Massachusetts Institute of Technology

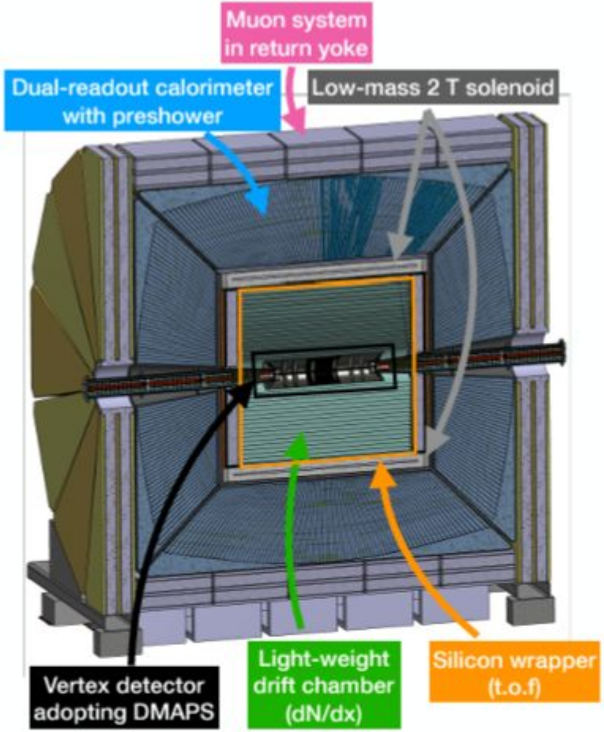
Vertex Detector Study for FCC-ee

Nate Martinez,
Marina Malta Nogueira, Jan Eysermans,
Mariarosaria D’Alfonso, Christoph Paus

10/16/24

IDEA Detector Concept

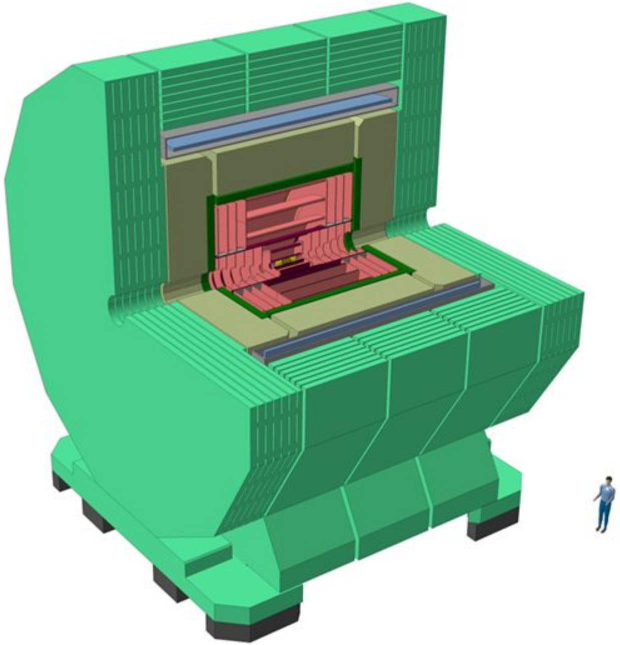
- IDEA (Innovative Detector for e+e- Accelerators) is a proposed detector design for FCC-ee as well as other future electron-positron colliders.
- The design consists of:
  - Silicon pixel vertex detector.
  - Large-volume extremely light drift wire chamber.
  - Layer of silicon micro-strip detectors for timing.
  - Thin low-mass superconducting solenoid coil.
  - Dual-readout calorimeter with preshower detector.
  - Muon chambers based on μRWELL technology inside the magnet return yoke.



https://indico.cern.ch/event/1298458/contributions/5987291/attachments/2875496/5035607/Silicon%20tracker%20optimisation_Armin%20Ilg.pdf

CLD Detector Concept

- CLD (CLIC-Like Detector) is a proposed detector design for FCC-ee similar to the design planned for the Compact Linear Collider (CLIC).
- The design consists of:
    - Silicon vertexing and tracking.
    - Highly granular electromagnetic calorimeter and hadron calorimeter.
    - Solenoid coil outside calorimeter system.



https://cds.cern.ch/record/2697140/files/1911.12230.pdf

Goals

- Evaluate differences between the IDEA and CLD vertex detector in full simulation.
    - Focusing on validating their geometry.
- Analyze the number of components crossed by a particle for both IDEA and CLD as a function of the angles theta and phi.
- Validate the background and signal process configurations:
    - Compare the nominal configuration for the two detectors.
    - Conduct a dedicated study on the effect of the crossing angle.
    - Perform a dedicated study with the background originating from the (000)) vertex.
- Determine hit occupancy for IDEA and CLD in the background events.

Simulation of samples

Both GUINEA-PIG Incoherent Pair Creation (backgrounds) and Z→hadrons (signal, Whizard+Pythia6) have been produced at center-of-mass energy of 91 GeV (Z pole)

IDEA samples

- Stack: /cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh -r 2024-10-01
- Geometry: IDEA_o1_v03

CLD samples

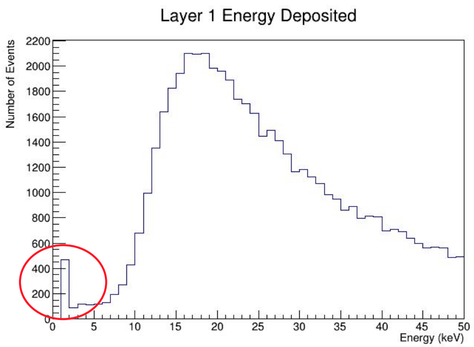
- Stack: /cvmfs/sw.hsf.org/key4hep/setup.sh -r 2024-04-12
- Geometry: CLD_o2_v05

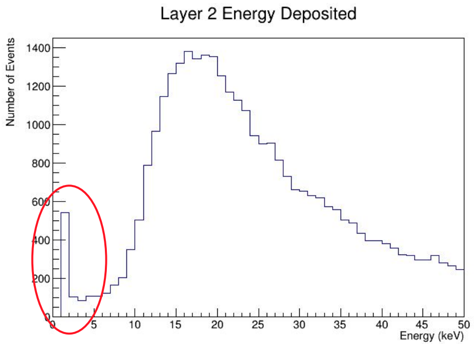
Energy Deposited

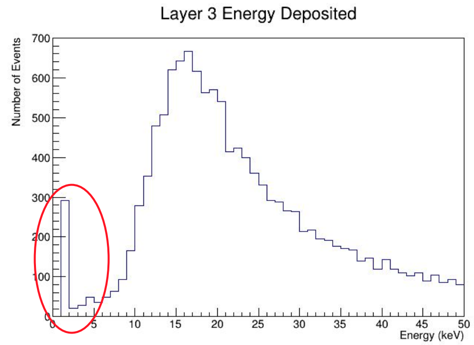
Guinea Pig Energy Deposited (1)

Distributions of energy deposited by particles as they pass through the layer.

- The energy deposited follows a Landau distribution.
- Discovered near 0 peak for energy deposited in each layer:



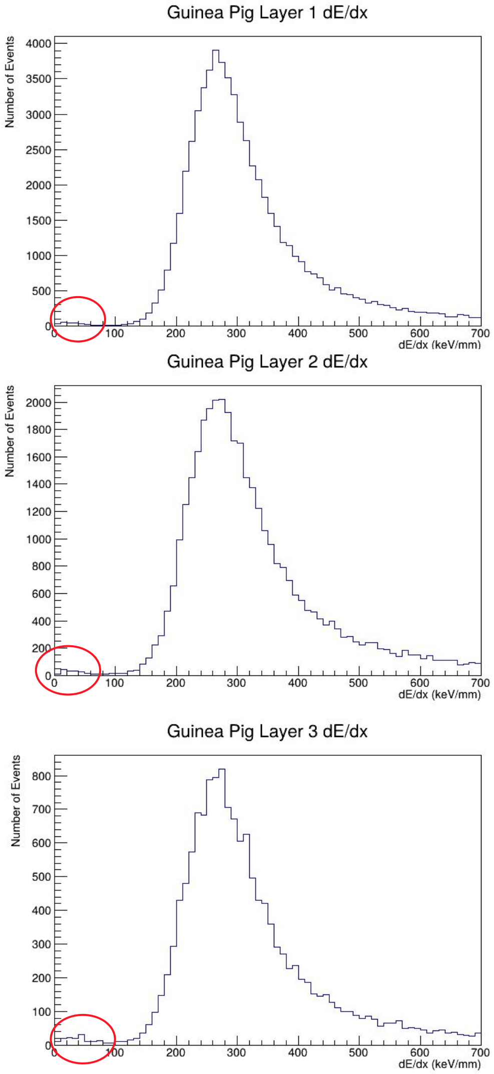




Guinea Pig Energy Deposited (2)

Distributions of energy deposited by particles as they pass through the layer.

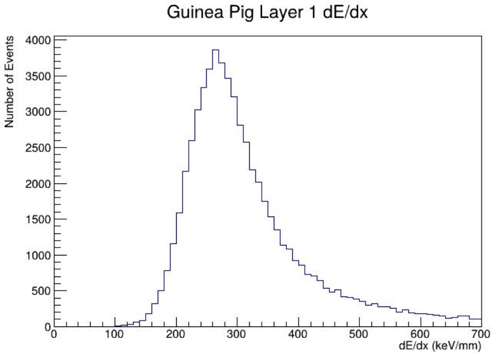
- The energy deposited follows a Landau distribution.
- Discovered near 0 peak for energy deposited in each layer:
    - Geant4 occasionally simulates very small step sizes which results in small energy deposited.
    - This can be resolved by dividing energy deposited by path length (dE/dx).

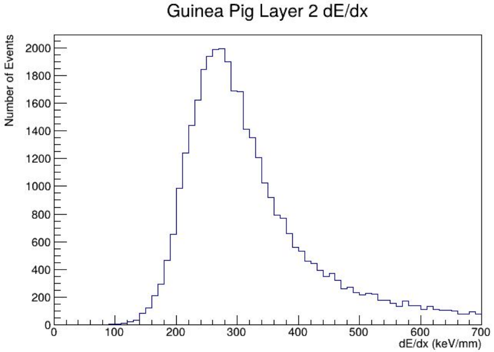


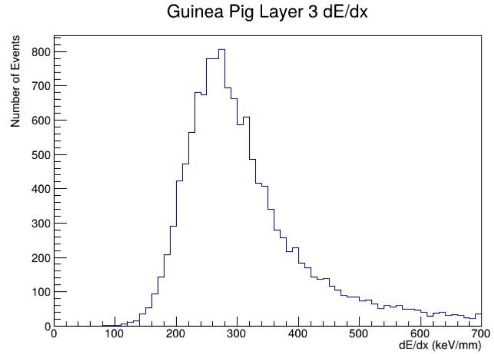
Guinea Pig Energy Deposited (3)

Energy deposited follows a landau distribution.

- Discovered near 0 peak for energy deposited in each layer:
    - Geant4 occasionally simulates very small step sizes which results in small energy deposited.
    - This can be resolved by dividing energy deposited by path length (dE/dx).
    - Also, in the event generation, sometimes very low energy "secondary" Monte Carlo particles are produced which can cause low energy hits. These can be removed with .isProducedBySecondary().







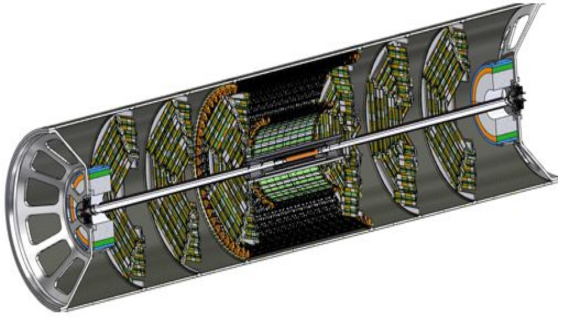
Trajectory Tracking

Trajectory Tracking

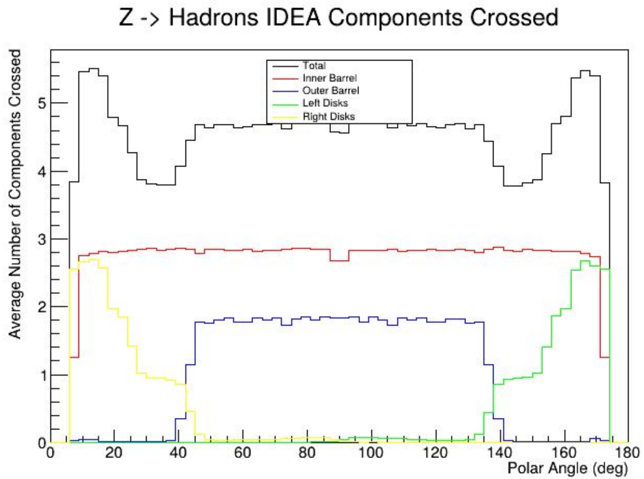
- The goal of this study is to determine the number of detector components each particle crosses.
- By iterating over MC Particles and utilizing Geant4's built-in association, the number of SimHits associated to each particle can be determined.
- In Signal events (Z -> Hadrons) particles have high momentum -> many components crossed.
- In Background events (IPC) particles have low momentum -> few components crossed.
- The objective is to identify regions of low acceptance.

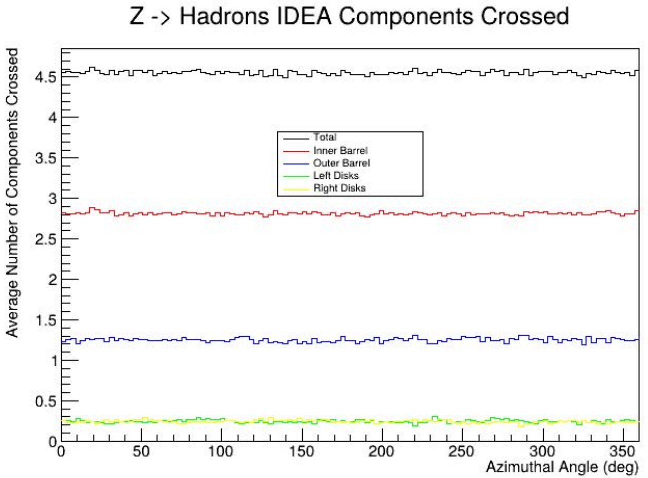
IDEA Trajectory Tracking

- These plots show the average number of components crossed as a function of phi and theta.
- IDEA has an inner barrel (3 layers), outer barrel (2 layers) and disks (3 each side).
- Reduced acceptance at 30 deg and 150 deg in theta.



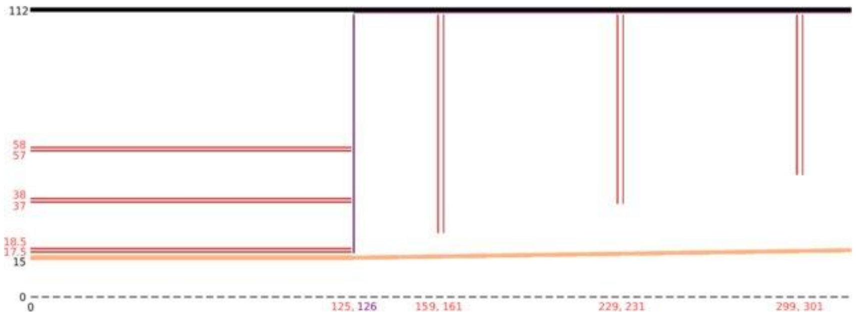
Layer #	Radius [mm]	No staves	No modules /stave	Total Length [mm]	Active Area [cm²]	Power [W]
1	13.7	15	6	217.40	241.92	12
2	23.7	24	10	346.20	645.12	32
3	34 & 35.60	36	16	539.40	1548.29	77

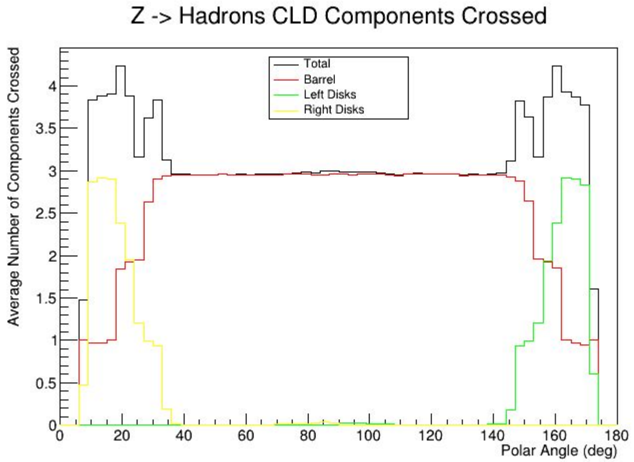




CLD Trajectory Tracking

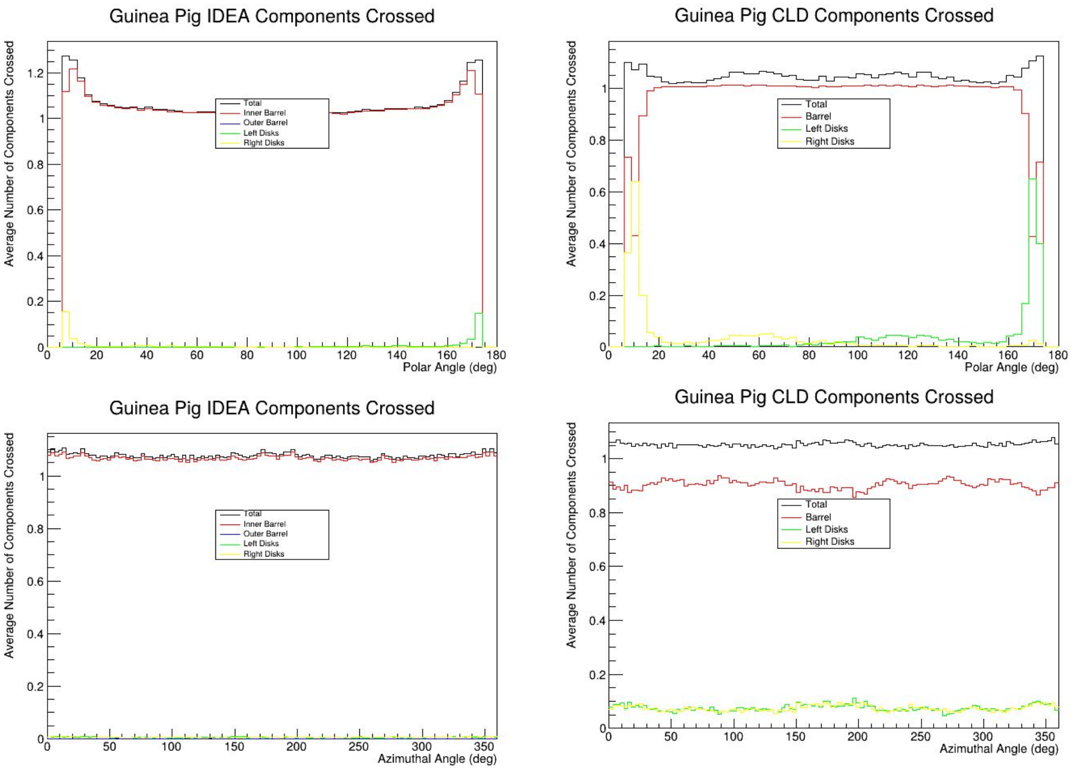
- These plots show the average number of components crossed as a function of phi and theta.
- The CLD detector has 3 barrel double layers and 3 double-layered disks on each side (shown below)
- Here double layers treated as a single one.
- More uniform acceptance.





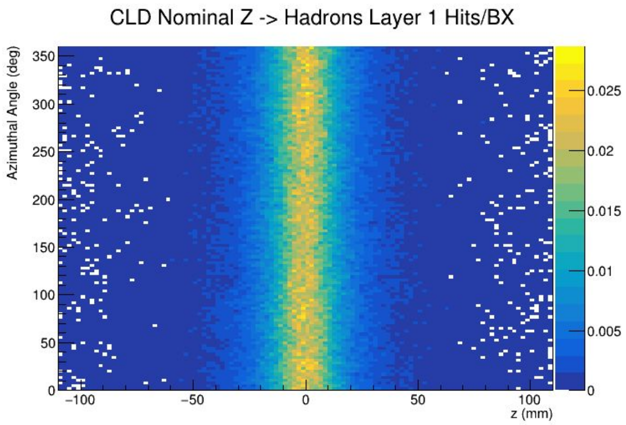
Trajectory Tracking - Guinea Pig

- For IDEA and CLD, it is very rare for the background particles to cross more than just the inner layer.

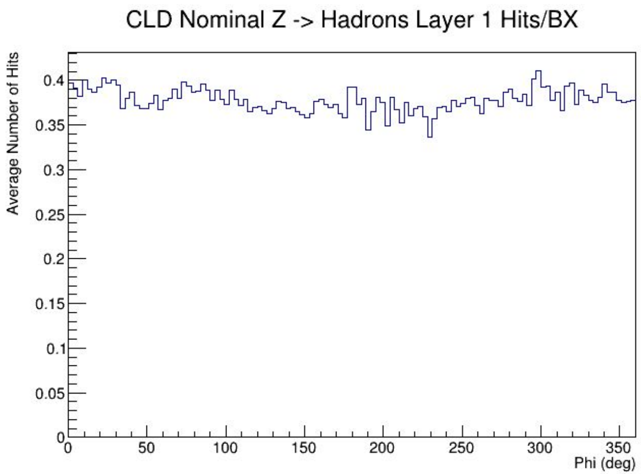


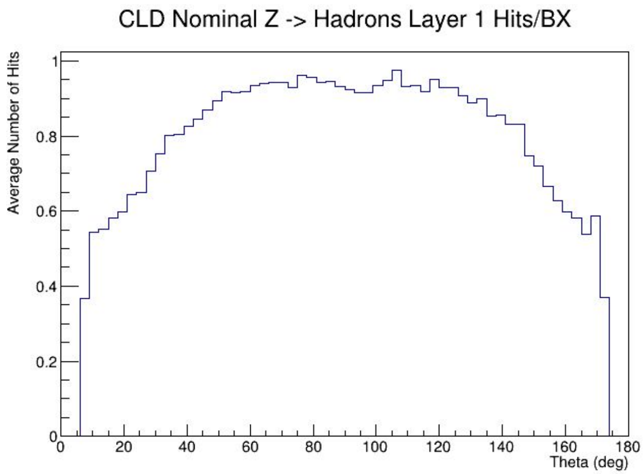
Hit Maps

CLD Z -> Hadron

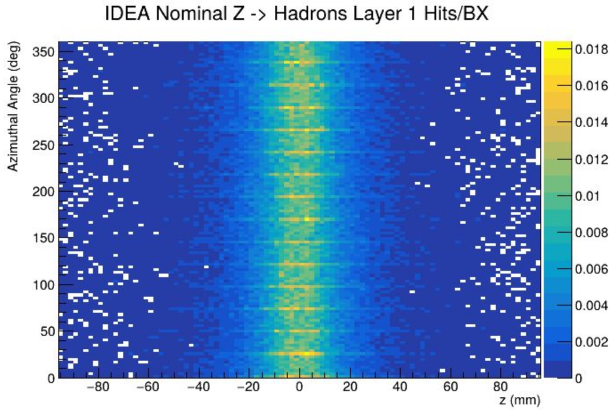


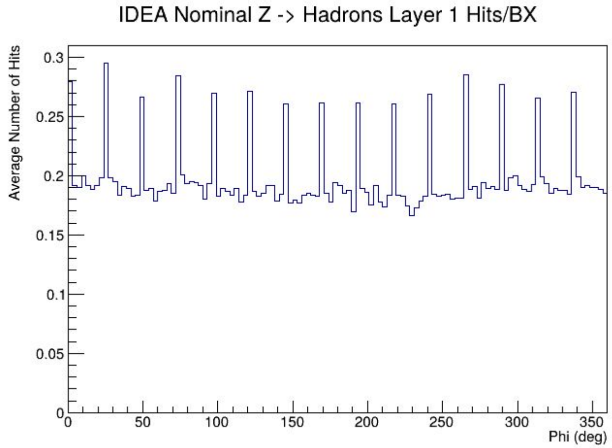
- These plots show the average number of hits per event as a function of z and phi (above), phi (top right), and theta (bottom right).
- Uniform in phi and central in theta, as expected for Z -> Hadron events.

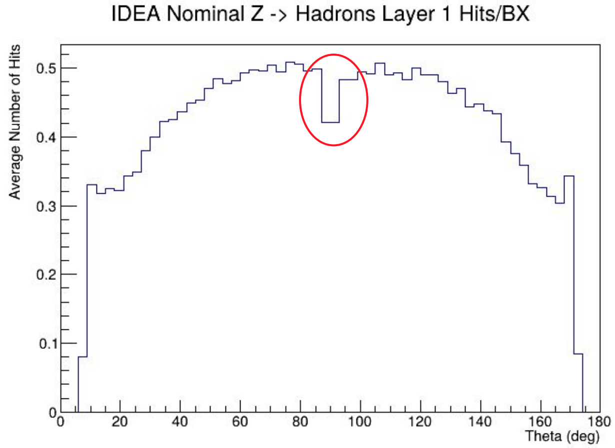




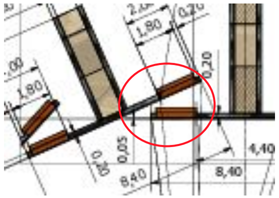
IDEA Z -> Hadrons





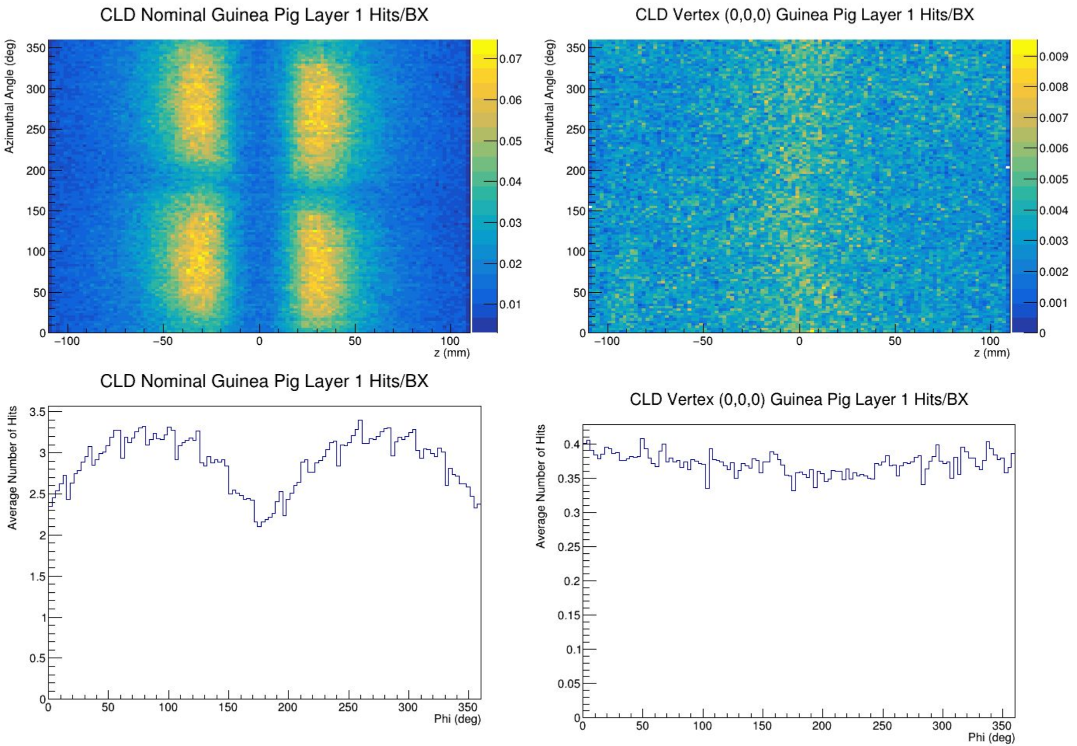


- For the Z -> Hadron events, a hole is clearly visible in the IDEA detector on the theta plot.
    - Likely a gap where the two halves of the detector come together.
- Spikes in phi are due to overlap between detector modules used by IDEA.



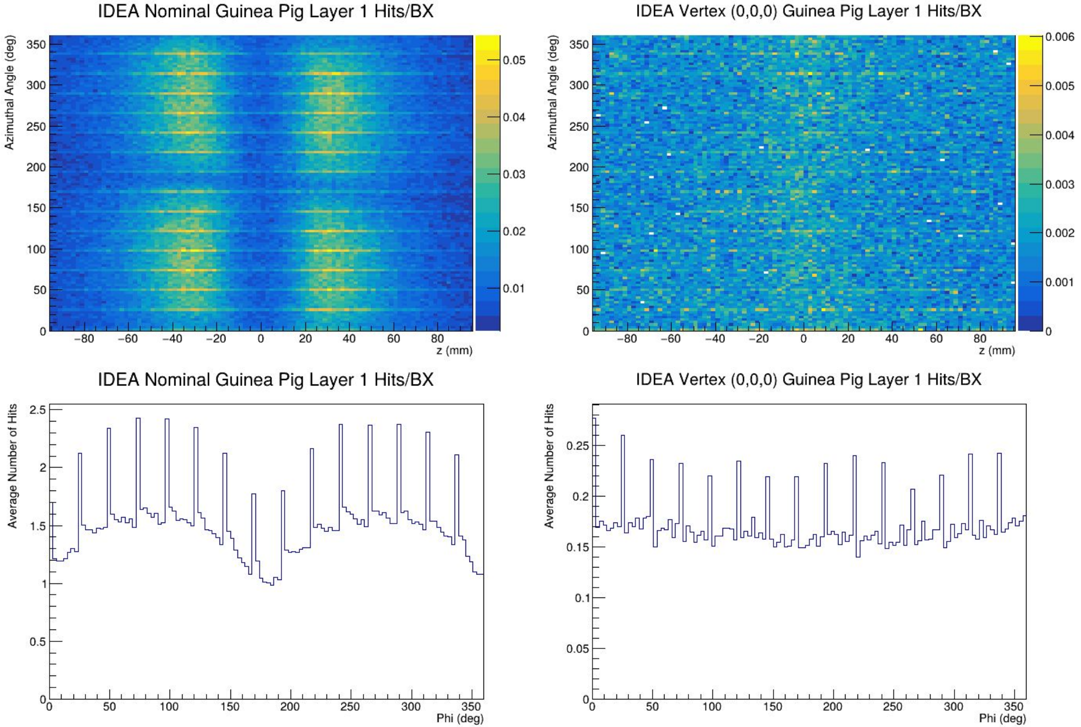
CLD Guinea Pig

- For the Guinea Pig events, a modulation in phi appears as well as a strange pattern in z.
- When the particles are placed at the vertex, these trends disappear, indicating they are an effect of the magnetic field on propagation.



IDEA Guinea Pig

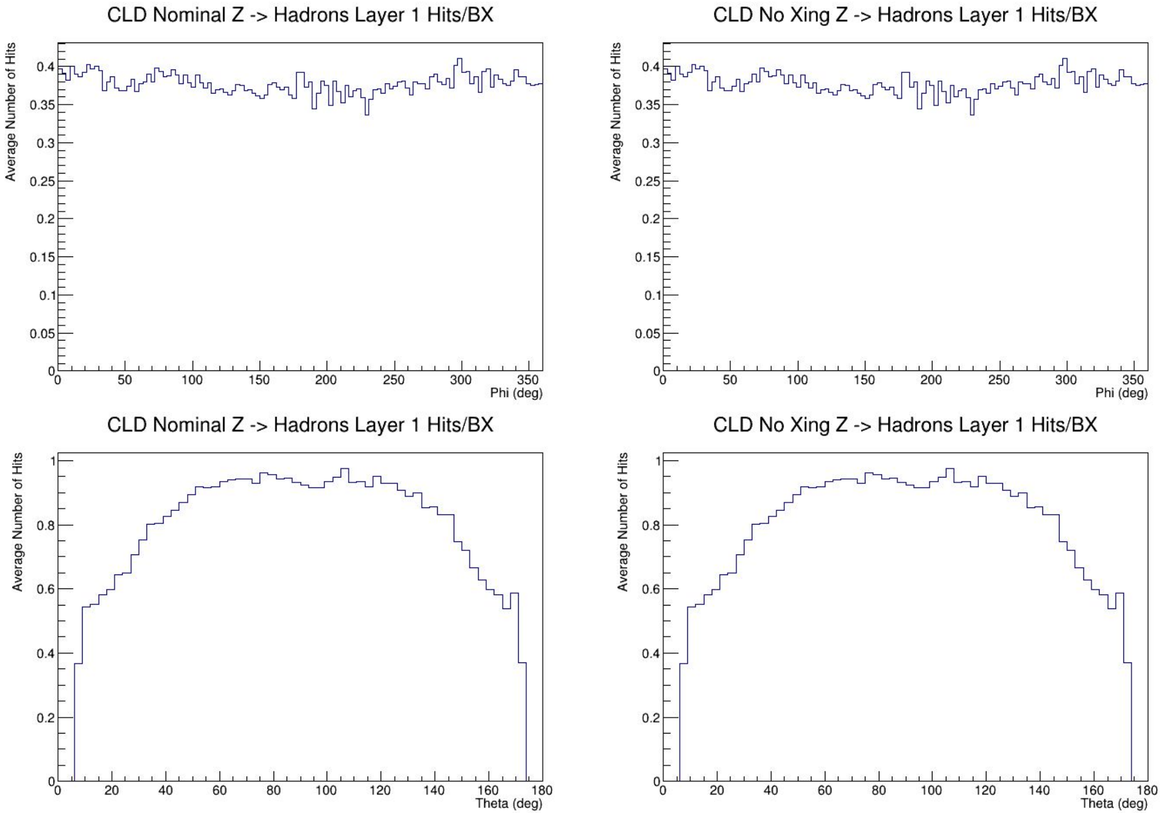
- Similar results are obtained for the IDEA detector.



Crossing Angle

- Samples produced without crossing angle.
- No difference is noticeable for the signal events.
- Can conclude the crossing angle has no effect on hit distribution.

X-ing | No X-ing



Occupancy

Method

- The occupancy O induced by a bunch crossing in a subdetector is defined as:
  - $O = \hbar \cdot A_{sensor} \cdot S_{cluster} \cdot S_{\mathrm{f}}$
  - $\hbar$ is the hit density per bunch crossing in each subdetector (hits/mm^2/BX)
  - A_{sensor} is the surface area of the sensors (25 µm × 25 µm)
  - $S_{cluster}$ is the average cluster size (5)
  - S_f is a safety factor (3 for this study)
- The occupancy was calculated for the Guinea Pig background in the first layer of both IDEA and CLD.
- The hit density is calculated at the module level (#hits per module / area module).

Occupancy

- The following results were obtained for the IDEA detector:
  - $\mathcal{O}_{max}(10^{-6}) = 110$
  - $\mathcal{O}_{avg}(10^{-6}) = 71$
- The following hits per module were obtained for the CLD detector (module area not known):
  - $hits_{max} = 186$
  - $hits_{average} = 163$
- Occupancy from Ciarma et al (2023*) for the CLD detector:
  - $\mathcal{O}_{max}(10^{-6}) = 70$

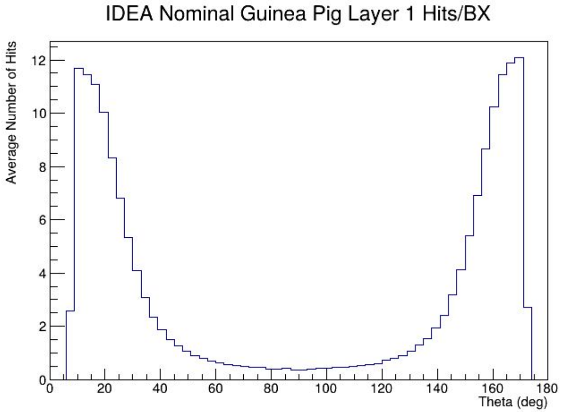
(*) https://cds.cern.ch/record/2887802

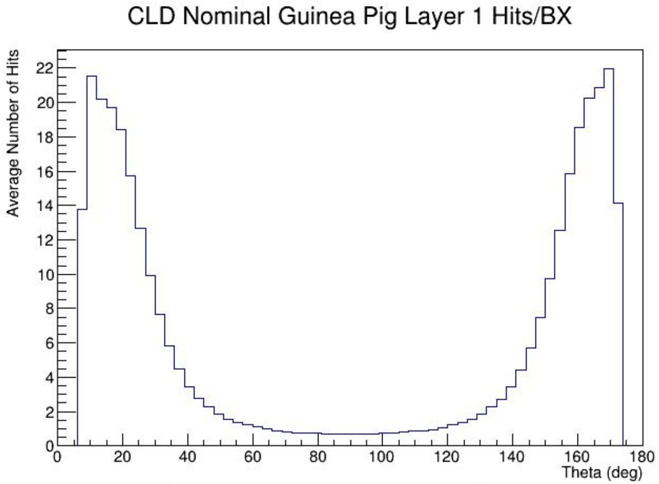
Summary

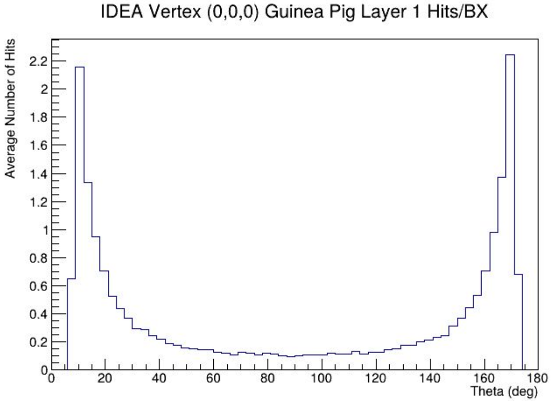
- Inefficiencies in Geant4 simulation:
    - Occasional small step size of a particle through a detector component.
    - “Secondary” Monte Carlo particles with very low energy are not tracked.
- Signal events (Z -> Hadrons) have much higher momentum and thus cross many detector components across most theta angles.
- Background events (Incoherent Pairs) have much lower momentum and thus typically only cross one or no detector components.
- In the IDEA detector, a hole at a theta of 90 deg is clearly visible.
- Spikes in hit density across phi occur for the IDEA detector due to module overlap.
- The incoherent pair propagation in the magnetic field causes an asymmetry in phi.
- Crossing angle appears to have no effect on hit distribution.
- Occupancy for the background events in both detectors is on the order of 10^{-4}.

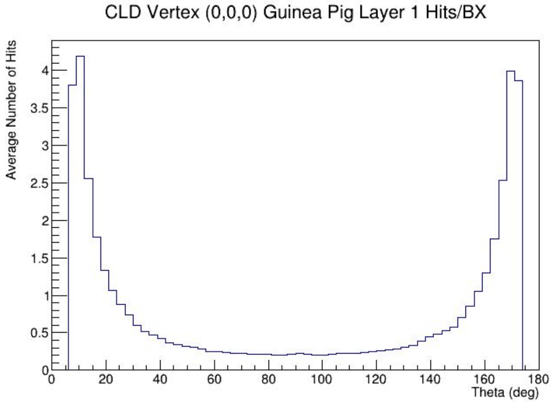
Massachusetts Institute of Technology

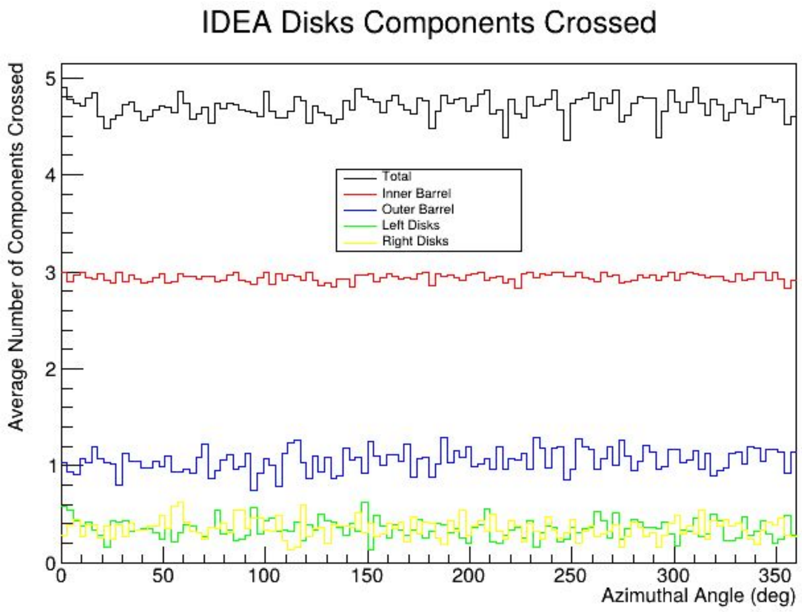
Backup

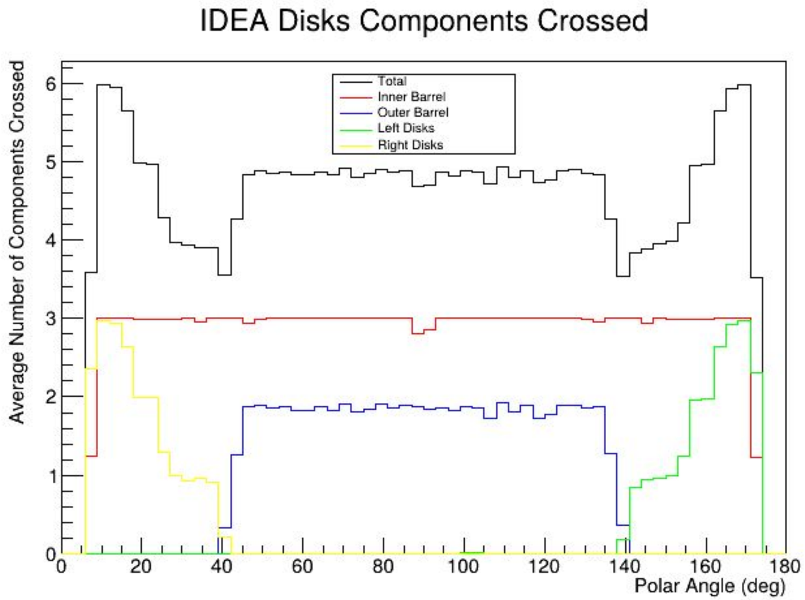

IDEA Nominal Guinea Pig Layer 1 Hits/BX
Average Number of Hits
Theta (deg)


CLD Nominal Guinea Pig Layer 1 Hits/BX
Average Number of Hits
Theta (deg)


IDEA Vertex (0,0,0) Guinea Pig Layer 1 Hits/BX
Average Number of Hits
Theta (deg)


CLD Vertex (0,0,0) Guinea Pig Layer 1 Hits/BX
Average Number of Hits
Theta (deg)


IDEA Disks Components Crossed
Average Number of Components Crossed
Azimuthal Angle (deg)
Total
Inner Barrel
Outer Barrel
Left Disks
Right Disks


IDEA Disks Components Crossed
Average Number of Components Crossed
Polar Angle (deg)
Total
Inner Barrel
Outer Barrel
Left Disks
Right Disks