Probing the nature of heavy neutrinos

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

Motivation

Some mysteries 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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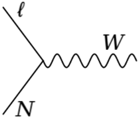
can be addressed by introducing new species of neutrinos.

Heavy Neutral Leptons at lepton colliders

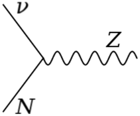
Let us assume that HNL couple only to the SM gauge bosons and Higgs:

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

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



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



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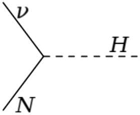

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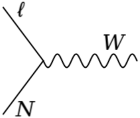

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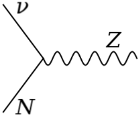

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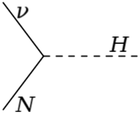
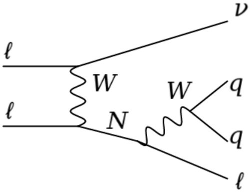
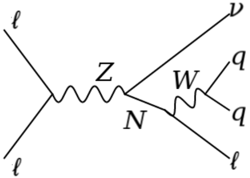


At lepton colliders, single production with subsequent decay into *qql* is particularly interesting, as it allows for direct reconstruction of N.

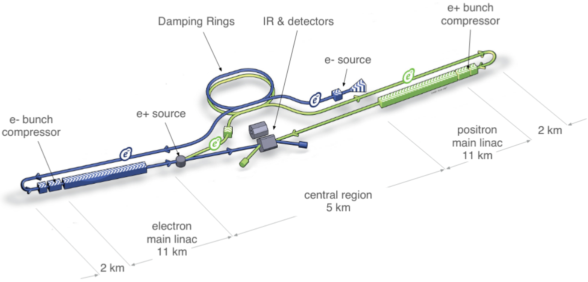




Lepton colliders

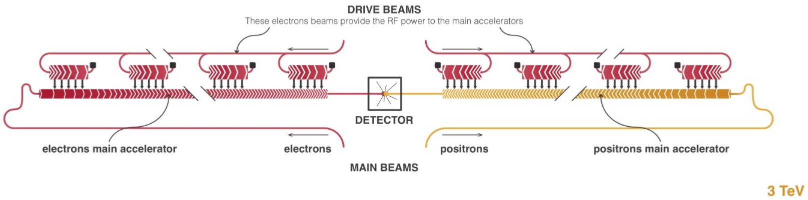
International
MUON Collider
Collaboration

International Linear Collider (ILC)



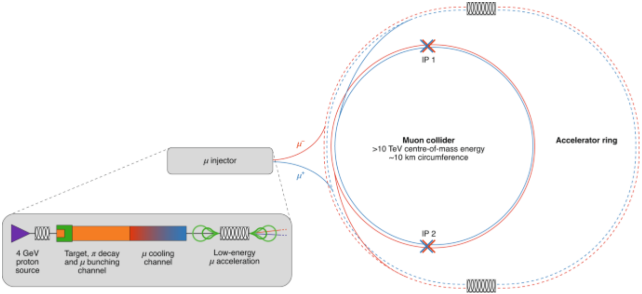
- superconducting accelerating cavities
- length of 31 km
- energy of 250-500 GeV, possible upgrade to 1 TeV
- polarisation for both beams (80%/30%)

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%

Muon Collider



- circular collider
- circumference of $\mathcal{O}(10\text{ km})$
- different energy stages considered: 125 GeV, 3 TeV, 10 TeV, 14 TeV...

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")
    - $\ell^+\ell^- \rightarrow N\nu \rightarrow qq\ell\nu$ ("signal")
    - ILC at 250GeV, 500GeV and 1TeV; CLIC at 3 TeV; MuC at 3 and 10 TeV
    - S/B $\sim 10^{-3}$, e.g. ILC500: $qql\nu$ background $\sim$ 10 pb, signal $\sim$ 10 fb

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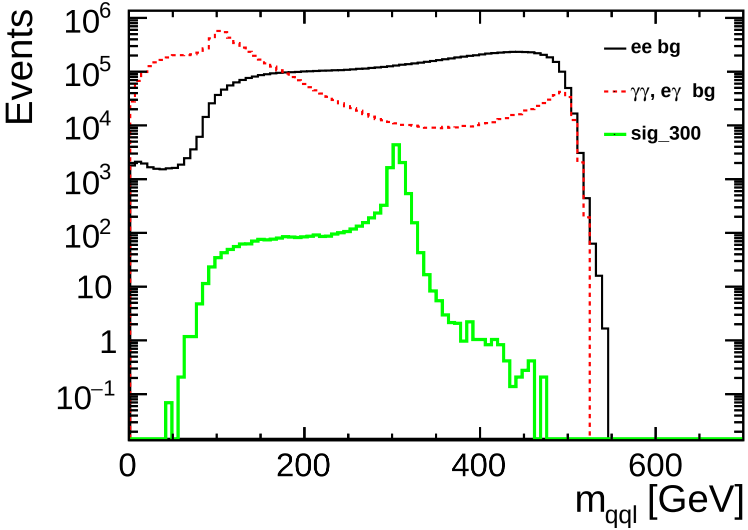
4. BDT training
5. CLs method to get final results

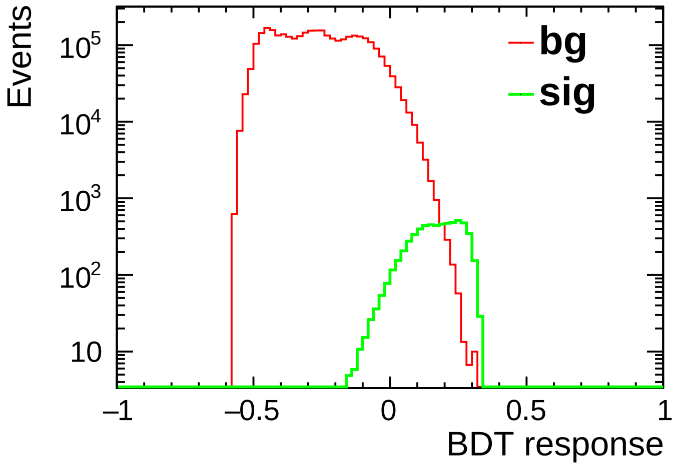
qql invariant mass



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

Boosted Decision Trees

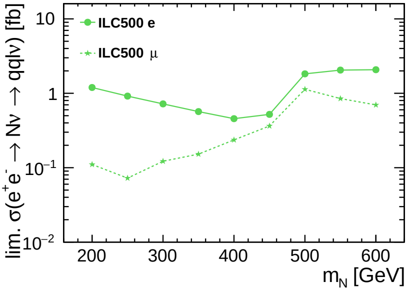
BDT trained with 8 input variables

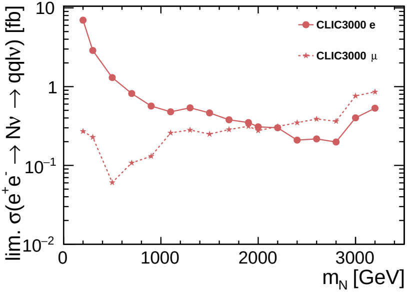


ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV, μ in the final state

CLs method

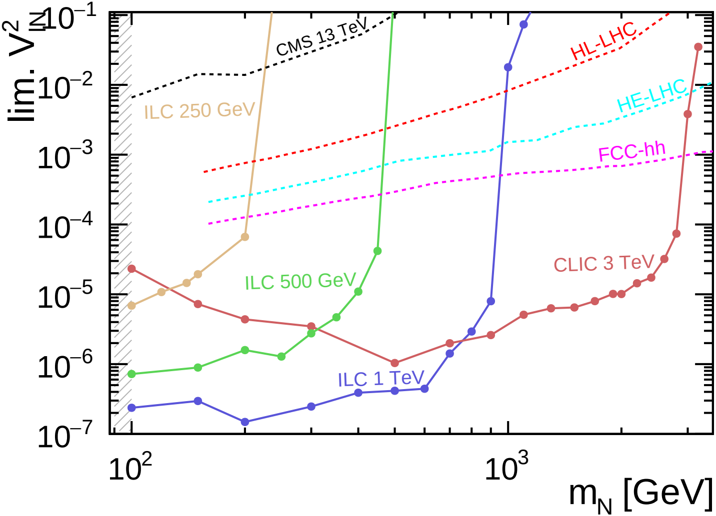
BDT response is used to build a model in RooStats to use the CL_s method (combining both channels, e^+e^-: normalisation uncertainties).





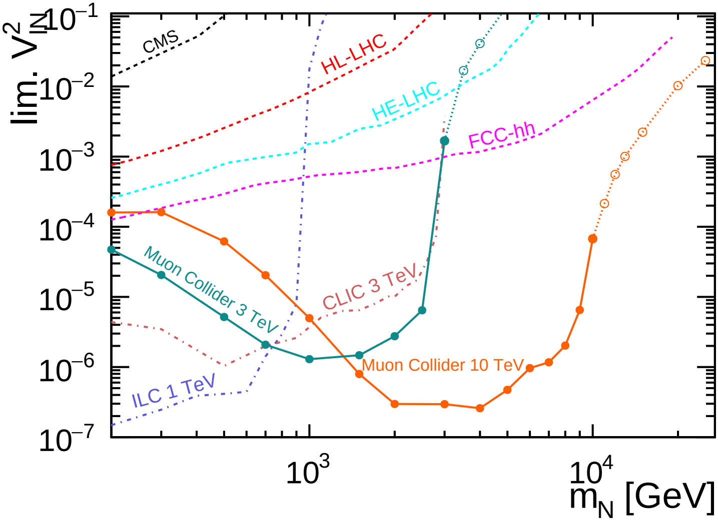
Results for e^+e^- colliders

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



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

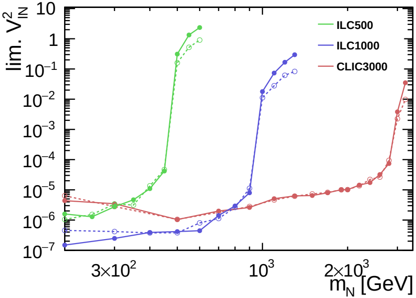
Results for the Muon Collider

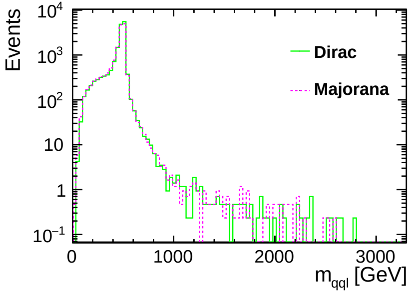


LHC analysis: [1812.08750], diff. assumption: $V_{eN} = V_{\mu N} \neq V_{\tau N} = 0$

Dirac vs. Majorana

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





CLIC 3 TeV

Are there any discriminant variables?

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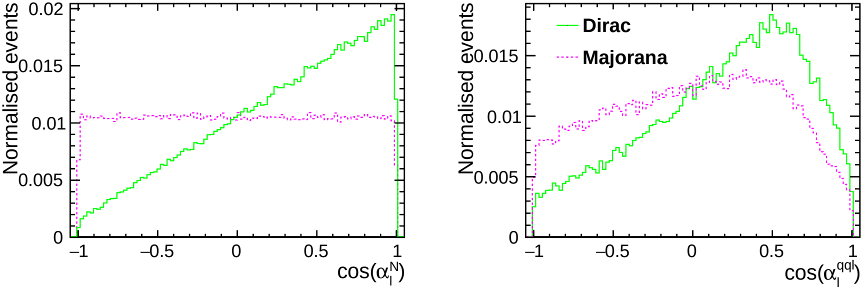
Lepton emission angle in the N rest frame:



generator vs. detector

CLIC 3 TeV

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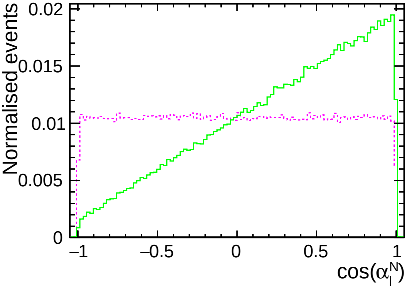
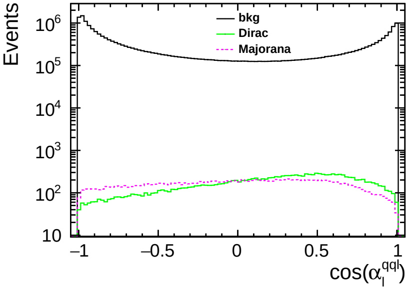


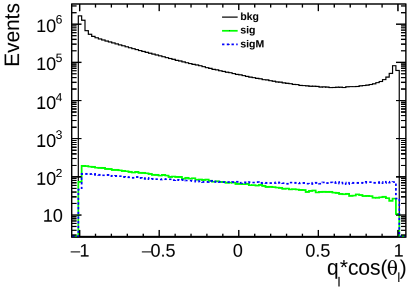


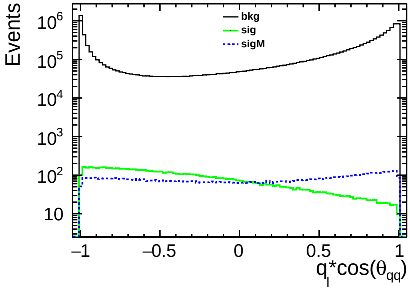
generator vs. detector

CLIC 3 TeV

More sophisticated variables...

Lepton and dijet 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:
   - Dirac vs. ($\alpha_{BDT} \cdot$ Majorana + Background)
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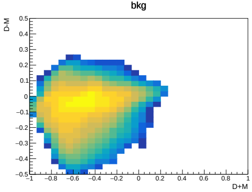

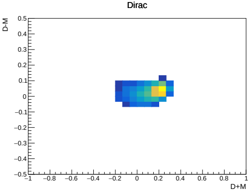

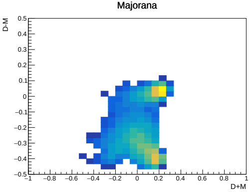

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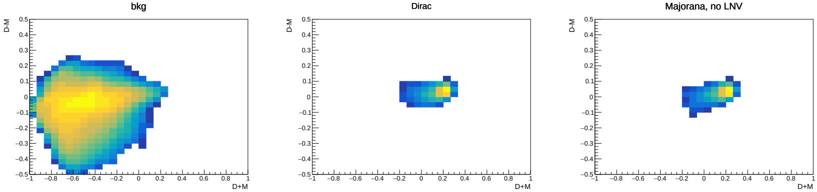

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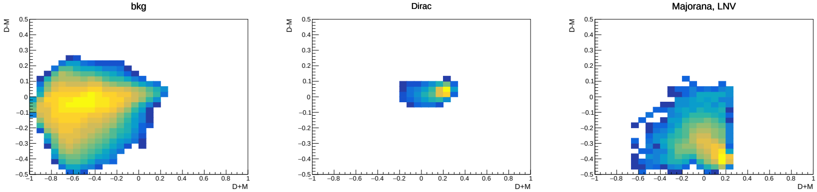

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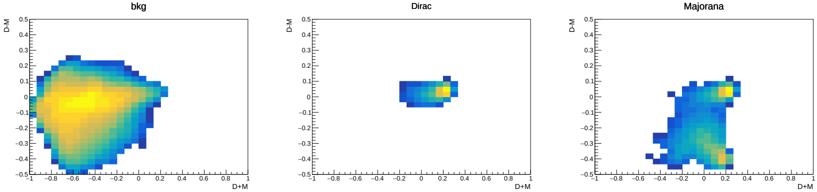

3. χ^2-like statistic:

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

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

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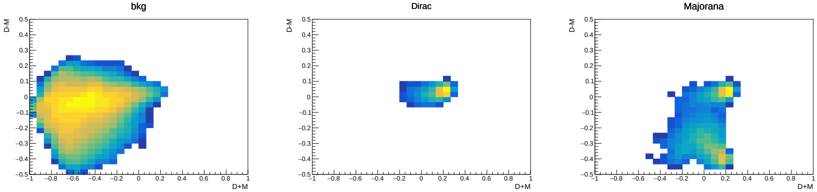

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$$T = T' + \mathrm{DOF} \quad (2)$$

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:

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

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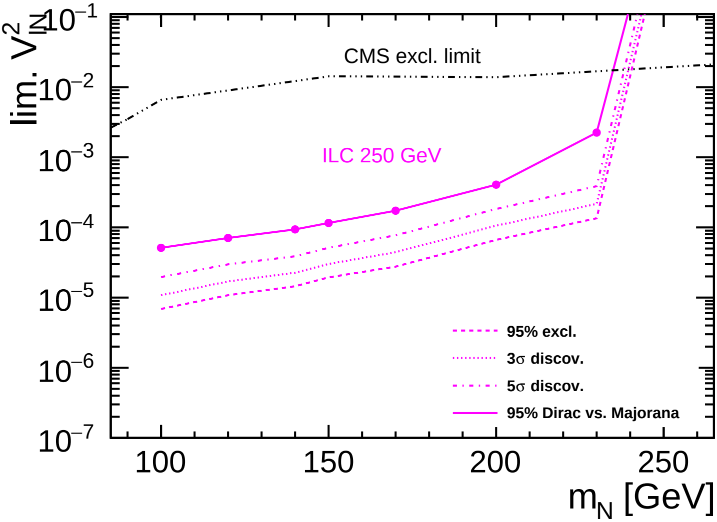
Technical realisation: signal scaling factor used in the BDT training α_{BDT} is varied to obtain the best limit for each m_N.

1. Train BDT for different values of α_{BDT}
2. For each α_{BDT}, calculate 95% CL limit α_{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



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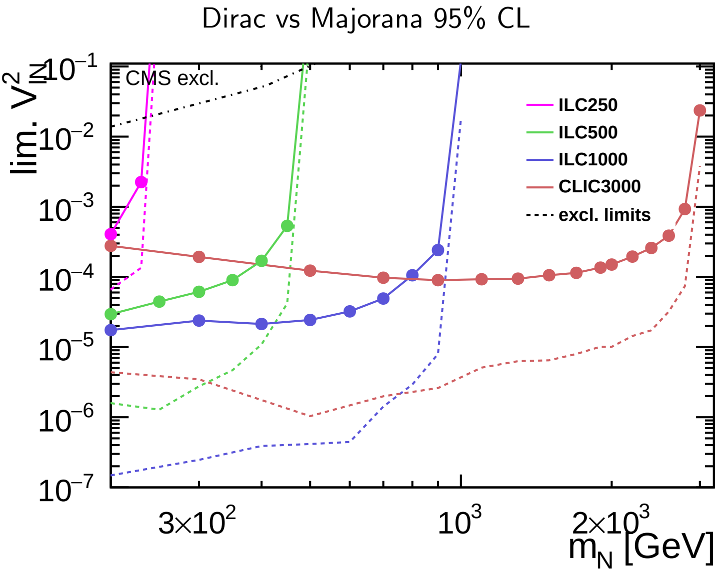


Conclusions

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; planning to finalise for LCWS'23

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:

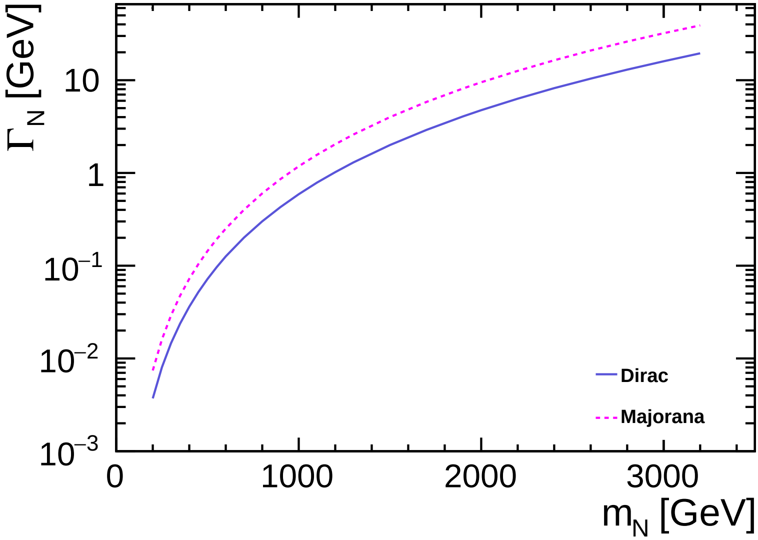
- 3 TeV: total luminosity of 5000 fb^{-1}
  - 4000 fb^{-1} for negative electron beam polarisation
  - 1000 fb^{-1} for positive electron beam polarisation

  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: 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