

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

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[arXiv: 2202.06703]

Neutrinos can be connected with some SM problems (e.g. dark matter density, baryon asymmetry, ...).

In many scenarios, there are heavy neutral leptons (HNL) which are weakly coupled to the SM and thus, long-lived.

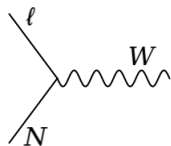
→ see other presentations at the workshop

In this talk, I will focus on prompt decays of the HNL.

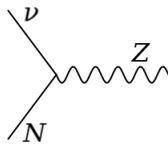
# The Standard Model with heavy neutrinos

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

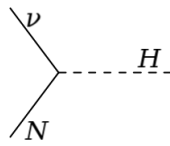
$$\mathcal{L}_{W-N-l}$$



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



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



Minimal scenario – without additional gauge bosons

- effective extension of the SM

[HeavyN FeynRules]

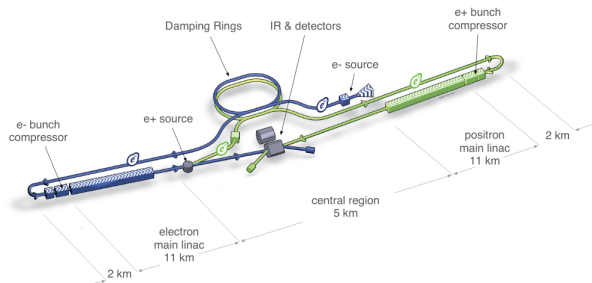
- widely analysed for searches at hadron colliders  
e.g. [arXiv:1411.7305], [arXiv:2008.01092], [arXiv:2011.02547]
- 3 new heavy neutrinos – Majorana or Dirac particles:  $N1$ ,  $N2$ ,  $N3$
- 12 free parameters:
  - 3 masses ( $\sim 10^2 - 10^3$  GeV)
  - 9 mixing parameters (3x3 mixing matrix for  $e, \mu, \tau$  and  $N1, N2, N3$ )

# Where to search for such neutrinos?

If we want to observe prompt decays, we have to reduce background...

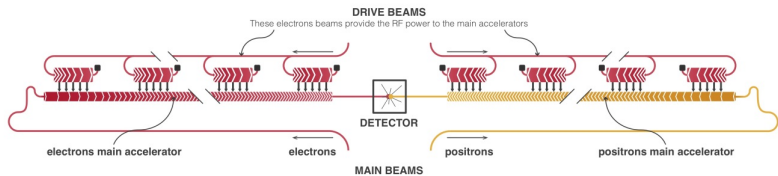


# International Linear Collider (ILC)



- superconducting accelerating cavities
- length of 31 km
- energy of 250-500 GeV, possible upgrade to 1 TeV
- polarisation for both beams (80%/30%)

# Compact Linear Collider (CLIC)



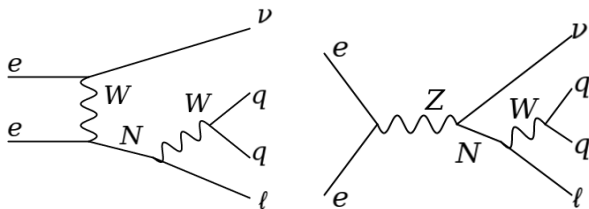
3 TeV

- two-beam accelerating scheme
- length of 11-50 km
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- electron beam polarisation of 80%

# 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 ( $qq\ell\nu$ ,  $qq\nu\nu$ ,  $ll\nu\nu$ ) and indirect (EWPOs, Higgs branching ratios).

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



- Dirac and Majorana neutrinos
- masses:

$$m_{N1} = 200\text{-}3200 \text{ GeV}$$
$$m_{N2} = m_{N3} = 10 \text{ TeV}$$

- couplings:

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

$V_{IN}^2 = 0.0003$  used for the generation of reference signal samples

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

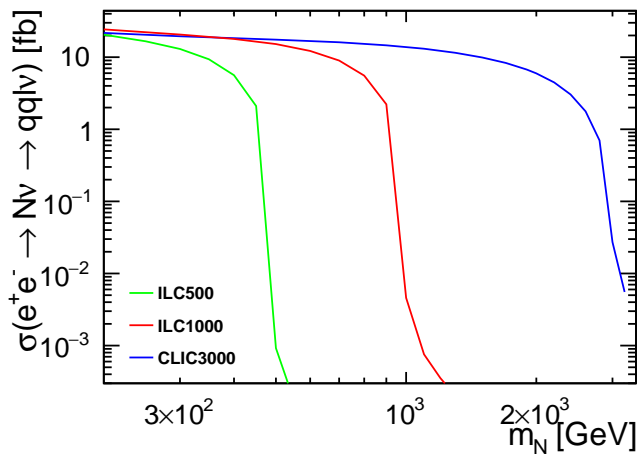
- considered collider scenarios:

ILC 500 GeV,  $1.6 \text{ ab}^{-1}$ ,  $(e^-, e^+) = (-80\%, +30\%)$

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

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

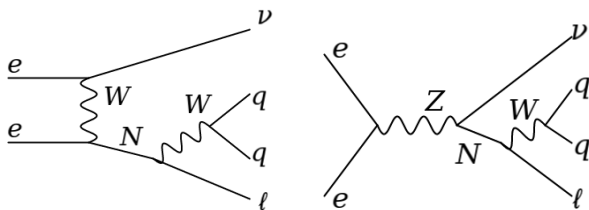
# Signal cross section



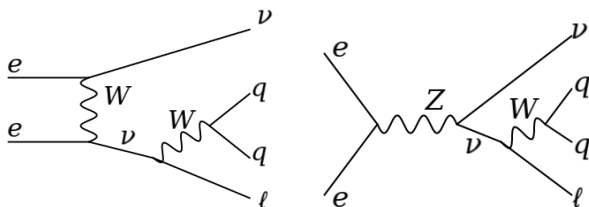
LR polarisation, including beam spectra

# Signal vs. background

Signal:



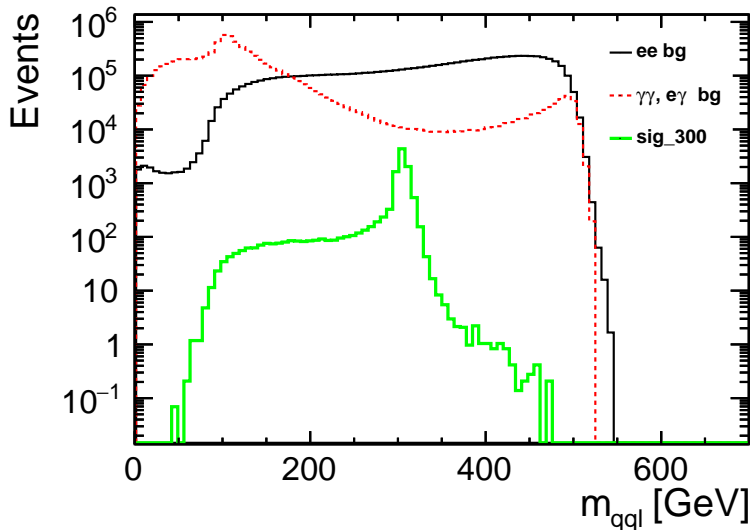
Background:



+ many other more important background channels...

- 1 Generating physical events with WHIZARD
  - $e^+e^- \rightarrow N\nu \rightarrow qq\nu$  ("signal")
  - processes without  $N$  propagators ("background"), also including  $e\gamma$  and  $\gamma\gamma$  background
- 2 Simulating detector response with DELPHES
- 3 Preselection of events matching the required signal topology
  - cuts optimised to search for  $N$ :  $qq\nu$  signature
- 4 Machine Learning via multi-variate analysis
- 5 Using CLs method to get final results

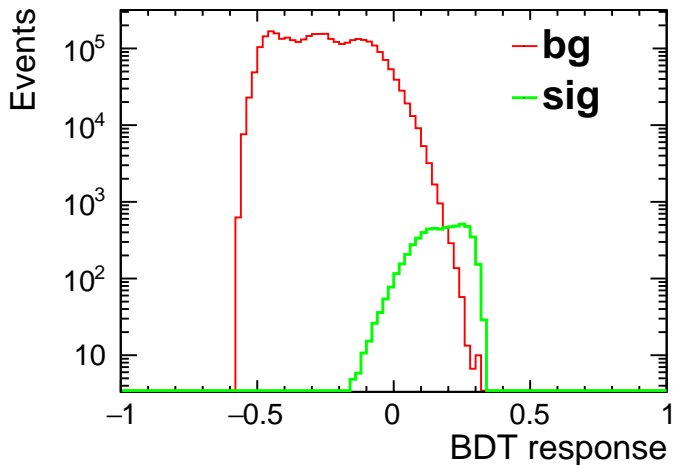
# $qq\ell$ invariant mass after the preselection



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

# Boosted Decision Trees

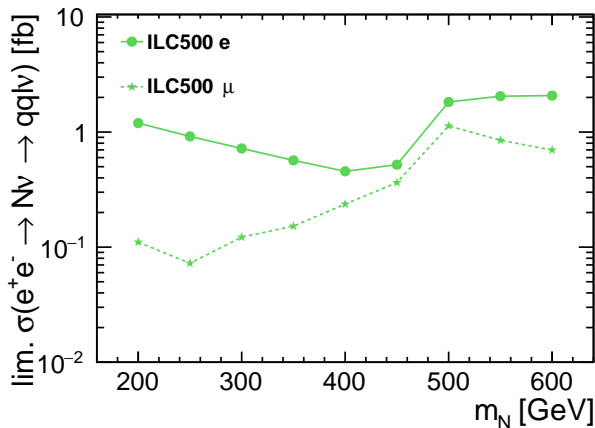
BDT trained with 8 input variables (see backup slides)



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

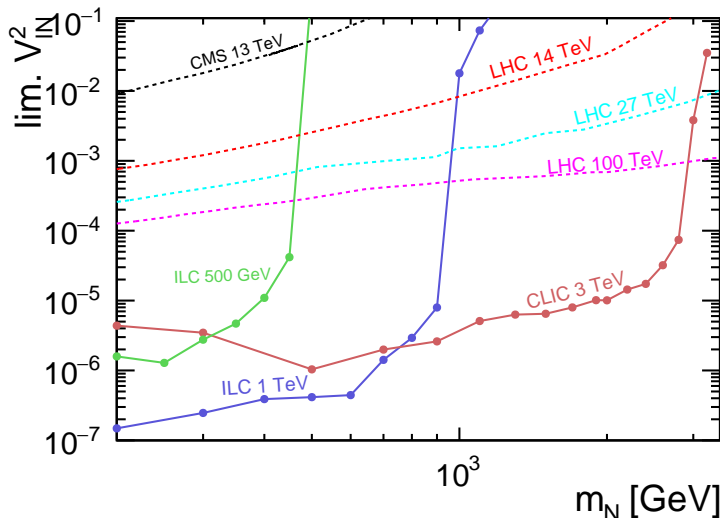
# CLs method

BDT response distribution is used to build a model in RooStats to use the CL<sub>s</sub> method (combining both channels, normalisation uncertainties).



# Final results

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



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

## But are the neutrinos *really* short-lived...?

For the lowest masses considered in our study (hundreds of GeV), the limits correspond to widths of a few keV and then,  $c\tau \ll 1$  nm.

Yes, they are!

Macroscopic lifetimes are expected for lower masses,  $\lesssim M_W$ .

- 1 At future  $e^+e^-$  linear colliders, heavy neutrinos could be observed directly (almost up to the kinematic limit).
- 2 The expected coupling limits are much stronger than those at LHC/FCC-hh.
- 3 The analysis is accepted for JHEP: [2202.06703]

# BACKUP: Running scenarios

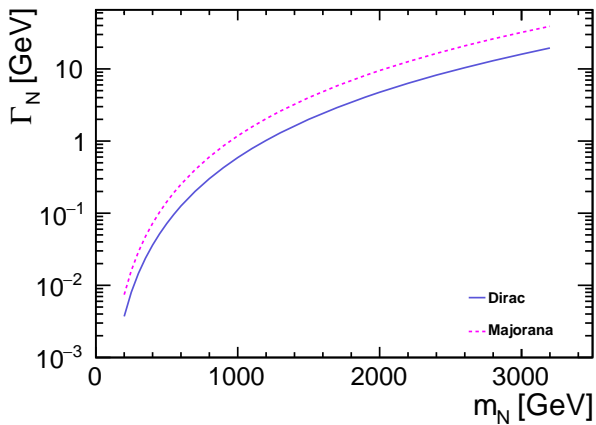
## ILC:

- 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

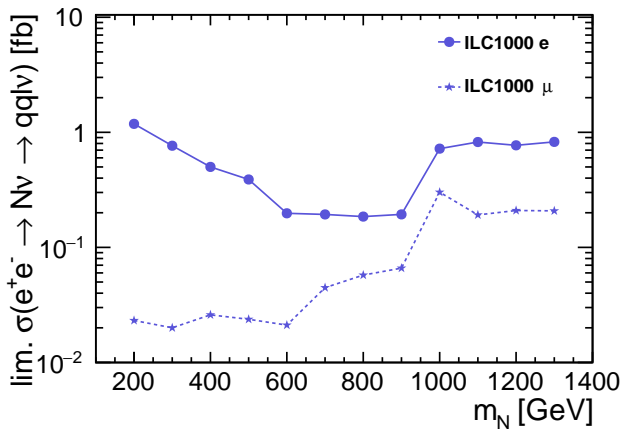
## CLIC:

- 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

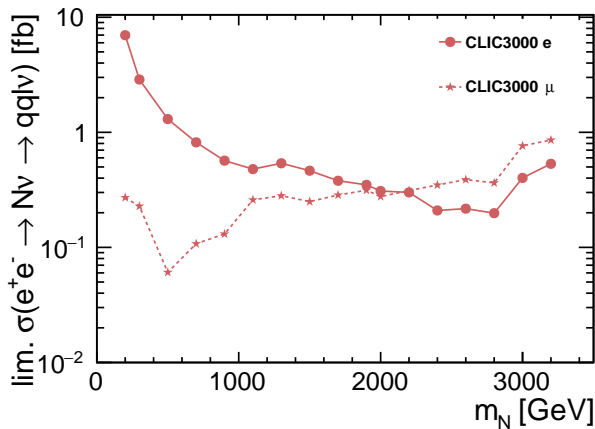
# BACKUP: Neutrino width



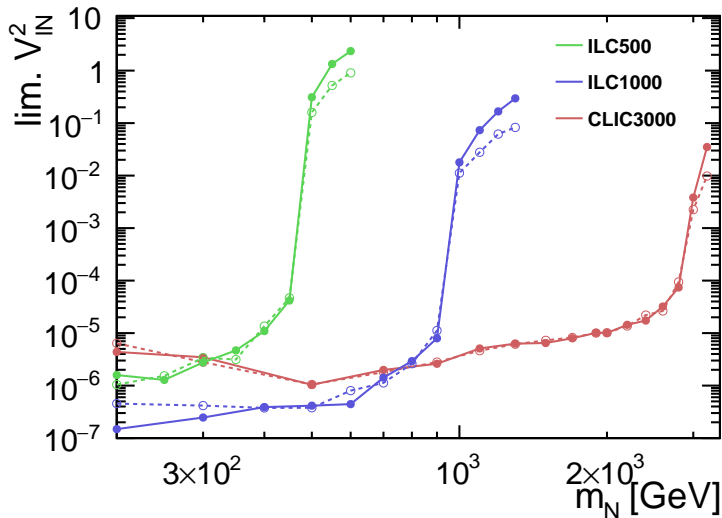
# BACKUP: Cross section limits – ILC1000



# BACKUP: Cross section limits – CLIC3000



# BACKUP: Dirac vs. Majorana



## BACKUP: BDT variables

- $qq\ell$  invariant mass
- angle between jets
- angle between dijet and lepton
- lepton energy
- $qq\ell$  energy
- lepton transverse momentum
- dijet transverse momentum
- $qq\ell$  transverse momentum