Search for Heavy Neutral Lepton at FCCee, and comparisons between Fast and Full Simulation

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Abstract

The Heavy Neutral Lepton (HNL) model extends the Standard Model by introducing right-handed neutrinos, which provide a plausible explanation for neutrino masses via the see-saw mechanism. This paper investigates the detection prospects for HNLs at the Future Circular Collider electron-positron (FCC-ee) experiment. The study focuses on comparing Fast and Full Simulations, evaluating tracking performance and reconstruction accuracy for long-lived HNL decays.

1 Introduction

The Standard Model (SM) has been incredibly successful in explaining a vast range of particle physics phenomena. However, it fails to account for the tiny masses of neutrinos, a problem elegantly addressed by the addition of Heavy Neutral Leptons (HNLs) through the see-saw mechanism. HNLs are right-handed neutrinos that could mix with SM neutrinos, leading to rare decay channels that produce detectable signatures, such as displaced vertices and di-leptons final state. The potential couplings of HNL participles to the Z bosons, as in the explored signatures, makes a Z-factory as the FCCee particularly relevant for searching for HNLs.

This study aims at exploring the sensitivity of the FCCee for the discovery of a HNL particle. A similar sensitivity study has already been done [12], based on Fast Simulation. In the presented document, such an exploration is ported and extended to include Full Simulation of the CLD detector [3], which is expected to better reproduced instrumental effects. In the Sec.2, the theoretical model as well as fast simulation based analysis are briefly presented. The Sec.3 shows a comparisons of the Fast and Full Simulations resolutions of the reconstructed tracks. While progressing with the Full Simulation analysis, problems of displaced track reconstruction efficiencies have been encountered. Their mitigation is presented in Sec.4. Finally, the Sec.5 presents the first sensitivity study for the search HNL at FCCee, based on Full Simulation. Note that this analysis is not yet finalised, but constitute a first step toward a complete study.

2 Model and fast simulation analysis

The Heavy Neutral Lepton (HNL) model [9, 10], which extends the Standard Model to explain neutrino masses, offers exciting opportunities for discovering long-lived particles (LLP). HNLs are introduced as right-handed neutrinos within the see-saw mechanism, providing a natural explanation for the tiny masses of neutrinos. This model can in particular leads signature with decay vertices significantly displaced with respect to the proximal vertex, indicating the existence of new physics particles with long lifetimes. This study focus on the production of an HNL particle decaying into charge leptons. In this di-lepton channel, see Fig 1, HNLs mix with standard neutrinos, resulting an associated production with a neutrino, and with decays that produce two electrons or muons, along with another neutrino[11]. Examples of corresponding LO Feynman diagrams can be seen in Fig.1.

Since HNLs interact weakly with other particles and can have long lifetimes, they might travel a significant distance before decaying,The observation of large decay lengths (distance from the primary vertex to the secondary vertex) would constitute a very clear sign of new physics.

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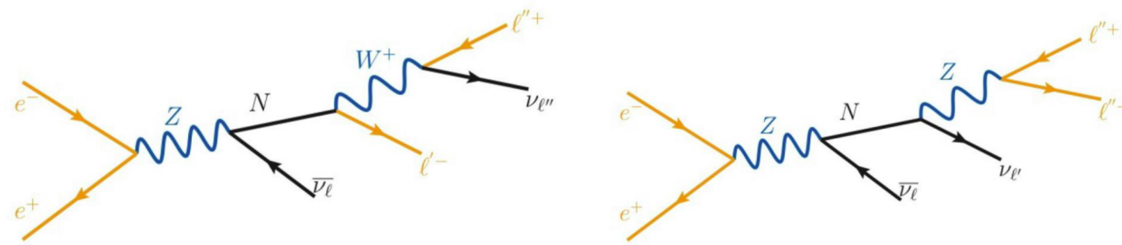


Figure 1: Leading Order Feynman diagrams for the production of HNL particles, produced in association with a neutrino, and decaying into a pair of charge lepton and another Neutrino. Taken from [12].

The event generation is performed using MadGraph [2], a tool for simulating high-energy physics processes. In this study, HNLs are generated with masses of 30, 50, 70, and 90 GeV and a mixing angle of 1.41×10^{-6}. The corresponding cross sections used for HNL production at these masses are listed in Table 1.

30 GeV	6.637×10^{-10} pb
50 GeV	4.535×10^{-10} pb
70 GeV	1.968×10^{-10} pb
90 GeV	1.749×10^{-12} pb

Table 1: Cross sections used for HNL production at different masses.

A di-electron channel analysis has been conducted using fast simulation, as detailed in [12]. In Fast Simulations, detector responses effects are usually taken into account by smearing the resolutions of generated particles. Fast Simulation is performed using the Delphes [5] program, which employs parametrized detector responses to approximate tracking and calorimetry effects, significantly reducing computational costs while maintaining a good description of the detector resolution. To have robust comparisons with Full Simulation, the Delphes detector card [1] used contains a description of the full silicone CLD tracker [3].

The analysis presented in this document is however based on Full Simulation. Full simulation refers to the use of GEANT4 [1], a detailed framework that models the interactions of particles with the detector material, such as energy losses, multiple scattering, nuclear interactions or secondary particle production. This approach is expected to provide a more accurate description of detector effects, but it is computationally expensive.

After the simulation, event reconstruction is performed using Key4hep [6]. Reconstruction is the process of converting raw detector signals into higher-level physics objects, such as tracks and particle candidates. This involves identifying hits in the detector, associating them to particle trajectories, and estimating key parameters like momentum and impact parameters.

3 Tracking resolution comparisons for full & fast simulation

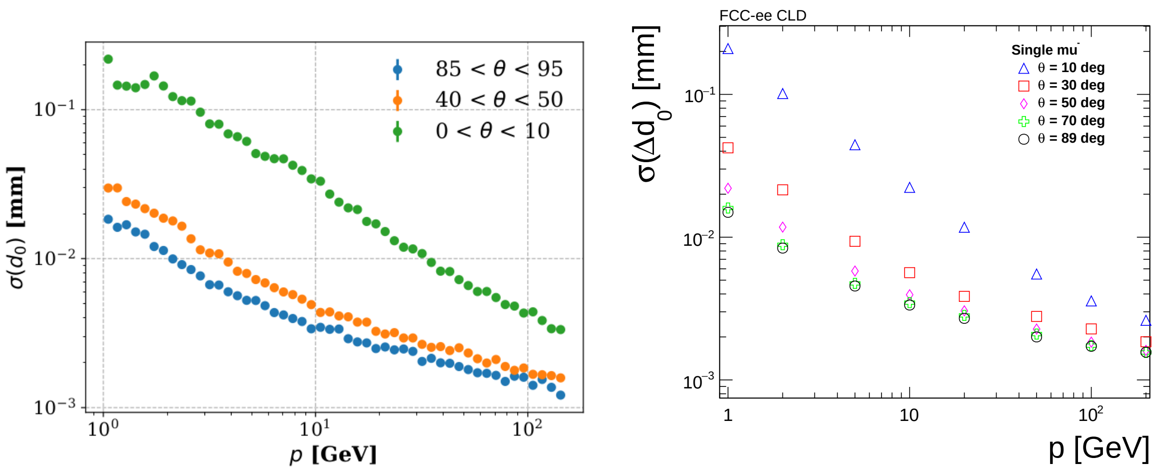
In this section, the differences in track resolutions between Fast and Full Simulations are compared. This give insight of the expected differences between Fast and Full Simulations performances.

The tracking performance has been compared between Fast and Full simulations using single prompt muon tracks, generated with a particle gun producing muons with momenta of 10 GeV and 100 GeV and a flat distribution in θ. The tracking performance in Full Simulation has been performed using the Key4DetPerformance framework [2]. Due to technical reasons, plots for track resolutions plots in Fast and Full Simulations could not be combined easily and are instead shown side by side.

The results show that both simulations yield comparable tracking resolutions, as illustrated in Figs. 2, 3, 4, and 5. This highlights that fast simulation provides a reliable alternative to the more resource-intensive full simulation without significant loss in precision. The transverse impact parameter, d_0, measures the closest

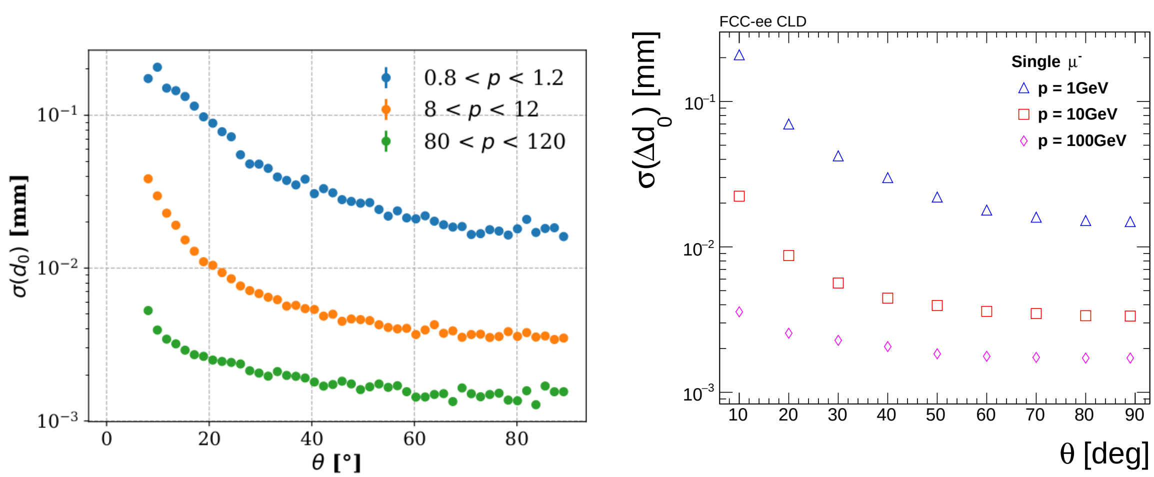
[1] github.com/delphes/validation_delphes_card_CLD.tcl
[2] github.com/key4hep/k4DetPerformance

approach of a track to the primary interaction point in the transverse plane. While fast simulation performs well for prompt muon tracks, its performance for displaced tracks has not been studied in this analysis.



(a) (b)

Figure 2: d_0 resolution in single muon events as a function of momentum for Fast (a) and Full (b) Simulations.



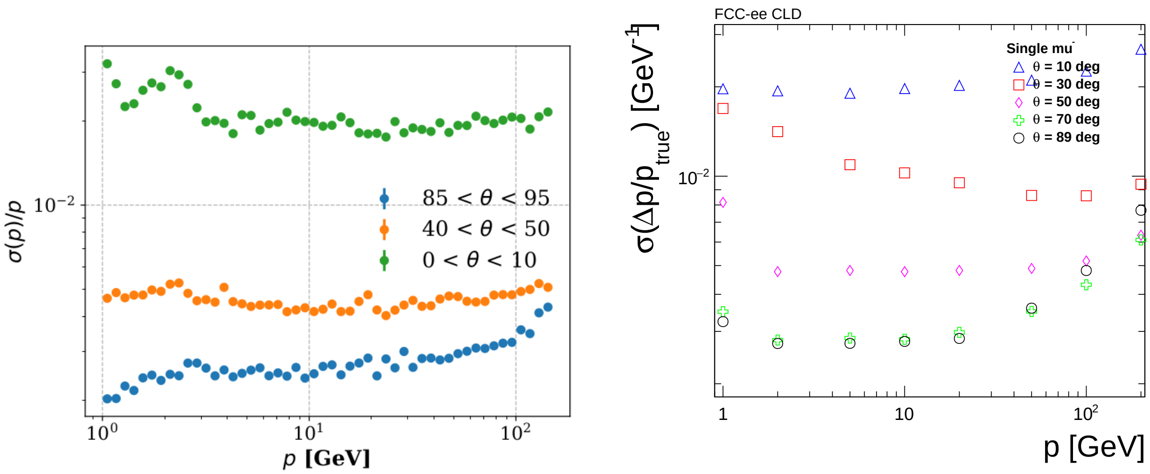
(a) (b)

Figure 3: d_0 resolution in single muon events as a function of polar angle θ for Fast (a) and Full (b) simulations.

4 Displaced Tracks reconstruction in Full Simulation

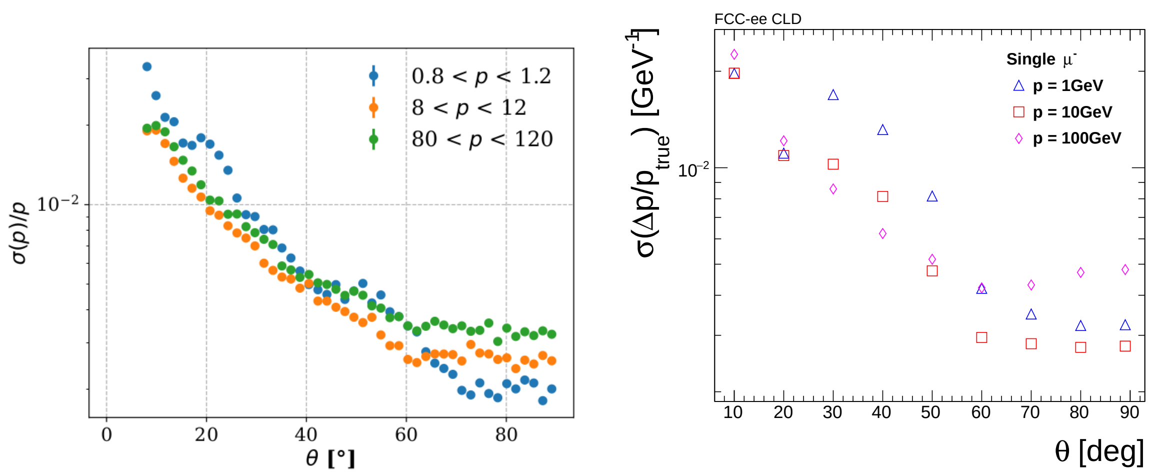
The track reconstruction for CLD is based on the Conformal Tracking [4]. The Conformal Tracking employs conformal mapping followed by Cellular Automaton Track Finding for pattern recognition. In conformal mapping, coordinates (x,y) in Euclidean space are transformed into (u,v) coordinates in conformal space, where trajectories (in the transverse plane) passing through the origin are converted into straight lines. This transformation means that displaced tracks do not appear as straight lines in conformal space. To reconstruct displaced tracks, conformal tracking uses an additional *step 5* (or displaced track step) after all prompt tracks are reconstructed, by utilising the remaining hits.

The reconstruction of prompt tracks is performed in a stepwise manner:



(a) (b)

Figure 4: Relative momentum p resolution in single muon events as a function of momentum for Fast (a) and Full (b) simulations.



(a) (b)

Figure 5: Relative momentum p resolution in single muon events as a function of as a function of polar angle θ for Fast (a) and Full (b) simulations.

- **Step 0** consists in the building of cellular track candidates using the hits in the vertex barrel as the seeding collection,
- **Step 1** performs the extension of cellular track candidates found in step 0, limited to the set of hits in the vertex end-caps,
- **Step 2** performs cellular track candidates building to recover remaining hits in the combined vertex barrel and end-cap detectors, with tighter cuts at first to reconstruct higher-p_T tracks,
- **Step 3** performs cellular track candidates building with looser cuts to reconstruct low-p_T tracks,
- **Step 4** extends all the candidates obtained using hits in the tracker barrel and end-cap detectors.

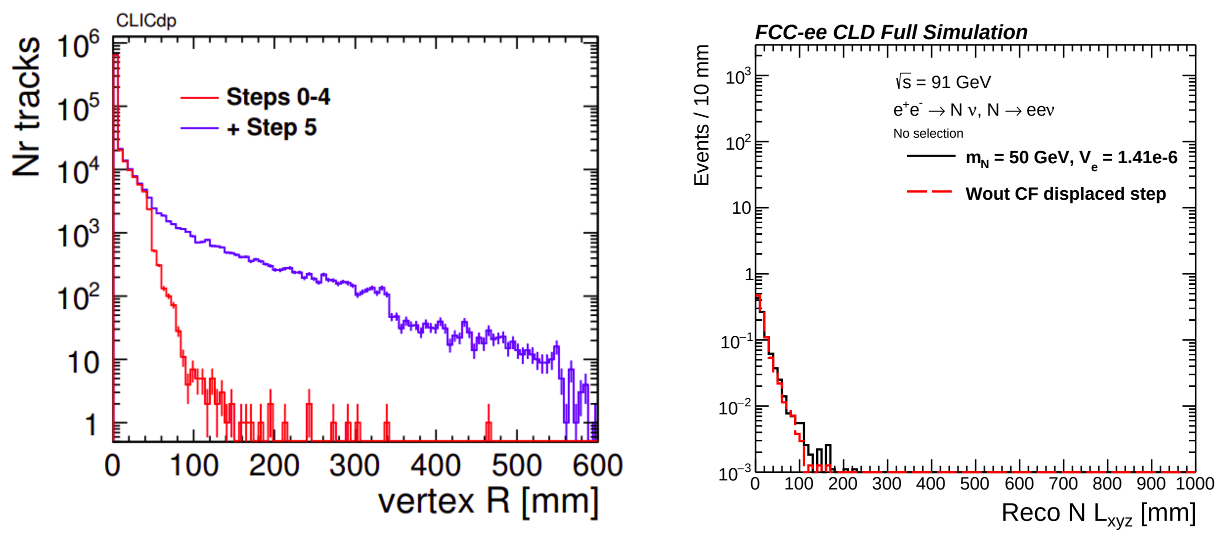
At each step, the hits used for track reconstruction are removed from the hit collection before proceeding to the next step. After these steps, displaced track reconstruction is performed in another setp, the Step

5. Unlike the previous steps, which use the seed hits from the innermost detector layers, Step 5 begins by forming track candidates from hits in the outermost layers of the tracker and progressively extends them inward.

The CLD detector being heavily inspired from the CLIC detector, very similar tracking performances are expected for the two detector concepts. A previous study on the performance of Conformal Tracking at CLIC [4] shows a non-zero tracking efficiency for tracks produced up to ∼60 cm from the centre of the detector (decay lenght, DL), with a decreasing efficiency as a function of the DL. It is indeed expected that the efficiency for tracks with large DL is affected by the limited number of measurement points in the CLD full silicone tracking system. However, after performing the CLD reconstruction on Full Simulation events, we observed no reconstructed tracks beyond a displacement of ∼10 cm, and not ∼60 cm as expected.

Figure 6 compares the performance of displaced vertex reconstruction at CLIC (6a) with that of HNL reconstruction at CLD (6b). As it can be seen, the CLD reconstruction shows no tracks beyond ∼10 cm (6b), while the CLIC reconstruction show tracks up to ∼60 cm. This suggests that the *step 5* procedure is not functioning as expected.

This observation led to an optimisation study of the reconstruction parameters for CLD, focusing in particular on *MaxCellAngle* and *MaxCellAngleRZ*, which define the angular search window for the next hit. It was found that the initial values were too restrictive, limiting the reconstruction efficiency. Figure 7 shows the reconstruction with corrected values of *MaxCellAngle* and *MaxCellAngleRZ*.



(a) (b)

Figure 6: Number of reconstructed tracks with the Conformal Tracking as a function of the distance of the generated decay vertex with respect to the detector centre for the CLIC detector with $t\bar{t}$ events (a) and for the CLD detector with an HNL model ($MaxCellAngle$ parameters = 0.1) (b).

5 Full simulation analysis

In this study, we analyse generated HNLs at a center-of-mass energy ($\sqrt{s}$) of 91 GeV and an integrated luminosity of 150 ab^{-1}. Due to a reconstruction issue, the electron identification does not show good performance, especially for electrons coming from displaced vertices. For this reason, the analysis relies on tracks associated with Pandora Particles [8], regardless of their particle identification. The analysis is performed using FCCanalysis [7]. Monte Carlo (MC) electrons with a status code of 1 are matched to reconstructed tracks within $\Delta R < 0.2$. Then, Pandora particles that match both the MC electron and the reconstructed track within the same ΔR criterion are used for the analysis.

Events must then contain exactly such two reconstructed electrons tracks with a total charge of zero and an invariant mass outside the Z boson region, specifically $m_{ee} < 50$ GeV and $m_{ee} > 2$ GeV at reconstructed

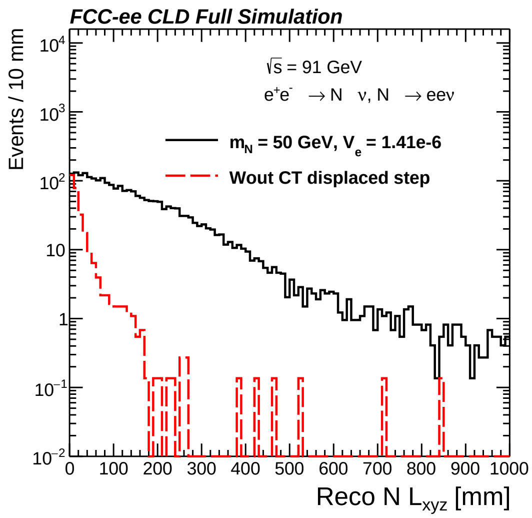


Figure 7: Number of reconstructed tracks with the Conformal Tracking as a function of the distance of the generated decay vertex with respect to the detector centre, for the CLD detector with an HNL model, with and without *step5* optimization ($MaxCellAngle$ parameters = 0.5).

level. The invariant mass reconstruction is done the Pandora Particles associated to the tracks, therefore including calorimeter information. Additionally, the missing transverse energy must satisfy $\not p > 10$ GeV.

After event selection, vertices are reconstructed using vertex reconstruction available in the FCCanalysis package. The vertex reconstruction is done using all the available tracks with $\chi^2/ndf < 10$. After the reconstruction, the vertices are required to have a normalised $\chi^2/ndf < 10$.

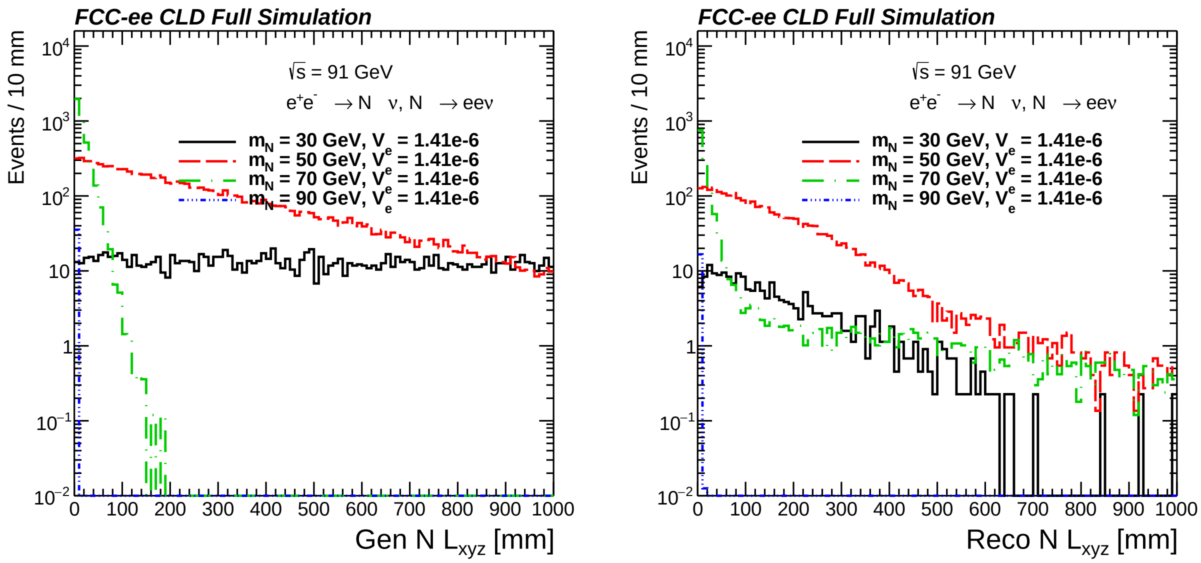
Concerning the signal benchmarks, the cross sections used are scaled by a factor of 10^5 compared to the ones in Tab. 1, corresponding to mixing angles of 1.41×10^{-6}, ensuring a reasonable number of expected events. For large HNL life time, such as the 30 GeV mass case, the average DL might exceed the tracker volume, leading to much lower mean tracking efficiency. Therefore, the requirement of two reconstructed electrons already removes a significant fraction of signal events for $m_N = 30$ GeV. For $m_N = 50$ GeV, the same selection reduces the signal event number by approximately one order of magnitude. For 70 and 90 GeV, the reconstruction efficiency is notably higher, as these scenarios exhibit minimal displacement. More detailed studies on the impact of the events selection is currently being performed.

Figure 8 displays the generated and reconstructed vertex displacement after all selection criteria are applied for different HNL masses. As expected, the vertex reconstruction efficiency decreases with increasing displacement. This behaviour aligns with expectations.

The decrease in reconstruction efficiency for tracks with large displacements stems from the reduced number of hits when decays occur in the outermost tracker layers.

Figure 9 present the distributions of vertex displacement for the signal and for the dominant background ($Z \to \tau^+\tau^-$). While for each signal benchmark point 50 thousand events are produced, 1 million background events have been generated. The signal and background are passed through the Full Simulation and the CLD reconstruction. The background is normalised to a cross section of 1476 pb, as calculated by MadGraph at LO. An integrated luminosity of 150 fb^{-1} is used for both the signal and the background.

These distributions illustrate the challenge of isolating the signal, as it remains largely overshadowed by the background. The secondary vertex displacement is clearly a very powerful information to extract the signal from the background, with the cost of a lower signal selection efficiency. It has to be noted that a lack of MC simulations does not allow to describe properly the background beyond $\sim$10 cm.



(a) (b)

Figure 8: Distribution of decay lengths of the HNL at the generation (a) and reconstruction (b) levels for different HNL masses.

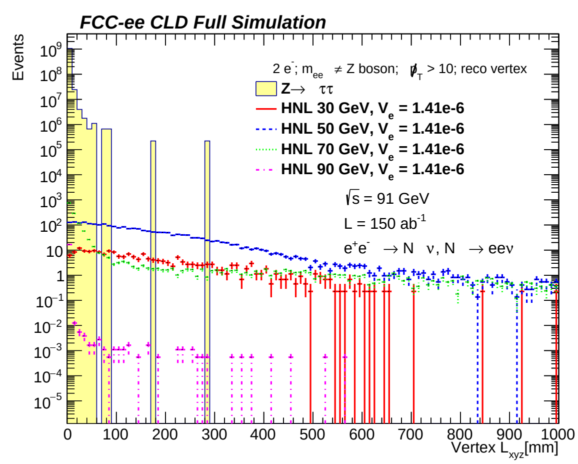


Figure 9: Distributions of reconstructed vertex displacement for the signal and the dominant backgrounds, normalised to an integrated luminosity of $150 fb^{-1}$.

6 Conclusion

In this study, we compared Fast and Full Simulations for the tracking and reconstruction of Heavy Neutral Lepton (HNL) decays at the FCC-ee. Our analysis demonstrates that Fast Simulation provides a good tracking for prompt tracks for prompt tracks. The presented search for HNL is based on the CLD Full Simulation, that is believed to provide a more realistic modelling of particles reconstruction. The results highlight the challenges in reconstructing displaced vertices with the CLD tracker geometry.

It has to be noted that the analysis presented here is not yet complete. Beyond a better understanding of the electron reconstruction, the events reconstruction has to be optimised and adapted to the cased of strongly displaced HNLs. After completing the background samples, and potentially generating more events, the sensitivity of the search has to be estimated based on a discriminating variable, potentially provided by a multi-variate analysis. The dominant systematics have also to be accounted for.

References

[1] S. Agostinelli et al. Geant4 – a simulation toolkit. *DOI:10.1016/S0168-9002(03)01368-8*, 2003.

[2] J. Alwall et al. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *arxiv.org/abs/1405.0301v2*, 2014.

[3] N. Bacchetta et al. CLD – a detector concept for the FCC-ee. *arXiv:1911.12230v3*, 2019.

[4] E. Brondolin et al. Conformal tracking for all-silicon trackers at future electron–positron colliders. *arXiv:1908.00256v1*, 2019.

[5] J. de Favereau et al. DELPHES 3, A modular framework for fast simulation of a generic collider experiment. *arXiv:1307.6346*, 2014.

[6] P. Fernandez Declara et al. The Key4hep turnkey software stack for future colliders. *DOI:10.22323/1.398.0844*, 2022.

[7] C. Helsens et al. Hep-fcc/fccanalyses: v0.10.0, 2024.

[8] J. S. Marshall, M. A. Thomson. The Pandora Particle Flow Algorithm. *arxiv.org/abs/1308.4537*, 2013.

[9] L.Wolfenstein. Different varieties of massive Dirac neutrinos. *DOI:10.1016/0550-3213(81)90096-1*, 1981.

[10] S.T. Petcov. On pseudo-Dirac neutrinos, neutrino oscillations and neutrinoless double β-decay. *DOI:10.1016/0370-2693(82)91246-1*, 1981.

[11] Y.-S Tsai. Decay Correlations of Heavy Leptons in $e^+ + e^- \to l^+ + l^-$. *DOI:10.1103/PhysRevD.13.771*, 1981.

[12] C. B. Verhaaren et al. Searches for long-lived particles at the future FCC-ee. *arXiv:2203.05502v4*, 2022.