CDC Hit Clean-up for Tracking

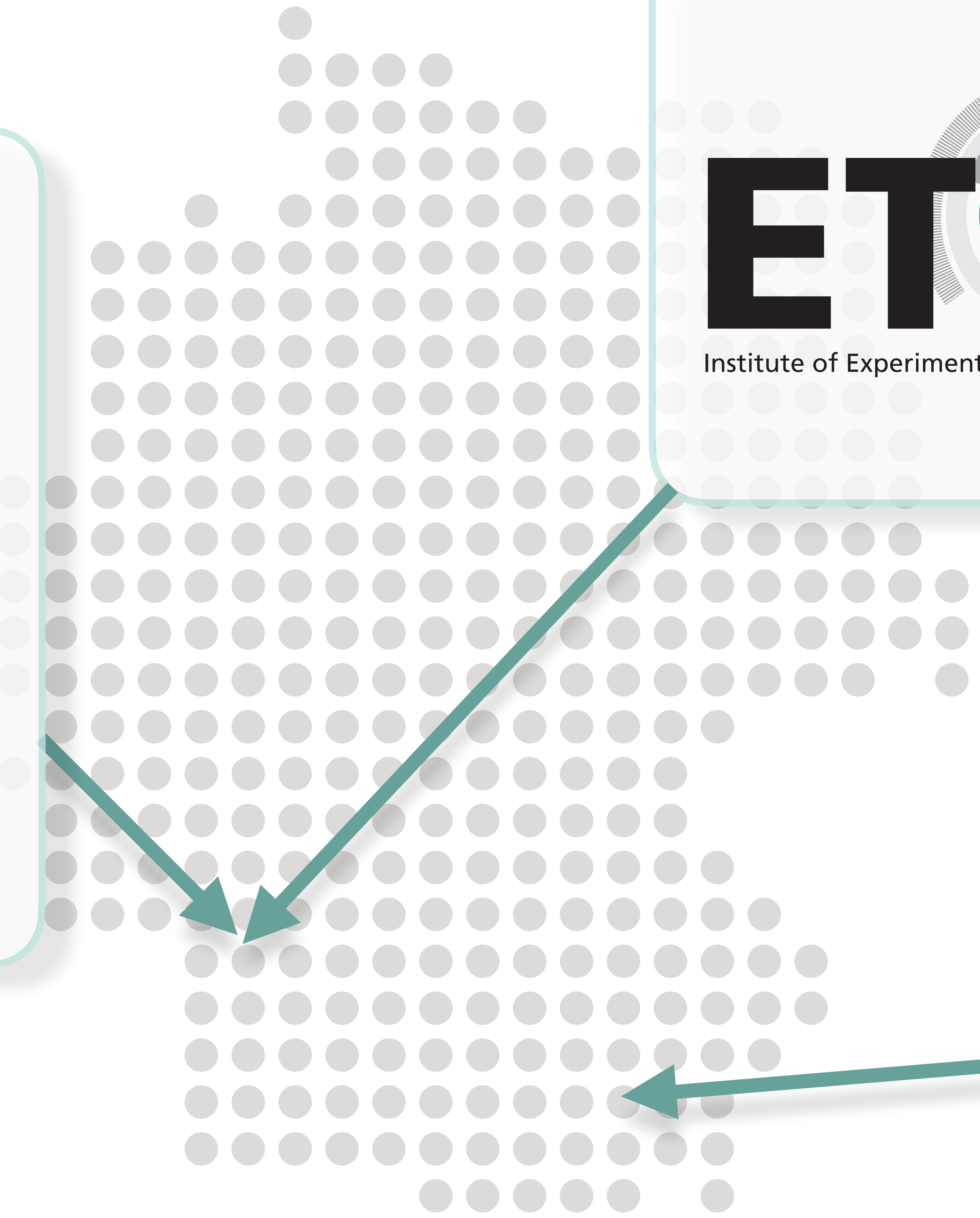
Greta Heine, Torben Ferber, Lea Reuter, Slavomira Stefkova, Giacomo De Pietro | October 01, 2024

AI Trigger Group at Belle II

Karlsruhe Institute of Technology

KIT ITIV

- Marc Neu
- **Kai Unger**
- Jürgen Becker
- Timo Justinger
- Valdrin Dajaku
- Felix Mältzer
- Till Rädler



KIT ETP

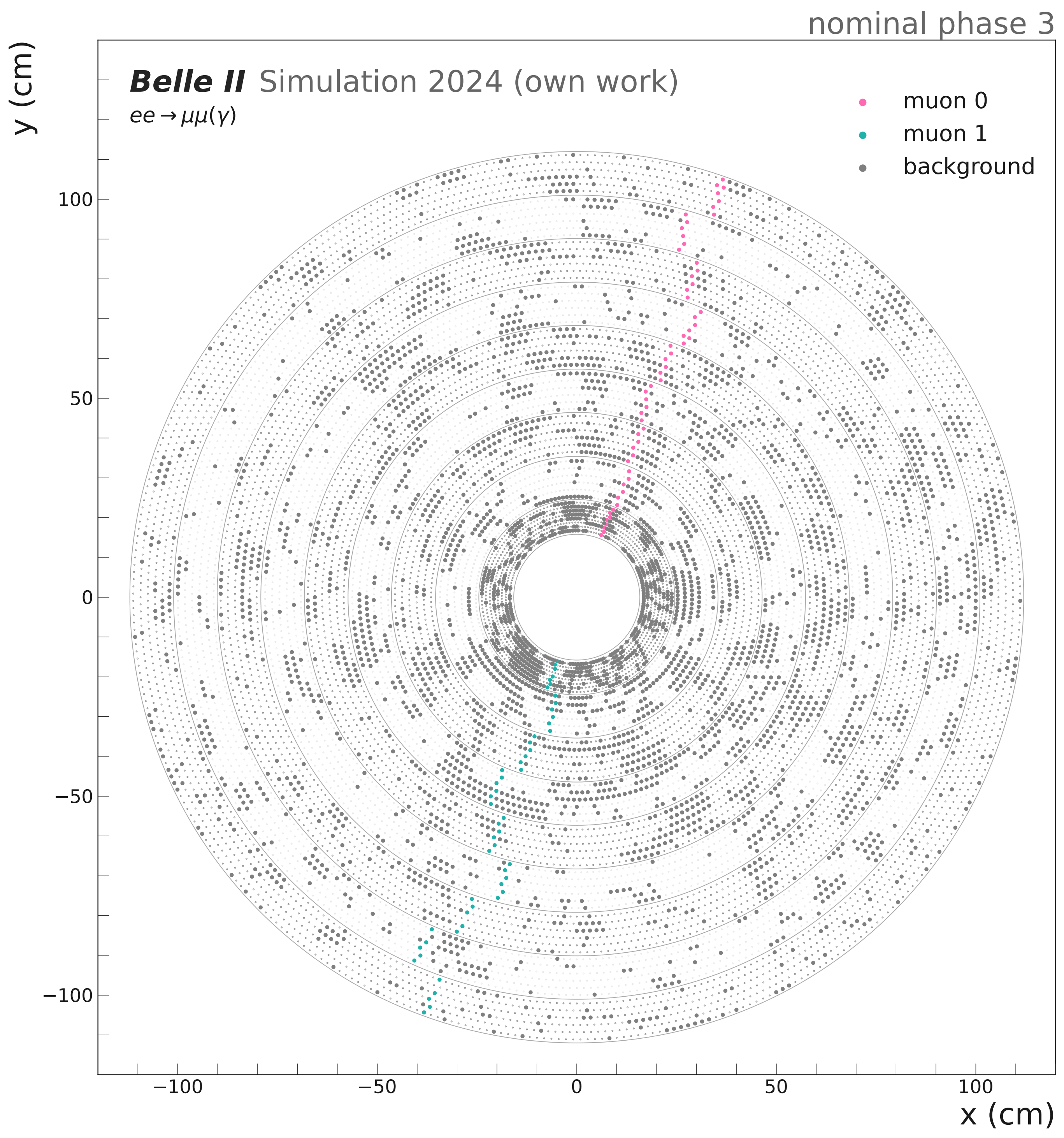
Institute of Experimental Particle Physics

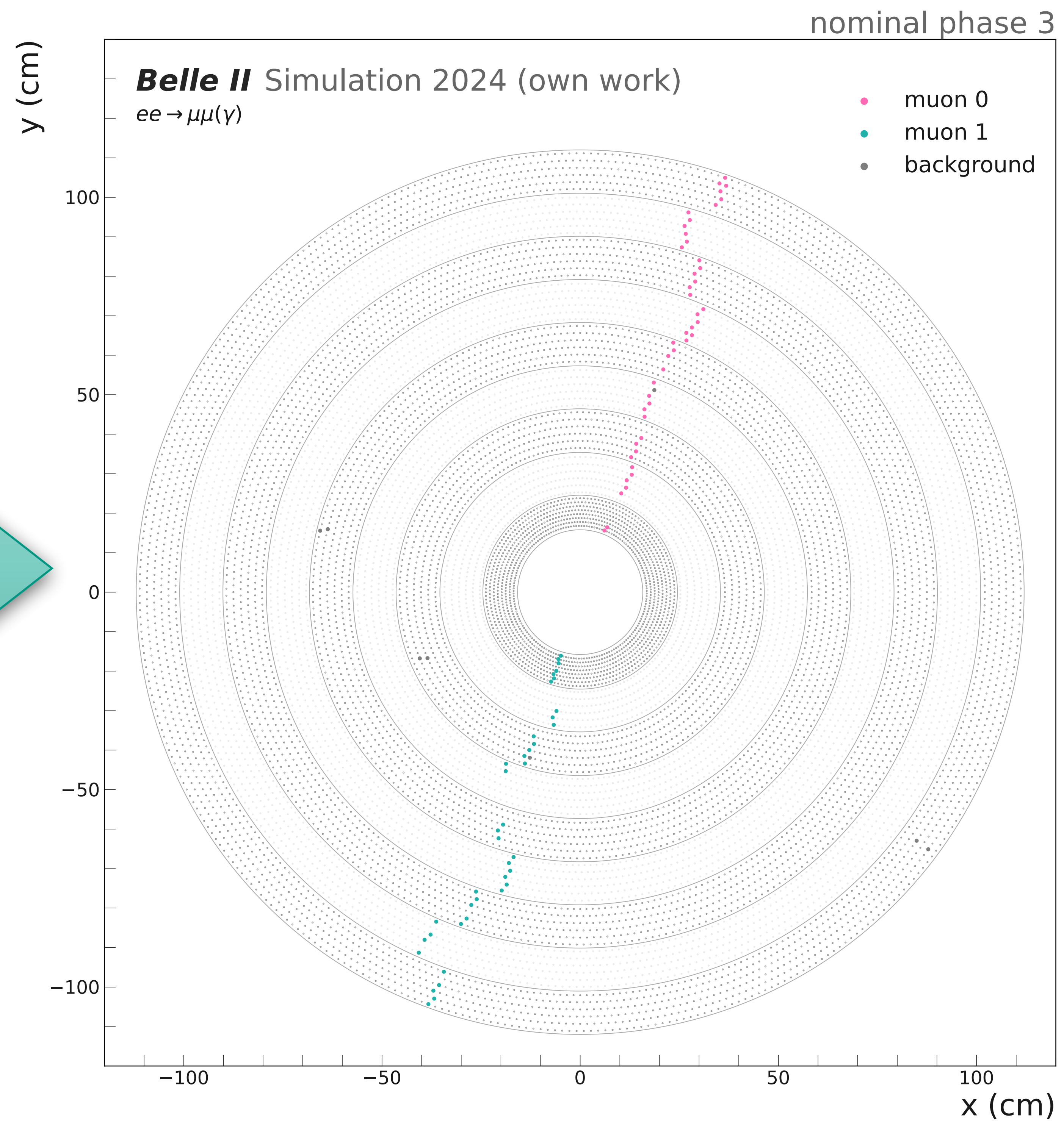
- **Lea Reuter**
- **Greta Heine**
- **Isabel Haide**
- **Torben Ferber**

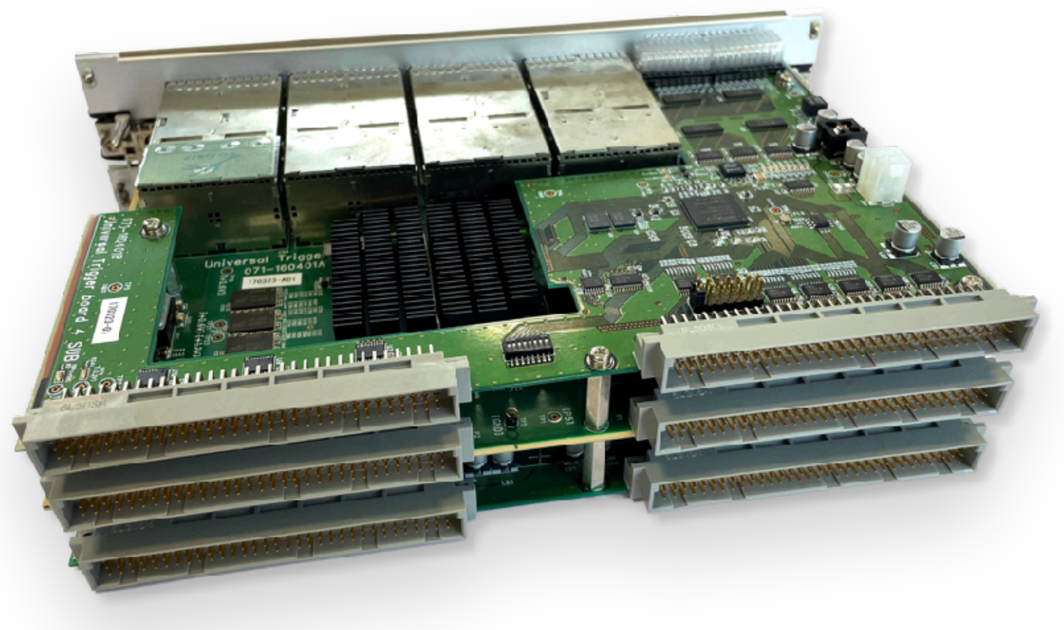
MPI

- **Timo Forsthofer**
- **Simon Hiesl**
- **Christian Kiesling**

CDC Hit Clean-up







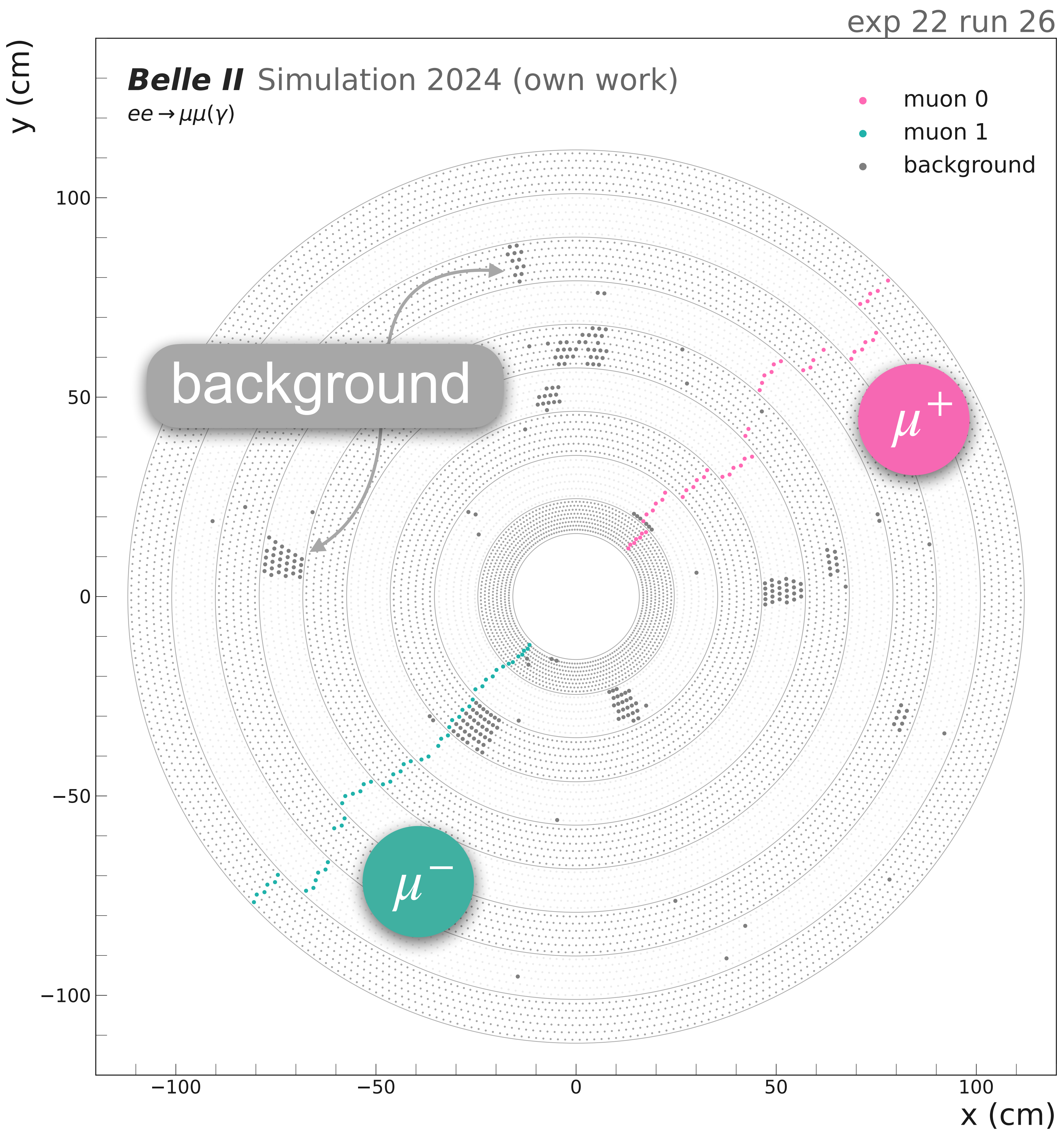
✨ Future ✨

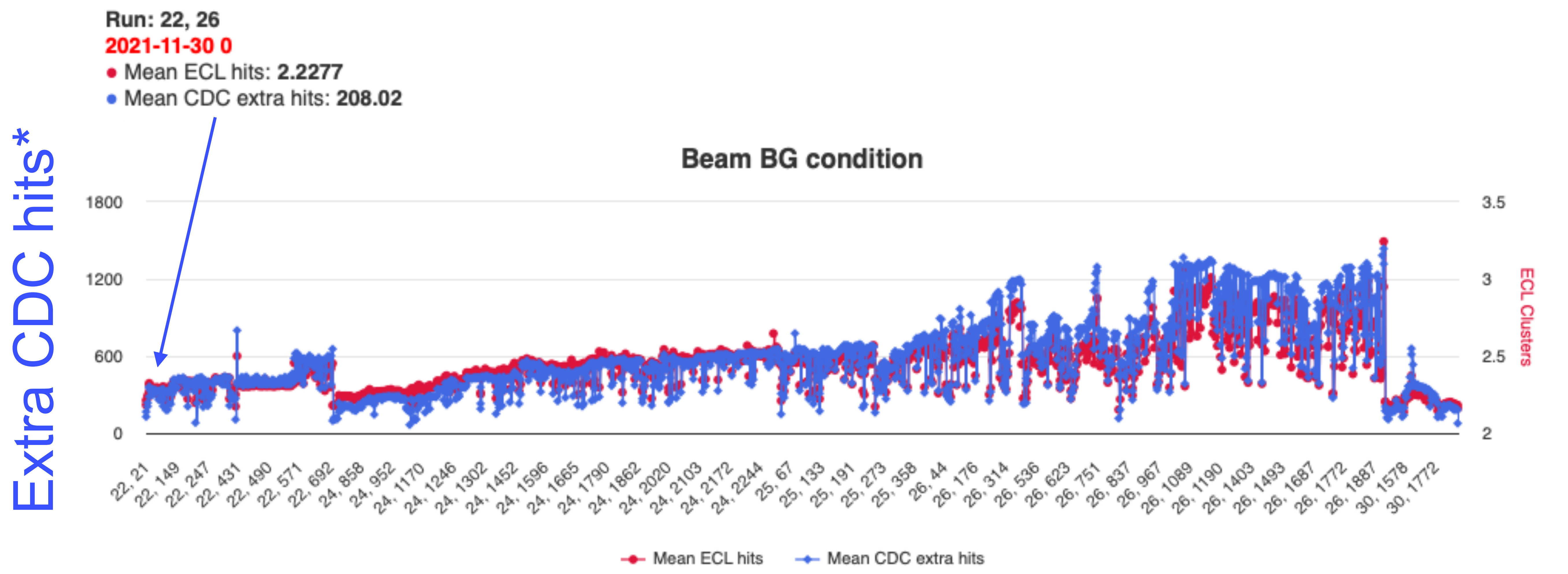
Today

The Problem

Challenge

Back in 2021…



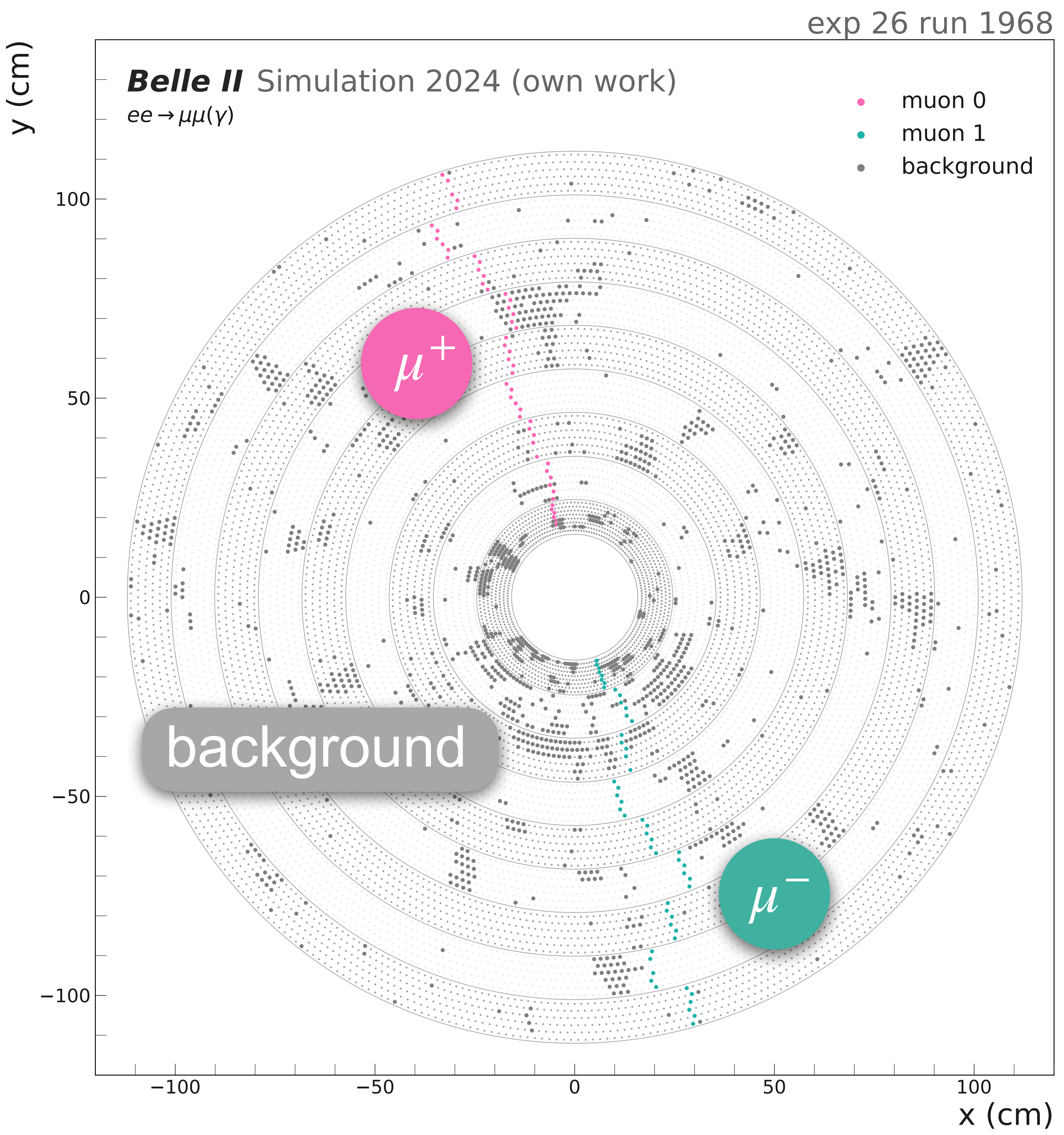


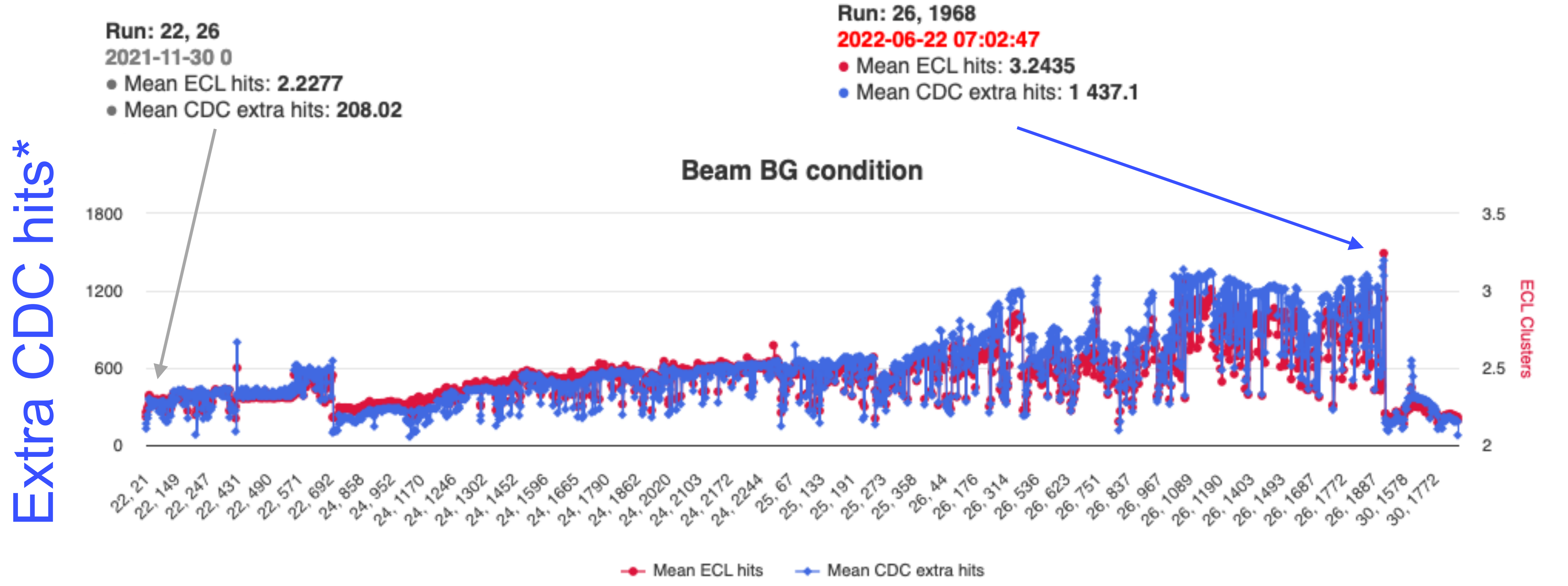
*The number of CDC hits in the event not assigned to any track.

- exp 22 run 26 run dependent
- ≈ 2% of wires hit
- low computing cost*

$^* t_{\mathrm{comp}} \propto n_{\mathrm{hits}}^2$

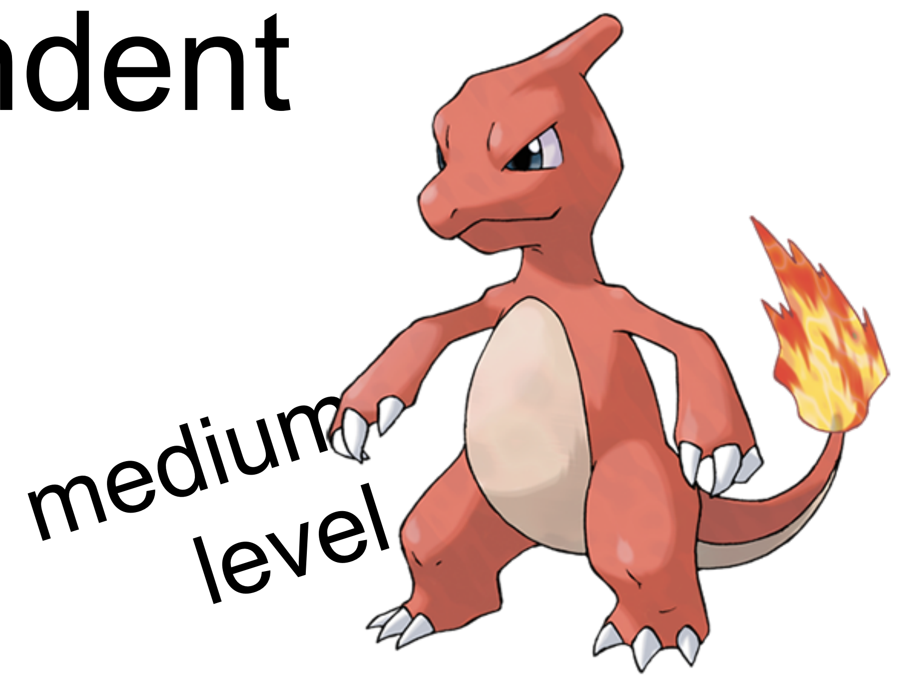
Highest measured luminosity… so far…





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

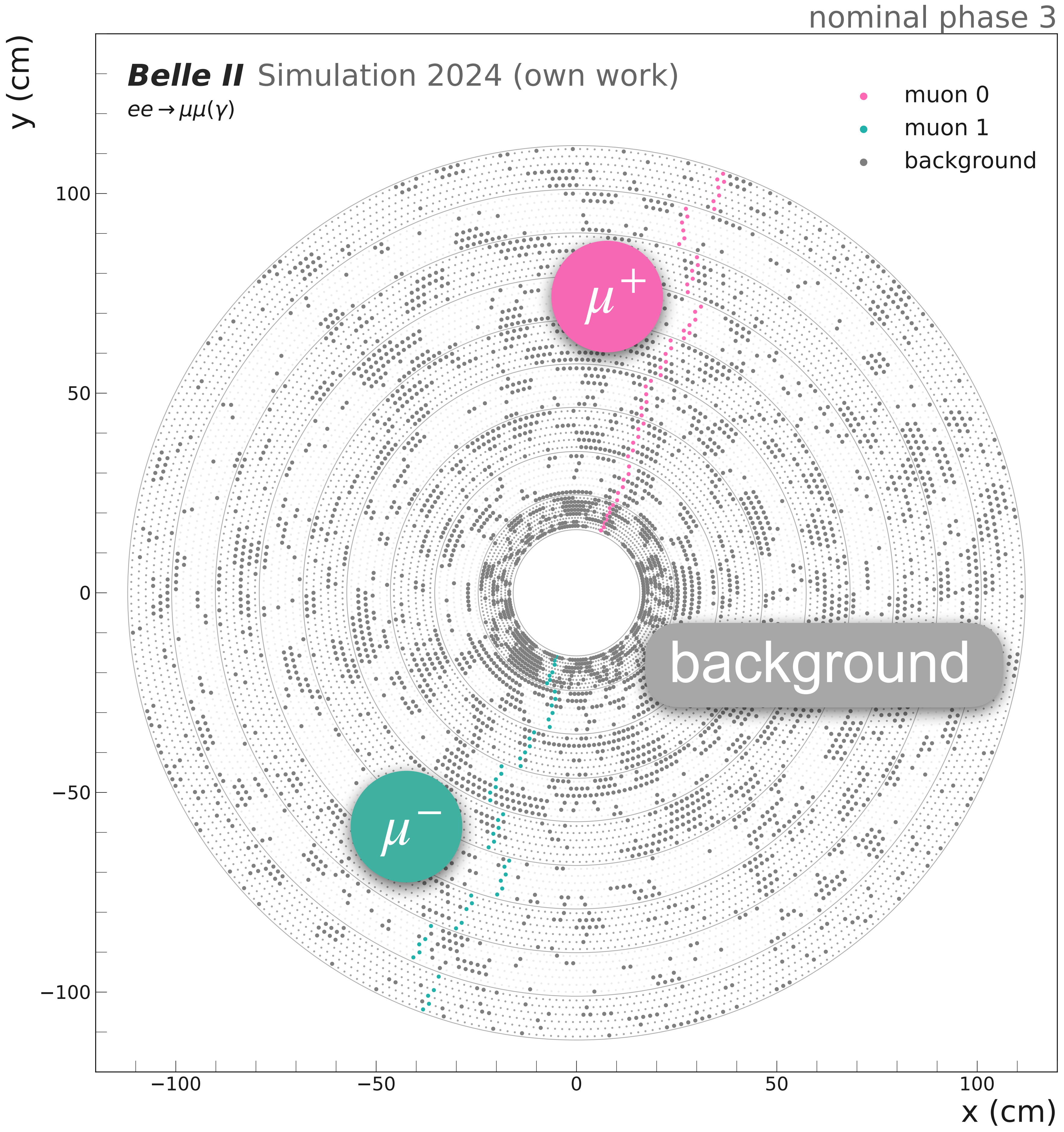
- exp 26 run 1968 run dependent
- ≈ 10% of wires hit
- moderate computing cost*

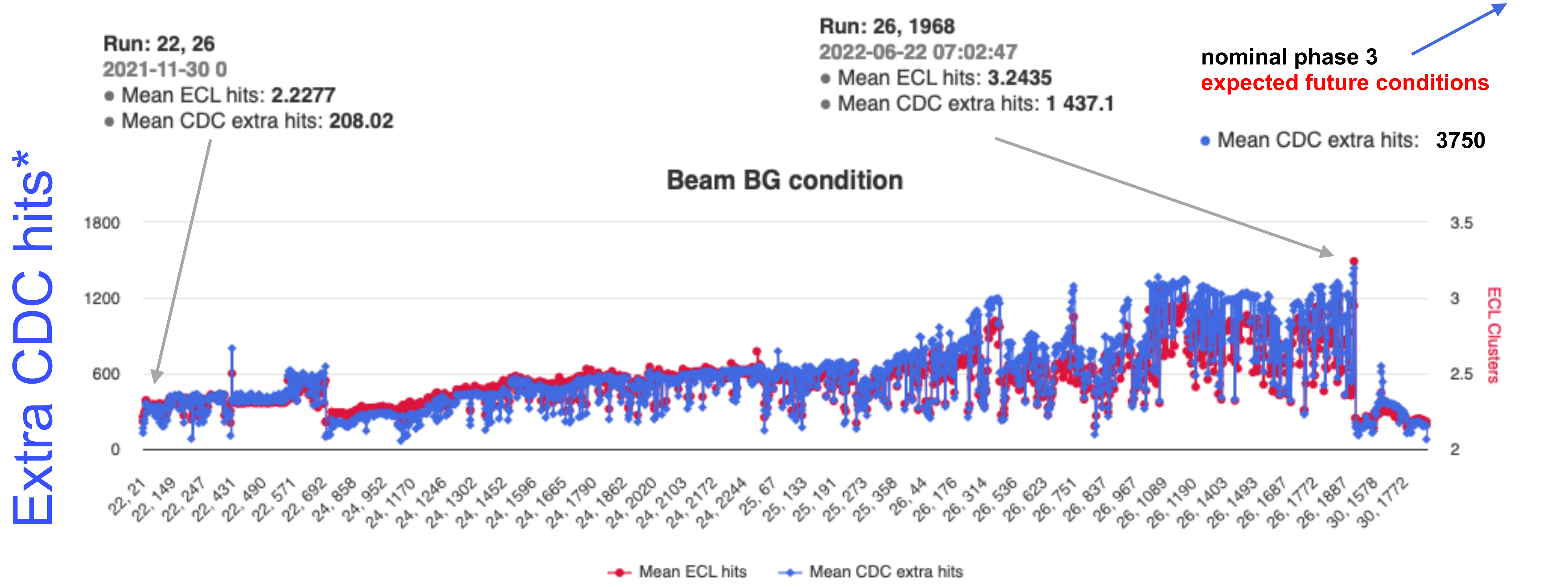


* $t_{\text{comp}} \propto n_{\text{hits}}^2$

01.10.2024 Greta Heine - greta.heine@kit.edu

Expected future conditions





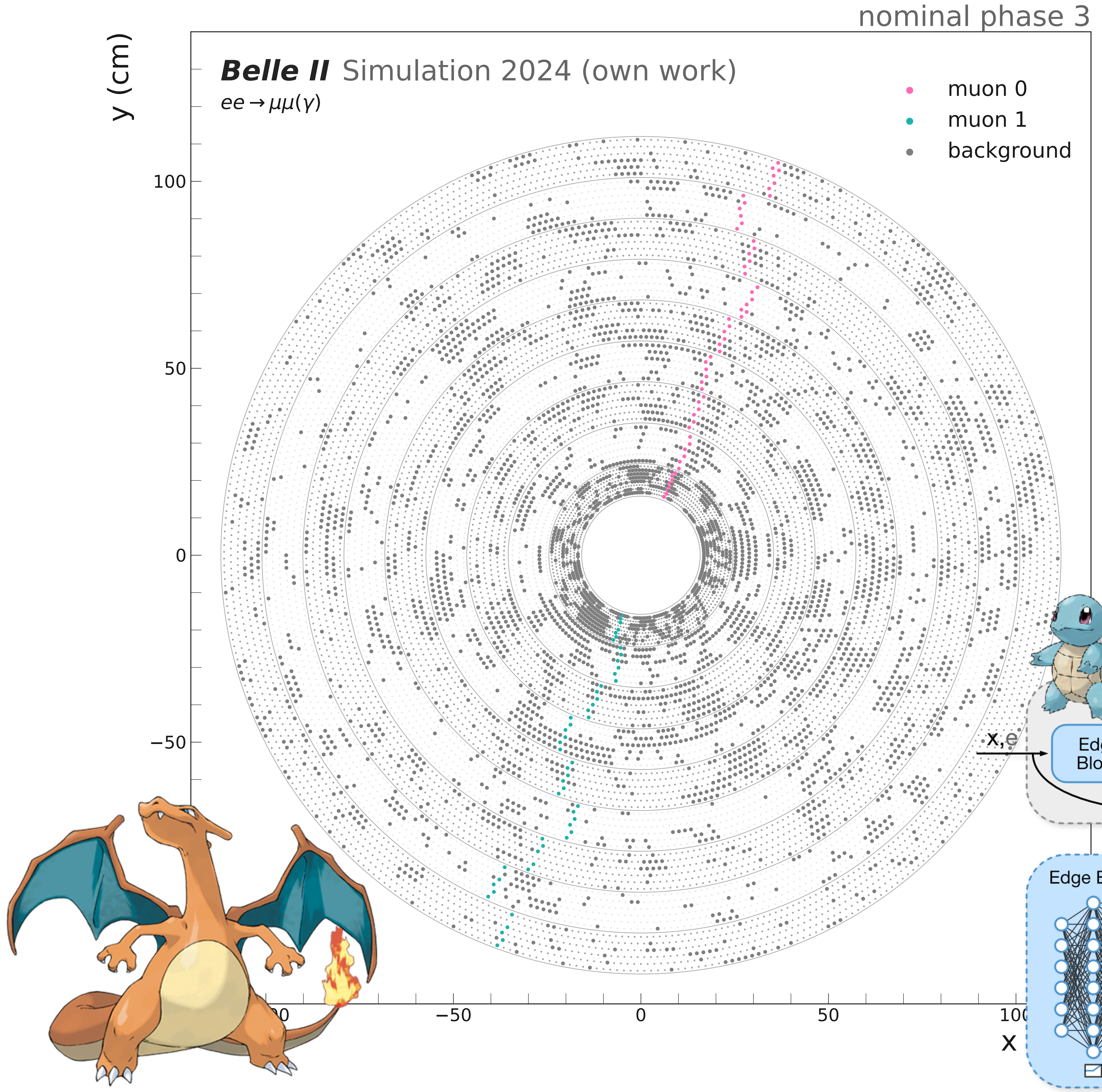
*The number of CDC hits in the event not assigned to any track.

- nominal phase 3 run independent
- ≈ 27% of wires hit
- high computing cost*

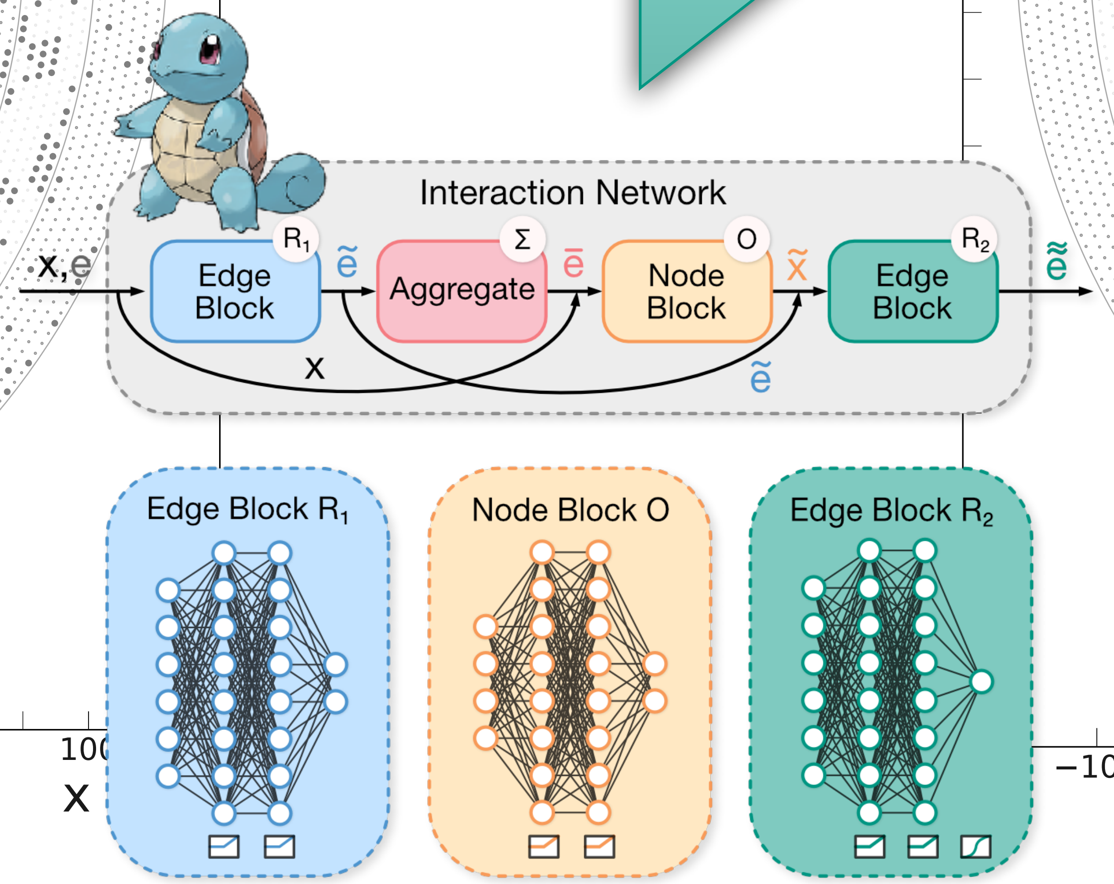
* $t_{\text{comp}} \propto n_{\text{hits}}^2$

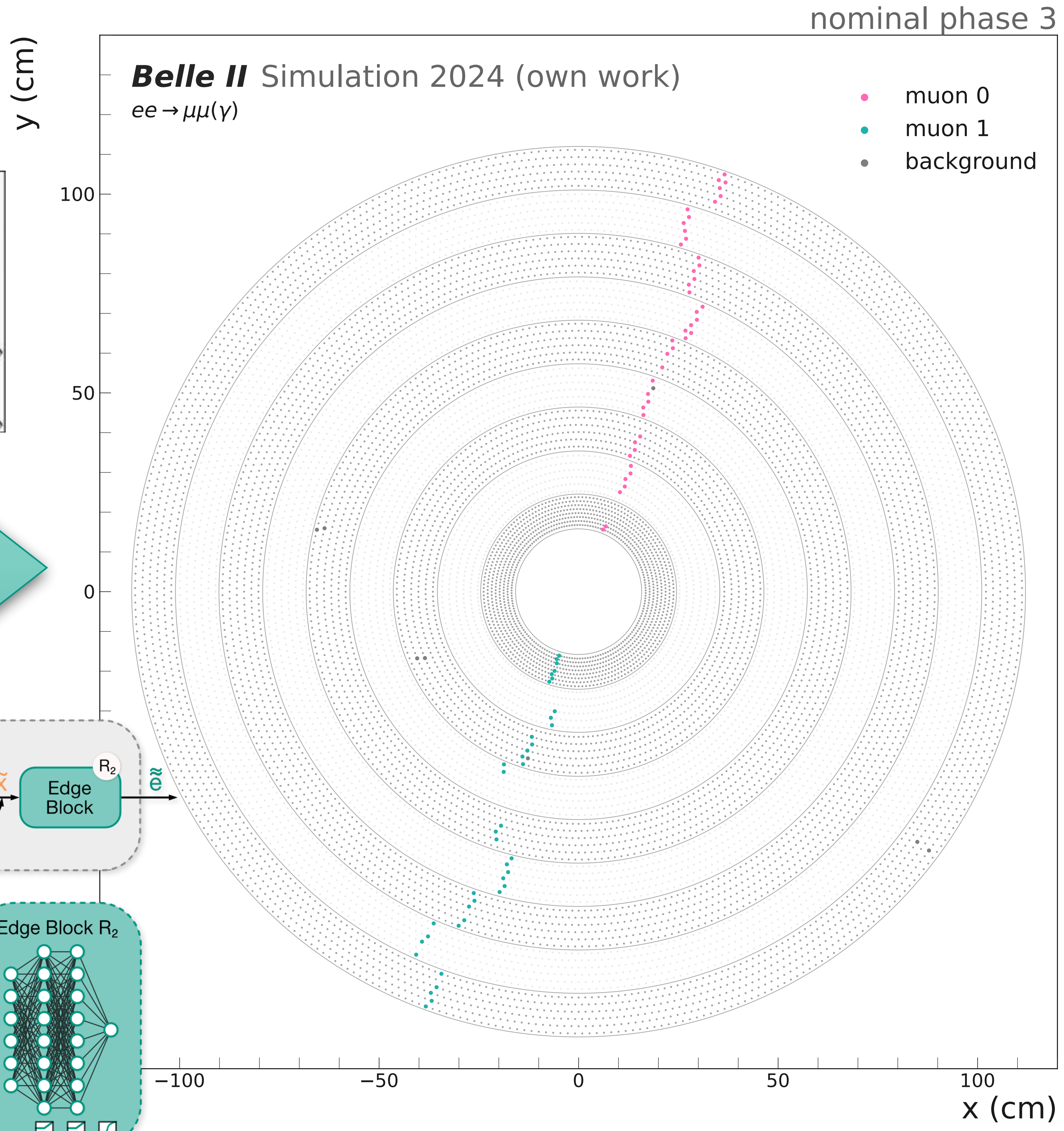
Hit Clean-up

Hit Clean-up

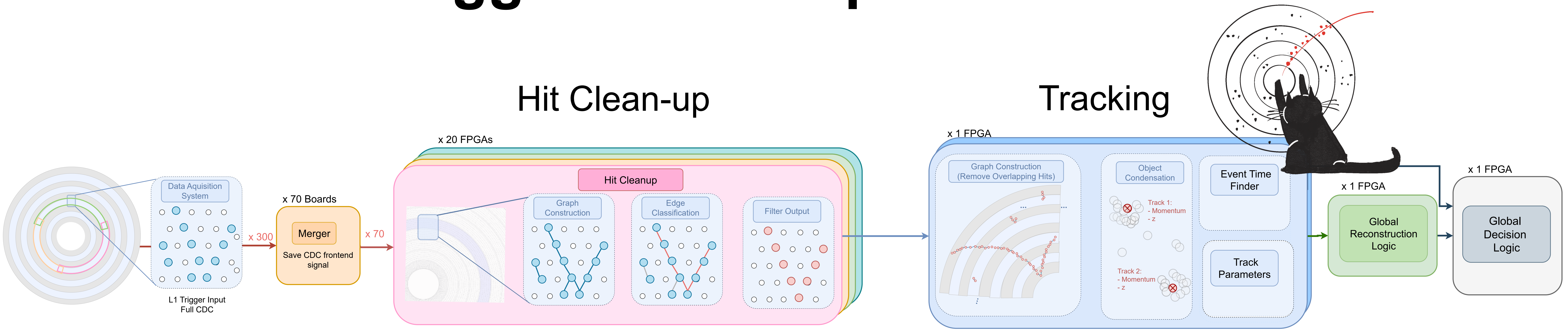

nominal phase 3
Belle II Simulation 2024 (own work)
$ee \to \mu\mu(\gamma)$
muon 0
muon 1
background
y (cm)
x


nominal
HP:
Beam Background
Hit Clean-Up
:L50
HP:
92/123
It's super
effective!

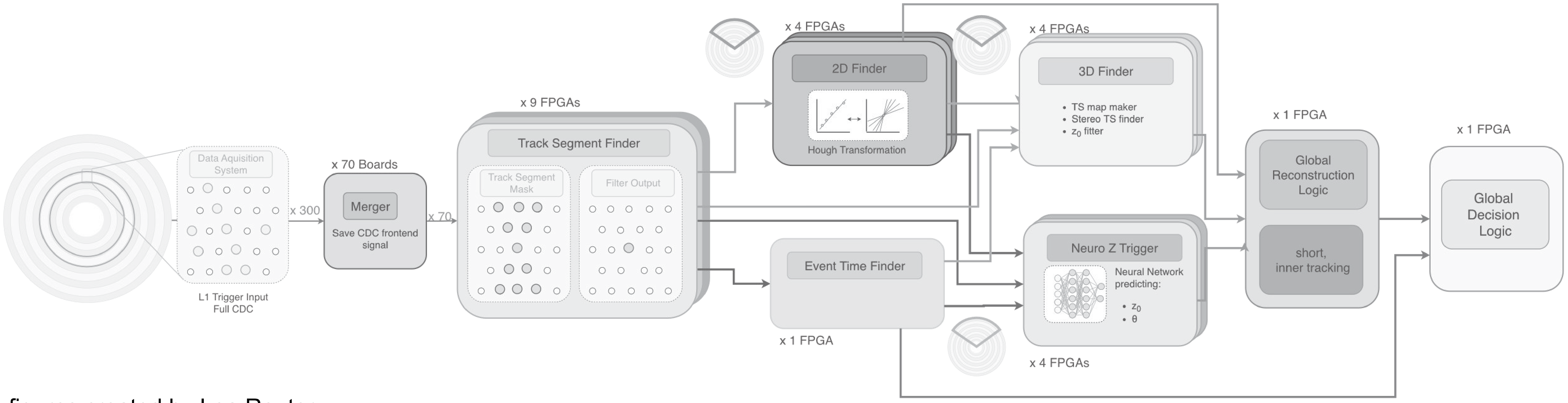

Interaction Network
x, e
Edge Block
R_1
$\tilde{e}$
Aggregate
Σ
$\bar{e}$
Node Block
O
$\tilde{x}$
Edge Block
R_2
$\tilde{\tilde{e}}$
x
$\tilde{e}$
Edge Block R_1
Node Block O
Edge Block R_2


nominal phase 3
Belle II Simulation 2024 (own work)
$ee \to \mu\mu(\gamma)$
muon 0
muon 1
background
y (cm)
x (cm)

New CDC L1 Trigger LS2: Proposal



new



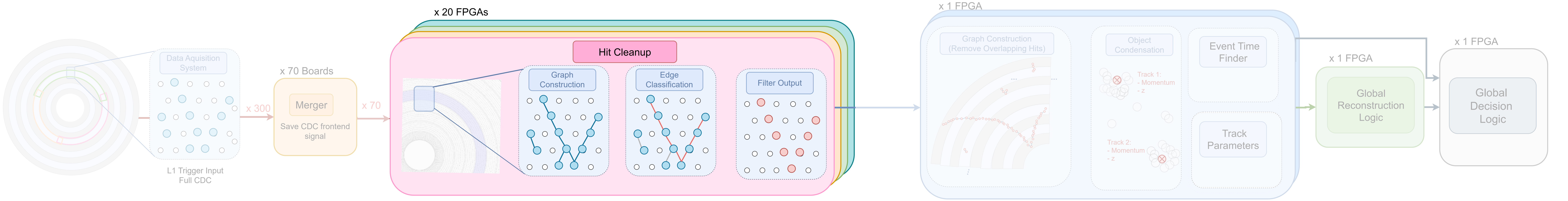
current

figures created by Lea Reuter

New CDC L1 Trigger LS2: Proposal

Hit Clean-up

Tracking



new

Preliminary starting points

Scope

- 14336 sense wires
- 20 FPGAs

Trigger Input Signal

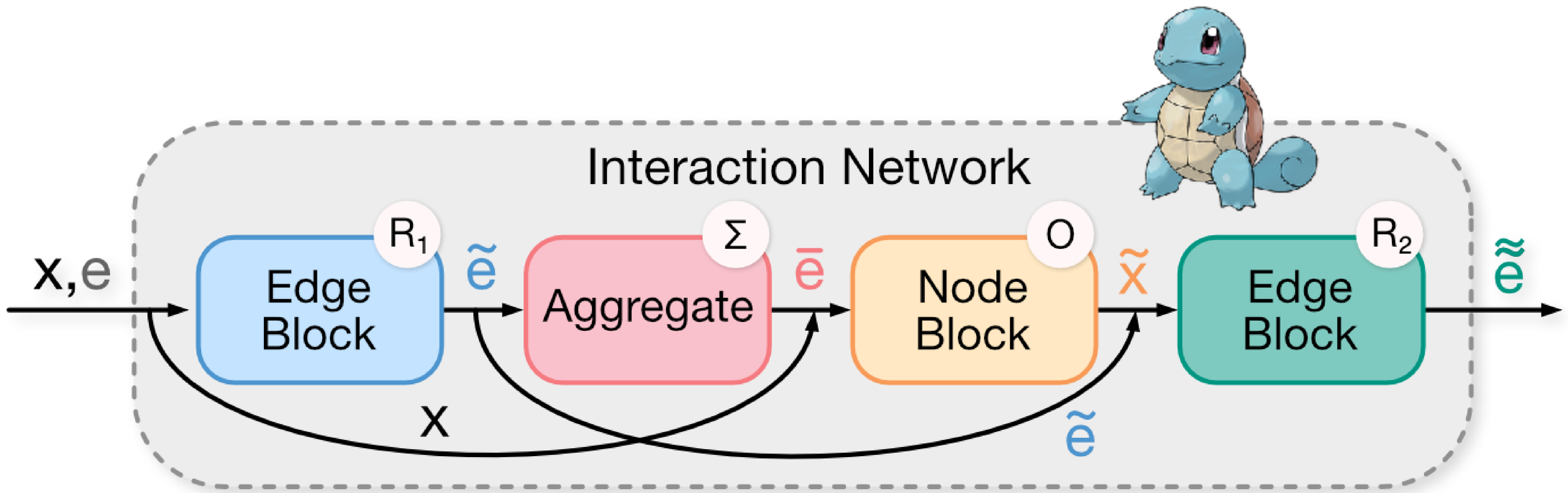
- up to 978 sense wires per FPGA
- 1 bit hit + 5 bit timing + 4 bit ADC

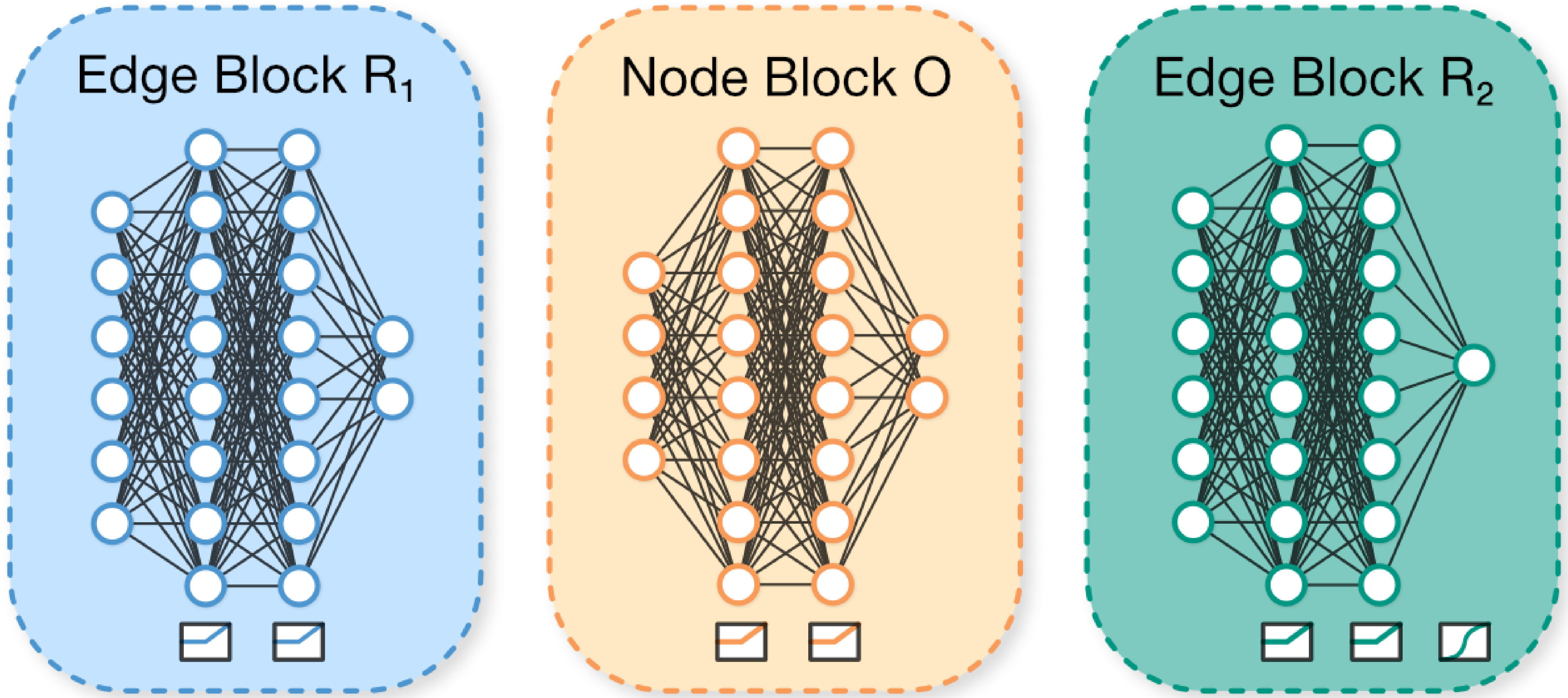
Hardware Requirements

- 1 - 2 μs for all processing
- Throughput up to 312.96 Gbit/s per FPGA

How does it work?

Interaction Network a Graph Neural Network Architecture





- Interaction network model by [Battaglia et al.]() with PyTorch Geometric
- GNNs can easily adapt to different geometries, input sizes and sparsity of data
- light-weight (only 500 parameters)
- implementation available in [hls4ml]()

```
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

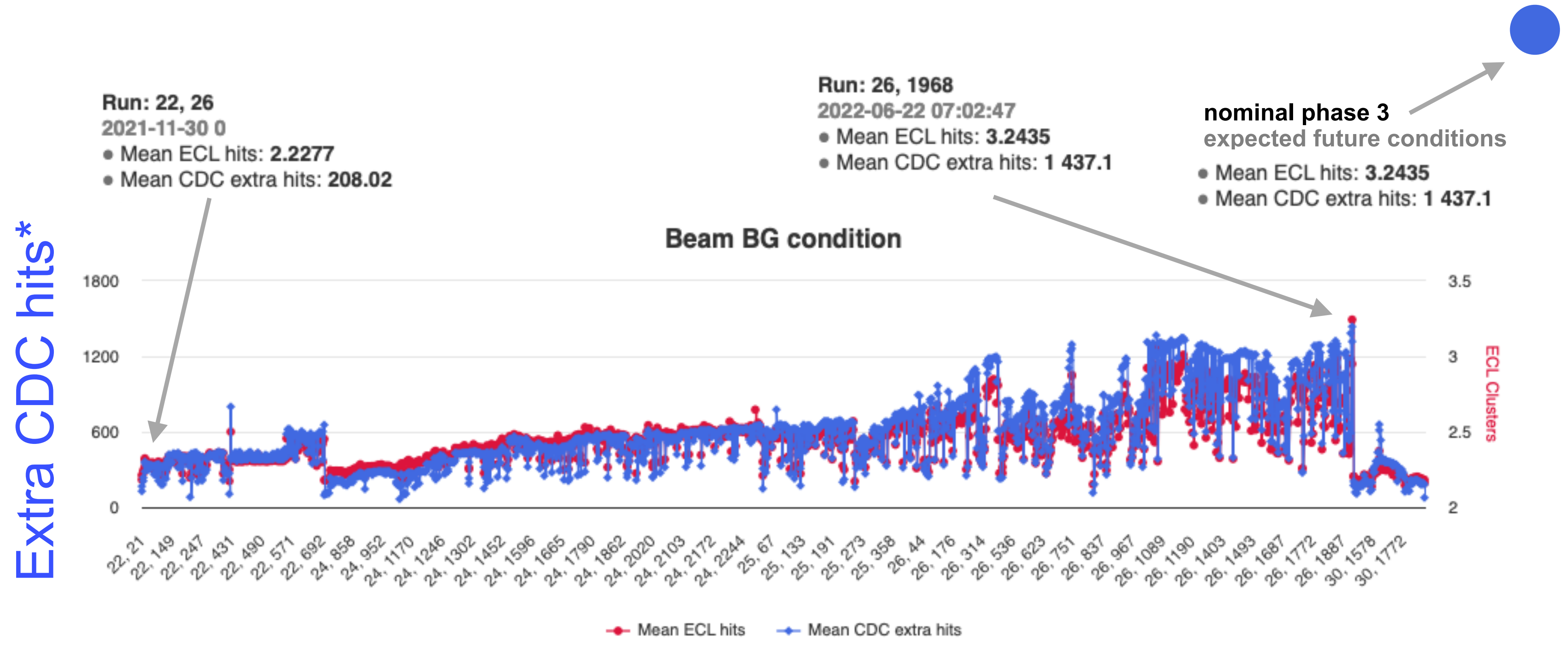
Edge block R2

1-dim edge-level output

Training samples

background conditions

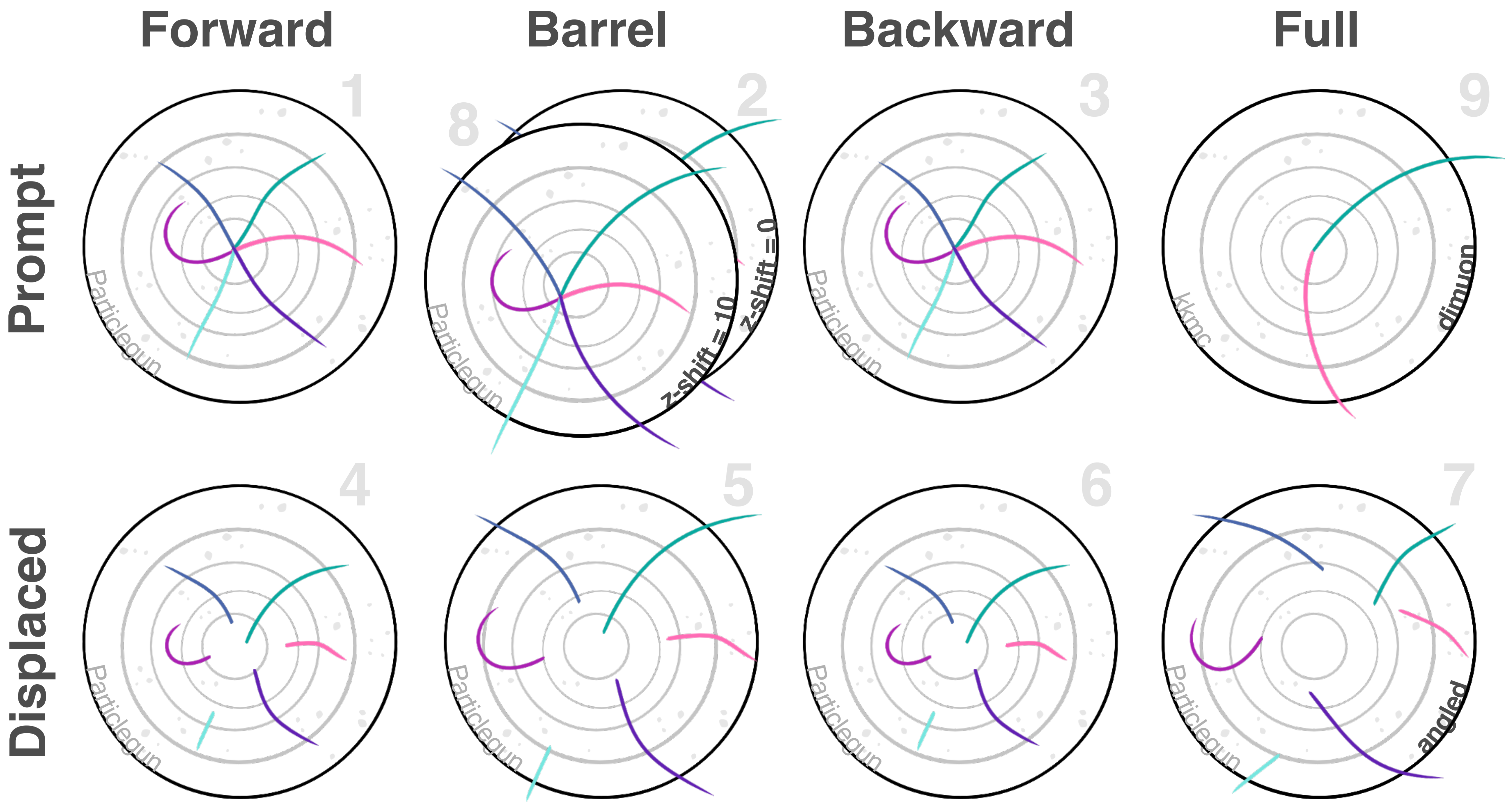
- 1) experiment 22 run 26
- 2) experiment 26 run 1984*
- 3) nominal phase 3



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

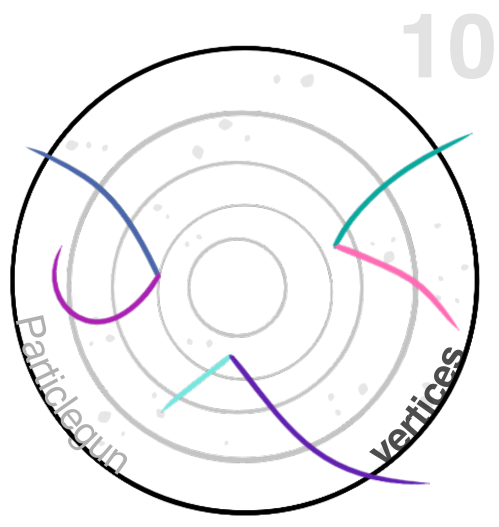
technical sample mix

- KKMC μμ(γ) samples
- particle gun tracks
  - prompt
  - z-shifted
  - displaced (& non-pointing)
  - non-pointing displaced vertices
  - + enriched** with low pT tracks



Sample Details

```
particles: muons
nTracks: 1 to 6 (uniform)
momentum: 0.05 to 6 GeV (uniform)
low_mom: 0.05 to 0.4 GeV (uniform)
low pT enrichment: poisson(1)
```



* 15% less background than exp 26 run 1968, but 25 times more samples available (50K vs. 2K) ** additional poisson distributed low momentum tracks for curlers

Graph Encoding

node attributes

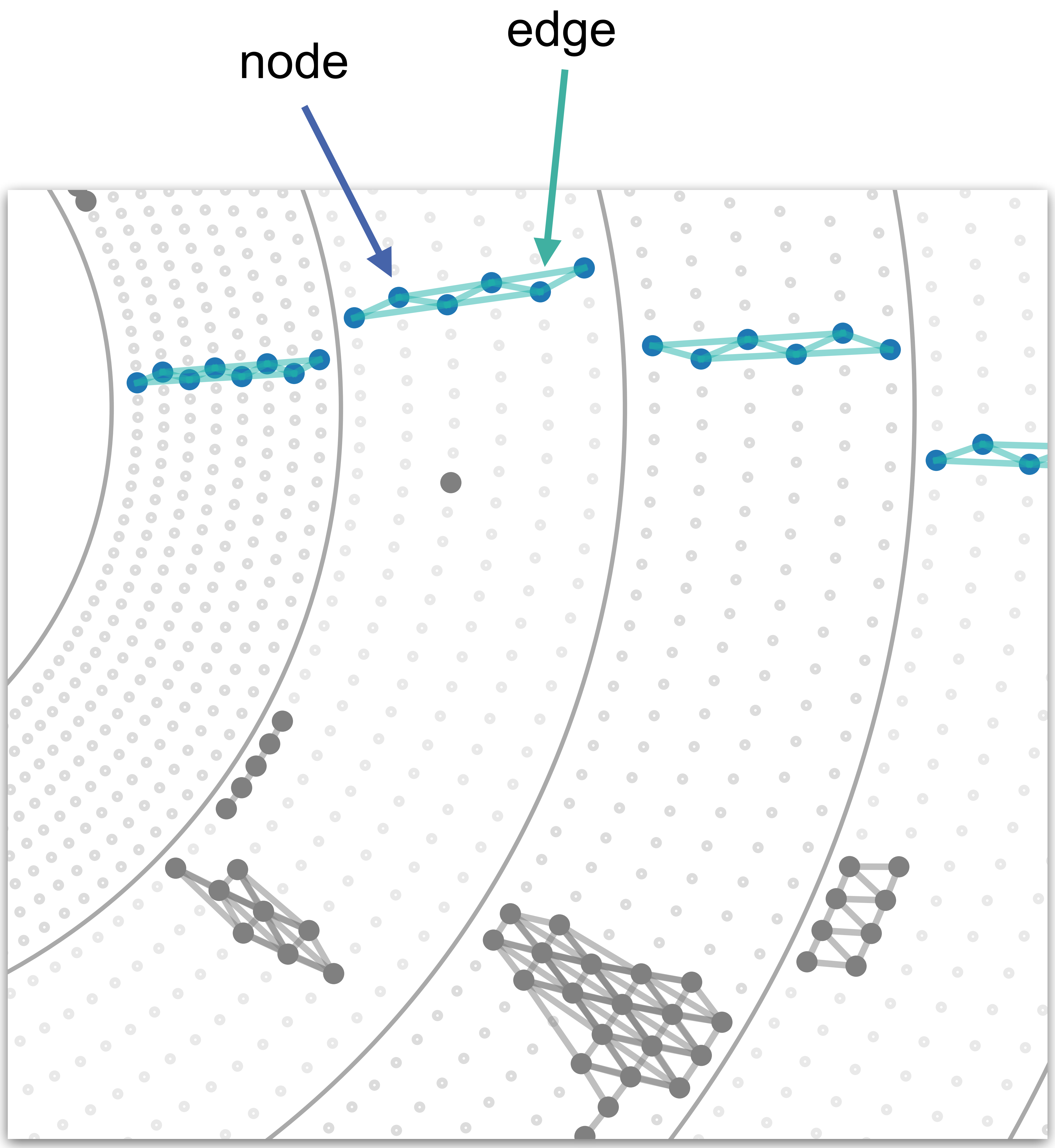
- wire coordinates (x, y)
- ADC (energy) and TDC (time)

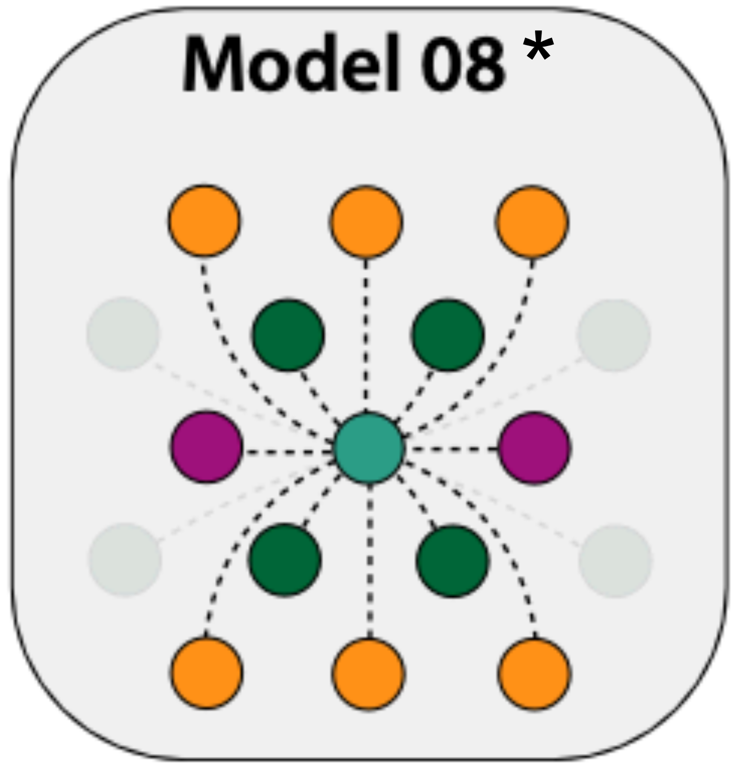
edge attributes

- dr, dφ, dTDC

truth labels

- MC truth





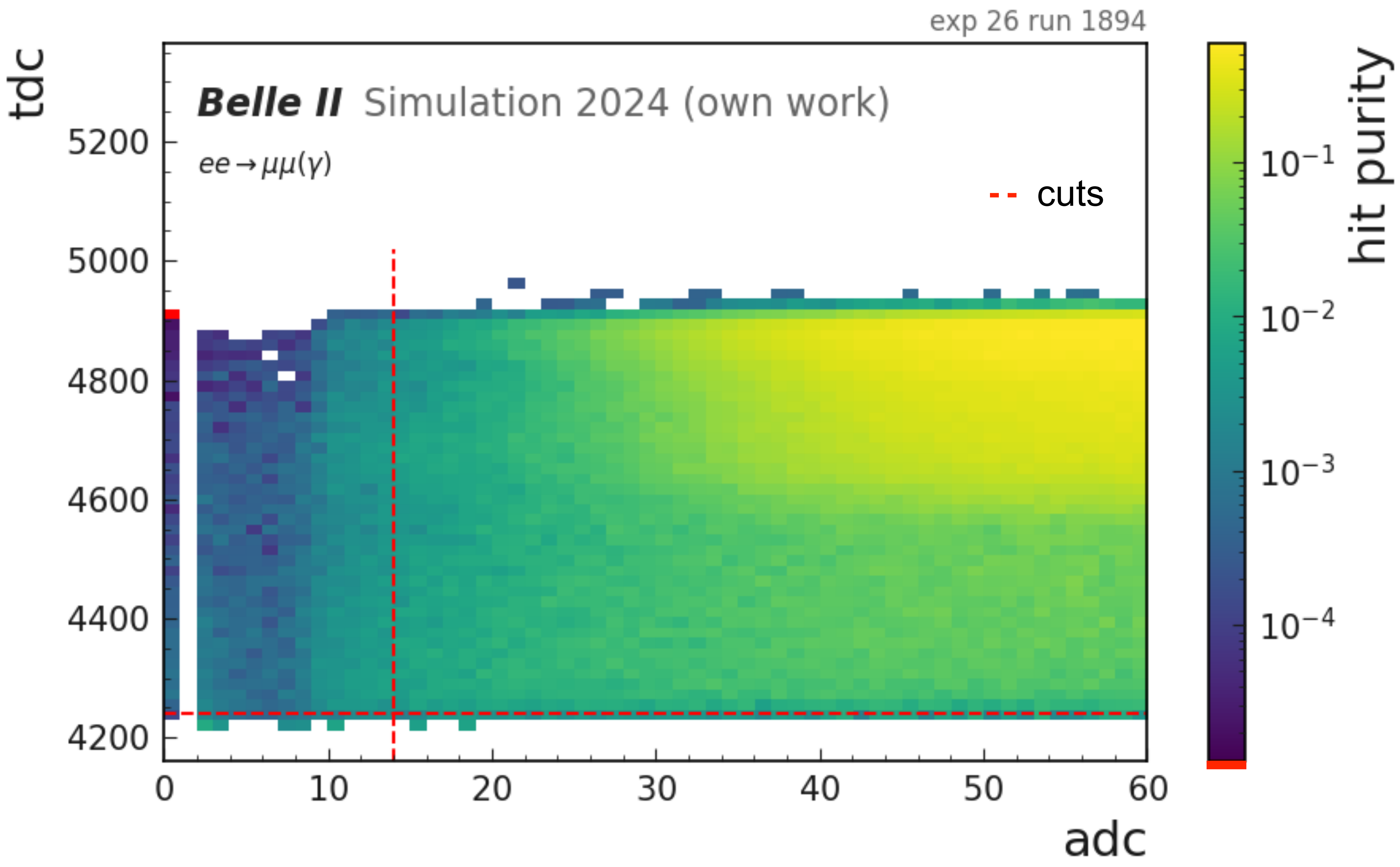
See also
[arXiv:2307.07289](https://arxiv.org/abs/2307.07289)
(graph building with lookup tables)

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

Preliminary ADC and TDC cuts

- apply ADC and TDC cuts before training
- reduction of input data size
- better balance between signal and background hits (→ better training)

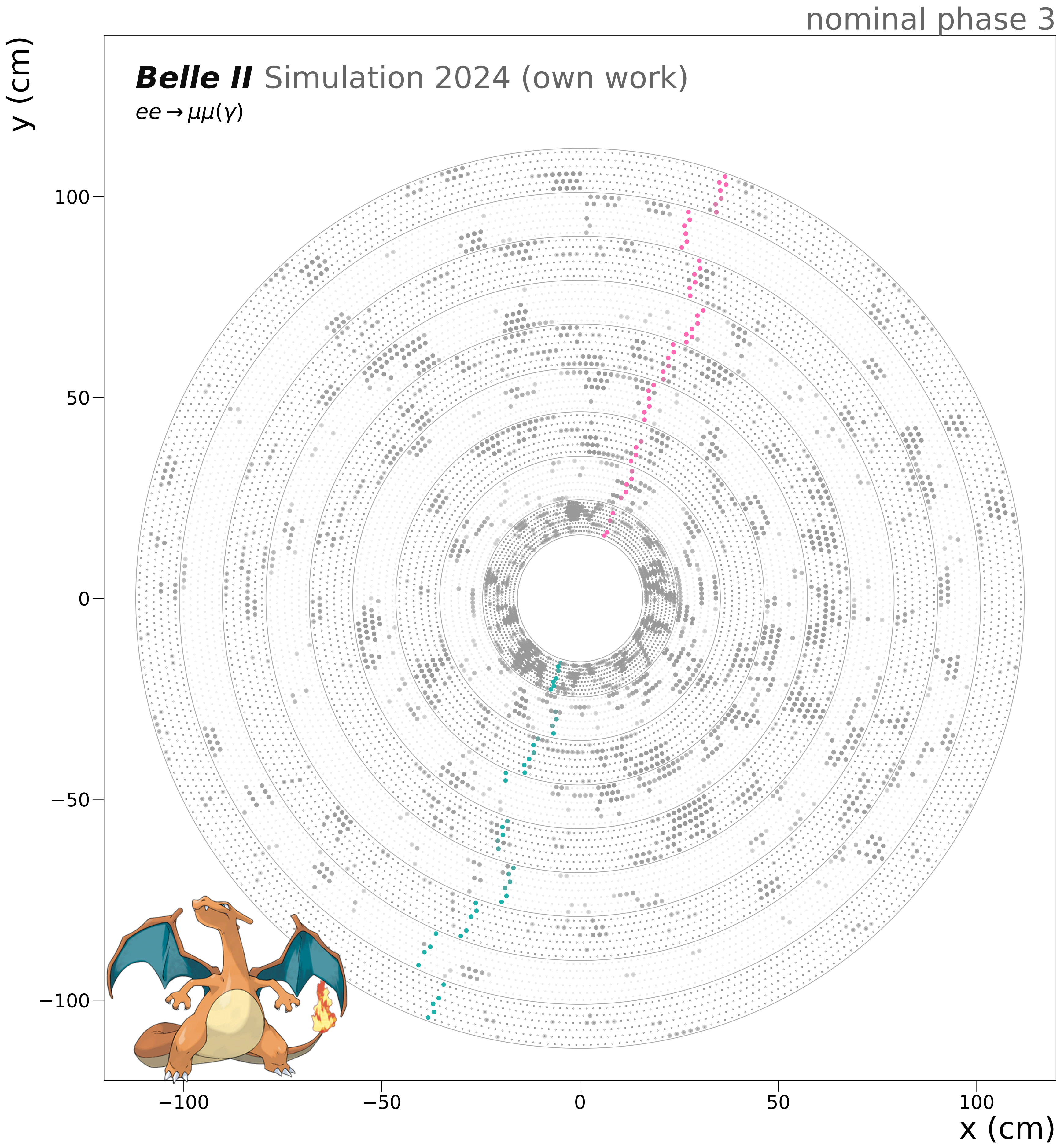
- preliminary cut positions*
  - adc < 14
  - tdc < 4240
  - hit efficiency 99.5113% +- 0.0058%
  - background rejection 44.3164% +- 0.0096%
  - hit purity 9.2392% +- 0.0073%
    (before: 5.3893% +- 0.0043%)

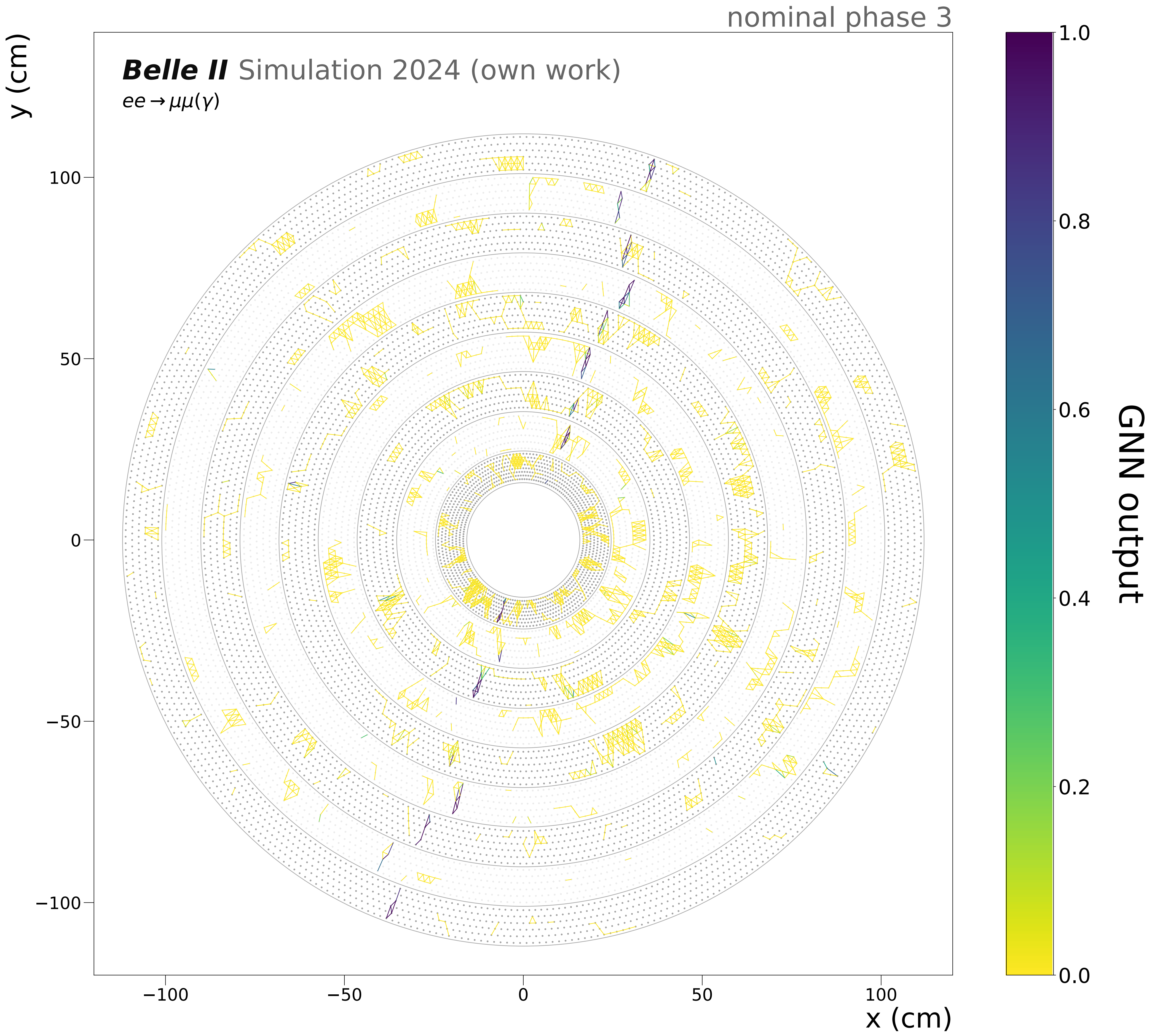


* for full precision ADC and TDC information (not TRG level), ** as starting point, not optimized yet

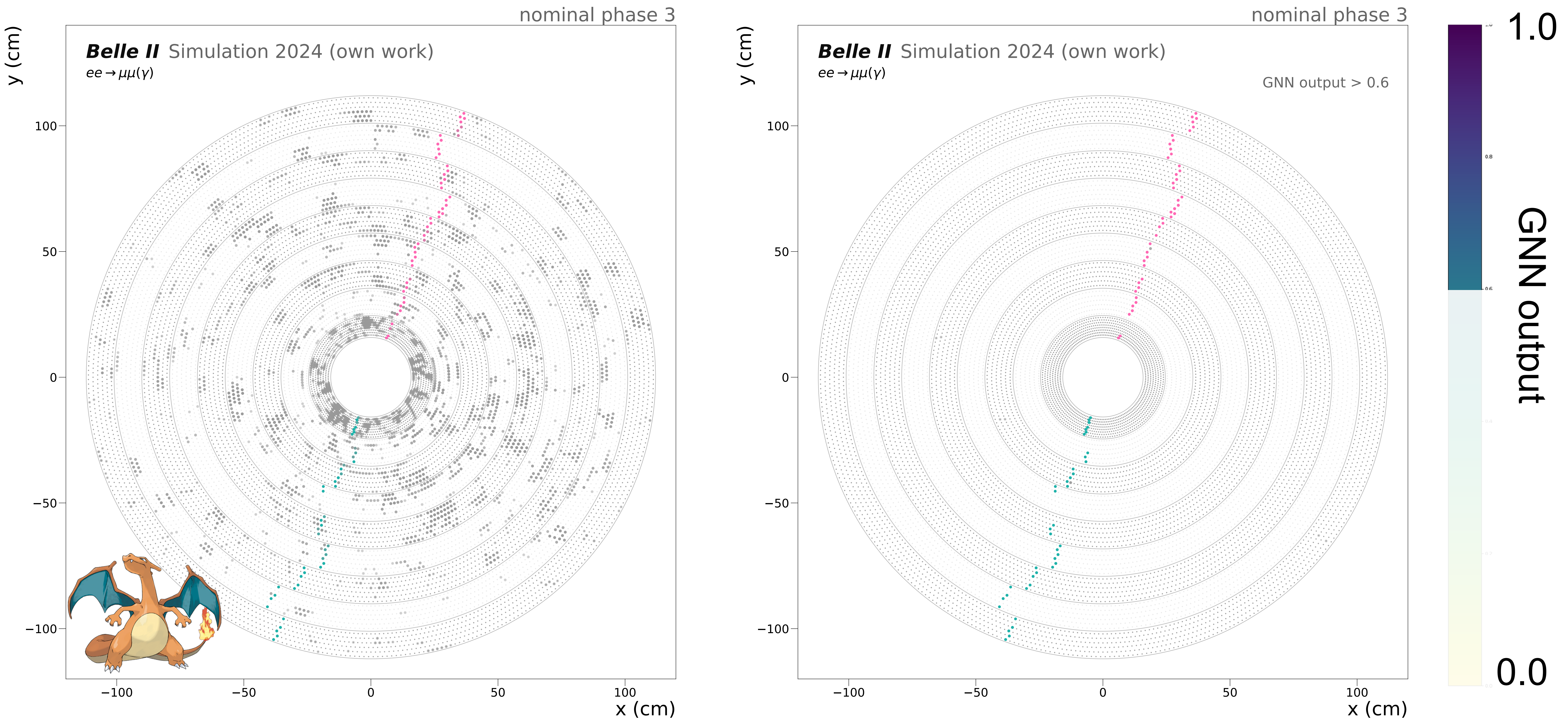
Results

Example GNN Output on edge level



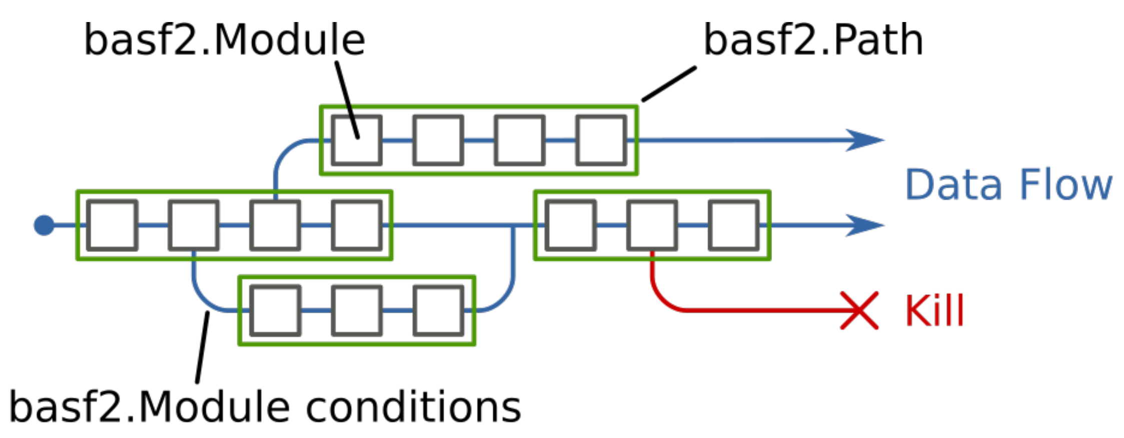


Example GNN Output on hit level



Evaluation on basf2 tracking

optimization of Hit Cleanup settings based on tracking performance



Include Hit Cleanup as basf2 module into tracking

- use CDCWireHit* Background Flag to mark hits as background for tracking
- tracking from release 06-00-08
- monitor tracking performance and execution time
- optimize free parameters of HitCleanup on track charge efficiency

Free Parameters**

- training on CDCWireHits or CDCHits
- x and y position at z=0 or middle of wire
- preliminary ADC and TDC cuts
- GNN cut

Evaluation Samples

- $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
- KKMC generator
- 1000 events

Tracking Modules

Preparation and Hit Cleanup
RegisterEventLevelTrackingInfo
TFCDC_WireHitPreparer
HitCleanup

Track Finding
TFCDC_ClusterPreparer
TFCDC_SegmentFinderFacetAutomaton
TFCDC_AxialTrackFinderLegendre
TFCDC_TrackQualityAsserter
TFCDC_StereoHitFinder
TFCDC_SegmentTrackCombiner
TFCDC_TrackQualityAsserter
TFCDC_TrackQualityEstimator
TFCDC_TrackExporter
IPTrackTimeEstimator
CDCHitBasedT0Extraction
CDCTrackingEventLevelMdstInfoFiller

Track Fitting
SetupGenfitExtrapolation
FullGridChi2TrackTimeExtractor
TrackFinderMCTruthRecoTracks
MCRecoTracksMatcher
IPTrackTimeEstimator
Combined_DAFRecoFitter
TrackCreator

* dataobject used in tracking instead of CDCHits. Includes wire efficiencies. **current state of work, more to come (e.g. including TOT)

Evaluation on basf2 tracking

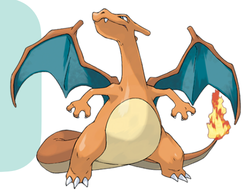
run 22 exp. 26

	charge_efficiency*	efficiency*	fake_rate*	clone_rate*	hit_efficiency	total time	time_finding	time_fitting	time_HitCleanup
basf2 only	95.19% +- 0.54%	95.70% +- 0.51%	0.26% +- 0.13%	0.07% +- 0.07%		78.9 +- 49.6 ms/call	8.9 +- 6.8 ms/call	68.2 +- 64.2 ms/call	
best Hit Clean-up model**	↑ 96.58% +- 0.46%	↑ 96.84% +- 0.44%	↑ 0.19% +- 0.11%	↑ 0.00% +- 0.00%	86.19%	↓ 112.6 +- 48.3 ms/call	↑ 5.6 +- 4.0 ms/call	↑ 57.4 +- 52.9 ms/call	47.8 +- 18.2 ms/call

run 26 exp. 1984

	charge_efficiency*	efficiency*	fake_rate*	clone_rate*	hit_efficiency	total time	time_finding	time_fitting	time_HitCleanup
basf2 only	87.41% +- 0.83%	88.04% +- 0.81%	2.20% +- 0.38%	0.00% +- 0.00%		120.6 +- 71.8 ms/call	45.4 +- 21.1 ms/call	70.9 +- 86.5 ms/call	
best Hit Clean-up model**	↑ 93.05% +- 0.64%	↑ 93.24% +- 0.63%	↑ 0.59% +- 0.20%	0.00% +- 0.00%	85.61%	↓ 197.8 +- 62.2 ms/call	↑ 13.6 +- 6.9 ms/call	↑ 61.3 +- 60.0 ms/call	119.0 +- 28.5 ms/call

nominal-phase 3



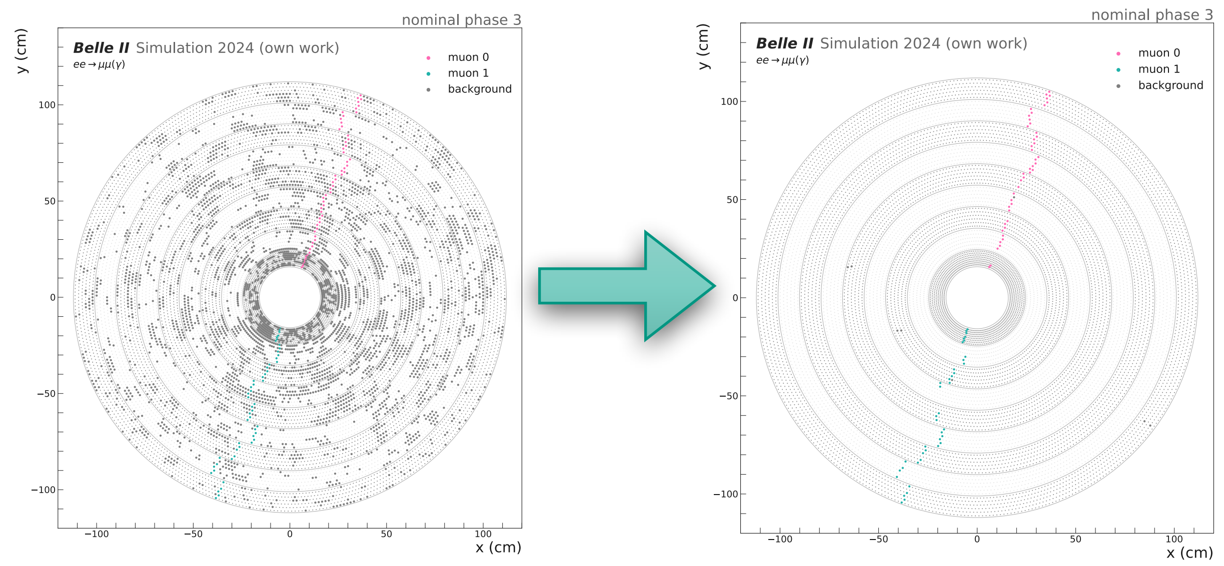
	charge_efficiency*	efficiency*	fake_rate*	clone_rate*	hit_efficiency	total time	time_finding	time_fitting	time_HitCleanup
basf2 only	78.20% +- 1.05%	78.46% +- 1.04%	6.82% +- 0.69%	0.00% +- 0.00%		346.3 +- 154.4 ms/call	195.2 +- 52.5 ms/call	146.3 +- 166.3 ms/call	
best Hit Clean-up model**	↑ 91.96% +- 0.69%	↑ 92.73% +- 0.66%	↑ 2.36% +- 0.39%	↑ 0.00% +- 0.00%	81.72%	↑ 266.6 +- 59.4 ms/call	↑ 21.6 +- 8.9 ms/call	↑ 60.2 +- 56.2 ms/call	179.1 +- 24.6 ms/call

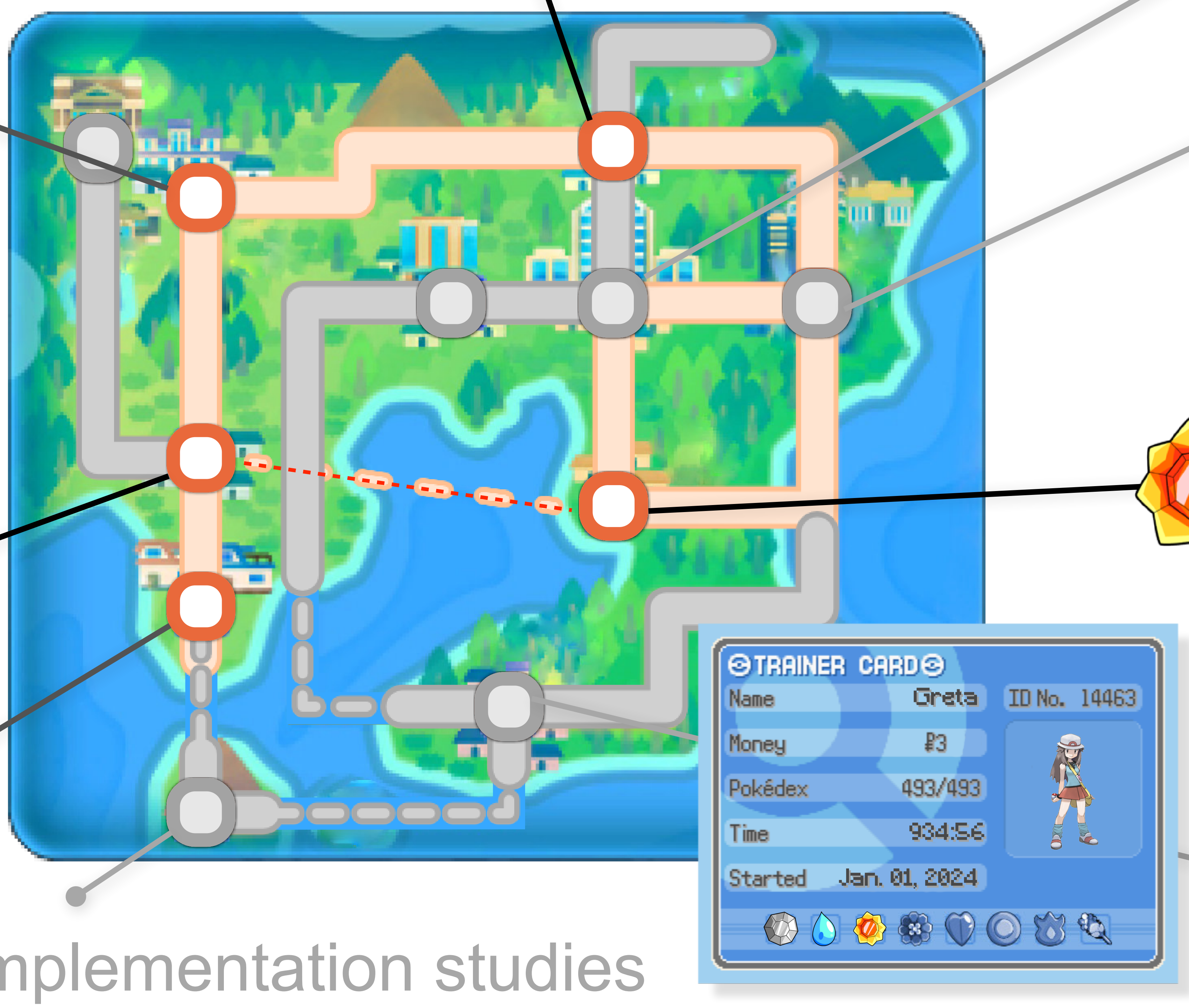
*track fitting metrics **current state of work, more to come, best settings: CDCWireHits, z=0 coordinates, ADC > 9, TDC > 4240 , GNN cut 0.2

Roadmap

Evaluation on tracking
- integration into basf2 tracking
- get full tracking metrics (efficiencies, purities, fake rates etc.)
- monitor execution time
- optimize settings

First Implementation of Hit Clean-Up

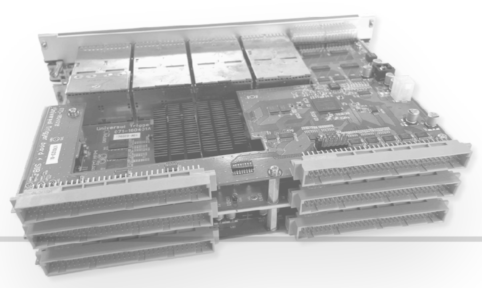




Graph Building on FPGA
arXiv:2307.07289

Getting Started

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



Comparison with BDT Clean-up and Neuro Z Trigger

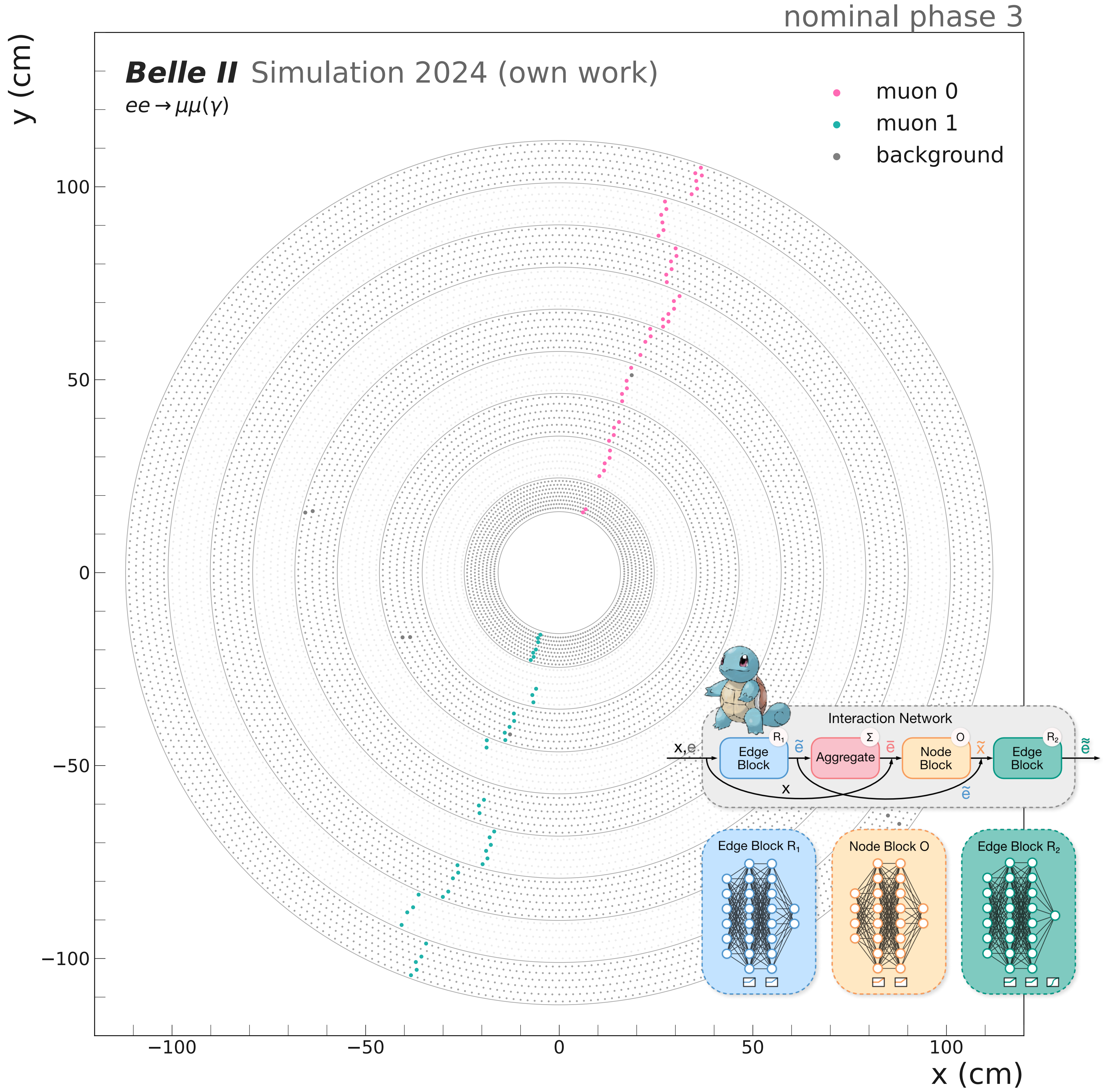
Evaluate on other samples:
- $B\bar{B}$
- displaced samples
- K_S
- bhabha
- protons …

First performance check on TRG like resolutions
- TRG layers
- TDC resolution
- ADC resolution

CDC Segmentation
- segmentation by superlayer & angle on 20 FPGA boards
- handle overlaps
- handle merging of FPGA outputs

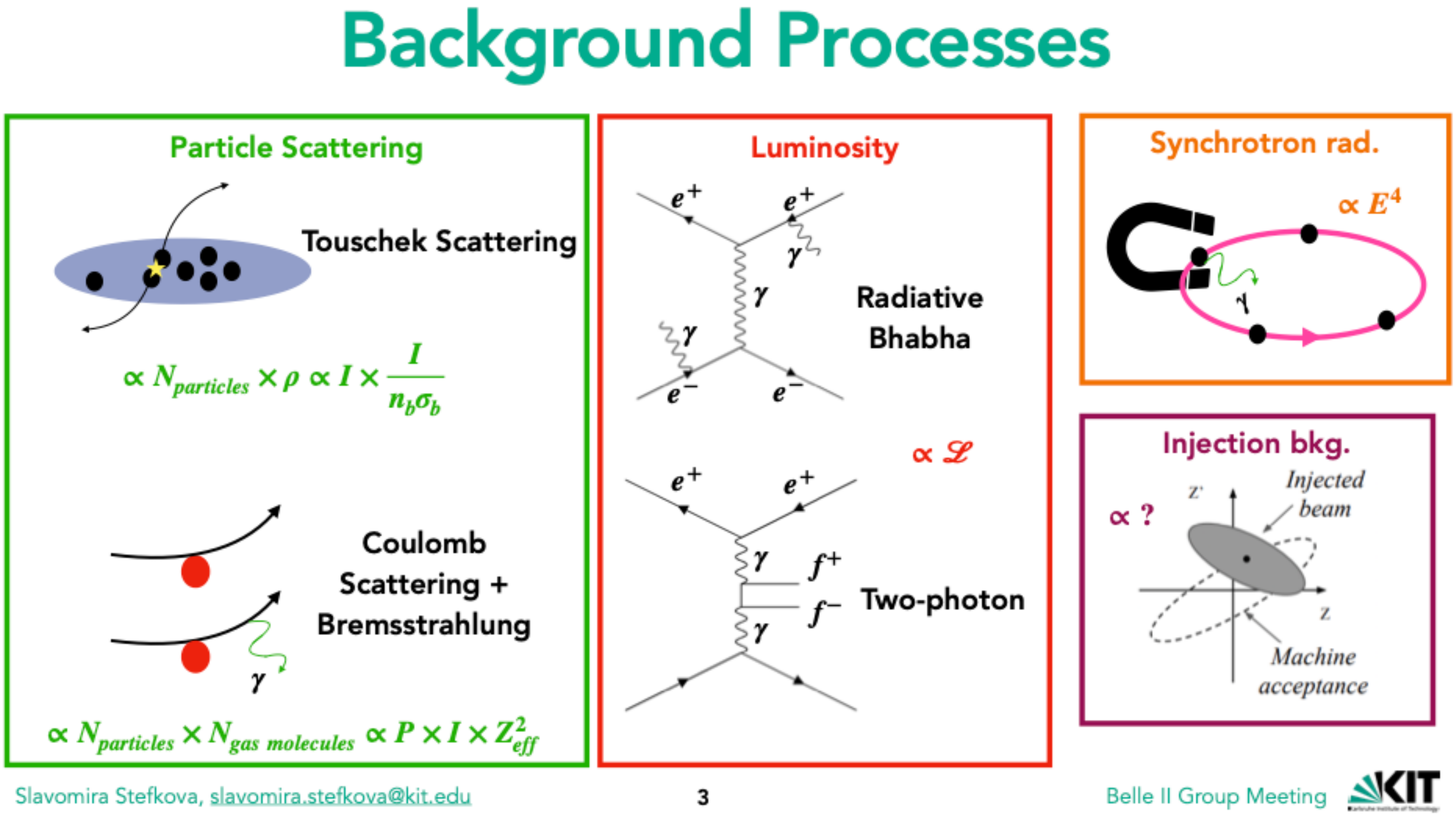
Summary

- Hit Clean-up algorithm **removes background hits** reliably for KKMC muon pairs
- it can significantly **improve tracking** (e.g. experiment 0, KKMC muon pairs):
  - track charge fitting efficiency 78.2% → 92.0%
  - track fitting fake rate 6.8% → 2.4%
  - hit cleanup significantly reduces the time needed for track finding and track fitting at high backgrounds
  - potential for further time improvement by implementation in C++ instead of Python
- implementation on **L1 TRG level** is planned
  - first studies on L1 TRG conditions are carried out
  - next steps include optimization on L1 TRG conditions and implementation studies



Backup

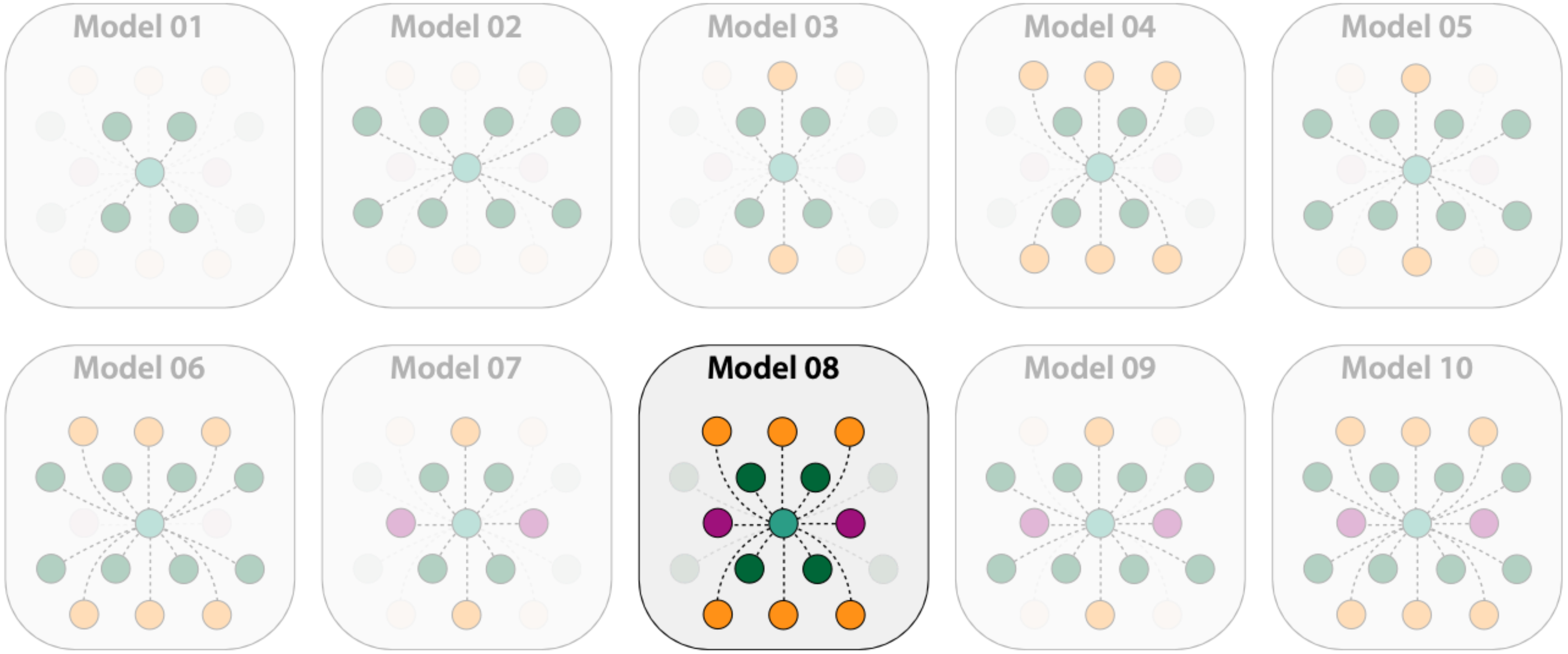
Belle II backgrounds

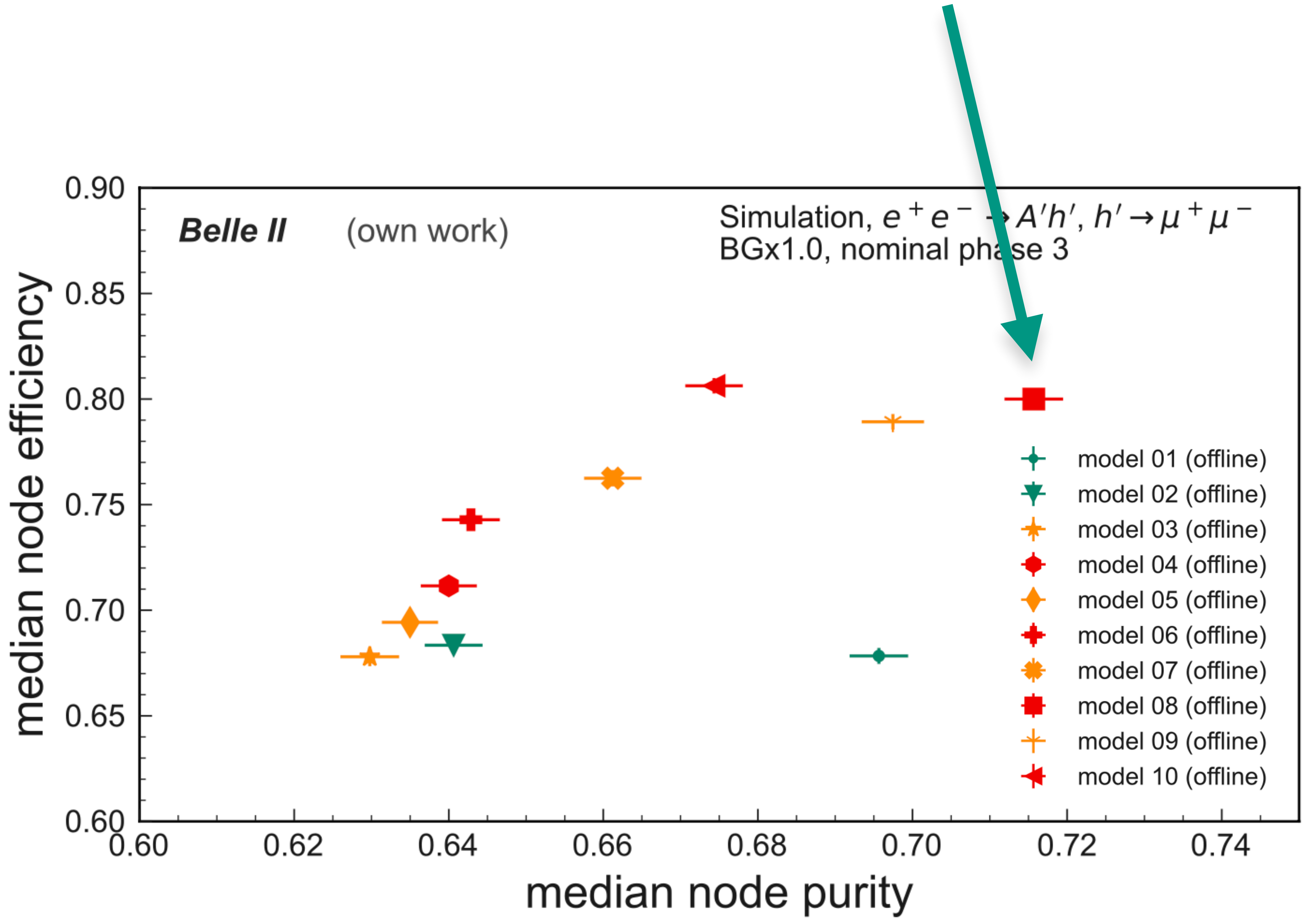


Graph Building Models

- investigation of 10 different graph building models

model 08

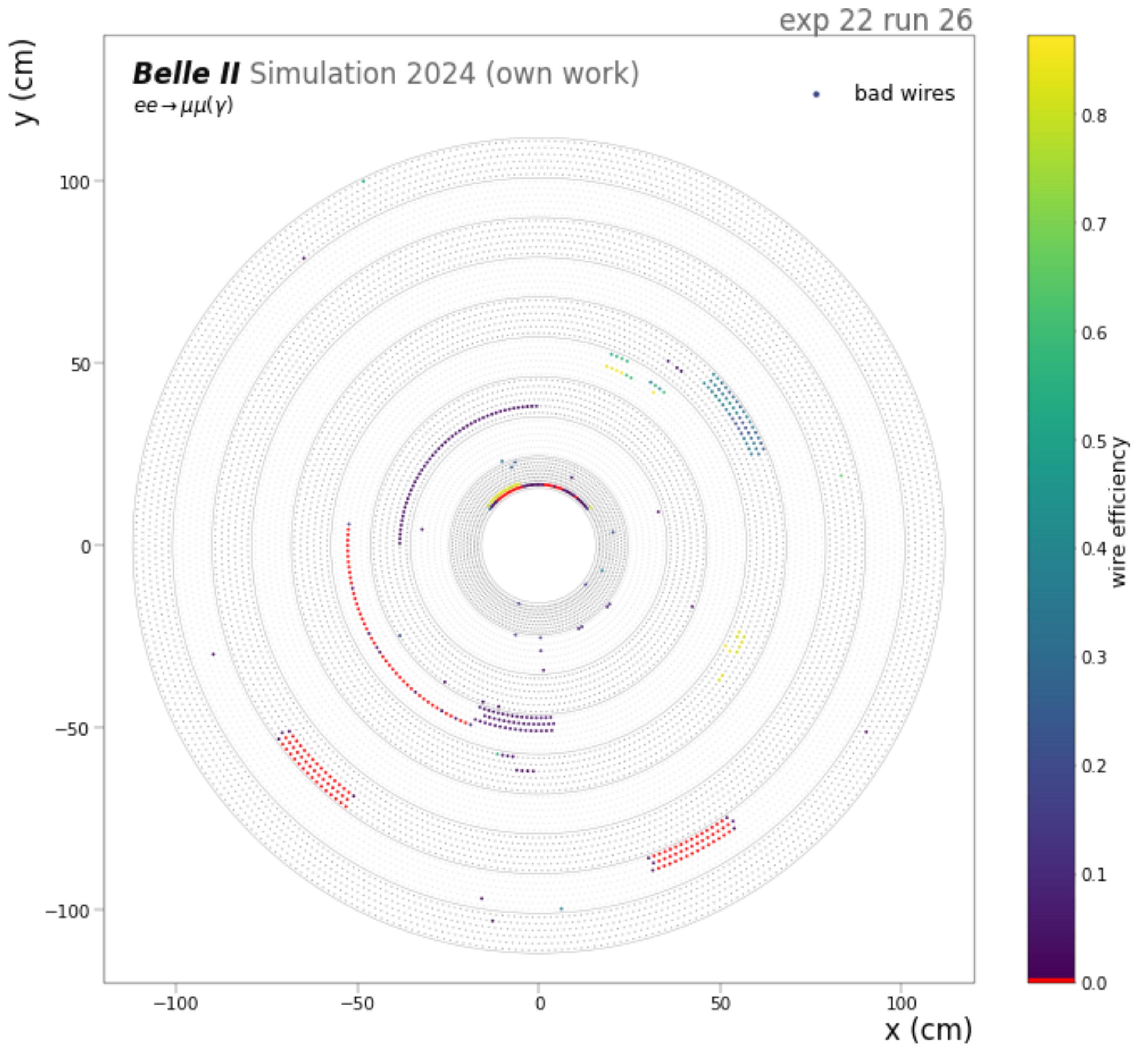




Master thesis „Graph-Building and Input Feature Analysis for Edge Classification in the Central Drift Chamber at Belle II“ of Philipp Dorwarth, May 2023

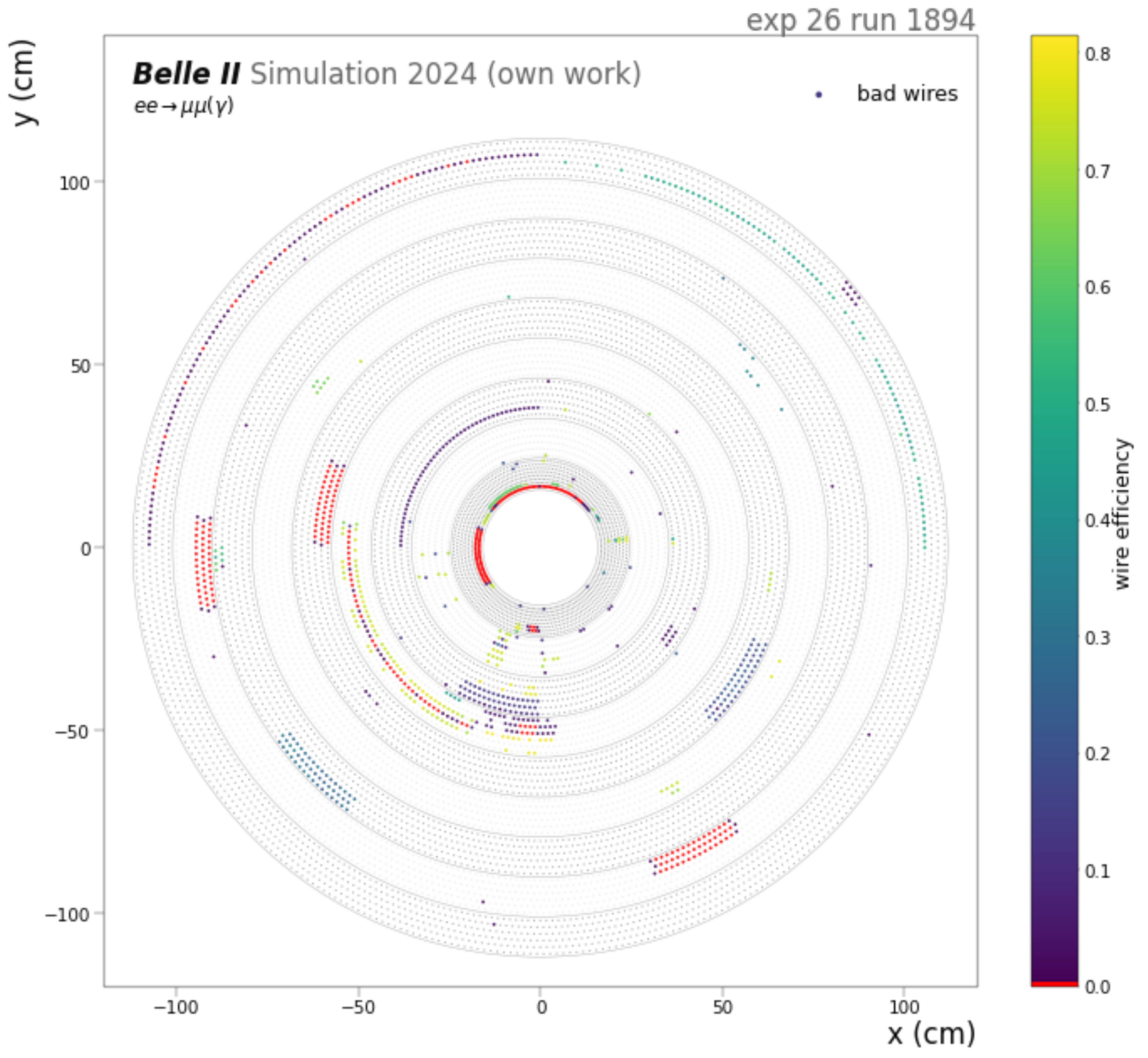
Wire efficiencies

exp 22 run 26




```
configured globaltags (highest priority first) are
mc_production_MC15rd_a_exp22_bucket28,
data_reprocessing_prompt, online, release-06-00-07
data_reprocessing_prompt
```

exp 26 run 1894




```
configured globaltags (highest priority first) are
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data_reprocessing_prompt, online, release-06-00-07
data_reprocessing_prompt
```
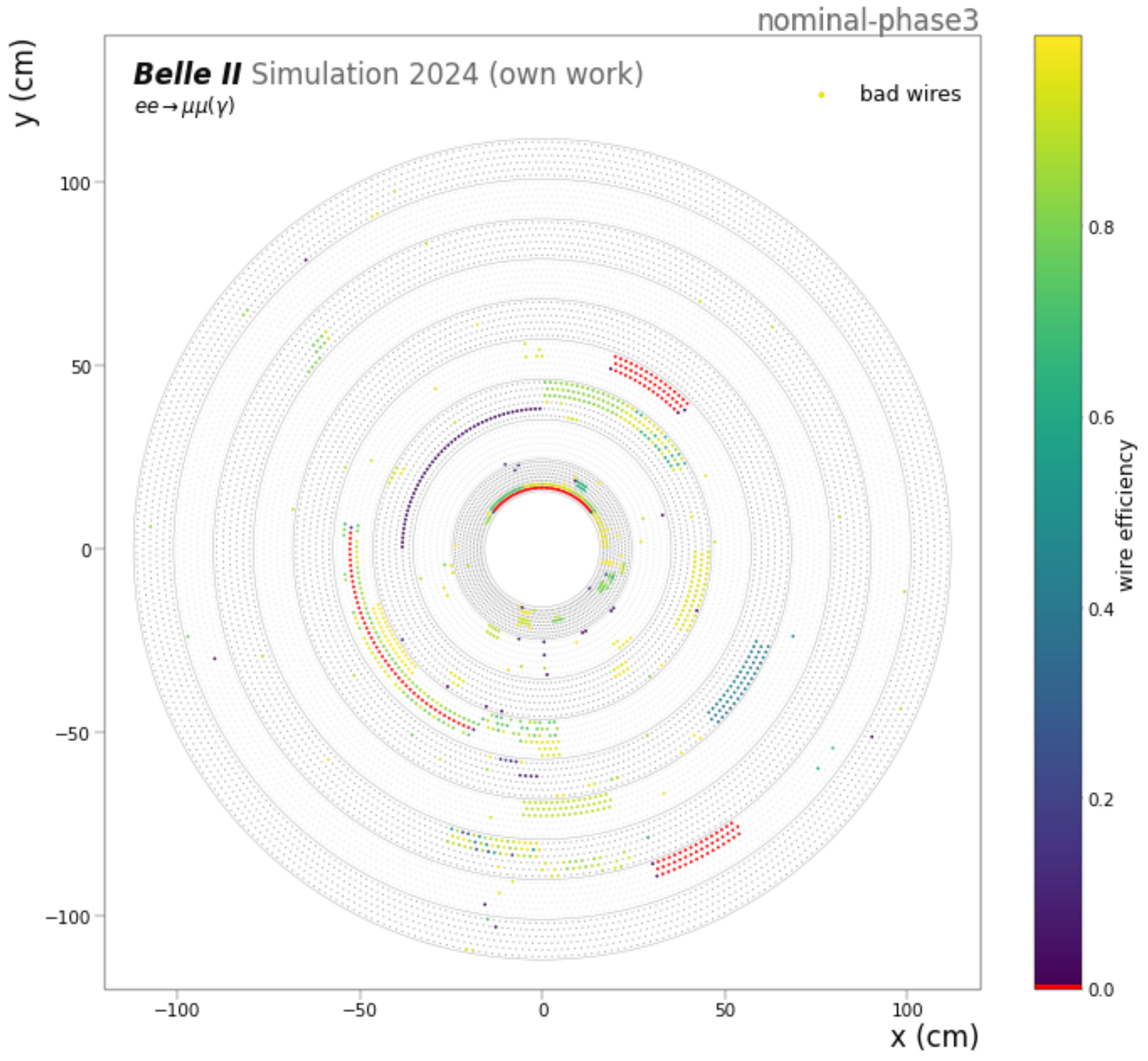
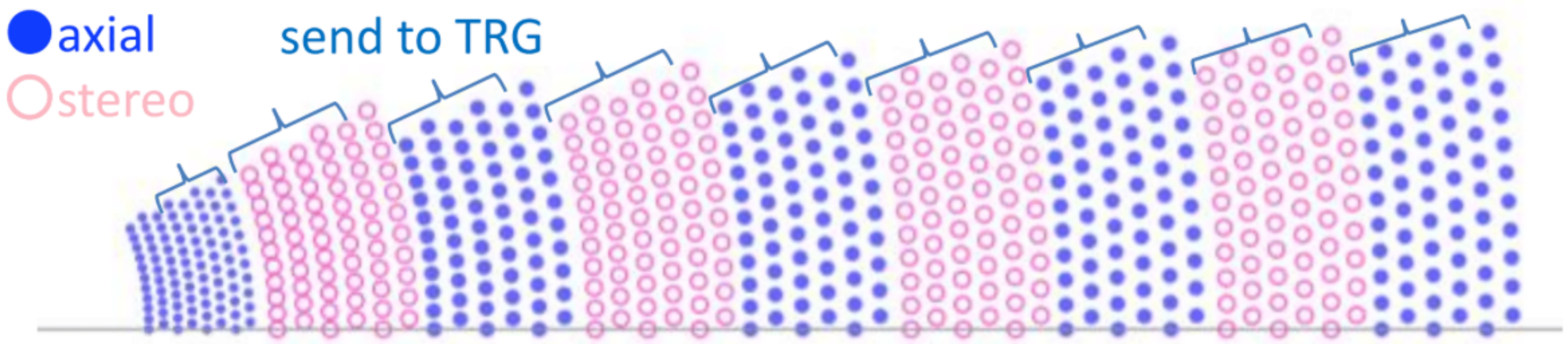

nonimal-phase3

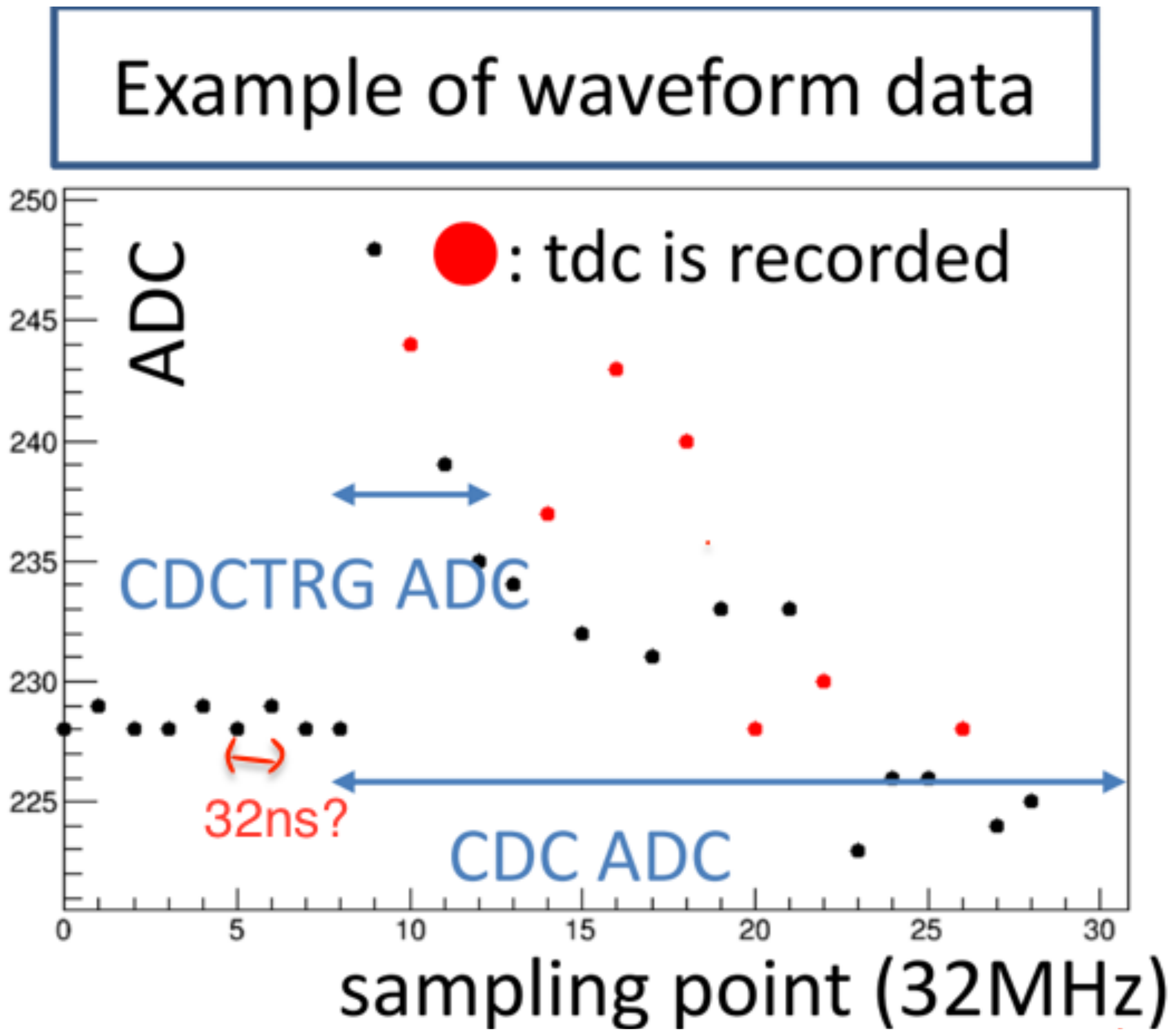



```
configured globaltags (highest priority first) are
mc_production_MC15ri_a, release-06-00-07
mc_production_MC15ri_a
```

Trigger-like LS2 Conditions

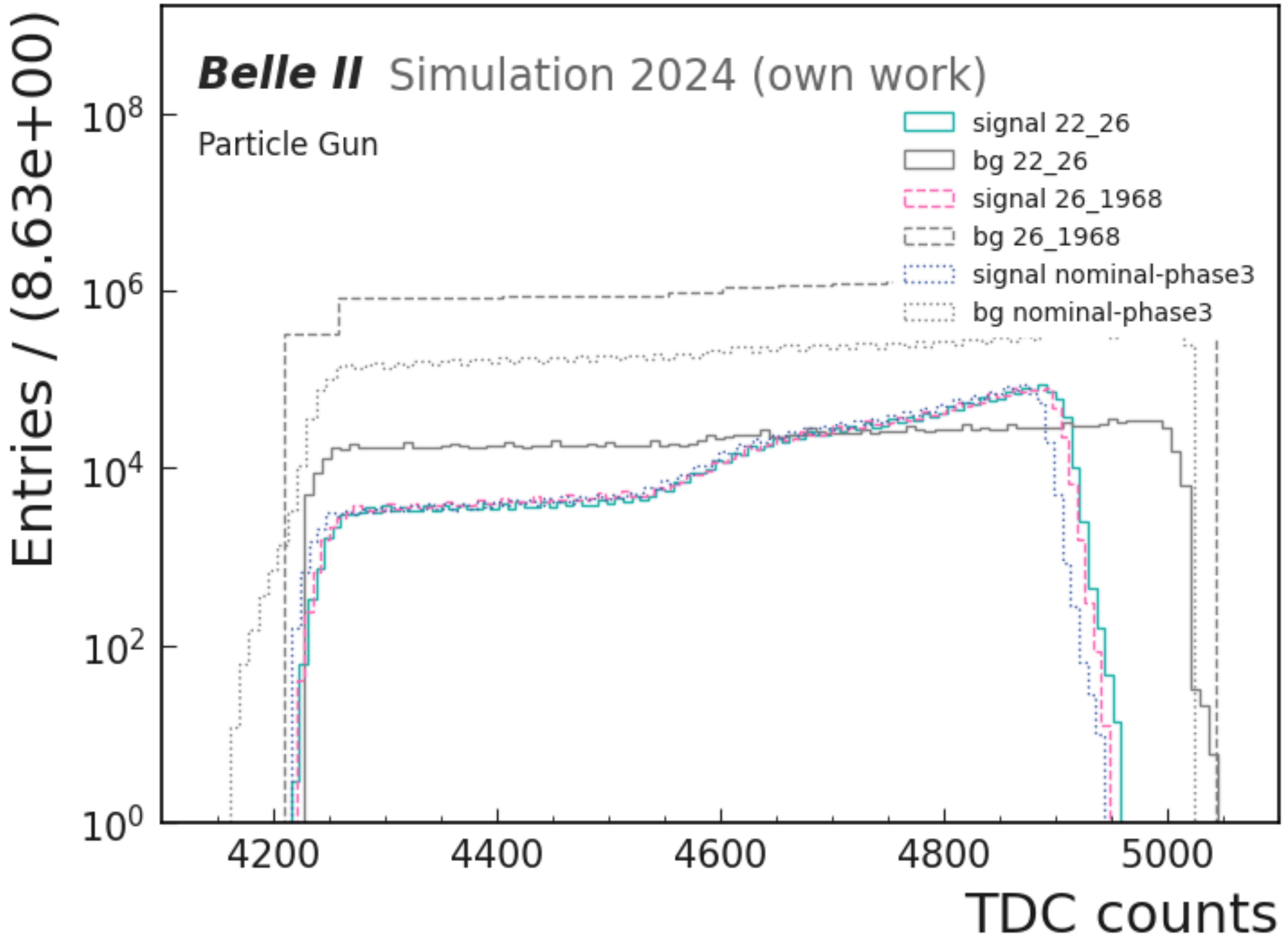
- conversation with Koga-san
- **TDC**
  - 2ns resolution → half resolution
  - no absolute time information because no EventT0 → remove absolute TDC
- **ADC**
  - sum of 3 points instead of 25 → different distribution, how to emulate?
  - 4 bit resolution (= 15 thresholds) → remap to 15 bins
- **both**
  - 5/6 wires in each super layer → remove non-TRG layers





TDC reduced resolution

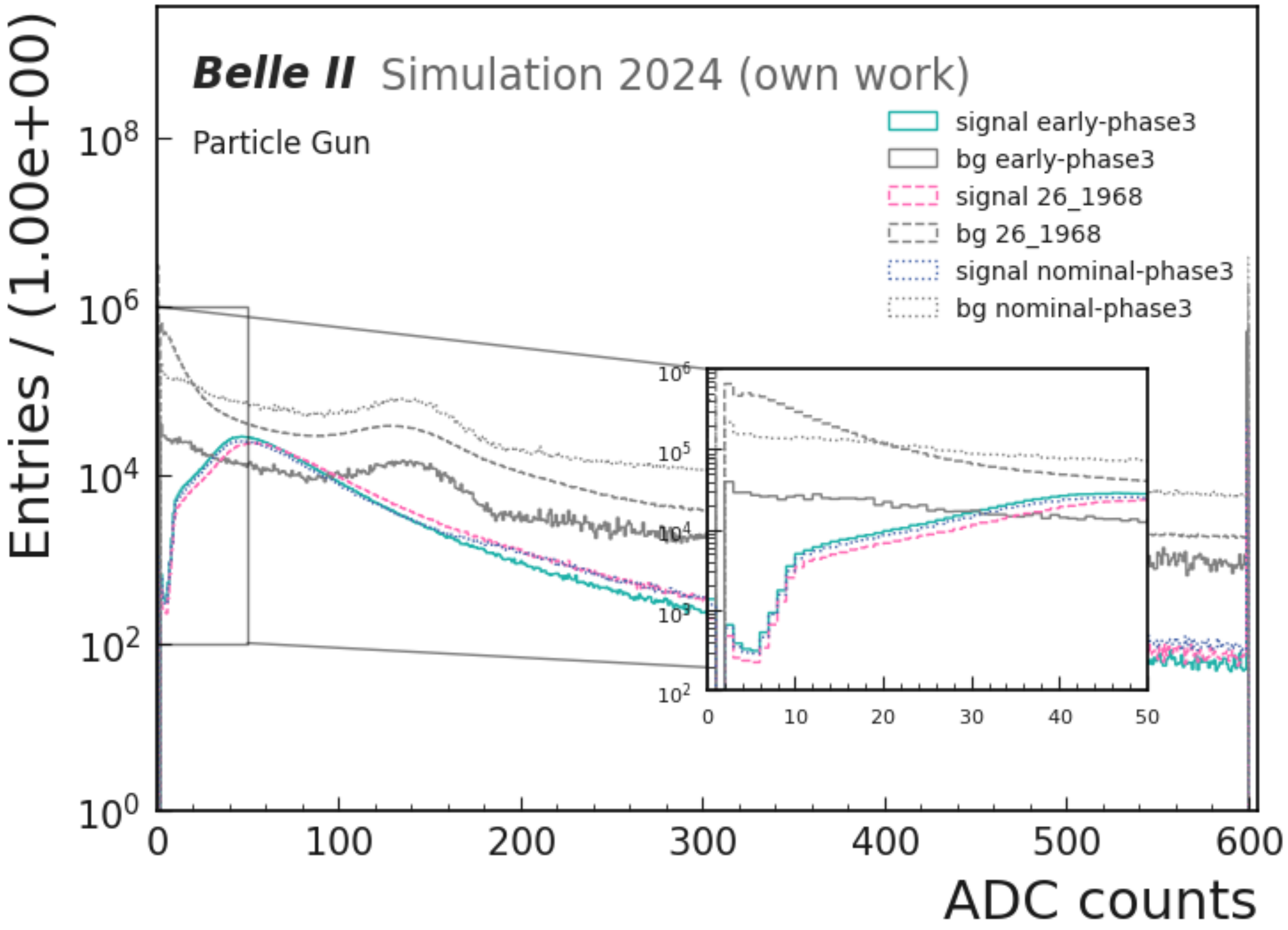
- definition (Philipp thesis): $\tau \cdot \mathrm{TDC}_{\mathrm{count}} = \mathrm{T}_{\mathrm{stop}} - \mathrm{T}_{\mathrm{evt}} - \mathrm{T}_{\mathrm{tof}} - \mathrm{T}_{\mathrm{drift}} - \mathrm{T}_{\mathrm{prop\text{-}delay}} - \mathrm{T}_{\mathrm{time\text{-}walk}},$
- offline resolution: 1ns
- TRG resolution: 2ns
- **reduce resolution by factor 2 b**



tdc
4833
4724
4656
4878
4866
...
4583
4583
4581
4578
4583

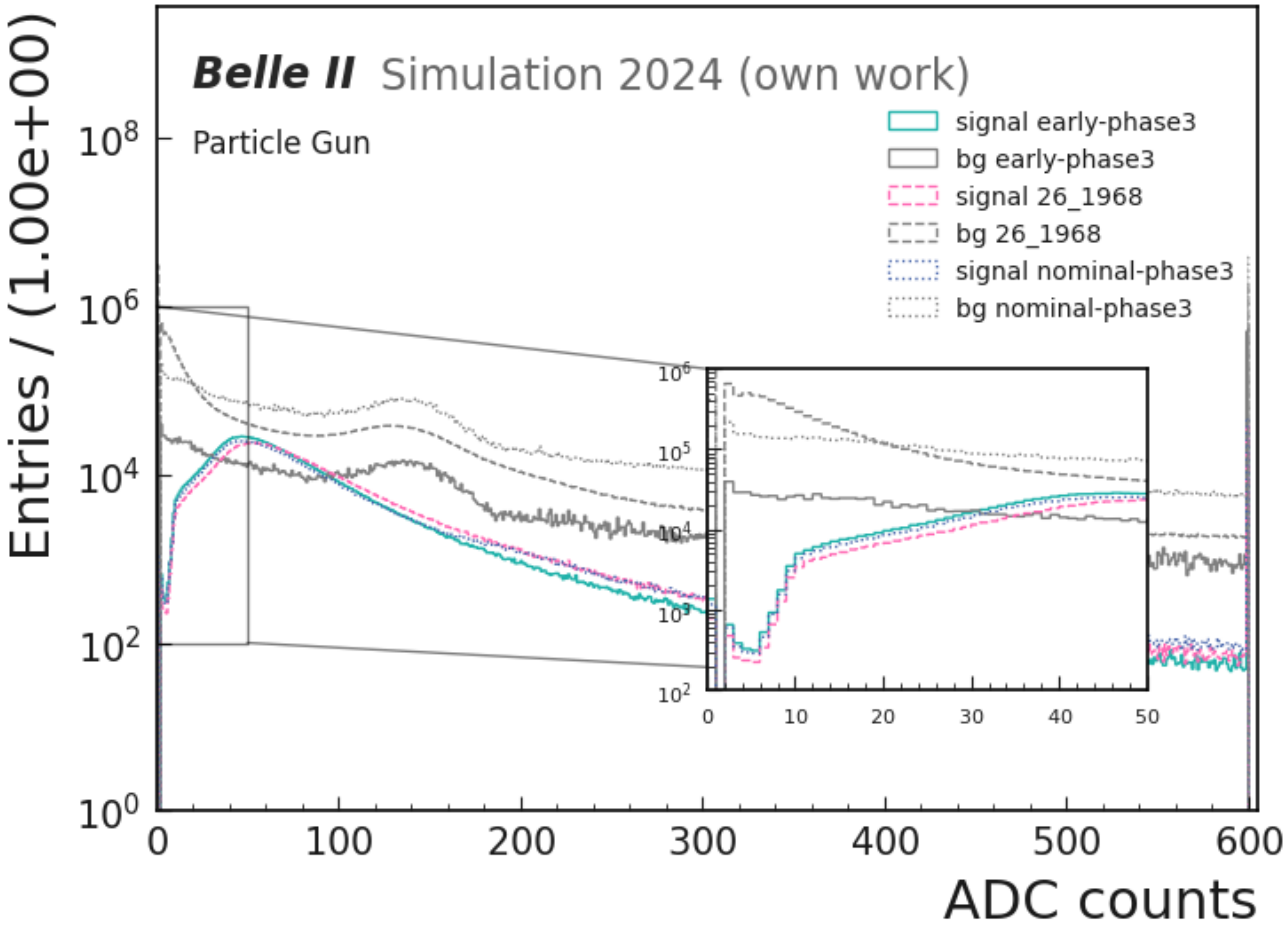
ADC bins

- bin 0: [0,14] (only for evaluation)
- 4 different binning modi
  - flat signal
  - flat background
  - flat noise
  - equidistant

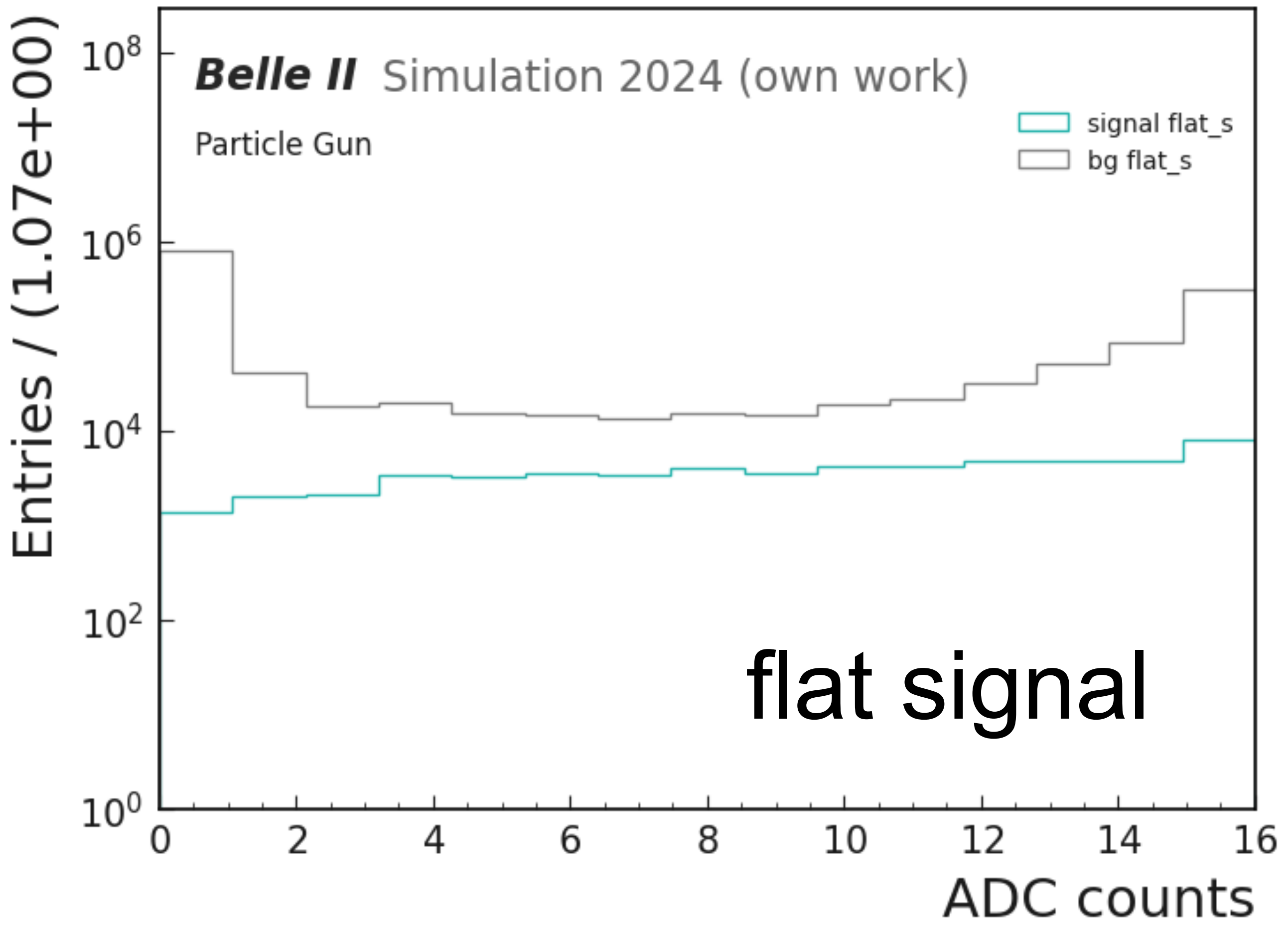


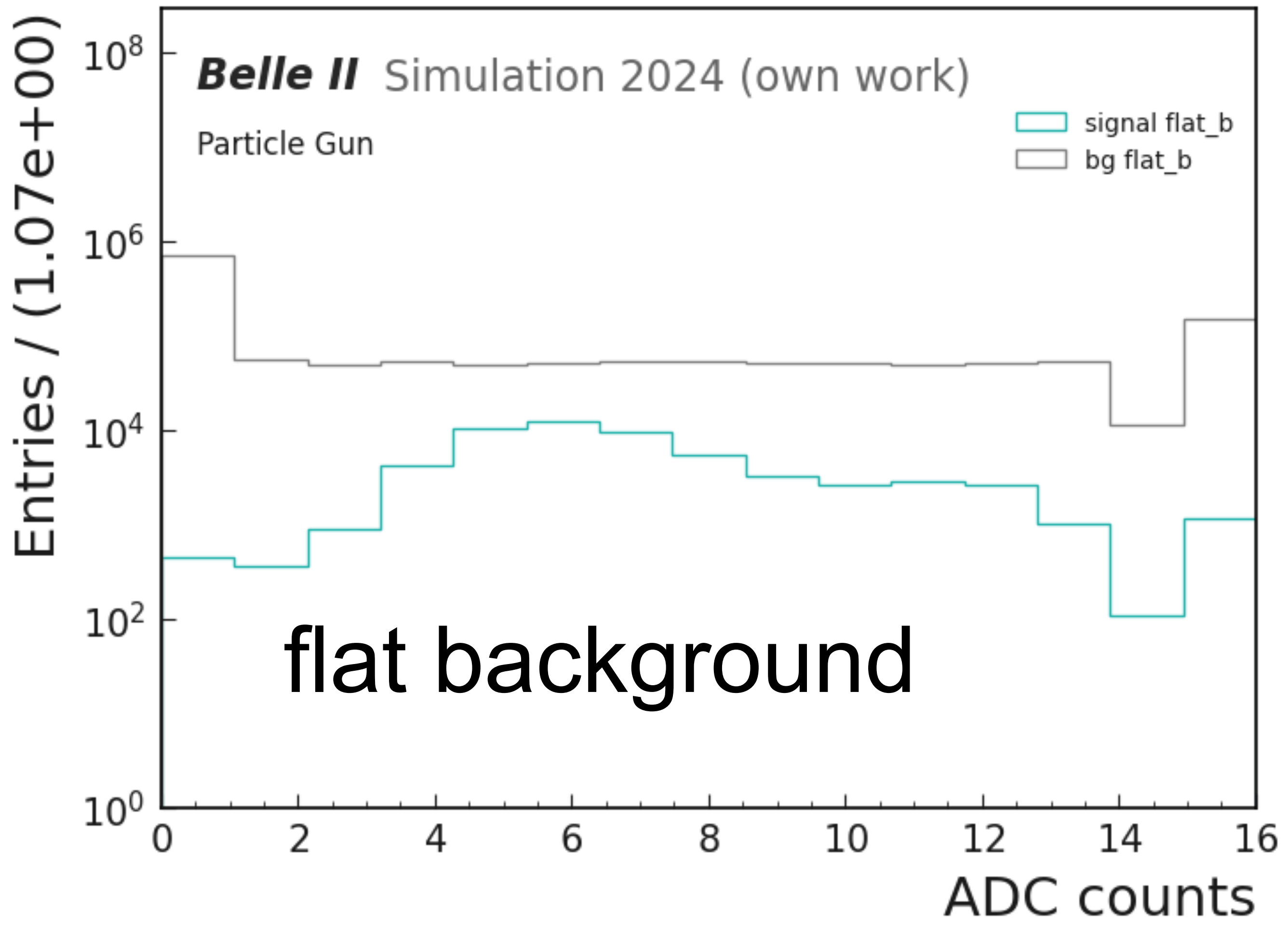
ADC bins

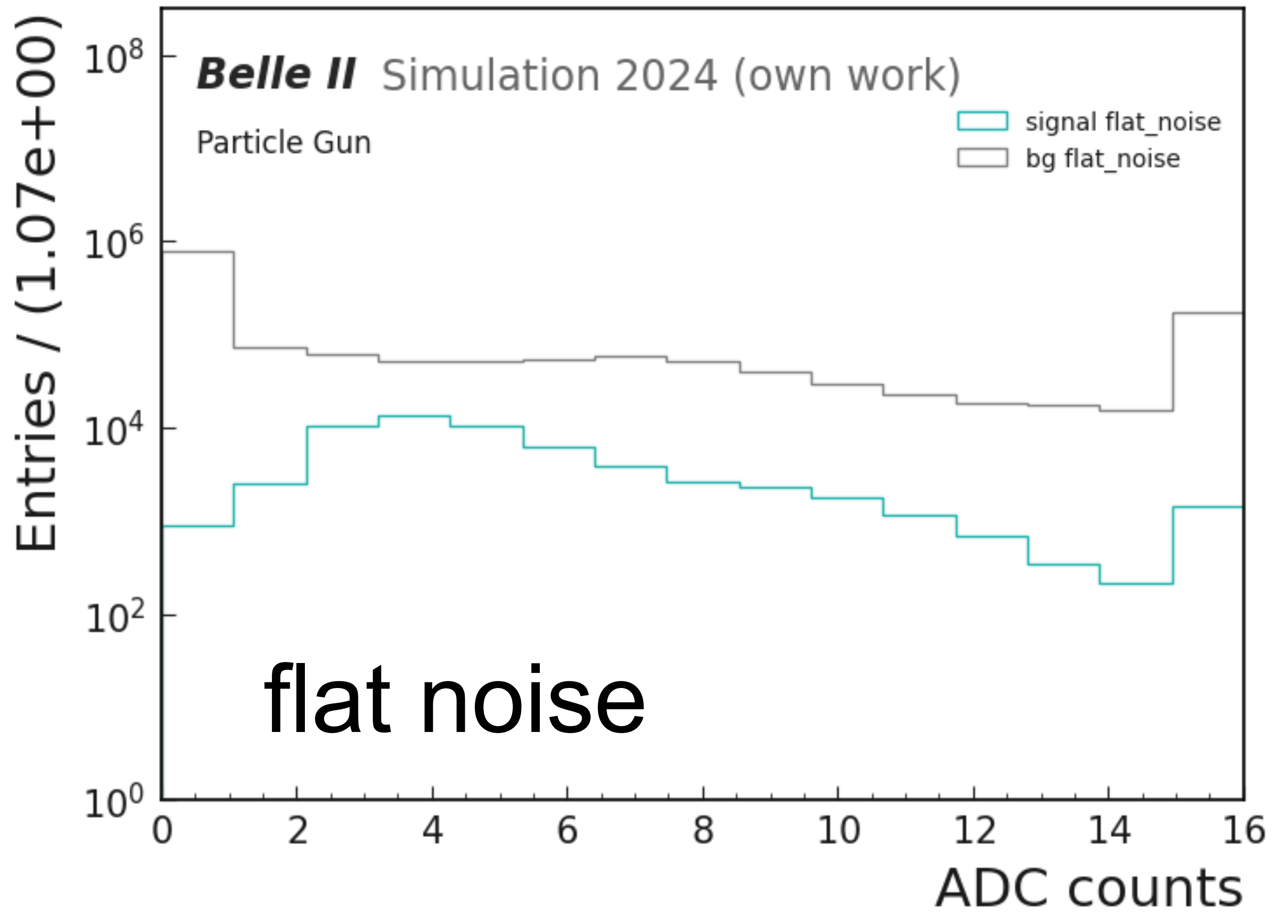
- train
  - 1000 events
  - 4 binning modi + full
  - background 26_1968
  - sample: displaced and angled particle gun
- inference
  - 100 events
  - 4 binning modi
  - background 26_1968
  - dimuon
  - trained on 4 binning modi + full

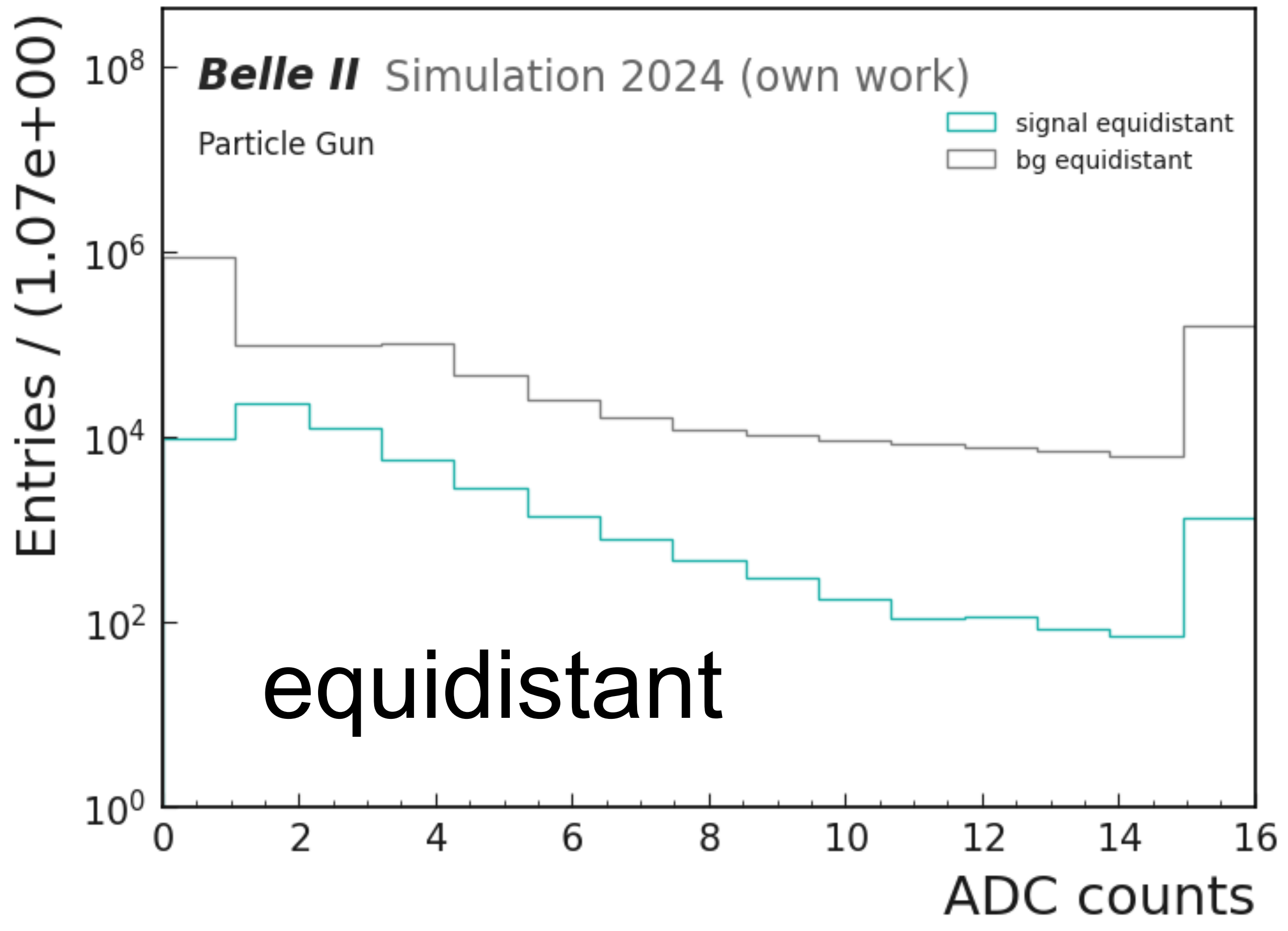


ADC binning modi



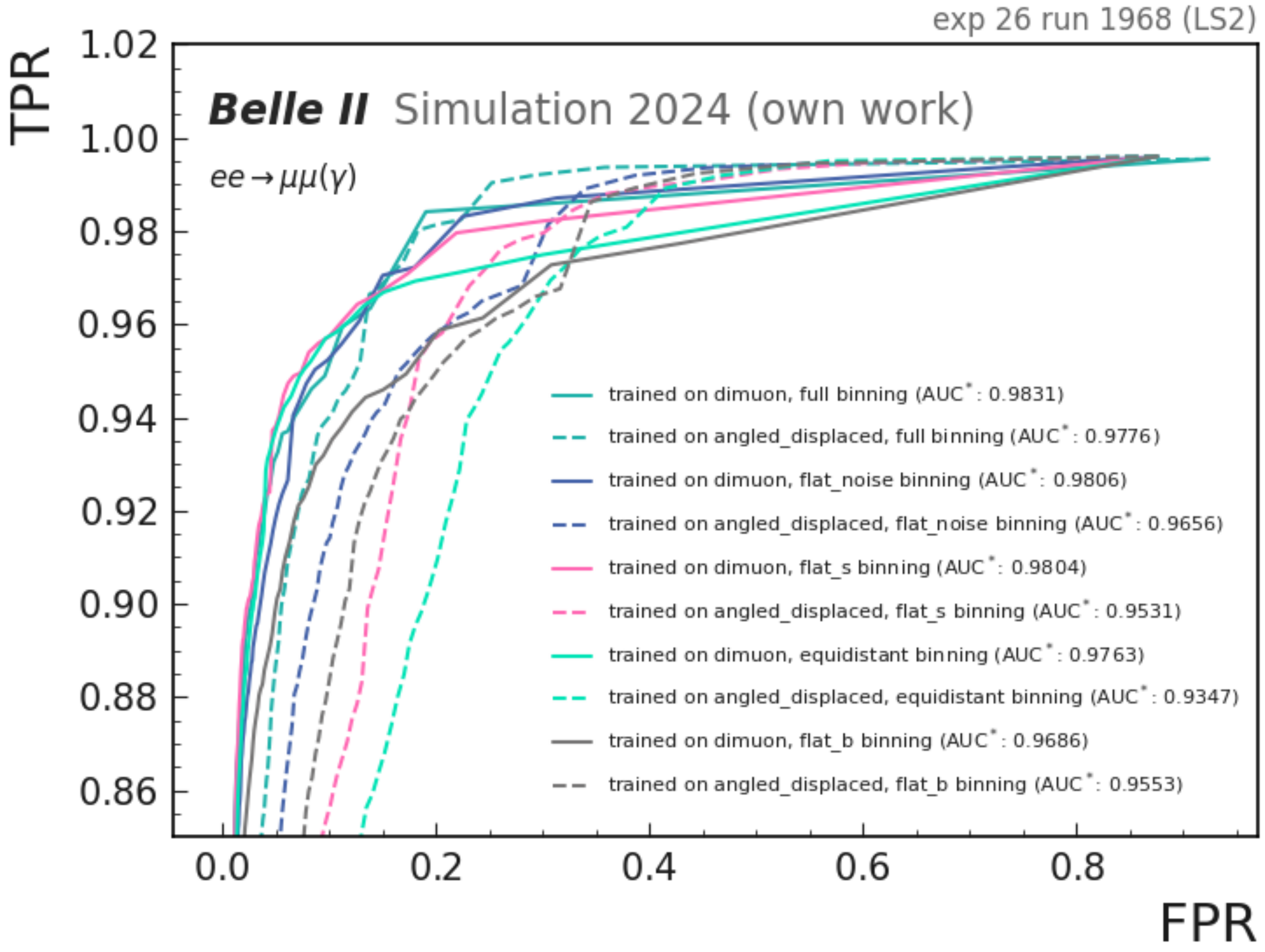






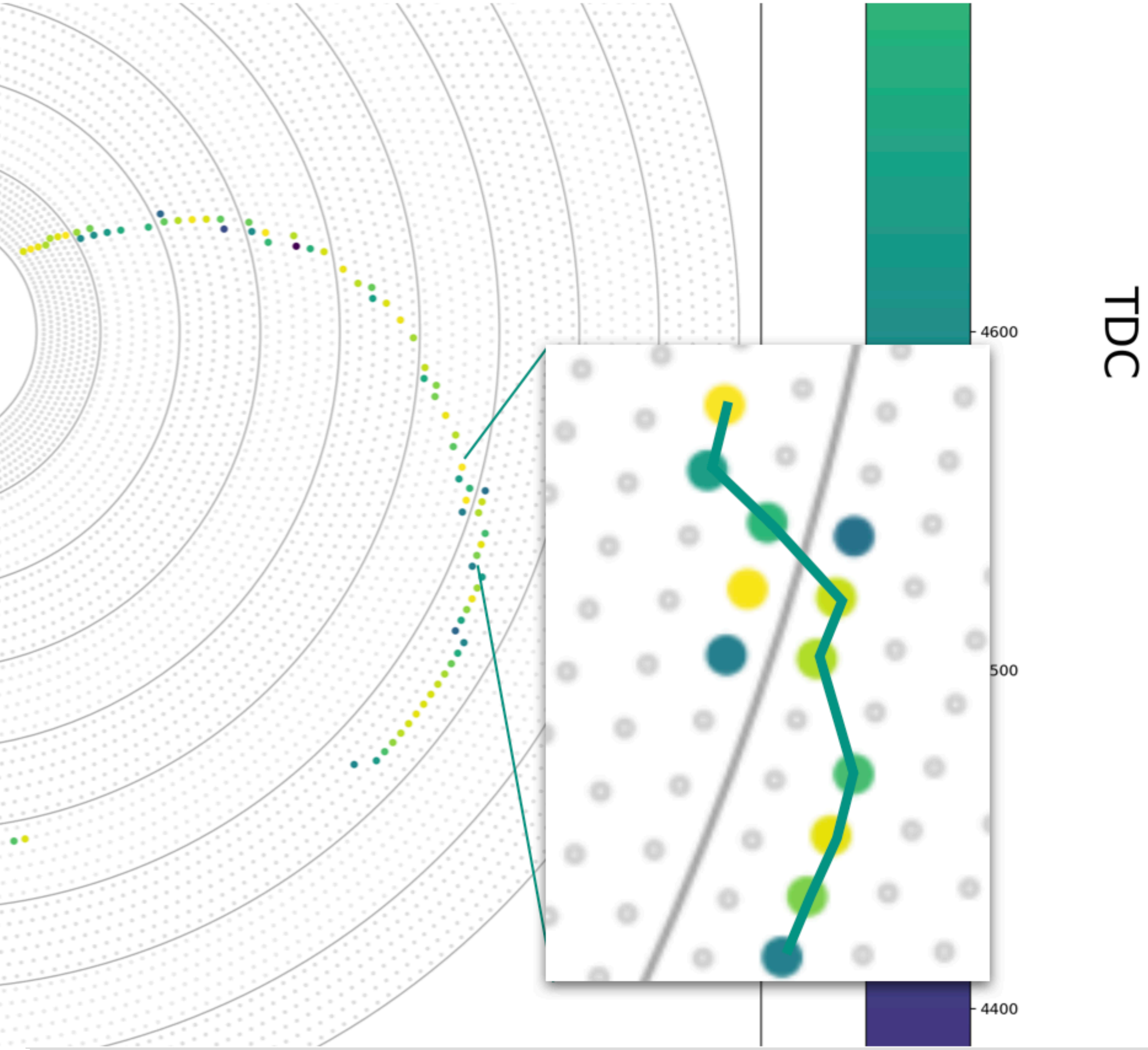
- first bin overcrowded due to huge 0 bin
- deviations in last bin due to ADC clipping
- recheck: fixed binning for different background levels

ADC binning performance



- for reduced binning flat noise performs best (AUC = 0.9806)
- advantage of flat noise:
  - stable for different signal types
  - need to check stability for different backgrounds

True Hit Definition



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