



GNN application in drift chamber of BESIII/STCF

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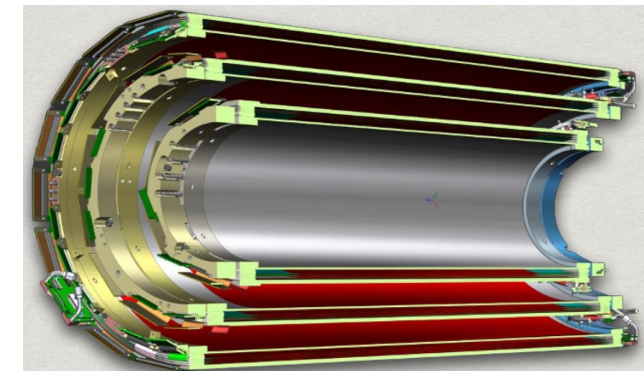
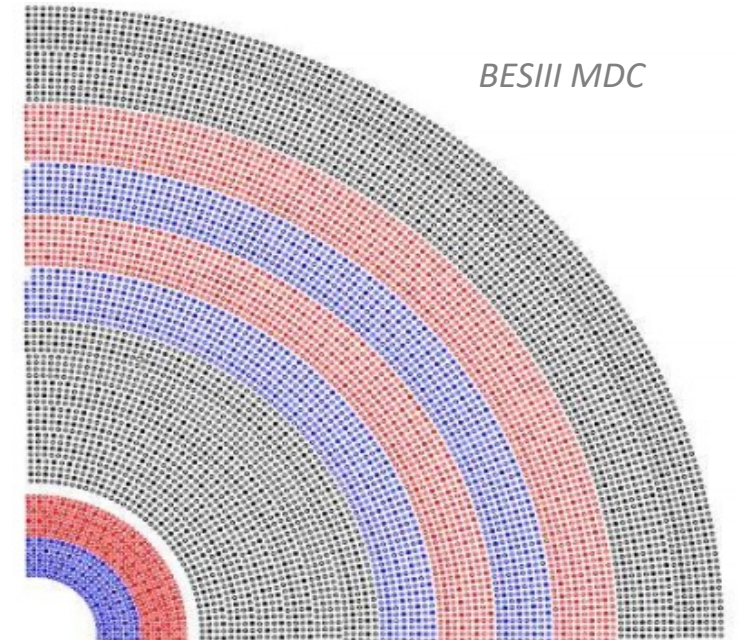
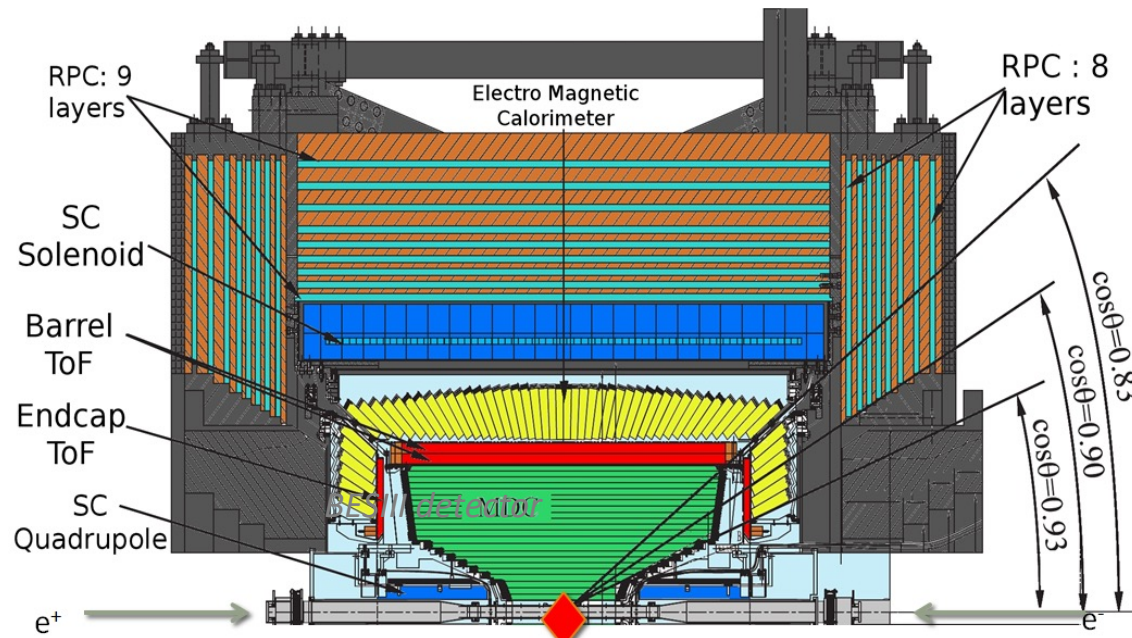
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The 7th International Workshop on Future Tau Charm Facilities

2025-11-25

BESIII experiment and tracking system

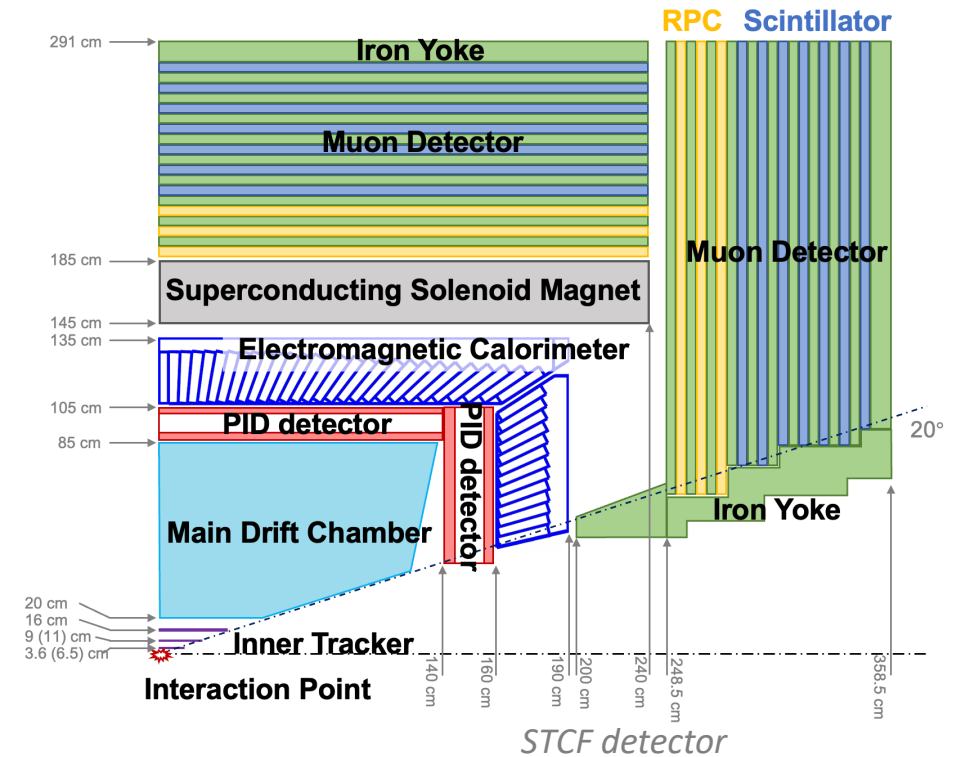
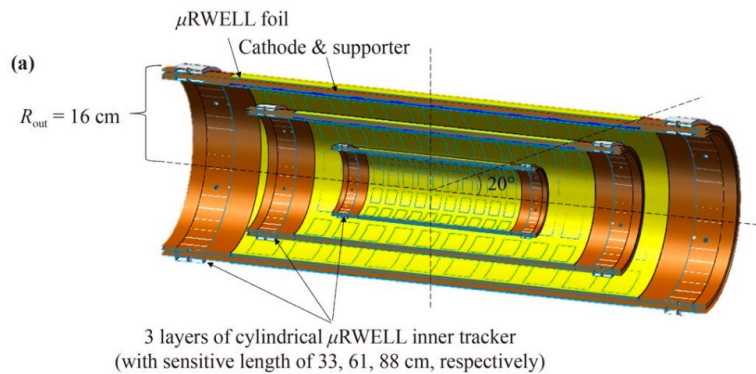
- ◆ Beijing electron-positron collider (BEPCII)
 - Peak luminosity : $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - CMS: 2.0 - 4.95(5.6) GeV, τ -charm region
- ◆ Main Drift Chamber (MDC) at BESIII
 - 43 sense wire layers
 - 5 axial wire super-layers, 6 stereo wire super-layers
 - dE/dx resolution : 6%
 - Momentum resolution : 0.5% @ 1 GeV/c



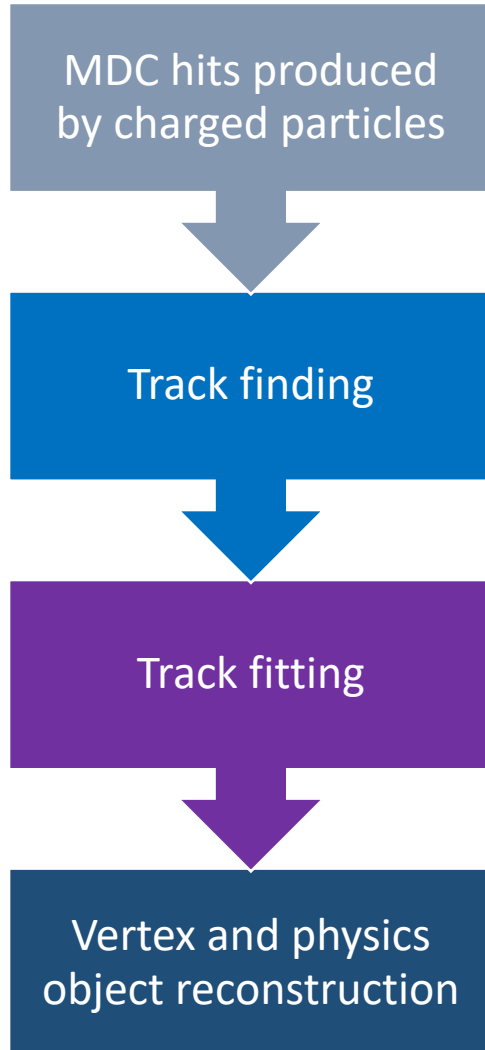
CGEM inner tracker

STCF tracking system

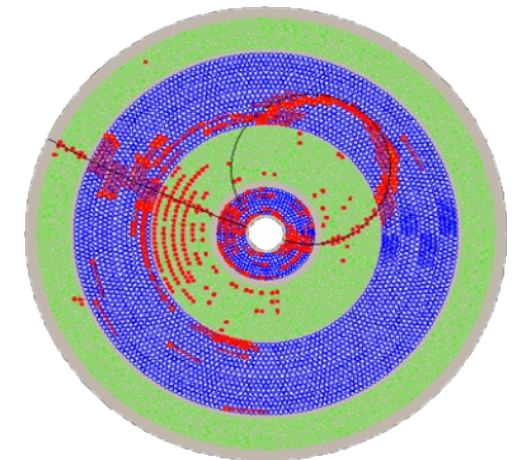
- ◆ Super Tau-Charm Facility (STCF)
 - High Luminosity: $> 0.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} @ 4 \text{ GeV}$
 - CMS: 2 - 7 GeV
- ◆ Several detector design options under study
- ◆ Main Drift Chamber (MDC) at STCF
 - 48 sense wire layers
 - 4 axial wire super-layers, 4 stereo wire super-layers
 - dE/dx resolution : $\sim 6\%$
 - Momentum resolution : $0.5\% @ 1 \text{ GeV}/c$
- ◆ Inner tracker
 - ITK: μRWELL , CMOS MAPS



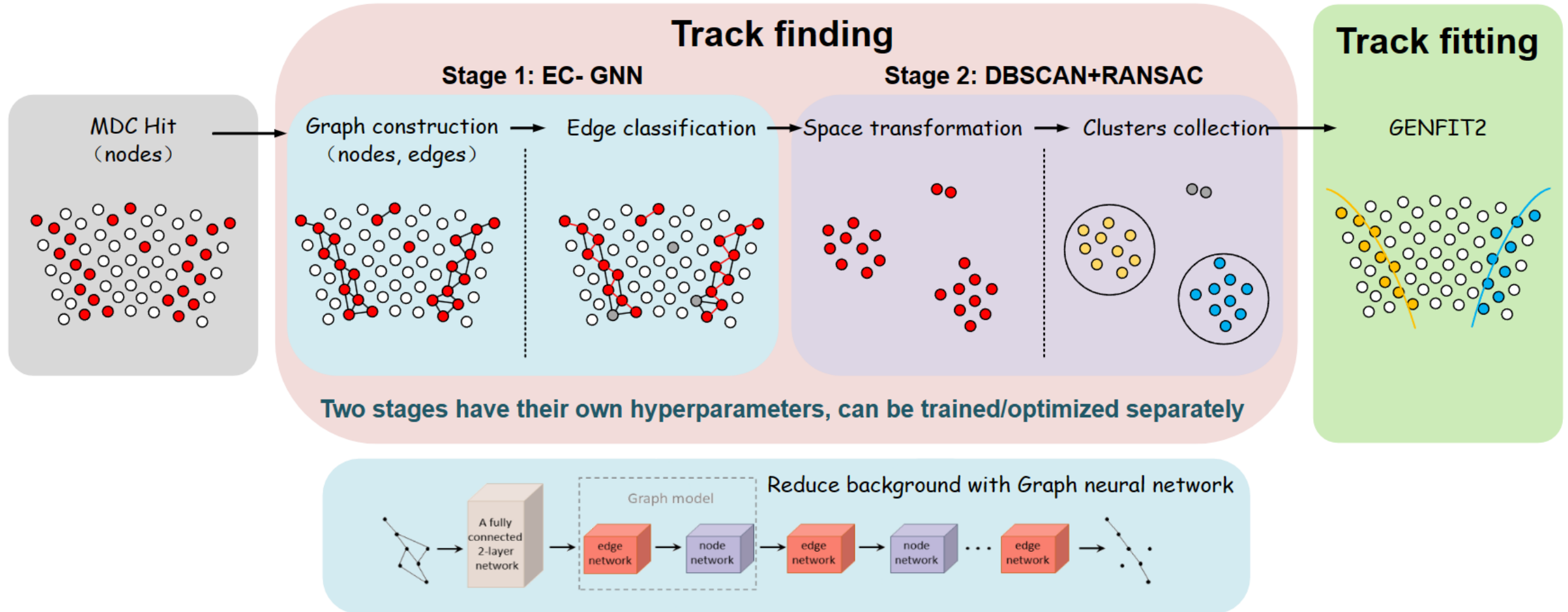
Traditional tracking in drift chamber



- ◆ Build candidate tracks and perform hits assignment
 - Global approach : Hough Transform (HOUGH)
 - Local approach :
 - Template Matching (PAT)
 - Track Segment Finding (TSF)
 - Combinatorial Kalman Filter (CKF)
- ◆ Estimate the track parameters
 - Global fit : Least Square Method, Runge-Kutta Method
 - Recursive fit : Kalman filter

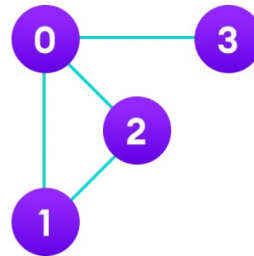
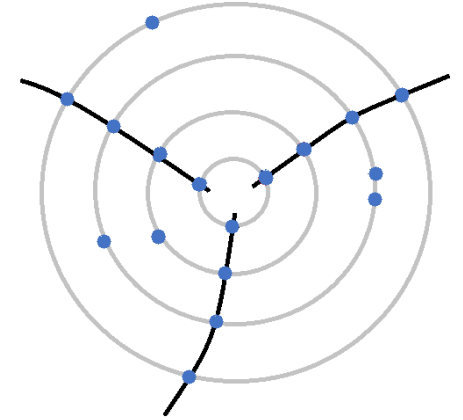
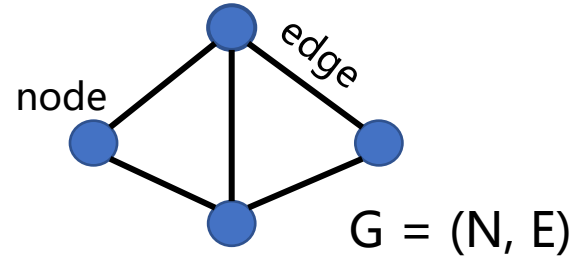


Methodology: GNN based tracking pipeline



Graph representation

- ◆ A type of neural network that are specifically designed to operate on graph-structured data
- ◆ Graph elements: nodes, edges
- ◆ From graph to track
 - nodes \rightarrow hits
 - edges \rightarrow track segments
- ◆ The storage structure of graphs
 - Adjacency matrix ✓
 - Adjacency table
 - Orthogonal list
 - Adjacency multiple table
 - Edge set array
 -



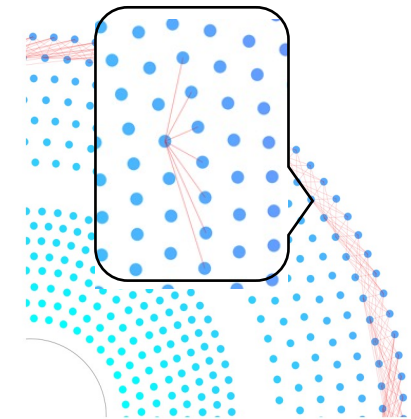
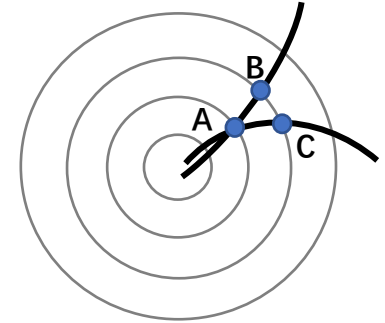
	0	1	2	3
0	0	1	1	1
1	1	0	1	0
2	1	1	0	0
3	1	0	0	0

Graph construction at BESIII

To reduce the number of fake edges during graph construction

Pattern Map based on MC simulation at BESIII

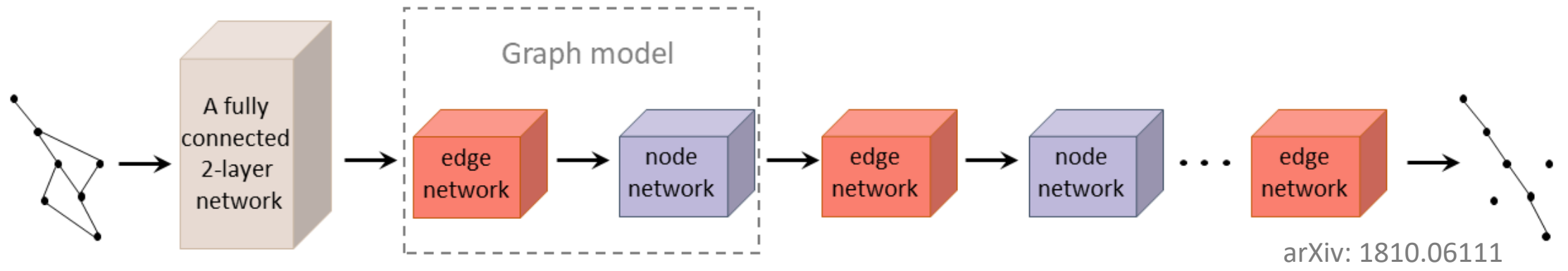
- ◆ Definition of valid neighbors
 - Hits on the same layer
 - Two adjacent sense wires on the left and right
 - Hits on the next layer
 - The collection of sense wires that could potentially represent two successive hits on a track
 - To reduce the size of the graphs, the Pattern Map is further reduced based on a probability cut ($>1\%$)
- ◆ Edge assignment based on Pattern Map
 - Hit with its neighbors on the same layer and next layer
 - Hit with its neighbors' neighbors on one layer apart
 - Edge label: two hits of this edge belongs to same track or not.
- ◆ Graph representation
 - Node features (raw time, position coordinates r, φ of the sense wires), adjacency matrices, edge labels



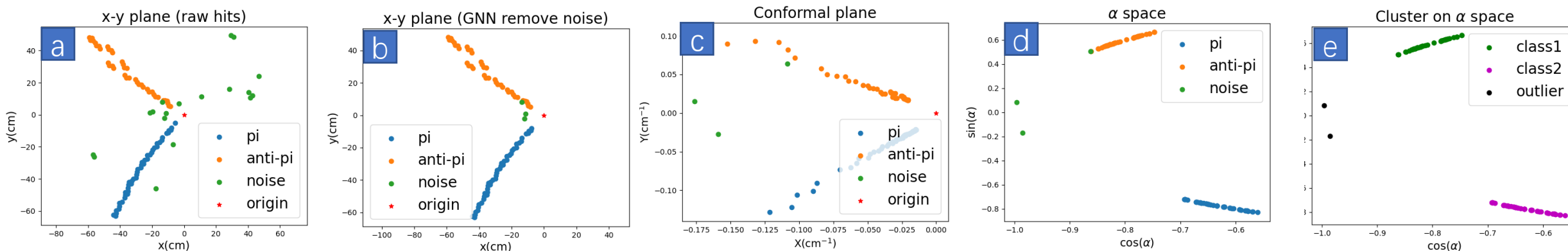
A wire on layer13 and its neighbors on layer14

GNN edge classifier based on PyTorch

- ◆ Input network
 - Node features embedded in latent space
- ◆ Graph model
 - Edge network computes weights for edges using the features of the start and end nodes
 - Node network computes new node features using the edge weight aggregated features of the connected nodes and the nodes' current features
 - MLPs
 - 8 graph iterations
 - Strengthen important connections and weaken useless or spurious ones



Clustering based on DBSCAN



◆ Transform to Conformal plane

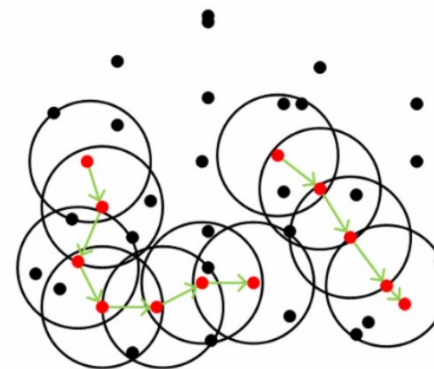
- $X = \frac{2x}{x^2+y^2}$ $Y = \frac{2y}{x^2+y^2}$
- Circle passing the origin
- transform into a straight line

◆ Transform to ' α ' parameter plane

- Hits connected in the X-Y plane in a straight line
- α as the angle between the straight line and X axis
- The parameter space as $\cos\alpha$ and $\sin\alpha$

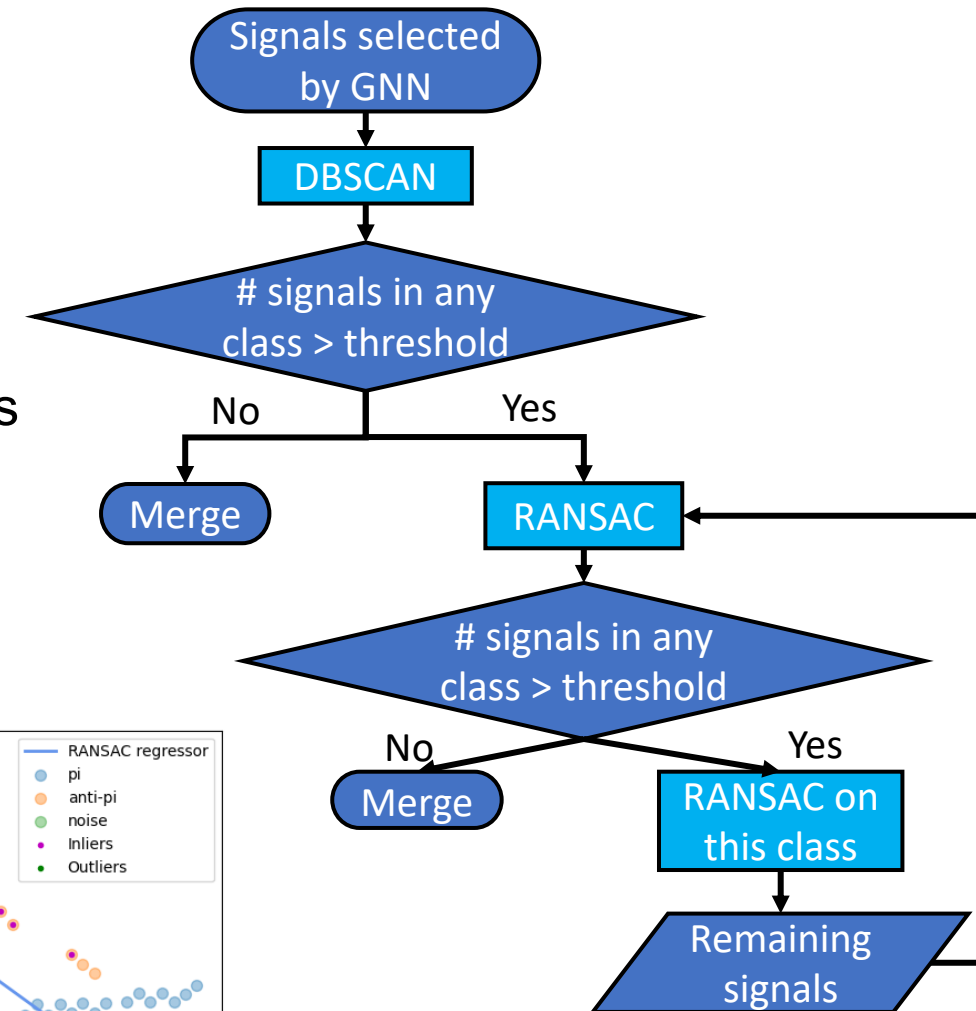
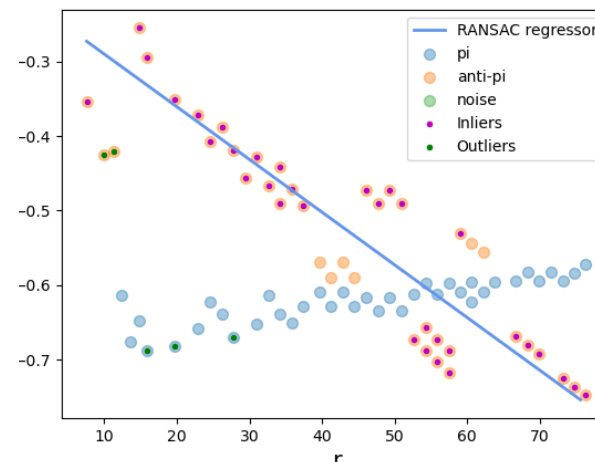
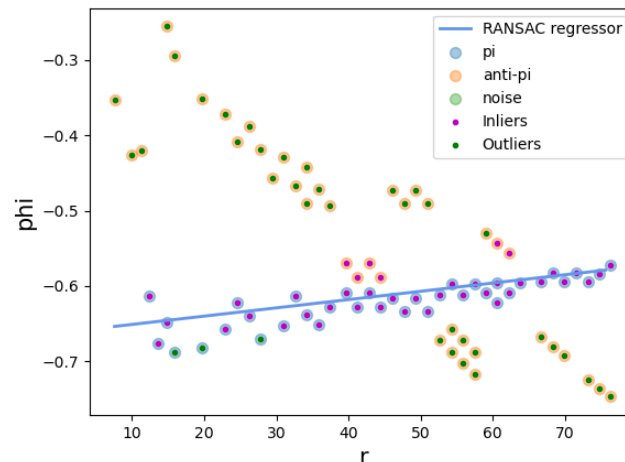
◆ DBSCAN clustering in ' α ' parameter plane

- Density-Based Spatial Clustering of Application with Noise
- Hits in a cluster are considered to be in the same track



Clustering salvage algorithm RANSAC

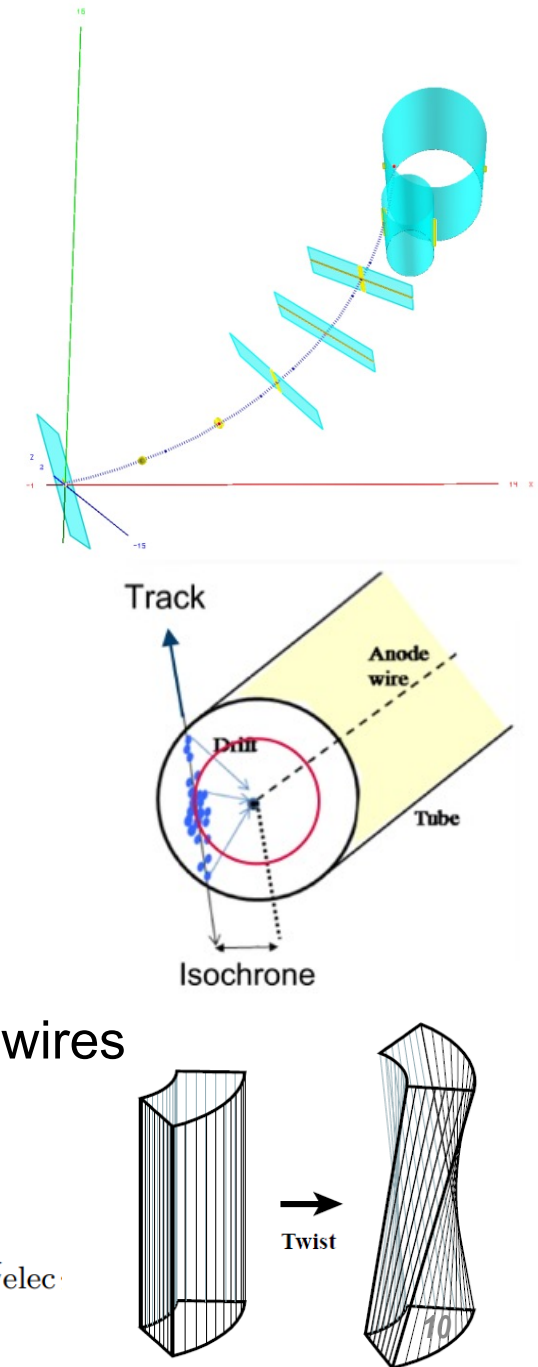
- ◆ Random sample consensus (RANSAC)
 - Estimate a mathematical model from the data that contains outliers
 - Its good robustness to noise and outliers
 - Model can be specified
- ◆ RANSAC is triggered by the events when DBSCAN fails
 - Polar coordinate space
 - linear model
 - Inliers \rightarrow a track , outliers \rightarrow other tracks
 - Stop condition: outliers $<$ threshold



Track fitting

- ◆ Genfit2
 - A Generic Track-Fitting Toolkit
 - Experiment-independent framework
 - PANDA, Belle II, FOPI and other experiments
 - Deterministic annealing filter (DAF) to resolving the left-right ambiguities of wire measurements
- ◆ Configuration: Detector geometry and materials; TGeoManager
- ◆ Input :
 - Signal wire position, initial values of position and momentum
 - particle hypothesis for e, μ, π, k, p
- ◆ Fitting procedure:
 - Start 1st try: drift distance roughly estimated from TDC、ADC of sense wires
 - Iteration to update information of drift distance, left-right assignment, hit position on z direction and entrancing angle in the cell et al.

$$t_{\text{drift}} = t_{\text{TDC}} - t_{\text{EST}} - t_{\text{flight}} - t_{\text{wp}} - t_{\text{elec}}$$



Performance of filtering noise at BESIII

◆ Dataset

- Single-particle ($e^\pm, \mu^\pm, \pi^\pm, K^\pm, p/\bar{p}$) MC sample
- $0.2 \text{ GeV}/c < p < 3.0 \text{ GeV}/c$
- Mixed with BESIII random trigger data as background (~45% hits)
- Train: Validation: Test = 4: 1: 1

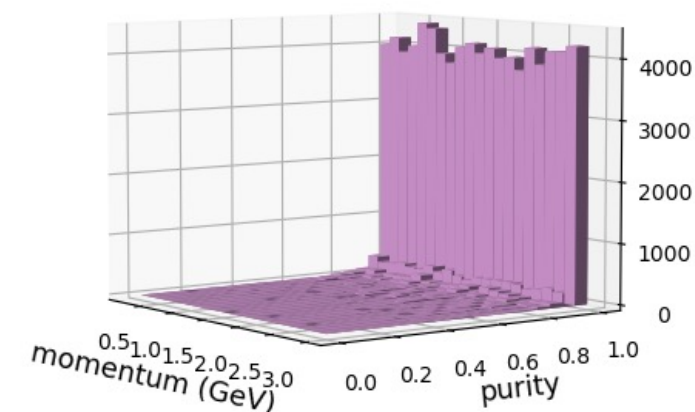
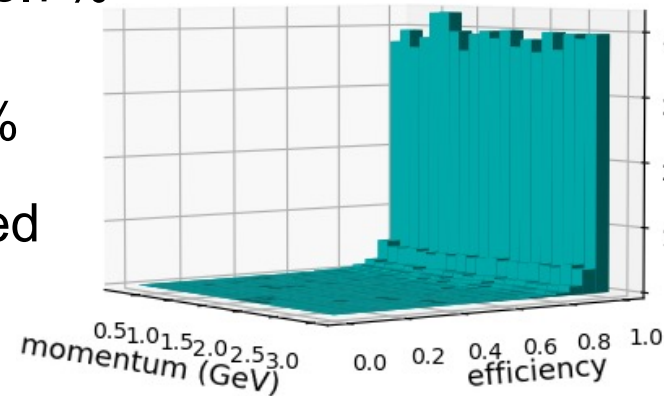
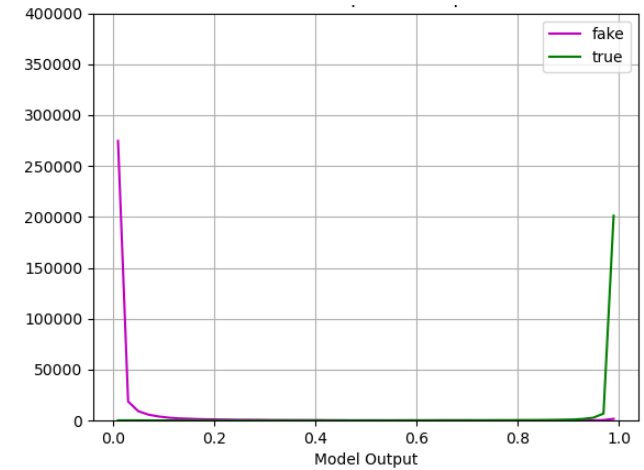
◆ Hit selection performance

- The preliminary results show that GNN provides high efficiency and purity of hits selection

- Hit selection Efficiency : $\frac{N_{signal}^{predicted}}{N_{signal}^{real}}$ 98.7%

- Hit selection Purity : $\frac{N_{signal}^{predicted}}{N_{all}^{predicted}}$ 96.5%

- Efficiency and purity can be balanced by adjusting the model parameter



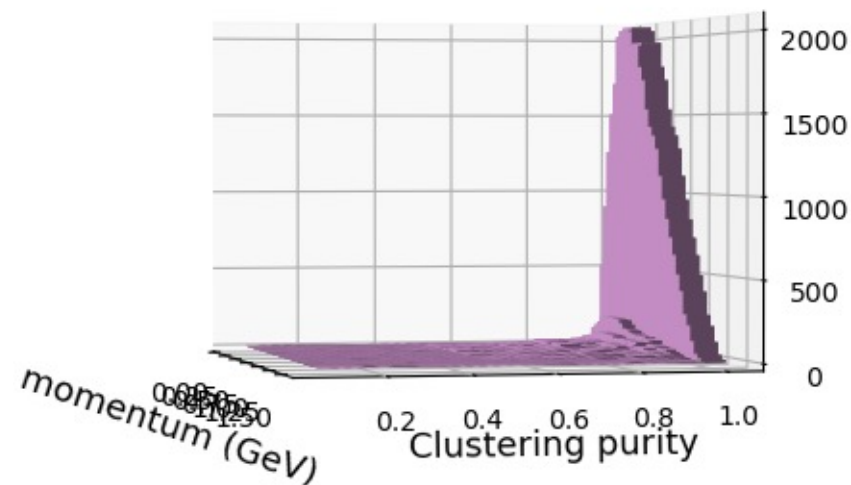
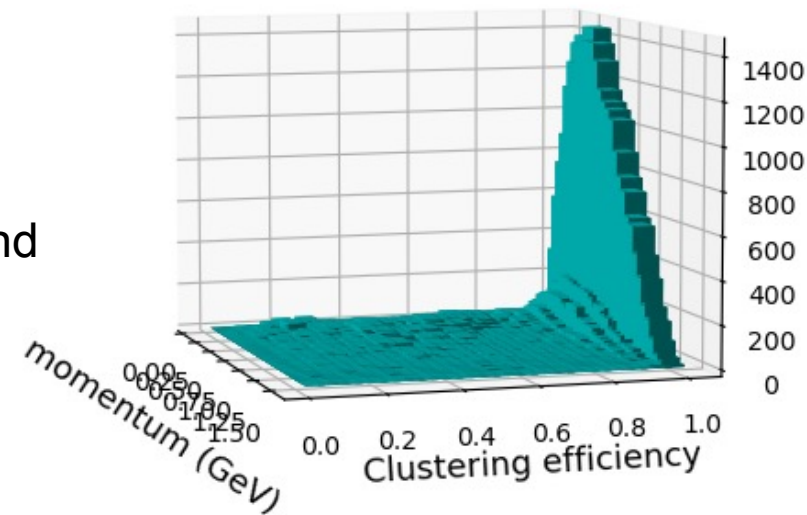
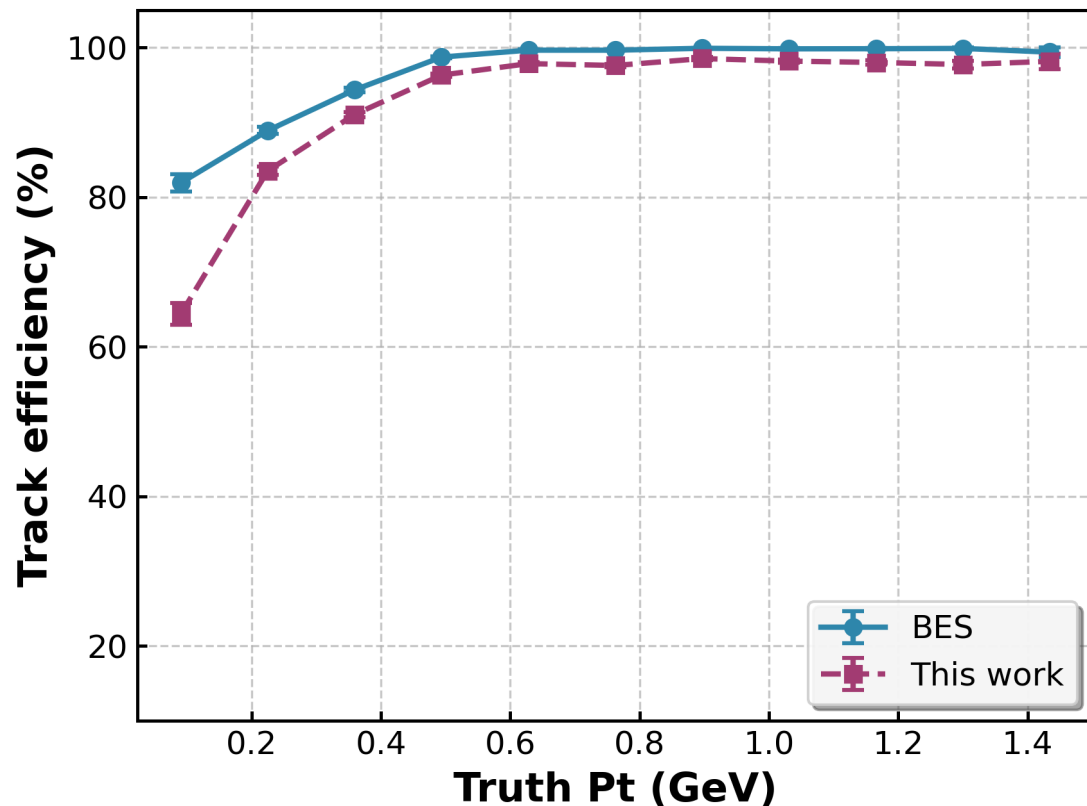
Preliminary tracking performance at BESIII

- ◆ Particle reconstructed performance

- $J/\psi \rightarrow \rho^0 \pi^0 \rightarrow \gamma\gamma \pi^+ \pi^-$ from MC simulation

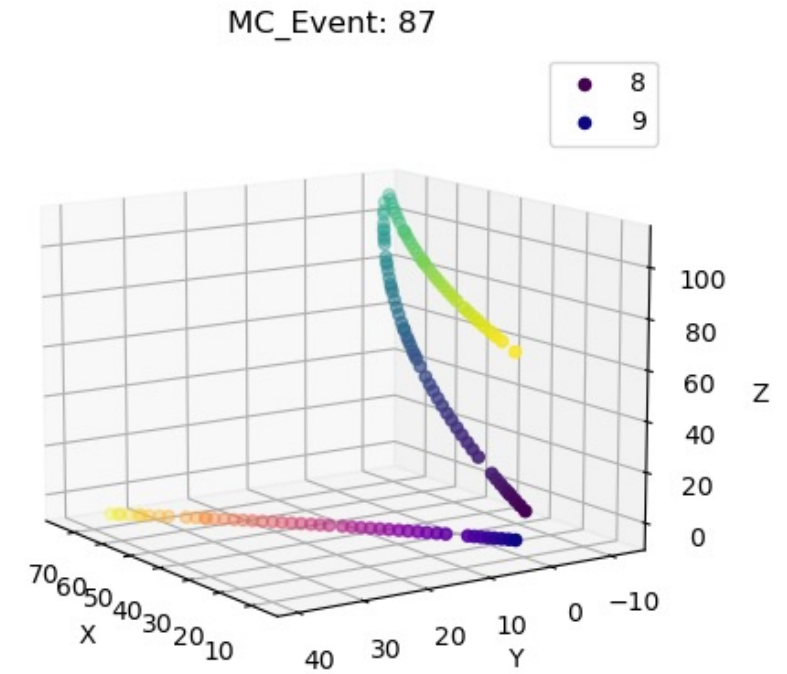
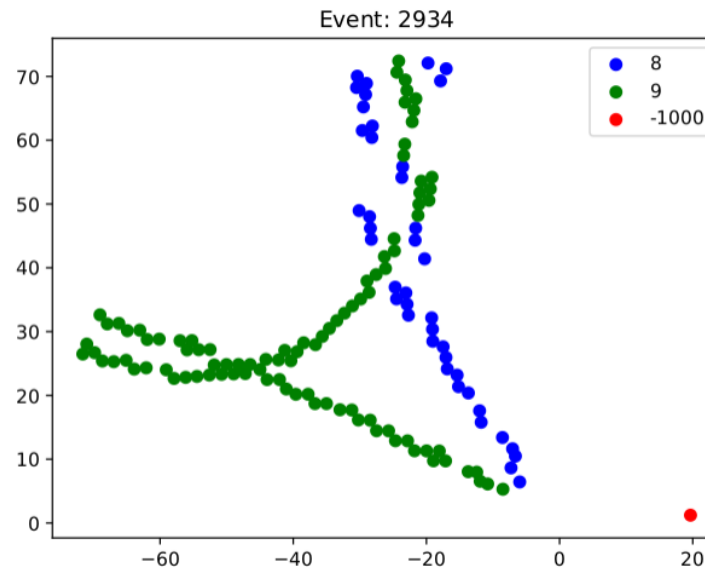
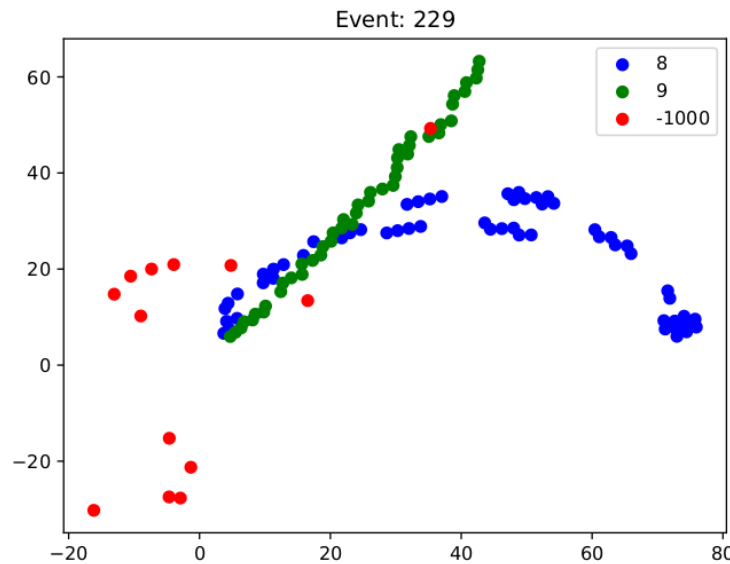
- $\text{track eff} = \frac{N_{\text{rec tracks}}}{N_{\text{total tracks}}}$

- ◆ Potential difference of fitting quality requirement between Genfit and Kalman fit in BESIII



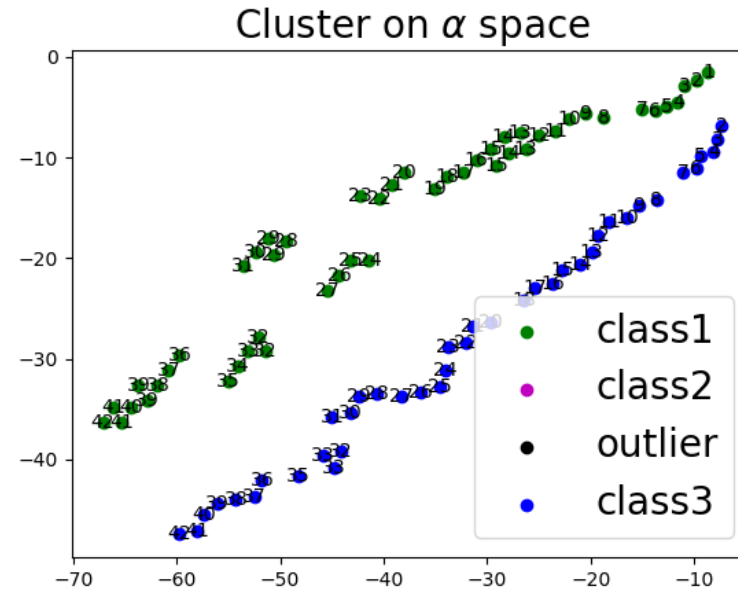
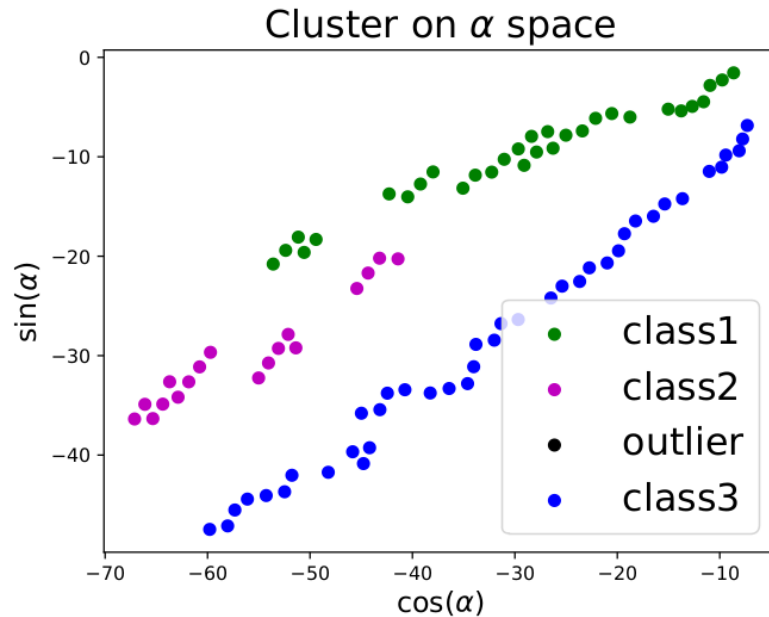
Sources of efficiency loss

- ◆ Efficiency loss during track finding (clustering):
 - multi-circular, decays,
 - interaction with detector boundary/material, scattering
 - 2D crossing tracks or too close to each other



Further modification of track finding

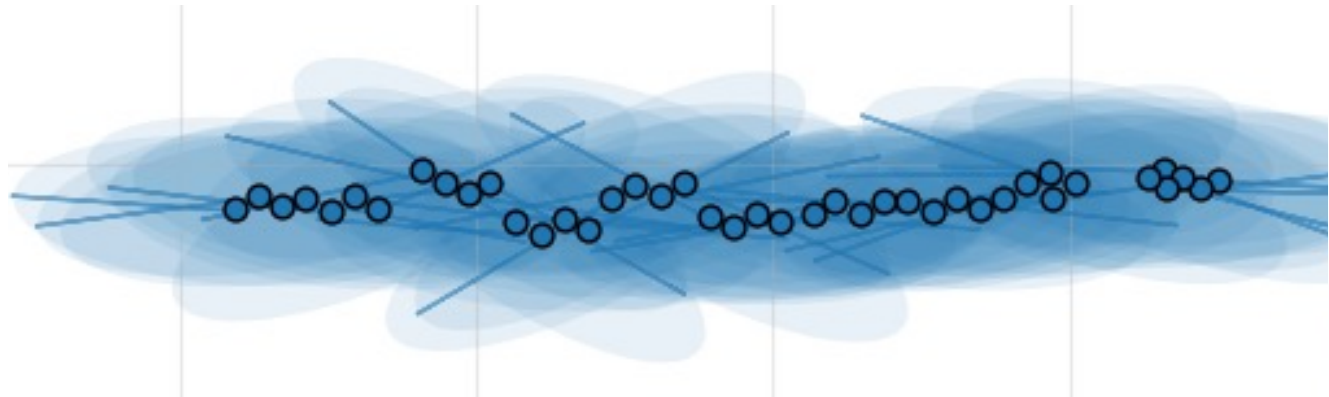
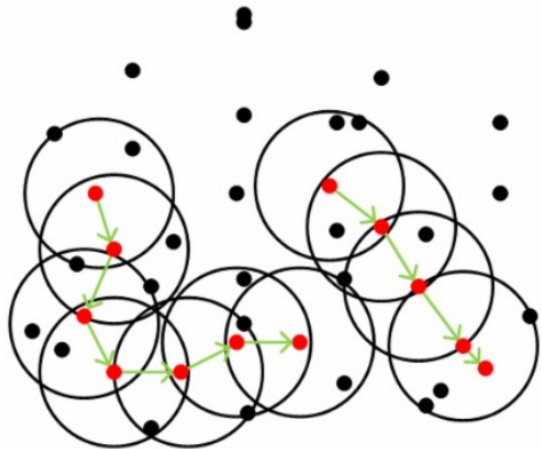
- ◆ Since z position of hits is unknown, 2D information has large deviation for stereo wires
- ◆ Breaking into parts especially for tracks with large polar angle
- ◆ Re-combination at super layers level



DBSCAN using elliptical neighborhood

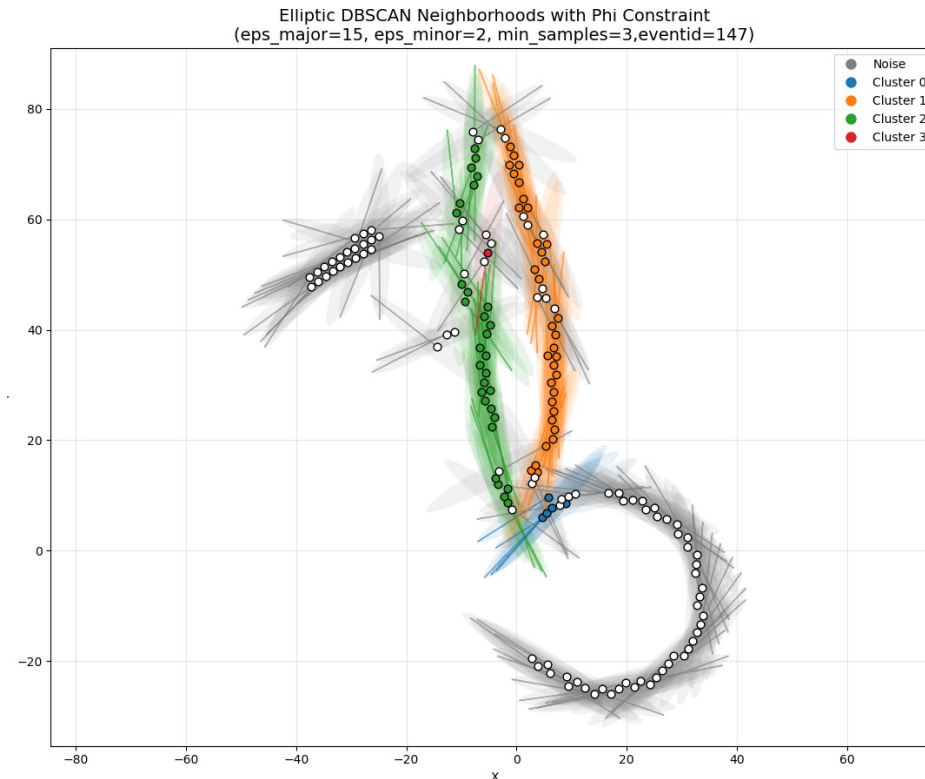
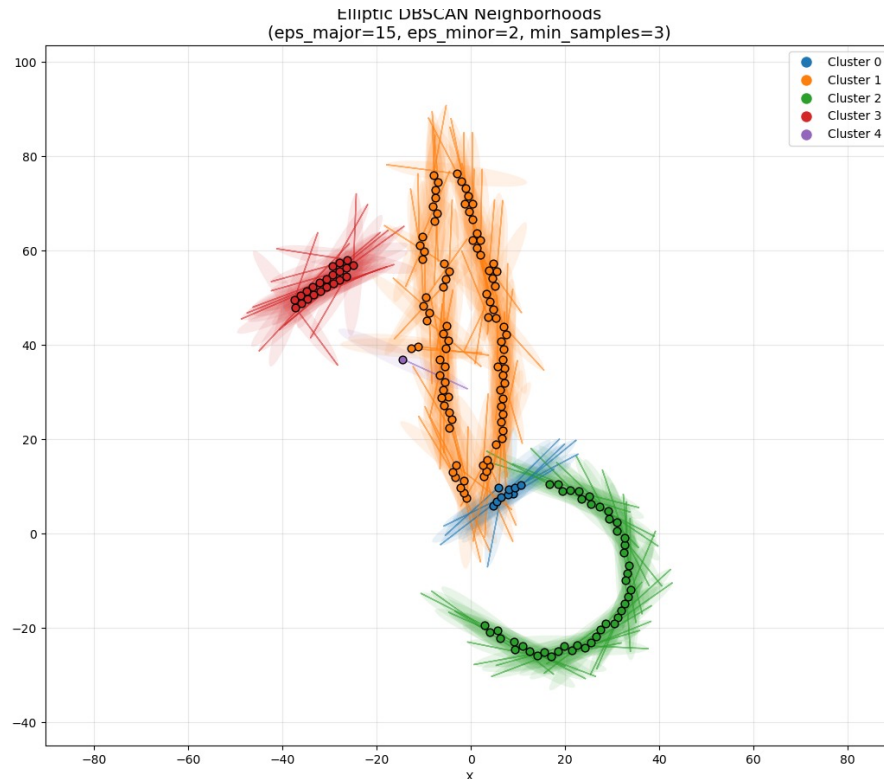
- ◆ Circular neighborhood is replaced with an elliptical neighborhood
- ◆ Local orientation of each point is determined based on PCA considering points within its neighborhood

Parameters	Meaning	value
eps_major	long axis	15cm
eps_minor	short axis	10cm
min_samples	min neighbors	3
k (orientation calculation)	neighbors for PCA	5

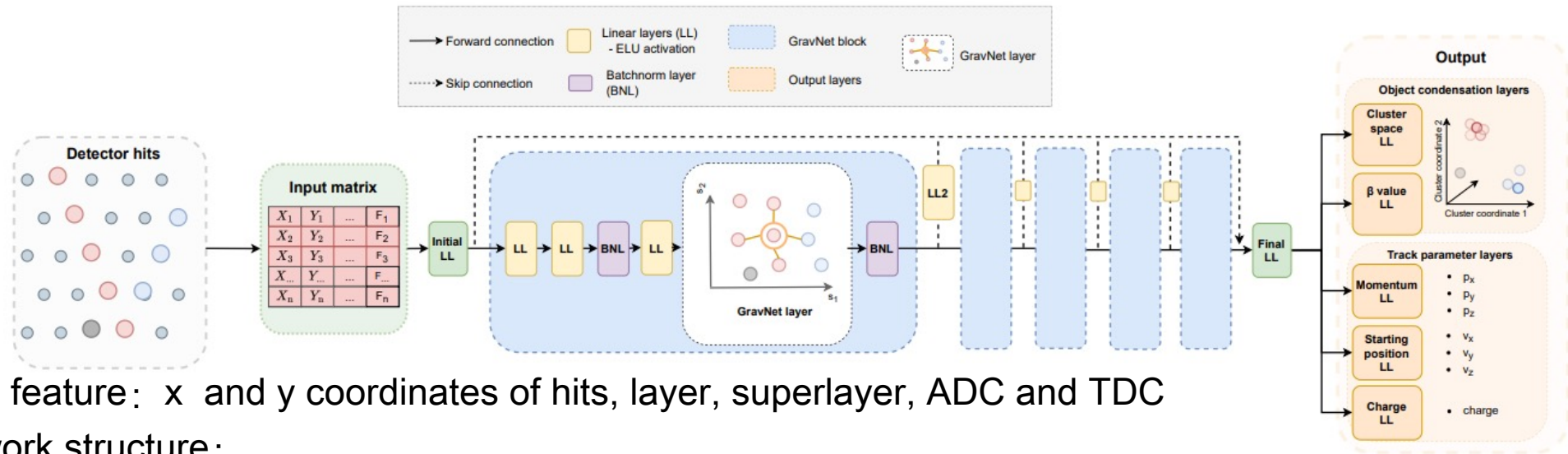


Split cluster via abnormal point

- ◆ Abnormal point detection:
 - large di-angle between direction of PCA and direction to the IP
- ◆ Further attempts:
 - assign large weight for hits in the same superlayer
 - veto hits in the same payer, same superlayer but another group



Object Condensation(OC) using GNN

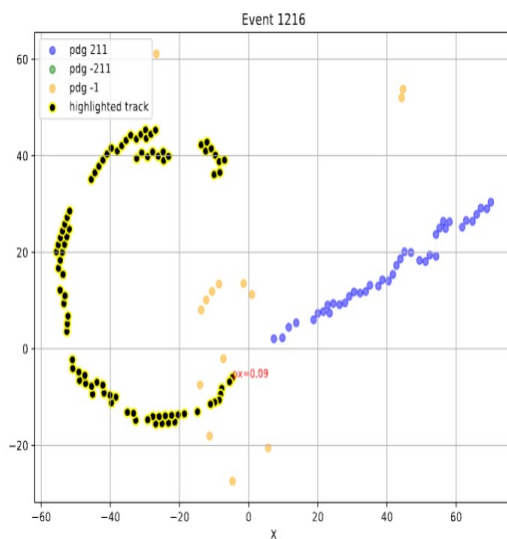


- ◆ Input feature: x and y coordinates of hits, layer, superlayer, ADC and TDC
- ◆ Network structure:
 - Initial LL with ELU activation and batch normalization.
 - Multiple stacked GravNet blocks with skip connections. Each block includes :
 - A GravNet layer(GNN layer) that learns a latent space to determine neighborhood relationships and pass message.
 - Linear layers (LL) and batch normalization layers (BNL).
 - Final LL to generate output representations
- ◆ Output:
 - Object condensation layers :
 - Cluster coordinates (for grouping hits belonging to the same track).
 - β -values (confidence scores for cluster centers).
 - Track parameter prediction layers: $q, p_x, p_y, p_z, v_x, p_y, v_z$

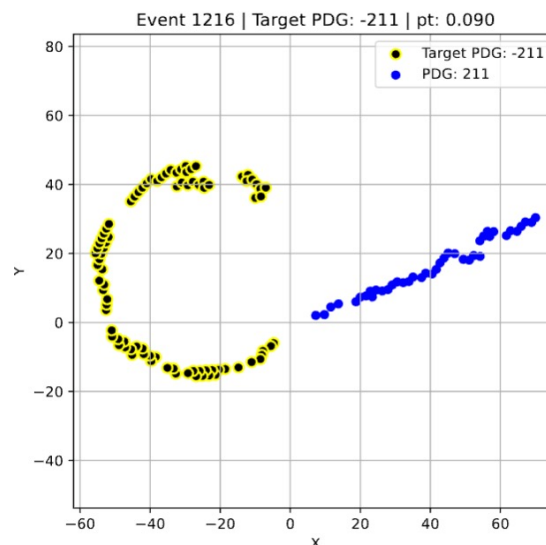
Comput.Softw.Big Sci. 9 (2025) 1, 6

Track finding result via OC

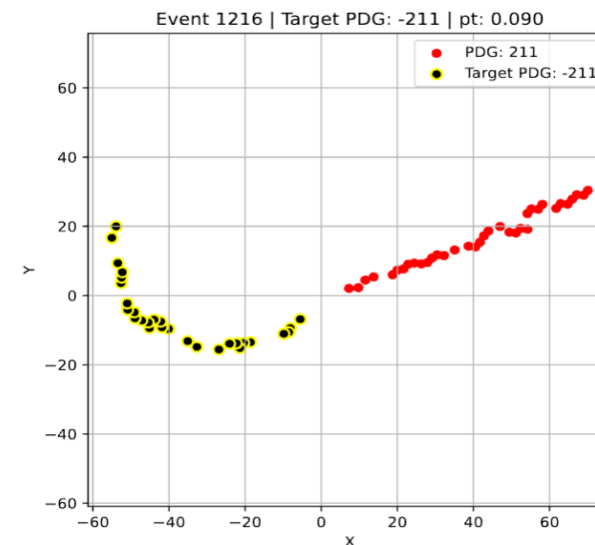
□ circling track



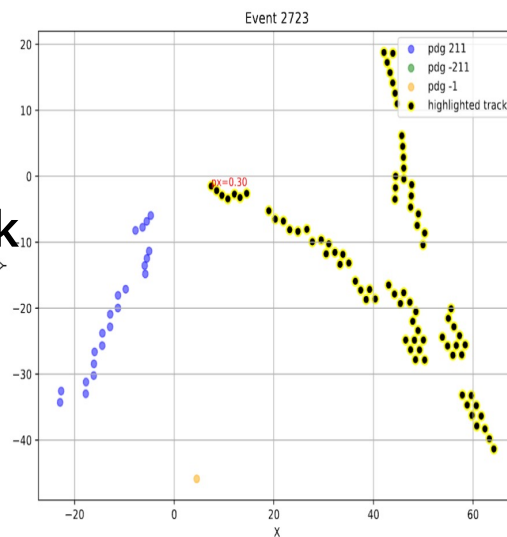
truth



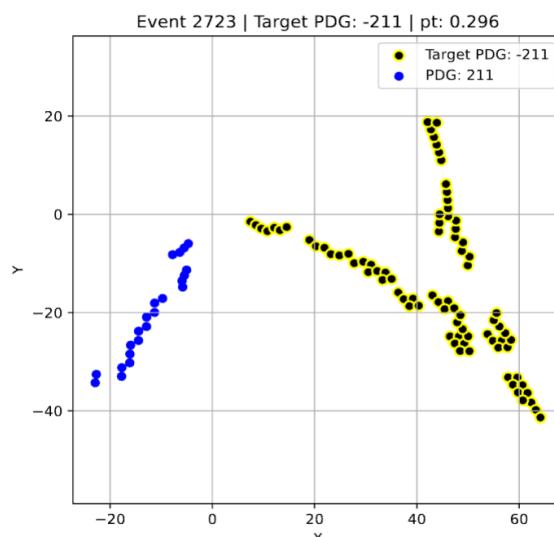
OC clustering results



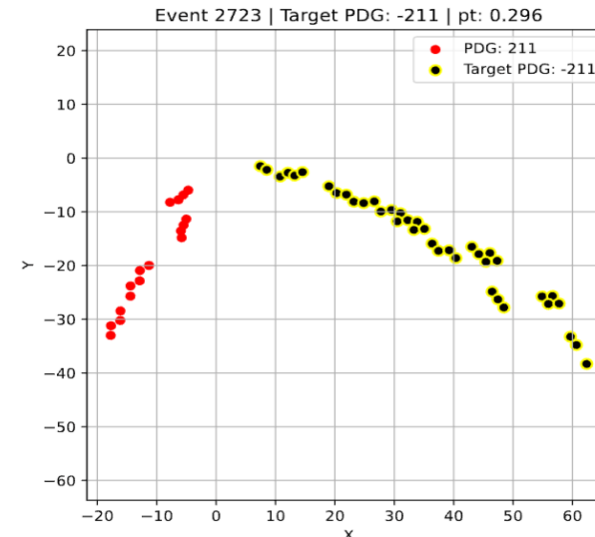
BESIII PATTSF



truth



OC clustering results

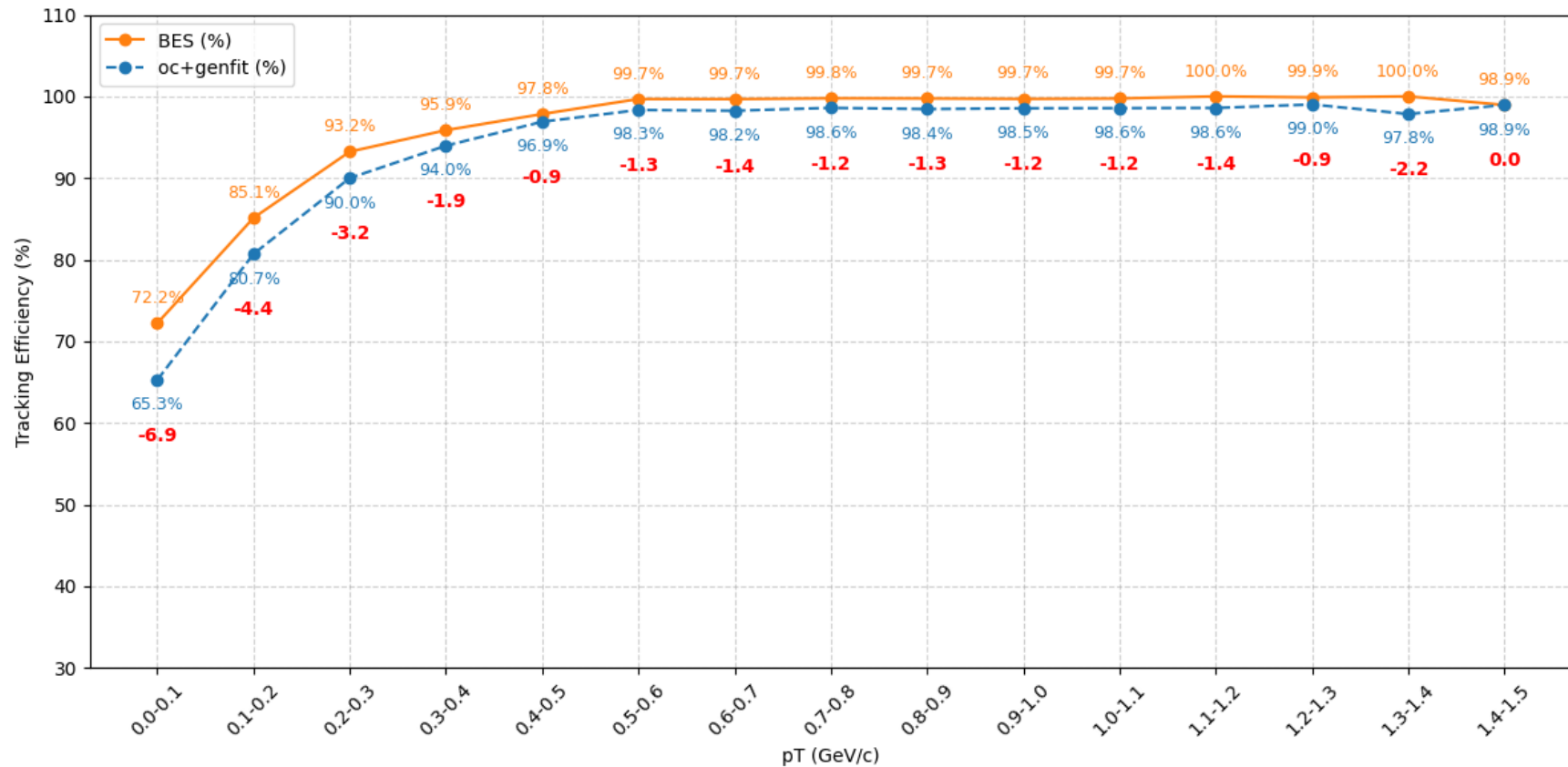


BESIII PATTSF

□ scattered track

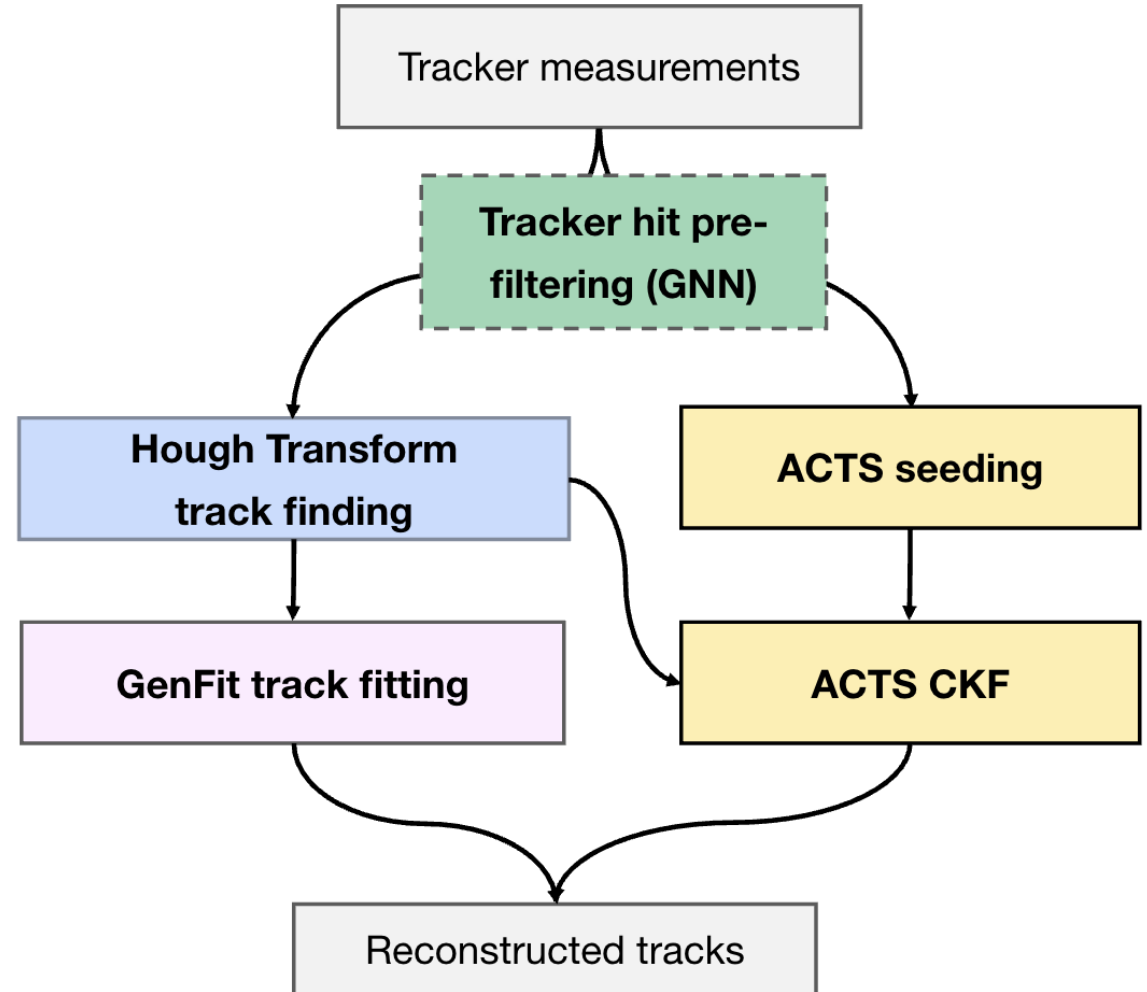
Current performance of OC+Genfit

- ◆ On-going:
 - Data cleansing for training sample
 - Improve robust of fitting



STCF tracking software

- ◆ Hough transform track finding
- ◆ Genfit track fitting
- ◆ GNN as hit prefiltering process
- ◆ ACTS:
 - ACTS seeding (combined with Hough)
 - ACTS CKF



Graph construction at STCF

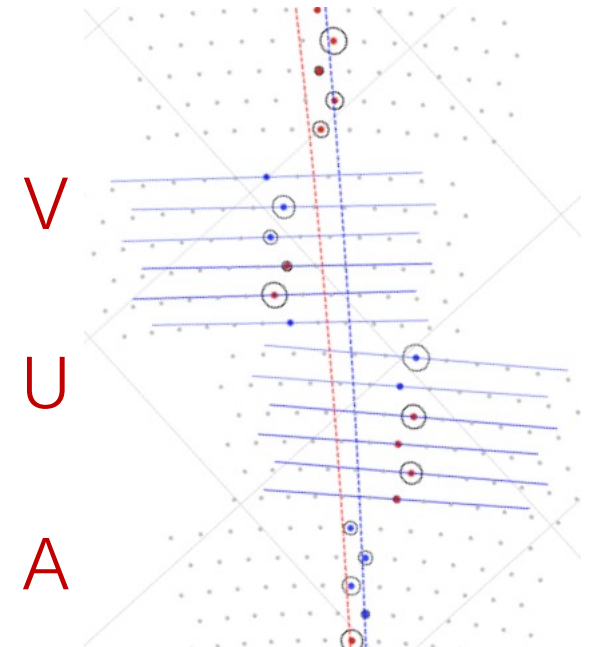
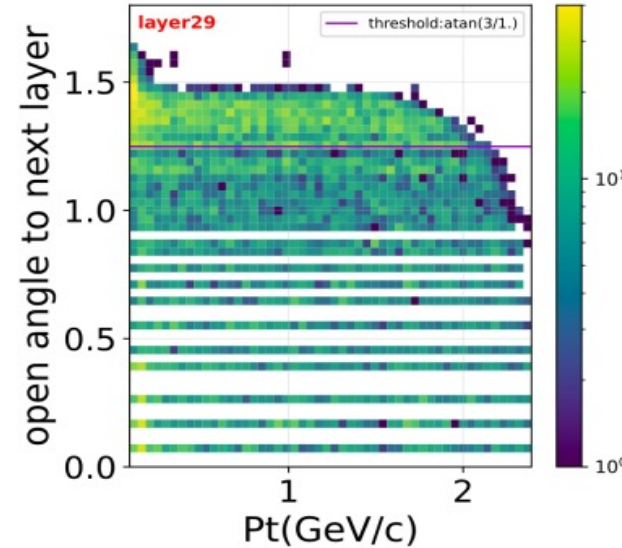
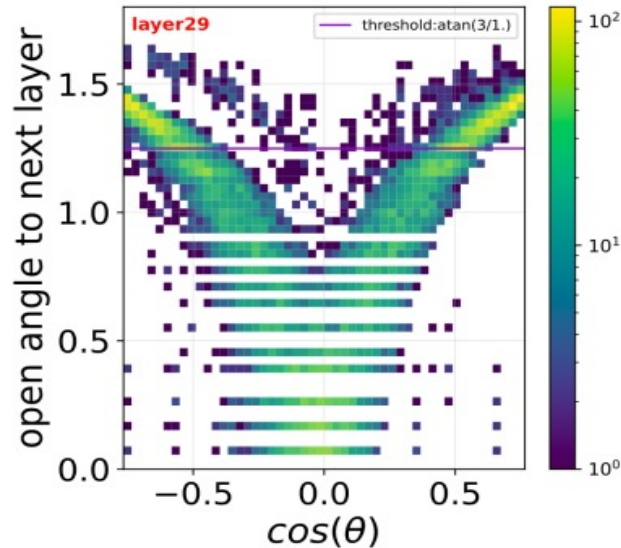
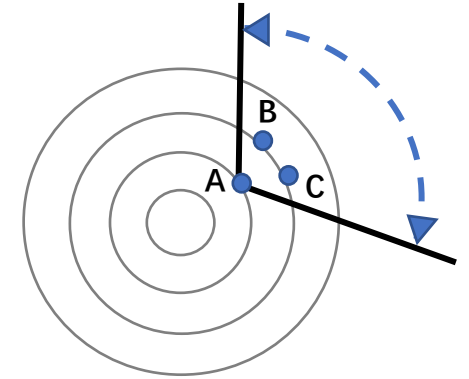
Geometric cut at STCF

◆ Edge assignment

- Hit and two adjacent hits on the left and right sides (same layer)
- Within a certain opening angle (the next layer and one layer apart)
- The junction of U-V superlayers (layers 11 and 29) appropriately amplify the threshold

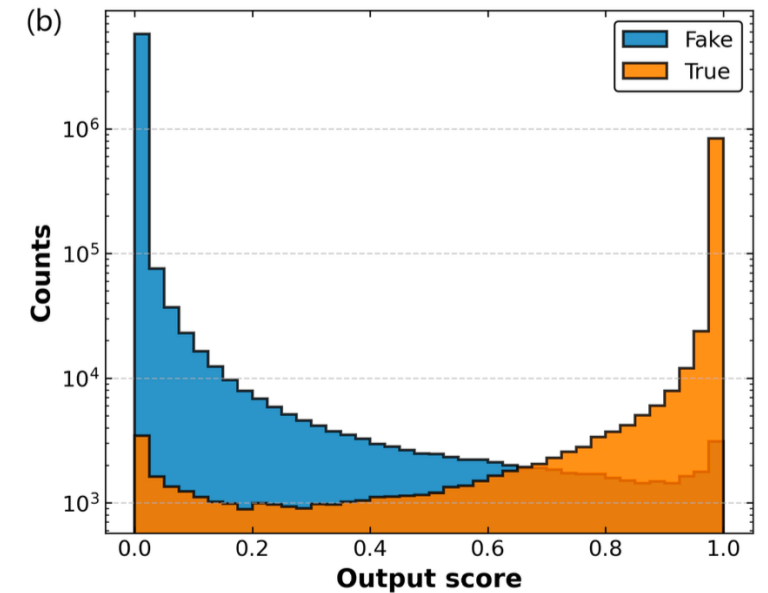
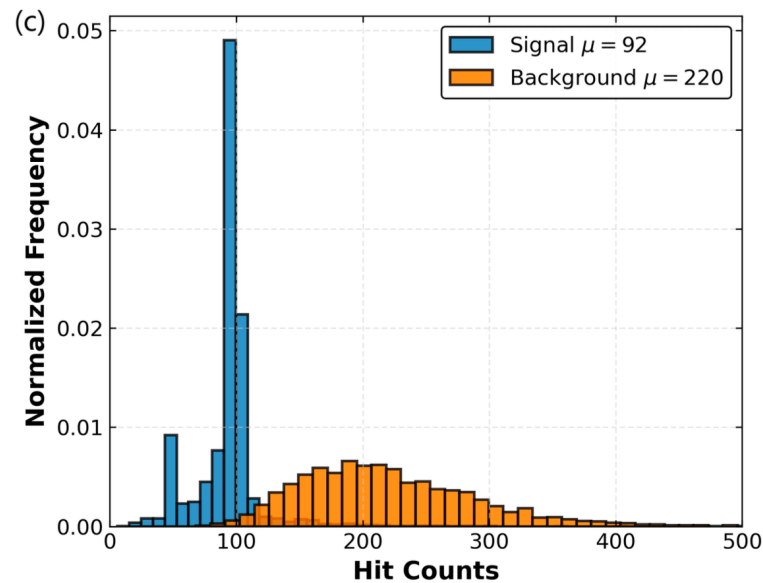
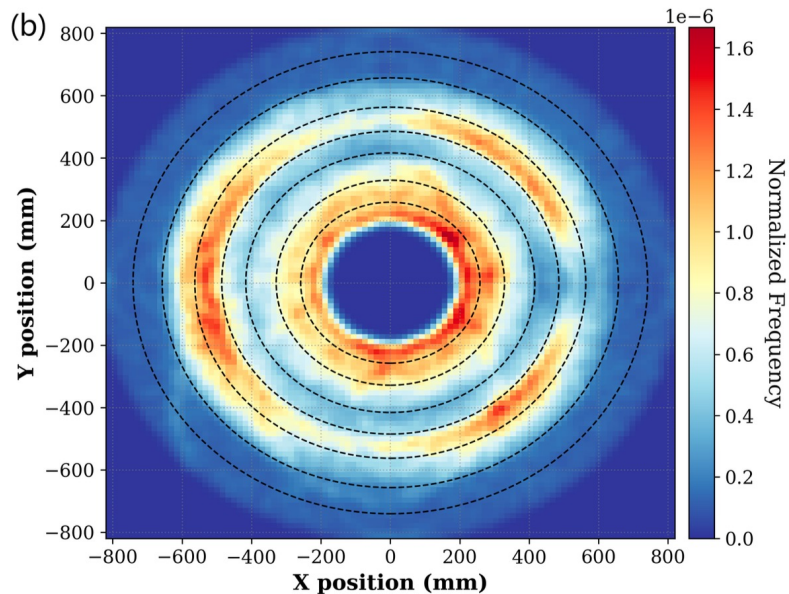
◆ Graph representation

- Node features (raw time, position coordinates r , ϕ of the sense wires), adjacency matrices, edge labels



Performance of noise filter

- ◆ PHSP $J/\psi \rightarrow \rho^0 \pi^0 \rightarrow \gamma \gamma \pi^+ \pi^-$
- ◆ Noise rejection rate of 86.8% while maintaining 98.2% signal selection efficiency

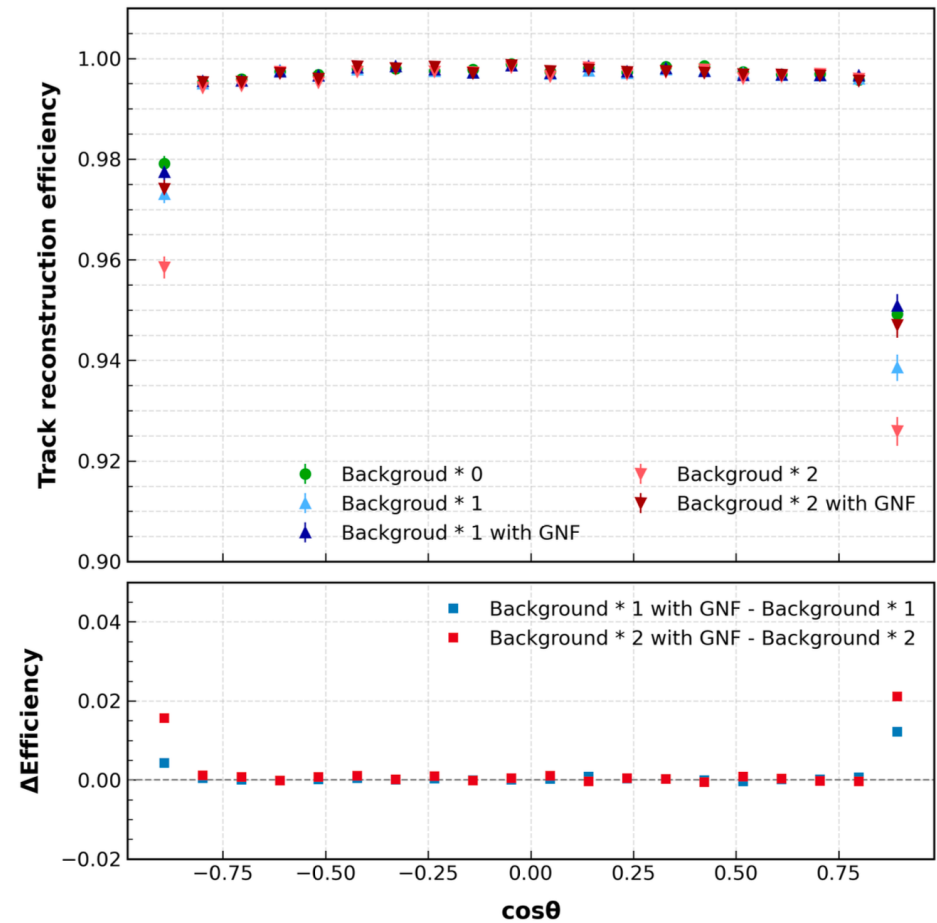
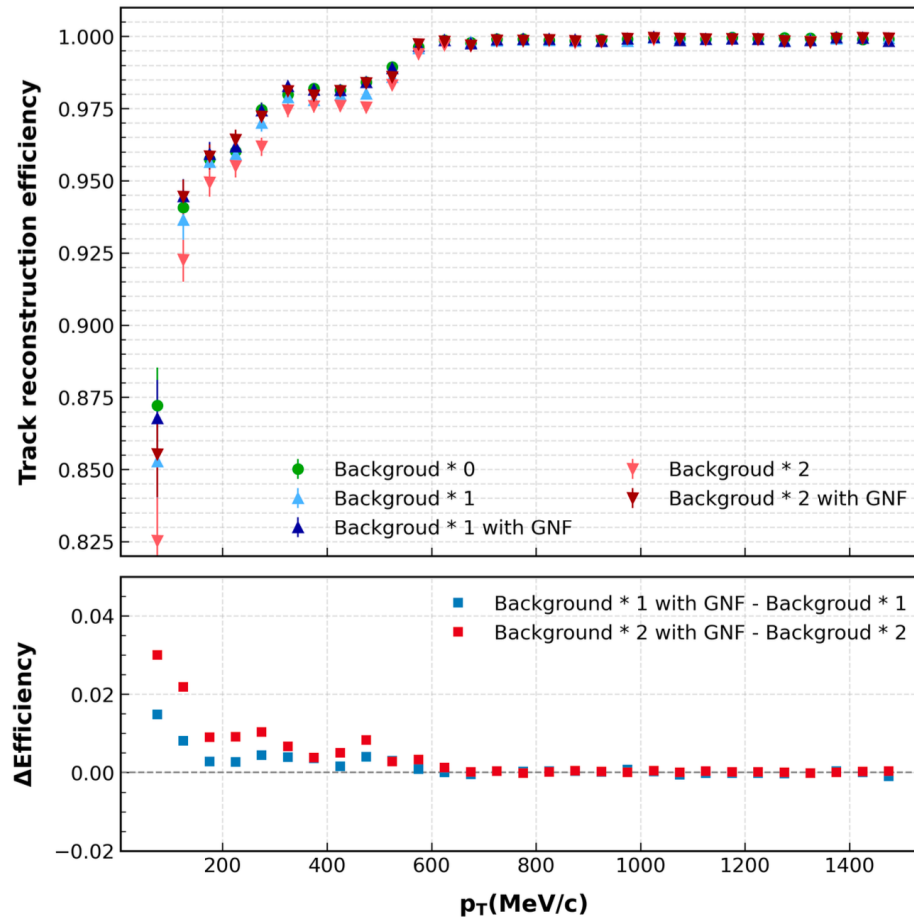


Noise hit distribution

Tracking performance after noise filter

- ◆ Oscar version 2.6.0; PHSP $J/\psi \rightarrow \rho^0 \pi^0 \rightarrow \gamma \gamma \pi^+ \pi^-$
- ◆ Improve tracking efficiency with GNF, especially for tracks near MDC boundary.
- ◆ Reduce fake track rates.

arxiv:2507.09224



Summary

- ◆ A novel tracking algorithm prototype based on machine learning method for BESIII/STCF is under development
 - GNN to distinguish the hit-on-track from noise hits.
 - Clustering method based on DBSCAN and RANSAC to cluster hits from multiple tracks
- ◆ Preliminary results on MC data shows promising performance
- ◆ Outlook
 - Further optimization: circular, scattering..
 - Performance verification concerning events with more tracks and long lived particle
 - Check the reconstruction time consumption

Thank you!

backup

Z regression and 3D clustering

- ◆ GNN regression for z coordinate prediction
 - structure similar as edge classification GNN
 - Lost function:
 - averaged distance between predicted and real position
- ◆ Clustering:
 - 3D parameter space: $\sin\alpha$, $\cos\alpha$, z/r

