Soutenance à mi-parcours

Comité de suivi Individuel

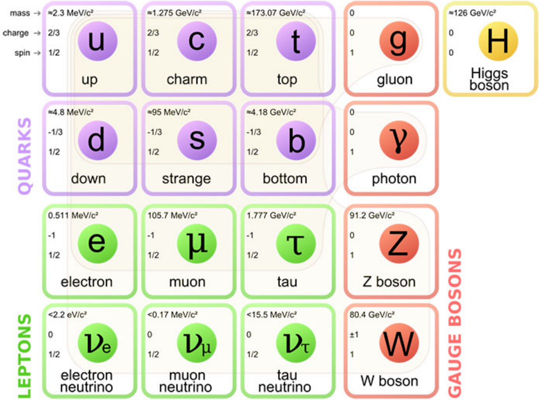
Gaelle Sadowski

6 june 2024

Table of Contents

Table of Contents

Standard Model of particle physics



Based on quantum field theory, describes how particles interact via exchange of gauge bosons

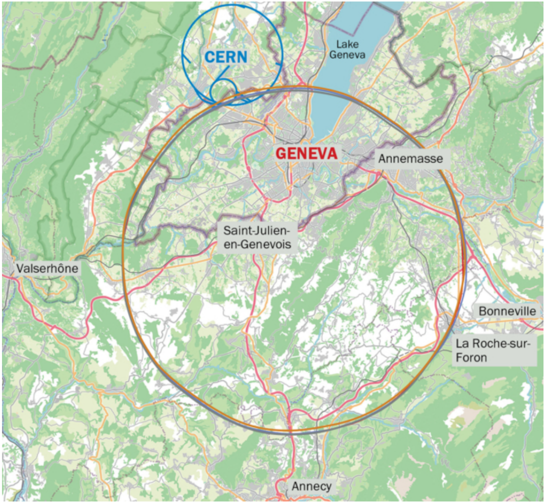
Fundamental Particles

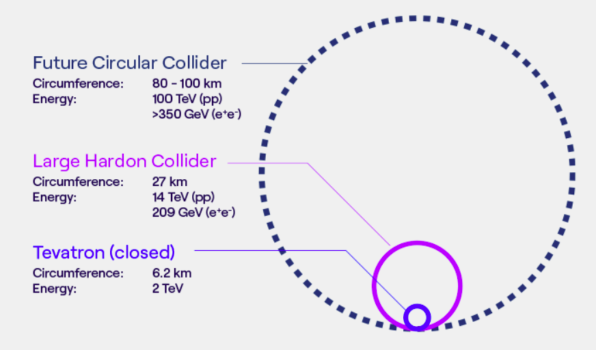
- **Quarks:** Building blocks of matter (protons and neutrons), 6 flavours
- **Leptons:** Electrons and neutrinos, 3 flavours and their corresponding neutrinos
- **Gauge Bosons:** Force carriers. Include photon (electromagnetism), W and Z bosons (weak force), and gluons (strong force)
- **Higgs Boson:** Provides mass to other particles via the Higgs mechanism

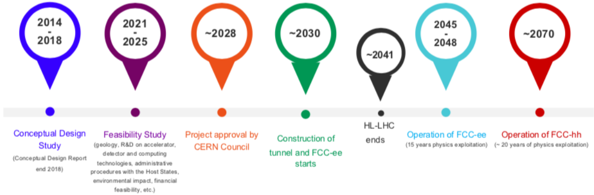
Why Go Beyond the Standard Model

- Does not include gravity
- Does not explain dark matter and dark energy
- ...

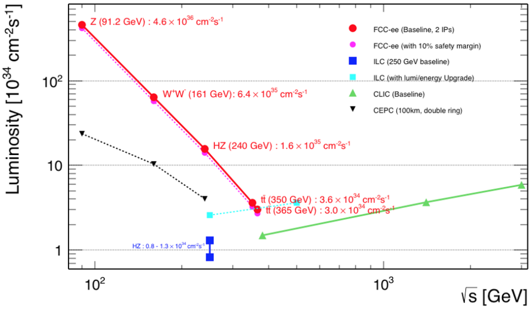
FCC (Future Circular Colider)







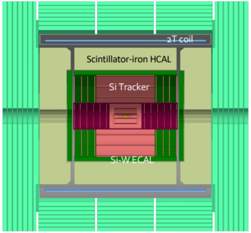
Future Colliders



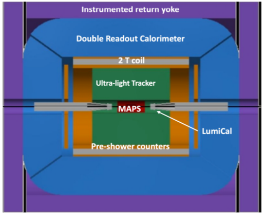
Importance of e^+e^- Colliders

- **Less Background Noise**
- **Well-defined Initial State**
- **High Precision Measurements:** can produce very clean environments with well-defined initial conditions, allowing for extremely precise measurements such as detecting subtle deviations from SM predictions that could provide indirect evidence of new physics

Detector concept at FCCee



CLD



IDEA

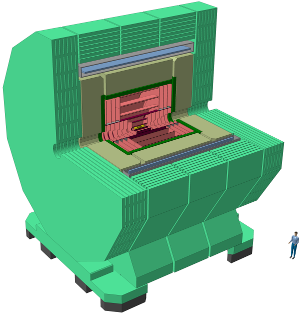
- Consolidated option based on the detector design developed for CLIC[a]
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil outside calorimeter system
- Long standing concept, largely studied with full simulation

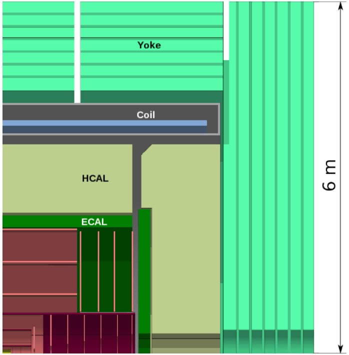
- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil inside calorimeter system

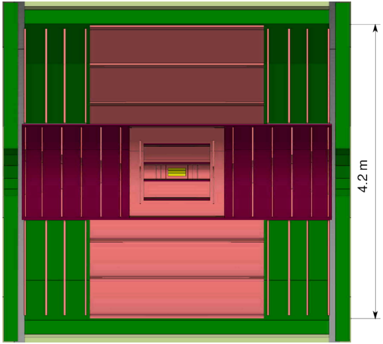
[a] CLIC detector

Goals

- Define different geometries for vertex and tracker
- Study detector tracking and vertexing performance for physics, as well as flavour identification and sensitivity to new physics
- Full Simulation is needed to have more precise results, the detector concept CLD* will be used for these studies

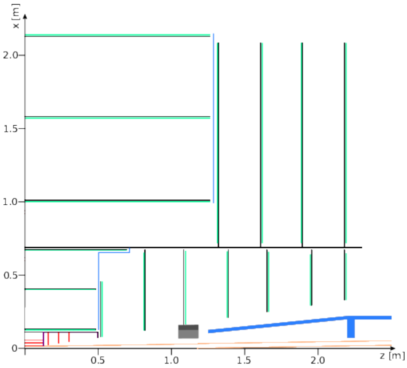




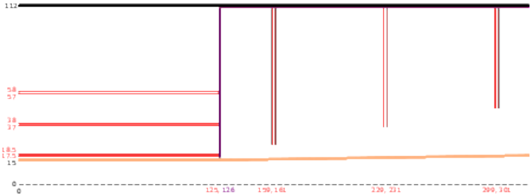


*CLIC-like detector

CLD tracker geometry



- **Vertex Detector** with 3 μm spatial resolution pixels



- **Inner and Outer Silicon Tracker**, mostly 50 μm pitch strips
  - 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
  - 200 μm Silicon thickness, 50 μm $\times$ 0.3 mm cell size, 7 μm $\times$ 90 μm single point resolution (except first inner tracker disk, 5 $\times$ 5 μm^2)
- Tracking optimisation with **full silicon tracker**

  - large material budget
  - No space for PID[a]

  - robust technology
  - high single point resolution
  - tune to sustain higher particle rate

[a] Particle identification detector

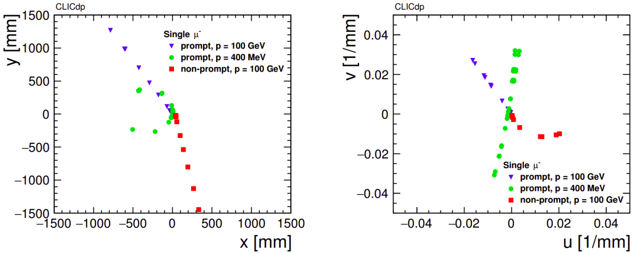
More details on CLD_o1_v04

Tracking

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

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

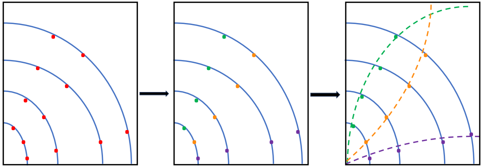


- **Cellular Automaton Track Finding:** for pattern recognition

*Conformal Tracking @CLIC

Tracking

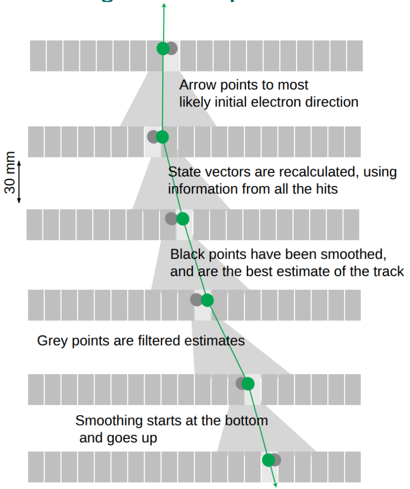
Track Finding

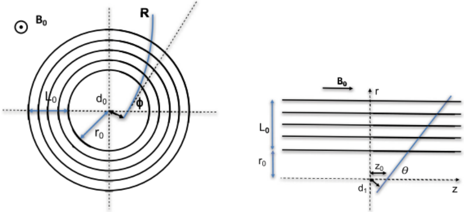


- **VXDBarrel:** build track seeds in the vertex barrel
- **VXDEndcap:** extend track seed through the vertex endcaps
- **LowerCellAngle1:** build track candidates with tight cuts for high-p_T tracks
- **LowerCellAngle2:** build track candidates with looser cuts to reconstruct low-p_T tracks
- **Tracker:**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

Tracking

Track Fitting and Track parameters





- Kalman Filter for track fitting to determine the best track parameters
  - Curvature Ω
  - Azimuthal Angle ϕ_0
  - Impact Parameter d_0
  - Z-position z_0
  - Slope $\tan\lambda$

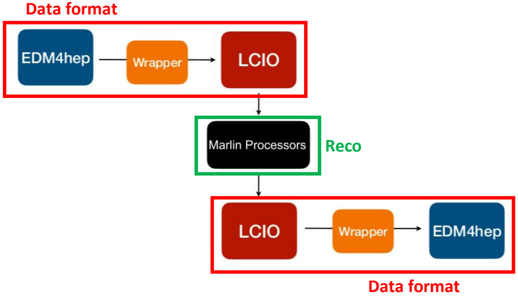
  Furthermore we can also calculate:
  - momentum p
  - transverse momentum p_T
- We usually consider d_0 and p_T resolution because they are complementary and give information on the track quality

FCC Software

Simulation and Reconstruction

- Simulation and reconstruction are done with key4HEP software

- Reconstruction is done with Marlin, using **lcio** format as input/output
  - Possibility of using EDM4hep format via wrappers
  - ⚠ But it had never really been used before; several bugs were discovered during the conversion, making it impossible to run the reconstruction...
    I made several bug reports and the issues were fixed by experts



FCC Software

FCCAnalyses – Fast Sim & Full Sim

- Originally designed for Delphes
  - ► Matching procedures between simulated particles and reconstructed particles/tracks (needed to estimate tracking resolutions), not compatible with a full simulation output
  - ✓ Creation of a workaround allowing the matching, but only working in the case of single-particle events (particle gun)

Fast Sim (Delphes)

- No reconstruction, only smearing of simulated position, no account for tracking efficiency (for displaced tracks)

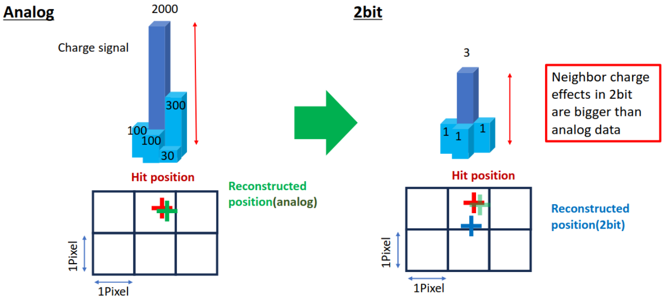
Full Sim

- Geant4 simulation with particle-matter interaction.

Table of Contents

Digitisation

Neighbour charge sharing

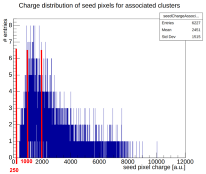


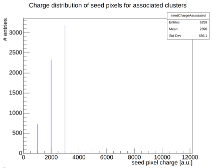
Towa Katsuno

- Analog signal takes too long and requires too much power
- Digitiation will transform analog signal for pixel charge to binary signal (1bit, 2 bit, 3bit,...)
- residuals position is the difference between hit position in detector and the reconstructed hit position
- Reconstructed hit position is determine with the charge sharing with the neighbours inside the cluster
- **Cluster:** centered on the seed pixel (with the largest side) and made of a grid of 3x3 pixels. Neighbour pixels are referring to pixel next to the seed pixel within a cluster.

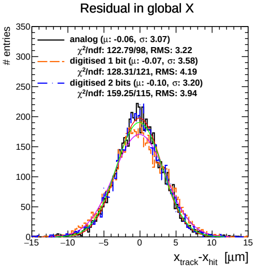
CE65

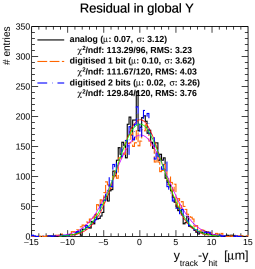
- Use of existent framework
  - Implementation of digitisation for seed pixel signal





  - Compare position residuals depending on N_{bits}



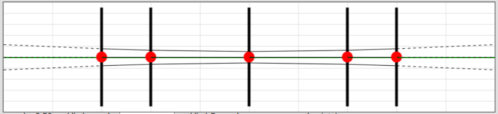


analog → red fit, 1 bit → purple fit, 2 bit → green fit

CE65

Spacial resolution

$$\sigma^2_{res} = \sigma^2_{tel} + \sigma^2_{DUT} + \sigma^2_{m.s.}$$



x-scale: 2.50 cm/div | y-scale: 5 µm/div | *Drag planes or measured points!*

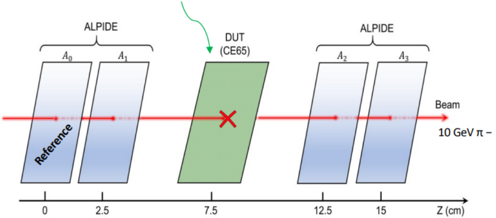
Particle: π⁺ / π⁻ (Pion) | Momentum: 10 GeV/c

Layout		Sensor			Tracking	MC track position		
Plane #	Position (cm)	Thickness (% X/X_0)	Resolution (µm)	Tracking used	Resolution (µm)	real (µm)	measured (µm)	reconstructed (µm)
	-5				5.77	0.0		0.0
1	0	0.05	5.0	☑	3.87	0.0	0.0	0.0
2	2.5	0.05	5.0	☑	3.19	0.0	0.0	0.0
3	7.5	0.05	5.0	☐	2.60	0.0	0.0	0.0
4	12.5	0.05	5.0	☑	3.19	0.0	0.0	0.0
5	15.0	0.05	5.0	☑	3.87	0.0	0.0	0.0
	20.0				5.77	0.0		0.0

equidistant | all as #1 | all as #1 | MC | measure | MC & measure

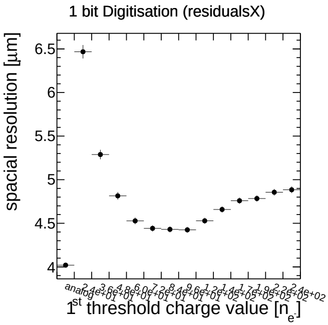
σ^2_{tel} and $\sigma^2_{m.s.}$ determined with telescope tracking tool

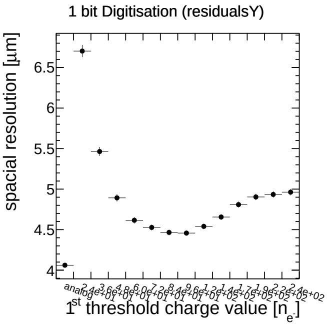
- Experimental set up used (file used: `PS-A4_HV10-beam.raw`)



CE65

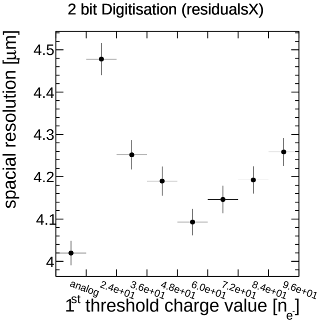
Threshold optimisation for 1 bit

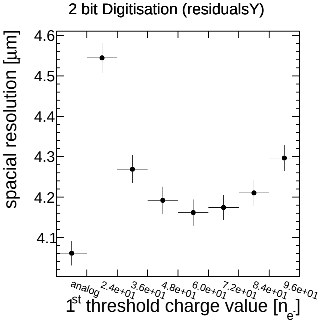




- Spacial resolution as function of 1st threshold cut
- Only 1 threshold to optimise
- Optimium $\sigma_{residualsX} \longrightarrow$ 17 % difference

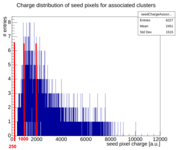
CE65





- 3 thresholds to optimise...

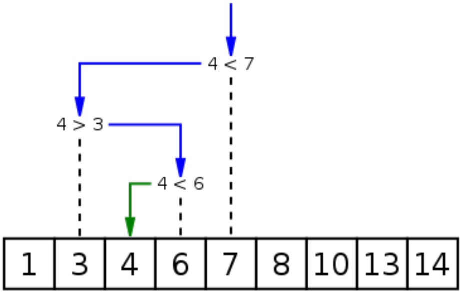
- Scan of 1^{st} threshold value
- 2^{nd} and 3^{rd} thresholds visually choose



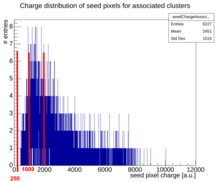
CE65

Thresholds optimisation for 2 bits

- Optimisation with binary search algorithm (dichotomy)



- Results highly dependent on initial conditions
  - Method used: starting with arbitrary values and get a first optimum



  - Start again with the previously found optimum
  - Repeat until no better optimum found
  - Redo with other starting values and so on

  ⇒ very long
  - Need to investigate charge sharing between hit pixel (seed) and neighbours for optimisation

CE65

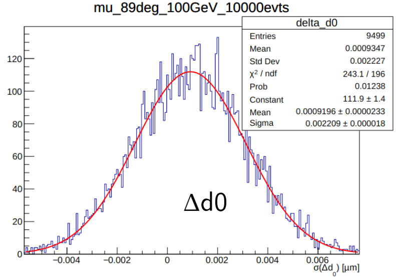
Conclusion

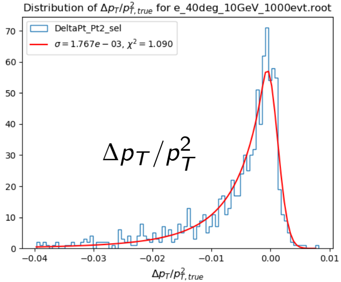
- Implementation of a digitisation code
- Look at first results, good result for 2 bits digitisation
- Next steps
  - Analysis of new test beam data to compare result
  - Need to investigate charge sharing between hit pixel (seed) and neighbours for optimisation

Table of Contents

Tracking resolution

- Simulate **particle gun** events
  - Single particle event with fixed momentum and θ and flat ϕ
  - Done with muons, electrons and pions
- Matching reconstructed tracks – simulated particle
- Calculation of resolution: $\sigma(\Delta = \text{reco - true})$
  - For p and pT, resolution: $\sigma((\Delta = \text{reco - true}) \; / \; \text{true}^2)$
  - Resolution is the width of the gaussian fit, or crystal ball fit for electron momentum
- Calculate resolutions by changing VTX resolution
  - Defined as the smearing for simulated hits with resolution VTX values (3 μm, 5 μm,...) as the Gaussian width
- Non existent framework to produce performance plots, need to create one

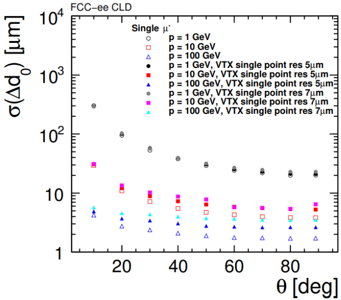




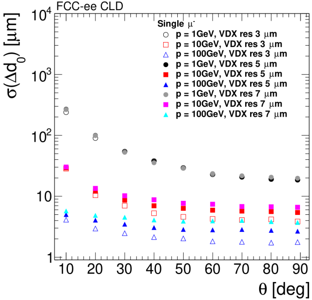
Tracking Performance

First step: reproduce performance plot with different framework – CLD_o1_v04 geometry

CLD - A Detector Concept for the FCC-ee
arXiv:1911.12230v3



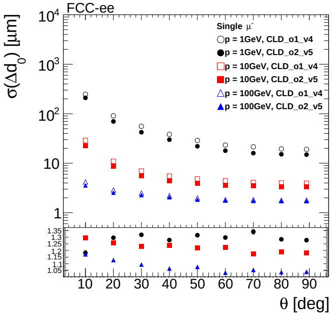
Current study



- New implementation of the performance plots gives comparable results than the CLD paper
- Study of new geometries is possible

Effect of shortened vertex detector and BeamPipe material budget

BeamPipe and Vertex geometry – CLD_o1_v04 & CLD_o2_v05 = smaller more realistic BeamPipe, adapted Vertex



- Improvement of the d_0 resolution in the new geometry (o2_v05)
  - **Smaller vertex radius compensates fully for the increased material budget in beam pipe**

CLD_o1_v04

- BeamPipe **radius**: **15** mm
- BeamPipe **material**: Beryllium
- BeamPipe **thickness**: **1.2** mm + 5 μm gold
- **X/X0 = 0.45 %**

CLD_o2_v05

- BeamPipe **radius**: **10** mm
- BeamPipe **material**: AlBeMet 0.35 mm + paraffin 1 mm + AlBeMet 0.35 mm
- BeamPipe **thickness**: **1.7** mm + 5 μm gold
- **X/X0 = 0.61 %** ⇒ **+ 33 % material budget**

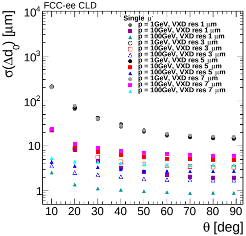
Vertex Barrel [mm]	R_1	R_2	R_3	L
o1_v04	17.5	37	57	125
o2_v05	**13.0**	**35**	**57**	**109**

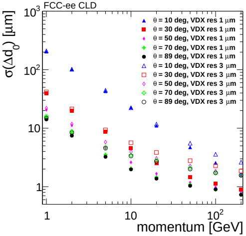
CLD_01_v04: BeamPipe material 100 % Be, BeamPipe radius = 15 mm
CLD_02_v05: BeamPipe material AlBeMet + paraffin, BeamPipe radius = 10 mm

Effect of vertex spatial resolution

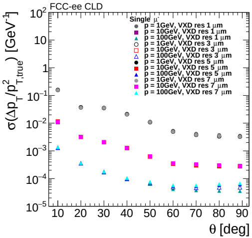
d_0 & pT resolution – single μ^- – CLD_o2_v05 (10k events)

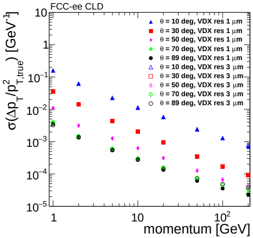
- d_0
  As expected, very sensitive to intern layer, particularly at high p_T
  Material budget is dominant for low p_T



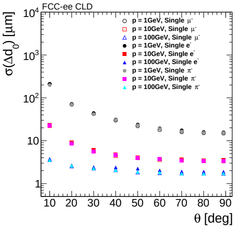


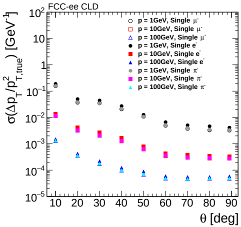
- p_T
  Effect is smaller, some effect at high impulsion in barrel





- μ^-, e^- & π^-

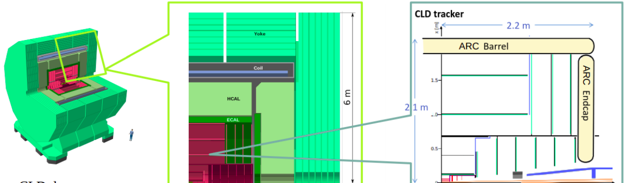




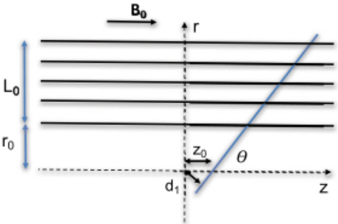
Digitisation is made by smearing simulated hits with spatial resolution values as the Gaussian width

CLD with PID

Tracker geometry – CLD_o2_v05 & CLD_o3_v01 = ARC*



CLD detector



doi.org/10.1016/j.nima.2018.08.078

$\Longrightarrow$ **Need space**

Outer Tracker Barrel [mm]	R_1	R_2	R_3
o2_v05	1000	1568	2136
o3_v01	**1000**	**1446.8**	**1849.2**

Outer Tracker Endcap [mm]	Z_0	Z_1	Z_2	Z_3
o2_v05	1310	1617	1883	2190
o3_v01	**1310**	**1547**	**1752**	**1990**

Inner tracker endcap was shrunk as well

$$\Delta d_0|_{res} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\frac{\Delta p_T}{p_T}|_{res} \approx \frac{12\sigma_{r\phi}p_T}{0.3B_0L_0^2}\sqrt{\frac{5}{N+5}}$$

$\Rightarrow$ **lever arm reduced by 10 %**

$\Rightarrow$ p_T **res should degrade by** $\approx 20\%$

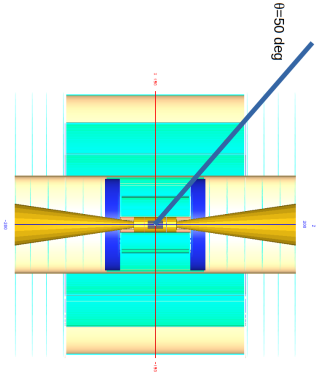
CLD_03_v01: CLD_02_v05 with shrunk Outer Tracker + PID detector

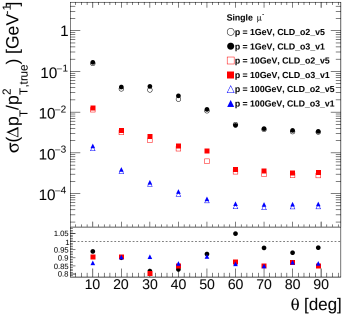
*10.1016/j.nima.2019.02.009 and adapted trackers

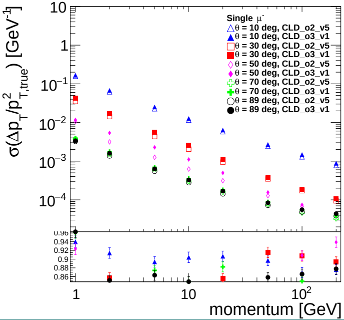
CLD with PID

Tracker geometry – CLD_o2_v05 & CLD_o3_v01

- p_T resolution depend mainly on lever arm
- Differences observed are compatible with analytic formula
- For $\theta = 50\ °$: transition Barrel / Endcap





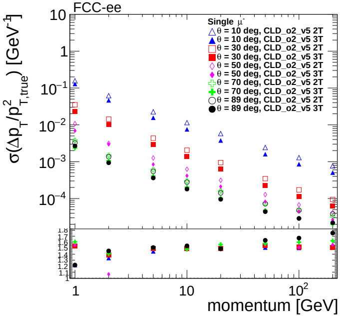


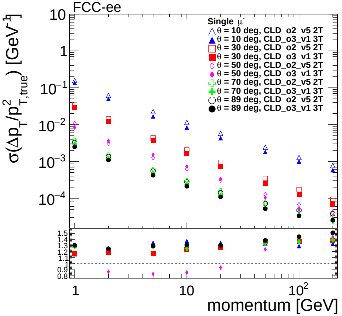
CLD_03_v01: CLD_02_v05 with shrunk Outer Tracker + PID detector

Tracking performance

Effect of magnetic field

- Magnetic field of **2 T** is imposed for Z peak
- **2 T** to **3 T** increase p_T resolution and compensate the loss of p_T resolution caused by the shrunk tracker





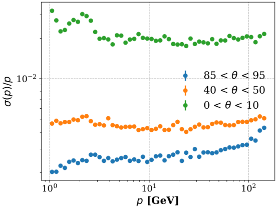
CLD: magnetic field = 2 T

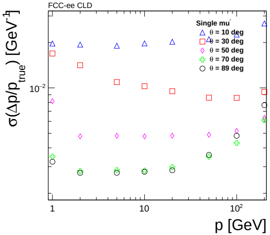
Comparison with Fast Simulation

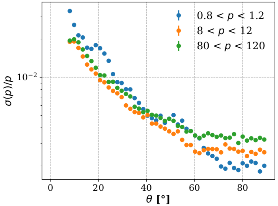
Full Sim & Fast Sim tracking performance – impulsion resolution

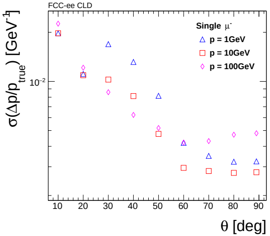
Full Sim

Fast Sim







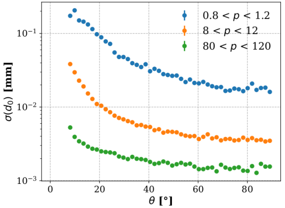


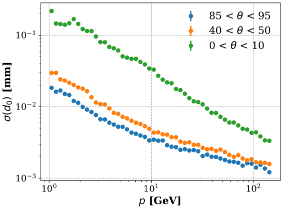
- Impulsion resolution is comparable for FCC-CLD fast and full simulation

Comparison with Fast Simulation

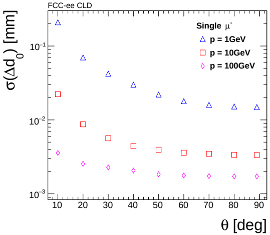
Full Sim & Fast Sim tracking performance – d_0 resolution

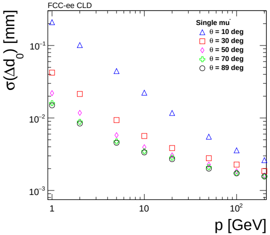
Fast Sim





Full Sim





- d_0 resolution for FCC-CLD fast and full simulation are in agreement

Tracking performance

Summary

- Study track resolution with different single point resolution and tracker (beam pipe) geometries
- Code validated by reproducing CLD paper results (geometry CLD_o1_v04)
- Several spatial resolution for vertex tested, also for 1 micron, to test extreme case (while probably not realistic)
- Improvement of the d0 resolution in the geometry with smaller beam pipe (CLD_o2_v05)
- $\approx$ 20 % degradation of p_T resolution in CLD_o3_v01 with ARC
- Can be recovered by increasing magnetic field to 3 T, p_T resolution even better
- Track resolutions are comparable for FCC-CLD fast and full simulation, for prompt tracks
- Need to investigate vertex reconstruction as well

Table of Contents

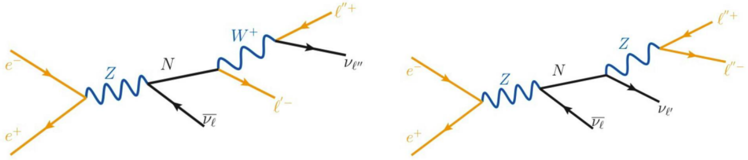
HNL studies

Model

- Heavy Neutral Leptons (HNLs), also known as sterile neutrinos, are hypothetical particles that extend the Standard Model
- HNLs are neutral leptons with masses much larger than the SM neutrinos.
  Unlike SM neutrinos, they do not interact via the weak force but only through mixing with the SM neutrinos

HNL studies

- Generation of Long Lived Particle within the Heavy Neutral Lepton model
- Inherits from FCCee paper (Alimena&al arXiv:2203.05502v4)

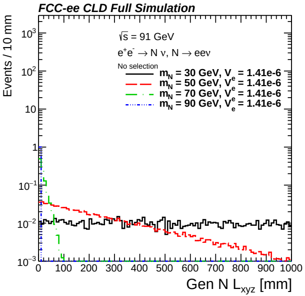


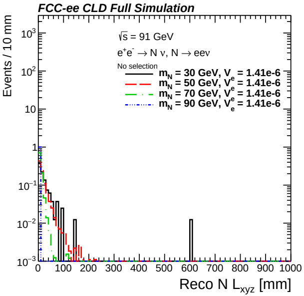
- Production made in the di-electron channels
  - Allows for some comparisons with Fast Sim
  - Very first Full Sim analysis
  - Analysis possibly to be ported on other LLP models

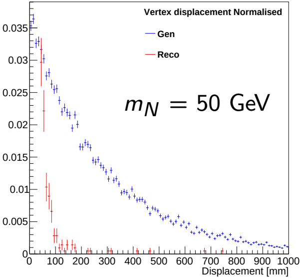
HNL studies

Simulation issue

- We made the generation ourselves
- Issue related to status code with Pythia, fixed now







HNL studies

Reconstruction issue

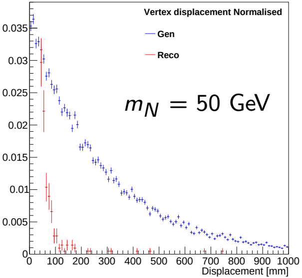
- **Reconstruction issue with CLD_o2_v05 geometry**, smaller radius for first double layer in vertex detector required re-optimisation of track seeds
  - **CLD_o1_v04 geometry used in this HNL study**

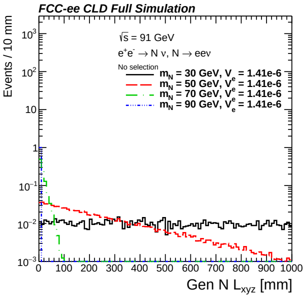
CLD_01_v04: BeamPipe material 100 % Be, BeamPipe radius = 15 mm

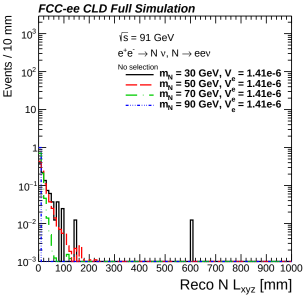
HNL studies

Reconstruction issue

- **Reconstruction issue with CLD_o2_v05 geometry**, smaller radius for first double layer in vertex detector required re-optimisation of track seeds
  - **CLD_o1_v04 geometry used in this HNL study**
- **No track reconstruction is observed beyond a displacement of 100mm.**





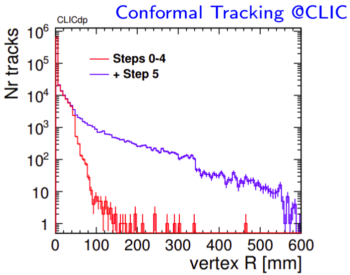


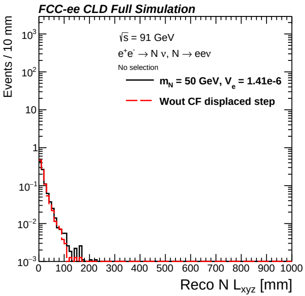
CLD_01_v04: BeamPipe material 100 % Be, BeamPipe radius = 15 mm

HNL study

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





$\Longrightarrow$ Whereas, Conformal Tracking previous study with CLIC dectector suggests a significantly effective reconstruction of displaced tracks

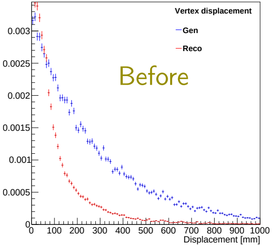
Step 5 is not working as it should

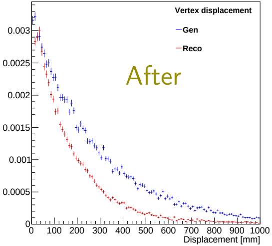
HNL study

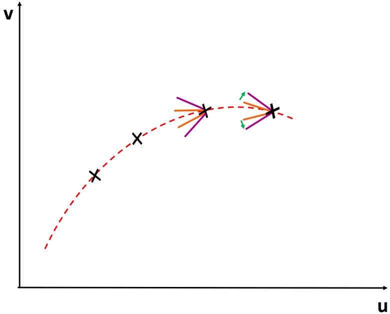
Investigation in conformal tracking

Parameters in step 5:

- **MaxCellAngle: 0.1 $\longrightarrow$ 0.5**
- **MaxCellAngleRZ: 0.1 $\longrightarrow$ 0.5**
- Chi2Cut
- MinClustersOnTrack
- MaxDistance
- SlopeZRange
- HighPTCut







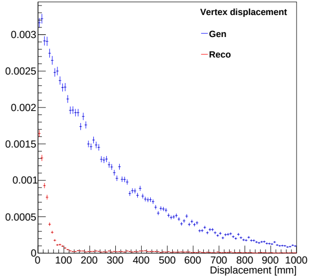
$\times$**2 vertices**, window for extension to next hit was too small for the displaced step in conformal tracking [a]

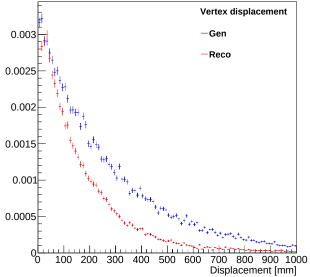
[a] The choice of the 0.5 value was somewhat arbitrary, and further optimisation is required. see bug report

HNL study

Electron reconstruction efficiency

- Issue with electron reconstruction
  - Electrons reconstruction efficiency
    top plot → HNL vertex with reconstructed electron tracks
    bottom plot → HNL vertex with all reconstructed tracks
    ⇒ e^- are not reconstructed properly
  - Reconstructed objects are mainly photons
  - As tracks are present, issue should come from track / cluster association





HNL study

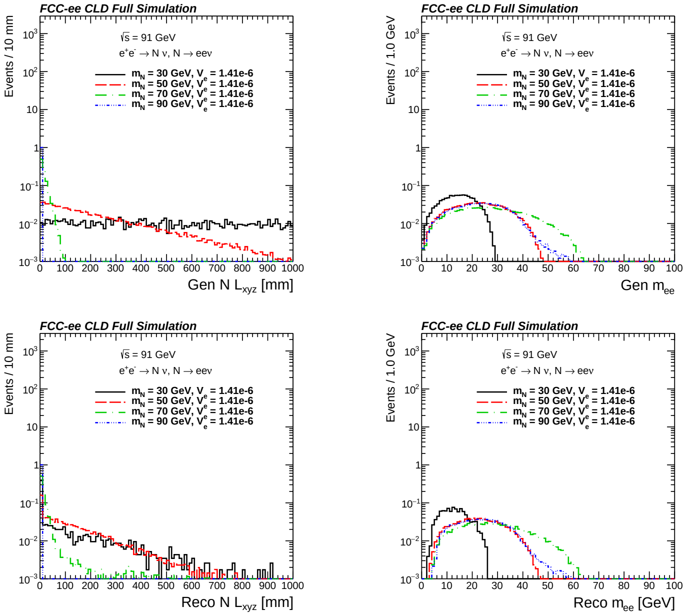
Results (considering all reconstructed tracks)

- **Object selection:**
- Gen HNL vertex r < 1500 and $|z| < 2000$, to match tracker acceptance
- Considering all reconstructed particles matched with Gen electrons ($\Delta R < 0.4$)
- Reco particles momentum > 5 GeV
- **Event selection:**
  - Exactly 2 reco particles with sum charge == 0
  - Invariant mass incompatible with a Z boson : $m > 96$ && < 86 GeV
- Vertex reconstruction with reconstructed tracks

HNL study

Results (considering all reconstructed tracks)

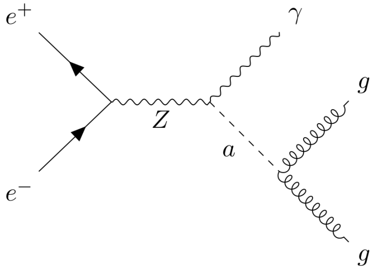
- Displaced tracks are now correctly reconstructed
- Reconstructed vertices up to 600 mm displacement, as expected form Conformal Tracking paper
- Invariant "di-lepton" mass match Gen level



HNL study

Conclusion

- Method to generate HNL events with correct displacement implemented and tested
- Displaced tracks correctly reconstructed
- Next steps
  - Study electron/track reconstruction efficiencies
  - Study displaced vertex reconstruction efficiency
  - Reproduce fast sim analysis
  - Study impact of tracker geometry on physics performance
  - Project to study another LLP model with axion-like particle



Summary & Outlook

- Study track resolution with different single point resolution for different trackers geometries, resolution, magnetic field,...
- Investigation in Conformal Tracking, displaced tracks are now correctly reconstructed
  - Need to investigate electron reconstruction
- Implementation of a digitisation code for CE65
  - Need to investigate neighbours charge sharing for optimisation
- Finish the analysis

Formation and talks

A.79 Calcul Parallèle	21 h
Congrès des doctorants	5 h
MOOC Intégrité scientifique	10 h
Integrity charter in Scientific profession	3 h
Formation 1er Secours PSC1	8 h
Effective reading	12 h
TOTAL	59 / 54 h

Conférence Benezra-Kern	1 h
Conférence EcatalytiX	6 h
Lectures on Common Analysis Techniques in Flavour Physics	18 h
The Vlasov-Boltzmann Equation in Astrophysics	20 h
TOTAL	45 / 54 h

8-21 septembre 2024 : CERN Computing School – Formation validée à hauteur de 18h par l'école doctorale.

Talk: 23 novembre 2023 : FCC France (Strasbourg).

Talk: 31 janvier 2024 : FCC workshop (Annecy).

Talk: Juillet 2024 : The 2024 International Workshop on Future Linear Colliders (LCWS2024) – remote.

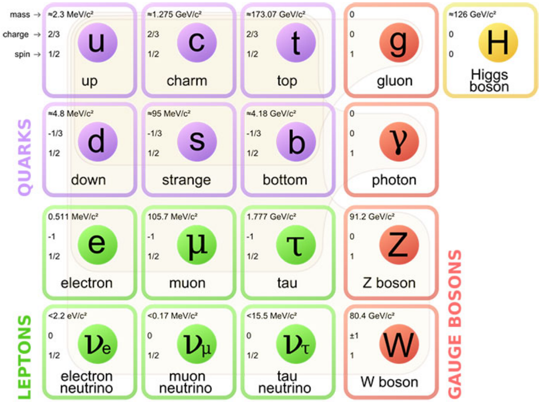
Backup

Tracking performance

Summary

- Study track resolution with different single point resolution and tracker (beam pipe) geometries
- Code validated by reproducing CLD paper results (geometry CLD_o1_v04)
- Several spatial resolution for vertex tested, also for 1 micron, to test extreme case (while probably not realistic)
- Improvement of the d0 resolution in the geometry with smaller beam pipe (CLD_o2_v05)
- $\approx$ 20 % degradation of p_T resolution in CLD_o3_v01 with ARC
- Can be recovered by increasing magnetic field to 3 T, p_T resolution even better
- Track resolutions are comparable for FCC-CLD fast and full simulation, for prompt tracks
- Need to investigate vertex reconstruction as well

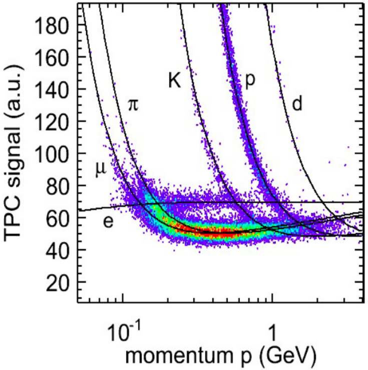
Standard Model of particle physics



Why Go Beyond the Standard Model

- **Unification of Forces:** Gravity is not included, and attempts to unify the strong, weak, and electromagnetic forces require new physics beyond the SM
- **Dark Matter and Dark Energy:** Not account for dark matter and dark energy, which constitute about 95% of the universe's mass-energy content.
- **Matter-Antimatter Asymmetry:** The observed imbalance between matter and antimatter in the universe cannot be fully explained by CP violation
- **Neutrino Masses:** Neutrino oscillations implies that neutrinos have mass, which the SM cannot explain

PID - Particle identification



- **Energy Loss (dE/dx):** The energy a particle loses through matter, depends on its mass and charge