Heavy Neutral Lepton study with CLD Full Simulation

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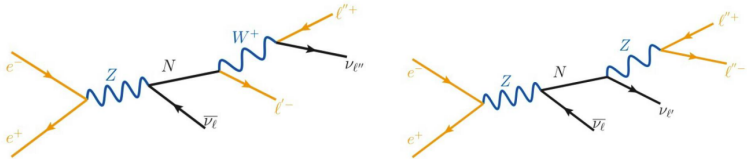
HNL study

- First attempt for physics analysis with long lived particle in **Full Simulation**
  - CLD_01_v04 geometry used (updates with more recent geometries planned)
  - Analysis performance is highly dependent on tracking performances
- Generation of Long Lived Particle within the Heavy Neutral Lepton model
- Reproduce the analysis from (Alimena&al arXiv:2203.05502v4) with **Full Simulation**
- Allow for FastSim / FullSim comparison
- Di-electrons channel
- The lighter the HNL particle, the longer the lifetime.

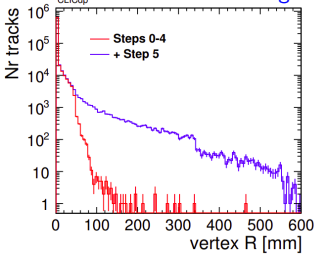


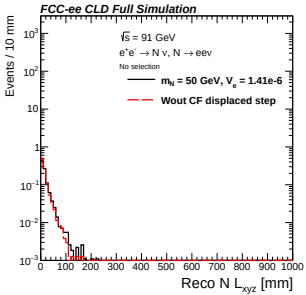
HNL study

Tracking issue – Investigation in conformal tracking

- **VXDBarrel:** build track seeds in the vertex barrel
- **VXDEndcap:** extend track seed through the vertex endcaps
- **LowerCellAngle1:** build track candidates with tight cuts for high-p_T tracks
- **LowerCellAngle2:** build track candidates with looser cuts to reconstruct low-p_T tracks
- **Tracker:** extends all existing partial tracks through the tracker
- **Displaced (step5):** build additional tracks with optimised cuts for displaced tracks from all the leftover hits

Conformal Tracking @CLIC





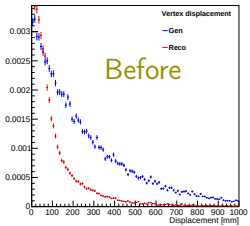
⇒ In latests reconstruction, the Step5 does not provide the expected tracking efficiency

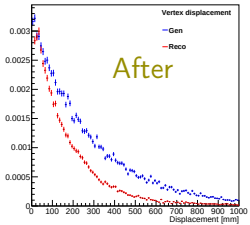
HNL study

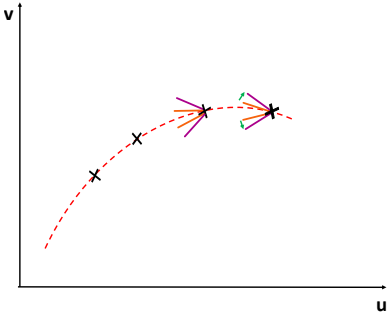
Tracking issue – Investigation in Conformal Tracking

Parameters in step 5:

- **MaxCellAngle:** 0.1 ⟶ 0.5
- **MaxCellAngleRZ:** 0.1 ⟶ 0.5
- Chi2Cut
- MinClustersOnTrack
- MaxDistance
- SlopeZRange
- HighPTCut





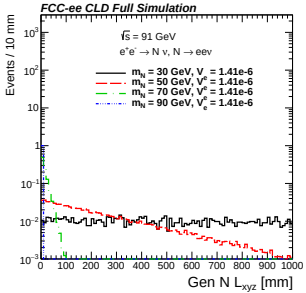


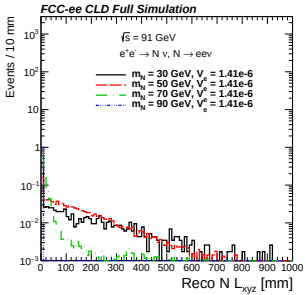
×**2 vertices**, window for extension to next hit was too small for the displaced step in conformal tracking

HNL study

Tracking issue – Vertex reconstruction (considering all reconstructed tracks)

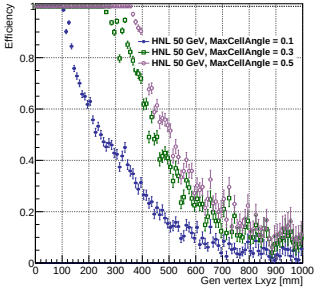
- Reconstructed vertices up to 600 mm displacement, as expected from Conformal Tracking paper

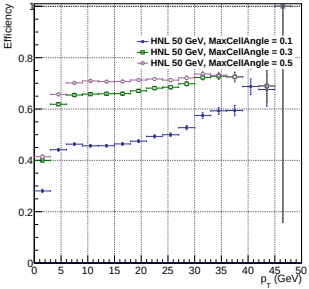


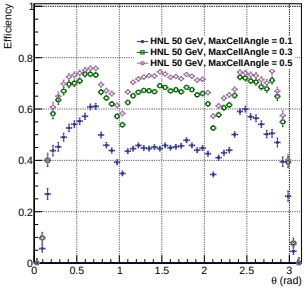


HNL study

Tracking issue – Investigation in Conformal Tracking – Efficiency and Fake Rate







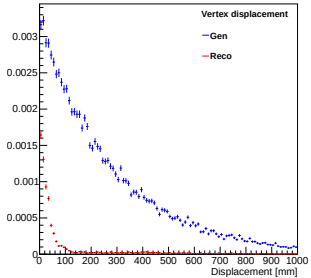
- Increasing *MaxCellAngle* and *MaxCellAngleRZ* improves tracking efficiency significantly
- Therefore, the value 0.5 is adopted for the rest of the analysis
- Fake rate remains elevated (10–20%) and exceeds expectations from CLD baseline *

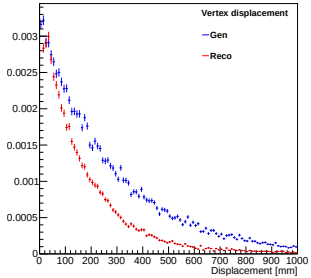
*arxiv.org/pdf/1911.12230

HNL study

Track - Cluster association issue

- Issue with electron reconstruction
  - Electrons reconstruction efficiency
    top plot → HNL vertices with reconstructed electron tracks
    bottom plot → HNL vertices with all reconstructed tracks
  - Tracks are present
  - Pandora particles are mainly photons
    ⇒ e^- are not reconstructed properly
  - Issue also observed for prompt tracks CLDConfig/issues/43





HNL study

Analysis

- **"Reco electron":** a reconstructed track matched to a status-1 MC electron within $\Delta R < 0.2$
  - Final electron candidate: Pandora particle matched to both a reco track and an MC electron ($\Delta R < 0.2$)
- **Object selection:**
- "Reco electrons" momentum > 1 GeV
- **Event selection:**
  - Exactly 2 "reco electrons" with sum charge == 0
  - Invariant mass incompatible with a Z boson : 2 GeV $< m_{ee} <$ 50 GeV
  - Missing transverse energy $\not{p} > 10$ GeV
- Vertices are reconstructed using the two selected electron tracks
- Cross section for $Z \rightarrow \tau\overline{\tau}$ from fcc-ee/delphes/spring2021/idea/

HNL study

Analysis cut flow – x10^5 HNL cross sections

Active-sterile mixing $\lvert V_{eN}\rvert$	Cross Section [pb]	Expected events at 150 ab^{-1}
1×10^{-1}	2.29	343,200,000
1×10^{-2}	2.29×10^{-2}	3,432,000
1×10^{-3}	2.29×10^{-4}	34,320
1×10^{-4}	2.29×10^{-6}	343
1×10^{-5}	2.29×10^{-8}	3
1×10^{-6}	2.29×10^{-10}	0

- HNL cross sections depend mainly of the mixing angle, 1.41×10^{-6} used for the Delphes analysis, first test with ($\times10^5$) on HNL cross sections

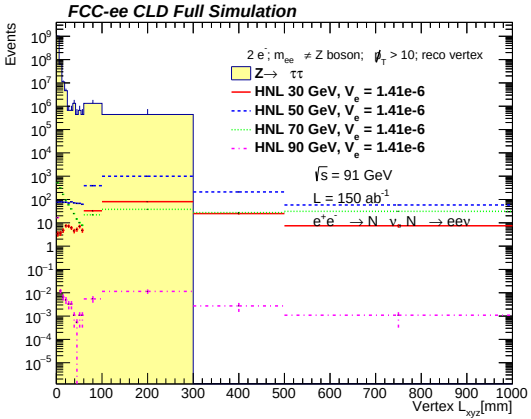
Process	HNL 30 [GeV]	HNL 50 [GeV]	HNL 70 [GeV]	HNL 90 [GeV]
Cross Section [pb] ($\times10^5$)	$(6.64\pm0.01)\times10^{-5}$	$(4.54\pm0.01)\times10^{-5}$	$(6.64\pm0.01)\times10^{-5}$	$(1.75\pm0.03)\times10^{-7}$
Before selection	$(1.00\pm0.00)\times10^{4}$	$(6.80\pm0.03)\times10^{3}$	$(2.95\pm0.01)\times10^{3}$	$(2.62\pm0.01)\times10^{1}$
Exactly 2 reco e	$(2.24\pm0.23)\times10^{1}$	$(6.18\pm0.09)\times10^{2}$	$(1.65\pm0.01)\times10^{3}$	$(1.66\pm0.01)\times10^{1}$
Invariant mass $\neq Z$ boson	$(2.17\pm0.22)\times10^{1}$	$(6.16\pm0.09)\times10^{2}$	$(1.54\pm0.01)\times10^{3}$	$(1.60\pm0.01)\times10^{1}$
$\not{p}_T > 10$ GeV	$(2.04\pm0.21)\times10^{1}$	$(5.31\pm0.09)\times10^{2}$	$(1.41\pm0.01)\times10^{3}$	$(1.57\pm0.01)\times10^{1}$
Reconstructed vertex	$(1.97\pm0.21)\times10^{1}$	$(5.21\pm0.08)\times10^{2}$	$(1.37\pm0.01)\times10^{3}$	$(1.54\pm0.01)\times10^{1}$

Process	$Z\to e^+e^-$	$Z\to b\bar{b}$	$Z\to \tau^+\tau^-$	$Z\to e^+e^-\nu\bar{\nu}$
Cross Section [pb]	1.46×10^{3}	6.65×10^{3}	1.48×10^{3}	$(3.05\pm0.01)\times10^{-4}$
Before selection	$(2.19\pm0.01)\times10^{11}$	$(9.97\pm0.05)\times10^{11}$	$(2.21\pm0.01)\times10^{11}$	$(4.57\pm0.02)\times10^{4}$
Exactly 2 reco e	$(1.98\pm0.01)\times10^{11}$	$(9.05\pm0.13)\times10^{10}$	$(8.80\pm0.02)\times10^{9}$	$(3.77\pm0.02)\times10^{4}$
Invariant mass $\neq Z$ boson	$(3.92\pm0.04)\times10^{10}$	$(9.05\pm0.13)\times10^{10}$	$(8.87\pm0.02)\times10^{9}$	$(3.76\pm0.02)\times10^{4}$
$\not{p}_T > 10$ GeV	$(6.71\pm0.05)\times10^{8}$	$(1.22\pm0.05)\times10^{10}$	$(3.30\pm0.01)\times10^{9}$	$(2.98\pm0.02)\times10^{4}$
Reconstructed vertex	$(6.10\pm0.05)\times10^{8}$	$(1.21\pm0.05)\times10^{10}$	$(3.24\pm0.01)\times10^{9}$	$(2.91\pm0.02)\times10^{4}$

- Cut on $|d_0| < 0.5$ removes several of magnitude of background

HNL study

Analysis stack – x10^5 HNL cross sections

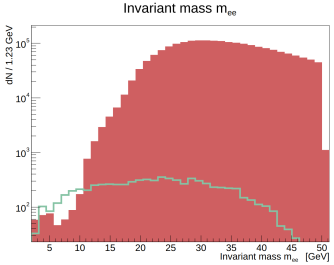


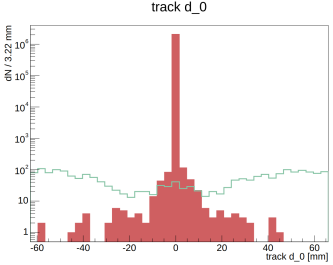
Strategy for signal extraction to be precisely defined:

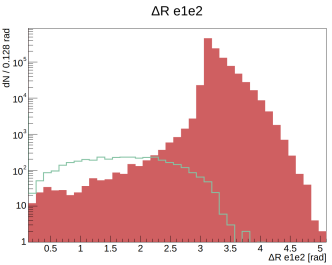
- Apply baseline selection to selected the event signatures, focus on the Ztautau background for simplicity,
- Identify discriminating variables, to be combined with a Boosted Decision Tree,
- Estimate the sensitivity (Limits) by fitting the BDT score, using the CMS "Combine" tool.

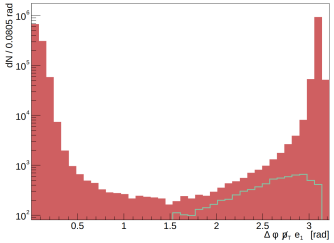
HNL study

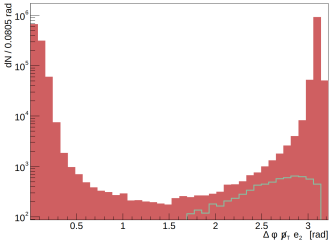
Discriminating variables – x10^5 HNL cross sections – 50 GeV HNL

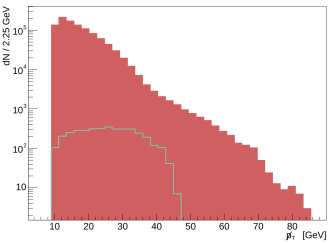






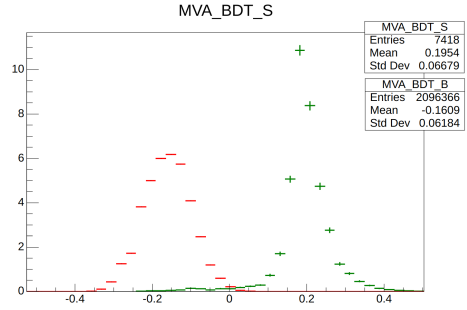


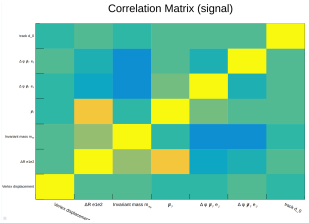


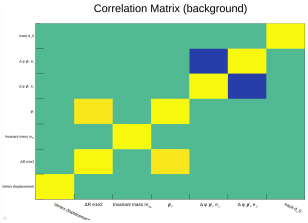


HNL study

BDT and limits – x10^5 HNL cross sections – 50 GeV HNL







- Signal extraction is challenging, a very large MC production for the backgrounds is needed

HNL study

Conclusion

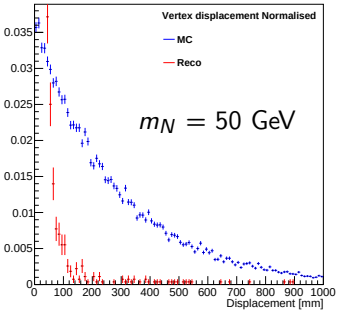
- Displaced tracks are now reconstructed better
- Discriminating variables have been identified and tested, and an initial selection has been implemented
- Signal extraction appears to be challenging
- Tracks are not associated to clusters
  - need to replace "2 electron selection" with tracks+constrains for highly displaced vertices
- Next steps
  - Extract limits
  - Study impact of tracker geometry on physics performance

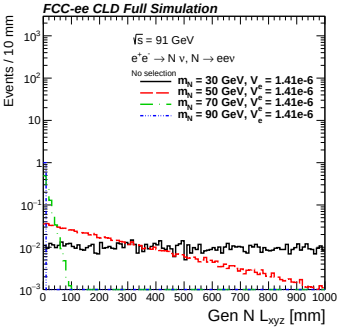
Backup

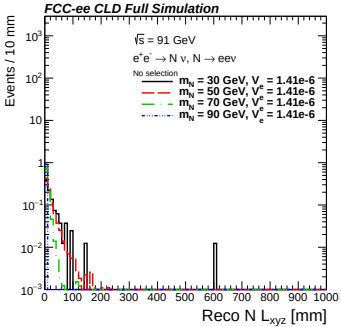
HNL study

Tracking issue for displaced tracks

- No reconstructed tracks for >10 cm displacement





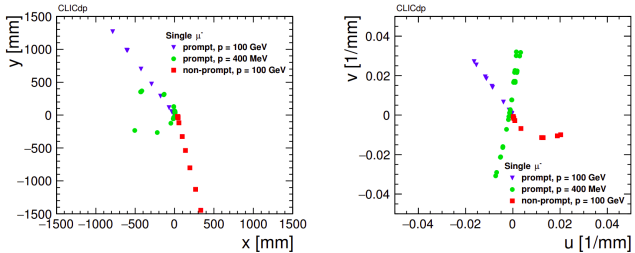


HNL study

Conformal Tracking†

- **Conformal mapping:** coordinates (x, y) in Euclidean space are converted to coordinates (u, v) in conformal space, circles passing through the origin are transformed into straight lines

$$u = \frac{x}{x^2 + y^2}, \quad v = \frac{y}{x^2 + y^2}$$



- Conformal Tracking makes hypothesis that tracks are prompt
- **Cellular Automaton Track Finding:** for pattern recognition

†Conformal Tracking @CLIC

HNL study

Analysis cut flow

Process	HNL 30 [GeV]	HNL 50 [GeV]	HNL 70 [GeV]	HNL 90 [GeV]
Cross Section [pb]	$(6.64 \pm 0.01) \times 10^{-10}$	$(4.54 \pm 0.01) \times 10^{-10}$	$(1.97 \pm 0.003) \times 10^{-10}$	$(1.75 \pm 0.003) \times 10^{-12}$
Before Selection	$(9.96 \pm 0.05) \times 10^{-2}$	$(6.80 \pm 0.03) \times 10^{-2}$	$(2.95 \pm 0.01) \times 10^{-2}$	$(2.62 \pm 0.01) \times 10^{-4}$
Exactly 2 reco e	$(2.09 \pm 0.02) \times 10^{-4}$	$(4.07 \pm 0.07) \times 10^{-3}$	$(1.48 \pm 0.01) \times 10^{-2}$	$(2.03 \pm 0.01) \times 10^{-4}$
Invariant mass $\neq Z$ boson	$(2.09 \pm 0.02) \times 10^{-4}$	$(4.07 \pm 0.07) \times 10^{-3}$	$(1.48 \pm 0.01) \times 10^{-2}$	$(2.02 \pm 0.01) \times 10^{-4}$
$\not{p}_T > 10$ GeV	$(1.83 \pm 0.02) \times 10^{-4}$	$(3.45 \pm 0.07) \times 10^{-3}$	$(1.35 \pm 0.01) \times 10^{-2}$	$(1.97 \pm 0.01) \times 10^{-4}$
Reconstructed vertex	$(1.74 \pm 0.02) \times 10^{-4}$	$(3.32 \pm 0.07) \times 10^{-3}$	$(1.29 \pm 0.01) \times 10^{-2}$	$(1.94 \pm 0.01) \times 10^{-4}$
$\lvert d_0 \rvert > 5$ mm	$(1.29 \pm 0.02) \times 10^{-4}$	$(2.59 \pm 0.06) \times 10^{-3}$	$(9.17 \pm 0.07) \times 10^{-3}$	0

Process	$Z \to e^+ e^-$	$Z \to b\bar{b}$	$Z \to \tau\bar{\tau}$	$Z \to e^+ e^- \nu\bar{\nu}$
Cross Section [pb]	1.46×10^3	6.65×10^3	1.48×10^3	$(3.05 \pm 0.01) \times 10^{-4}$
Before Selection	$(2.19 \pm 0.01) \times 10^{11}$	$(9.97 \pm 0.05) \times 10^{11}$	$(2.21 \pm 0.01) \times 10^{11}$	$(4.57 \pm 0.02) \times 10^4$
Exactly 2 reco e	$(1.98 \pm 0.01) \times 10^{11}$	$(9.05 \pm 0.13) \times 10^{10}$	$(8.80 \pm 0.02) \times 10^9$	$(3.77 \pm 0.02) \times 10^4$
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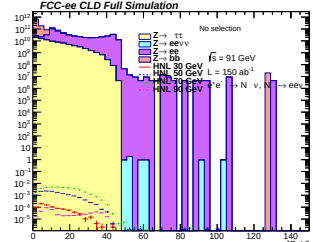
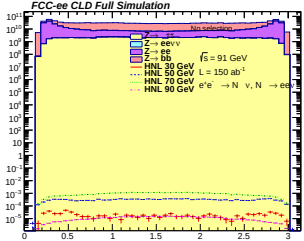
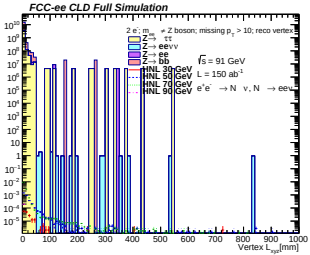
$\not{p}_T > 10$ GeV	$(6.71 \pm 0.54) \times 10^8$	$(1.22 \pm 0.05) \times 10^{10}$	$(3.30 \pm 0.12) \times 10^9$	$(2.98 \pm 0.02) \times 10^4$
Reconstructed vertex	$(6.10 \pm 0.52) \times 10^8$	$(1.21 \pm 0.05) \times 10^{10}$	$(3.24 \pm 0.12) \times 10^9$	$(2.91 \pm 0.02) \times 10^4$
$\lvert d_0 \rvert > 5$ mm	0	0	0	0

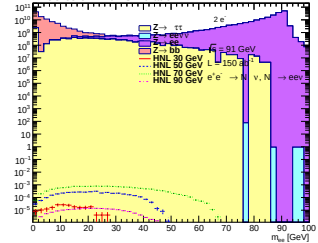
HNL study

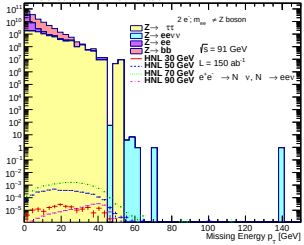
Analysis stack











HNL study

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1×10^{-1}	2.29	343,200,000
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1×10^{-3}	2.29×10^{-4}	34,320
1×10^{-4}	2.29×10^{-6}	343
1×10^{-5}	2.29×10^{-8}	3
1×10^{-6}	2.29×10^{-10}	0

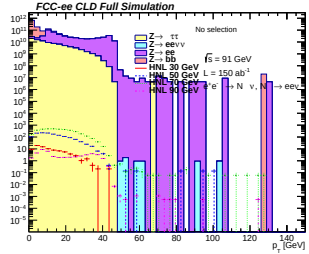
- HNL cross sections depend mainly of the mixing angle, 1.41×10^{-6} used for the Delphes analysis, first test with ($\times10^5$) on HNL cross sections

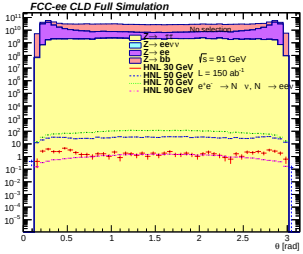
Process	HNL 30 [GeV]	HNL 50 [GeV]	HNL 70 [GeV]	HNL 90 [GeV]
Cross Section [pb] ($\times10^5$)	$(6.64\pm0.01)\times10^{-5}$	$(4.54\pm0.01)\times10^{-5}$	$(6.64\pm0.01)\times10^{-5}$	$(1.75\pm0.03)\times10^{-7}$
Before selection	$9.96\pm0.05\times10^{2}$	$6.80\pm0.03\times10^{2}$	$2.95\pm0.01\times10^{2}$	2.62 ± 0.01
Exactly 2 reco e	2.09 ± 0.21	40.7 ± 0.7	148 ± 0.9	2.03 ± 0.01
Invariant mass $\neq Z$ boson	2.09 ± 0.21	40.7 ± 0.7	148 ± 0.9	2.02 ± 0.01
$\not{p}_T>10$ GeV	1.83 ± 0.20	34.5 ± 0.7	135 ± 0.9	1.97 ± 0.01
Reconstructed vertex	1.74 ± 0.19	33.2 ± 0.7	129 ± 0.9	1.94 ± 0.01
$\lvert d_0\rvert>5$ mm	1.29 ± 0.16	25.9 ± 0.6	91.7 ± 0.7	0

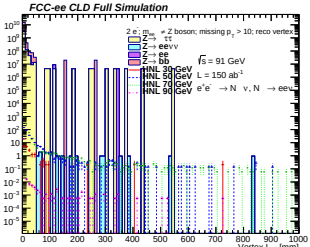
Process	$Z\to e^+e^-$	$Z\to b\bar{b}$	$Z\to\tau^+\tau^-$	$Z\to e^+e^-\nu\bar{\nu}$
Cross Section [pb]	1.46×10^{3}	6.65×10^{3}	1.48×10^{3}	$(3.05\pm0.01)\times10^{-4}$
Before selection	$(2.19\pm0.01)\times10^{11}$	$(9.97\pm0.05)\times10^{11}$	$(2.21\pm0.01)\times10^{11}$	$(4.57\pm0.02)\times10^{4}$
Exactly 2 reco e	$(1.98\pm0.01)\times10^{11}$	$(9.05\pm0.13)\times10^{10}$	$(8.80\pm0.02)\times10^{9}$	$(3.77\pm0.02)\times10^{4}$
Invariant mass $\neq Z$ boson	$(3.92\pm0.04)\times10^{10}$	$(9.05\pm0.13)\times10^{10}$	$(8.87\pm0.02)\times10^{9}$	$(3.76\pm0.02)\times10^{4}$
$\not{p}_T>10$ GeV	$(6.71\pm0.05)\times10^{8}$	$(1.22\pm0.05)\times10^{10}$	$(3.30\pm0.01)\times10^{9}$	$(2.98\pm0.02)\times10^{4}$
Reconstructed vertex	$(6.10\pm0.05)\times10^{8}$	$(1.21\pm0.05)\times10^{10}$	$(3.24\pm0.01)\times10^{9}$	$(2.91\pm0.02)\times10^{4}$
$\lvert d_0\rvert>5$ mm	0	0	0	0

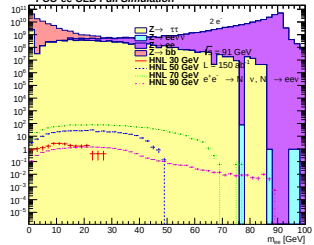
HNL study

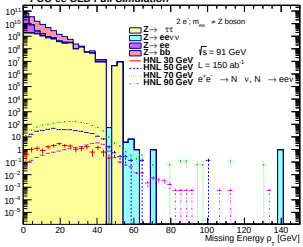
Analysis stack – x10^5 HNL cross sections











- Signal extraction appears to be challenging

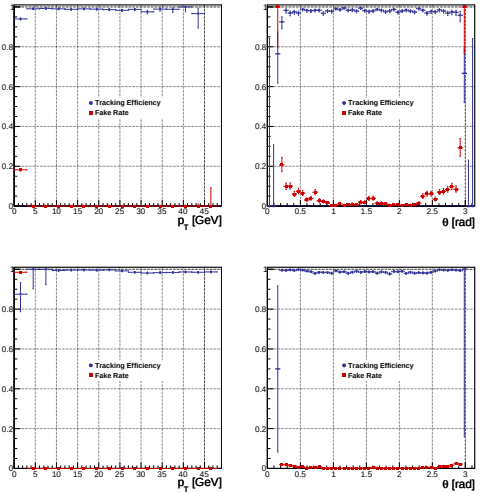
HNL study

Tracking Efficiency

Tracking Efficiency defined as $\frac{GenElectronsMatched2Tracks}{AllGenElectrons}$

Fake Rate defined as $\frac{TracksNotMatched}{AllRecoElectrons}$

- Tracking Efficiency and Fake Rate for Z $\rightarrow \tau\tau$
  - Good tracking efficiency and low fake rate
- Tracking Efficiency and Fake Rate for Z $\rightarrow ee$
  - Good tracking efficiency and low fake rate



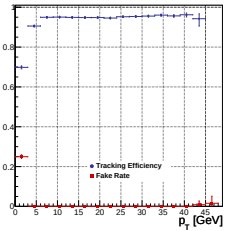
HNL study

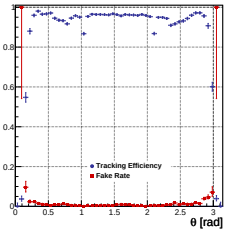
Tracking Efficiency

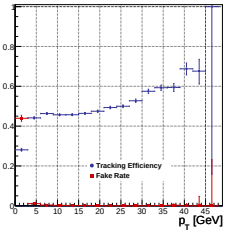
Tracking Efficiency defined as $\frac{GenElectronsMatched2Tracks}{AllGenElectrons}$

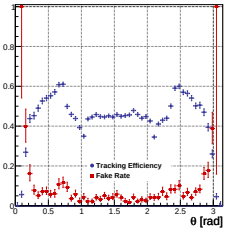
Fake Rate defined as $\frac{TracksNotMatched}{AllRecoElectrons}$

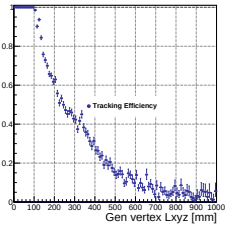
- Tracking Efficiency and Fake Rate for **HNL** $m_N = 70$ **GeV**
  - Lower efficiency compared to 90 GeV
- Tracking Efficiency and Fake Rate for **HNL** $m_N = 50$ **GeV**
  - The more vertices are displaced, the lower the efficiency





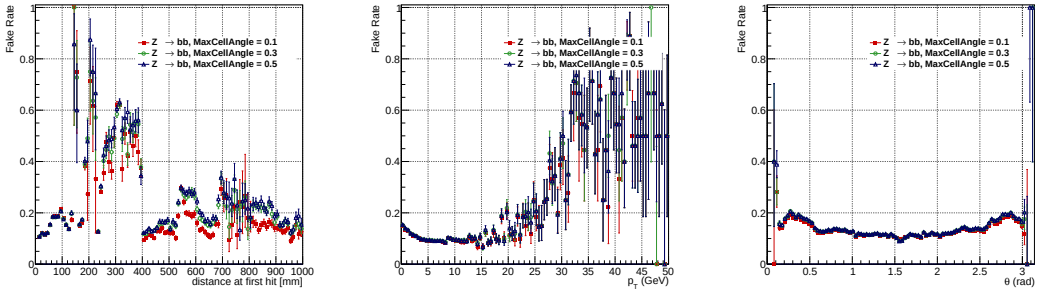






HNL study

Tracking issue – Investigation in Conformal Tracking – Efficiency and Fake Rate



- Although the values of *MaxCellAngle* and *MaxCellAngleRZ* do not significantly affect the Fake Rate, it remains higher than expected compared to the CLD note ‡.

‡ arxiv.org/pdf/1911.12230