Probing Heavy Neutral Leptons in the semi-leptonic channel with $e\nu jj$ final state at the FCC-ee using Machine Learning Techniques

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This analysis focuses on utilizing machine learning techniques to enhance the sensitivity of heavy neutral lepton (HNL) searches for the electron-dijet final state at the electron-positron Future Circular Collider (FCC-ee). Using machine learning techniques, this work significantly improves upon traditional cut-and-count methods in identifying potential HNL signals. The targeted mass range for HNLs is between $10\,\mathrm{GeV}$ and $80\,\mathrm{GeV}$, with mixing angles $10^{-4} \leq |V_{eN}|^2 \leq 10^{-10}$.

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1 Introduction

Heavy Neutral Leptons (HNLs) are promising candidates to address some of the most significant unanswered questions in particle physics, including the origin of neutrino masses, the nature of dark matter, and the observed matter-antimatter asymmetry in the universe [1]. These hypothetical particles are predicted in several extensions of the Standard Model, such as the seesaw mechanism, which provides an elegant explanation for the smallness of neutrino masses. Discovering or setting limits on the properties of HNLs could therefore have profound implications for our understanding of fundamental physics.

The Future Circular Collider (FCC-ee) is a proposed high-energy lepton collider that will operate with unprecedented luminosity and energy precision. Unlike proton-proton colliders like the Large Hadron Collider (LHC), the FCC-ee offers a cleaner collision environment, ideal for precision studies of electroweak interactions and searches for new physics, including HNLs. The high luminosity and Z-pole run of the FCC-ee, where approximately 10^{12} Z bosons are expected to be produced, provide a unique opportunity to explore HNLs with exceptional sensitivity.

The analysis presented here leverages the Z resonance run of the FCC-ee, focusing on the electron-dijet final state as a potential signature of HNL production and decay. In particular, this work aims to enhance the sensitivity of HNL searches by employing advanced machine learning techniques, which significantly improve upon the traditional cut-and-count approach that has been commonly used in past analyses.

The analysis explored HNL masses ranging from $10\,\mathrm{GeV}$ to $80\,\mathrm{GeV}$, with mixing angles in the range of $10^{-4} \leq |V_{eN}|^2 \leq 10^{-10}$.

2 Machine Learning Techniques and Sensitivity Improvement

In traditional HNL searches, a cut-and-count approach is often employed to discriminate signal from background events. While effective, these methods are limited in terms of the complexity of the events they can analyze. In contrast, machine learning techniques, specifically Deep Neural Networks (DNNs), can handle multi-dimensional data more effectively, providing enhanced sensitivity.

For DNN models a binary classification was used, meaning that they were trained to distinguish HNL signals from background events. To achieve maximum sensitivity, separate training was conducted for each individual signal mass point. For DNN training, the variables mentioned in Table 1 were used.

Object	**Variables**
Leading electron	E, ϕ, d_0, σ_{d_0}, ΔR_{ejj}
Neutrino	E_{miss}, θ
Di-jet system	ΔR_{jj}, ϕ
Vertex and tracks	n_{tracks}, $n_{\text{primary tracks}}$, χ^2_{vertex}

Table 1: Variables used for the DNN training.

One unique feature of HNL production at the FCC-ee is the ability to distinguish between prompt and long-lived HNLs [2]. HNLs with small mixing angles and low masses can exhibit extended decay lengths, creating a distinct long-lived signature that is rare in the context of most Standard Model particles. By training multivariate models utilizing also the transverse impact parameter and its significance, the analysis demonstrated effective discrimination between prompt and long-lived HNLs across the studied parameter space.

The enhanced sensitivity of machine learning models is depicted in Figure 1 , which shows sensitivity as a function of the HNL mass and the mixing angle. The DNN method demonstrates improved performance over the traditional cut-and-count approach across the entire mass range for an integrated luminosity of $L = 10$ fb^{-1}. In particular, the DNN offers an improvement of approximately one order of magnitude in mixing angle reach. However further optimization is needed to fully exploit its potential. With more sophisticated architectures and better hyperparameter optimization, the DNN could significantly enhance our analysis sensitivity in future work. In the same plot, the DNN performance is shown after normalizing to the full expected luminosity of the FCC-ee at $L = 205$ ab^{-1}. Using MC stats representative to the 205 ab^{-1} dataset will also be essential to fully explore the analysis sentivity and power of ML methods. Current MC stats are 3-4 order of magnitudes lower than that.

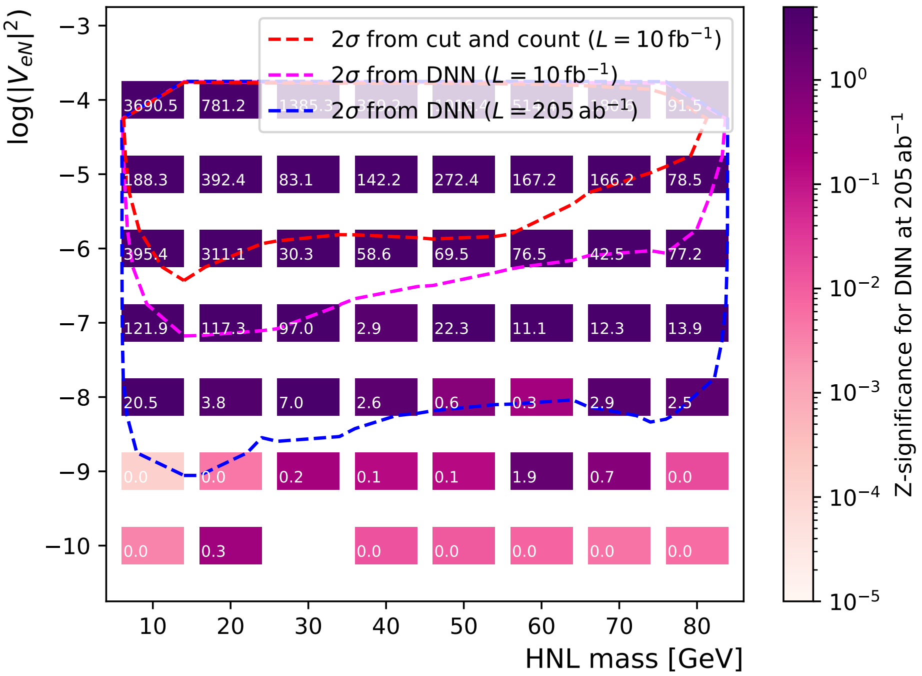

Figure 1: Sensitivity plot for HNL masses ranging from 10 to 80 GeV, and mixing angles between $|V_{eN}|^2 = 10^{-4}$ and 10^{-10}. The magenta line marks the 2σ contour for the DNN analysis, while the red line represents the 2σ contour from the cut-and-count study normalized to an integrated luminosity of $L = 10$ fb^{-1}. The blue line marks the 2σ contour for the DNN analysis normalized to an integrated luminosity of $L = 205$ ab^{-1}.

3 Conclusion

The analysis presented here underscores the power of machine learning techniques in advancing the search for heavy neutral leptons at the FCC-ee. By employing Deep Neural Networks, this work outperforms traditional approaches and opens new avenues for the exploration of physics beyond the Standard Model. The ability to differentiate between prompt and long-lived HNLs further strengthens the case for FCC-ee as a powerful discovery tool for weakly interacting new particles.

4 References

[1] A. M. Abdullahi, e. a. Barham Alzas, *The present and future status of heavy neutral leptons*, Journal of Physics G: Nuclear and Particle Physics **50** (2023) 020501, URL: http://dx.doi.org/10.1088/1361-6471/ac98f9.

[2] C. Collaboration, *Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at* $\sqrt{s} = 13, \mathrm{TeV}$, JHEP **07** (2022) 081, URL: http://dx.doi.org/10.1007/JHEP07(2022)081.