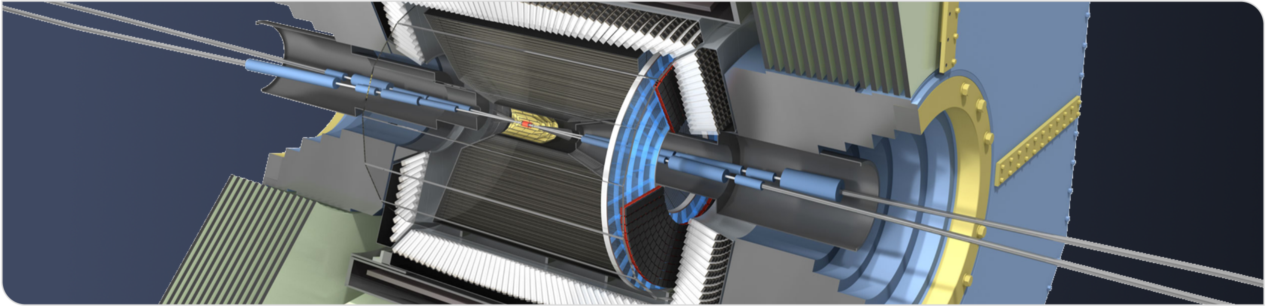
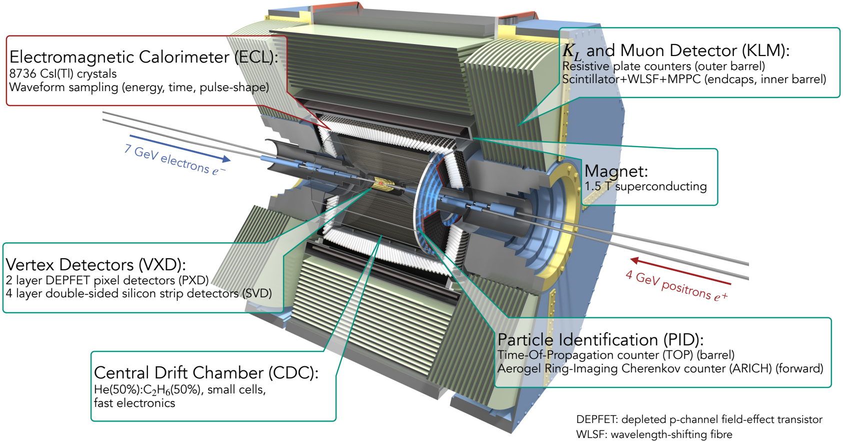
Improved Clustering in the Belle II Electromagnetic Calorimeter with Graph Neural Networks

CHEP 2023 - Track 9: Artificial Intelligence and Machine Learning

Isabel Haide, Florian Wemmer, Jonas Eppelt, Torben Ferber | 11. May 2023

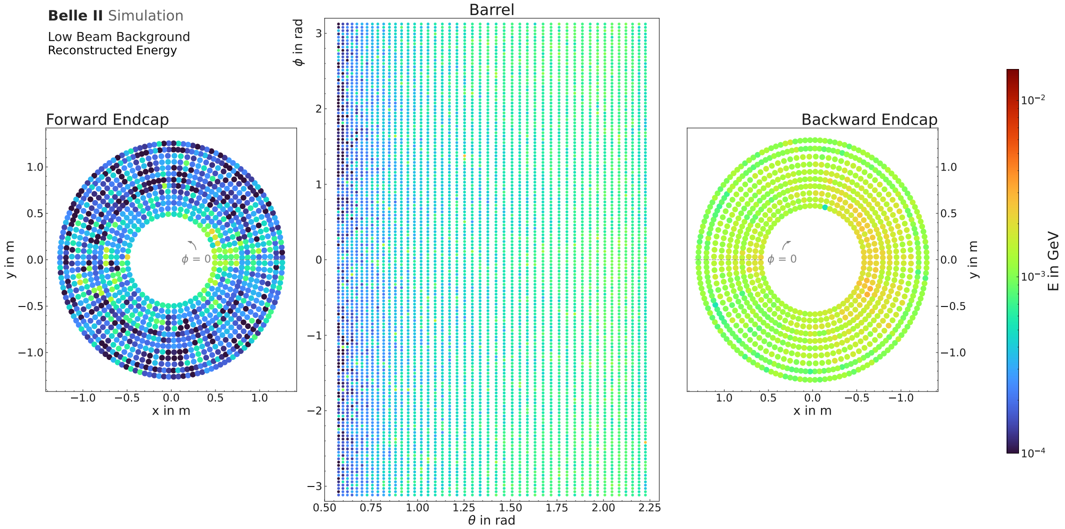


The Belle II Detector



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fibre
MPPC: multi-pixel photon counter

Beam Background in the ECL



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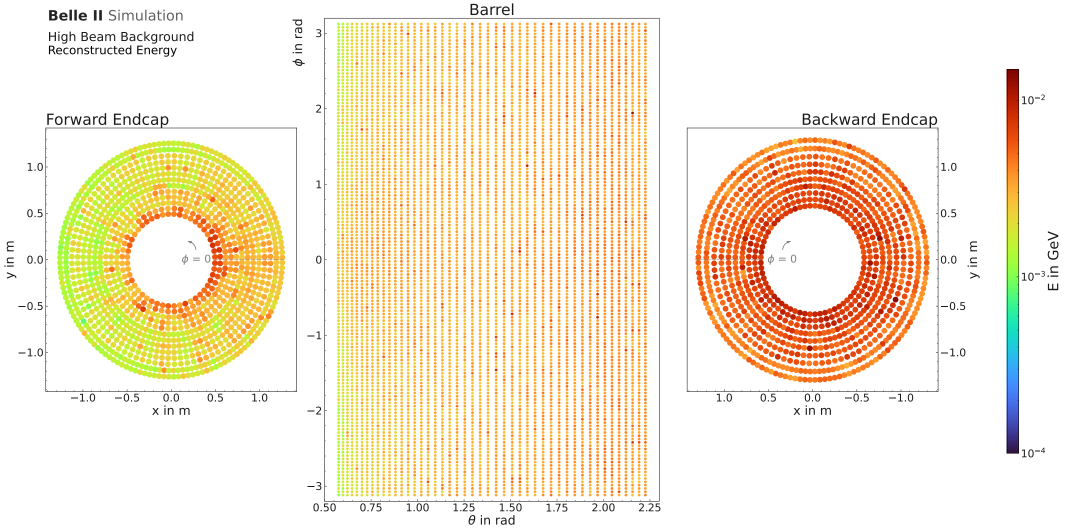
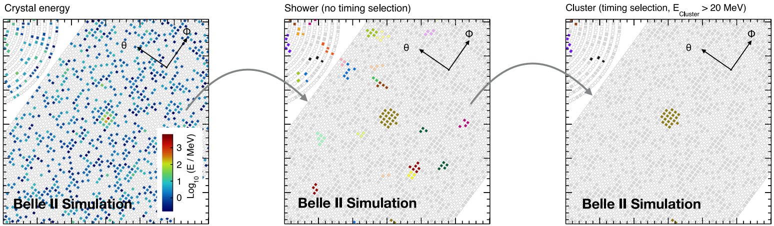


Clustering Algorithms

- Clustering in the ECL is done at two separate times from data taking to physics analysis:
  1. During **online reconstruction** for Level 1 trigger decisions



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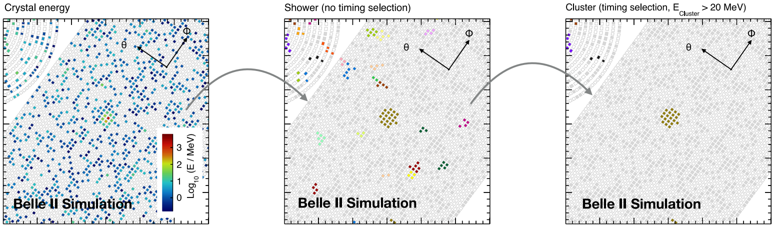
     - Challenges: Unknown number of (potentially overlapping) clusters, real-time predictions, small network sizes



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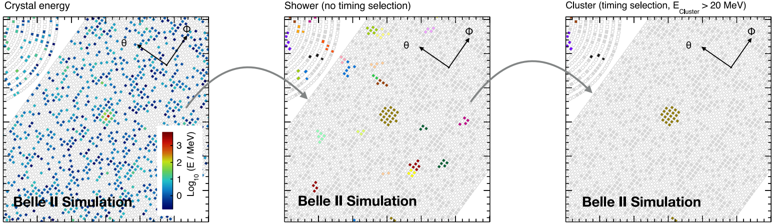

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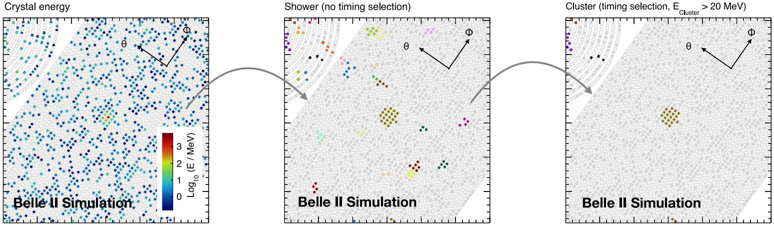

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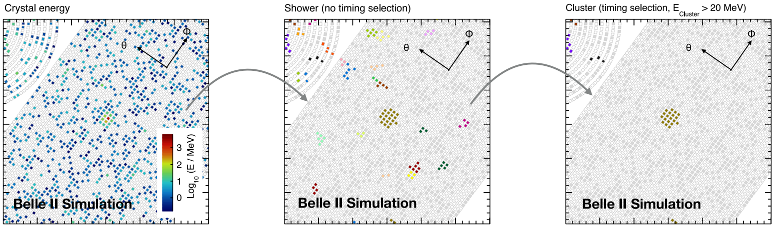

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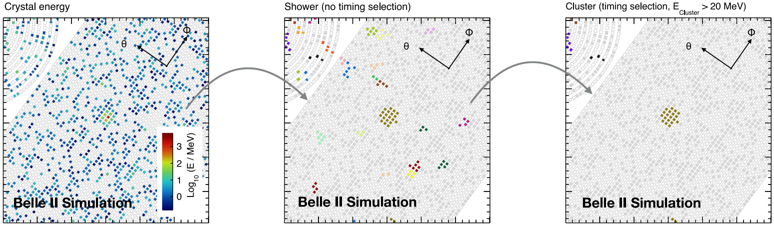
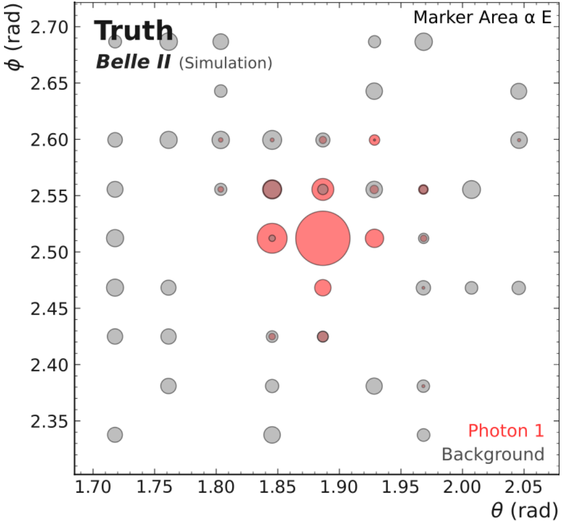
- High background levels with increasing luminosity are additionally challenging
- Irregular geometry in the endcaps and varying input sizes provide a good opportunity for **Graph Neural Networks**



Fuzzy Clustering Algorithm for Photon Reconstruction

Network Input:

- 9x9 grid of crystals centered on local maximum
- 1-2 photon cluster(s)
- Networks trained for both low and high beam background



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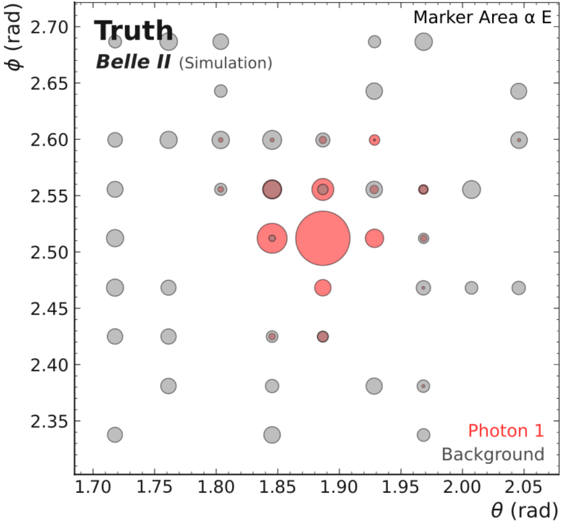
- Cluster energy depositions
- Fuzzy clustering:

  $\Rightarrow$ Assign weights $w_i \in [0, 1]$ with $i \in \{\text{bkg, photon 1, (photon 2)}\}$

  $\Rightarrow \sum_i w_i = 1$ per crystal



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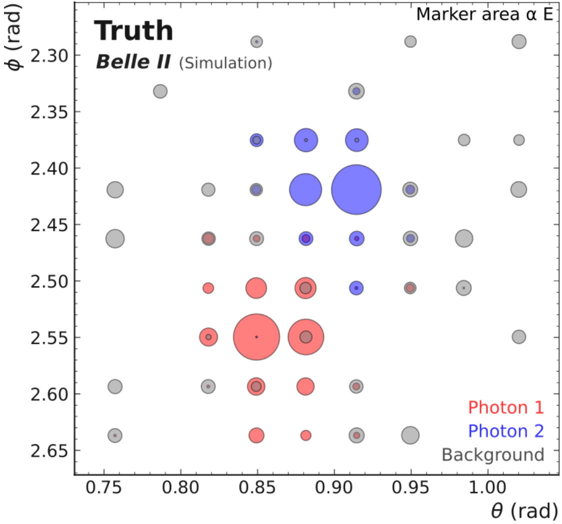


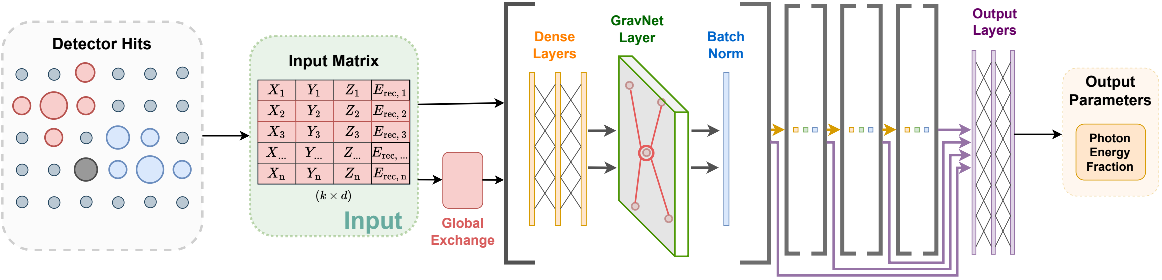
Fuzzy Clustering Algorithm for Photon Reconstruction

GravNet (arXiv:1902.07987) :

- End-to-end learning of representation spaces
- Adaptable to any detector geometry, easy addition of input features

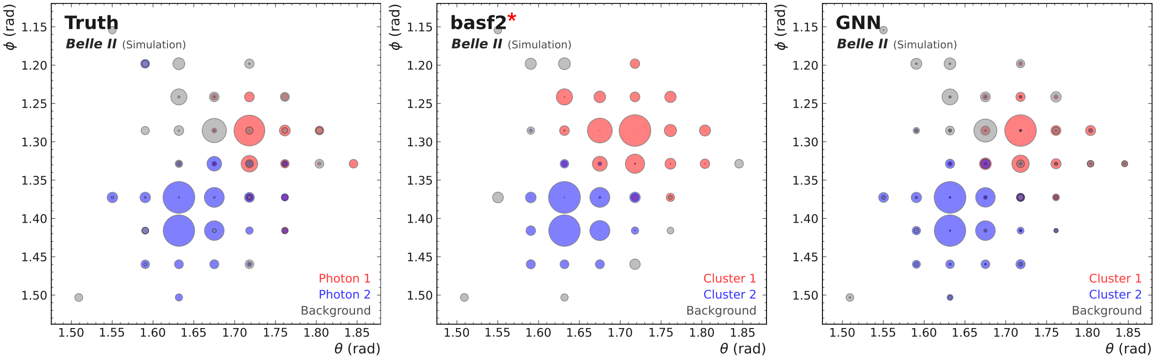
Features:

- Each crystal hit in 9x9 grid becomes node
- Node Features: Crystal Properties, Energy, Time, Pulse Shape Discrimination arXiv:2007.09642



Adapted from L. Reuter

Results: Fuzzy Clustering

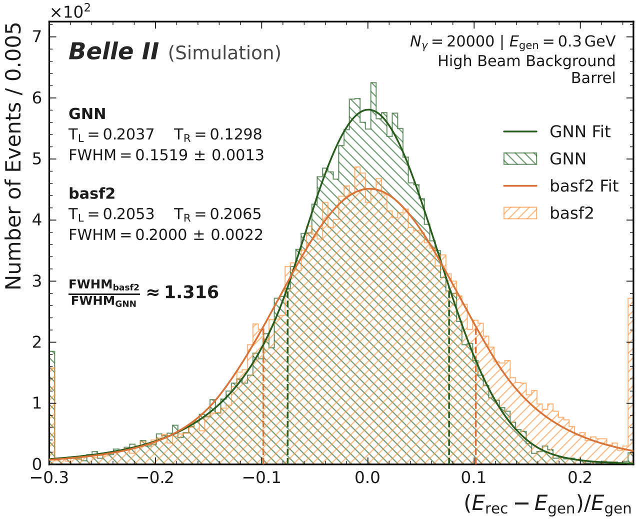


*basf2 (The Belle II Analysis Software Framework): arXiv:1809.04299
Calorimeter reconstruction in basf2: arXiV:1808.10567

Results: Fuzzy Clustering

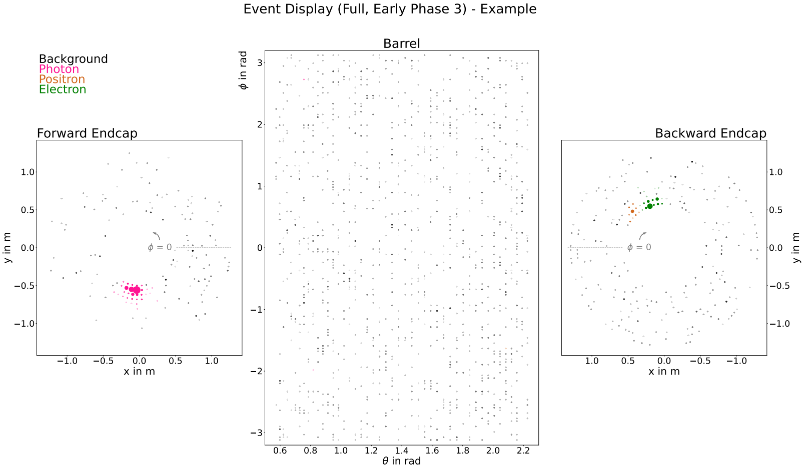
Summary:

- First application of GNN clustering algorithm at Belle II with:
  - Realistic detector geometry
  - Realistic beam background levels
- Improvements in energy resolution:
  - Single photons: Up to 30 % improvement with high beam background
  - Overlapping photons: Over 35 % improvement for the low energy photon in asymmetric photon pairs



Object Condensation (OC) for ECL Clustering

High improvements in photon energy resolution through fuzzy clustering, **but:**

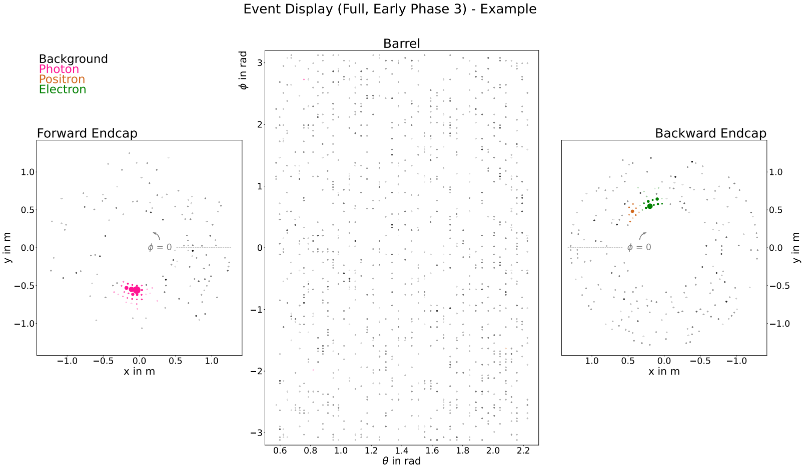


Object Condensation (OC) for ECL Clustering

Karlsruhe Institute of Technology

High improvements in photon energy resolution through fuzzy clustering, **but:**

- In online reconstruction number of clusters is unknown



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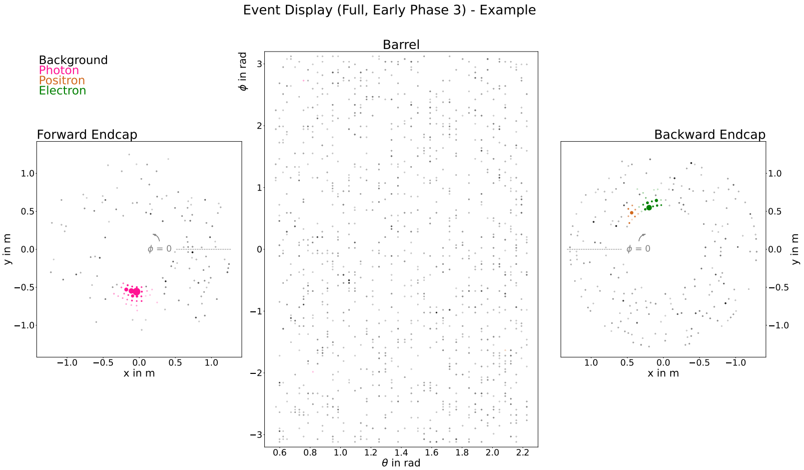

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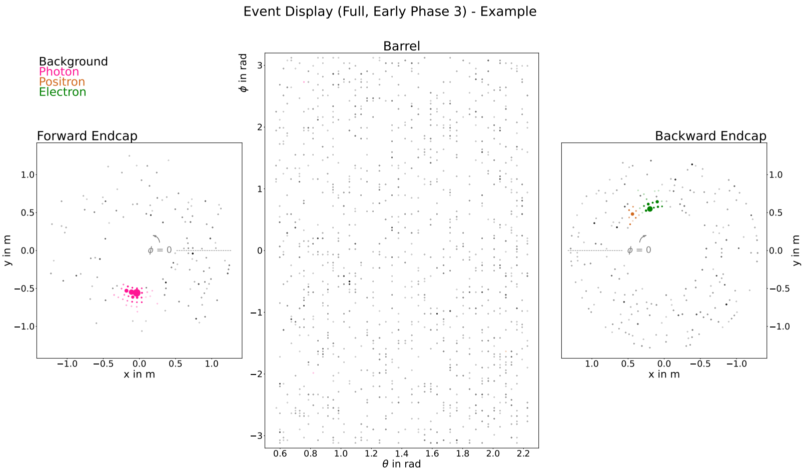

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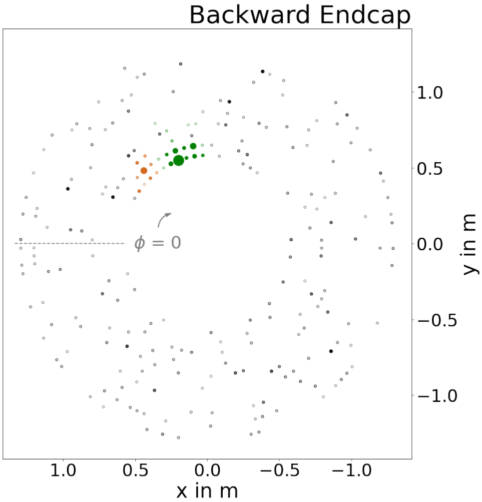

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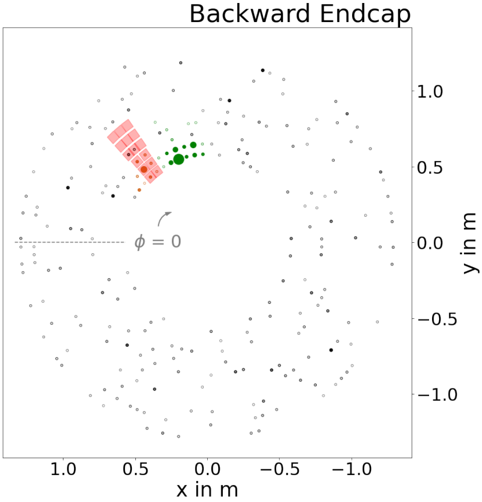

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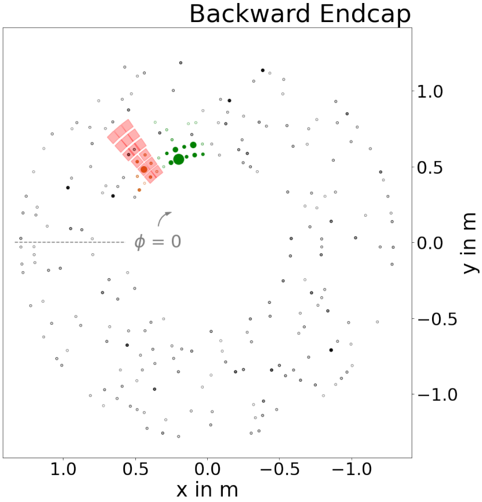
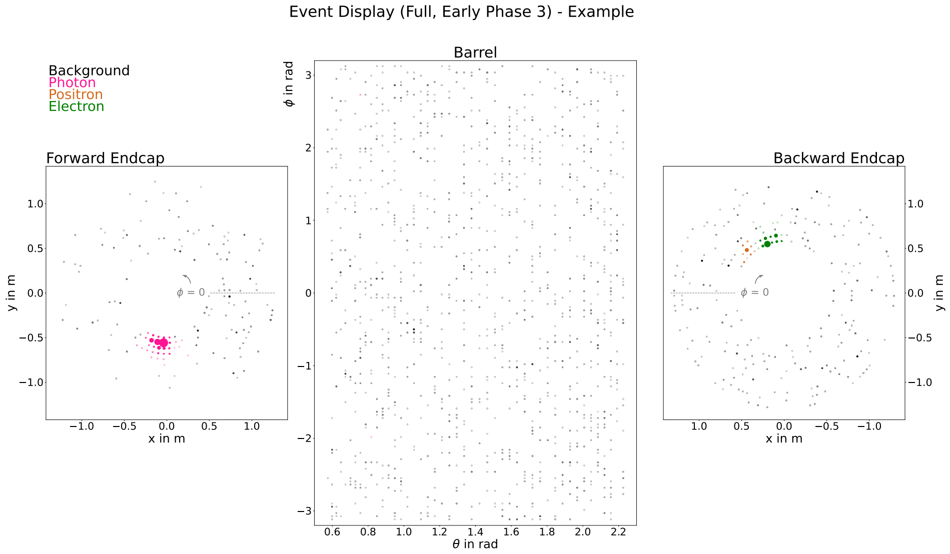
Trigger efficiency needs to be improved for higher backgrounds and overlapping clusters

- Better Bhabha detection, SM decays such as $e^+e^- \to \pi\pi\gamma$
- Low multiplicity searches, such as $e^+e^- \to a(\to \gamma\gamma)\gamma$



Inference for Object Condensation



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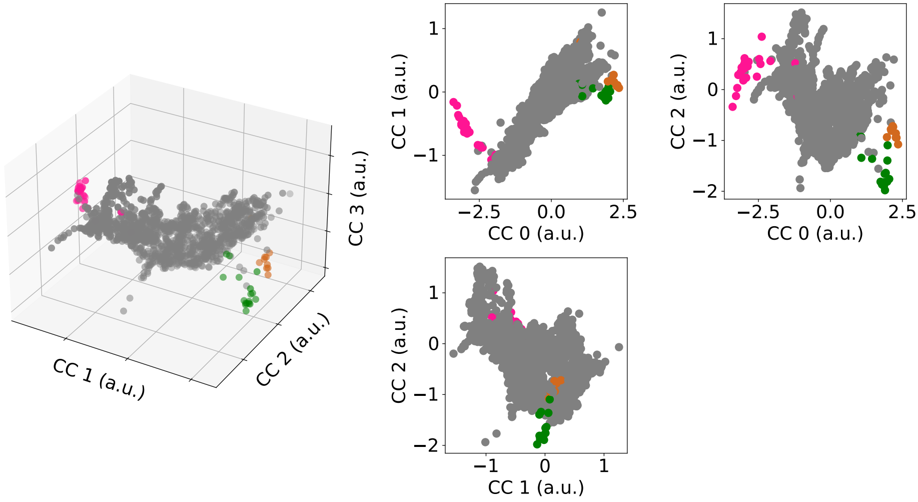

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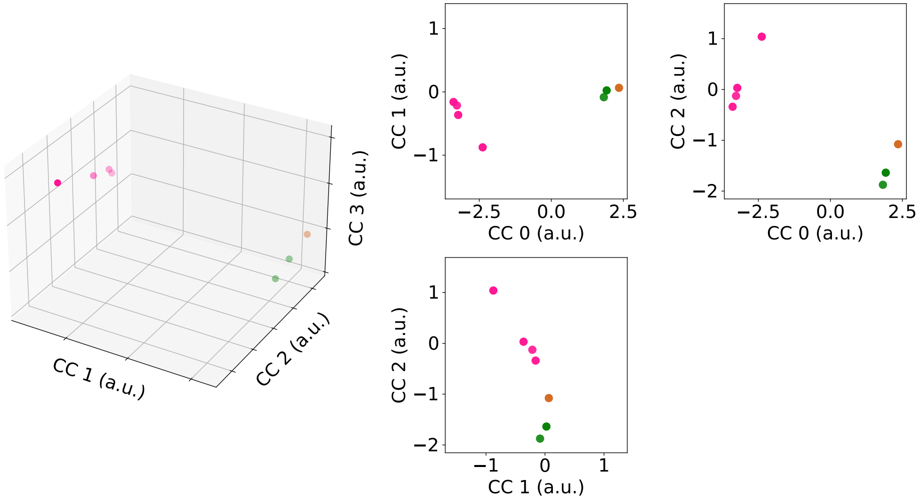

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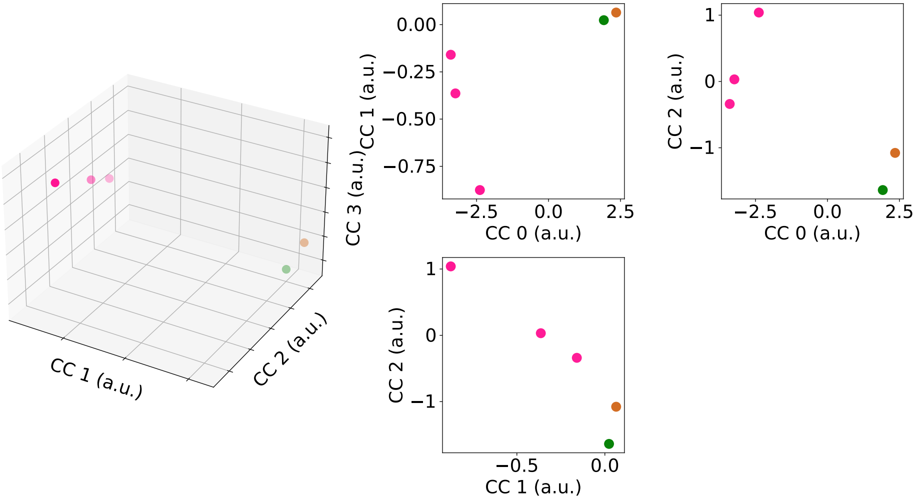

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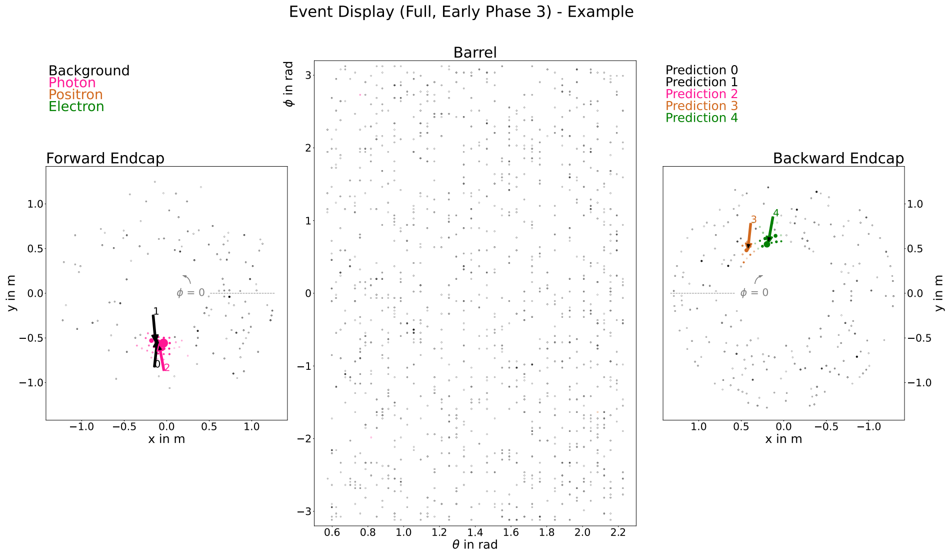


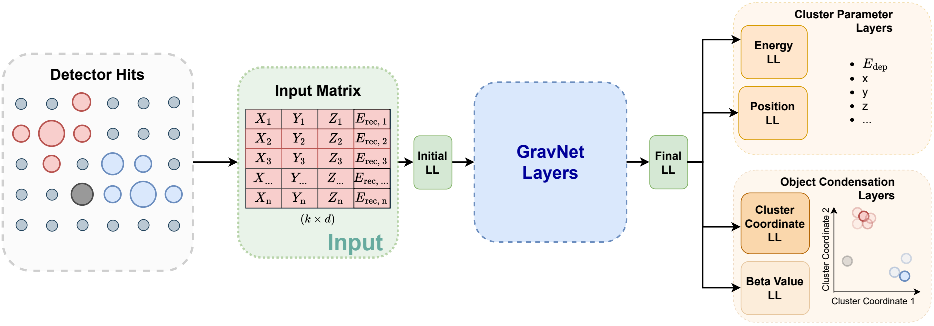
Algorithm Overview

Object Condensation:

- One-shot algorithm for both detection and reconstruction of clusters (arXiv:2002.03605)
- Irregular geometry and varying input sizes in the ECL
  $\rightarrow$ GNN as base algorithm

Fast Inference:

- OC introduces potential to cluster vertices from same object together
- Each vertex gets a β-value assigned
  $\rightarrow$ Vertex with highest β-value invokes potential (= condensation point)
- Condensation points carry prediction for clusters

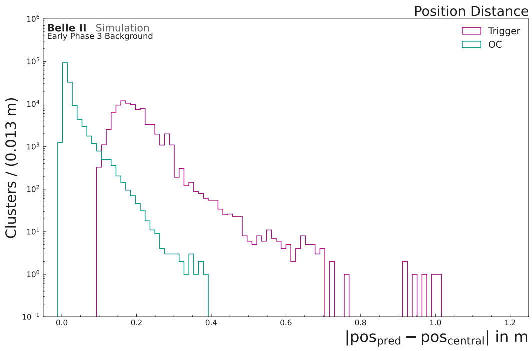


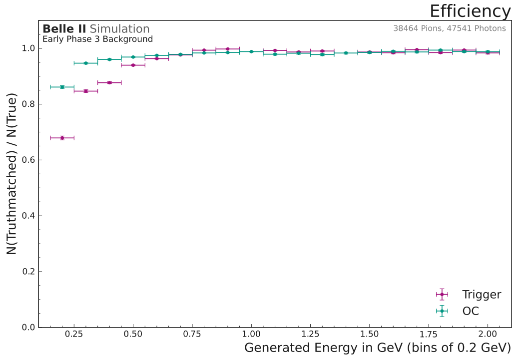
Adapted from L. Reuter

Current OC Improvements

- Network is trained on charged pions and photons between 0.05 and 2 GeV energy
- Training on 1-6 particles, inference on up to 10

- Network predicts number of clusters and respective cluster parameters
- Current GNN has only 12414 parameters

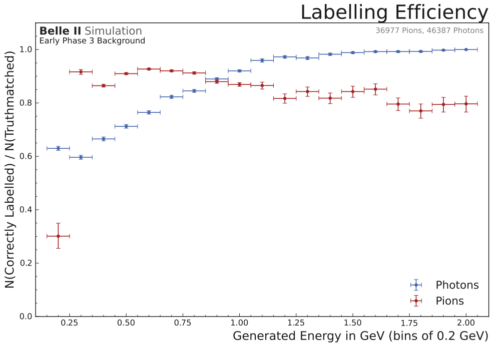




Results: Object Condensation

Summary:

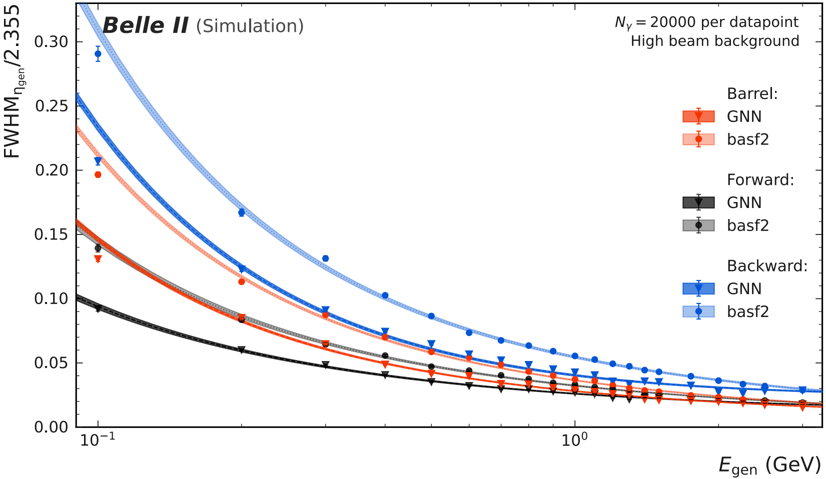
- First application of GNN object condensation at Belle II with:
  - Realistic detector geometry
  - Realistic beam background levels
- Improvements:
  - Increased efficiency over current trigger algorithm
  - Improved position resolution



Further Steps:

- Easy implementation of new prediction parameters
  $\rightarrow$ Addition of particle identification
- OC can improve trigger efficiency
  $\rightarrow$ implementation for testing on physics applications

Energy Resolution



Background Robustness