Searching for heavy neutral leptons through exotic Higgs decays

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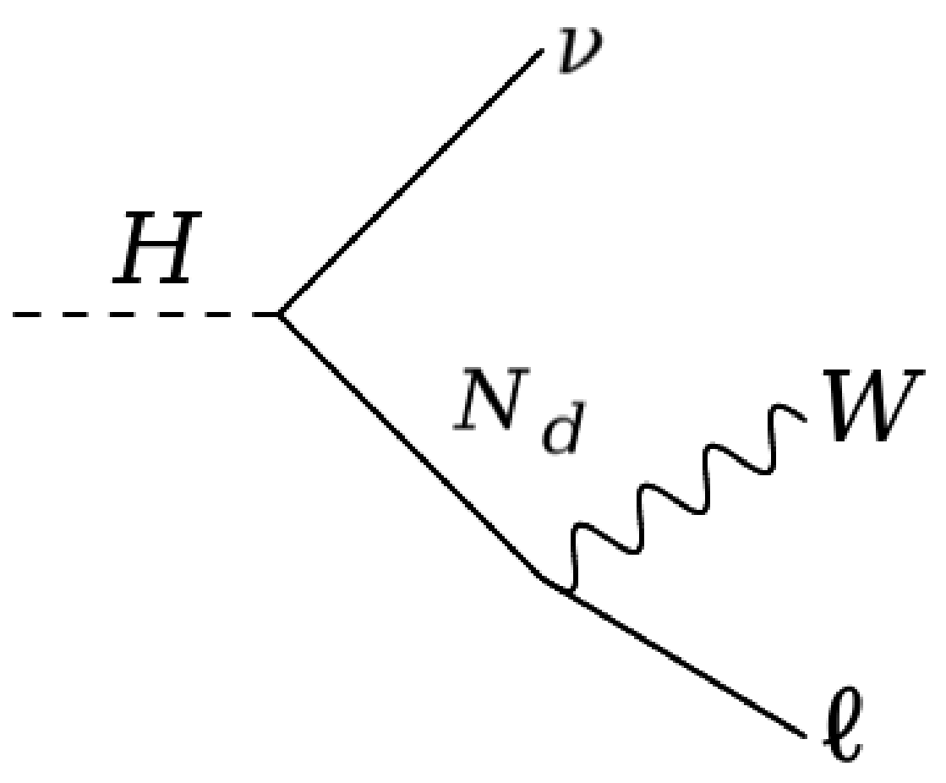
Abstract

In this study we investigate the feasibility of detecting heavy neutral leptons (N_d) through exotic Higgs decays at the proposed International Linear Collider (ILC), specifically in the channel of $e^+ e^- \to qqH$ with $H \to \nu N_d \to \nu\, lW \to \nu\, l\, qq$. Analyses based on full detector simulations of the ILD are performed at the center-of-mass energy of 250 GeV for two different beam polarization schemes with a total integrated luminosity of 2 ab^{-1}. A range of heavy neutral lepton masses between the Z boson and Higgs boson masses are studied. The 2σ significance reach for the joint branching ratio of $BR(H \to \nu N_d)\, BR(N_d \to lW)$ is about 0.1%, nearly independent of the heavy neutral lepton masses, while the 5σ discovery is possible at a branching ratio of 0.3%. Interpreting these results in terms of constraints on the mixing parameters $|\varepsilon_{id}|^2$ between SM neutrinos and the heavy neutral lepton, it is expected to have a factor of 10 improvement from current constraints.

Heavy neutral leptons

- Several Beyond Standard Model (BSM) theories predict heavy neutral leptons (HNL, denoted N_d here)
- Can solve several problems:
  1) Give mass to the SM neutrinos via type-I Seesaw mechanism [1,2]
  2) Explain matter-antimatter asymmetry [3]
- If $m_{N_d} < m_H$: $H \to N_d \nu$ is predicted
- Decays via weak force for many models
- In this study, assume:
  1) N_d mixes with all SM neutrinos (mixing angles ε_{ed}, $\varepsilon_{\mu d}$, $\varepsilon_{\tau d}$) *
  2) Decays: $N_d \to l\, W$ and $N_d \to \nu Z$ *
  3) $m_Z < m_{N_d} < m_H$
  4) Short-lived

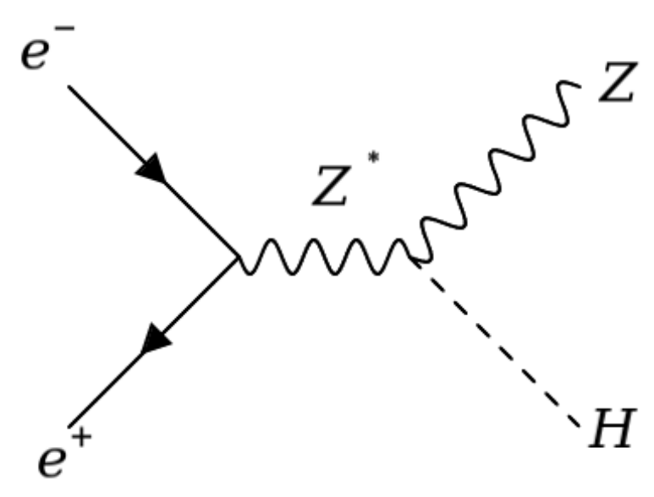


*These assumptions are only made when constraining the mixing angles. For our mass range, typically $BR(N_d \to l\, W) > 80\%$

International Linear Collider

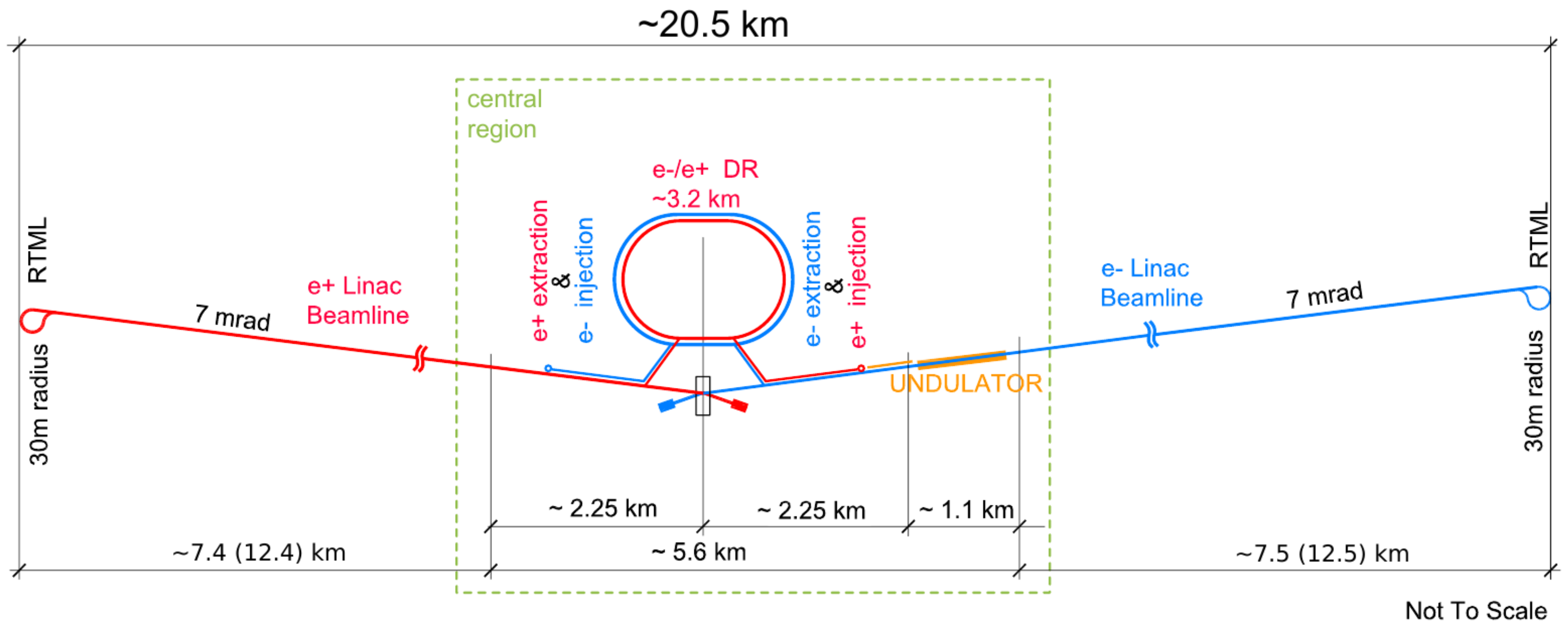
Problem: No signs of BSM at colliders yet
- Higgs boson one of the least understood particles
  →Might be connected to BSM
  →Precision measurements of Higgs are crucial

Solution: International Linear Collider (ILC)
- Main goal: Detailed studies of the Higgs boson, mainly produced from Higgs-strahlung at 250 GeV→
- Linear accelerator enables polarized beam
- Main candidate location: Iwate prefecture, Japan
- Already existing detector designs



Properties of ILC

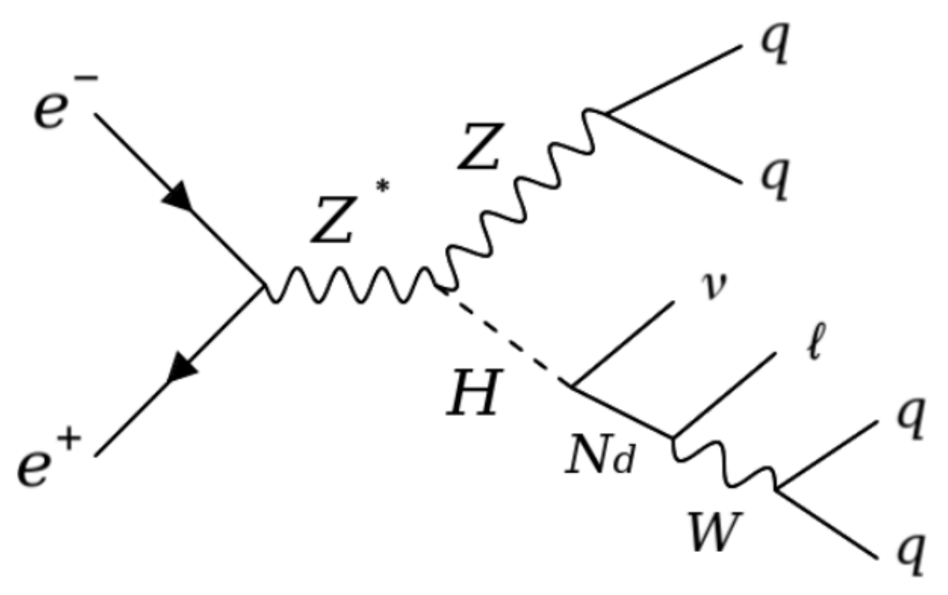
Colliding particles	e+ e-
Accelerator shape	Linear
Center-of-mass energy	250, 350, or 500 GeV
Length	~20 km (for 250 GeV)
Beam polarization	e-: ±0.8, e+: ±0.3
Integrated luminosity	~2000 fb^{-1}



Goal

What is the sensitivity of the ILC for detecting heavy neutral leptons using exotic Higgs decays?

Signal



Free parameters

1) HNL mass
2) $BR(H \to N_d\nu)BR(N_d \to l\, W)$

Method

Data

- Full detector simulations
  1) Event generation: Whizard
  2) Parton shower + hadronization: Pythia6
  3) Detector simulation: Geant4 (ILD detector model)
  4) Reconstruction: Marlin
- Beam polarizations: (-0.8, +0.3), (+0.8, -0.3)
- 1000 fb^{-1} of each beam polarization
- √s = 250 GeV

Signal

- Simulated N_d masses: 95, 100, 105, 110, 115, 120 GeV
- 200 000 events / beam polarization

Background

- Pre-made full detector simulation events for ILC

Pre-selection

Used to extract relevant parameters for upcoming steps

Requirements
1) At least one isolated lepton
   - Use neural network lepton finder
   - Pre-trained, part of ILC software
2) Cluster rest of particles to 4 jets
   - Durham clustering
3) Pair jets to Z, W by minimizing

$$\chi^2 = \left(\frac{m_W - m_{12,jet}}{\Delta m_{W,jet}}\right)^2 + \left(\frac{m_Z - m_{34,jet}}{\Delta m_{Z,jet}}\right)^2$$

   - Mass resolution calculated from MC truth

- Background remaining: ~25%*
- Signal remaining: ~90%*

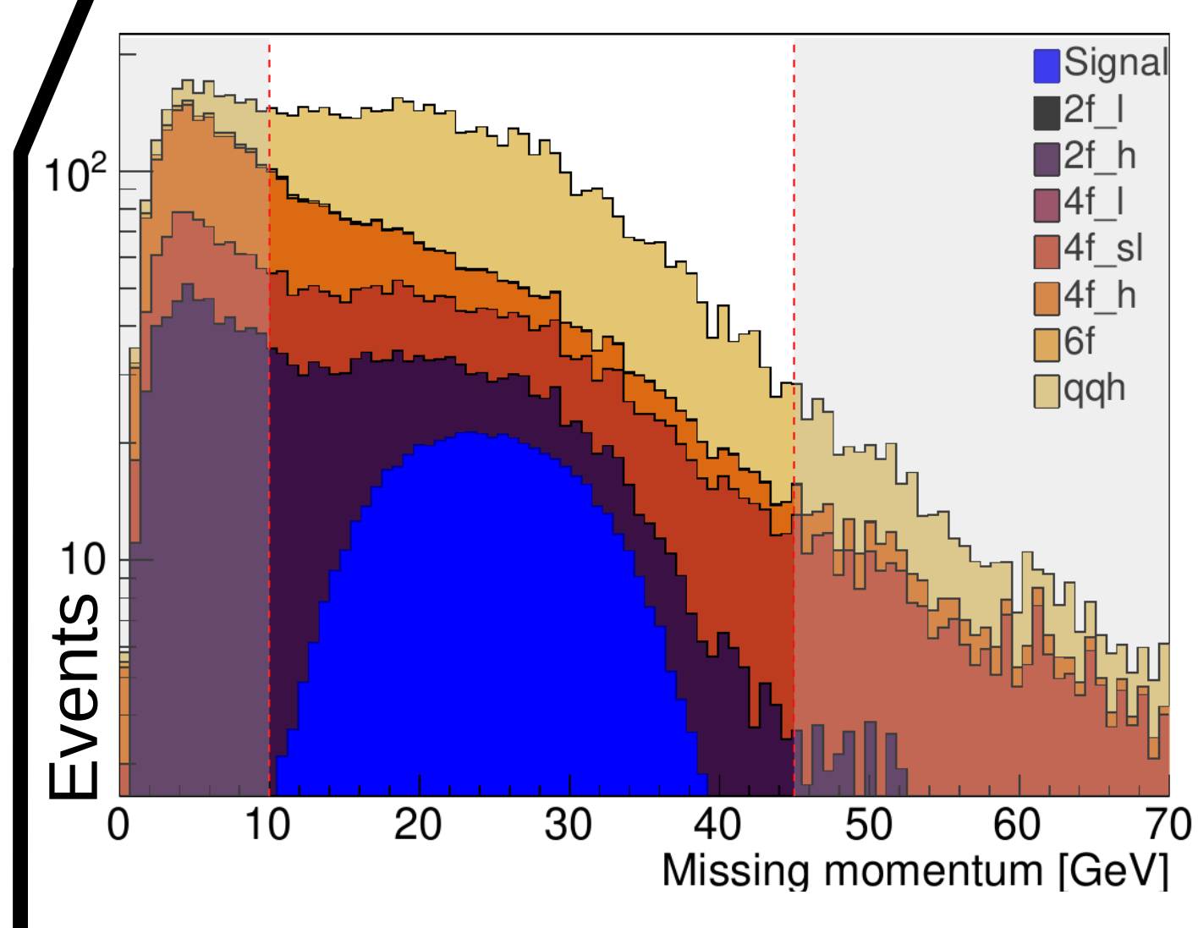
*Percentages are not exact as they vary depending on beam polarization and HNL mass

Rectangular cuts

- Cuts are optimized to maximize significance
- Separate cuts for each HNL mass and beam polarization

- Background remaining: ~10^{-5}*
- Signal remaining: ~50%*

Example cut:



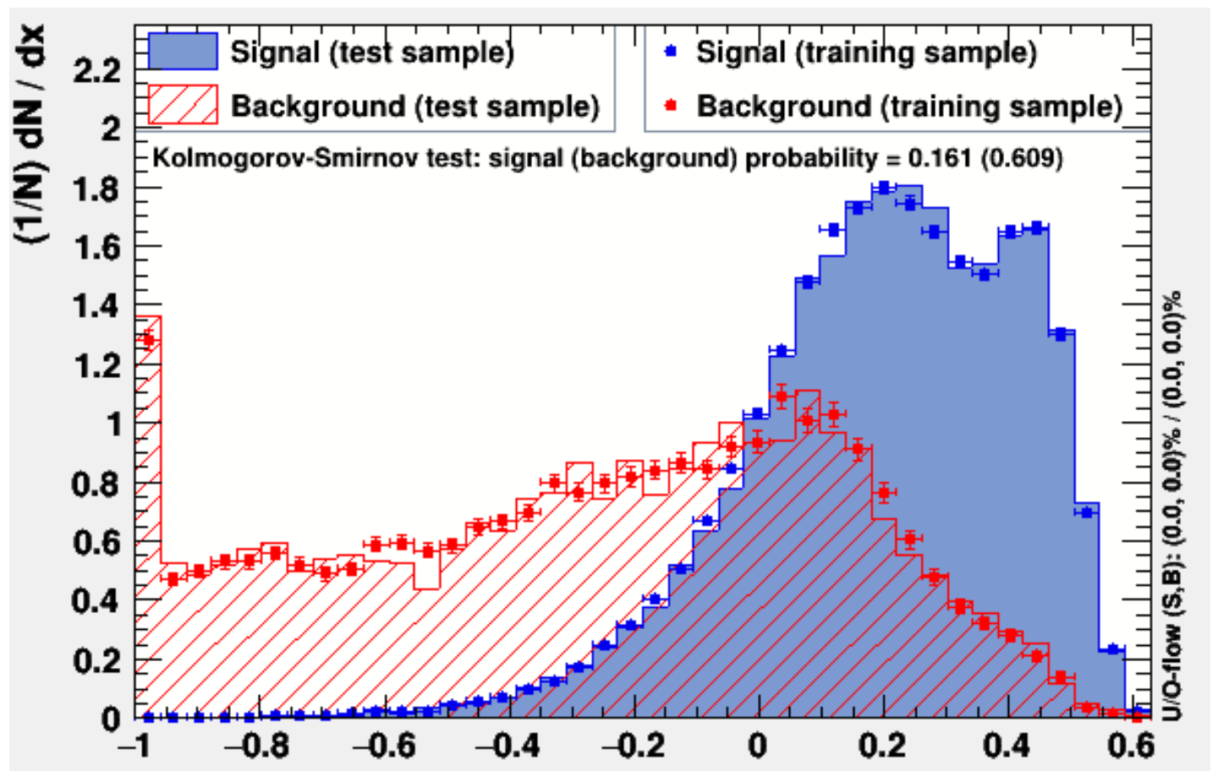
HNL mass=100 GeV, (+0.8, -0.3) beam polarization

Machine learning cuts

- Boosted decision tree (BDT)
- Apply cut on BDT output to maximize significance
- 12 input parameters (reconstructed HNL mass, Higgs mass etc.)
- Train separate BDTs for each HNL mass and beam polarization

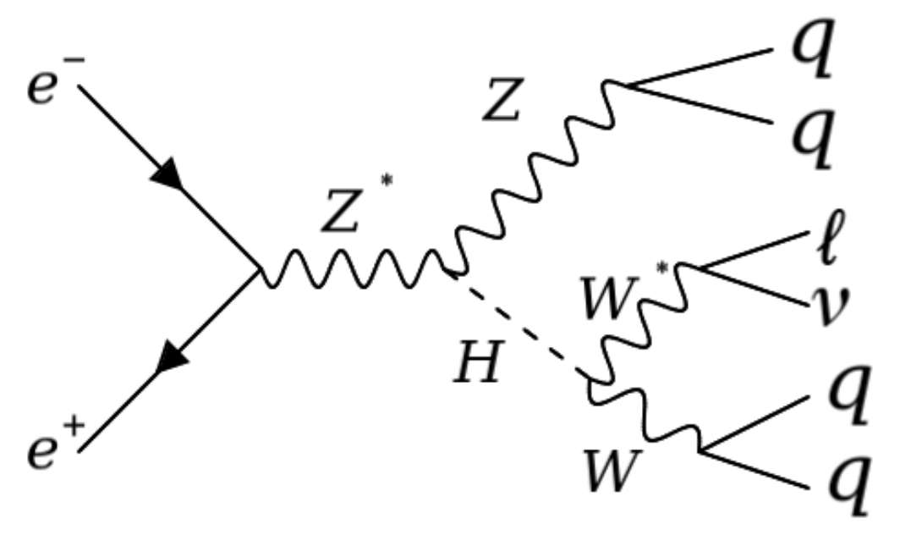
Background remaining**:** ~$3 \cdot 10^{-6}$*
Signal remaining: ~25%*

Example BDT output:



Results

- Largest background:



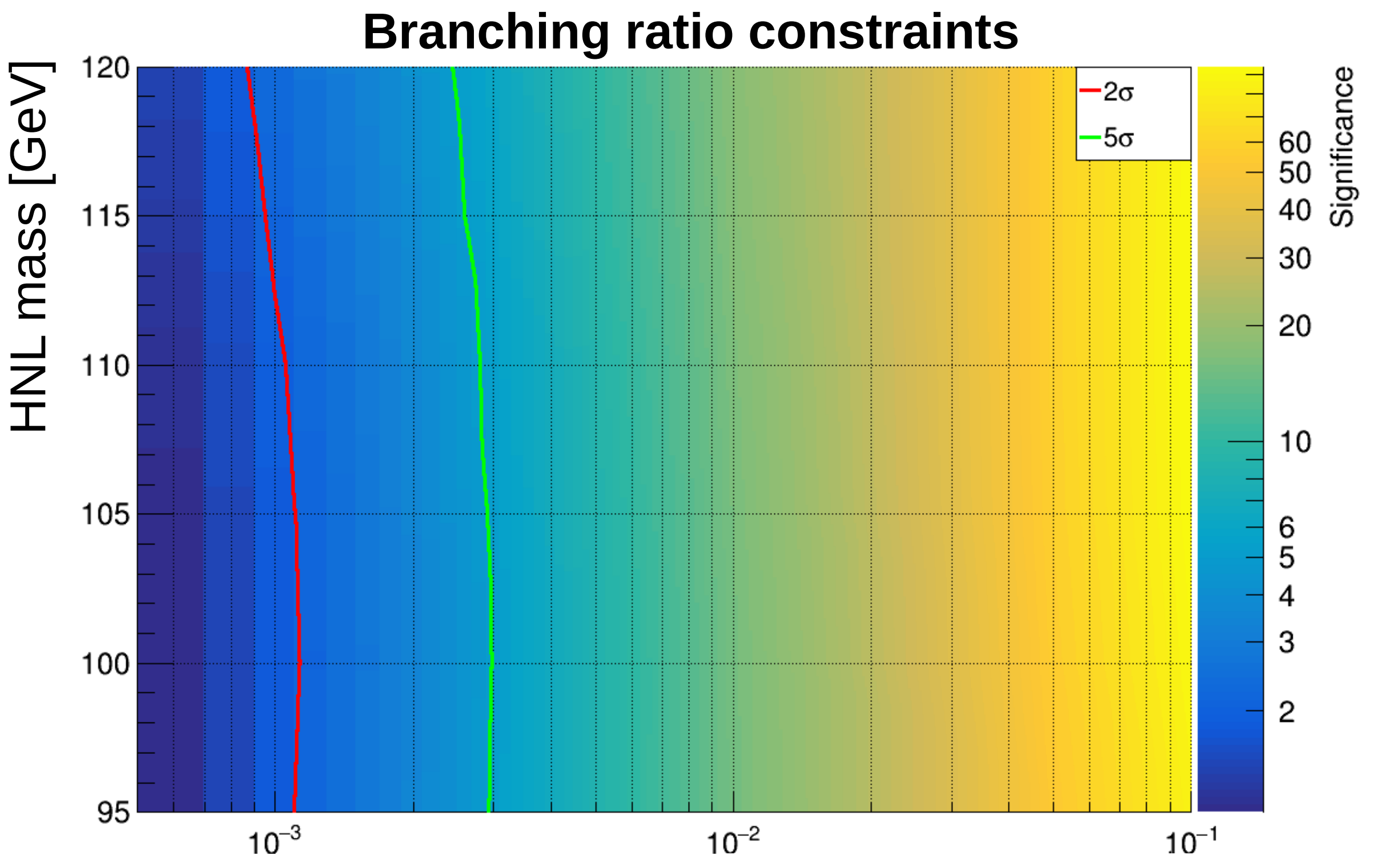
- Discovery (5σ) of HNL possible at BR > ~0.3%
- Exclusion (2σ) of HNL possible at BR > ~0.1%
- Equal sensitivity for all HNL masses
- **25x better than HL-LHC** [4]

- Calculate mixing angle between SM neutrinos and HNL using the branching ratio
- **10x improvement on mixing angle constraint** compared to current constraints [5,6]

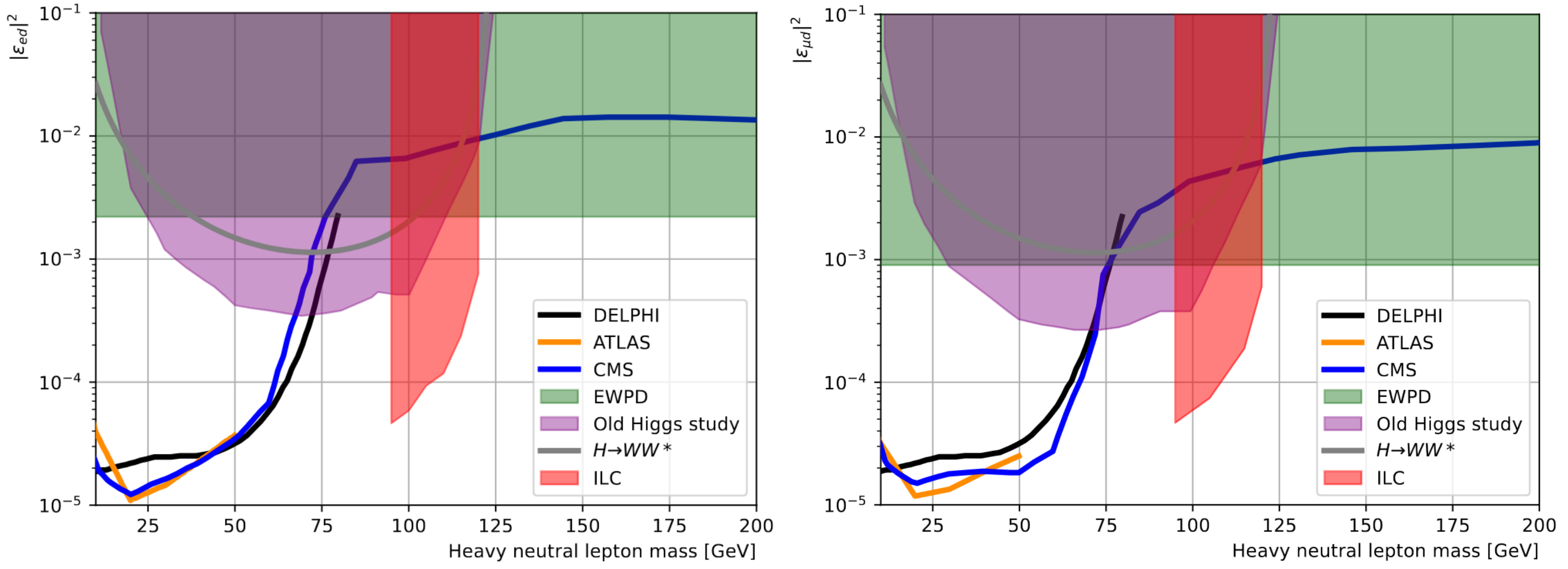
- **First ever full detector simulation** study for exotic Higgs decays to HNL

- ILC enables high-precision measurements of exotic Higgs decays

Branching ratio constraints



Mixing angle constraints



Summary

- Heavy neutral leptons (HNL, N_d) are predicted by many theories
- ILC is a proposed collider that can be used for high-precision studies of the Higgs boson
- In this study, the first ever full detector simulation of searching for the $H \to N_d\nu$ exotic decay was performed
- The proposed ILD detector was simulated, at √s = 250 GeV, with 1000 fb^{-1} each of the beam polarizations (-0.8, +0.3), (+0.8, -0.3)
- Both rectangular cuts and BDT cuts were used to remove background
- $BR(H \to N_d\nu)BR(N_d \to l\, W)$ could be constrained to 0.1%
  → **25x improvement compared to HL-LHC**
- Mixing angle could be constrained to ~10^{-4}
  →**10x improvement compared to current constraints**

References

[1] T. Yanagida, Horizontal Symmetry and Masses of Neutrinos, Progress of Theoretical Physics 64, 1103 (1980), https://academic.oup.com/ptp/article-pdf/64/3/1103/5394376/64-3-1103.pdf.

[2] A. Das, P. S. Dev, and C. Kim, Constraining sterile neutrinos from precision higgs data, Physical Review D 95, 10.1103/physrevd.95.115013 (2017).

[3] E. Hall, T. Konstandin, R. McGehee, H. Murayama, and G. Servant, Baryogenesis from a dark first-order phase transition, Journal of High Energy Physics 2020, 10.1007/jhep04(2020)042 (2020).

[4] A. Das, Y. Gao, and T. Kamon, Heavy neutrino search via semileptonic higgs decay at the LHC, The European Physical Journal C 79, 10.1140/epjc/s10052-019-6937-7 (2019).

[5] . D. Bolton, F. F. Deppisch, and P. B. Dev, Neutrinoless double beta decay versus other probes of heavy sterile neutrinos, Journal of High Energy Physics 2020, 10.1007/jhep03(2020)170 (2020).

[6] A. Das, Y. Gao, and T. Kamon, Heavy neutrino search via semileptonic higgs decay at the LHC, The European Physical Journal C 79, 10.1140/epjc/s10052-019-6937-7 (2019).

Image: ESA (2023)