Graph Neural Network-based Algorithm for Track Finding in the CBM Experiment

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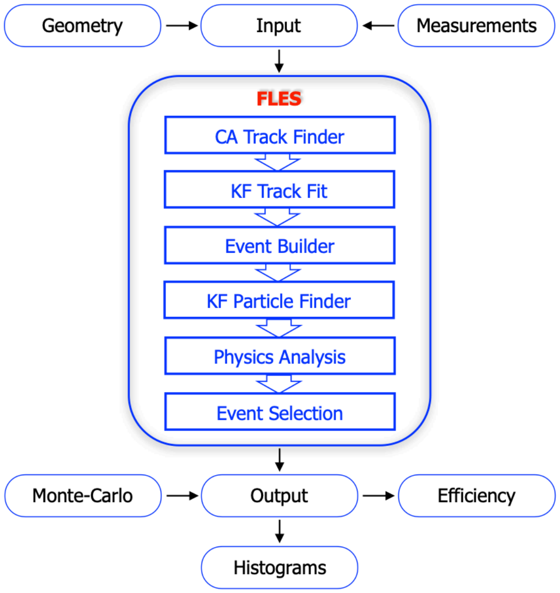
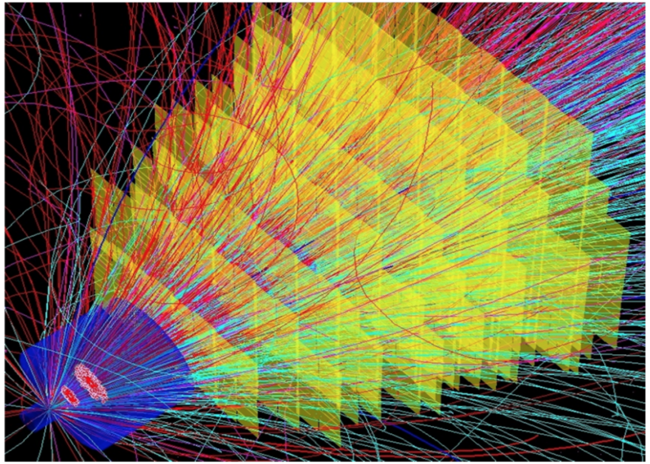
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
HFHF
GSI
FAIR
CBM

Compressed Baryonic Matter (CBM) Experiment

- **Goal:** Explore QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions
- Unprecedented **10MHz** event rate will allow study of rare events



Architecture of FLES



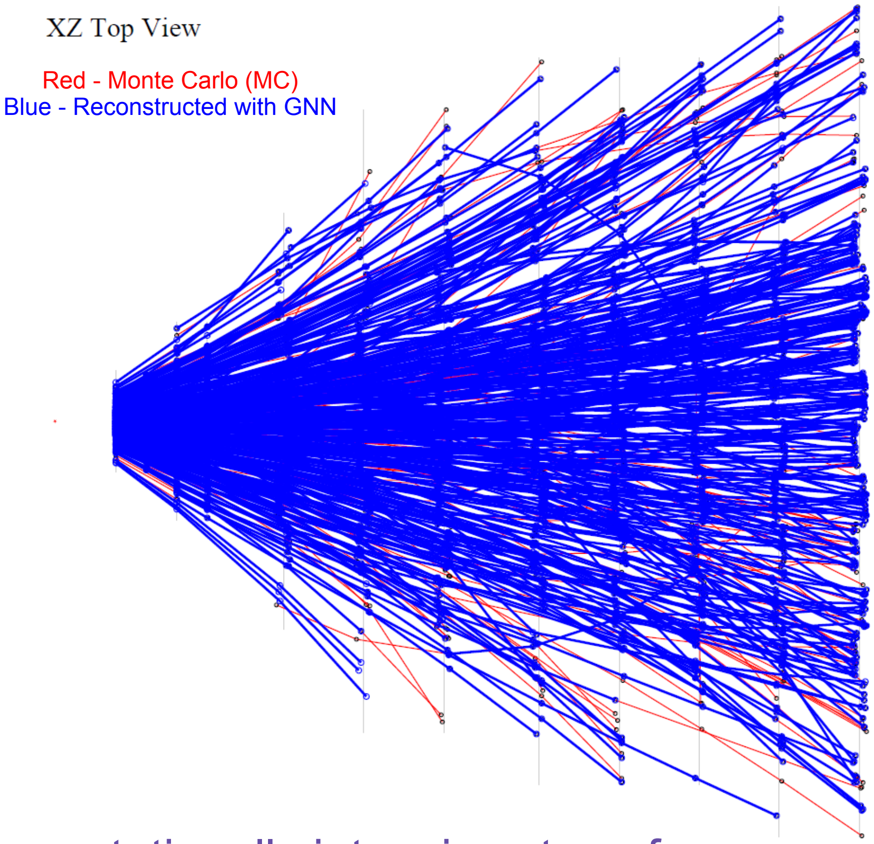
Tracks from central 25 A.GeV AuAu event with GEANT simulation of tracking stations

- **F**irst-**L**evel **E**vent **S**elector (**FLES**) is responsible for real-time reconstruction and filtering of events from continuous data stream. Fully software-based trigger.
- Requires **fast** and **high-precision** track finding algorithm

Track Finding

- Algorithm to group hits produced by one particle together
- Hits registered on two detectors
  - **M**icro **V**ertex **D**etector (**MVD**) - 4 MAPS stations
  - **S**ilicon **T**racking **S**ystem (**STS**) - 8 double-sided Silicon strip stations
- Both detectors lie in magnet allowing **1%** momentum resolution
- On average a 10A.GeV AuAu collision produces
  - *1000s* of charged particles
  - **~400** reconstructible tracks (≥ 4 hits)

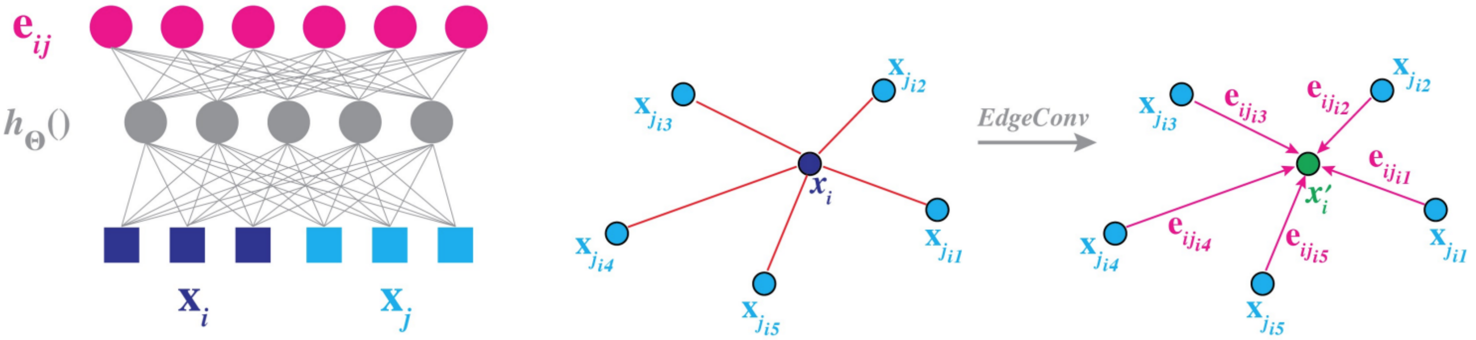
Event display for 10A.GeV Central AuAu



Track Finding is the most computationally intensive step of reconstruction

Graph Neural Network (GNN)-based tracking algorithm

We apply a custom **Graph Edge Convolution** message passing (similar to Kipf and Welling 2017)



Computing edge feature (left) and message passing via EdgeConv
Wang et al. 1801.07829

Our algorithm has the following features:

- Direct use of physics with **KF**
- Uses ensemble of **small, focused networks** rather than one big, black box
- Aimed at improving reconstruction of short-lived particles ➔ **Independent of Primary Vertex** (PV)

Broad steps of algorithm

1. **Sparse Graph Creation** with Metric Learning
2. **Doublet Filtering** via GNN
3. **Triplet** creation, fitting and filtering with KF
4. **Candidate Construction**, fitting and filtering with MLP Classifier
5. **Candidate Competition** with conditional strip exchange

Sparse Graph Creation - Metric Learning

- Train MLP with **hinge loss** to learn coordinate transformation ($\mathbb{R}^3$ to $\mathbb{R}^6$) where:
  - Hits from the same track clustered together
  - Different track clusters pushed apart

Cluster hits from same track

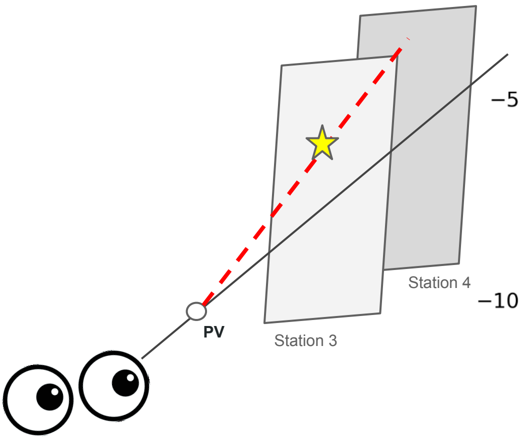
Margin

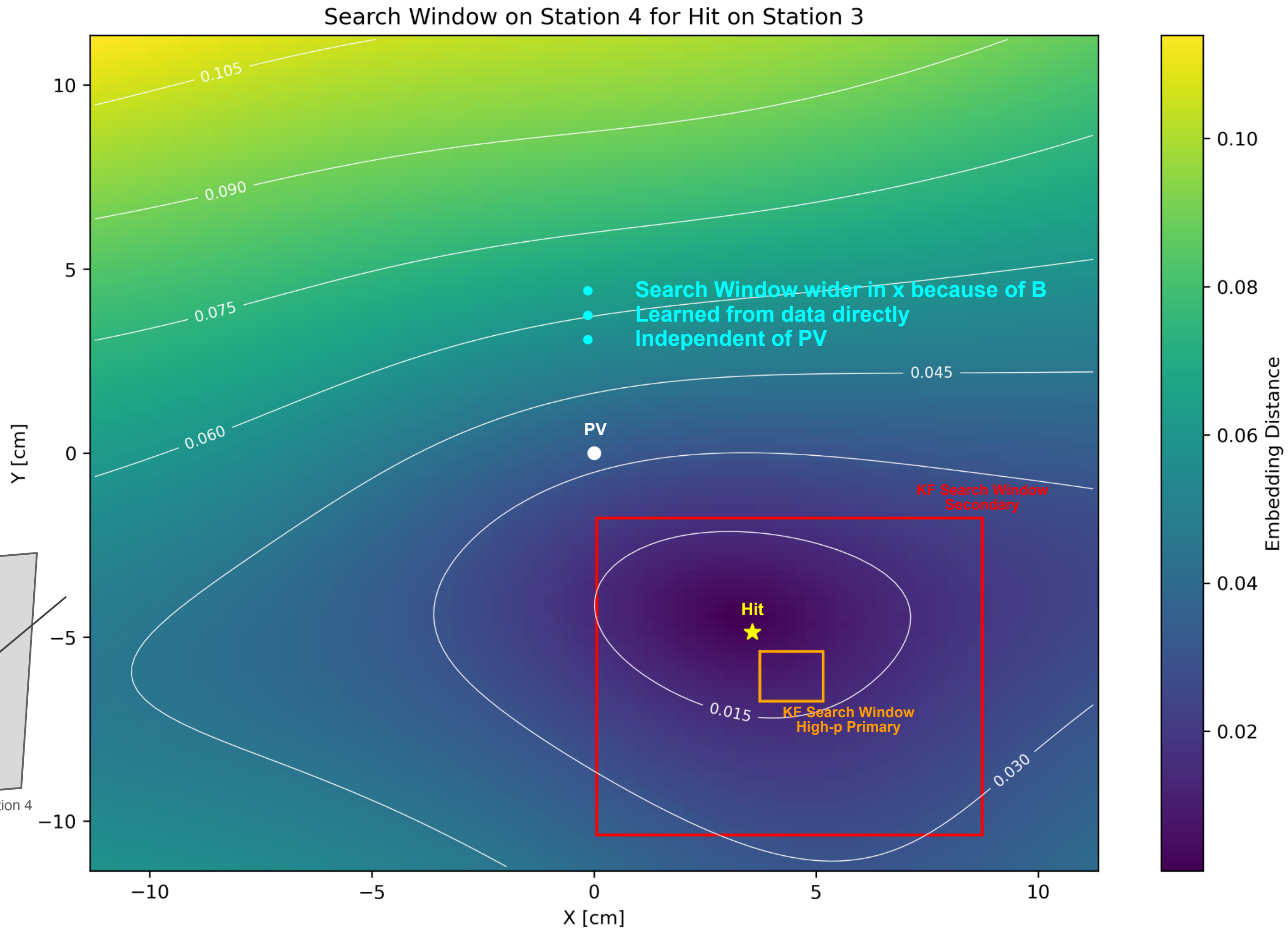
$$\mathcal{L} = \frac{1}{n_{true}} \sum_{true} d_{true}^2 + \frac{1}{n_{fake}} \sum_{fake} \max(\lambda - d_{fake}^2, 0)$$

Hits from different tracks pushed apart

Front-on View

Hits with lower embedding distance(blue) are ranked higher when creating doublets.
Compared with KF search window.

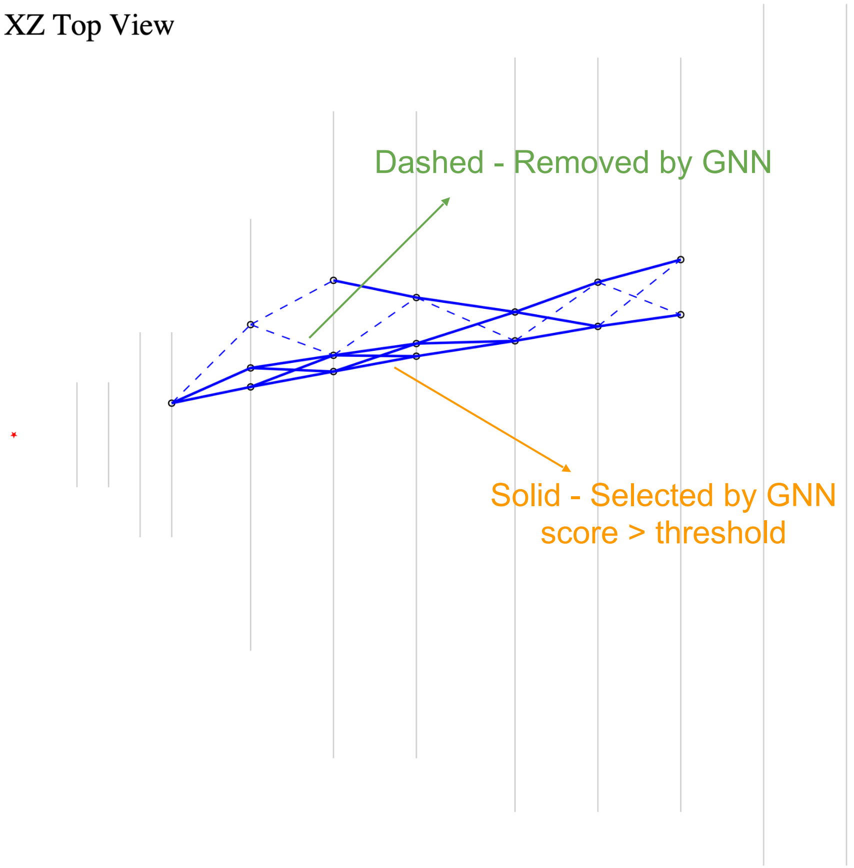




GNN - Filter Doublets

- Doublets created from **k-Nearest Neighbours** on learned distance are edges of graph
- GNN with custom **edge convolution** message passing
- All doublets with **score < threshold** are filtered out
- Trained on sparse graph created with metric learning (not random graph)

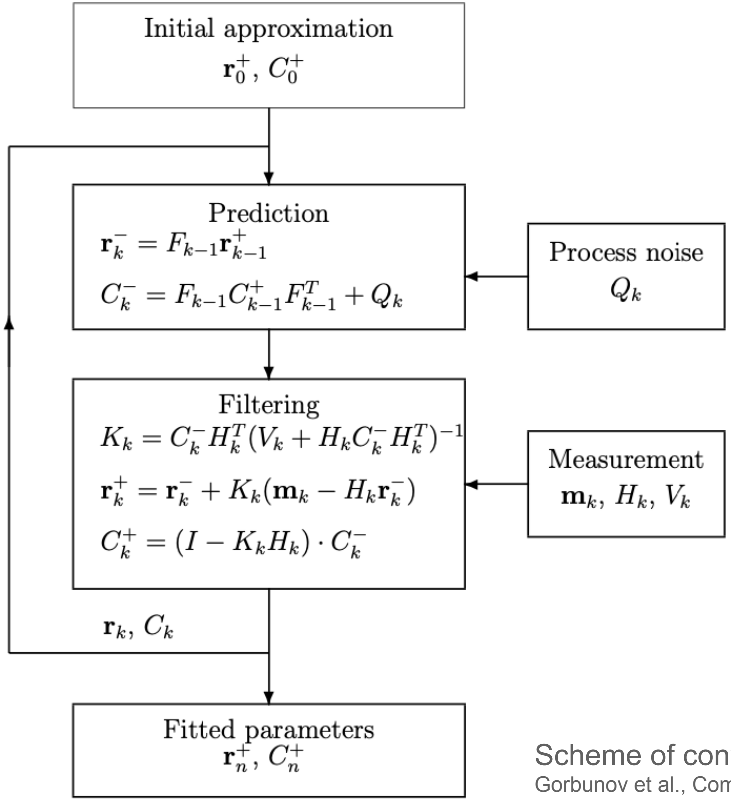
GNN filtering reduces triplet combinatorics significantly



Event display showing GNN filtering on small event

Kalman Filter (KF)

- Computes **unbiased mean** and **minimum covariance** parameters for the state of a linear system
- Minimizes **risk**
- **Recursive**: The state estimate becomes <u>independent</u> of initial estimate as observations are added

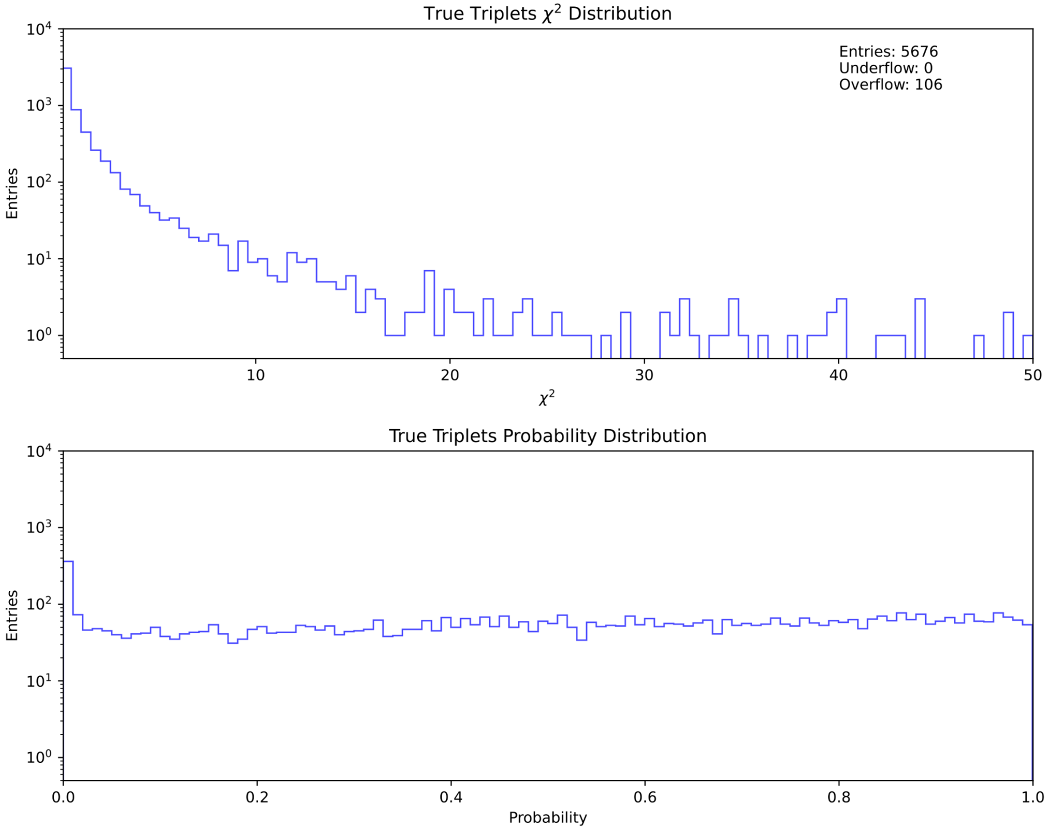


Scheme of conventional Kalman Filter.
Gorbunov et al., Comp. Phys. Comm. 178 (2008) 374

KF is an *<u>optimal</u>* linear estimator

Fit Triplets - KF

- Doublets sharing middle hit form **triplets**
- Triplets fit with KF to get track parameters
- A **fit quality measure χ^2** is defined using fit parameters and measurements
- Bottom shows probability that observed χ^2 exceeds the value χ^2 by chance, even for a correct model = 1 - cdf(x) where x is χ^2 -distributed
- Work only with triplets from this point onwards

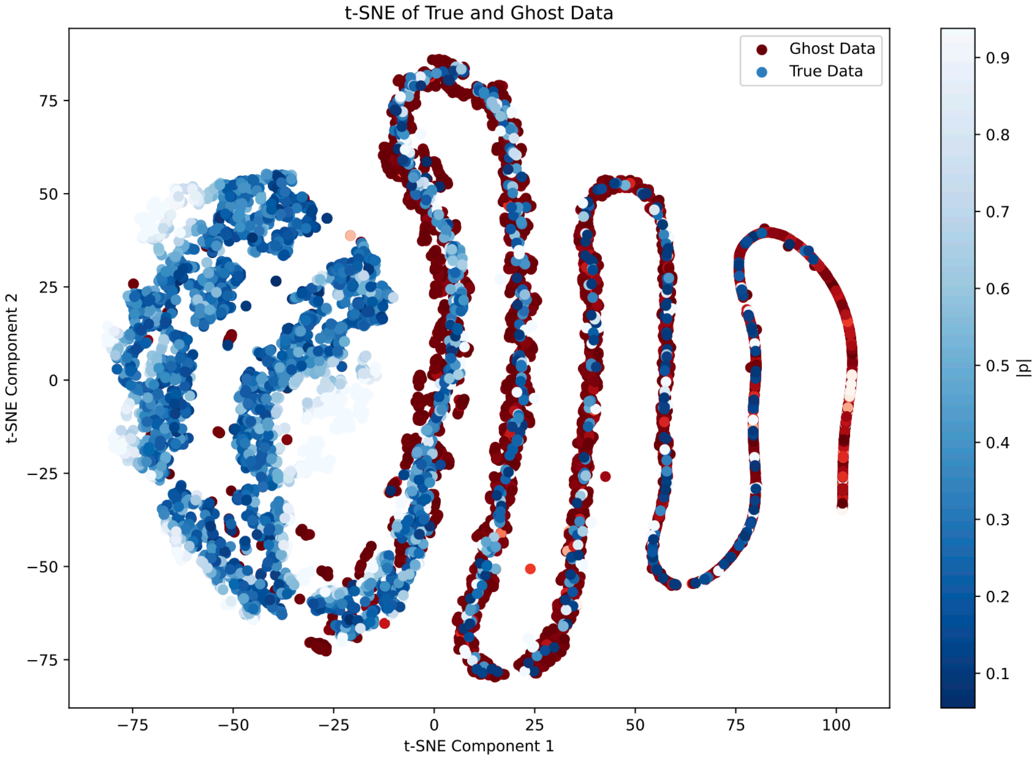


Flat probability distribution shows KF fit is correct

Track candidates and t-SNE analysis

t-SNE is a non-linear dimensionality reduction technique for visualizing complex data

- Overlapping triplets are combined to form **track candidates**
- Clones and ghosts dominate the set of track candidates created
- Fit track candidates with KF
- We train **MLP classifier** to filter out ghost candidates
  - 13 input features from KF fit
  - 3 hidden layers of width 32
- Candidates with score below threshold are removed from candidate pool



t-SNE shows perfect classification into true and ghost candidates is impossible

Track Competition

- We need to find true tracks from overlapping tree of filtered track candidates
  - Remove Clones - Multiple reconstructions of one true track
  - Remove Ghost - Tracks without corresponding true track

Algorithm

1. Track candidates **sorted** by length(longer) and χ^2 (smaller)
2. Iterate down sorted list and
   a. Add track to reconstructed list if all hits are on active strips
   b. If any hits are inactive
      1. Search among found tracks for one that uses strip
      2. If found track is longer and has higher χ^2 – Exchange strip ownership. Now both tracks are found
   c. Mark all strips of hits in track as inactive
3. Result is list of reconstructed tracks

This novel ‘***altruistic***’ competition scheme allows more shorter tracks to be reconstructed

New track competition method outperforms CA!

Results - Efficiency

Avg over 1k events
High-p: p > 1 GeV/c
Minimum 4 hits

Track Category	CA Efficiency (%)	GNN Efficiency (%)	Change (%)	N MC Tracks
All tracks	95.7	96.9	▲ 1.2	412
Primary high-p	99.1	99.2	▲ 0.1	232
Primary low-p	97.3	98.2	▲ 0.9	97
Secondary high-p	95.5	96.7	▲ 1.2	29
Secondary low-p	78.6	84.3	▲ 5.7	53
Clone level	5.1	5.1	▬ 0.0	-
Ghost level	2.2	2.9	▼ 0.7	-
MC tracks/ ev found	394/412	399/412	▲ 5	-

MC track is found if ≥70% hits of a reconstructed track match

Results for 10 A.GeV Central Au+Au collisions ➔ Most challenging reconstruction conditions

We show improvement over the CA Track Finder!

Results - Short-lived Particles

Particle	CA	GNN	Change (%)	Total MC
K^0_S	3553	3713	▲ **4.5**	4289
Λ^0	7222	7522	▲ **4.0**	8903

10 A.GeV Central AuAu
Avg over 1k events

- Count short-lived particles with both decay products reconstructed
- GNN finds **~4%** more short-lived particles compared to CA Track Finder
- Similar improvement expected for other decays

Summary

- Full Artificial Neural Network based algorithm implemented in CBMROOT using **ANN4FLES** package - No external dependencies!
- Improved overall track finding efficiency by **1.5%**
- Improved low-momentum secondary track efficiency by **6%**
- Improved S/B and reconstruction counts for short-lived particles

KEY REFERENCES:

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