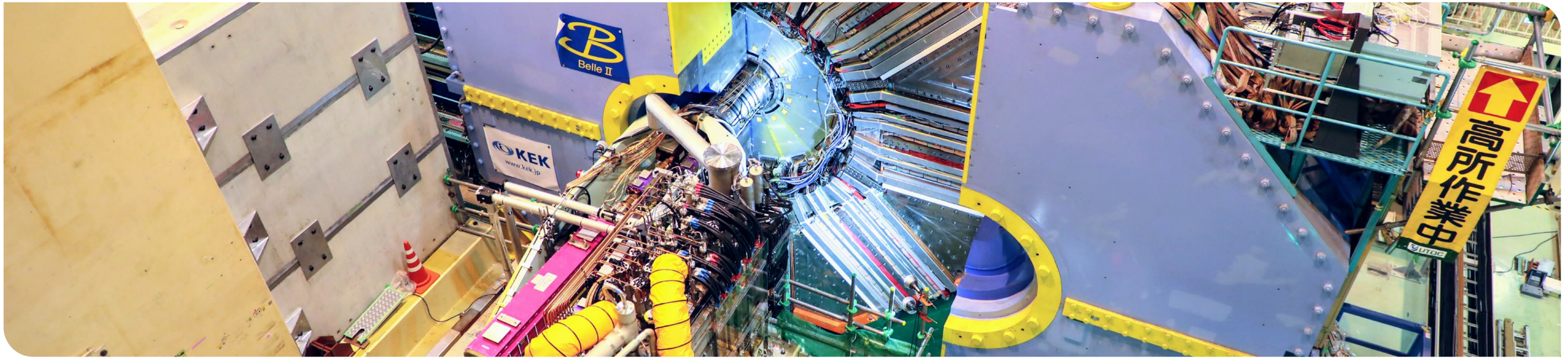
Karlsruhe Institute of Technology

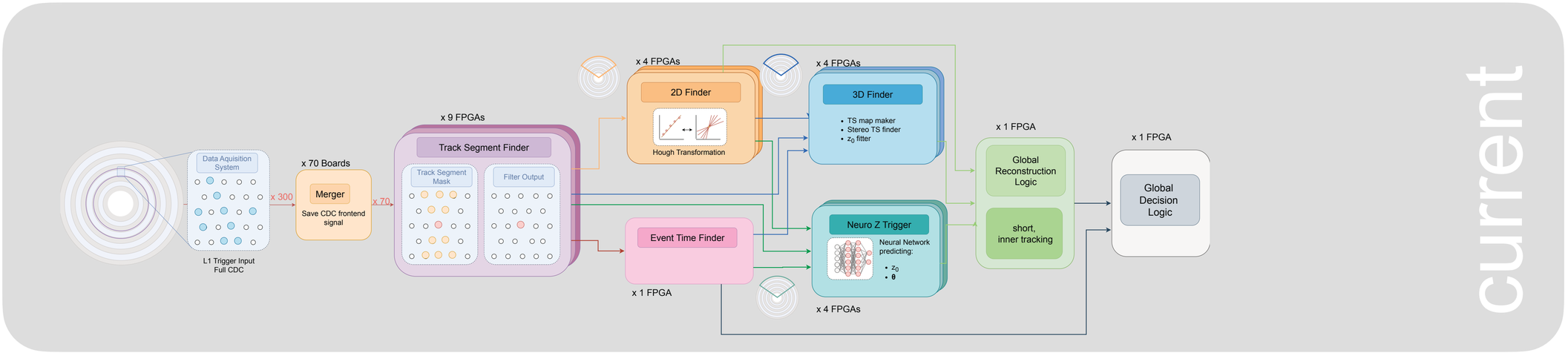
Institute of Experimental Particle Physics

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

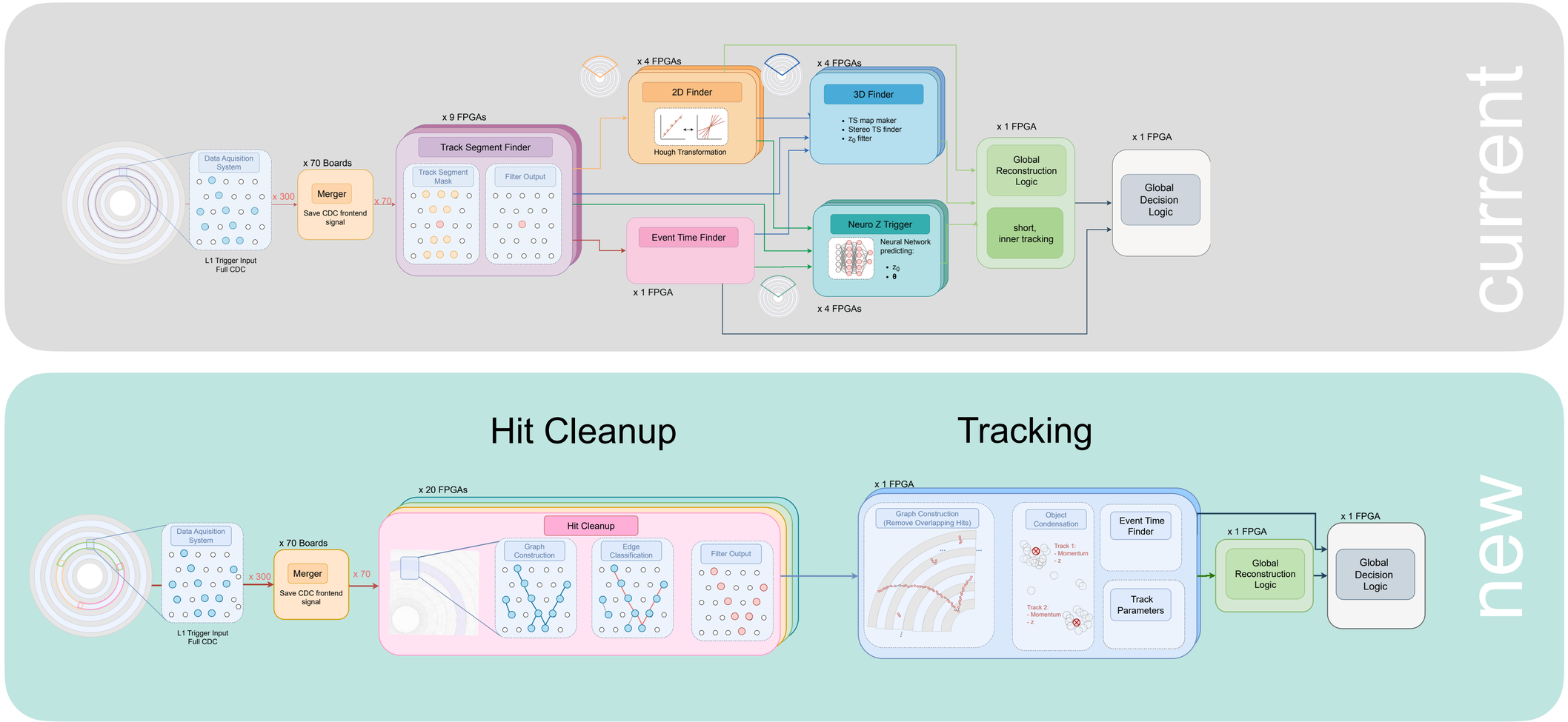
Greta Heine, Torben Ferber, Lea Reuter, Slavomira Stefkova | 10.04.2024



New CDC Trigger



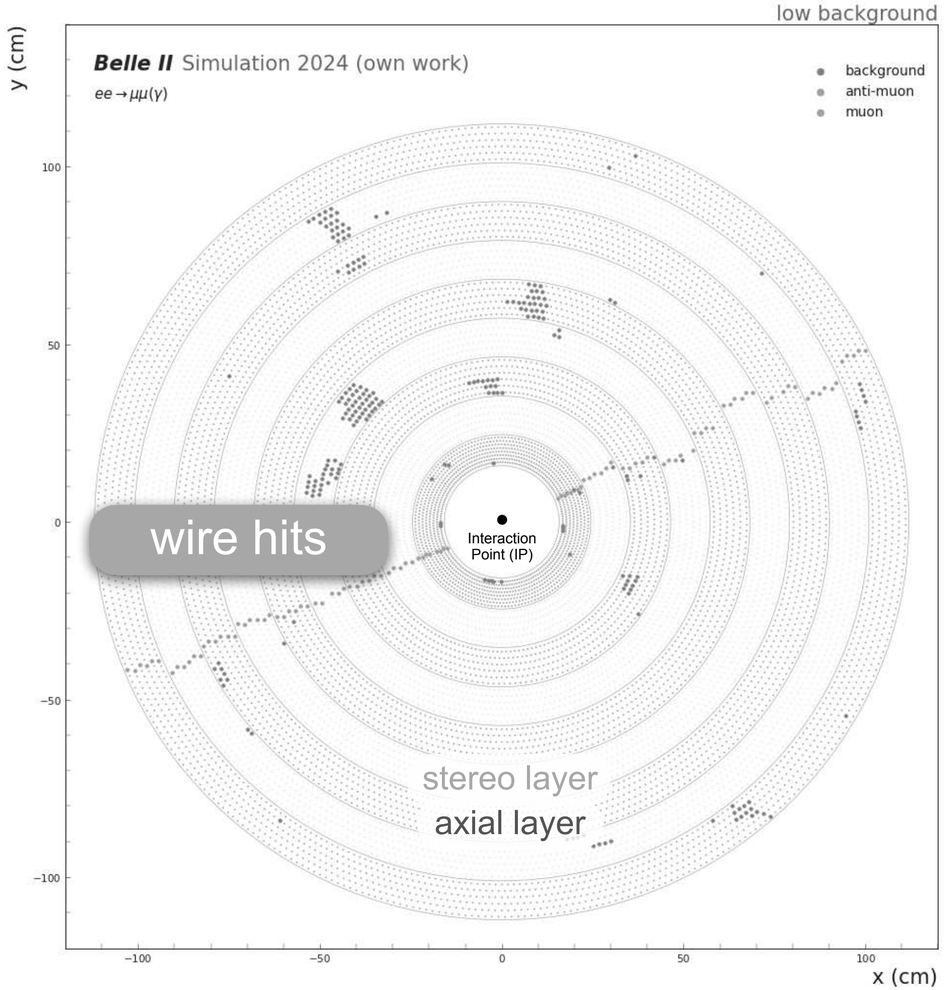
New CDC Trigger



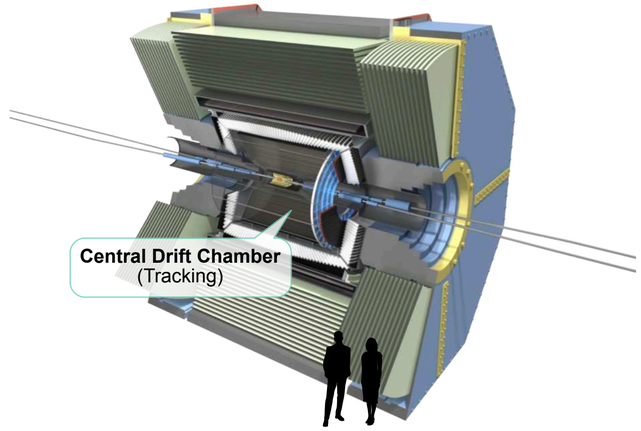
The Problem

The Problem Challenge

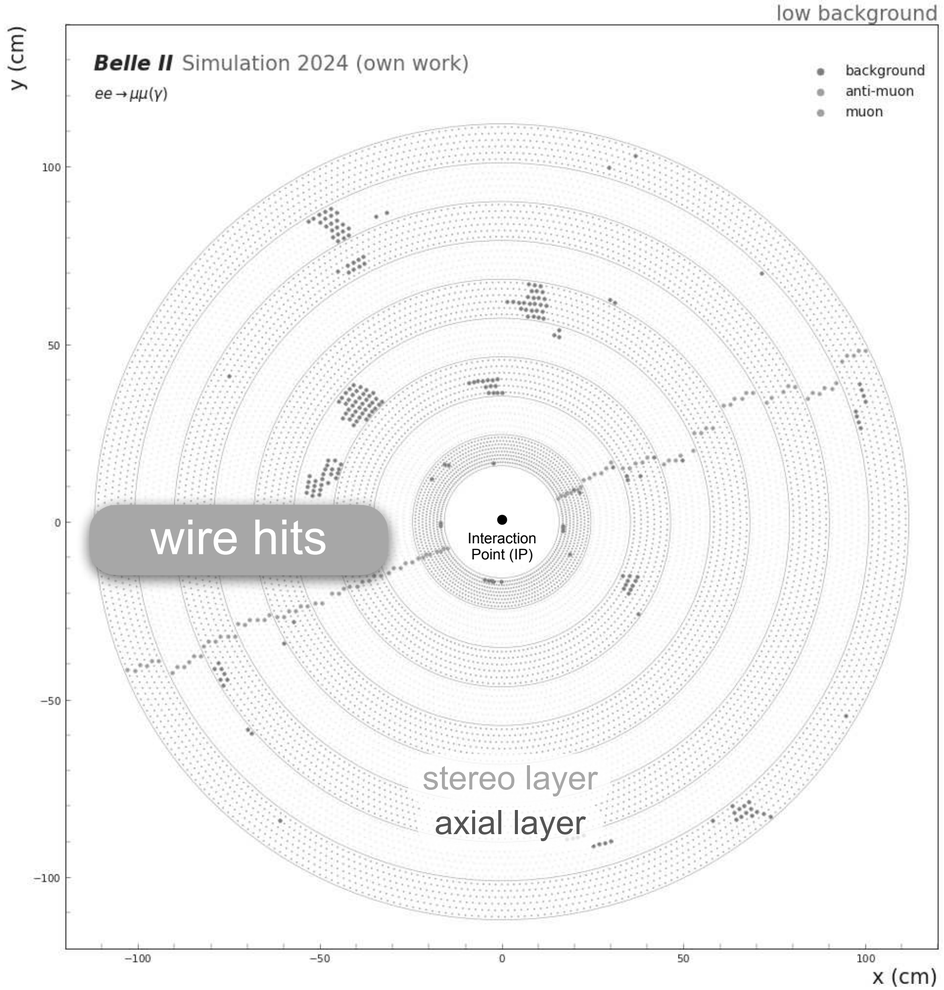
Central Drift Chamber Event Display



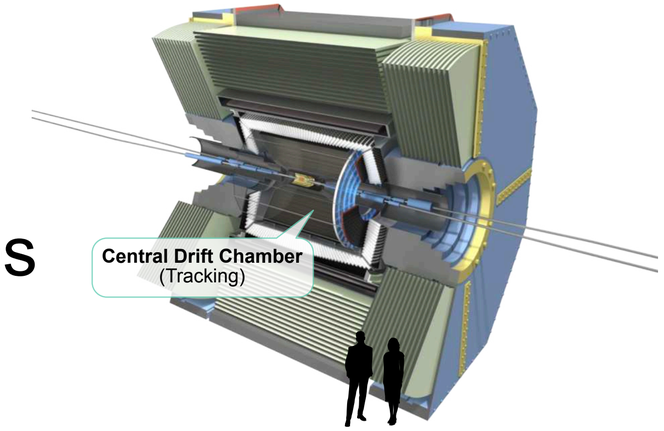
- xy projection



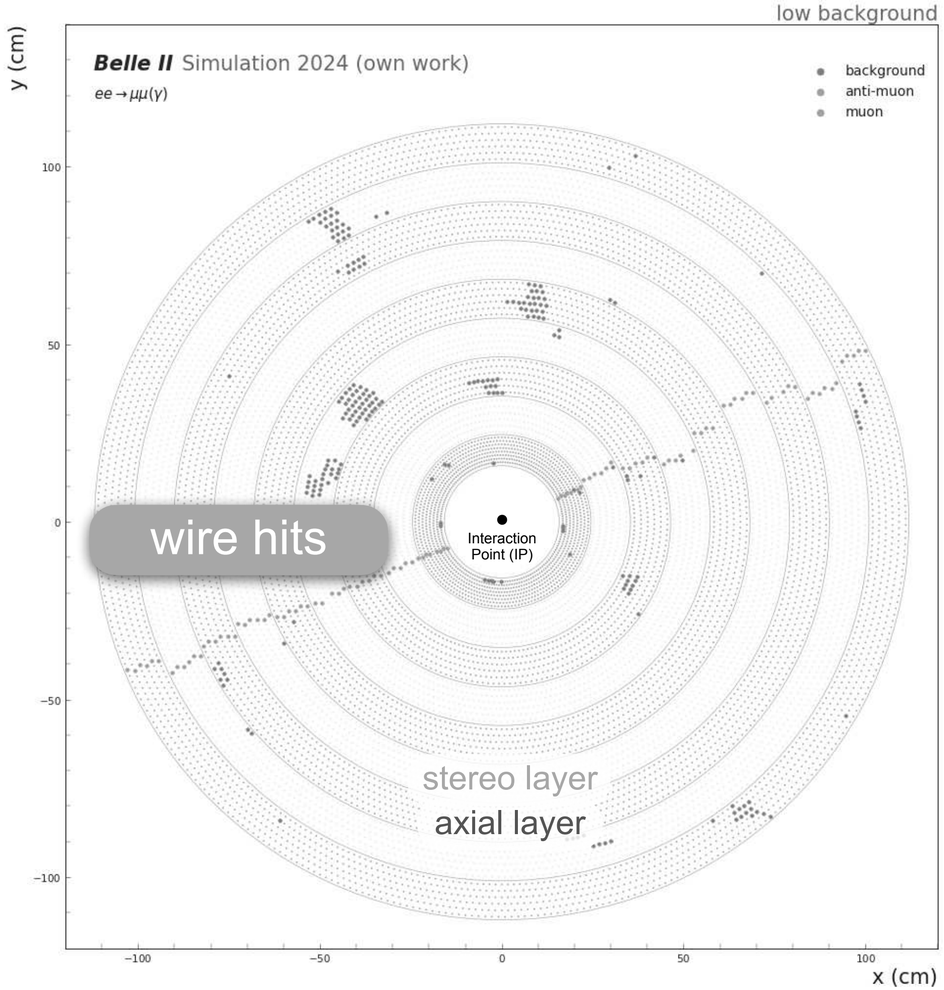
Central Drift Chamber Event Display



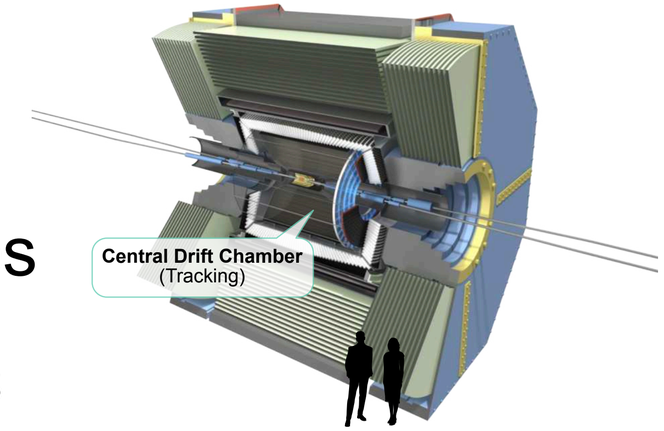
- xy projection
- ≈ 15 000 wires



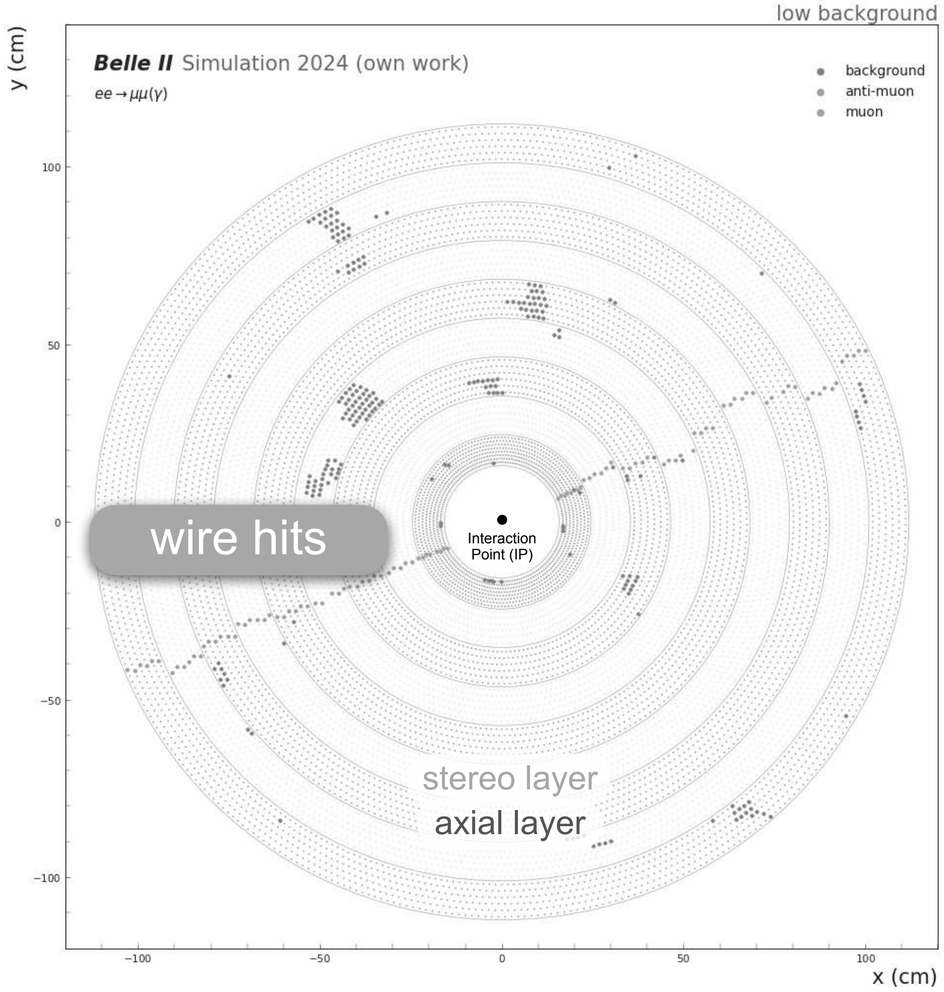
Central Drift Chamber Event Display



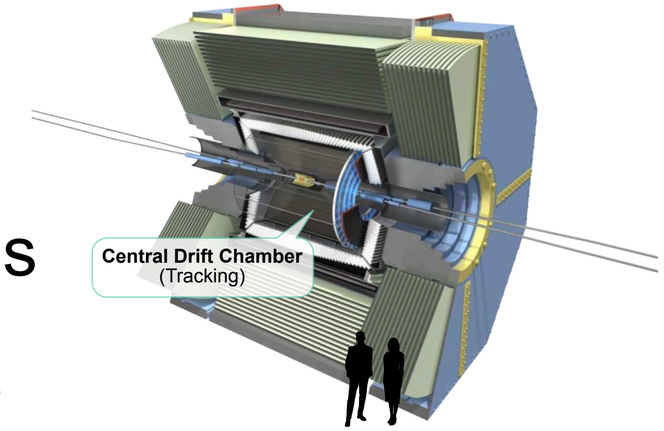
- xy projection
- ≈ 15 000 wires
- 9 super layers

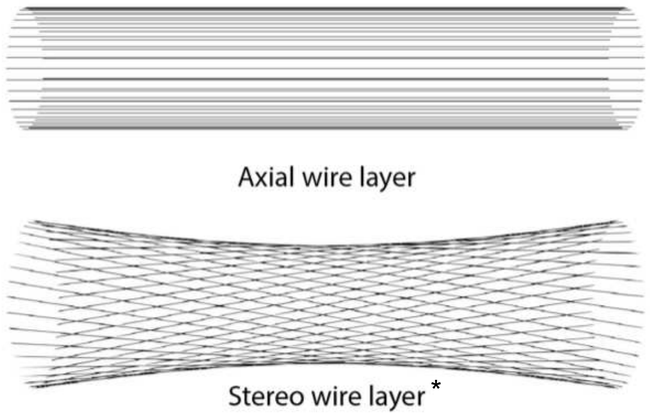


Central Drift Chamber Event Display



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

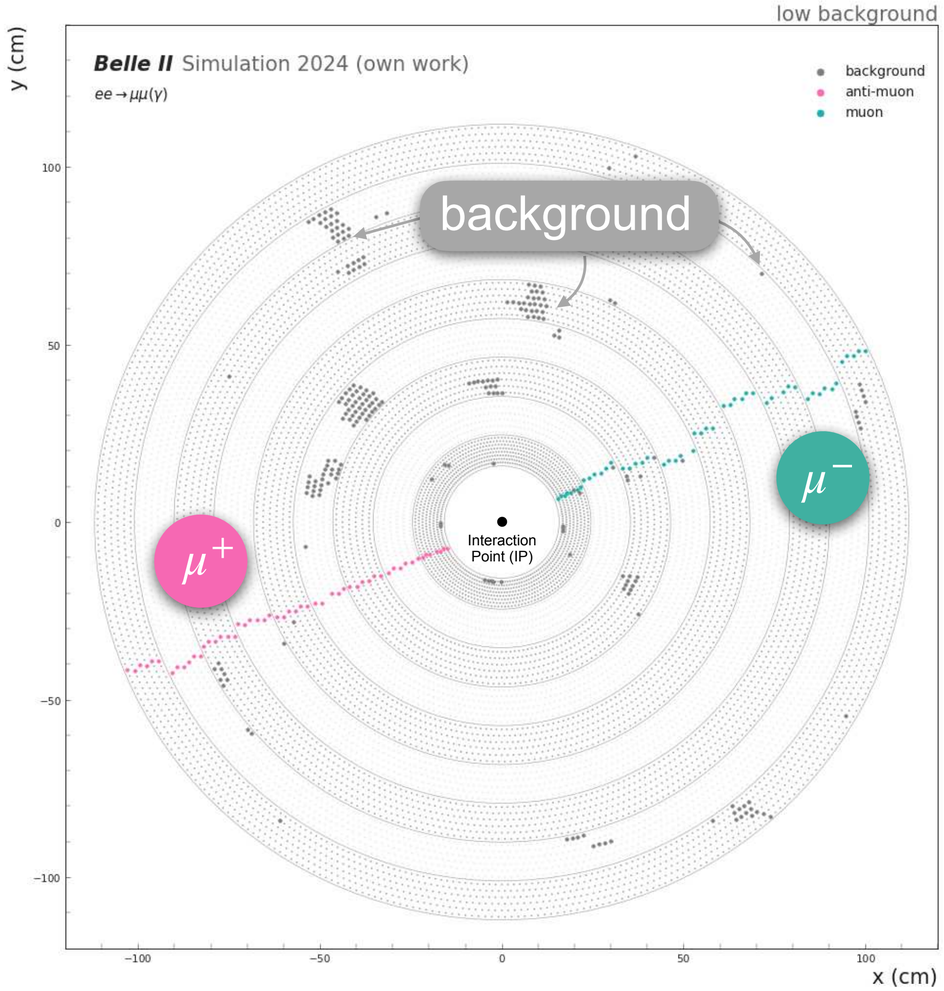




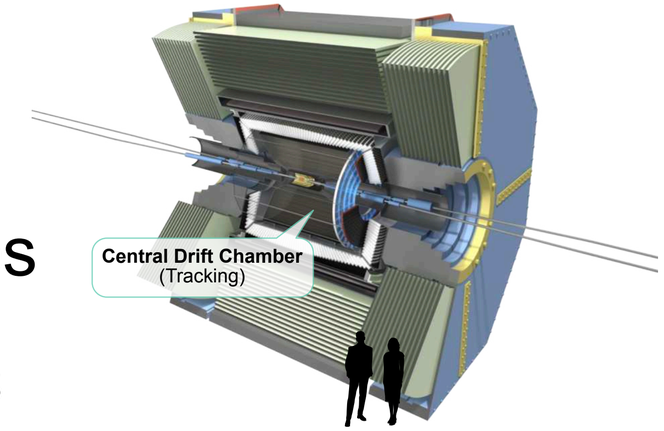
3D information

*rotation is hugely exaggerated for illustration

Central Drift Chamber Event Display

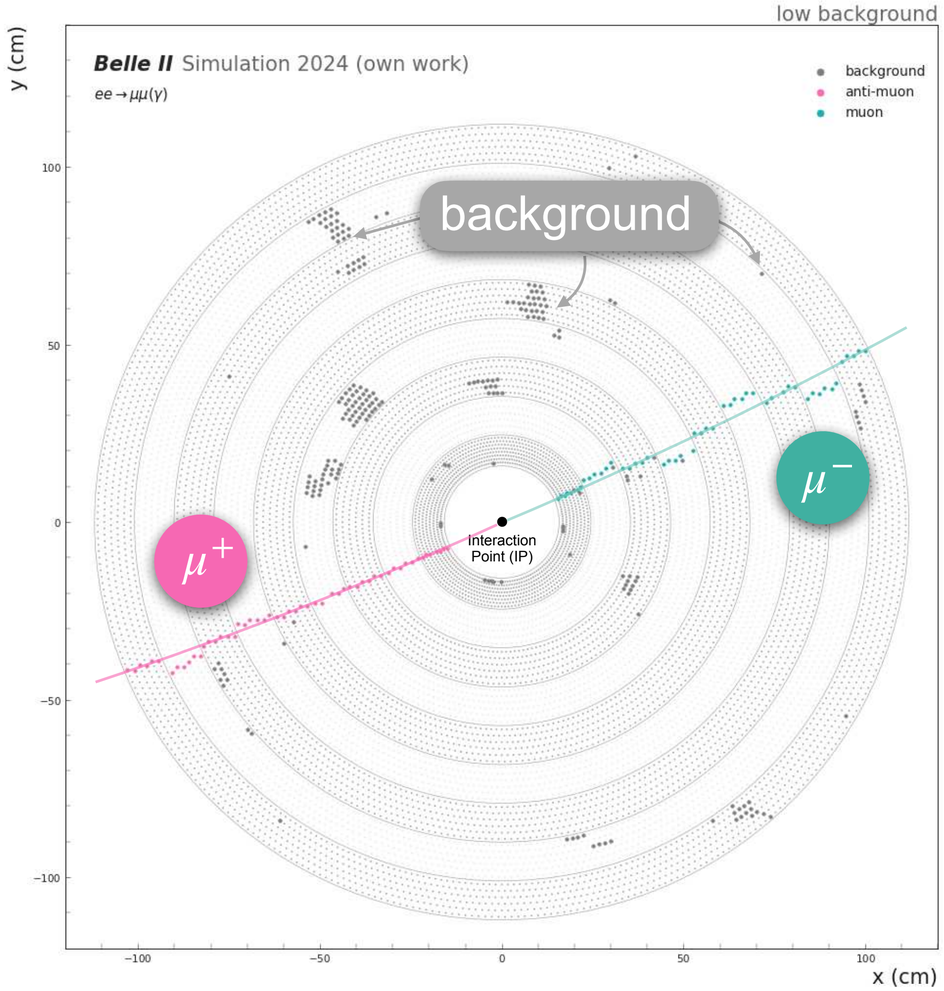


- xy projection
- ≈ 15 000 wires
- 9 super layers
- alternating axial and stereo layers



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

Central Drift Chamber Event Display

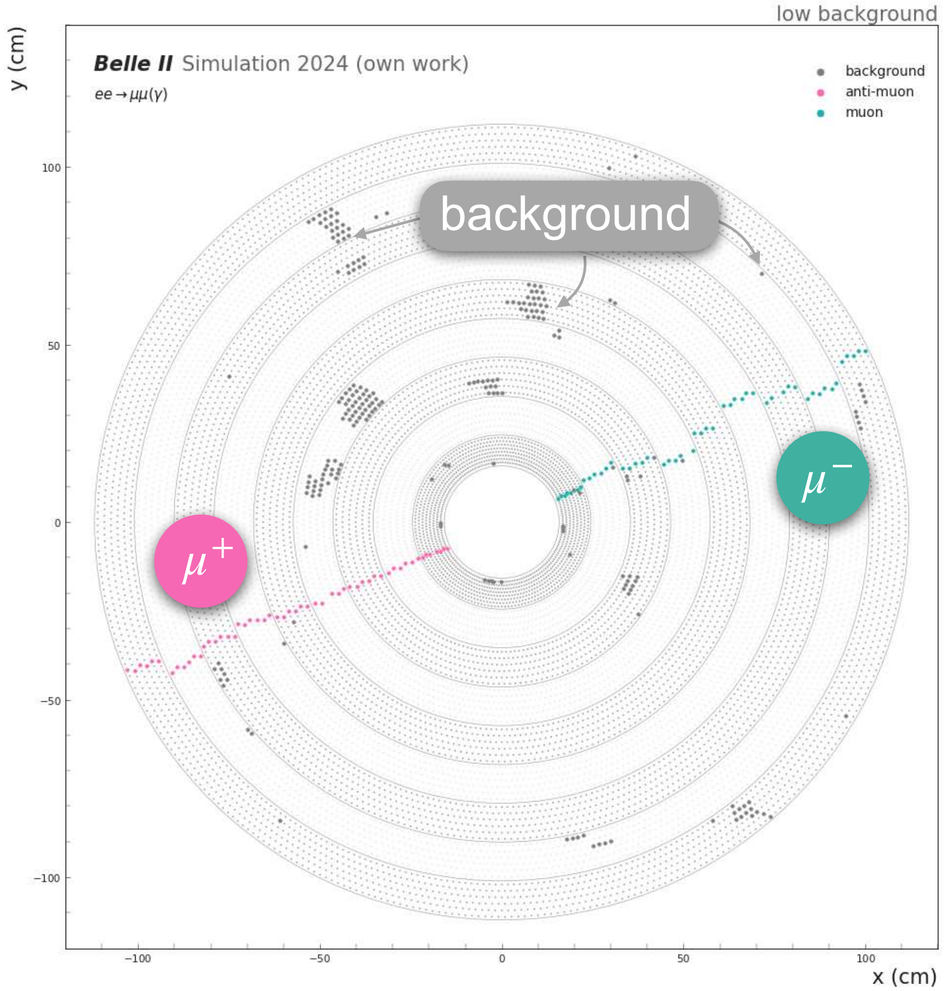


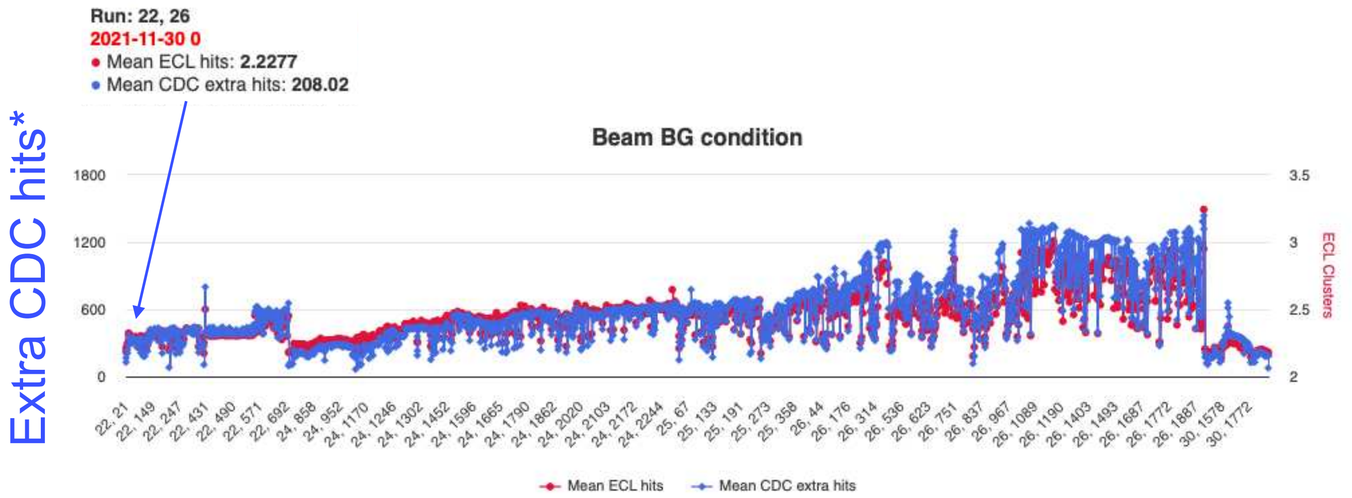
Tracking

1) reject background hits
2) identify signal hits (track finding)
3) estimate curvature $\propto p_T$ for trigger decision

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

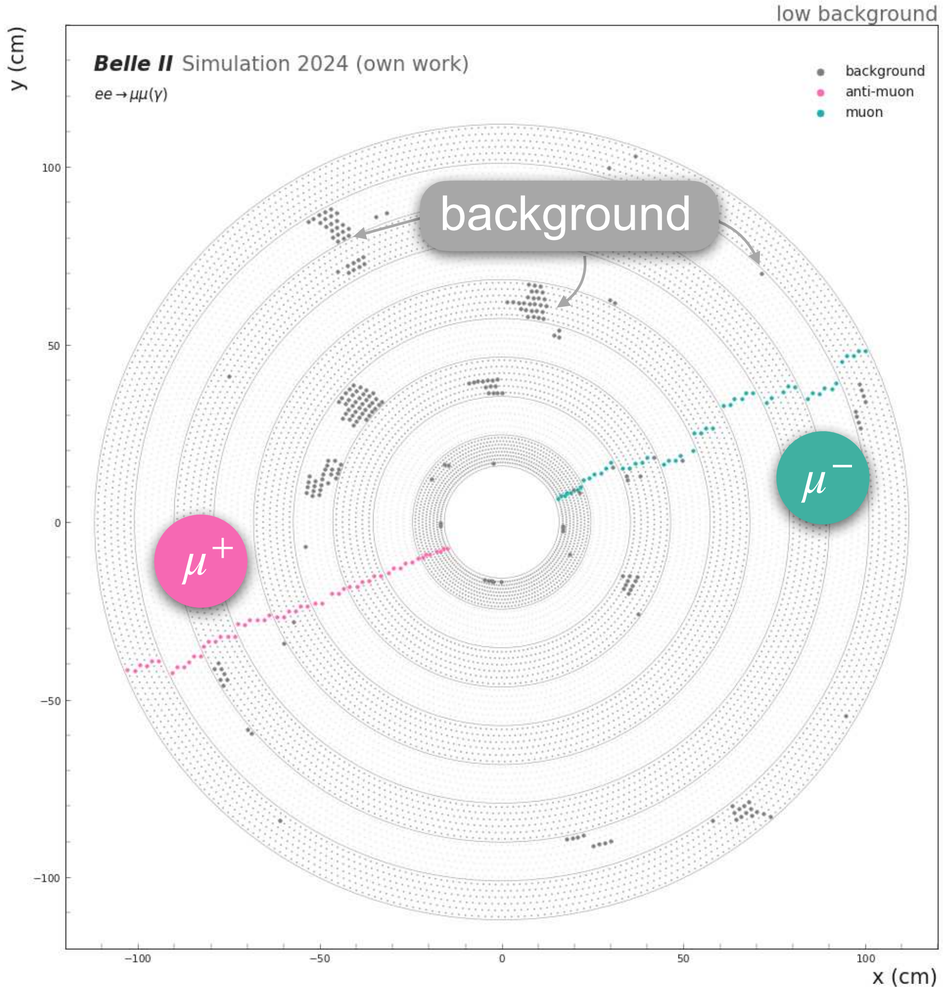
Back in 2021…

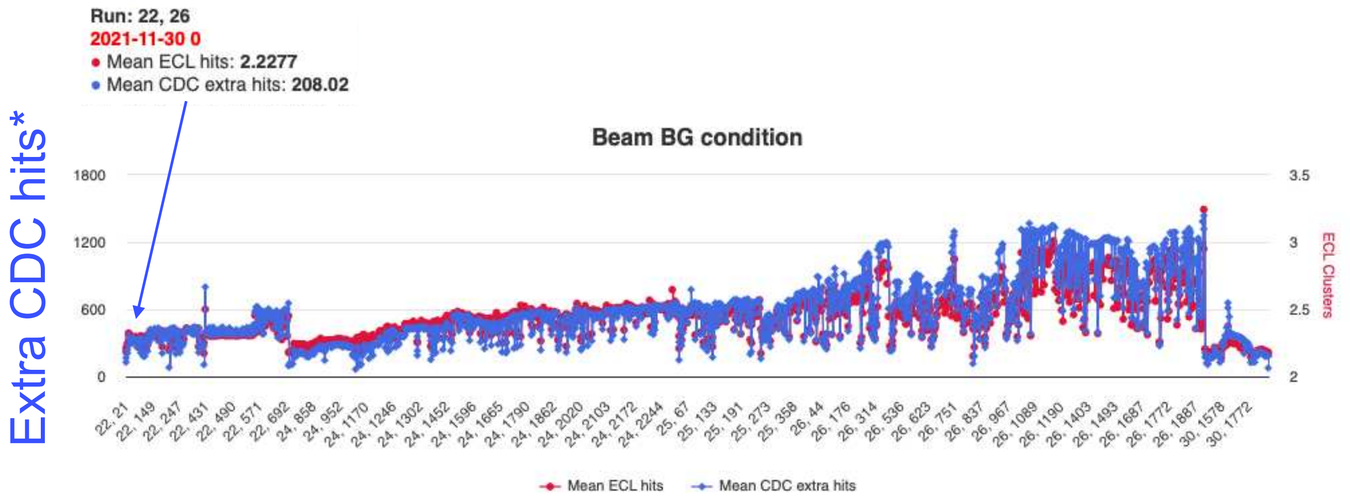




*The number of CDC hits in the event not assigned to any track.

Back in 2021…

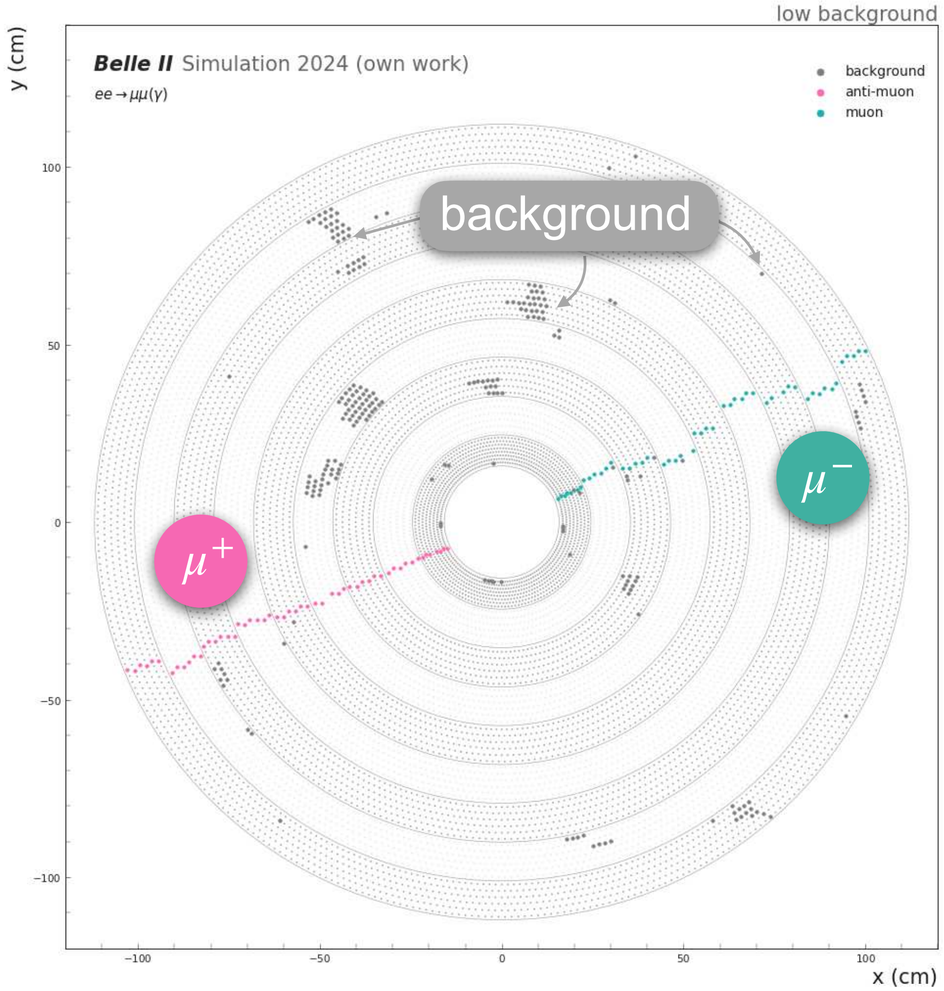


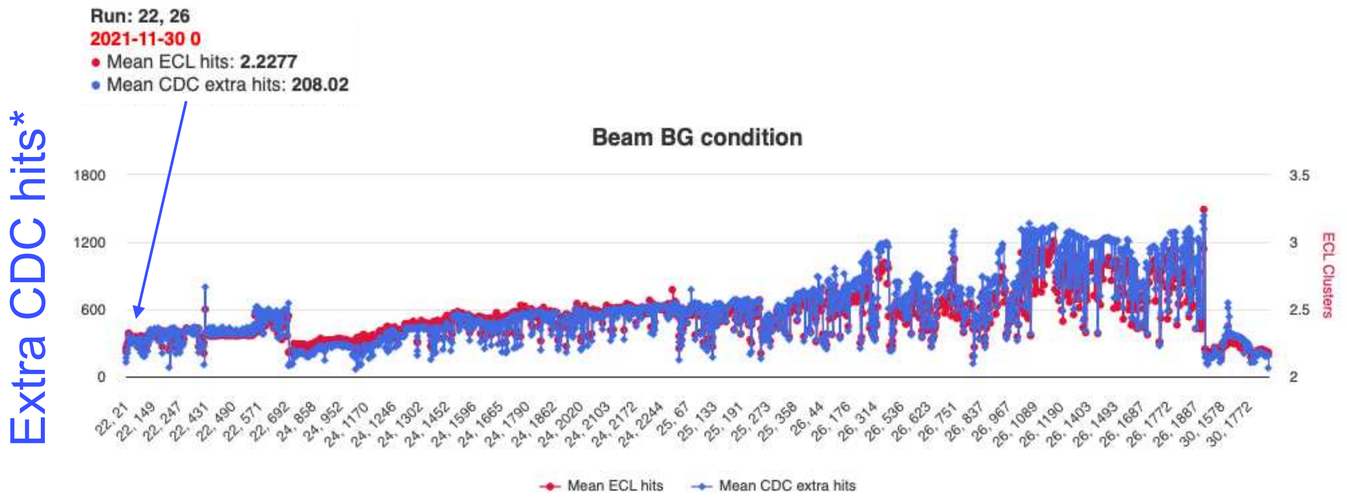


*The number of CDC hits in the event not assigned to any track.

- low background (2021)
- ≈ 1.9% of wires hit
- low computing cost

Back in 2021…



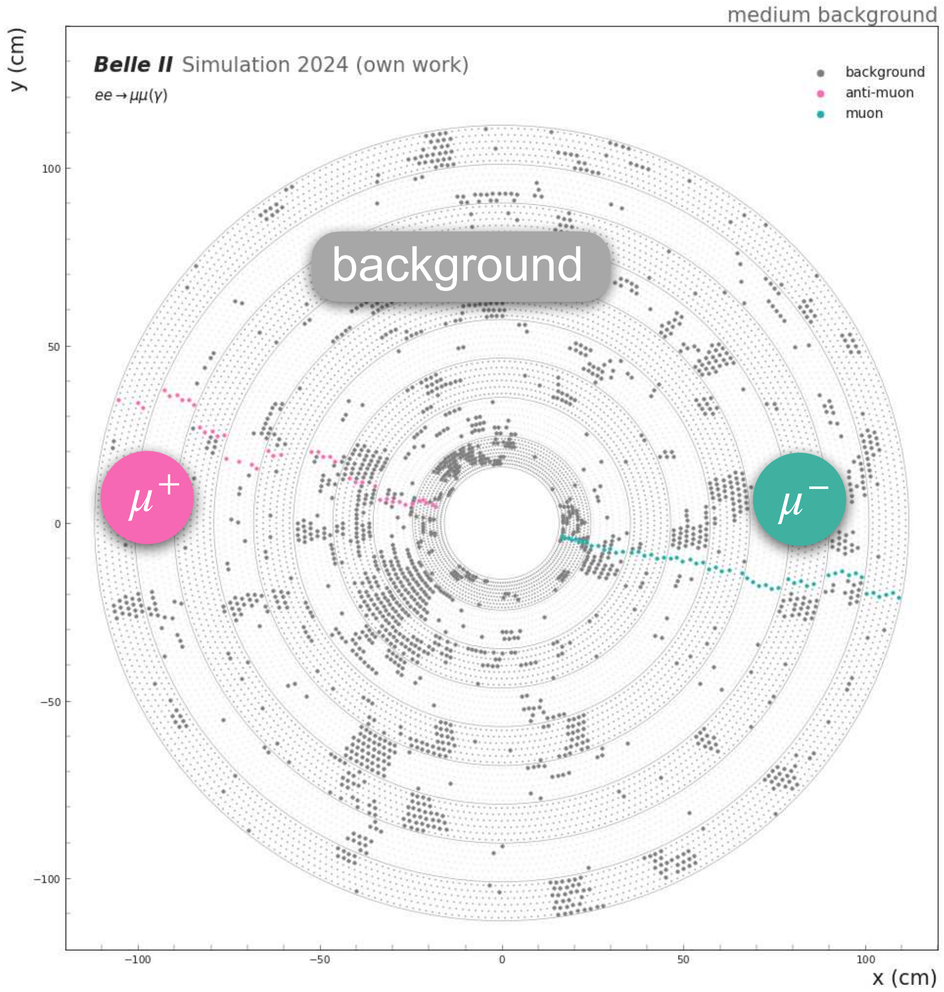


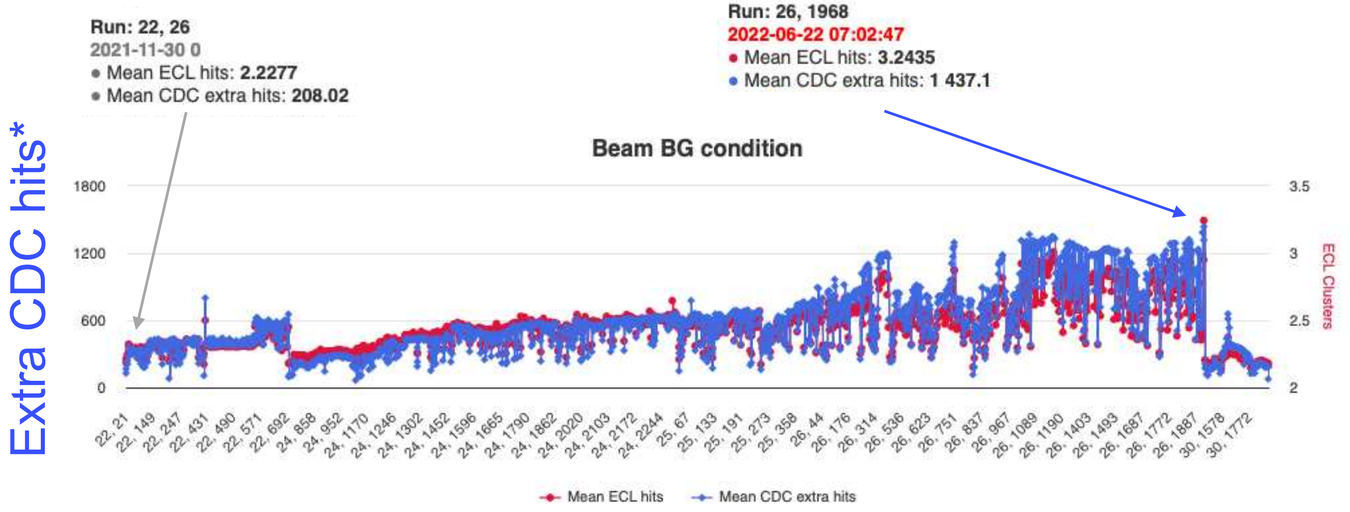
*The number of CDC hits in the event not assigned to any track.

- low background (2021)
- ≈ 1.9% of wires hit
- low computing cost



Now…





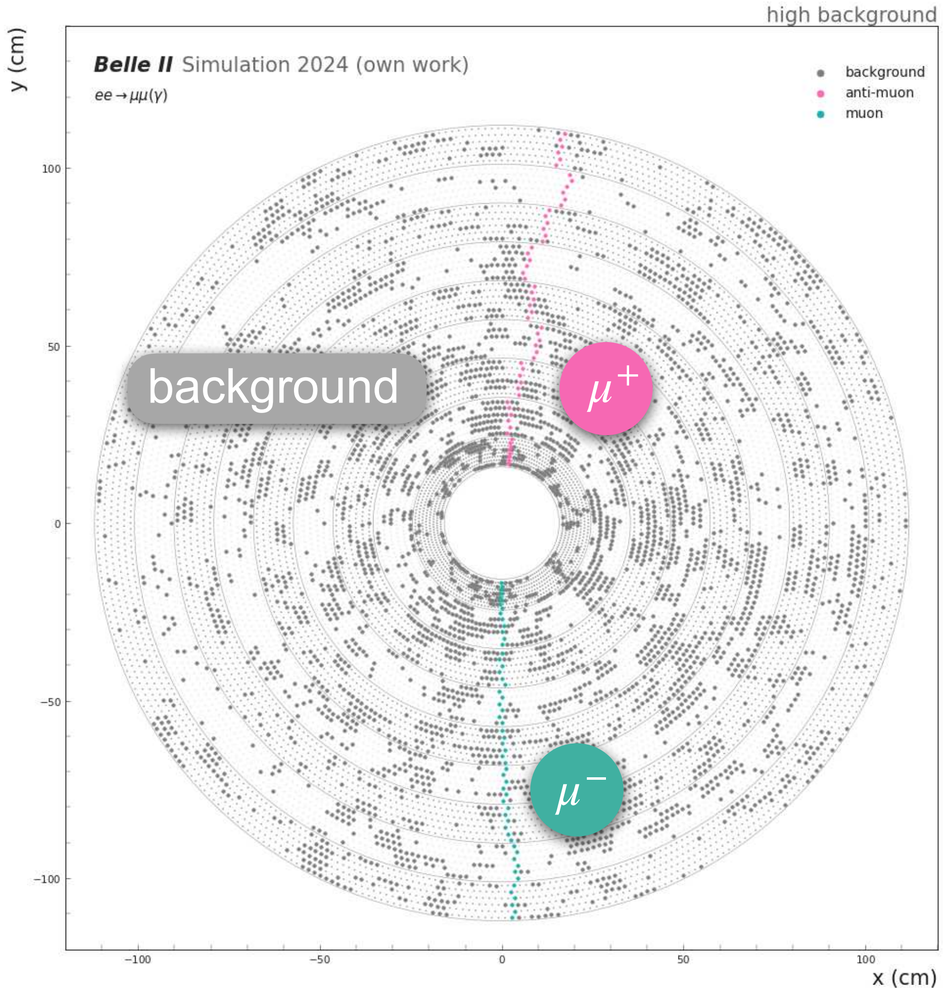
*The number of CDC hits in the event not assigned to any track.

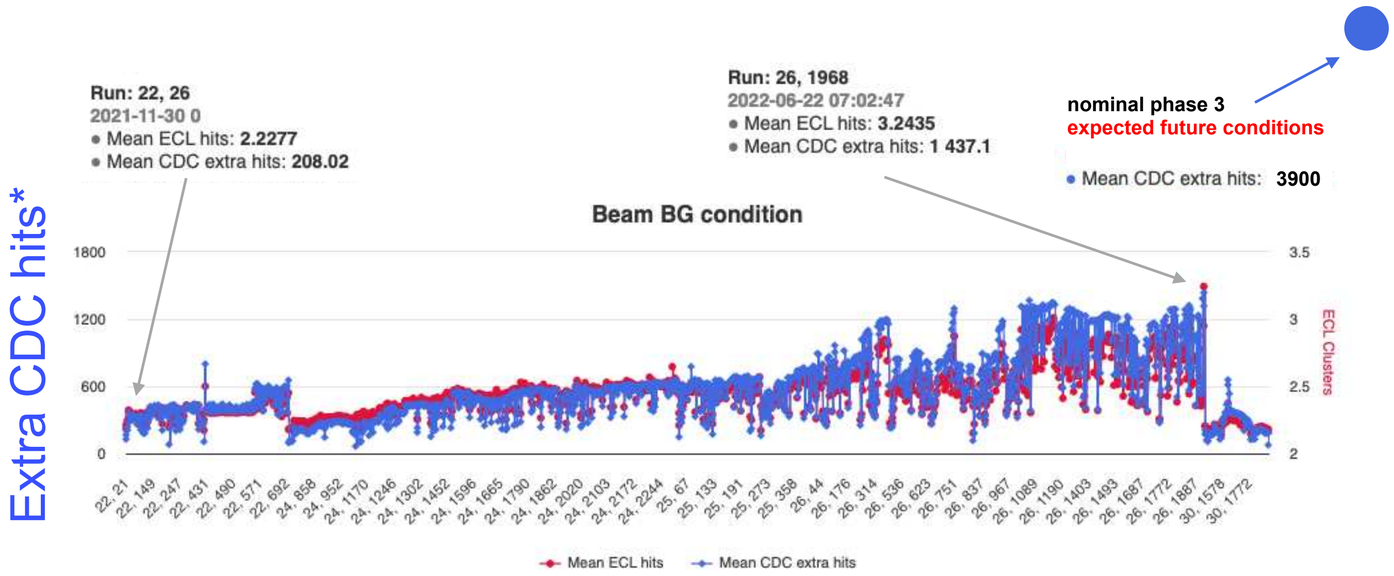
- medium background (2022)
- ≈ 10.5% of wires hit
- moderate computing cost

a bit harder



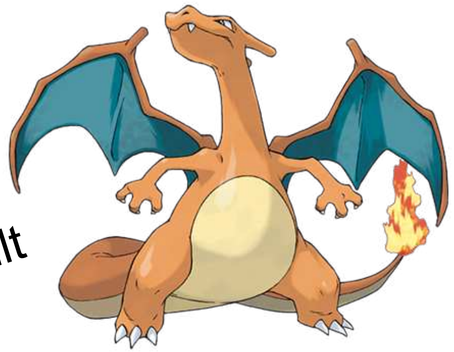
Future…





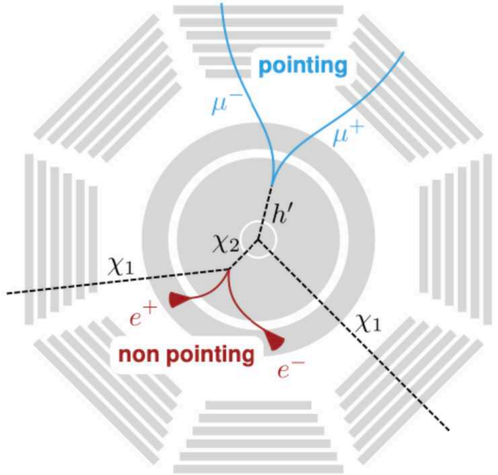
*The number of CDC hits in the event not assigned to any track.

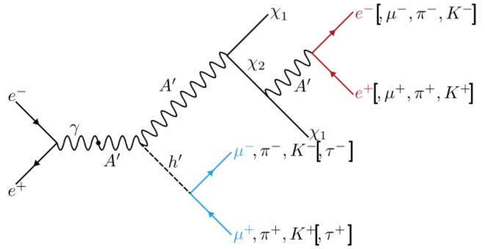
- high background (future)
- ≈ 27.1% of wires hit
- high computing cost



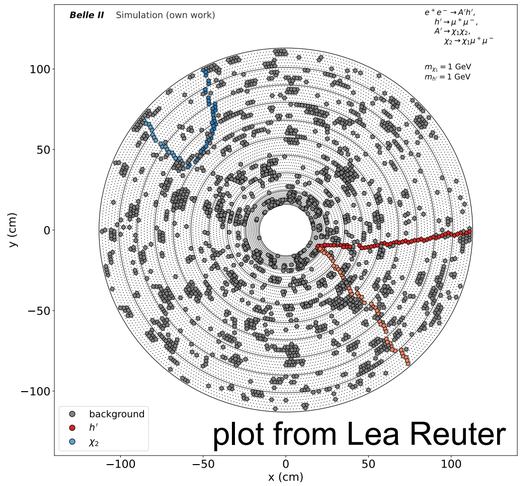
Displaced vertices

- tracks not originating from the IP





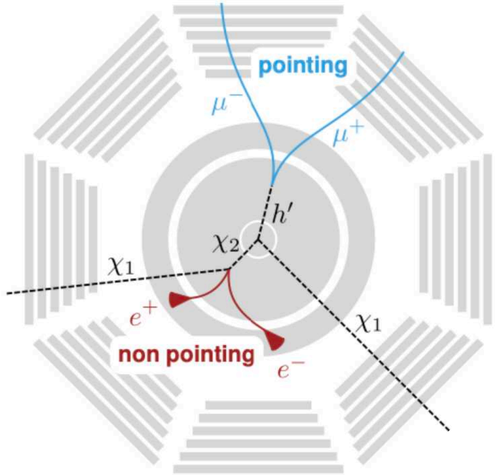
Plots from Patrick Ecker

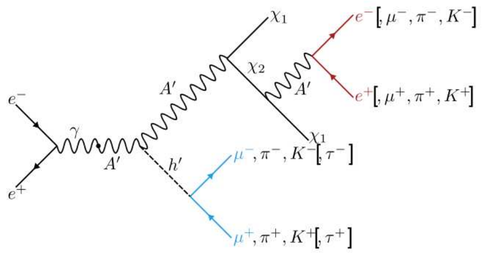


plot from Lea Reuter

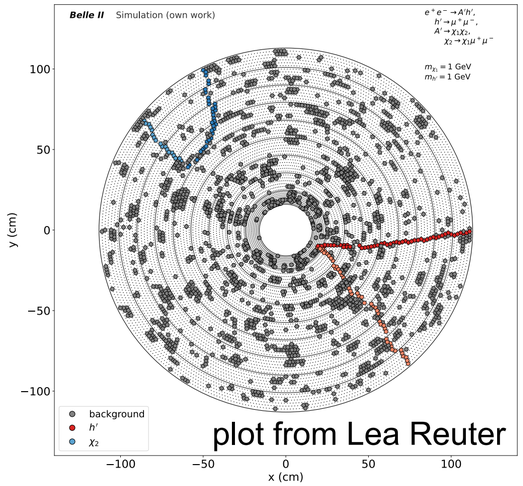
Displaced vertices

- tracks not originating from the IP



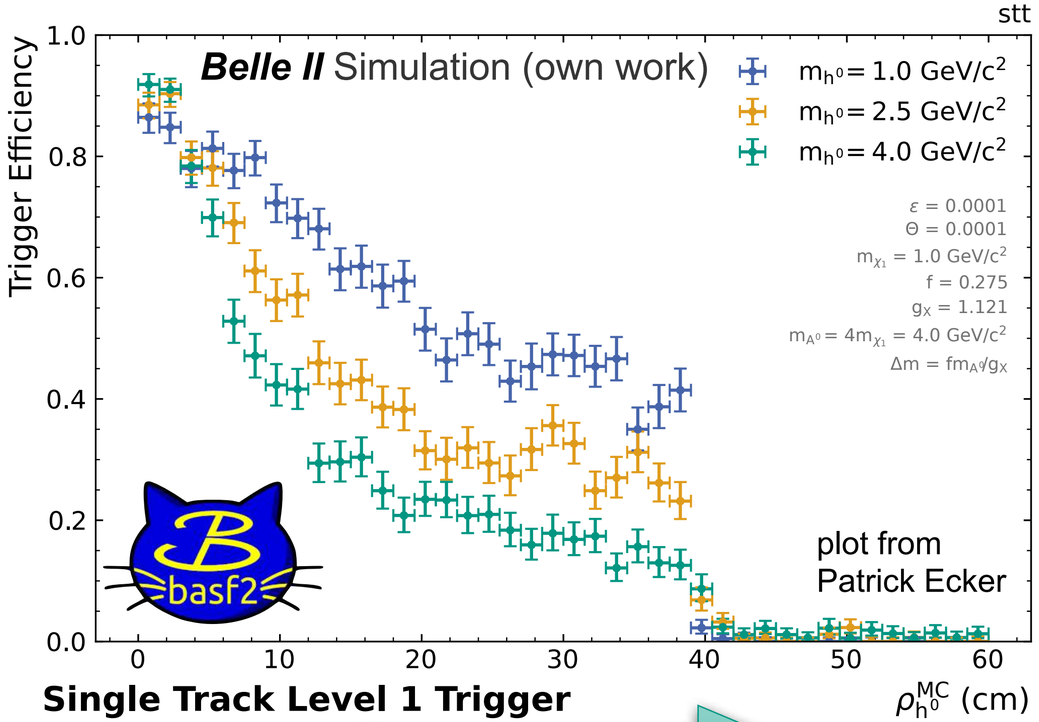


Plots from Patrick Ecker



efficiency

Current Tracking Algorithm



higher displacement

Real time tracking: the challenges

Tracking

plot from Lea Reuter

Real time tracking: the challenges

Tracking

- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)



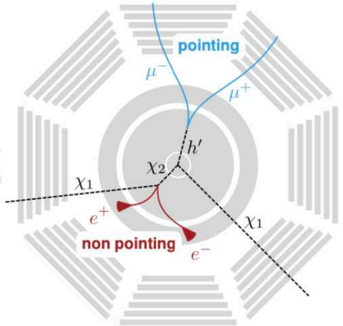
plot from Lea Reuter

Real time tracking: the challenges

Tracking

- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)
- displaced vertices





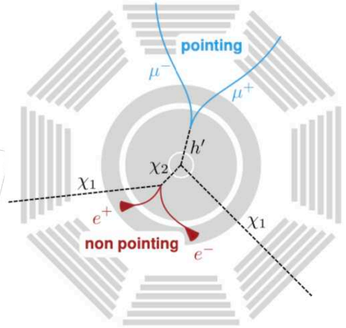
plot from Lea Reuter

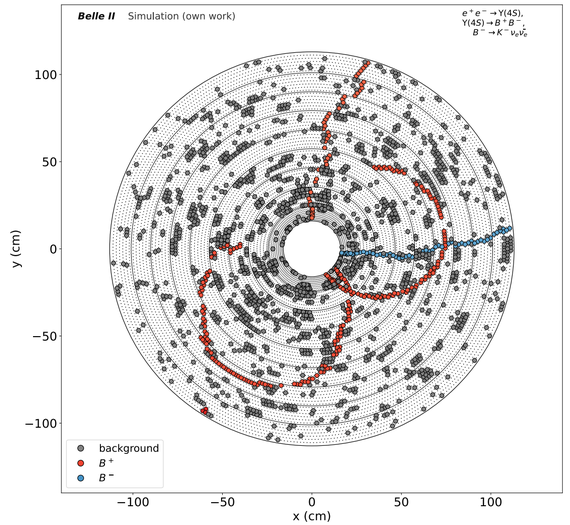
Real time tracking: the challenges

Tracking

- increasing number of background hits ($t_{\text{comp}} \propto n^2_{\text{hits}}$)
- displaced vertices
- low track multiplicity







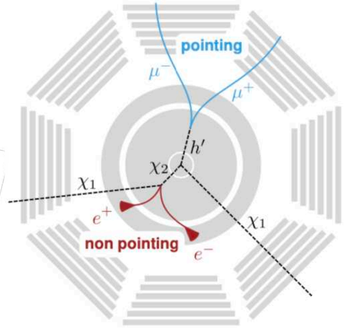
plot from Lea Reuter

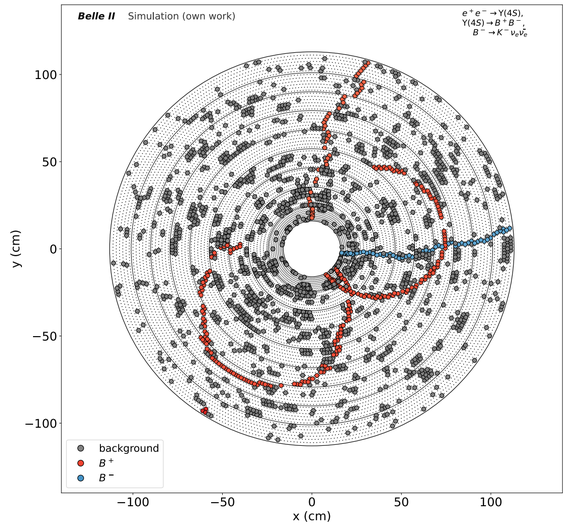
Real time tracking: the challenges

Tracking

- increasing number of background hits ($t_{\text{comp}} \propto n^2_{\text{hits}}$)
- displaced vertices
- low track multiplicity
- z-resolution







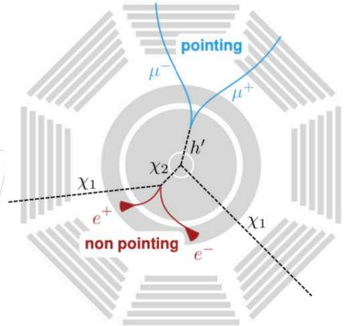
plot from Lea Reuter

Real time tracking: the challenges

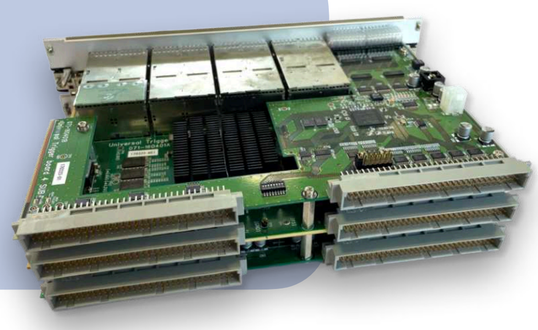
Tracking

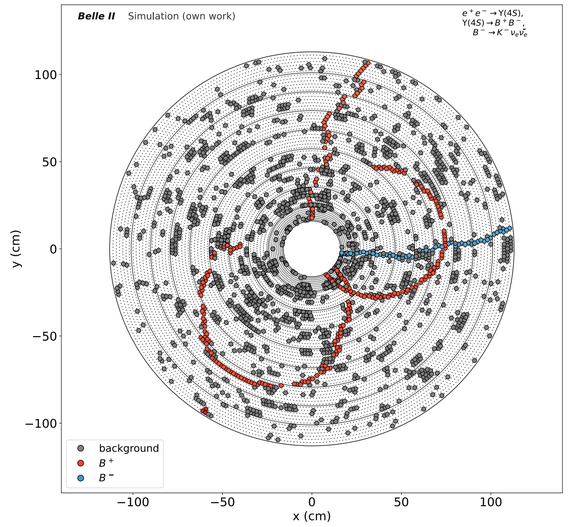
- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)
- displaced vertices
- low track multiplicity
- z-resolution





Implementation





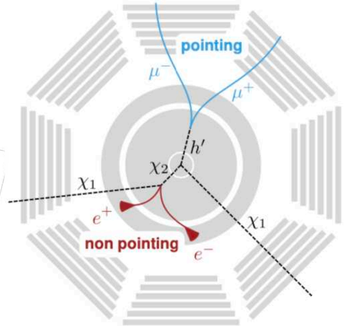
plot from Lea Reuter

Real time tracking: the challenges

Tracking

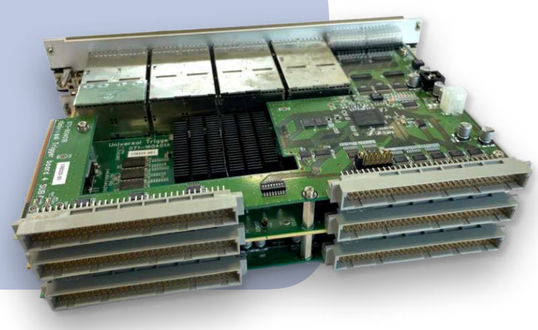
- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)
- displaced vertices
- low track multiplicity
- z-resolution

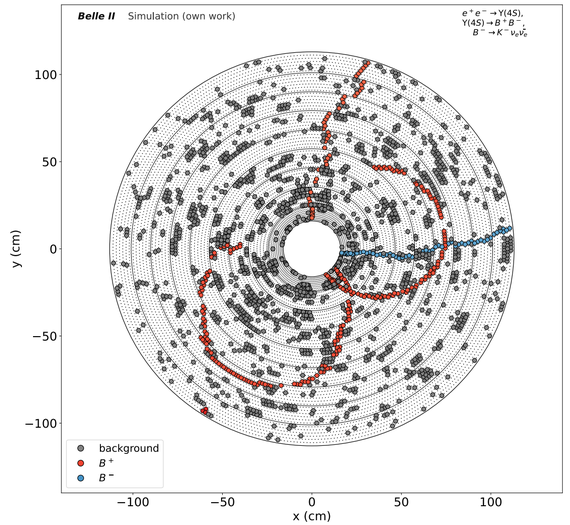




Implementation

- sub-microsecond latency





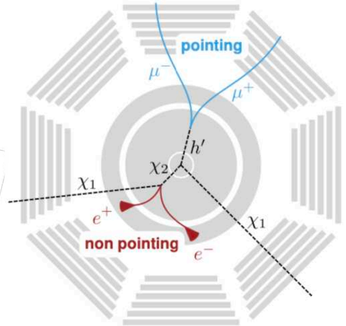
plot from Lea Reuter

Real time tracking: the challenges

Tracking

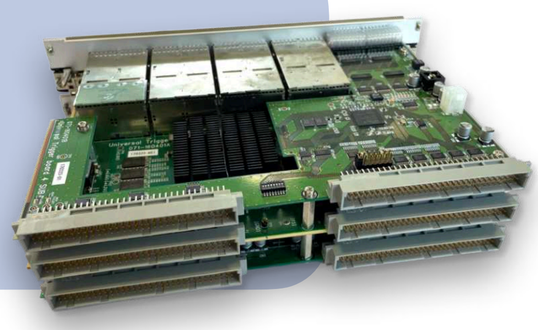
- increasing number of background hits ($t_{\text{comp}} \propto n_{\text{hits}}^2$)
- displaced vertices
- low track multiplicity
- z-resolution

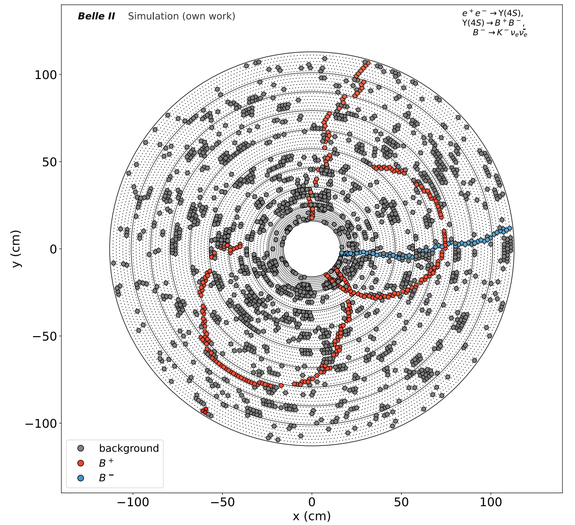




Implementation

- sub-microsecond latency
- limited computing resources

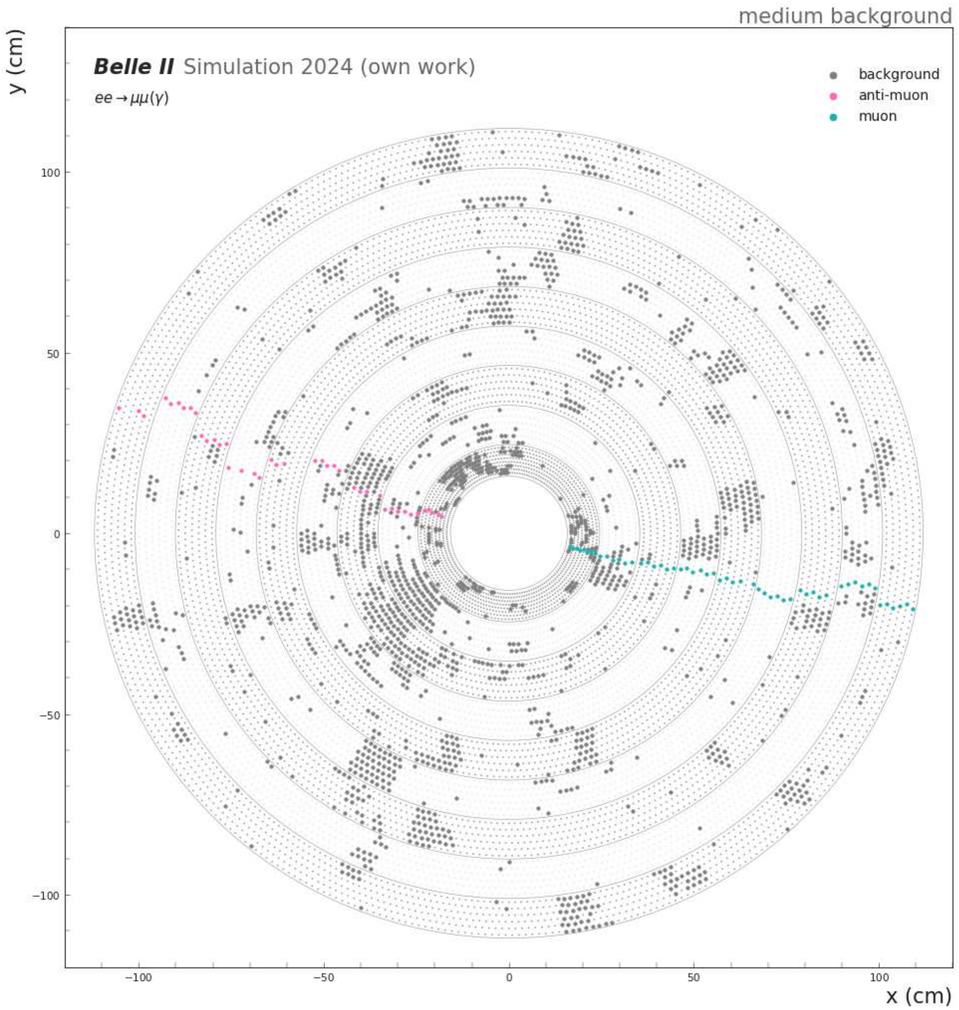




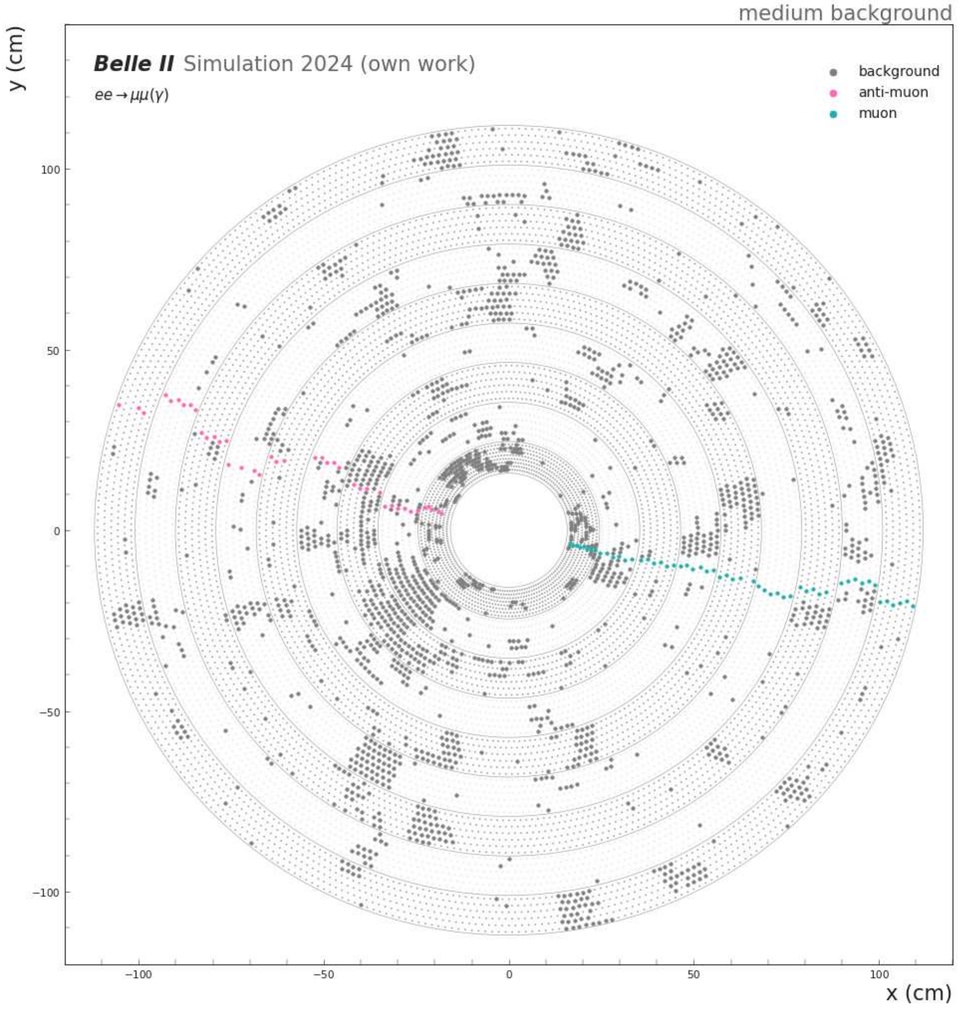
plot from Lea Reuter

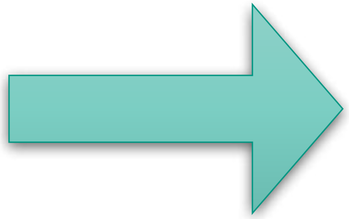
The (intermediate) Goal

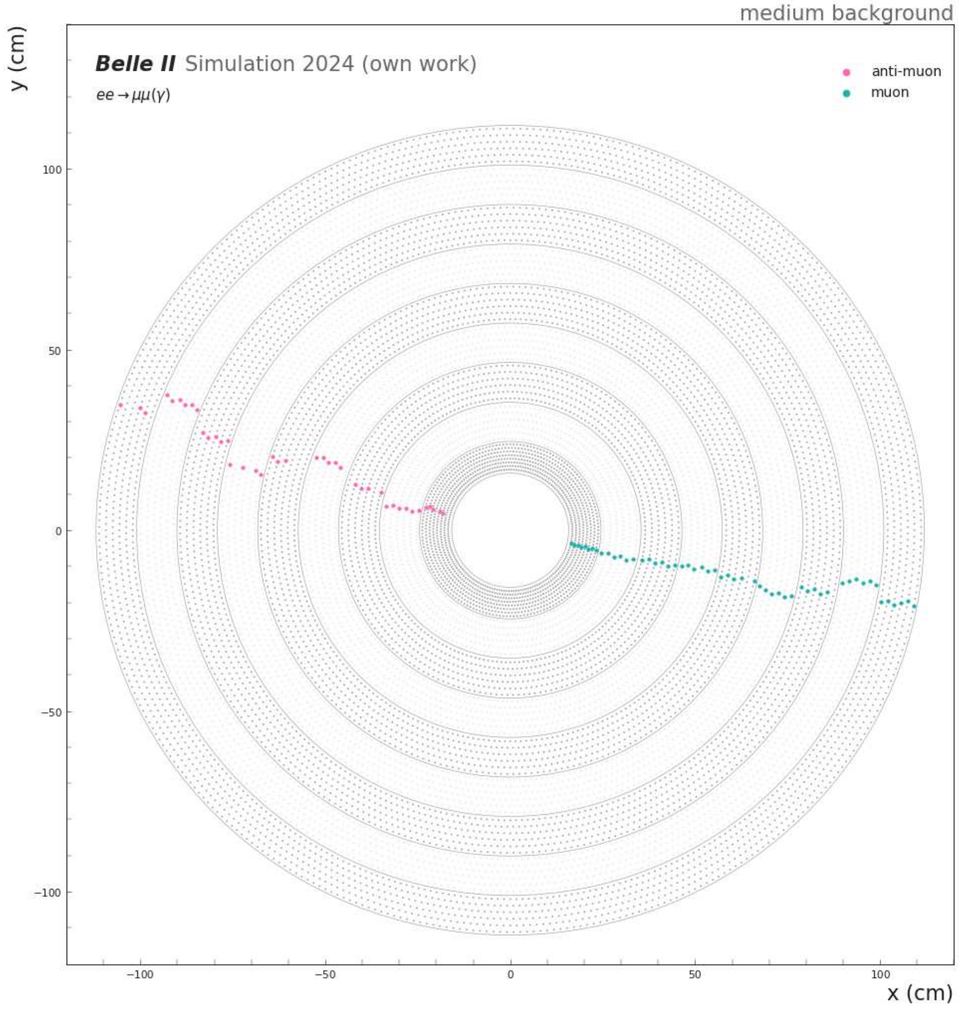
Hit Cleanup


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
−100
−50
0
50
100

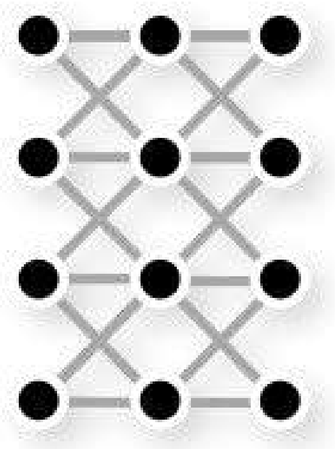
Hit Cleanup

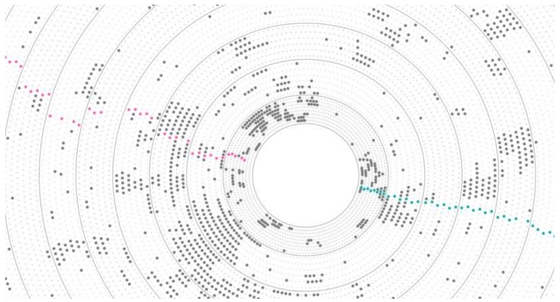

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Belle II Simulation 2024 (own work)
$ee \to \mu\mu(\gamma)$
background
anti-muon
muon
y (cm)
x (cm)
100
50
0
−50
−100



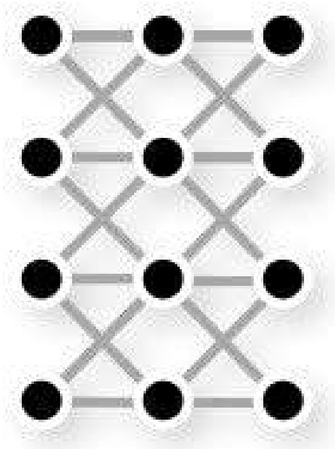

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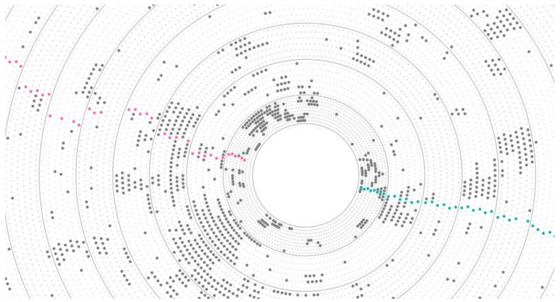
Hit Cleanup: with a Graph Neural Network

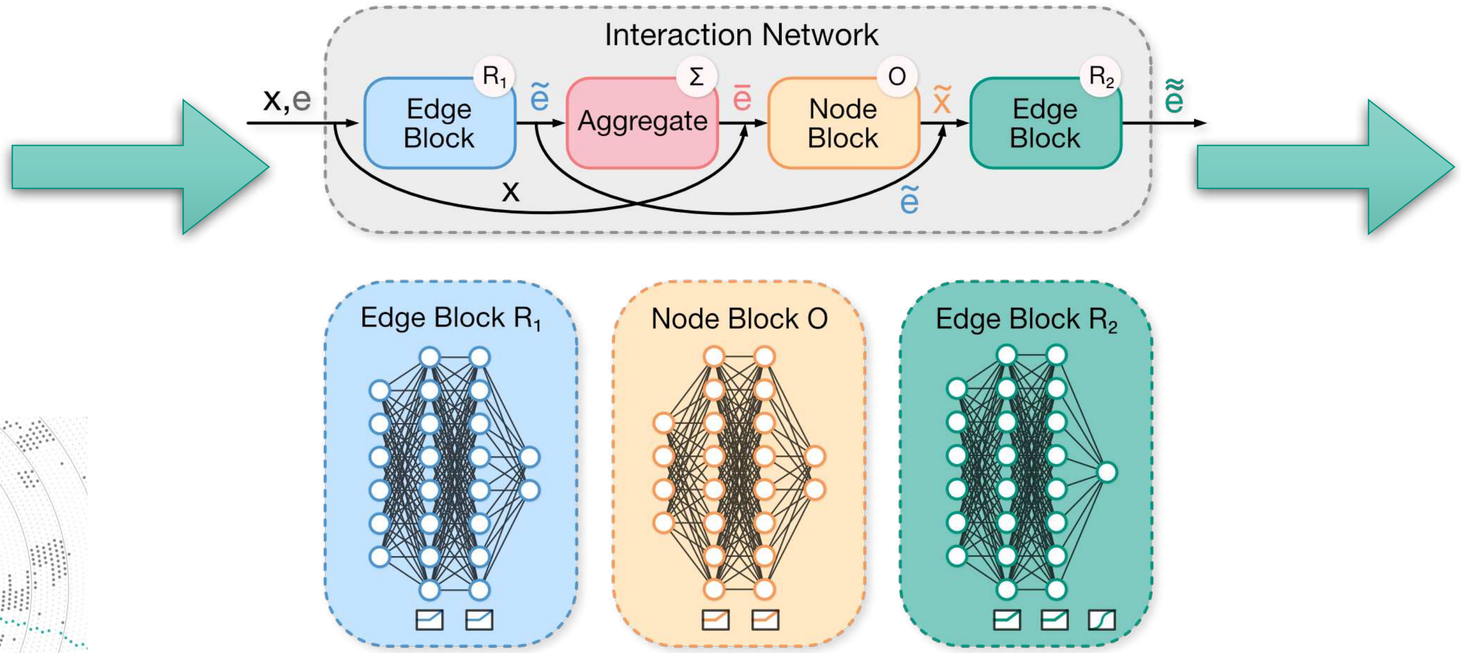




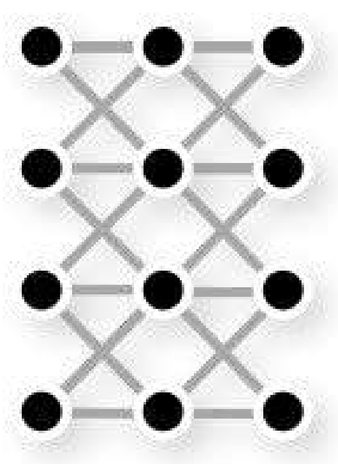
Hit Cleanup: with a Graph Neural Network

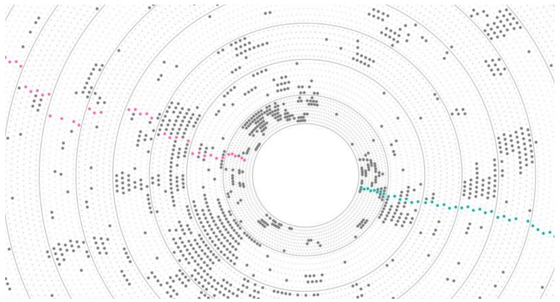


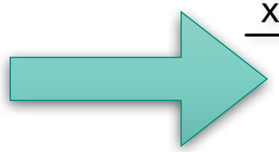


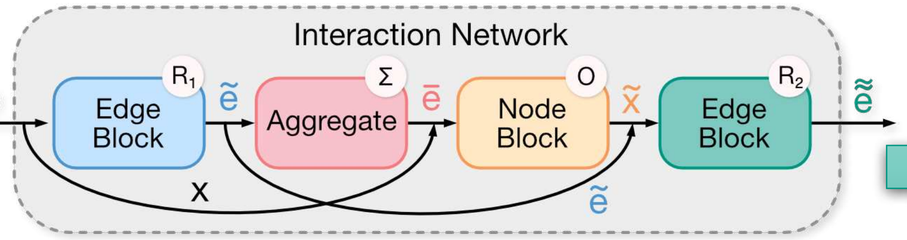


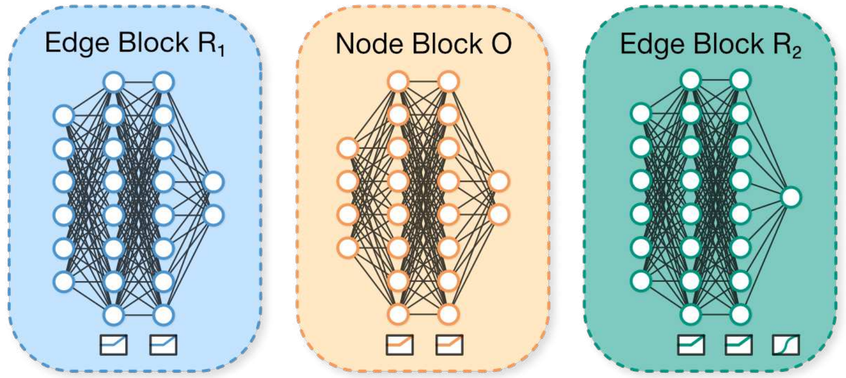
Hit Cleanup: with a Graph Neural Network

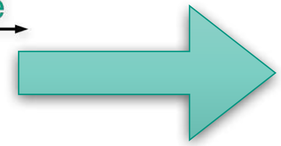


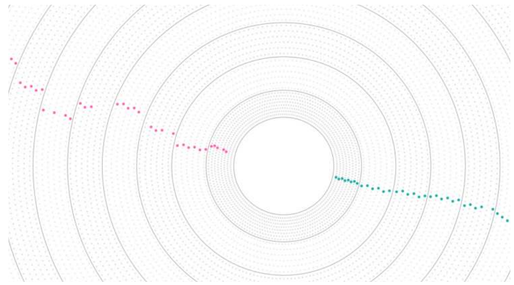






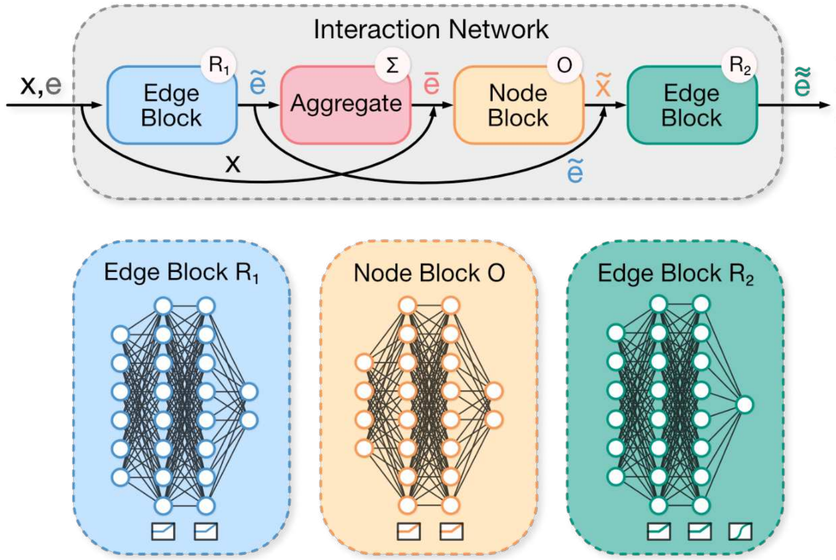






Interaction Network

- Interaction network model by Battaglia et al. with PyTorch Geometric
- Inputs: hit information encoded in graphs
- Outputs: edge-level predictions




```
InteractionNetwork(node_dim: 4, edge_dim: 3, hidden_size: 8)
+--------------------+------------+
|      Modules       | Parameters |
+--------------------+------------+
| R1.layers.0.weight |     88     |
|  R1.layers.0.bias  |     8      |
| R1.layers.2.weight |     64     |
|  R1.layers.2.bias  |     8      |
| R1.layers.4.weight |     24     |
|  R1.layers.4.bias  |     3      |
| O.layers.0.weight  |     56     |
|  O.layers.0.bias   |     8      |
| O.layers.2.weight  |     64     |
|  O.layers.2.bias   |     8      |
| O.layers.4.weight  |     32     |
|  O.layers.4.bias   |     4      |
| R2.layers.0.weight |     88     |
|  R2.layers.0.bias  |     8      |
| R2.layers.2.weight |     64     |
|  R2.layers.2.bias  |     8      |
| R2.layers.4.weight |     8      |
|  R2.layers.4.bias  |     1      |
+--------------------+------------+
Total Trainable Params: 544
```

Edge block R1

for edge feature updates

Node block O

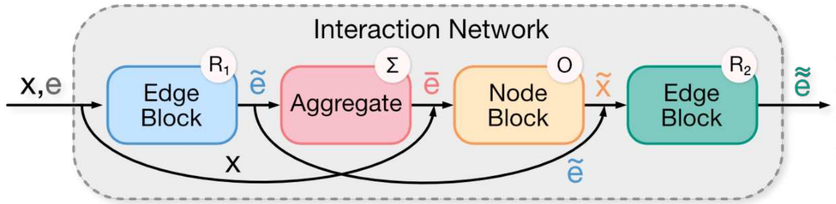
for hit feature updates

Edge block R2

1-dim edge-level output

Interaction Network

- Interaction network model by Battaglia et al. with PyTorch Geometric
- Inputs: hit information encoded in graphs
- Outputs: edge-level predictions




```
InteractionNetwork(node_dim: 4, edge_dim: 3, hidden_size: 8)
+--------------------+------------+
|      Modules       | Parameters |
+--------------------+------------+
| R1.layers.0.weight |     88     |
|  R1.layers.0.bias  |     8      |
| R1.layers.2.weight |     64     |
|  R1.layers.2.bias  |     8      |
| R1.layers.4.weight |     24     |
|  R1.layers.4.bias  |     3      |
| O.layers.0.weight  |     56     |
|  O.layers.0.bias   |     8      |
| O.layers.2.weight  |     64     |
|  O.layers.2.bias   |     8      |
| O.layers.4.weight  |     32     |
|  O.layers.4.bias   |     4      |
| R2.layers.0.weight |     88     |
|  R2.layers.0.bias  |     8      |
| R2.layers.2.weight |     64     |
|  R2.layers.2.bias  |     8      |
| R2.layers.4.weight |     8      |
|  R2.layers.4.bias  |     1      |
+--------------------+------------+
Total Trainable Params: 544
```

Edge block R1
for edge feature updates

Node block O
for hit feature updates

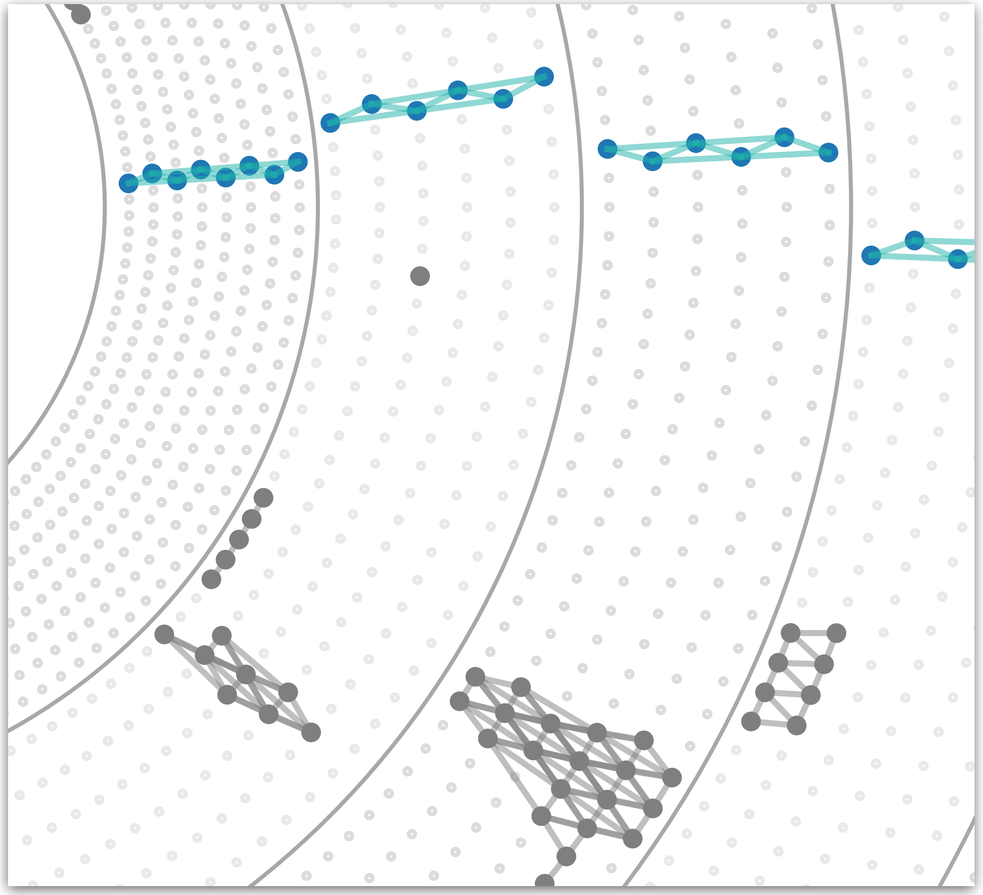
Edge block R2
1-dim edge-level output

Step 1: Build graphs from hits
Step 2: ???
Step 3: Profit.

Graph Building

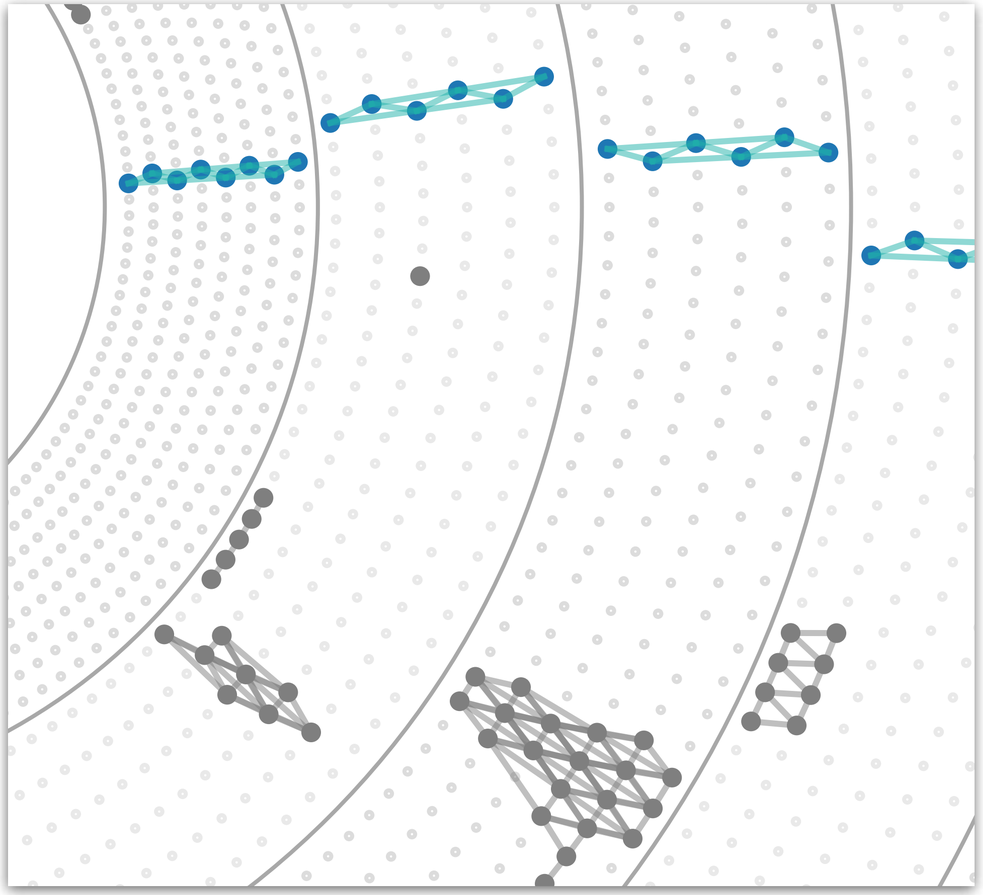


Graph Building



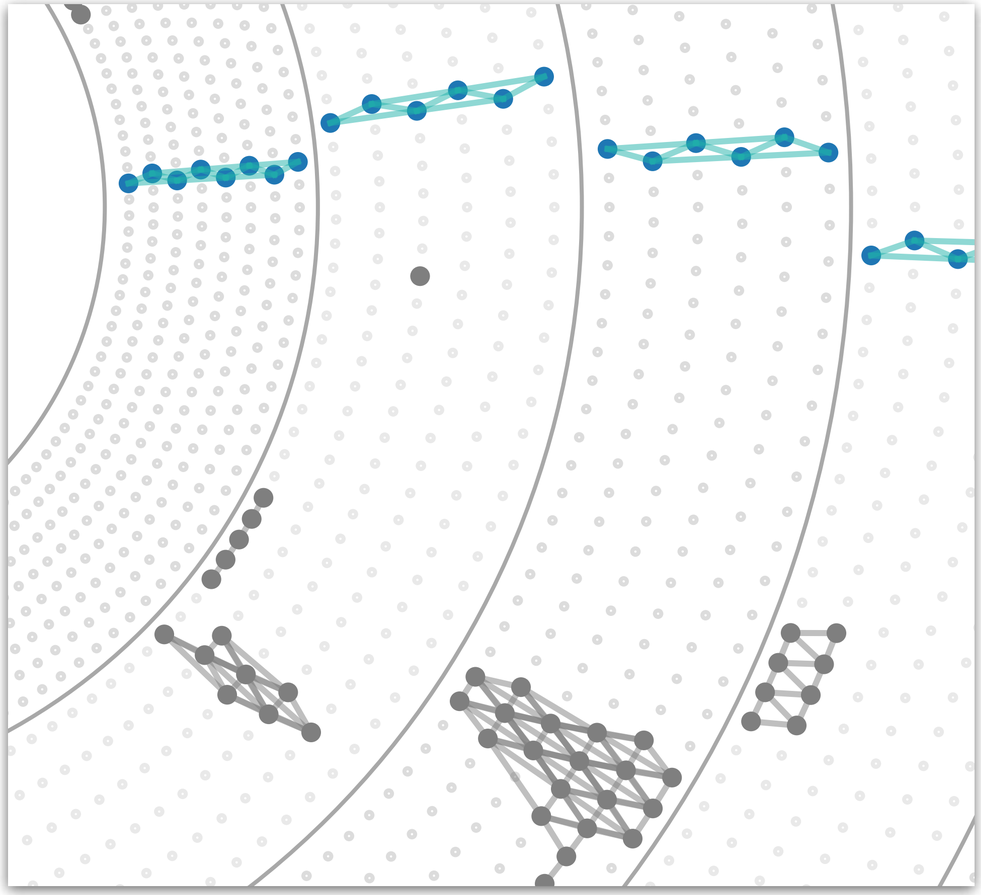
Graph Building

- connect hits to graphs



Graph Building

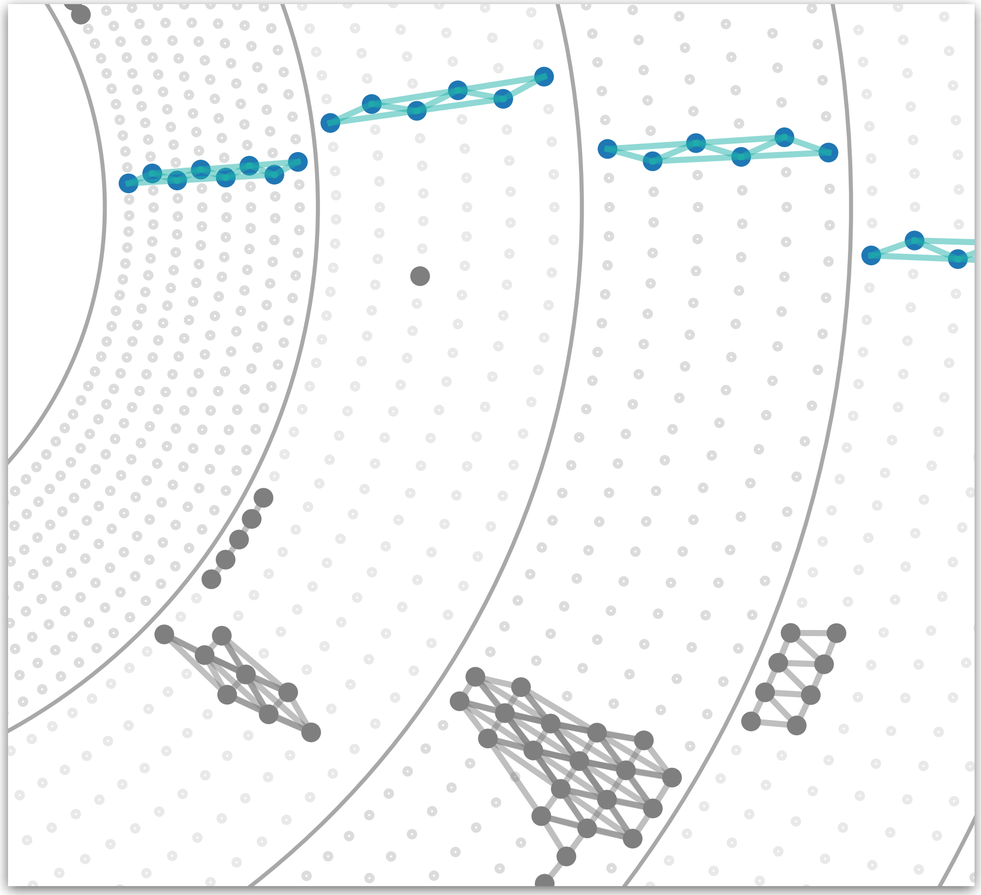
- connect hits to graphs
- connect *just the right amount* of hits with each other



Graph Building

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

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

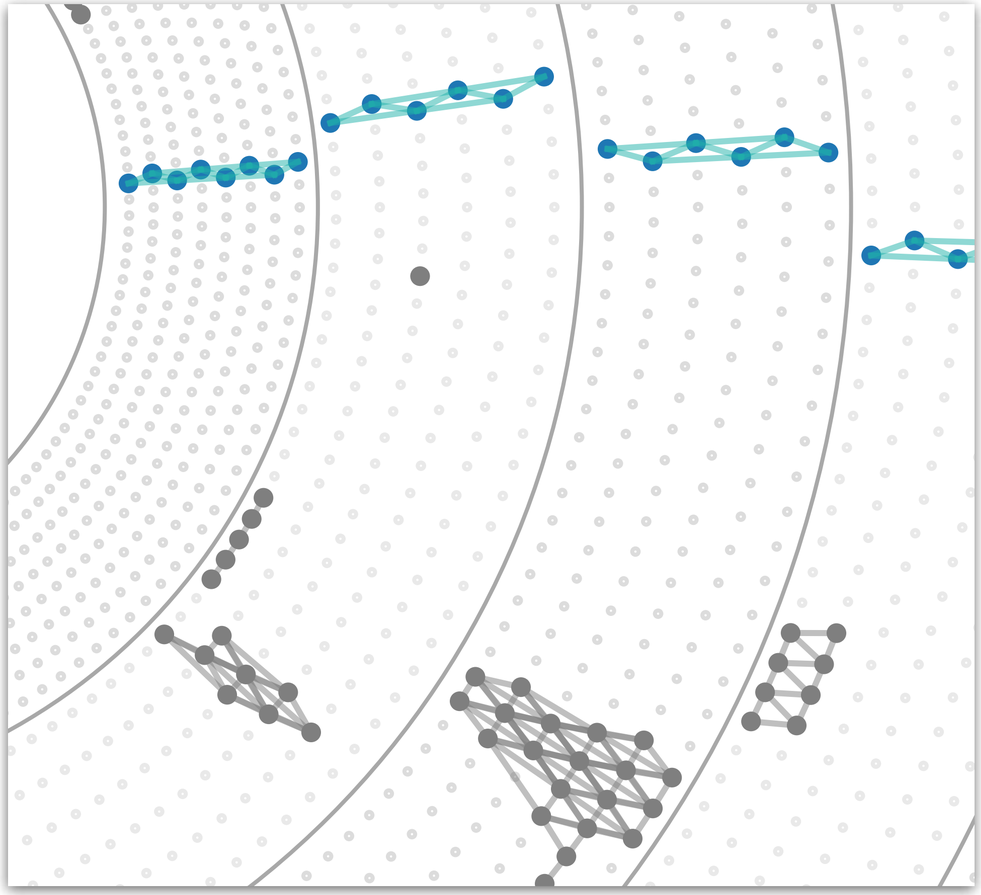


Graph Building

- 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



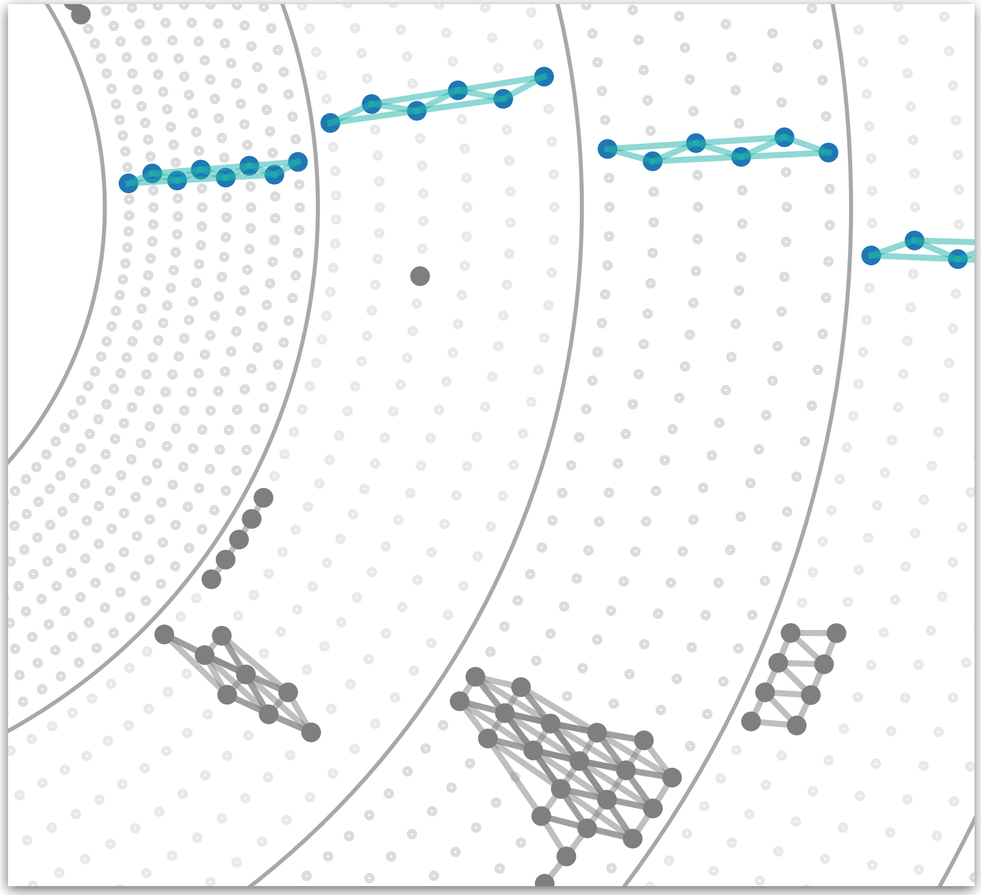
Graph Building

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

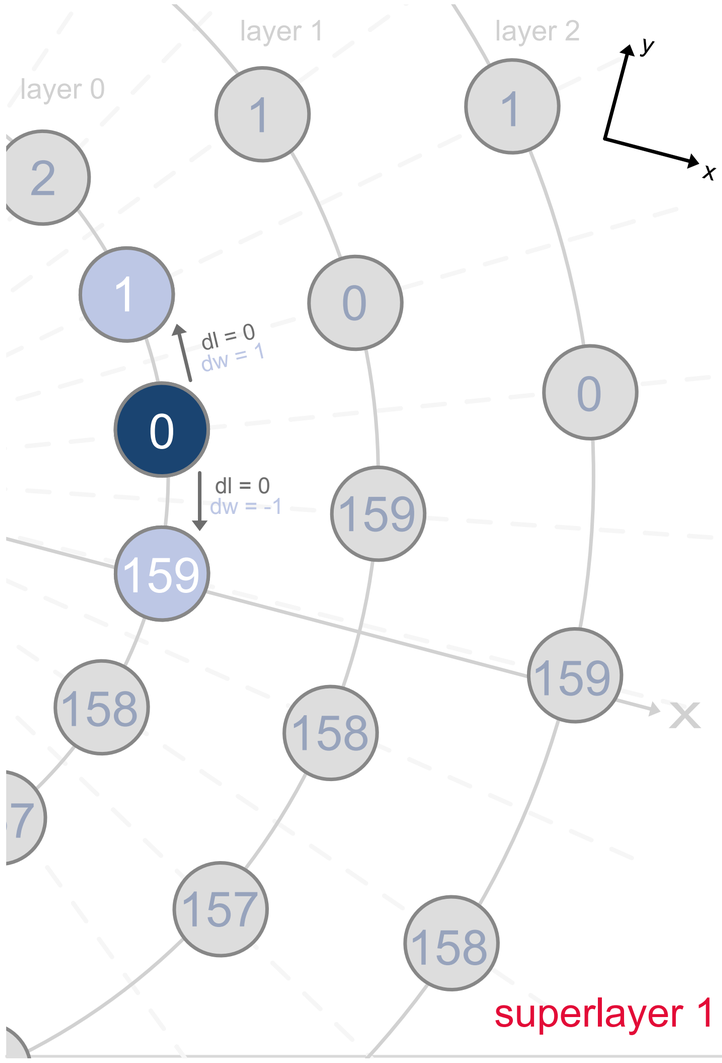
$$n_{edges} = \frac{1}{2} n_{hits}(n_{hits} - 1) \approx n_{hits}^2$$

- design goal

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

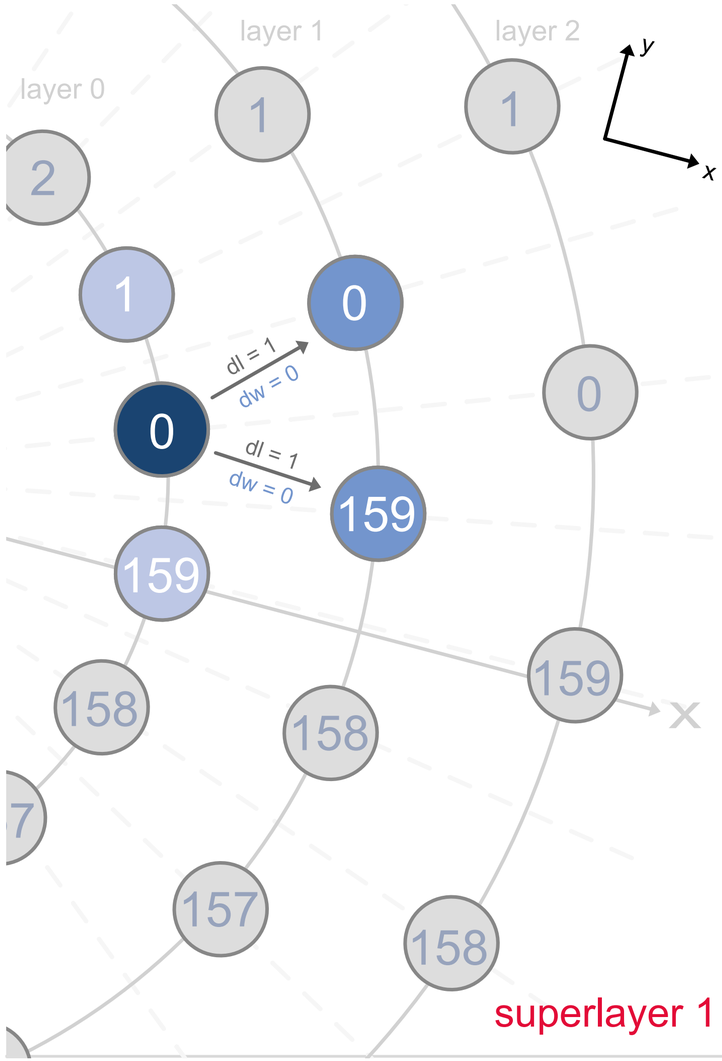


Graph Building



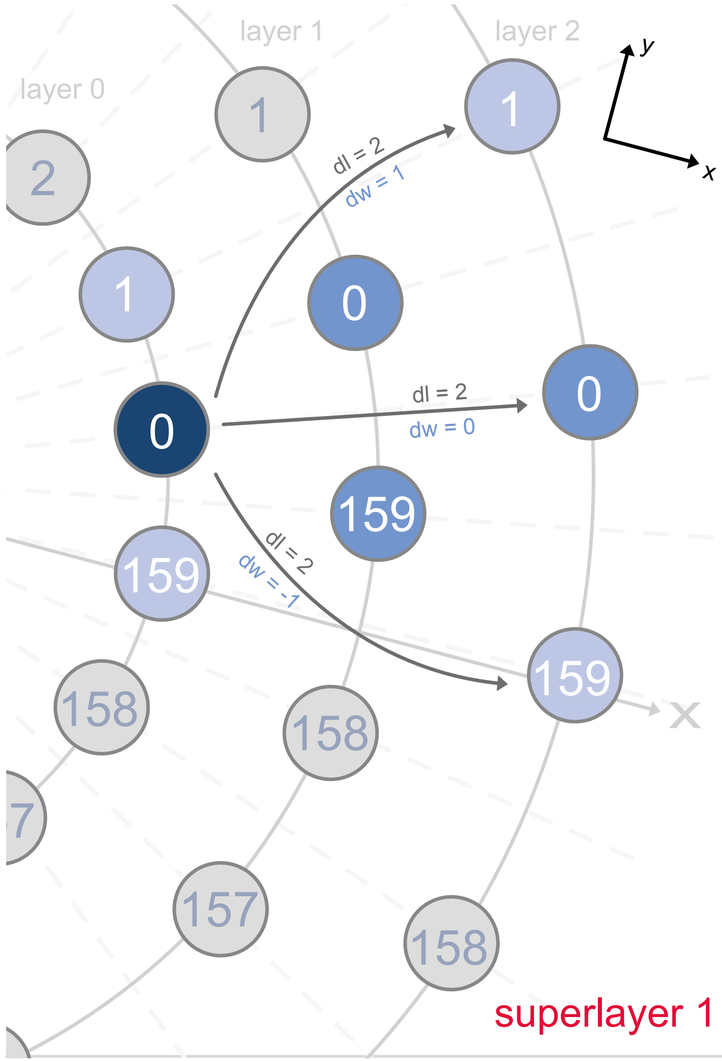
- same layer connections with 2 nearest neighbour wires (if hit)

Graph Building



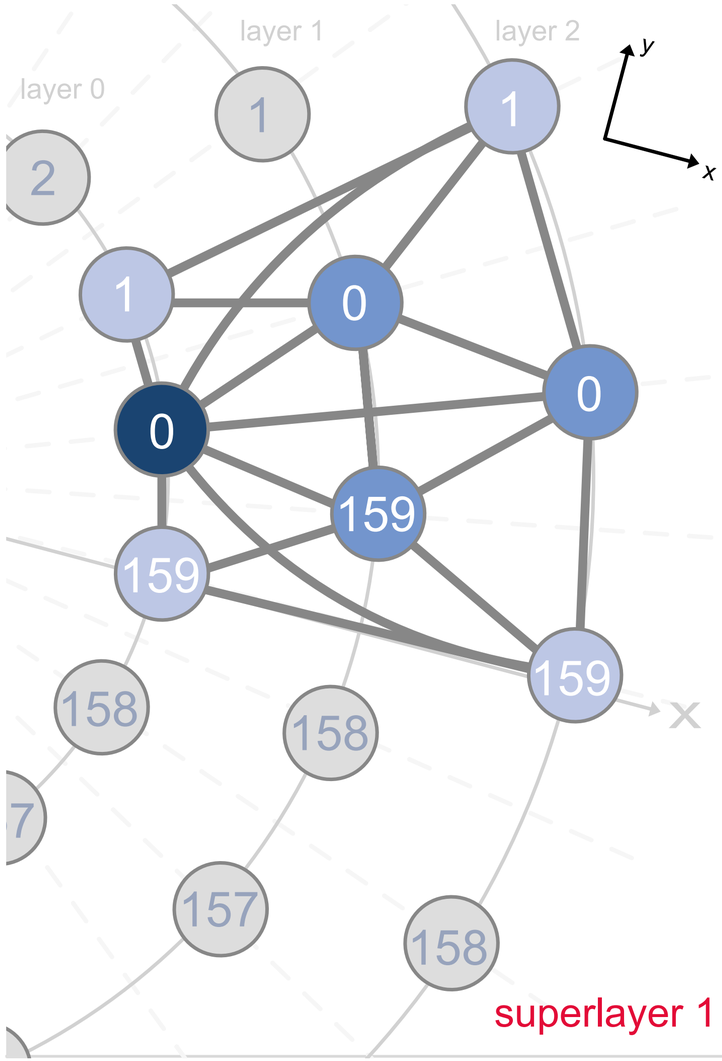
- same layer connections with 2 nearest neighbour wires (if hit)
- next layer connections with 2 nearest neighbours

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

Graph Building

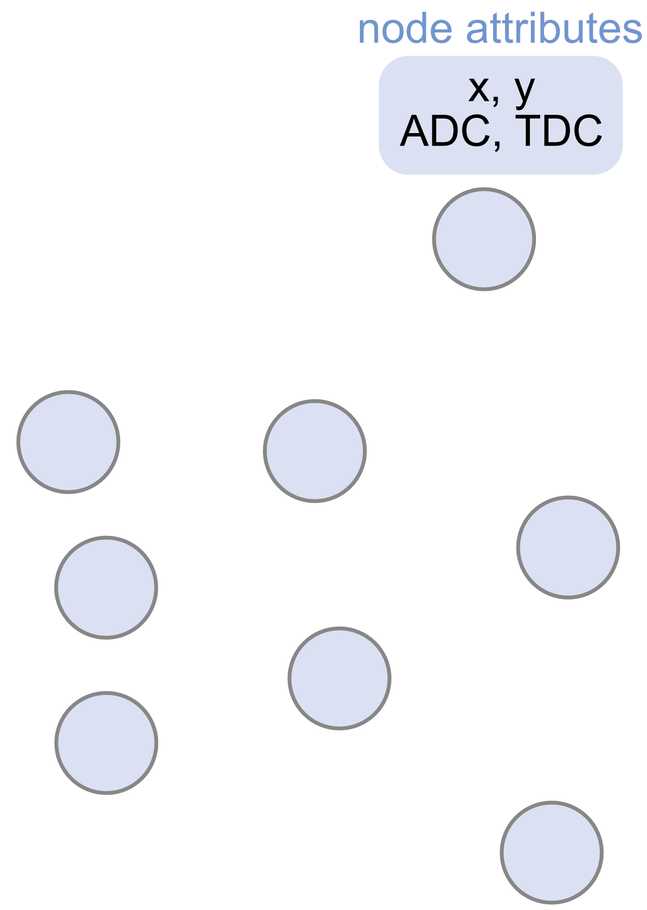


- same layer connections with 2 nearest neighbours
- next layer connections with 2 nearest neighbours
- next to next layer connections with 3 nearest neighbours
- build all possible (allowed) connections

Graph Building: Features

node attributes

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



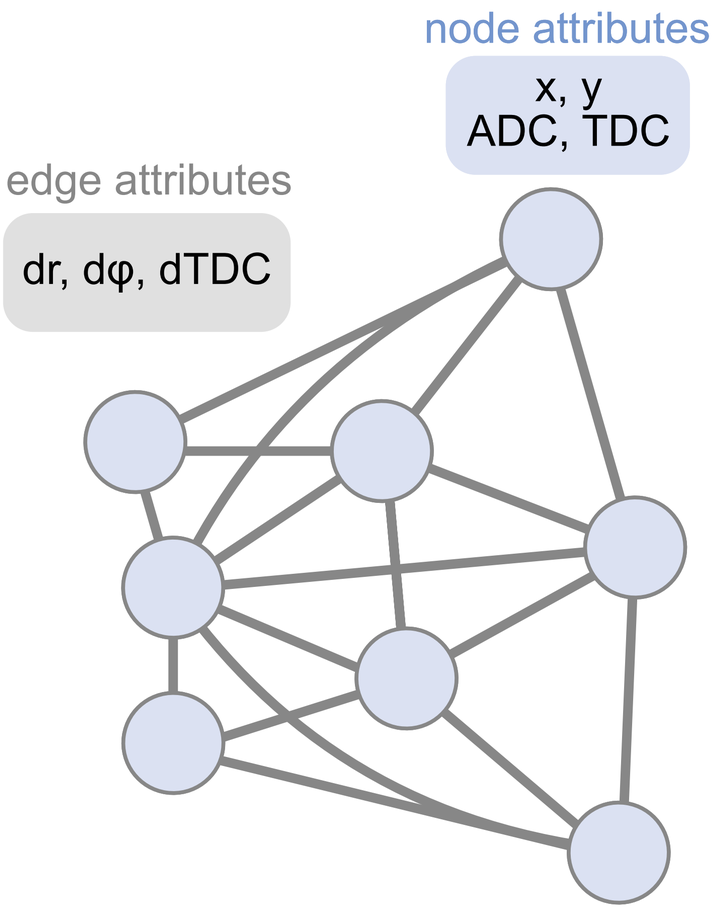
Graph Building: Features

node attributes

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

edge attributes

- dr, dφ, dTDC



Graph Building: Features

node attributes

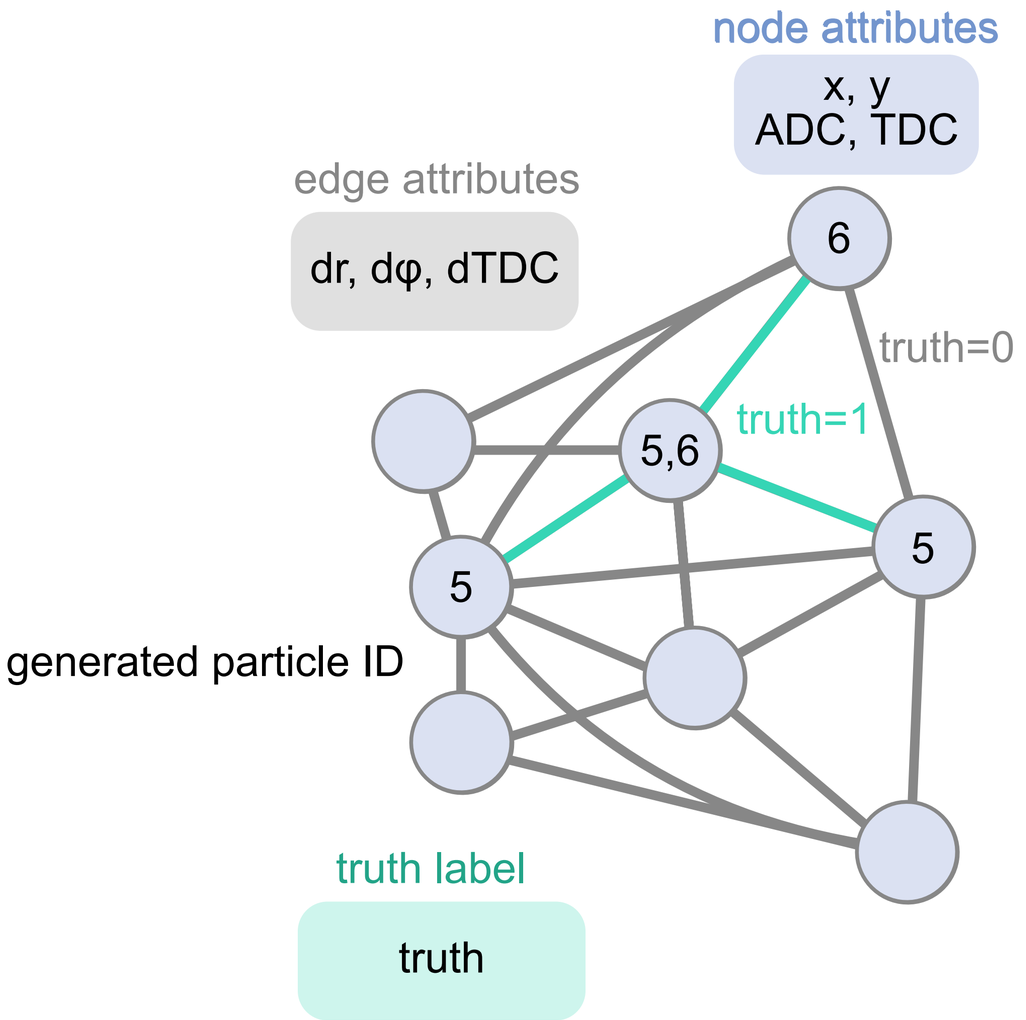
- wire coordinates (x, y)
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edge attributes

- dr, dφ, dTDC

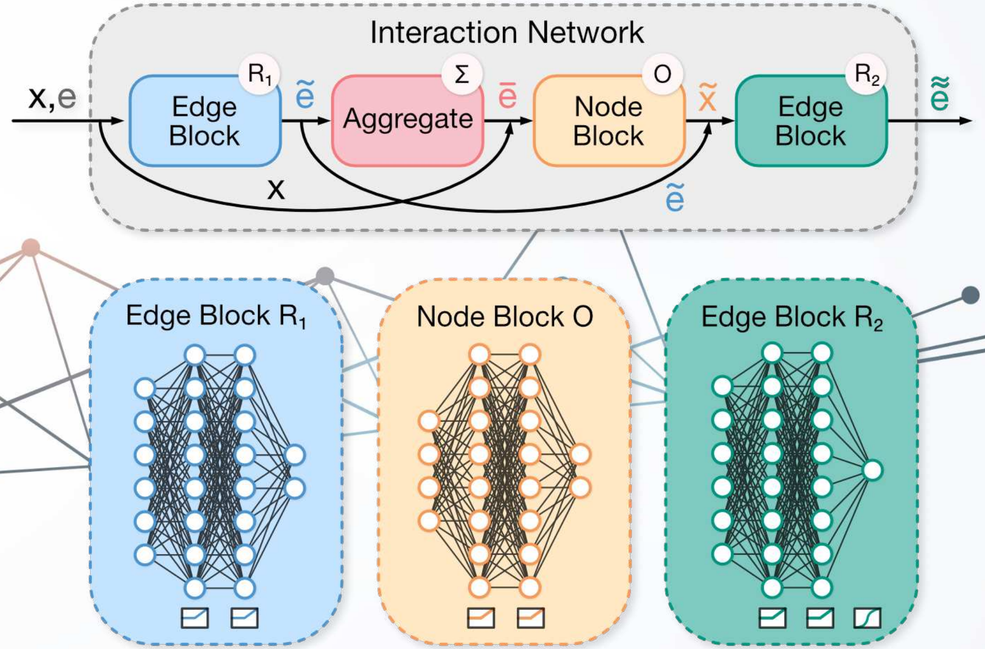
truth labels

- truth

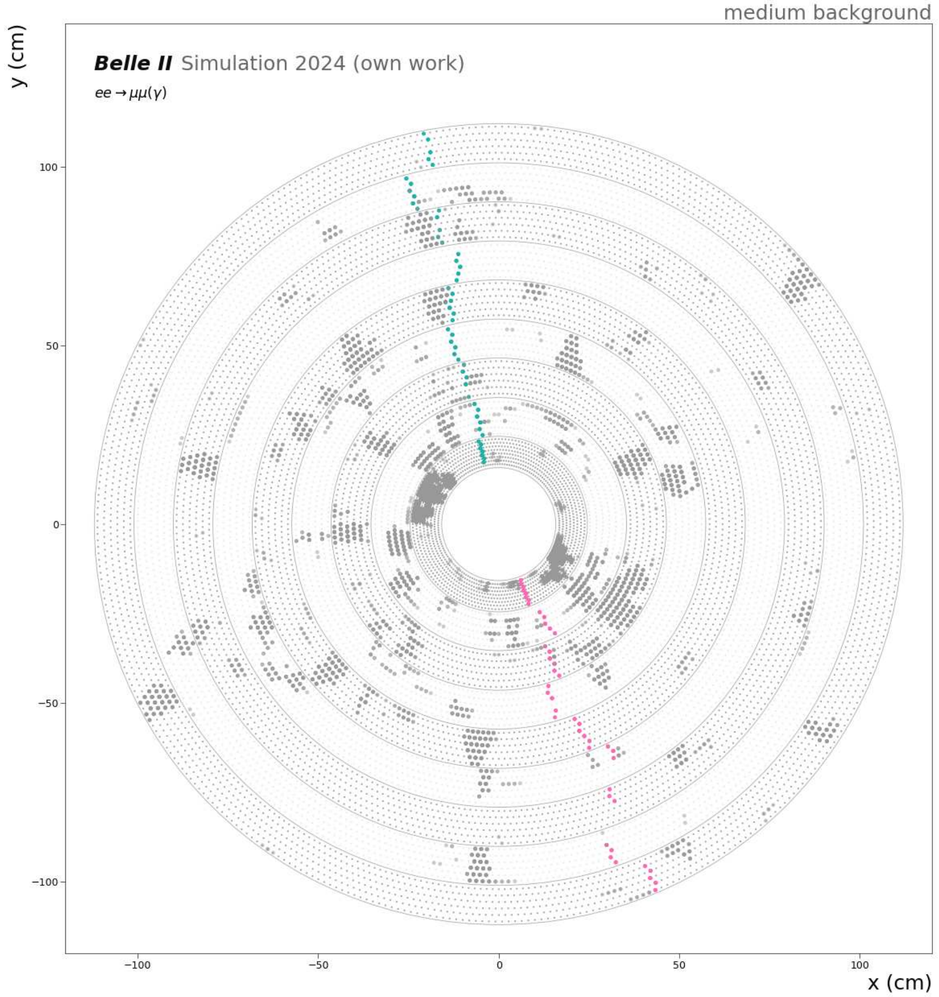


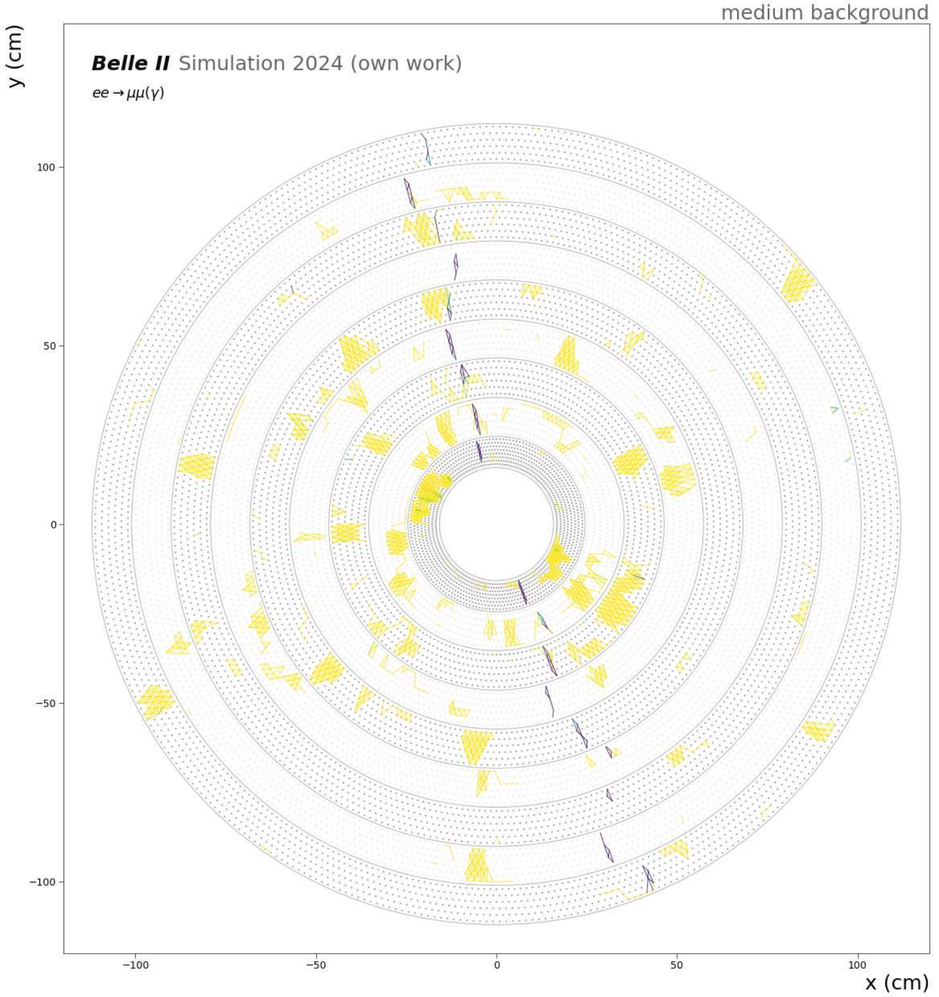
Hit Cleanup




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

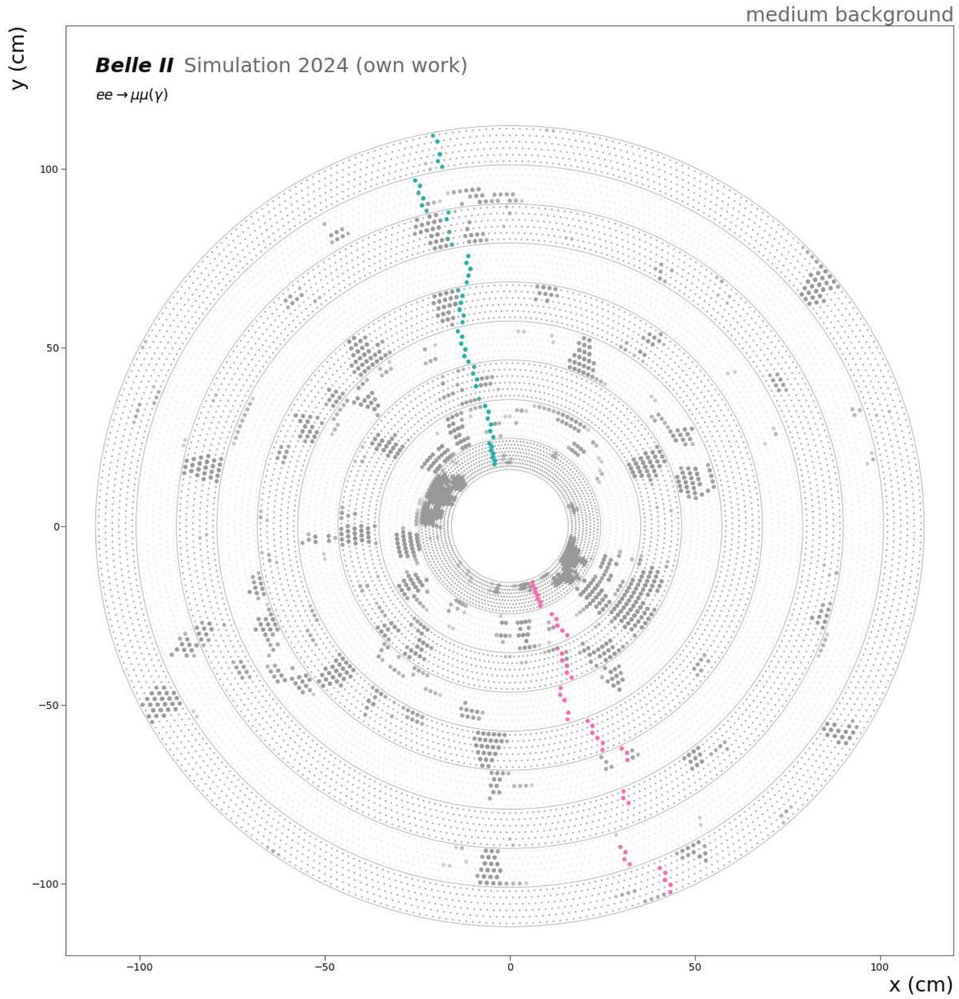
Graph Neural Network Output

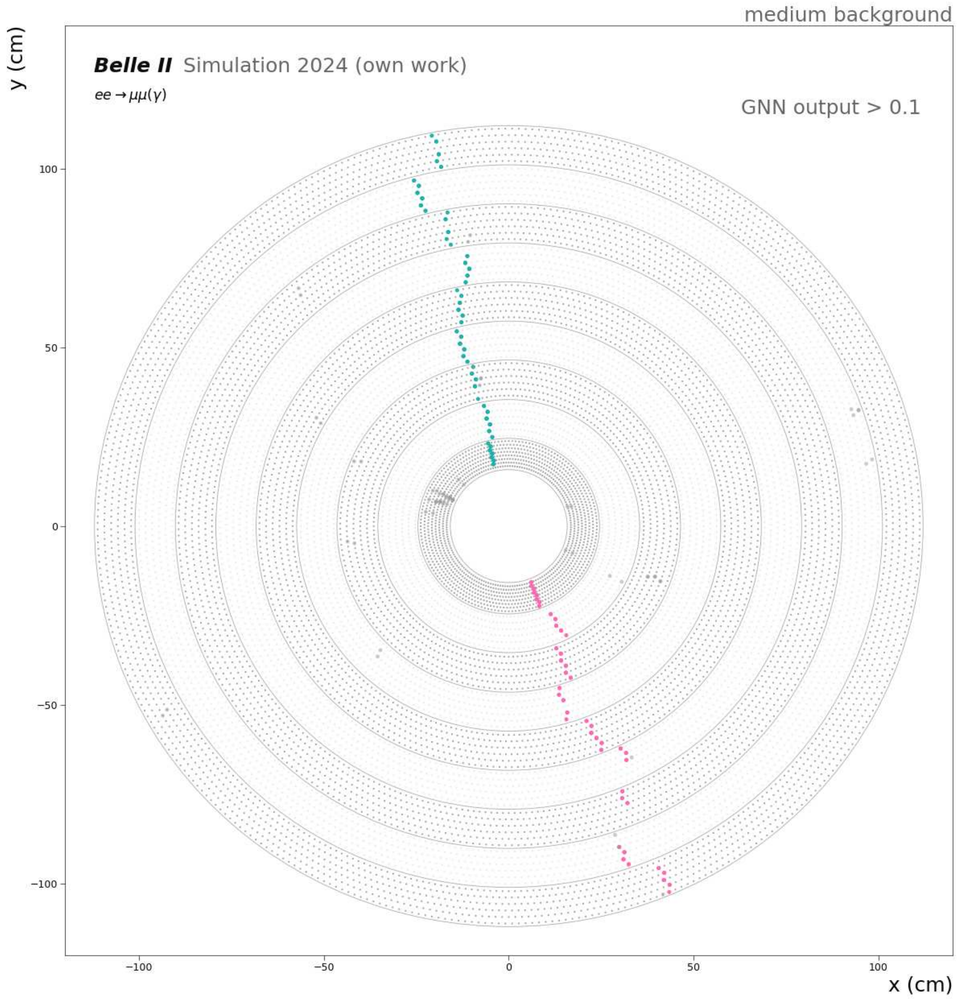


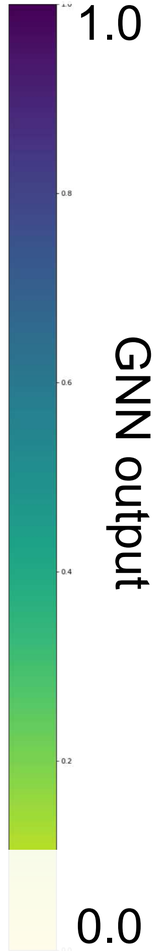




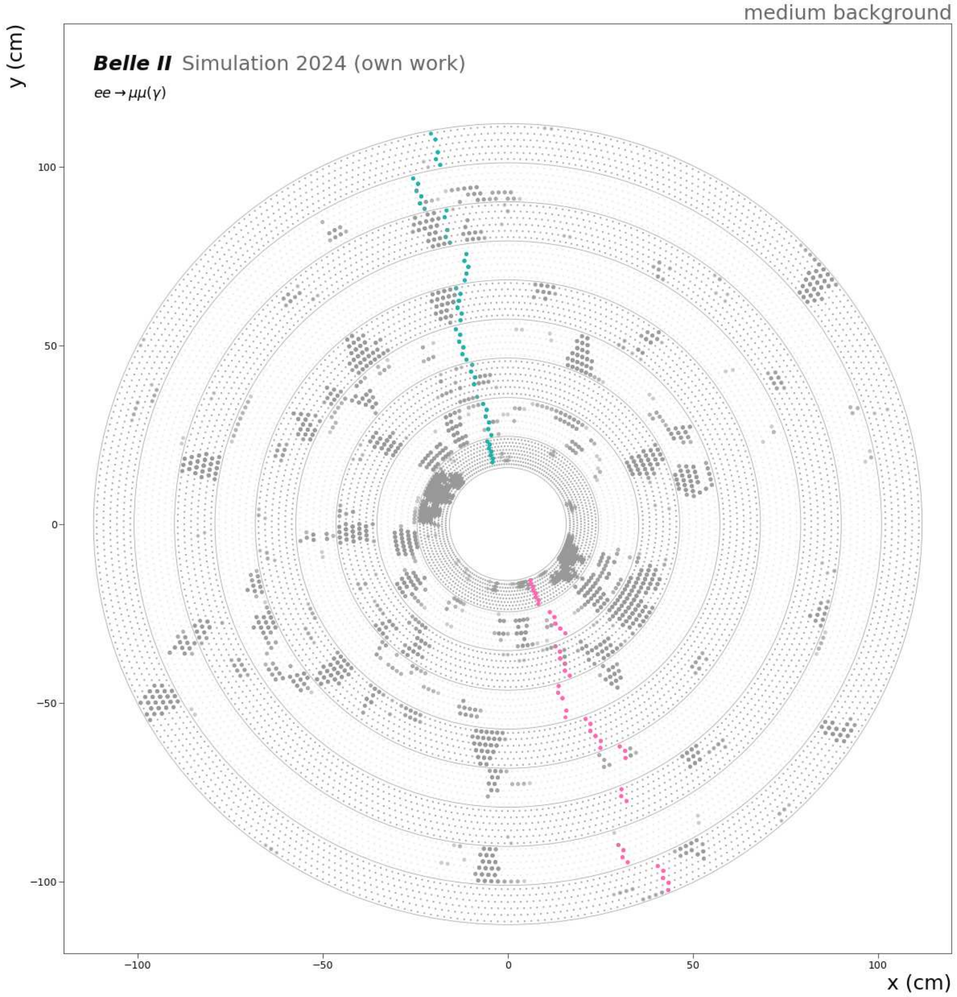
Graph Neural Network Output

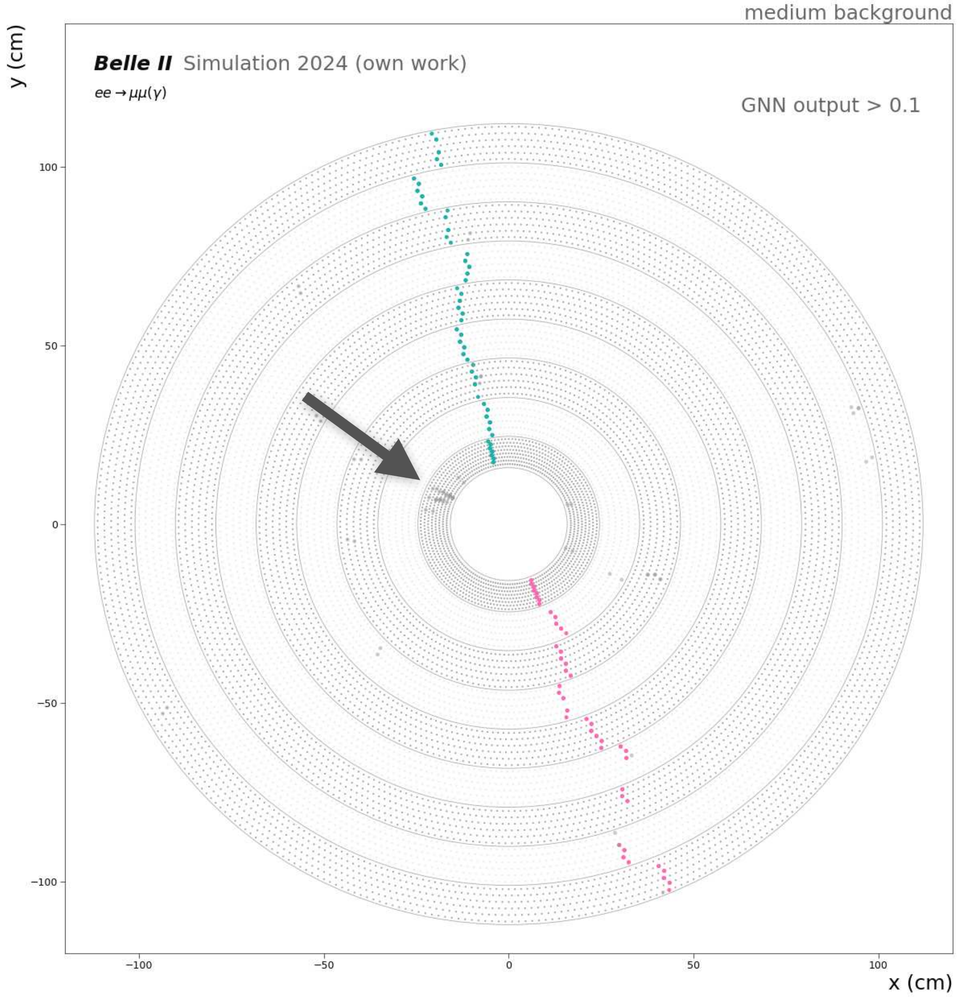


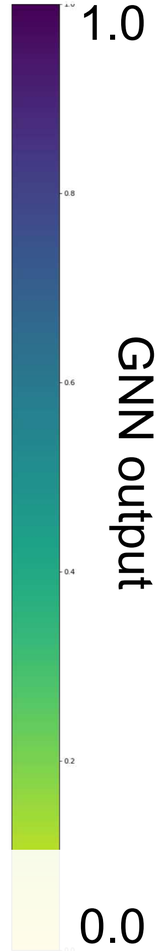




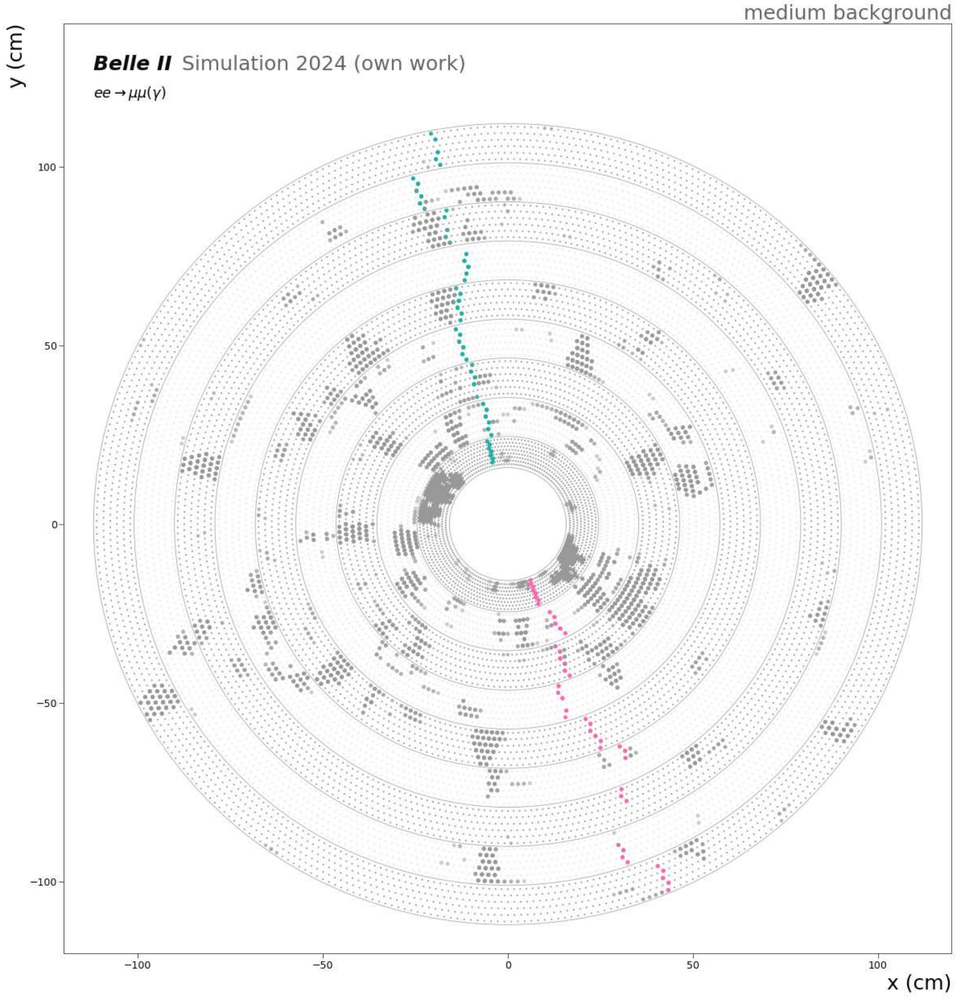
Graph Neural Network Output

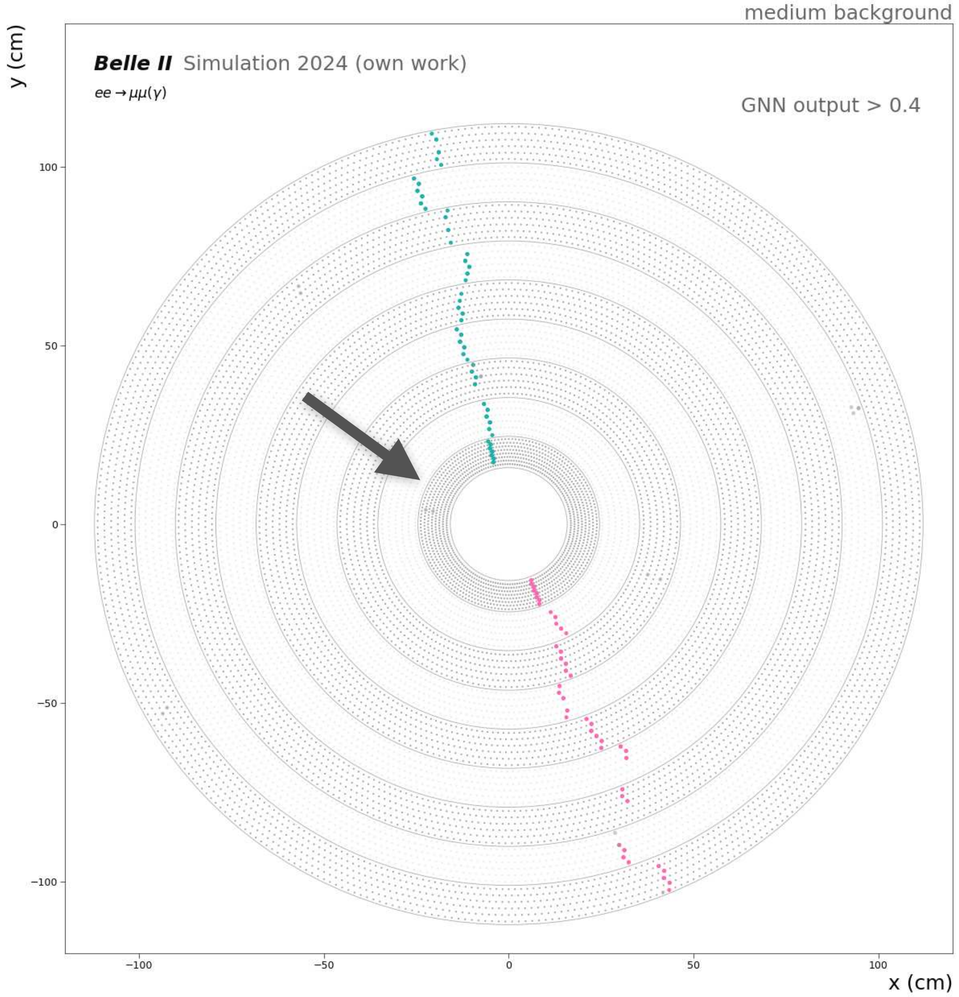


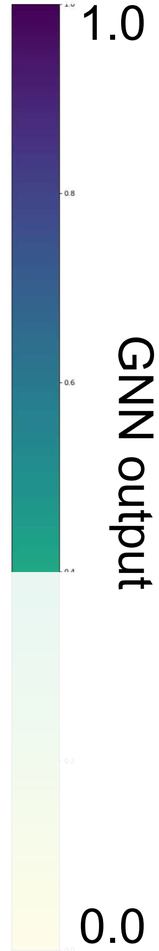




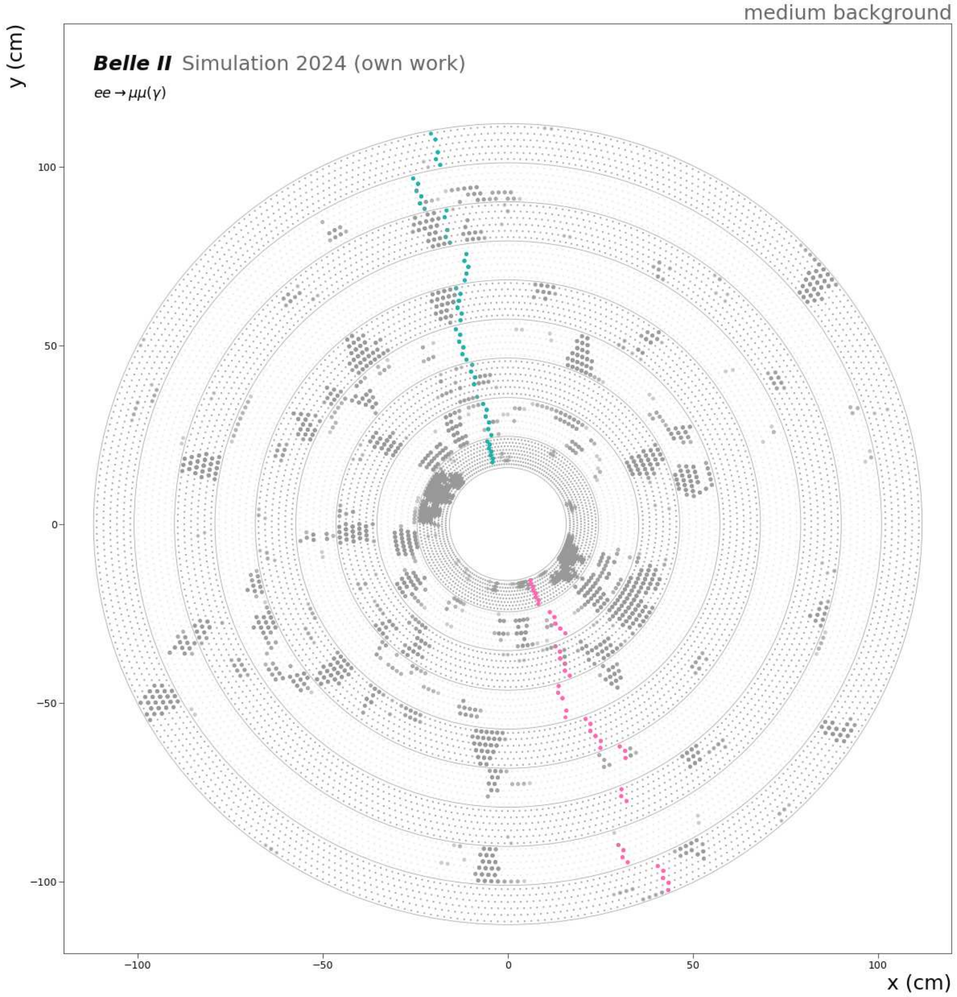
Graph Neural Network Output

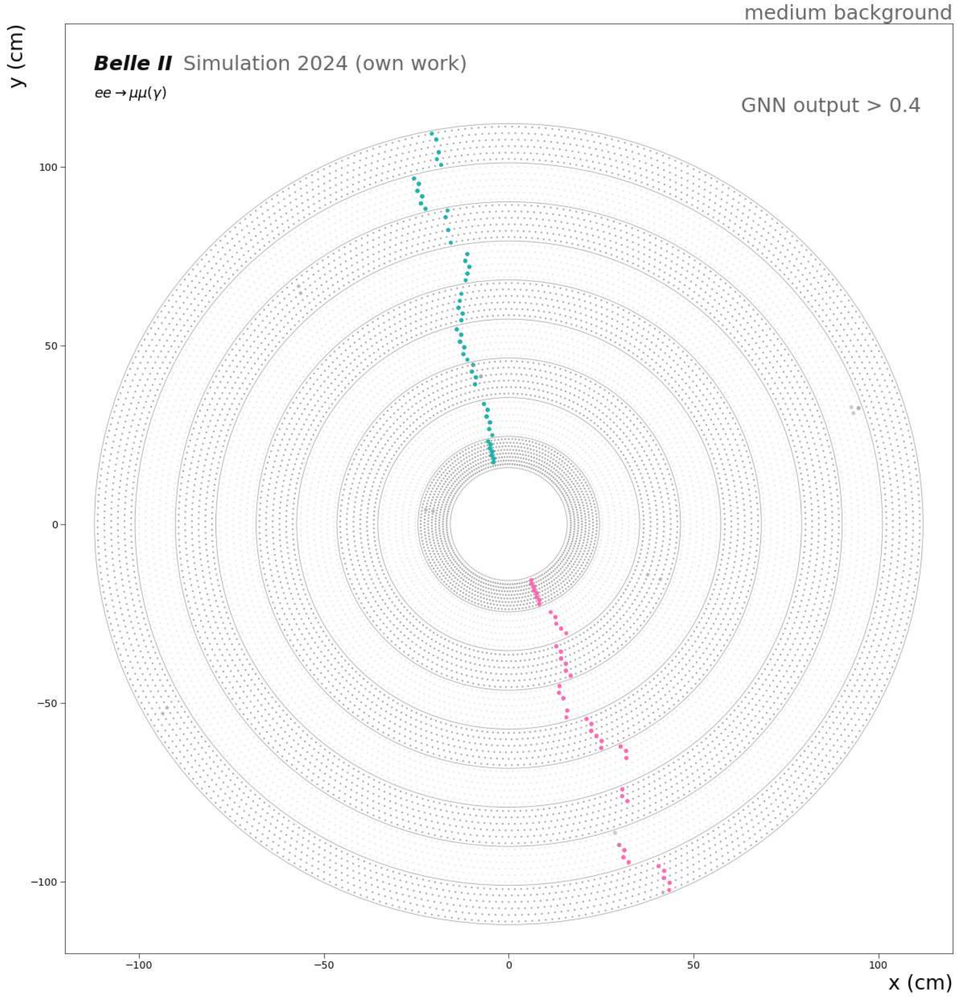


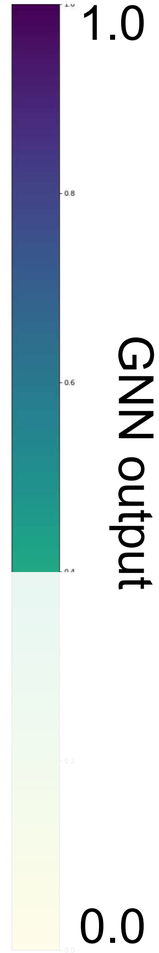




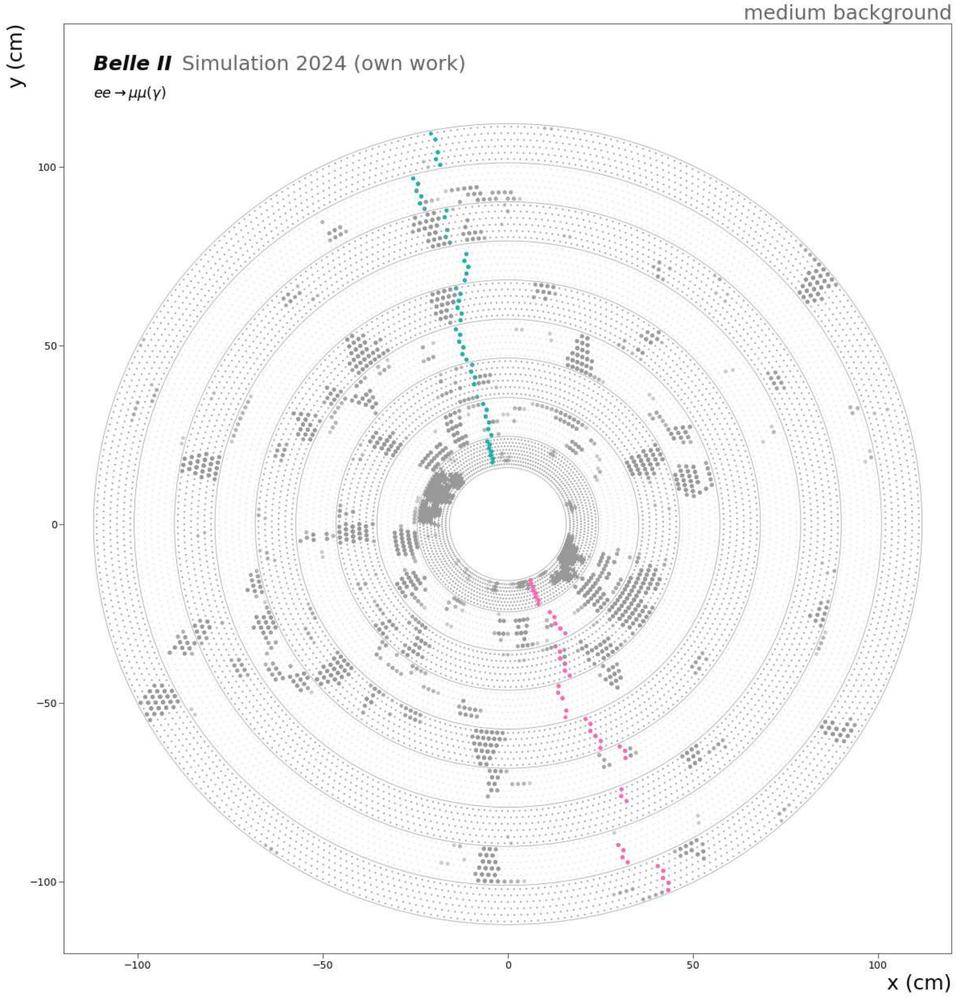
Graph Neural Network Output

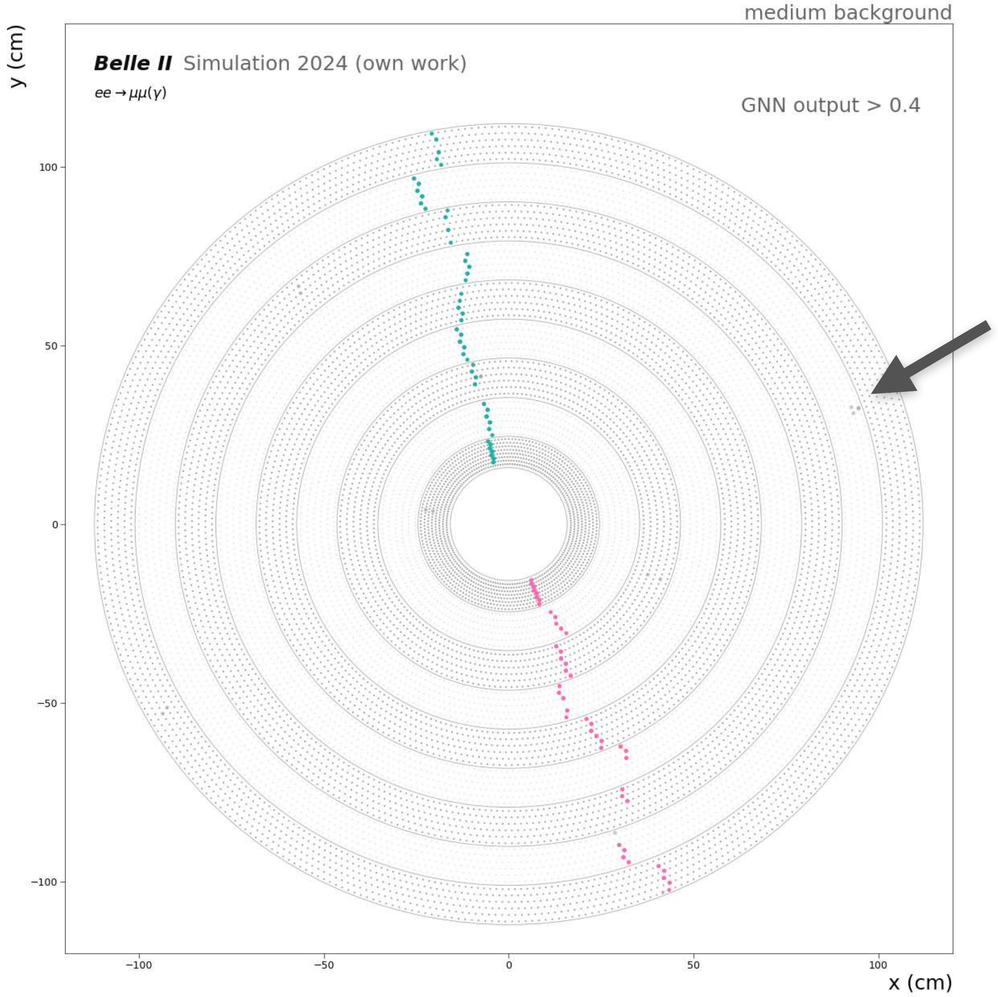


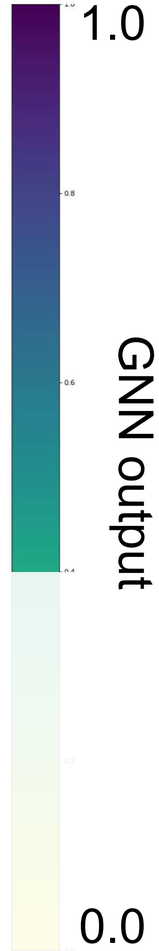




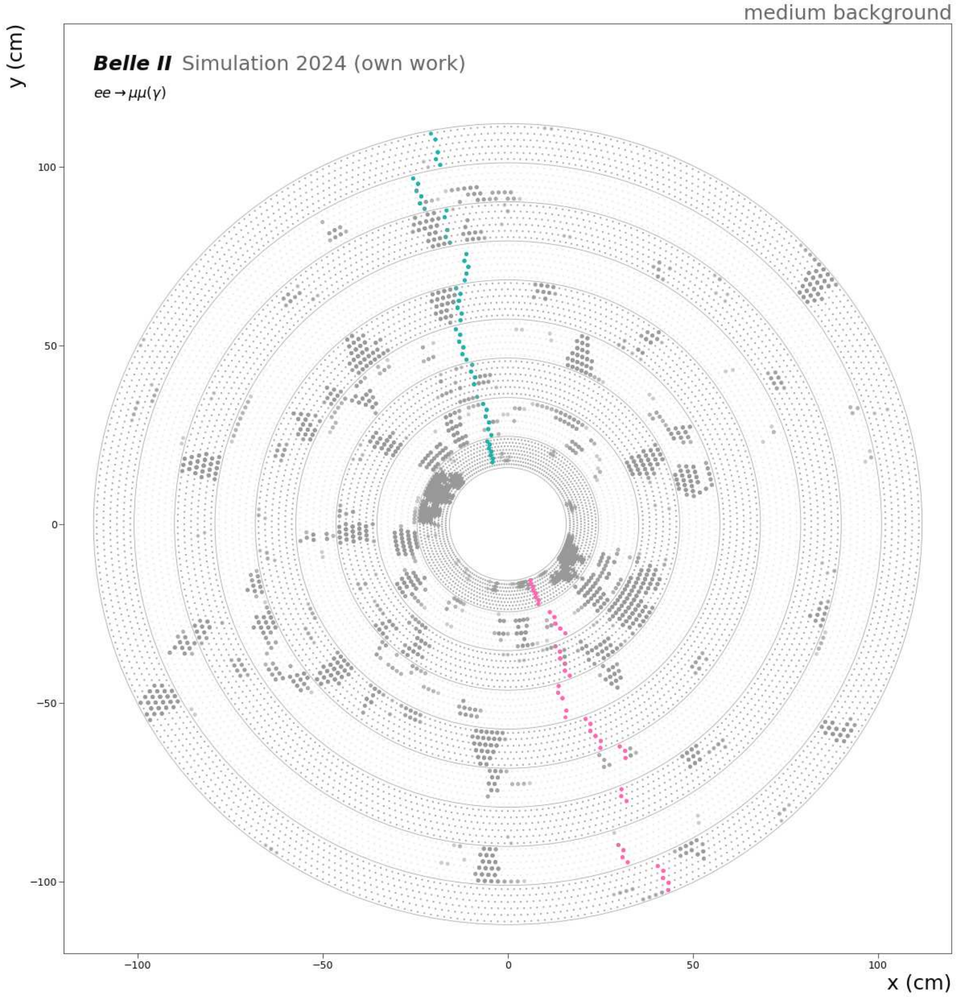
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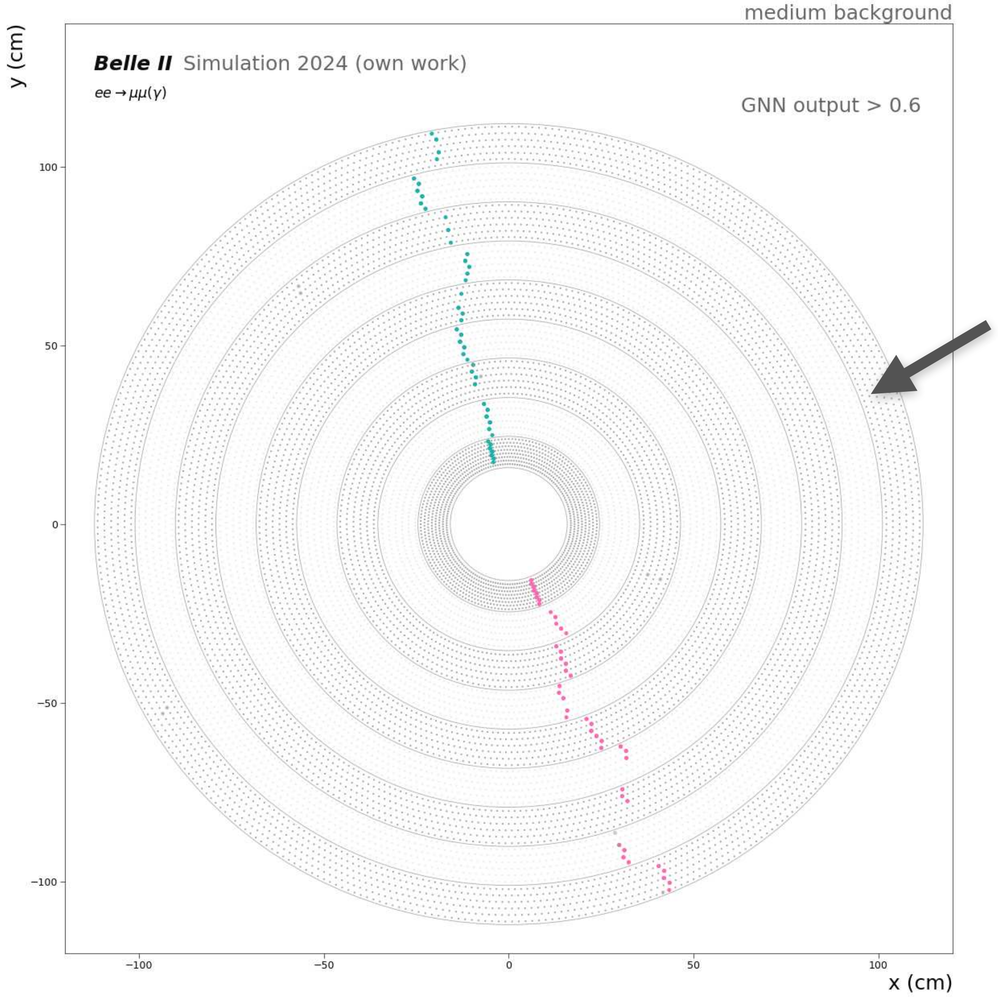


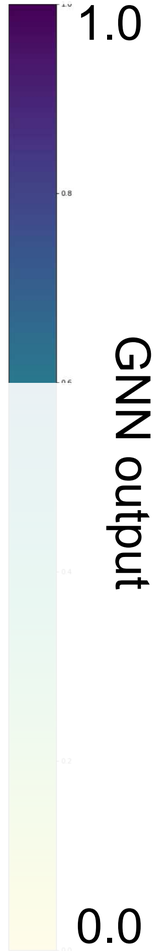




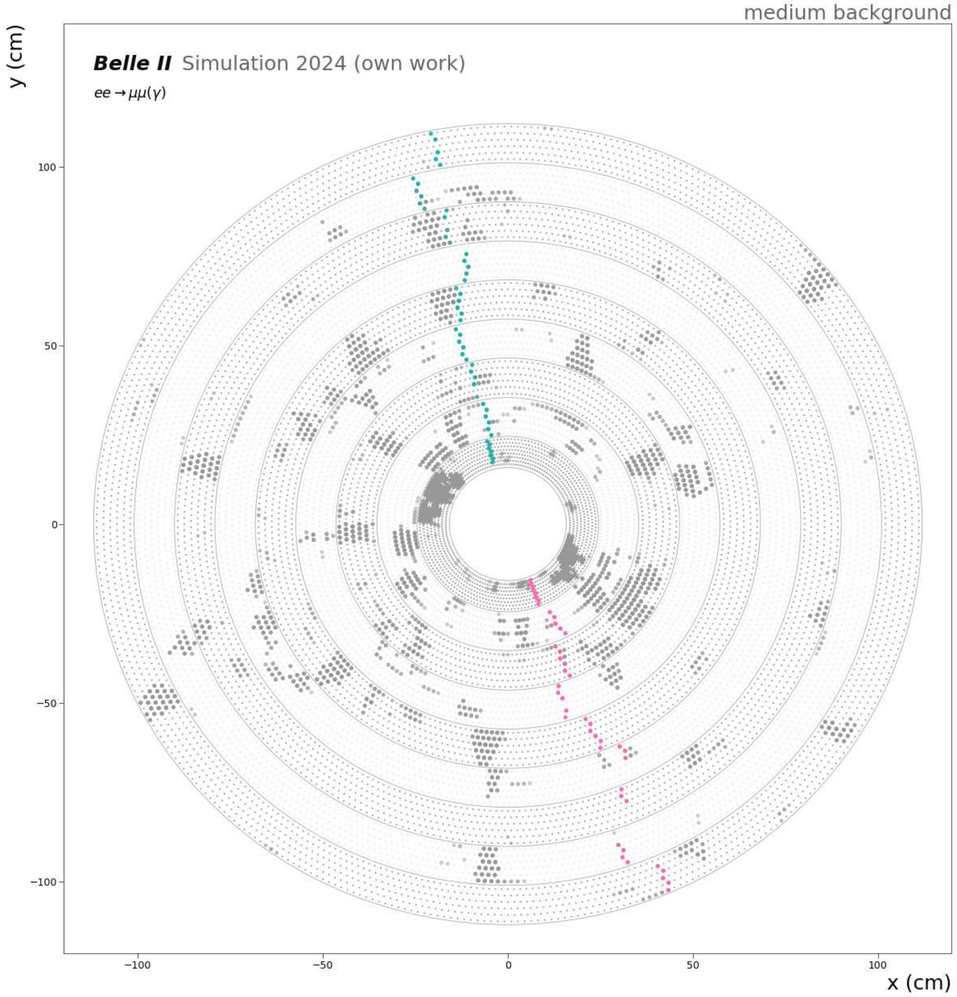
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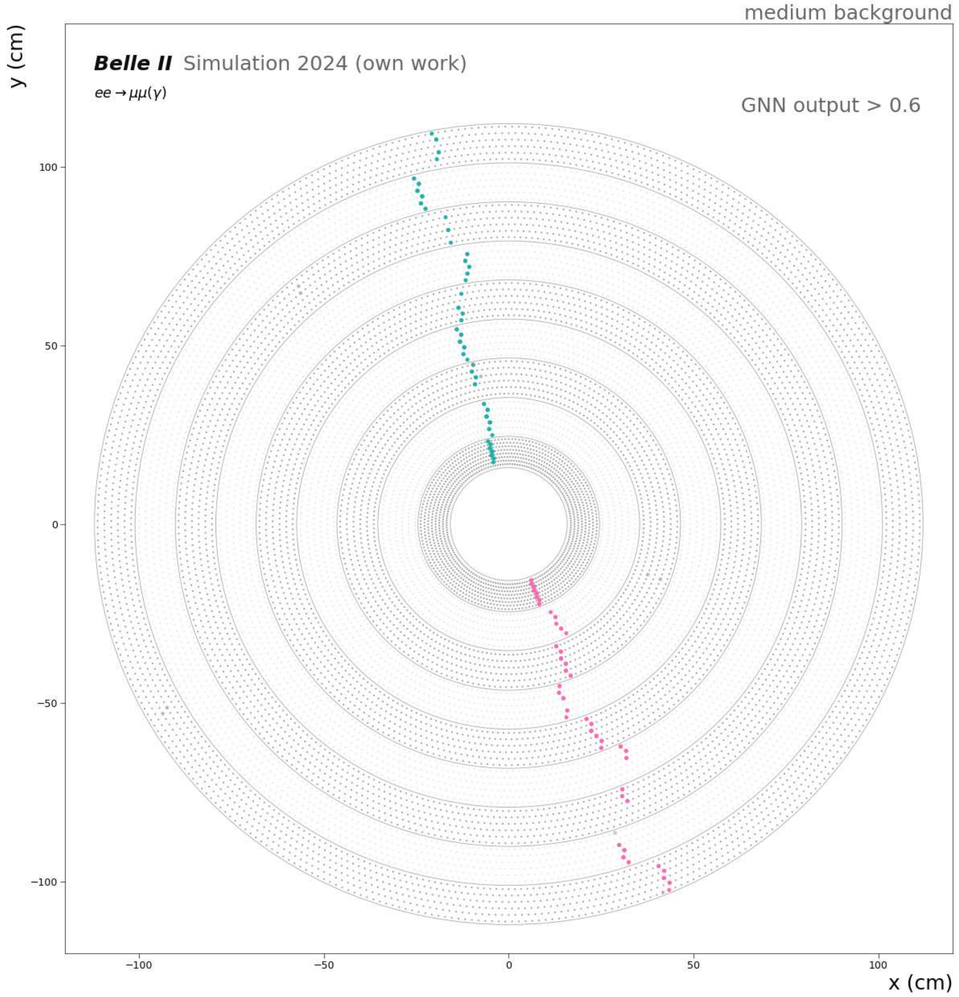


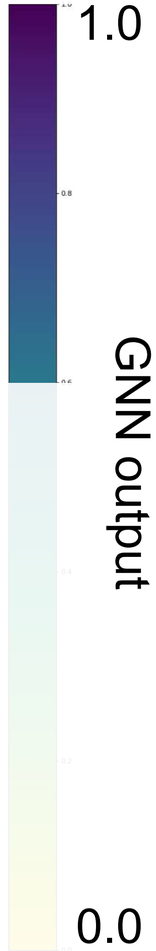




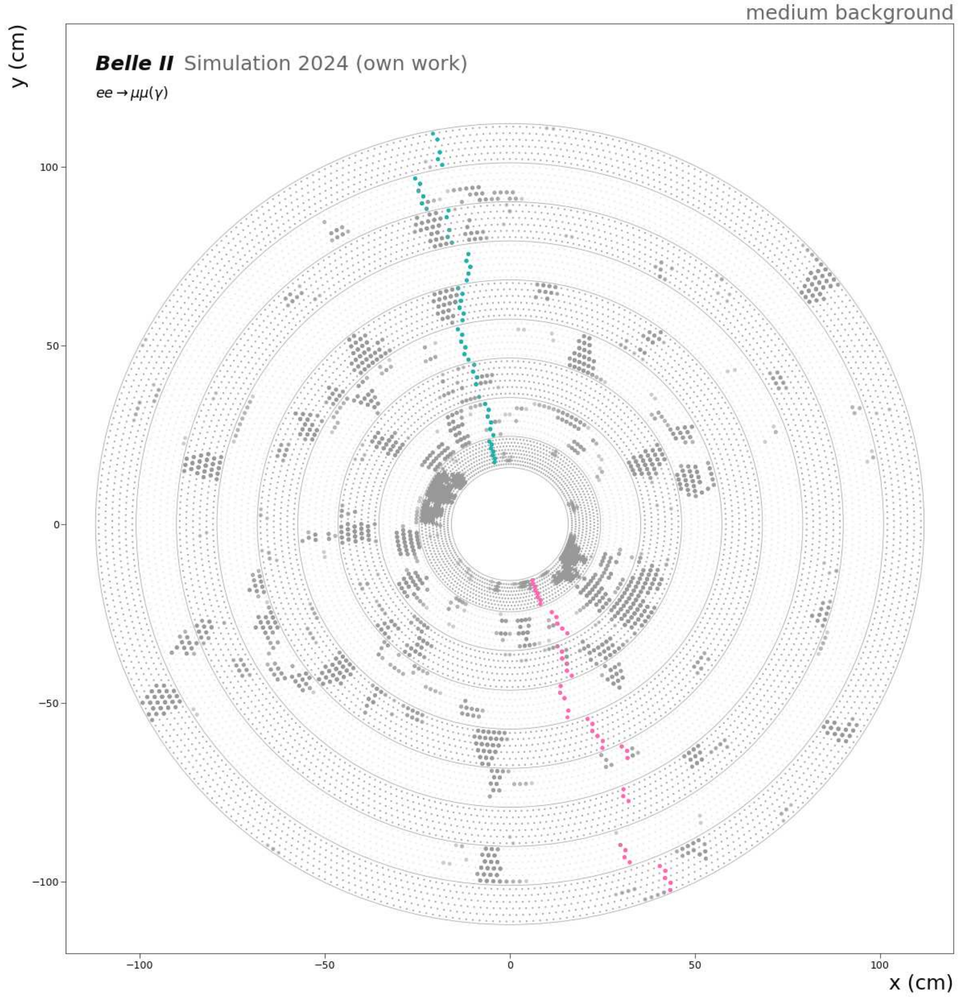
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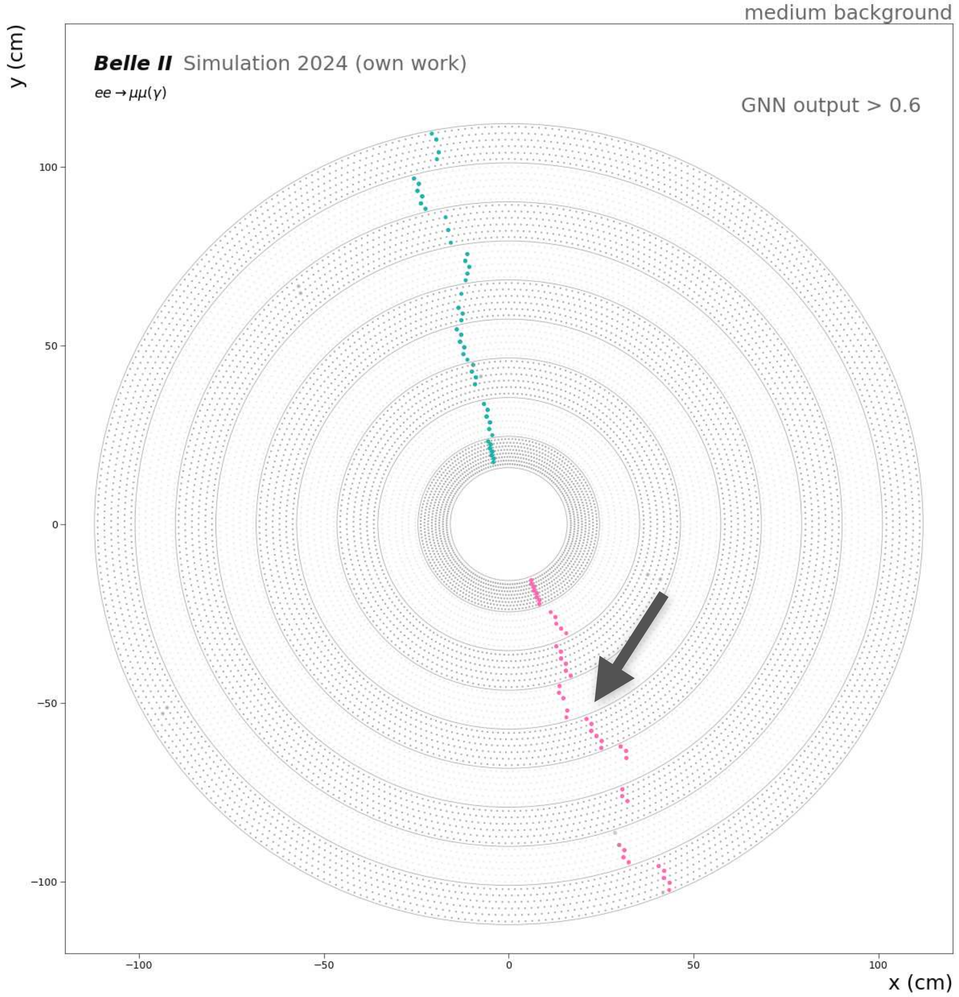


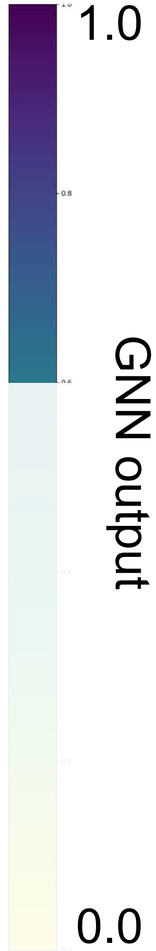




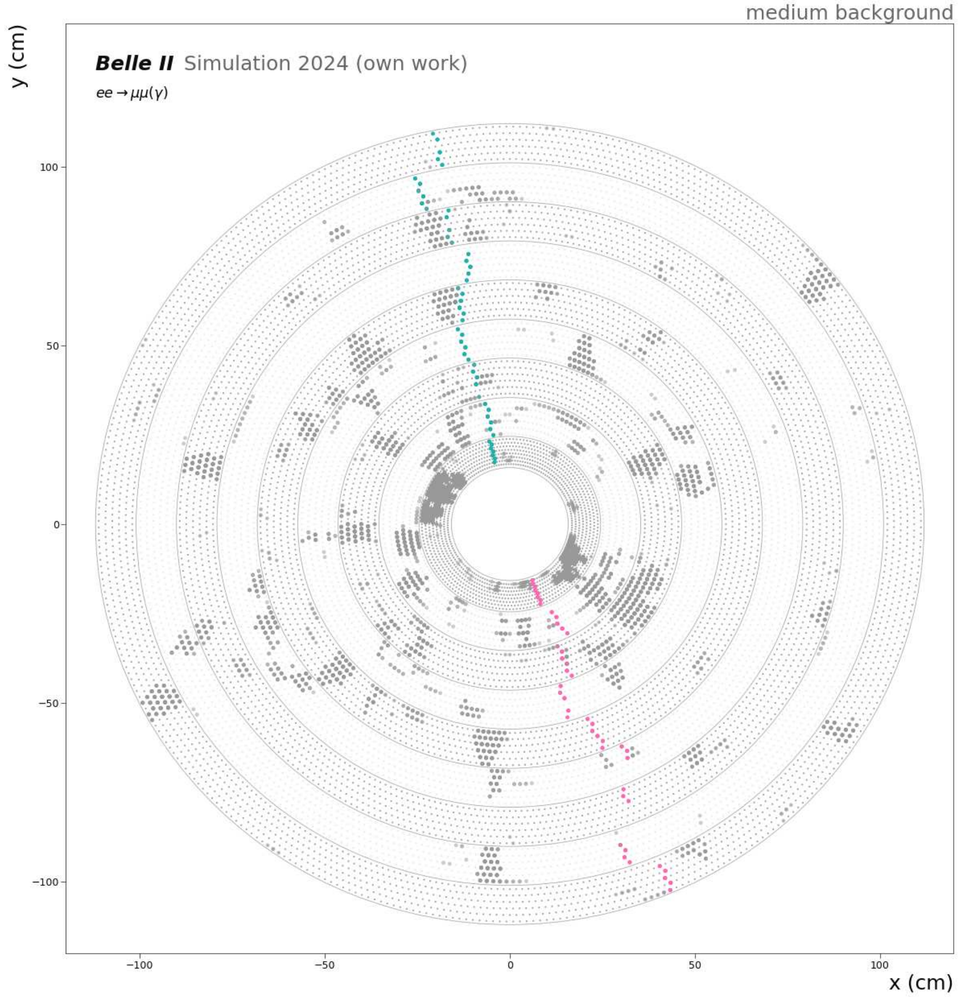
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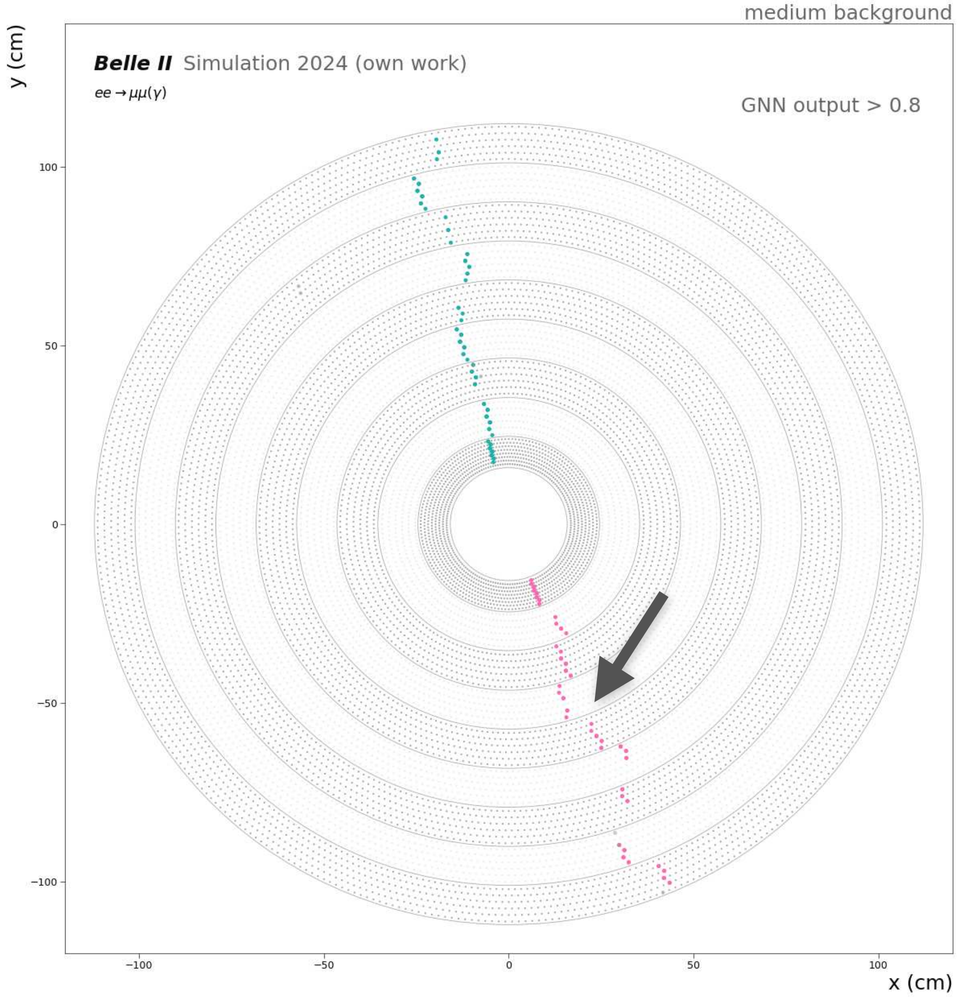


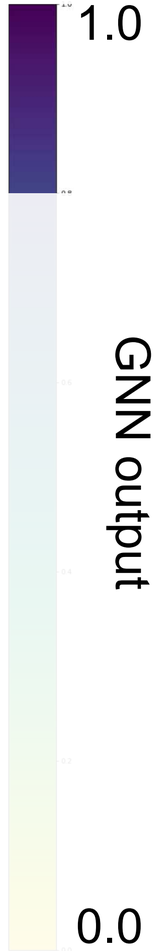




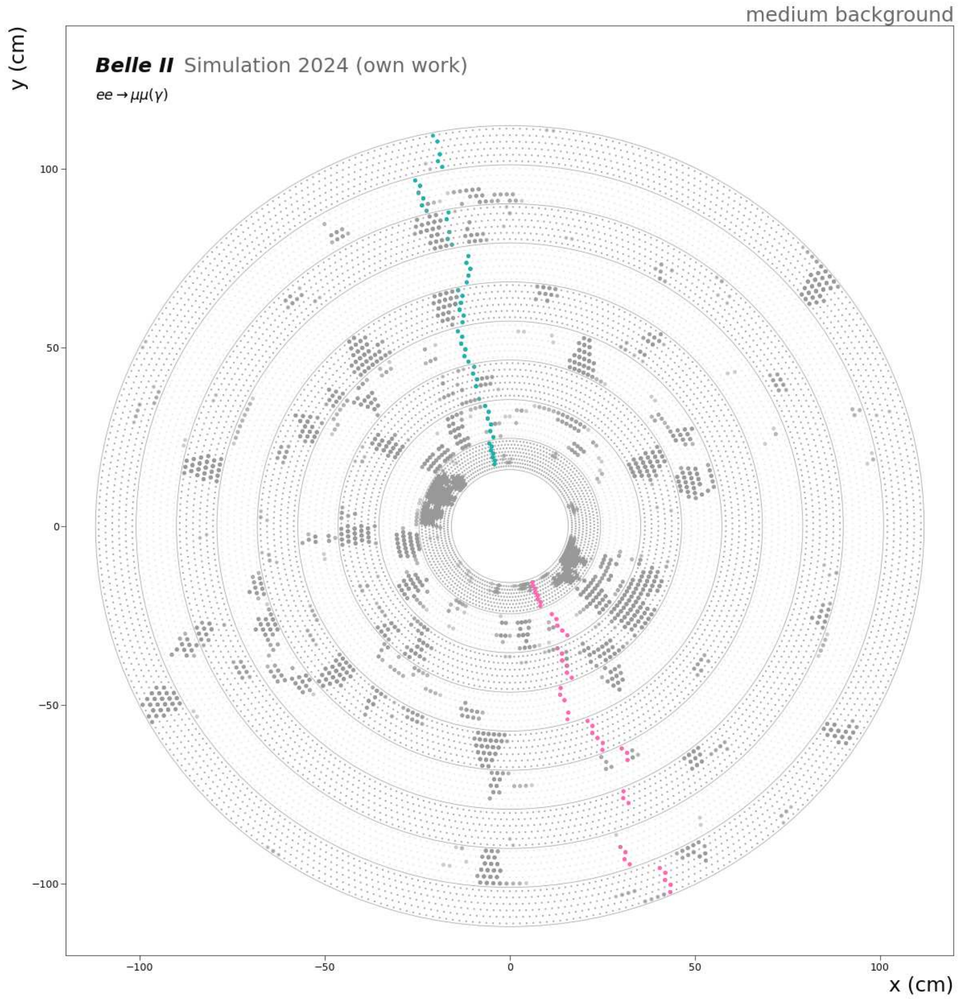
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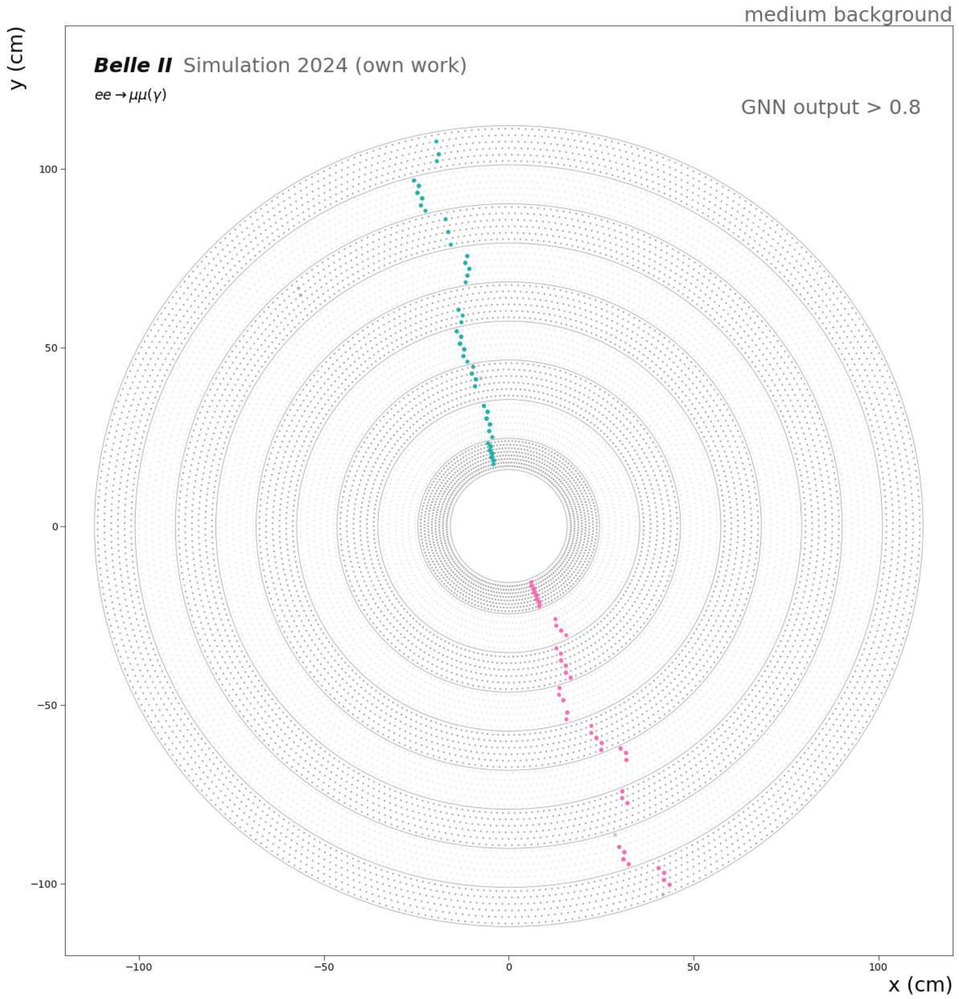


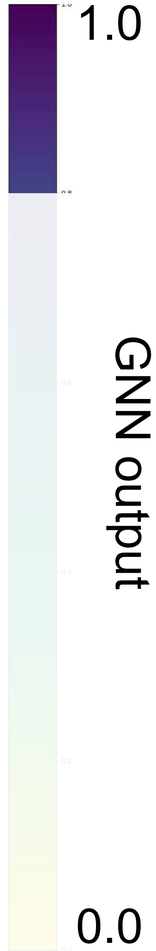




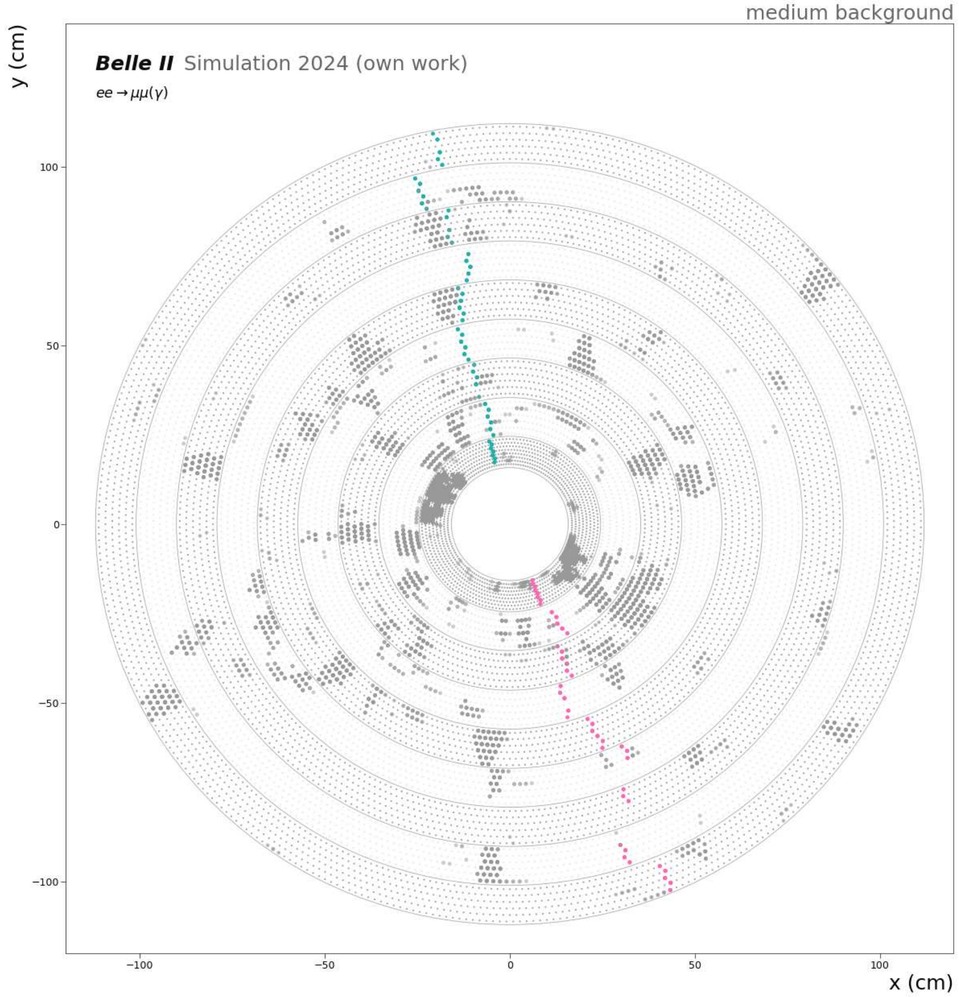
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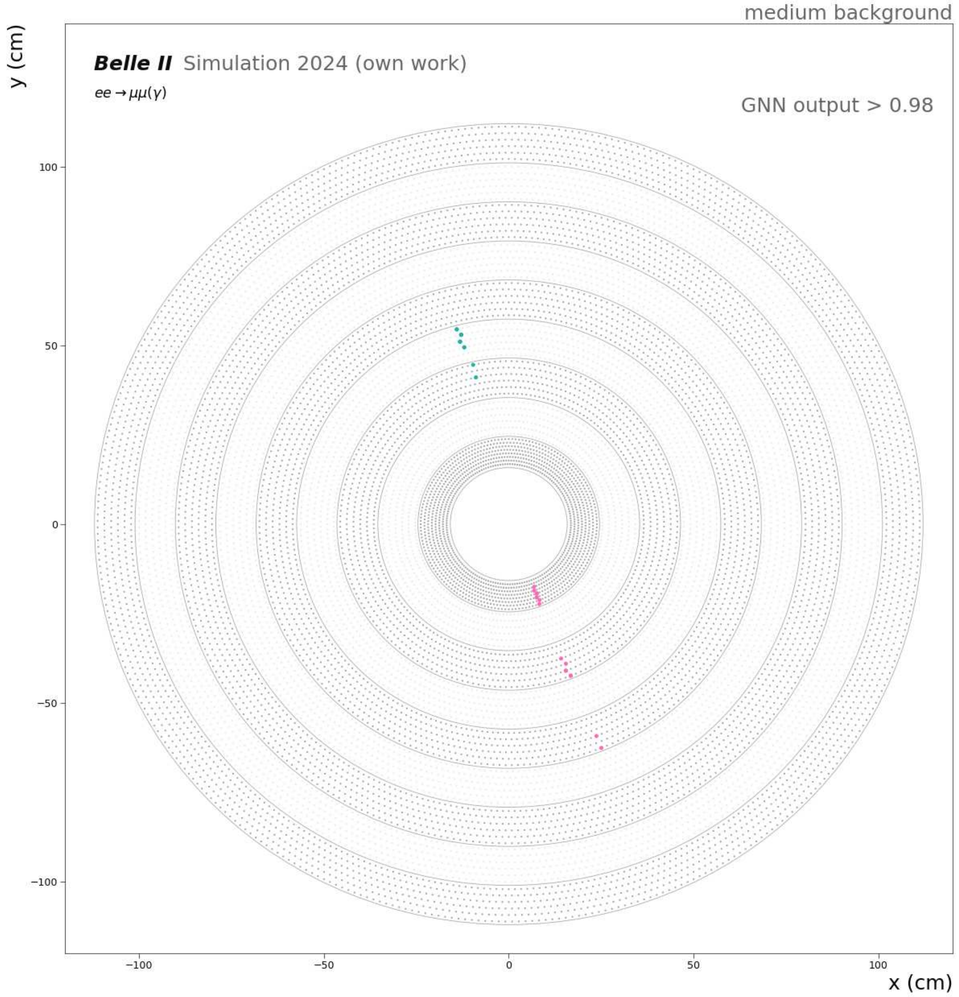


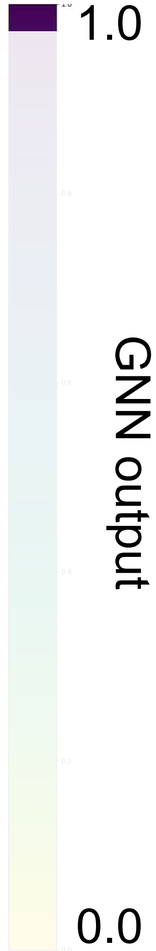




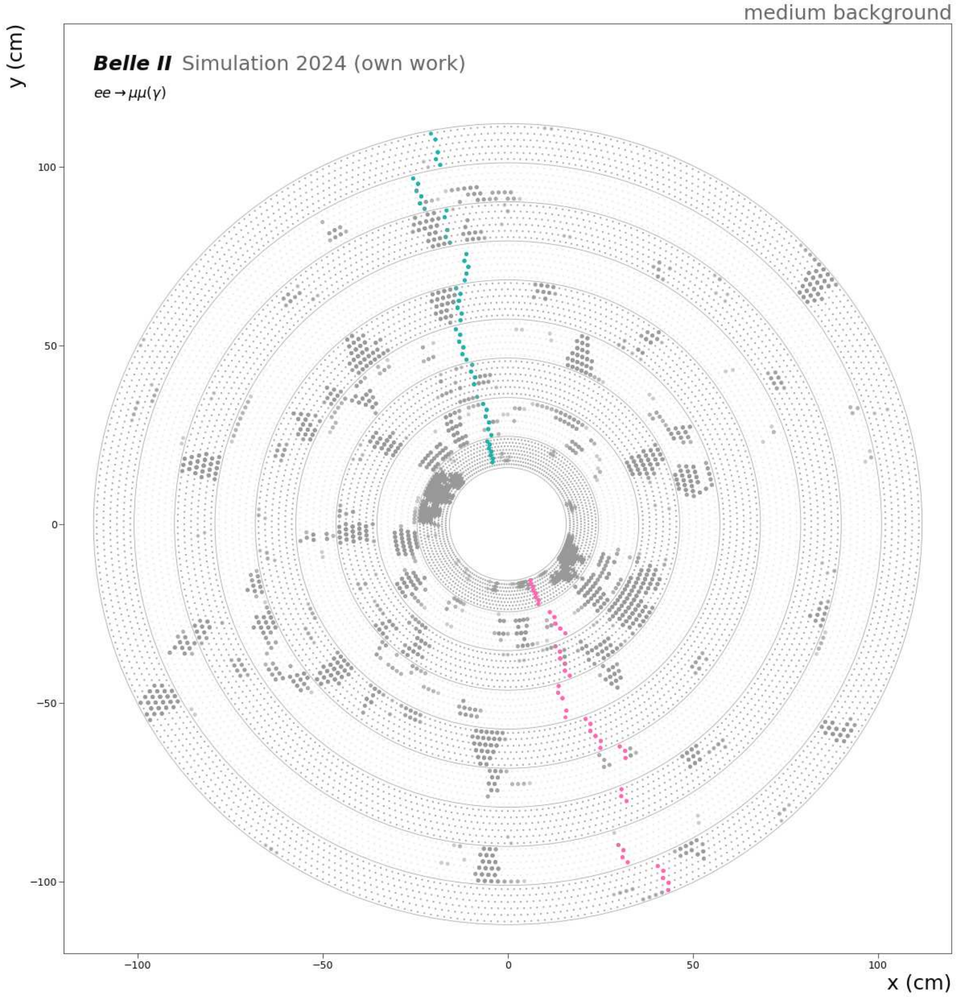
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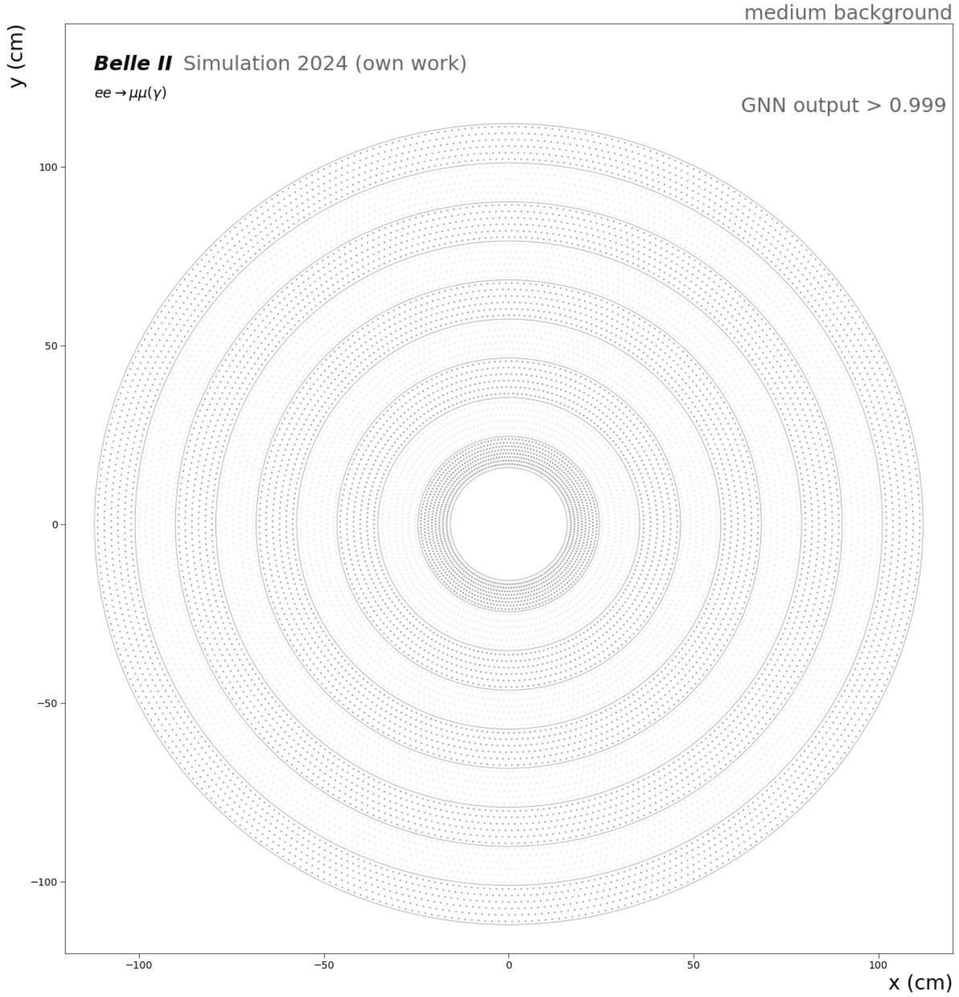


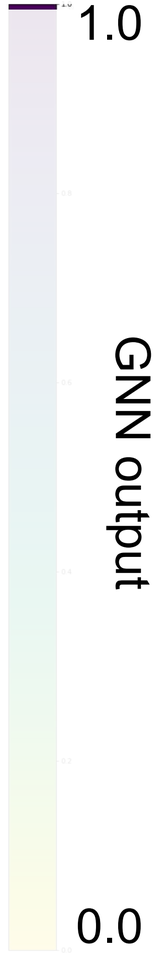




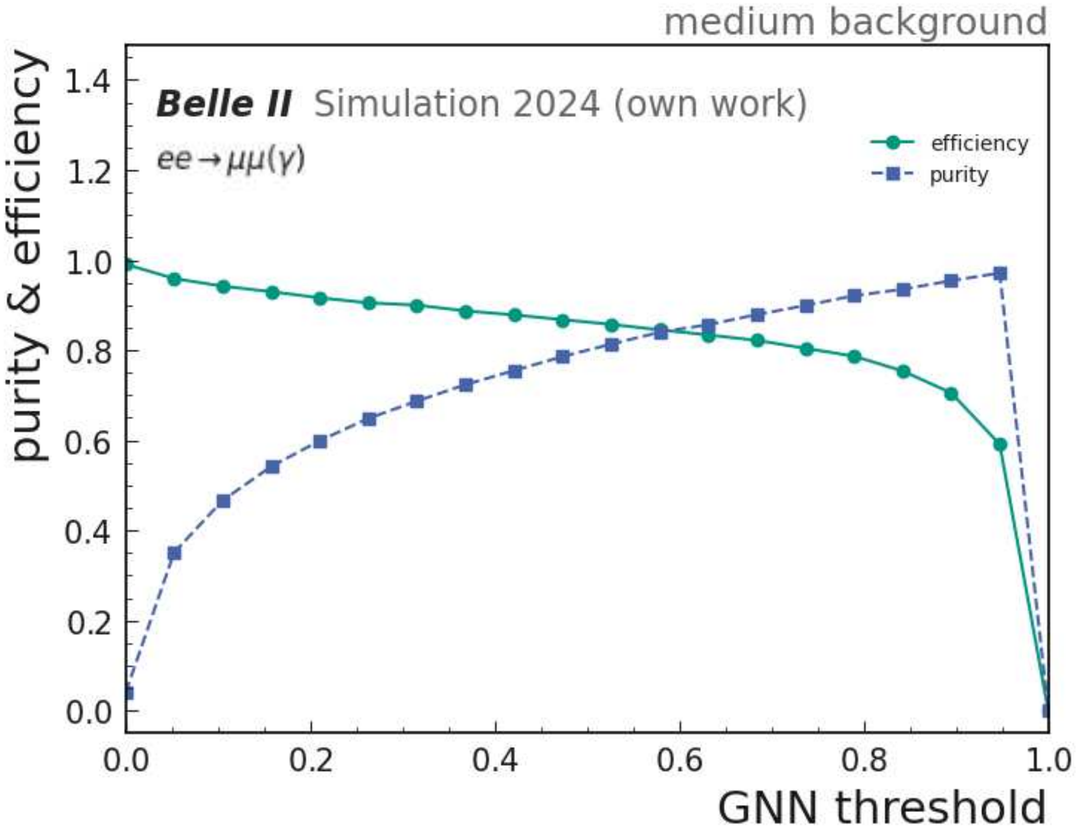
Graph Neural Network Output







Hit Cleanup Results



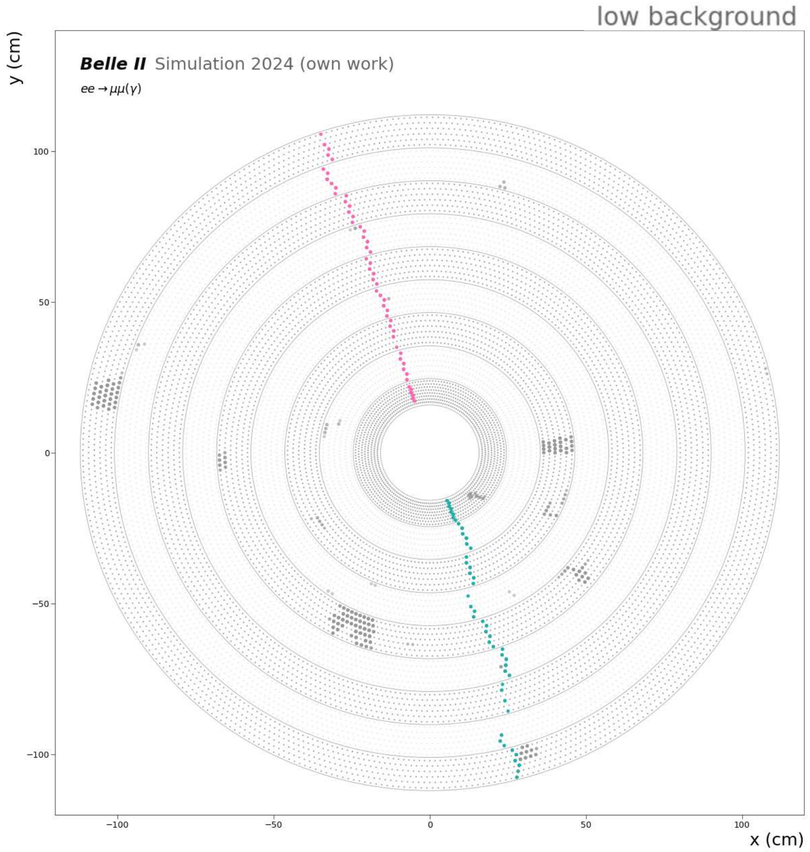
$$\text{efficiency} = \frac{\text{kept signal hits}}{\text{all signal hits}}$$

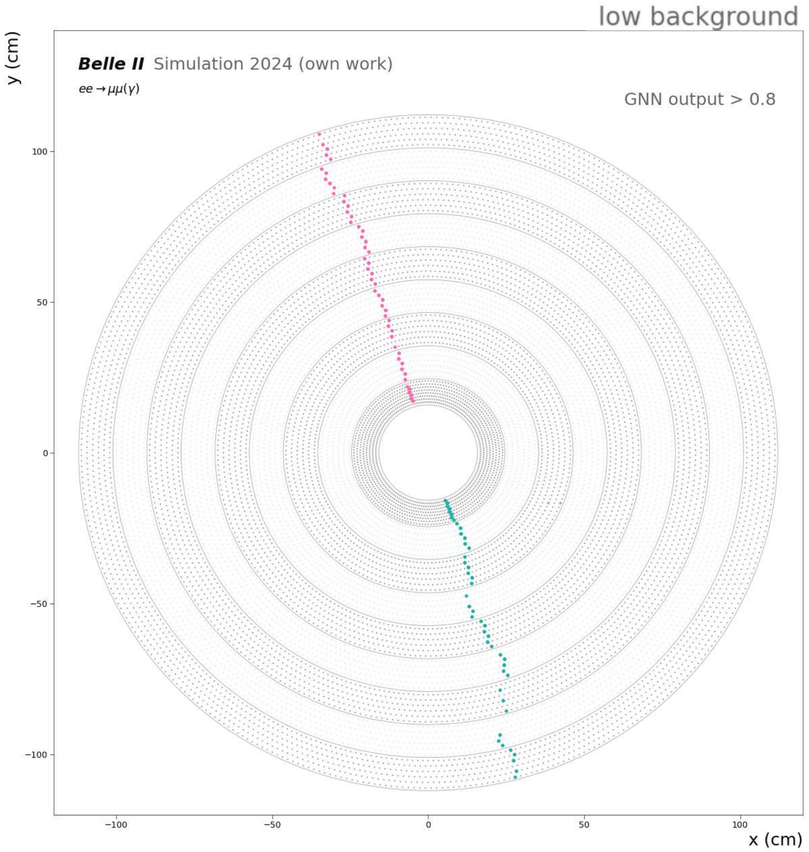
„how much of signal hits kept“

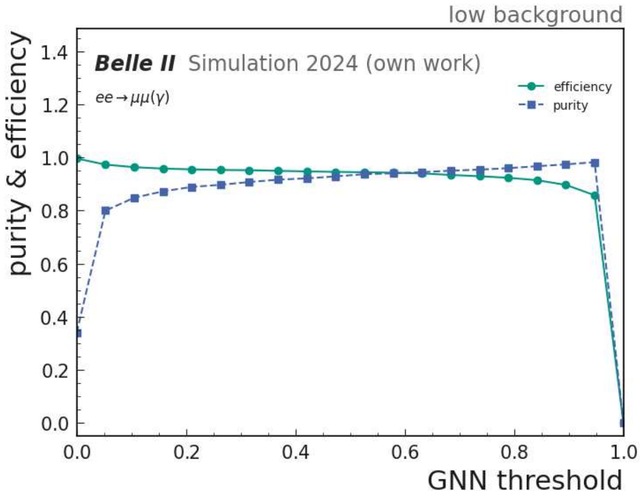
$$\text{purity} = \frac{\text{kept signal hits}}{\text{all kept hits}}$$

„how much of kept hits are signal“

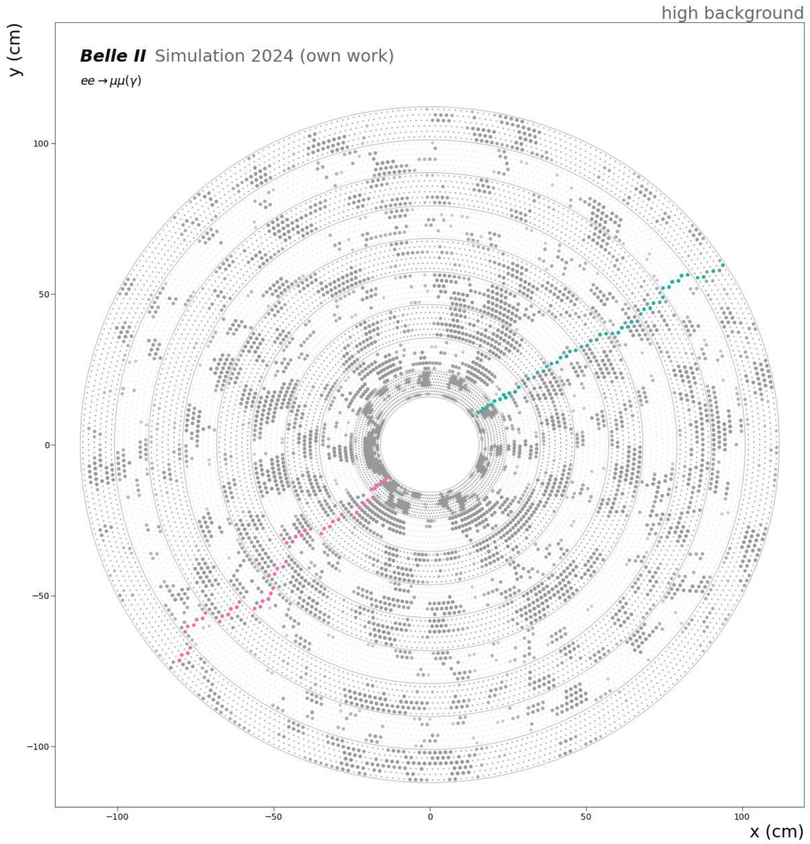
Hit Cleanup Example Low Background

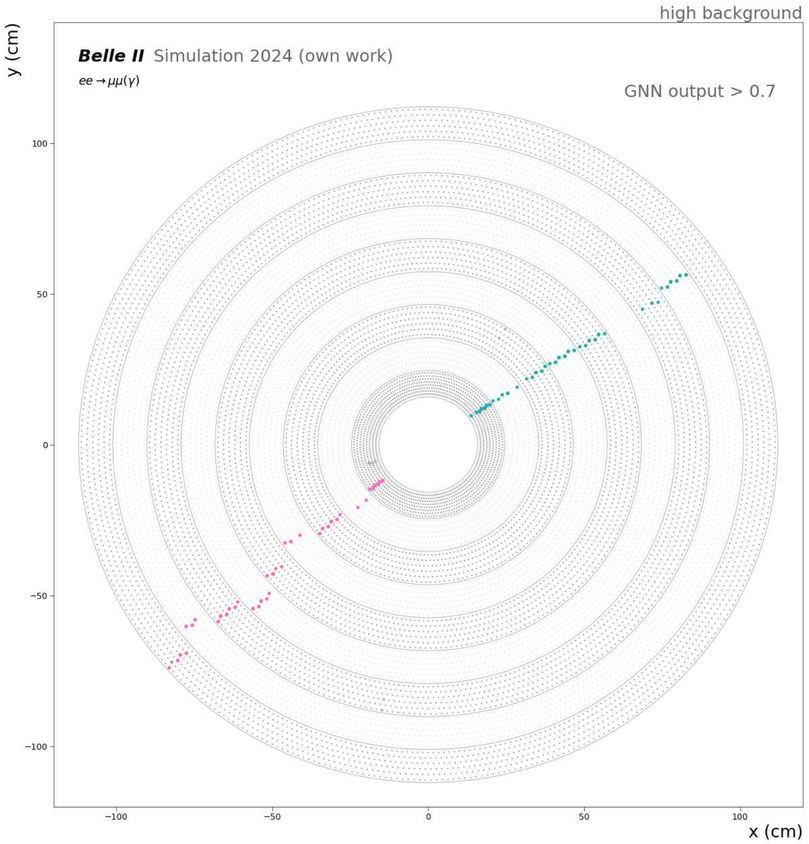


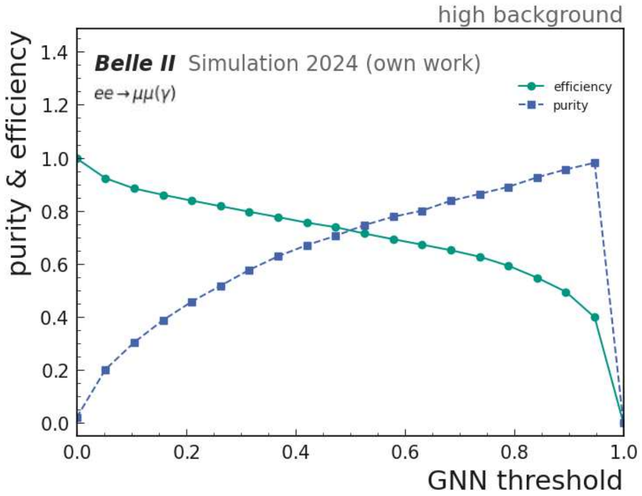




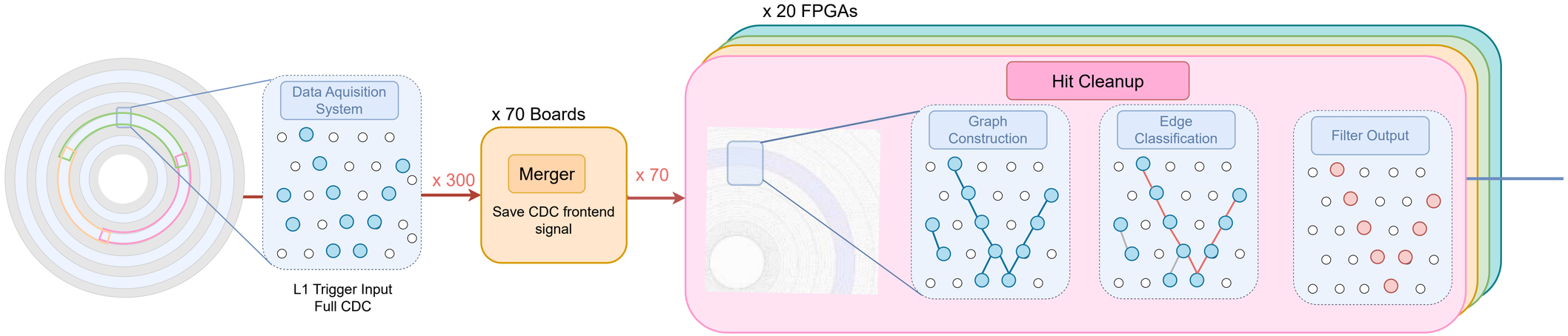
Hit Cleanup Example High Background







Next steps towards implementation



CDC segmentation

- segmentation by superlayer & angle on 20 FPGA boards
- handle overlaps
- handle merging

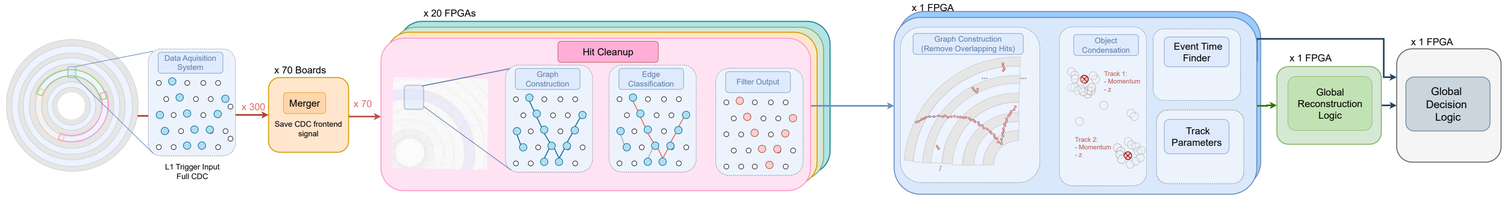


FPGA implementation



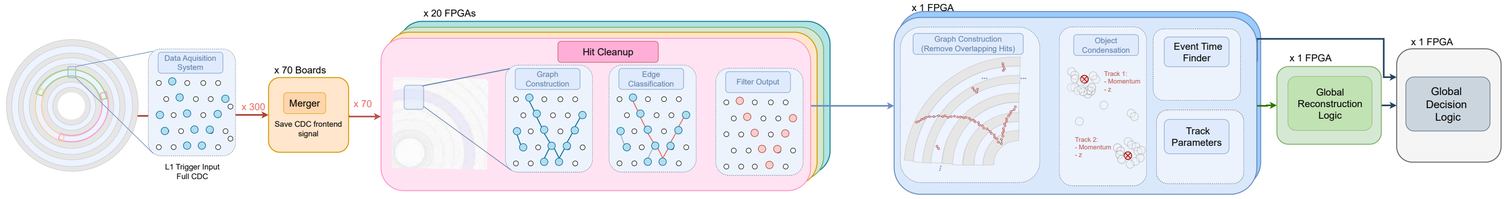
- size reduction studies (quantization, graph size compression, pruning, etc.)
- implementation (hls4ml)

Summary



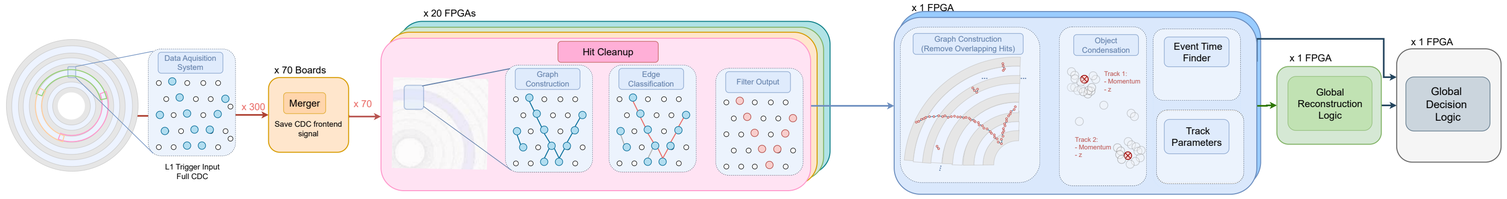
Karlsruhe Institute of Technology

Summary



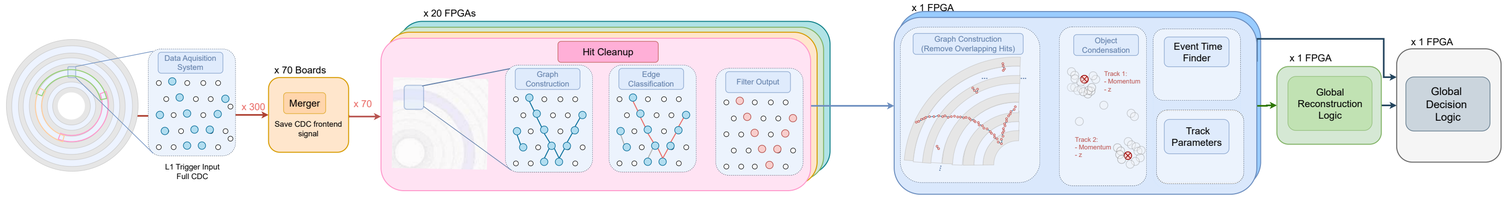
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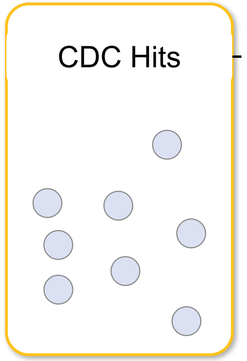
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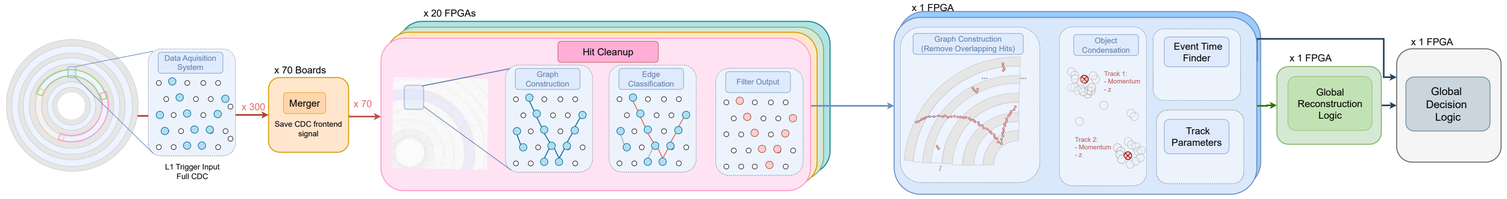


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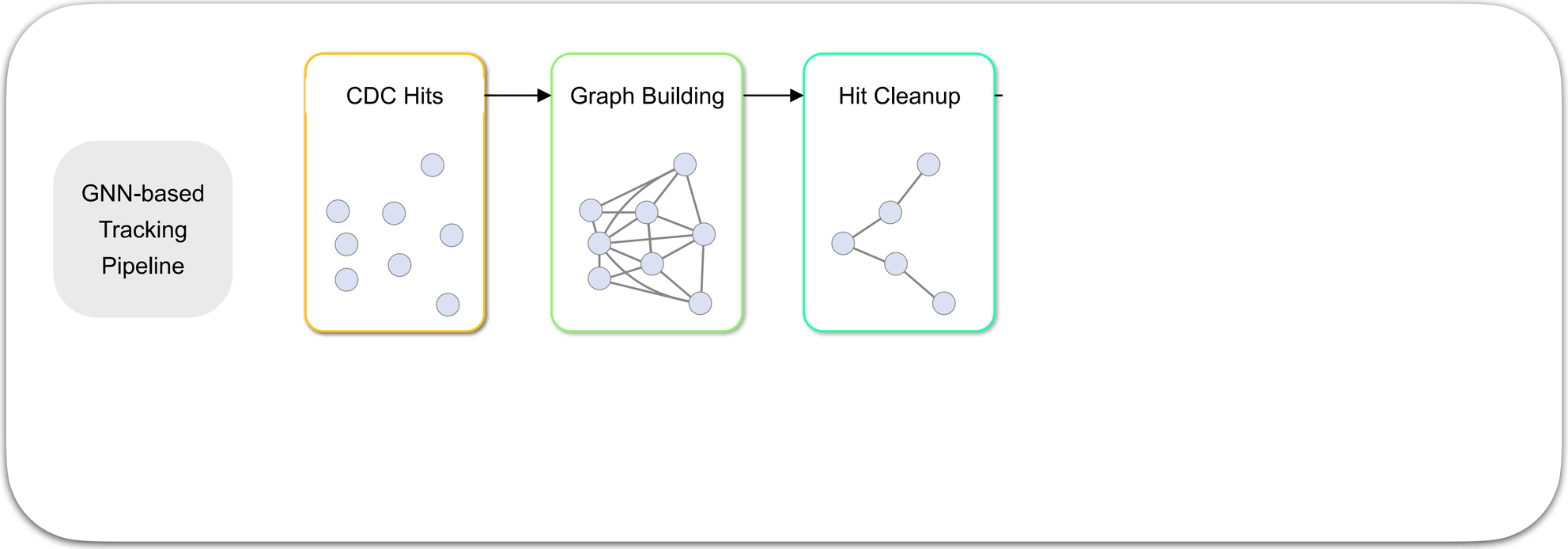
GNN-based Tracking Pipeline



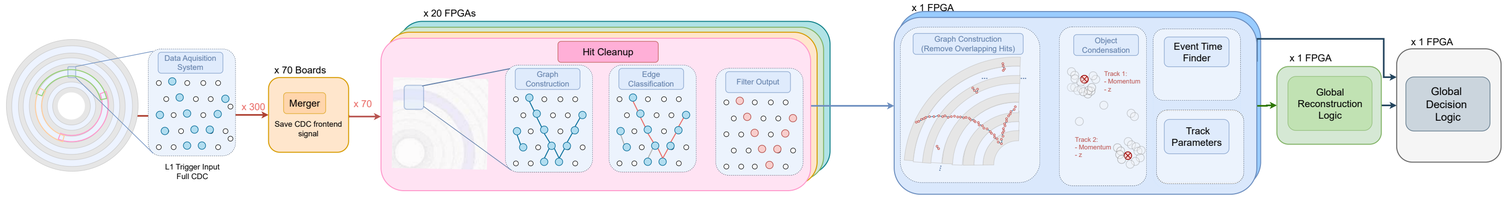
Summary



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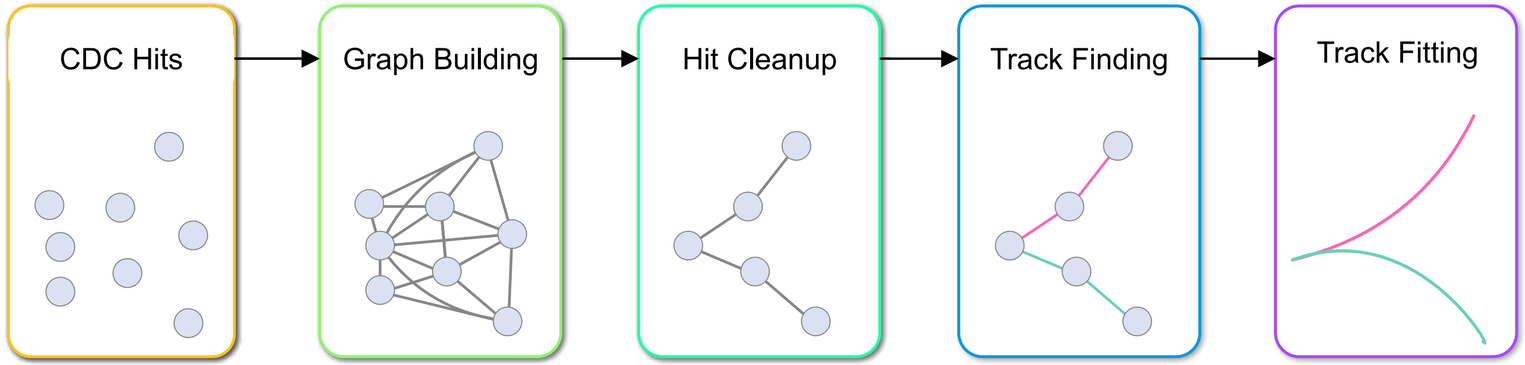


Summary

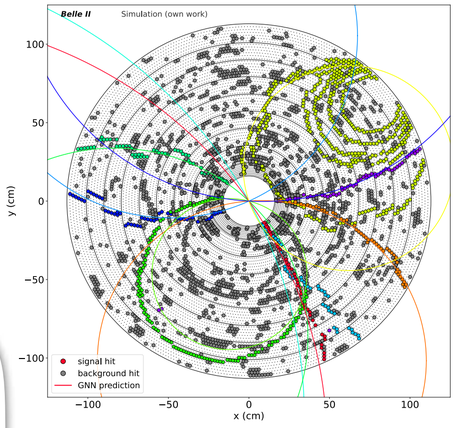


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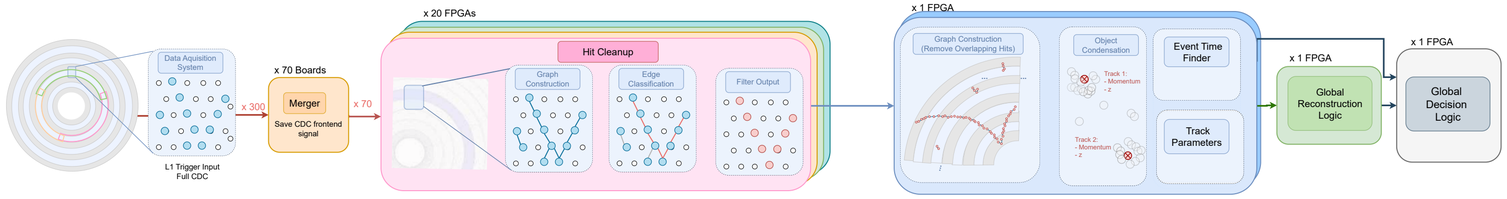


offline solution exists,
but with very large networks

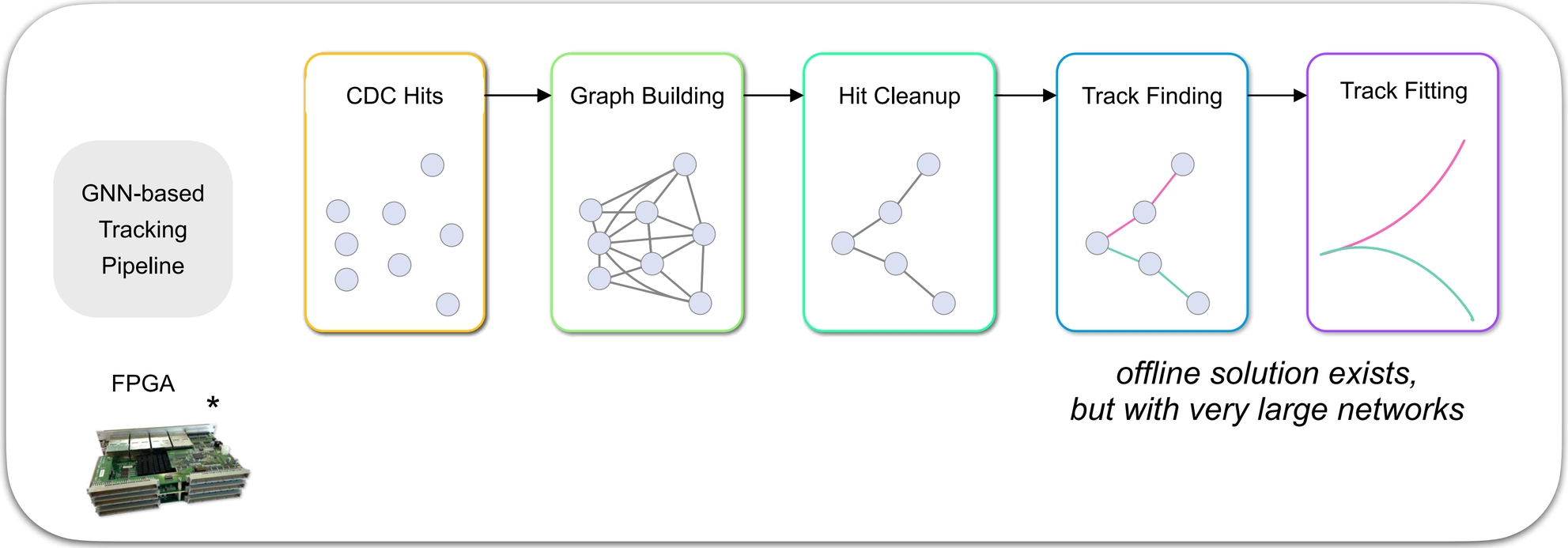


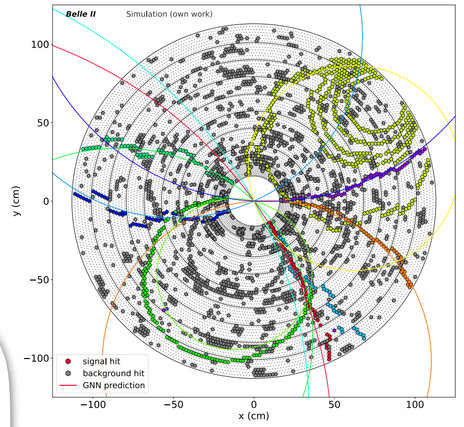
plot from Lea Reuter

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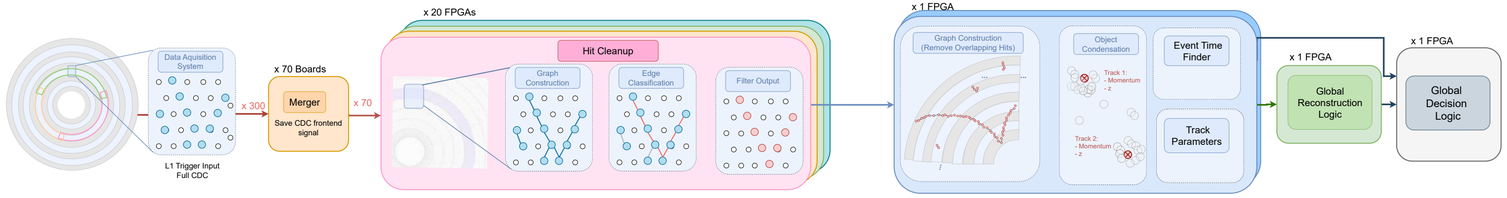




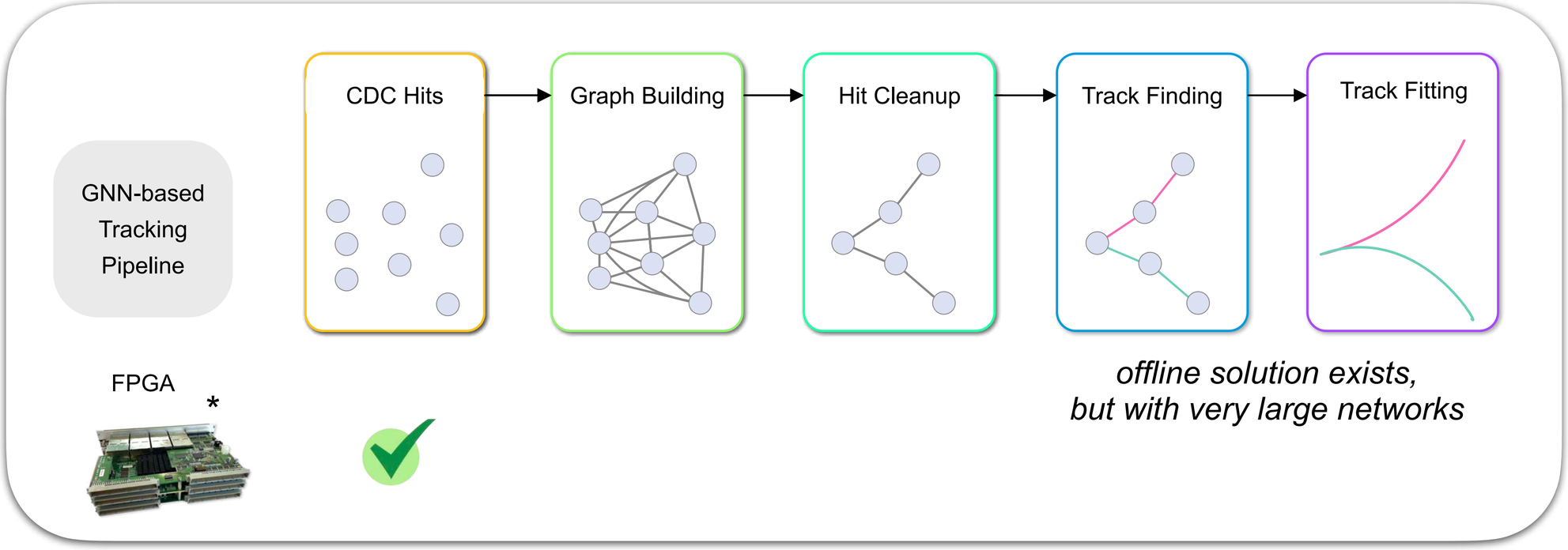
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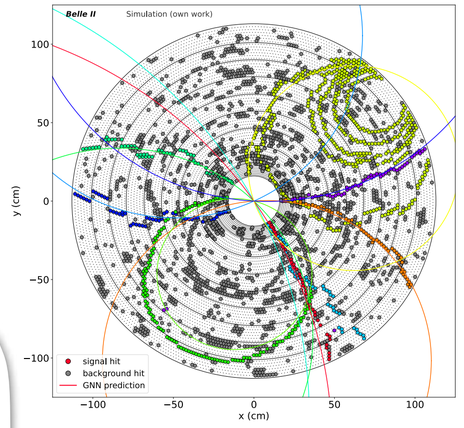
* Collaboration with ITIV (Department of Electrical Engineering and Information Technology at KIT)

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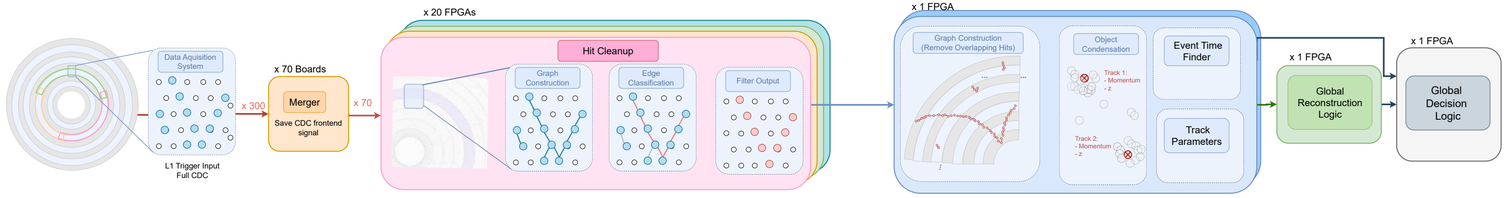




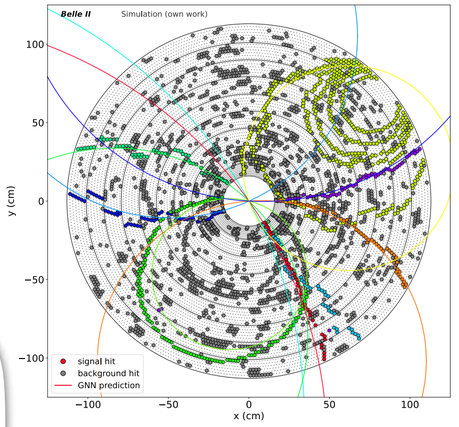
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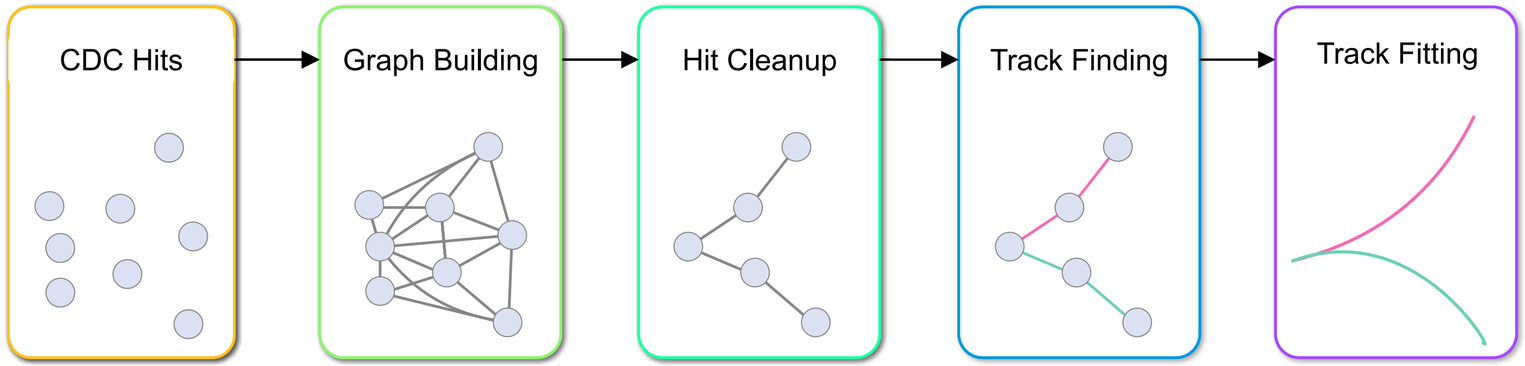


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plot from Lea Reuter

GNN-based Tracking Pipeline



FPGA *



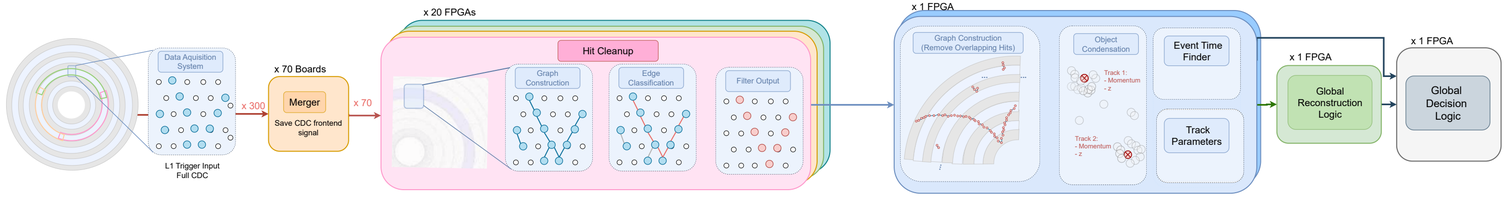
arXiv:2307.07289

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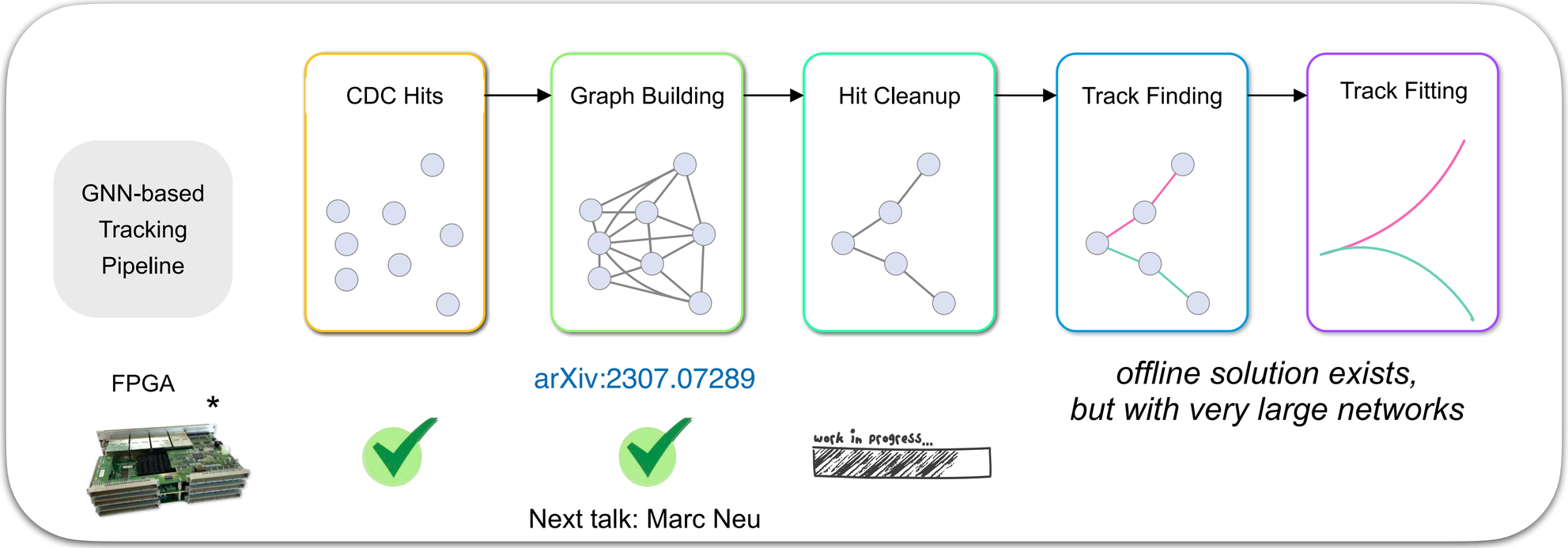
Next talk: Marc Neu

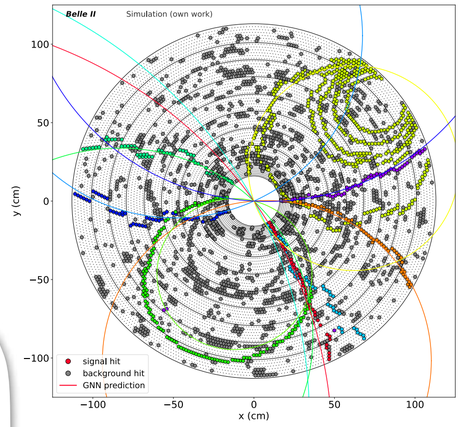
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- hit clean up with GNNs shows promising results





plot from Lea Reuter

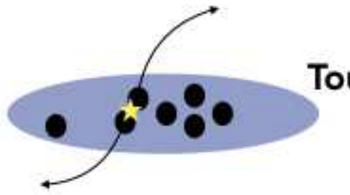
* Collaboration with ITIV (Department of Electrical Engineering and Information Technology at KIT)

Backup

Belle II backgrounds

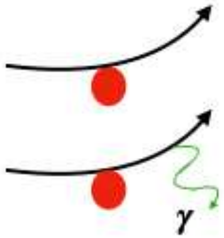
Background Processes

Particle Scattering



Touschek Scattering

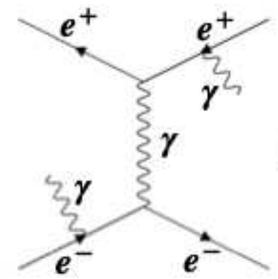
$$\propto N_{particles} \times \rho \propto I \times \frac{I}{n_b \sigma_b}$$



Coulomb Scattering + Bremsstrahlung

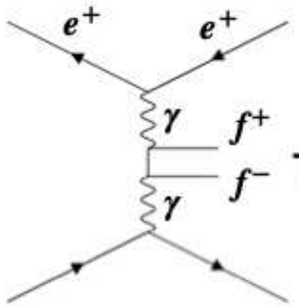
$$\propto N_{particles} \times N_{gas\ molecules} \propto P \times I \times Z_{eff}^2$$

Luminosity



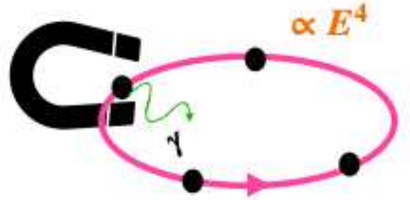
Radiative Bhabha

$\propto \mathscr{L}$



Two-photon

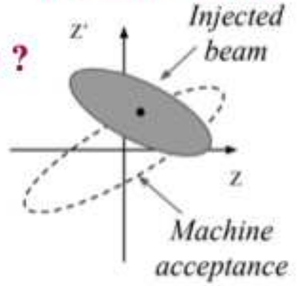
Synchrotron rad.



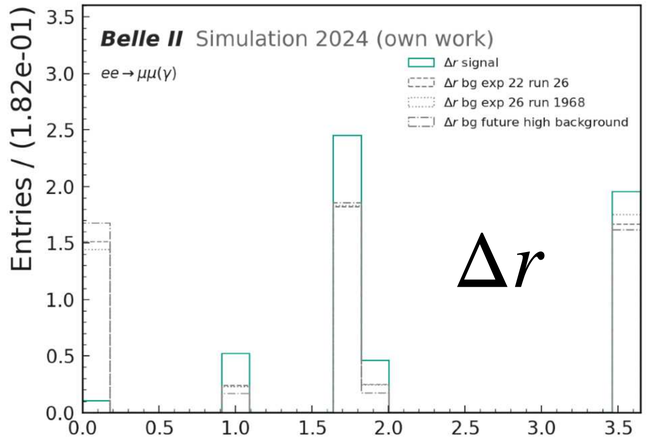
$\propto E^4$

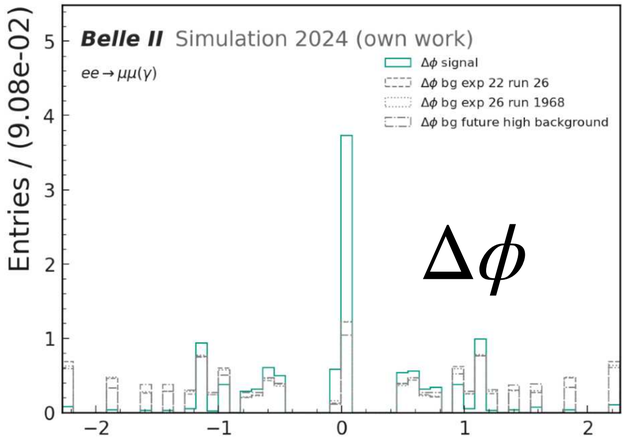
Injection bkg.

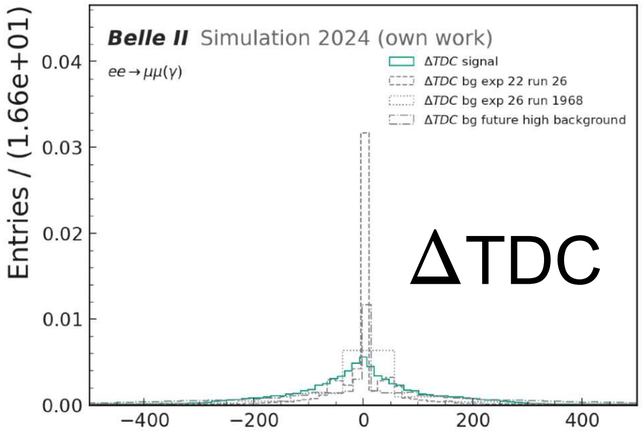
$\propto$?

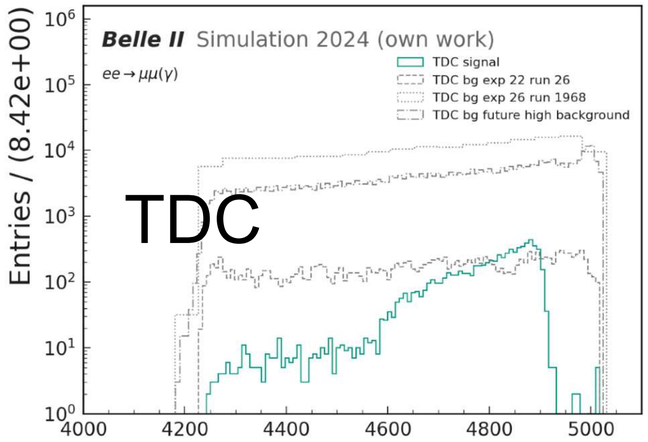


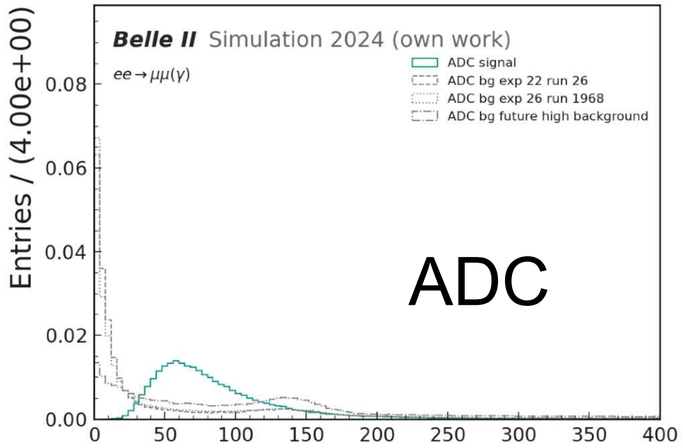
Feature Distributions



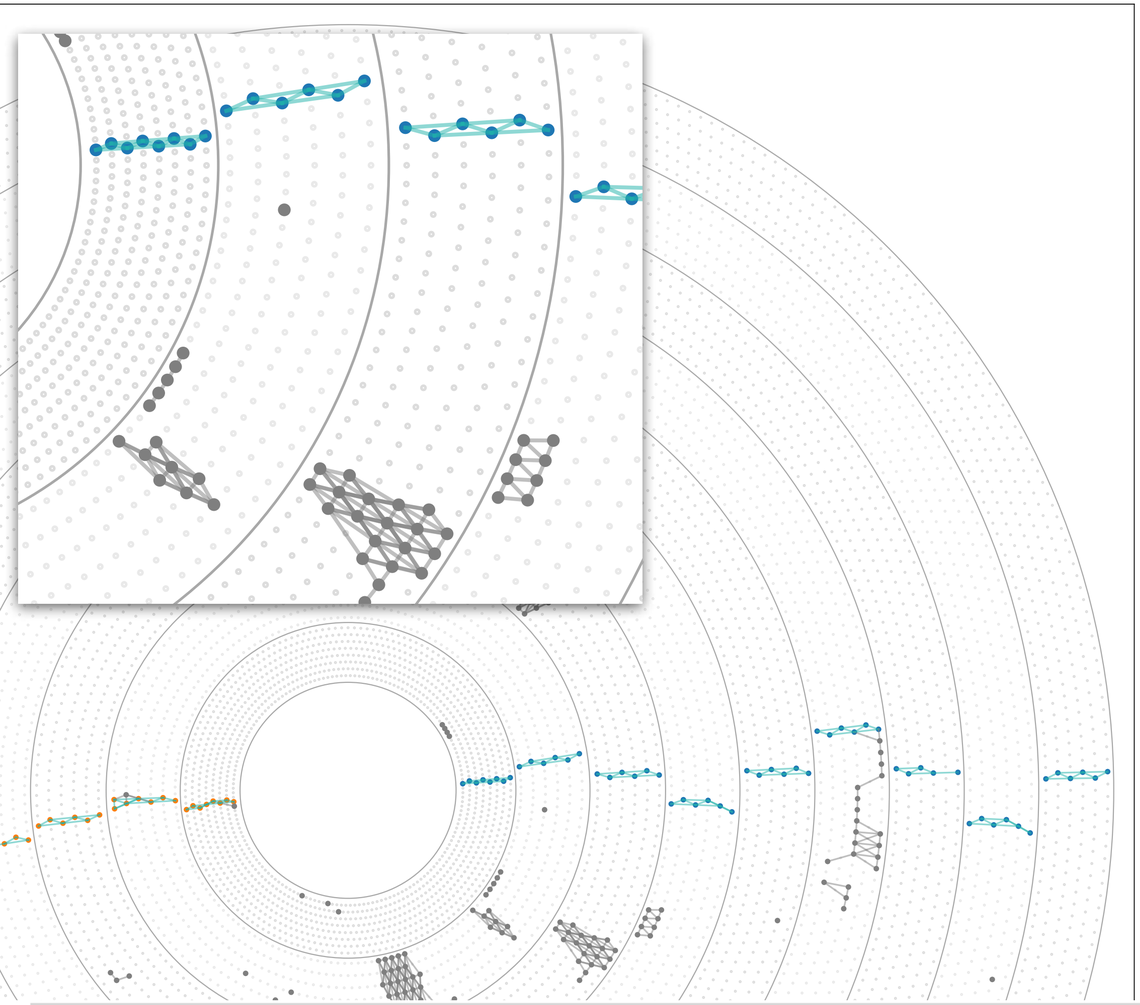








Graph Building: Results



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

Graph Building Models

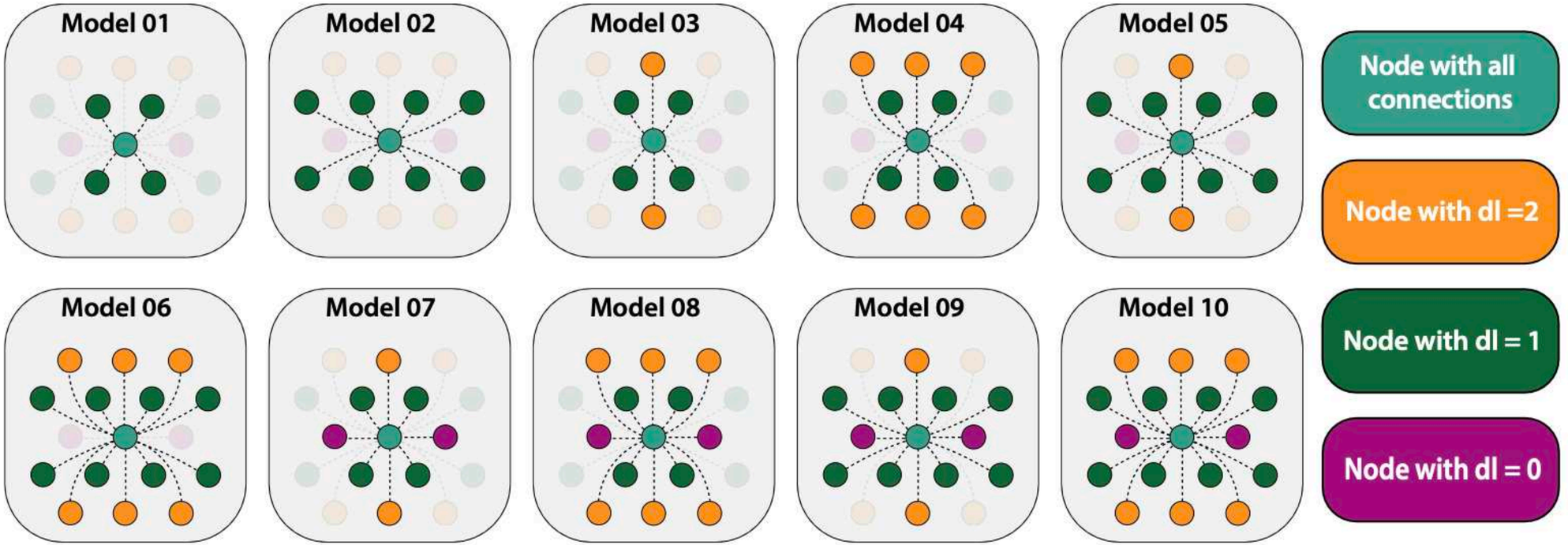
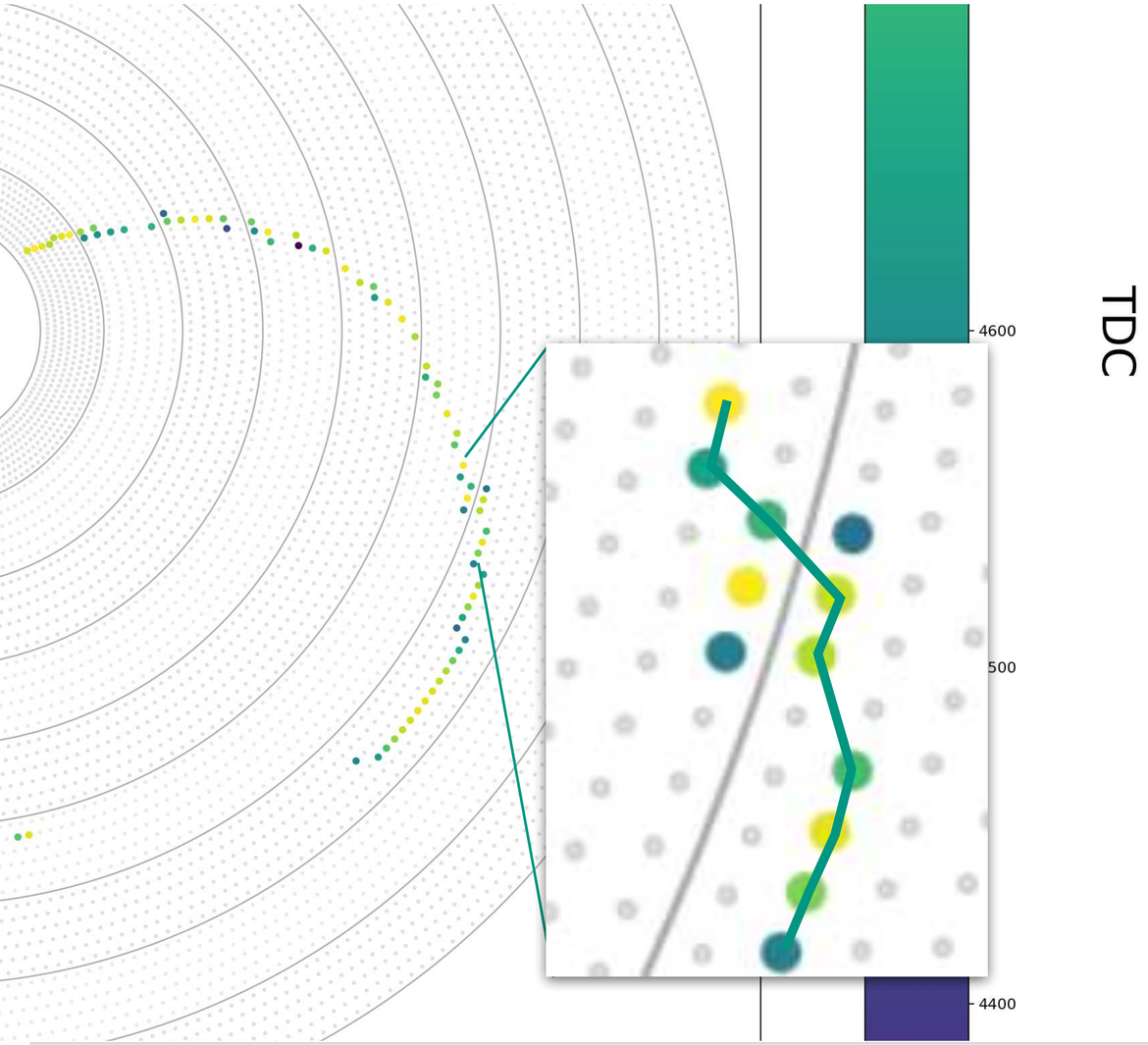


Figure 7.9.: Ten different graph-building patterns analyzed in this thesis, showing possible connections for a node in the Central Drift Chamber.

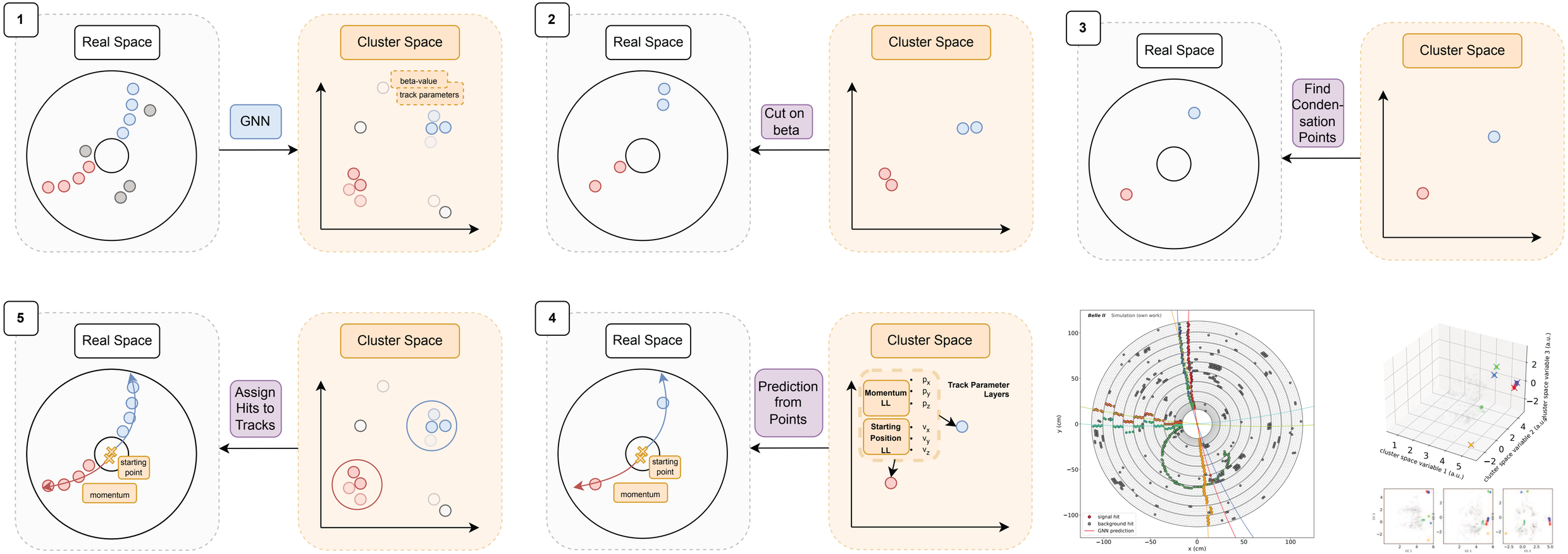
Masterthesis „Graph-Building and Input Feature Analysis for Edge Classification in the Central Drift Chamber at Belle II“ of Philipp Dorwarth, May 2023

True Hit Definition

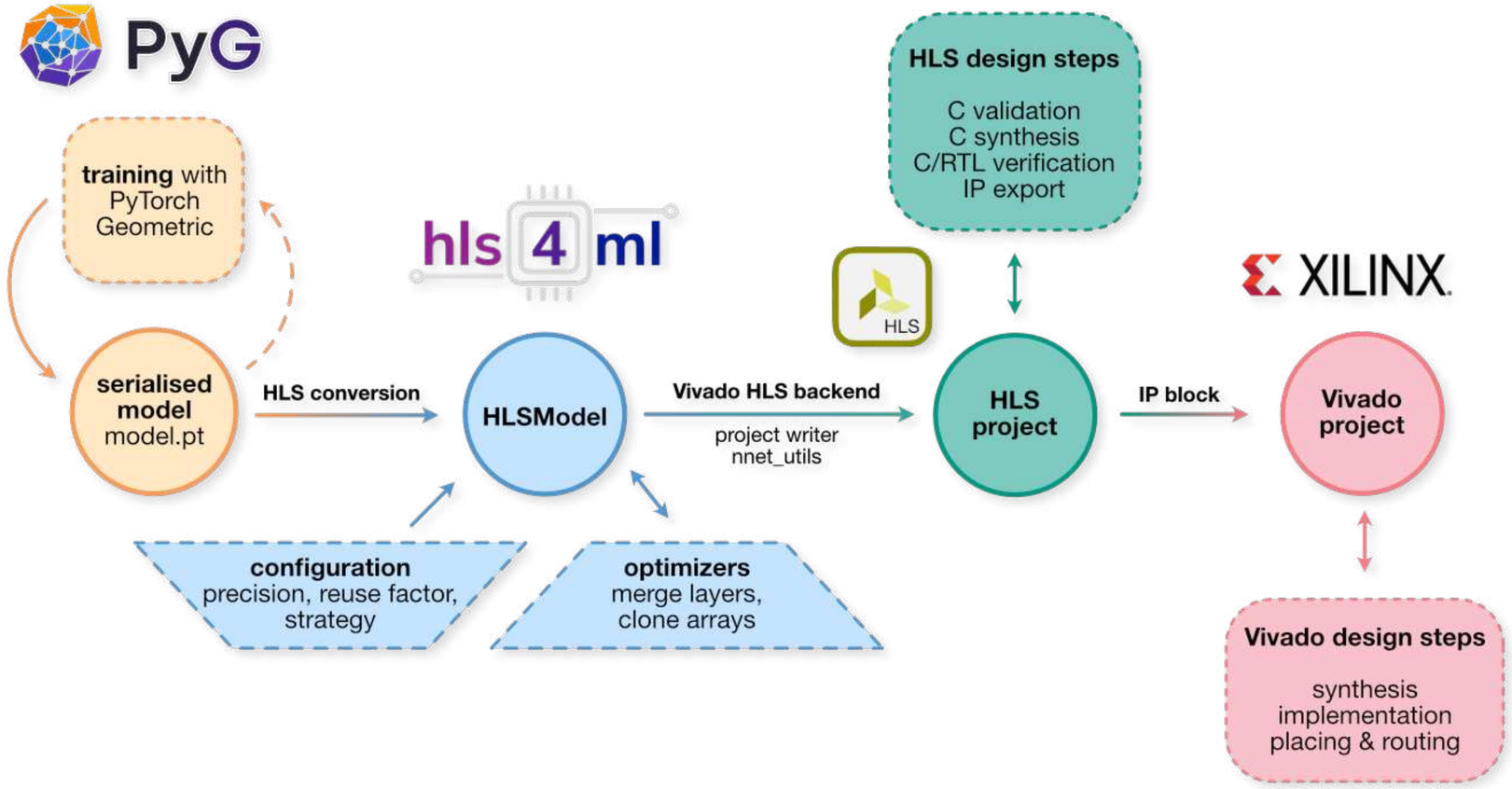


- What hits do we want to keep?
  1) all hits from signal particles?
  2) or only some?

Object Condensation Track Finding (offline)



Highlevel Synthesis for Machine Learning (hls4ml)



- automatic translation of ML models to hardware level
- based on Vivado HLS
- fast prototyping by automated workflow
- several configuration parameters

Design Optimisation

Quantization

- reduction of number of bits used representing the NN model (precision)
- data representation by arbitrary precision fixed-point data format *ap_fixed<W,I>*
- bit widths directly affect resource usage

Compression

- reduction of model parameter number
- number of model parameters strongly depends on the number of hidden nodes/ neurons

Pipelining

- key advantage of FPGAs: throughput acceleration by parallelisation and pipelining
- total latency = iteration latency + II · (number of functions -1)
- pipelining includes task parallelism, pipelining within a run, of runs or within a task