

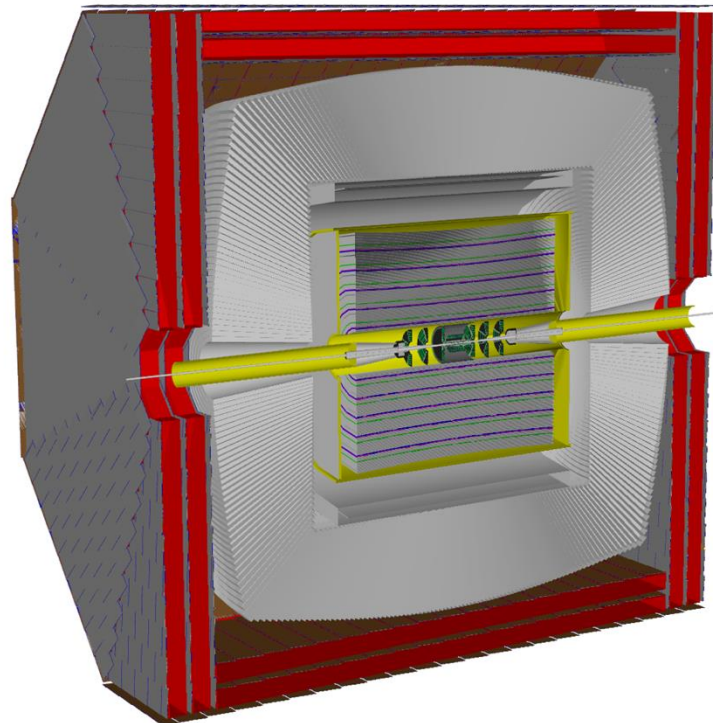
Mahmoud Al-Thakeel

# FULL SIMULATION OF IDEA MUON SYSTEM: PERFORMANCE STUDIES AND LLPS DETECTION

FCC Software & Physics group Meeting, 15<sup>th</sup> October 2025

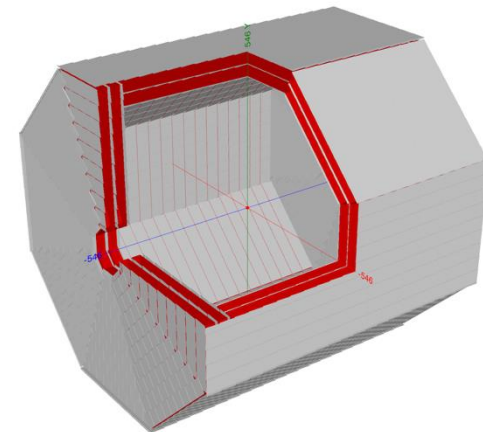
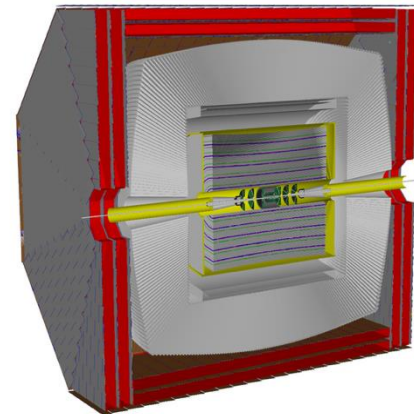


ALMA MATER STUDIORUM  
UNIVERSITÀ DI BOLOGNA



## Quick recap on IDEA Muon system in Full-Simulation:

- **Geometric modeling:** Complete barrel and endcap  $\mu$ RWELL chamber description with realistic gas gaps, and readout strips. Designed in 3 polyhedron(octagon) stations composed of arrays of  $50 \times 50 \text{ cm}^2$ . (The design is flexible for future modification of parameters)
- **Geometry coverage:** The Muon system extends in theta  $8^\circ < |\theta| < 172^\circ$ , pseudorapidity  $|\eta| < 2.56$  and with complete  $\phi$  coverage.
- **Sensitive detector integration:** Full digitization chain of space resolution and  $\mu$ RWELL efficiency.
- **Magnetic field interface:** Integration with the 2T solenoid field inside the solenoid volume and -1.7T outside the solenoid for accurate track reconstruction. Full detailed field map is needed for more accurate implementation.
- **Reconstruction:** reconstruction algorithms for tracking and vertexing have been designed for muon-system and especially displaced-vertex cases.



# Reconstruction Algorithm for Displaced tracks:

Implementation of a **new** tracking algorithm adopted for IDEA Muon system and displaced tracks, Key features of the algorithm:

## Triplet Seeding Approach

The code implements a triplet-based seeding strategy:

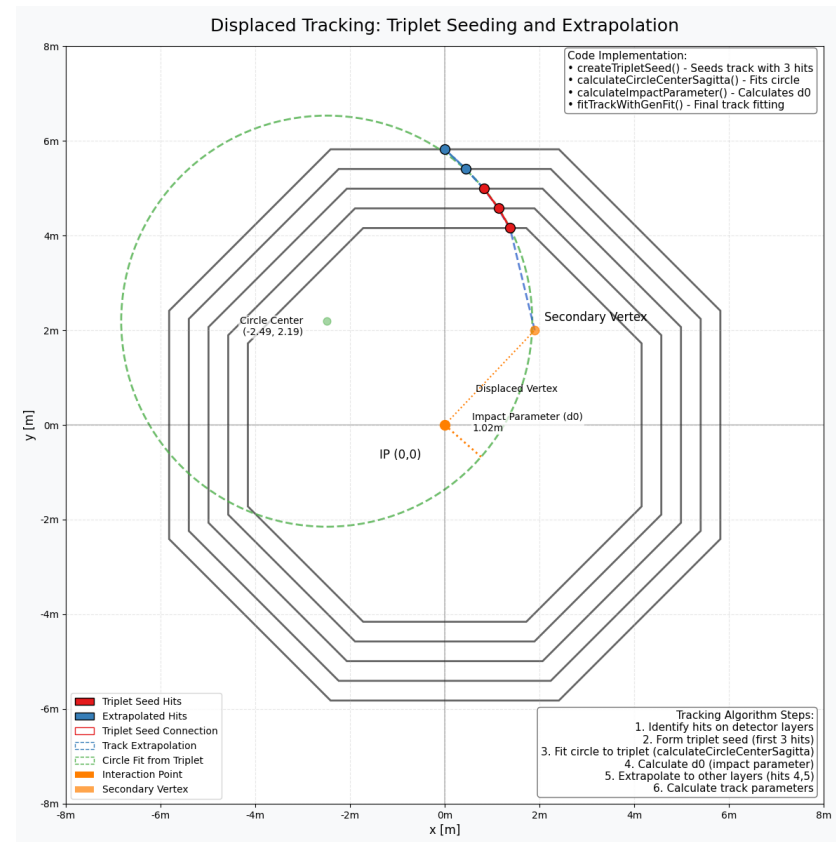
1. Hits are grouped by their layer IDs
2. The algorithm then forms triplets by selecting hits from three different layers
2. Systematically iterating through all possible combinations (3 nested loops)
3. For each potential triplet, it calls createTripletSeed to evaluate if the hits form a valid track seed

**Triplet Validation:** Distance check and Angle consistency

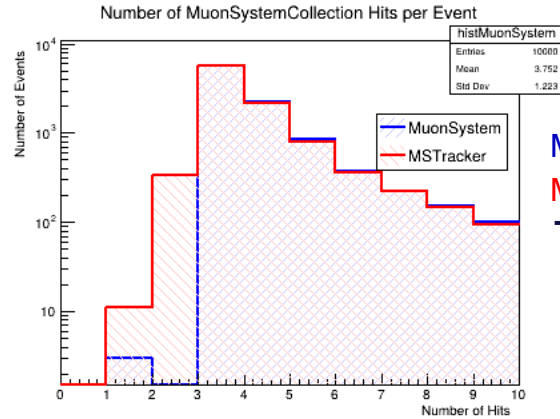
**Circle fitting:** Attempts to fit a circle through the projected hit positions in the x-y plane using **sagitta** method

**Calculates track parameters:**

- I. Momentum (pT):** Using the relation  $p_T = 0.3 \times B \times R$  (where B is magnetic field in Tesla and R is radius in meters)
- II. Phi angle:** From circle center and hit positions
- III. Charge sign:** Based on clockwise/counterclockwise determination
- IV. Z component:** Linear fit along the track path to get theta/eta
- V. Impact parameters:** Using calculateImpactParameter which models field transitions



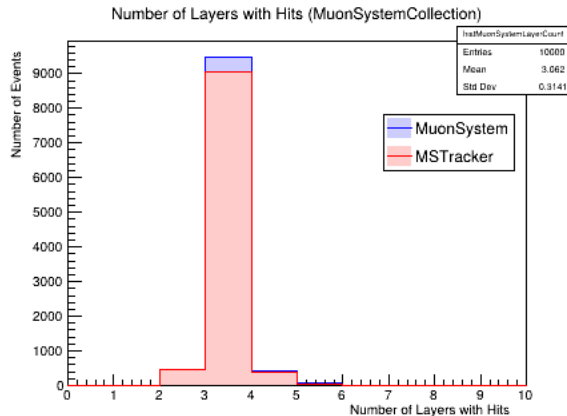
# Muon system Digitization:



MuonSystem collection (SimHits)

MTracker collection (DigiHits)

To have a track we need at least 3 digi hits in 3 different layers



## Layer-Based Muon Hit Analysis Summary

MuonSystem: 99.97% events with  $\geq 3$  hits

MuonSystem: 99.97% events with  $\geq 3$  hits in  $\geq 3$  layers

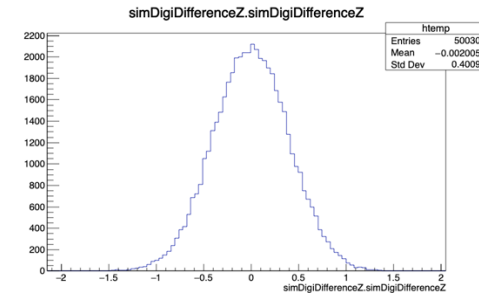
MTracker: 96.55% events with  $\geq 3$  hits

MTracker: 95.41% events with  $\geq 3$  hits in  $\geq 3$  layers

SimHits

DigiHits

98% efficiency for  $\mu$ RWELL



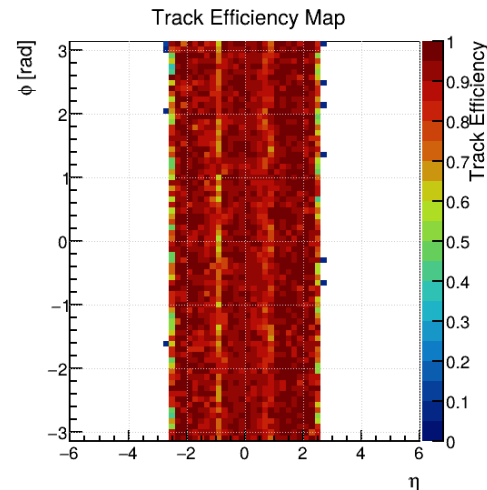
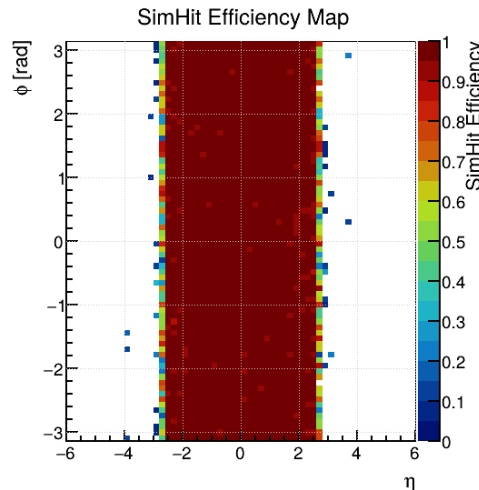
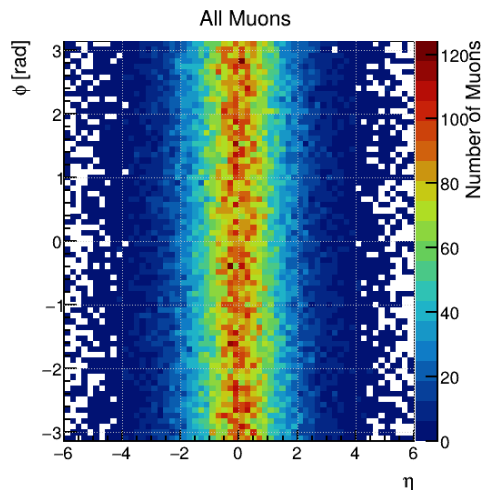
Smearing

# Muon system Performance:

## Detection Efficiency and Geometric Acceptance

- The standard design of the IDEA muon-system is **3 layers** of  $\mu$ RWELL chambers each of area  $50 \times 50 \text{ cm}^2$ , and the current  $\mu$ RWELL candidate is  $400 \text{ }\mu\text{m}$  in space resolution
- **(SimHit: The detector has at least one hit from the passing particle)**
- Track efficiency drops at some regions due to several factors:
  - Lack of having at least 3 hits in at least 3 different layers.
  - Transition region between barrel and endcap.
  - The absence or very low values of magnetic field at some regions, especially in the endcap.

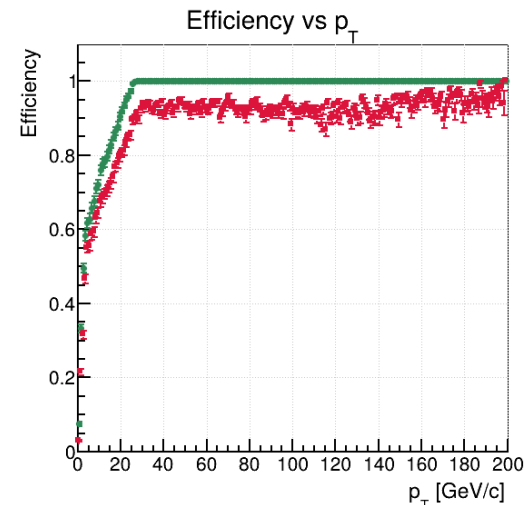
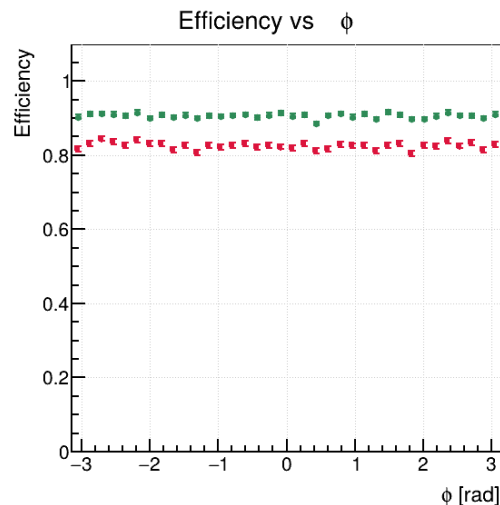
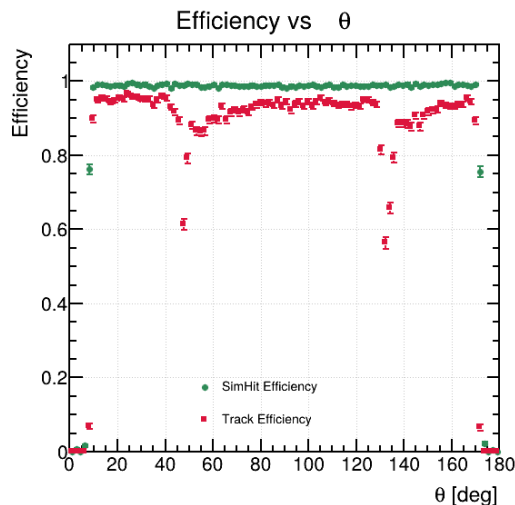
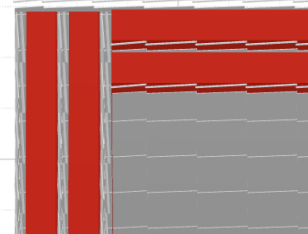
Test by **100k** Muon gun,  
uniformly distributed  
angle and energy range  
(0:200 GeV)



# Muon system Performance:

## Kinematic Performance Characteristics

- kinematic dependencies of reconstruction efficiency:
- Key performance metrics from **82,548** reconstructed muons out of **100,000** muons :
  - **SimHit detection efficiency: 90.7%** with excellent angular uniformity
  - **Track reconstruction efficiency: 82.5%**
  - **Angular coverage:** Optimal performance for barrel and endcap region, but the track efficiency drops at the transition regions between the barrel and the endcap around  $45^\circ$  and  $135^\circ$  in  $\theta$ .
- All the above studies have been done without applying cuts for geometric coverage nor momentum threshold.

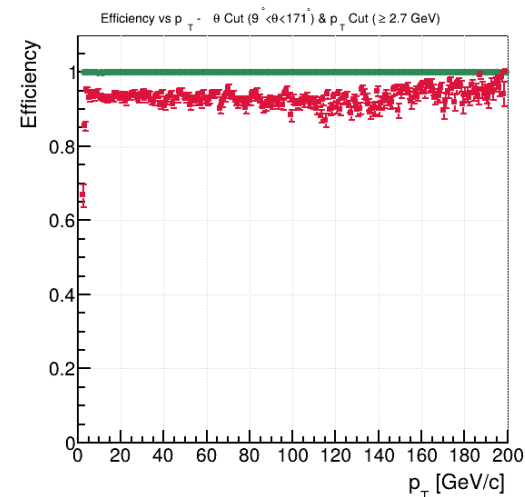
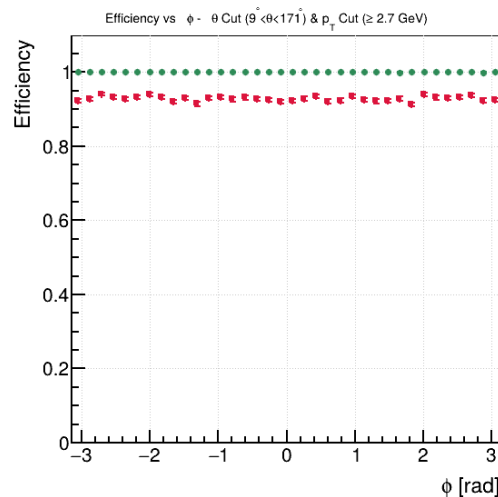
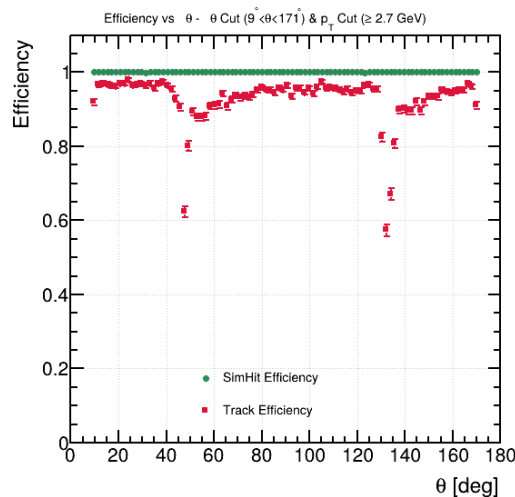


# Muon system Performance:

## Performance Enhancement Through Selection Cuts

- **Geometric acceptance cut:**  $9 < \theta < 171$  corresponding to the muon system's  $\eta$  coverage.
- **Momentum threshold cut:**  $P_T \geq 2.7$  GeV to ensure muons reach the muon system through the magnetic field.
- Overall, the combined cuts yield remarkable performance improvements:
  - **Event selection:** 87.9% of events pass combined quality criteria
  - **SimHit efficiency:** Increased from 90.7% to 100.0%
  - **Track efficiency:** Improved from 82.5% to 92.8%

Track reconstruction processes barrel and endcap regions **independently**



# Muon system Performance:

## Performance Enhancement due to combined-region reco

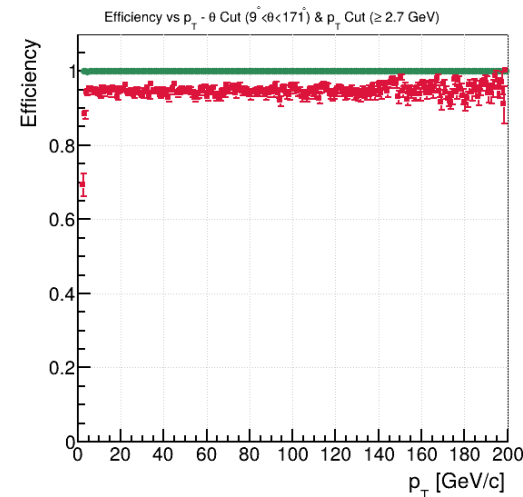
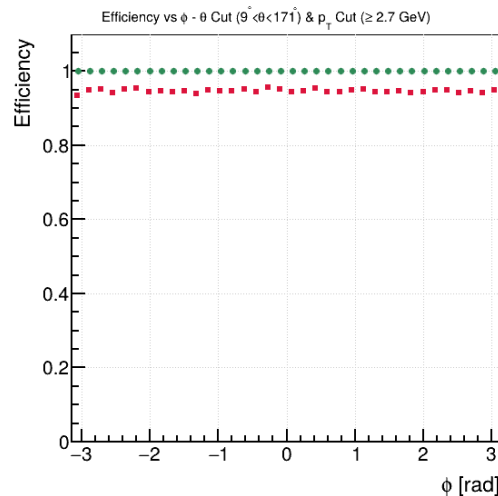
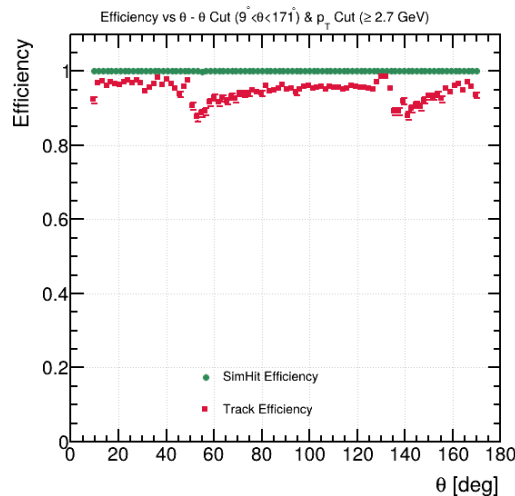
- **Track efficiency:** Improved from 92.8% to 94.5%
- DigiHits quality candidates ( $\geq 3h, \geq 3l$ ): 82,787
- DigiHits quality with tracks: 82,764

**Remember:** DigiHits efficiency  $\sim 95\%$

**Quality Track efficiency** = # Reco tracks/# Quality candidates ( $\geq 3$  hits,  $\geq 3$  layers)  $\sim 99.97\%$

**Overall, the standard design of IDEA muon-system of 3 Layers and 98% of  $\mu$ RWELL, will have a maximum efficiency of around 95%**

Track reconstruction processes barrel and endcap regions together



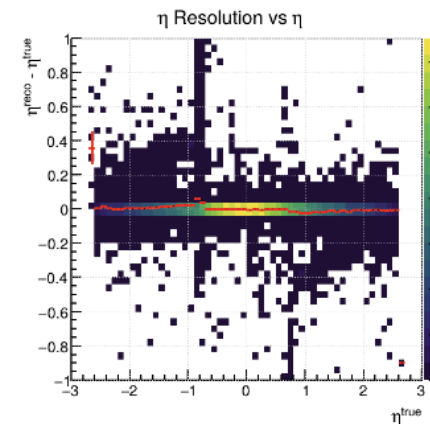
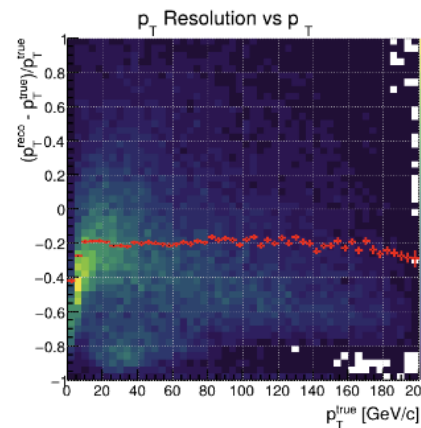
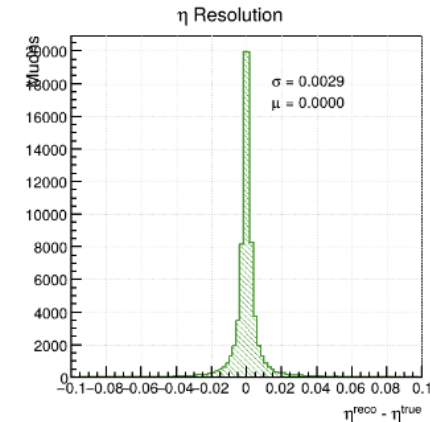
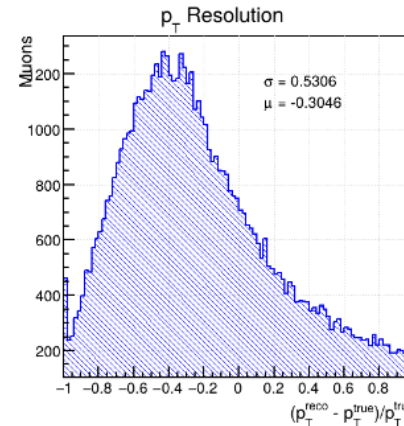
# Muon system Performance:

- The  $\mathbf{P}_T$  residual distribution exhibits a broad spread with a significant negative bias ( $\mu = -0.3$ ), indicating systematic challenges in momentum reconstruction that require calibration improvements.
  - Track fitting require improvement, for the moment it doesn't include material effects. But this can't guarantee big impact on  $\mathbf{P}_T$  resolution, since there are other factors, like space resolution and lever-arm.

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\frac{p_T}{0.3BL^2} \sigma_{\text{spatial}} \sqrt{\frac{720}{N+4}}\right)^2 \left(\frac{0.016}{BL} \sqrt{\frac{X}{X_0}}\right)^2$$

- In contrast, the  $\eta$  residual displays narrow Gaussian peaks centered near zero ( $\sigma_\eta = 0.0107$ ), reflecting excellent angular resolution capabilities.

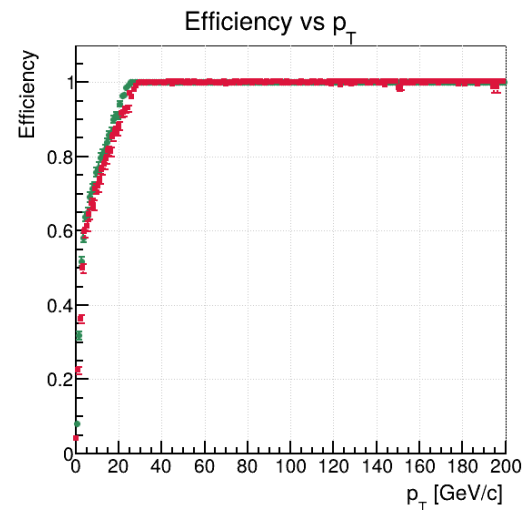
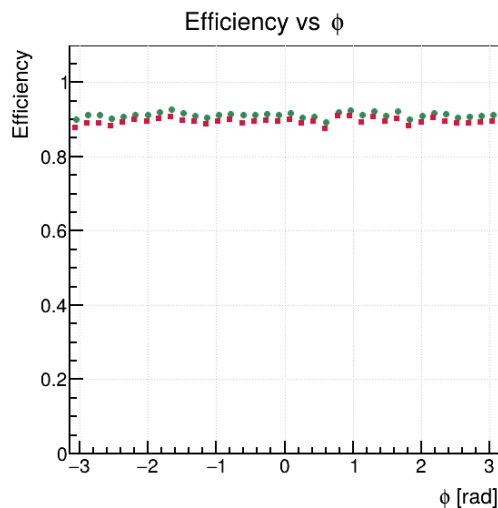
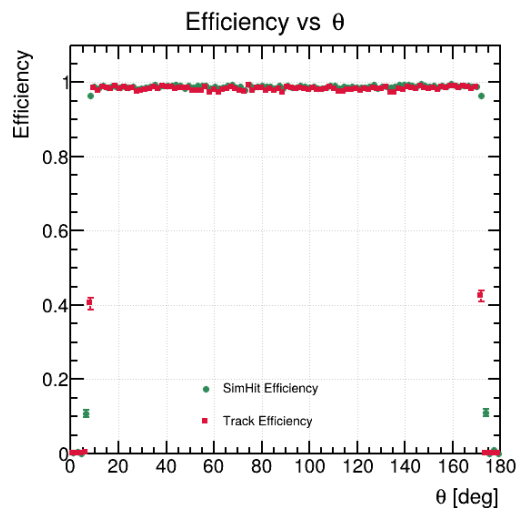
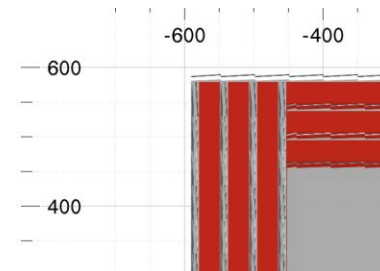
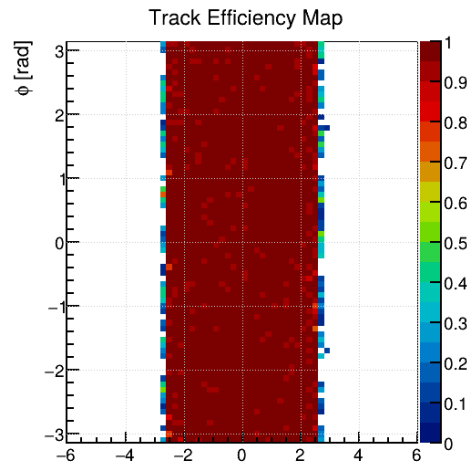
## Resolution Performance



# Muon system Performance:

**4-Layers**

- **SimHit detection efficiency:** **91.2%**
- **Track reconstruction efficiency:** **89.3%**  
Without applying selection cuts.
- Transition regions effect (efficiency drop) disappear.



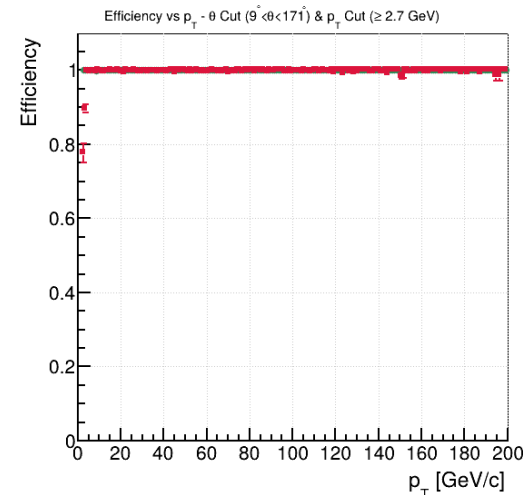
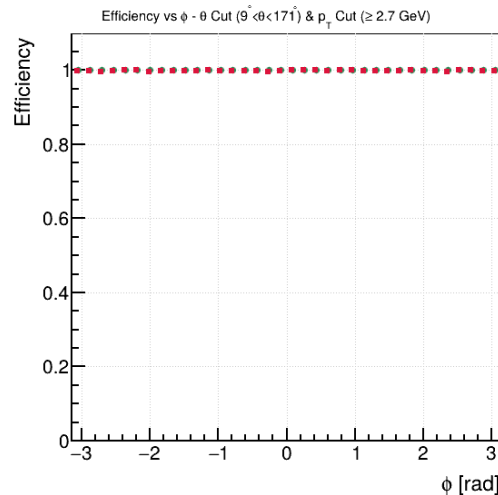
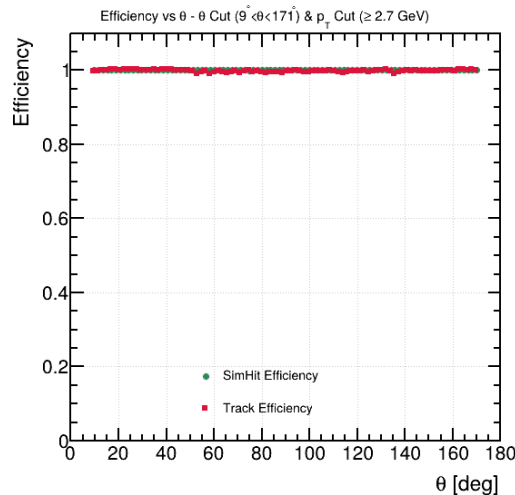
# Muon system Performance:

## 4-Layers Reco with acceptance cuts

- **Track efficiency: 99.7%** after applying selection cuts in 4 layers
- DigiHits quality candidates ( $\geq 3h, \geq 3l$ ): 89,104
- DigiHits quality with tracks: 89,102

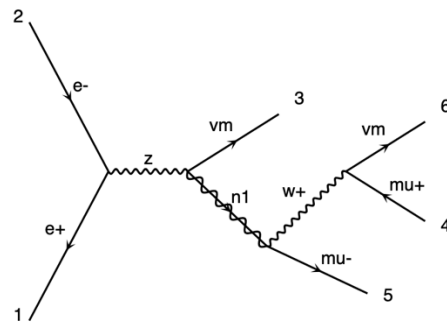
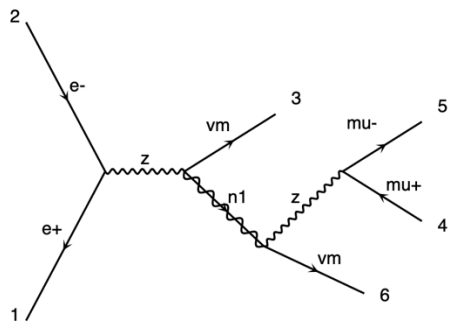
**Quality Track efficiency** = # Reco tracks/# Quality candidates ( $\geq 3$  hits,  $\geq 3$  layers)  $\sim$  **100%**

**Overall, 4-Layers IDEA muon-system of 98% of  $\mu$ RWELL efficiency can reach an efficiency of 100%**



# Long-Lived Particles Detection: HNL Physics Case

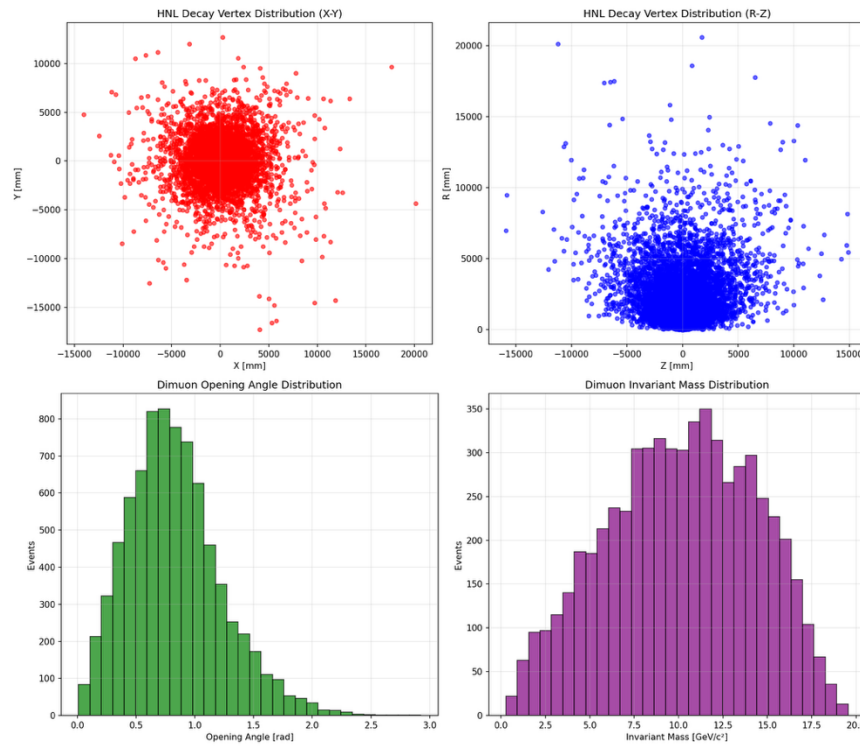
- One of the main goals of having a precise muon system is to be able to standalone detect Long-Lived Particles (LLPs)
- The interaction between Heavy Neutral Leptons and Standard Model neutrinos is governed by the mixing matrix elements, particularly the parameter  $U_{\mu N}$ . This mixing determines how likely it is for  $N1$  to be produced in processes involving muons and, subsequently, how it decays back into SM particles.
- For the generation of events, we use `MadGraph5_aMC@NLO` together with `Pythia8`, employing the model `SM_HeavyN_CKM_AllMasses_LO`. In this model, we can set the mixing parameters and HNL masses independently. As an example, we consider the following configuration:
  - $m_{N1} = 20 \text{ GeV}$ , representing a relatively light HNL.
  - $m_{N2} = m_{N3} = 10 \text{ TeV}$ , effectively decoupling the heavier HNLs from the phenomenology.
  - $V_{eN1} = 0$  and  $V_{\tau N1} = 0$ , meaning  $N1$  mixes only with muons.
  - $V_{\mu N1} = 1.0 \times 10^{-5}$ , which is small enough to give a long-lived signature.
  - $W_{N1} = \text{auto}$  to automatically compute the total decay width of  $N1$ .



# LLPs Detection:

## HNL Generator-Level Physics Characteristics

- Uniform azimuthal distribution of decay vertices with exponential radial decrease, directly reflecting the HNL lifetime characteristics ( $\tau$  distribution)
- Generator-level vertices span from millimeters to tens of meters, setting the physics requirements for displaced vertex detection

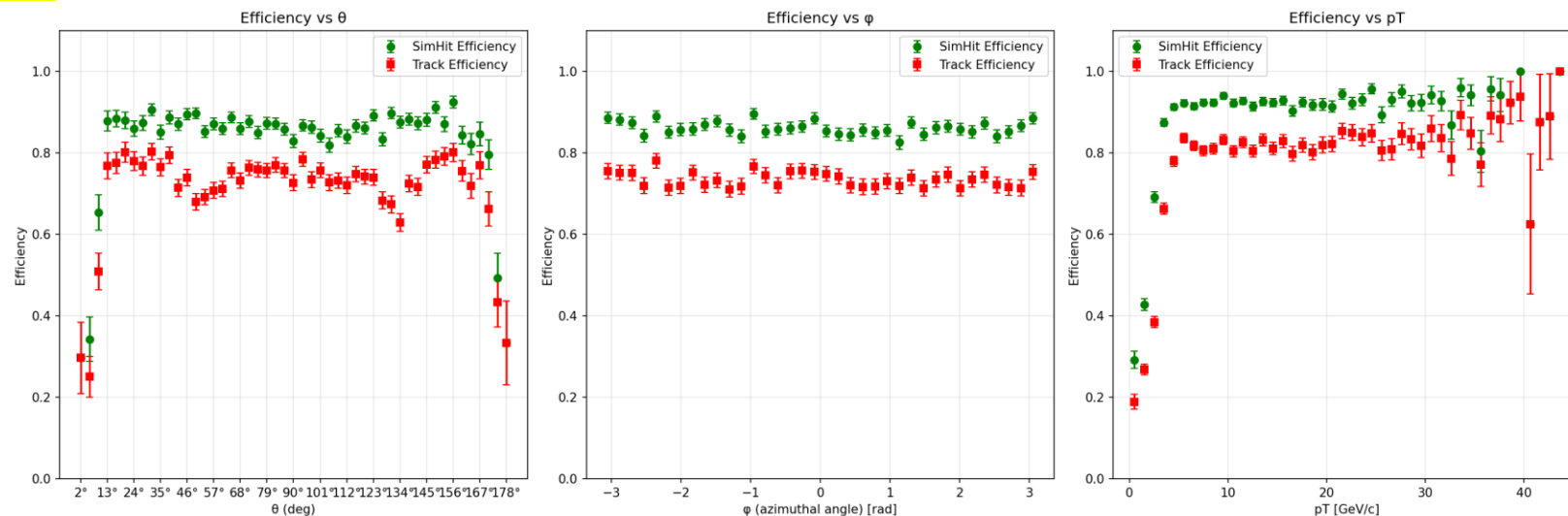


# LLPs Detection:

## Detection Efficiency Performance

- The detector maintains high SimHit efficiency ( $> 85\%$ ) across most acceptance regions, with track efficiency showing more kinematic dependence, particularly at low  $P_T$  and extreme polar angles.
- SimHit efficiency achieves excellent performance above  $P_T \sim 5$  GeV/c, reaching plateau values near 95%. Track efficiency shows similar behavior with a plateau near 82% above  $P_T \sim 5$  GeV/c. Below 5 GeV/c, muons have difficulty reaching the muon system.

### 3-Layers

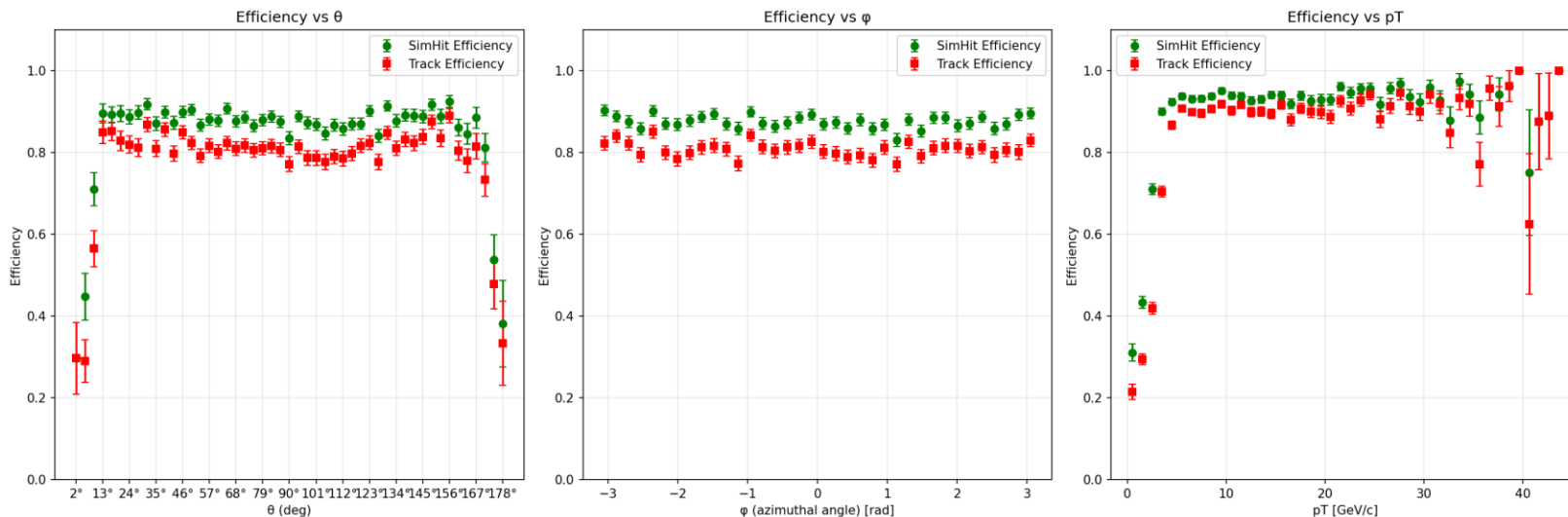


# LLPs Detection:

## Detection Efficiency Performance

- SimHit efficiency go up to 87.5%
- Track efficiency shows plateau near 90% above  $P_T \sim 5$  GeV/c.

### 4-Layers



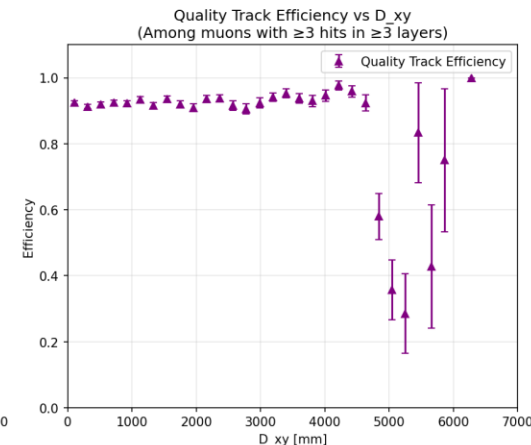
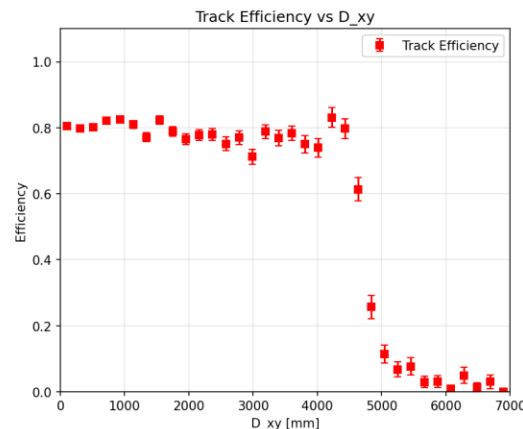
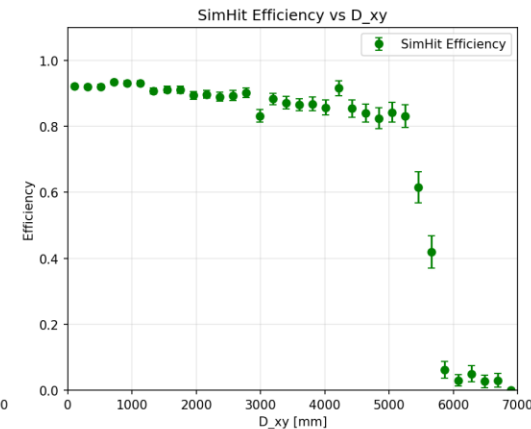
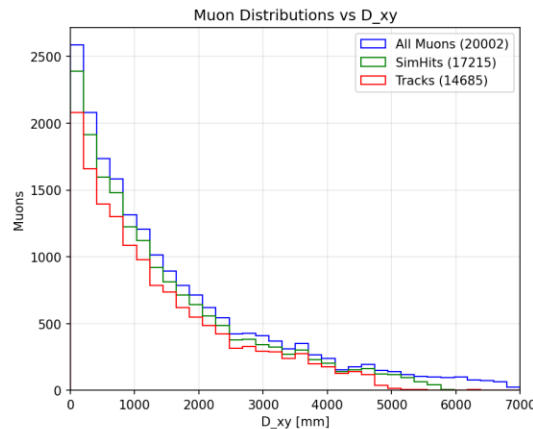
## LLPs Detection:

- The total sample includes 20,002 muons, with 17,215 producing at least one SimHit (86.1% SimHit efficiency) and 14,685 successfully reconstructed as tracks (73.4% overall track efficiency)
- Stable performance (~75-85%) for displacements up to 4.5 meters
- Sharp drop-off beyond 4.5 meters as tracks approach detector boundaries.
- The quality track efficiency analysis shows a plateau around 92.2%.

### 3-Layers

No selection cuts applied.  
No geometry acceptance applied.

## Efficiency vs Displacement



## LLPs Detection:

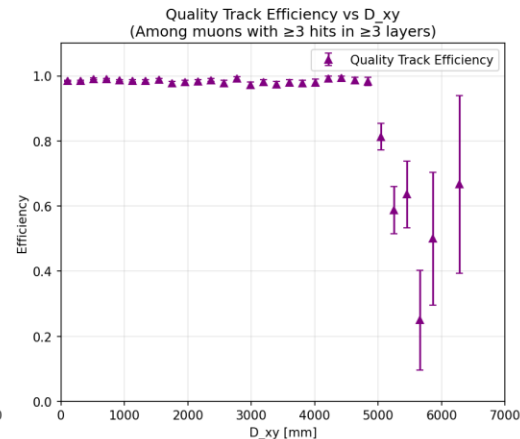
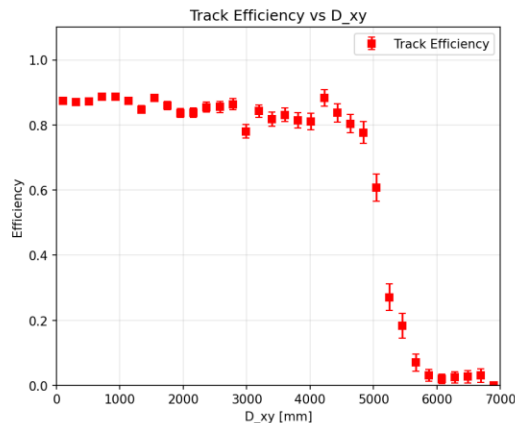
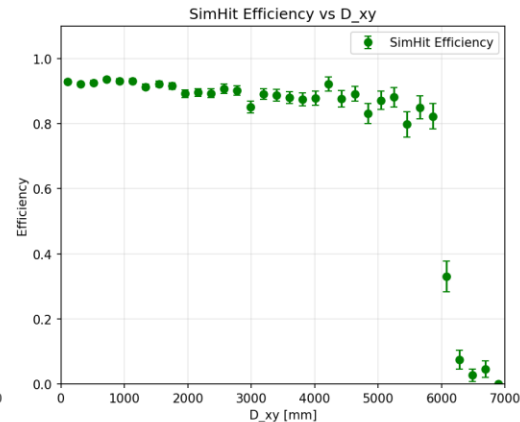
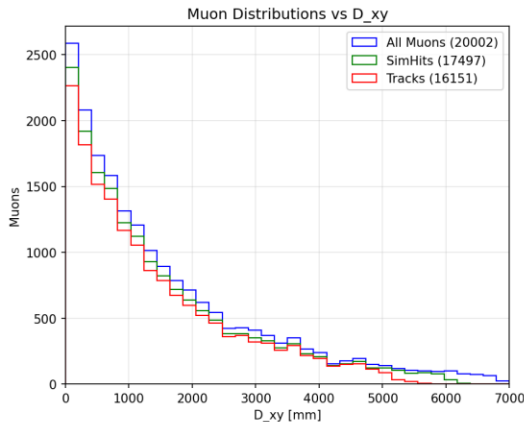
- Around 1500 more muons have been reconstructed.
- Track efficiency goes up to 80.7%
- Quality track efficiency goes up to 98.2%

No selection cuts applied.

No geometry acceptance applied.

4-Layers

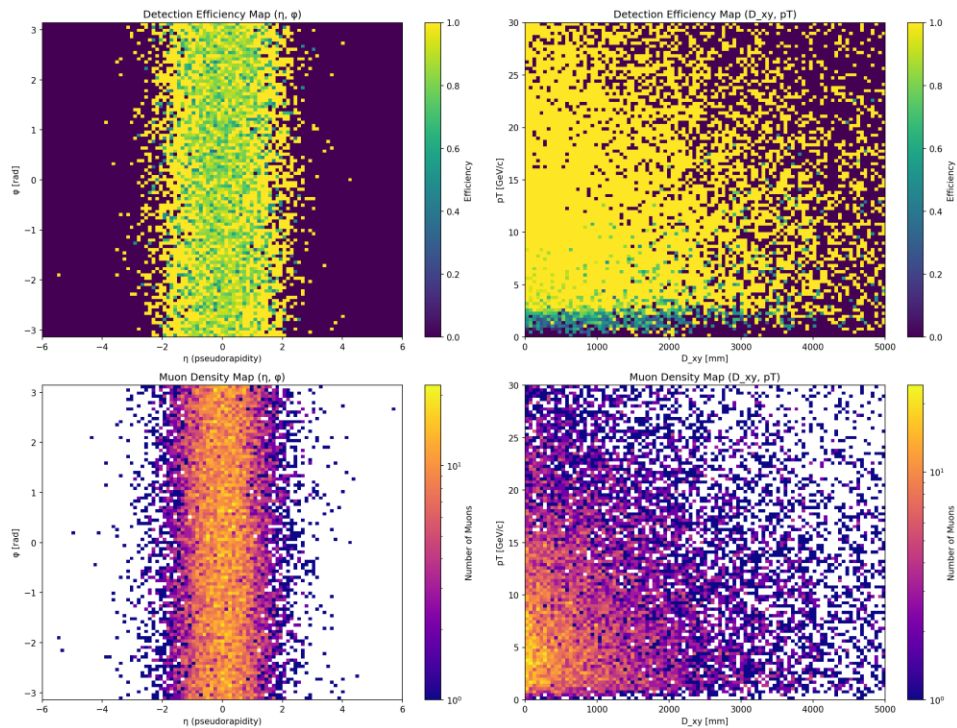
### Efficiency vs Displacement



# LLPs Detection:

## Efficiency vs Displacement

- Excellent performance for high- $P_T$  muons across all displacement ranges, with degradation only at very low momentum.
- Central region ( $|\eta| < 2$ ) demonstrates excellent detection coverage for all displacement ranges

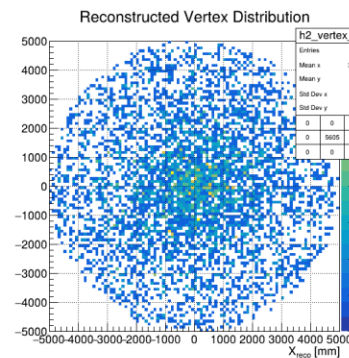
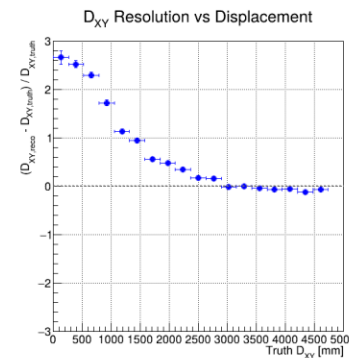
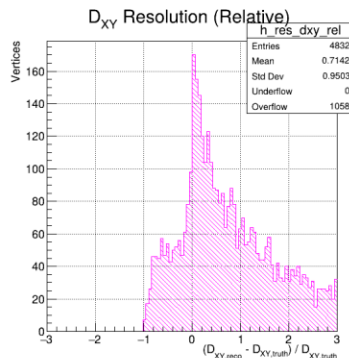
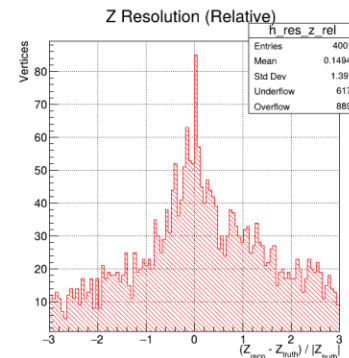
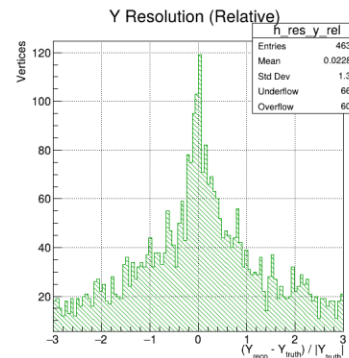
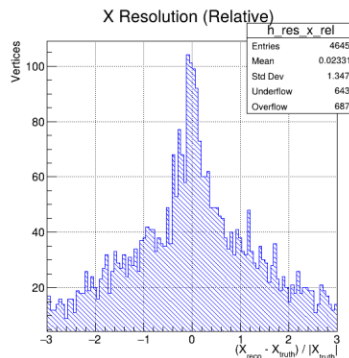


3-Layers

# LLPs Detection:

- ( **$R < 2.1 \text{ m}$** ) The volume inside the solenoid. The reconstruction shows degraded resolution close to the interaction point, with bad relative resolution. This poor performance stems from the different track segment inside the solenoid that standalone muon system can't reconstruct.
- ( **$R > 2.1 \text{ m}$** ) Beyond the solenoid boundary, vertex resolution reaches optimal performance with relative resolution values centered around zero

## Vertex Reconstruction



3-Layers

## Summary:

- **Detector Setup:** Full  $\mu$ RWELL barrel + endcap modeled with realistic geometry, gas gaps, and readout strips;  $\theta \in [8^\circ, 172^\circ]$ ,  $|\eta| < 2.56$ ; integrated with 2 T magnetic field inside the solenoid and -1.7T outside the solenoid.
- **Tracking Algorithm:** Based on Triplet-based seeding then extrapolation + simple fitting; has above 98% efficiency.
- **Vertexing Algorithm:** Designed for **displaced-vertex reconstruction** in **Long-Lived Particle (LLP)** topologies. Vertex resolution optimal beyond solenoid ( $R > 2.1$  m); degraded near interaction point due to standalone reconstruction limitations
- **Performance (3 Layers):**
  - Track efficiency  $\approx 83 \rightarrow 95\%$  (after selection cuts)
  - Transition-region inefficiency (barrel-endcap) mitigated by joint reconstruction.
- **Performance (4 Layers):** Efficiency  $\rightarrow \sim 100\%$ ; transition-region loss eliminated.
- **LLP (HNL) Case:**
  - Benchmark:  $m_{n1} = 20$  GeV,  $V_{\mu N_1} = 10^{-5}$ .
  - Track efficiency  $\approx 75$ -90% (plateau  $> 5$  GeV).
  - Stable up to 4.5 m displacement; quality-track  $\approx 98.2\%$ .



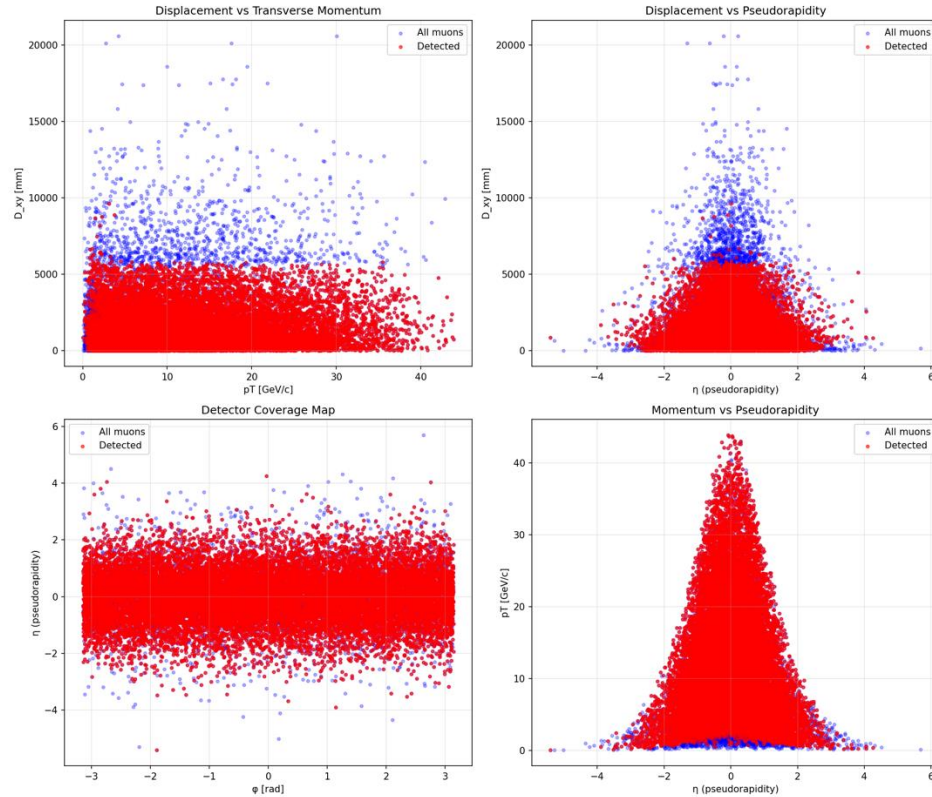
THANK YOU  
FOR YOUR ATTENTION.

Backup:

# LLPs Detection:

## Efficiency vs Displacement

- Multi-dimensional correlation analysis for HNL events.



# LLPs Detection:

- High displaced vertex reconstruction.

## Vertex Reconstruction

