CBM RICH RING RECONSTRUCTION USING MACHINE LEARNING

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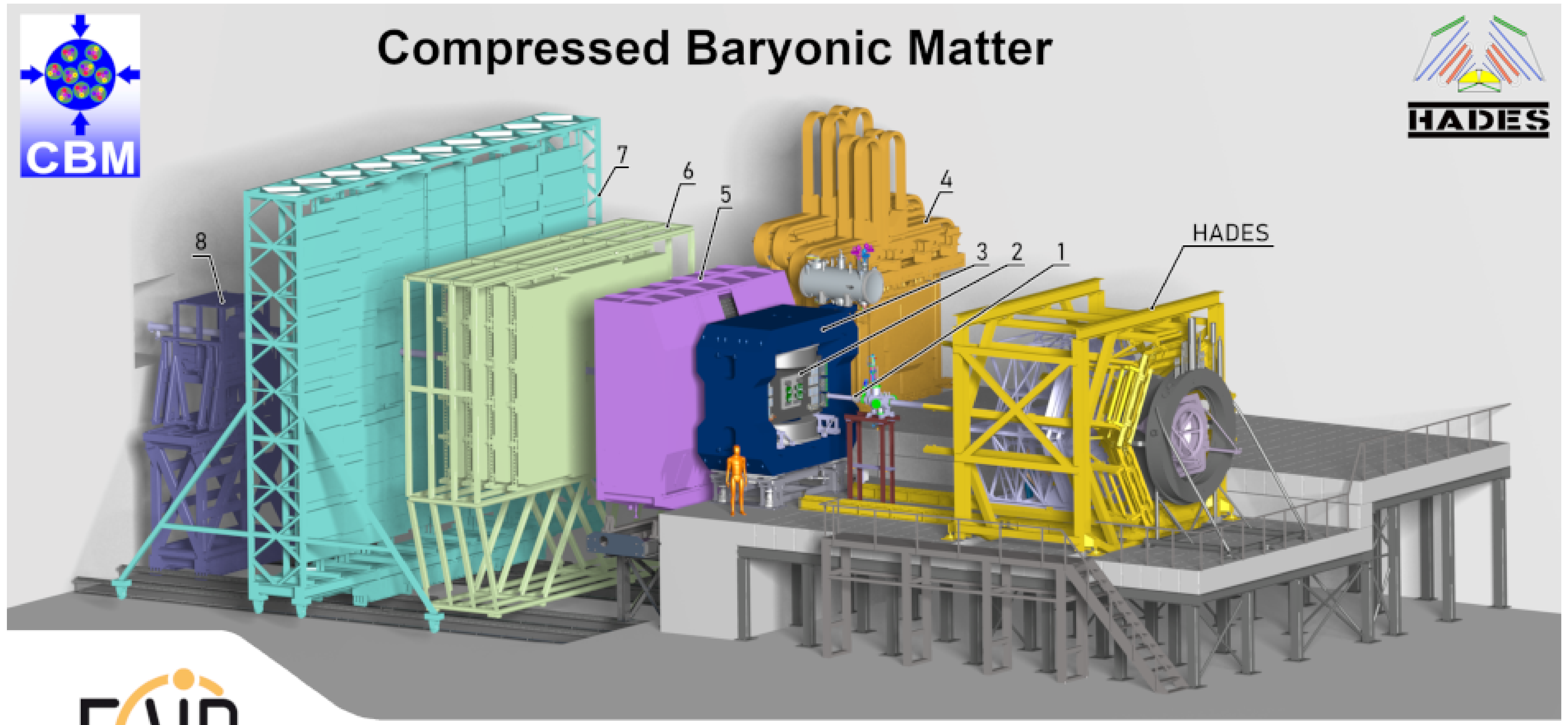
CBM RICH

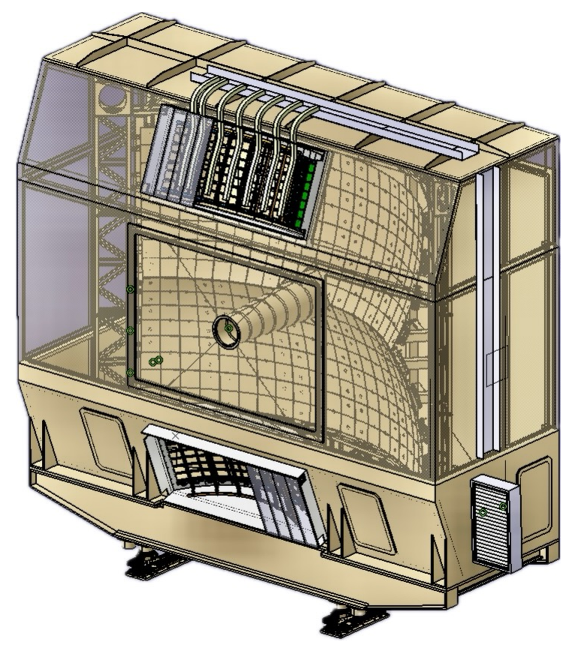


1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

FAIR GSI

Compressed Baryonic Matter (CBM) experiment

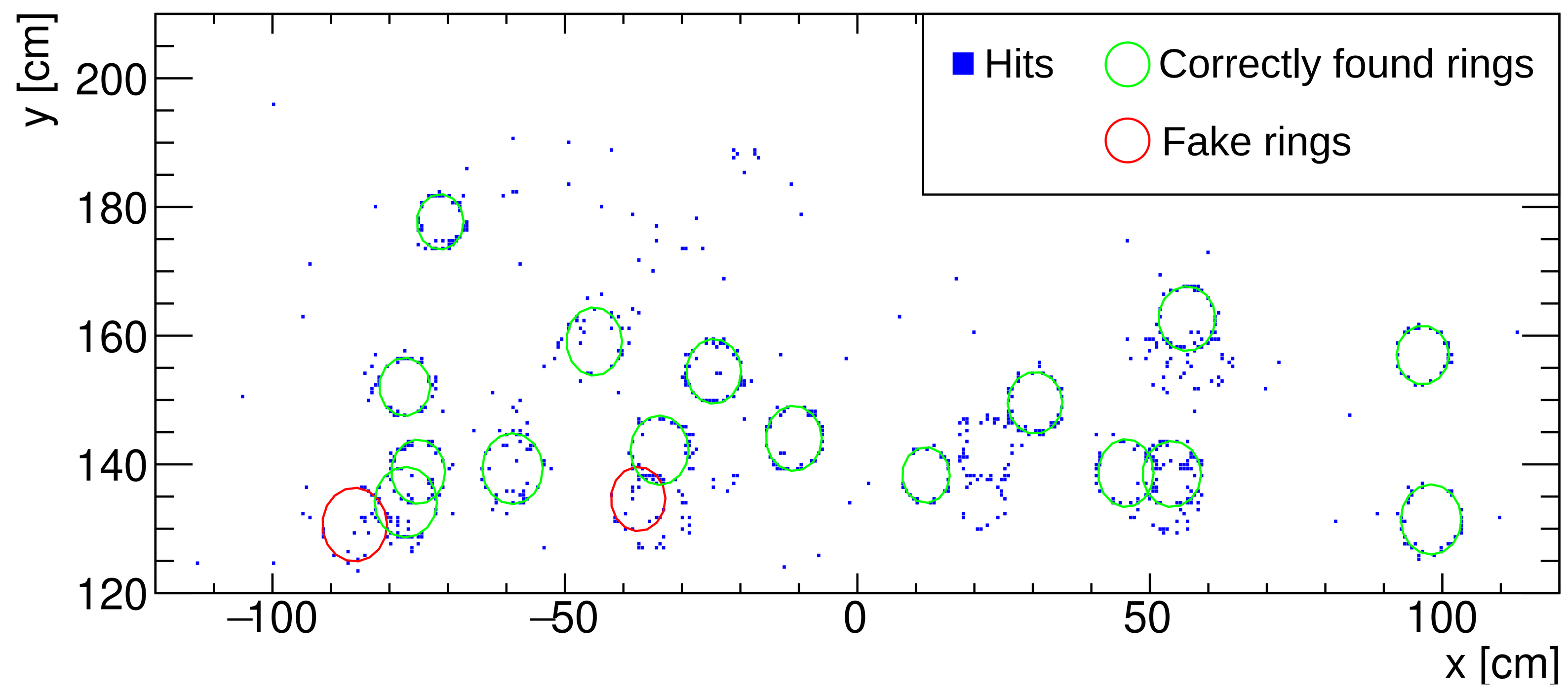
- High statistics heavy-ion fixed target experiment
- Interaction rates up to 10 MHz with SIS100 beam at FAIR energy range: Au from 2 to 11 AGeV, protons from 3 to 29 GeV
- Data acquisition via triggerless free-streaming readout
- Event selection in software by online reconstruction and trigger



Ring-imaging Cherenkov (RICH) detector

- Single-mirror focusing setup using a segmented spherical mirror design
- Two cylindrical shaped photodetectors for high-quality ring-imaging
- Equipped with 8x8 channel Hamamatsu H12700 multi-anode photomultiplier tubes
  → in total ~ 65,000 channels
- CO_2 as radiator gas
- Pion threshold of 4.65 GeV/c
- Provides electron/pion separation from lowest momenta up to 6 - 8 GeV/c with a pion suppression factor > 100

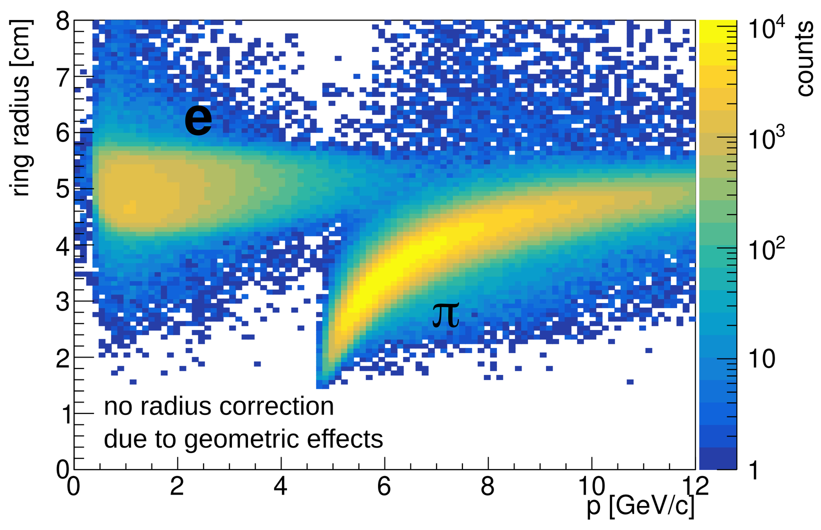
RICH ring reconstruction

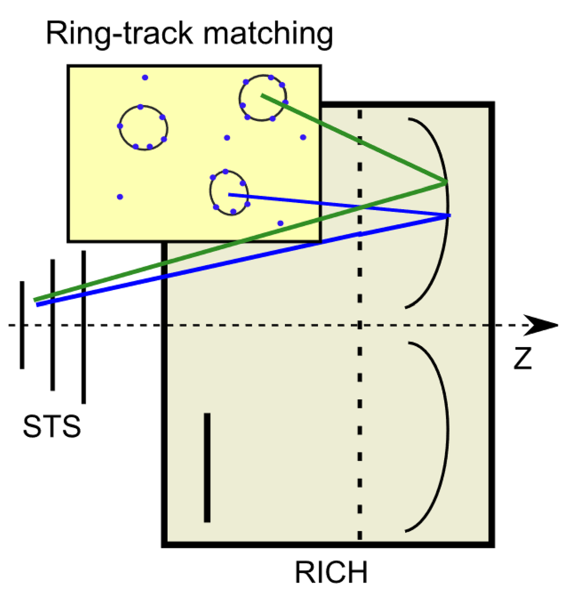


CBM RICH single-event-display of upper photo camera @ 11 AGeV Au+Au central. Rings shown are reconstructed using a circle Hough Transform ringfinder.

Ring reconstruction difficulties

- Rings with different sizes and number of hits
- Often with slightly elliptical ring structure
- Overlapping rings and noise
- Partial and smeared ring recognition
- Very crowded central region, with most pion rings located there
- Minimization of fake rings to reduce particle miss-identification





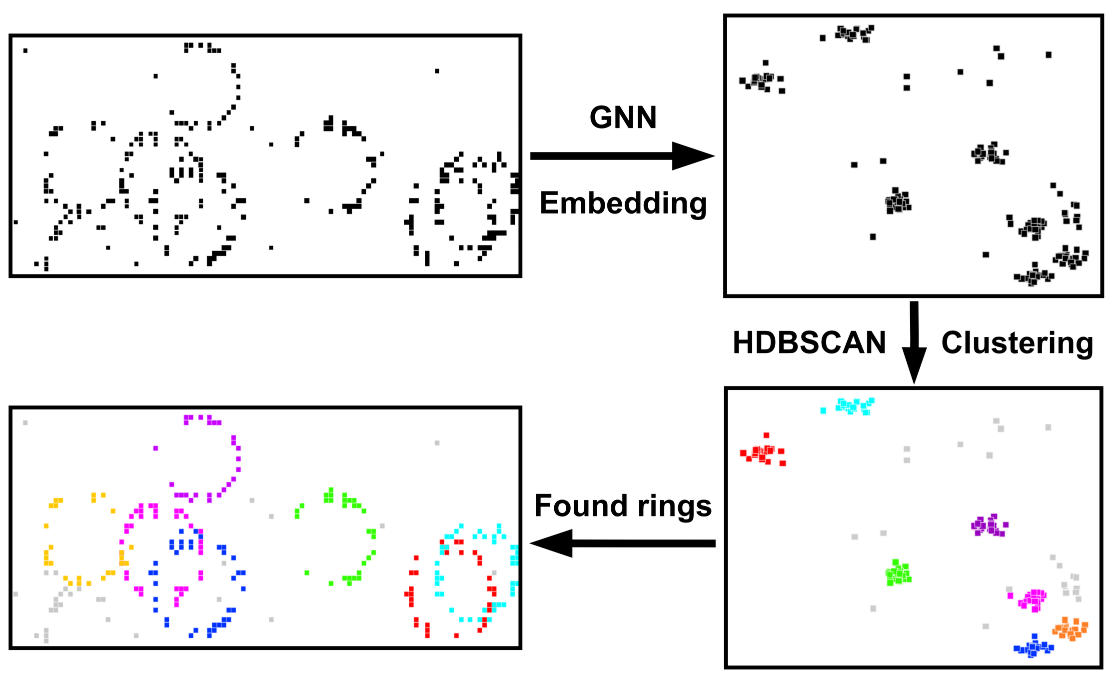
RICH particle identification

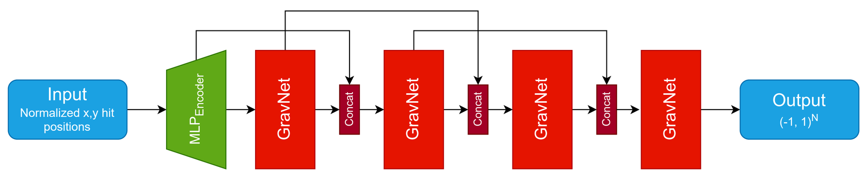
- Ring track matching by closest distance
  → Particle identification based on ring size
  → Requires precise ring centers and ellipse fit parameters
- On average for each 11 AGeV Au+Au central collision:
  – 350 track projections from Silicon tracking system (STS)
  – 40 secondary electrons (mostly without STS tracks) from photon conversions in material upstream of RICH
  – 9 pions
  – < 1 primary electrons (i.e. electrons from primary vertex)
  – Electron rings: 29 hits/ring, Pion rings: 20 hits/ring
  – 500-600 hits/photodetector

ML ring reconstruction chain

GNN + HDBSCAN ring reconstruction chain

- Transform hit point cloud to an embedding space, using a graph neural network (GNN)
- Clustering using HDBSCAN in the embedding space
- Ellipse fitting on found rings in the input space





- Input normalized hit positions → encoder multilayer perceptron
- GravNet GNN layers with dynamic edge construction
- Concatenate previous layer outputs via skip connections
- Output via tanh activation to N dimensional embedding space

- GNN trained supervised on 50,000 simulated 11 AGeV Au+Au central events
- Optimized with contrastive loss, idea: pull together hits from the same object and push apart hits from different objects.
  → Object separation in embedding space

Contrastive loss function

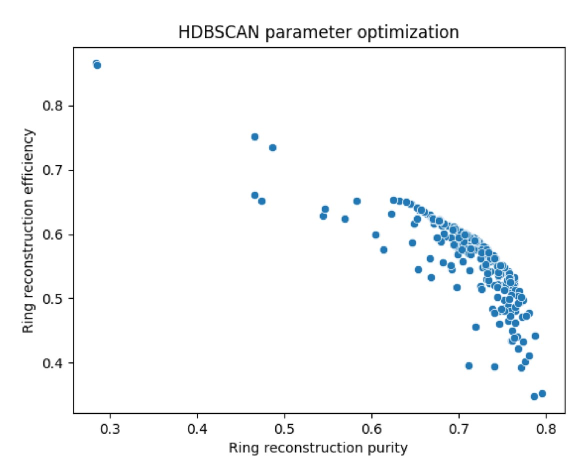
$$\text{Loss}_{\text{Total}} = \text{Loss}_{\text{Attraction}} + \text{Loss}_{\text{Repulsion}}$$

$$\text{Loss}_{\text{Att.}} = \frac{1}{N_{objects}} \sum_{k \in objects} \frac{1}{N^{(k)}_{hit\,pairs}} \sum_{i>j} d_{ij}^{2\,(k)} e_{ij} \qquad e_{ij} = \begin{cases} 1 & \text{, hit i and j from the same object} \\ 0 & \text{, otherwise} \end{cases}$$

$$\text{Loss}_{\text{Rep.}} = \frac{1}{N_{non\,zero\;entries}} \sum_{i,j \notin noise\,hit} max(-\log(d_{ij}), 0)^2 \, (1 - e_{ij})$$

HDBSCAN parameter optimization

- Crucial step to maximize efficiency and purity
- Use of Bayesian optimization, minimizing Loss = - (log(Efficiency) + log(Purity))



Efficiency calculation

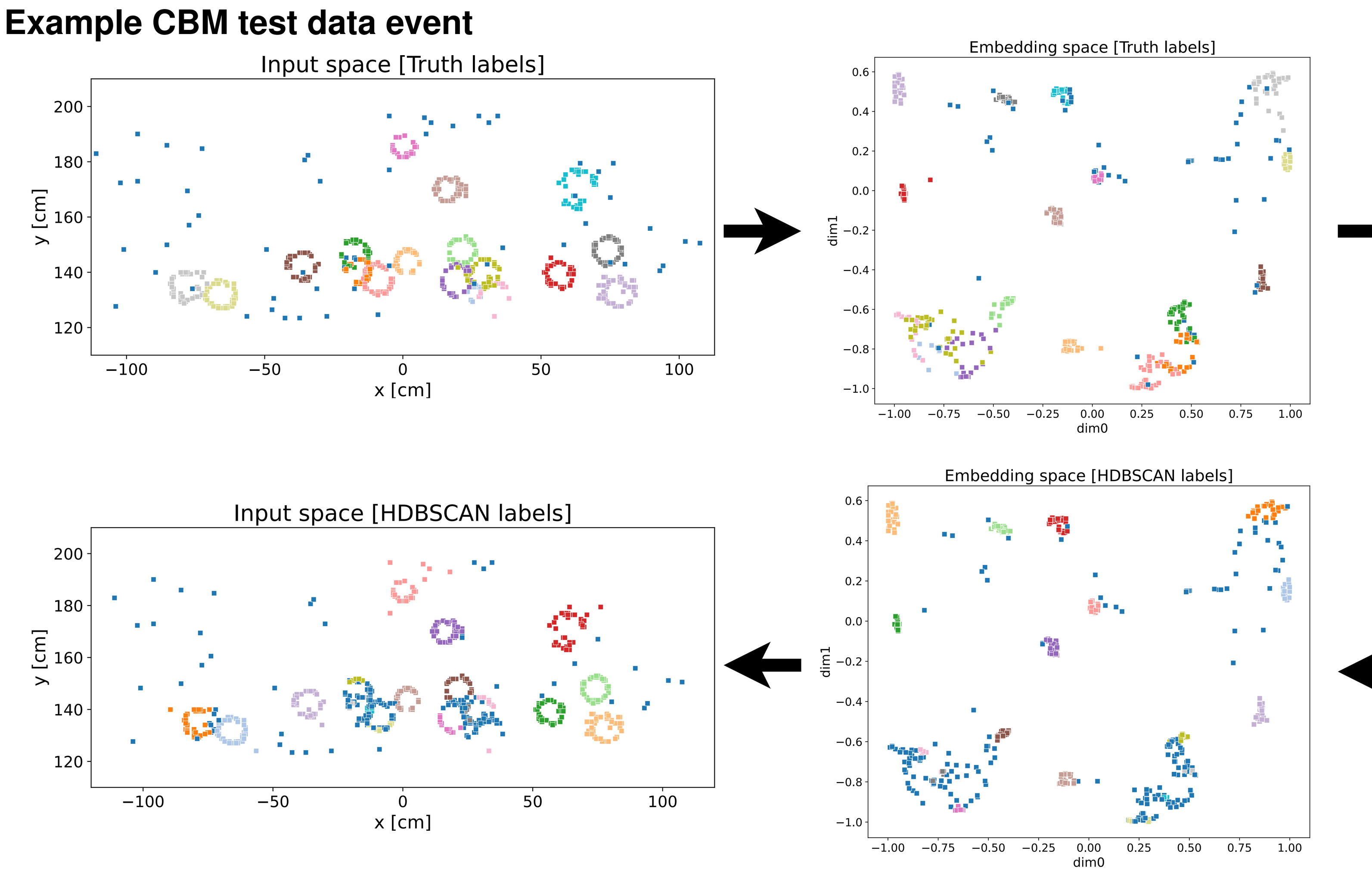
$$\text{Efficiency} = \frac{\#\text{True reconstructed rings}}{\#\text{Accepted rings}} \qquad \text{Purity} = \frac{\#\text{True reconstructed rings}}{\#\text{Reconstructed rings}}$$

Accepted ring: ≥ 7 hits from the same particle

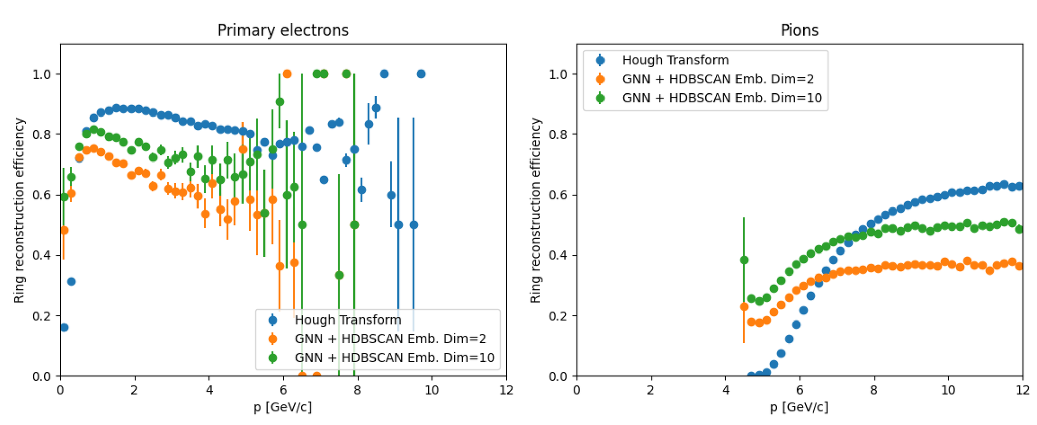
True reco. ring: $\geq 70\%$ of matched hits are from the same particle

Results

Example CBM test data event



11 AGeV Au+Au central collision event. GNN + HDBSCAN with embedding dimension of 2. (Truth labels shown for visualization)



	PrimEl Eff.	Pion Eff.	All Eff.	Purity
Hough Transform	**0.8565**	0.2524	0.5559	**0.8570**
GNN + HDBSCAN Emb. Dim=2	0.7196	0.2884	0.5470	0.7290
GNN + HDBSCAN Emb. Dim=10	0.7864	**0.3837**	**0.6197**	0.7288

GNN + HDBSCAN evaluated on 1/6 of the Hough Transform statistics (600k events)

Results on CBM simulation data

- GNN + HDBSCAN reconstruction chain already looking promising for (isolated) low momentum particles, i.e. smeared rings, more elliptical structures and rings with fewer hits
- Overlapping ring recognition is not performing well yet
- A larger embedding dimension does increase efficiency
- Overall, currently not yet competitive with the Hough Transform ringfinder, especially regarding purity

Outlook

- Improve GNN architecture and loss function
- Use global/local transformations
- Auxiliary noise classification downstream task
- Include hit timestamps

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