GNN驱动的BESIII多探测器联合径迹重建: 一种端到端统一范式

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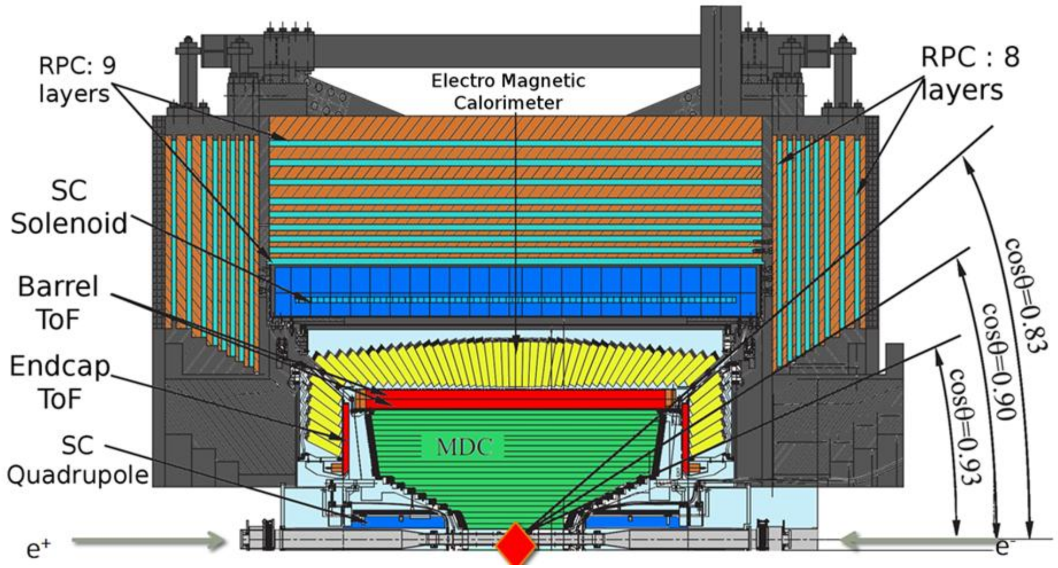
Outline

1. Introduction
2. Graph Neural Network (GNN) for track reconstruction
3. Performance on MDC & CGEM + ODC
4. Summary

Introduction of BESIII

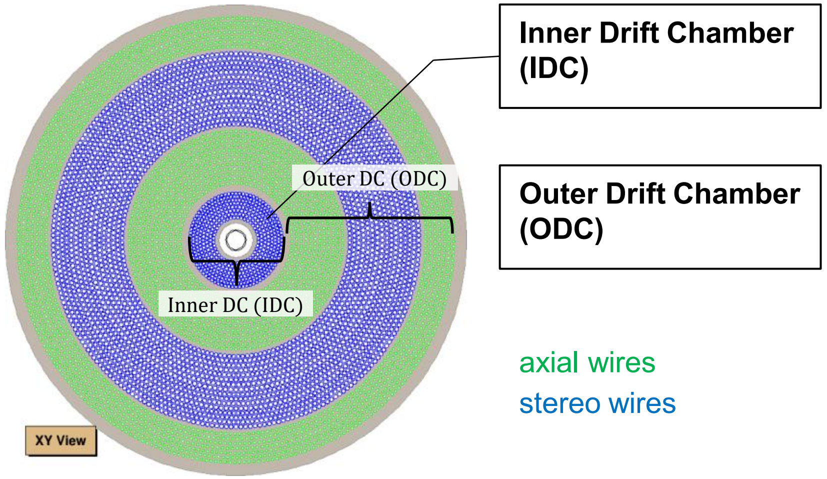
- **Be**ijing **S**pectrometer III (BESIII), a large general-purpose detector working in the τ-charm energy region operating at **B**eijing **E**lectron-**P**ositron **C**ollider II (BEPCII).
- Main studys
  - ✓ Light mesons and light baryons
  - ✓ Charmonium, including exotic mesons and baryons containing charmonium
  - ✓ QCD and τ physics
  - ✓ Searches for new physics



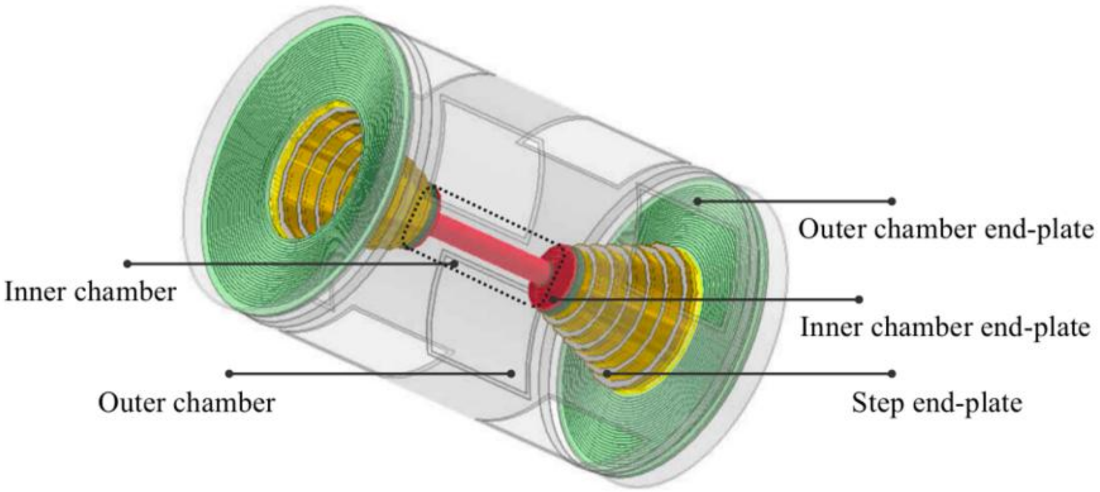
BESIII Tracking Detector - MDC

- Multi-layer Drift Chamber (MDC)
  - Provides precise position & momentum measurements
  - Enables dE/dx particle identification
  - Delivers fast trigger signals

MDC Parameter	Value
# layers	43
$\sigma(p)/p$	0.5@1GeV/c
$\sigma(xy)$	$135\mu m$
Acceptance	93% @4π



MDC X-Y in view

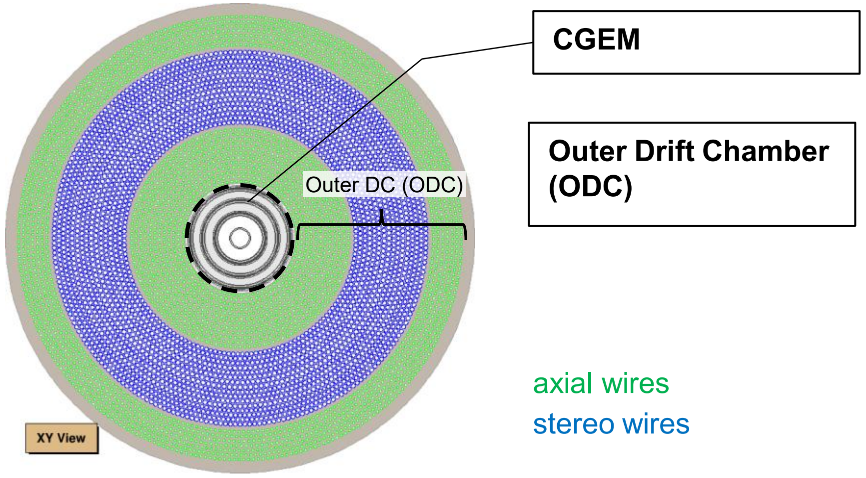


MDC in 3D view

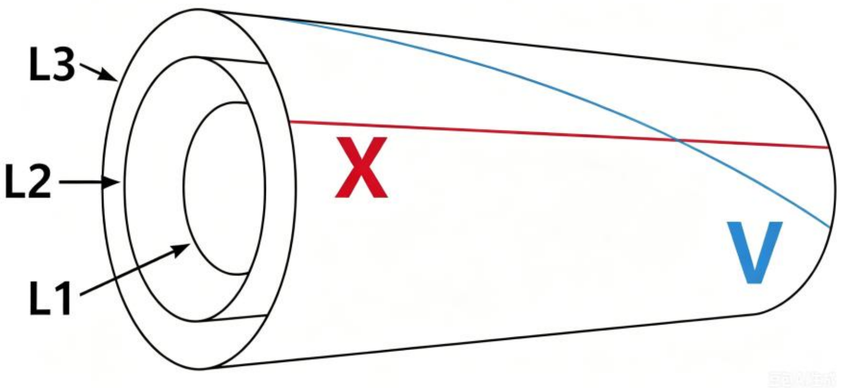
Detector Upgrade - CGEM+ODC

- Inner tracker - Cylindrical GEM detector (CGEM)
  - Beam-background resistant
  - High-rate capability
  - Better z resolution
  - Radiation-hard
- Outer tracker - Outer Drift Chamber (ODC)
  - Reuse MDC outer chamber
  - 35 layers

CGEM Parameter	Value
# layers	3
$\sigma(p)/p$	0.5@1GeV/c
$\sigma(\varphi)$	$130\sim150\mu m$ (charge + time)
$\sigma(z)$	$\sim300\mu m$



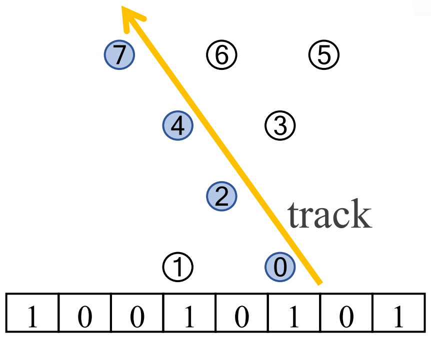
CGEM+ODC in X-Y view

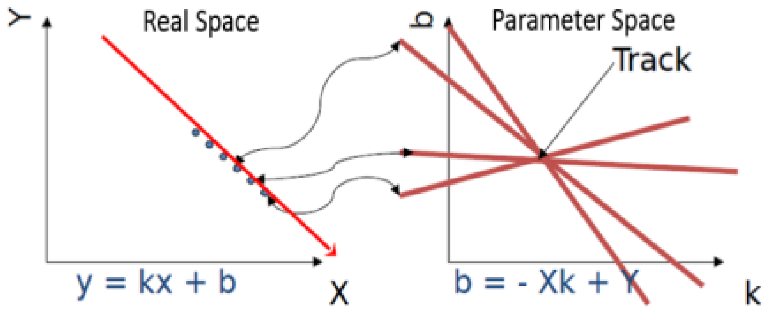


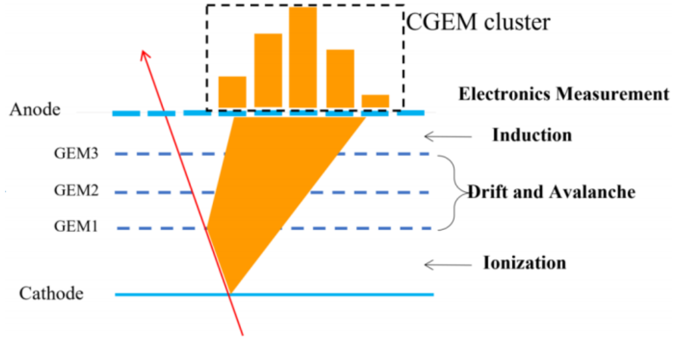
CGEM in 3D view

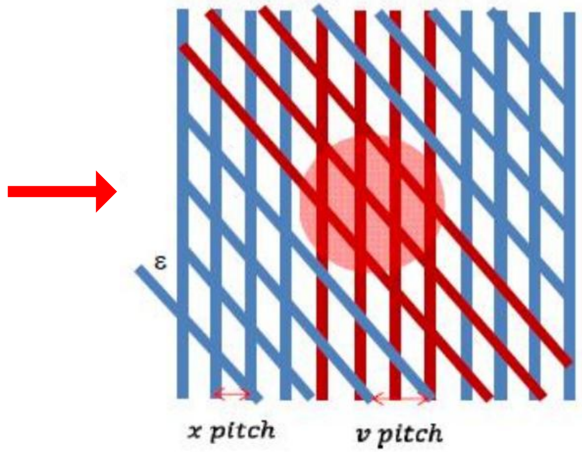
Tracking for BESIII

- Traditional tracking methods
  - Track finding: Pattern matching, Hough transform, etc.
  - Track fitting: Least-squares method, Kalman filter fitting, etc.
  - CGEM cluster reconstruction: Charge centroid method
- Baseline method
  - Traditional track finding + GenFit fitting
- Challenges
  - ✓ Manual parameter tuning (detector type, geometry, accuracy)
  - ✓ Difficult to optimize for low p_T, secondary vertices, high background
- Previous work on BESIII
  - ✓ GNN tracking for MDC in high p_T region
- Work to be done
  - ✓ Improve low p_T efficiency
  - ✓ Tracking development needed for CGEM+ODC



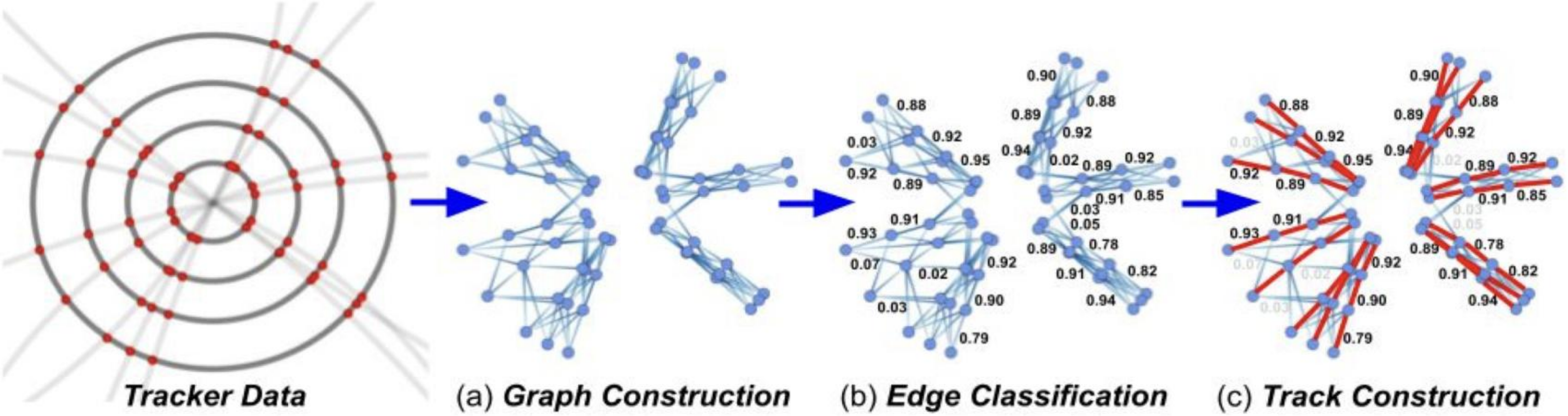






Introduction of GNN

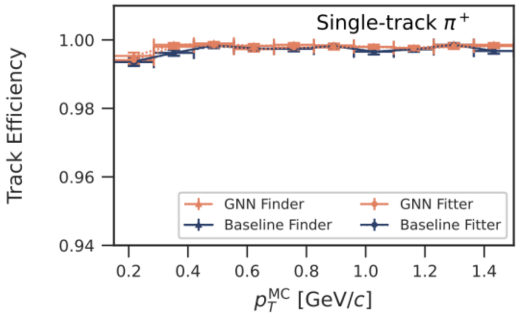
- **Graph Neural Network (GNN)**
  - An optimizable transformation over all attributes while preserving the symmetries of the graph
- **GNN for tracking**
  - Detector hits are naturally a set of points irregularly distributed in space
    - ✓ Nodes → hits
    - ✓ Edges → hit-hit associations
  - Graphs are permutation-invariant and can handle variable numbers of hits

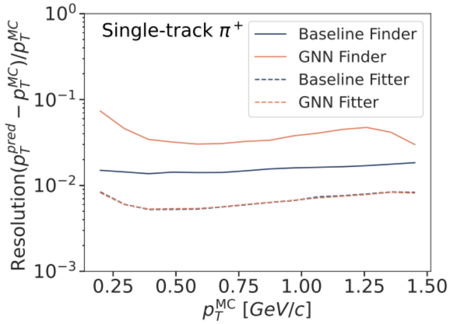


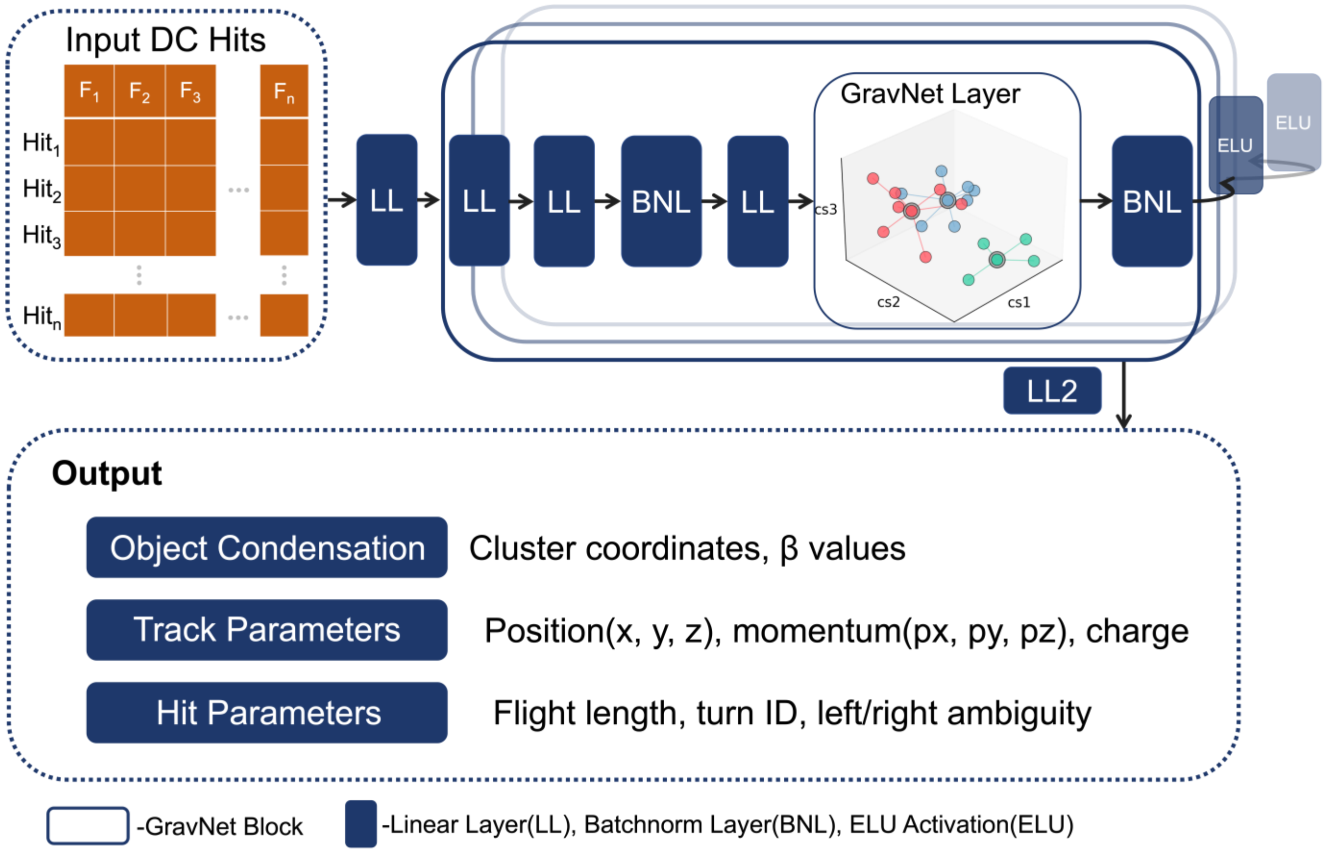
Source: IRIS-HEP, "Accelerated GNN Tracking," accessed June 13, 2025, https://iris-hep.org/projects/accel-gnn-tracking.html.

GNN Model for BESIII tracking

- Our model extends and supplements the approach presented in [CAT Finder]
- Model applied to BESIII [arXiv:2602.14571]
  - High momentum, low multiplicity scenarios
- Extending to Challenging Regime
  - Low momentum curling tracks
  - High multiplicity events
  - Joint detector reconstruction
    - CGEM (CGEM clusters) + ODC (ODC hits) tracking

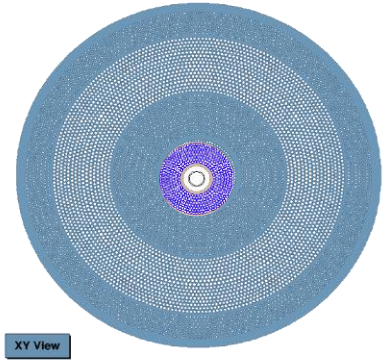




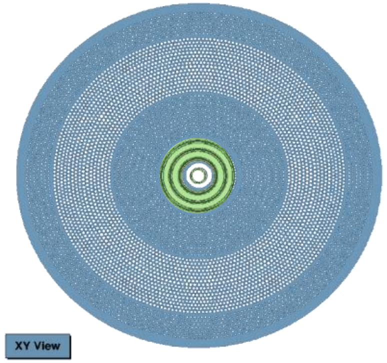


Datasets

MDC
43 layers



CGEM(3 layers) + ODC(35 layers)



MDC train & validation dataset

Event type	$P_T\ [GeV/c]$	$cos\theta$	$\phi\ [rad]$	Particle type	Number
Six-tracks	0.04 ~ 0.16	-0.93 ~ 0.93	0~2π	$\pi^+\pi^-\pi^+\pi^-p\bar{p}$	2×10^5

MDC test datasets

Event type	$P_T\ [GeV/c]$	$cos\theta$	$\phi\ [rad]$	Particle type	Number
Single-track	0.04 ~ 0.16	-0.93 ~ 0.93	0~2π	e^-	1×10^4
Double-tracks	0.04 ~ 0.16	-0.93 ~ 0.93	0~2π	$\pi^+\pi^-$	1×10^4
Four-tracks	0.04 ~ 0.16	-0.93 ~ 0.93	0~2π	$\pi^+\pi^-\pi^+\pi^-$	1×10^4
Six-tracks	0.04 ~ 0.16	-0.93 ~ 0.93	0~2π	$\pi^+\pi^-\pi^+\pi^-p\bar{p}$	1×10^4

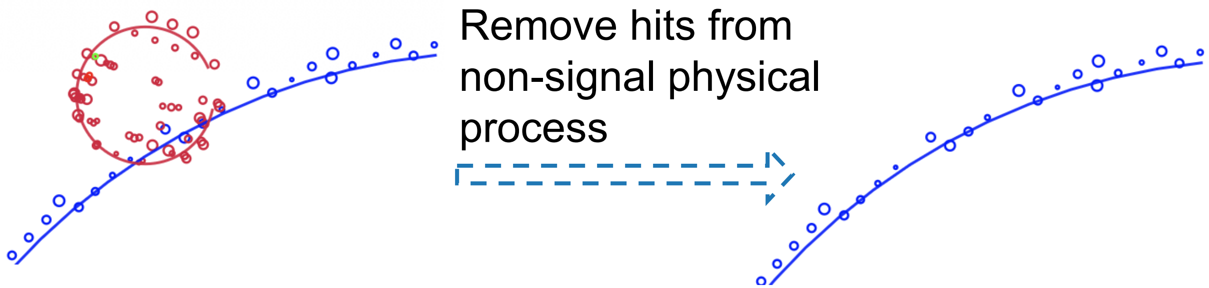
CGEM+ODC train, validation and test dataset 8:1:1

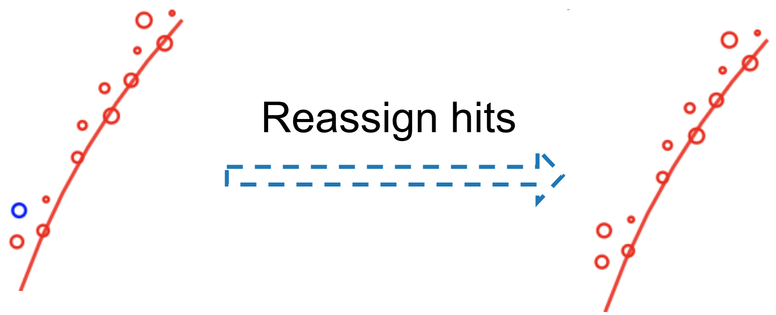
Event type	$P_T\ [GeV/c]$	$cos\theta$	$\phi\ [rad]$	Particle type	Number
Single-track	0.15~1.5	-0.93~0.93	0~2π	π^-	1.8×10^5

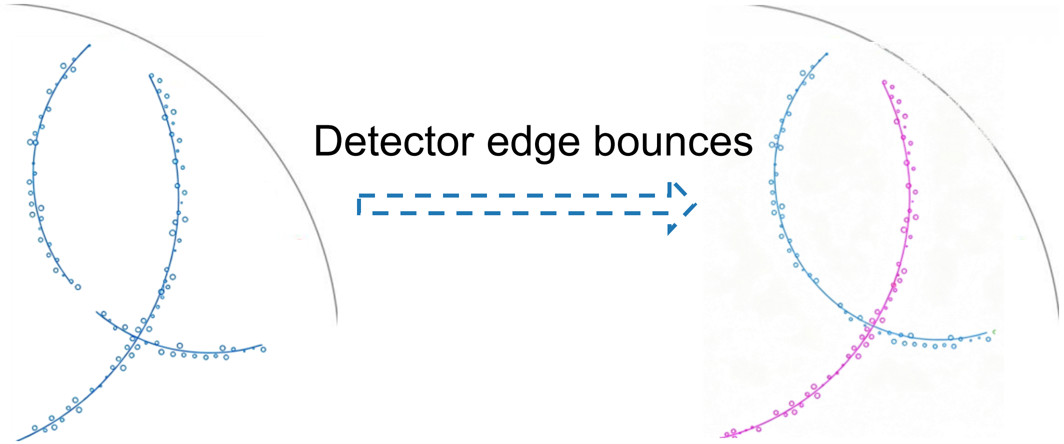
Monte Carlo full simulation of BESIII detectors
Mixed background from real data

Data Preprocessing

Category	Example process	Action
Low quality	Tracks with < 6 hits	Remove
	conv, compt	Remove
Relabeling	Decay tracks > 7 turns	Label as noise
	Ionized hits	Label as signal
Track splitting	Multi-turns track	Split
	Detector edge bounces	Split by turn







Tracking Quality Metrics

Hit efficiency

$$\epsilon_{hits} = \frac{N_{hit}^{matched}}{N_{hit}^{detectable}}$$

$N_{hit}^{matched}$ is the number of hits on the track that match the truth, and $N_{hit}^{detectable}$ is the number of detectable hits on the truth track associated with this reconstructed track.

Hit purity

$$p_{hits} = \frac{N_{hit}^{matched}}{N_{hit}^{assigned}}$$

$N_{hit}^{assigned}$ is the number of hits on the reconstructed track.

Track criteria

$$p_{hits} > 50\%, N_{hit}^{matched} > 6$$

MDC track efficiency

$$\epsilon_{track} = \frac{N_{track}^{matched}}{N_{track}^{detectable}}$$

$N_{\mathrm{track}}^{matched}$ is the number of reconstructed tracks that match the truth, and $N_{track}^{detectable}$ is the number of detectable tracks in the sample.

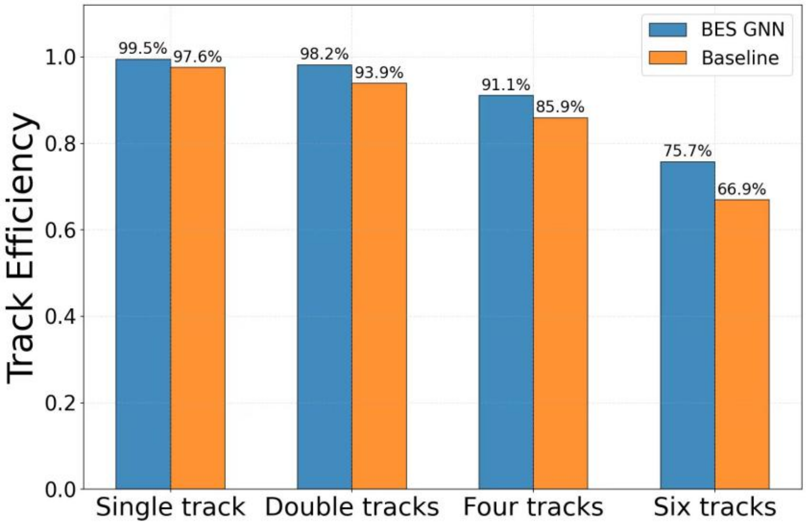
CGEM + ODC track efficiency

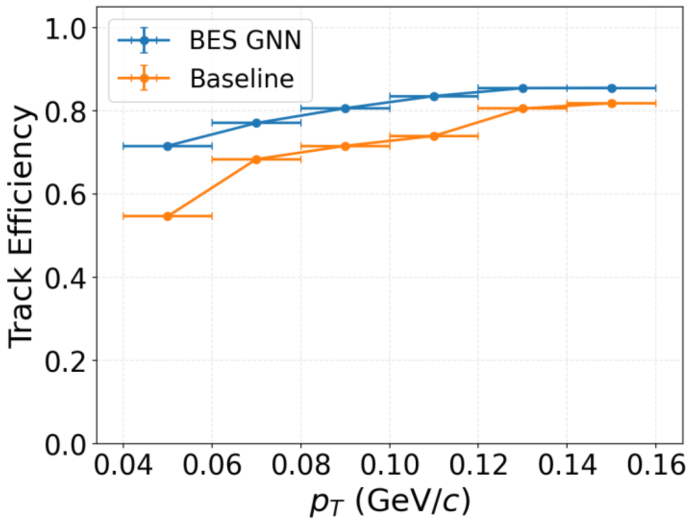
$$\epsilon_{track} = \frac{N_{ODC\_track}^{matched}}{N_{ODC\_track}^{detectable}}$$

$N_{ODC\_track}^{matched}$ is the number of reconstructed ODC tracks that match the truth, and $N_{ODC\_track}^{detectable}$ is the number of detectable tracks in the sample.

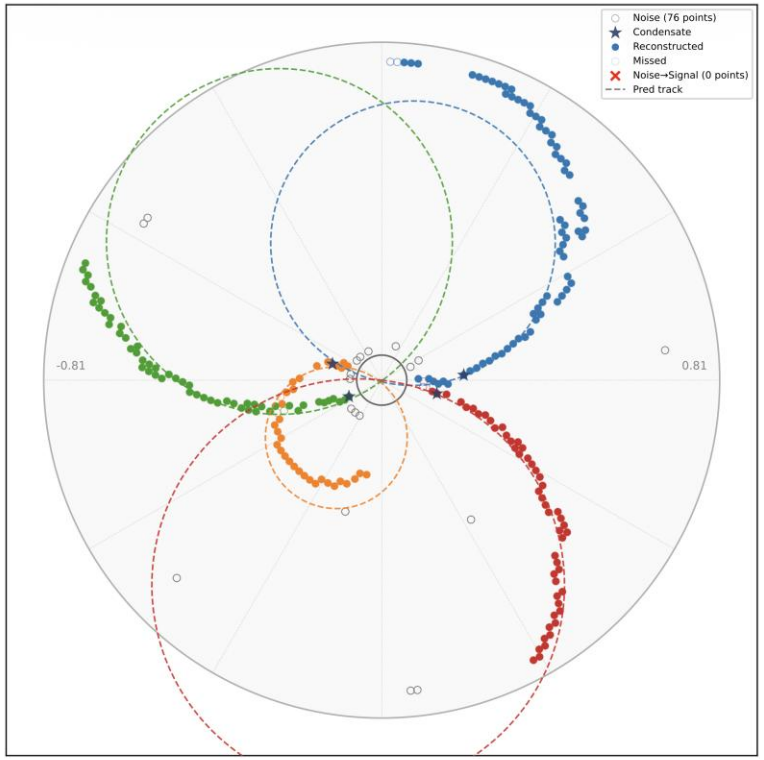
MDC performance

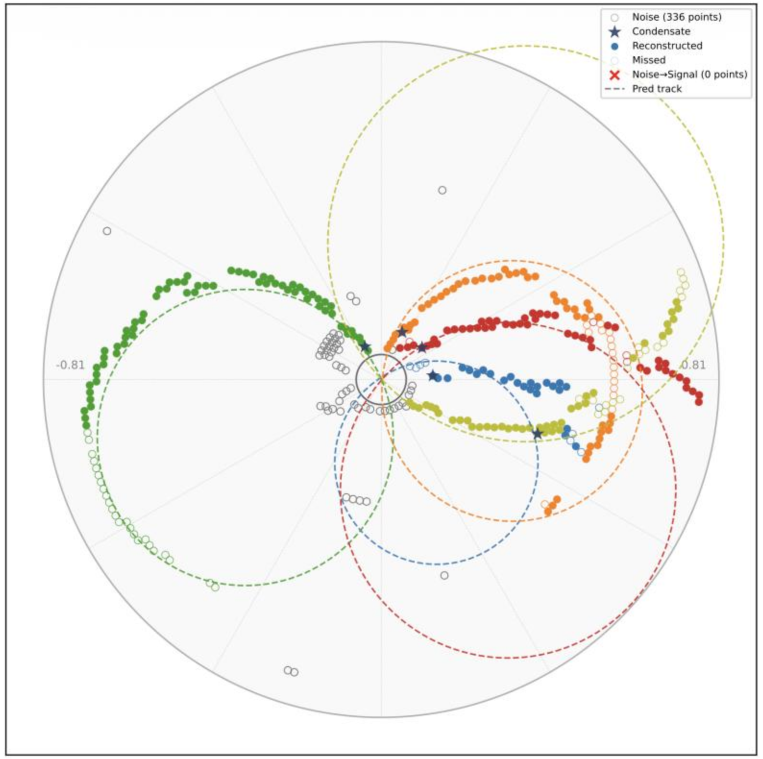
- Track efficiency improved ~10% @ p_T in (40MeV ~ 160 MeV)
- Hit efficiency and purity are comparable with baseline

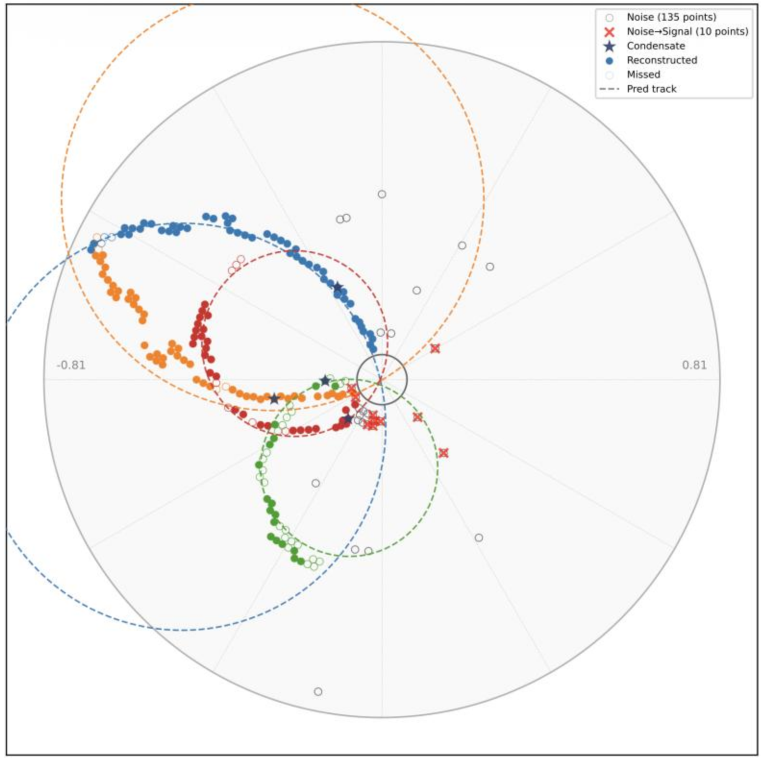




Event Display - MDC

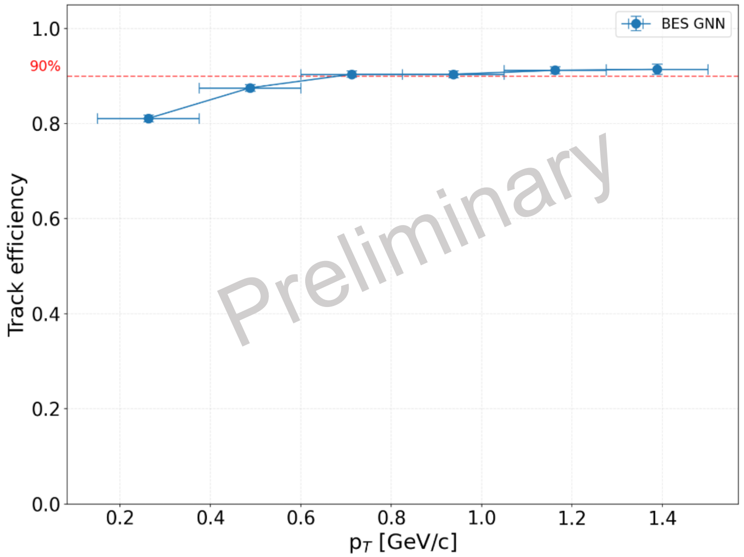




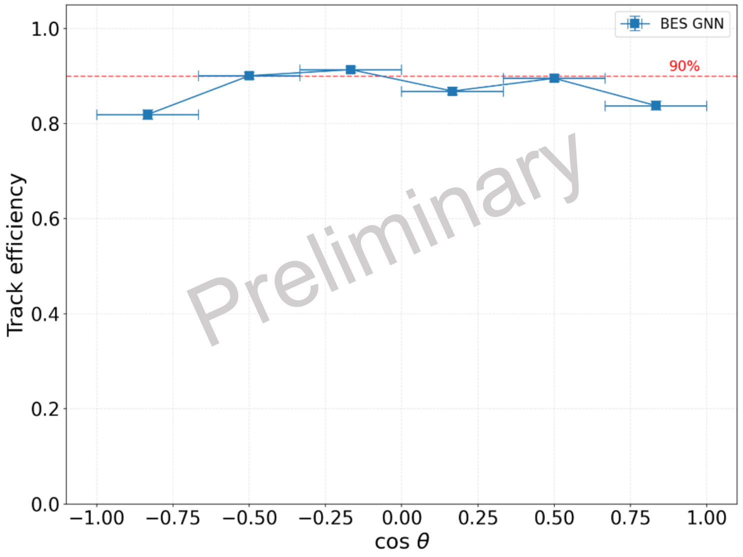


Track efficiency - CGEM + ODC

- **GNN-based joint tracking**
  - CGEM clusters + ODC hits → Tracks
- **Track efficiency**: ~90% (p_T > 0.5 GeV/c)

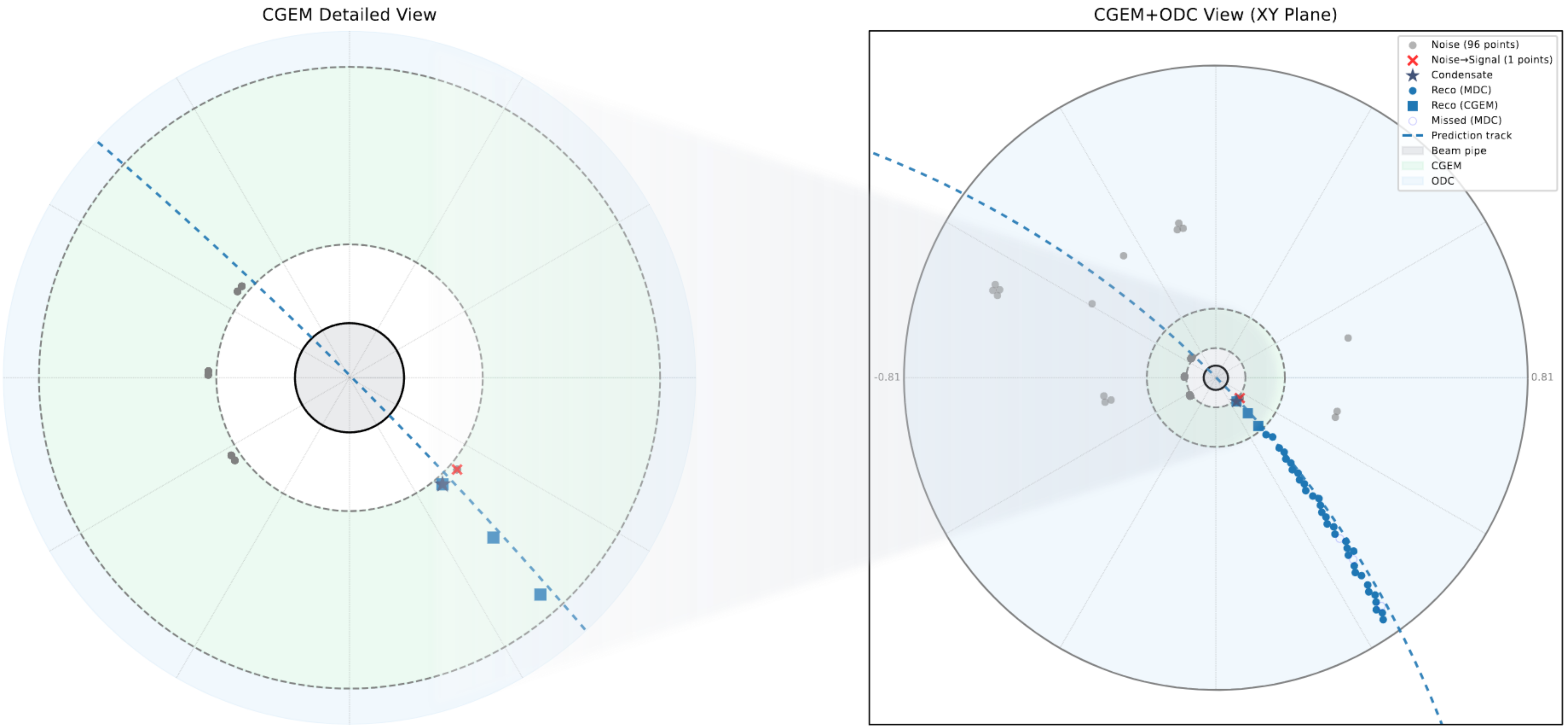


Track effiency vs p_T



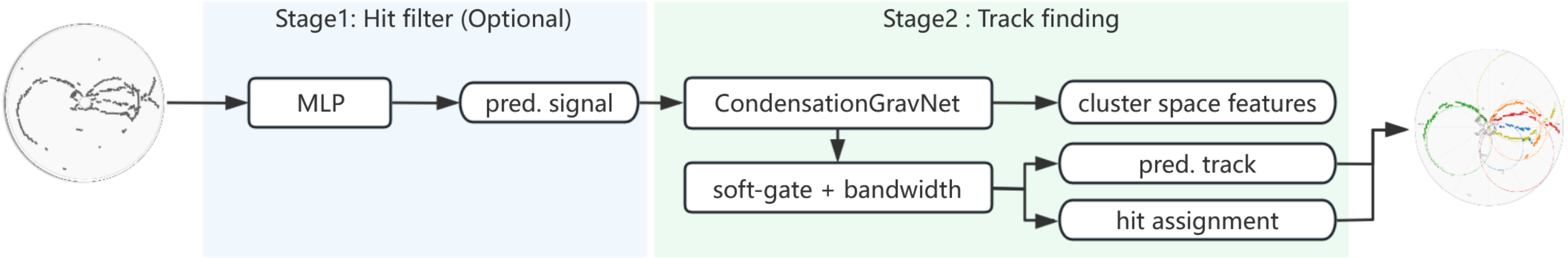
Track effiency vs $cos\theta$

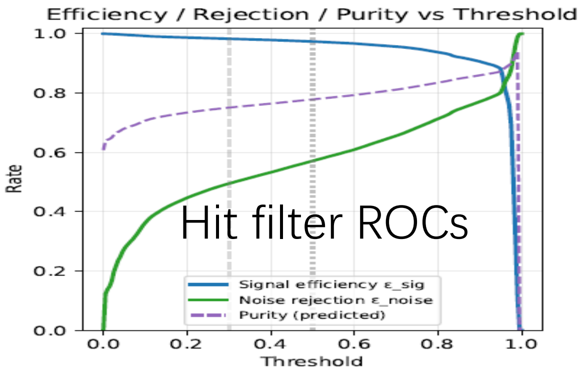
Event Display - CGEM + ODC

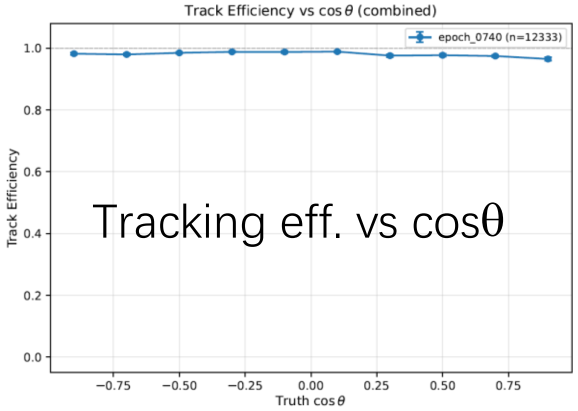


Adapting and Extending Approaches

- **Hit Filtering:** Fewer hits, cleaner tracking
- **Differentiable Clustering:** Learn clustering without manual tuning
- **Multi-stage Reconstruction:** Progressive track refinement







- Hit Filter
  98% signal retention with 60% noise reduction
- Efficiency
  97% Track Efficiency | 96% Hit Efficiency (Optimizing)

Summary

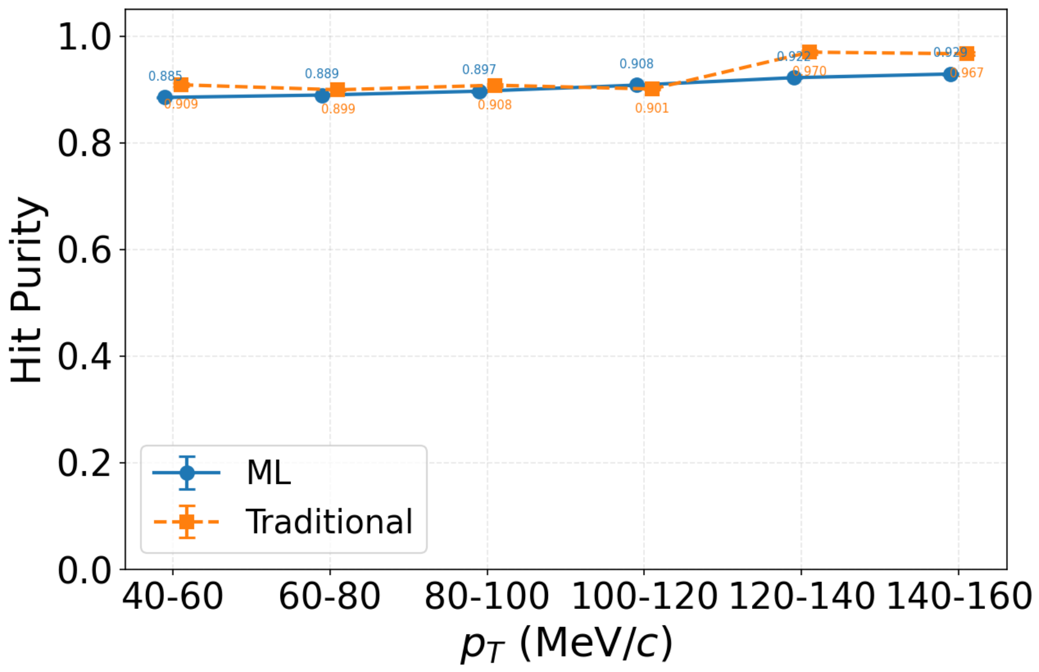
- End-to-end GNN tracking realized for MDC and CGEM + ODC
  - Low p_T MDC track and event quality improved
  - Combined CGEM + ODC tracking is promising
  - Key improvements on model architecture and training strategy

- Outlook
  - ✓ End-to-end GNN Tracking by using CGEM raw measurement (CGEM X and V strips + ODC hits → tracks)

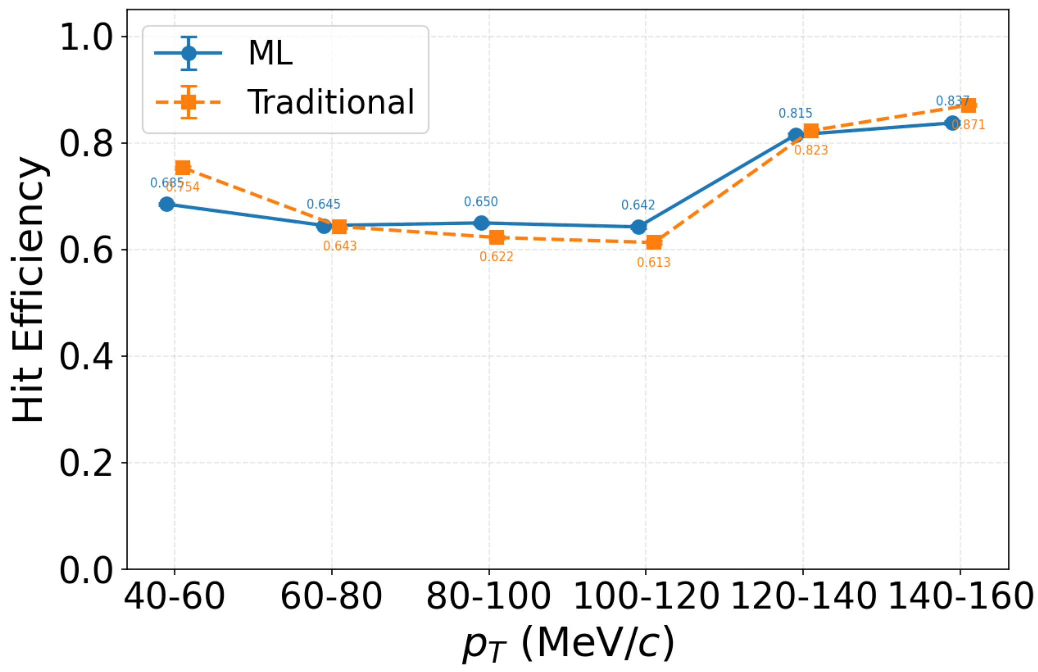
Thanks for your attention!

Backup: MDC hit efficiency and purity

- GNN is comparable with traditional tracking

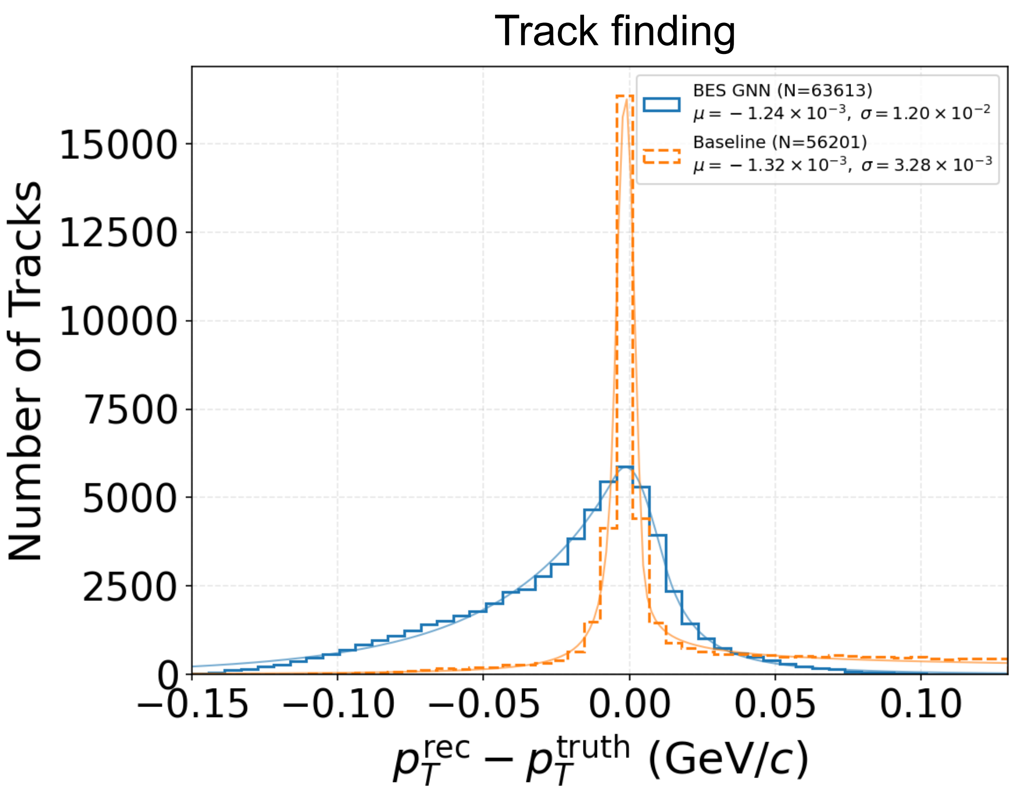


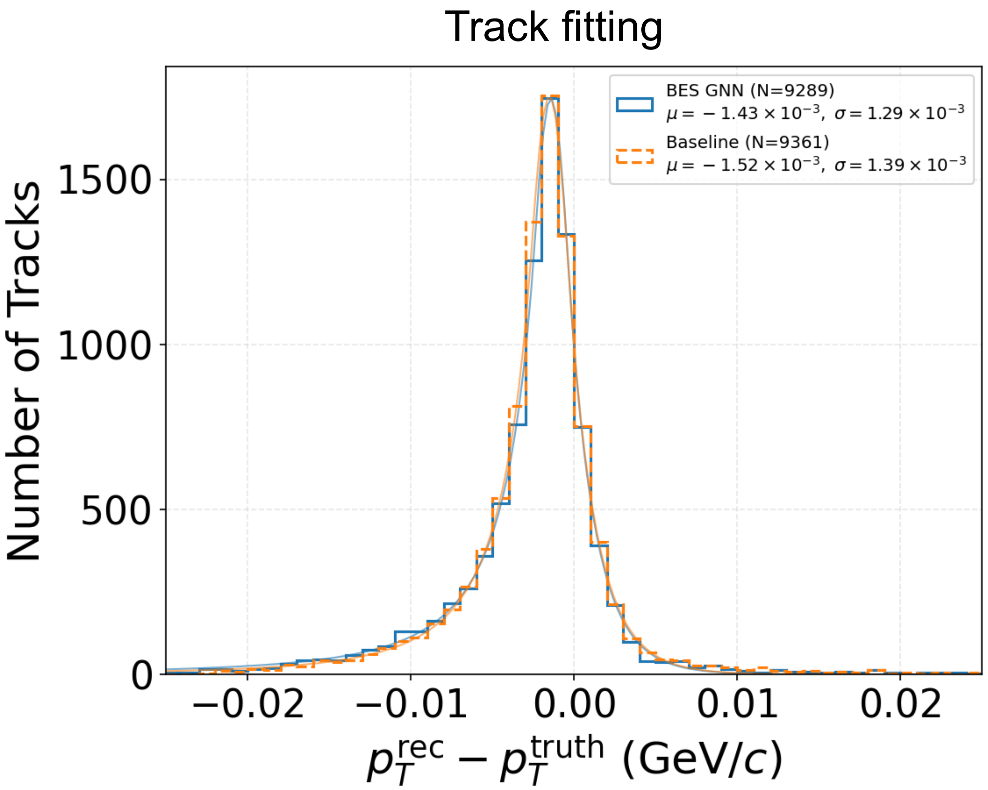
Hit purity vs p_T



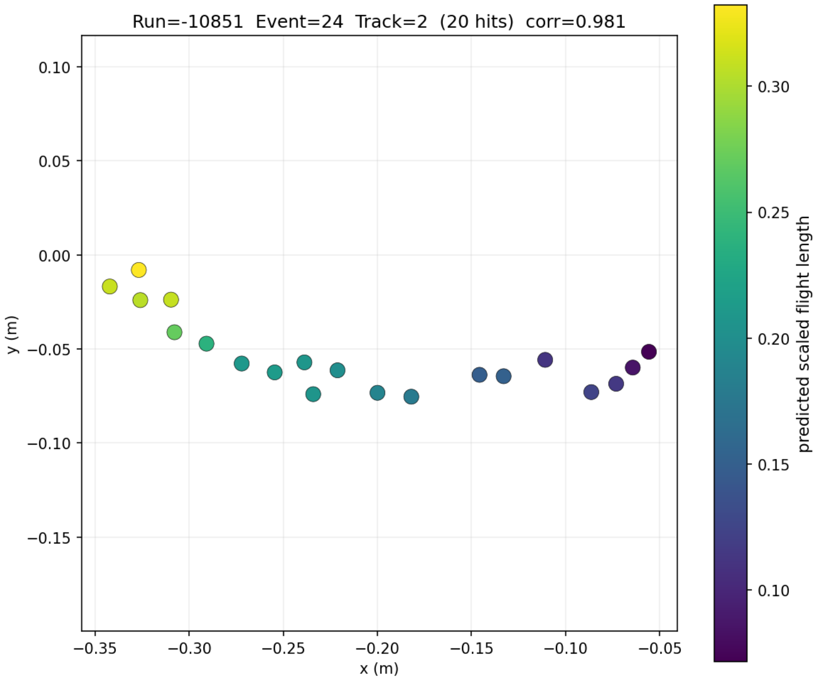
Hit efficiency vs p_T

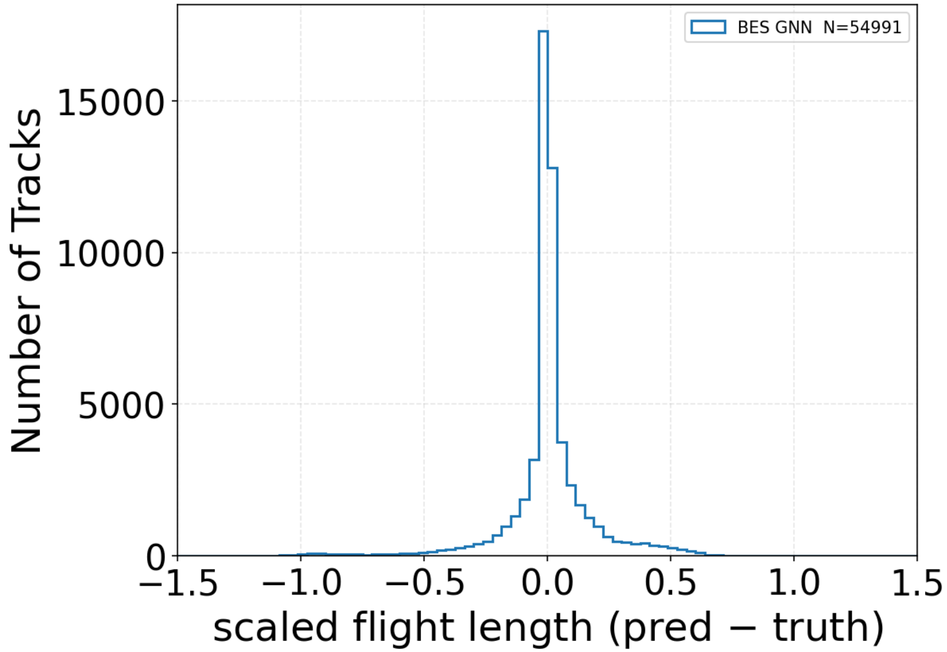
Backup: MDC track parameters





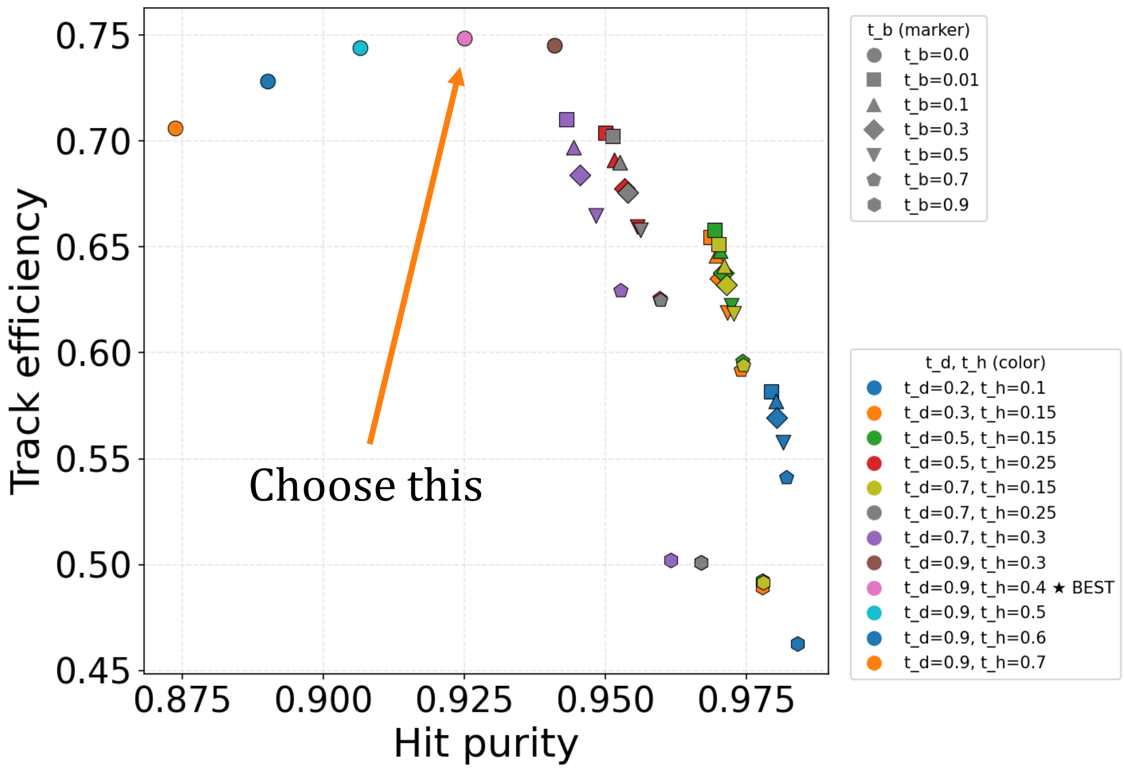
Backup: MDC hit flight length



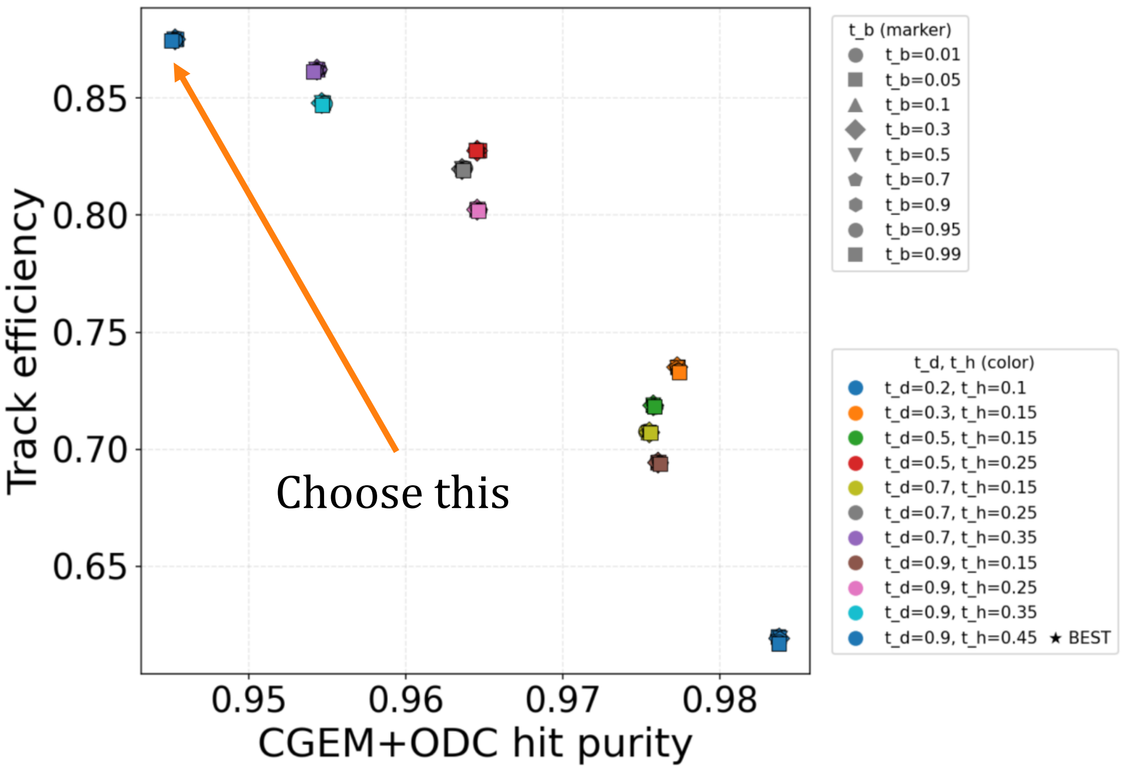


Backup: Optimization of post-processing thresholds

1. t_b: track candidate selection threshold
2. t_d: inter-track separation threshold
3. t_h: hit-to-track assignment distance threshold

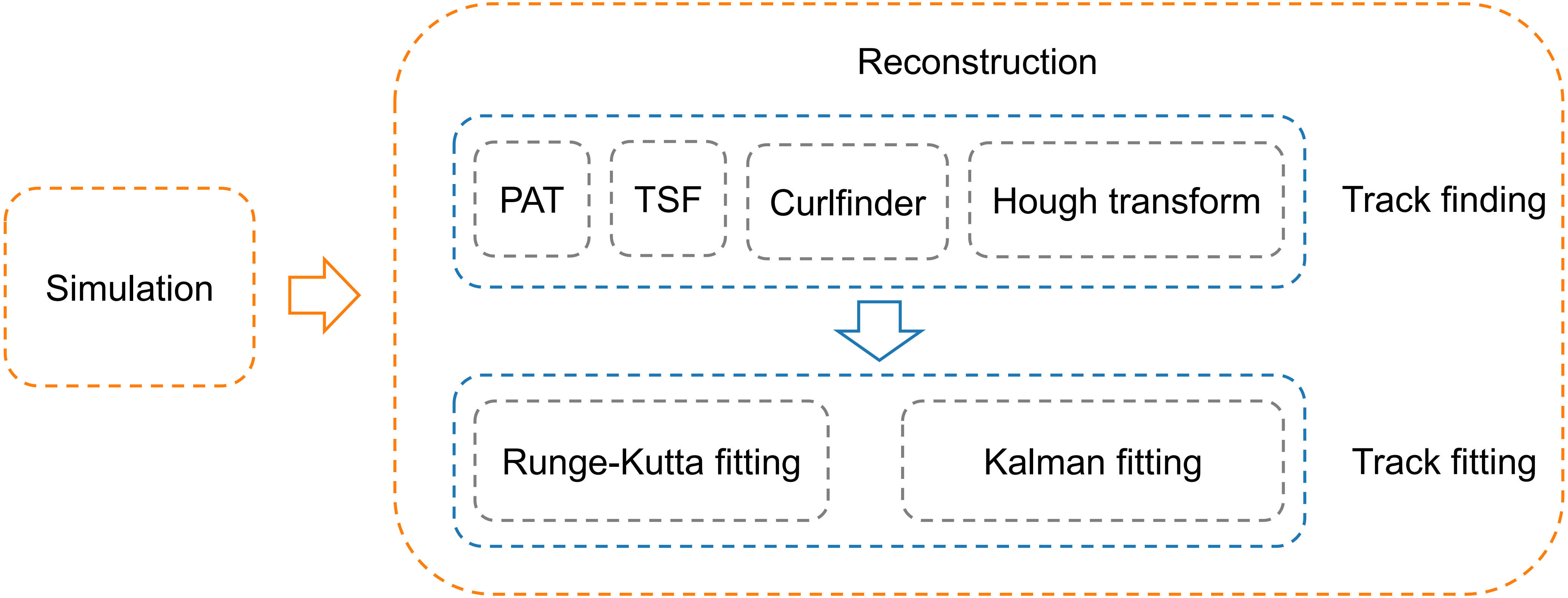


Optimization for MDC



Optimization for CGEM + ODC

Backup: MDC track reconstruction



Backup: CGEM+ODC track reconstruction