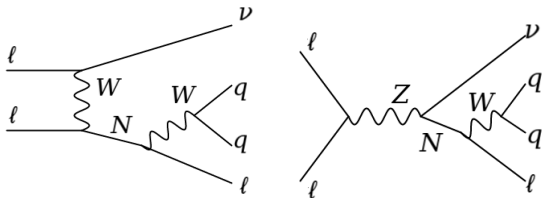
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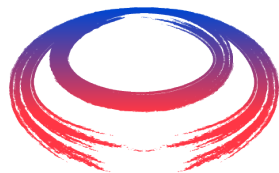
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At lepton colliders, single production with subsequent decay into  $qq\ell$  is particularly interesting, as it allows for direct reconstruction of  $N$ .



# Lepton colliders



International  
UON Collider  
Collaboration

# Analysis setup

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

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

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

- masses:

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

- 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

## ① Generating physical events with WHIZARD

- $l^+l^- \rightarrow N\nu \rightarrow qq\nu$  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:  $qq\nu$  background  $\sim 10$  pb, signal  $\sim 10$  fb

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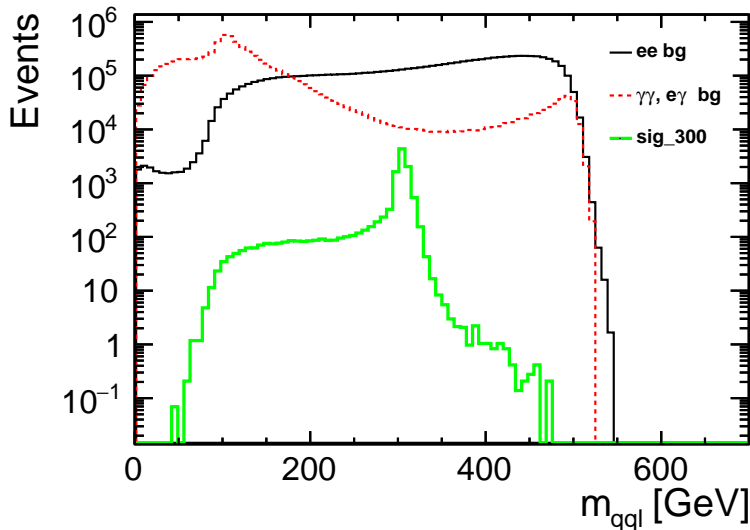


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- ④ BDT training
- ⑤ CLs method to get final results

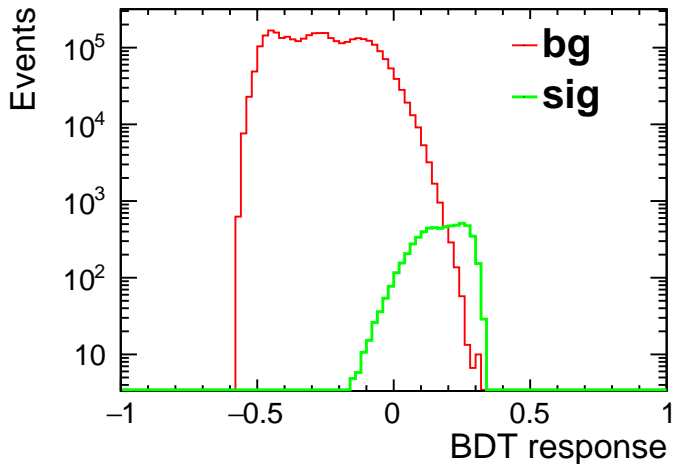
# $qq\ell$ invariant mass



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

# Boosted Decision Trees

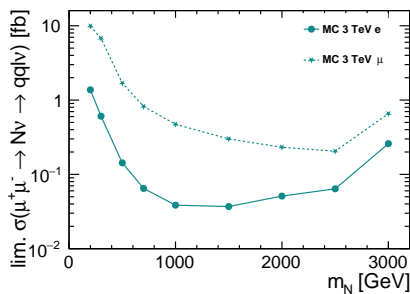
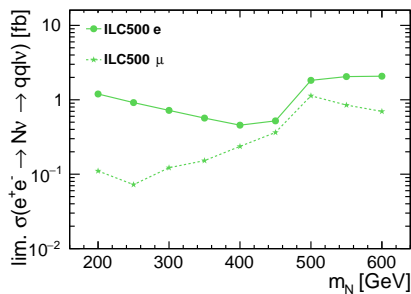
BDT trained with 8 input variables



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

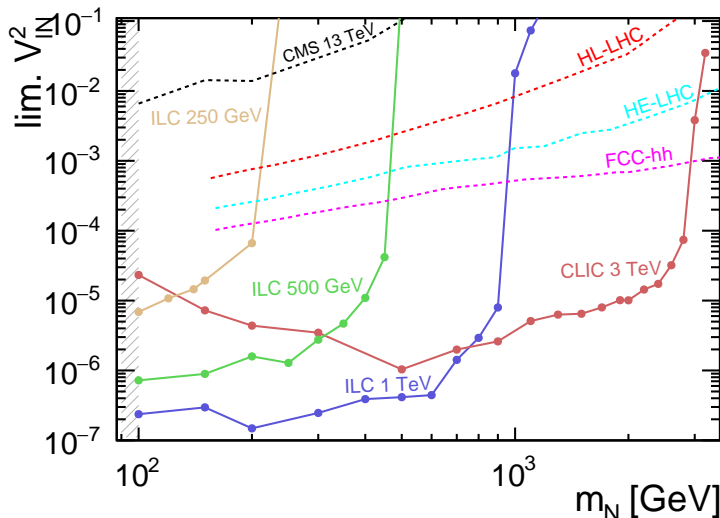
# CLs method

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



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

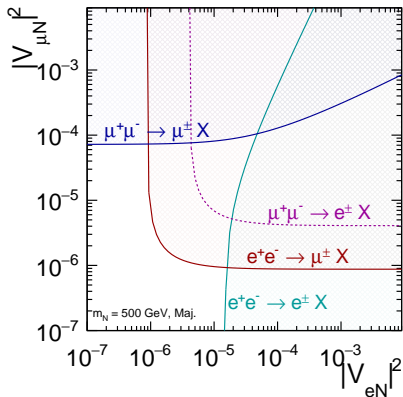
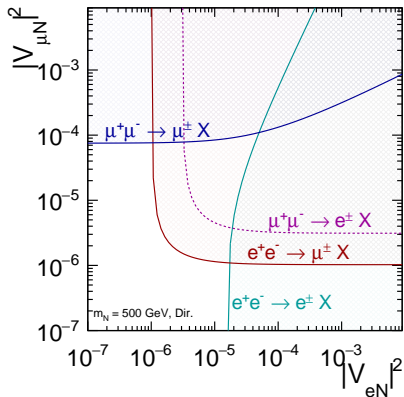
The cross-section limits can be translated into limits on the  $V_{IN}^2$  parameter.



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

# Dirac vs. Majorana

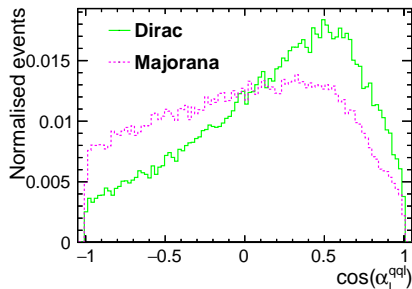
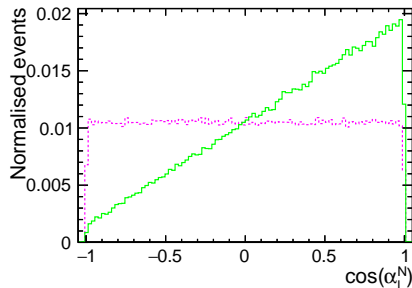
Exclusion limits are very similar for the Dirac- and Majorana-neutrino hypotheses





# Are there any discriminant variables?

Lepton emission angle in the  $N$  rest frame:

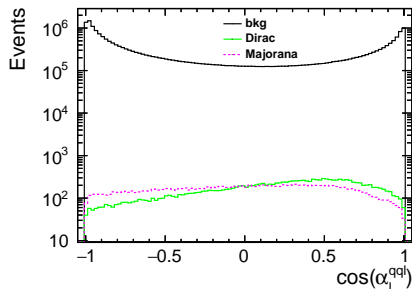
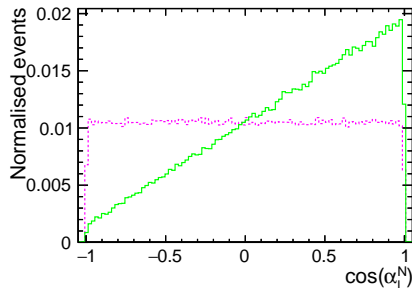


generator vs. detector

CLIC 3 TeV

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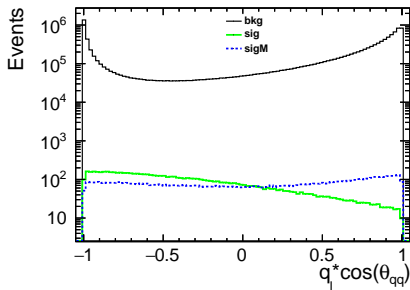
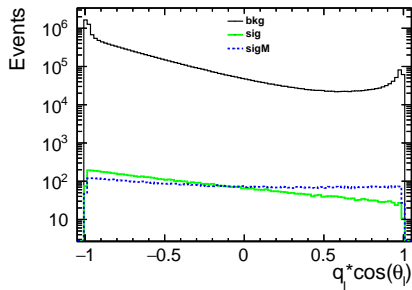


generator vs. detector

CLIC 3 TeV

# More sophisticated variables...

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



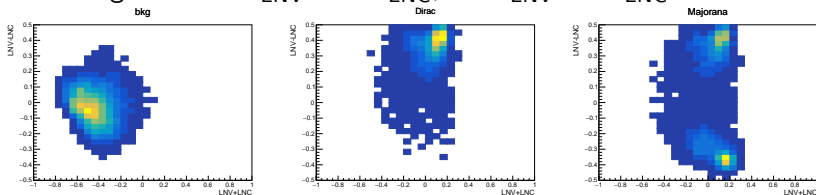
ILC 250 GeV,  $m_N = 150$  GeV

# How to distinguish the two species of neutrinos?

- 1 2 (independent) BDT trainings:
  - LNV vs. ( $\alpha_{BDT} \cdot \text{LNC} + \text{Background}$ )
  - LNC vs. ( $\alpha_{BDT} \cdot \text{LNV} + \text{Background}$ )

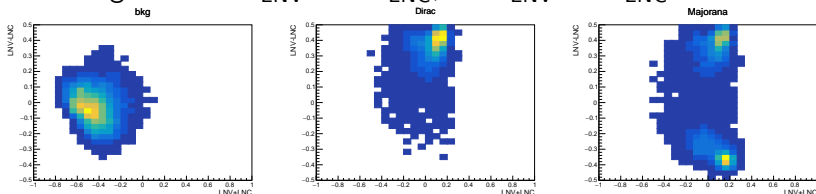
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- 2D histograms:  $\text{BDT}_{\text{LNV}} + \text{BDT}_{\text{LNC}}$ ,  $\text{BDT}_{\text{LNV}} - \text{BDT}_{\text{LNC}}$



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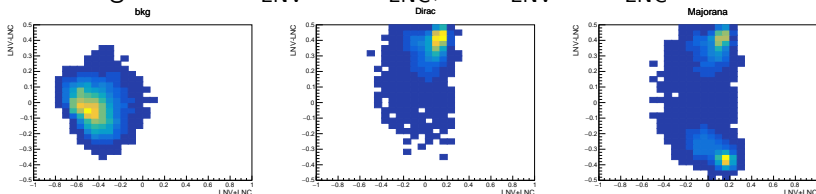
- $\chi^2$ -like statistic:

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

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

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- Statistical test:

$$T \geq \chi_{\text{crit}}^2(\text{DOF}) \Rightarrow \text{hypotheses distinguishable}$$

# How to set limits?

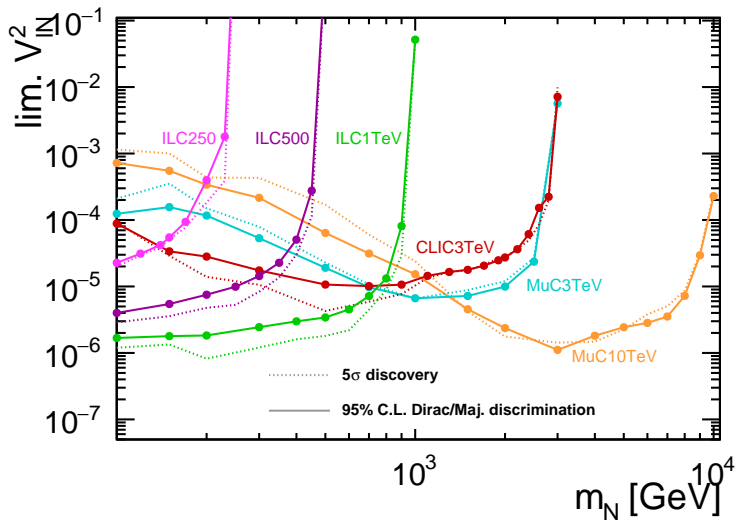
$$T' \rightarrow T'(\alpha_{lim}) = \sum_{bins} \frac{\alpha_{lim}^2 (D - M)^2}{B + \alpha_{lim} \cdot \frac{D+M}{2}}$$

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

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



# 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!).

- 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  $4000 \text{ fb}^{-1}$ 
  - $2 \times 1600 \text{ fb}^{-1}$  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  $8000 \text{ fb}^{-1}$ 
  - $2 \times 3200 \text{ fb}^{-1}$  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

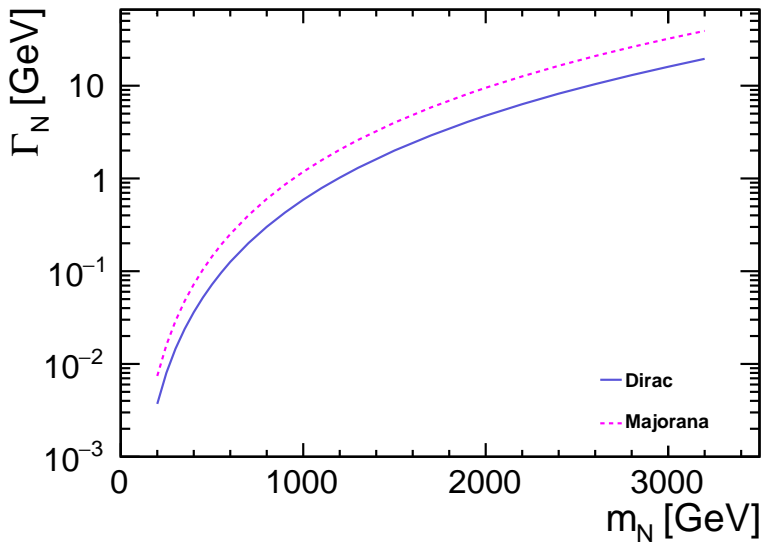
## CLIC:

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

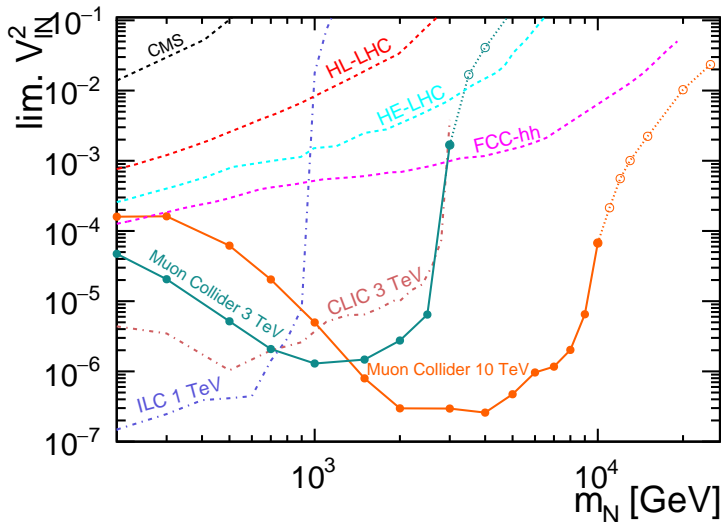
## Muon Collider:

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

# BACKUP: Neutrino width



# BACKUP: Results for the Muon Collider



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