

Probing the nature of heavy neutrinos

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based on:

[2202.06703]

[2301.02602]

and further development

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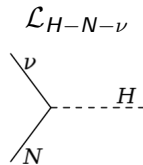
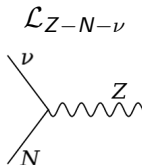
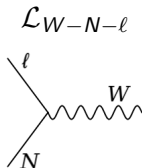
- dark matter density
- baryon asymmetry
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can be addressed by introducing new species of neutrinos.

Heavy Neutral Leptons at lepton colliders

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

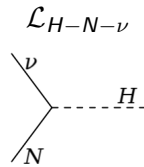
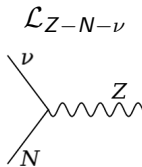
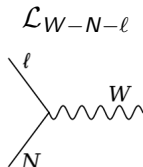
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{W-N-\ell} + \mathcal{L}_{Z-N-\nu} + \mathcal{L}_{H-N-\nu}$$



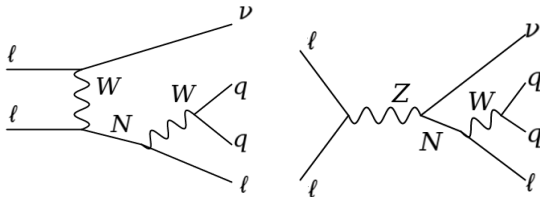
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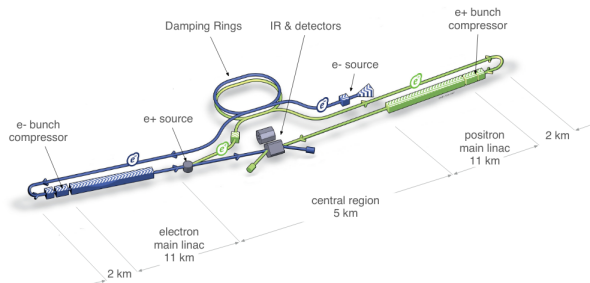
At lepton colliders, single production with subsequent decay into $qq\ell$ is particularly interesting, as it allows for direct reconstruction of N .



Lepton colliders

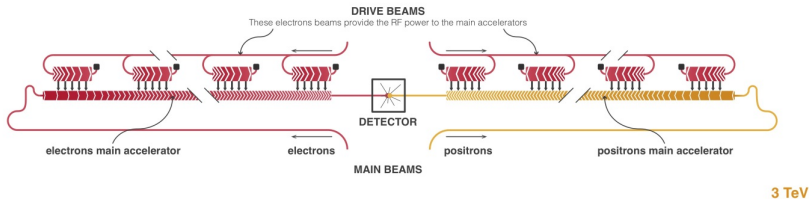


International Linear Collider (ILC)



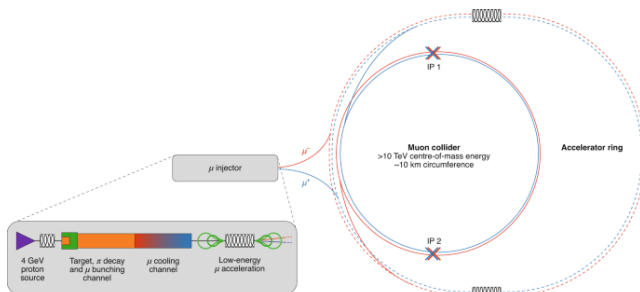
- superconducting accelerating cavities
- length of 31 km
- energy of 250-500 GeV, possible upgrade to 1 TeV
- polarisation for both beams (80%/30%)

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...

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

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

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

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

- 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

- 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: qq/ν background ~ 10 pb, signal ~ 10 fb

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 - cuts opt. to search for N : exactly 1 lepton and 2 jets in the final state

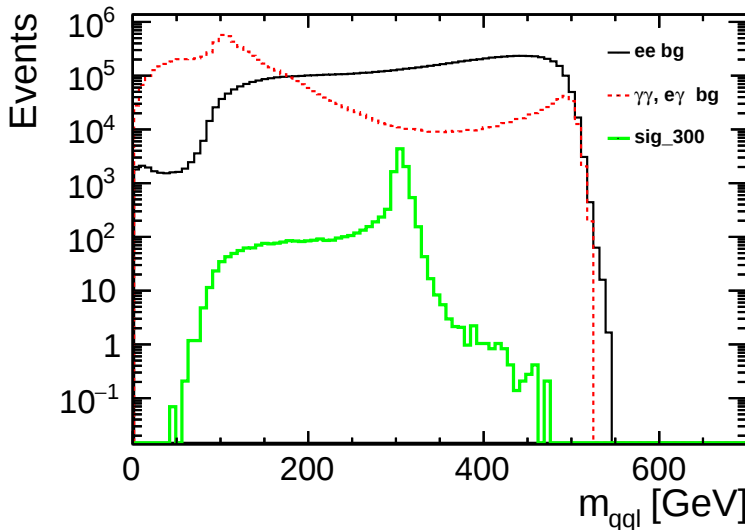
Analysis procedure

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

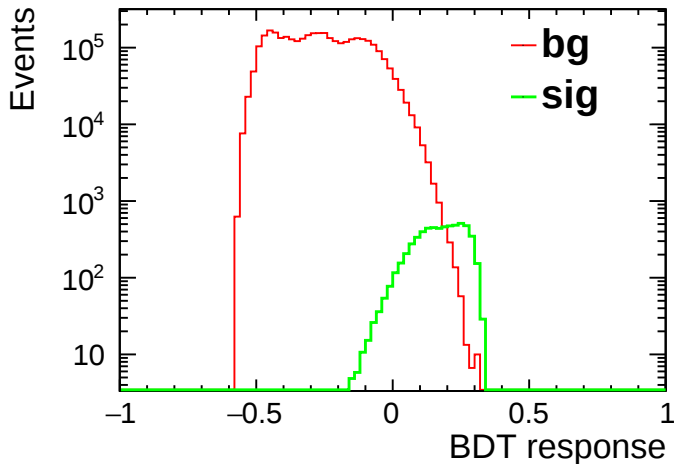
$qq\ell$ invariant mass



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

Boosted Decision Trees

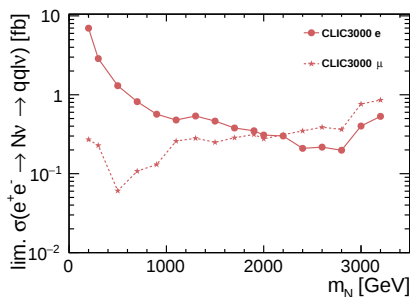
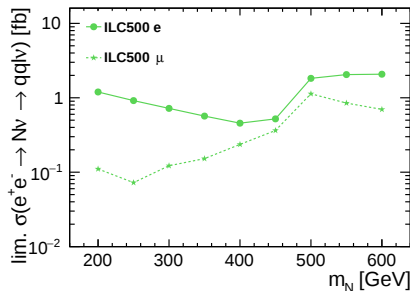
BDT trained with 8 input variables



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

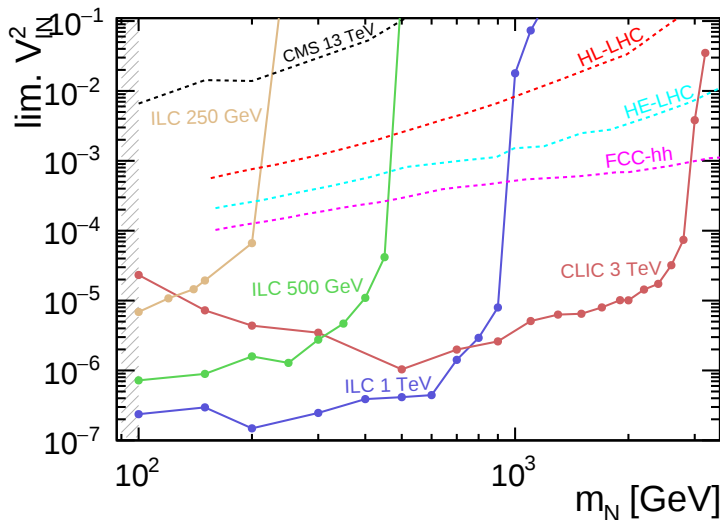
CLs method

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



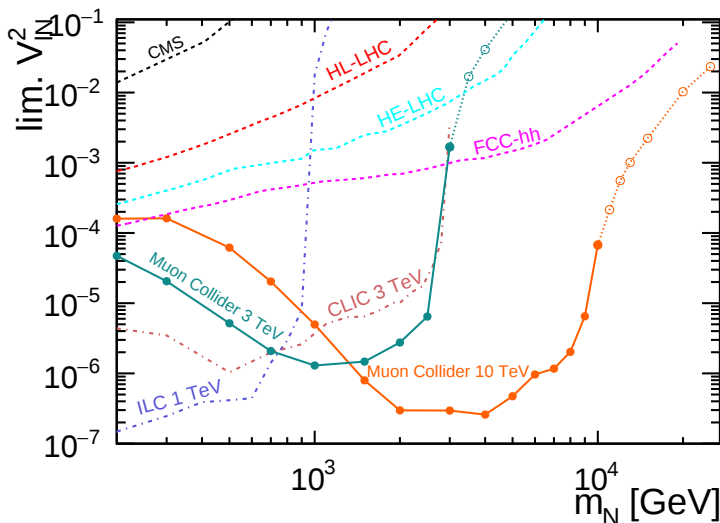
Results for e^+e^- colliders

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



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

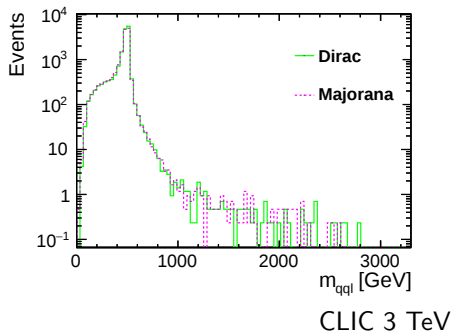
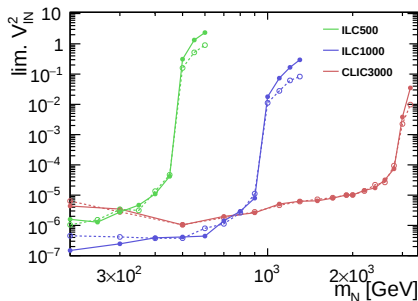
Results for the Muon Collider



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Dirac vs. Majorana

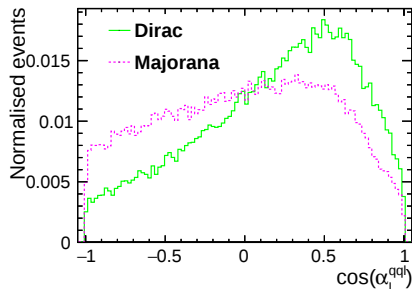
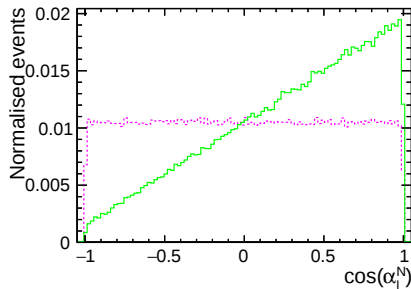
Exclusion limits are very similar for the Dirac and Majorana neutrino hypothesis, except for off-shell production.



Are there any discriminant variables?

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Lepton emission angle in the N rest frame:

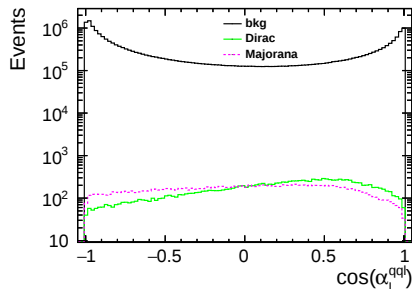
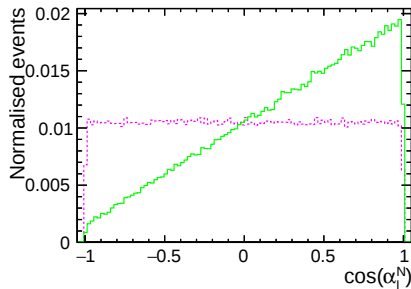


generator vs. detector

CLIC 3 TeV

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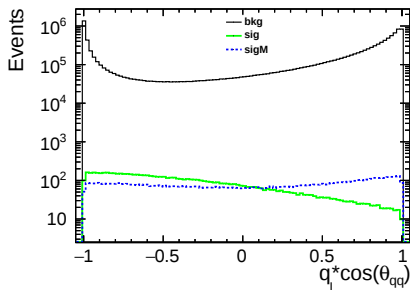
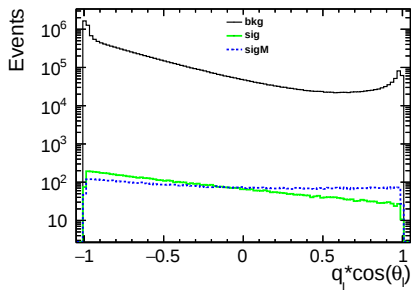


generator vs. detector

CLIC 3 TeV

More sophisticated variables...

Lepton and dijet directions relative to the electron (positron) beam for positive (negative) lepton charge q_l :



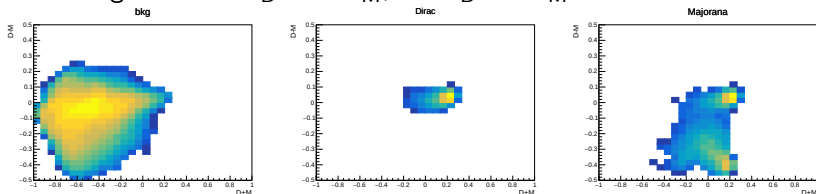
ILC 250 GeV, $m_N = 150$ GeV

How to distinguish the two species of neutrinos?

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

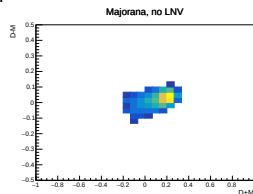
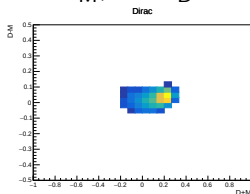
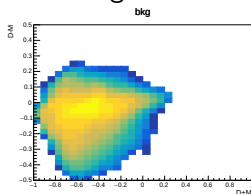
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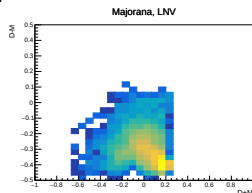
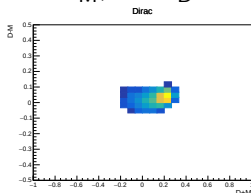
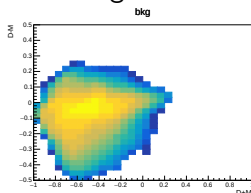
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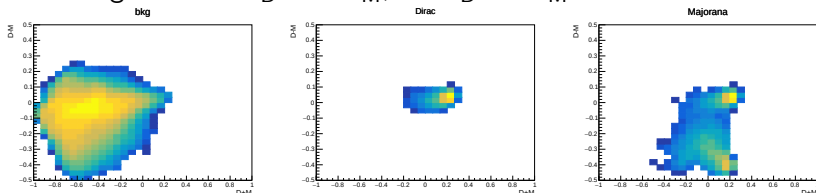
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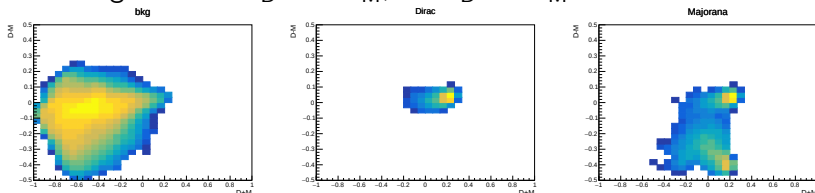
- 3 χ^2 -like statistic:

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

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

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- 4 Statistical test:

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

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 α_{lim} , for which:

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

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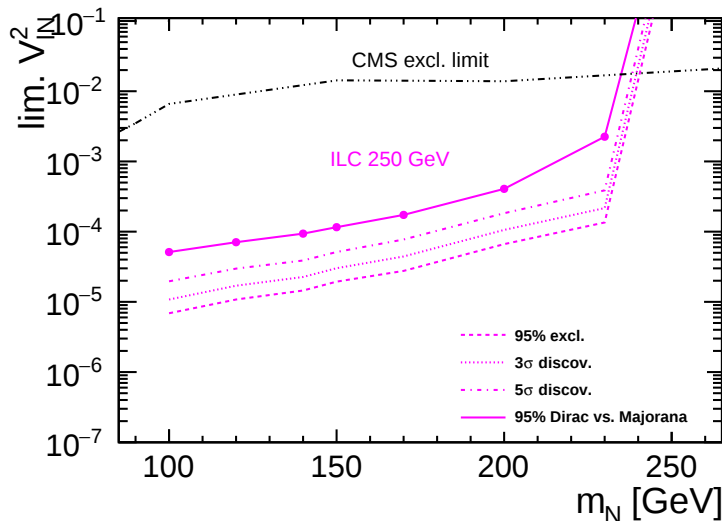
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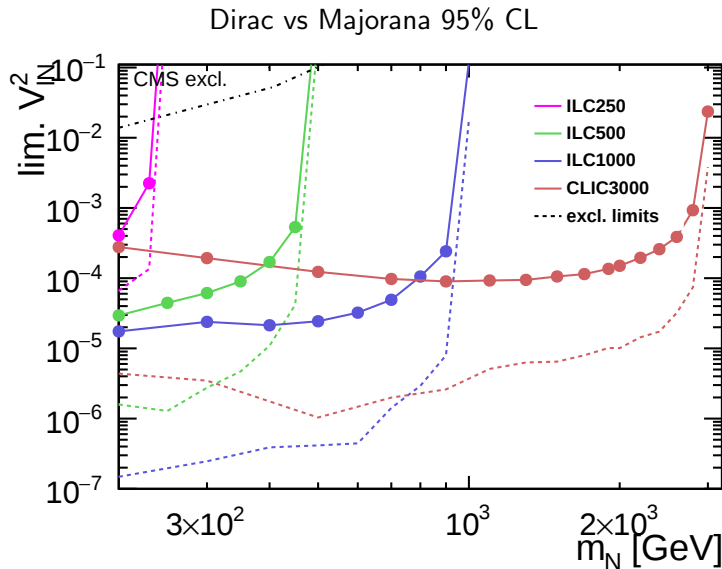
Technical realisation: signal scaling factor used in the BDT training α_{BDT} is varied to obtain the best limit for each m_N .

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

Dirac vs. Majorana – preliminary results for ILC250



Dirac vs. Majorana – preliminary results



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

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

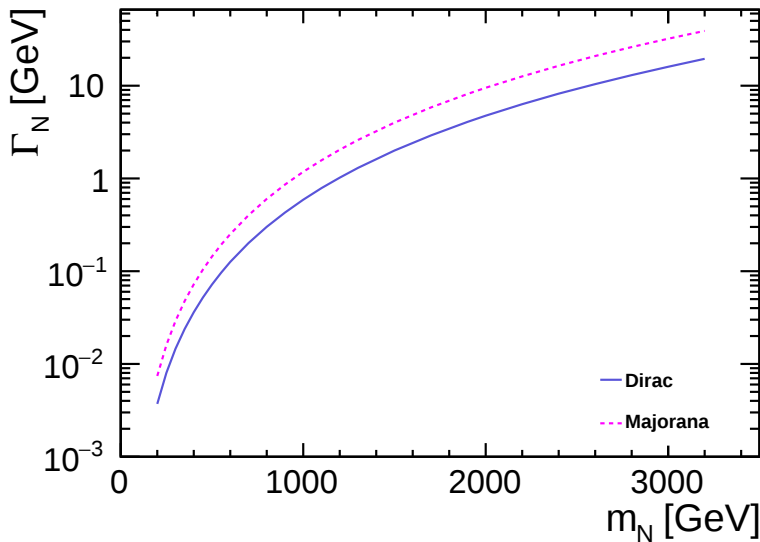
CLIC:

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

Muon Collider:

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

BACKUP: Neutrino width



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