Graph Neural Network Based End-to-End Track Reconstruction with Drift Chamber and CGEM at BESIII

Yunhe Yang[1,2*], Xinyu Zhuang[1,2], Yao Zhang[2,3]

Chunxu Yu[1,4], Yupeng Yan[4], Ayut Limphirat[4], Ye Yuan[2,3], Zhiyong Wang[2,3]

[1]Nankai University [2]Institute of High Energy Physics

[3]University of Chinese Academy of Sciences [4]Suranaree University of Technology

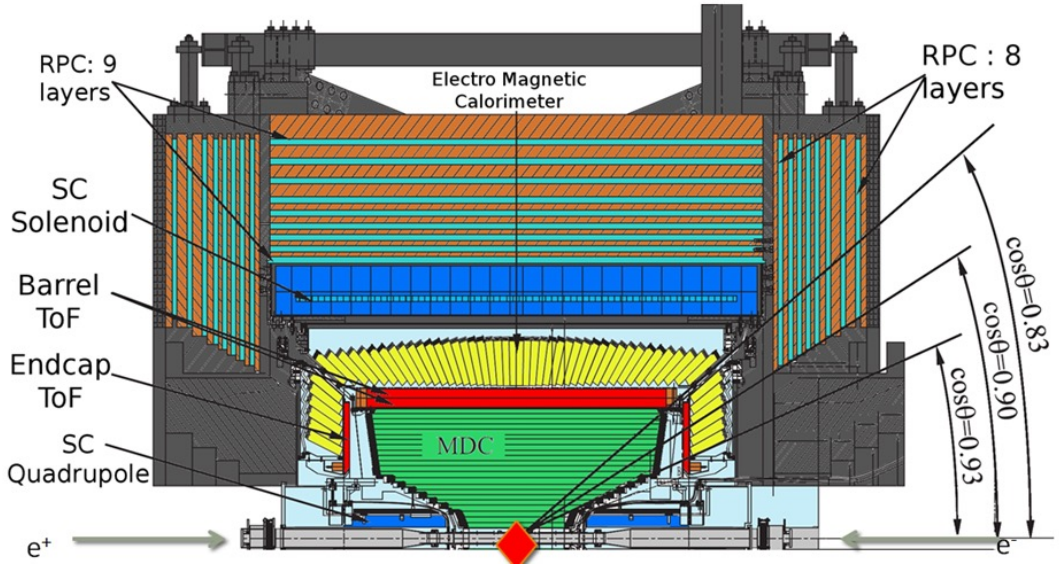
[*] 1120240100@mail.nankai.edu.cn

Outline

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

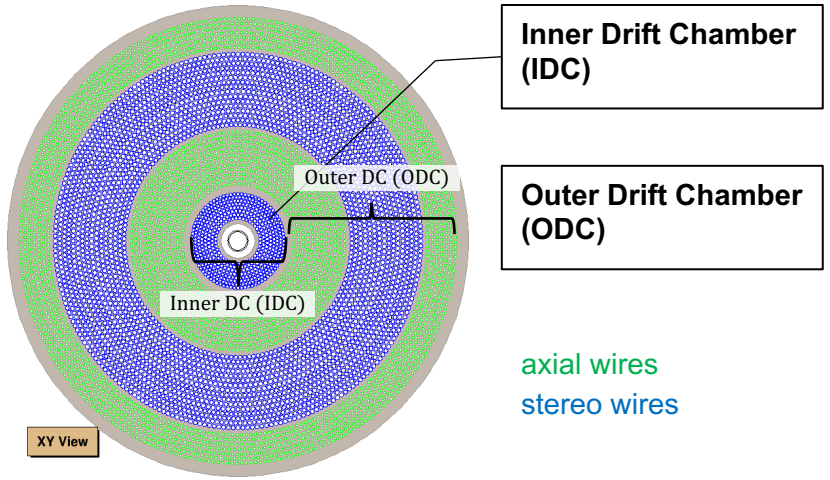
Introduction of BESIII

- BESIII is a large general-purpose detector working at the BEPCII in the tau-charm energy region.
- Main studys
  - ✓ Light hadron spectroscopy
  - ✓ Charmonium and exotic hadrons
  - ✓ QCD and tau physics
  - ✓ Searches for physics beyond the Standard Model

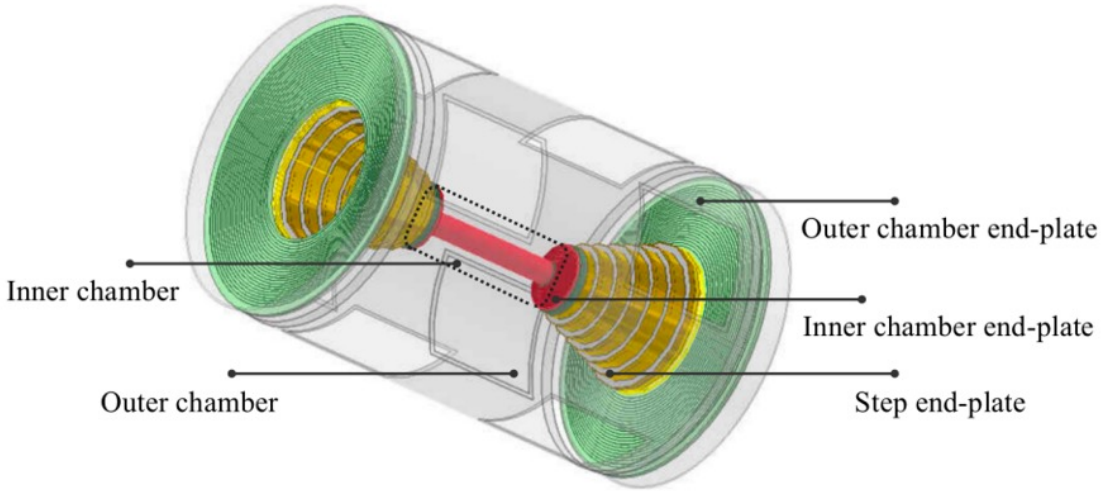


BESIII Tracking Detector - MDC

- Multi-layer Drift Chamber (MDC)
  - ✓ 43 layers in a 1 T magnetic field
  - ✓ Position & momentum measurements
  - ✓ dE/dx measurement for particle identification
  - ✓ Fast trigger signals



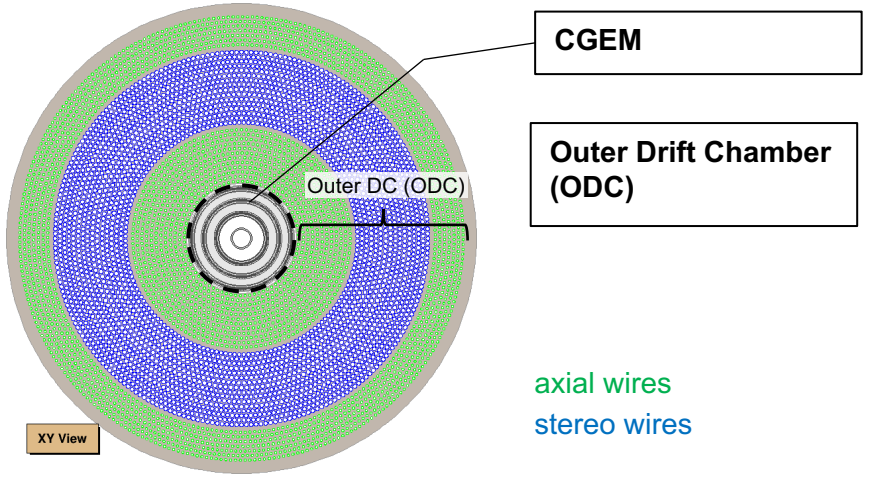
MDC X-Y in view



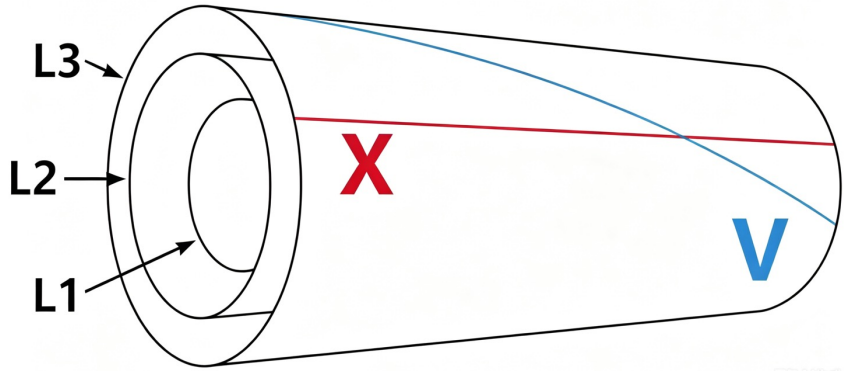
MDC in 3D view

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



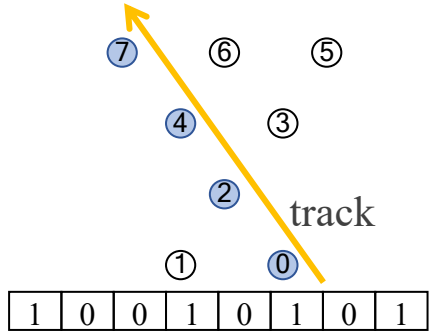
CGEM+ODC in X-Y view

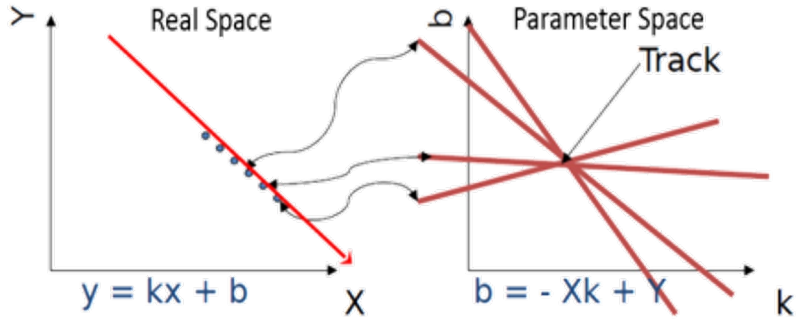


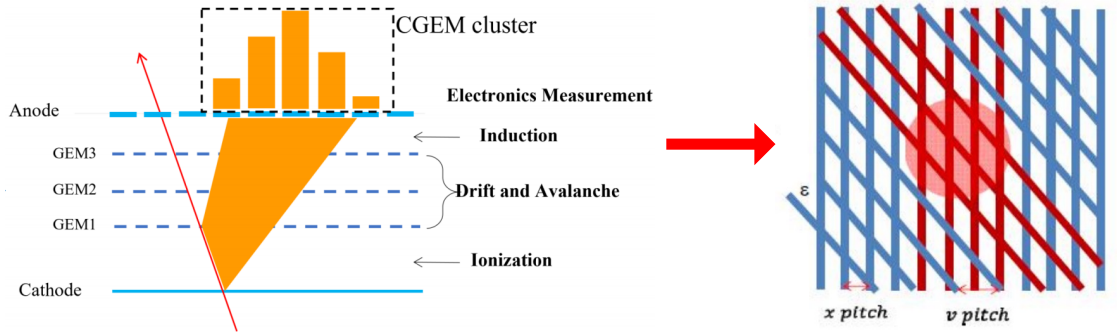
CGEM in 3D view

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 for low P_T, secondary vertices, high background
- Work to be done
  - ✓ Improve low P_T efficiency
  - ✓ Tracking development needed for CGEM+ODC

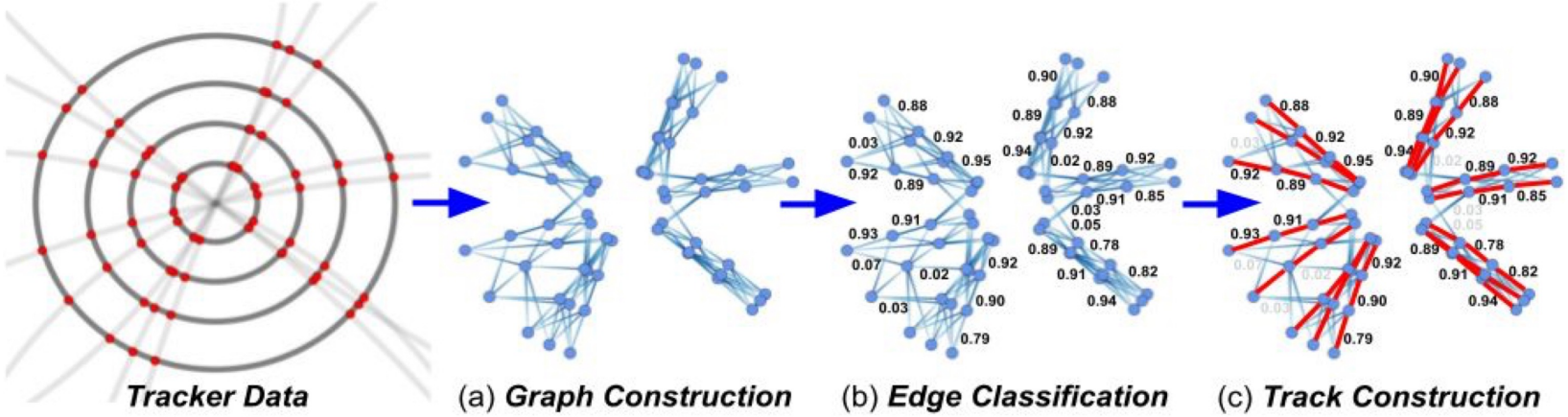






Introduction of GNN

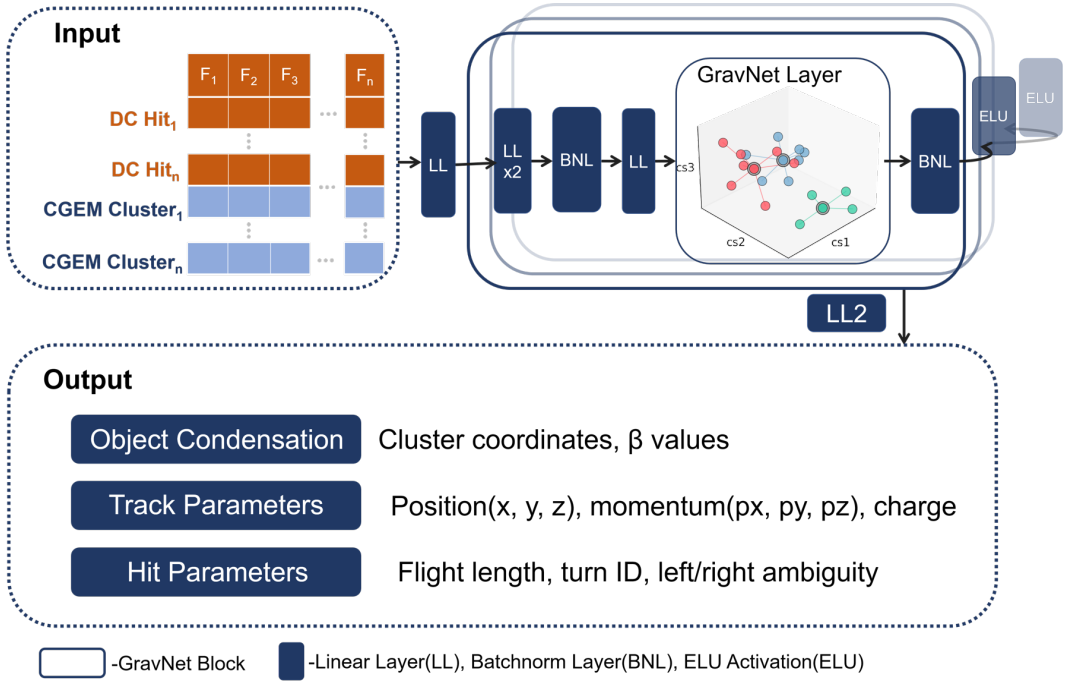
- **G**raph **N**eural **N**etwork (GNN)
  - ✓ An optimizable transformation over all attributes while preserving the symmetries of the graph
- GNN for tracking
  - ✓ Detector hits are naturally a set of points irregularly distributed in space
    - Nodes → hits
    - Edges → hit-hit associations
  - ✓ 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.

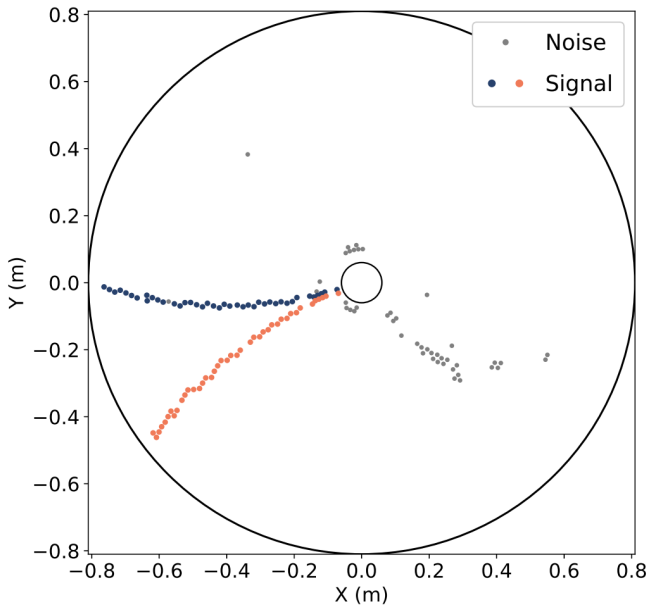
GNN Model for BESIII tracking

- Our model extends and supplements the approach presented in *CAT Finder*
- Extending to Challenging Regime
  - ✓ Low momentum curling tracks
  - ✓ Joint detector reconstruction: CGEM (CGEM clusters) + ODC (ODC hits) tracking

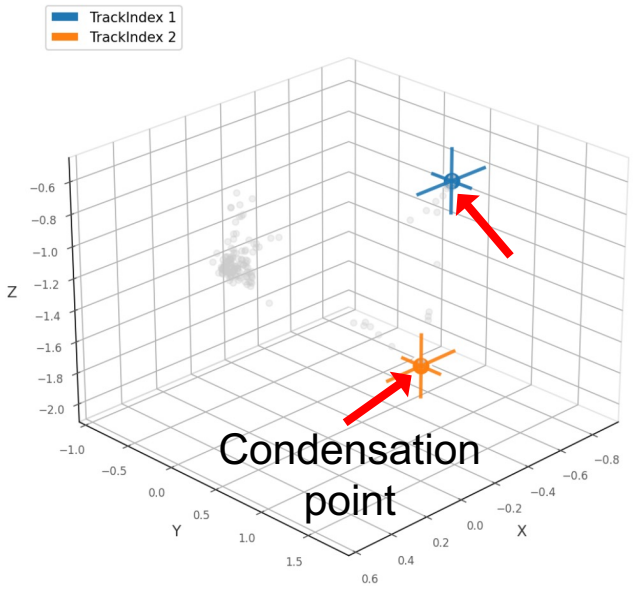


GNN Model for BESIII tracking

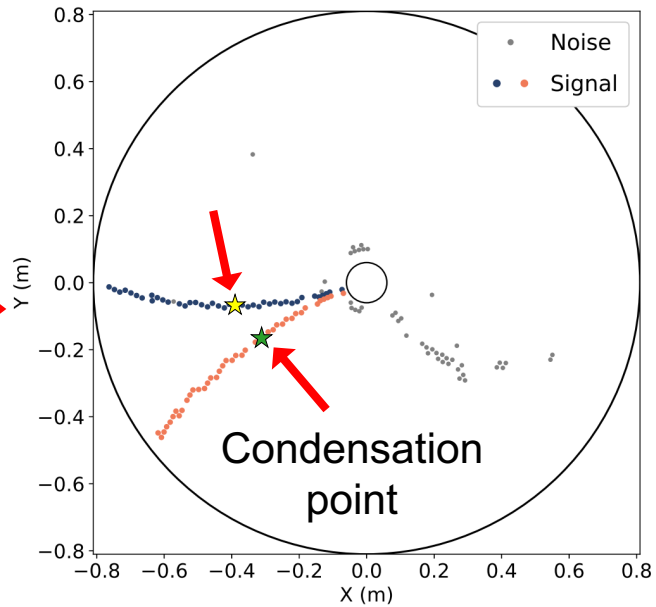
- Object condensation
  - ✓ Cluster in the latent space through attractive and repulsive potentials
  - ✓ Hits belonging to the same track are close to each other in the latent space
  - ✓ Group the hits belonging to the same track to a single condensation point



Physical space

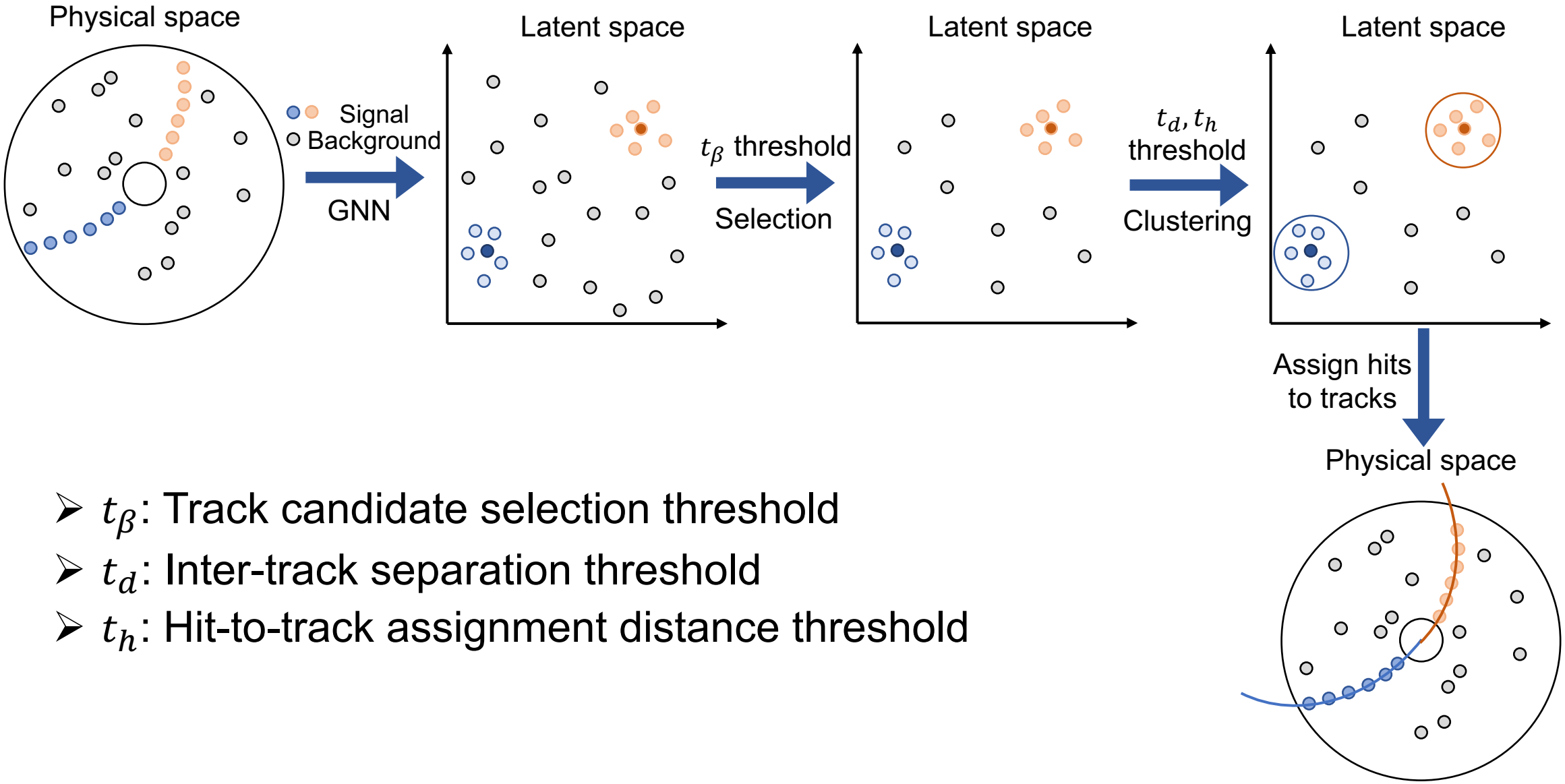


Latent space



Physical space

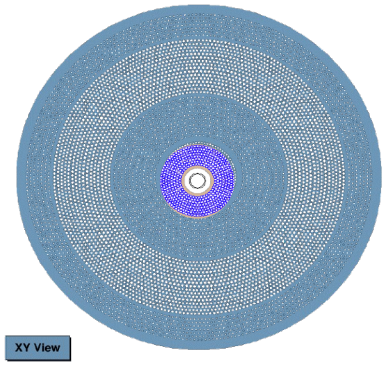
Model Post Processing



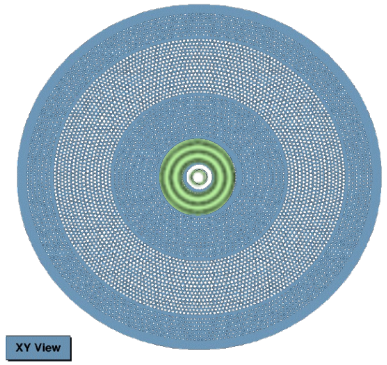
- t_β: Track candidate selection threshold
- t_d: Inter-track separation threshold
- t_h: Hit-to-track assignment distance threshold

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

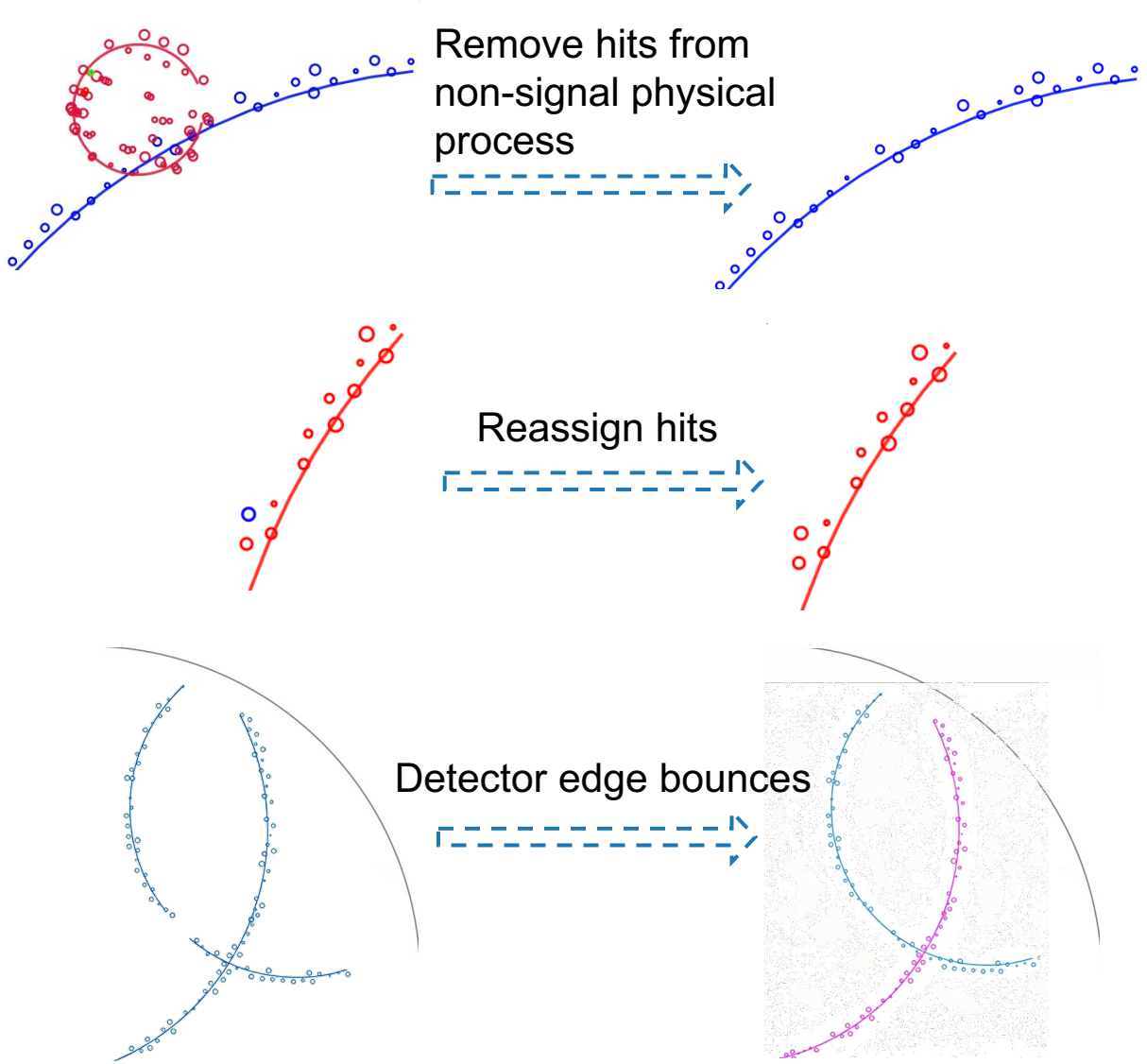
CGEM+ODC train, validation and test dataset 8:1:1

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.

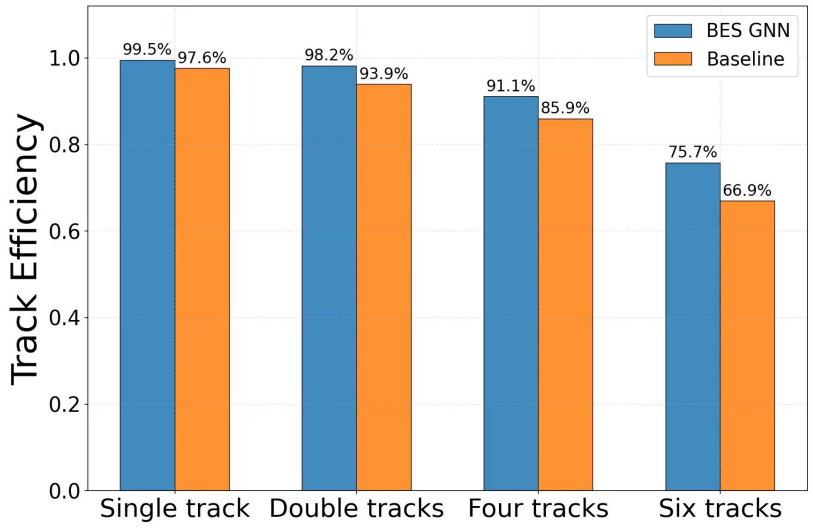
CGEM + ODC track efficiency

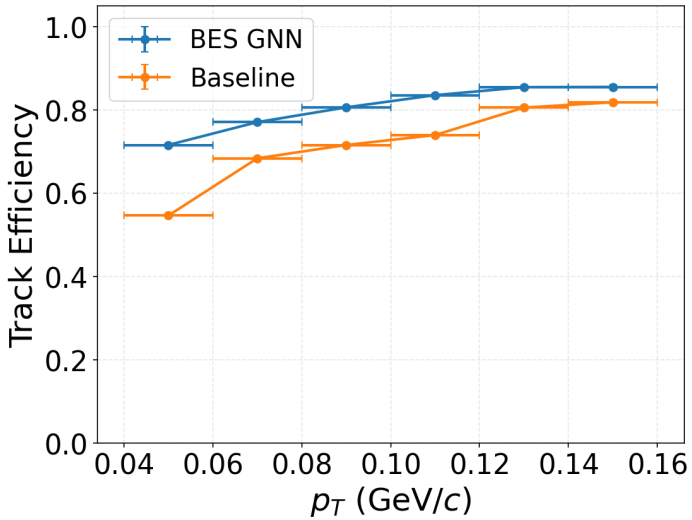
$$\epsilon_{track} = \frac{N_{ODC_track}^{matched}}{N_{ODC_track}^{detectable}}$$

$N_{ODC_\mathrm{track}}^{matched}$ 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.

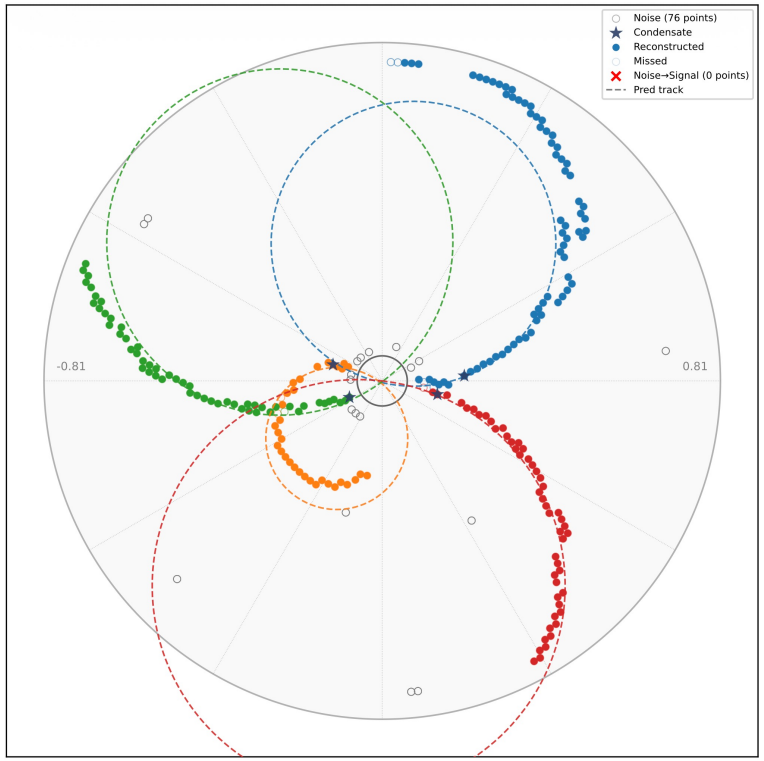
MDC performance

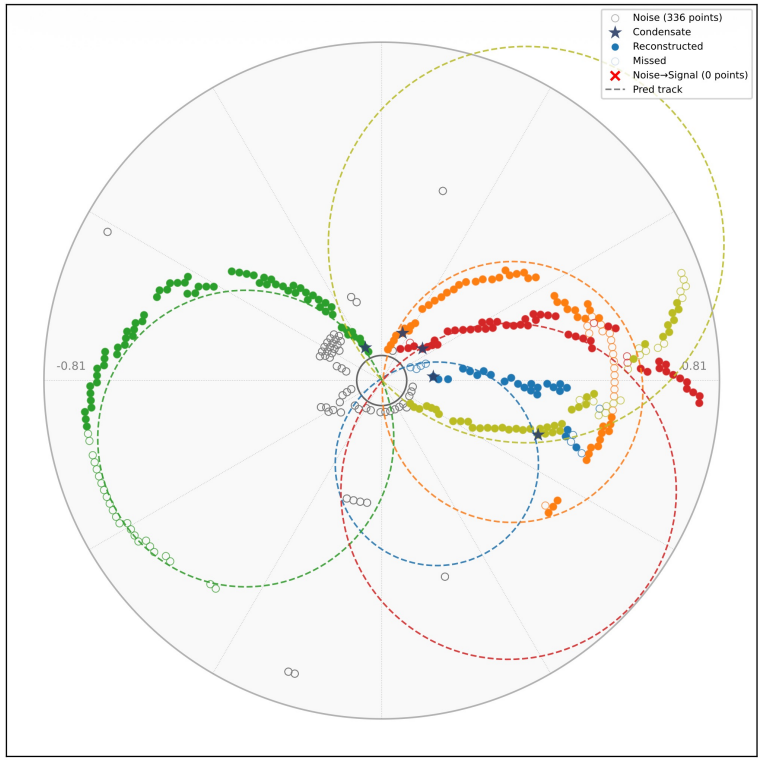
- Track efficiency improved ~10% @ p_T in (40MeV ~ 160 MeV)
- Hit efficiency and purity are comparable with baseline

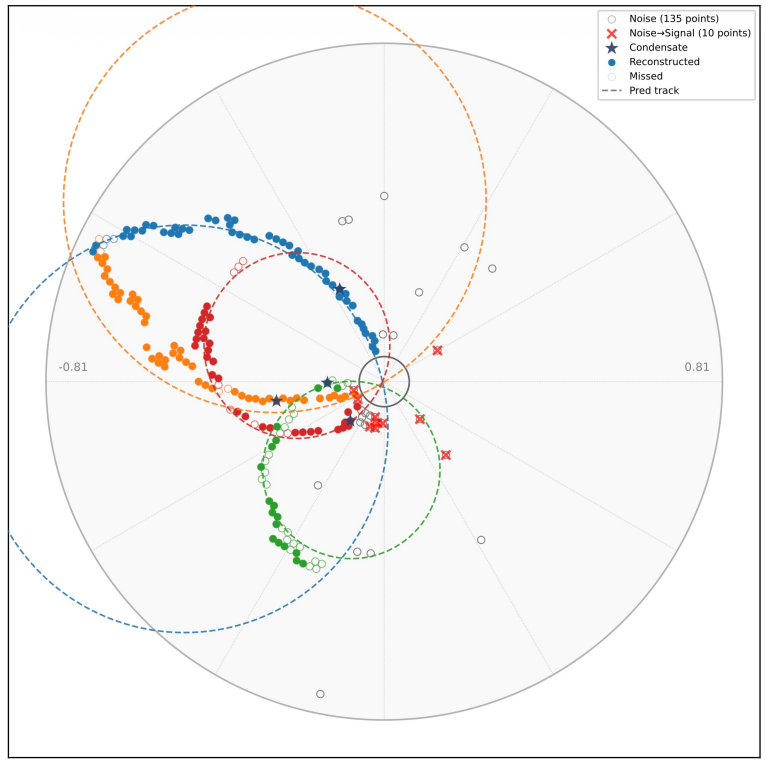




Event Display - MDC

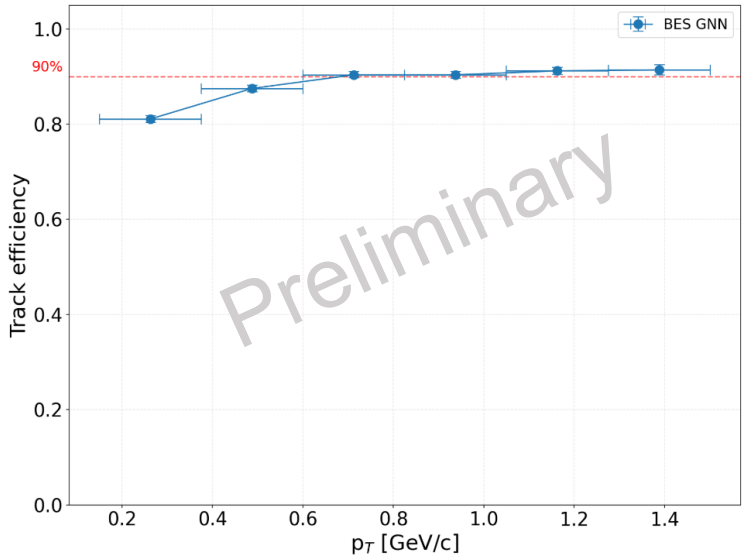




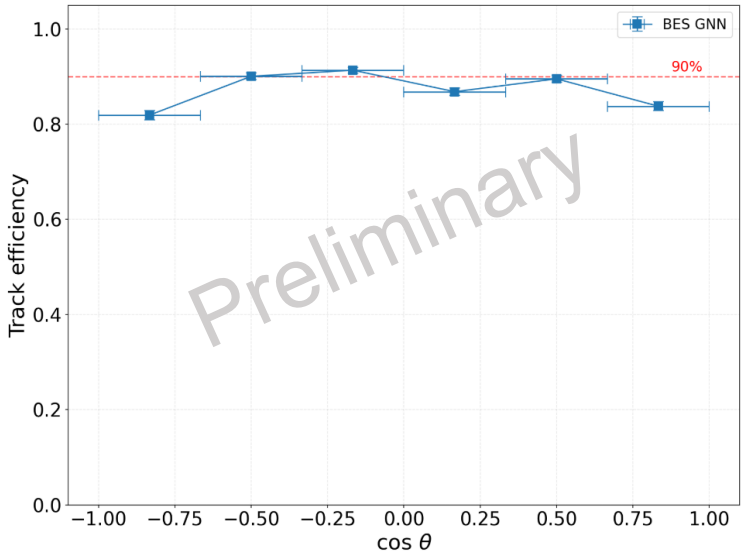


Track efficiency - CGEM + ODC

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

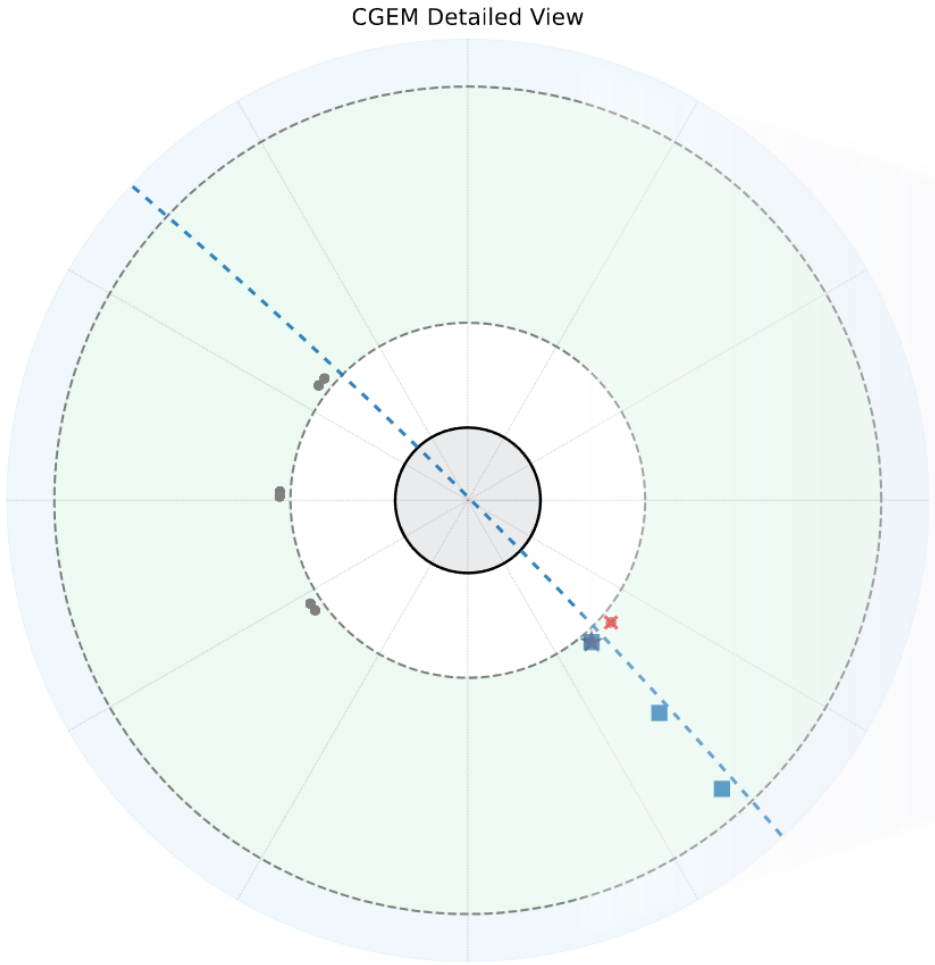


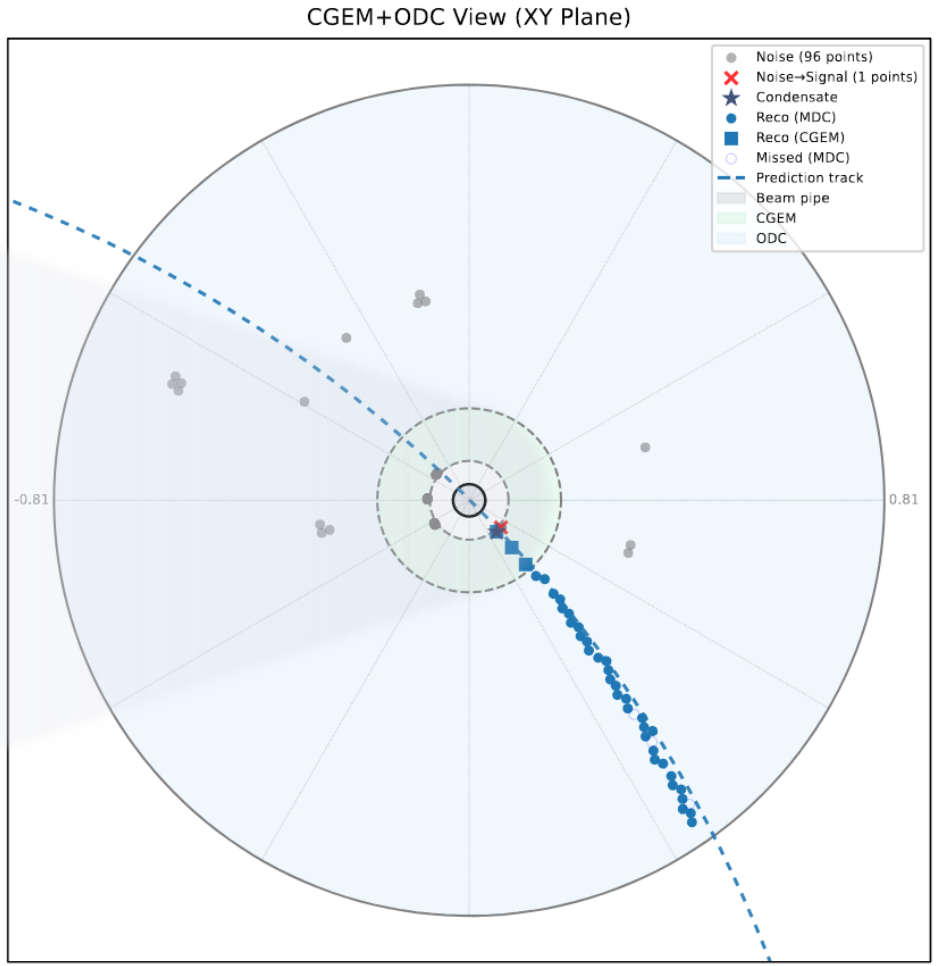
Track effiency vs p_T



Track effiency vs $cos\theta$

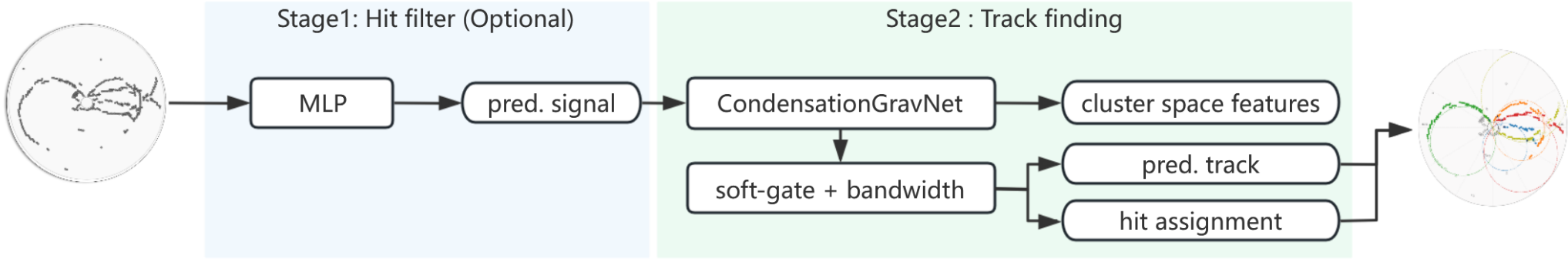
Event Display - CGEM + ODC

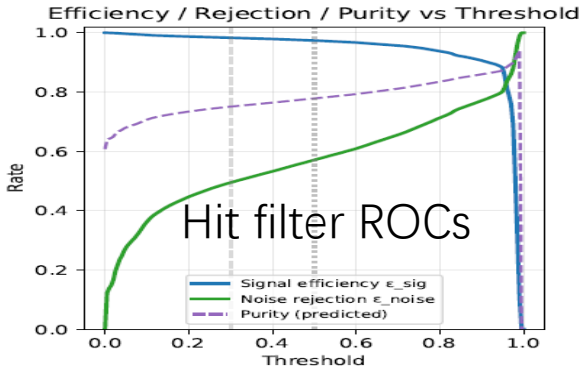


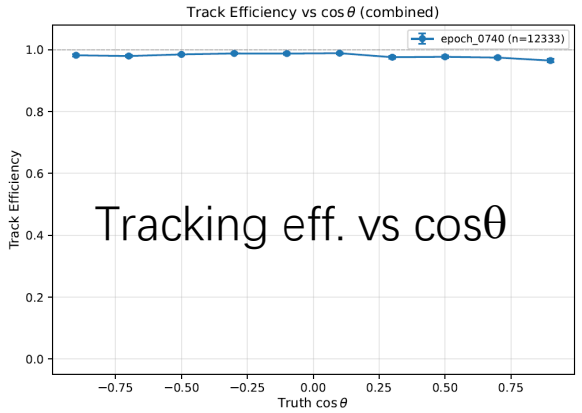


Adapting and Extending Approaches

- **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)

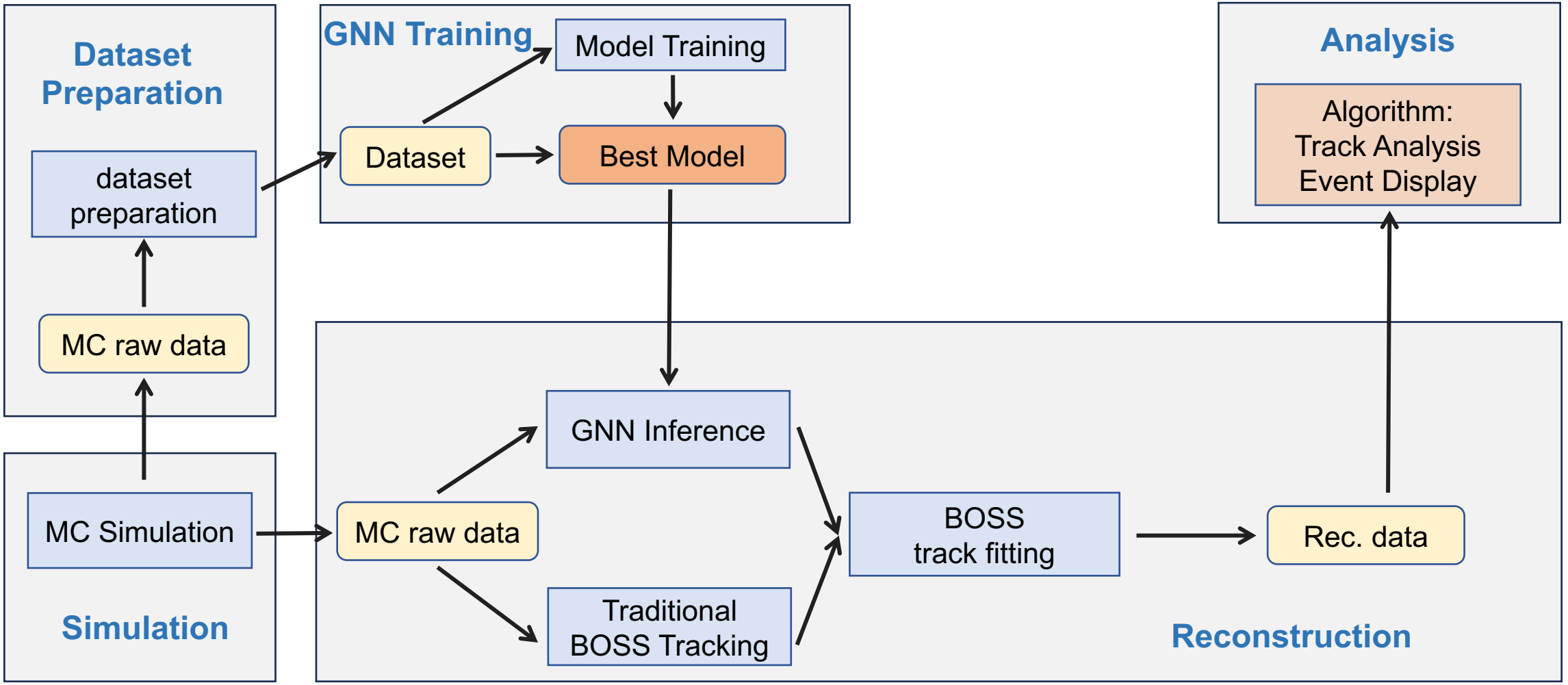
Summary

- 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)

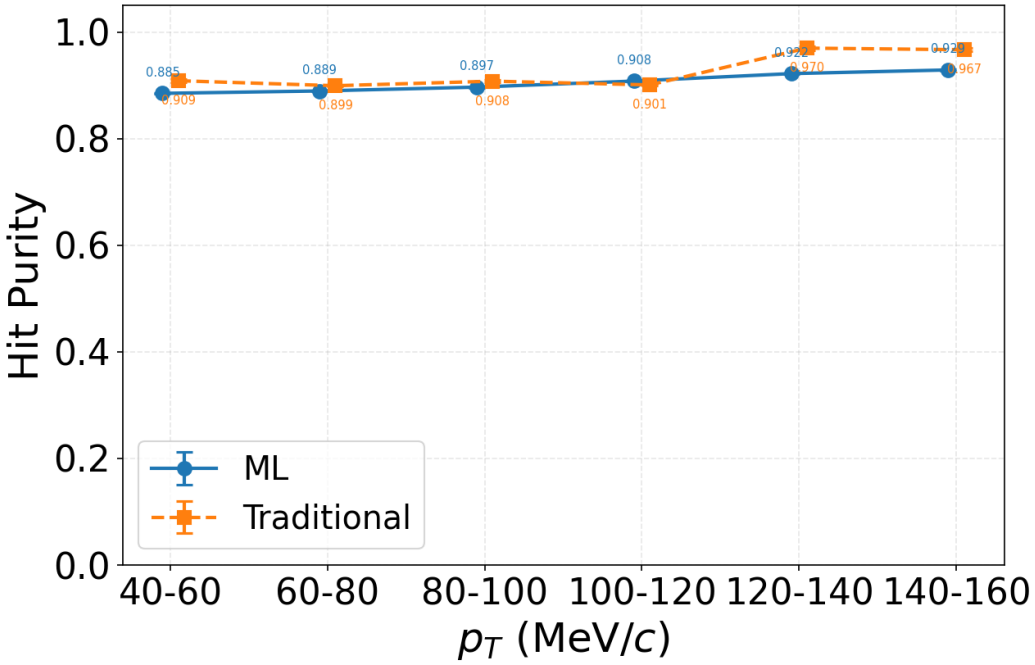
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Model Deploy

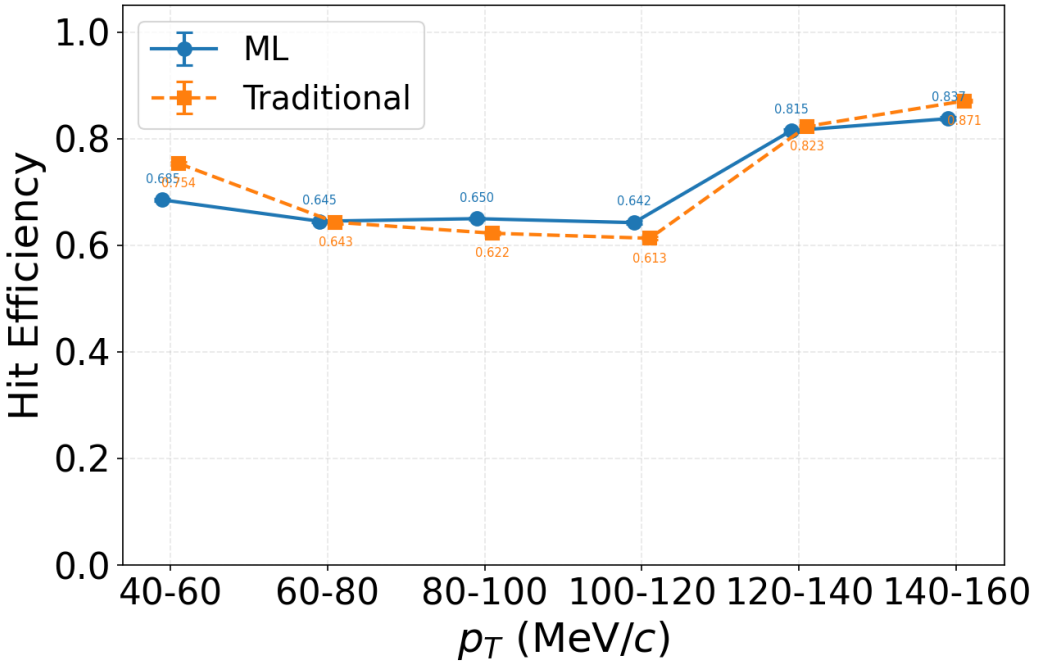


Backup: MDC hit efficiency and purity

- GNN is comparable with traditional tracking

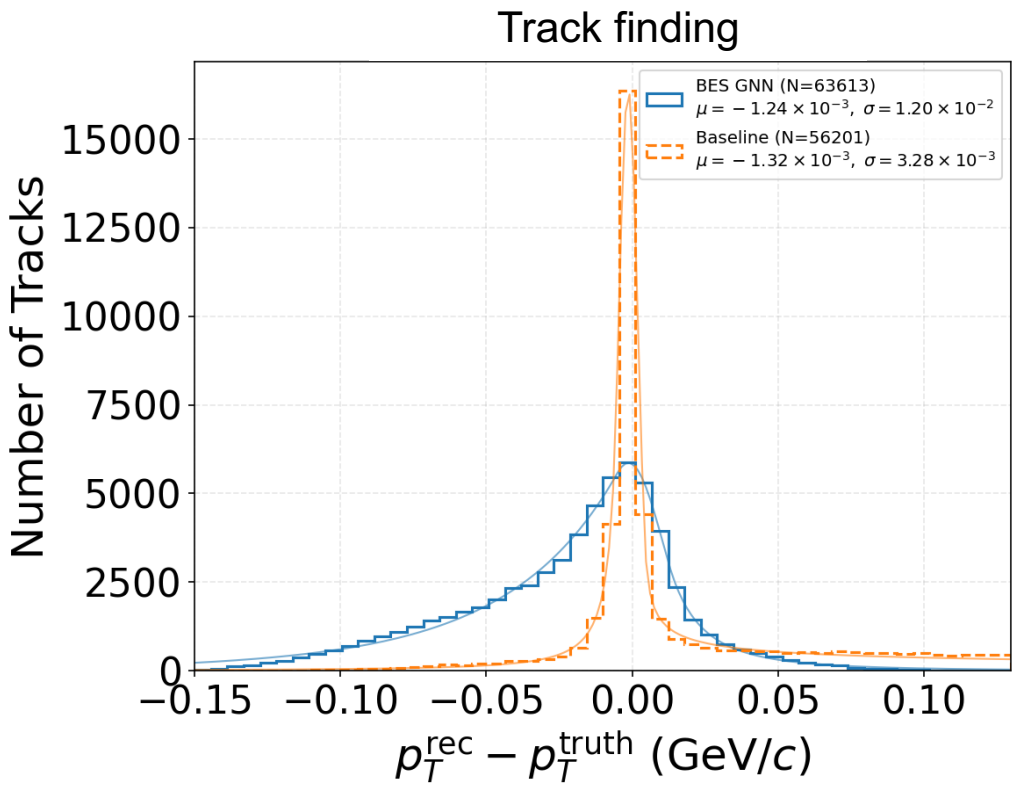


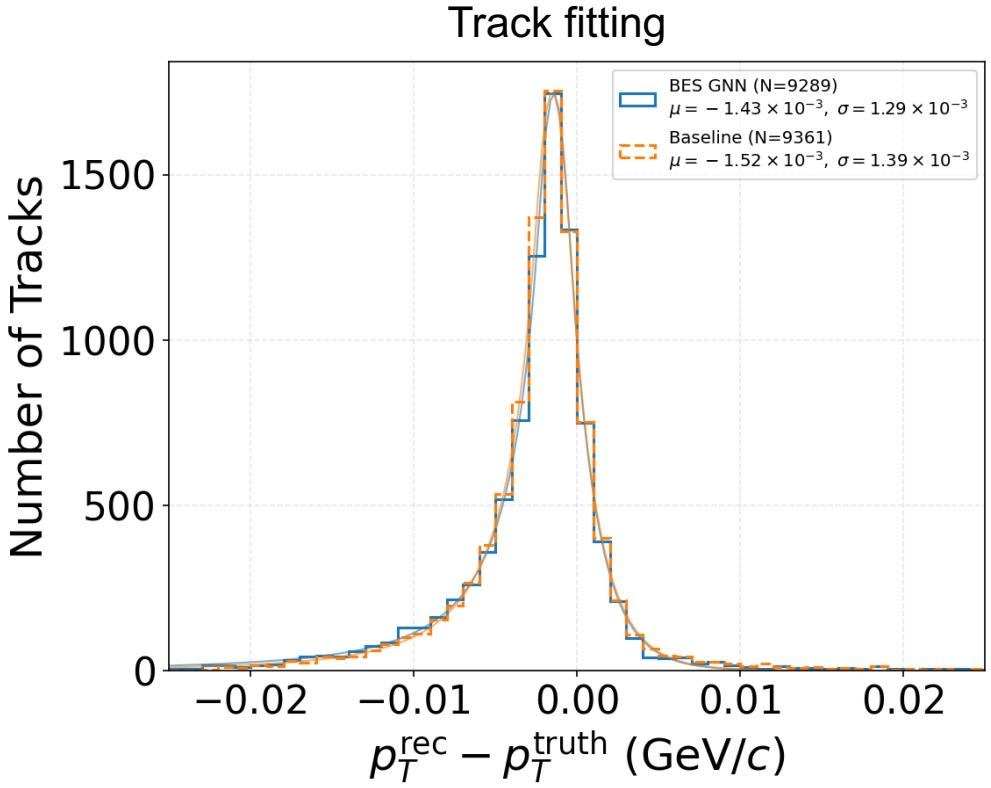
Hit purity vs p_T



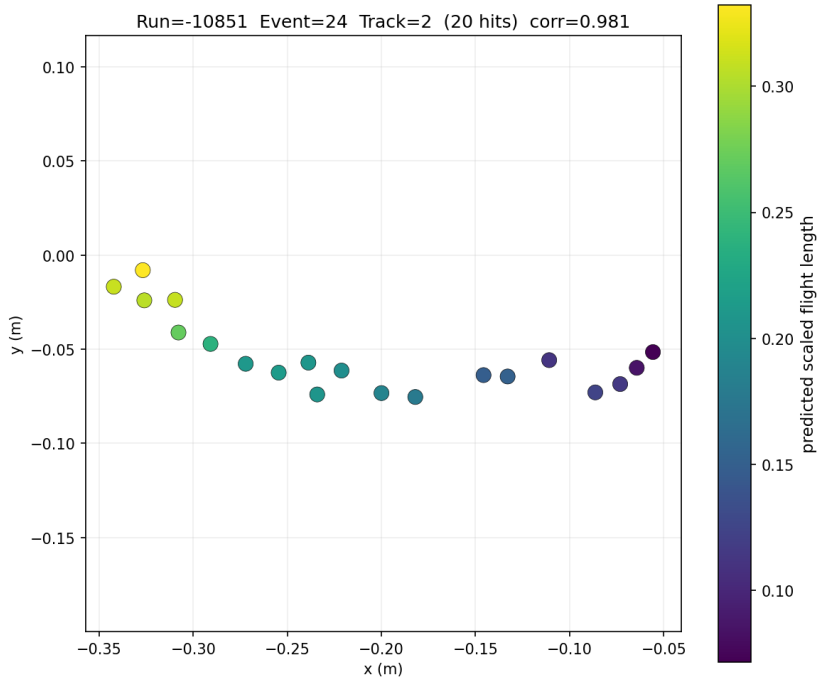
Hit efficiency vs p_T

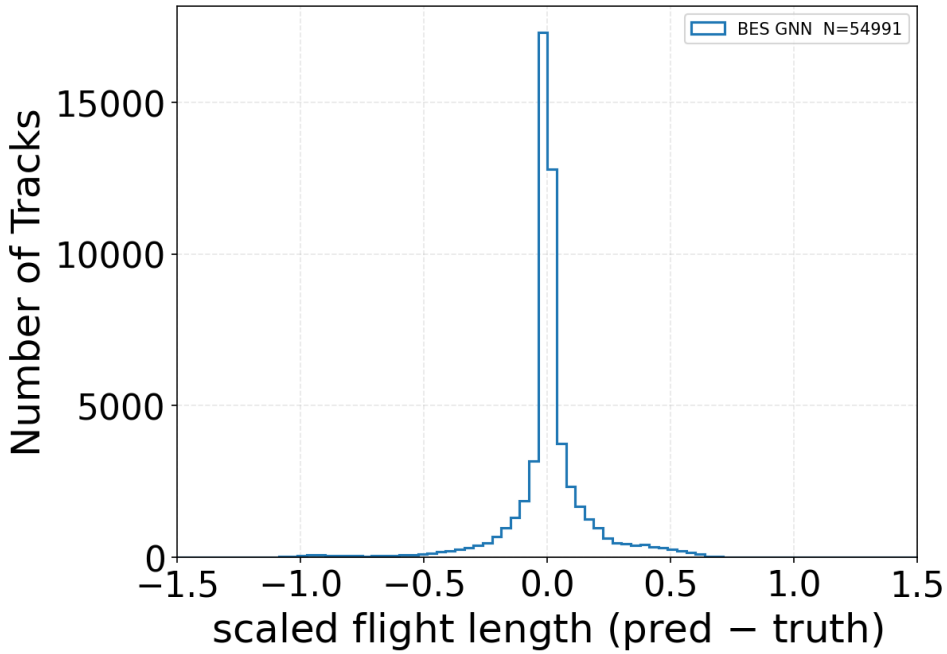
Backup: MDC track parameters





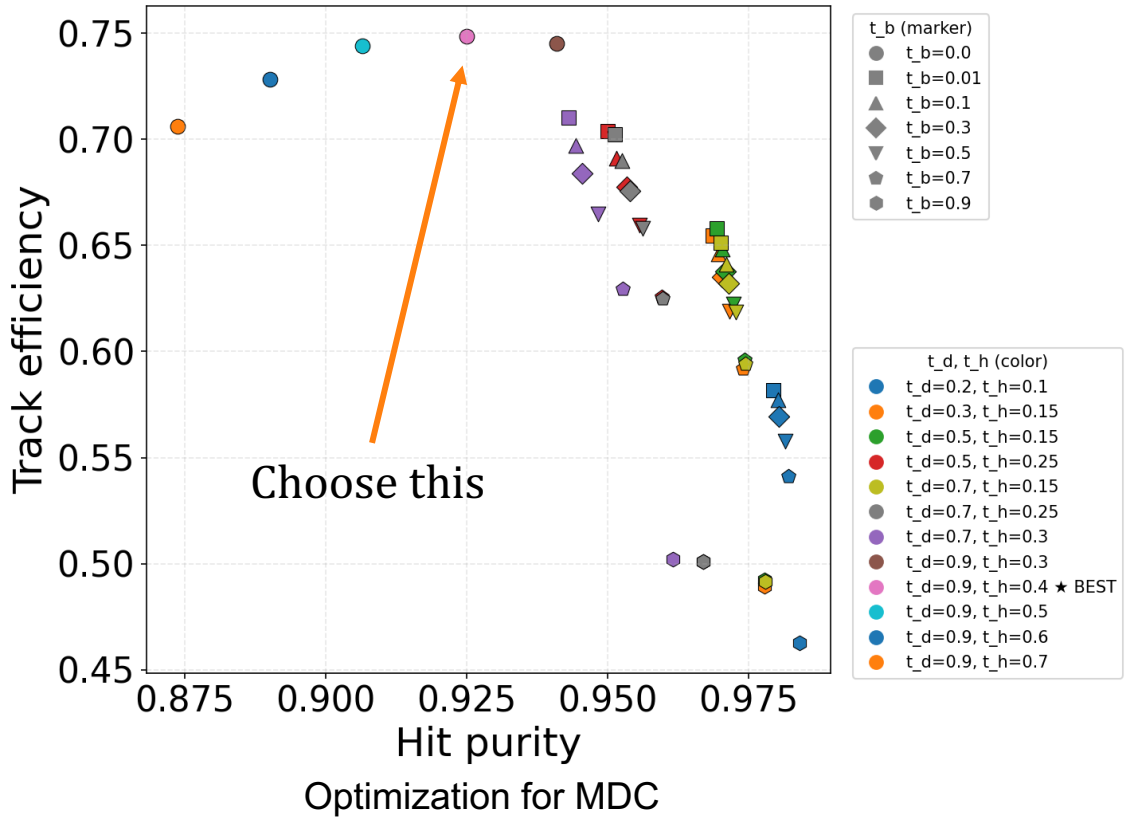
Backup: MDC hit flight length



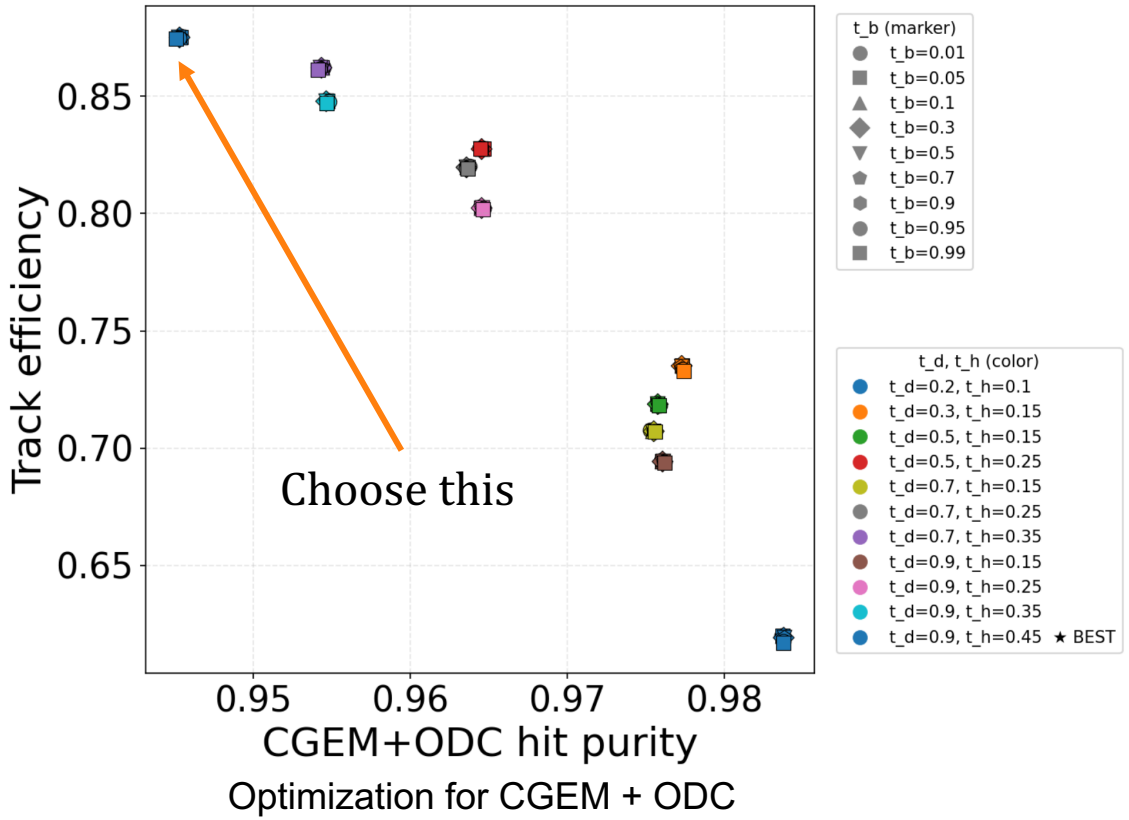


Backup: Optimization of post-processing thresholds

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