Reconstruction of Long-Lived Particles (LLPs) in IDEA Tracker at FCC-ee

Masters Thesis Status and Prospects

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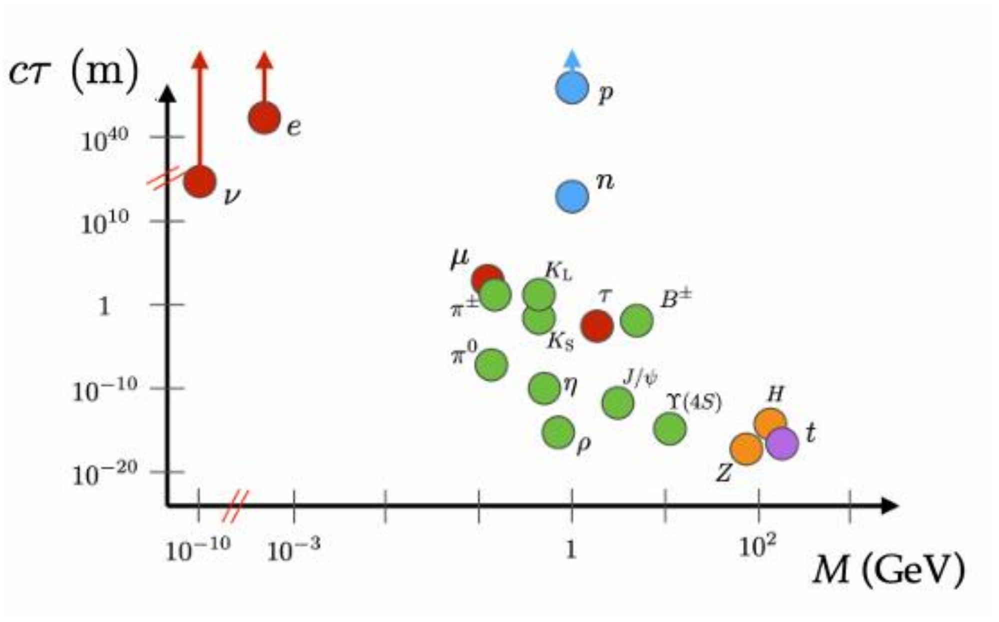
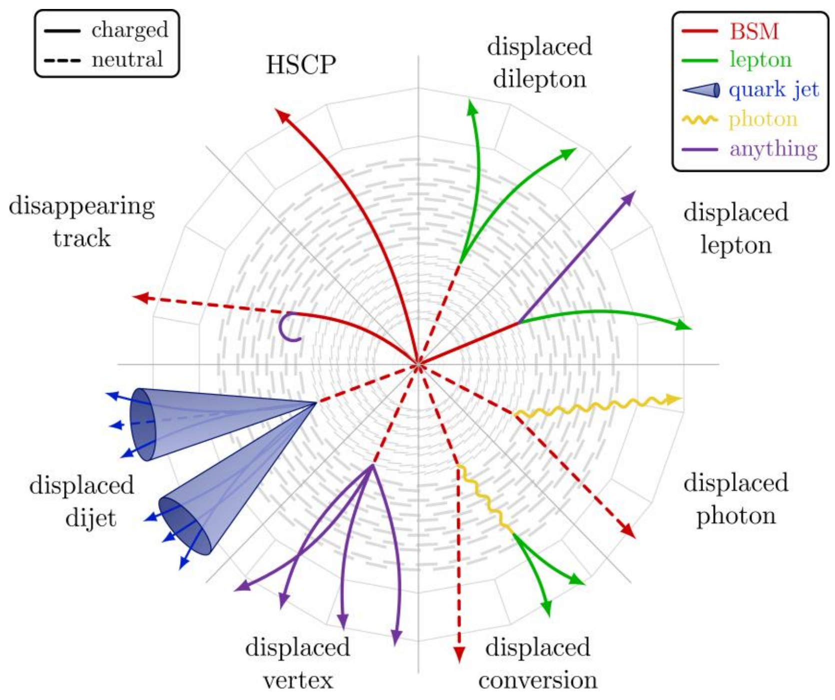
Intro to Long-Lived Particles

LLPs → Particles (SM *or* BSM) whose lifetimes are long enough to travel a **macroscopic distance.**

Standard Model LLPs



Experimental Signatures for BSM LLPs



This study will focus on beyond Standard Model LLPs

Juliette Alimena (CERN), on behalf of the FCC-ee LLP group

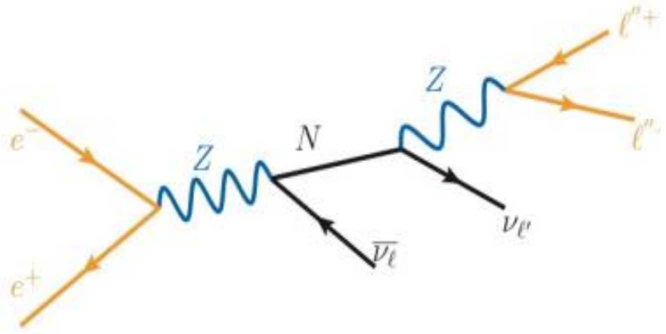
Motivation – Why LLPs

- **BSM motivation:** LLPs appear naturally in many models (see-saw neutrinos, axion-like particles, hidden valleys, SUSY, etc.)
- **Unresolved SM puzzles:** They could provide answers to
  - The **origin of neutrino masses**,
  - The **baryon asymmetry of the Universe (BAU)**, and
  - The nature of Dark Matter

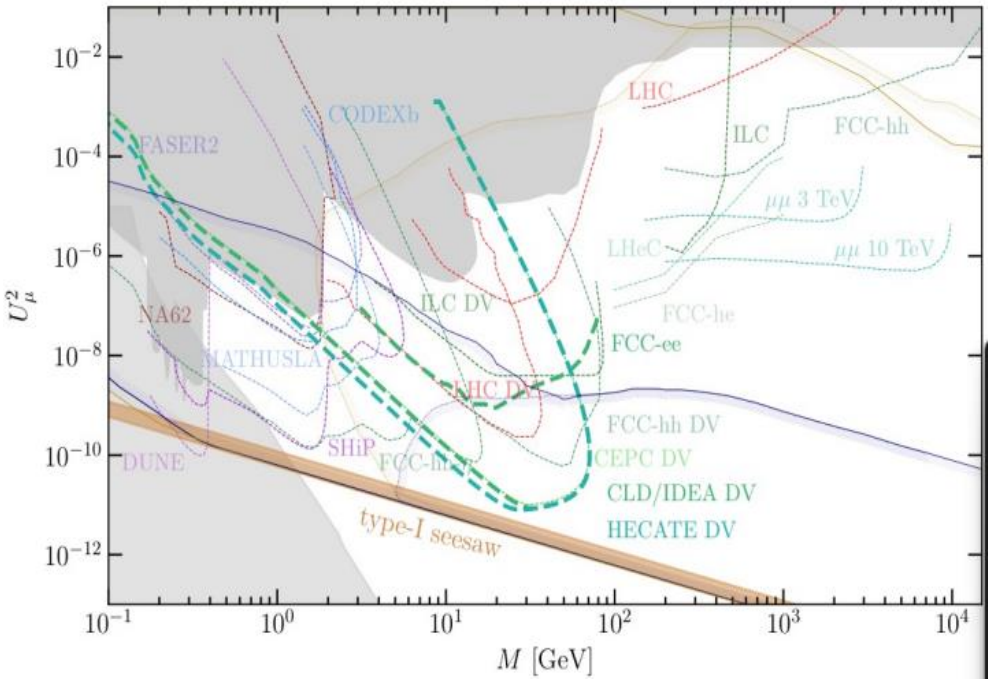
- Unique experimental signatures:
  - Displaced vertices, disappearing/broken tracks, delayed or stopped decays, unusual jets (“dark showers”)
  - These signatures are **rare in the SM**, giving LLP searches low background and high discovery potential.
- **Impact:** LLPs are a “smoking gun” of new physics — discovery would reshape our understanding of both particle physics and cosmology.

Motivation - Benchmarks

Example: Heavy Neutral Leptons



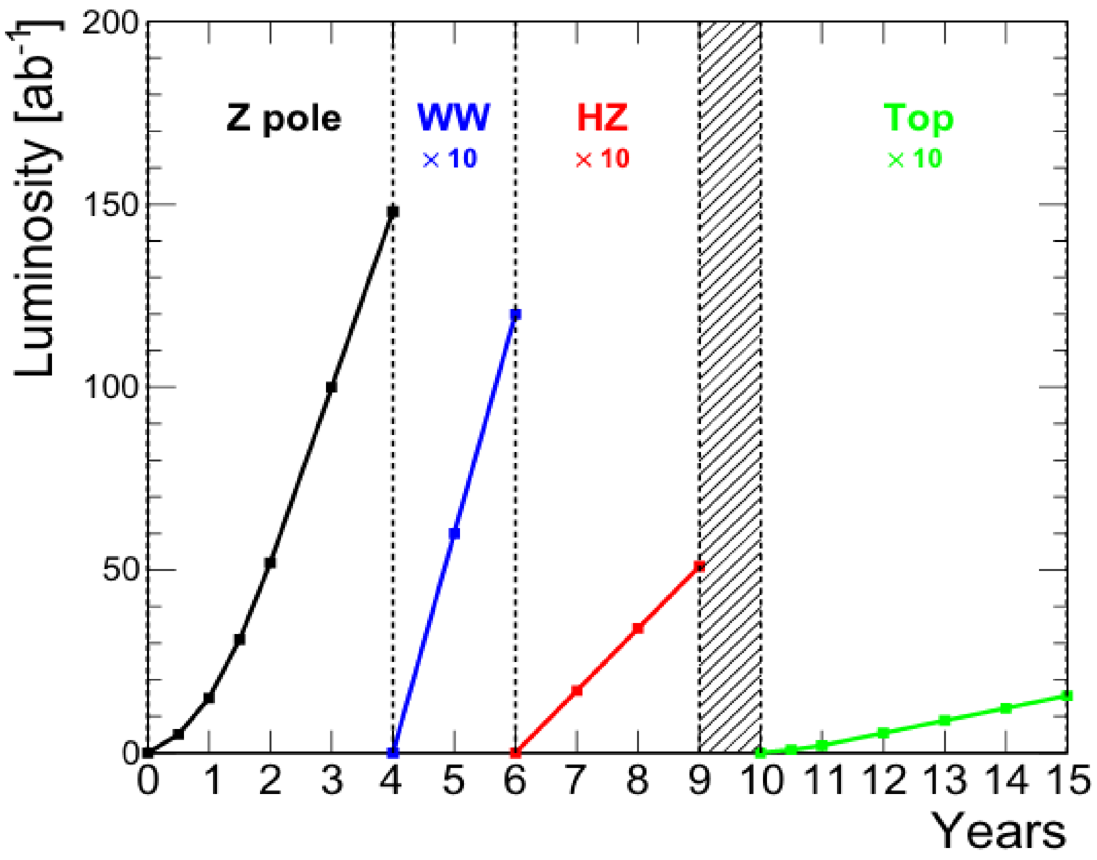
- Predicted in the **Type-I see-saw mechanism**, which explains the small but non-zero neutrino masses.
- Extend the SM by introducing **right-handed (sterile) neutrinos**, weakly mixed with active neutrinos.
- Can be **Dirac or Majorana** in nature.
- Address three major open questions in particle physics:
  1. **Origin of neutrino masses**.
  2. **Baryon asymmetry of the Universe** (via leptogenesis)
  3. **Nature of dark matter**



arXiv:2203.05502

FCC-ee Context

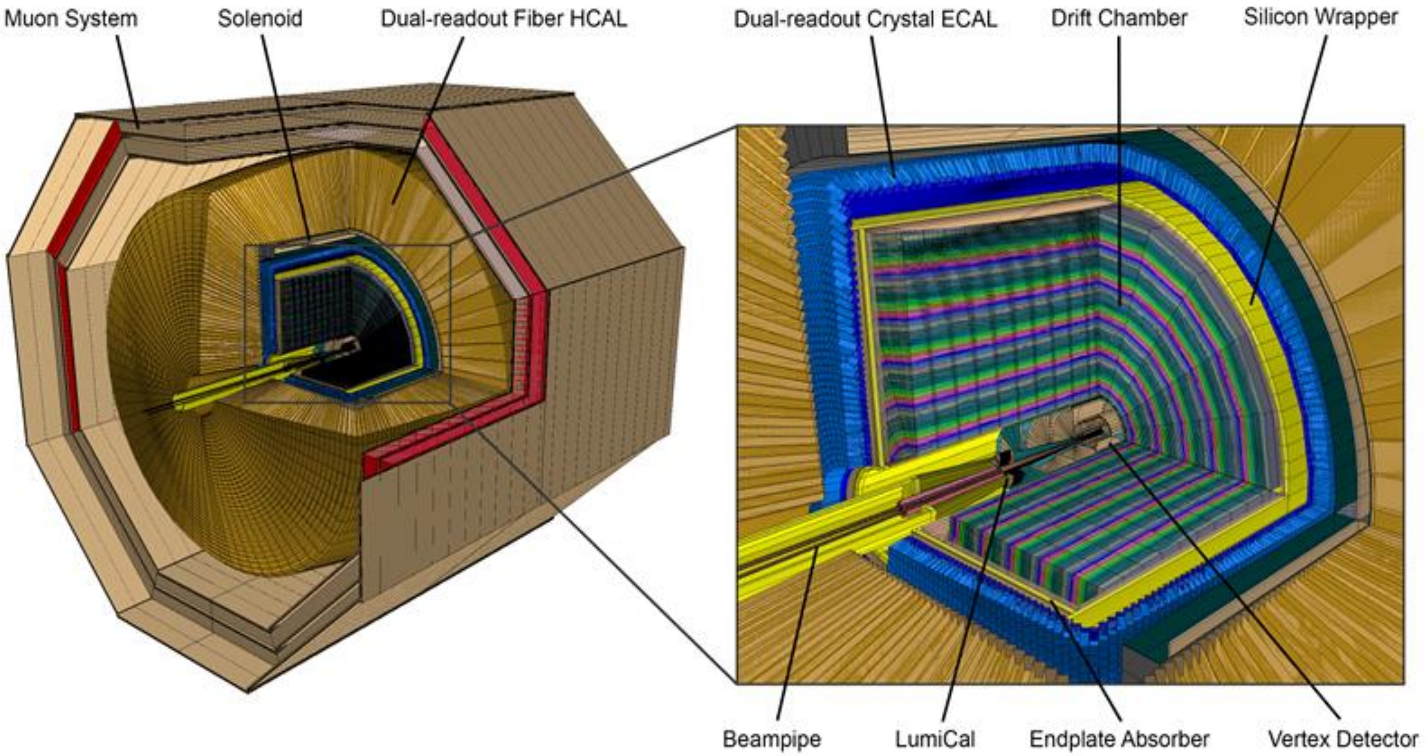
- Circular e^+e^- collider, $\sqrt{s}$ = 91–365 GeV.
- Unprecedented luminosity:
  - Z pole: **150 ab^{-1}** → ~10^{12} Z bosons (idea LLPs factory)
  - WW threshold, Higgsstrahlung, top threshold runs.
- Clean e^+e^- environment: ultra-low backgrounds
  - Ideal for displaced signatures
- Complementary to LHC: covers small couplings & long lifetimes inaccessible at hadron colliders.



FCC-ee Report

The Innovative Detector for E+e− Accelerator (IDEA)

- Specifically designed for FCC-ee
- Based on a sophisticated
  - Tracking system
  - Crystal dual-readout (DR) ECAL
  - DR fiber HCAL and
  - Muon detection system placed within the iron yoke that closes the magnetic field.



arXiv:2502.21223v4

The Innovative Detector for E+e− Accelerator (IDEA) – Tracking System

- **High granularity Silicon Vertex Detector**
  - Enables the precise measurement of the vertices (5 µm hit resolution)
- **The Drift Chamber (DCH)**
  - Lightweight, large volume (2 m radius) → Allows the tracks to be extended up to large radii to measure the charged particle momenta accurately.
  - Provides up to about 112 space-point measurements per track with excellent PID capabilities provided by the cluster counting technique.
- **The Silicon Wrapper**
  - Provides a last precise measurement before the Crystal ECAL, could also provide timing information.

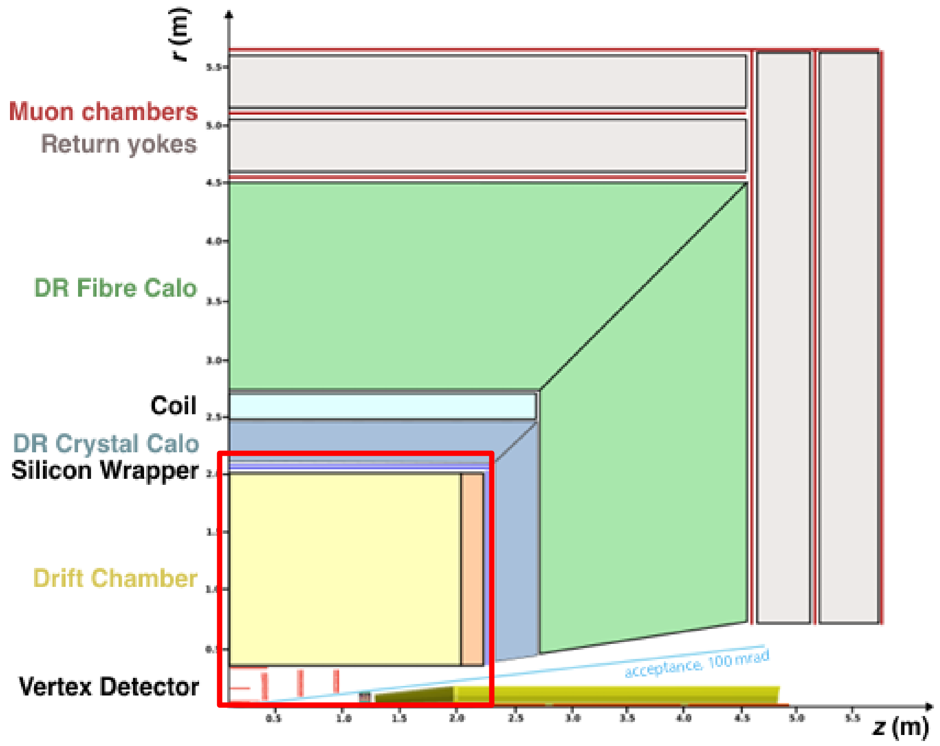


Figure 3: Overview of the IDEA detector layout.

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This Study – Reconstruction of LLPs in IDEA Tracker at FCC-ee.

Main Idea

- Reconstruct **Long-Lived Particles (LLPs)** with tracker detectors in IDEA, with emphasis on the **Drift Chamber (DCH)**.
- Extend tracking & reconstruction beyond prompt particles to include **displaced tracks**.
- Develop methods to identify **displaced vertices** feature of LLP decays.
- Benchmark the performance of **finding & fitting algorithms** for LLP signatures.

This Study – Reconstruction of LLPs in IDEA Tracker at FCC-ee.

What Has Been Done So Far

- Reviewed FCC-ee–relevant LLP benchmarks.
- Studied reconstruction techniques used at colliders.
- Implemented and tested **Track Finding & Fitting** algorithms.
- Understood the full **simulation** → **reconstruction workflow**.
- Ran an **end-to-end chain** with a muon particle gun.

General Overview of the Workflow

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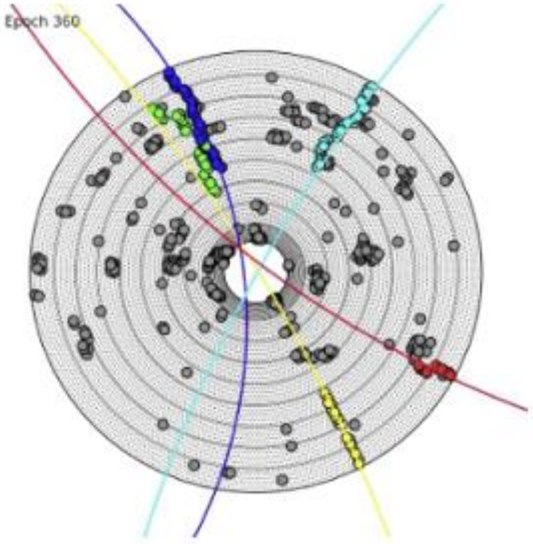
Digitization &Track Finder

Digitization

- **What**: Taking the *ideal hits* from simulation and turn them into *realistic detector signals*.
    - **Output**: Digitized hits.

Track Finding

- Cluster digitized hits into **candidate tracks**.
- **Method**: Geometric Graph Track Finding (GGTF)



FCCWorkshopTracking by Andrea De Vita

Key features:

- Works across multiple subdetectors.
- Independent of geometry and material assumptions.
- Learns hit patterns without explicit trajectory parametrizations

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Track Finding (Main Algorithm)- Geometric Graph Track Finding (GGTF)

Step 1. Preprocessing

- Hits from different subdetectors are converted into **geometric objects** (points, vectors) unified in 16D multvector representation. (VTX hits→ pts, DCH hits → vectors)

Step 2. Geometric Algebra Transformer (GATr)

- The multivector hits are passed through a special neural network (ONNX), each hit → 4D embedding vector (3-D + learned features (scalar **β**)).

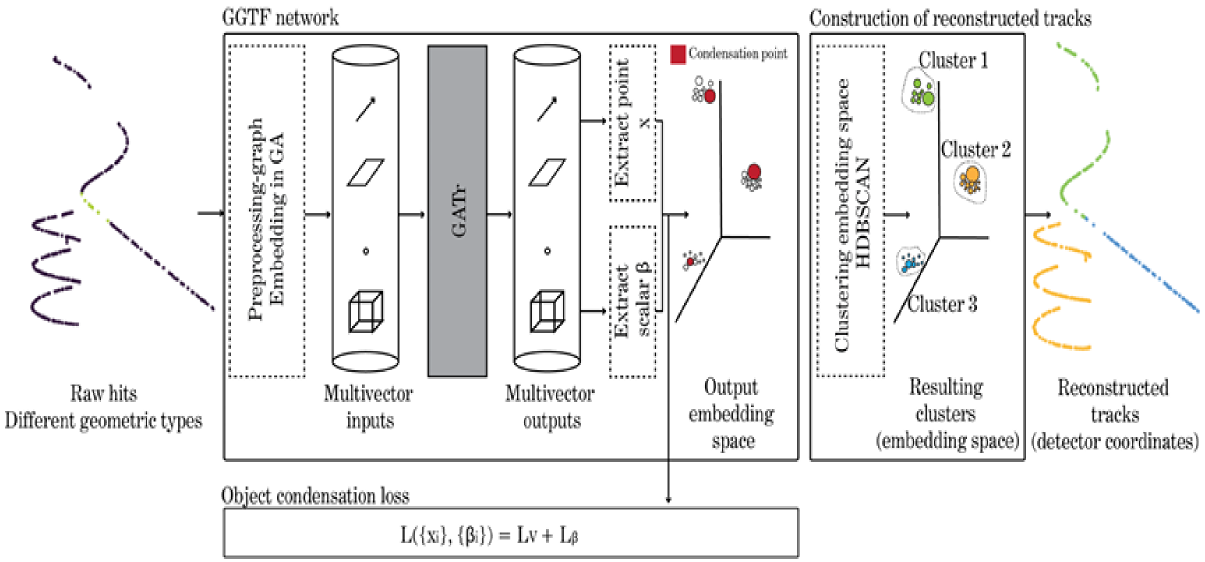
Step 3. Object Condensation Loss

- Encourages hits from the same track to cluster in embedding space.
- **Attractive potential**:- pulls same-track hits together.
- **Repulsive potential**:- pushes different-track hits apart.
- Scalar β ensures one condensation point per track.

Step 4. . Clustering → Track Candidates

- Hits clustered in embedding space
- Each cluster defines one reconstructed track.

⟹ **Output**: Reconstructed tracks



D. Garcia, B. Francois, M,Selvaggi GGNN based track finding CERN

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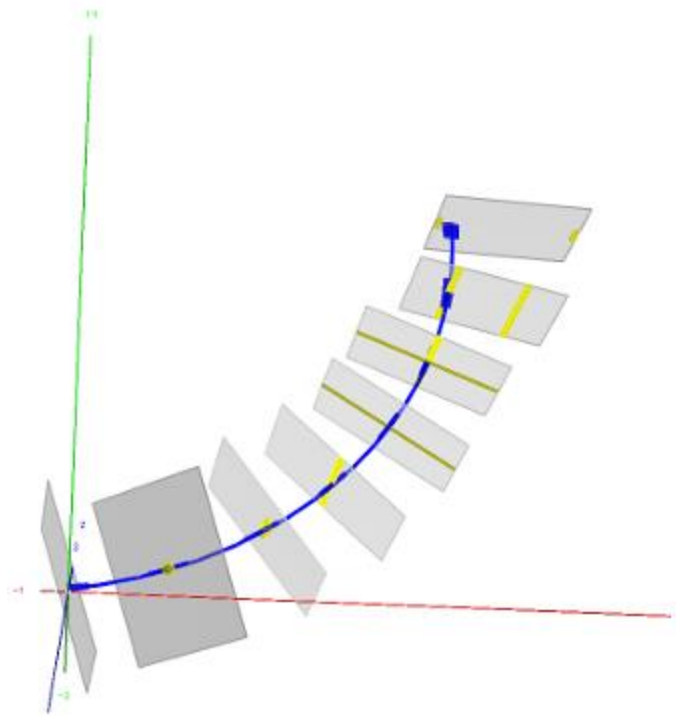
Track Fitting

Method: Genfit2

Inputs: Reconstructed tracks from Track Finder

- Uses **Kalman filtering** to refine the trajectory step by step, accounting for measurement errors and material effects (like scattering and energy loss).
- Uses Deterministic Annealing Filter (DAF) with β schedule (init → final → steps) to handle outliers.
- What it does: Each candidate track is fitted under 5 particle hypotheses: e, μ, π, K, p
- **Output:** Collection of fitted tracks from 5 particle hypothesis for analyis



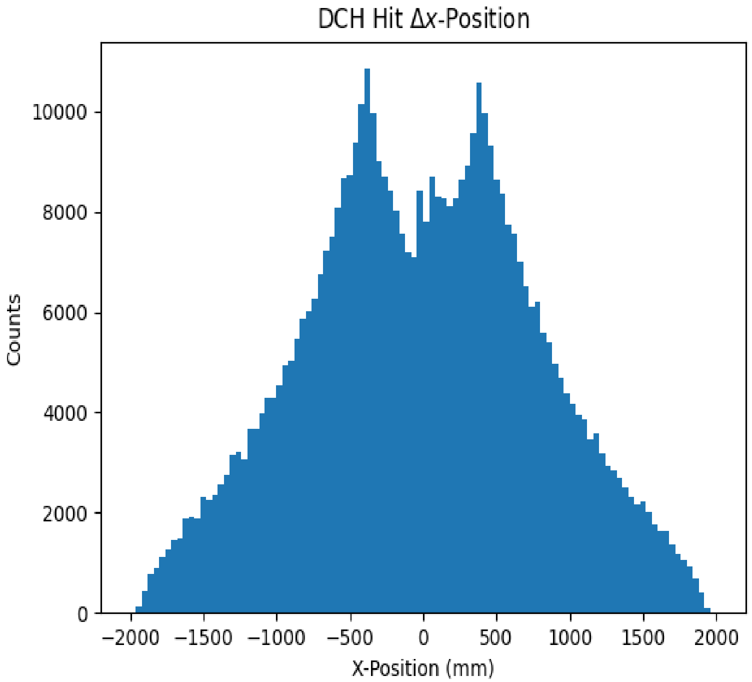
arXiv:1902.04405

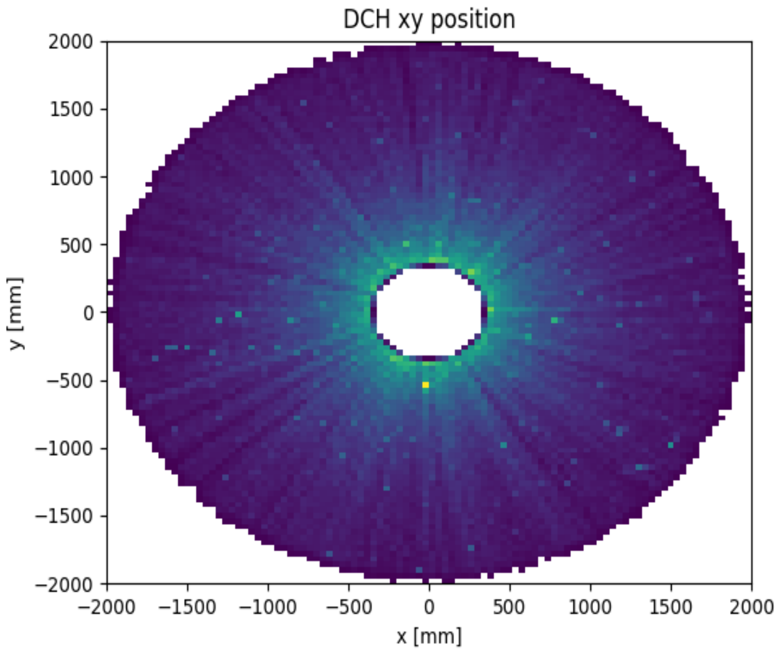
This Study – Reconstruction of LLPs in IDEA Tracker at FCC-ee.

Pre-fit plots for Hit position spectra for DCH

Distribution of position residuals for DCH hits associated with reco tracks

- The simulation involved only muons (mu-) generated in the IP.
- Results obtained with 1000 muon-gun events, uniformly distributed in direction and momentum (0.5–5 GeV)..





✓ Confirms hits are where we expect them in the detector geometry.

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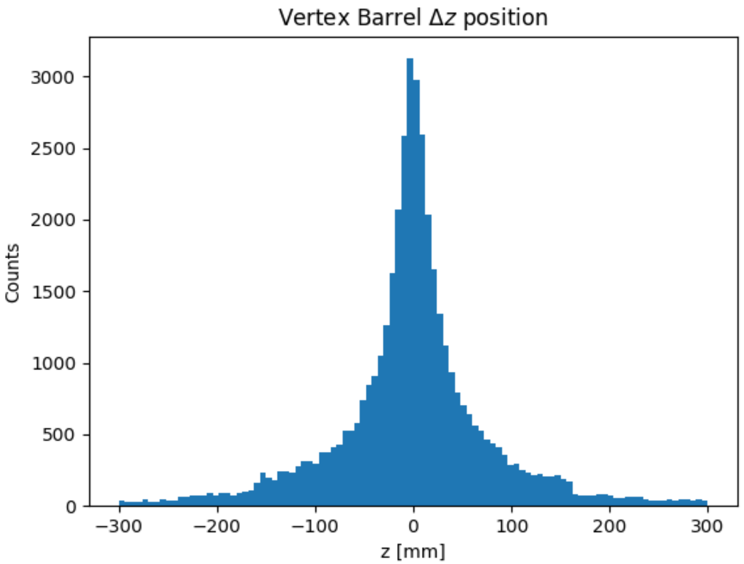
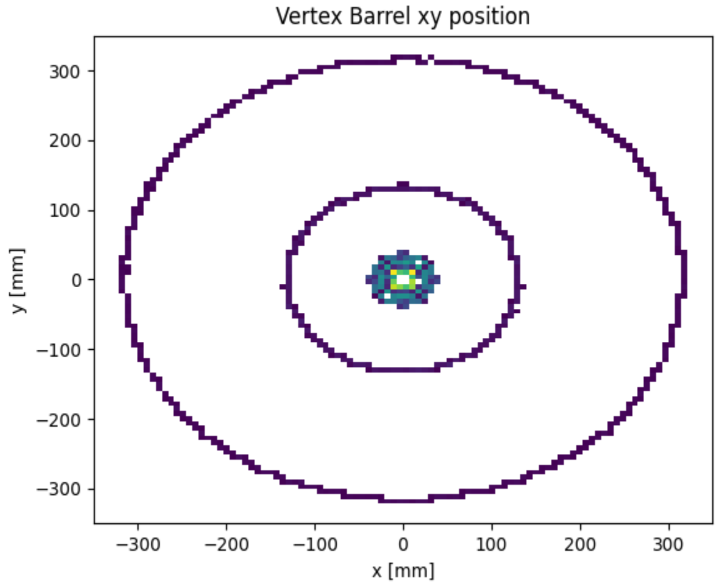
Pre-fit plots for Hit position Spectra for VTX

Distribution of residuals for VTX hits associated with reconstructed tracks.

- Peaks centered around 0 → tracks originate near the IP.
- Long tails: tracks at higher angles reaching the ends of the barrel, consistent with detector geometry.





✓ Confirms the vertex detector is active and producing hits close to the IP

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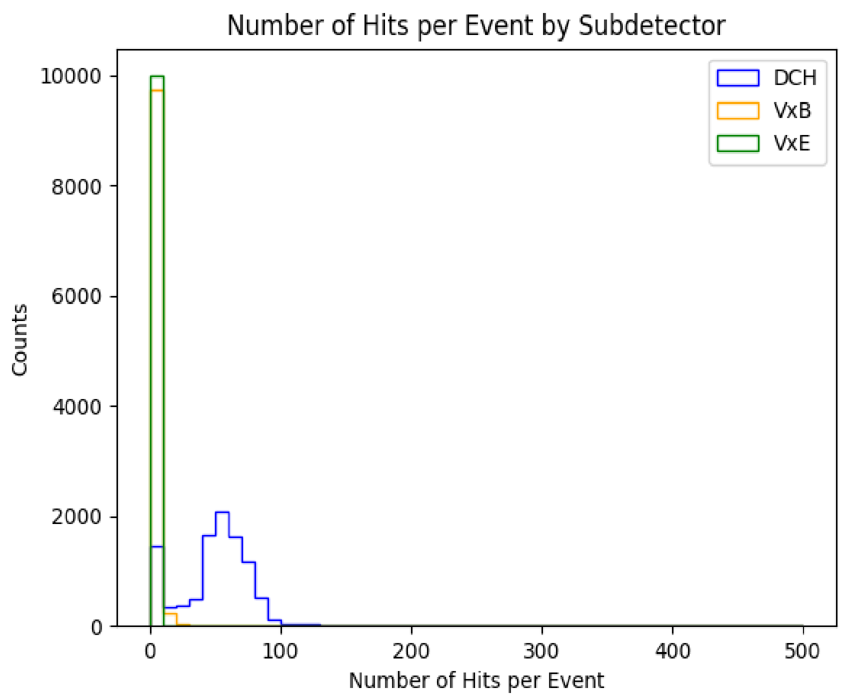
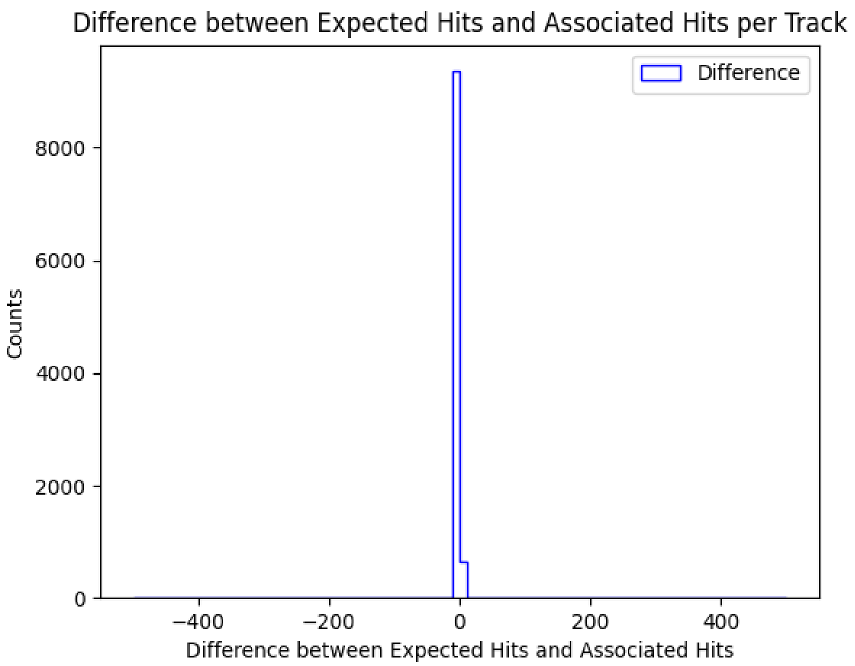
Some Plots After Track Finder





- The detector geometry and hit multiplicities are consistent with expectations.
- The pipeline is correctly reading and counting hits from different collections.

- The TrackFinder is behaving consistently: almost all expected hits are correctly accounted for.
- A good track-finding algorithm should associate nearly all available hits to tracks.

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Current Status

1. Studying the algorithm step by step to understand its behavior and expected outputs at each stage.

Clustering parameters

```
parser.add_argument("--tbeta", default=0.6, help="tbeta clustering parameter")
parser.add_argument("--td", default=0.3, help="td clustering parameter")
args = parser.parse_args()
```

β schedule

```
parser.add_argument("--Beta_init", default=100, help="OutputFile")
parser.add_argument("--Beta_final", default=0.1, help="OutputFile")
parser.add_argument("--Beta_steps", default=10, help="OutputFile")
args = parser.parse_args()
```

- What are these parameters really doing?
- Why are they assigned to these values by default?
- Are they optimized to handle displaced tracks?
- If not, how do we optimize them?

2. What are the most useful variables from the output root file (from particle gun) at each stage?

3. What are the necessary plots to validate track finding and track fitting algorithm.

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Next Steps;

- Validate pipeline with SM benchmark ($Z \rightarrow \mu\mu$).
- Optimize tracking for displaced tracks (focus on DCH).
- Apply to BSM LLP benchmark.
- Study DCH background performance.
- And hoping to contribute to FCC-ee LLP sensitivity projections.

Thank You!

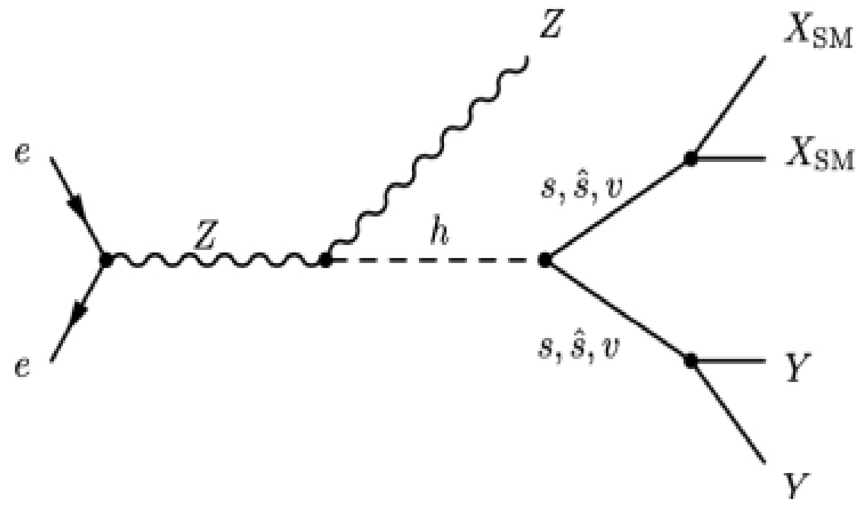
Questions & Feedbacks are welcome.

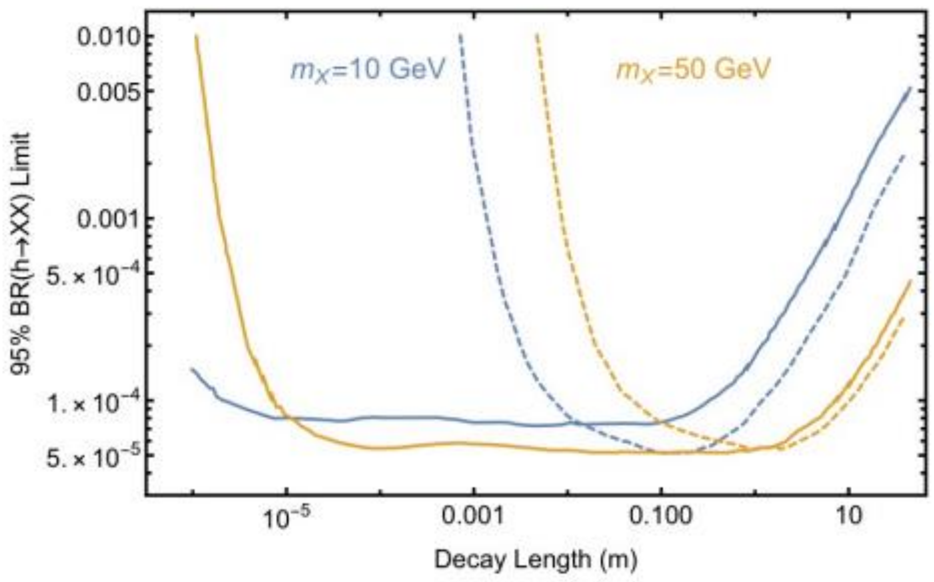
BACKUP

Motivation - Benchmarks

Exotic Higgs Decays

- Higgs boson can act as a **portal to hidden sectors** (Hidden Valley, Twin Higgs, SUSY Higgsinos, etc.).
- Hypothetical neutral LLPs may be produced in $h \to XX$
- Signatures:
  - **Displaced multi-track vertices** inside the tracker.
  - Displaced leptons/jets or missing energy.



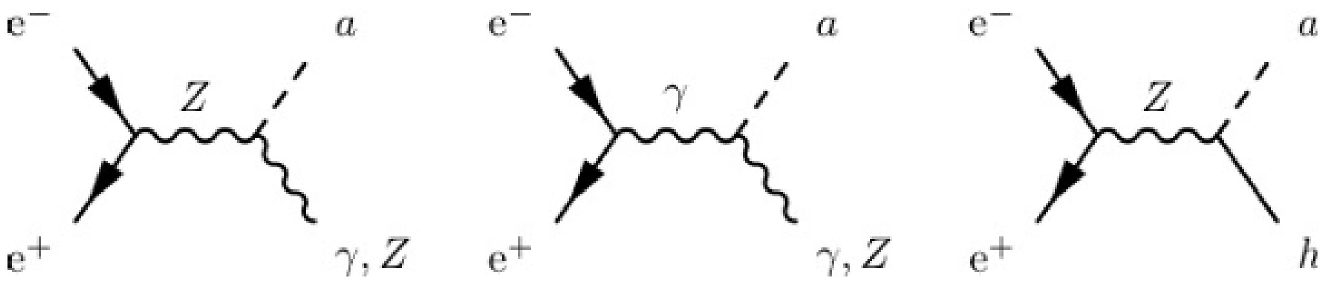


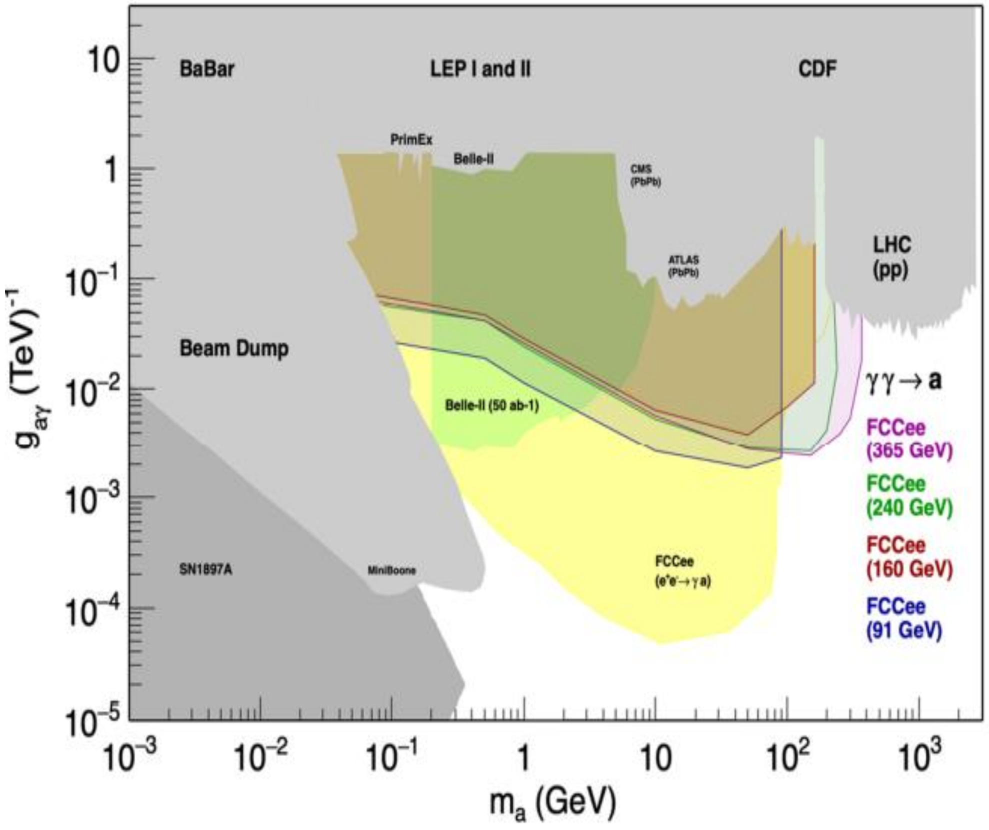
arXiv:2203.05502

Motivation - Benchmarks

Axion-Like Particles

- Predicted as **pseudo Nambu–Goldstone bosons** from broken global symmetries.
- Appear in models addressing the **strong CP problem** and are viable **dark matter candidates**.
- Characterized by **weak couplings** to SM particles → naturally **long-lived**.
- Typical FCC-ee search channels:





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