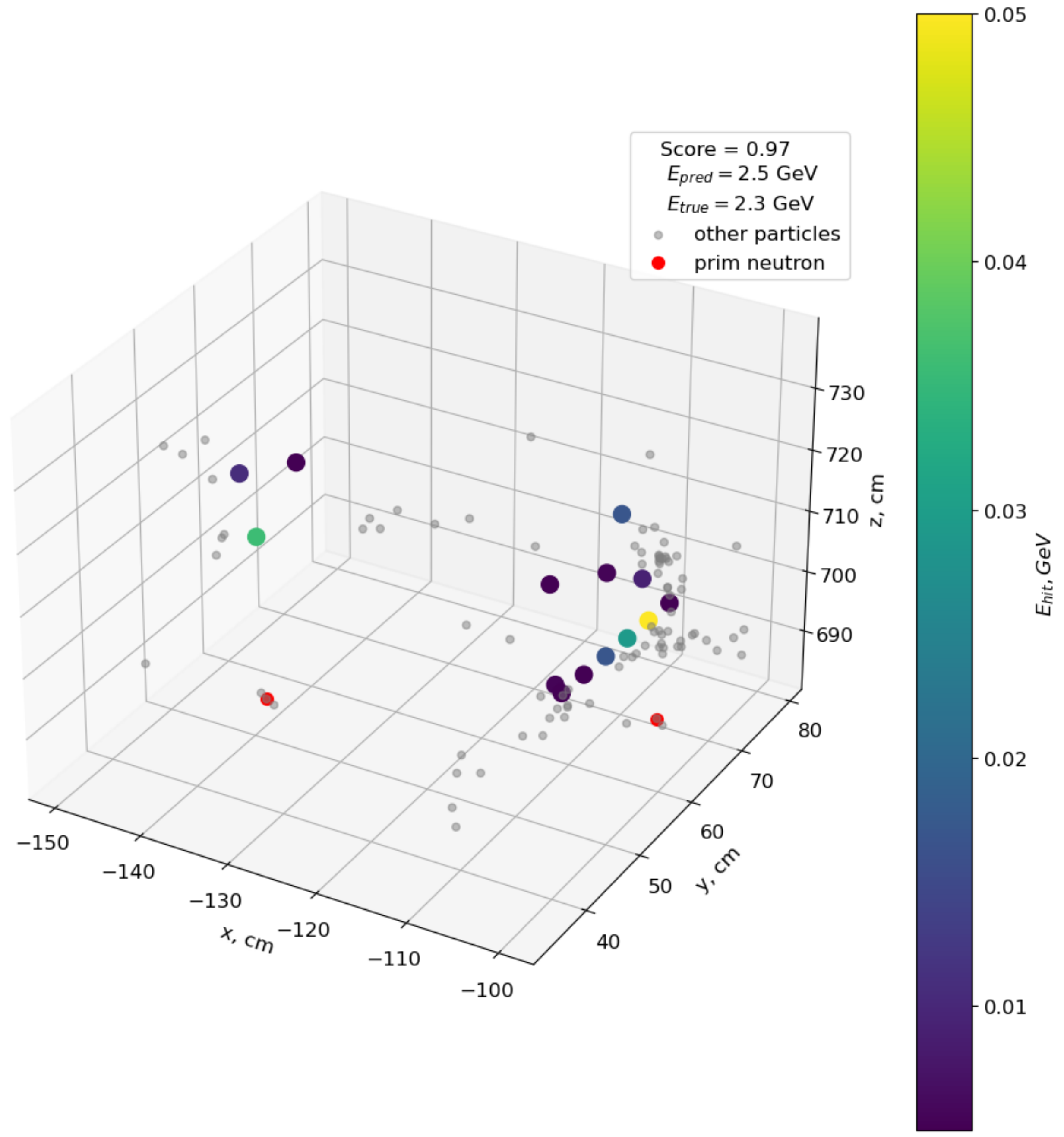
ML-based neutron reconstruction in the HGND at the BM@N experiment

BM@N 12th Collaboration Meeting,

Vladimir Bocharnikov, HSE University
on behalf of the HGND group

16.05.2024

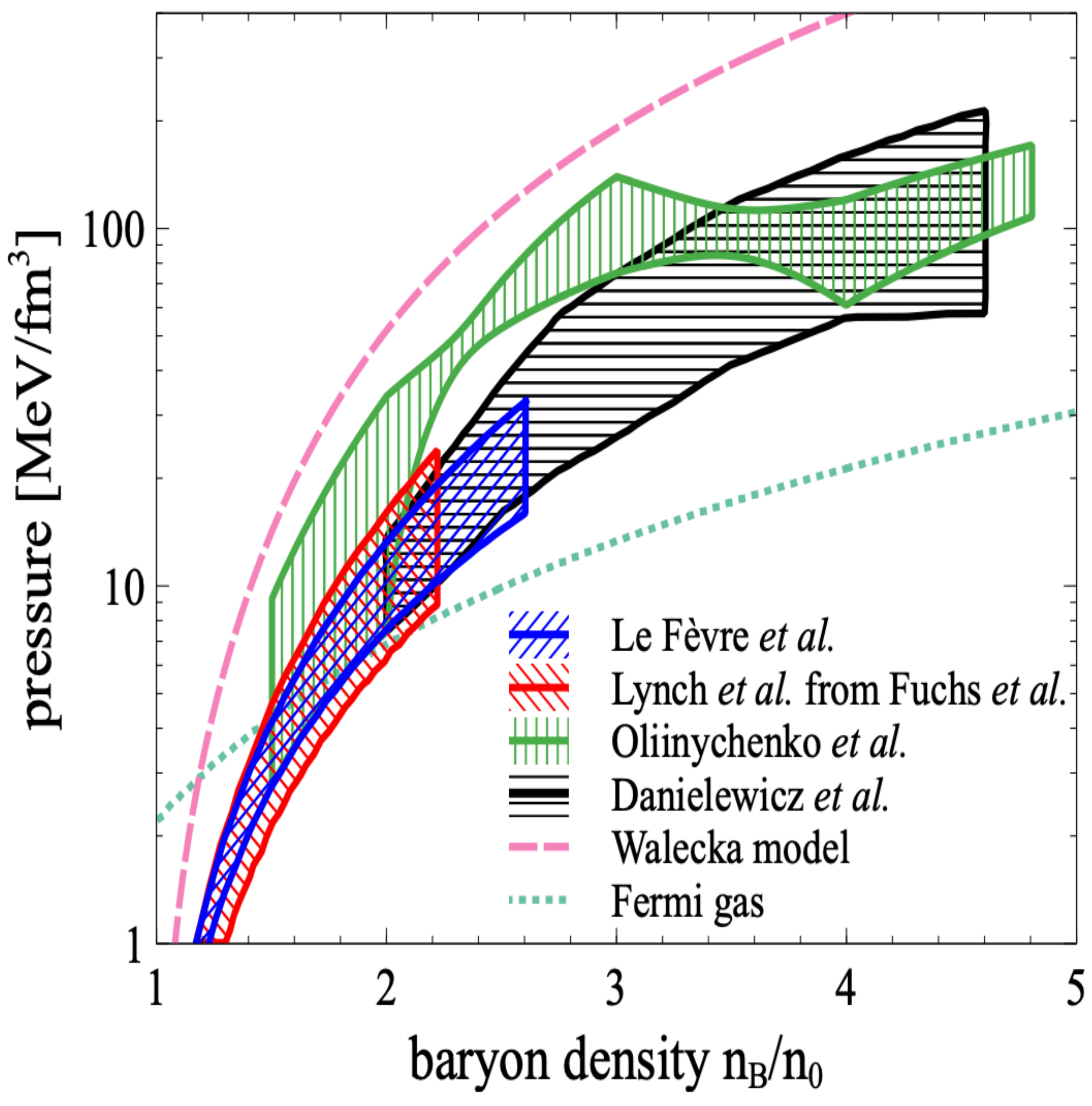


LAMBDA • HSE

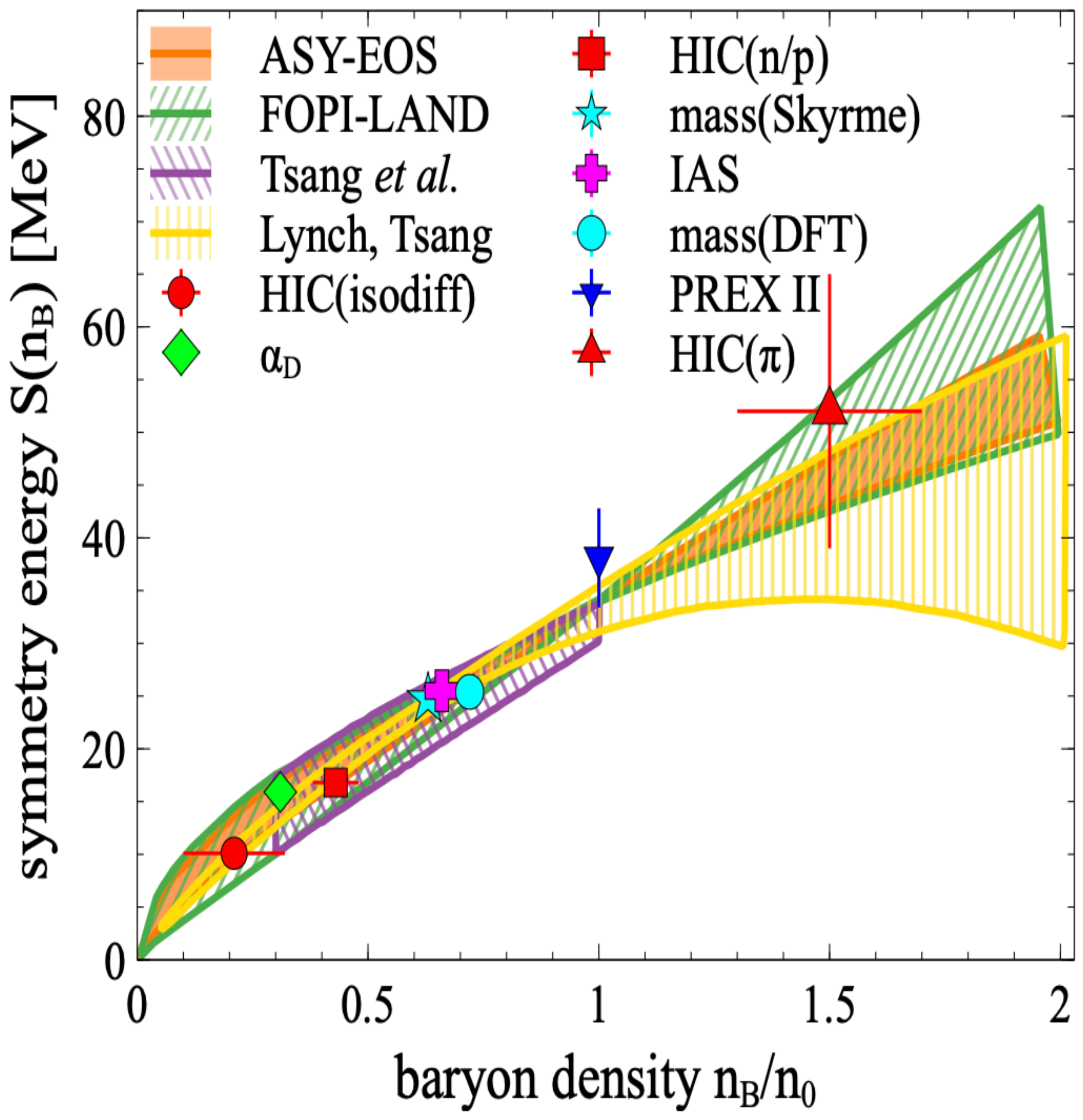
EOS for high baryon density matter

The binding energy per nucleon: $$E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

Symmetric matter



Symmetry energy



$\delta = (\rho_n - \rho_p)/\rho$ **- Isospin asymmetry**

- **Neutron flow** measurements are essential to further constrain symmetry energy
- Sensitive observables:

Anisotropy flow coefficients:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_{RP})], \quad v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle$$

A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080

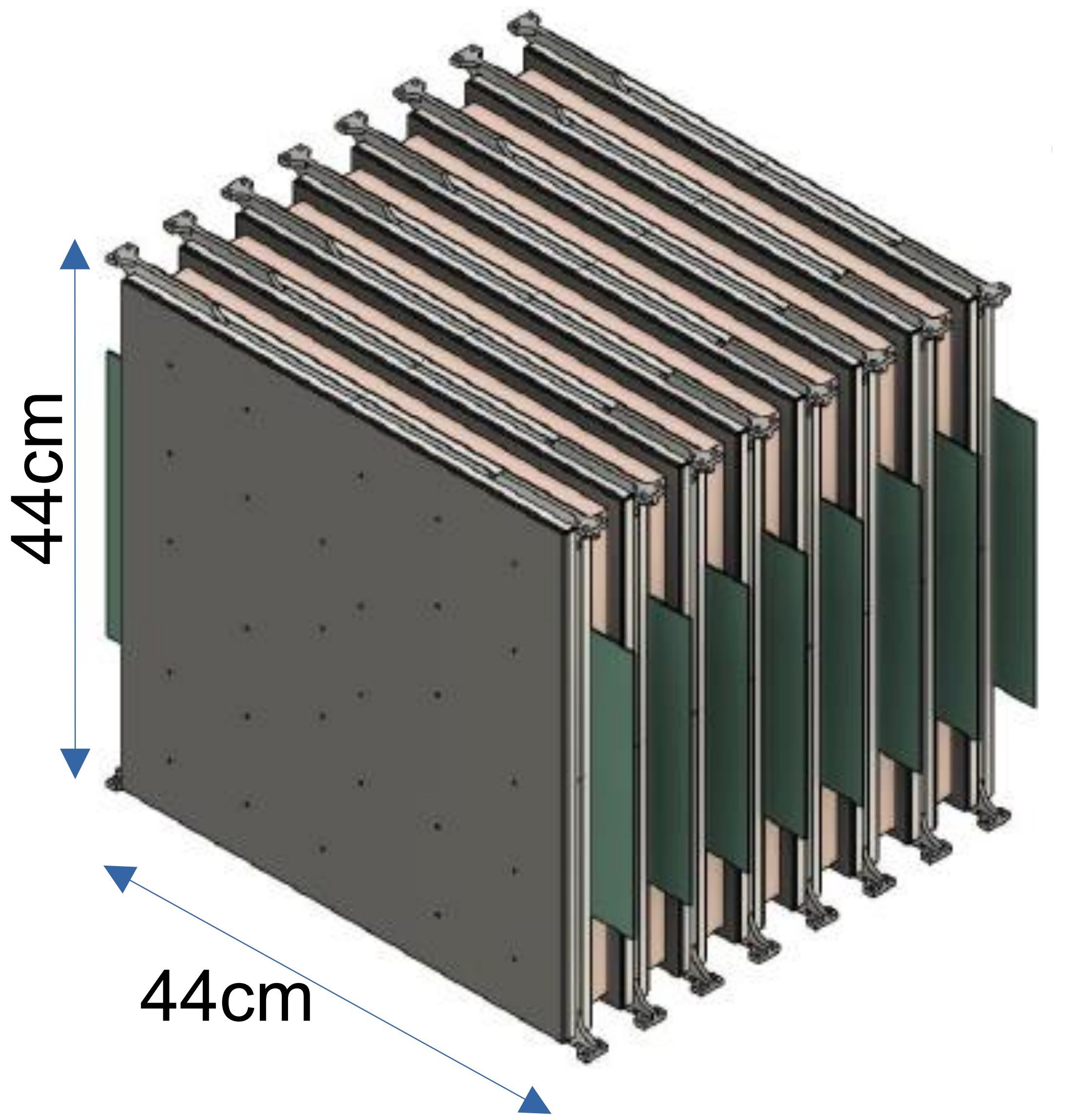
Motivation

Measurements of neutron flow and yields require **reconstruction of neutrons**

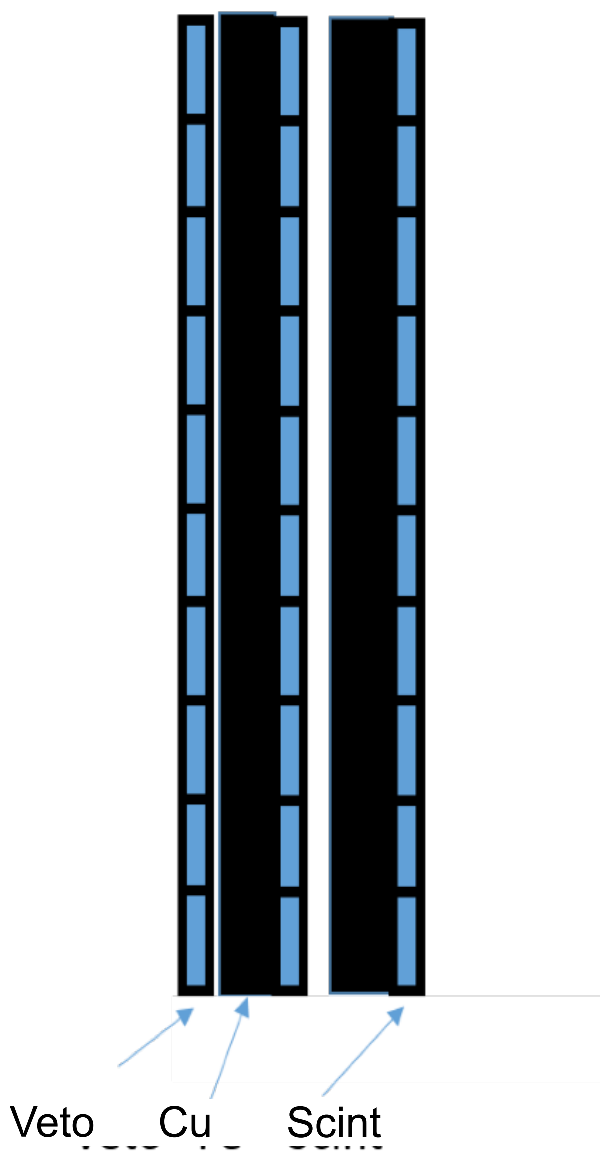
Neutron reconstruction task:

- **Identify neutrons** produced in reaction in presence of background
  ➡ use of **high granularity**
- Reconstruct neutron kinematics:
  - Kinetic energy — **time-of-flight** (ToF) method
  - Angular information can be extracted by “point-like” detector approximation or by use of high granularity
- Multi-parameter task ⇒ may benefit from **ML-based methods**

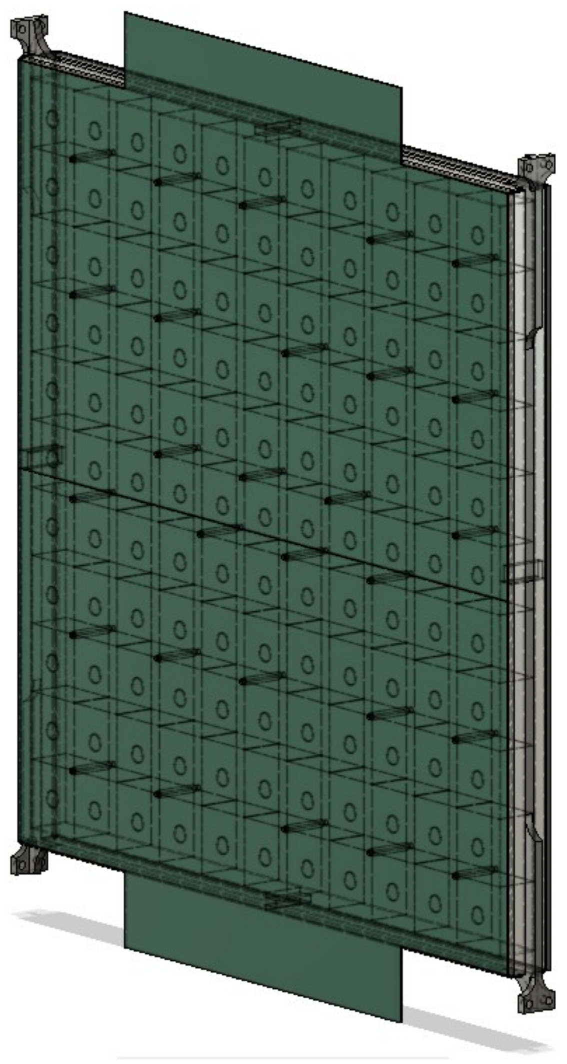
Highly granular time-of-flight neutron detector (HGND)

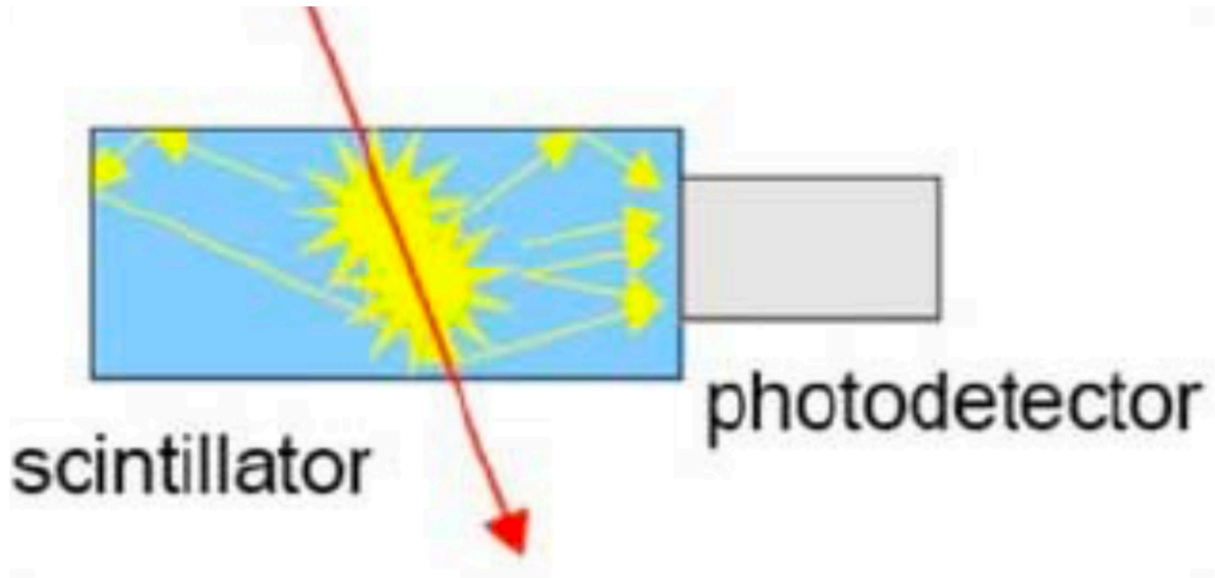


Longitudinal structure



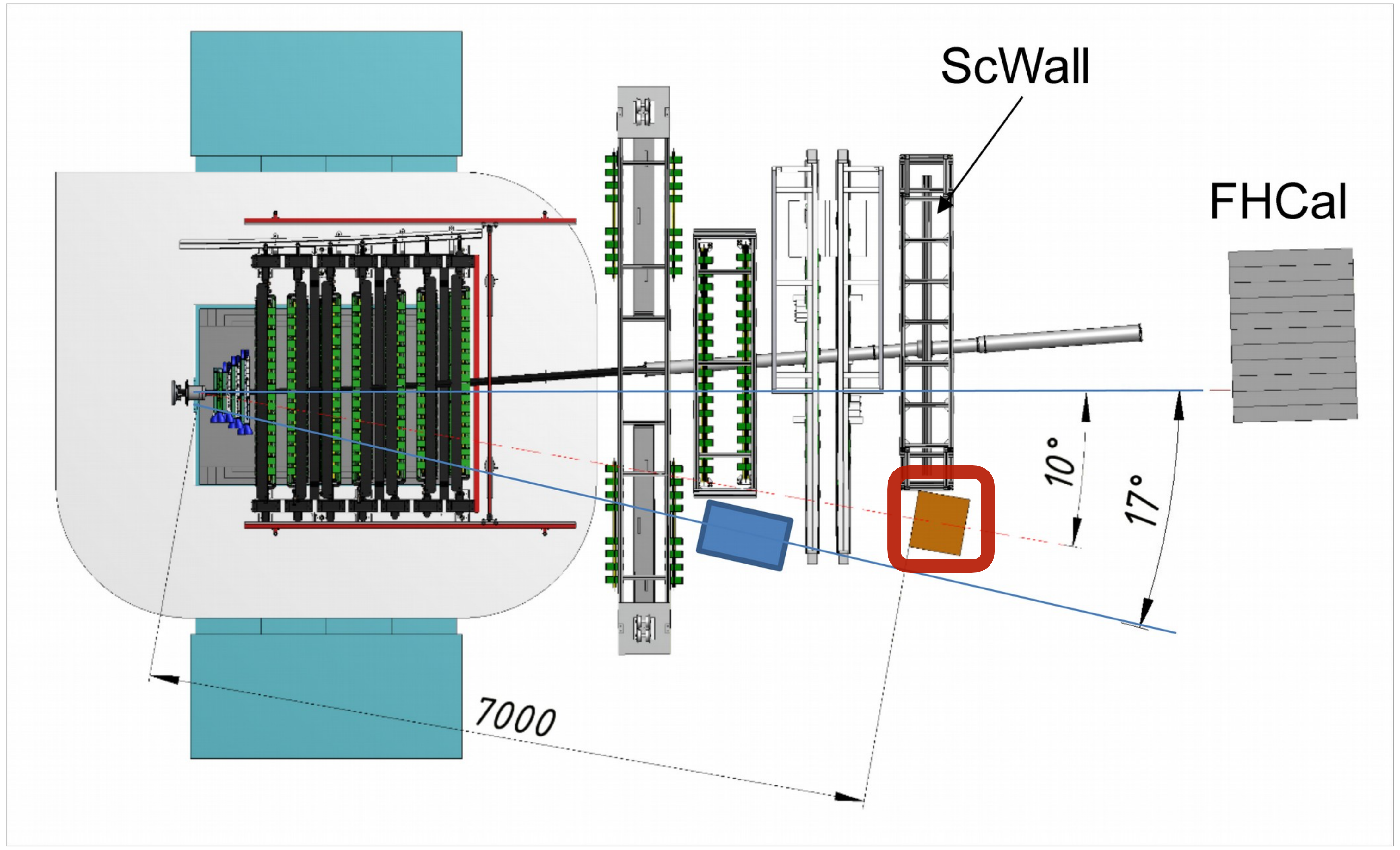
Active layer

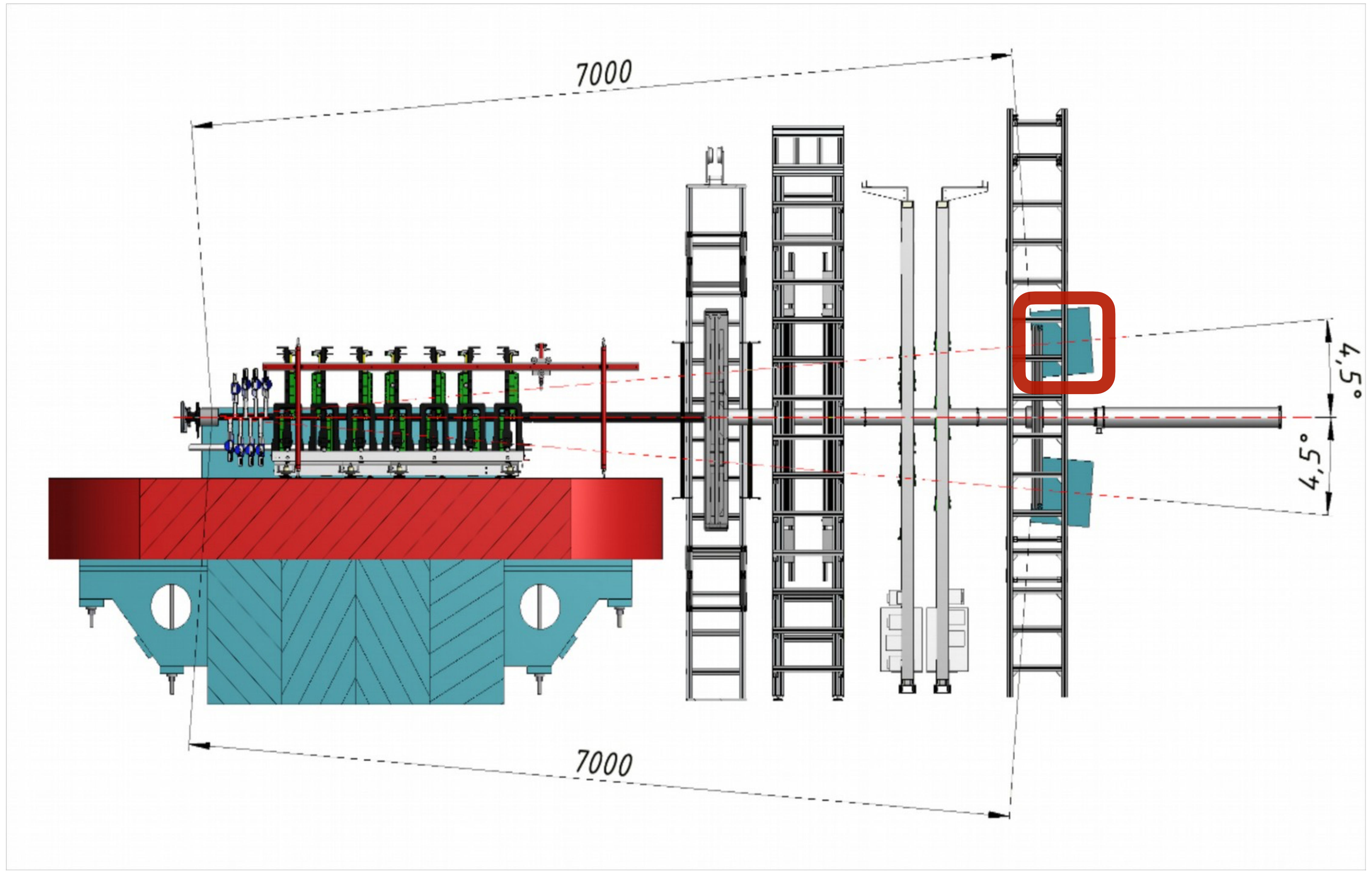




- (2x) 8 layers: *3cm Cu (absorber)* + *2.5cm Scintillator + 0.5cm PCB; 1st layer — 'veto' before absorber*
  - ➡Total length: ~0.5m, **~1.5 λ_{in}**
  - ➡ neutron detection efficiency ~60% @ 1 GeV
  - Transverse size: **44x44 cm^2**
  - *11x11 scintillator cell grid*
- scintillator cells:
  - size: 4x4x2.5 cm^3,
  - **total number of cells: 968 (x2)**
  - individual readout by SiPM
  - expected time resolution per cell: ~150 ps

Configuration and Simulations



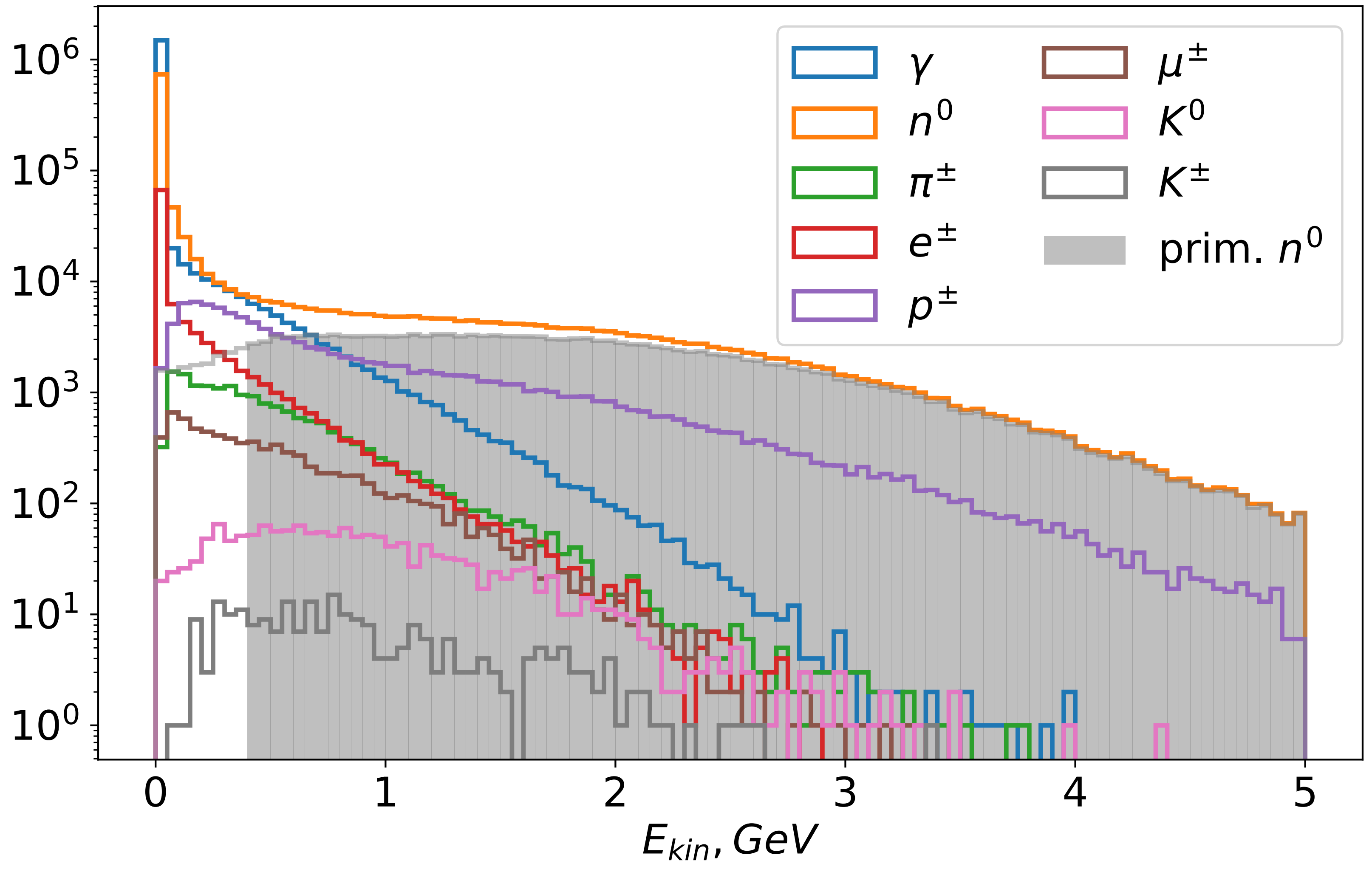


- HGND sub-detectors are located at **10º to the beam** axis at **~7m from the target**
- Monte-Carlo event simulations:
  - DCM-QGSM-SMM model + Geant4
  - **~600K events Bi+Bi @ 3 AGeV**
  - Only **top sub-detector** will be discussed further

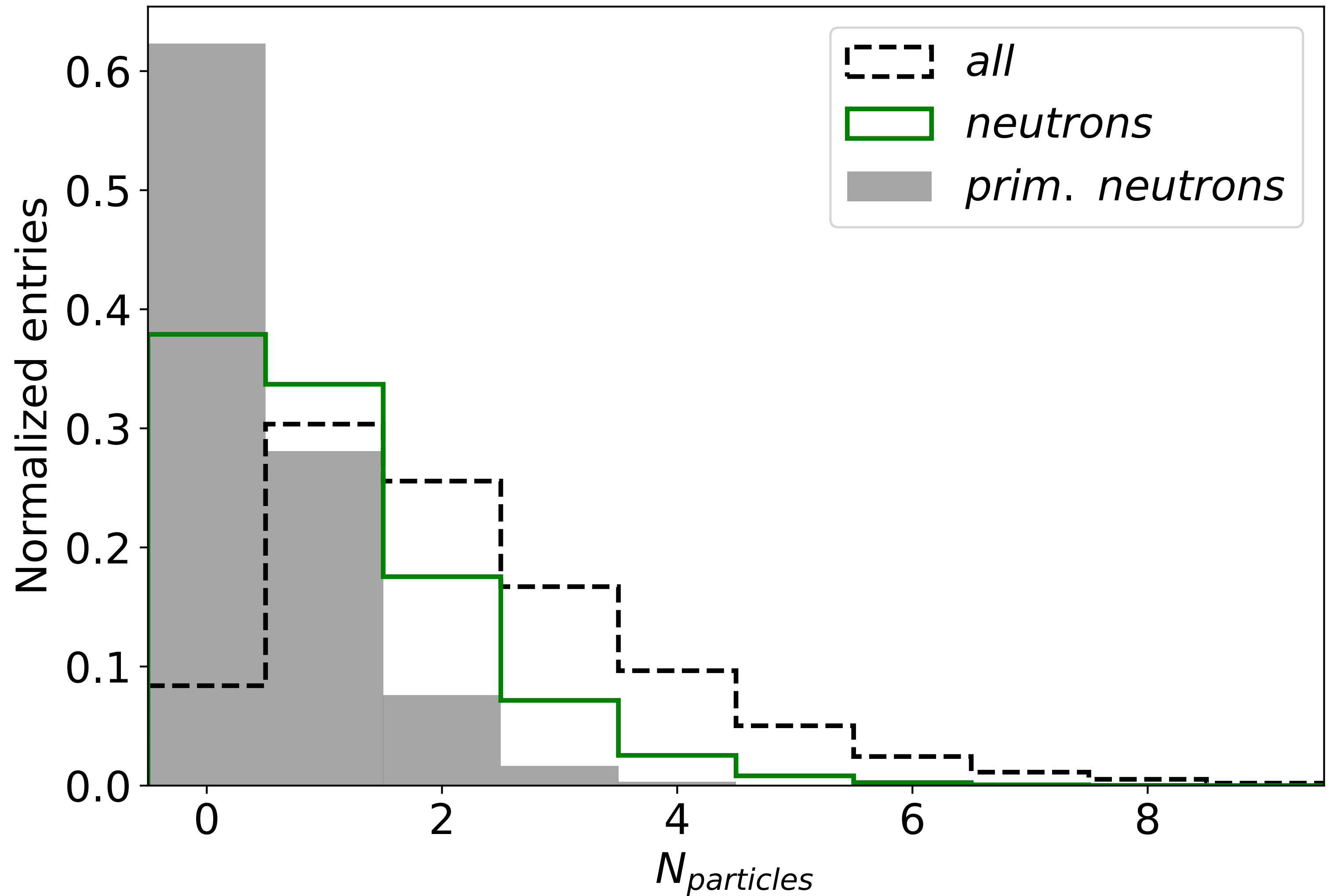
Particles entering the HGND

- Logical volume on the HGND upstream surface is used to capture particles in the detector acceptance
  - No access to hit-level labelling within event
  - ➡ particular hits caused by neutron species are not known
- **Primary neutrons:**
  - Produced in reaction
  - E_{kin} > 0.4 GeV to minimise admixture of background neutrons
    - Energy cut will be done after reconstruction to minimise bias
- **Binary identification problem** is approached. Events with neutron multiplicity >1 are considered as “single neutron events”
- Energy reconstruction is aimed to reconstruct energy of fastest signal neutron in event

Energy spectrum per particle type



Particle multiplicity



Neutron ToF energy

ToF energy for n^0 hypothesis:

$$E_{ToF} = m_n\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

- $t_{hit} + \mathcal{N}(0, \sigma = 150ps) < 40ns$
- hits with E_{ToF}>10GeV are set to 10 GeV

Fastest hit

- naive reconstruction
- bias from fast hits (bg + time uncertainty)

Reference hit

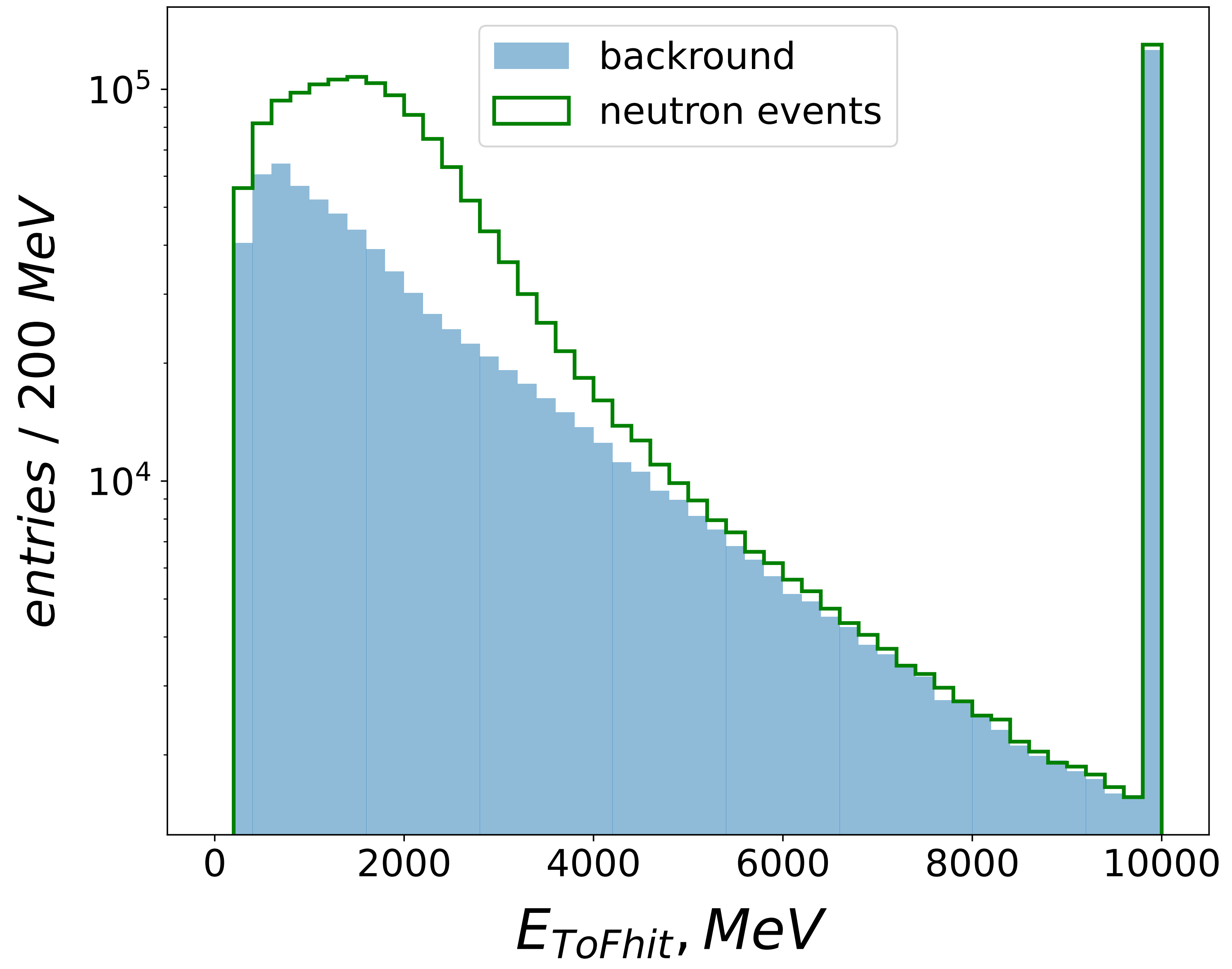
- MC truth hit with $\min(|E_{ToF} - E_n|)$

➡ suitable for neutron event labelling

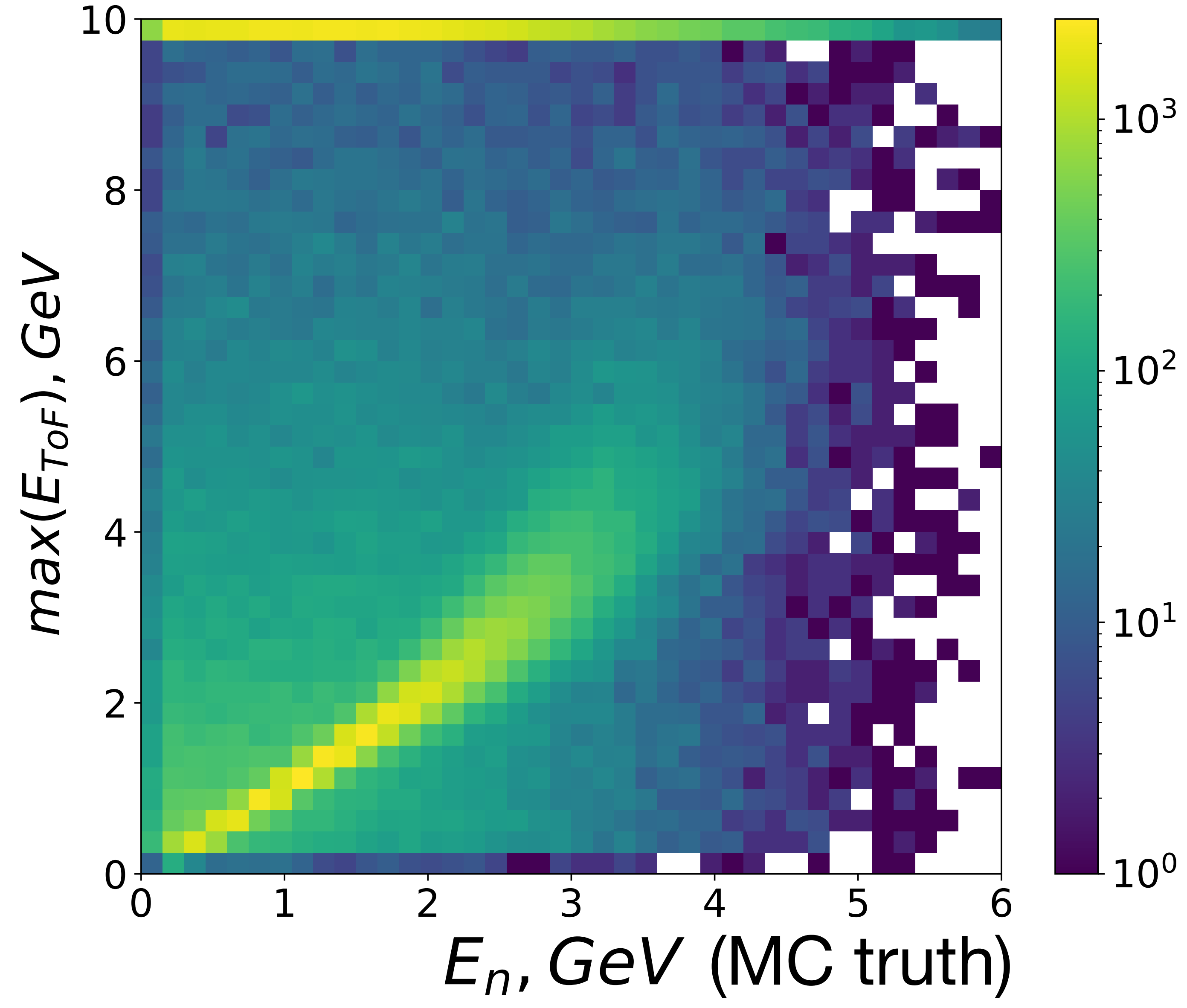
➡ additional estimation required

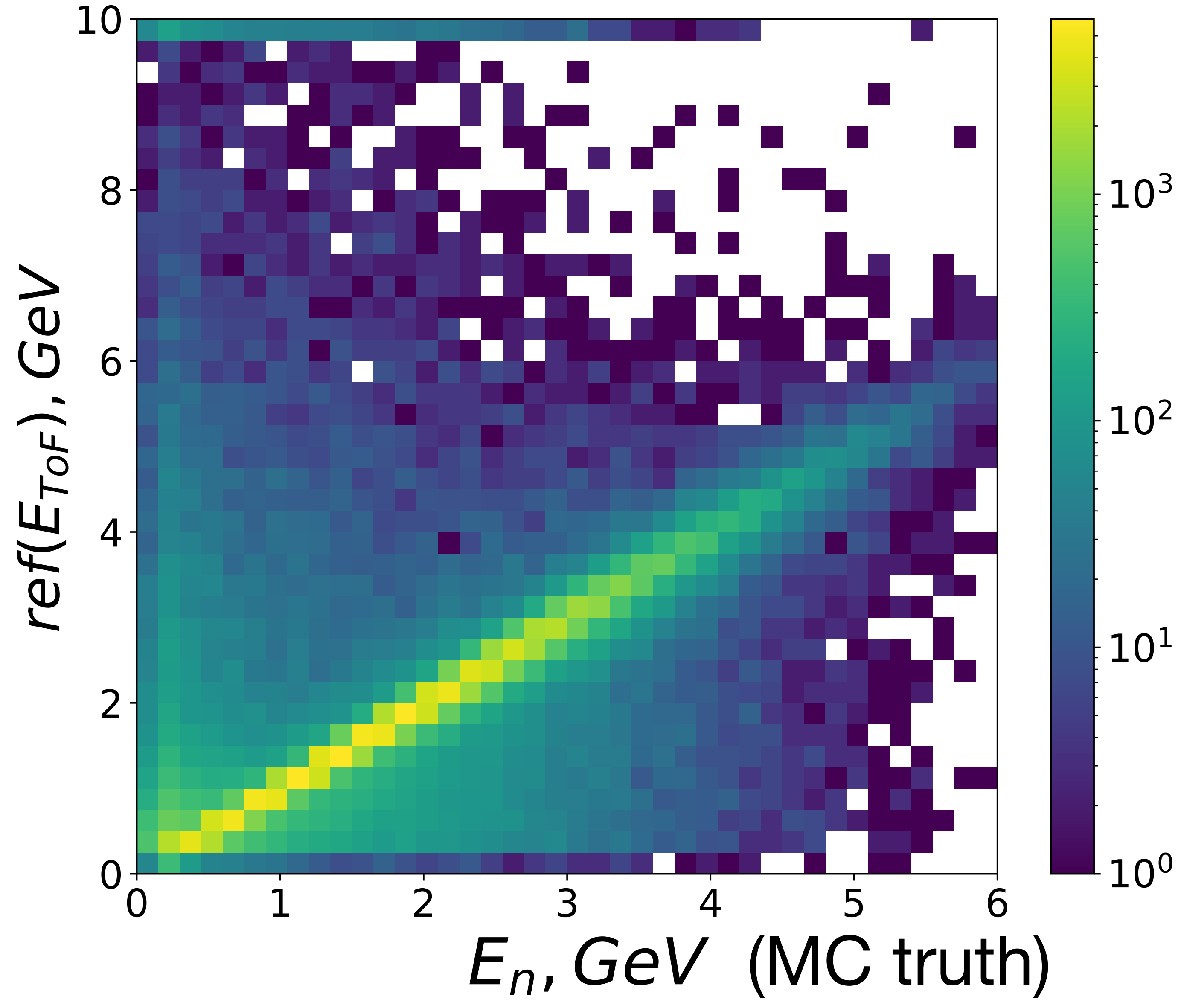
➡ we use ML approach

Hit ToF distribution



Events with a neutron (>100 MeV) passing upstream wall of the HGND at 10º±5º





Neutron detection inefficiency outside of diagonal

Graph Neural Networks (GNN)

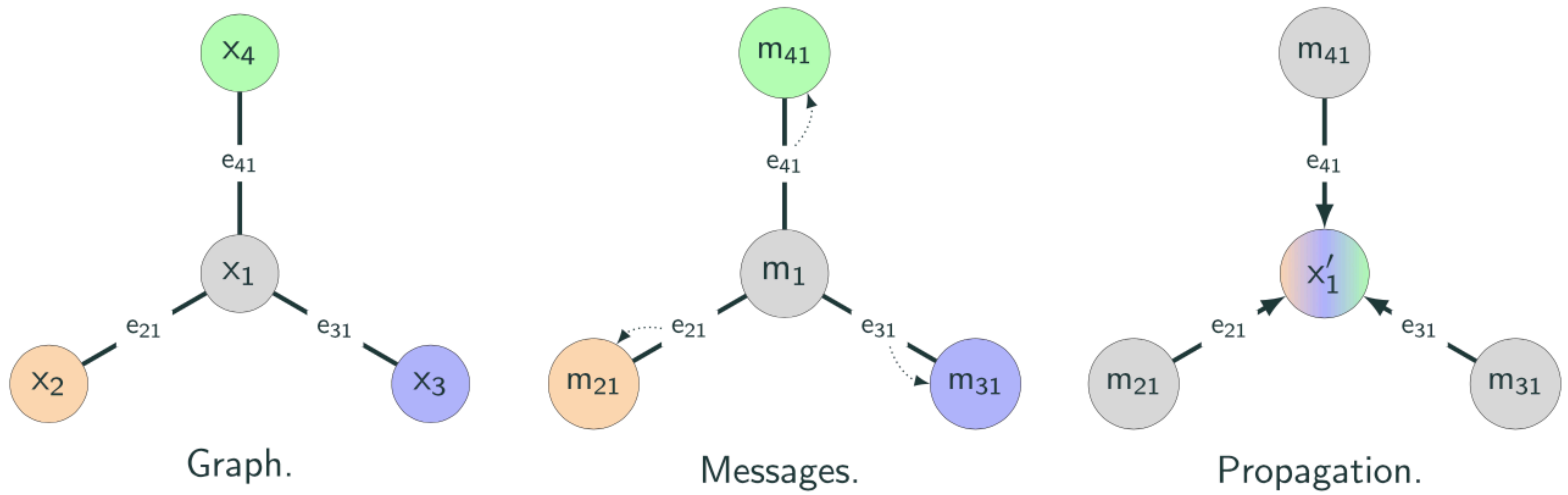
Why Graph Neural Networks:

- Natural vector event representation
  - Detector cell hits as graph nodes
- Easily applied to sparse data with variable input size
  - Typically we have signal only in small fraction of sensors
- Captures event structures
- Increasing number of successful implementations in HEP

Message passing architecture

Key idea:

- Edges propagate information between nodes in a trainable manner to encode local graph structures
- Node embeddings are then aggregated to a problem-specific value, e.g.:
  - Graph class “probability” — signal/background
  - Target value — neutron energy



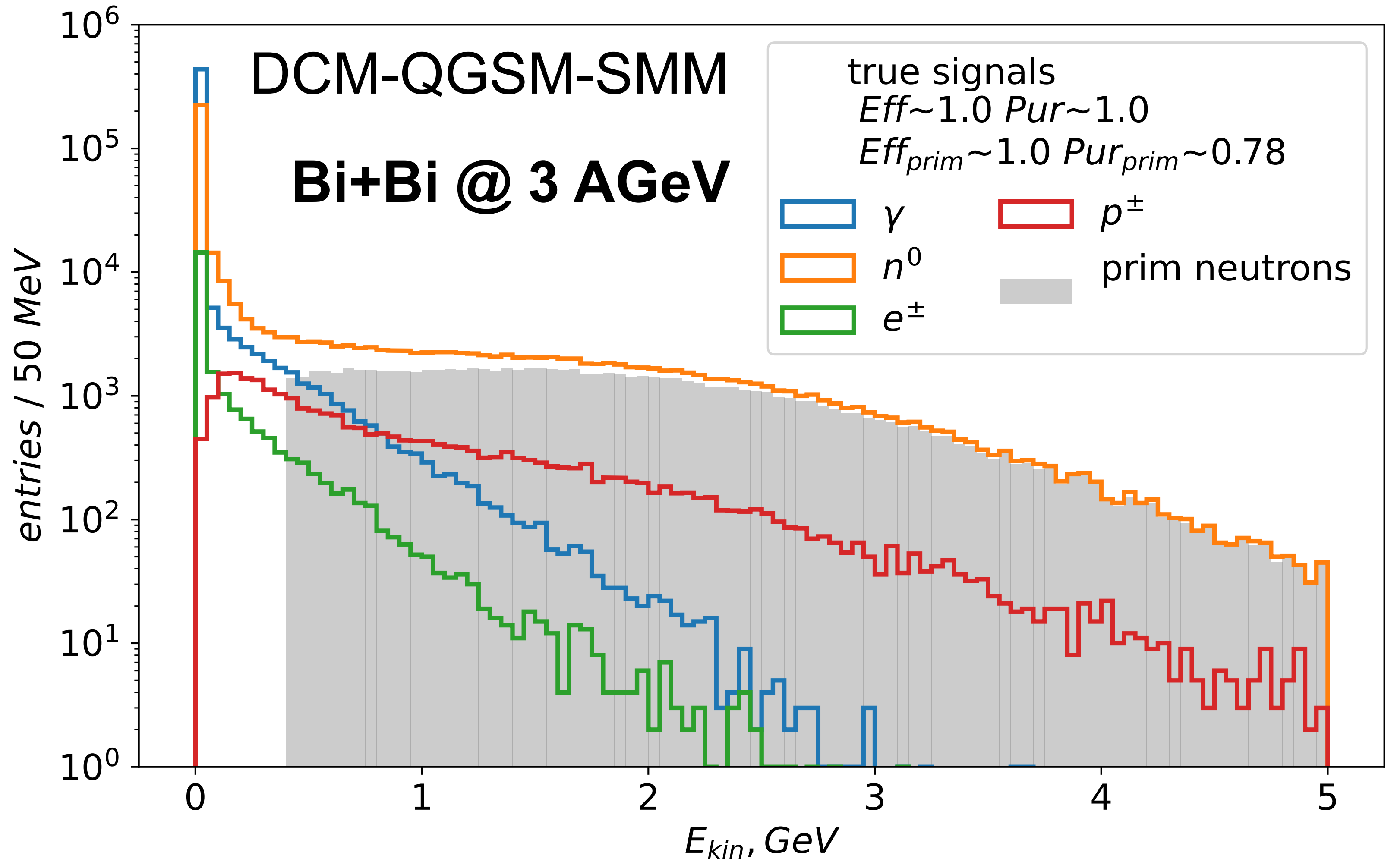
J. Gilmer *et al.*, “Neural message passing for quantum chemistry,” 2017.

Reconstruction procedure

Signal event labeling using upstream surface:

- at least 1 neutron: Ekin > 100 MeV, Angle to z axis 10°±5°, $\delta(E_{ref}) < 40\%$, $E_{target} = \max(E_n)$
- ~40% signal events
- significant background contribution
- more detailed MC particle tracking is under development to improve true neutron selection

Selected signal events. Energy spectrum



Graph construction:

- Nodes — hits. Observables per hit:
  - hit coordinates; Edep > 3 MeV ~ 0.5 MIP; EToF
  - additional global event node with 4 parameters
- Constructed event graphs are split 50/50% to train and test procedure
- **2 independently trained models:**
  - **Classification** GNN
    - target variable — signal label (0/1)
  - **Energy regression** GNN
    - target variable — $\max(E_n)$ per event
    - only signal events are used to train for energy regression model

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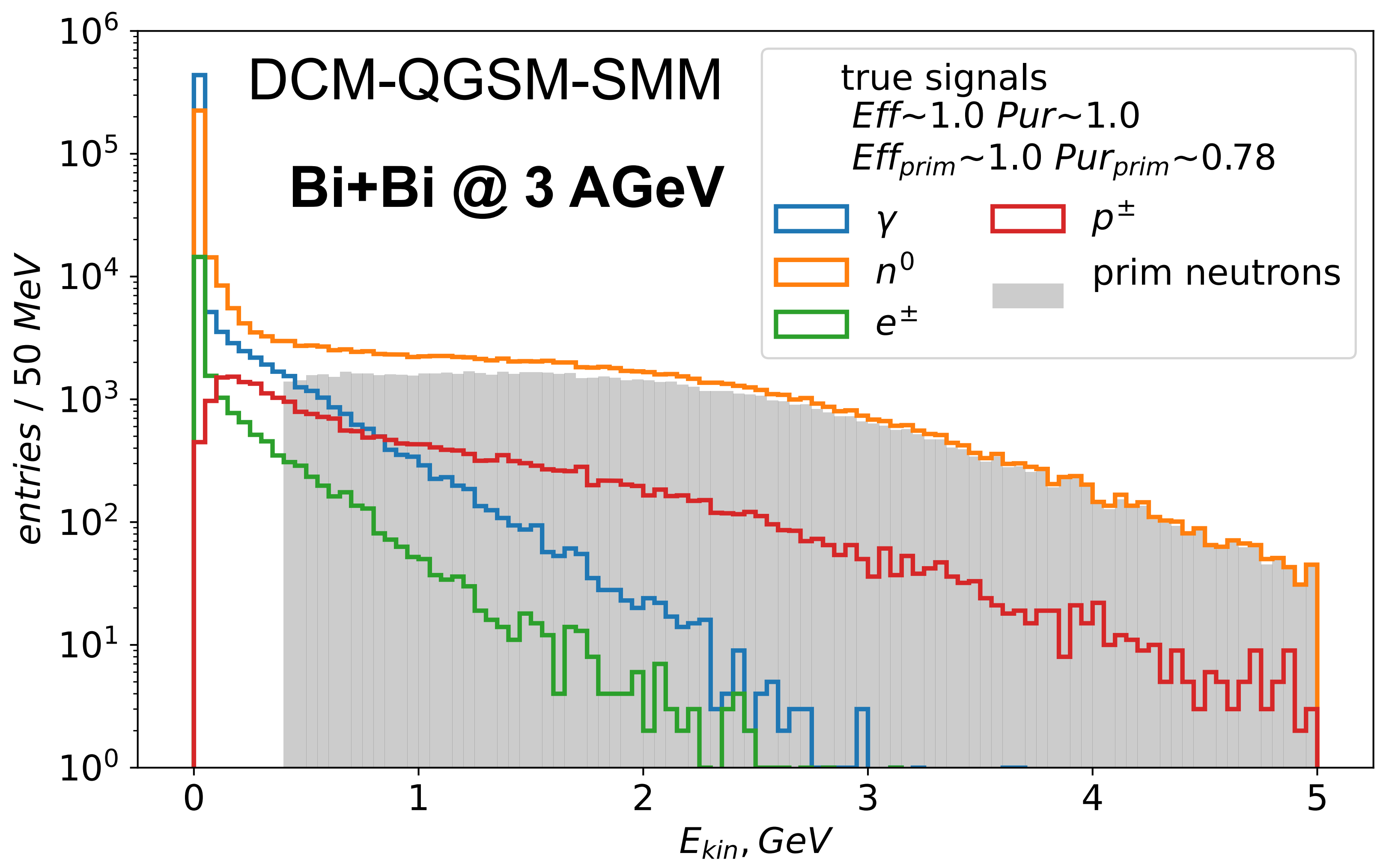

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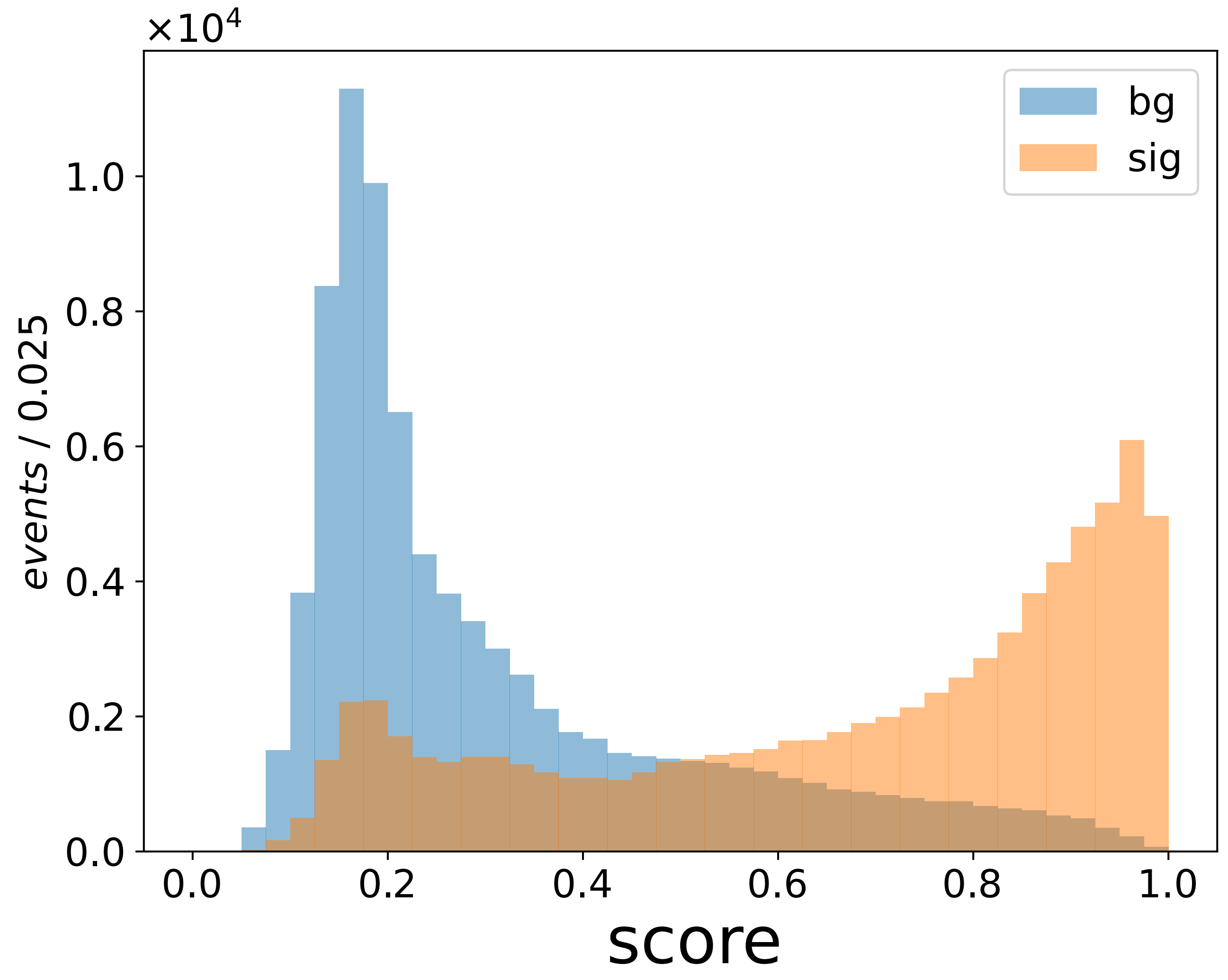
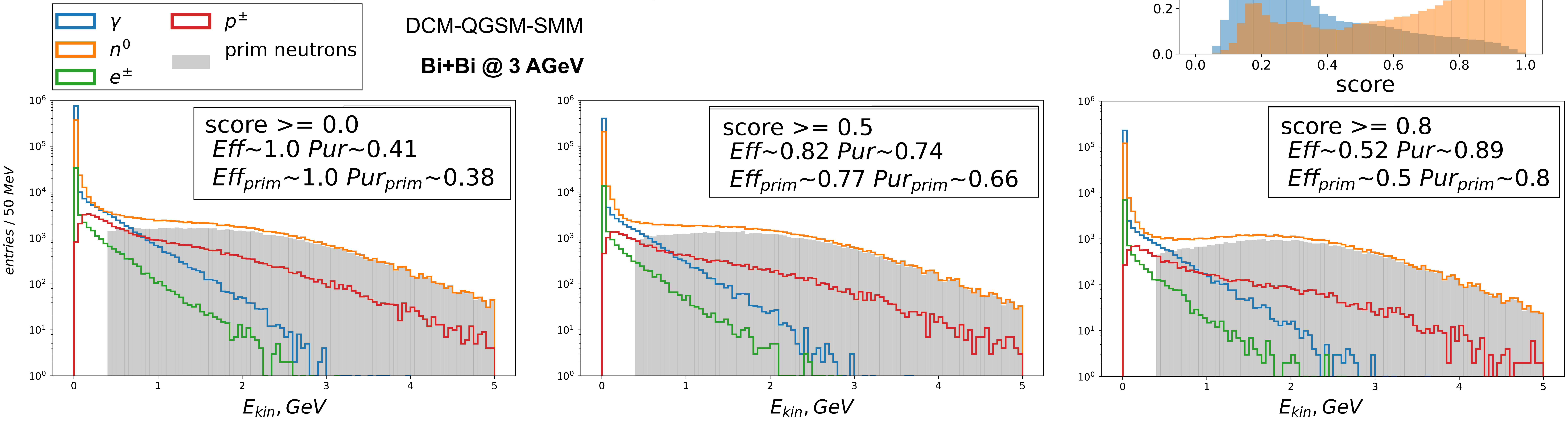
Classification performance

Test sample. 163327 events.

- Signal efficiency to purity ratio can be optimised by varying predictec class score threshold
- Model is capable to properly classify neutron events with background admixture
- Event-level examples are in the backup slides

ML event class prediction



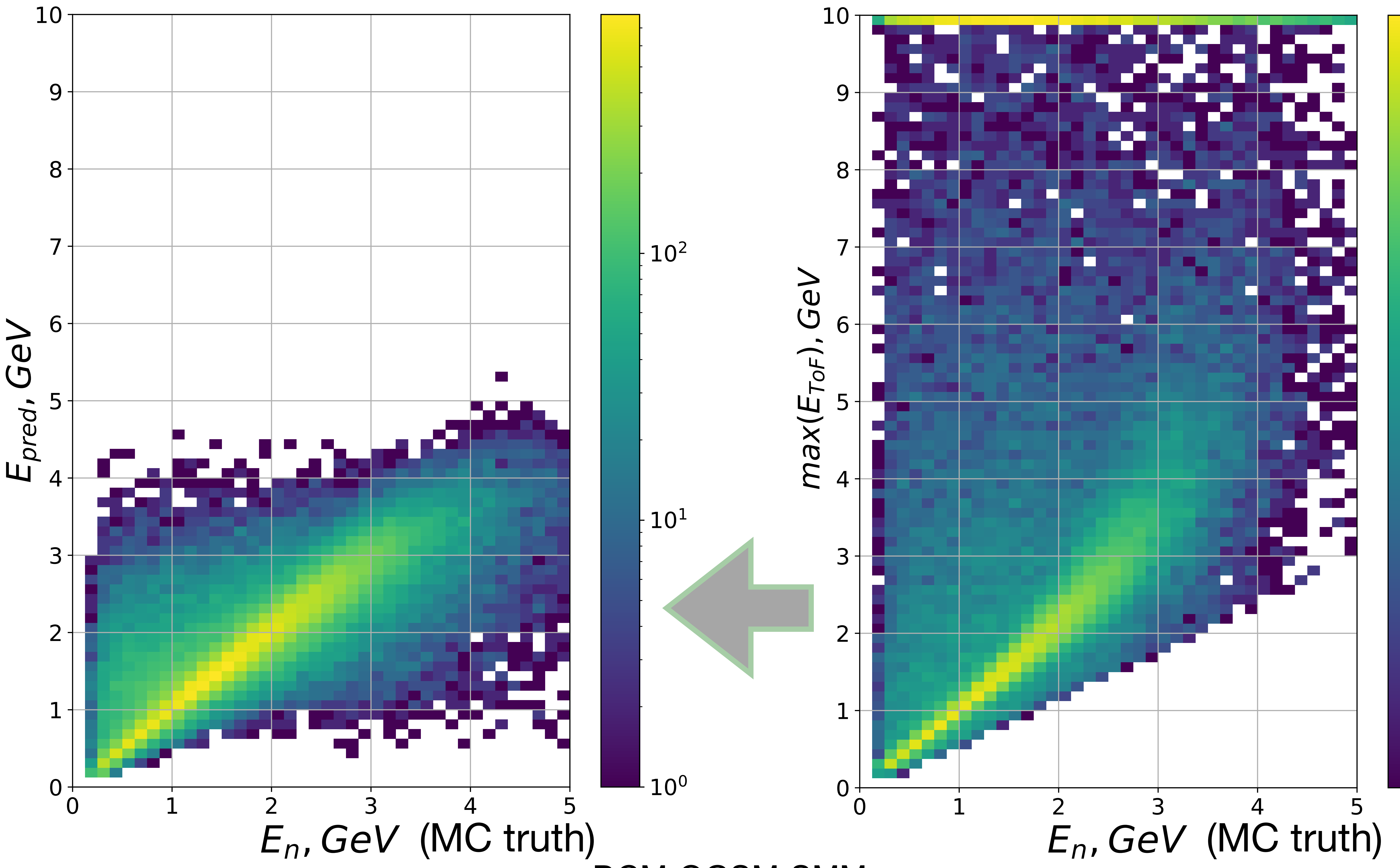


Neutron energy reconstruction

Test sample. 66159 signal events.

- well pronounced linear correlation up to 3-4 GeV
- For energies 2-4 GeV model compensates ToF overestimation
- Model tends to predict most probable values ⇒ asymmetric uncertainties

ML E_n prediction **Fastest hit E_{ToF} estimation**



DCM-QGSM-SMM

Bi+Bi @ 3 AGeV

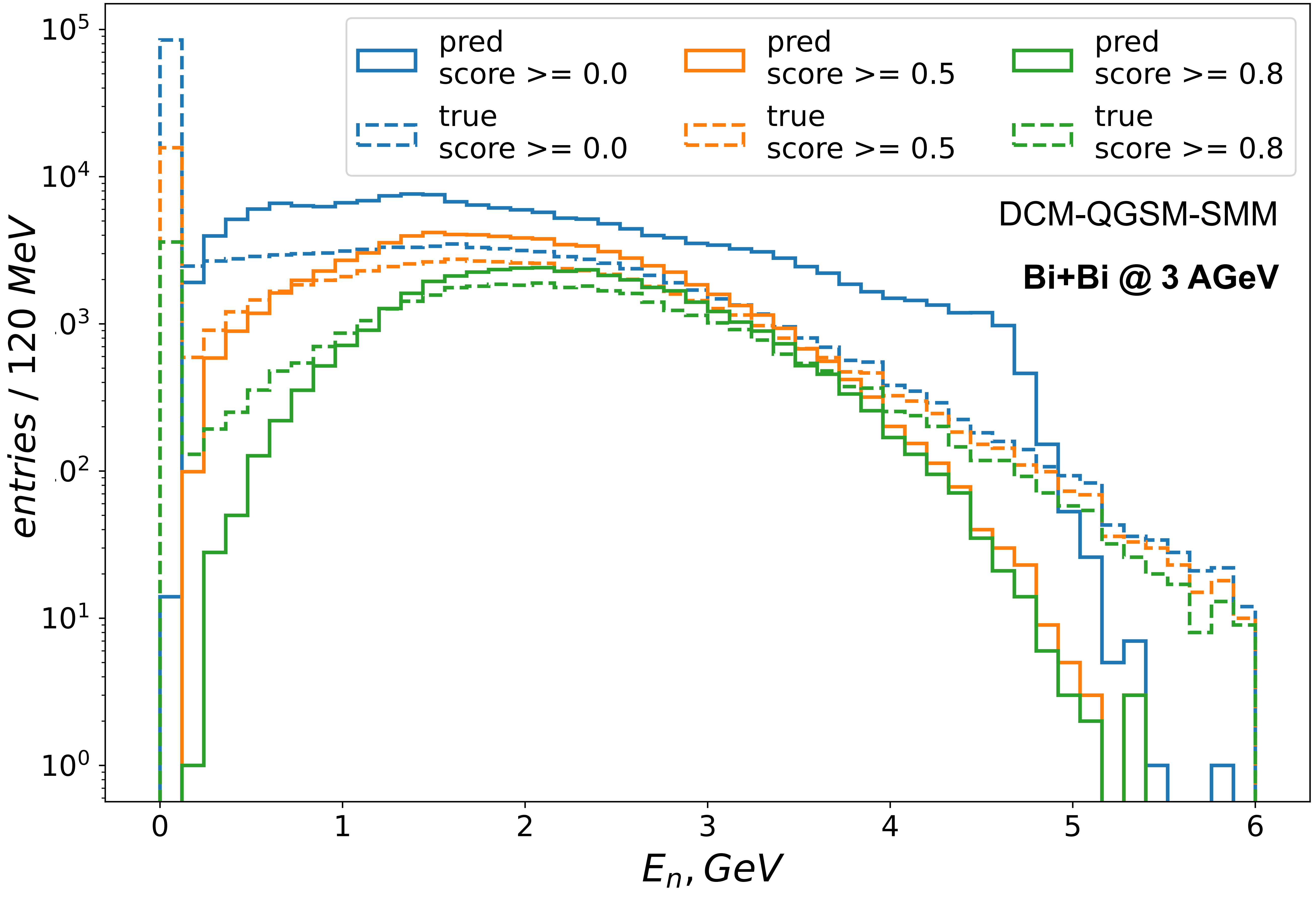
Neutron energy spectrum

Neutron energy spectrum for test dataset (163327 events) after applying classification and energy regression models

- Spectra become closer by increasing classification score threshold
- Tails are less consistent between true and predictions
- Energy reconstruction GNN was not trained to predict 0 energies ⇒

  background contribution spread over energy spectrum

  ➡ possible solution: combined training

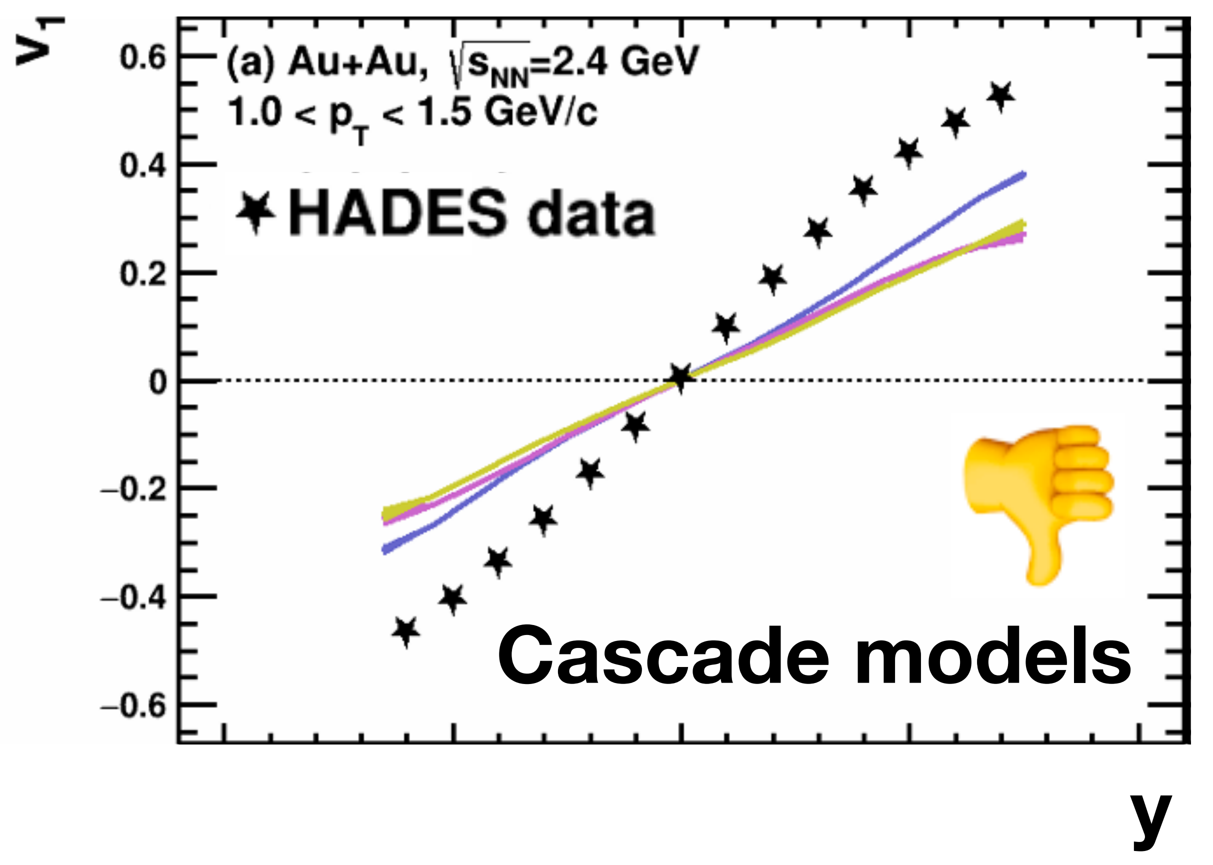


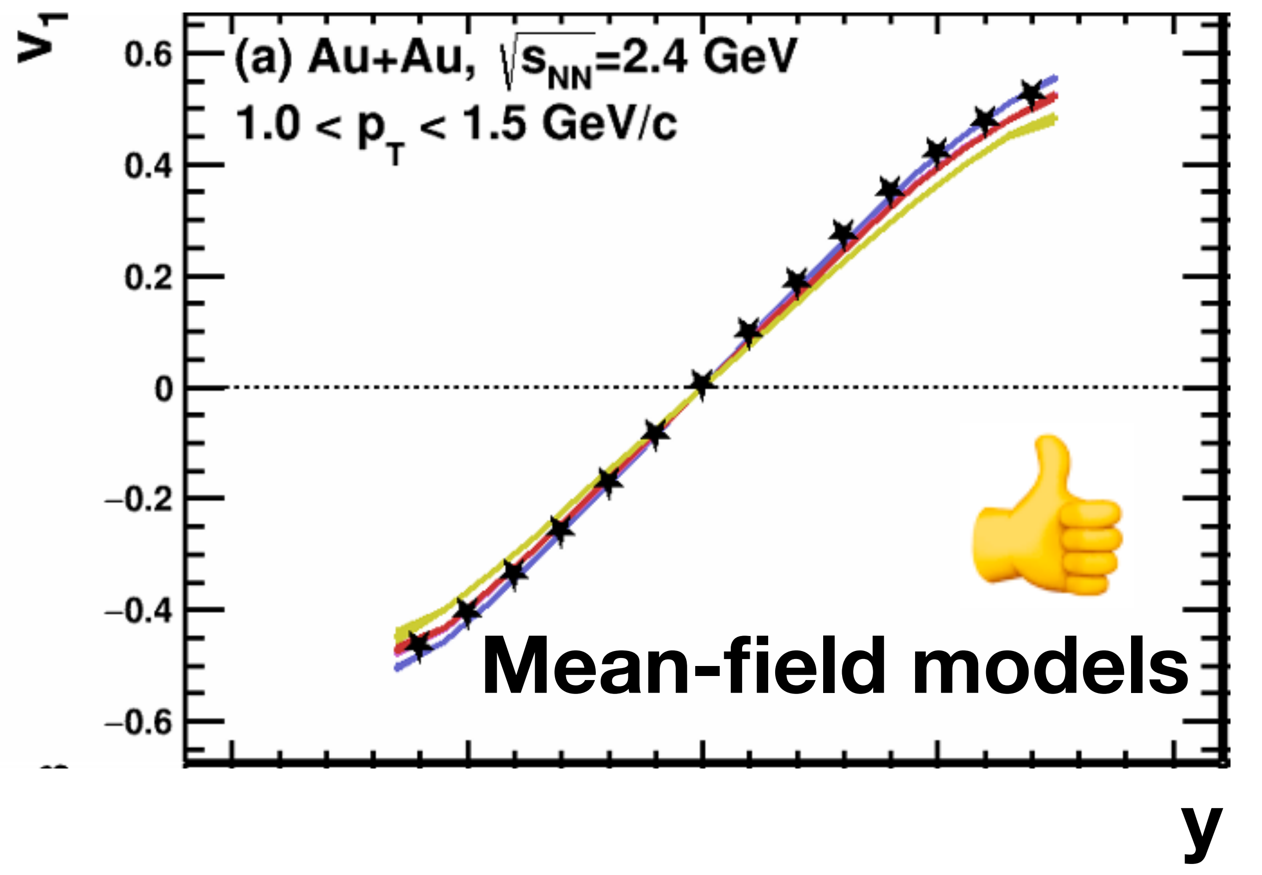
Primary + background neutrons

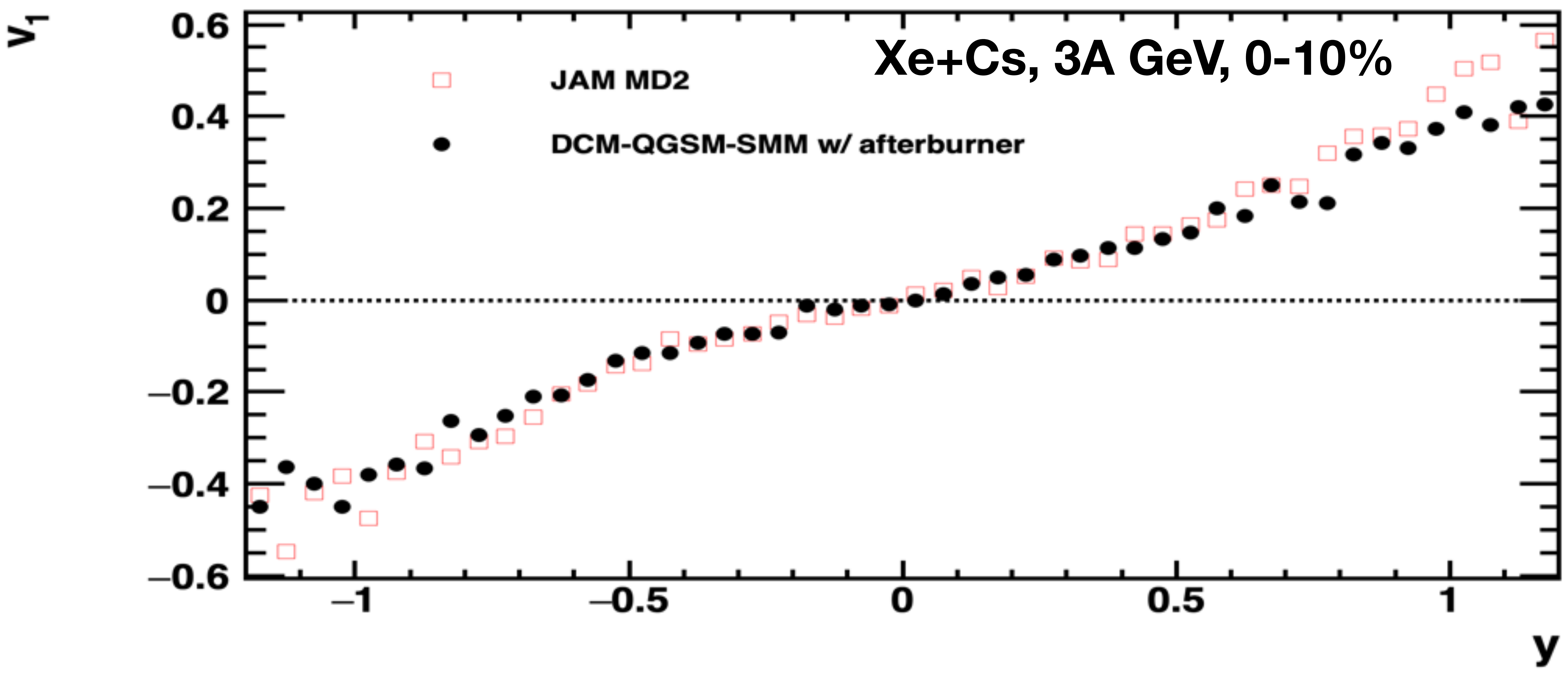
Neutron flow status

For a performance study of neutron flow measurements one needs model with:
- Realistic spectator fragments
- Realistic flow signal

Problem: there is no such model at the moment!







Solution: make an afterburner for DCM-QGSM-SMM model to have realistic flow signal
- Simple afterburner has been prepared for the UniGen format

Next steps:
- Simulation and reconstruction within BmnRoot framework
- Flow measurements

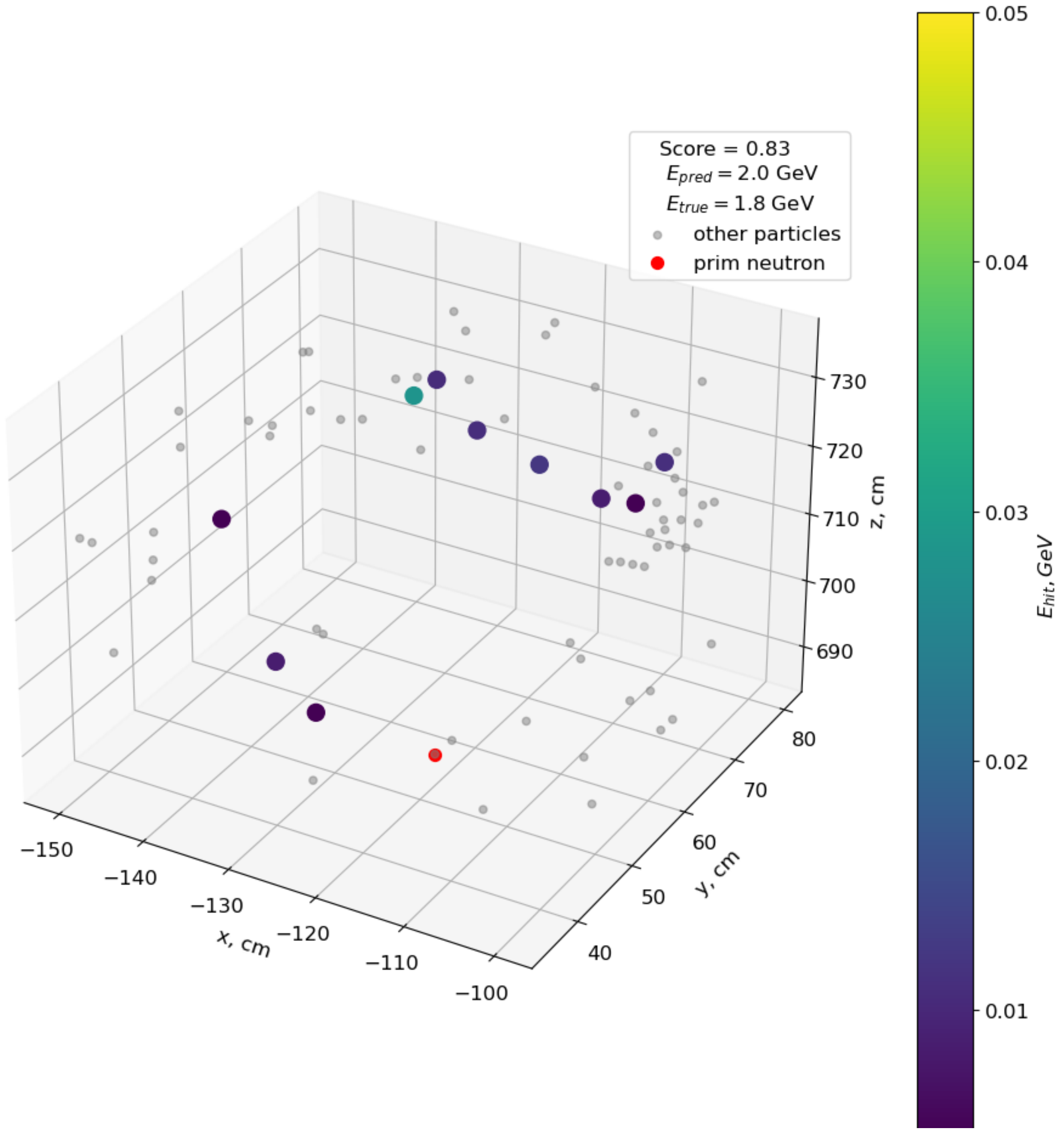
Slide by P. Parfenov

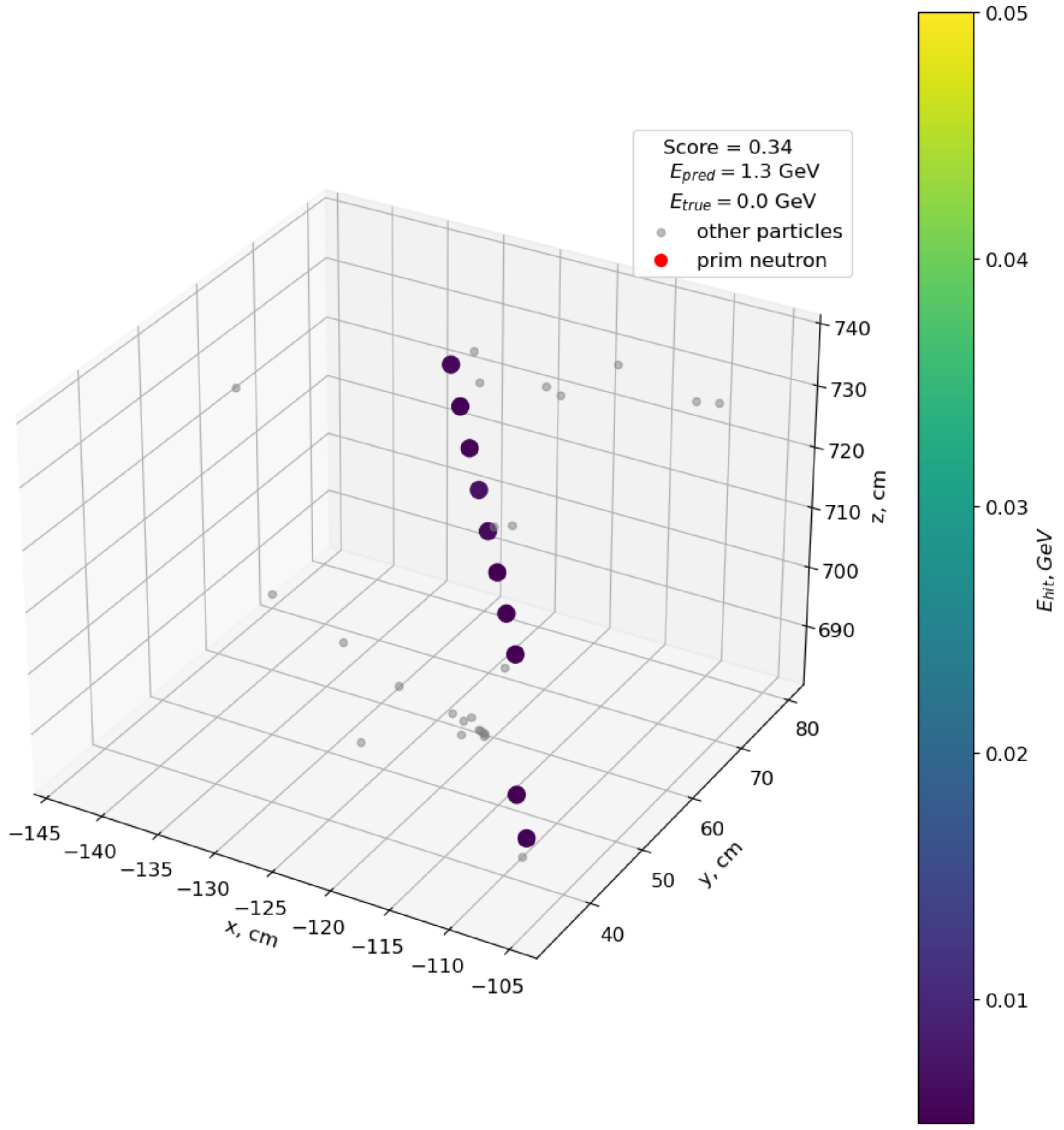
Summary and Outlook

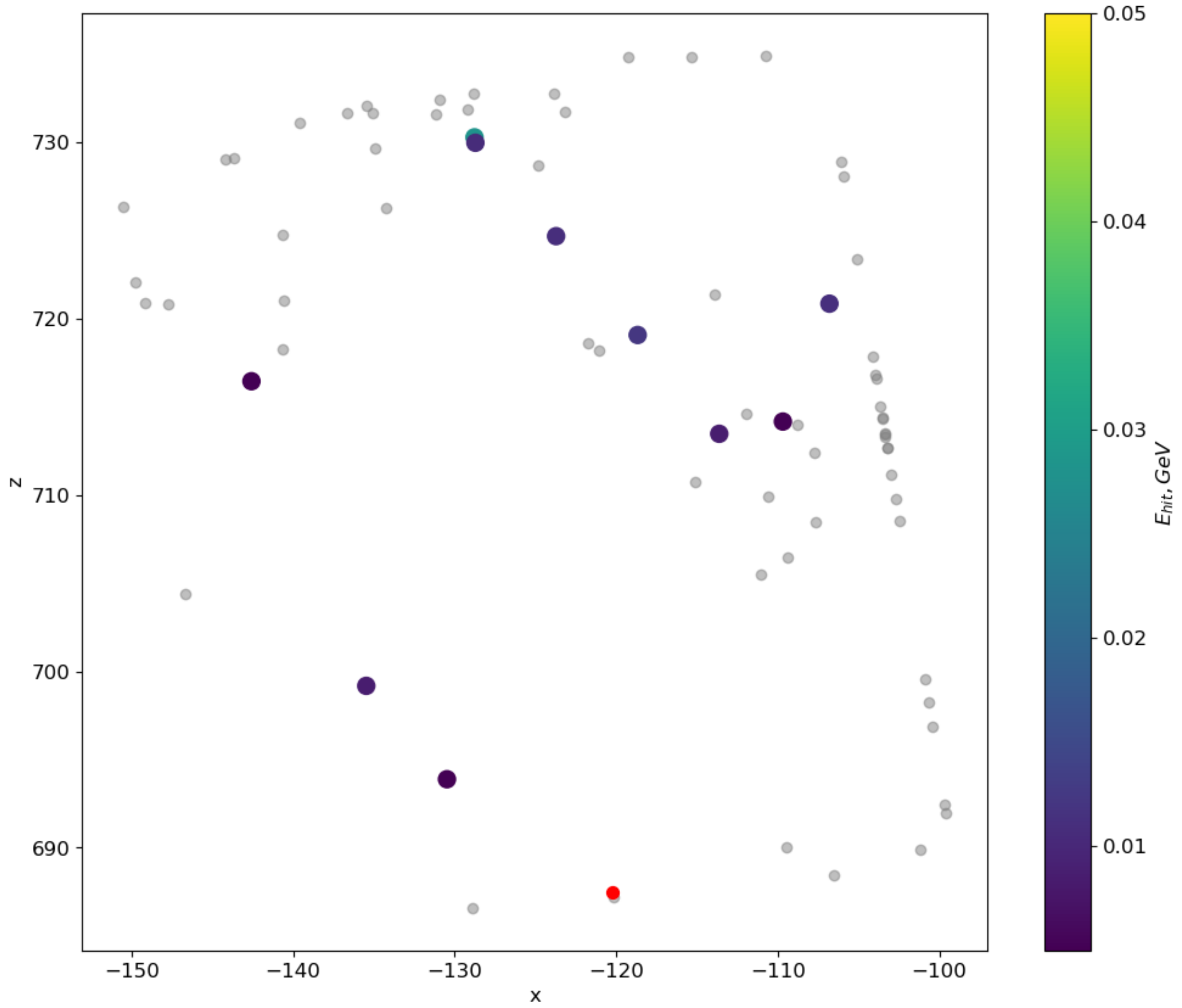
- Neutron reconstruction in the HGND is performed in 2 steps: classification, energy reconstruction. Machine learning approach and preliminary results are discussed.
  - High multiplicity scenario to be addressed
  - Hit-level labelling within event is under implementation in the BMNRoot
  - Utilise information of charged tracks projected to the HGND surface
  - Classical baseline neutron reconstruction is under development (see next talk)
- Performance study of neutron flow measurements is under preparation:
  - Afterburner for realistic flow signal in DCM-QGSM-SMM is prepared
  - Simulation and reconstruction is underway

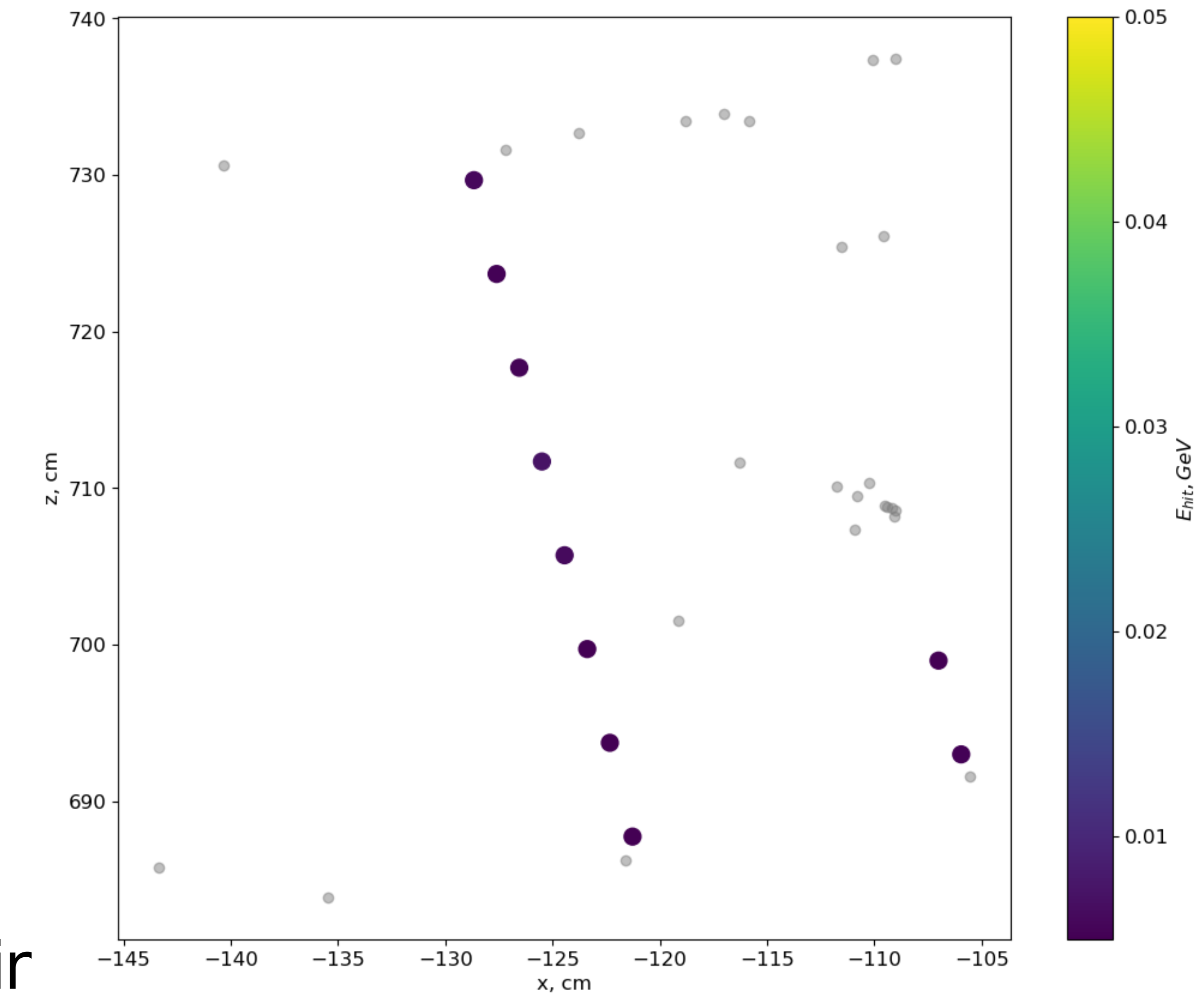
Backup

Neutron event classification

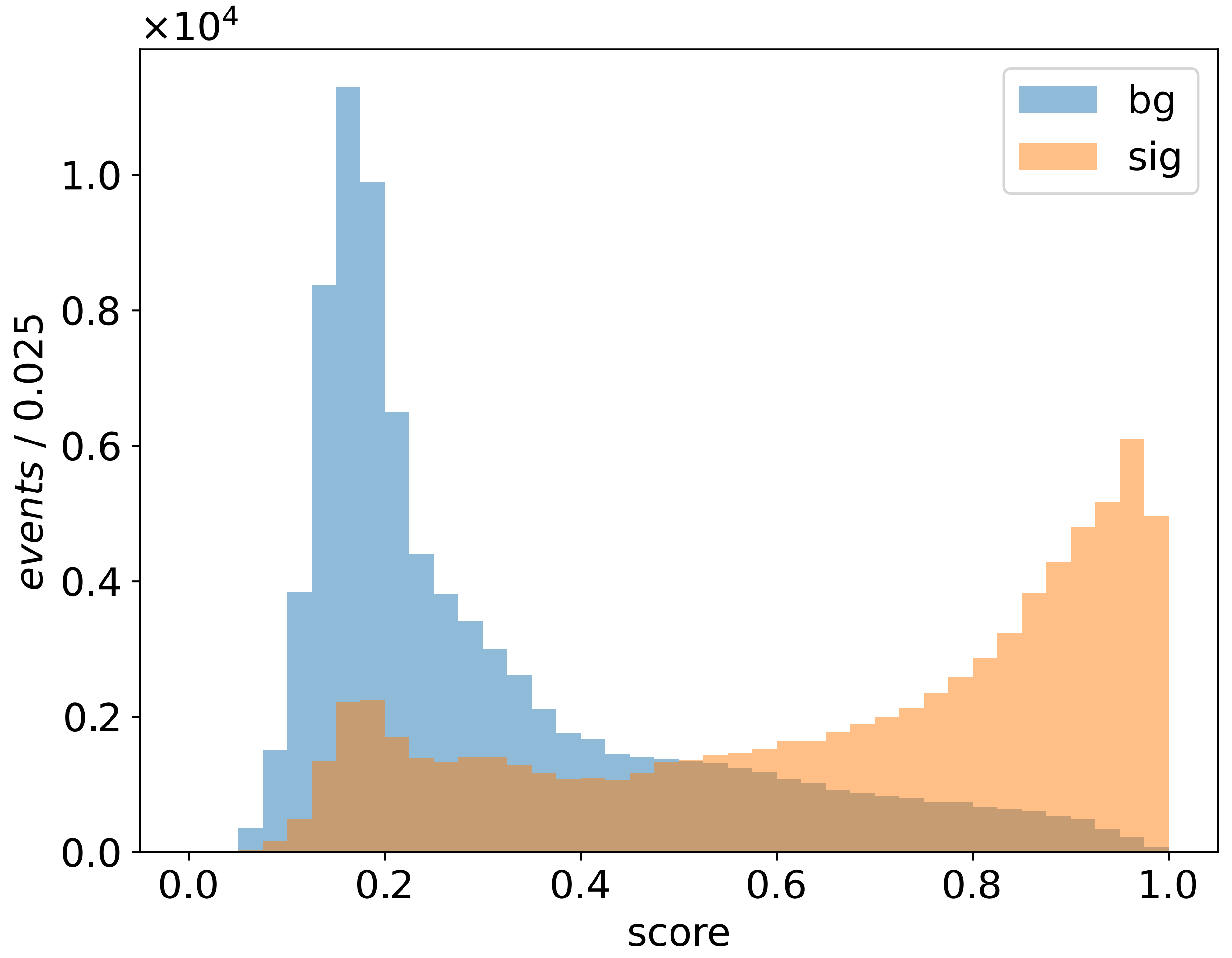


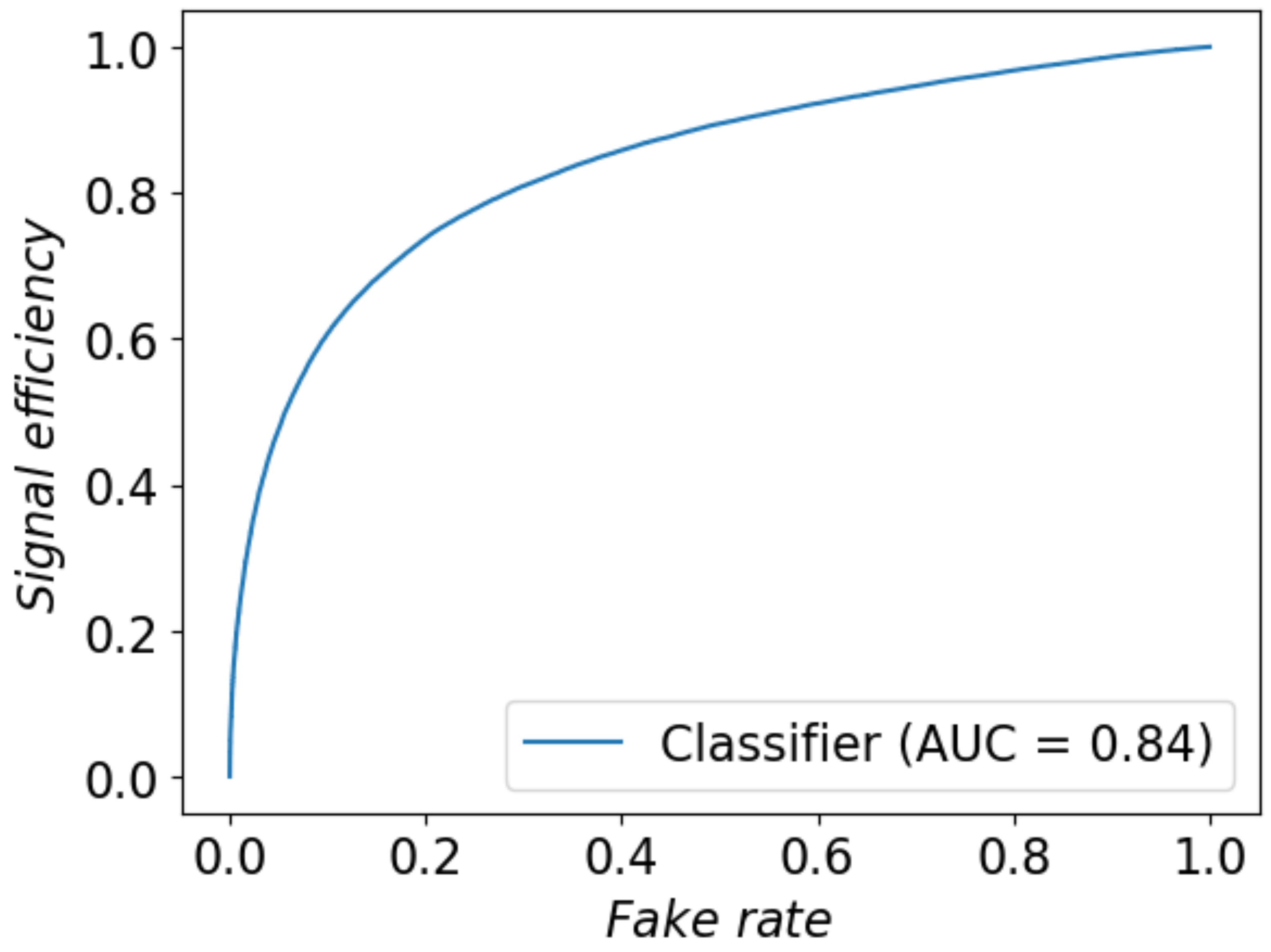






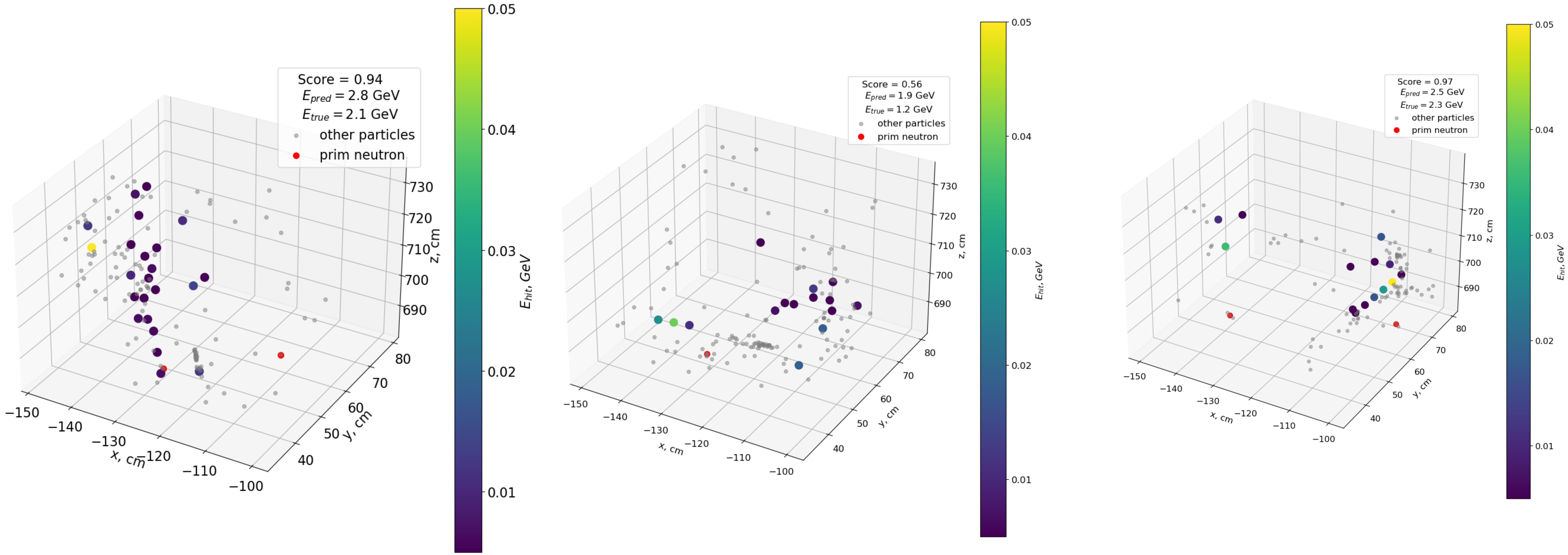
ML event class prediction





Neutron event classification

Event displays on test dataset



Neutron event classification

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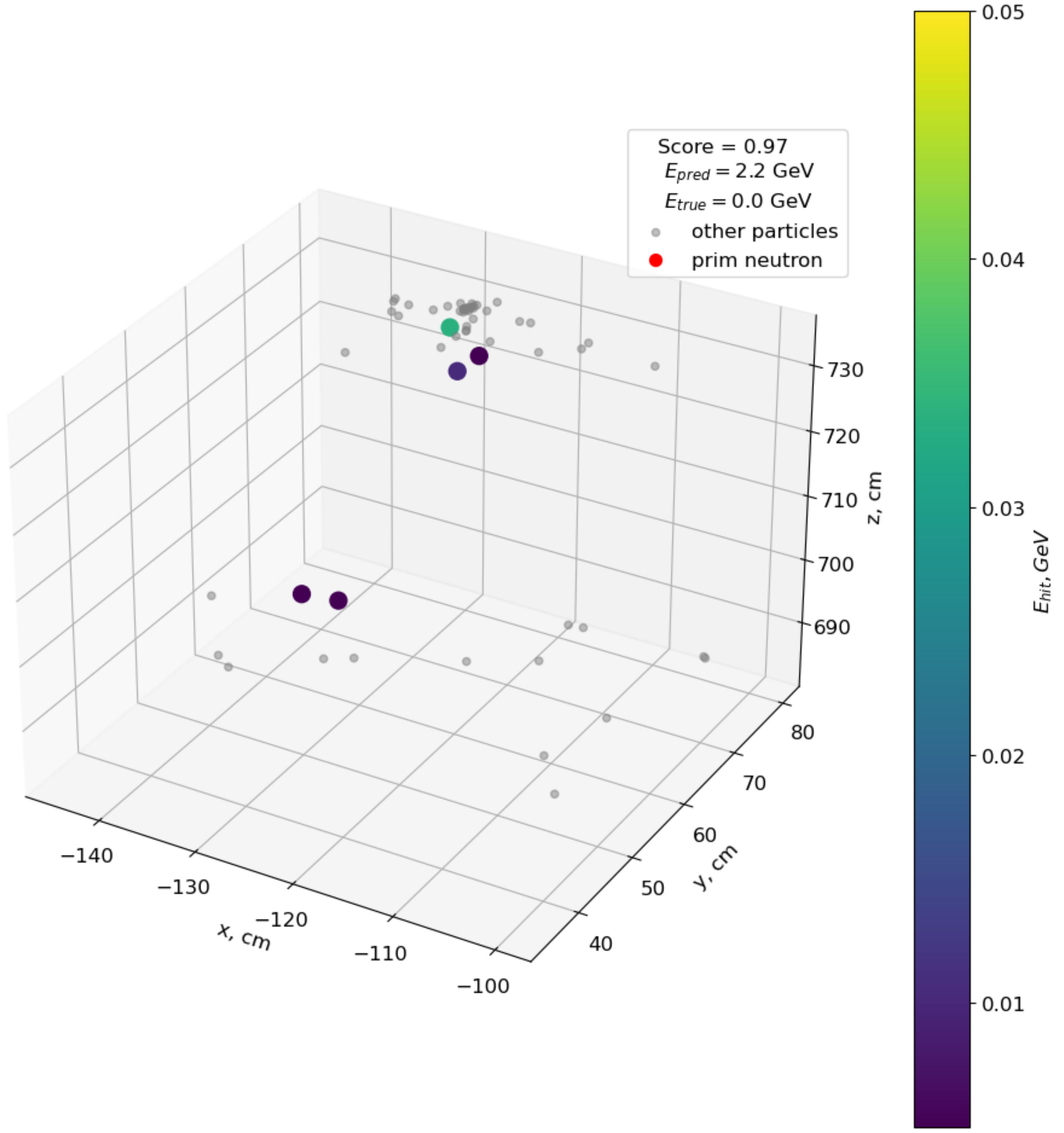
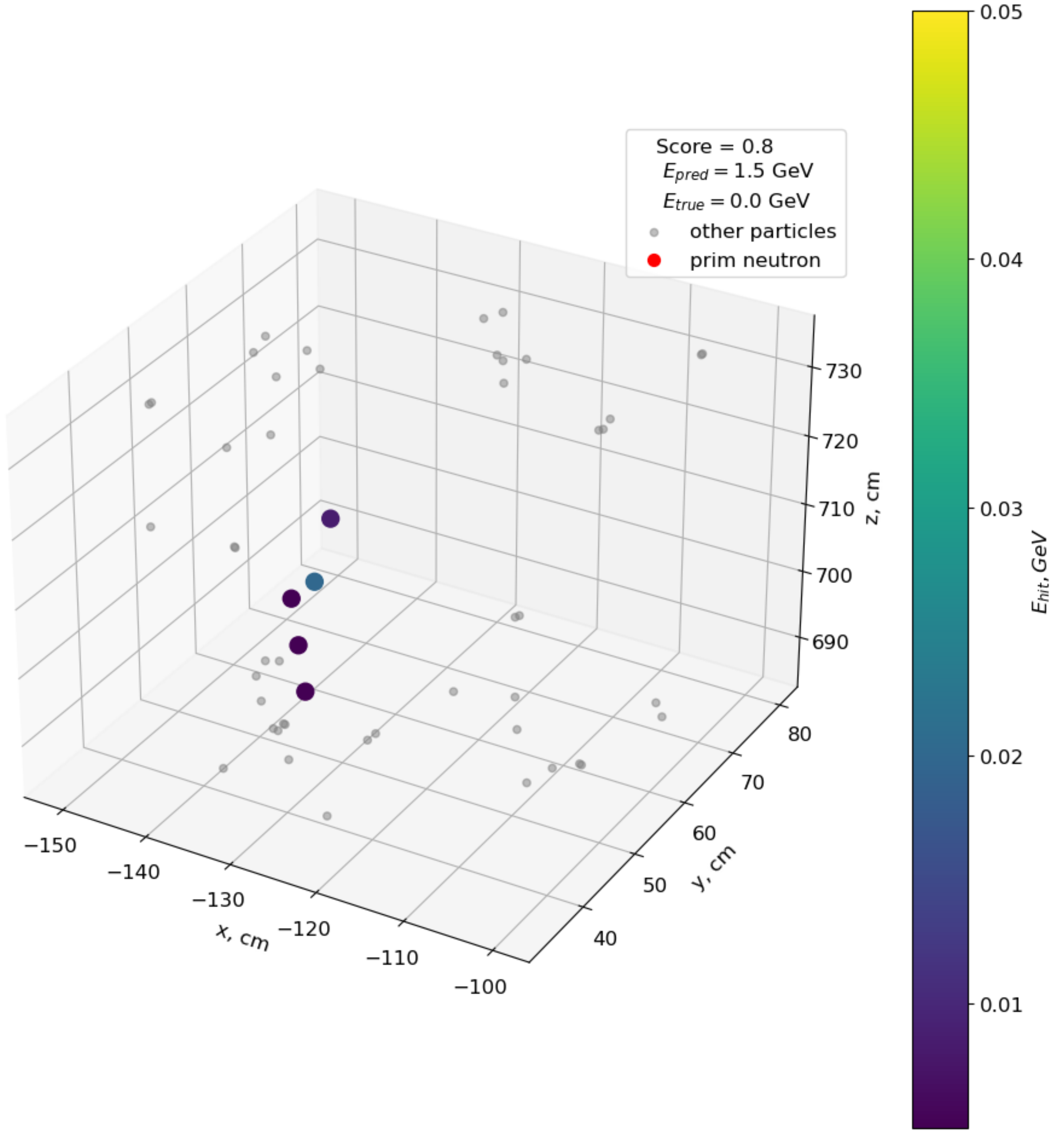
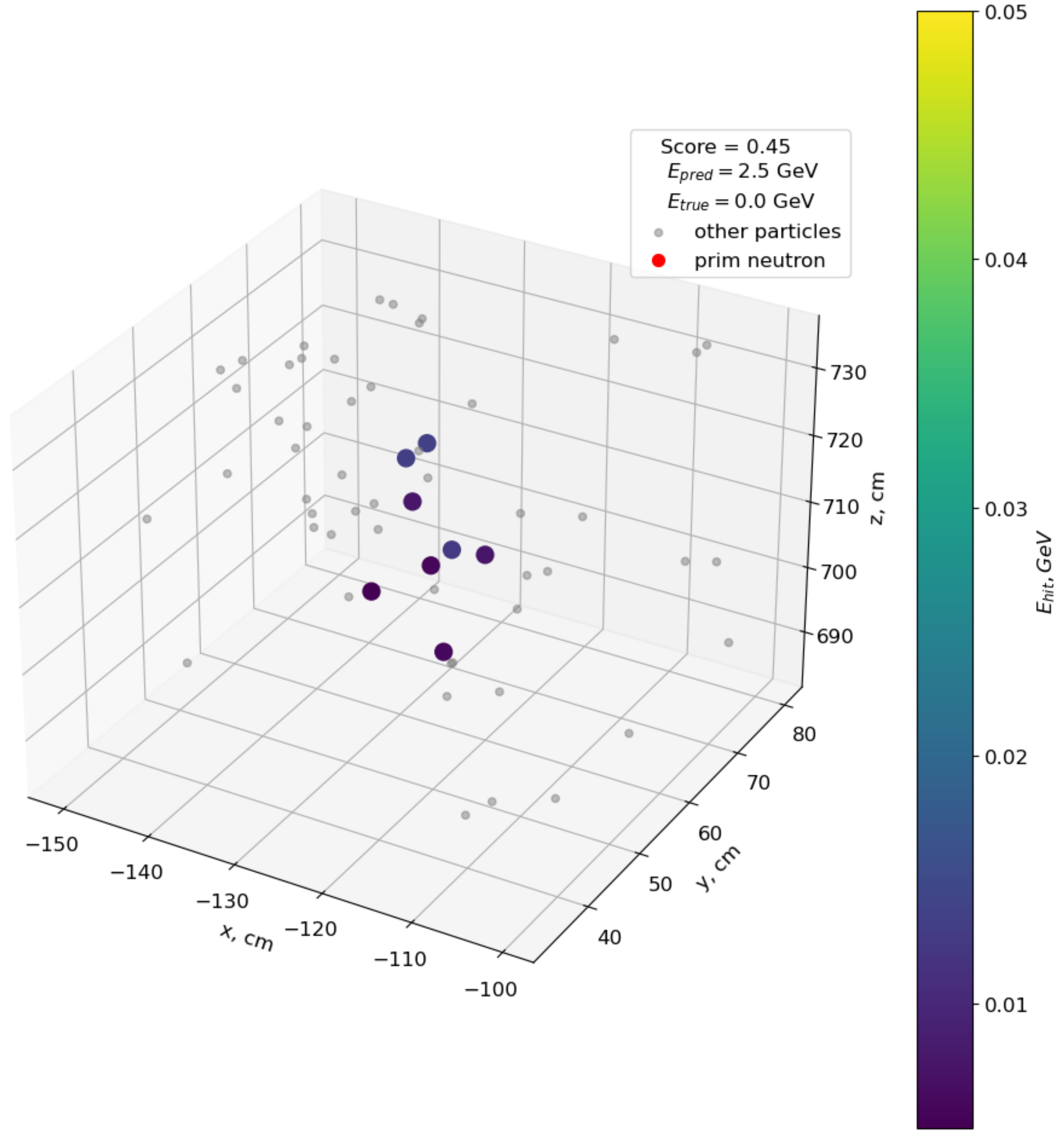


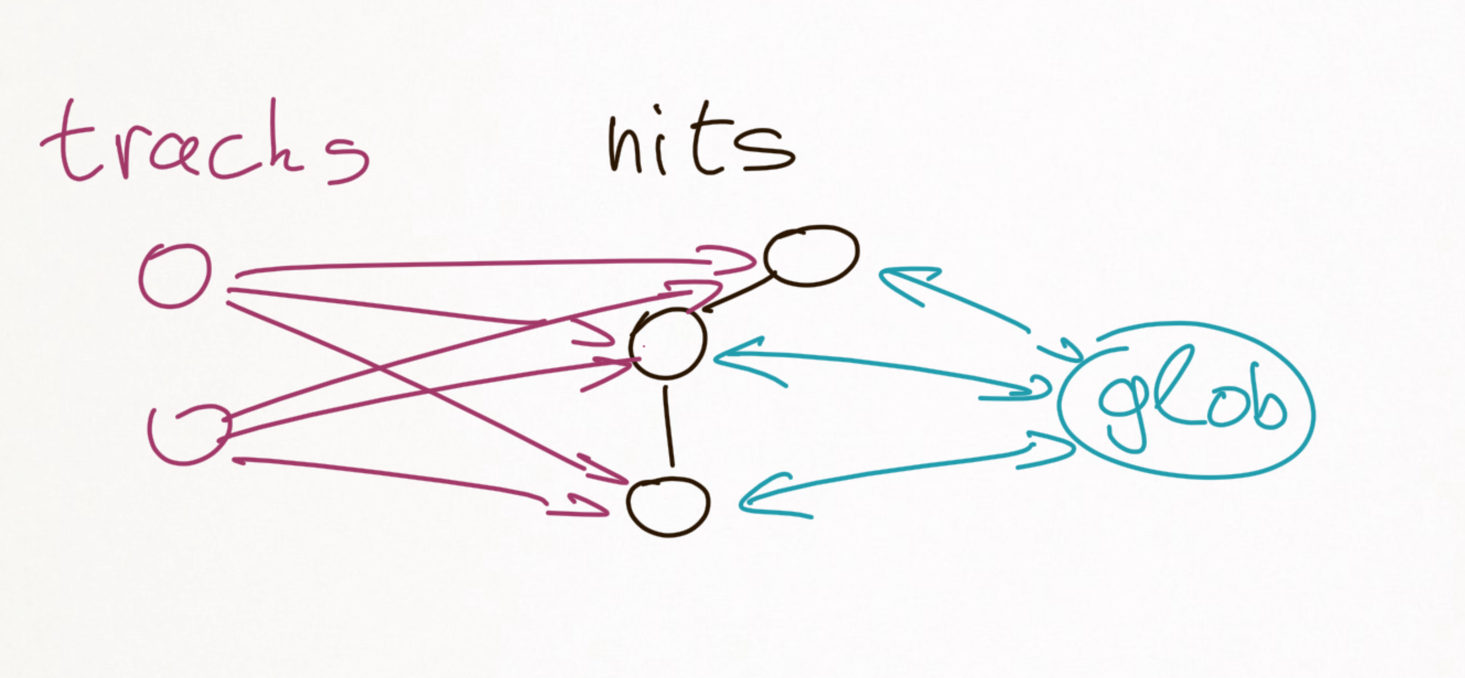




Heterogenious GNNs

Heterogenius GNN Model:

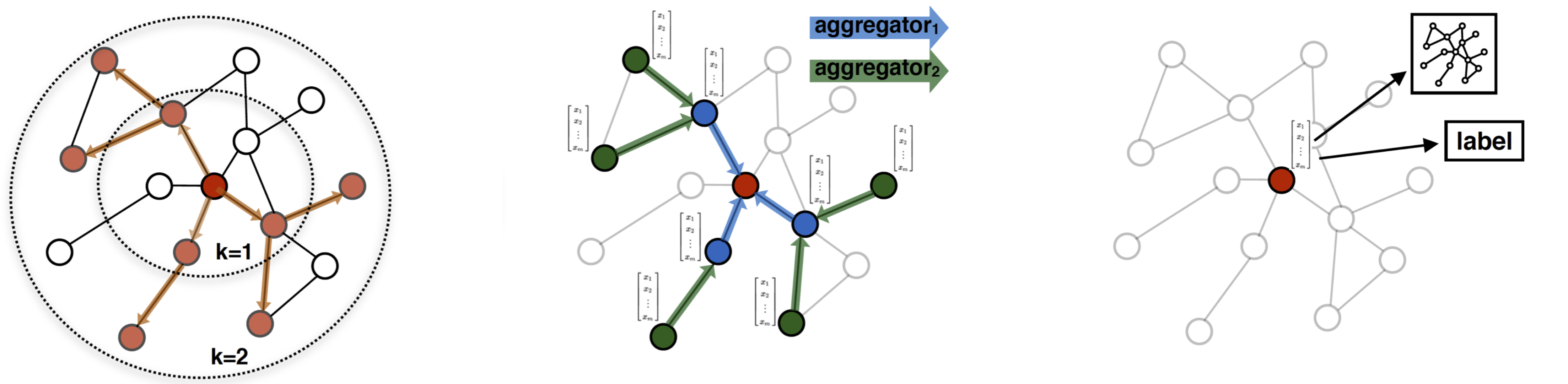
- graph construction:
  - Hit nodes
    - Edep, EToF, **pos**
  - Track nodes (e+-, p+-)
    - **pos**, **p**
  - global node
    - nHits, eToF_max, eToF_med,Esum



GNN Model architecture:

- Radius graphs with r = 5cm
- 8x GraphSAGE message passing layers with 512 hidden channels MLP readout layer
- Binary Cross Entropy loss function for event classification
  - Only signal events are used to train for energy regression model
- Mean Squared Error loss function for energy regression

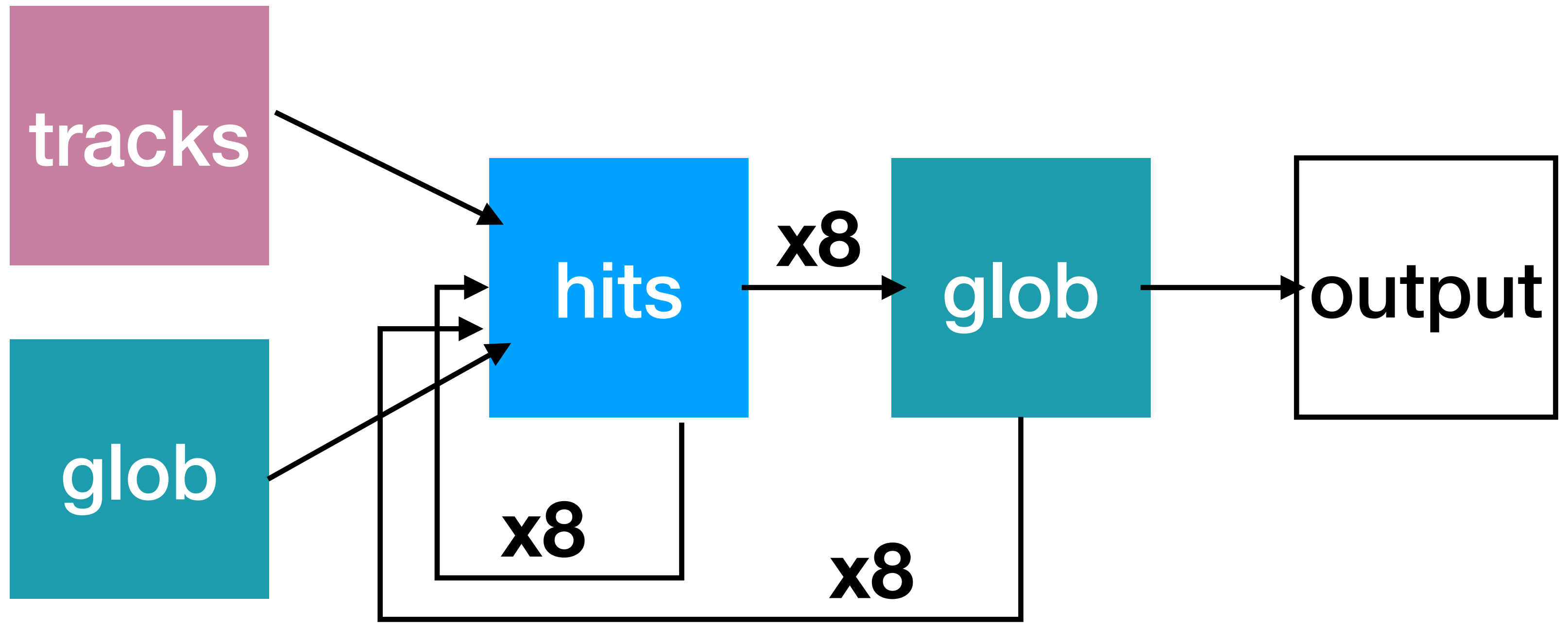
GraphSAGE (**SA**mple and aggre**G**at**E**) architecture GNN**:**



Sample neighbourhood of graph nodes

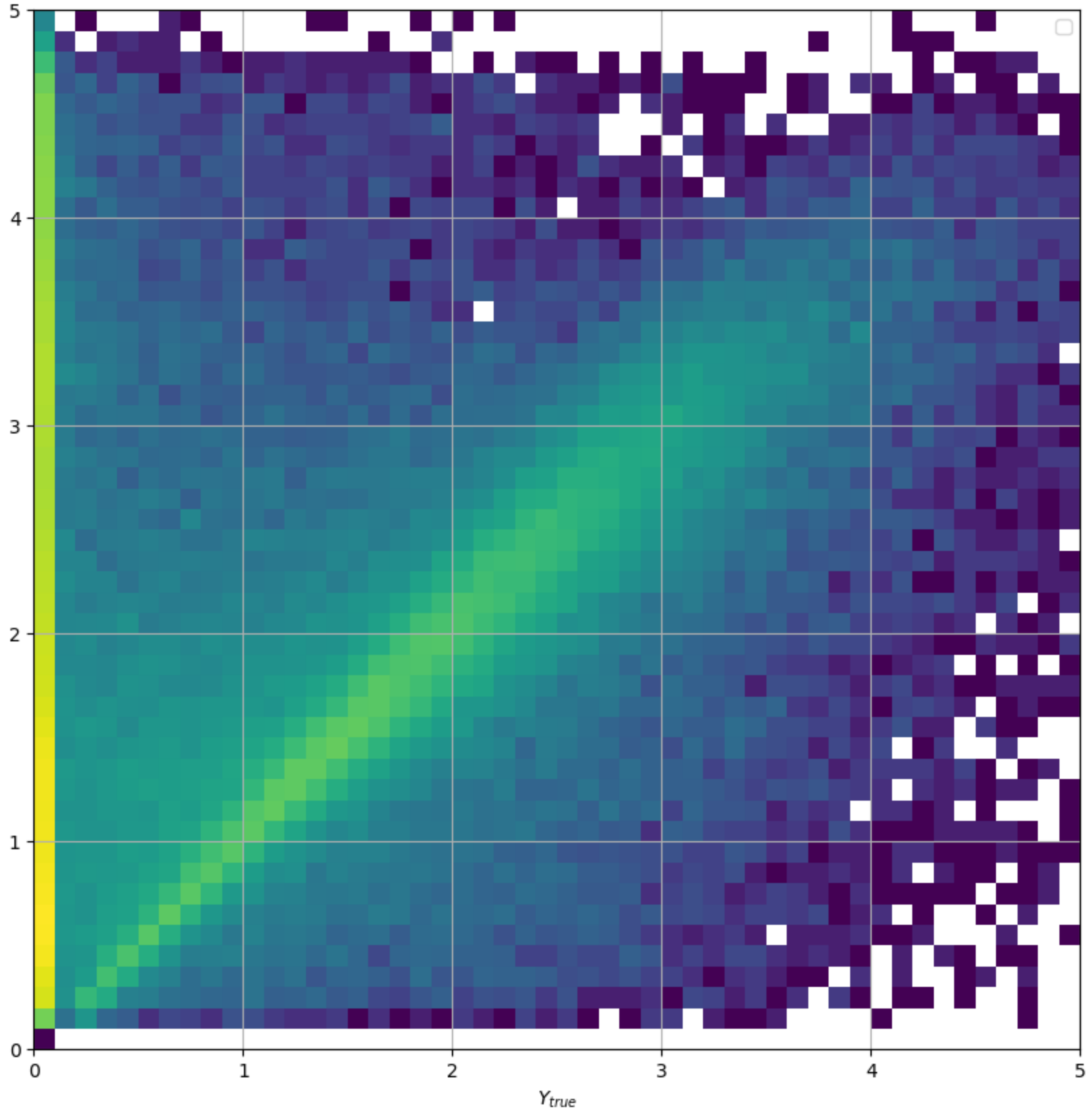
Aggregate feature information from neighbours

Get graph context embeddings for node using aggregated information

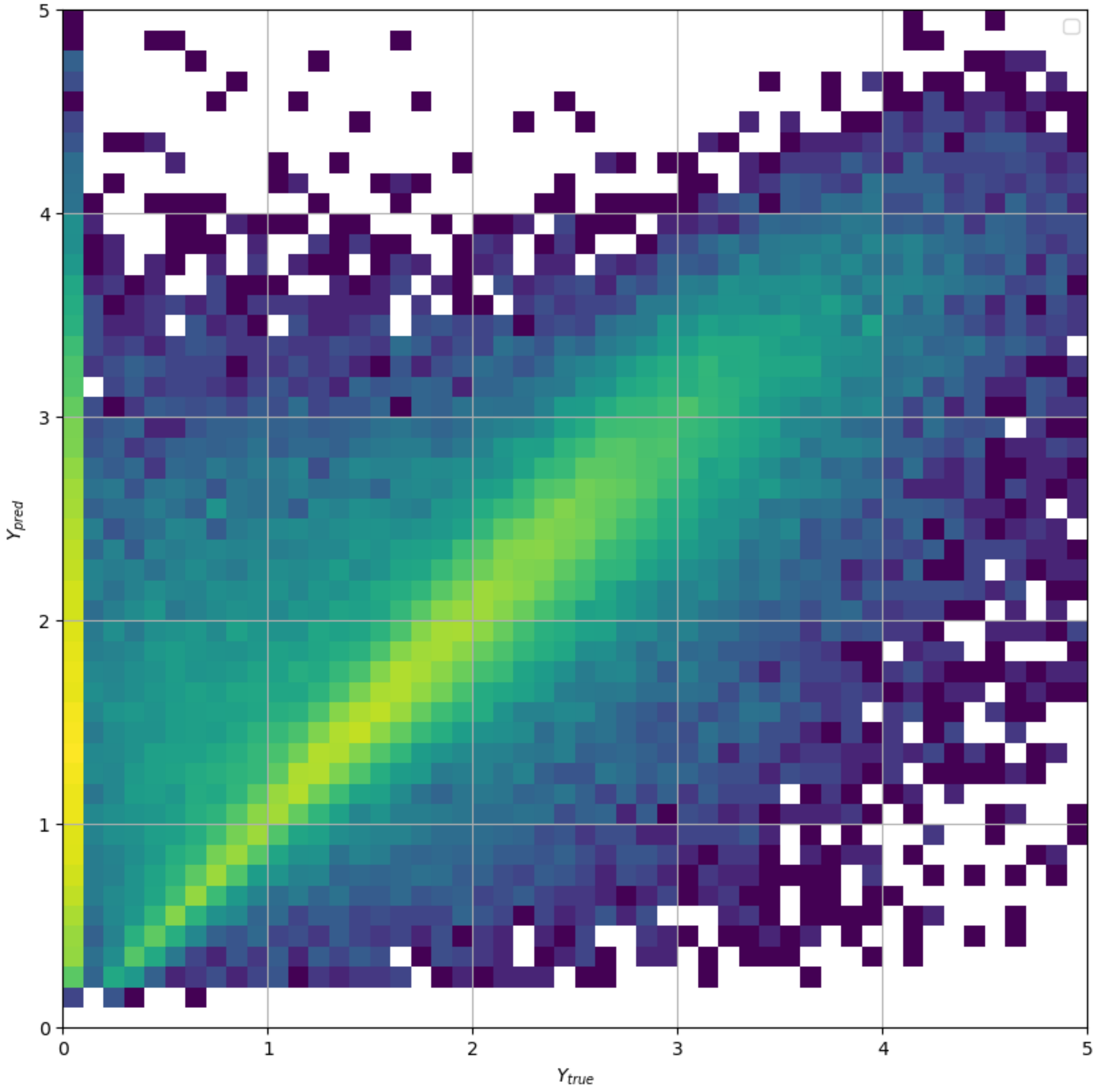


Neutron reconstruction

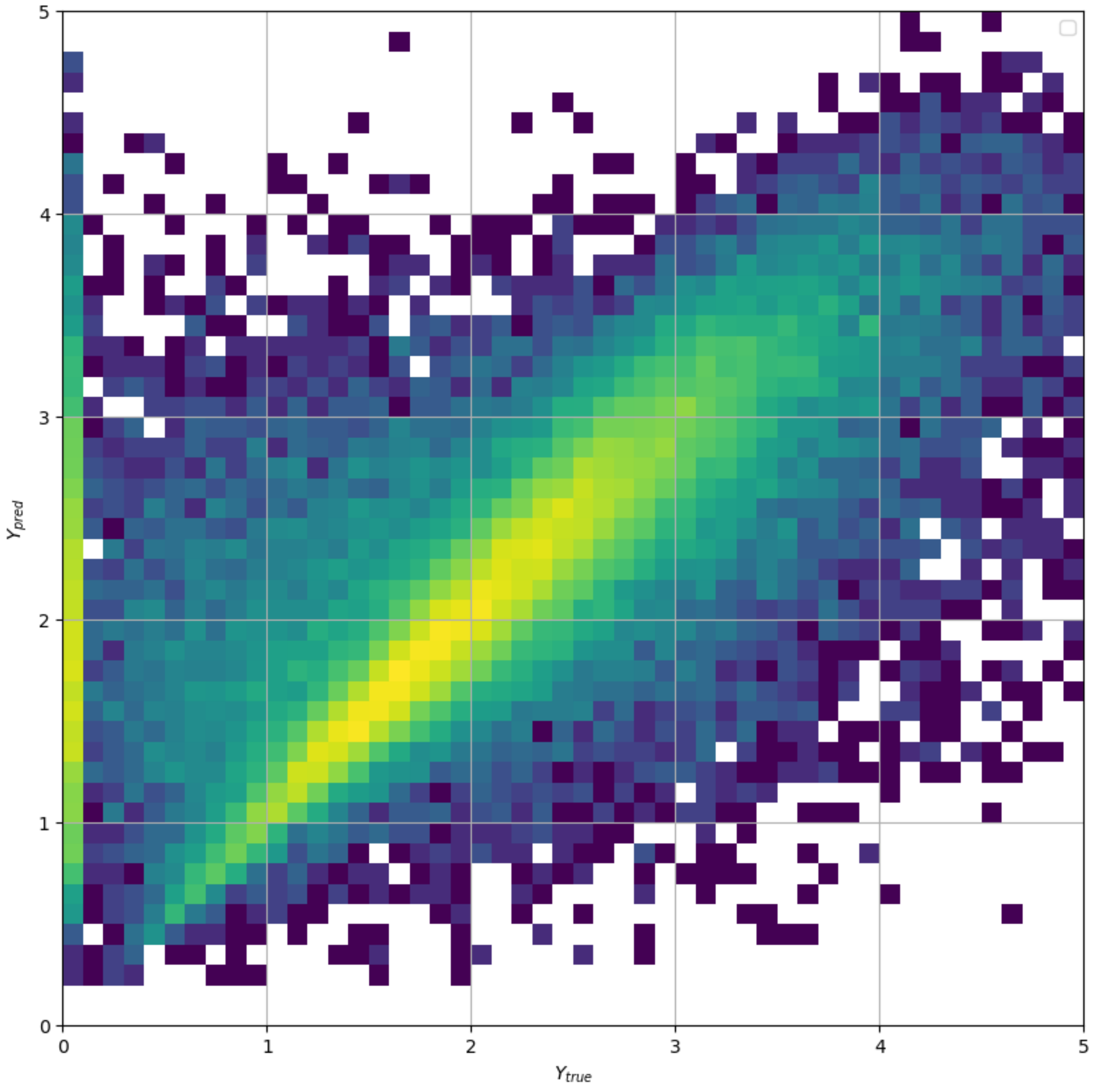
threshold = 0



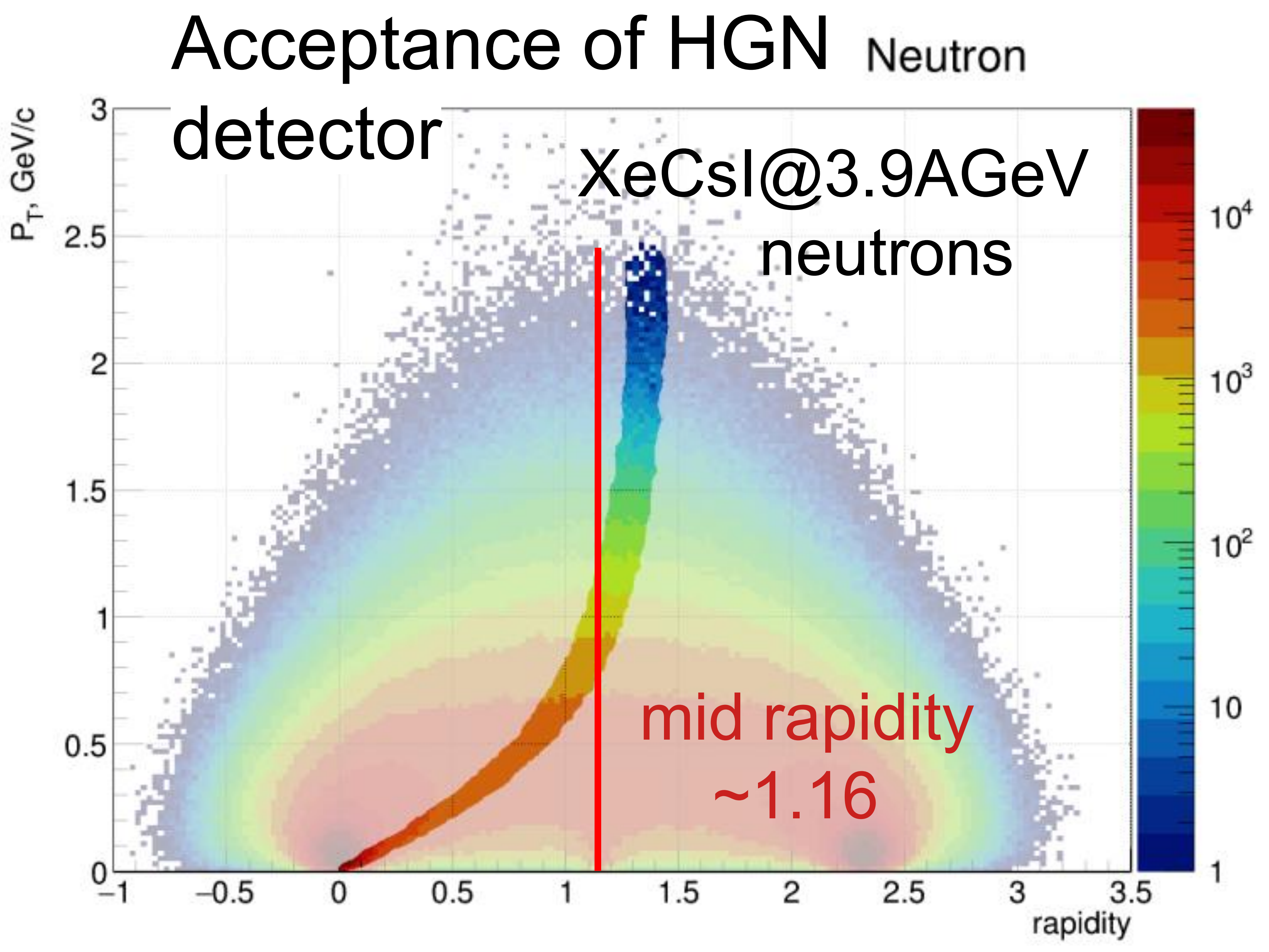
threshold = 0.5



threshold = 0.8



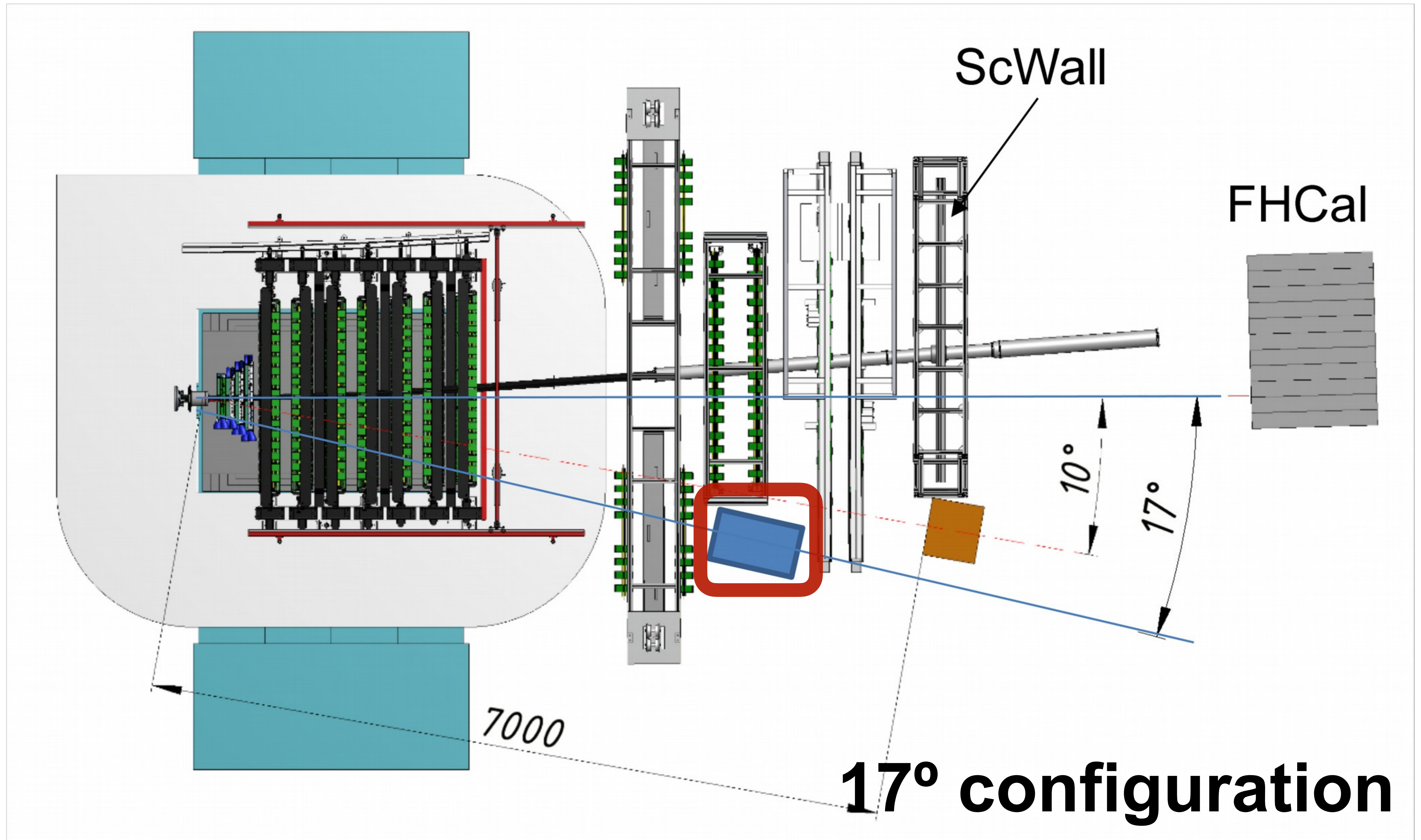
- Background contribution reconstructed energy is distributed similarly to signal neutrons

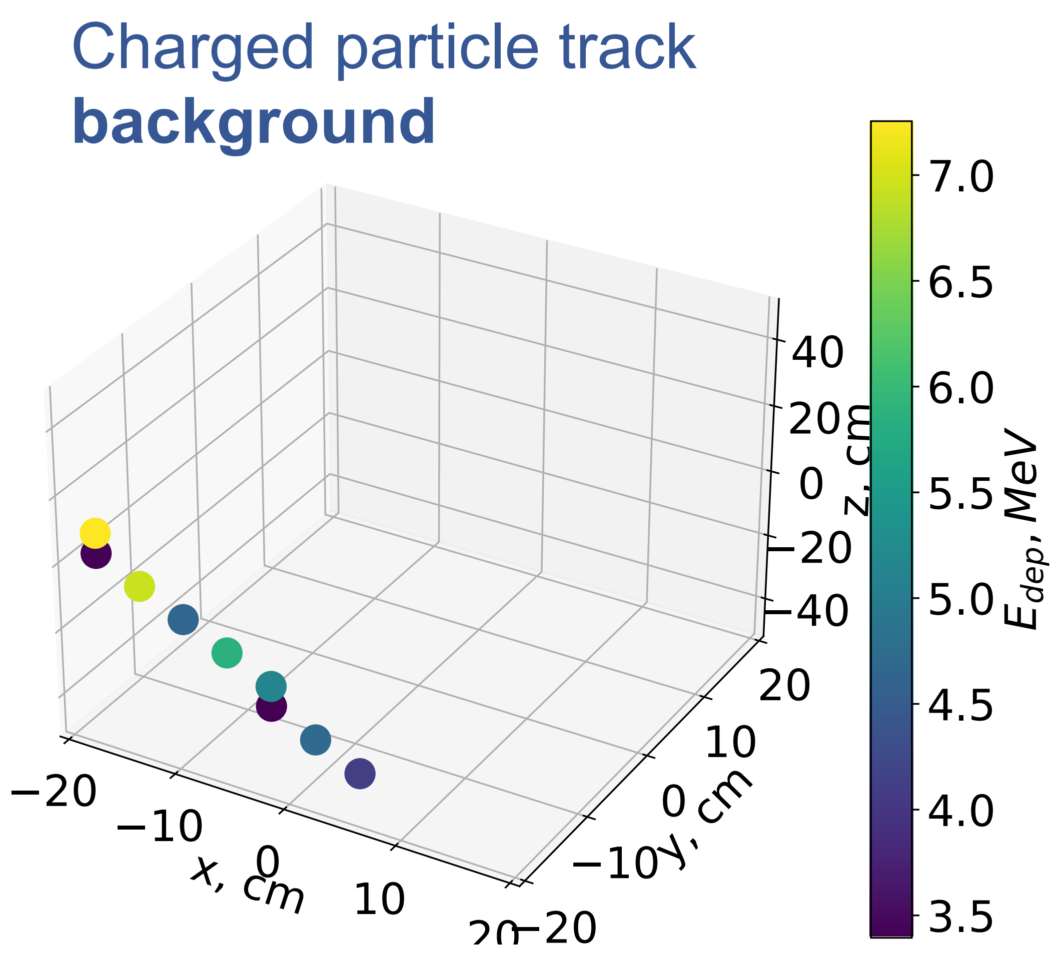


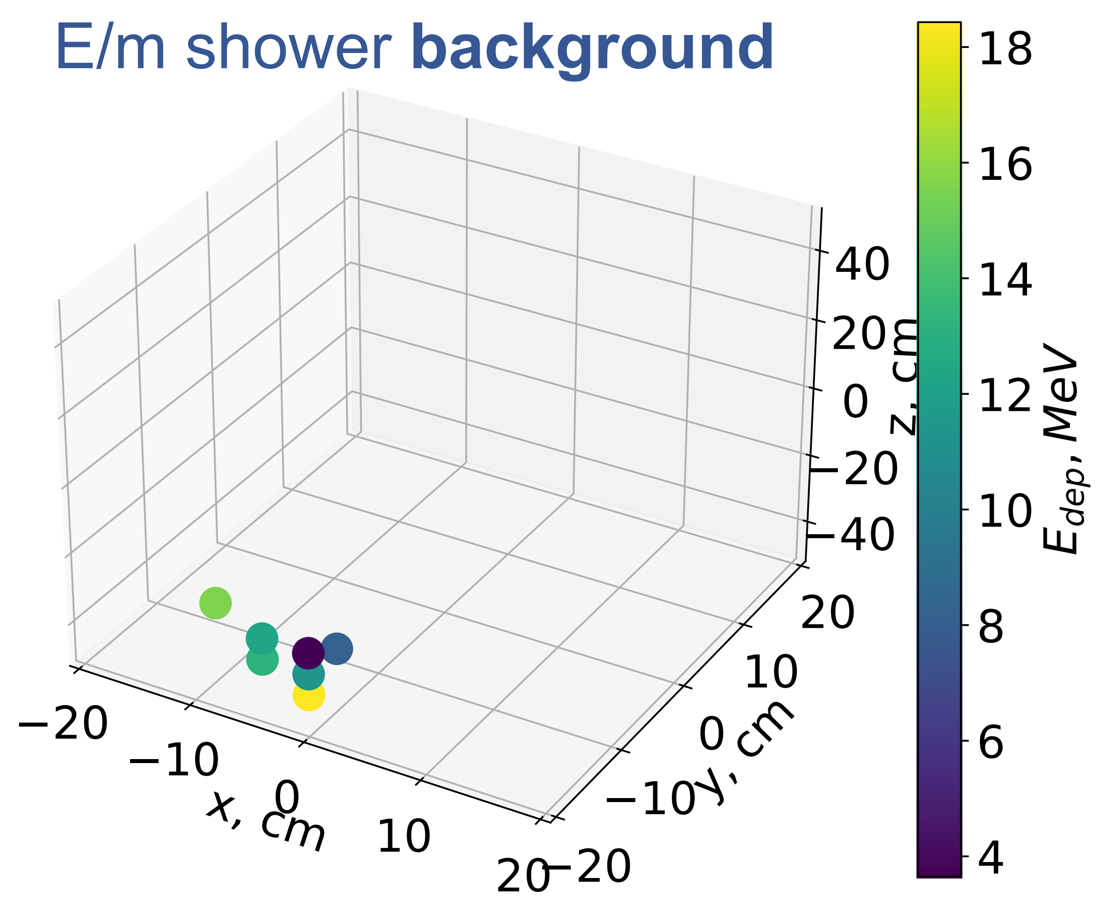
Acceptance of HGN detector
Neutron
XeCsI@3.9AGeV neutrons
mid rapidity ~1.16
P_T, GeV/c
rapidity

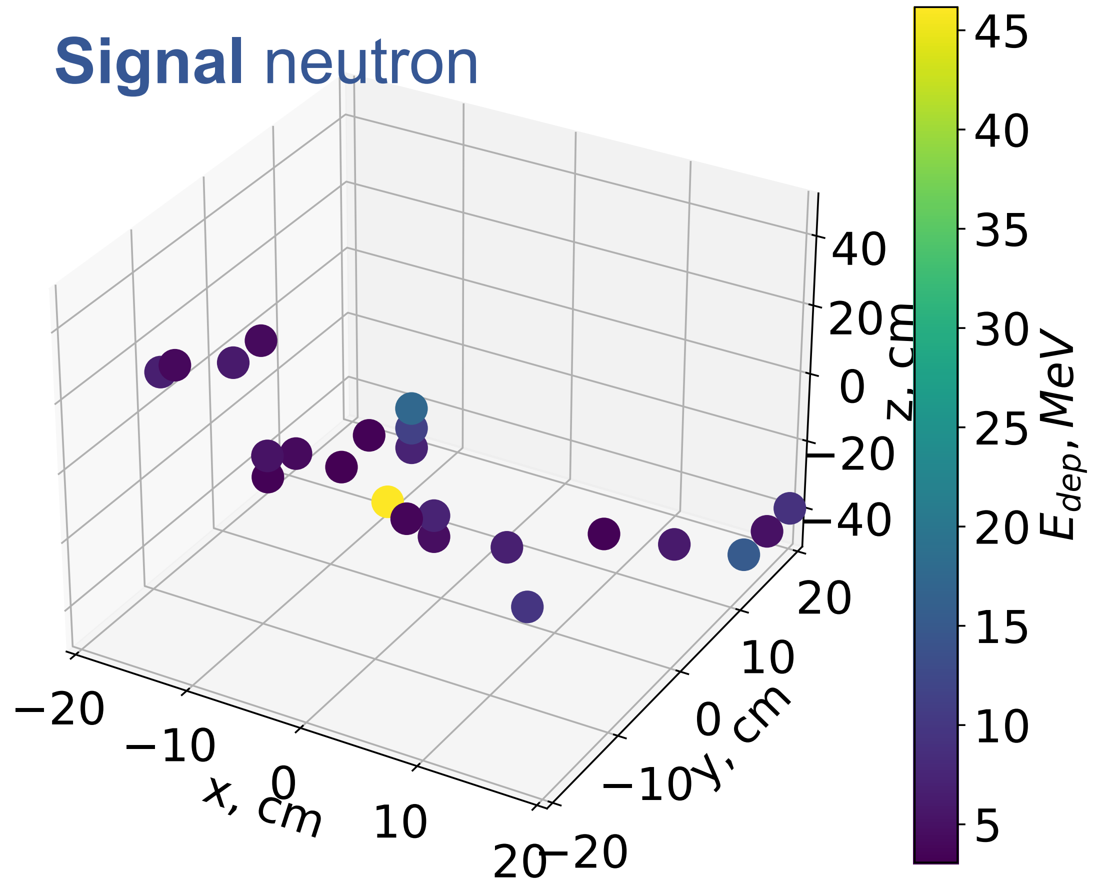
Imaging capabilities of the HGND

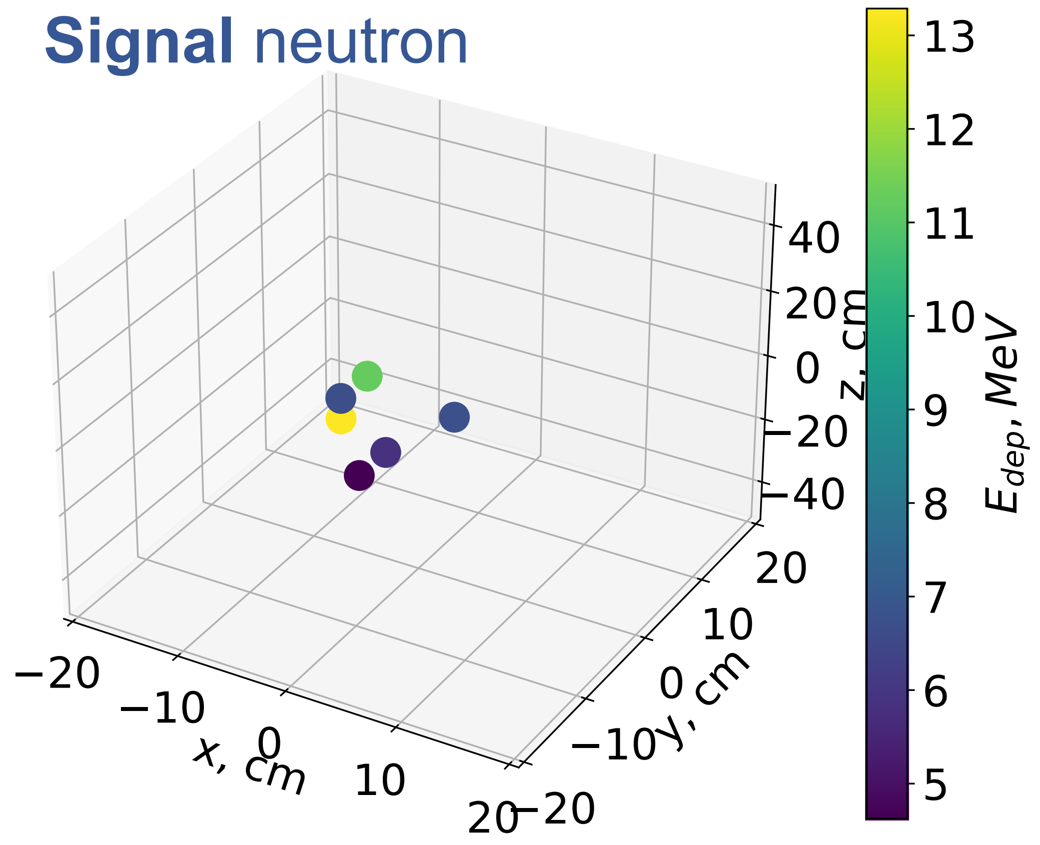
Detector image signatures:
- **tracks** of charged particles
- compact **electromagnetic showers**
- sparse and irregular **hadronic showers**
  - no upstream track for neutral hadrons (including **neutrons**)











V.

Data labeling

Observables per hit:

- $(x,y,z)_{hit}$
- E_{dep} (>3 MeV)
- $T_{hit}+\mathcal{N}(0,\sigma = 150ps) < 40ns$

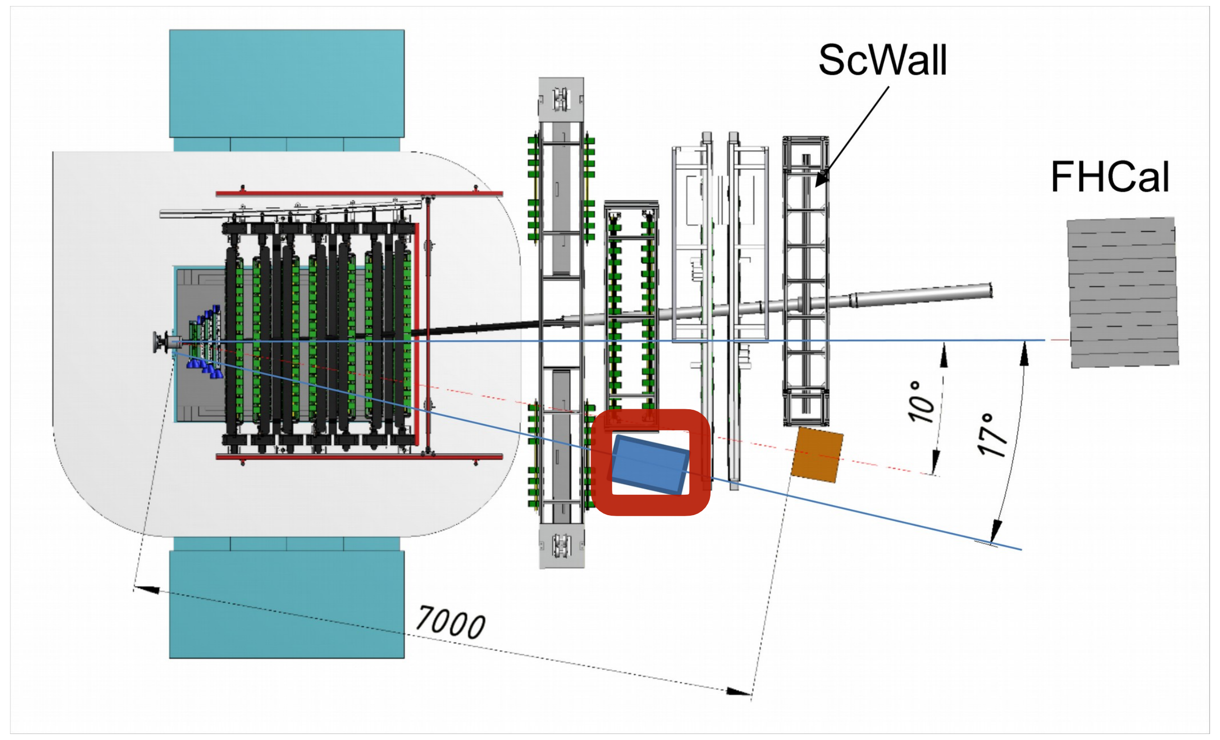
Signal event labeling:

- neutron,
- E_{kin} > 100 MeV,
- Angle to detector axis < 10º
- $\delta(E_{ToF})$ < 40%

272844 events in total

with deposition >3 MeV

- fastest - **21917 signals**
- median - **34670 signals**
- reference - **58949 signals**



17º configuration

Energy correlation for selected signal events: