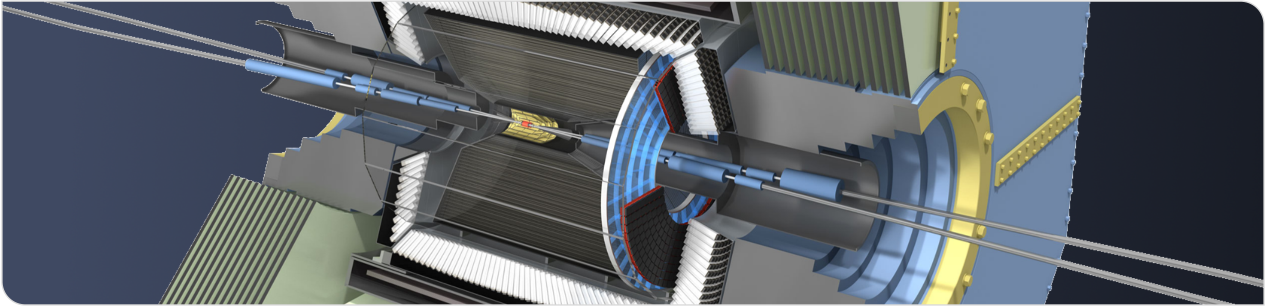
GNN-based Track and Vertex Finding

Belle II Trigger Workshop

Lea Reuter, Philipp Dorwarth, Slavomira Stefkova, Torben Ferber | 30th November 2022



Project members: Machine Learning for Trigger

KIT (ETP)

L. Reuter, I. Haide, P. Dorwarth,
P. Ecker, G. Heine, S. Stefkova, T. Ferber

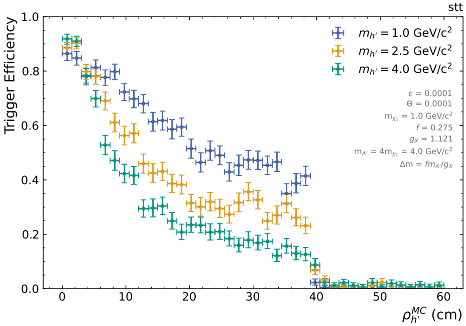
KIT (ITIV)

M. Neu, K. Unger, J. Becker

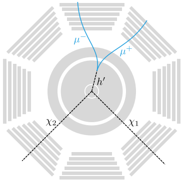
MPI (MPP)

E. Schmidt, F. Meggendorfer, C. Kiesling

Motivation



Credit: Patrick Ecker



Searches for displaced vertices

- Displaced vertices important signature in searches for new physics
- Example signal decay with dark photon A' and dark higgs h'

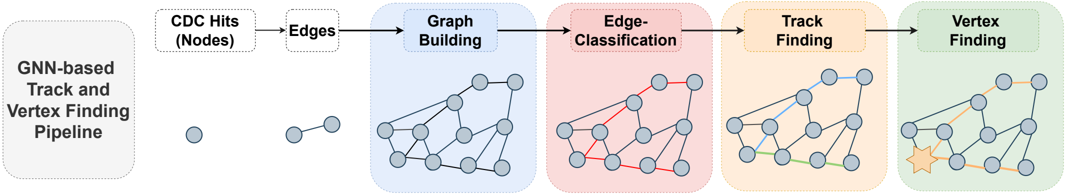
$$e^+e^- \to A'h',$$
$$h' \to \mu^+\mu^-,$$
$$A' \to \chi_1\chi_2,$$
$$\chi_2 \to \chi_1 e^+e^-$$

Challenge:

- Tracks with displacement larger than 40 cm are currently not triggered by **S**ingle **T**rack **T**rigger (stt)
- stt reconstruction efficiency decreases depending on displacement

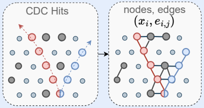
Approach with Graph Neural Networks

Variable number of CDC hits $\rightarrow$ utilize Graphs and Graph Neural Networks (GNN)

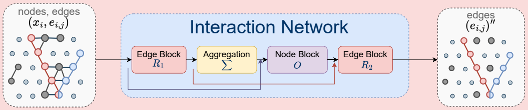


Approach with Graph Neural Networks

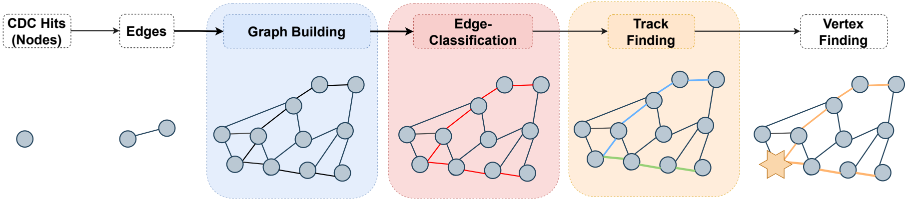
- Efficient and fast graph building needed



- Cleanup beam-background with **Interaction Network** (arxiv:2112.02048)



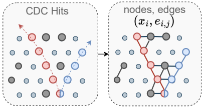
GNN-based Track and Vertex Finding Pipeline



- Find tracks using **Object Condensation** (arXiv:2002.03605)
- **Goal**: predict Track Fitting parameters and find condensation points

Approach with Graph Neural Networks: Track Finding

- Efficient and fast graph building needed



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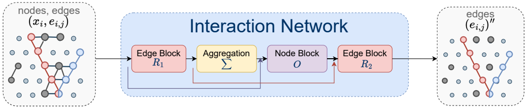

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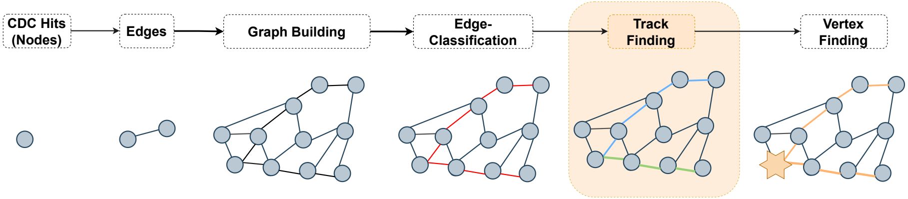

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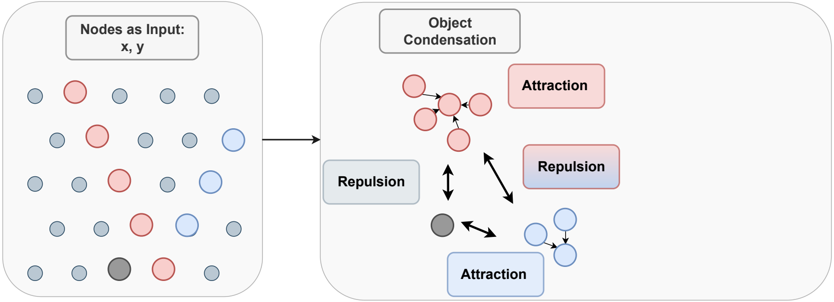
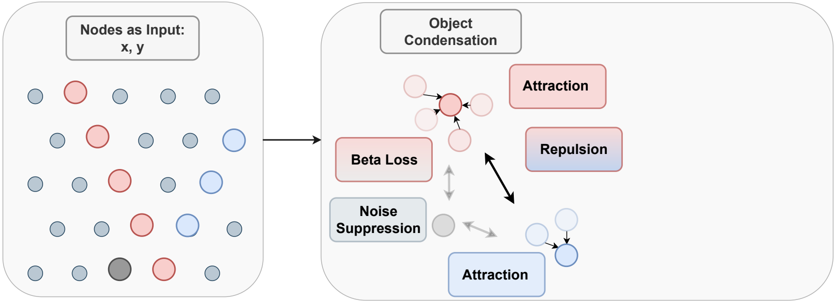
Object Condensation Track Finding Approach



→ Use nodes as input to Object Condensation (arXiv:2002.03605)

→ **Goal:** Find **unknown** and **variable** number of tracks and simultaneously predict track fitting parameters (momentum, displacement...)

Object Condensation Track Finding Approach



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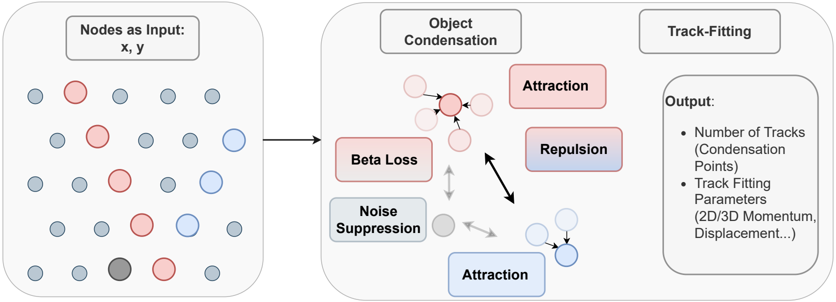

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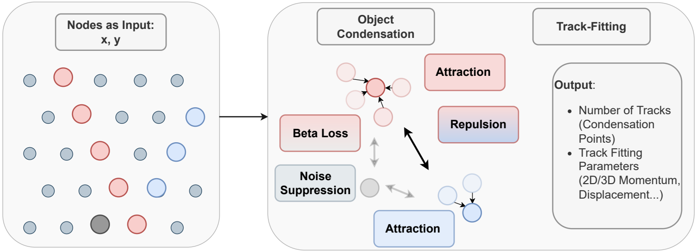
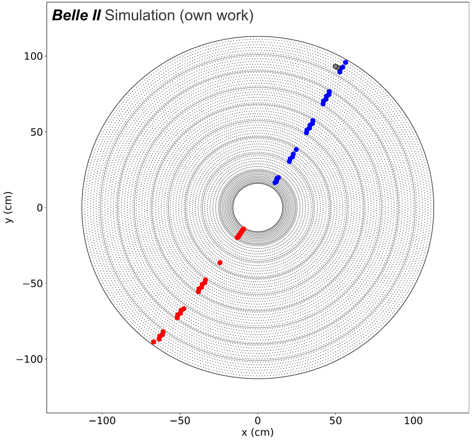


Start with a very simple case
$e^+e^- \rightarrow \mu^+\mu^-$ with no beam-background



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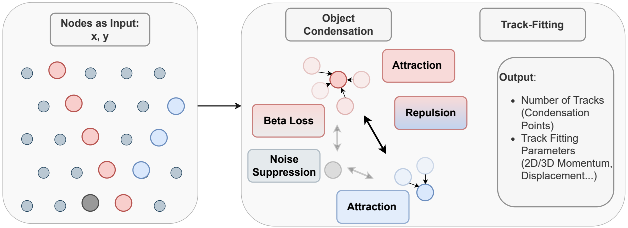
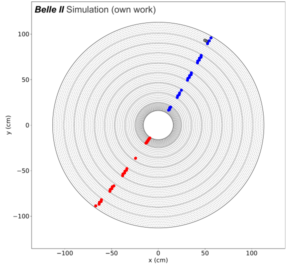
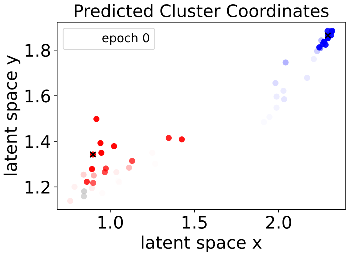
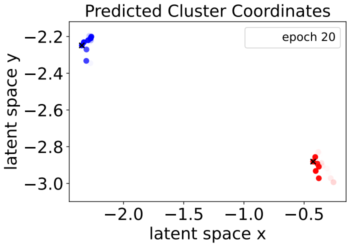
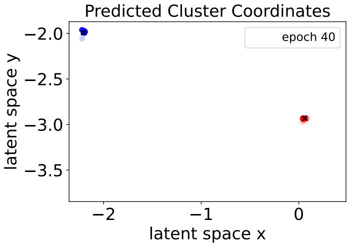
Object Condensation Track Finding Approach











Object Condensation Track Finding

More realistic scenario:

Simulated samples:

- Between 1 to 3 μ^- and μ^+
- Starting with early-phase3 beam background conditions
- **Not** displaced
- $\theta = [30, 120]$ °, so within barrel CDC
- Transverse momentum $p_t = [0.3, 5]$ GeV
- Release: `feature/BII-9379-store-cdchit-relations-to-all-particle`
- Globaltags: `main_2022-01-27` and `patch_main_release-07`
- Starting with BGx0 and early-phase 3 BGx1
  `/group/belle2/dataprod/BGOverlay/early_phase3/release-05-01-15/overlay/phase31/BGx1/set0/`

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Training

- Trained on 12 000 samples (very small sample size, model not yet optimized)
- Input features per node: Only use **2D-information**
  CDC hit x, y position
- Predicting: **unknown** and **variable** number of tracks n_{tracks} and 3D-Momentum
  p_x, p_y, p_z

Object Condensation Track Finding

Karlsruhe Institute of Technology

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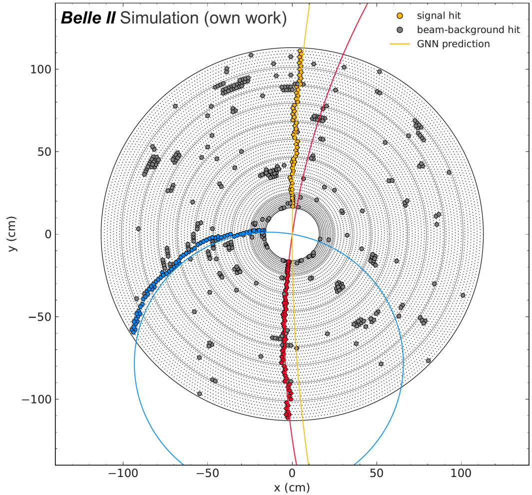
Assumption: Tracks starting at the Interaction Point, currently only momentum is predicted



Track Finding: Comparison with basf2

Evaluated on 30 000 samples with 1 to 3 particles (uniform distribution)

Found Tracks in Event	GNN (offline)[a]	TRGCDC2DFinderTracks	TRGCDCNeuroTracks	RecoTracks
Only signal tracks	91.5%	94.0%	93.8 %	90.6 %
Missing signal tracks	2.1 %	5.6 %	5.6 %	0.02 %
All signal tracks and additional tracks[a]	5.9 %	0.4 %	0.6 %	9.38 %
Missing signal tracks and additional tracks[b]	0.5%	0.01%	0.0 %	0.005 %
Per Track				
Efficiency	97.4%	94.4%	94.4%	99.98%
Precision	95.8 %	99.8%	99.7%	93.3%

- Efficiency $= \frac{n_{\text{SignalTracks},\text{pred}}}{n_{\text{SignalTracks},\text{truth}}}$
- Precision $= \frac{n_{\text{SignalTracks},\text{pred}}}{n_{\text{Tracks},\text{pred}}}$

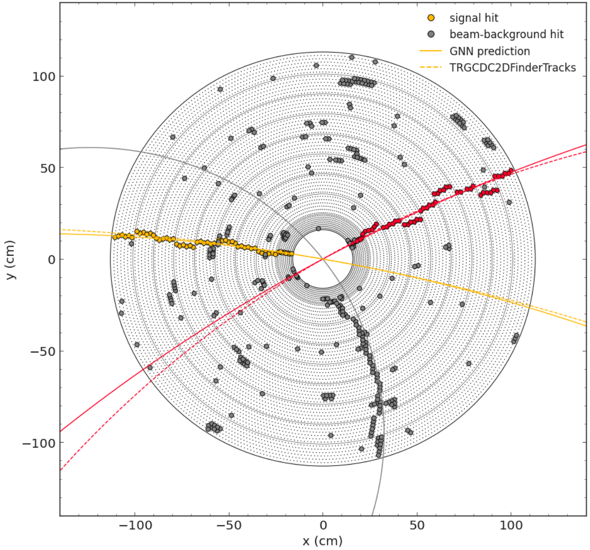
$\rightarrow$ **Why is the Precision nearly 100% and there are no beam-background tracks found for TRGCDC2DFinderTracks?**

[a]Not optimized mode, trained on small sample size
[b]additional tracks include beam-background (real tracks), fake and duplicate tracks

Track Finding: beam-background Tracks

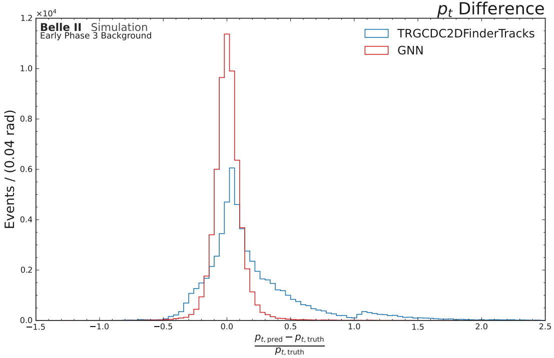
- Why is the TRGCDC2DFinderTracks not finding this beam-background track?
- Are there already event-time cuts applied?

→ Studies with Sally's beam-background overlays to distinguish between beam-background and fake tracks

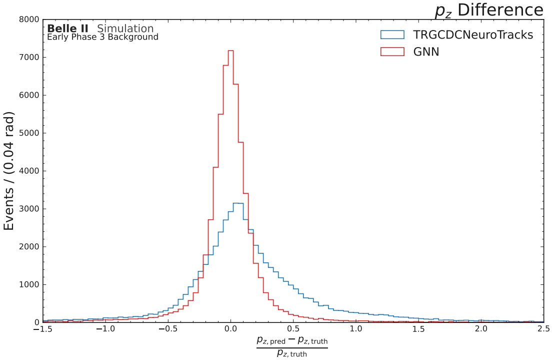


Track Finding: Resolution Comparison with L1 Trigger

GNN (offline) to L1 Trigger **TRGCDC2DFinderTracks** and **TRGCDCNeuroTracks** momentum resolution
Evaluated on 30 000 samples resulting in 60 000 Tracks



p_t resolution

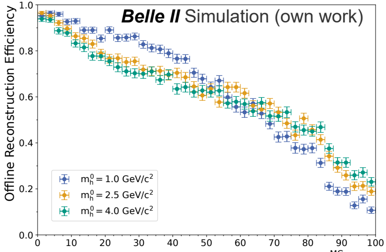


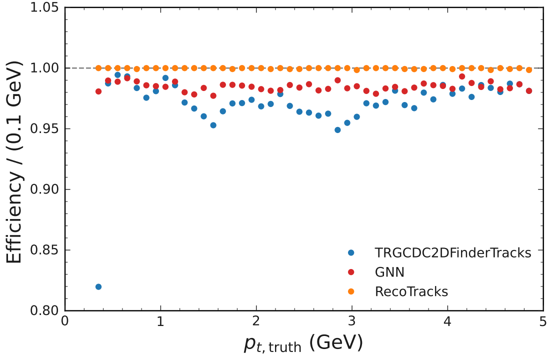
p_z resolution

Track Finding: Efficiency Comparison with L1 Trigger

GNN (offline) to L1 Trigger **TRGCDC2DFinderTracks** and offline **RecoTracks** (offline) efficiency
Evaluated on 30 000 samples resulting in 60 000 Tracks
1200 tracks per bin

For **offline reconstruction**, the challenge will be displaced tracks:

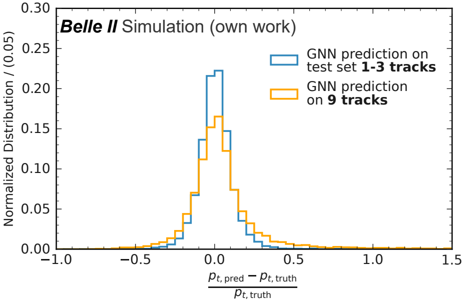




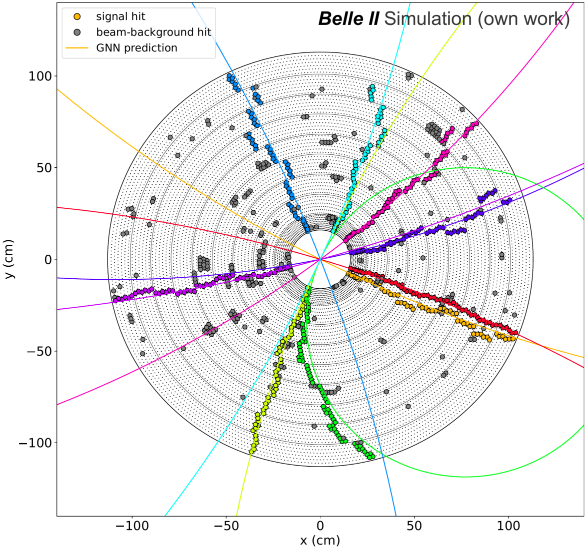
Efficiency per $p_{t,\mathrm{truth}}$

Track Finding: High Multiplicity Events

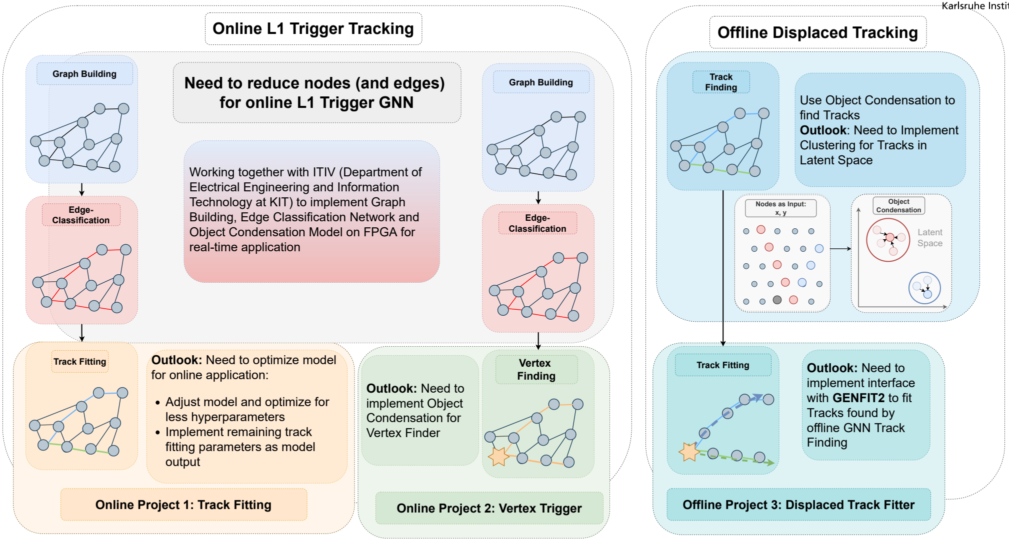
Object Condensation model is good in **generalizing**: Evaluation of previously trained model on high multiplicity events (9 particles)



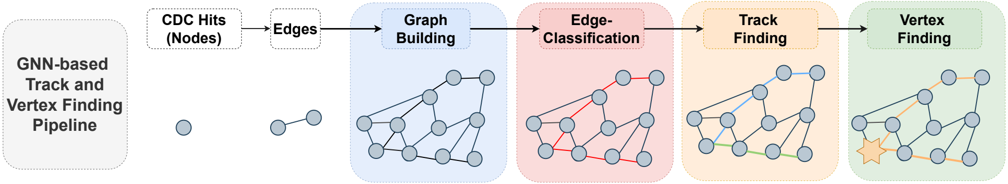
Promising results for GNN-based Tracking!

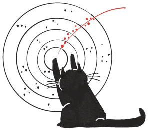


GNN Tracking Project Overview



Summary and Outlook





Current Status

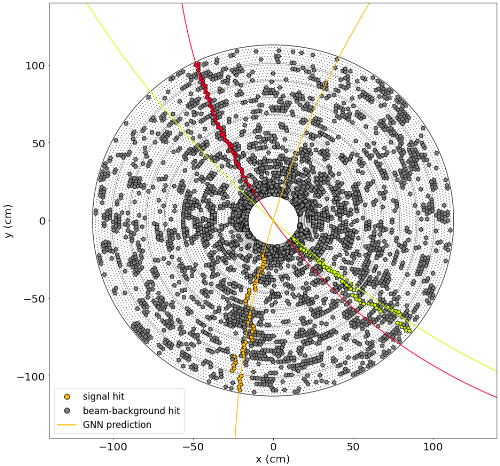
- Developing GNN-based Track and Vertex Finding Pipeline
- Performance measurement of different graph building methods and edge-classification
- Implemented Object Condensation for Drift Chamber Track Finding and testing on samples with current beam-background conditions

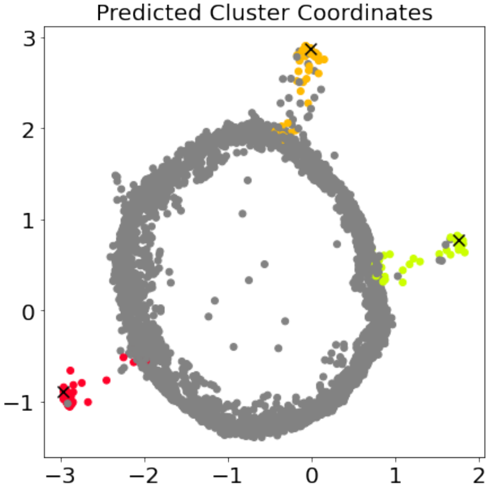
$\rightarrow$ **Have first full Track Finding and Fitting GNN model working**

Outlook

- Working together with ITIV (Department of Electrical Engineering and Information Technology at KIT) to implement Graph Building, Edge Classification Network and Object Condensation Model on FPGA for real-time application
- Extend Object Condensation to predict displaced tracks offline and online and develop Vertex Finding
- Evaluate Object Condensation on Data/MC for displaced vertex Example
  $e^+e^- \rightarrow \Phi\gamma,$
  $\Phi \rightarrow K_{S^0} K_{L^0}$

Track Finding: Nominal Beam-Background





Accessing basf2 Track Objects for Comparison Studies

TrackReconstructer=['TRGCDC2DFinderTracks', 'TRGCDCNeuroTracks'] per event:

- loop over tracks found by respective TrackReconstructer
- Relation with 'CDCTriggerSegmentHits'
- 'CDCTriggerSegmentHits' relation with 'MCParticle'
- track MC ID is equivalent to the most frequent number of MC IDs of the related track segments, else its classified as background
- Write out all tracks per event for each Track Reconstructor
- Track Properties are accessed by HelixObject
  foundmom=track.getMomentum(1.5)
  foundmom.Pt(), foundmom.Phi(), foundmom.Theta(), foundmom.X() ...

For offline RecoTracks:

- Loop over found 'RecoTracks'
- Relation with 'Tracks'
- Fit for Track: getTrackFitResultWithClosestMass(Belle2.Const.ChargedStable(211)) Pion Hypothesis
- Track Properties then accessed as above from the fit object