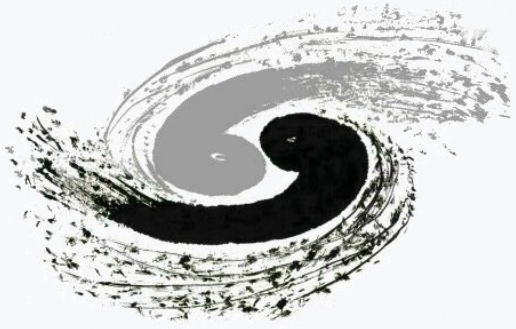
Track Reconstruction for the COMET Drift Chamber

Zhaoke Zhang[1,2]
on behalf of COMET Tracking group

1 Institute of High Energy Physics , Chinese Academy of Sciences

2 University of Chinese Academy of Sciences



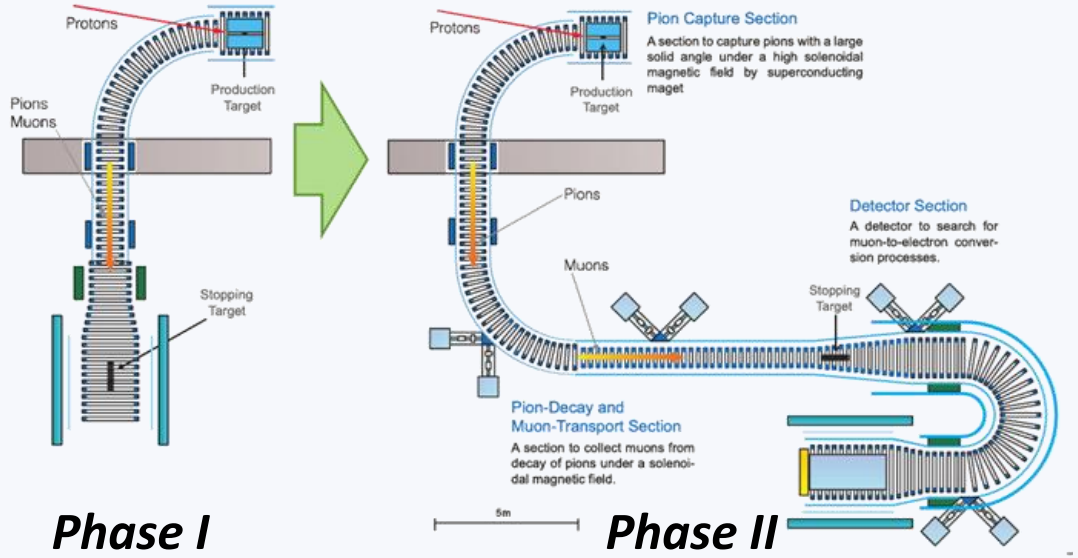
CHEP 2026 - May 25,2026

Outline

- Introduction to COMET
- COMET Tracking detectors
- Track Reconstruction for drift chamber
- Summary

CLFV and μN → eN Conversion

- Charged lepton flavor violated(CLFV)
  - $Br(\mu^+ \rightarrow e^+ + e^- + e^+) < 1.0 \times 10^{-12}$ (SINDRUM 1988)
  - $Br(\mu^- + Au \rightarrow e^- + Au) < 7.0 \times 10^{-13}$(SINDRUM II 2006)
  - $Br(\mu^+ \rightarrow e^+ + \gamma) < 1.5 \times 10^{-13}$ (MEG II 2025)
- COMET(COherent Muon Electron Transition)
  - $Br(\mu^- + Al \rightarrow e^- + Al)$
    - Phase I : 3.1×10^{-15}
    - Phase II : 2.6×10^{-17}



Signal and Physics Backgrounds

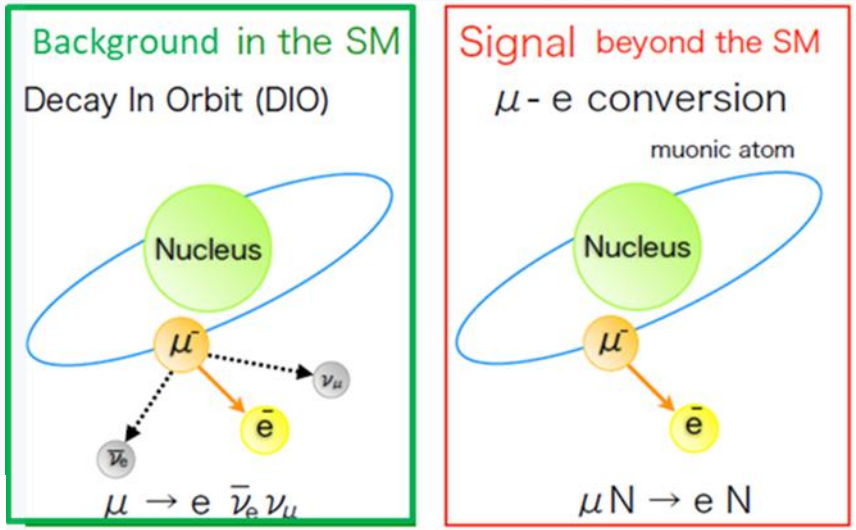
- Signal:

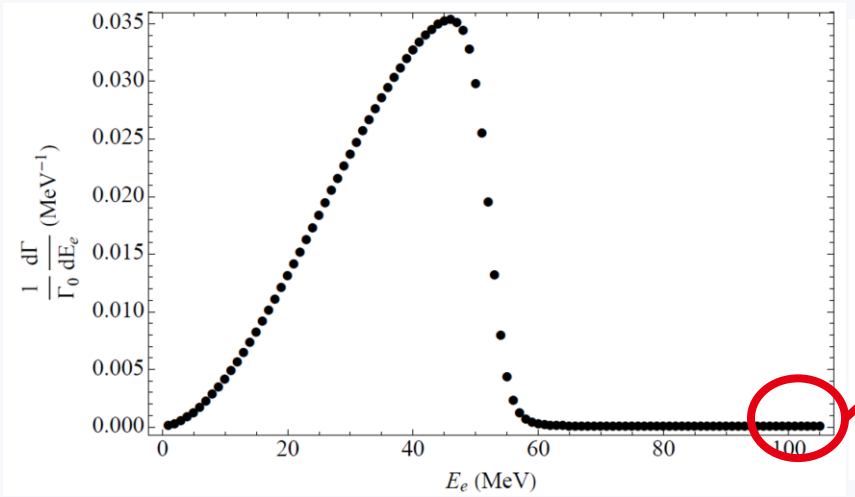
$$\mu^- + Al \rightarrow e^- + Al$$

$$E_e = m_\mu - B_\mu - E_{recoil} = 104.97\ MeV$$

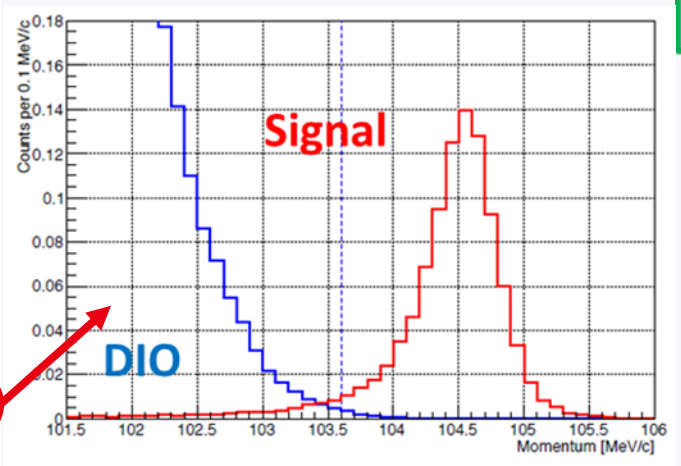
- Main background:

$$\mu^- + Al \rightarrow e^- + Al + \bar{\nu_e} + \nu_\mu$$





Branching ratio of DIO background



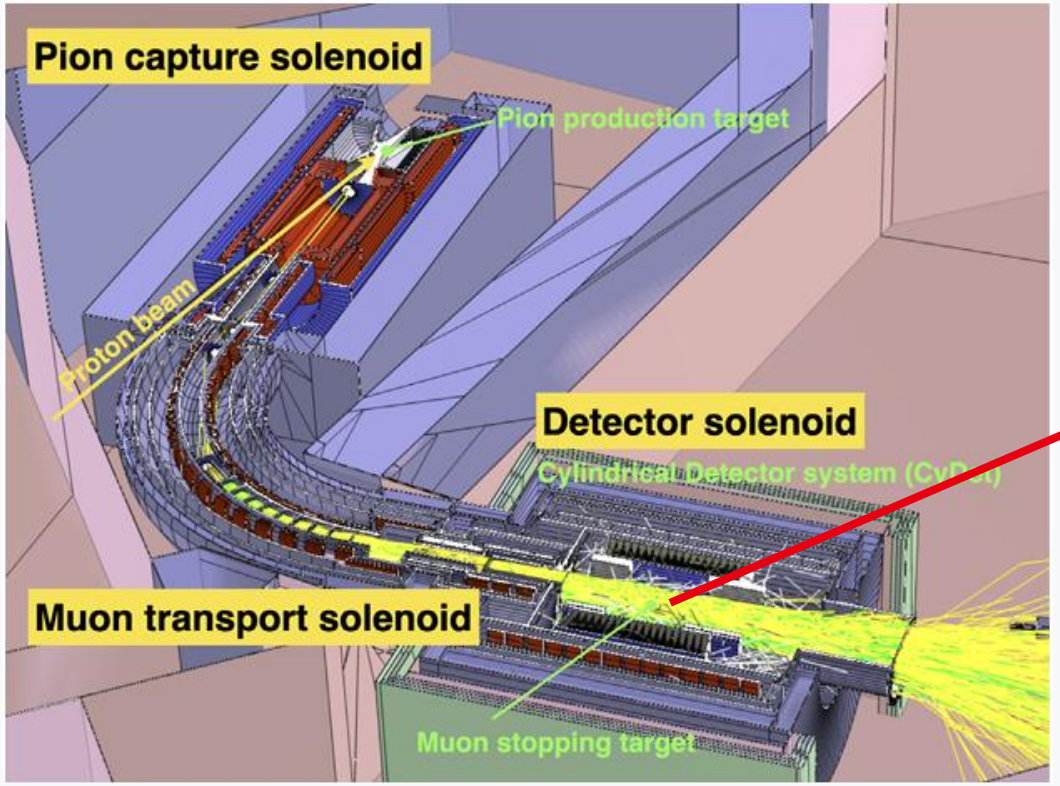
Momentum distribution of COMET Phase-I

Tracking requirements:

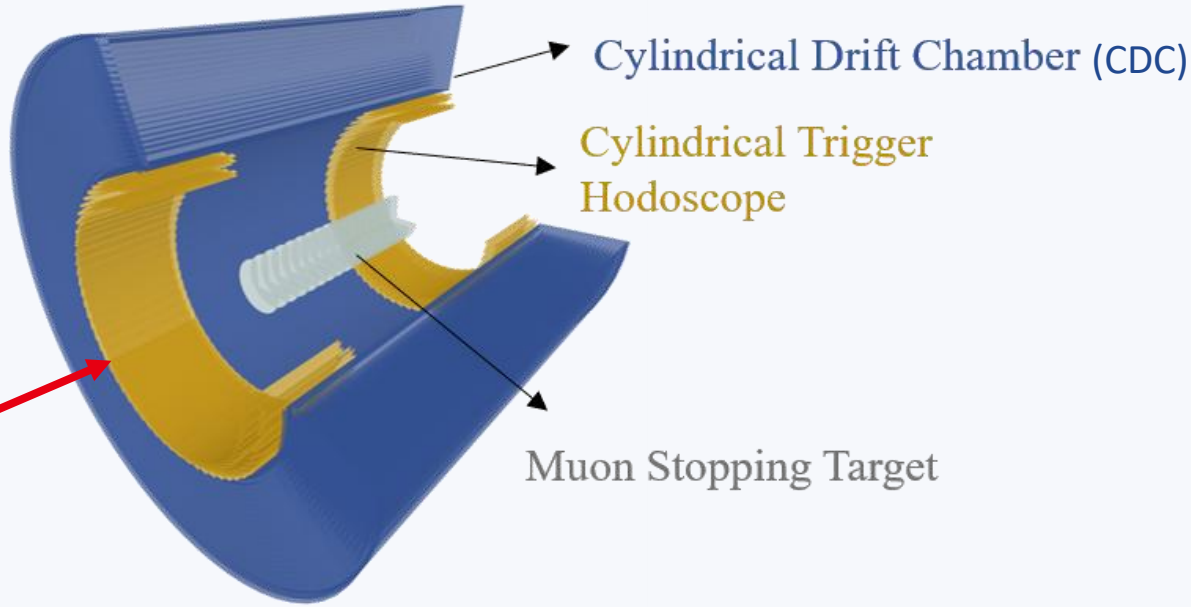
$\sigma(p)$ < 200keV/c

No tail > 2MeV/c

COMET Phase-I Detectors



COMET Phase-I Beamline



COMET Phase-I Detectors: CyDet

Challenges for CDC tracking

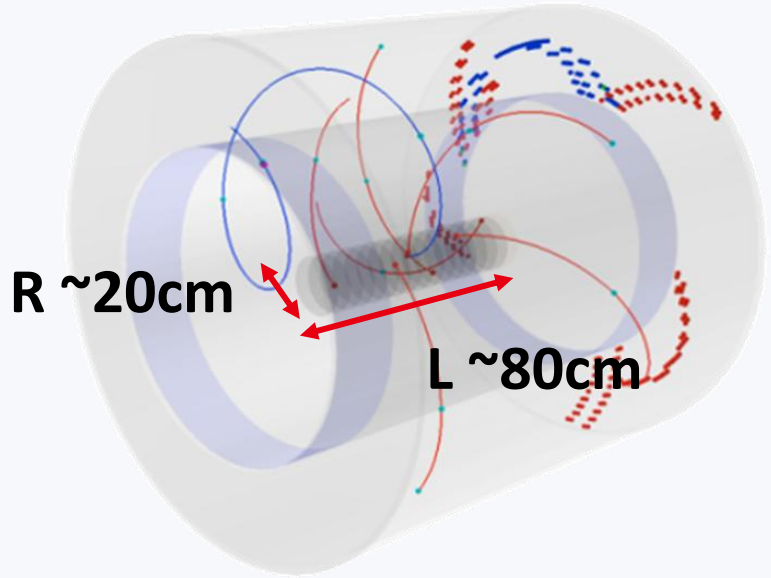
1. **No track seed from other subdetectors**
   - no vertex detector
   - Tracks originate from a broad region

2. **Signal is low momentum electron tracks**
   - All tracks curling inside the detector

3. **Multi-turn tracks with overlapped hits**
   - Multi-turn tracks: ~1/3 of total
   - Hits overlap between turns

4. **All stereo layers**
   - hard to calculate z position

5. **High occupancy**



Track Reconstruction Chain

Hit filtering → **Track finding** → **Track fitting** → **Track selection**

GBDT

U-Net

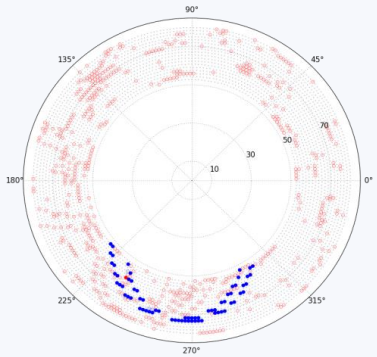
Cellular Automaton（CA）

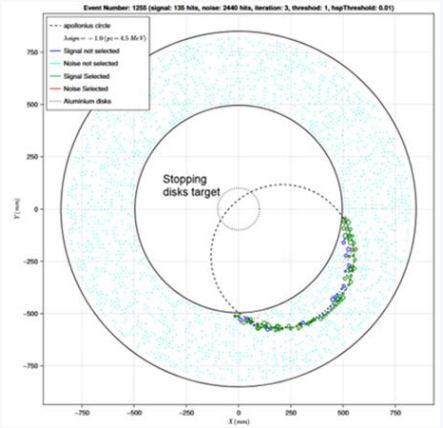
RANdom SAmple Consensus（RANSCA）

GPU-Accelerated Algorithm

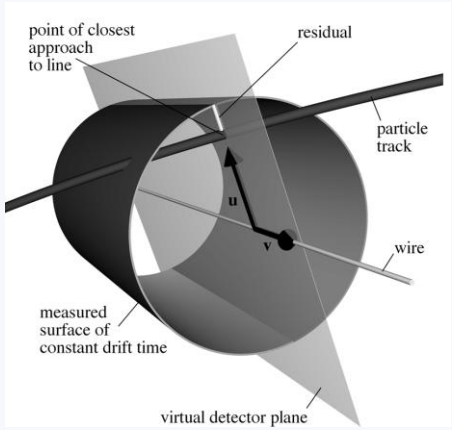
GENFIT

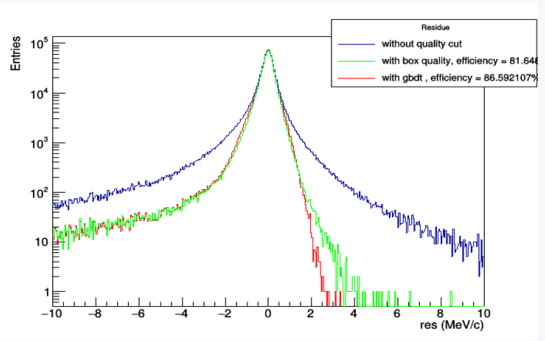
GBDT





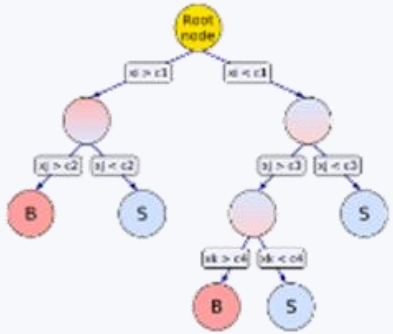
Most important





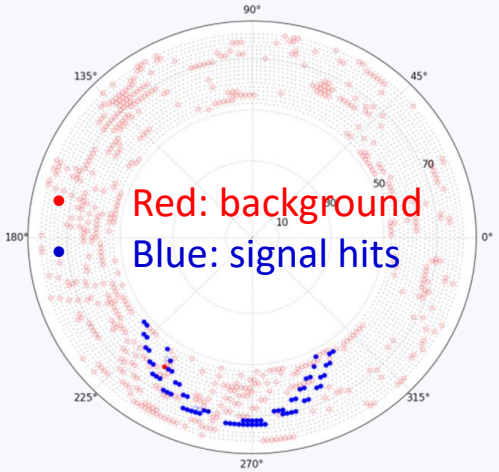
Hit Filtering

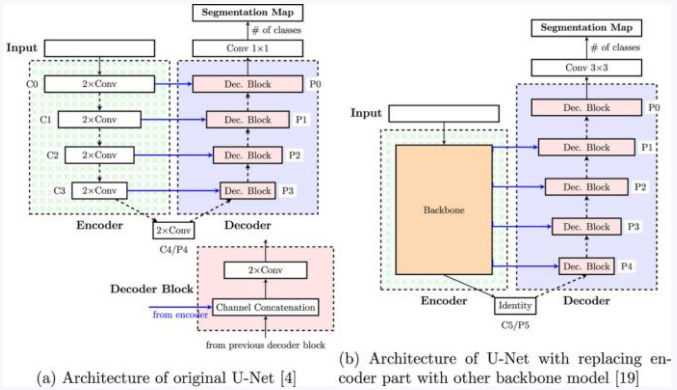
1. Hit filtering with **G**radient **B**oosted **D**ecision **T**rees(GBDT)
   - Classify hits using local, neighbor and shape features
   - Reweighted Inverse Hough Transform



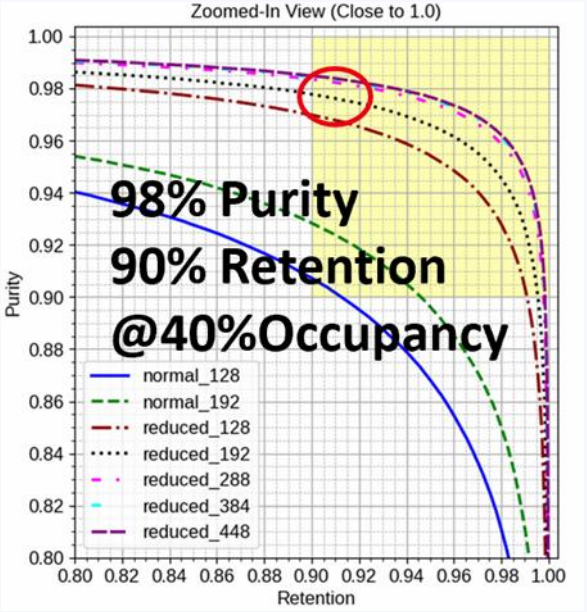
GBDT

2. Hit filtering with U-net https://doi.org/10.1093/ptep/ptaf048
   - Treats CDC hits as 2D image → semantic segmentation
   - Input features are hit timing, ADC, CTH hit





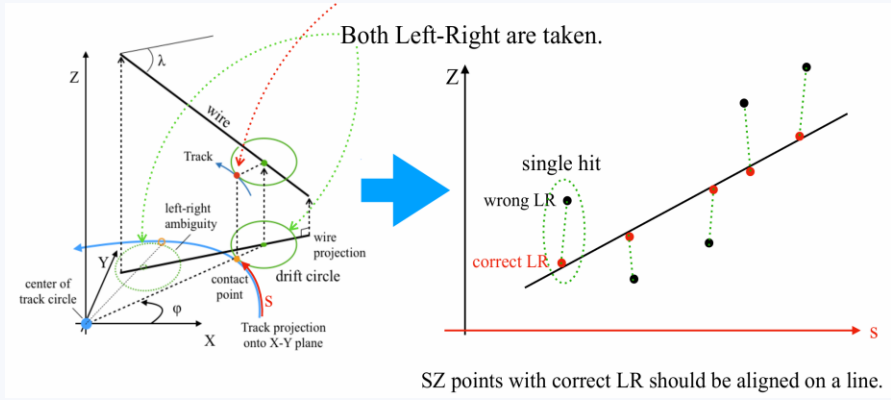
U-Net

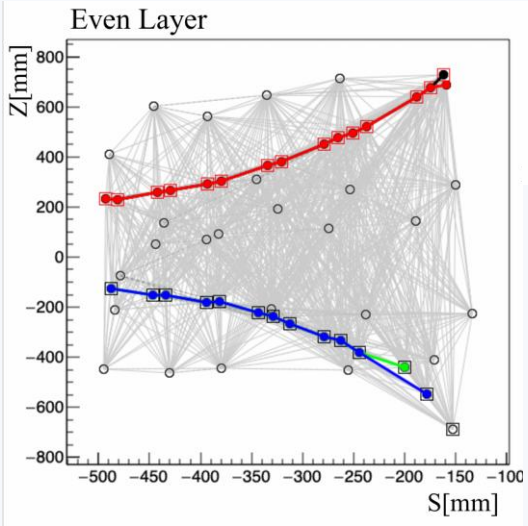


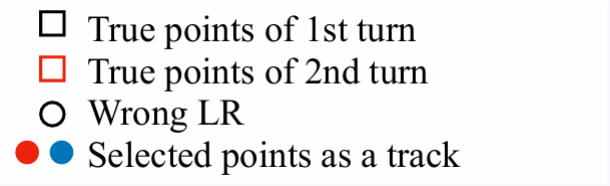
U-Net performance

Track Finding with Cellular Automaton

- Cellular Automaton(CA) is a grid of cells that evolve based on neighbor states
- Steps:
  1. Get initial circle from Hough Transformation
  2. Transform to z-s plane(s is flight length)
     - LR ambiguity →one hit, two point
  3. Connect the suitable hits as segment
  4. Iterate to update segment's state
  5. Pick the smoothest one
- Tracking efficiency@10% occupancy
  - 95% for single turn
  - 94% for double turn

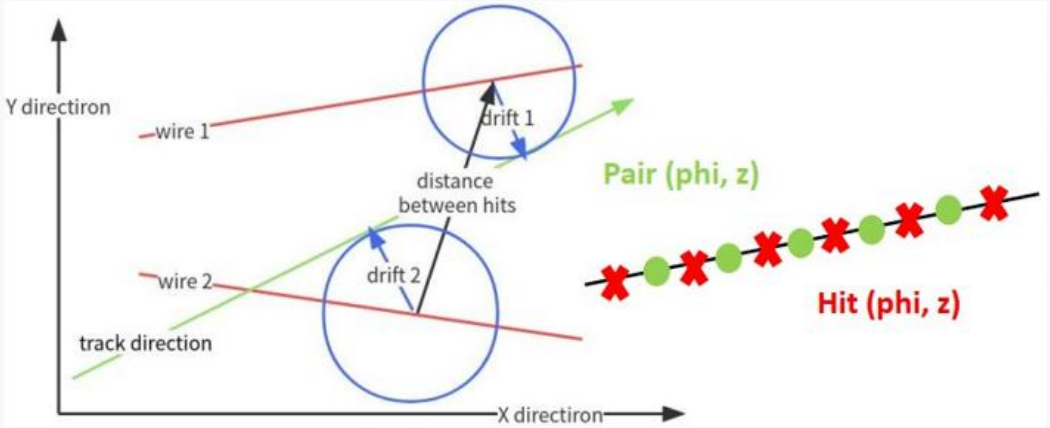


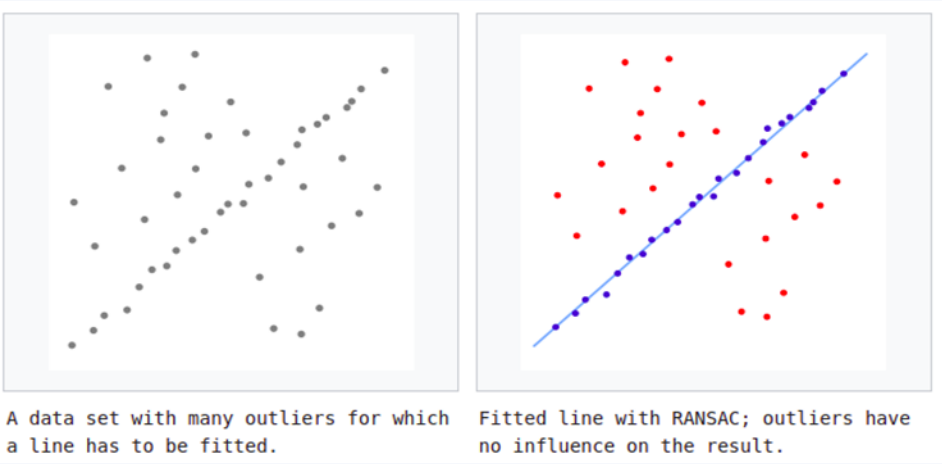




Track Finding with RANSAC

- Random Sample Consensus (RANSAC):
  - Iteratively estimate parameters from data that contains outliers
- Steps:
  1. Create pairs:
     $$F(\overrightarrow{w_1}, \overrightarrow{w_1}, d_1, d_2, \varphi_{track}, Zpair, \Delta Z, LR),$$
     $$Z_{pair} = \frac{Z_1+Z_2}{2}, \Delta Z = Z_1 - Z_2$$
  2. Linear fitting of pairs -> helix
  3. Peak searching of candidate helix





A data set with many outliers for which a line has to be fitted.

Fitted line with RANSAC; outliers have no influence on the result.

For single turn events:

Track finding efficiency: 95.1%

Momentum resolution: 214 keV/c

0.5 second for each event

Resolution:

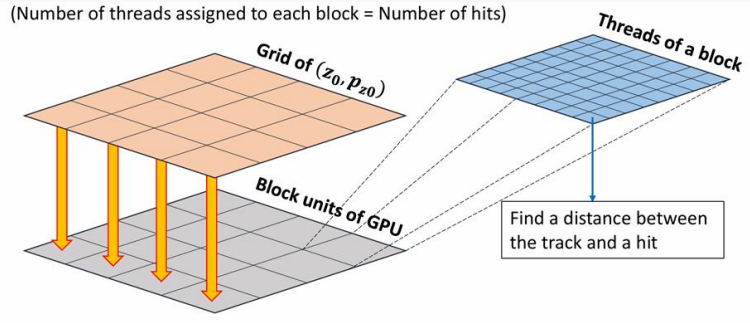
$$\sigma_x = 0.24 \text{ mm}, \sigma_y = 0.24 \text{ mm}, \sigma_y = 4.3 \text{ mm},$$

$$\sigma_{px} = 1.0 \text{ MeV/c}, \sigma_{py} = 1.0 \text{ MeV/c}, \sigma_{pz} = 4.9 \text{ MeV/c}$$

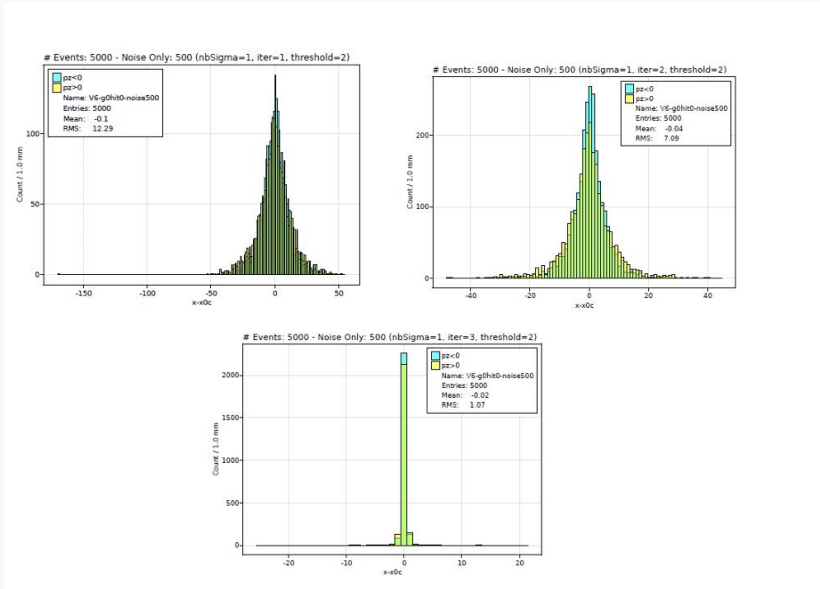
Track Finding with GPU-Accelerated

1. Scan track seed (https://doi.org/10.1016/j.cpc.2020.107606)
   - Runge-Kutta-Nyström propagation
   - Best-matched track parameters are determined by the minimization of the total DOCA
   - GPU-Accelerated——one seed ,one block
2. Interval arithmetic voting (hal-04413938)

   Parameter Space a 4D grid (voxels) over helix parameters (xc,yc,R,z0)
   - Apollonius condition Voting
   - GPU-Accelerated Brute Force
   - Iterative progressive



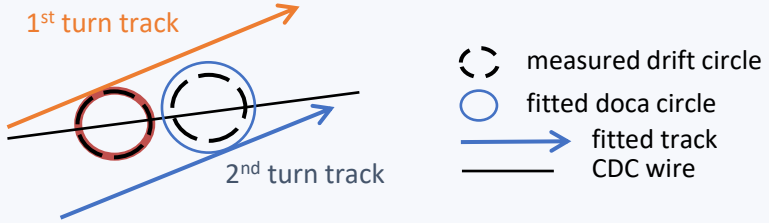
Scan track seed



Iteration of interval arithmetic voting

Track Fitting

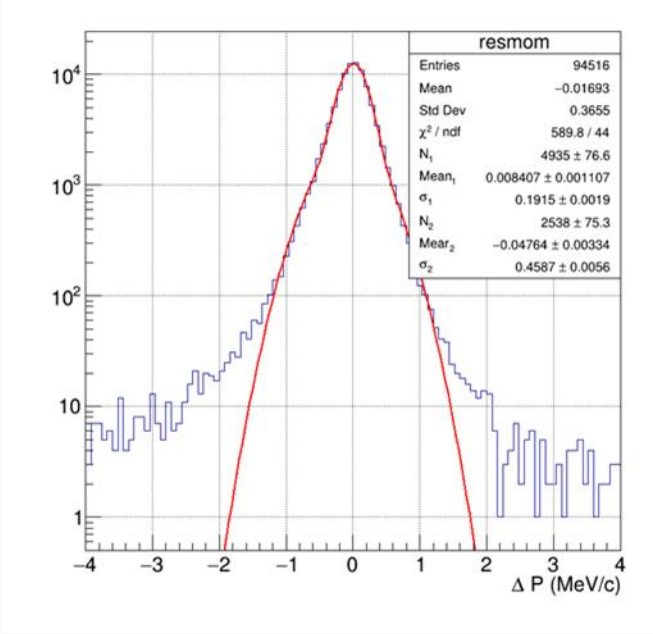
- Based on GenFit - A Generic Track Reconstruction Toolkit
- Implementation of track fitting
  - Field Map Interface
  - Customized Material
  - CDC Measurement Customization
  - Fitter Wrapper
  - Data Converter
  - Track Extrapolation Tools
  - Multi-Turn Track Fitting



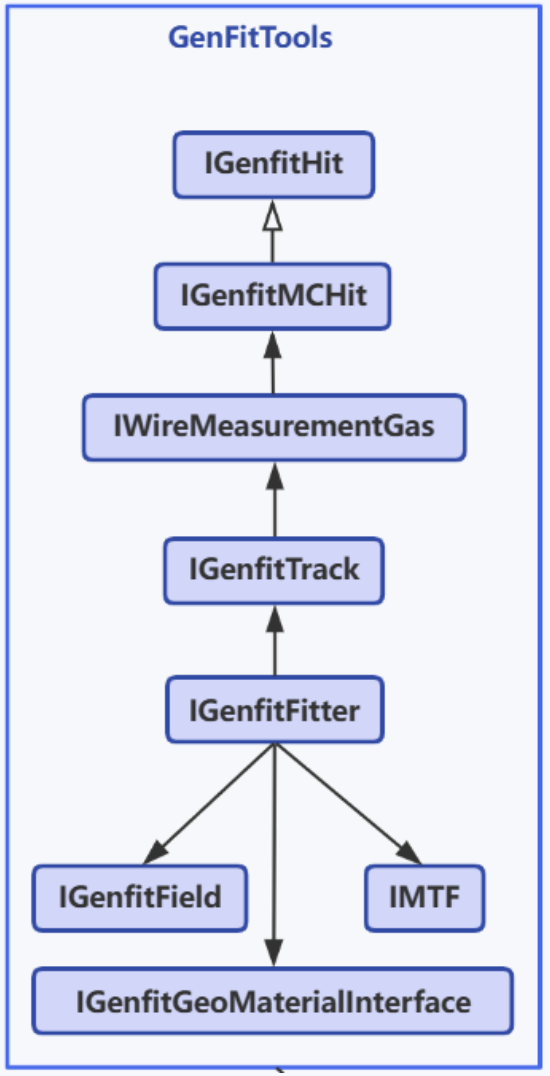
The possibility of hit *i* assigned to track *j* is defined as matrix Φ

$$(\Phi)_{ij} = \varphi_{ij} = \varphi(y_i; Hx_j, V_i), \quad p_{ikj} = \frac{\varphi_{ikj}}{\sum_l \sum_\alpha \varphi_{i\alpha l} + c}.$$

Weighted measurement for multi-turn tracks



Momentum distribution



GenFitTools

Tracking Performance

- RANSAC track finder + track fitting
- Single-turn and double-turn events, without noise

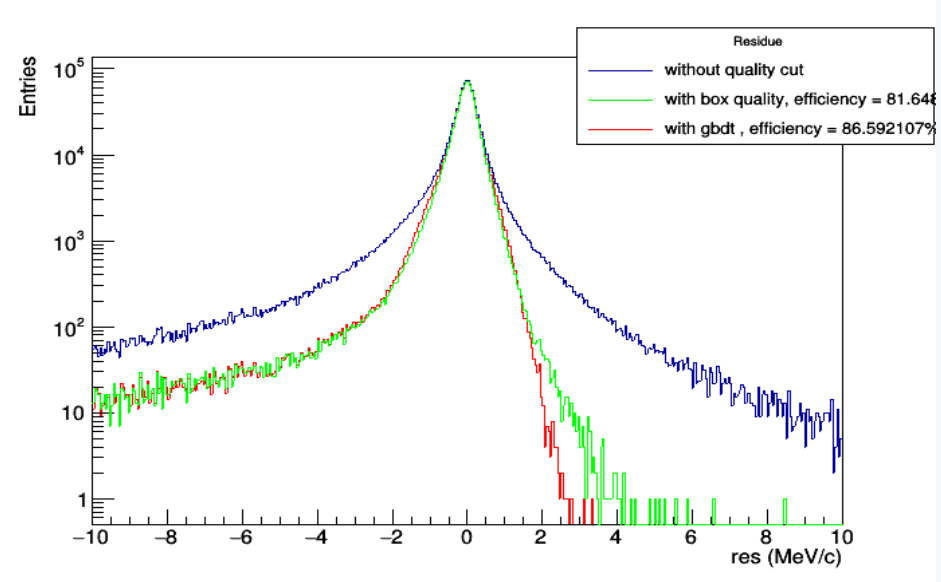
	Tracking		Tail	Mom resolution (body)
	finding	fitting		
Single Turn	96.2%	99.4%	1.6%	214keV
	95.6%			
Double Turn	99.46%	98.9%	25.9%	209keV
	98.36%			

Track Selection

- High-momentum tail from DIO can be misidentified as fake signal
- High quality track selection with GBDT
  - Good events or Signal events are event with |residue| < 1MeV /c
  - Bad events or Signal events are event with residue > 2MeV /c

Features for selection

Input Variable	Brief Description
NHit	Number of Hit
Chi2	χ^2
NDF	degrees of freedom
FittedMomX	Fitted momentum along beam axis
MaxLayer	max layer of hit fitted
chi2Const	Pearson test on hit residue
errmomX	Fitted error on p_X- from GENFIT M_{error}
errmomY	Fitted error on p_Y - from GENFIT M_{error}
errmomZ	Fitted error on p_Z- from GENFIT M_{error}
errZ	Fitted error on Z - from GENFIT M_{error}
errX	Fitted error on X - from GENFIT M_{error}
errY	Fitted error on Y - from GENFIT M_{error}
NHitFailed	NHit rejected by GENFit



Keep 87% of the signal with no tail > 4MeV/c

Summary

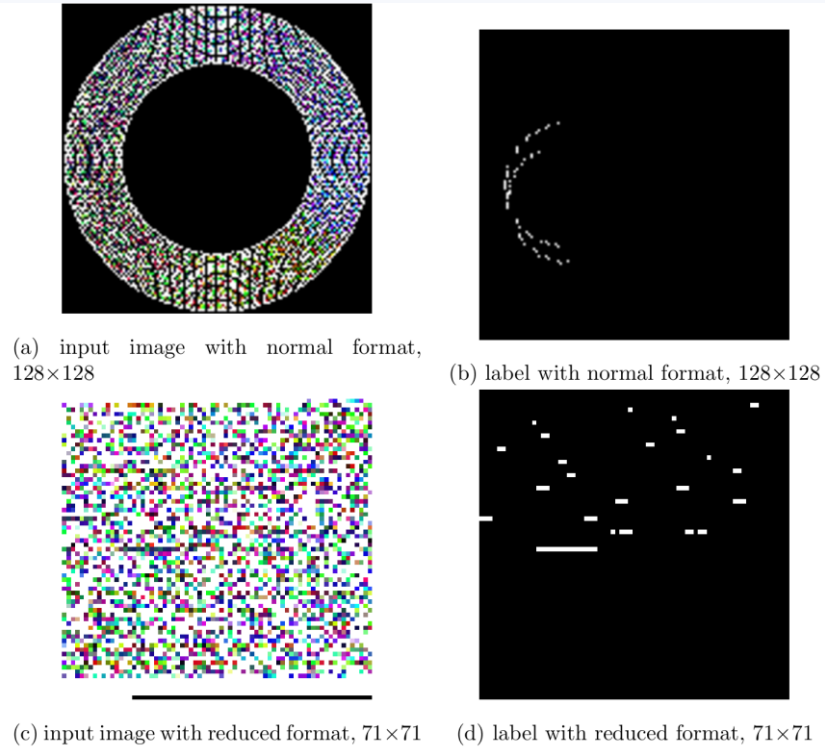
- Tracking is the key to achieving the physics goals of COMET
- However, tracking remains challenging
- The complete tracking chain has been established

Thank you !

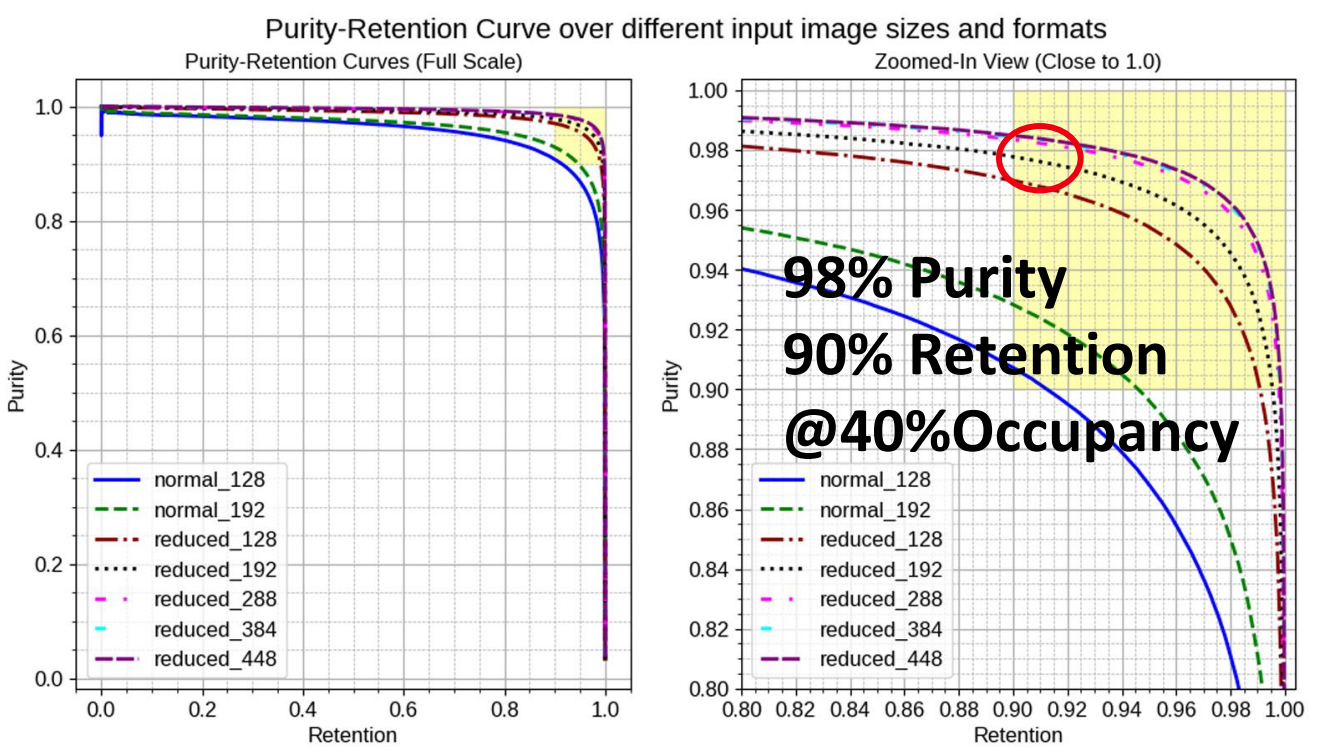
Hit filtering with U-Net

arXiv:2408.04795v2?
published

- Model is U-Net + EfficientNet encoder (pre-trained on ImageNet)
- Input features are Hit timing, ADC, azimuthal angle to the CTH
- Treats CDC hits as 2D image → semantic segmentation



The input image and label



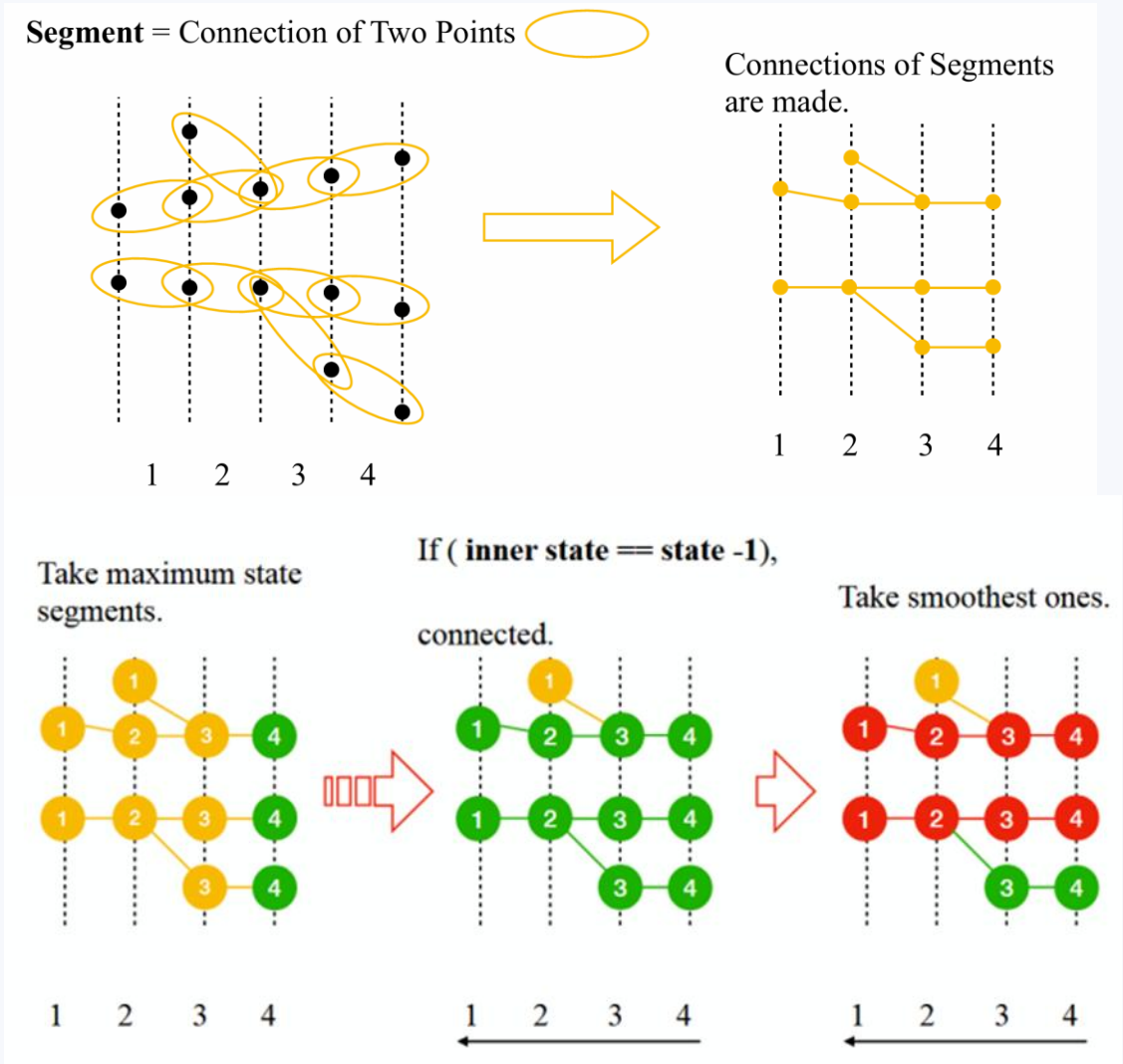
Purity-Retention curves for different input image sizes and formats.

Track Finding with Cellular Automaton

- We can connect the hits as segment if some criteria is satisfied with **state 1**
- Evolve through all layers and pick the smoothest one

Occupancy	0%	10%	20%	30%	40%
Single-Turn	96%	93%	62%	22%	4%
Double-Turn	95%	93%	90%	80%	53%

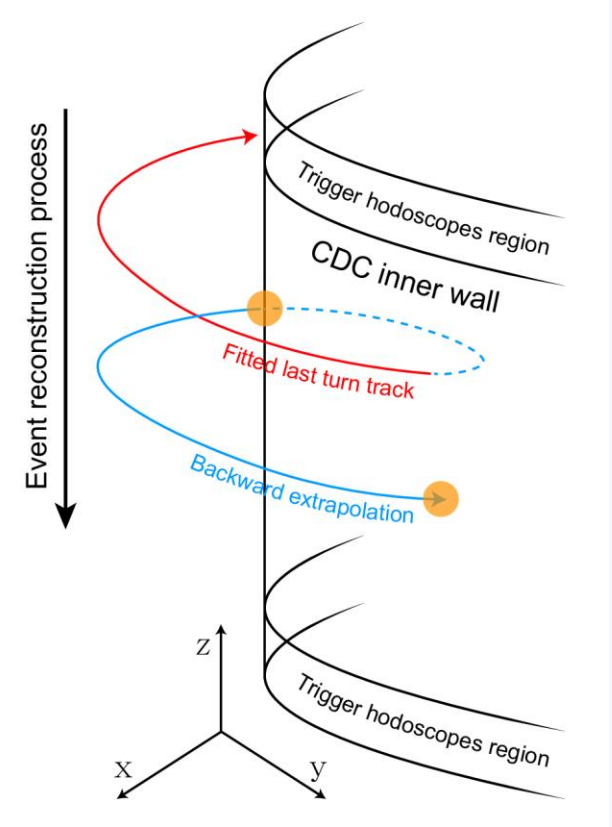
Bad performance @ high occupancy



Track Finding with GPU-Accelerated

https://doi.org/10.1016/j.cpc.2020.107606

- **Build the seeds set with track parameter$(\theta, p_x, p_y, p_z, z)$**
  - (θ, p_x, p_y) -> Hough Transform
  - (p_z, z) -> Trigger Hodoscopes range
- **Parallel Seed Scanning for the last turn**
  - Runge-Kutta-Nystrom (RKN) extrapolation
  - Calculate the residual sum of squares based on the Distance of Closest Approach
  - GPU-Accelerated——one seed ,one block
- **Backward extrapolation**
  - obtain the longitudinal seeds of the previous turn
  - Iterate → full multi-turn reconstruction



Track Finding by solving the Apollonius Problem

Apollonius problem: find a circle tangent to three drift circles ⟨hal-04413938⟩

Exhaustive search over all hit triples → time ∝ N^3(C(N,3))

GPU + interval arithmetic → time ∝ N

by Wilfrid da Silva, Patrice Lebrun, Sorbonne University/IN2P3