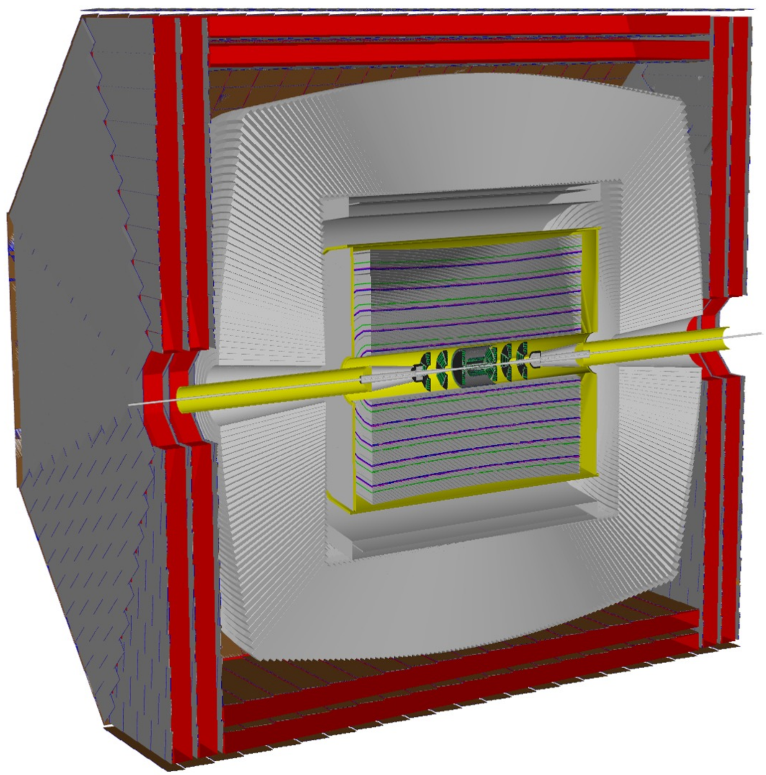
Mahmoud Al-Thakeel

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



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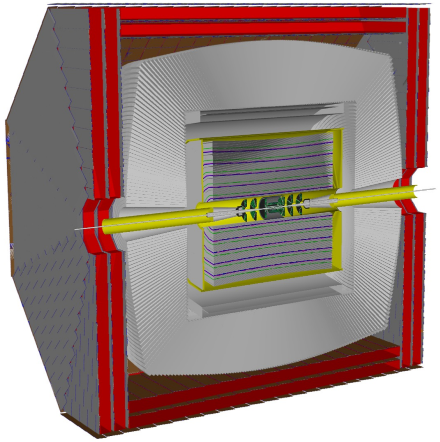
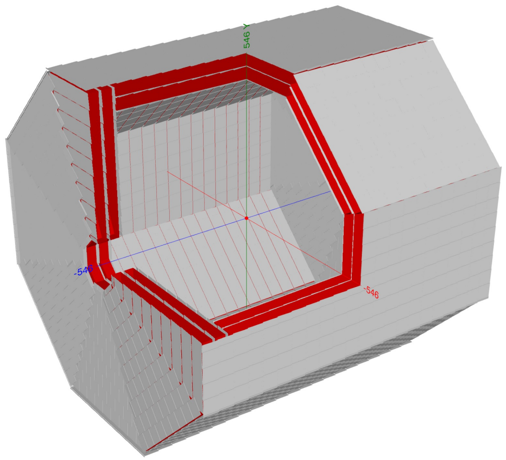
Quick recap on Muon system implementation in Full-Simulation:

- **Geometric modeling**: Complete barrel and endcap µRWELL chamber description with realistic gas gaps, and readout strips. Designed in 3 polyhedron(octagon) stations composed of arrays of 50 x 50 cm^2.
- **Sensitive detector integration**: Full digitization chain of space resolution and µRWELL 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.
- **Geometry coverage**: The Muon system extends in theta 8°< |θ| <172°, pseudorapidity |η| < 2.56 and with complete ϕ coverage.





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:

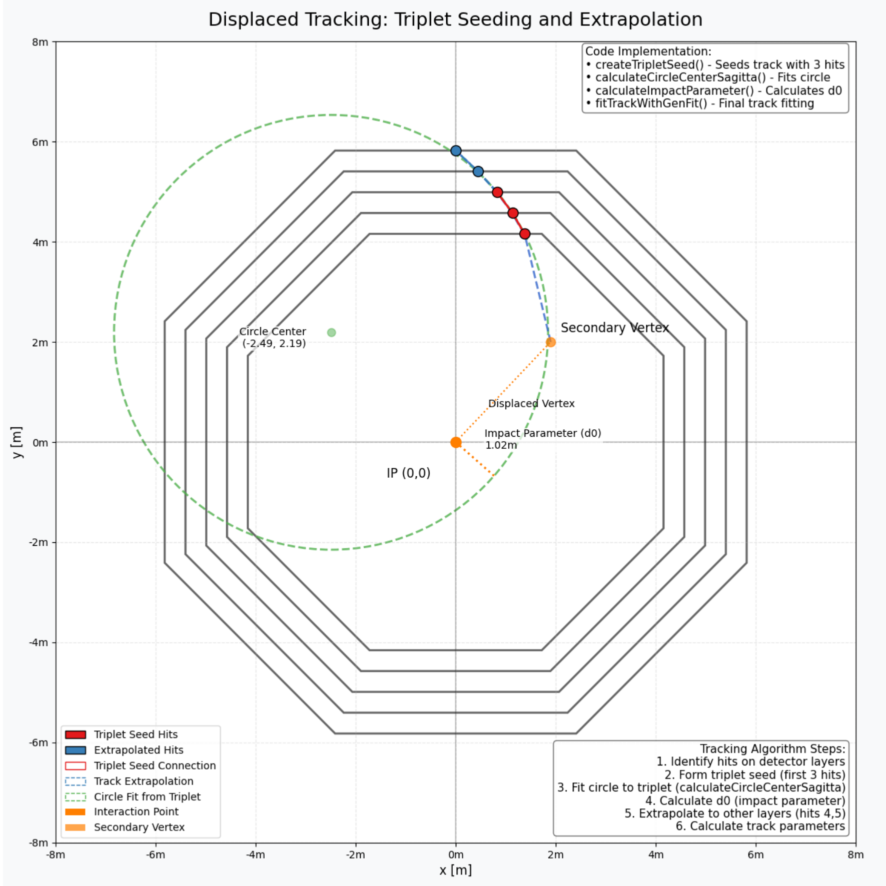
1. Hits are grouped by their layer IDs
2. The algorithm then forms triplets by selecting hits from three different layers
2. Systematically iterating through all possible combinations (3 nested loops)
3. For each potential triplet, it calls createTripletSeed to evaluate if the hits form a valid track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

Triplet Validation: Distance check and Angle consistency

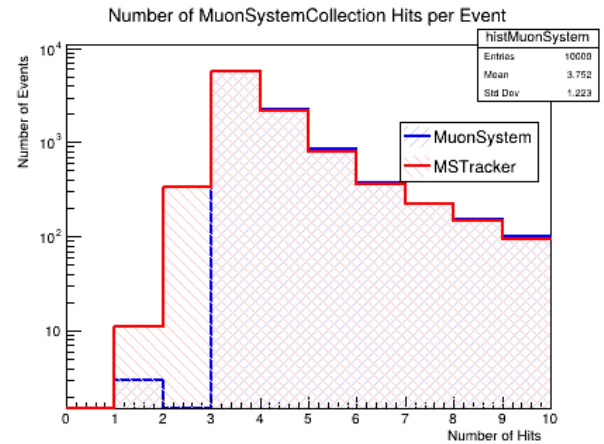
Circle fitting: Attempts to fit a circle through the projected hit positions in the x-y plane using **sagitta** method

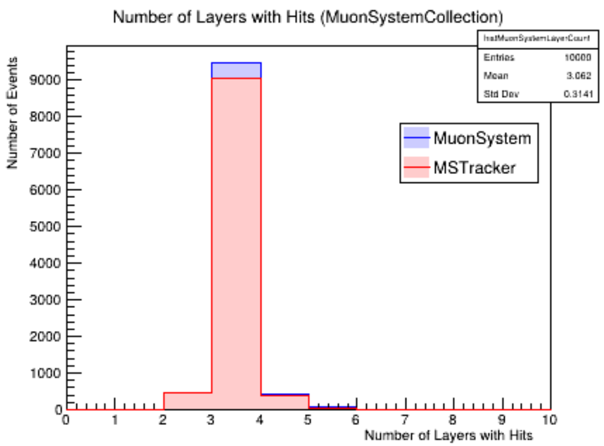
Calculates track parameters:

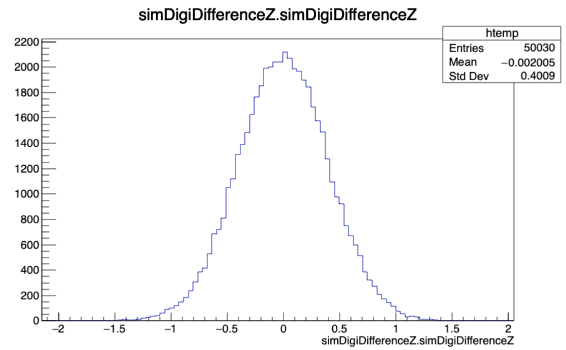
I. **Momentum (pT)**: Using the relation pT = 0.3 × B × R (where B is magnetic field in Tesla and R is radius in meters)
II. **Phi angle**: From circle center and hit positions
III. **Charge sign**: Based on clockwise/counterclockwise determination
IV. **Z component**: Linear fit along the track path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



Muon system Performance:







Smearing

Layer-Based Muon Hit Analysis Summary

MuonSystem: 99.97% events with >= 3 hits

MuonSystem: 99.97% events with >= 3 hits in >= 3 layers

MSTracker: 96.55% events with >= 3 hits

MSTracker: 95.41% events with >= 3 hits in >= 3 layers

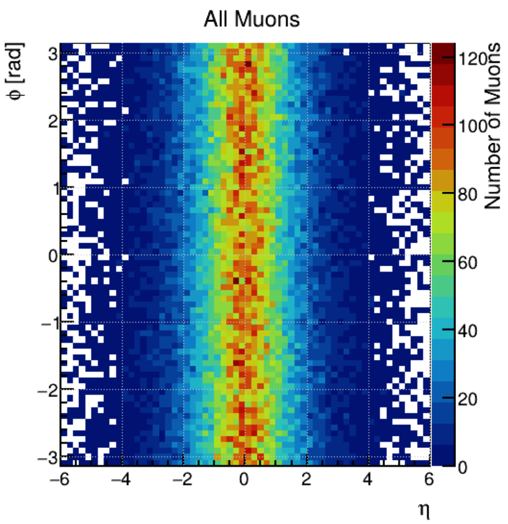
SimHits

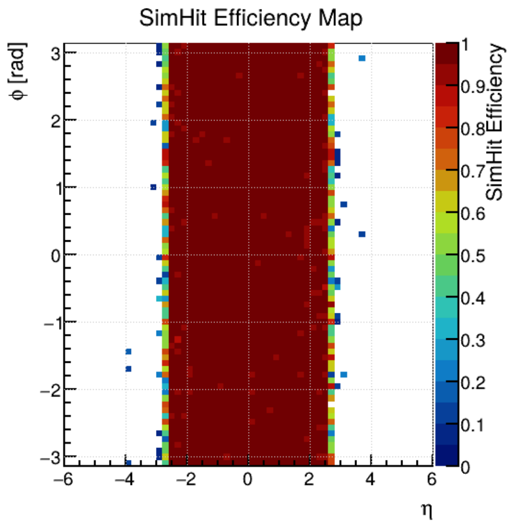
DigiHits

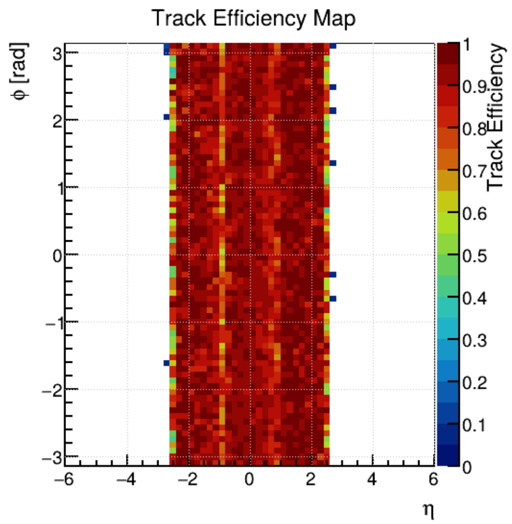
98% efficiency for uRWELL

Muon system Performance: **Detection Efficiency and Geometric Acceptance**

- The standard design of the IDEA muon-system is 3 layers of μRWELL chambers each of area 50×50 cm^2, and the current μRWELL candidate is 400 μm in space resolution
- (**SimHit: The detector has at least one hit from the passing particle**)
- The SimHit efficiency map demonstrates near-unity detection efficiency ≈ 1.0 throughout the acceptance region), while track reconstruction maintains high efficiency with well-defined geometric boundaries ~ eta ***$-2.56 < \eta < 2.56$*** which corresponds in theta to ***$8.84^\circ < |\vartheta| < 171.16^\circ$***.
- 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.



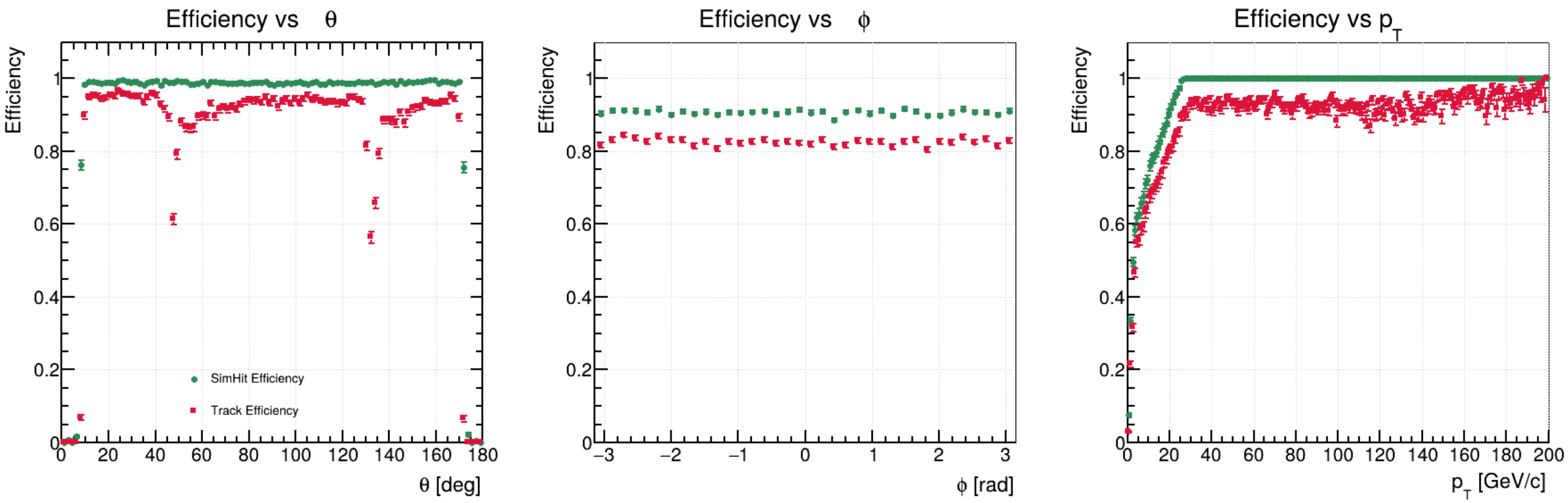




Muon system Performance:

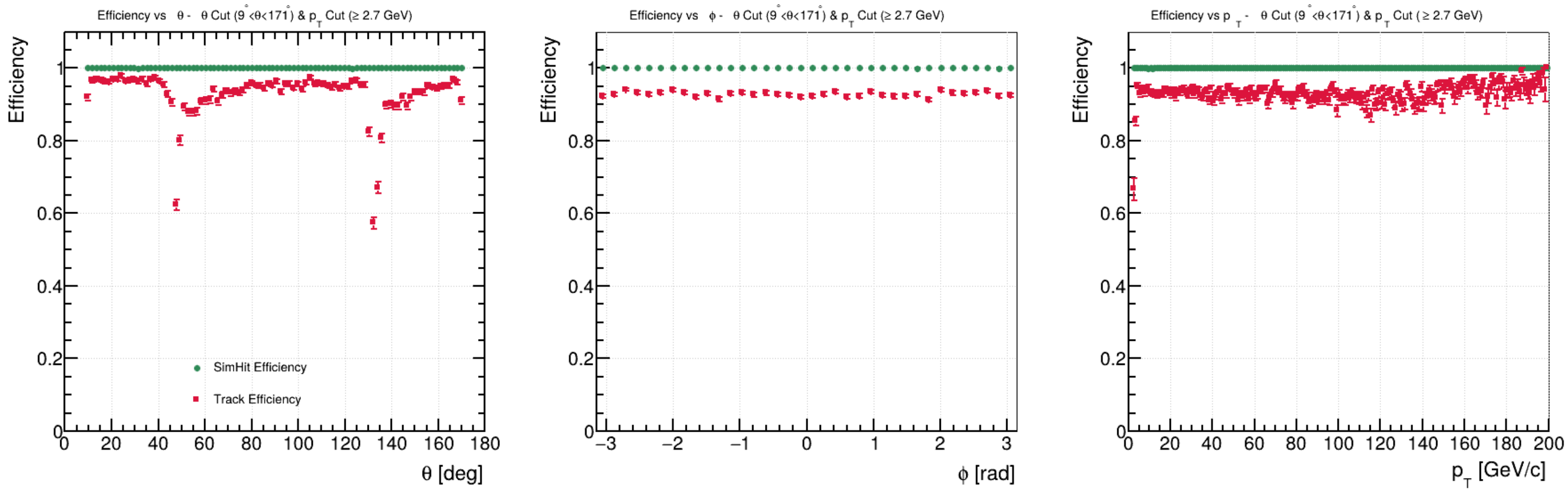
Kinematic Performance Characteristics

- kinematic dependencies of reconstruction efficiency:
- Key performance metrics from **82,548** reconstructed muons out of **100,000** muons generated uniformly by a particle gun:
  - **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◦ and 135◦ in θ.
- All the above studies have been done without applying cuts for geometric coverage nor momentum threshold.



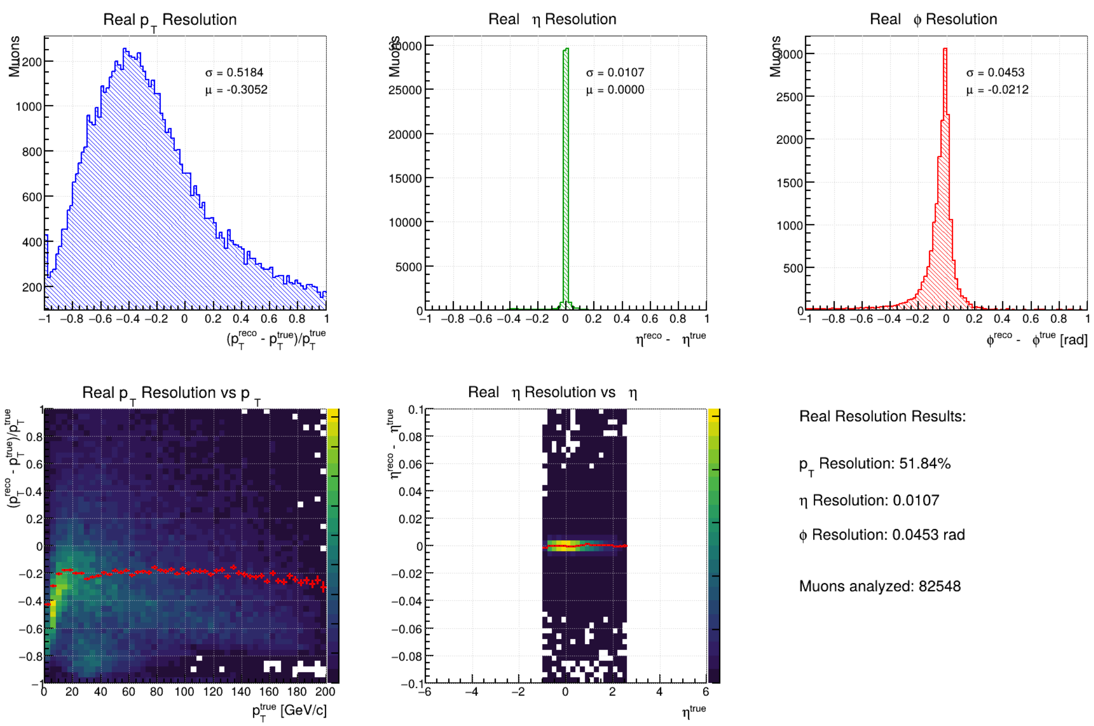
Muon system Performance: Performance Enhancement Through Selection Cuts

- **Geometric acceptance cut**: 9 < θ < 171 corresponding to the muon system's η 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%



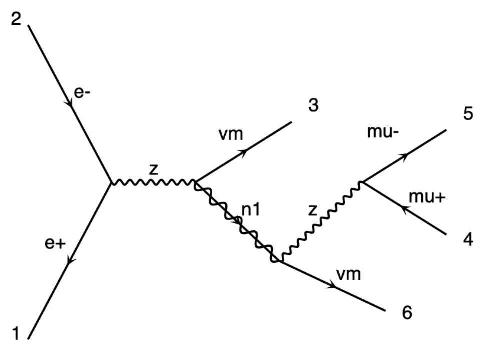
Muon system Performance: **Resolution Performance**

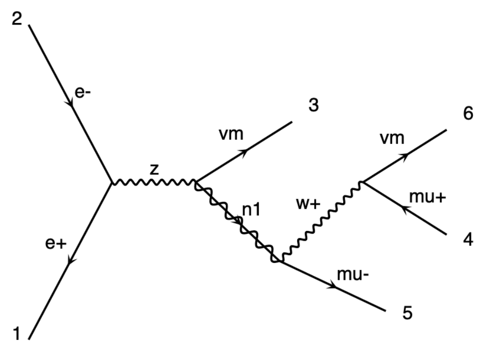
- The P_T residual distribution exhibits a broad spread with a significant negative bias (μ = −0.31), indicating systematic challenges in momentum reconstruction that require calibration improvements.
- In contrast, the η and ϕ residuals display narrow Gaussian peaks centered near zero (ση = 0.0107, σϕ = 0.0453 rad), reflecting excellent angular resolution capabilities.



Long-Lived Particle 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:
  - **mN1** = 20 GeV, representing a relatively light HNL.
  - VeN1 = 0 and Vτ N1 = 0, meaning N1 mixes only with muons.
  - **VμN1** = 1.0×10^{-5}, which is small enough to give a long-lived signature.
  - mN2 = mN3 = 10 TeV, effectively decoupling the heavier HNLs from the phenomenology.
  - Wn1 = auto to automatically compute the total decay width of N1.

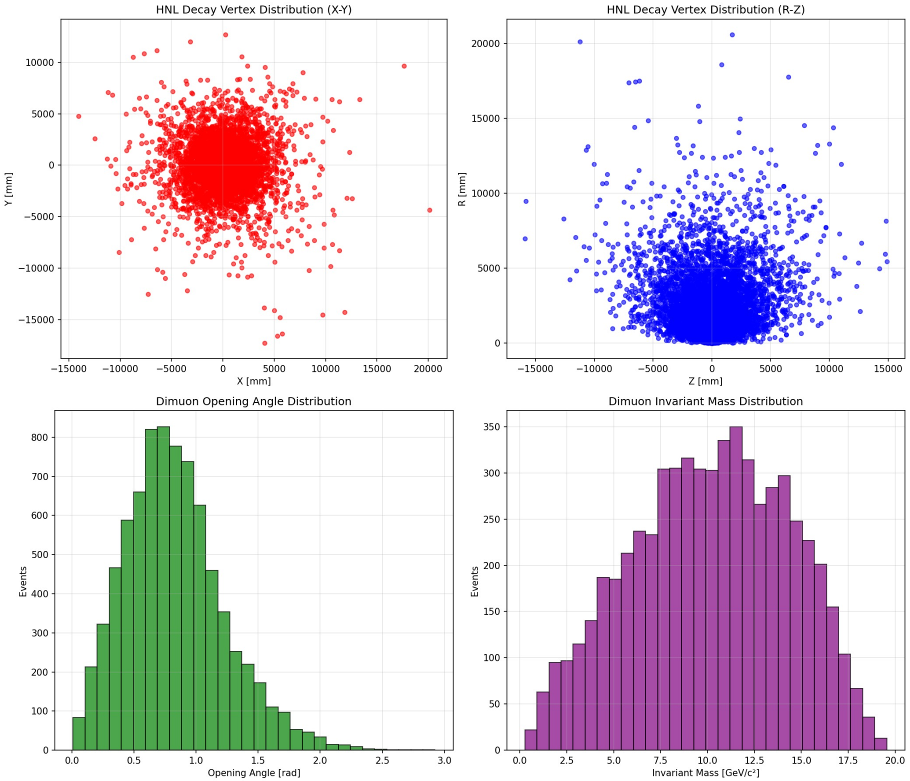




LLPs Detection:

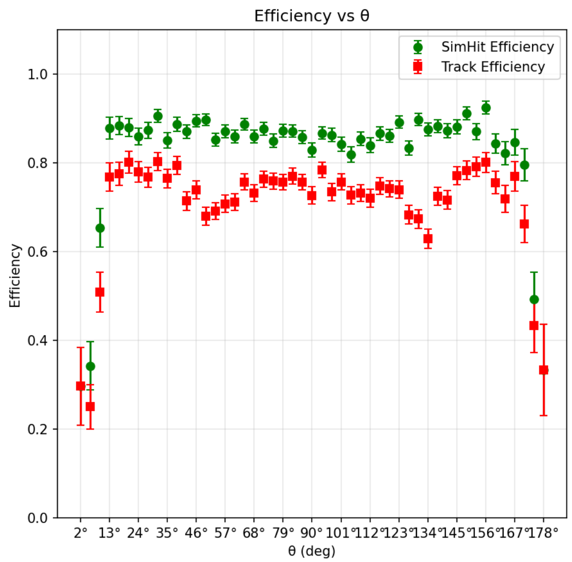
HNL Generator-Level Physics Characteristics

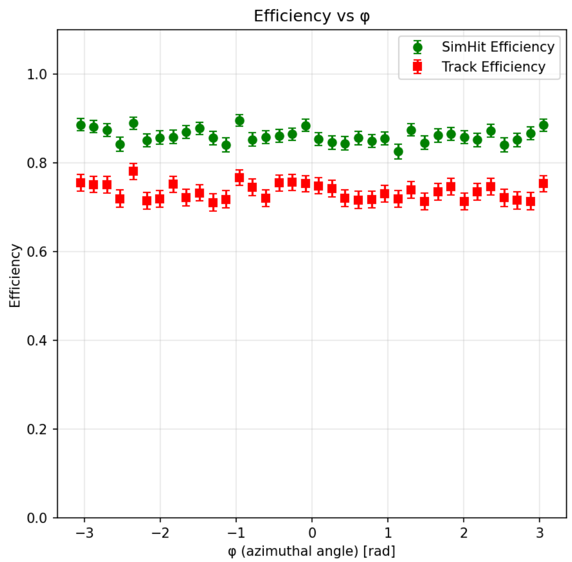
- Uniform azimuthal distribution of decay vertices with exponential radial decrease, directly reflecting the HNL lifetime characteristics (cτ distribution)
- Generator-level vertices span from millimeters to tens of meters, setting the physics requirements for displaced vertex detection

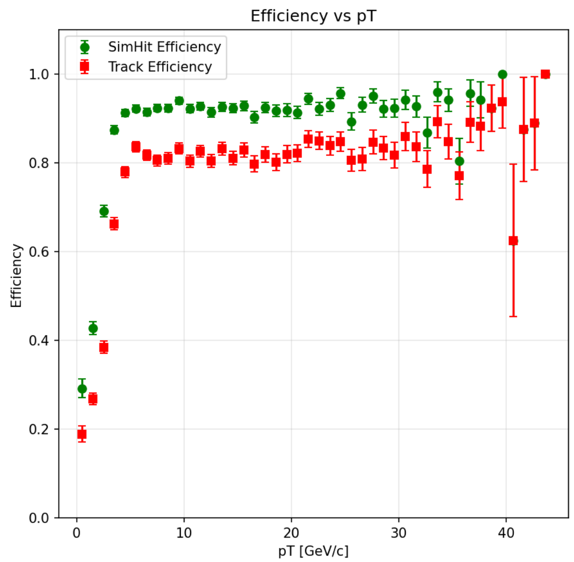


LLPs Detection: Detection Efficiency Performance

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



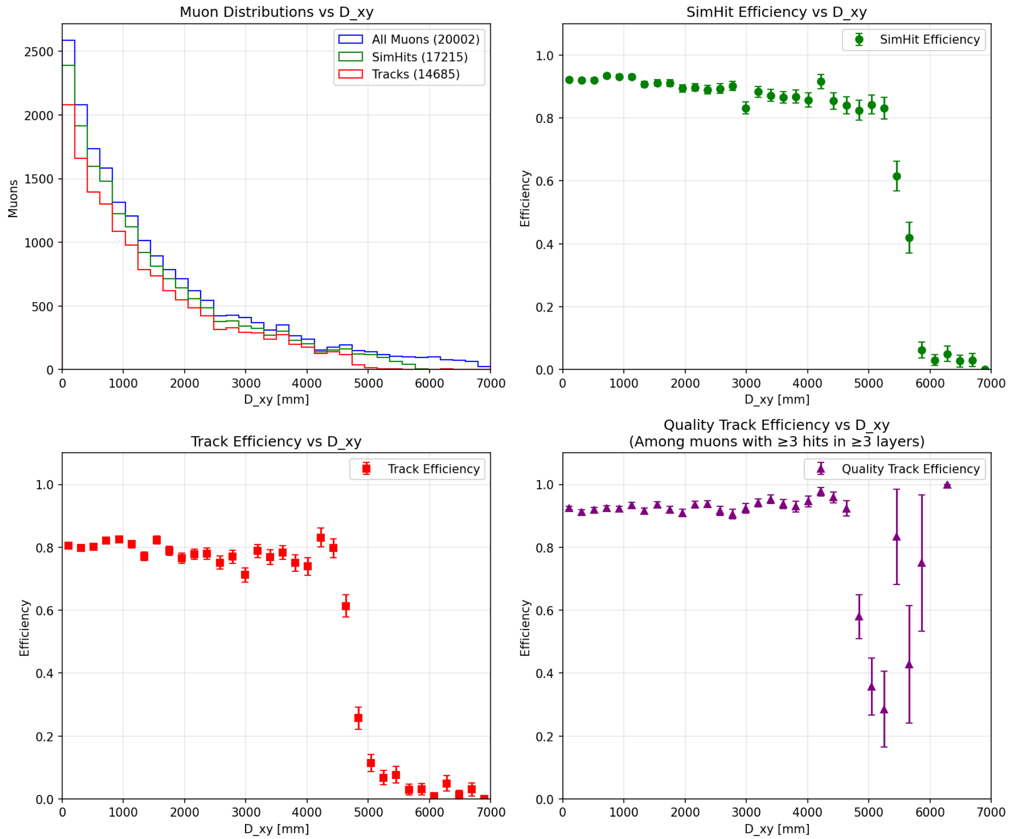




LLPs Detection:

Efficiency vs Displacement

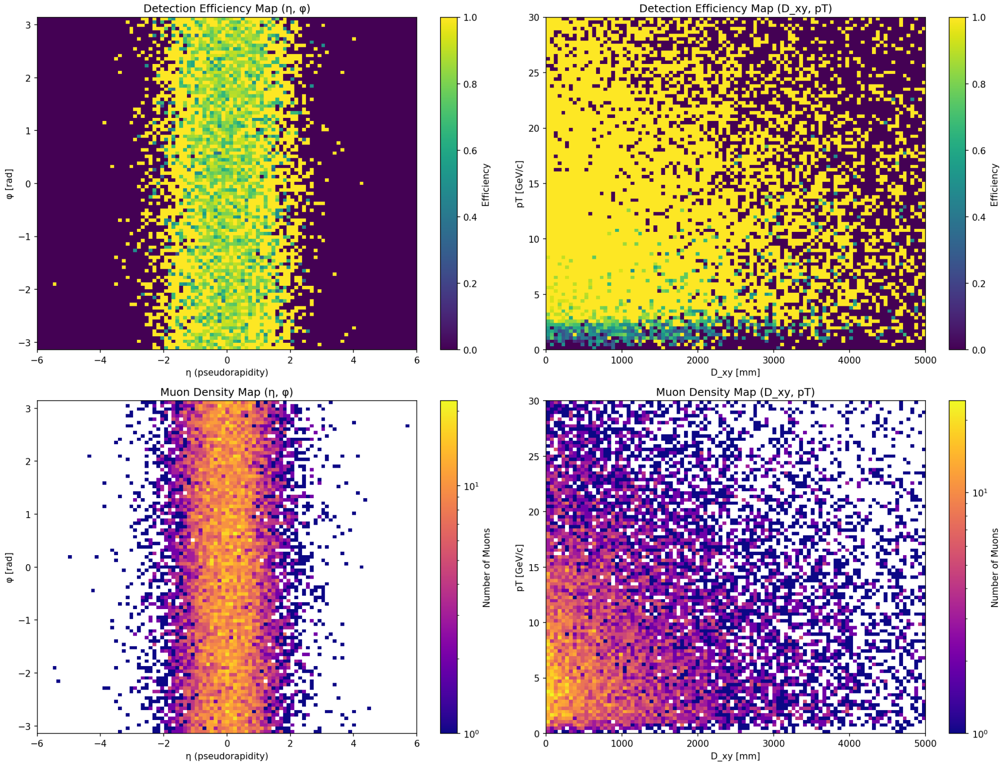
- The total sample includes 20,002 muons, with 17,215 producing at least one SimHit (86.1% SimHit efficiency) and 14,685 successfully reconstructed as tracks (73.4% overall track efficiency)
- Stable performance (~75-85%) for displacements up to 4.5 meters
- Sharp drop-off beyond 4.5 meters as tracks approach detector boundaries.
- The quality track efficiency analysis shows 15,852 quality candidates (**muons with ≥3 hits across ≥3 layers**), of which 14,613 achieved successful track reconstruction (92.2% quality track efficiency).



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 (|η| < 2) demonstrates excellent detection coverage for all displacement ranges

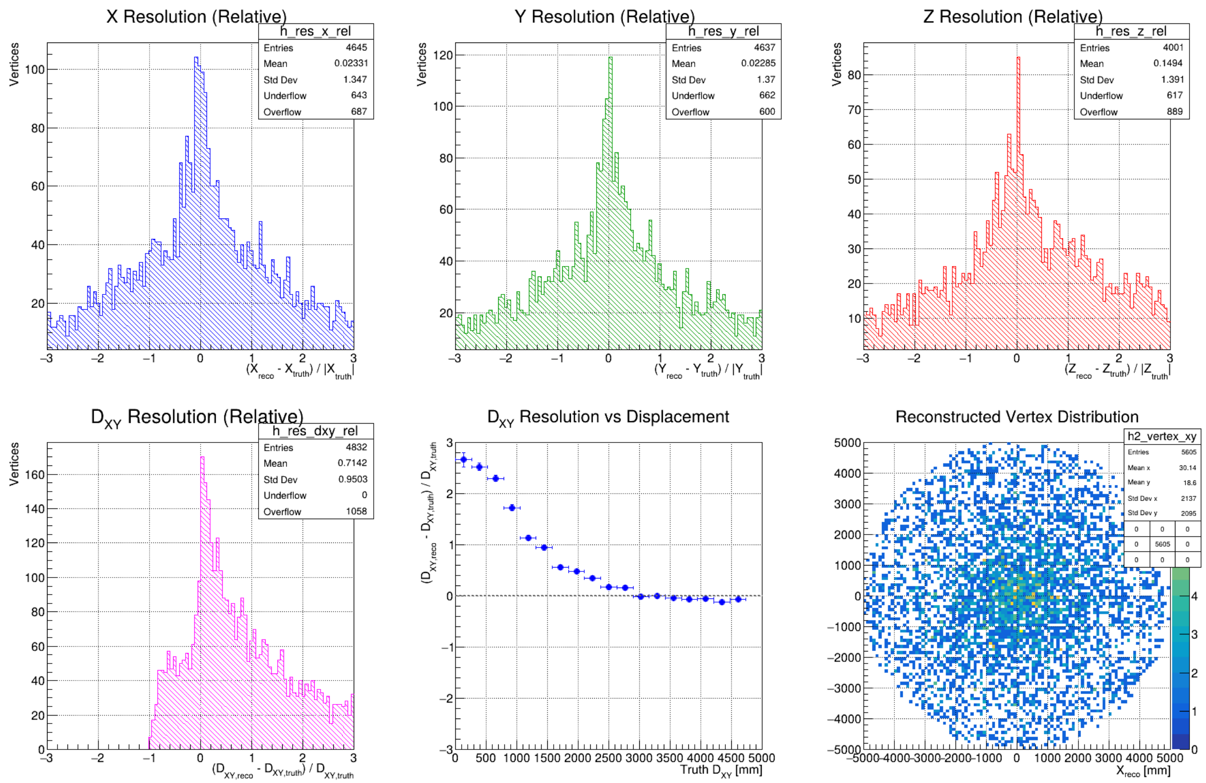


LLPs Detection:

Vertex Reconstruction

- (**R < 2.1 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 m**) Beyond the solenoid boundary, vertex resolution reaches optimal performance with relative resolution values centered around zero



Summary:

- The comprehensive analysis demonstrates excellent HNL event-level performance with 9,246/10,000 events (92.5%) containing detected muons, averaging 1.9 detected muons per event.
- High efficiency coverage: 86.1% SimHit efficiency across the full volume
- Displaced vertex sensitivity: Stable tracking performance up to 4-5 meters displacement covering 92.4% of all muons
- Quality reconstruction: 92.2% quality track efficiency suitable for precision vertex reconstruction.
- Momentum sensitivity: Efficient detection of high-pT muons characteristic of heavy HNL decays, while momentum resolution needs enhancement.
- Physics performance: 79.7% dimuon reconstruction efficiency enabling HNL mass studies.
- Vertex reconstruction capability: The muon system demonstrates effective vertex reconstruction for displacements greater than 2.1 m, where the majority of reconstructible HNL events are expected. The relative resolution of approximately less than 20% for transverse displacement measurements provides sufficient precision for distinguishing signal events from background processes while maintaining high efficiency for displaced vertex identification.
- Complementarity: Unique coverage compared to vertex detector-based and inner tracker searches, extending sensitivity to large displacement scales beyond the reach of traditional vertex detectors. This capability provides complementary coverage essential for comprehensive LLP search programs targeting Beyond Standard Model physics

Thank you for your attention.

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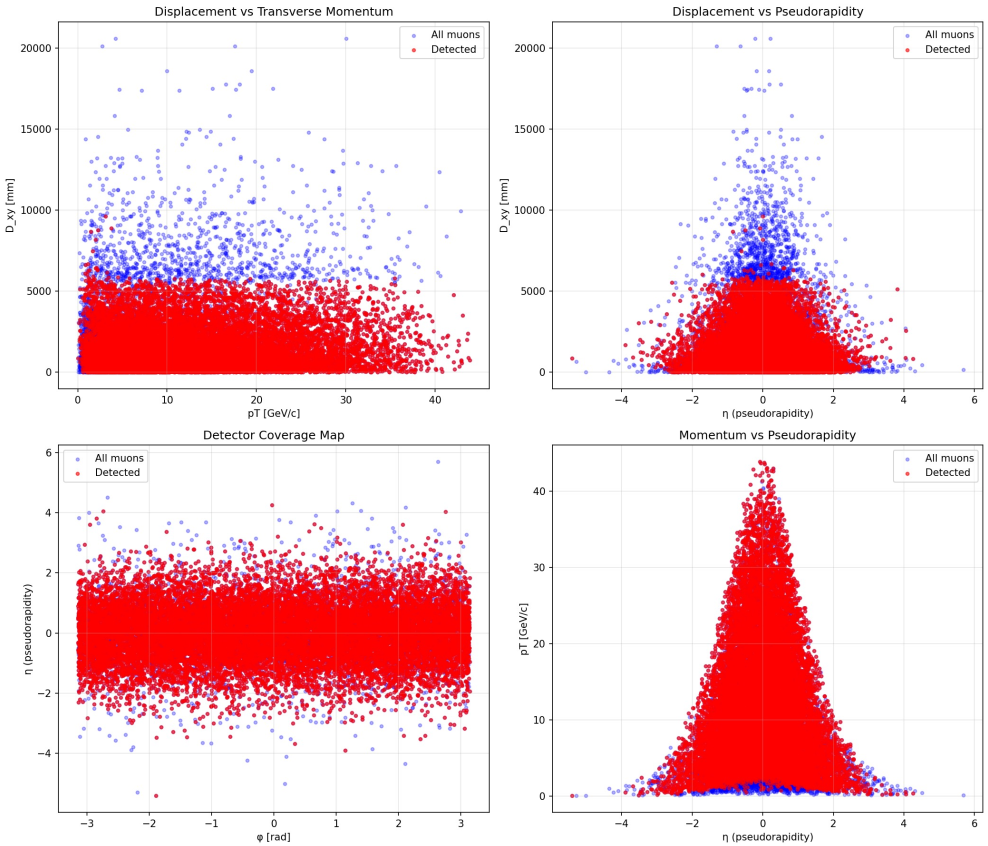
Backup:

LLPs Detection: Efficiency vs Displacement

- Multi-dimensional correlation analysis for HNL events.



LLPs Detection: **Vertex Reconstruction**

- High displaced vertex reconstruction.