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

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Motivation

Some problems of the Standard Model:

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

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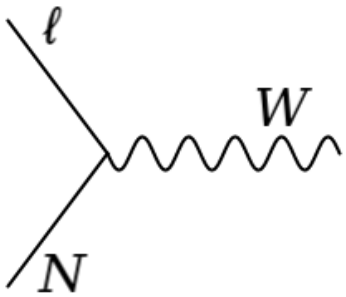
can be solved by introducing new species of neutrinos.

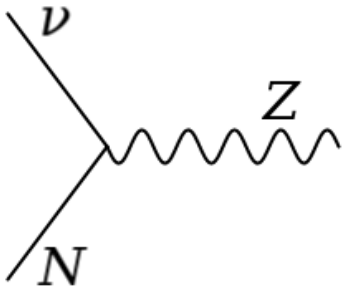
The Standard Model with heavy neutrinos

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

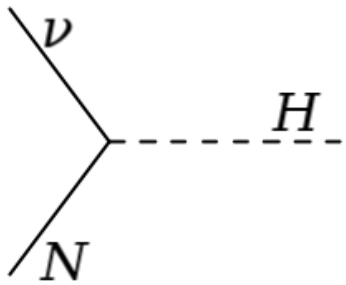
$\mathcal{L}_{W-N-l}$



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



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



Minimal scenario – without additional gauge bosons

HeavyN model: The Standard Model + Heavy Neutrinos

- effective model developed by R. Ruiz, D. Alva, T. Han... [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*)

Where to search for such neutrinos?

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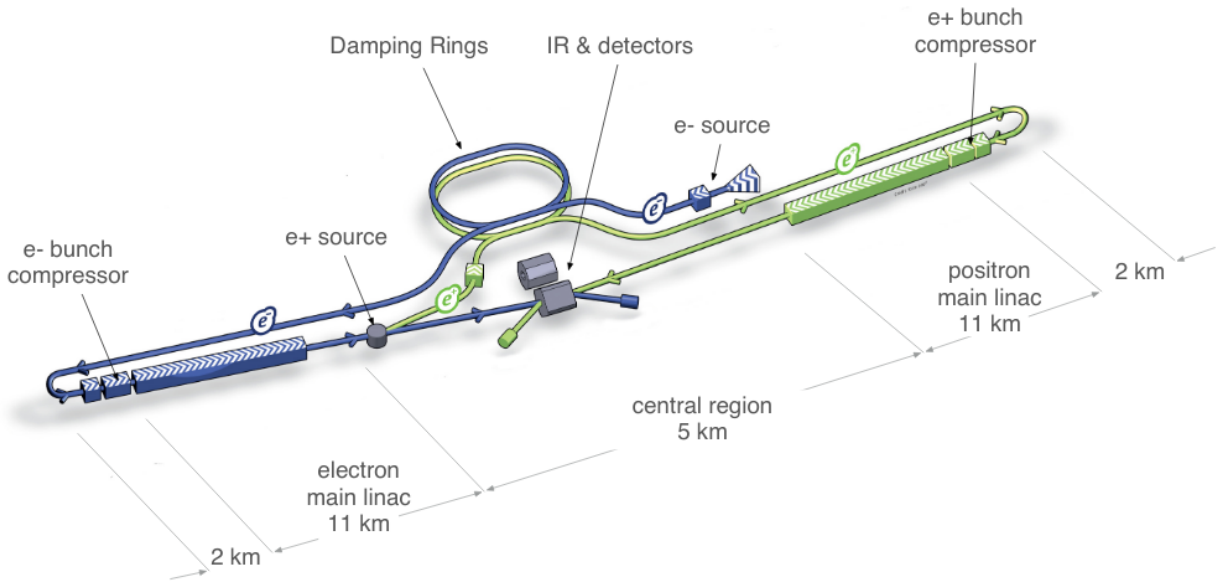
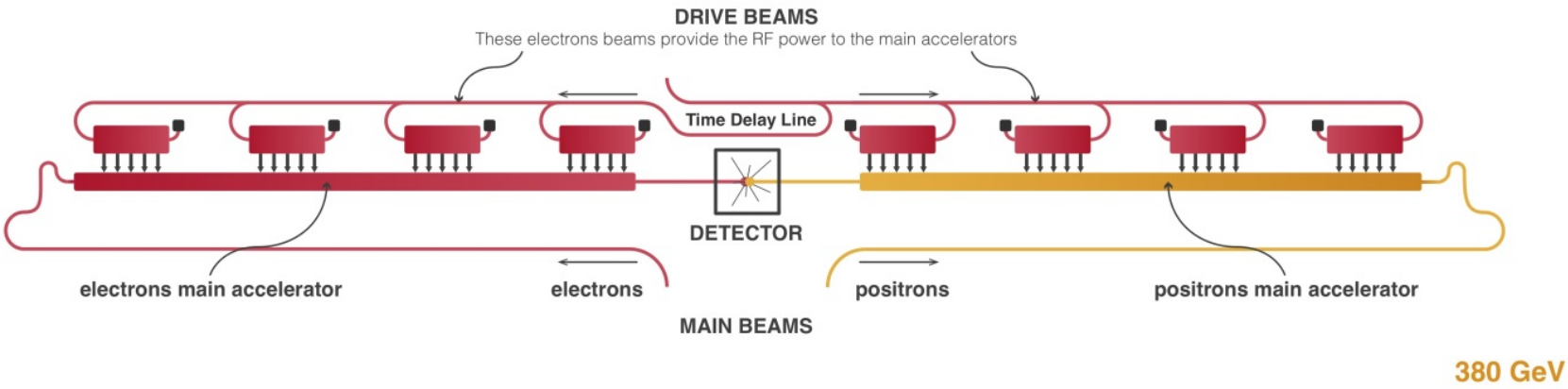
International Linear Collider (ILC)



- 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)

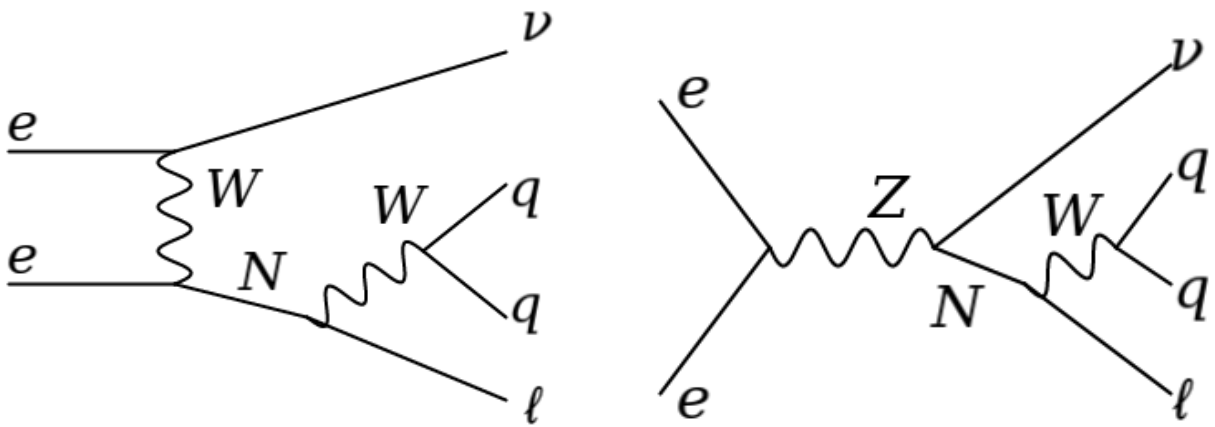


- two-beam accelerating scheme
- length of 11-50 km
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- electron beam polarisation of 80%

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

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



Our setup

- Dirac and Majorana neutrinos
- masses:

$$\mathrm{m}_{N1} = 200\text{-}3200 \text{ GeV}$$
$$\mathrm{m}_{N2} = \mathrm{m}_{N3} = 10 \text{ TeV}$$

- couplings:

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

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

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

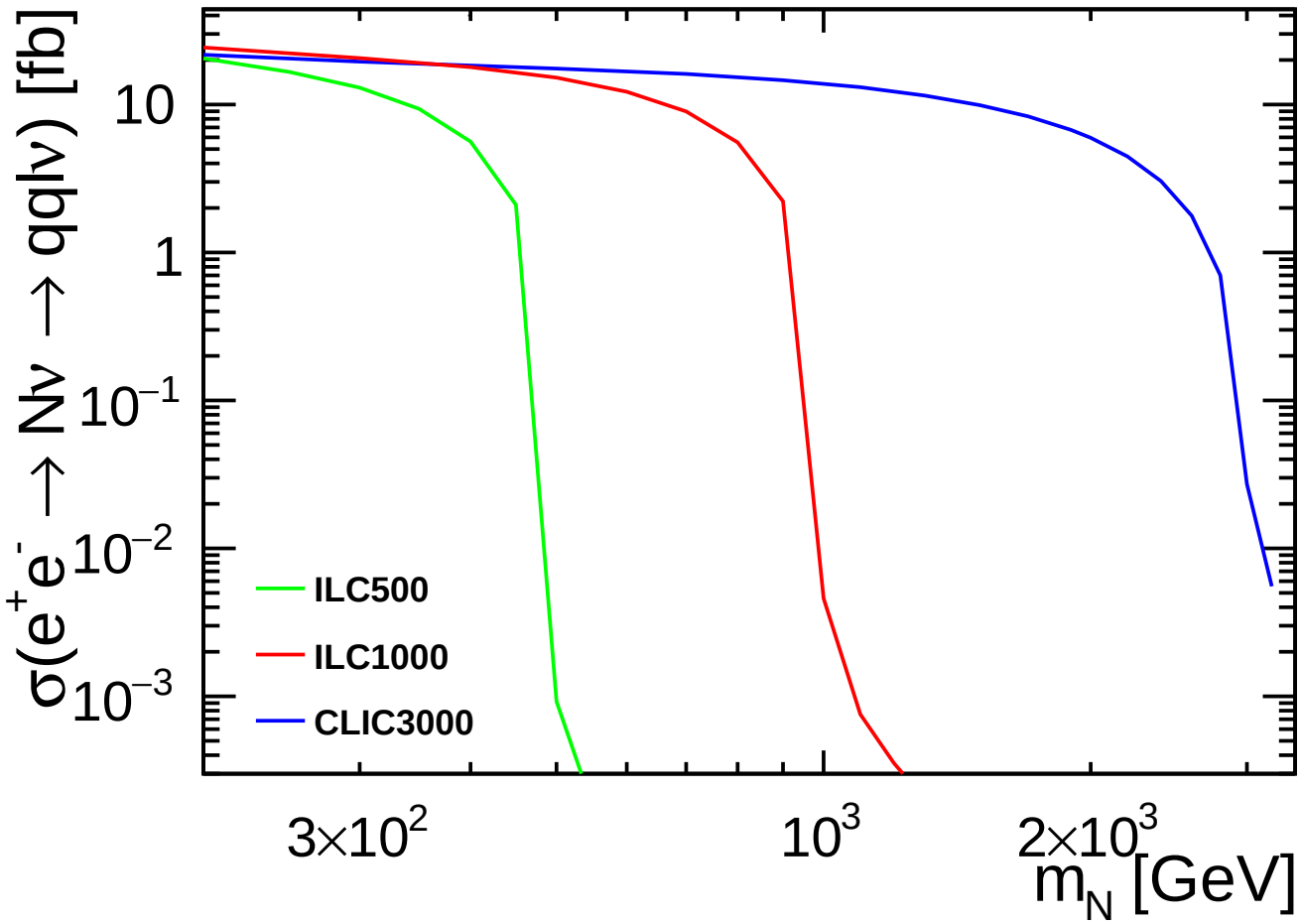
- considered collider scenario:

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

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

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

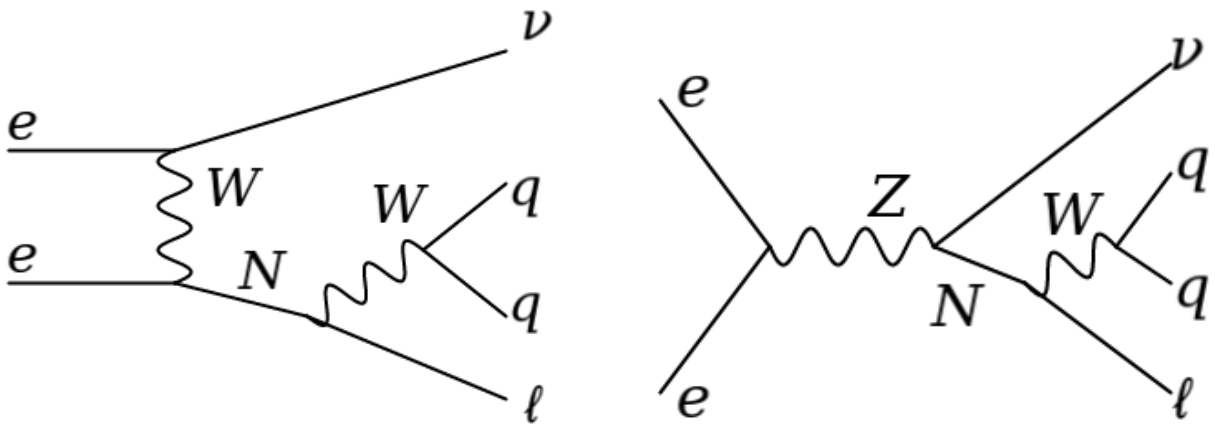
Signal cross section



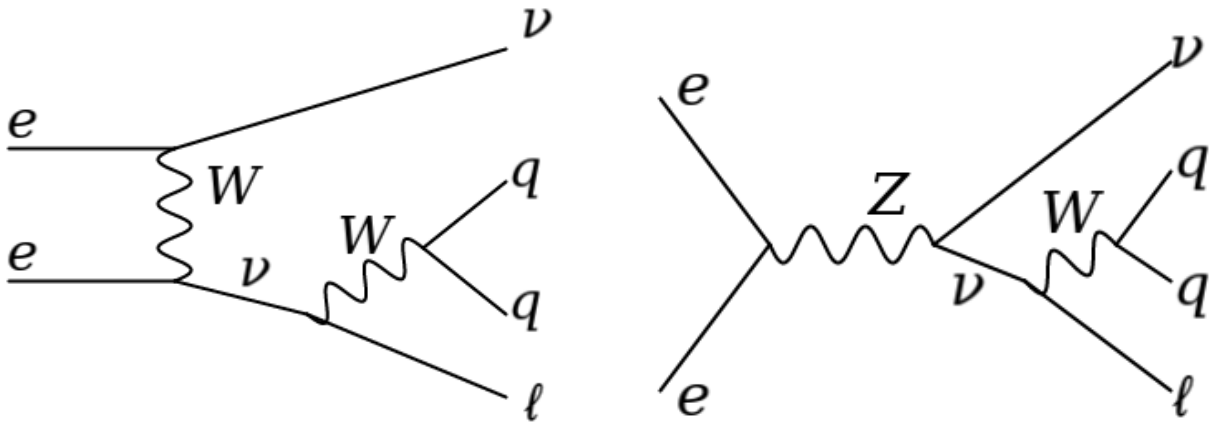
LR polarisation, including beam spectra

Signal vs. background

Signal:



Background:



+ many other more important background channels...

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
5. Using CLs method to get final results

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)
  - ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb

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  - ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb
- Detector simulation:
  - DELPHES 3.4.2
  - simulating ILC detector using *delphes_card_ILCgen.tcl*, CLIC detector – *delphes_card_CLICdet_Stage3_fcal.tcl*

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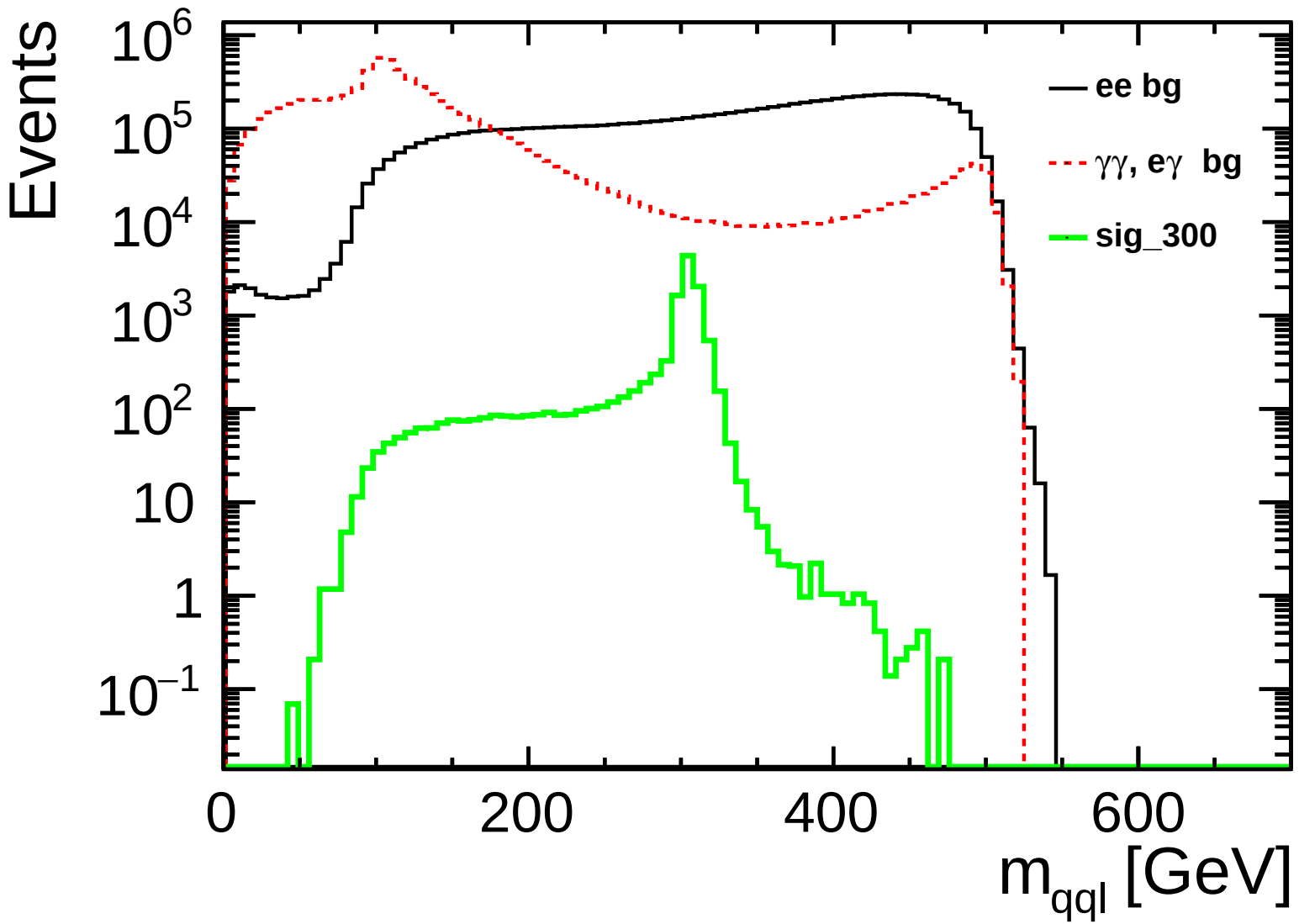
  - simulating ILC detector using *delphes_card_ILCgen.tcl*, CLIC detector – *delphes_card_CLICdet_Stage3_fcal.tcl*
- Preselection:
  - cuts optimised to search for N: exactly 1 lepton and 2 jets in the final state

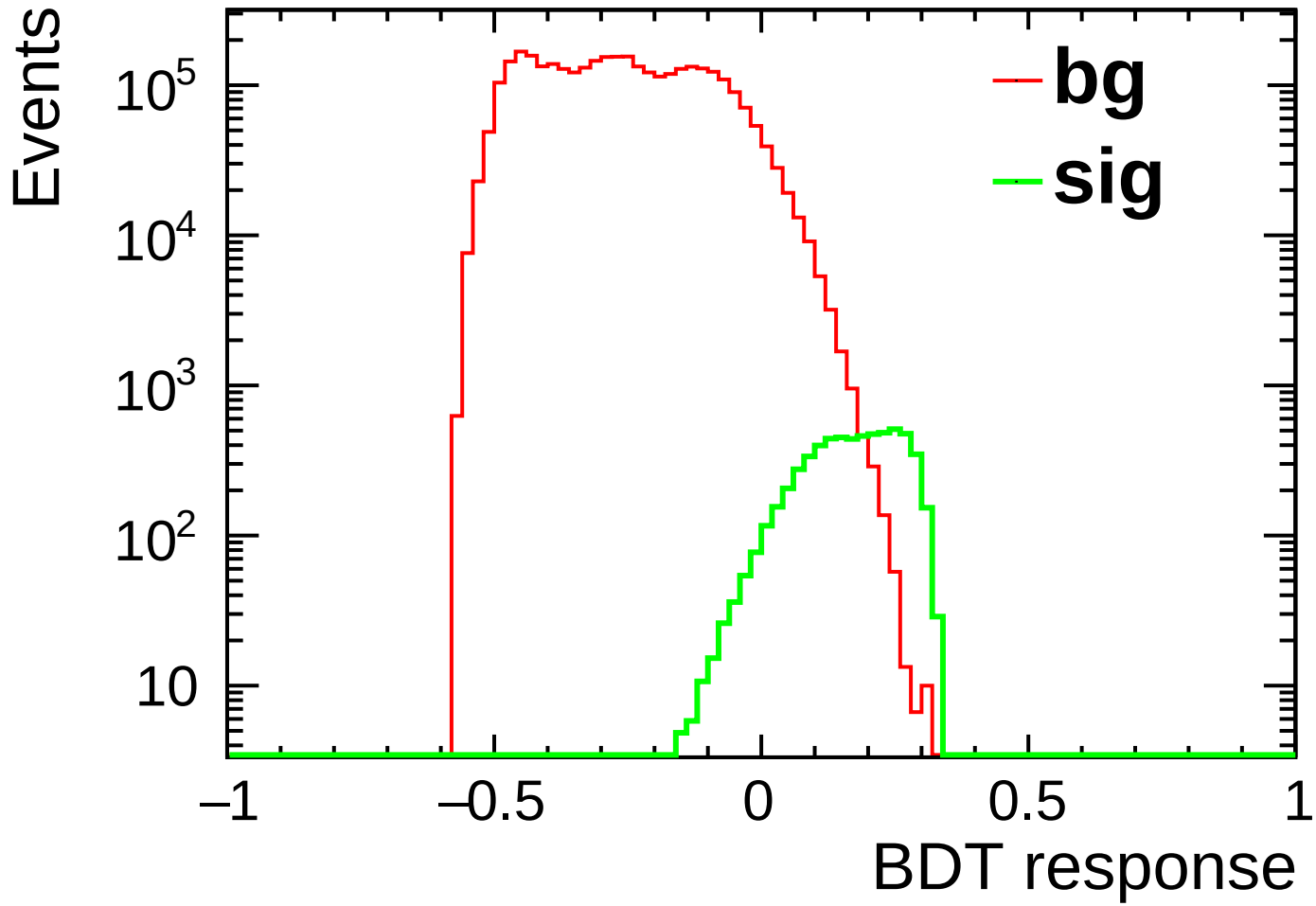
qql invariant mass



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

Boosted Decision Trees

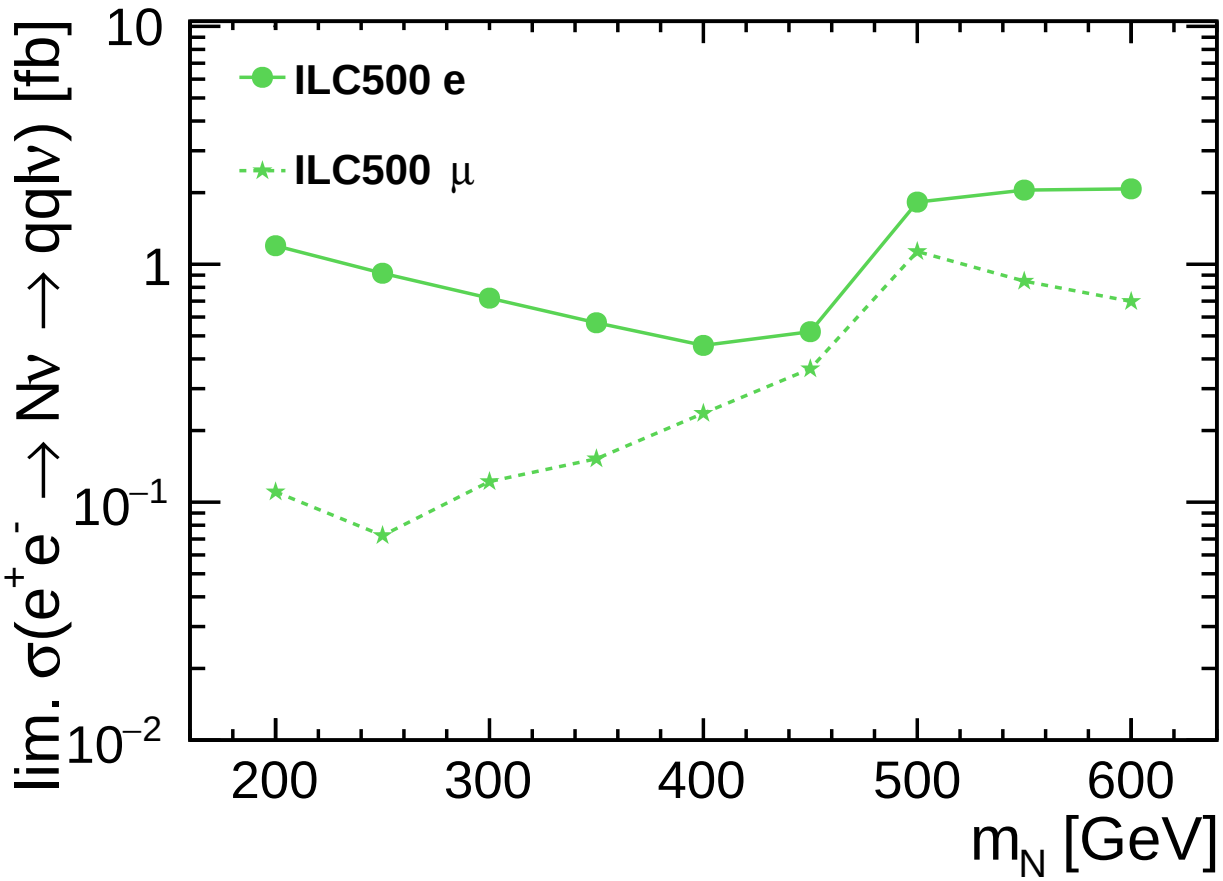
BDT trained with 8 input variables (see backup slides)



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

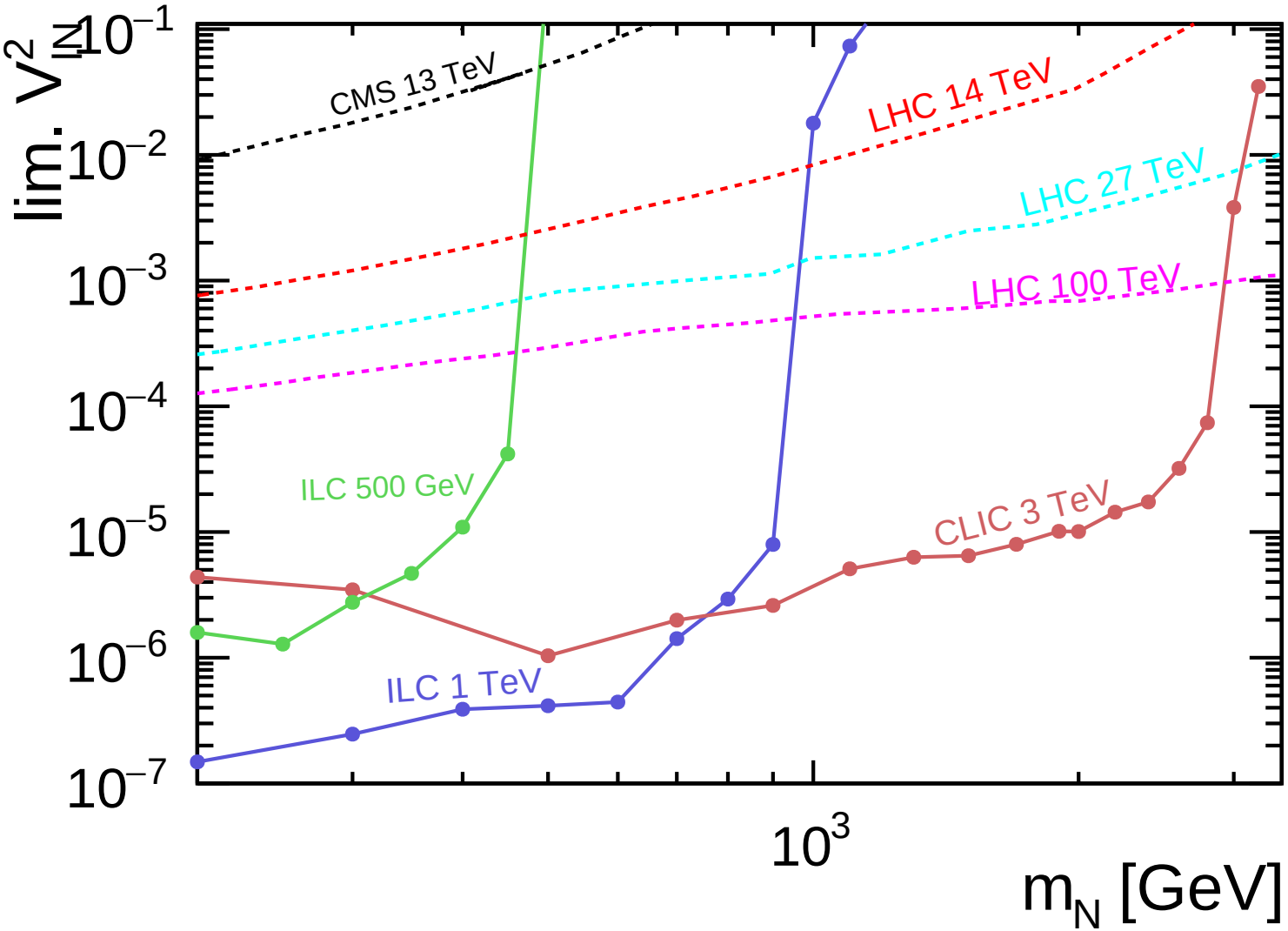
CLs method

BDT response is used to build a model in RooStats to use the CL_s method (combining both channels, systematic uncertainties).
The cross-section limit is calculated by scaling the reference scenario to obtain a significance of 1.64 (95% CL) for the optimal BDT response cut.



Final results

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



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

Conclusions

1. We searched for heavy neutrinos at future e^+e^- linear colliders using events generated with WHIZARD and detector simulation from DELPHES.
2. Heavy neutrino production can be observed almost up to the kinematic limit.
3. The expected coupling limits are much stronger than those at LHC/FCC-hh.
4. Accepted for JHEP (**today!**): [2202.06703]

References

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arXiv:1306.6352, 2013.

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Heavy Neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14$, 27, and 100 TeV.
Journal of High Energy Physics, 2019, Jun. 2019.

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

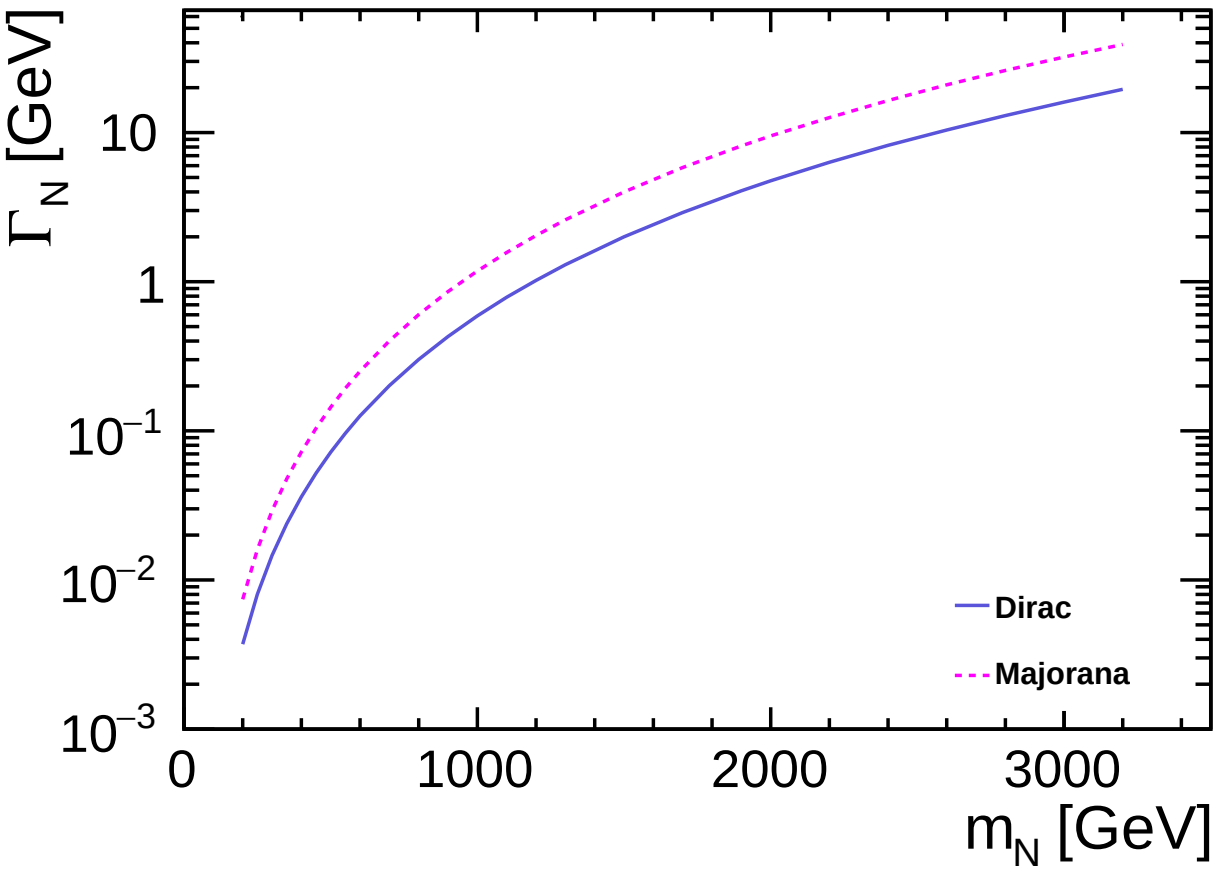
  assuming polarisation of $\pm 80\%$ for electrons and $\pm 20\%$ for positrons

CLIC:

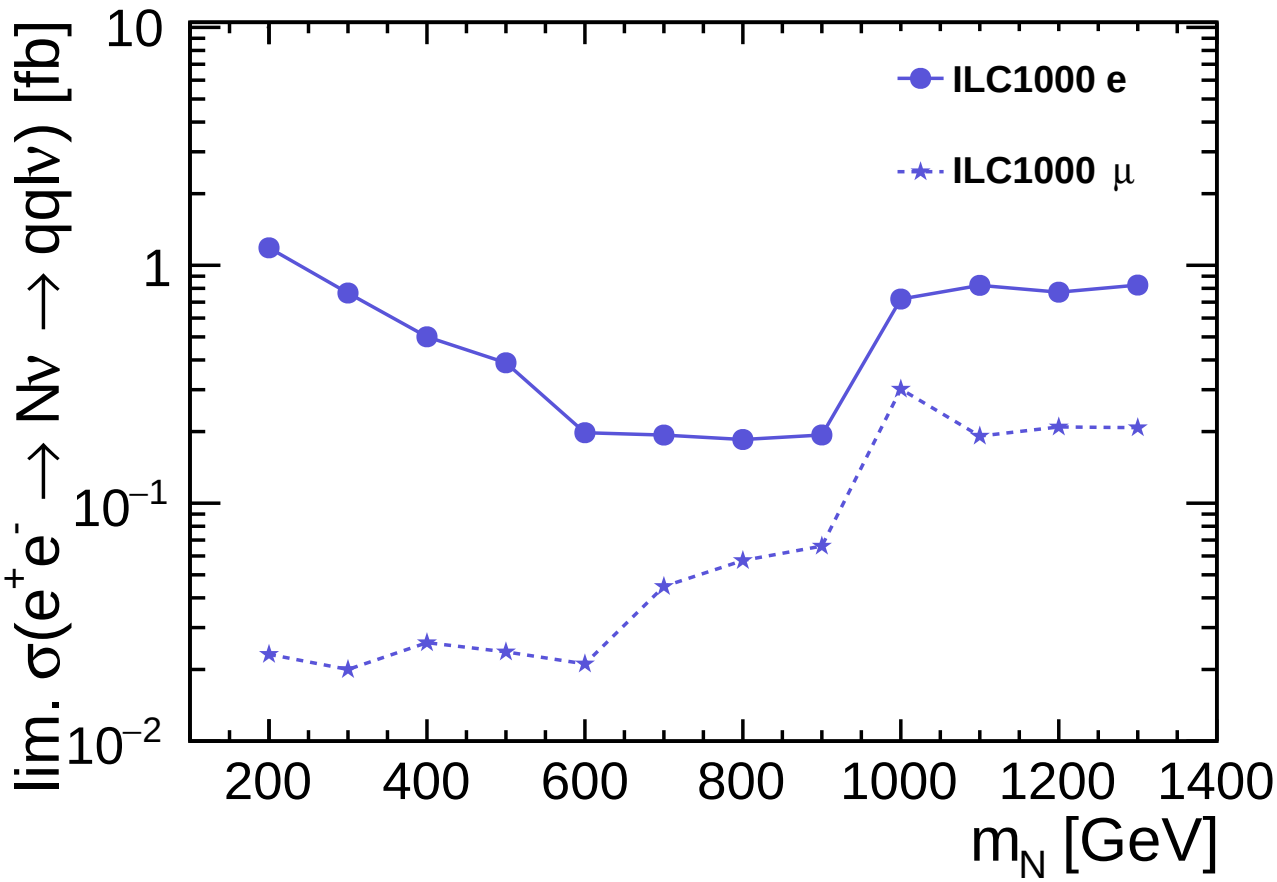
- 3 TeV: total luminosity of 5000 fb^{-1}
  - 4000 fb^{-1} for negative electron beam polarisation
  - 1000 fb^{-1} for positive electron beam polarisation

  assuming polarisation of $\pm 80\%$ for electrons

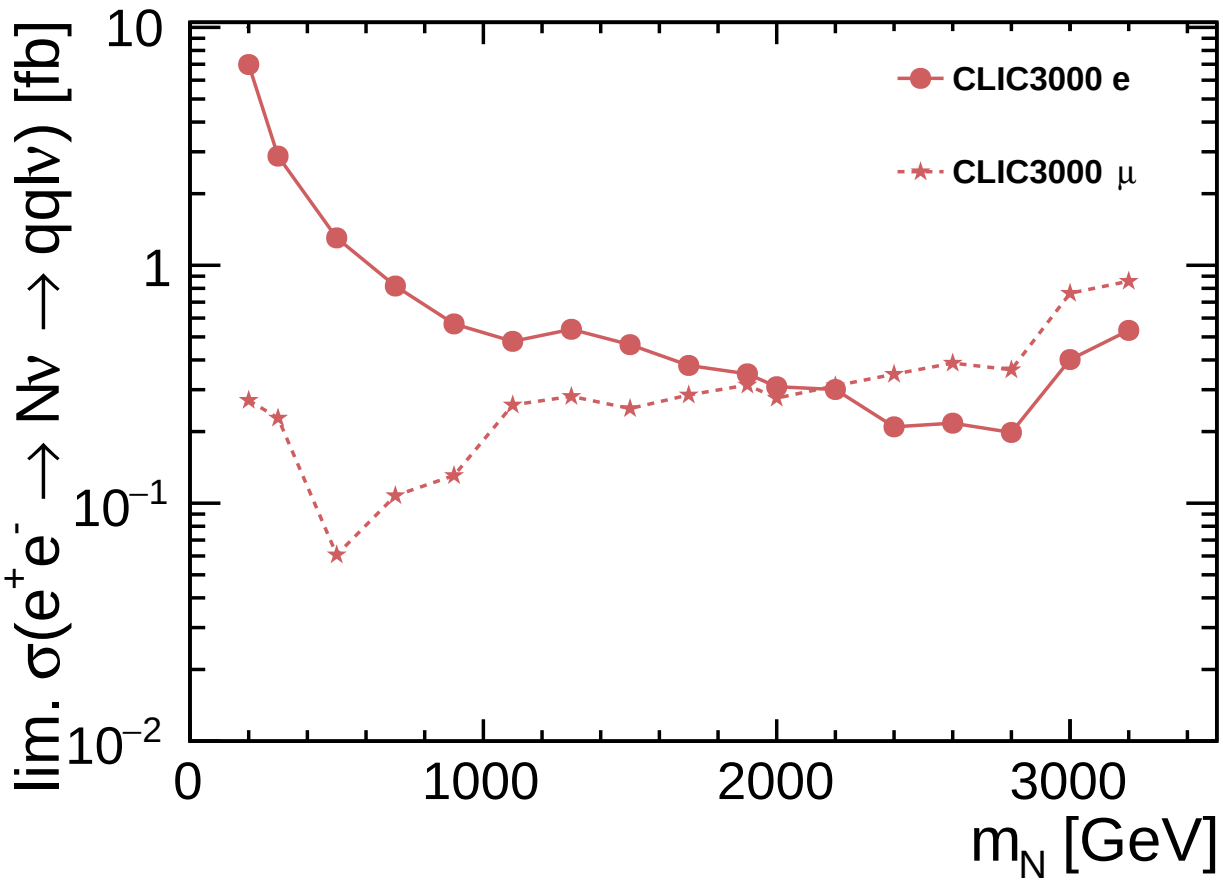
BACKUP: Neutrino width



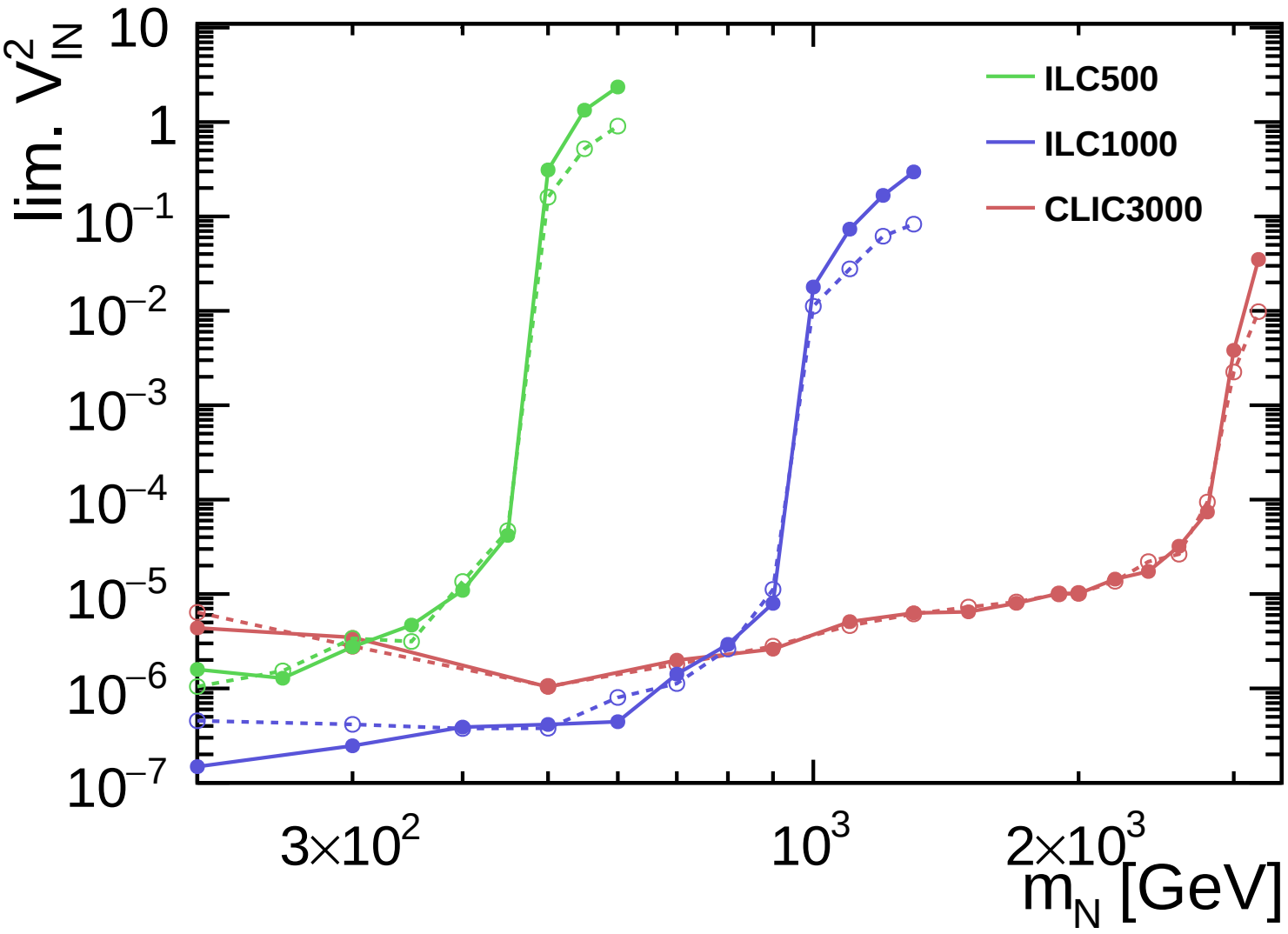
BACKUP: Cross section limits – ILC1000



BACKUP: Cross section limits – CLIC3000



BACKUP: Dirac vs. Majorana



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