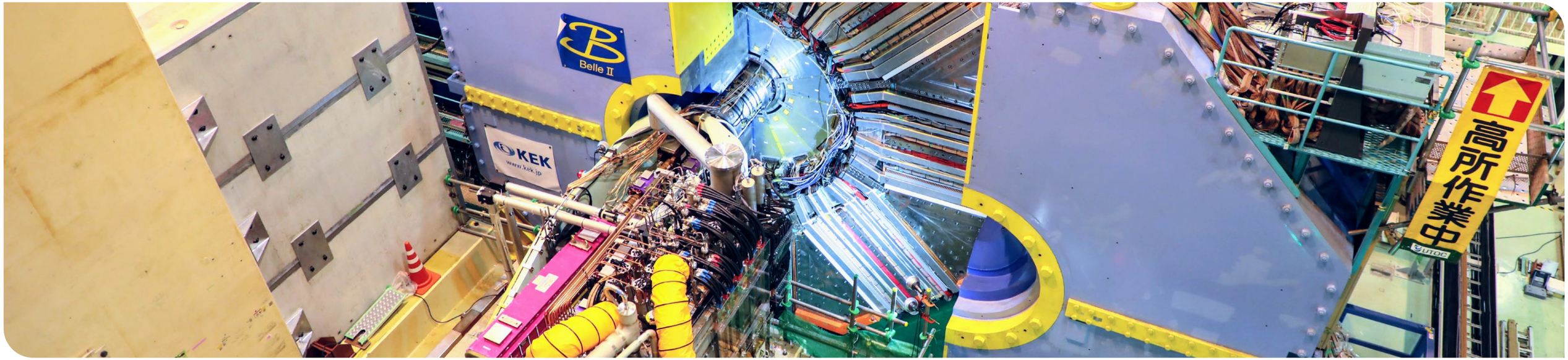
Karlsruhe Institute of Technology

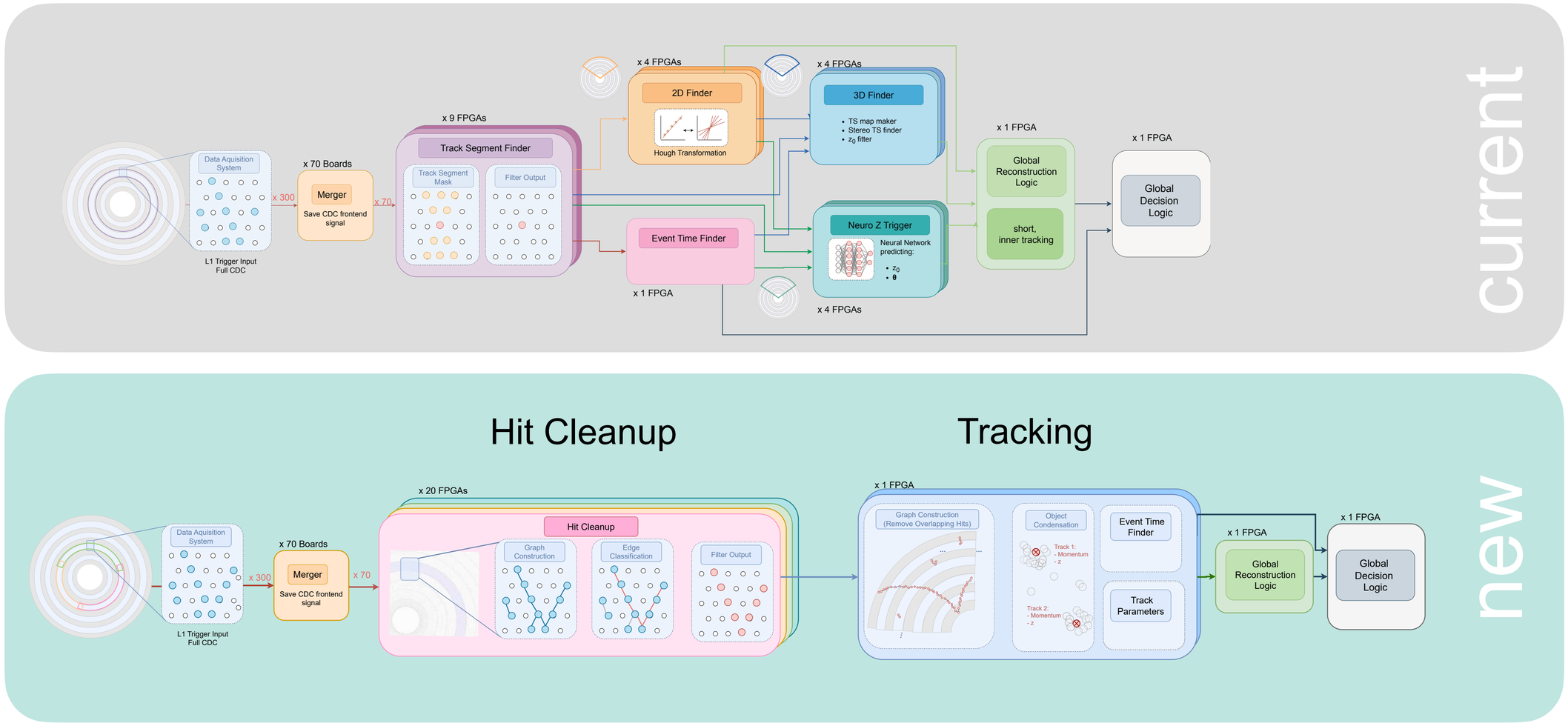
Institute of Experimental Particle Physics

Hit Cleanup with GNNs for real-time tracking at Belle II

Greta Heine, Torben Ferber, Lea Reuter, Slavomira Stefkova | 08.04.2024

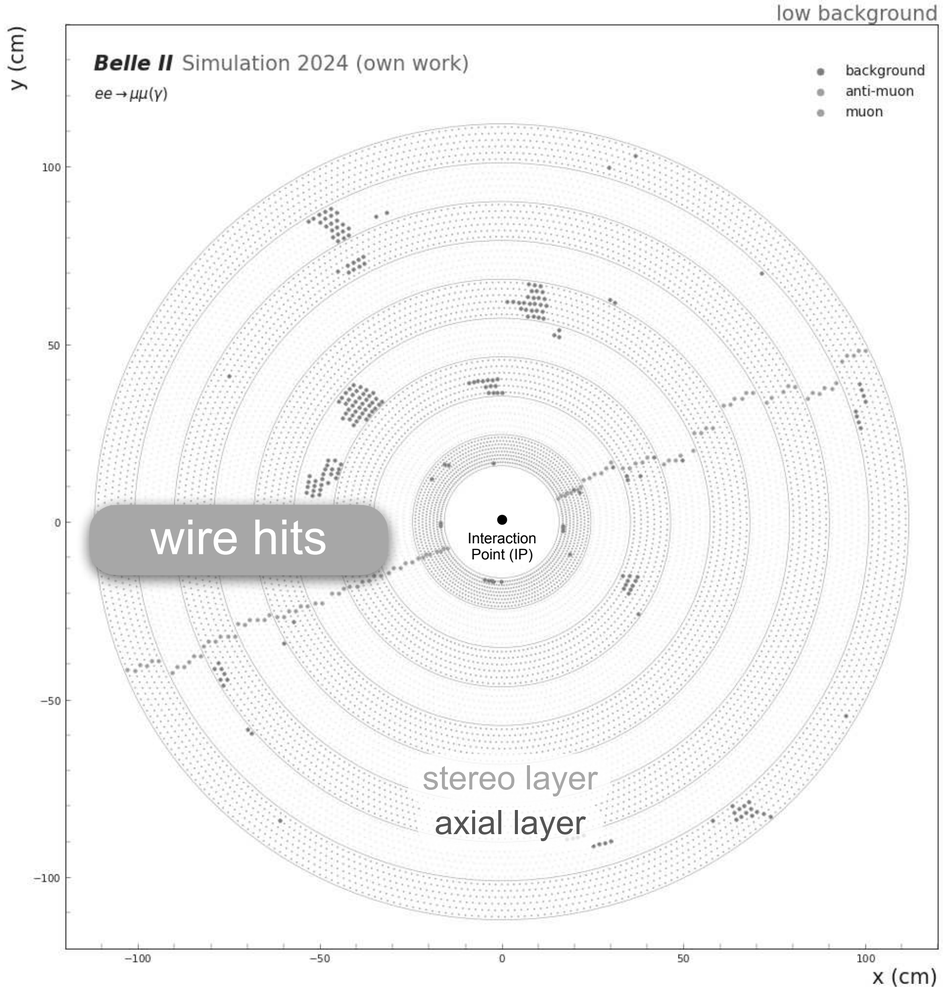


New CDC Trigger

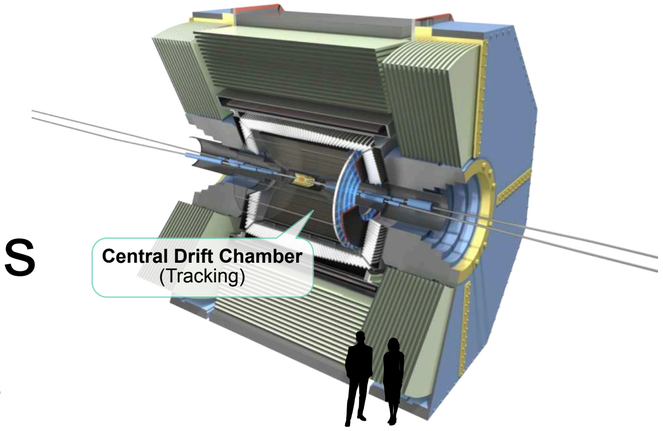


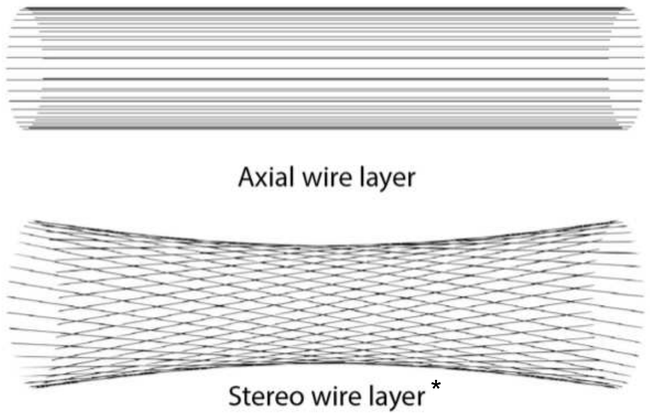
The Problem Challenge

Central Drift Chamber Event Display



- xy projection
- ≈ 15 000 wires
- 9 super layers
- alternating axial and stereo layers

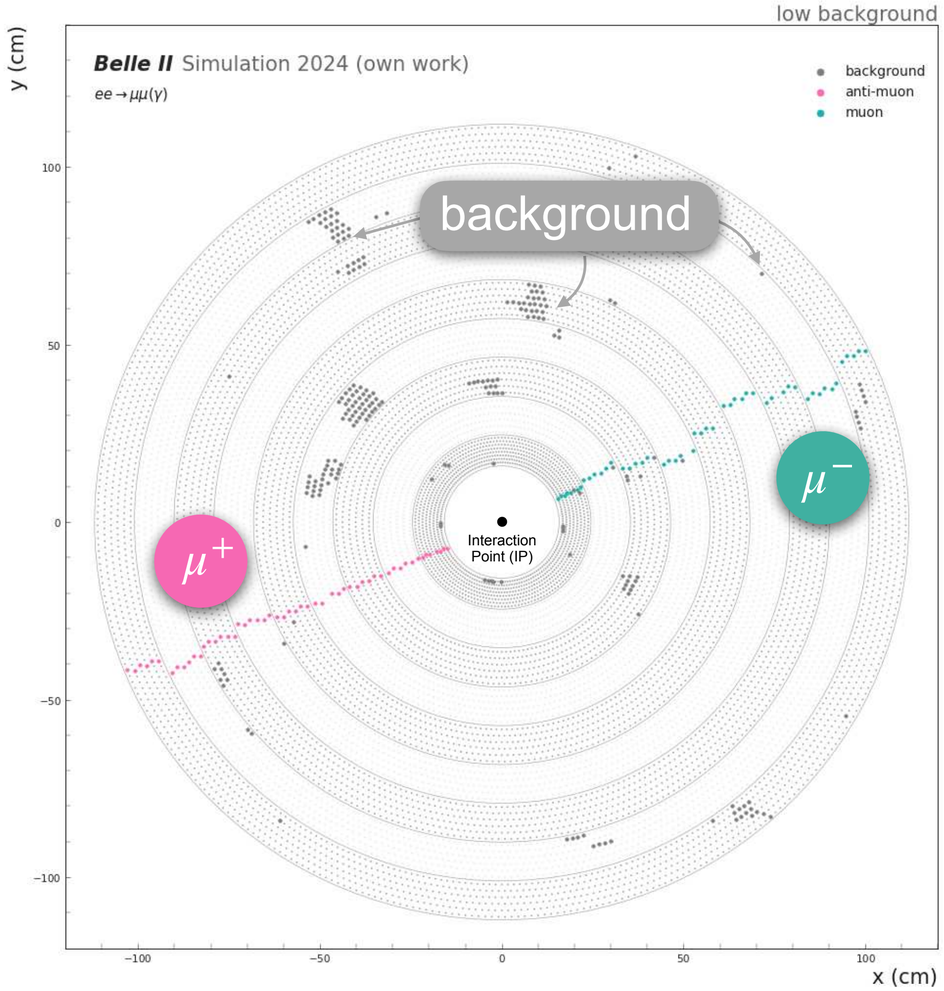




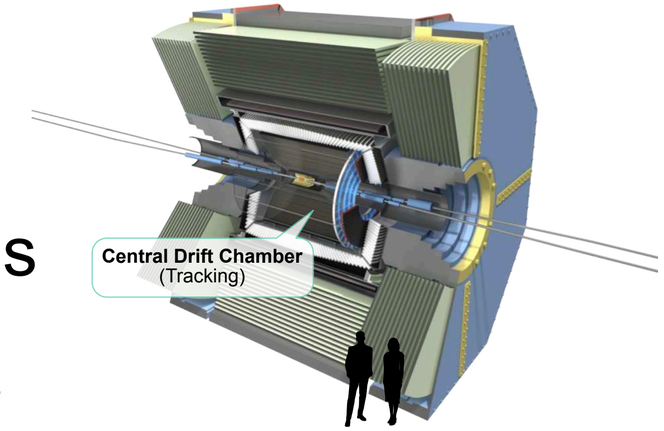
3D information

*rotation is hugely exaggerated for illustration

Central Drift Chamber Event Display

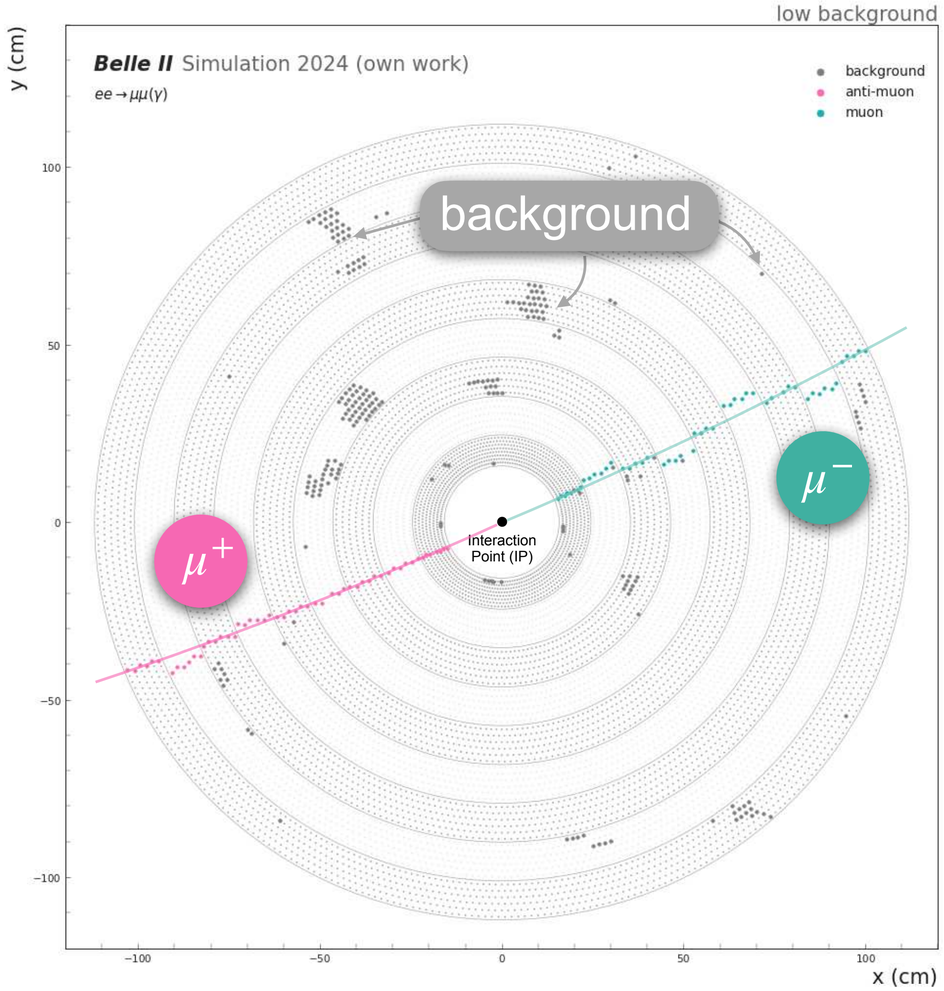


- xy projection
- ≈ 15 000 wires
- 9 super layers
- alternating axial and stereo layers



- MC simulated $\mu^+\mu^-$ pair
- overlayed with real background

Central Drift Chamber Event Display



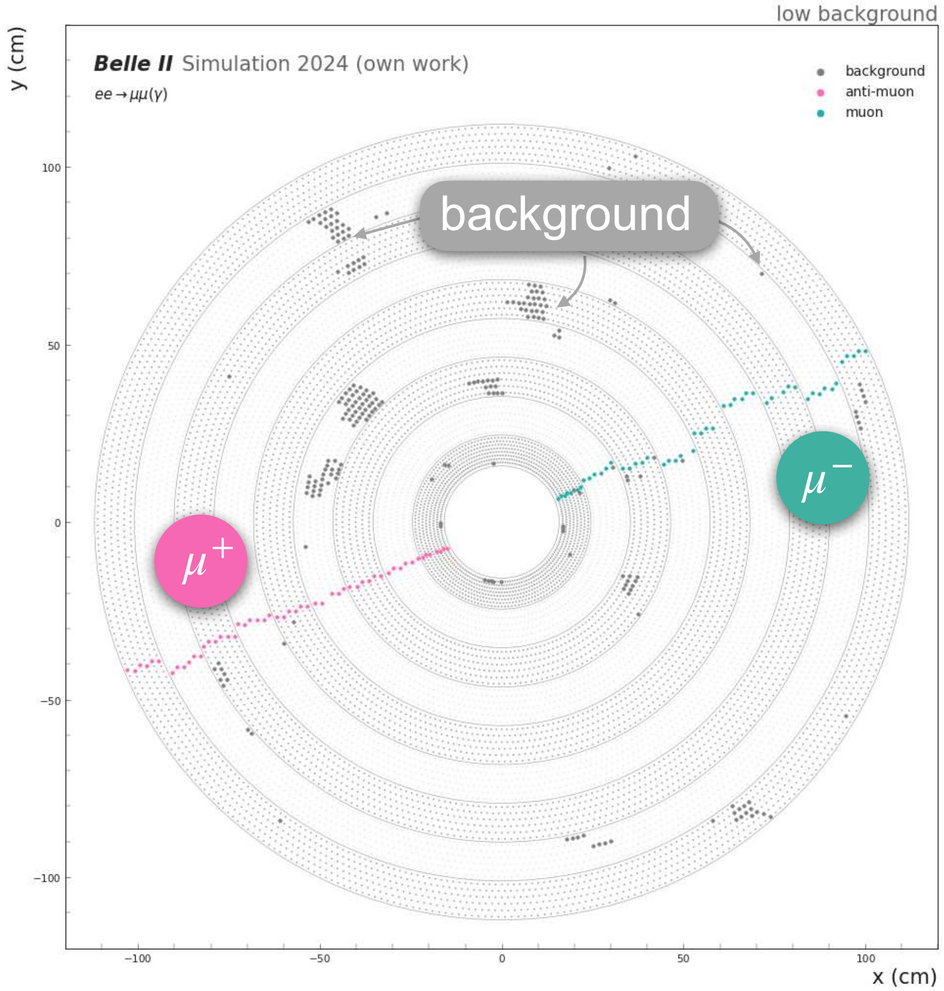
Tracking

1) identify signal hits (track finding)

2) reconstruct curvature $\propto p_T$ (track fitting)

- MC simulated $\mu^+\mu^-$ pair
- overlayed with real background

Back in 2021…



Tracking

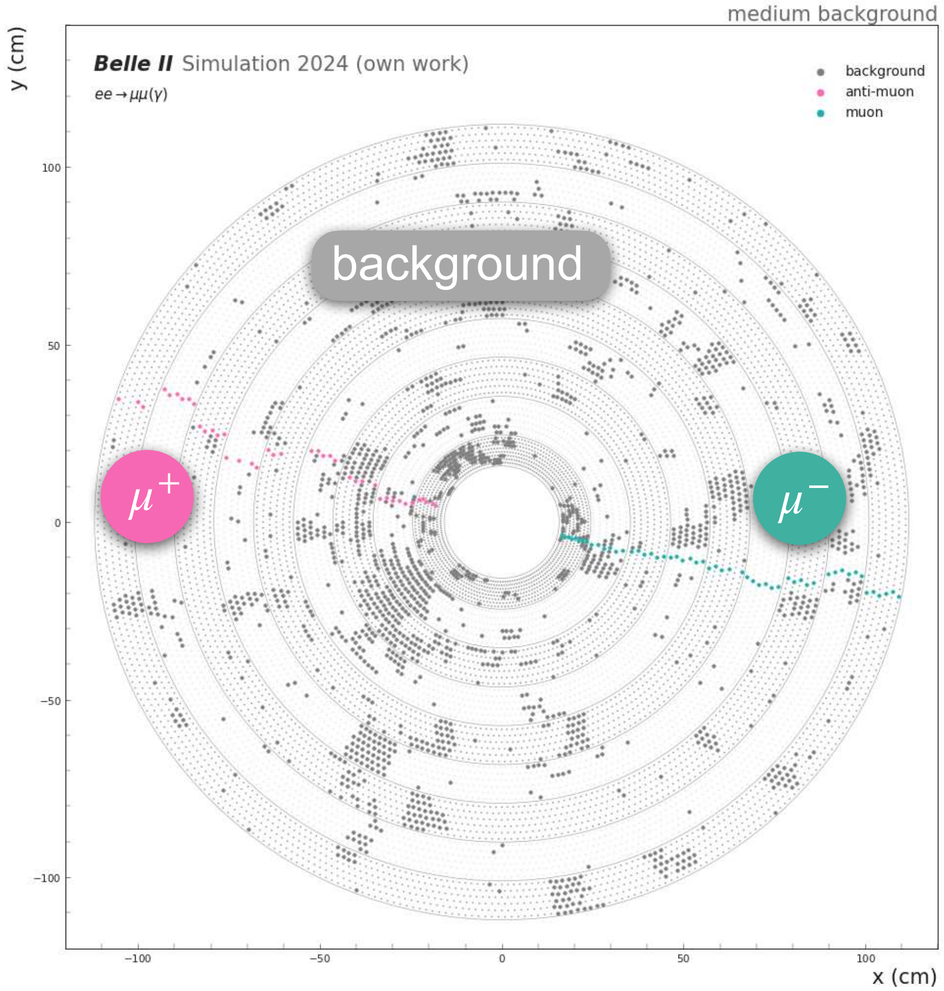
1) identify signal hits (track finding)

2) reconstruct curvature $\propto p_T$ (track fitting)

- low background
- $\approx$ 1.3% of wires hit
- low computing cost

easy

Now…



Tracking

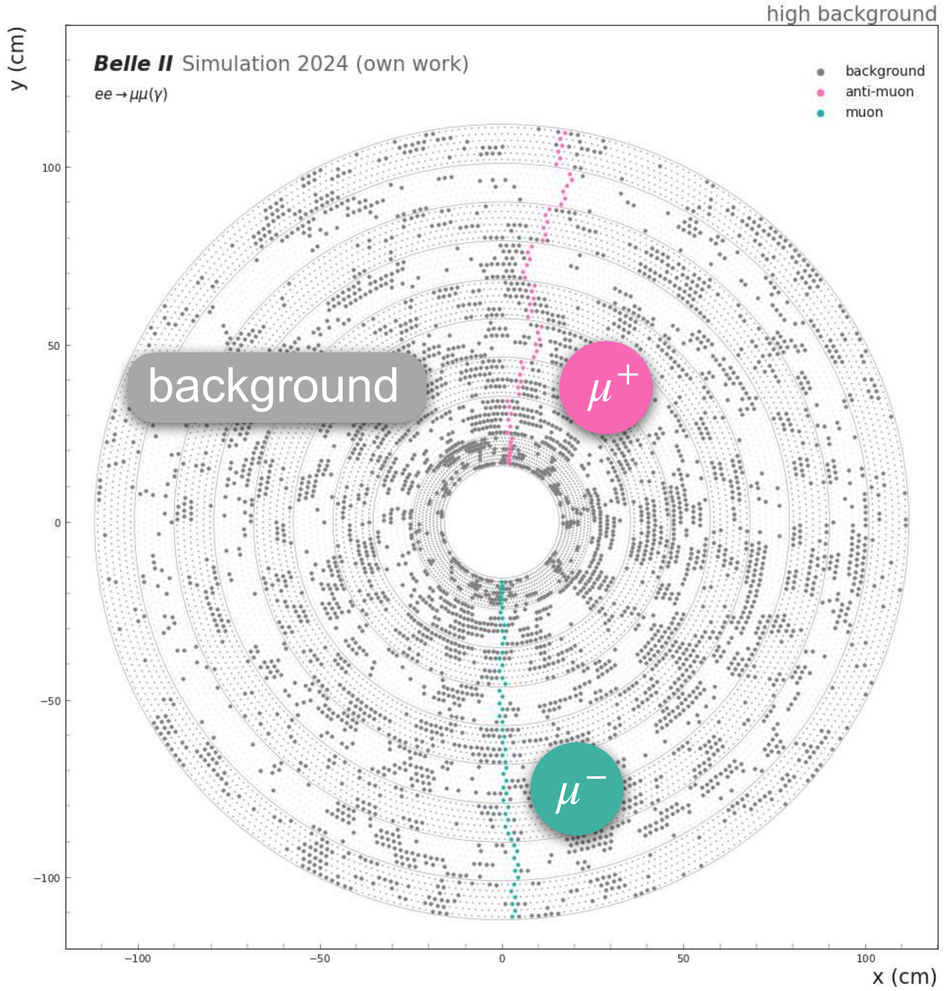
1) identify signal hits (track finding)

2) reconstruct curvature $\propto p_T$ (track fitting)

- medium background
- $\approx$ 12.5% of wires hit
- moderate computing cost

a bit harder

Future…

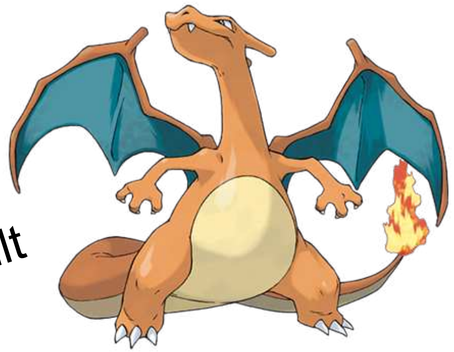


Tracking

1) identify signal hits (track finding)

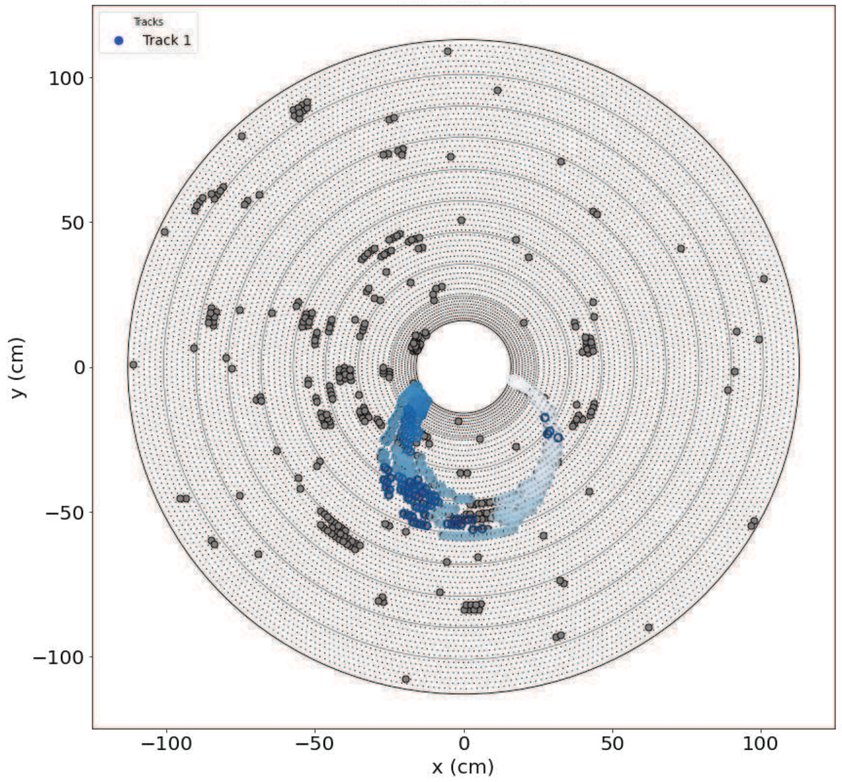
2) reconstruct curvature $\propto p_T$ (track fitting)

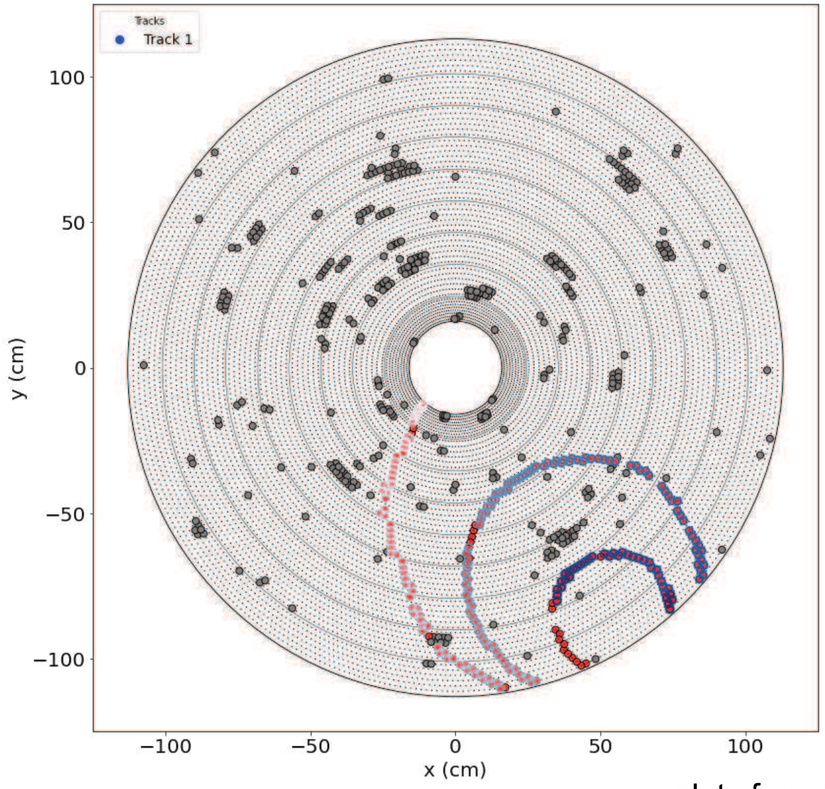
- high background
- $\approx$ 27.1% of wires hit
- high computing cost



Low p_T Tracks

- curling tracks at low p_T

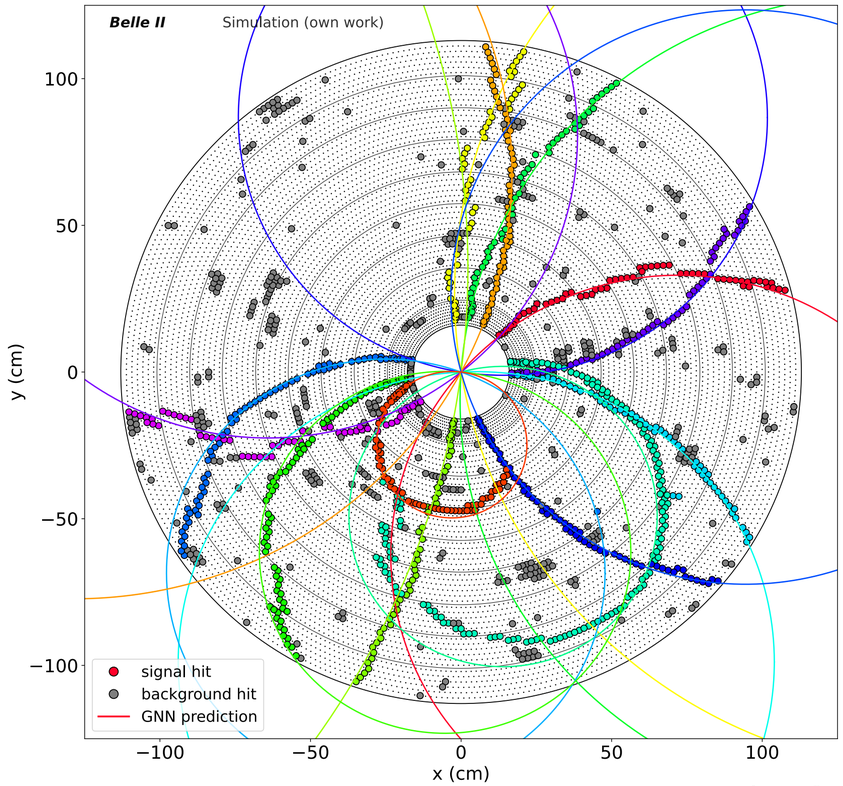




plots from Lea Reuter

High multiplicity

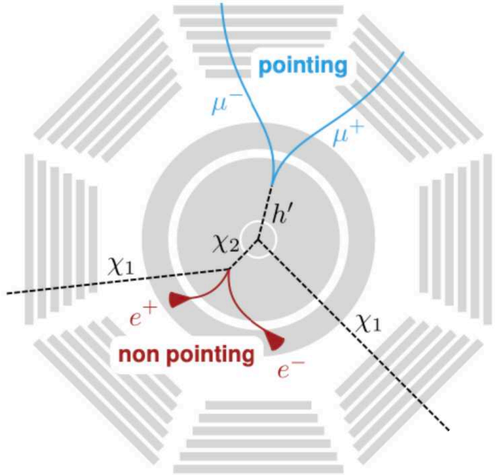
- multiple tracks per event

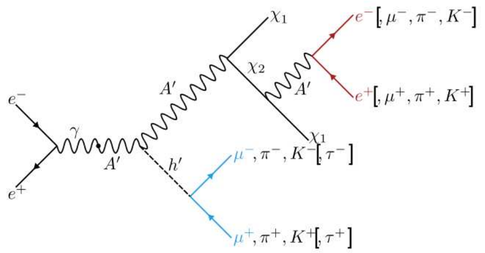


plots from Lea Reuter

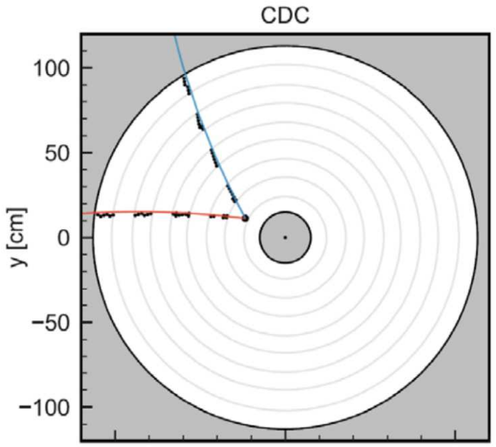
Displaced vertices

- tracks not originating from the IP





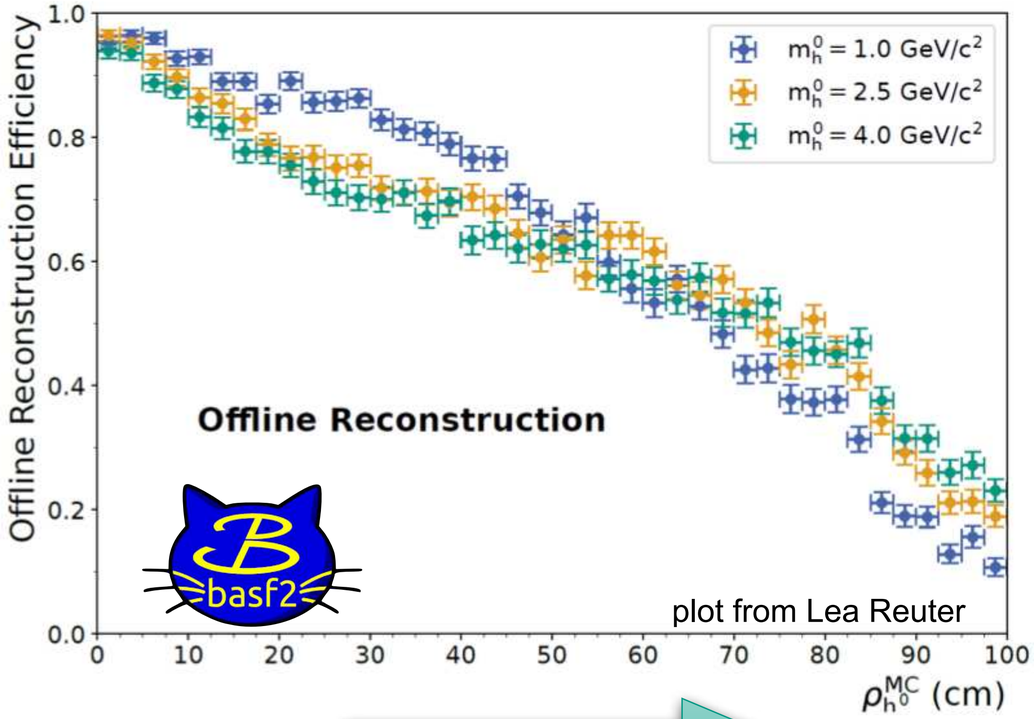
Plots from Patrick Ecker



plot from Christian Kiesling

efficiency

Current Tracking Algorithm



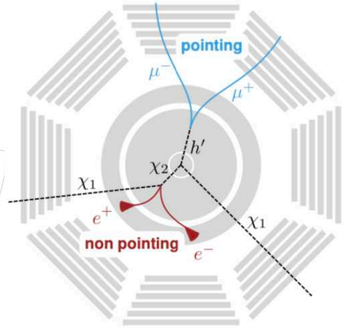
plot from Lea Reuter

higher displacement

Tracking: the challenges

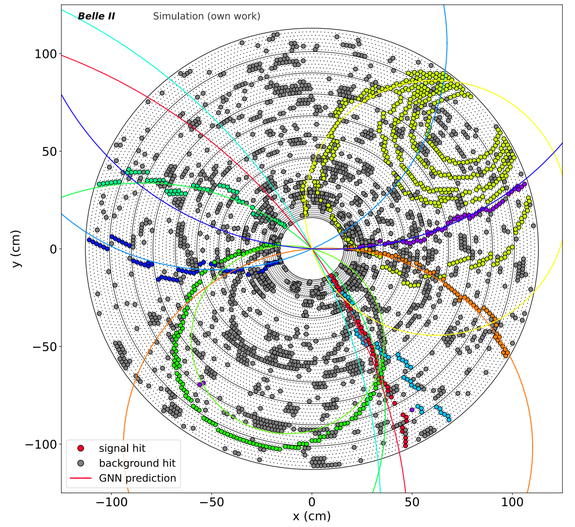
Tracking

- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)
- low p_T tracks
- high track multiplicity
- displaced vertices



Trigger Tracking

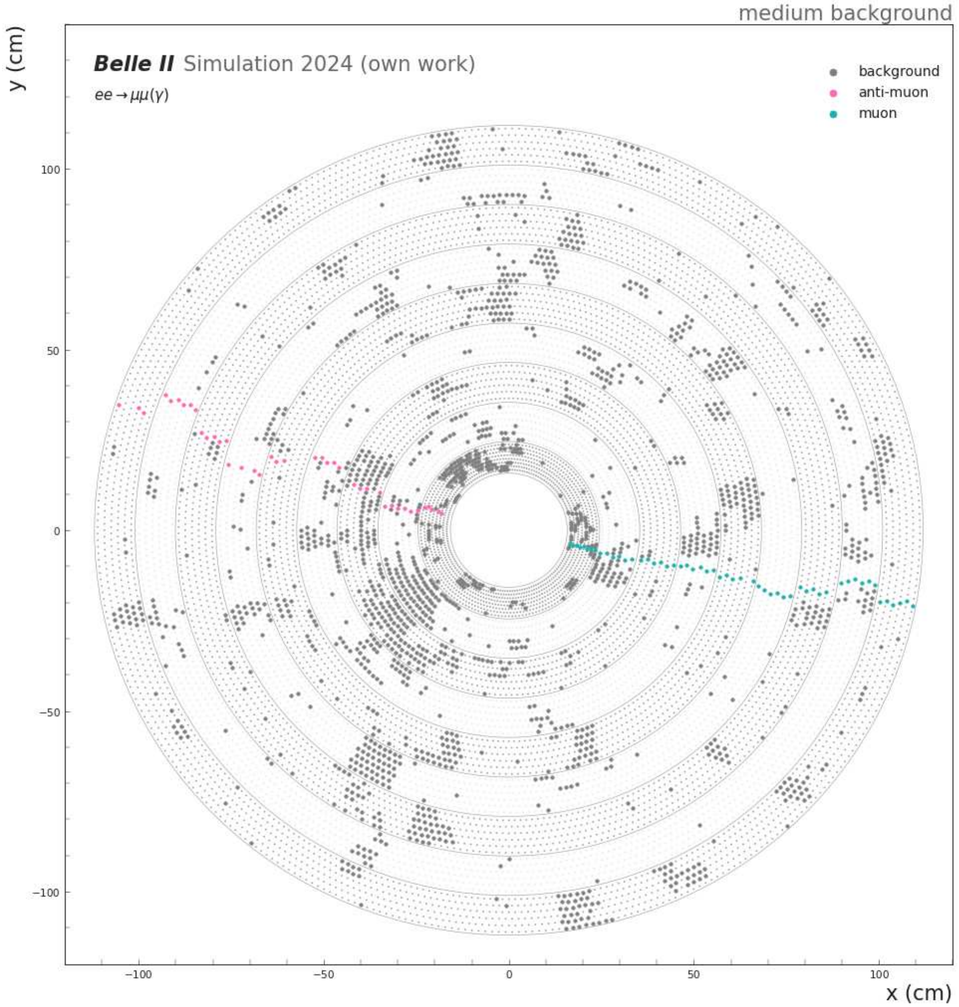
- sub-microsecond latency
- limited computing resources

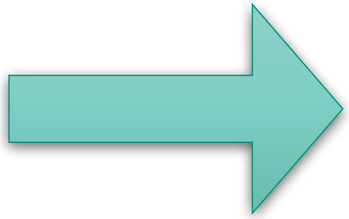


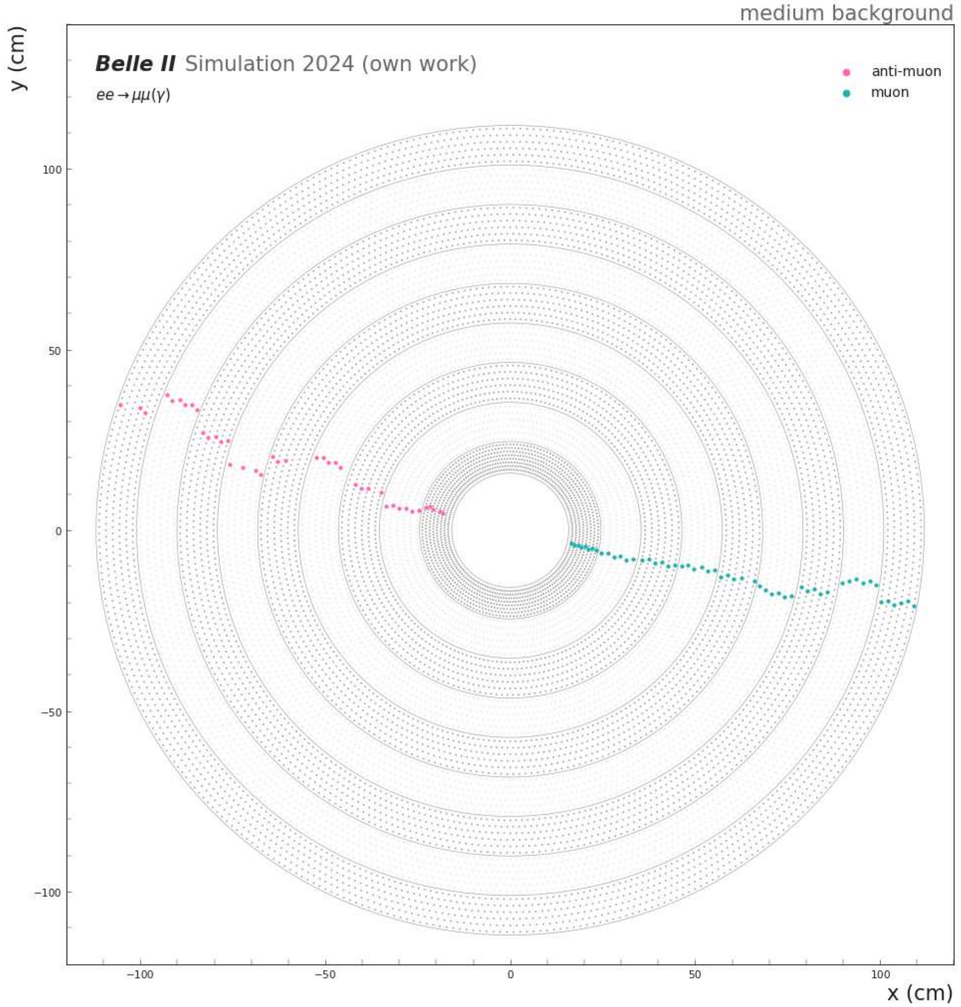
plot from Lea Reuter

The (intermediate) Goal

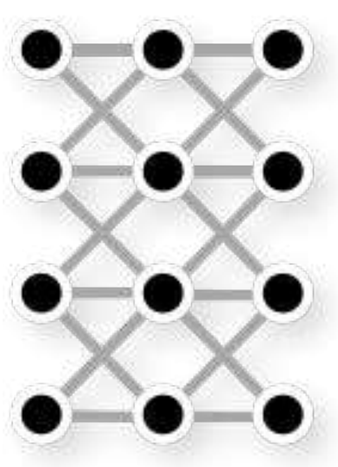
Hit Cleanup

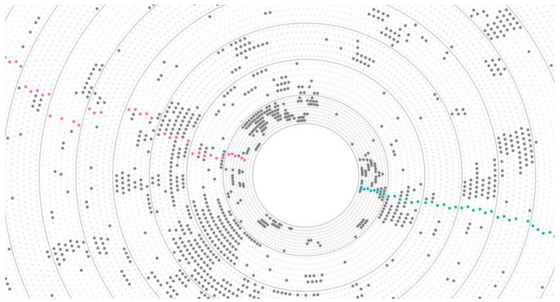

medium background
Belle II Simulation 2024 (own work)
$ee \to \mu\mu(\gamma)$
background
anti-muon
muon
y (cm)
x (cm)
100
50
0
−50
−100

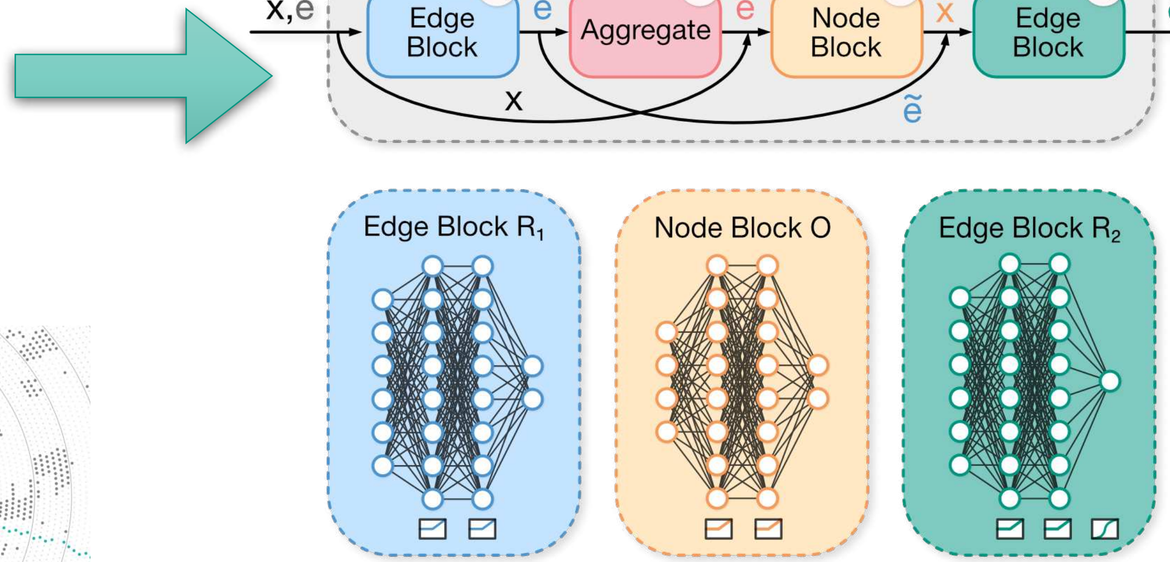


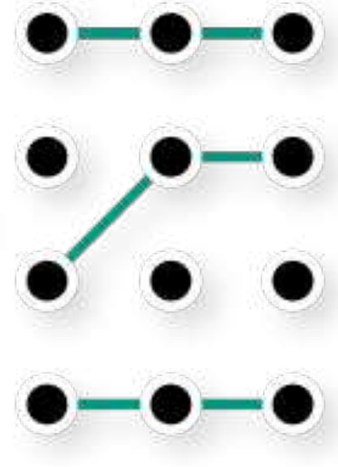

medium background
Belle II Simulation 2024 (own work)
$ee \to \mu\mu(\gamma)$
anti-muon
muon
y (cm)
x (cm)
100
50
0
−50
−100

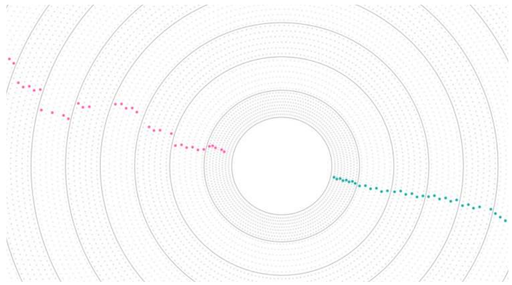
Hit Cleanup: with a Graph Neural Network











Graph Building

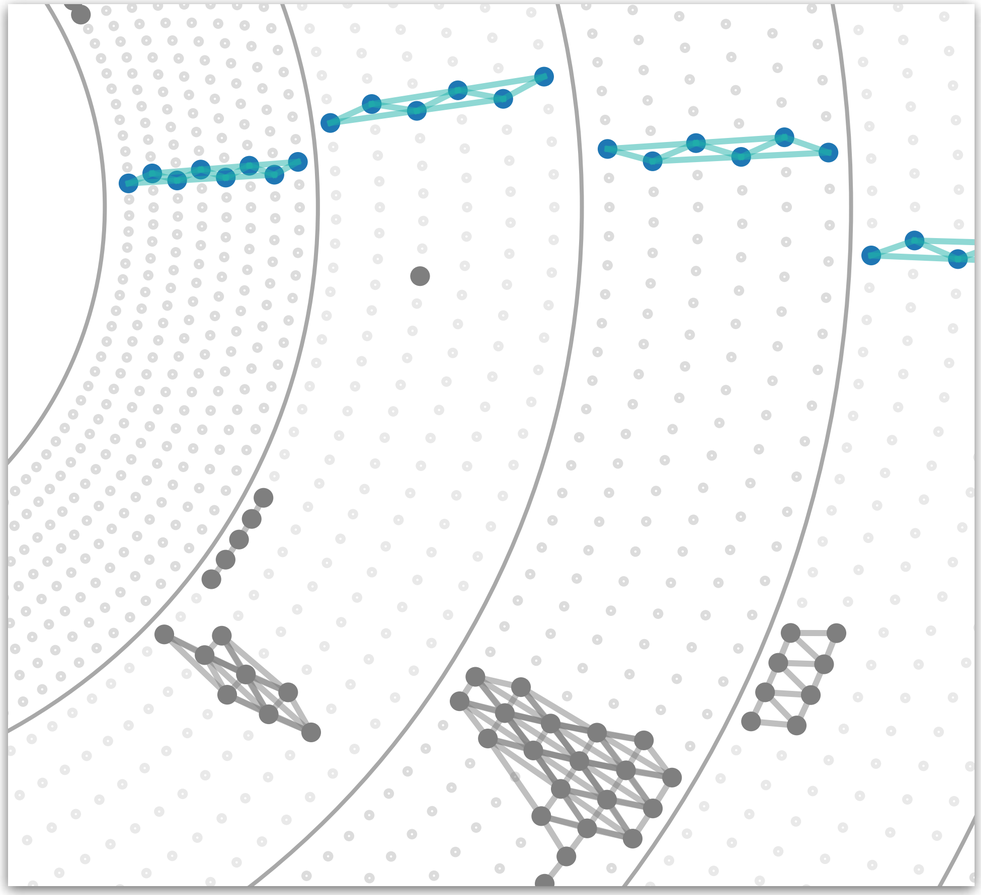
Graph Building

- connect hits to graphs
- connect *just the right amount* of hits with each other
- fully connected graph

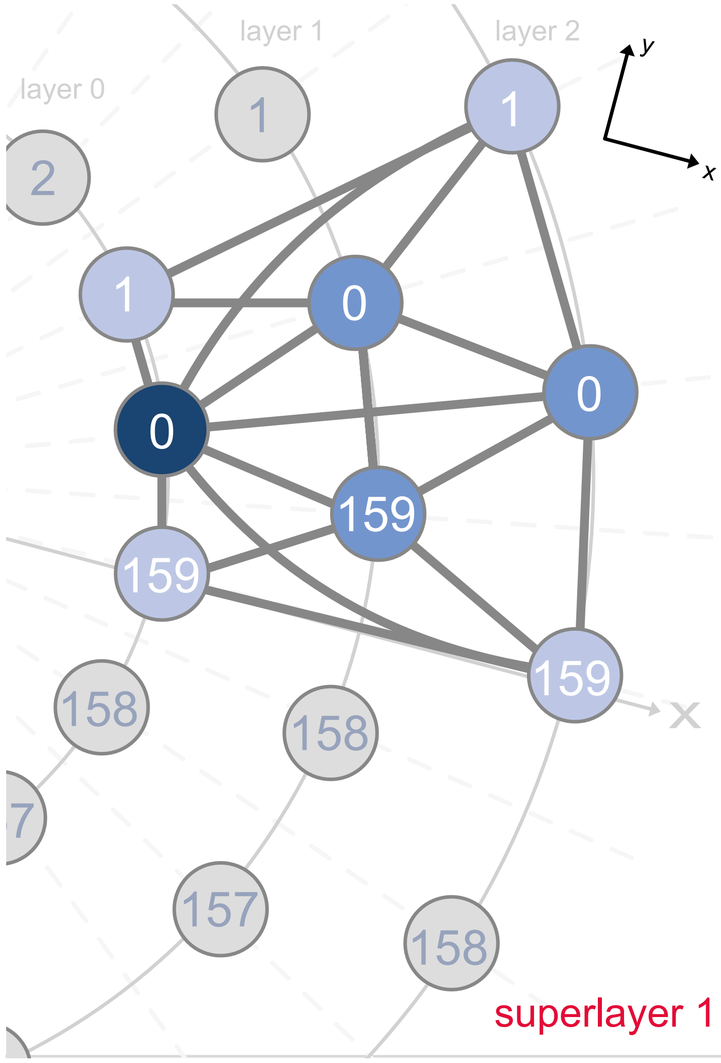
$$n_{edges} = \frac{1}{2} n_{hits}(n_{hits} - 1) \approx n_{hits}^2$$

- design goal

$$n_{edges} \approx 2 \cdot n_{hits}$$



Graph Building



- same layer connections with 2 nearest neighbours
- next layer connections with 2 nearest neighbours
- next to next layer connections with 3 nearest neighbours
- build all possible (allowed) connections

Graph Building: Features

node attributes

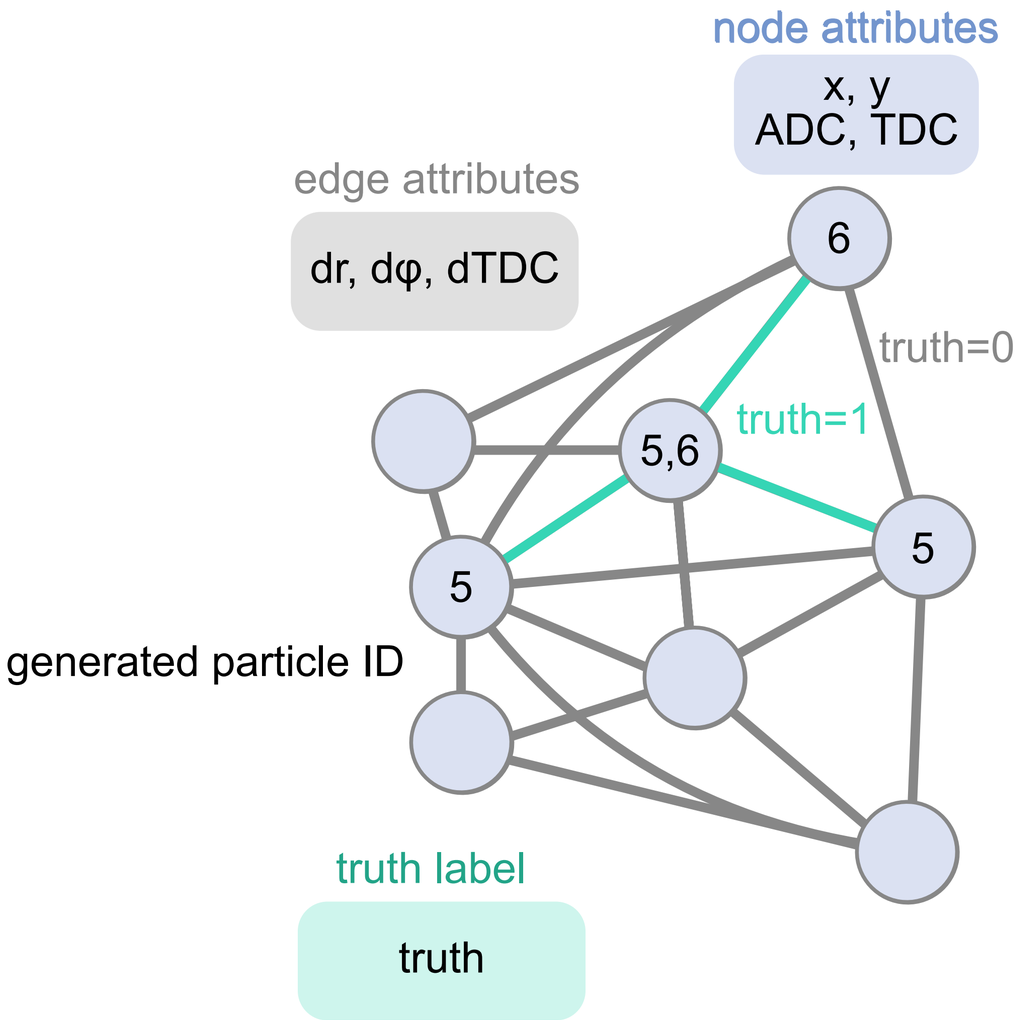
- wire coordinates (x, y)
- ADC (energy) and TDC (time)

edge attributes

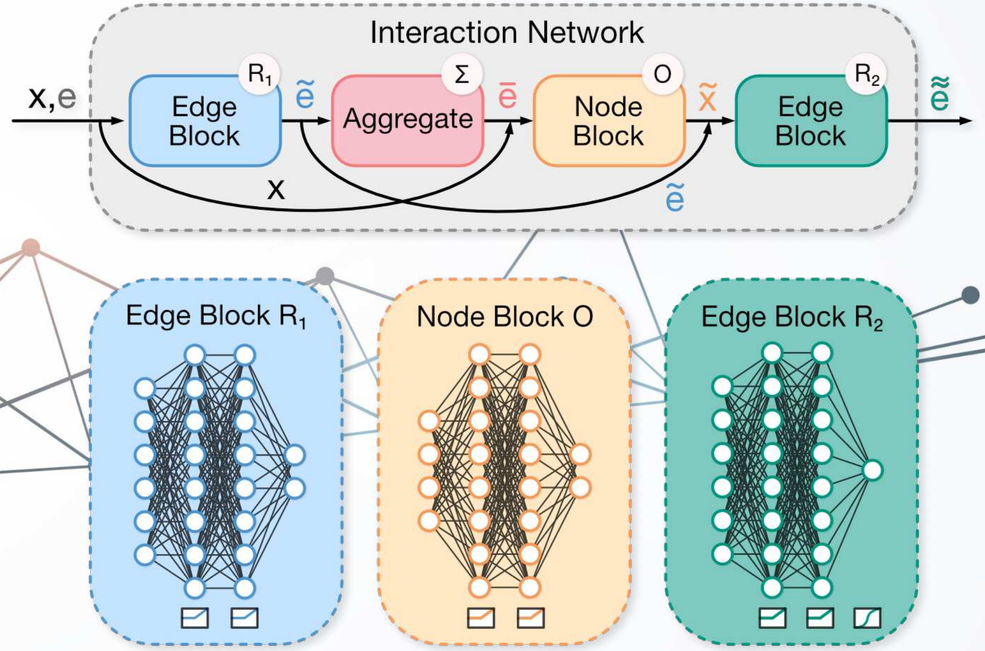
- dr, dφ, dTDC

truth labels

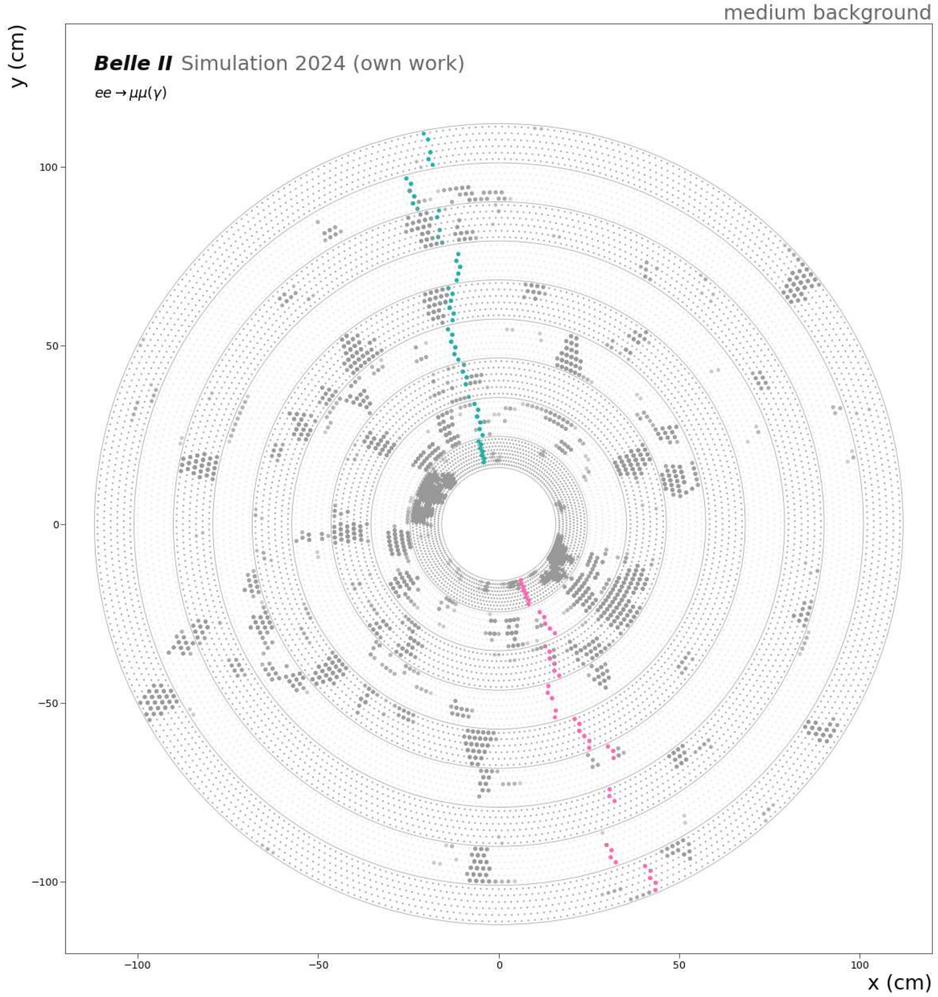
- truth

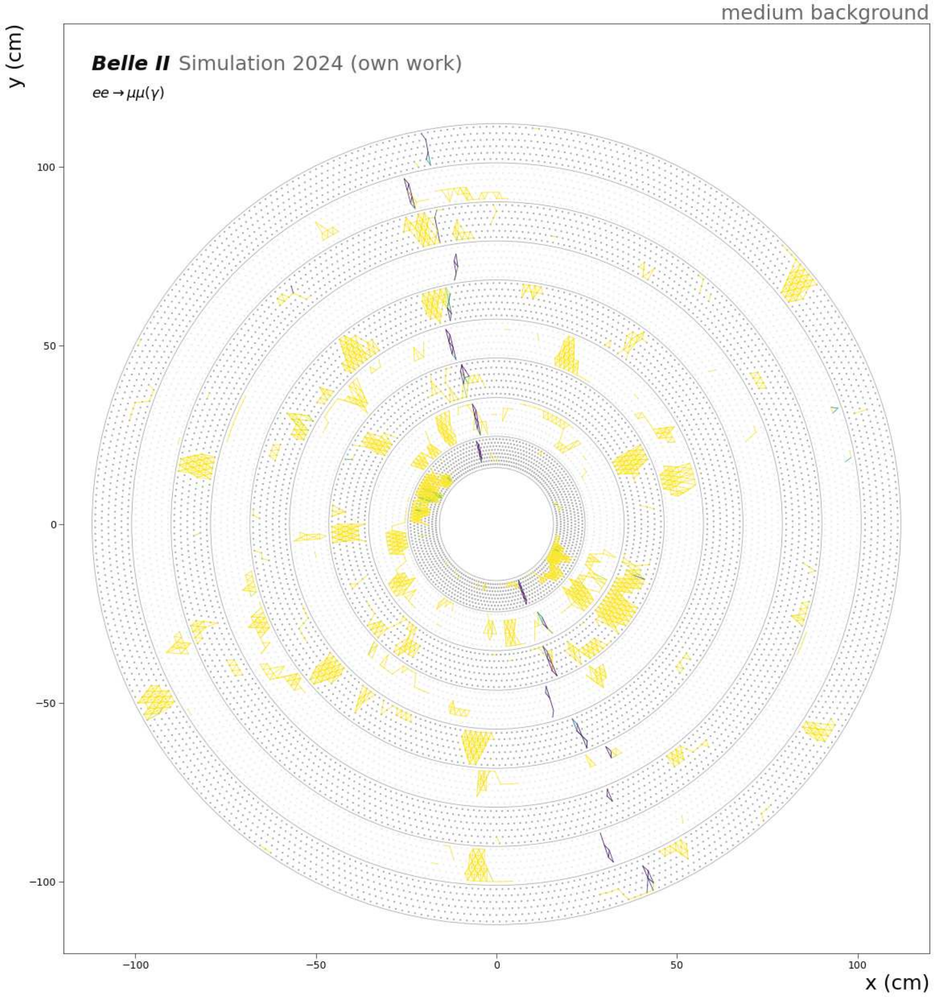


Hit Cleanup

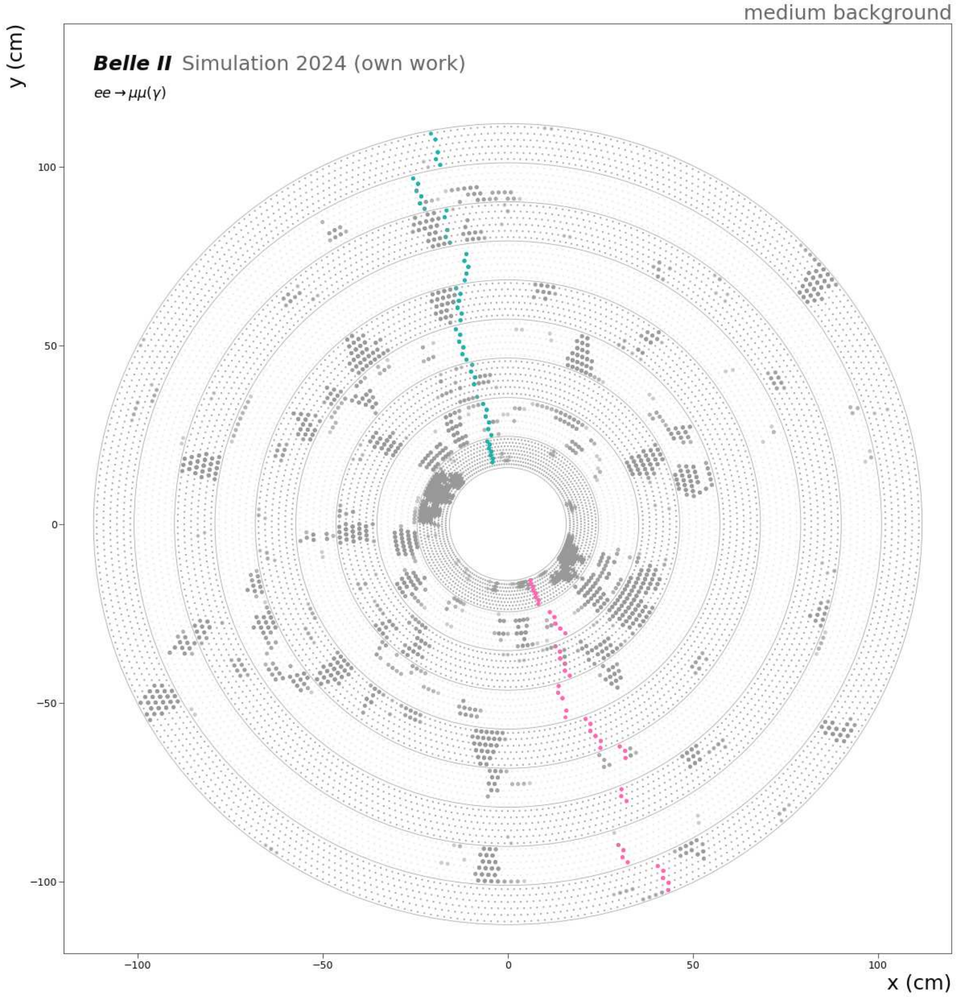

Interaction Network
x,e
Edge Block
R1
ẽ
Aggregate
Σ
ē
Node Block
O
x̃
Edge Block
R2
ẽ
x
ẽ
Edge Block R1
Node Block O
Edge Block R2

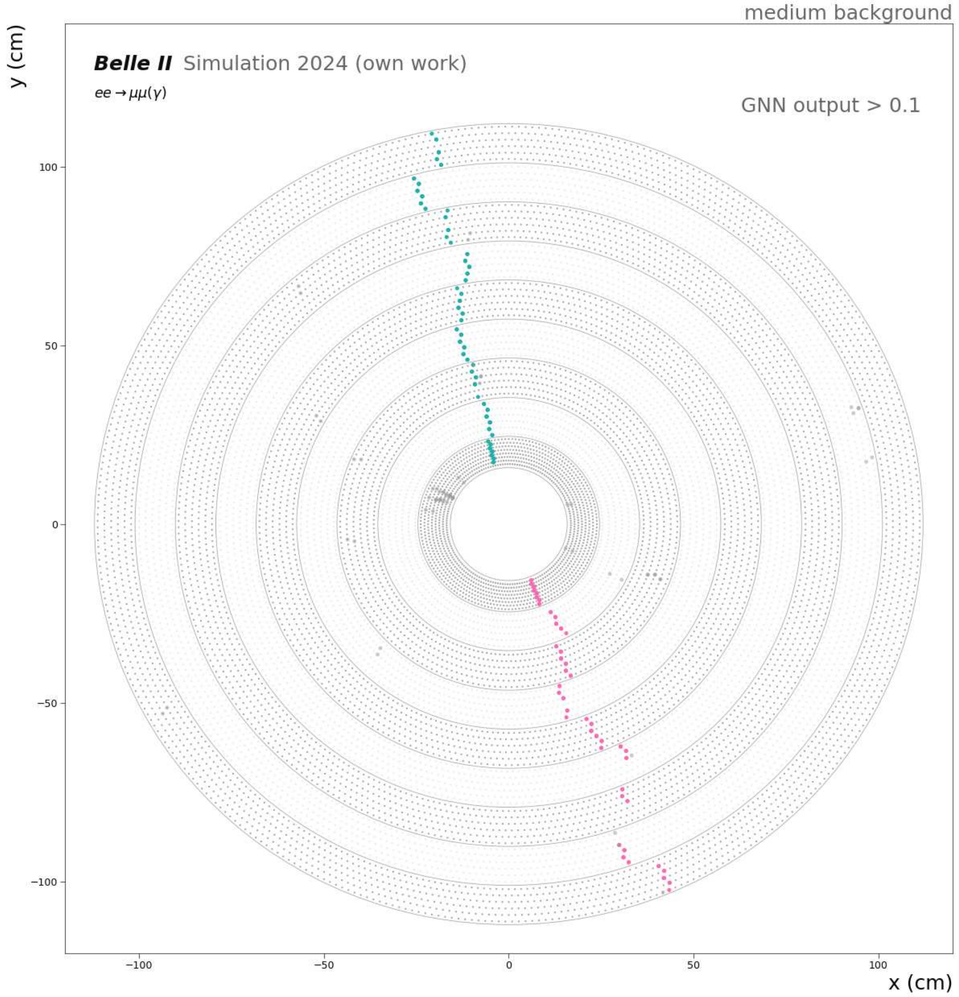
Graph Neural Network Output

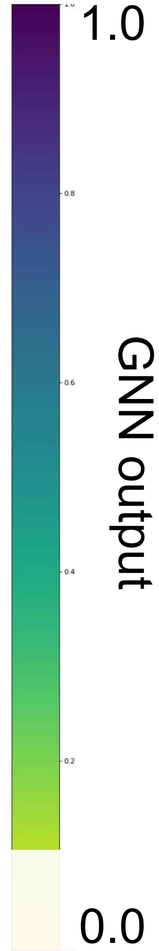




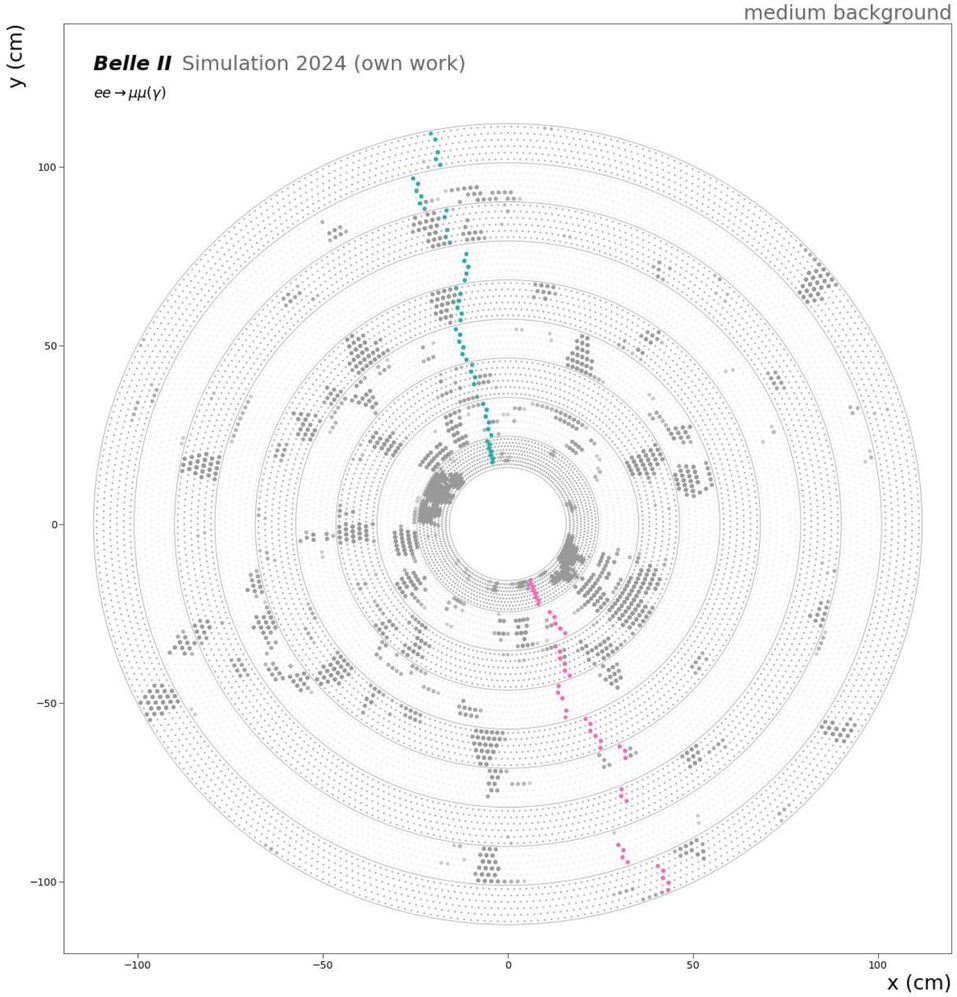
Graph Neural Network Output

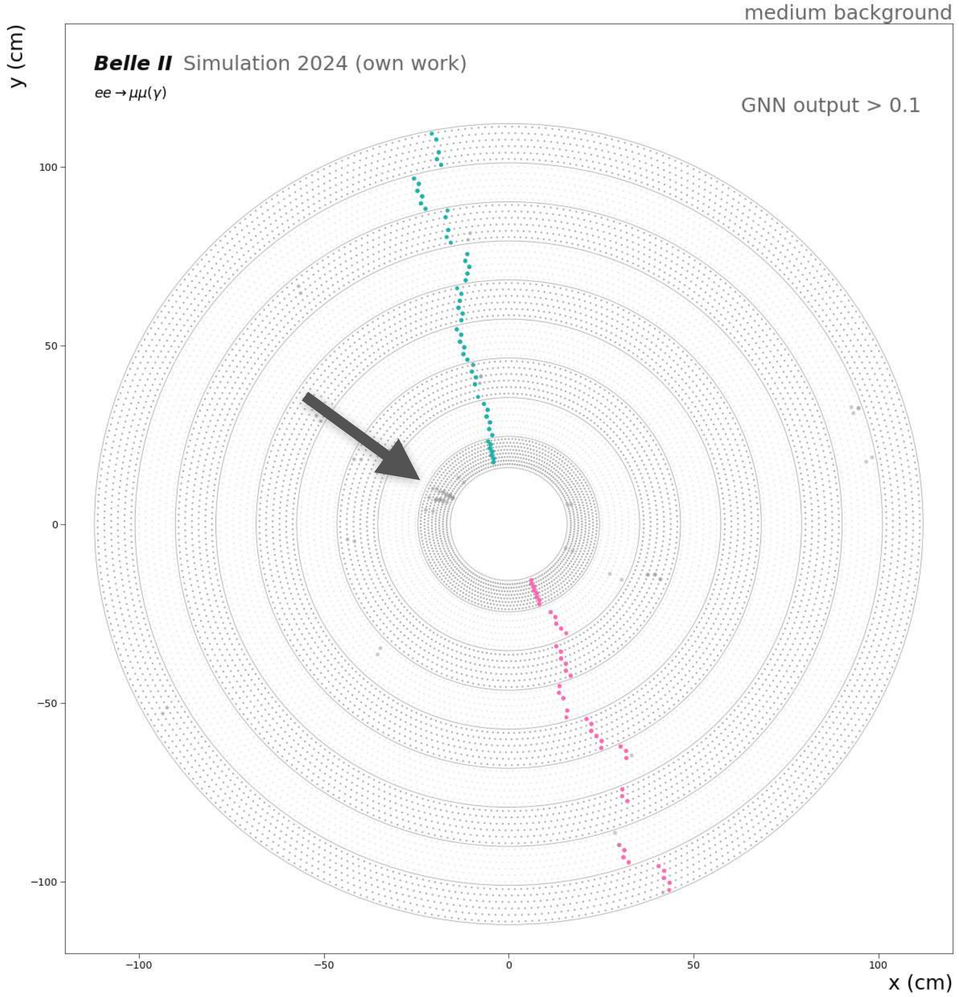


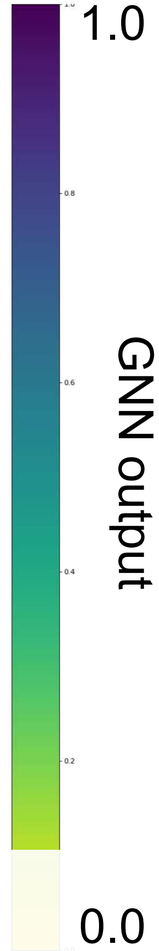




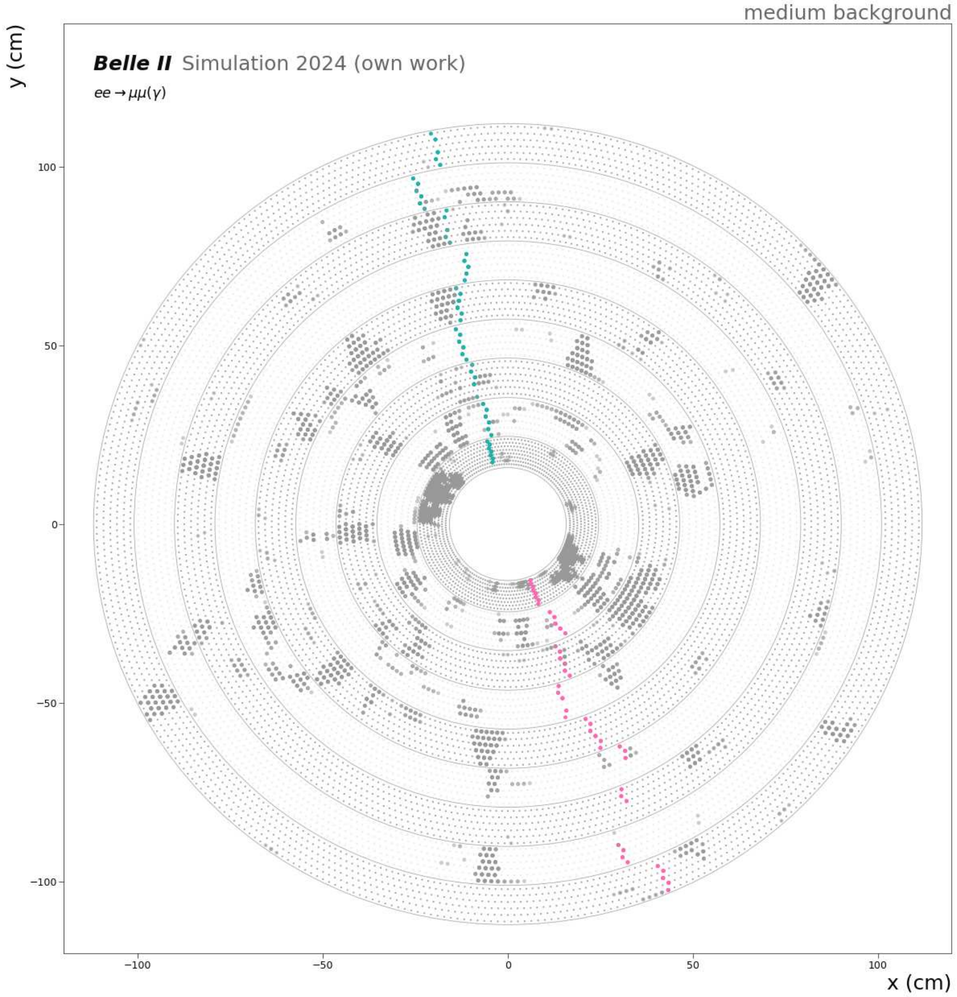
Graph Neural Network Output

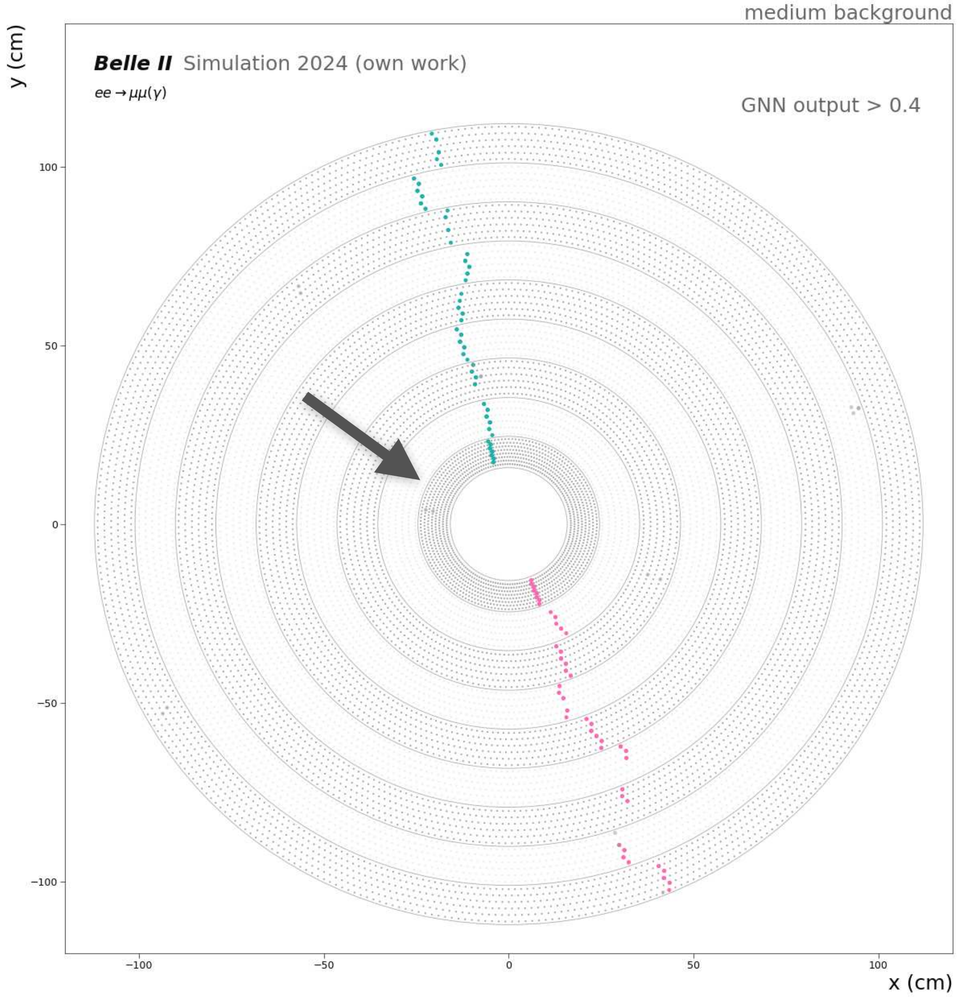


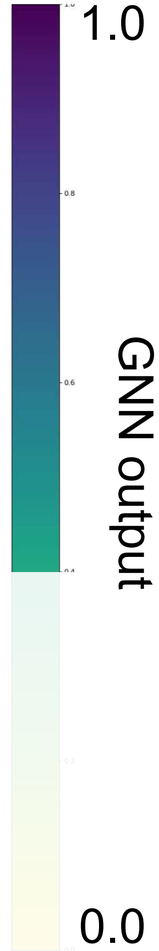




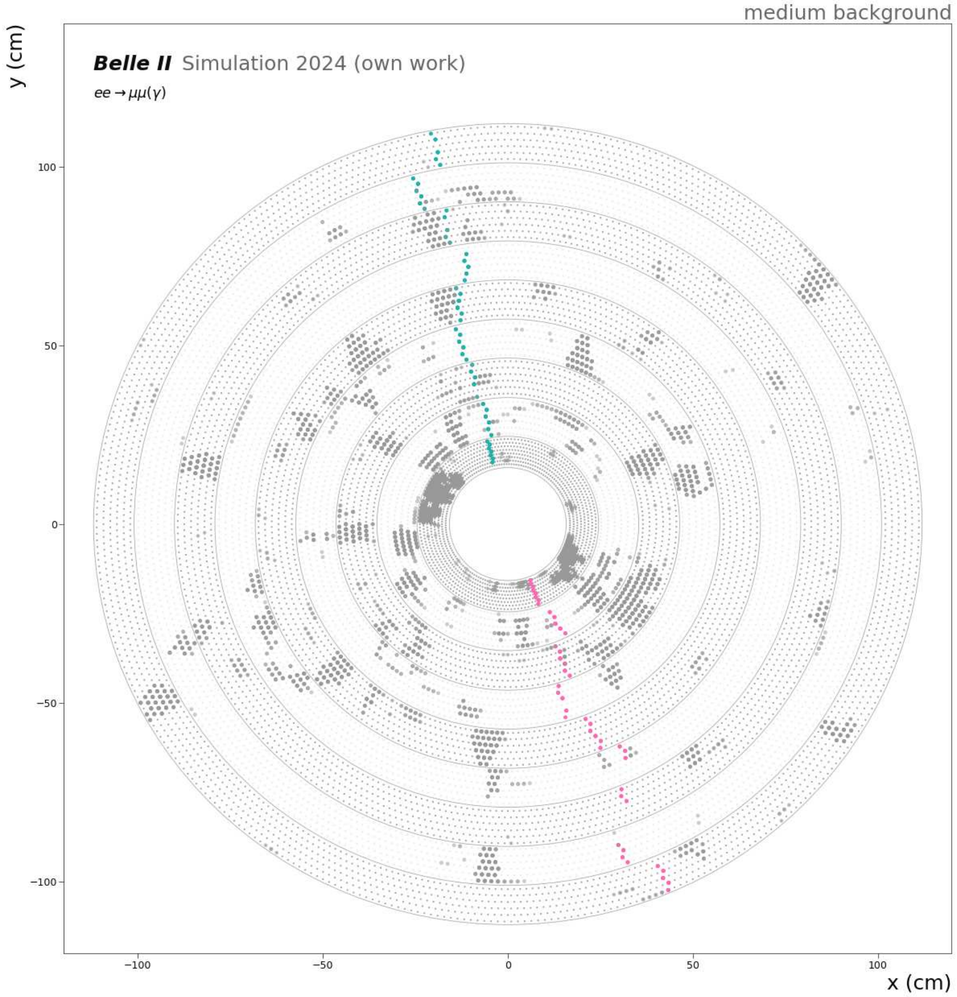
Graph Neural Network Output

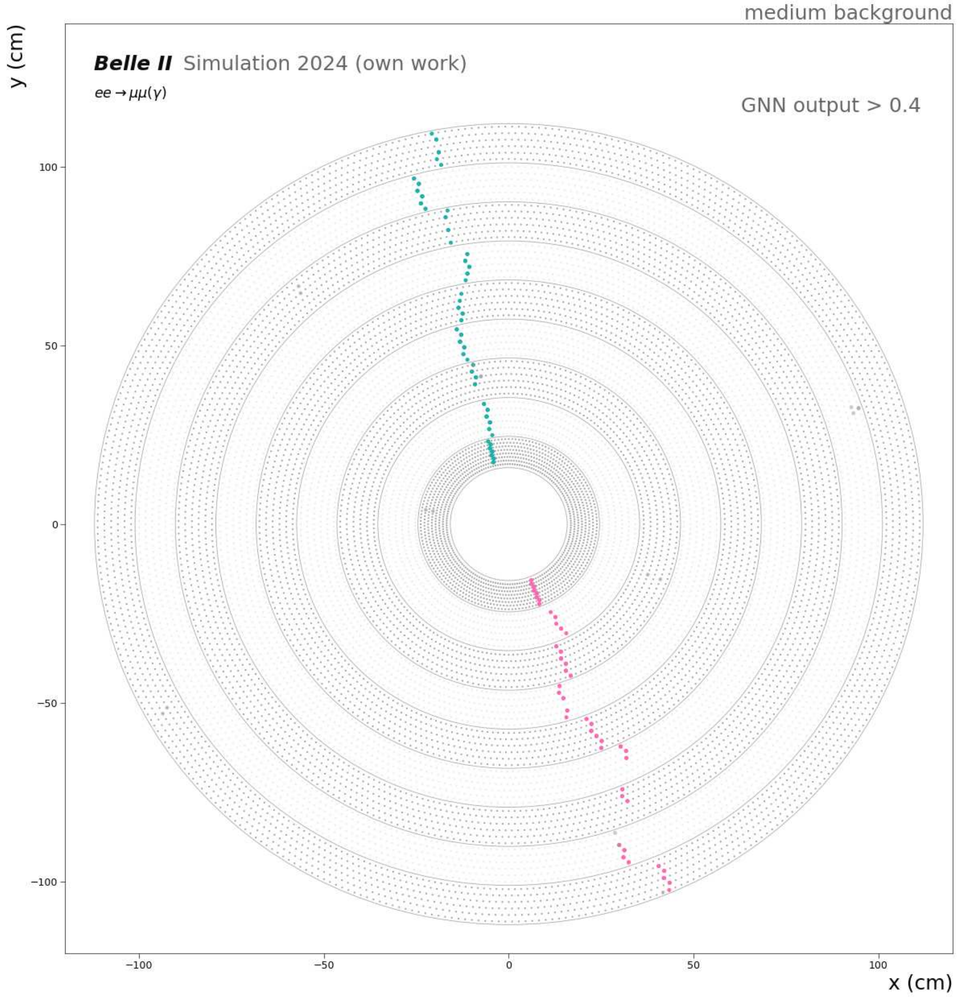


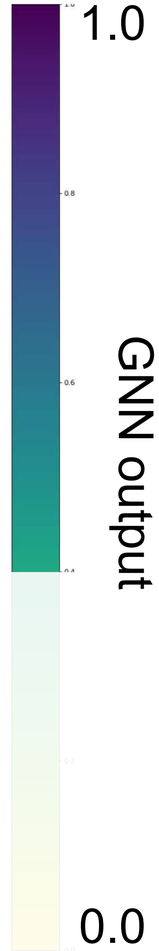




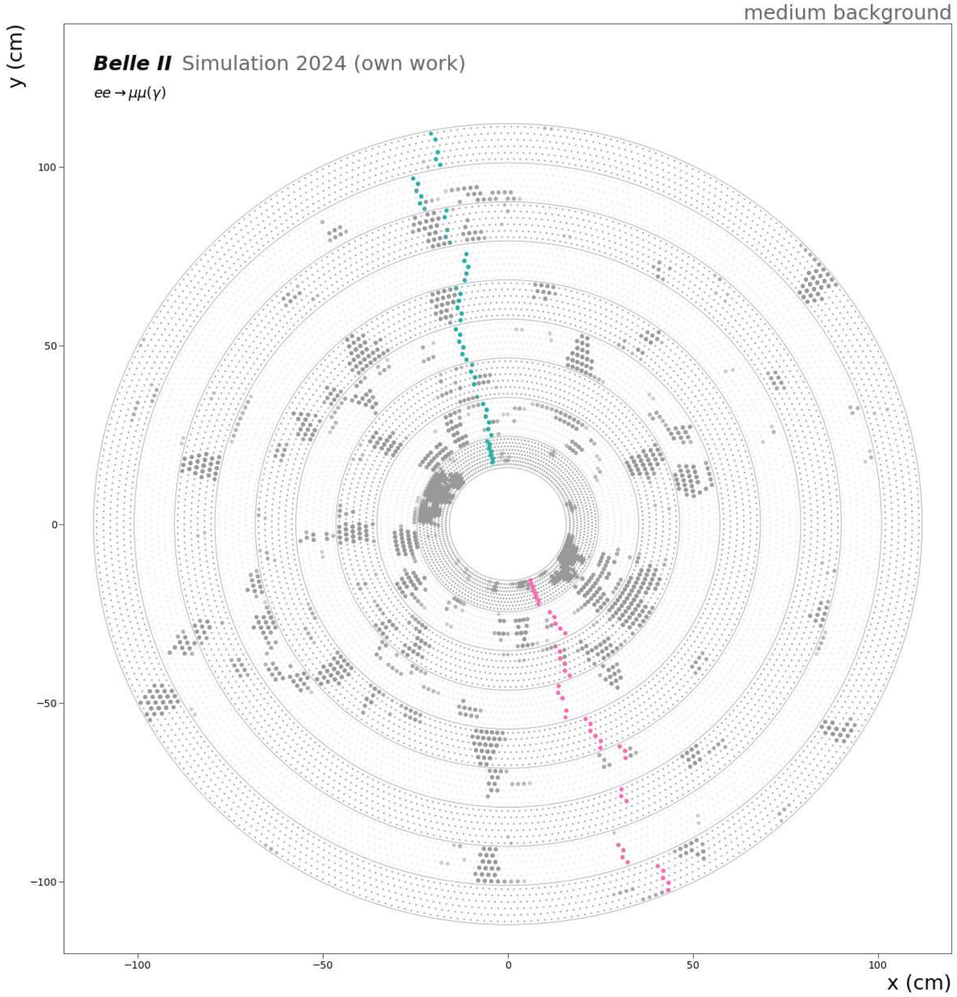
Graph Neural Network Output

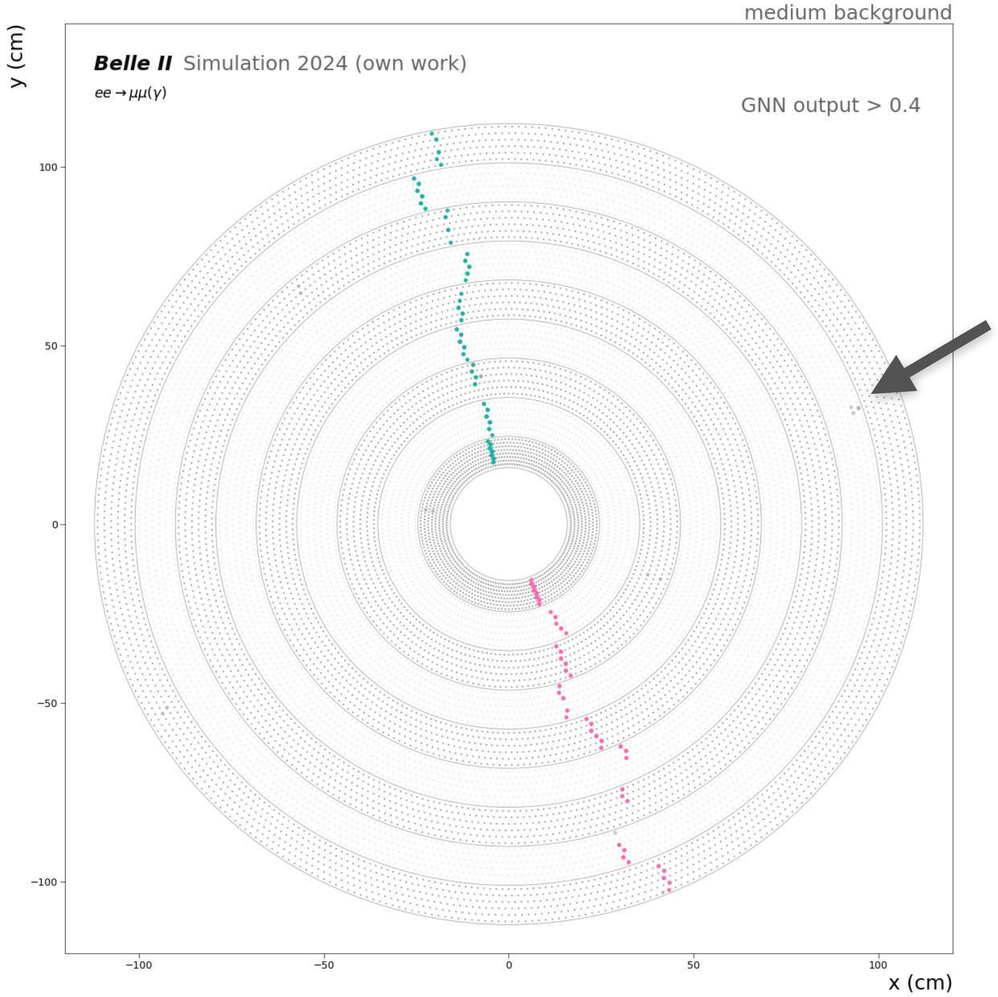


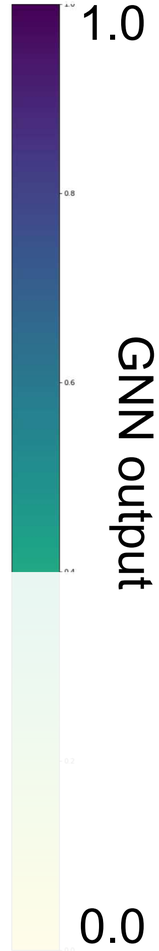




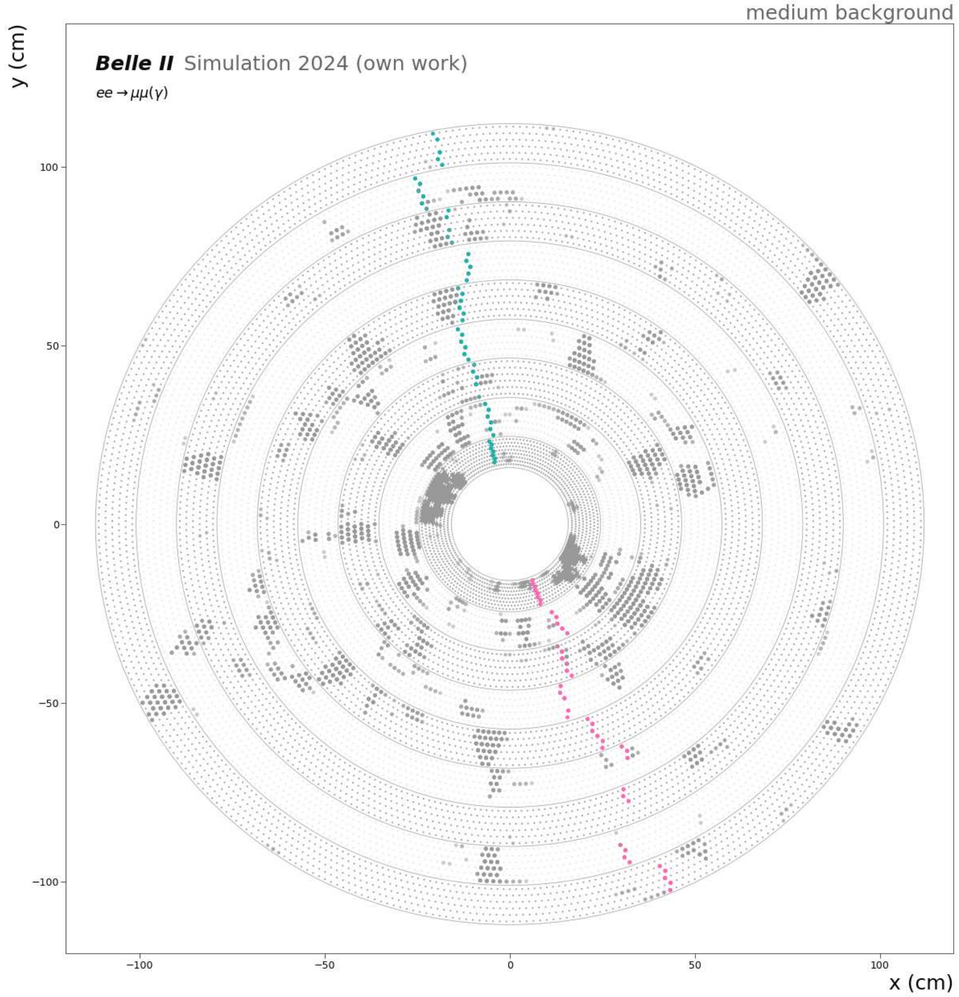
Graph Neural Network Output

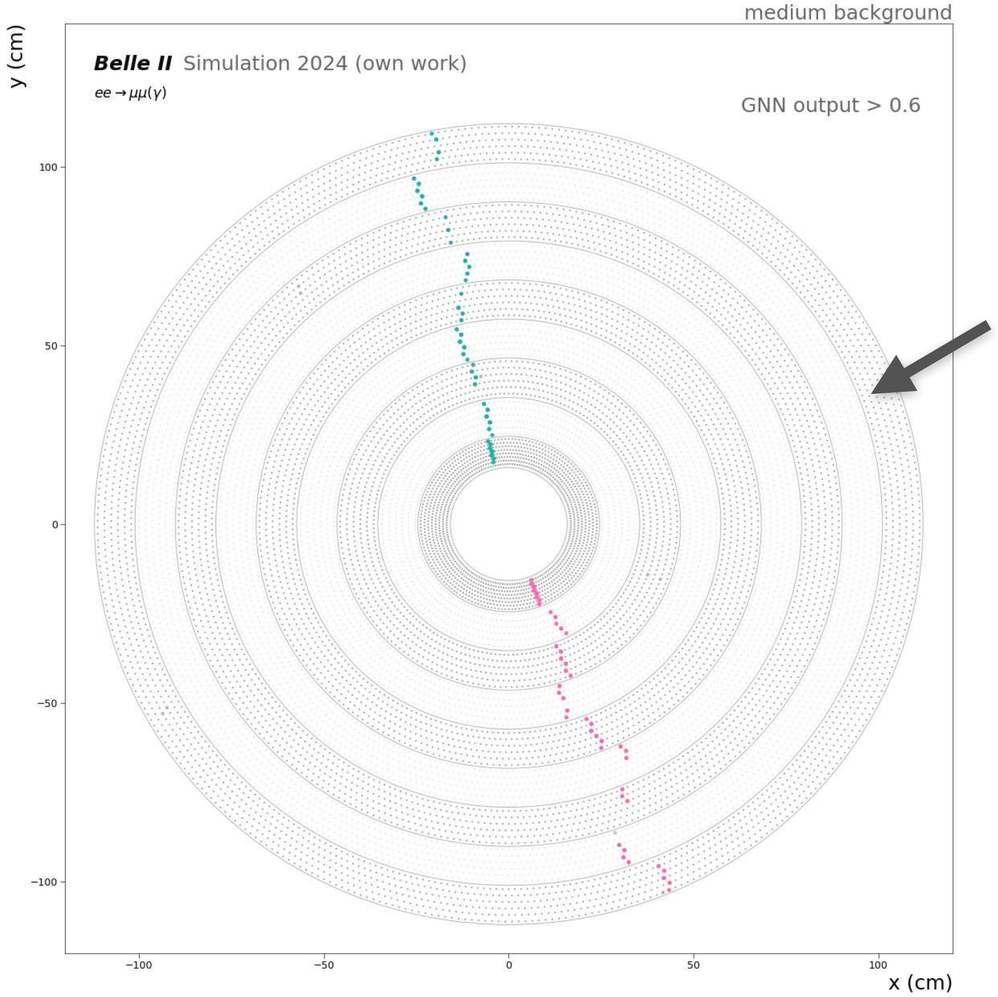


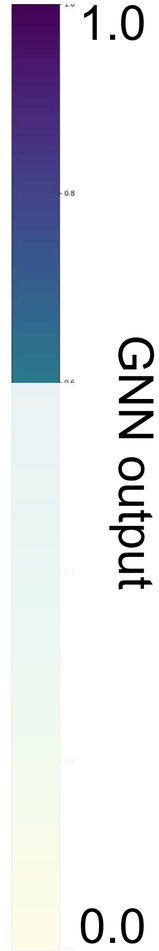




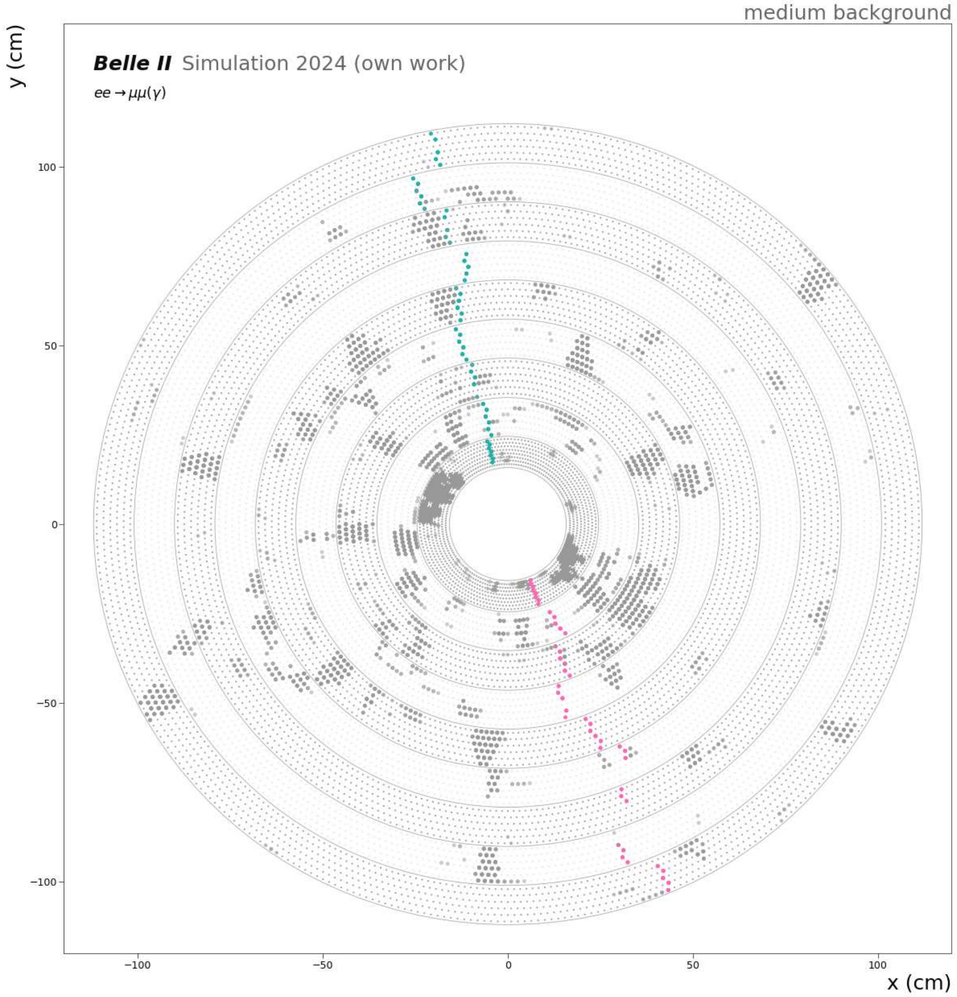
Graph Neural Network Output

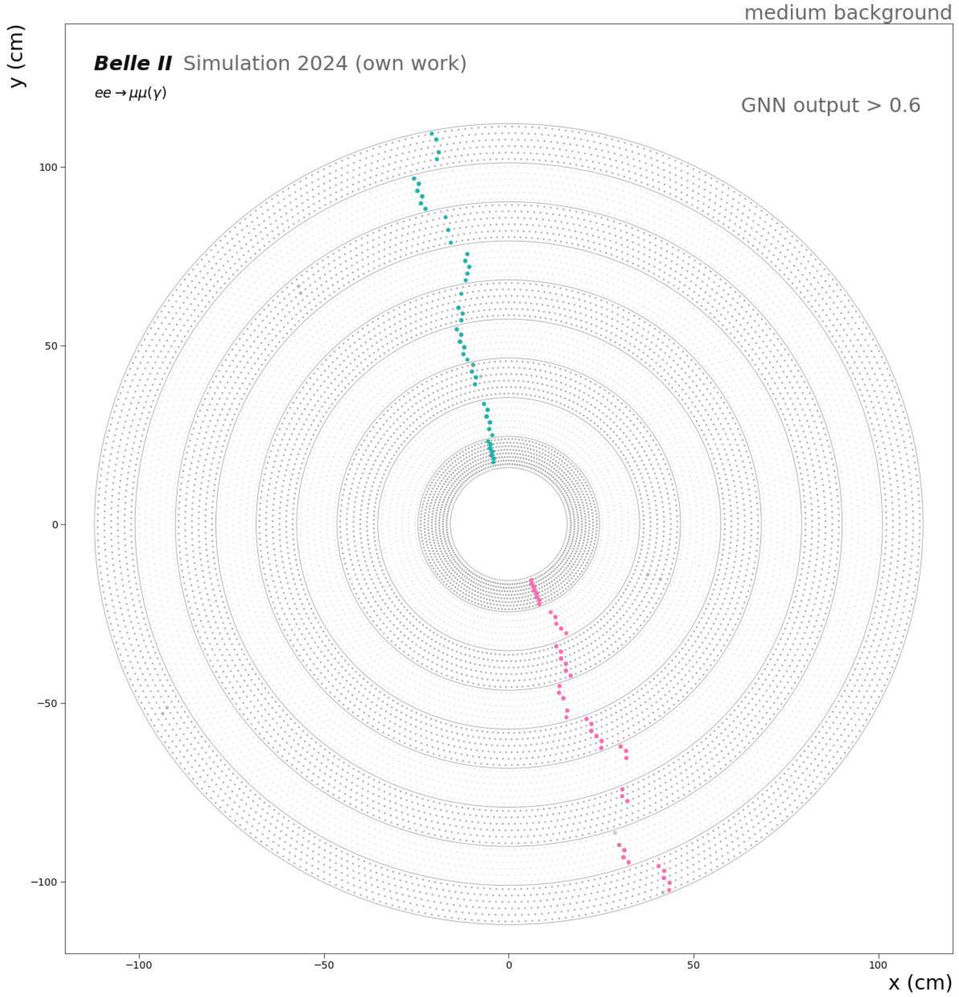


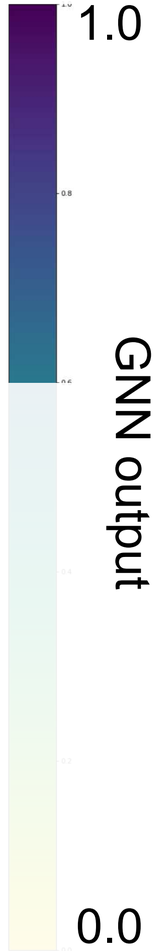




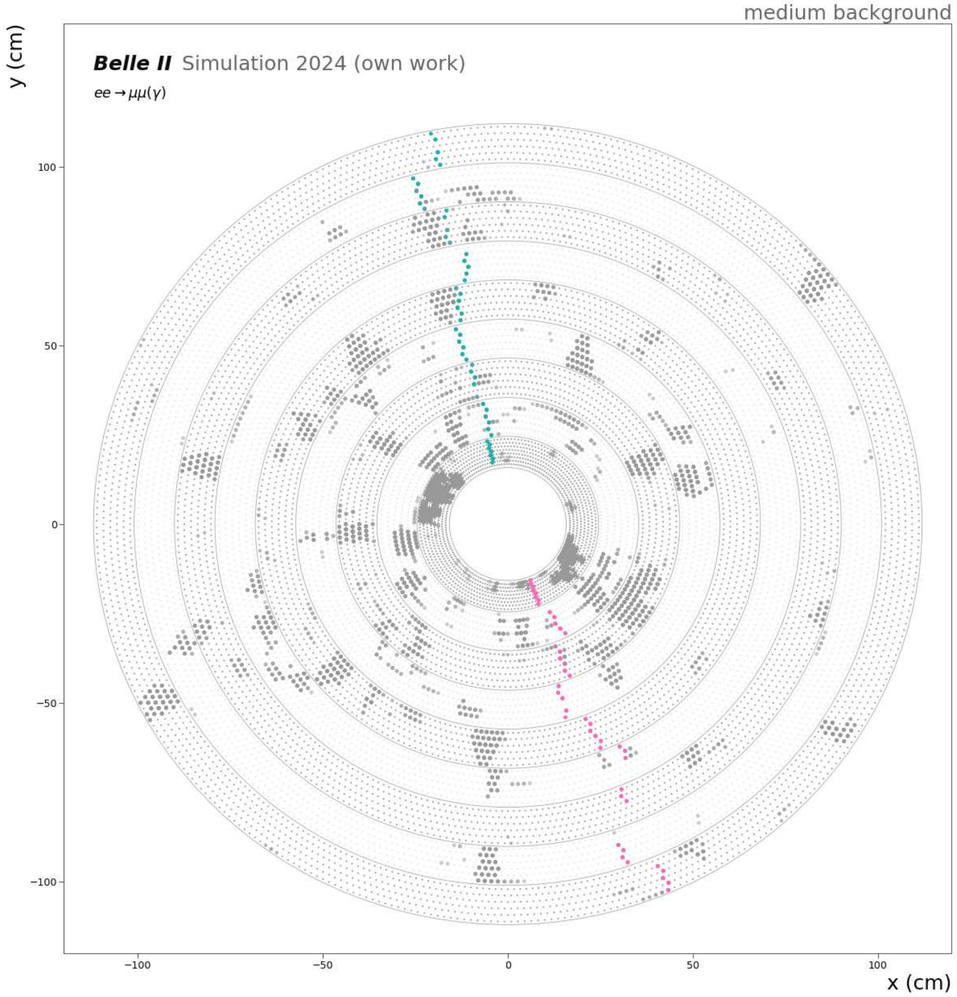
Graph Neural Network Output

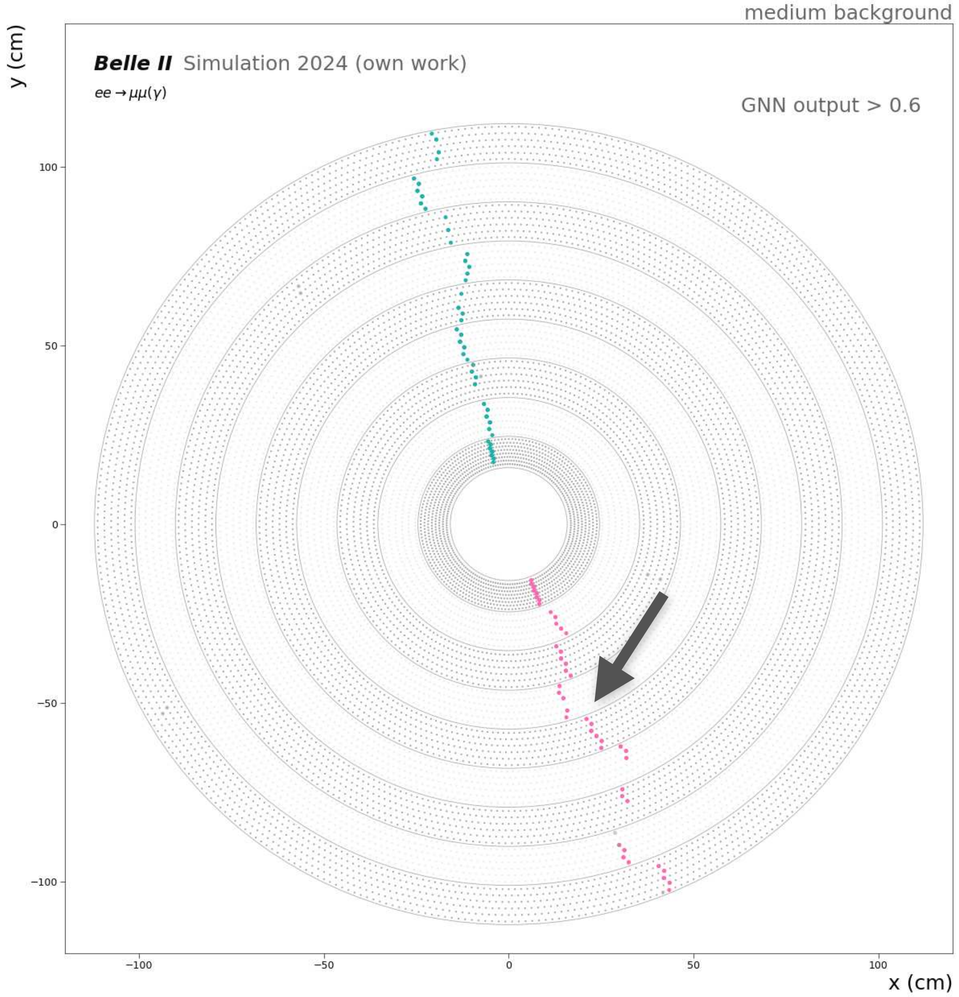


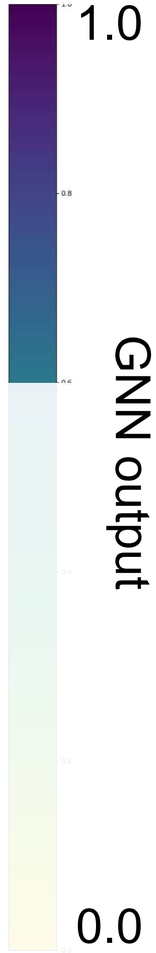




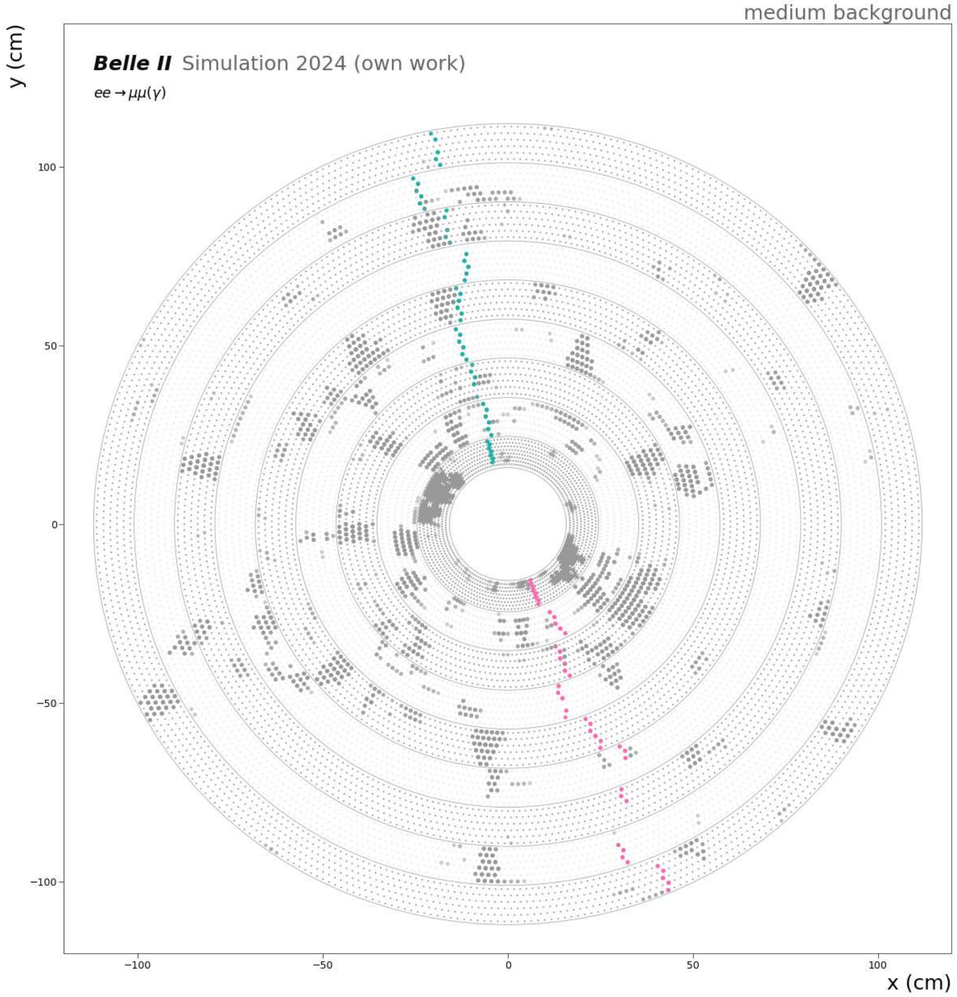
Graph Neural Network Output

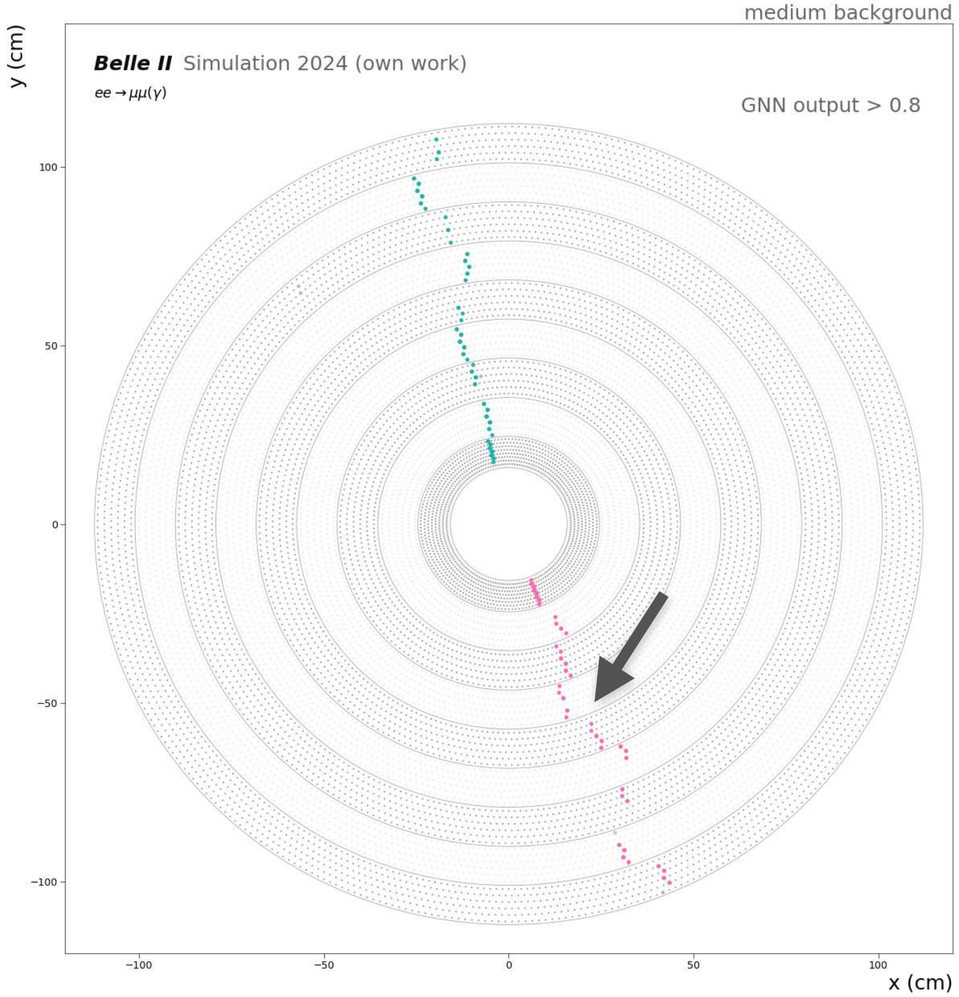


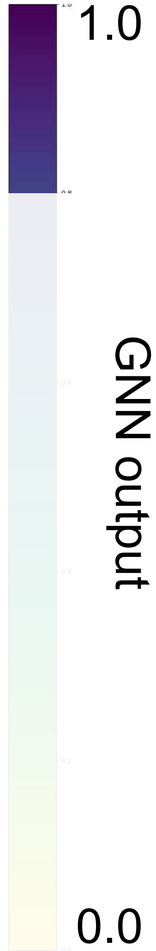




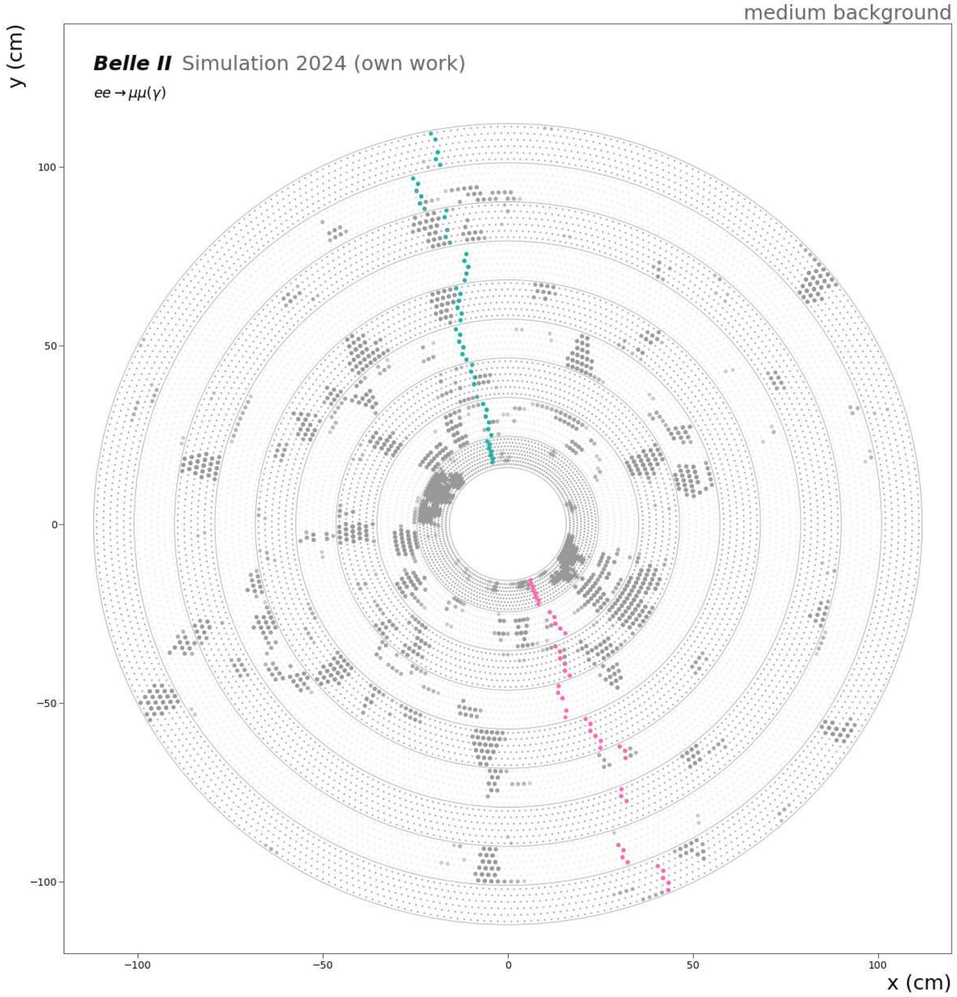
Graph Neural Network Output

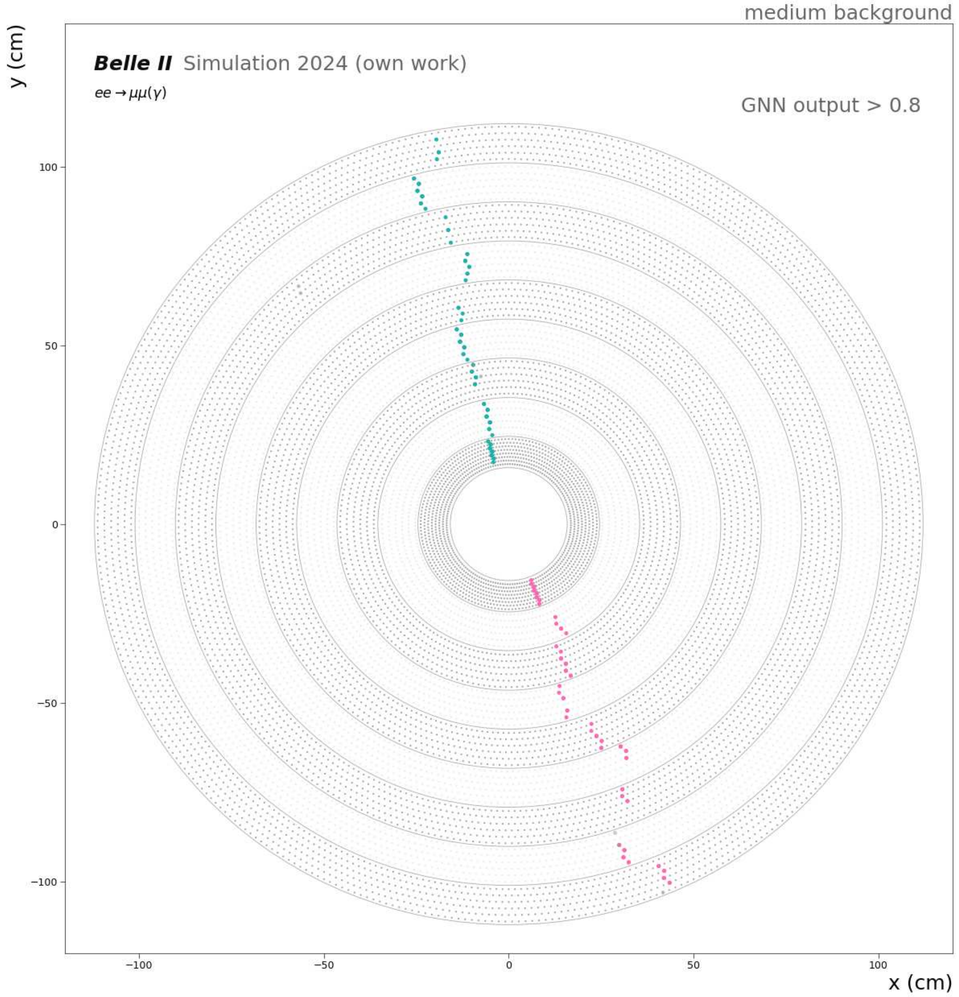


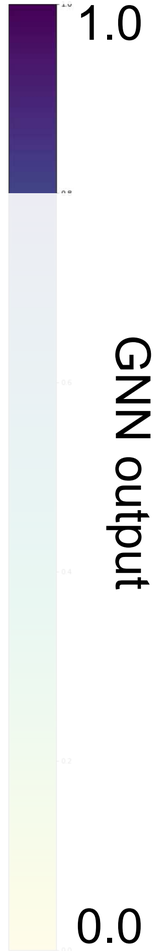




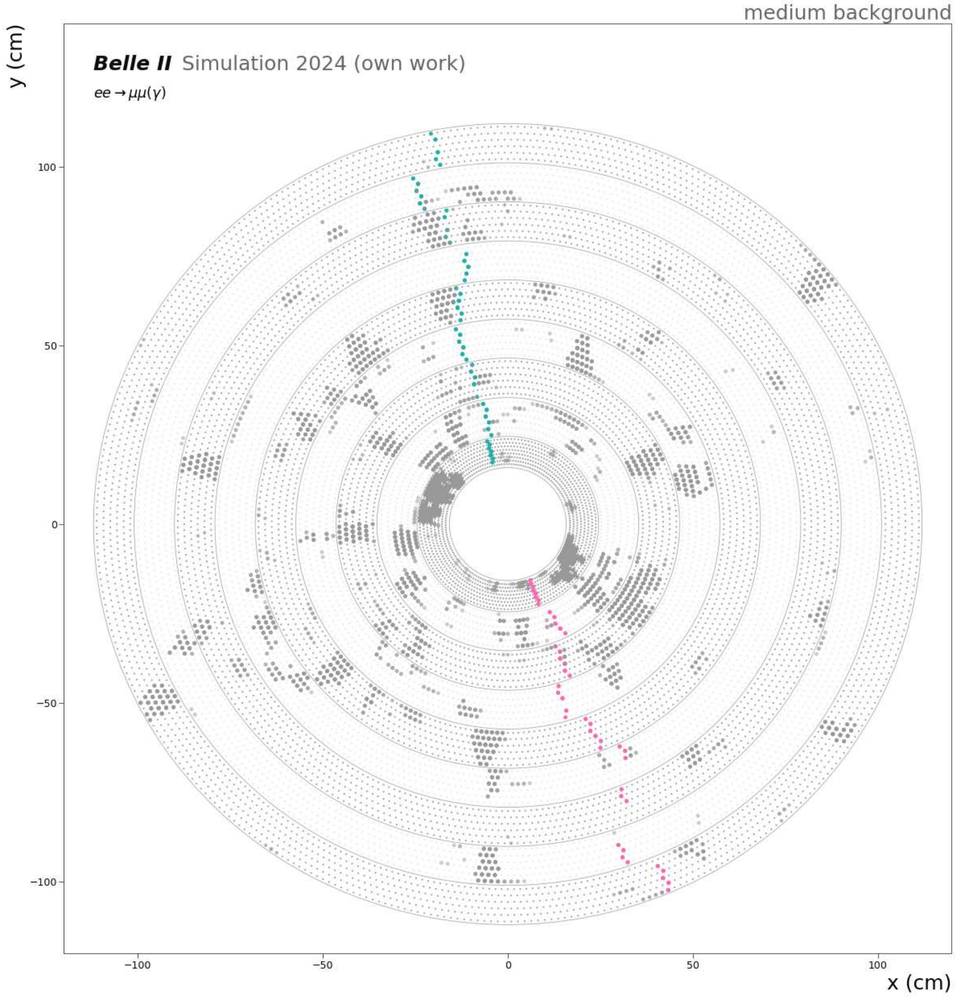
Graph Neural Network Output

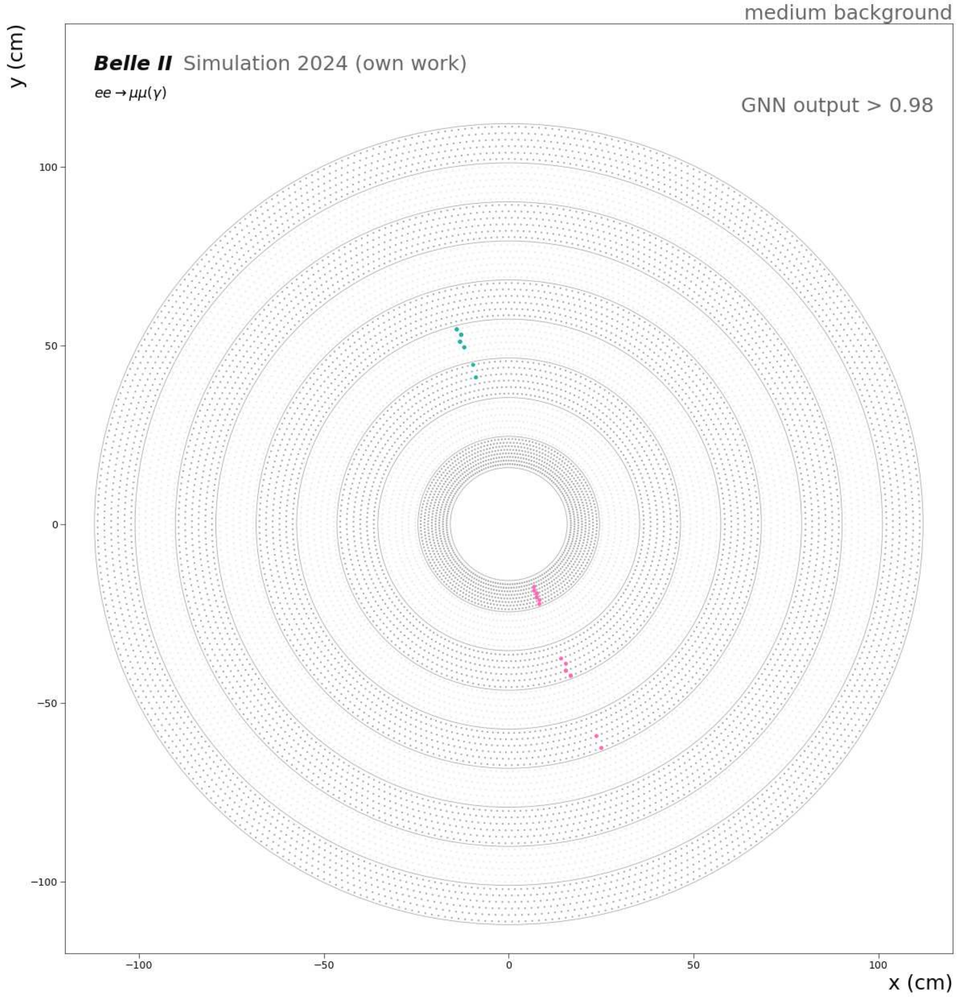


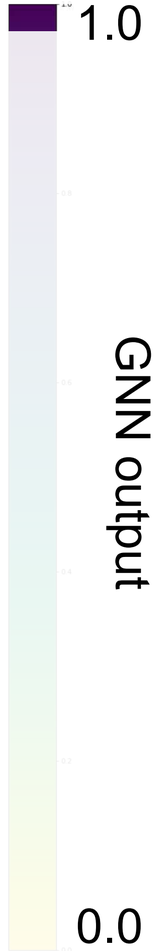




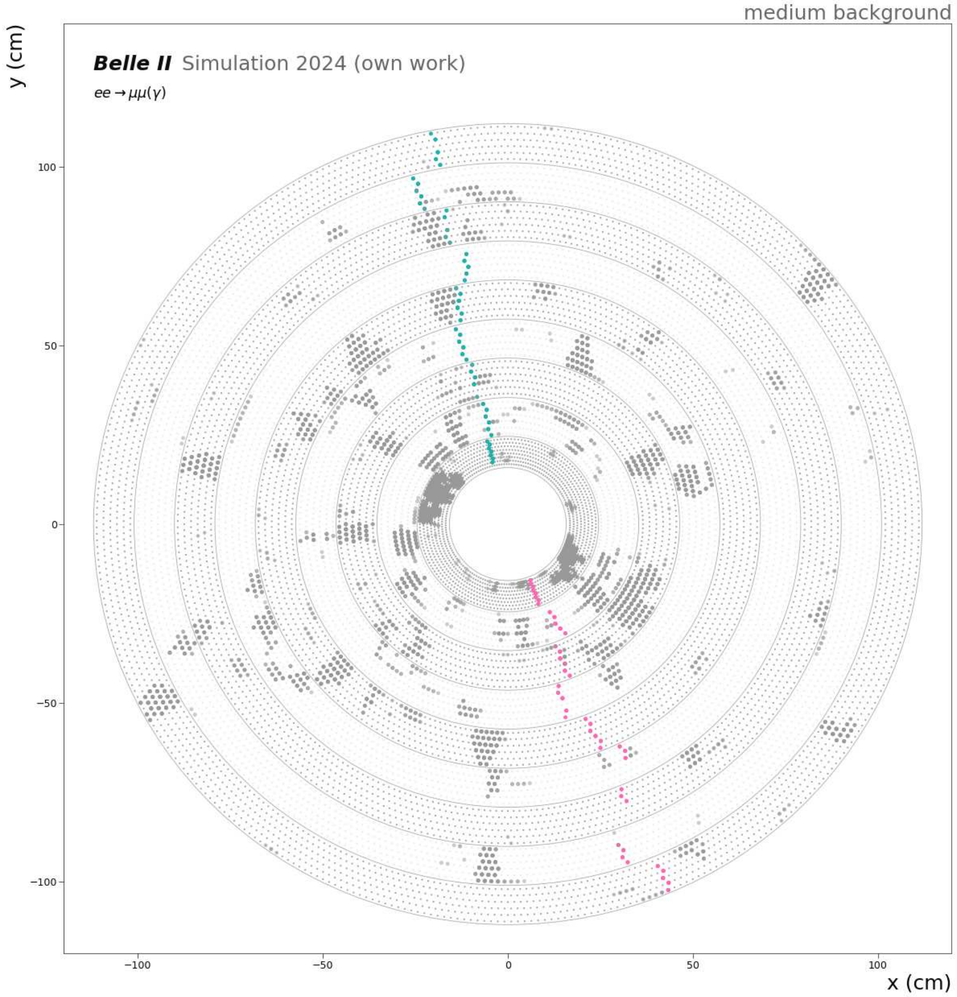
Graph Neural Network Output

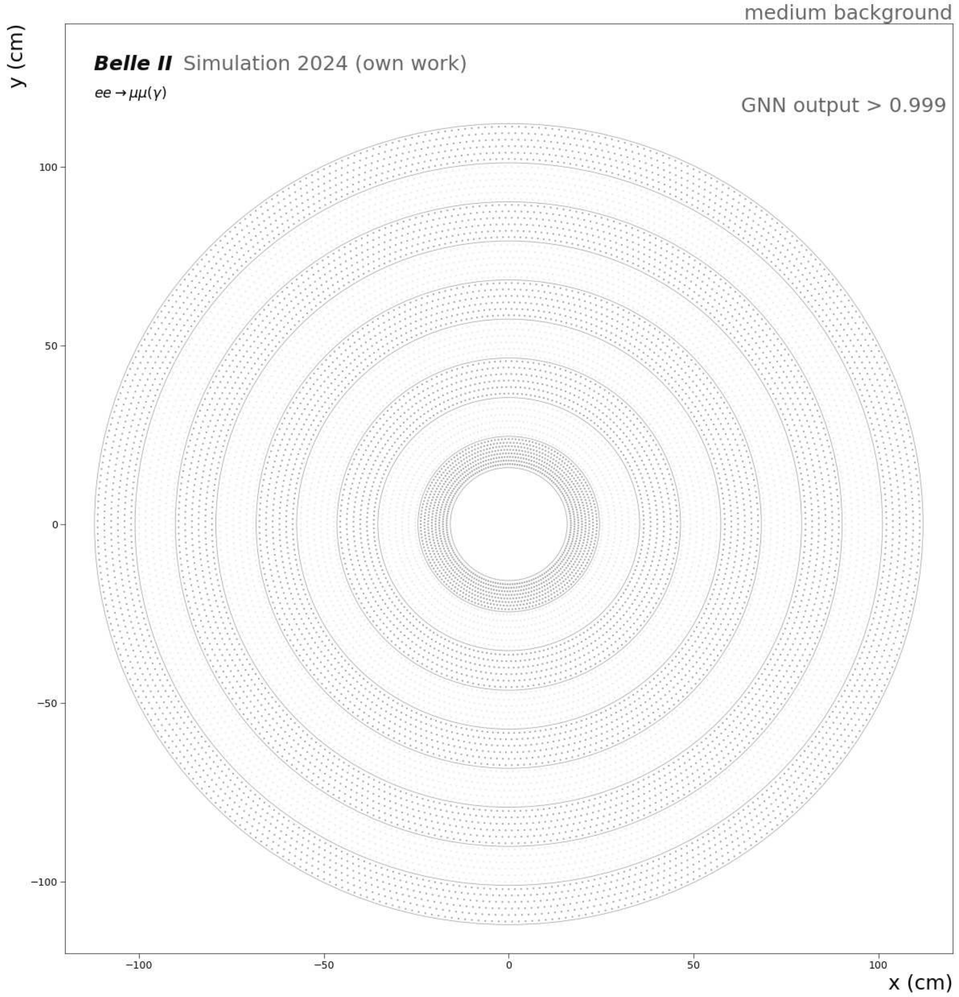


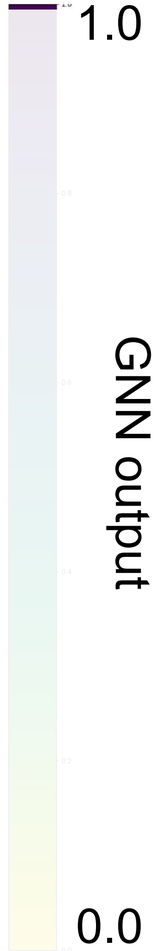




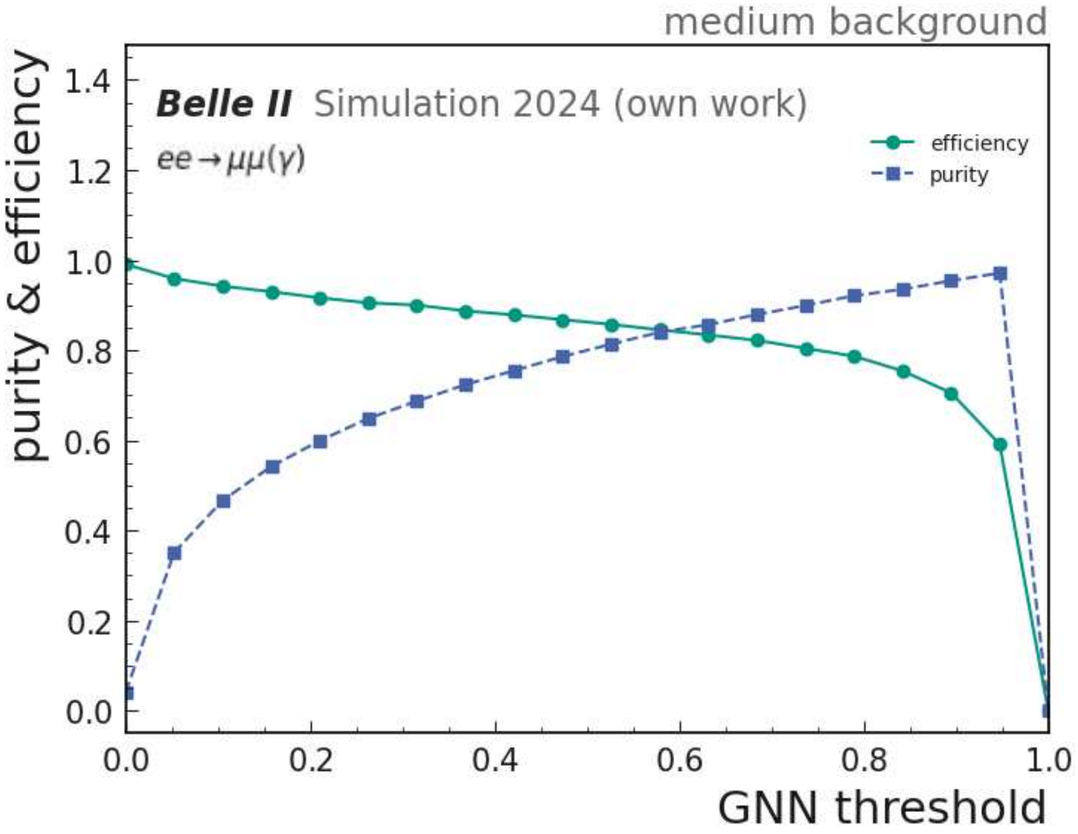
Graph Neural Network Output







Hit Cleanup Results



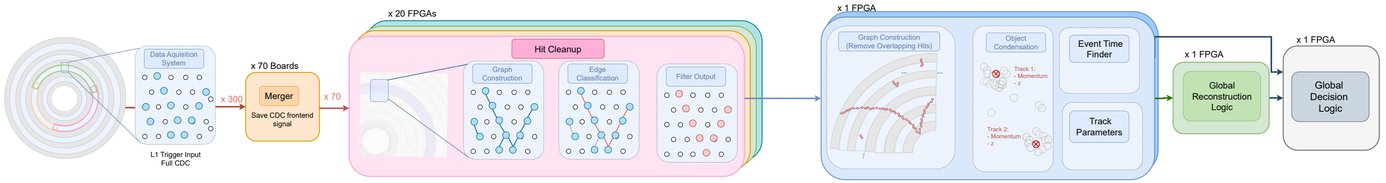
$$\text{efficiency} = \frac{\text{kept signal hits}}{\text{all signal hits}}$$

„how much of signal hits kept“

$$\text{purity} = \frac{\text{kept signal hits}}{\text{all kept hits}}$$

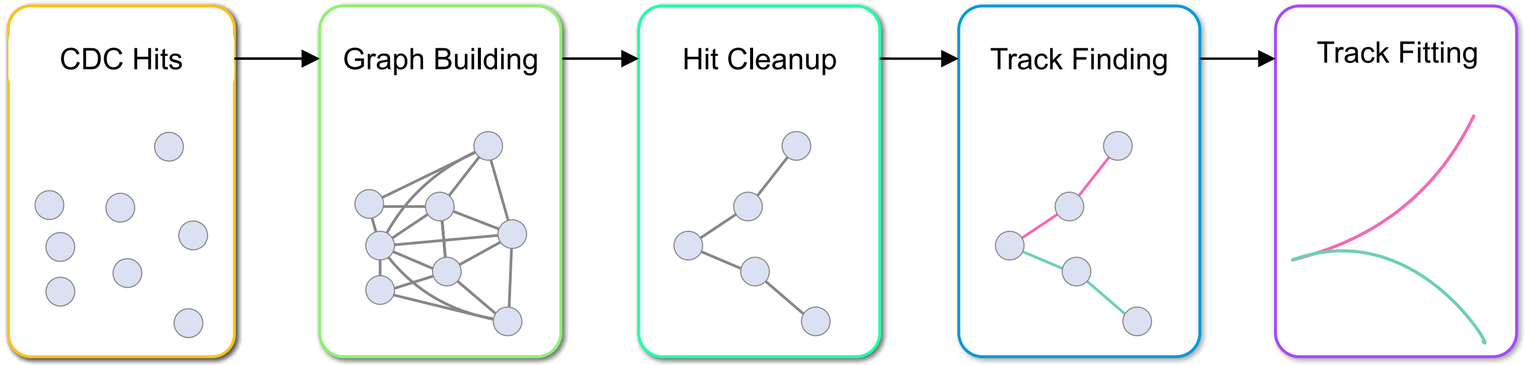
„how much of kept hits are signal“

Summary



- tracking/ trigger is challenging for higher backgrounds
- hit clean up with GNNs shows promising results

GNN-based Tracking Pipeline



FPGA *

arXiv:2307.07289

work in progress...

Next talk: Marc Neu

* Collaboration with ITIV (Department of Electrical Engineering and Information Technology at KIT)

Hit Cleanup Outlook

Tracking pipeline

- integrate hit cleanup into full tracking pipeline
- benchmark samples

offline

CDC segmentation

- segmentation by superlayer & angle
- overlaps, merging

offline

Data

- run on data
- compare with existing triggers

online

FPGA implementation

- size reduction studies
- implementation

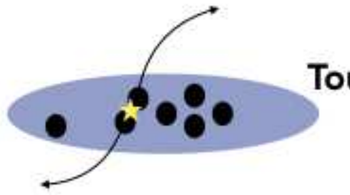
online

Backup

Belle II backgrounds

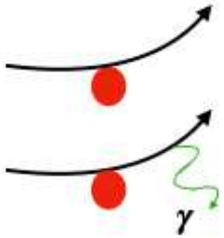
Background Processes

Particle Scattering



Touschek Scattering

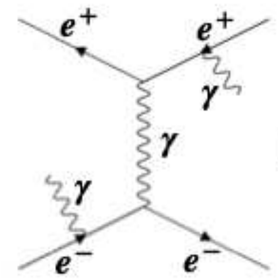
$$\propto N_{particles} \times \rho \propto I \times \frac{I}{n_b \sigma_b}$$



Coulomb Scattering + Bremsstrahlung

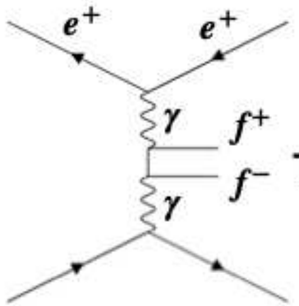
$$\propto N_{particles} \times N_{gas\ molecules} \propto P \times I \times Z_{eff}^2$$

Luminosity



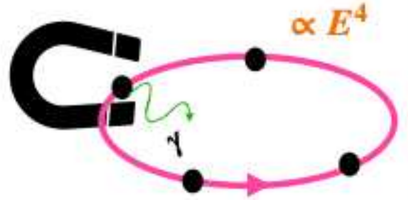
Radiative Bhabha

$\propto \mathscr{L}$



Two-photon

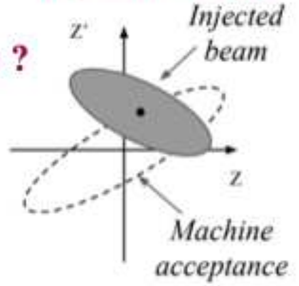
Synchrotron rad.



$\propto E^4$

Injection bkg.

$\propto$?

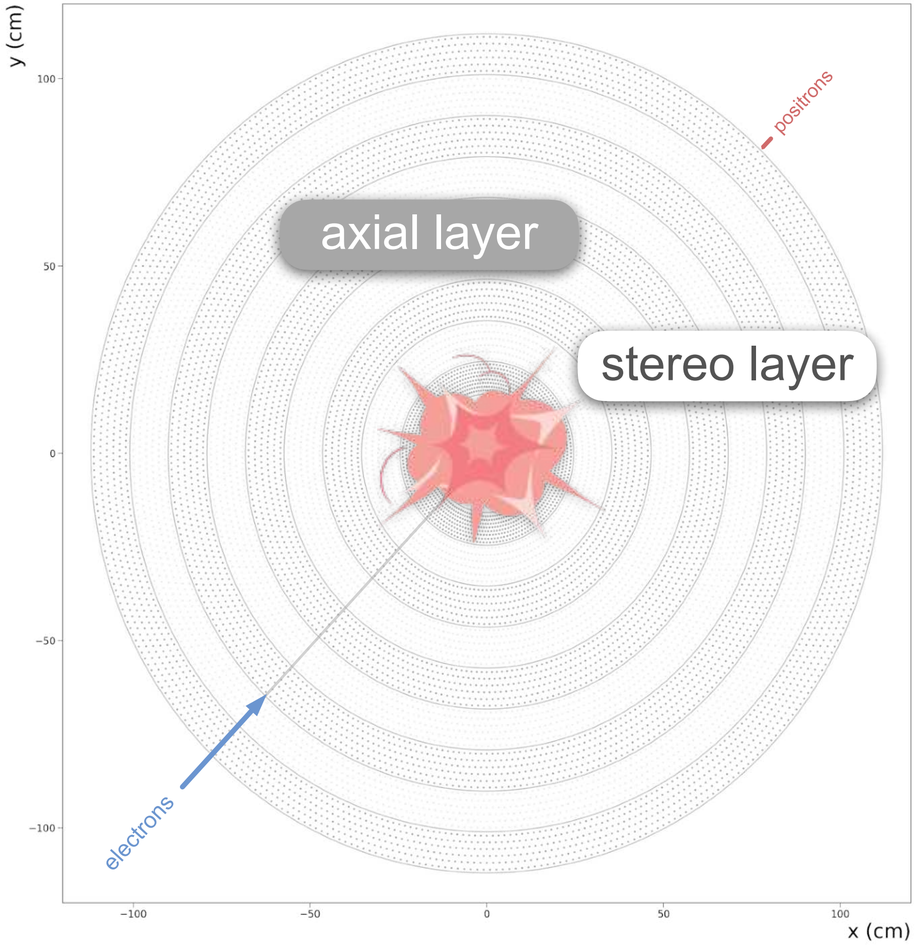


Slavomira Stefkova, slavomira.stefkova@kit.edu

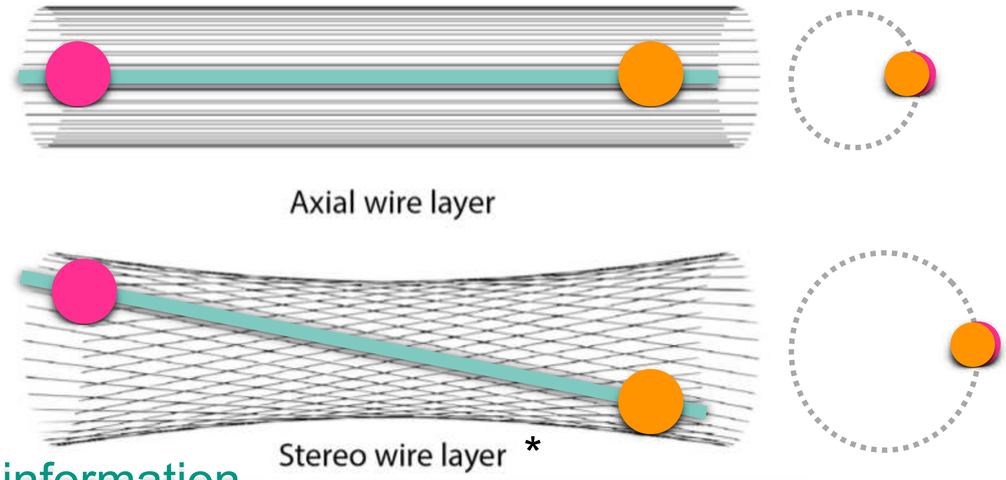
3

Belle II Group Meeting

Central Drift Chamber (CDC)



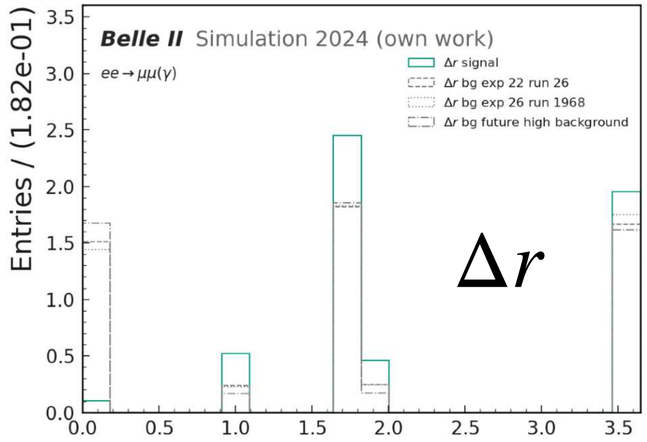
- xy projection
- ≈ 15 000 wires
- 9 super layers
- alternating axial and stereo layers

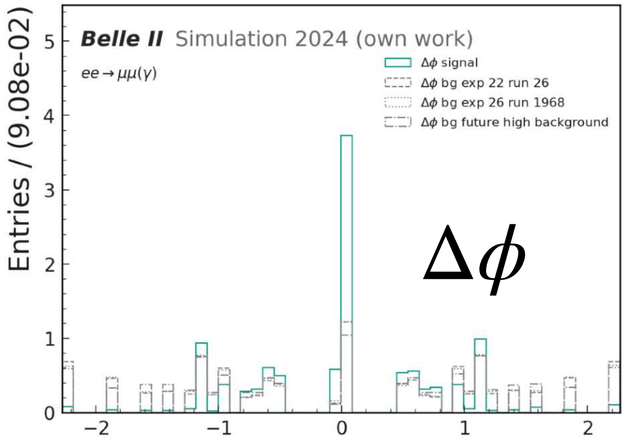


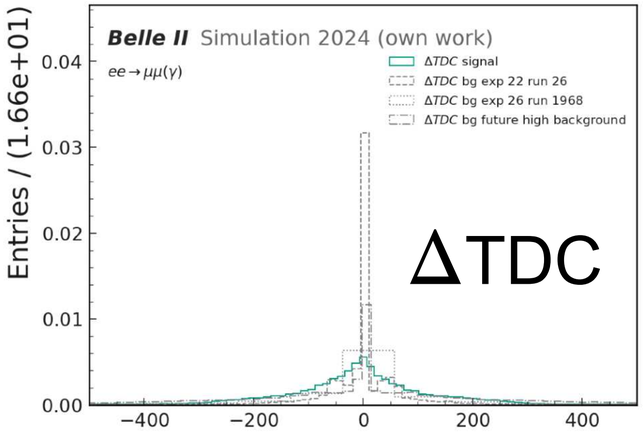
3D information

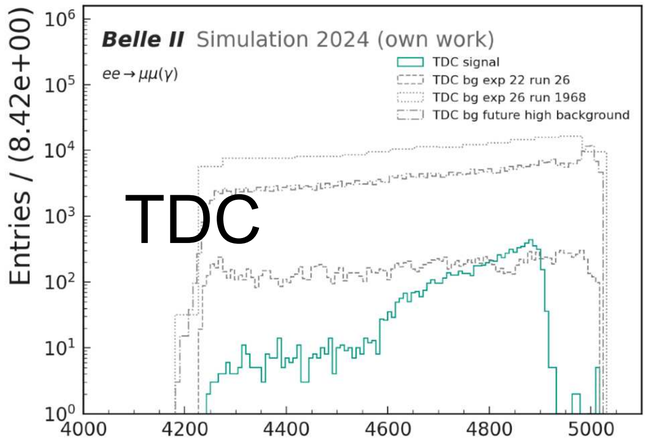
*rotation is hugely exaggerated for illustration

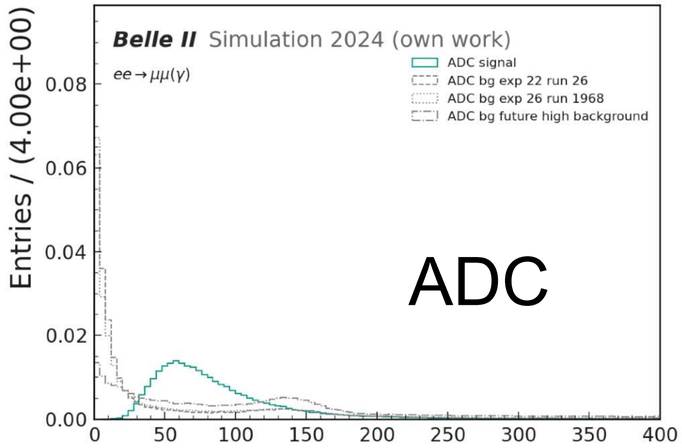
Feature Distributions



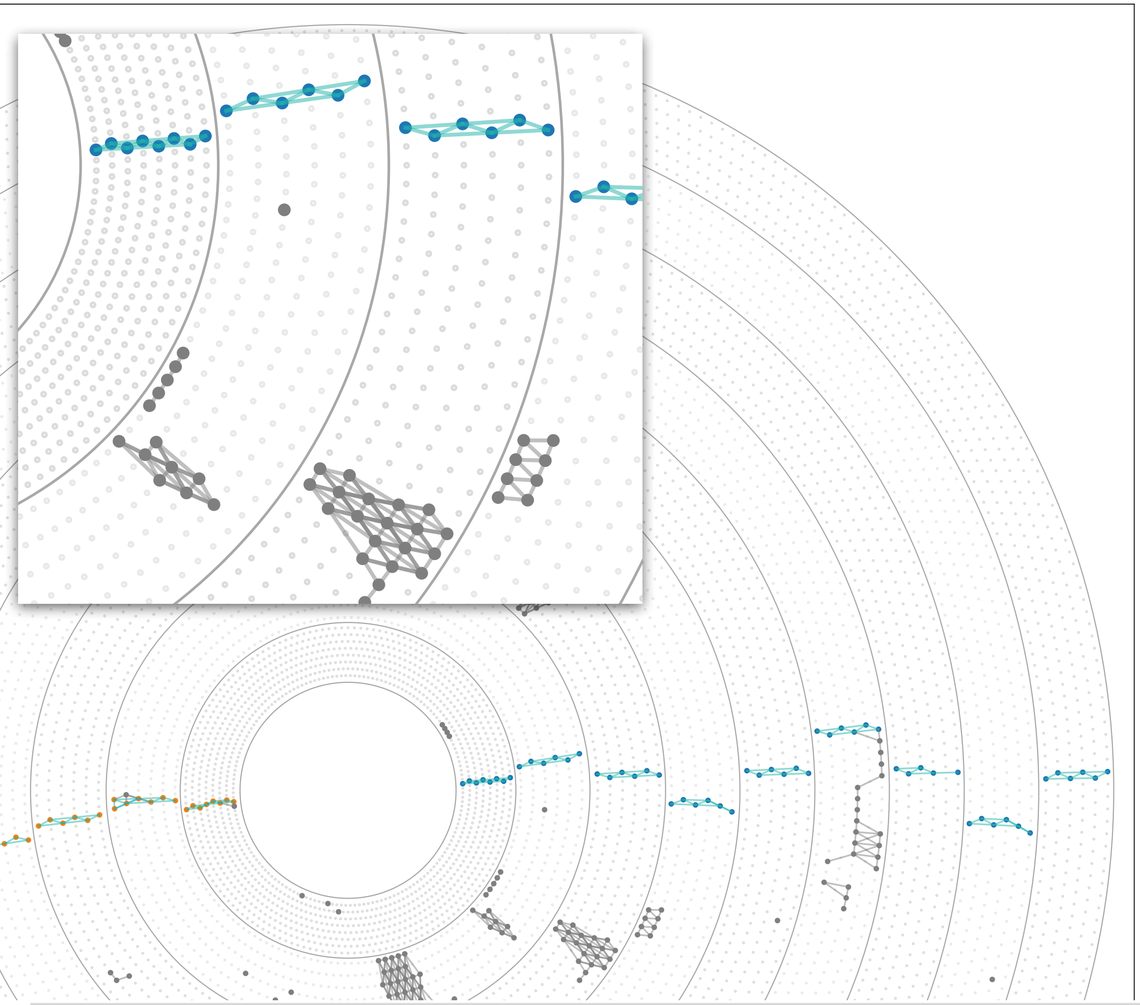






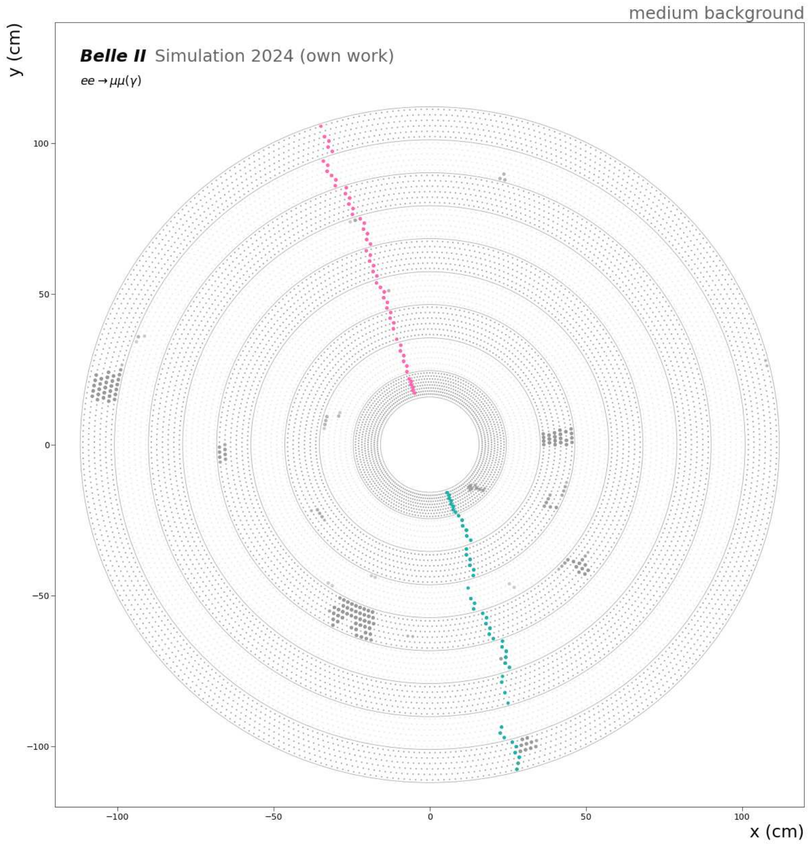


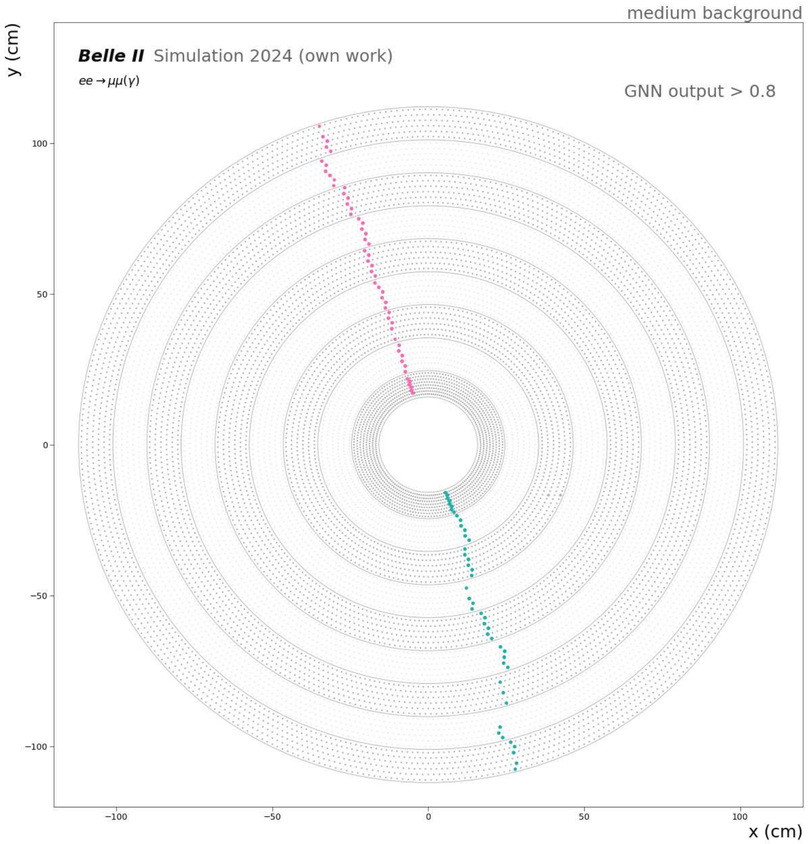
Graph Building: Results

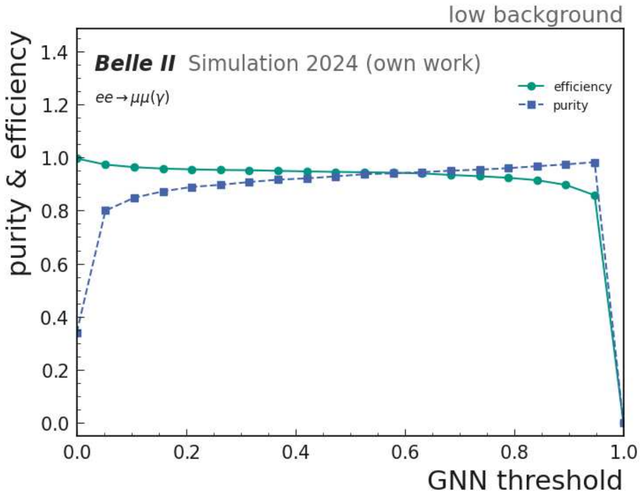


	low bg	medium bg	high bg
% Signal Hits	29.1%	3.7%	1.6%
# Hits	250	1800	3900
# Edges	500	4200	8200

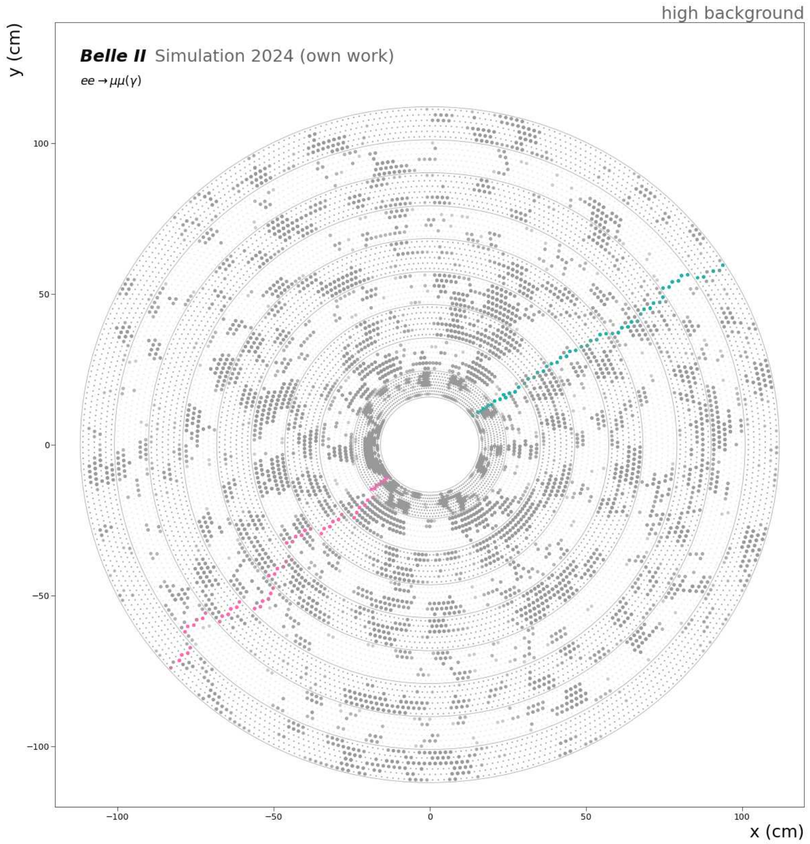
Hit Cleanup Example Low Background

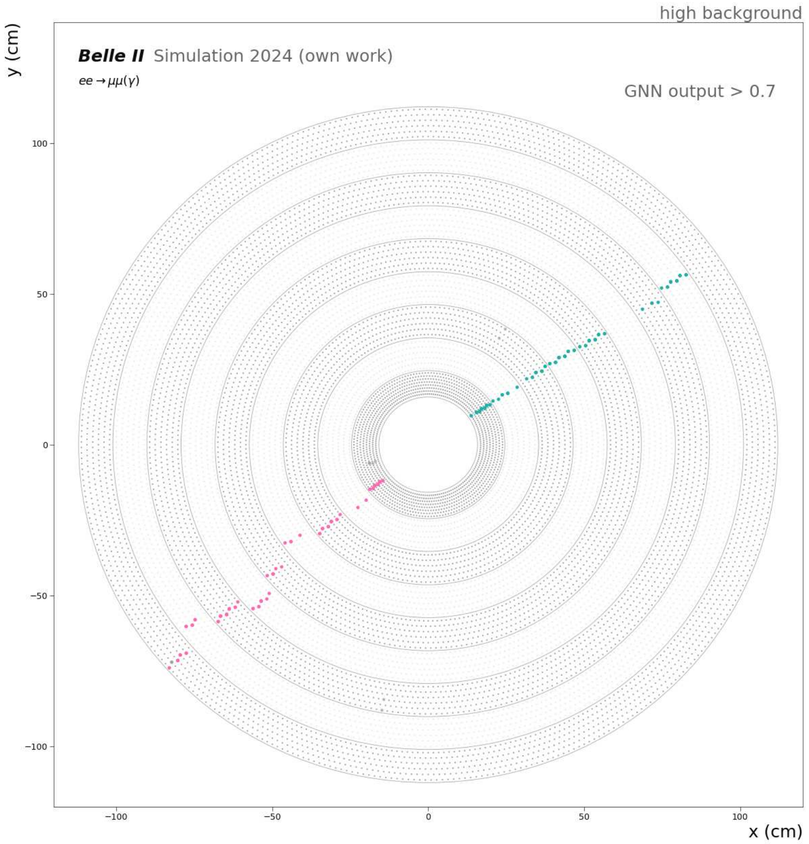


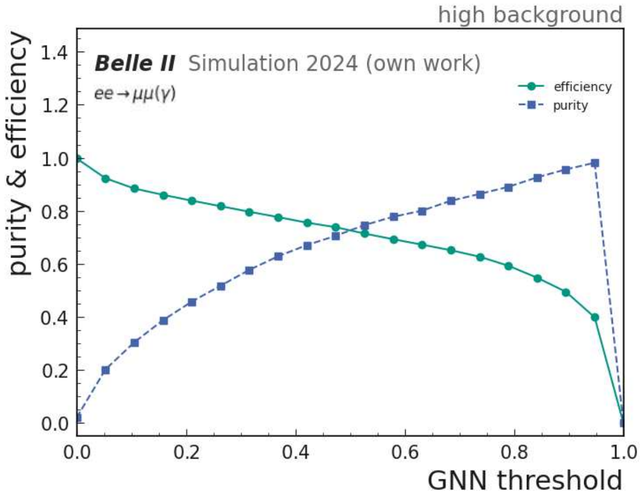




Hit Cleanup Example High Background







Graph Building Models

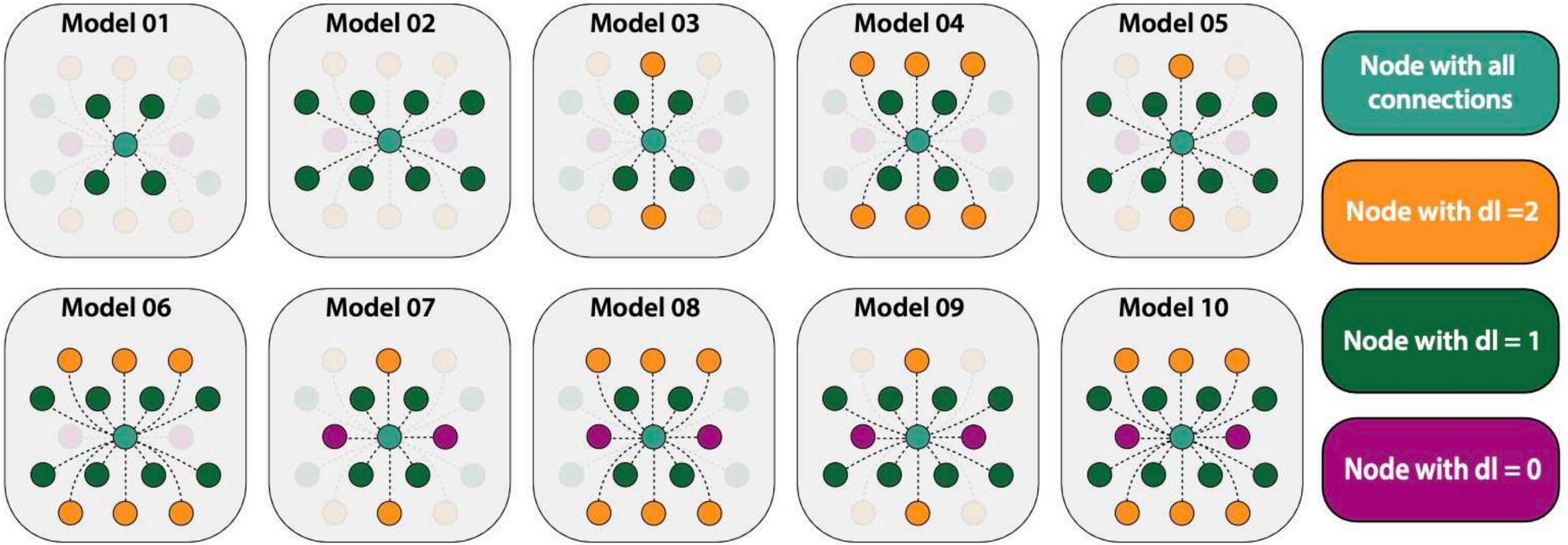
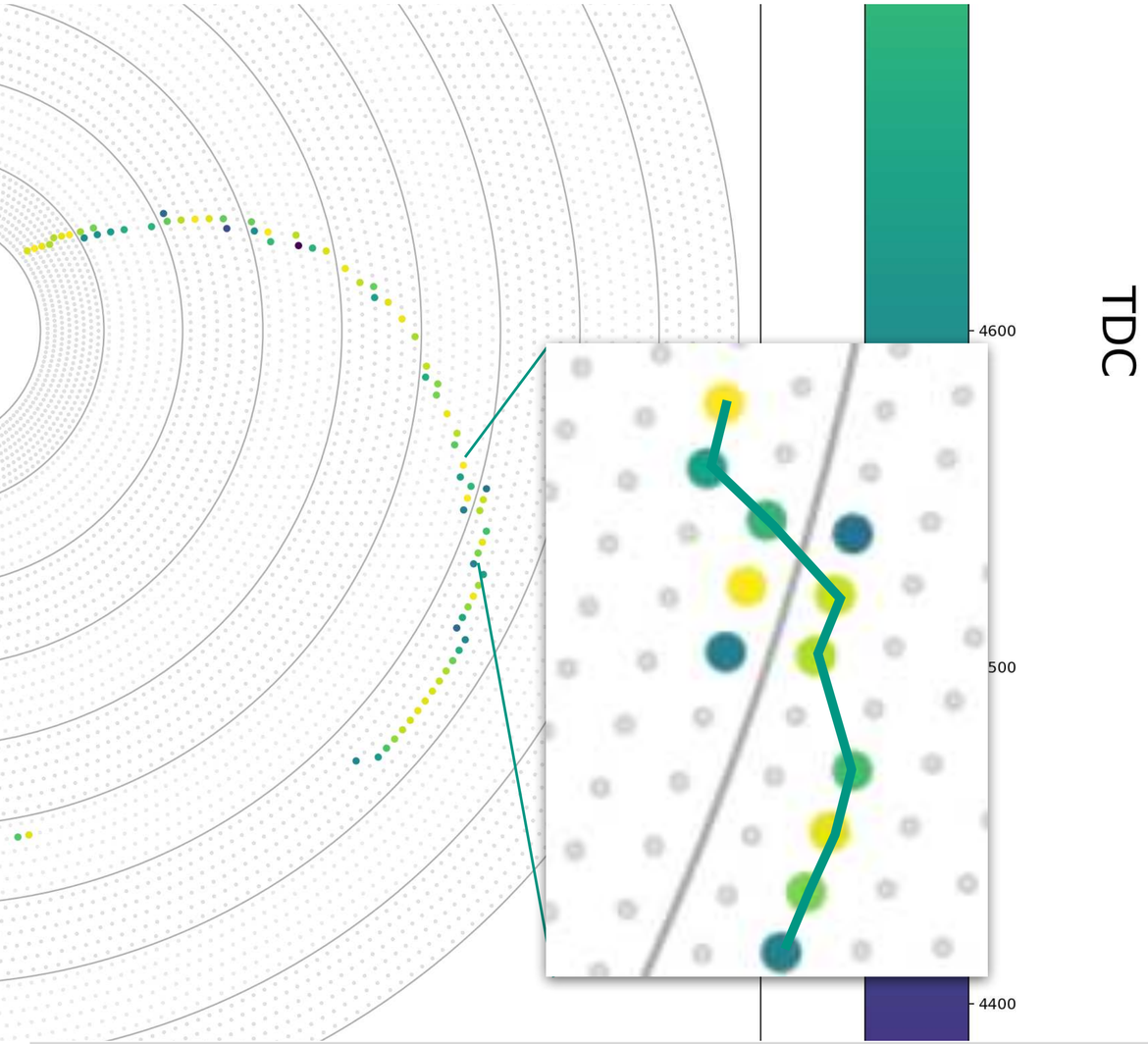


Figure 7.9.: Ten different graph-building patterns analyzed in this thesis, showing possible connections for a node in the Central Drift Chamber.

Masterthesis „Graph-Building and Input Feature Analysis for Edge Classification in the Central Drift Chamber at Belle II“ of Philipp Dorwarth, May 2023

True Hit Definition



- What hits do we want to keep?
  1) all hits from signal particles?
  2) or only some?

Object Condensation Track Finding