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

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## Motivation

- The Standard Model (SM) is successful in describing most of experimental results but it cannot explain such problems as the baryon asymmetry or the existence of dark matter.
- They could be potentially solved by introducing to the SM **heavy neutrinos** which would be produced at **future linear $e^+e^-$ colliders**.

## Future linear $e^+e^-$ colliders

- An **electron-positron Higgs factory** is foreseen as the highest-priority next large-scale collider facility.
- Two **linear** colliders are being considered: the **CLIC** and the **ILC**.
- In the presented analysis, 3 different collider options are studied:

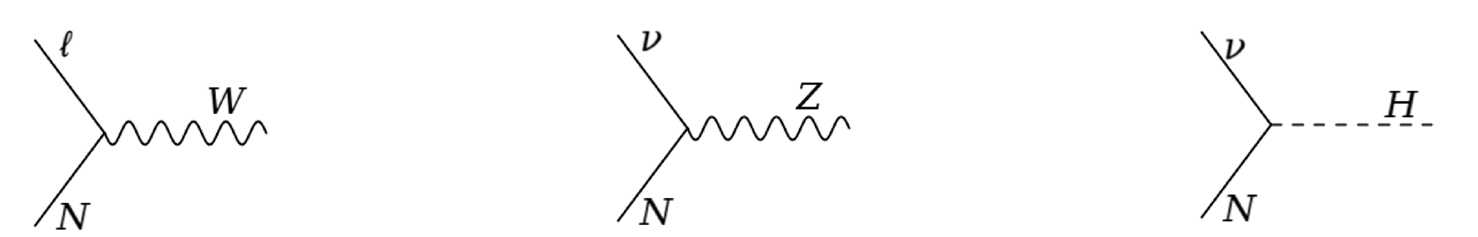
| scenario | collision energy [GeV] | int. luminosity [ab$^{-1}$] | $e^-/e^+$ beam pol. |
|---|---|---|---|
| ILC500 | 500 | 1.6 | -80% / +30% |
| ILC1000 | 1000 | 3.2 | -80% / +20% |
| CLIC3000 | 3000 | 4.0 | -80% / unpol. |

## Heavy neutrinos

- A **right-handed heavy neutrino**, which is a singlet under the SM gauge symmetry, can be introduced by adding new terms to the SM Lagrangian:

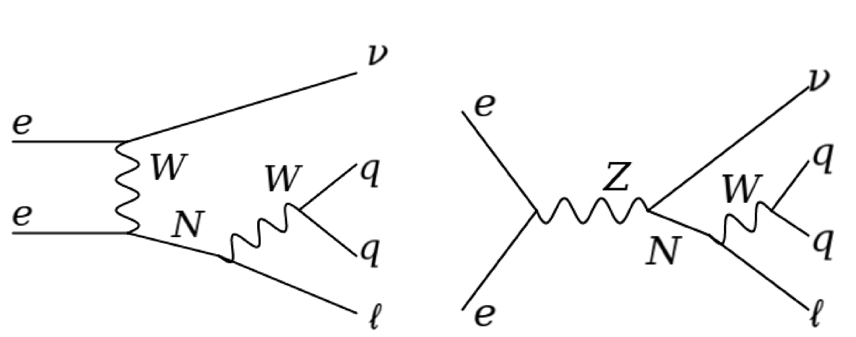
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WNl} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu},$$

where $\mathcal{L}_N$ – heavy neutrino propagator and the others introduce new vertices:




$-\frac{g}{\sqrt{2}} W^+_\mu \bar{N}_k V^*_{lk} \gamma^\mu P_L l^-$ $\qquad -\frac{g}{2\cos\theta_W} Z_\mu \bar{N}_k V^*_{lk} \gamma^\mu P_L \nu_l$ $\qquad -\frac{g m_N}{2 M_W} h \bar{N}_k V^*_{lk} P_L \nu_l$

- Such neutrinos could be observed at linear colliders in a **light-heavy neutrino pair production** process with a subsequent heavy neutrino decay into a lepton and two quarks:




## Event generation and detector simulation

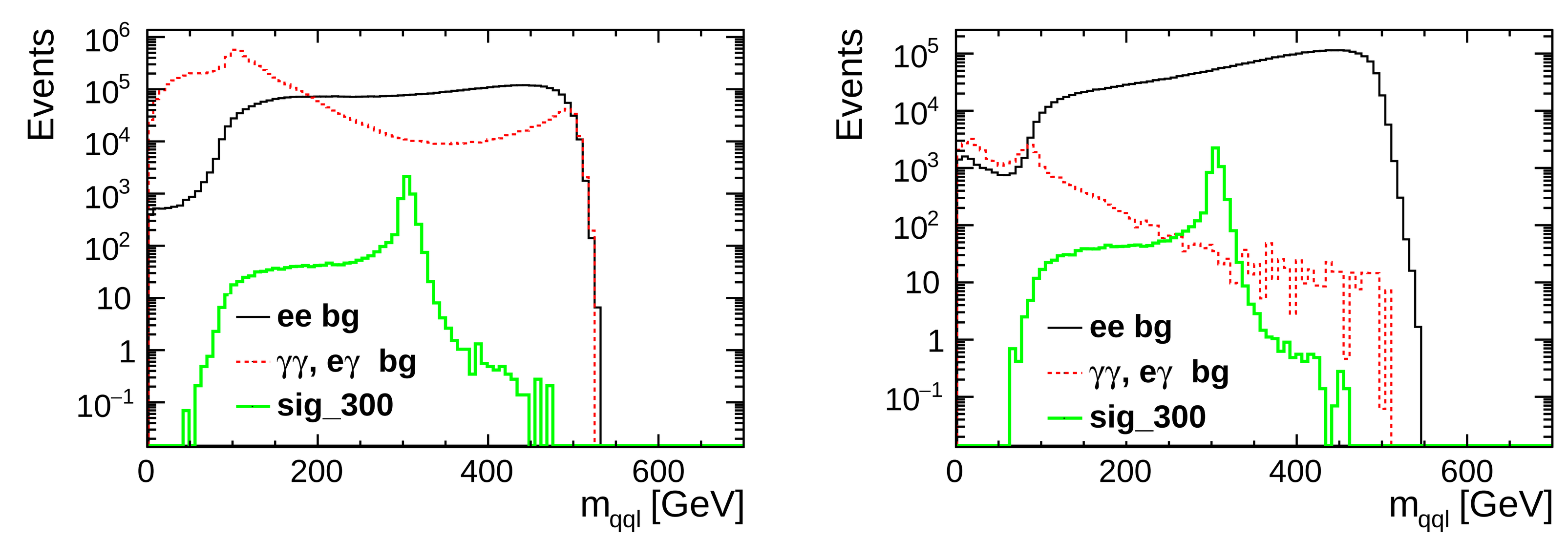
- Events were generated with Whizard 2.8.5 (v. 3.0.0 for the Majorana) [1].
- Both **ISR** and **beam energy spectra** were taken into account.
- The `HeavyN` model [2] with one heavy neutrino coupled to the SM was used in the study.
- Both **Dirac** and **Majorana** neutrinos with masses in the range **200-3200 GeV** were considered and all the couplings were set to the same value:

$$|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}|^2 \equiv V^2_{lN}.$$

- We also took **beamstrahlung** (BS) and **Equivalent Photon Approximation** (EPA) photon interactions into account.
- The following processes were studied:
  - ⋆ $e^+e^- \to qql\nu,\ qqll,\ llll,\ qql\nu l\nu,\ qqql\nu,\ qqqqll,$
  - ⋆ $e^\pm\gamma \to qql,$
  - ⋆ $\gamma\gamma \to qql\nu,\ qqll$ ($\gamma$ from BS or EPA).
- To test many different points in the parameter space, Delphes [3] with built-in cards for ILC and CLIC detectors was employed.

## Data analysis

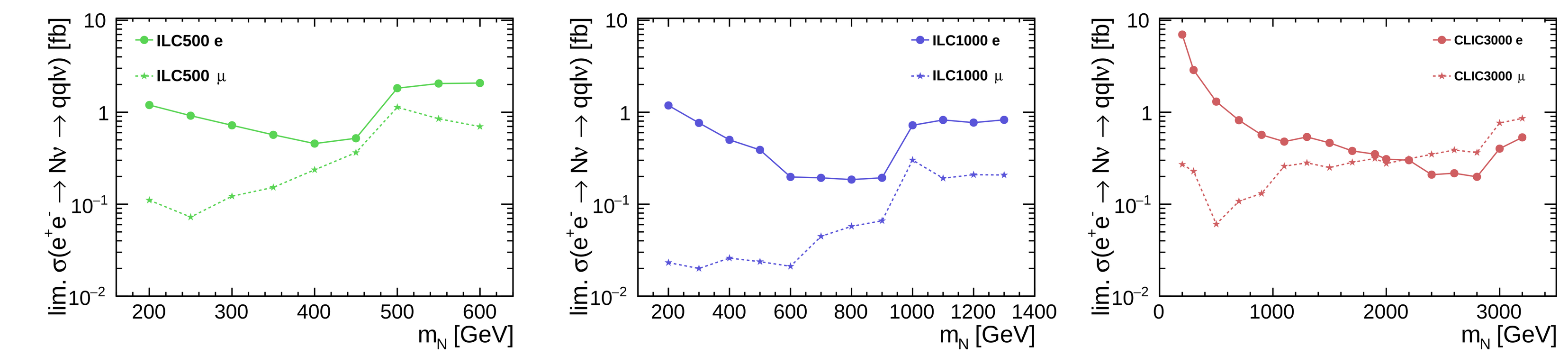
- Only events consisting of **two jets and one lepton** (electron or muon) were accepted for the analysis.
- In the figure below, the $qql$ invariant mass distributions are shown for ILC500 for an electron (left) and a muon (right) in the final state.




- The **Boosted Decision Trees** (BDT) method with 8 input variables describing lepton and dijet kinematics was used.
- To get final results, the **CLs method** basing on the BDT response was employed with:
  - ⋆ electron and muon channels combined,
  - ⋆ normalisation uncertainty applied.

## Cross section limits

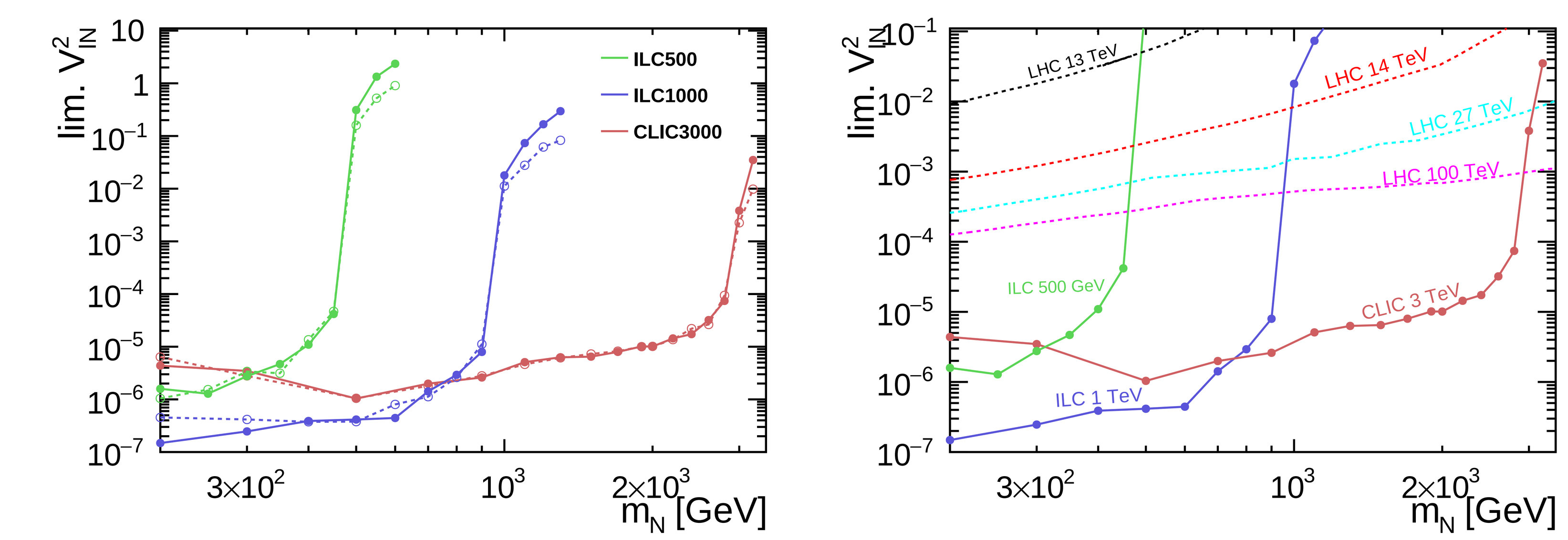
- By scaling results for the reference scenario, one can extract exclusion limits on the cross section for the considered process:




- In the most cases, results for the **muon channel** are more stringent than those for electrons.

## Coupling limits

- The above limits can be translated into limits on the $V^2_{lN}$ coupling parameter.
- *Left*: limits for **Dirac** (solid lines) and **Majorana** (dashed lines) neutrinos are very similar up to the energy thresholds; above the threshold, the splitting due to width-related effects is visible.
- *Right*: the results are compared with the **current limits** from the CMS (black line) and possible successors of the LHC (red, cyan, magenta lines) [4].




- Sensitivity of future $e^+e^-$ machines to heavy neutrino production is **orders of magnitude higher** than that of the hadron machines.

## References

[1] W. Kilian, T. Ohl, and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," *Eur. Phys. J.*, vol. C71, p. 1742, 2011.

[2] `https://feynrules.irmp.ucl.ac.be/wiki/HeavyN`.

[3] J. de Favereau *et al.*, "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," *JHEP*, vol. 02, p. 057, 2014.

[4] S. Pascoli, R. Ruiz, and C. Weiland, "Heavy neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14$ , 27, and 100 TeV," *JHEP*, vol. 06, p. 049, 2019.