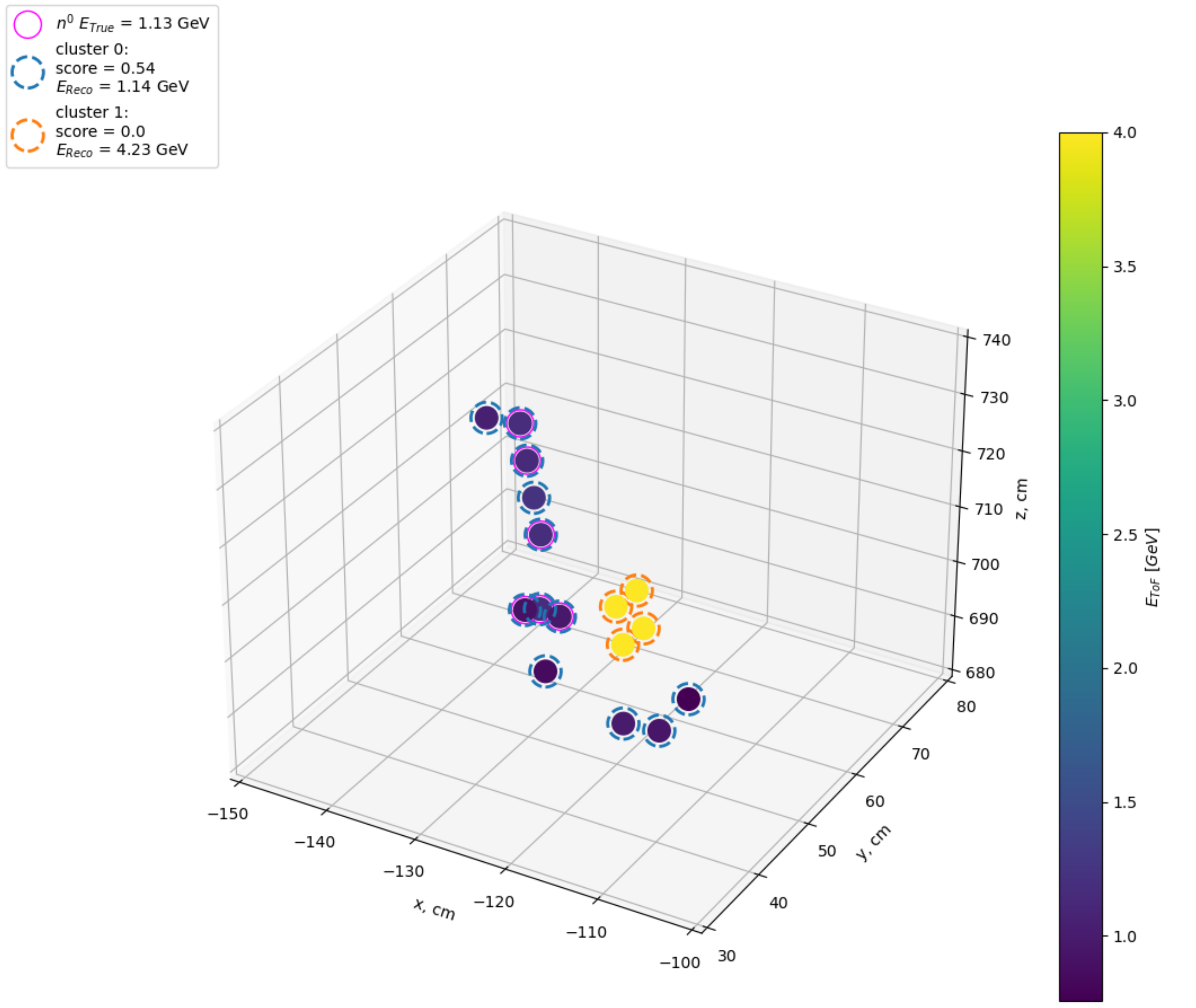
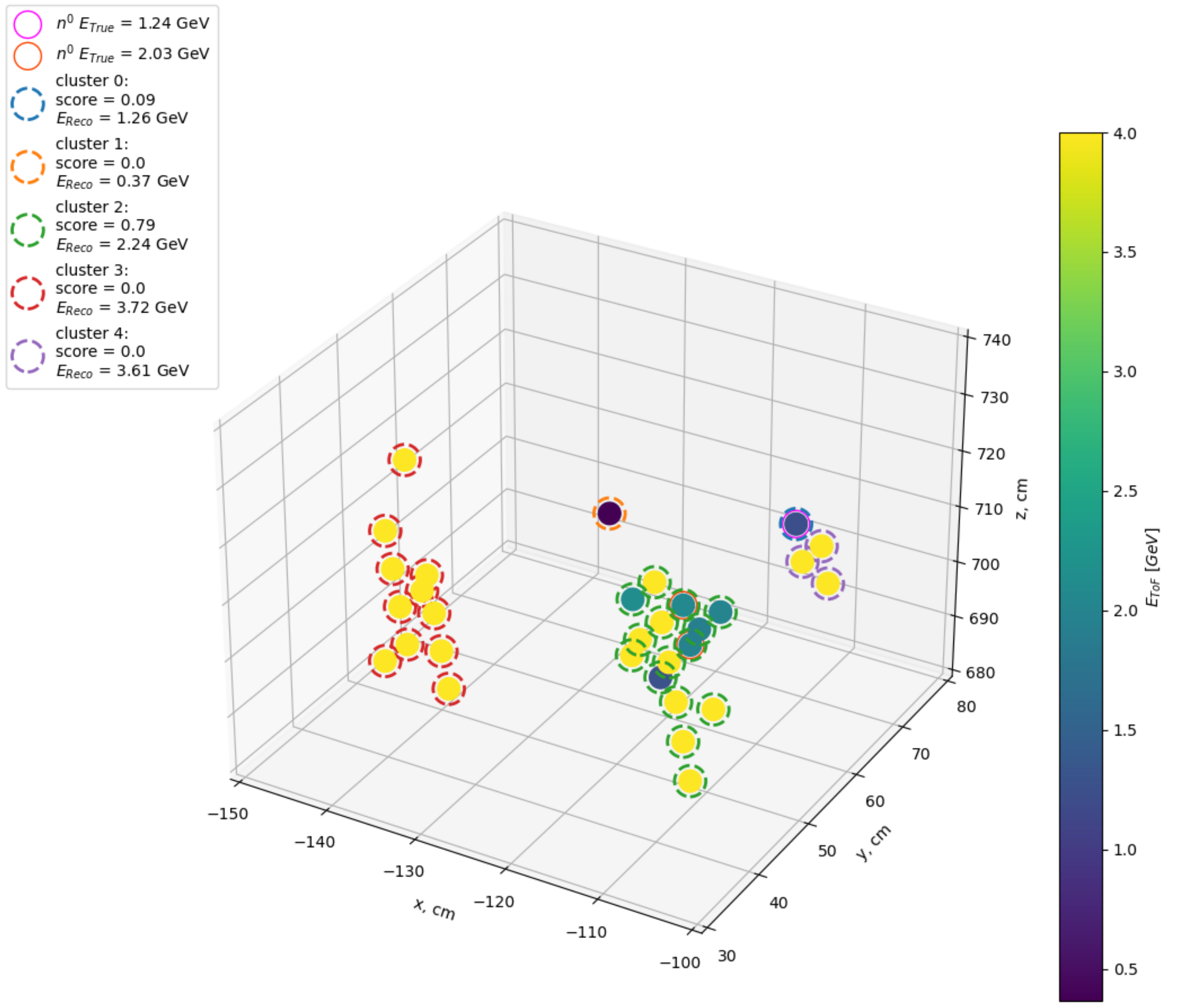
GNN-based neutron reconstruction in the highly-granular neutron detector at the BM@N experiment





Vladimir Bocharnikov

29.10.2025

HSE JINR BM@N FCS LAMBDA • HSE

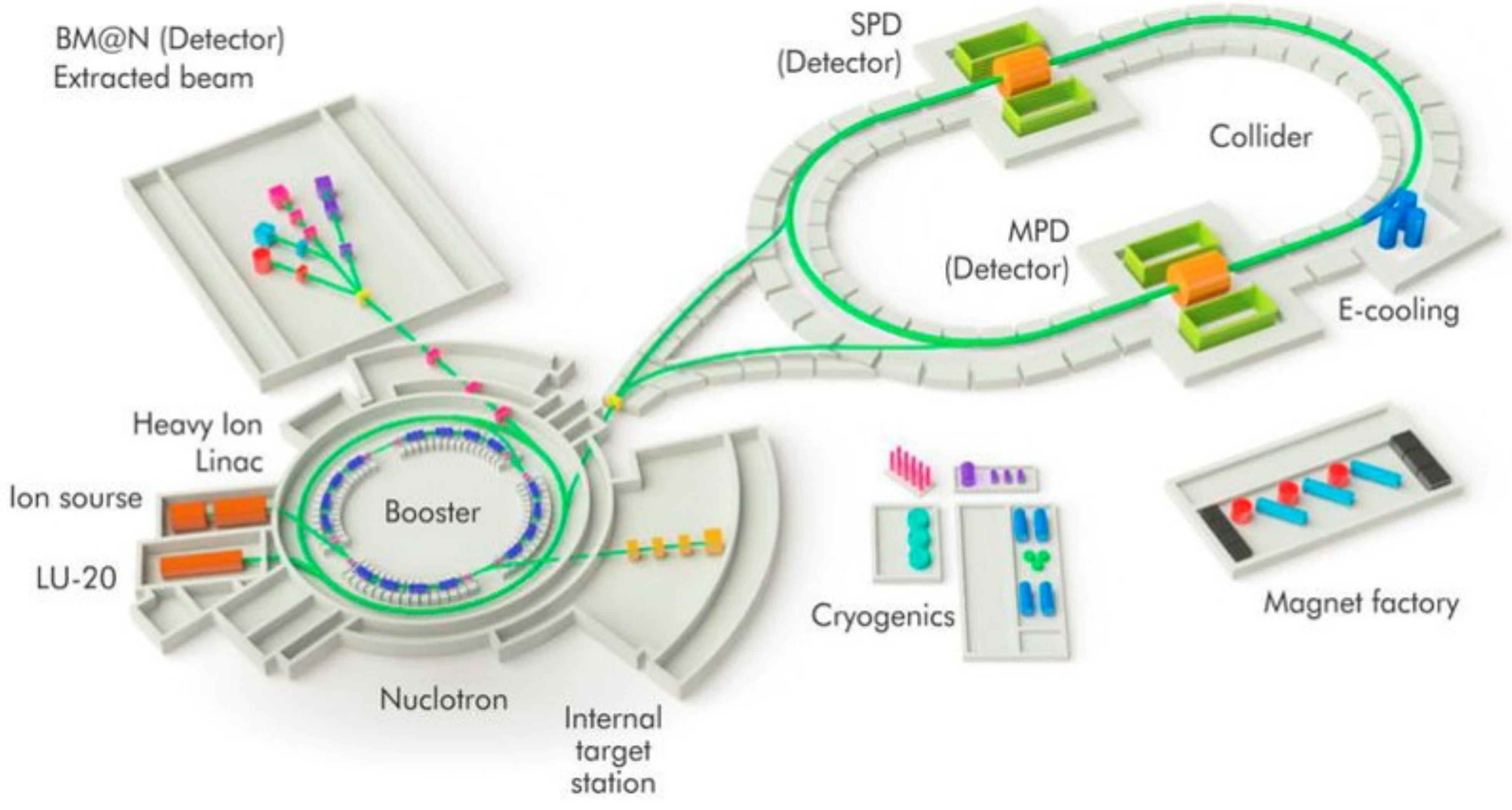
BM@N experiment

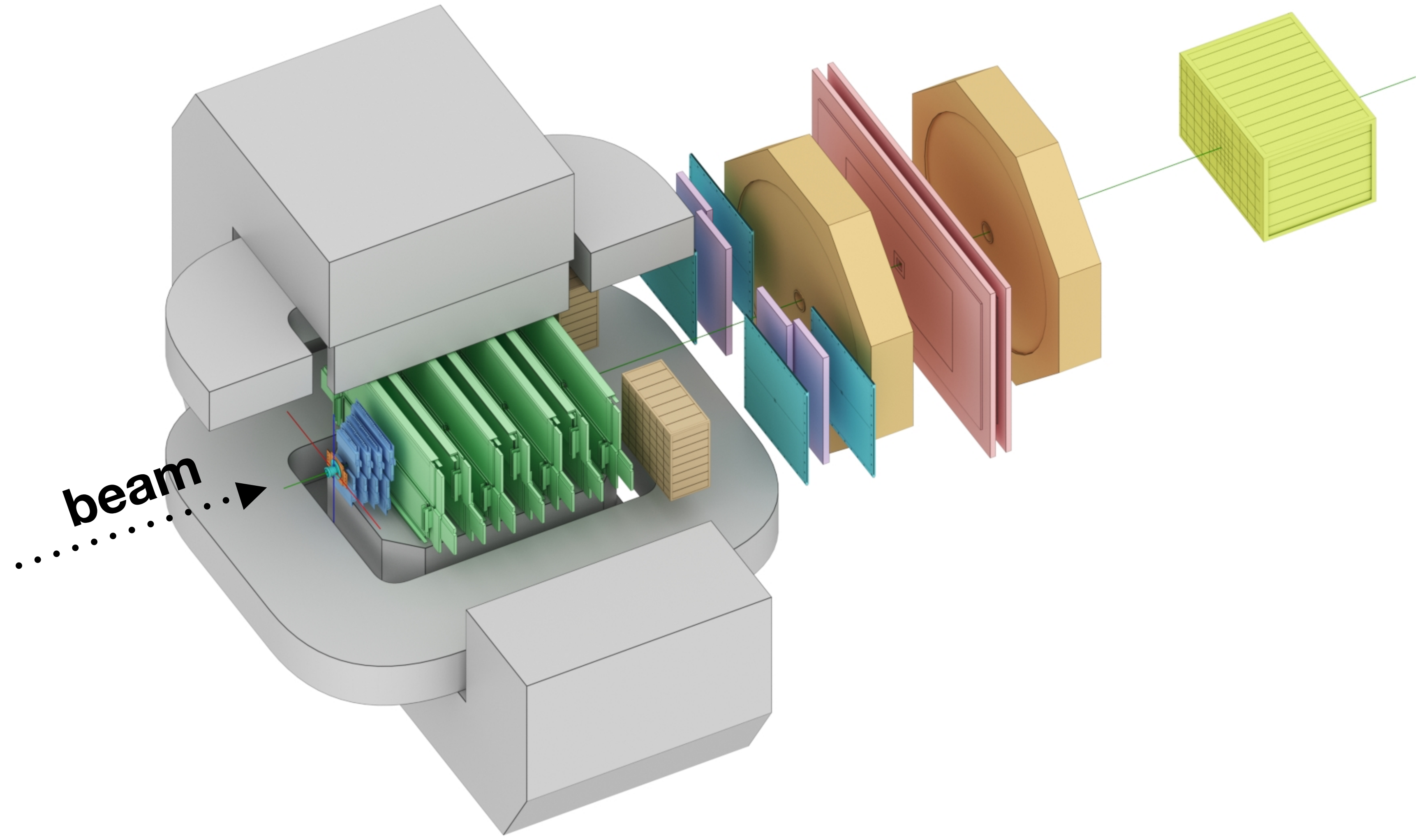
Studies of **B**aryonic **M**atter **at** the **N**uclotron (NICA, JINR Dubna)

- Heavy-Ion beam with energies up to 4A GeV interacts with fixed target

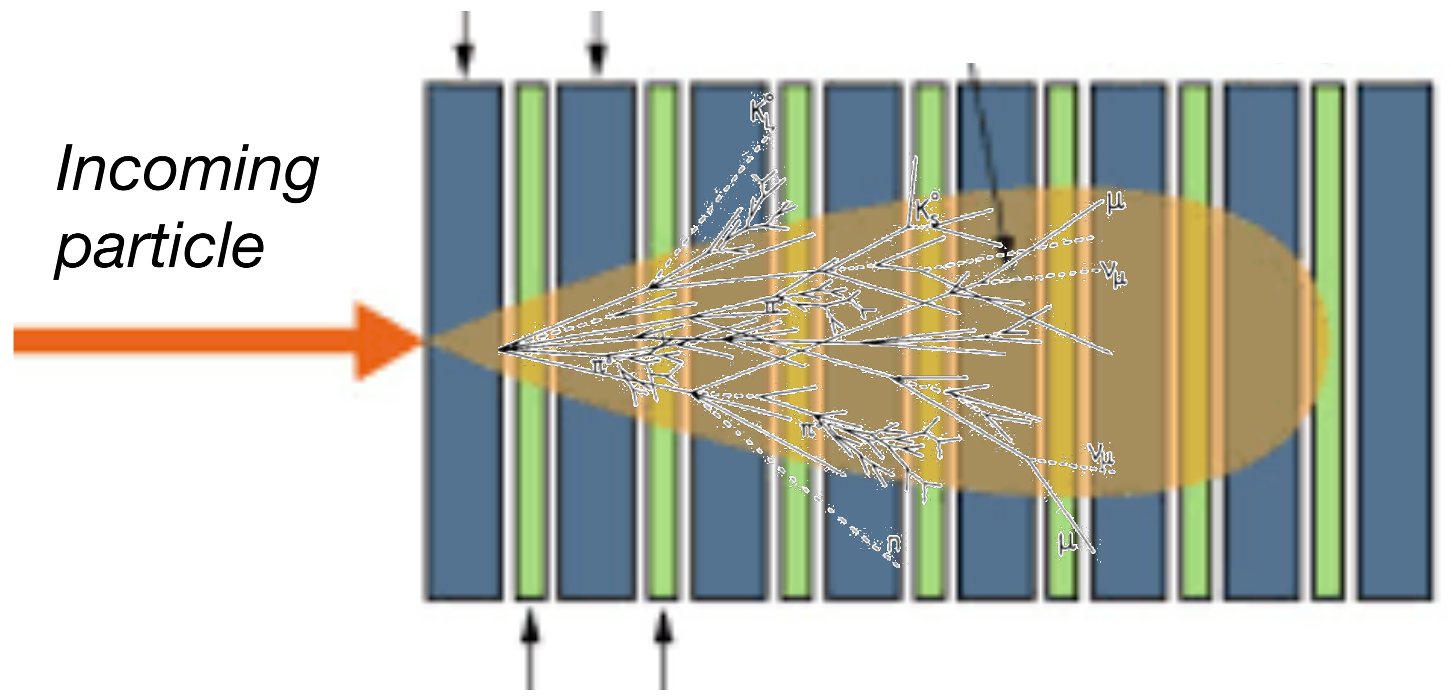
➡ investigate the **equation-of-state (EOS)** of **dense nuclear matter** which plays a central role for the dynamics of core collapse supernovae and for the stability of neutron stars.

- Azimuthal properties of produced particles - important tool for EOS studies
  - we focus on **neutron** flow and yields





Neutron detection



Calorimetry:

- Particles interact with matter
- Depends on particle type
  - Neutrons travel on a long distance w/o interaction before producing a shower
- Energy loss transferred to detectable signal
  - Light (e.g. scintillator) -> electric signal
  - Signal collected and acquired
  - *Good energy resolution for 5+ GeV n^0*
- In the end: digitized signal
  - Coordinates, energy deposition, time

Time-of-Flight (ToF) measurements:

- Time of arrival and distance to the production point gives momentum of a particle

➡ With known particle mass (neutron) we can calculate it's energy

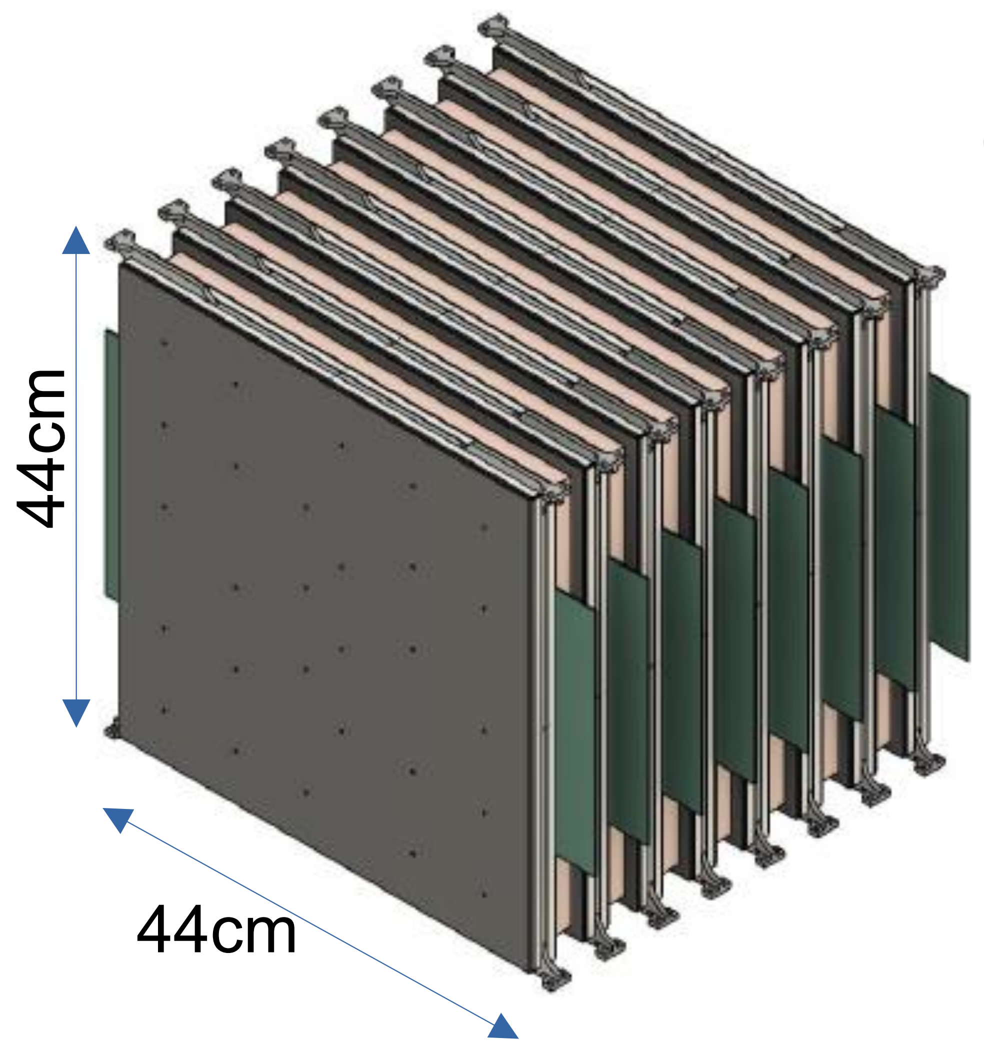
$$E_{ToF} = m_n \left(\frac{1}{\sqrt{1 - (\frac{v}{c})^2}} - 1 \right)$$

Good energy resolution up to 2-3 GeV n^0

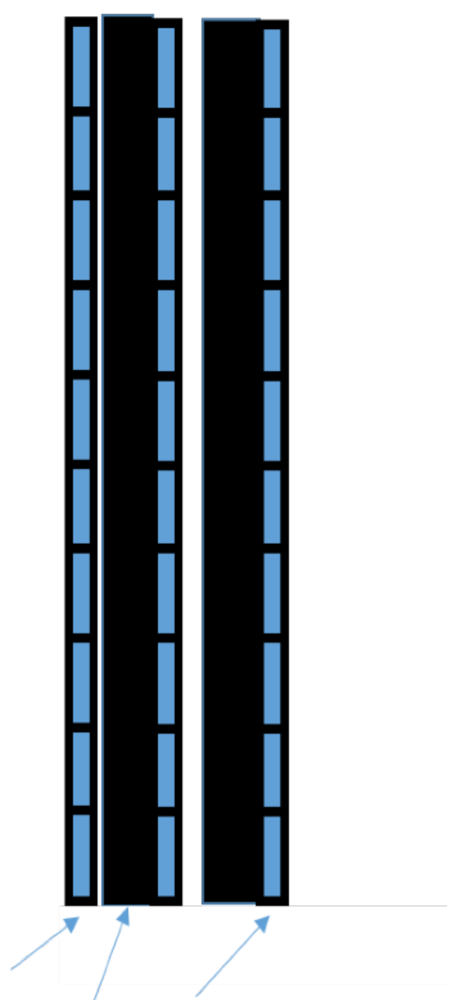
we use calorimeter image to identify neutron and ToF to reconstruct it's energy

Neutron is one of the most challenging particle types for reconstruction due to relatively low probability to interact with matter. Yield of visible energy is very low at energies < 1GeV

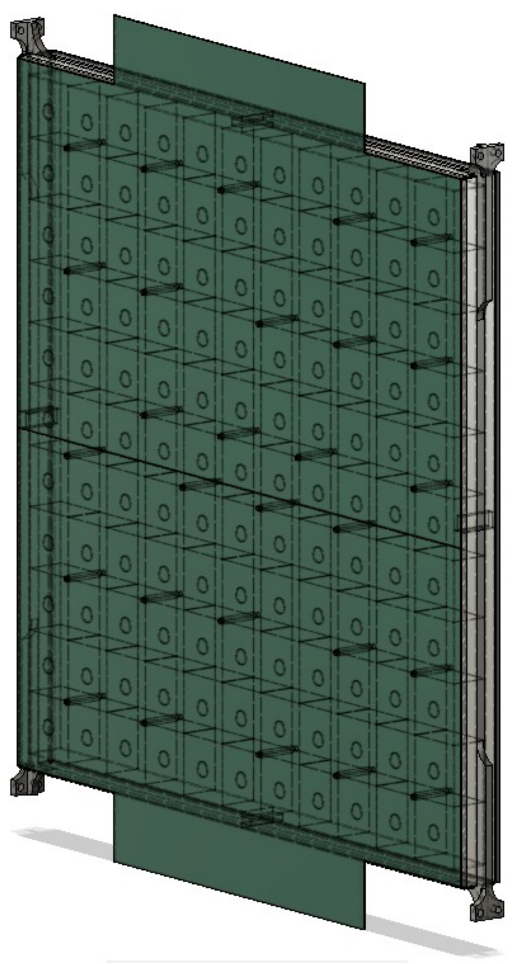
Highly granular time-of-flight neutron detector (HGND)

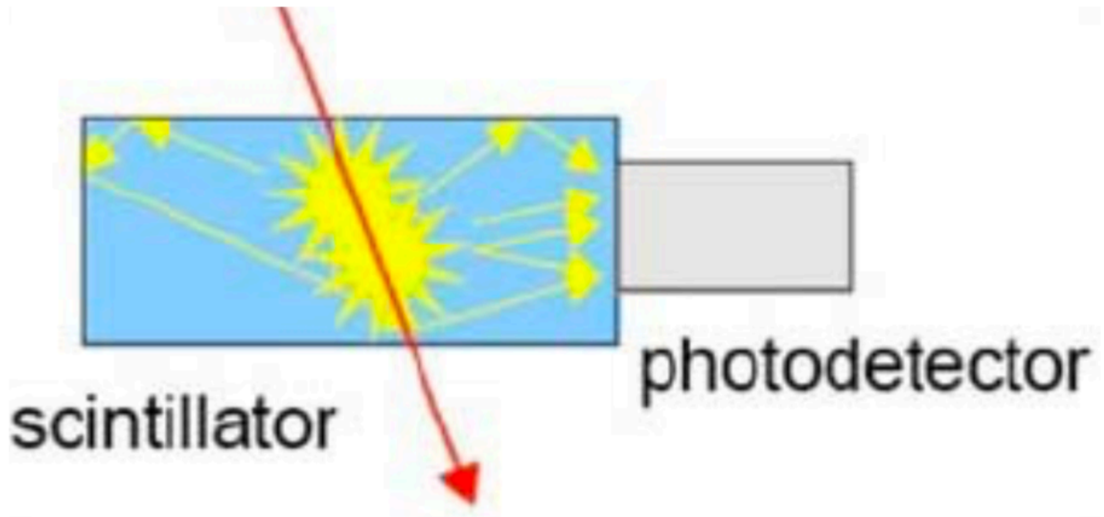


Longitudinal structure



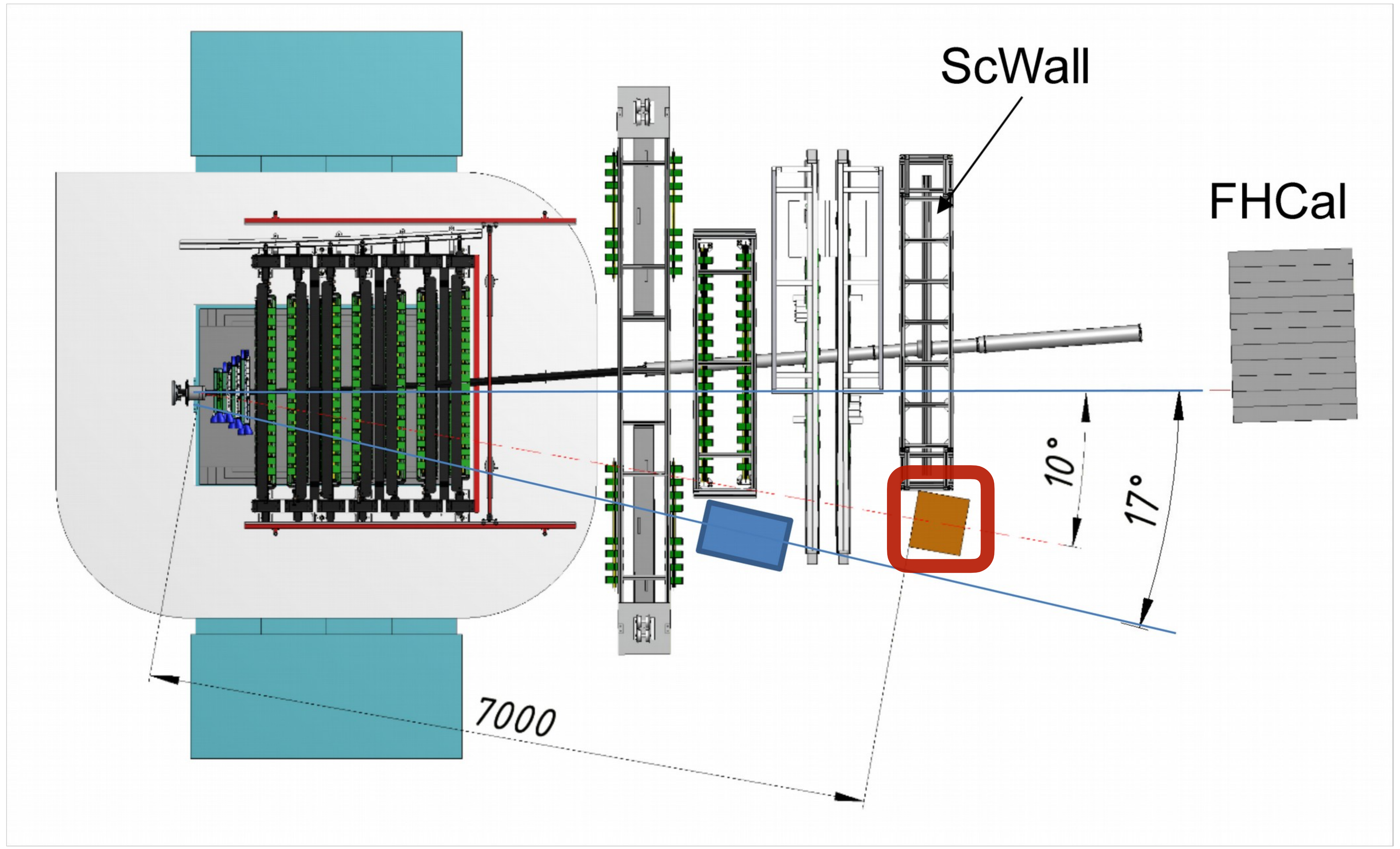
Active layer

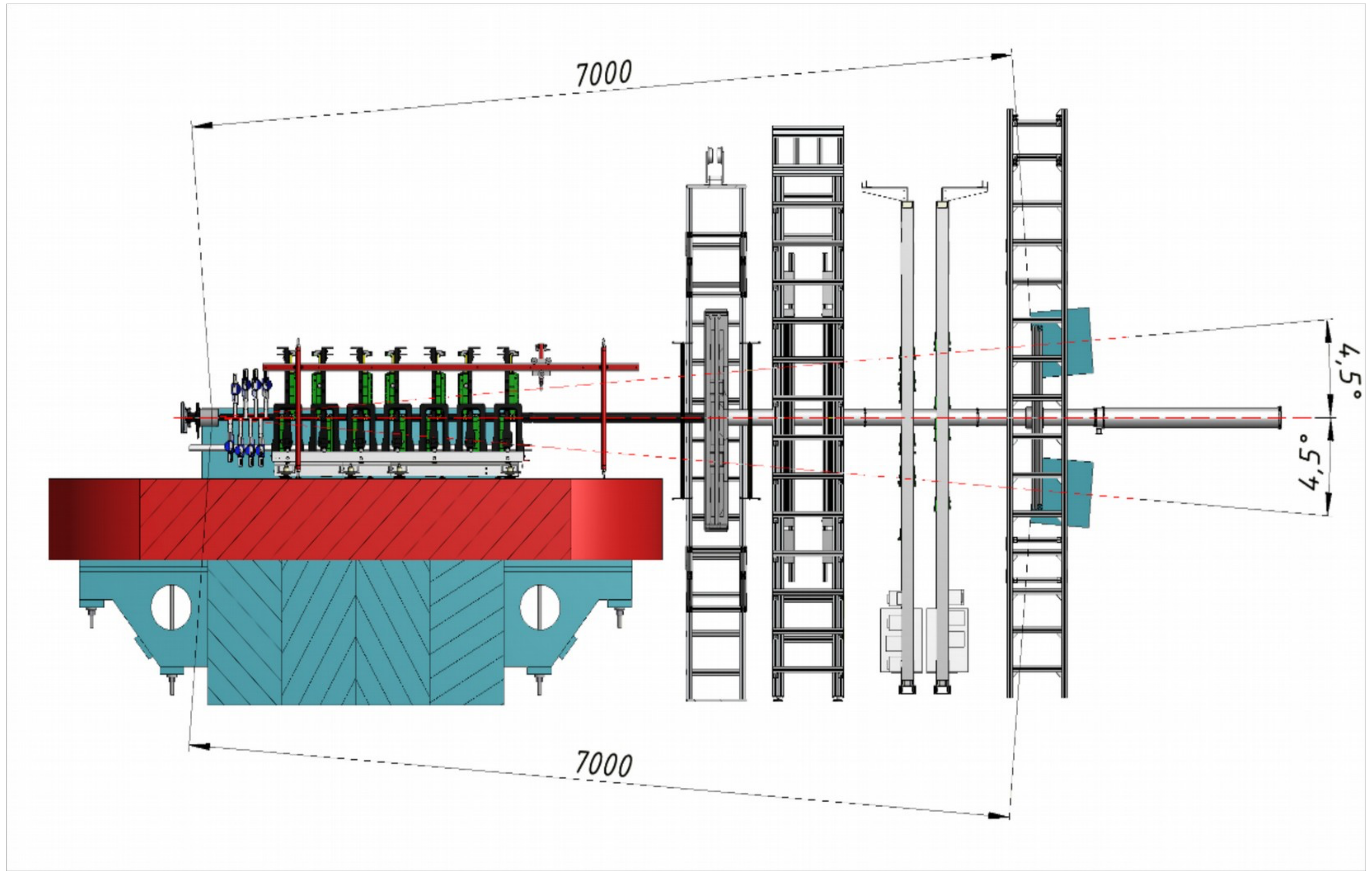




- (2x) 8 layers: *3cm Cu (absorber) + 2.5cm Scintillator + 0.5cm PCB; 1st layer — 'veto' before absorber*
  ➡Total length: ~0.5m, **~1.5 λ_{in}**
  ➡ neutron detection efficiency ~60% @ 1 GeV
  - Transverse size: **44x44 cm²**
  - *11x11 scintillator cell grid*
- scintillator cells:
  - size: 4x4x2.5 cm^3,
  - **total number of cells: 968 (x2)**
  - individual readout by SiPM
  - expected time resolution per cell: ~150 ps

Detector Setup and Simulations





- HGND sub-detectors are located at **10º to the beam** axis at **~7m from the target**
- Monte-Carlo event simulations with full detector setup model:
  - **3 AGeV Bi+Bi** DCM-QGSM-SMM model + Geant4 v11.2.0 FTFP_BERT
  - **~1M events**

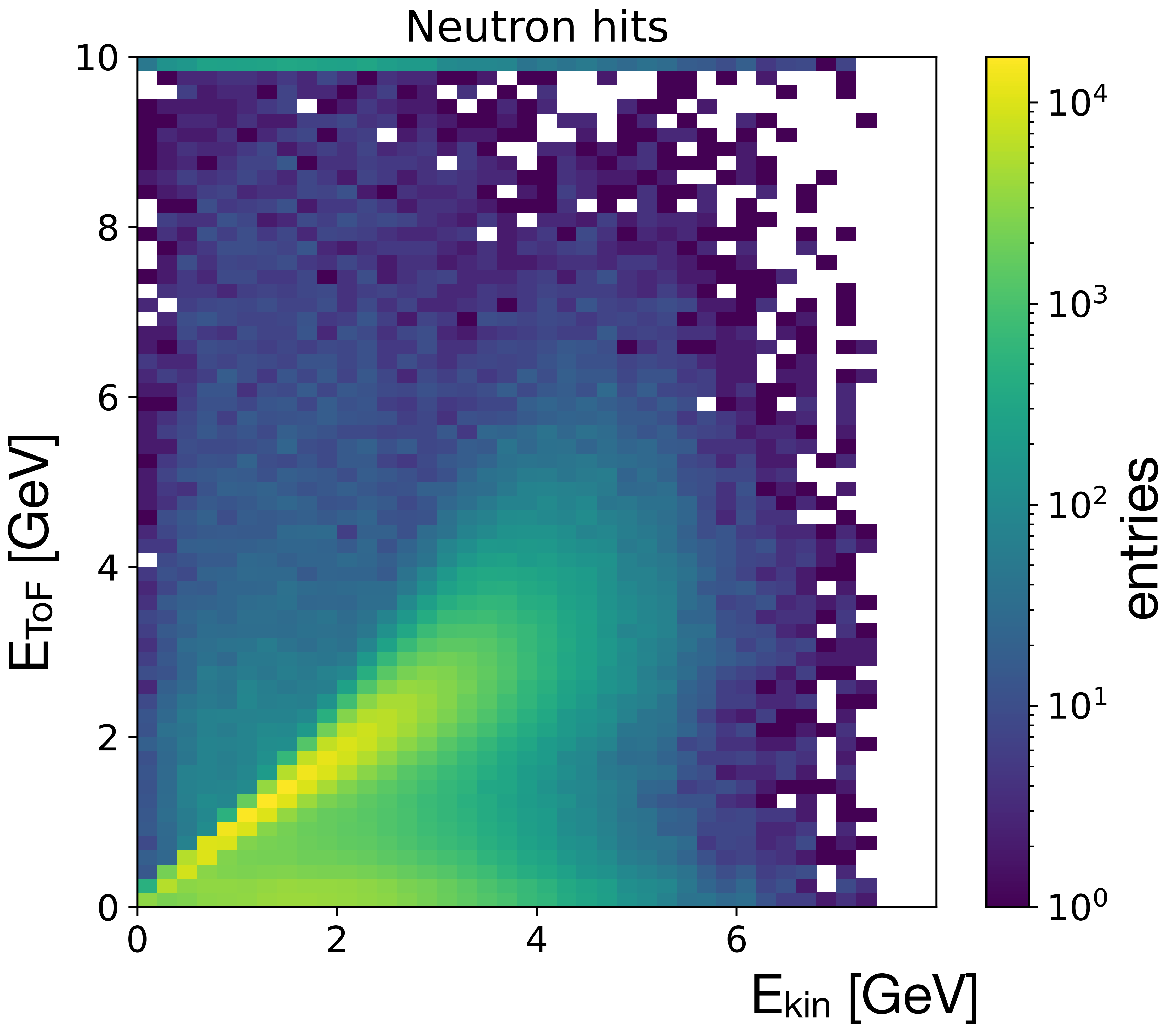
Hit Level Information

- E_{dep} > 3 MeV ~ 0.5 MIP
- **ToF energy** for n^0 hypothesis:

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

  - $t_{hit}+\mathcal{N}(0,\sigma_t = 150\text{ps})$
  - clip at 10GeV
- Each hit is linked with corresponding surface MC particle
- signal — neutrons passed the upstream HGND surface

ToF energy for neutron hits



- Underestimation - neutron shower development
- Overestimation - background contributions in the same hits

  ➡More precise labelling is under development

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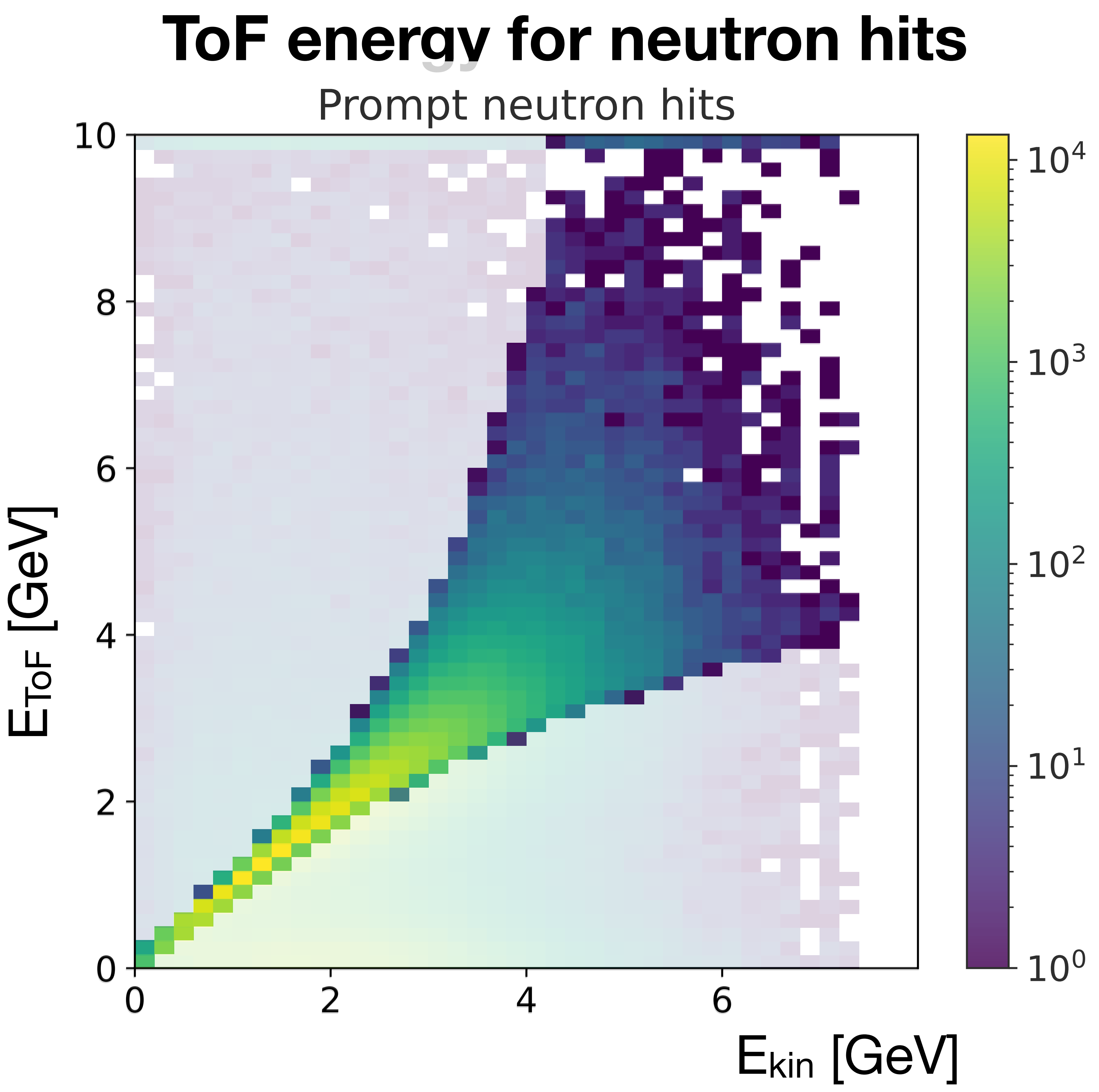
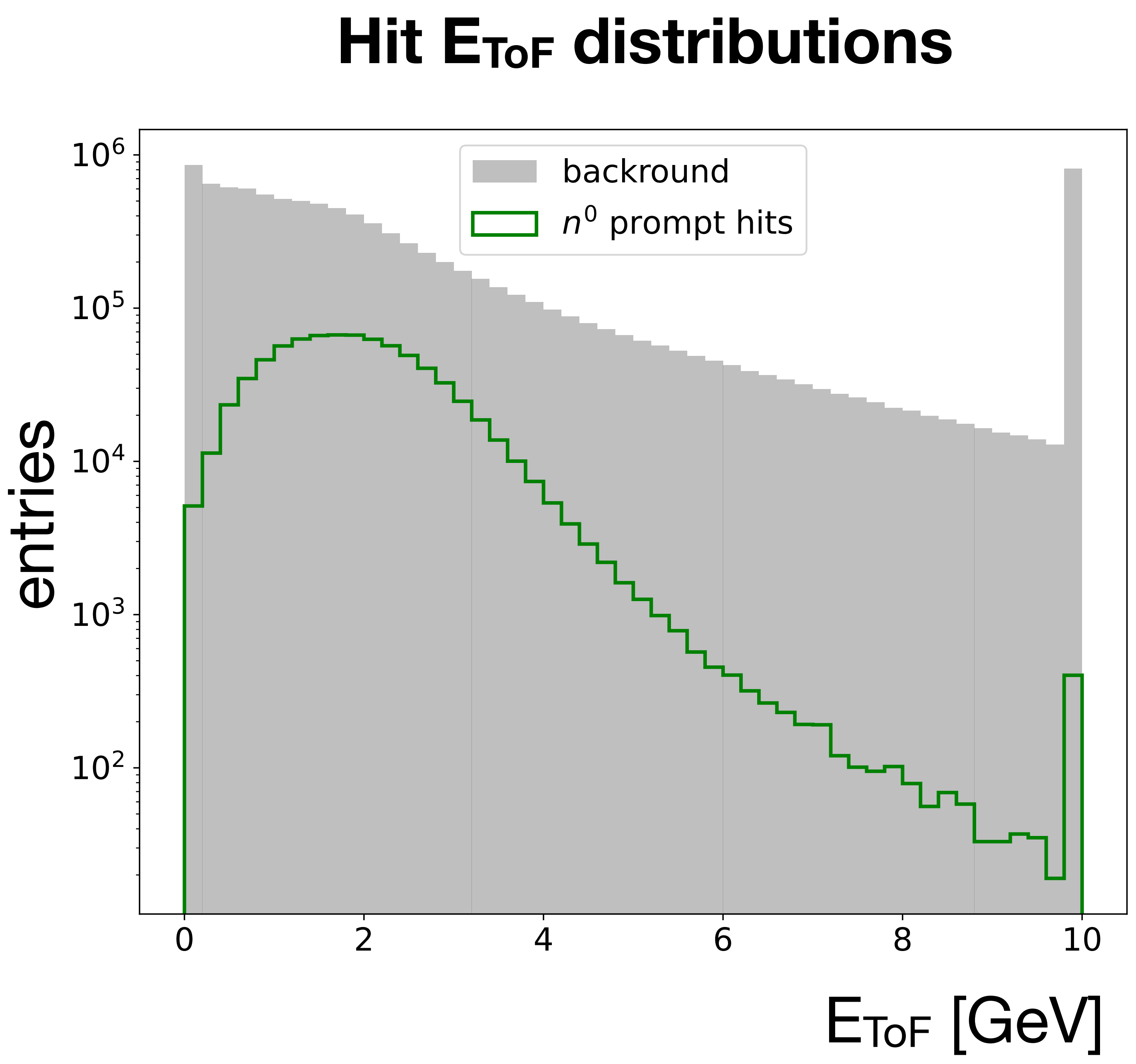
- **Prompt neutron deposition** selected by $\mathbf{E_n \in E_{ToF}(t_{hit} \pm 2\sigma_t)}$
  - other hits - background





- Underestimation - neutron shower development
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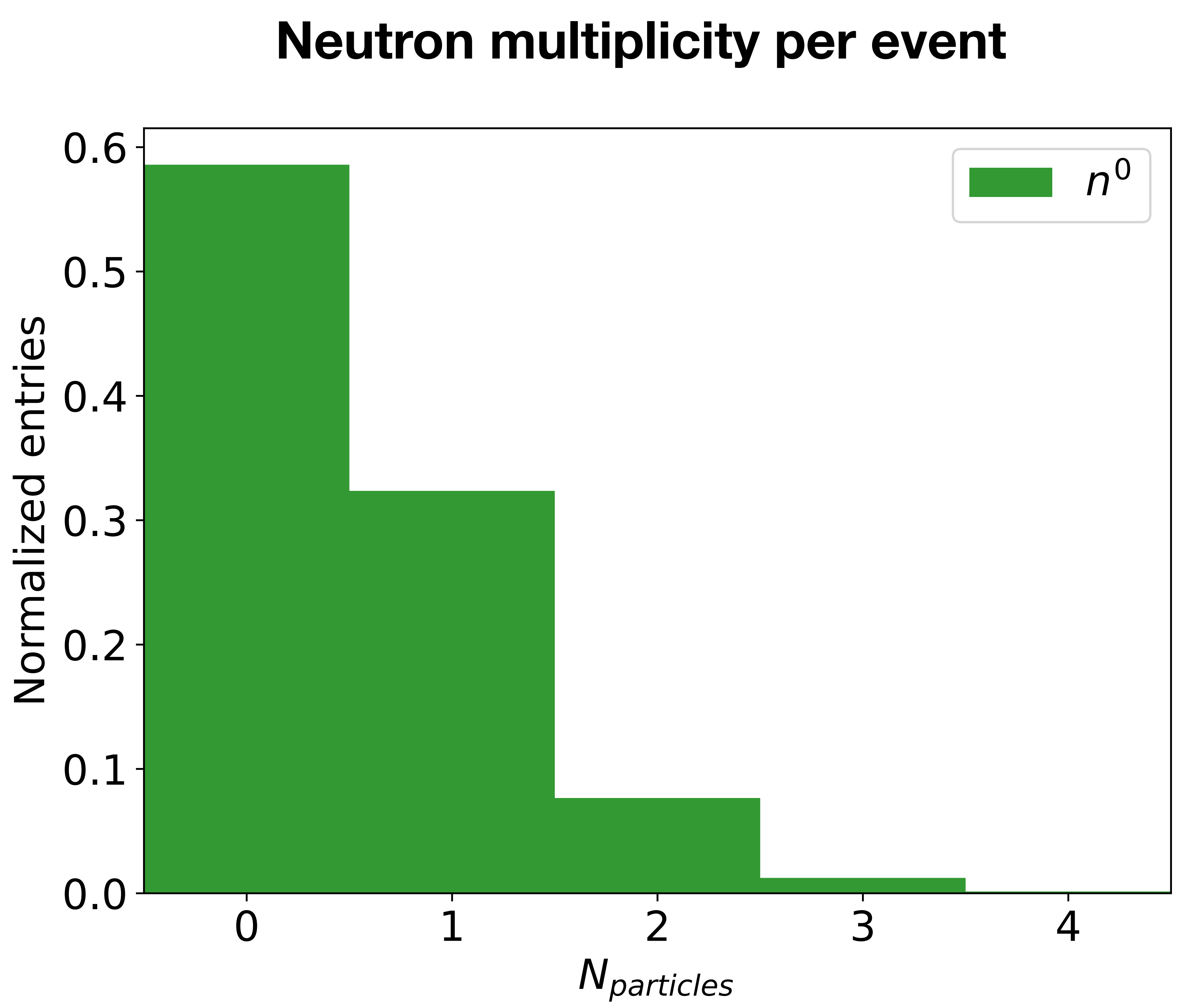
  - ➡More precise labelling is under development

Neutron Multiplicity

- Multiplicity counts require
  - existence of **prompt hit**
  - E_{n0} > 0.1 GeV
  - neutron passed upstream HGND surface

- Distributions normalised to number of events with energy deposition
  ➡Neutron detection efficiency is not discussed
- Reconstruction algorithm has to deal with neutron multiplicities > 1



Graph Neural Networks (GNN)

Why Graph Neural Networks:

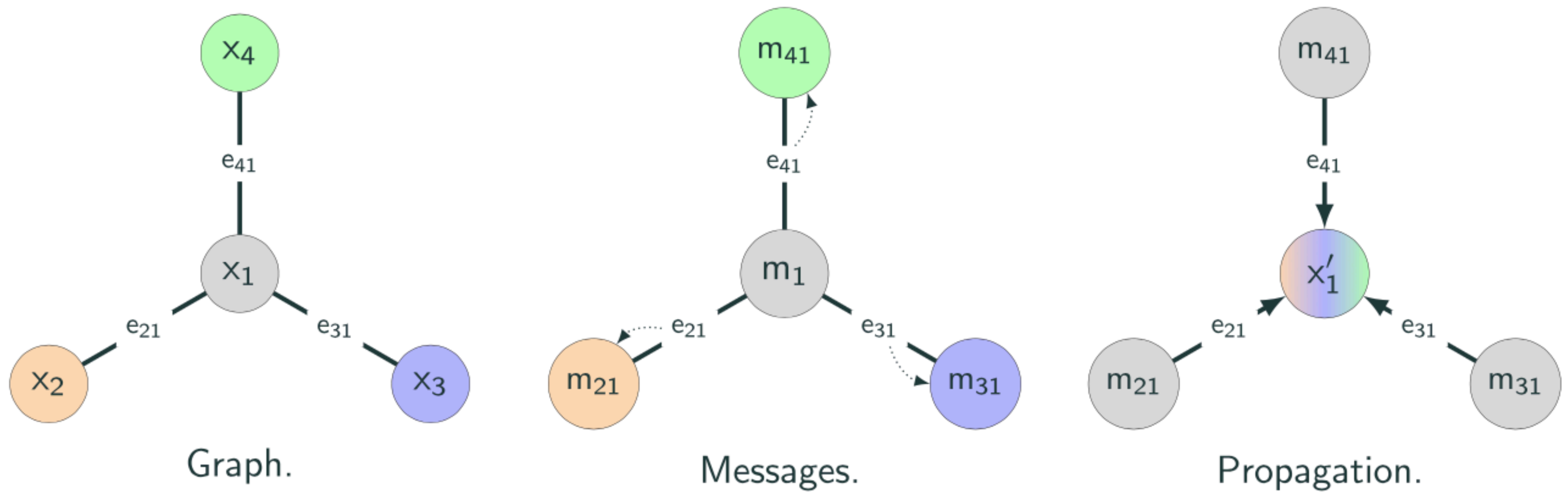
- Natural vector event representation
  - Detector cell hits as graph nodes
- Easily applied to sparse data with variable input size
  - Typically we have signal only in small fraction of sensors
- Captures event structures
- Increasing number of successful implementations in HEP

HEPML-LivingReview

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/hit class “probability” — signal/background
  - Target value — neutron energy



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

Graph Construction

- **Nodes — hits.** Observables per hit:
  - hit coordinates: layer, row, column
  - E_{dep} > 3 MeV ~ 0.5 MIP
  - hit time + $\mathcal{N}(0, \sigma = 150ps)$
  - E_{ToF}

- **Edges**
  - Predefined clustering:
    - radius graph. **R = 3.6 cells**
    - time window **1.5 ns**
    - cluster — **isolated subgraph**

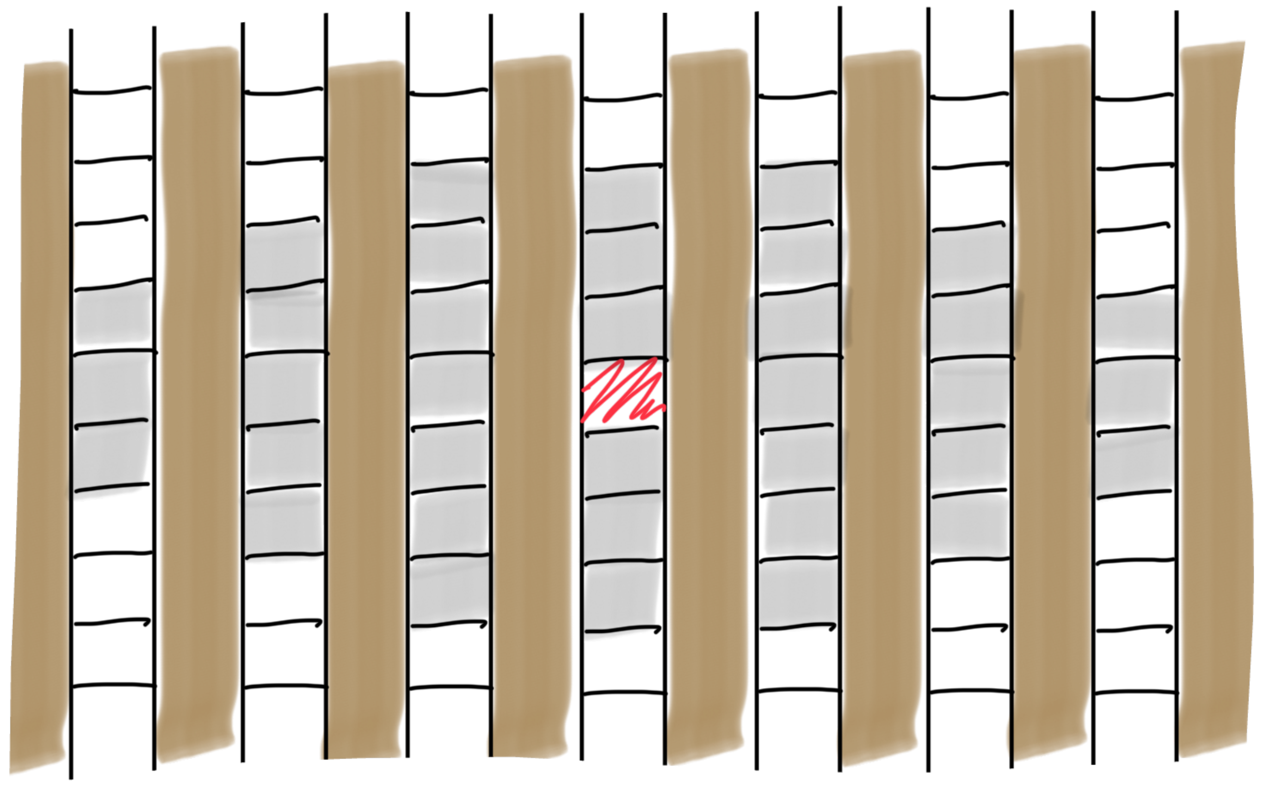
Labeling for further training

- Cluster level:
  - **Signal** cluster contains at least 1 **prompt neutron** hit
  - **Energy** of fastest neutron with prompt hit in a cluster

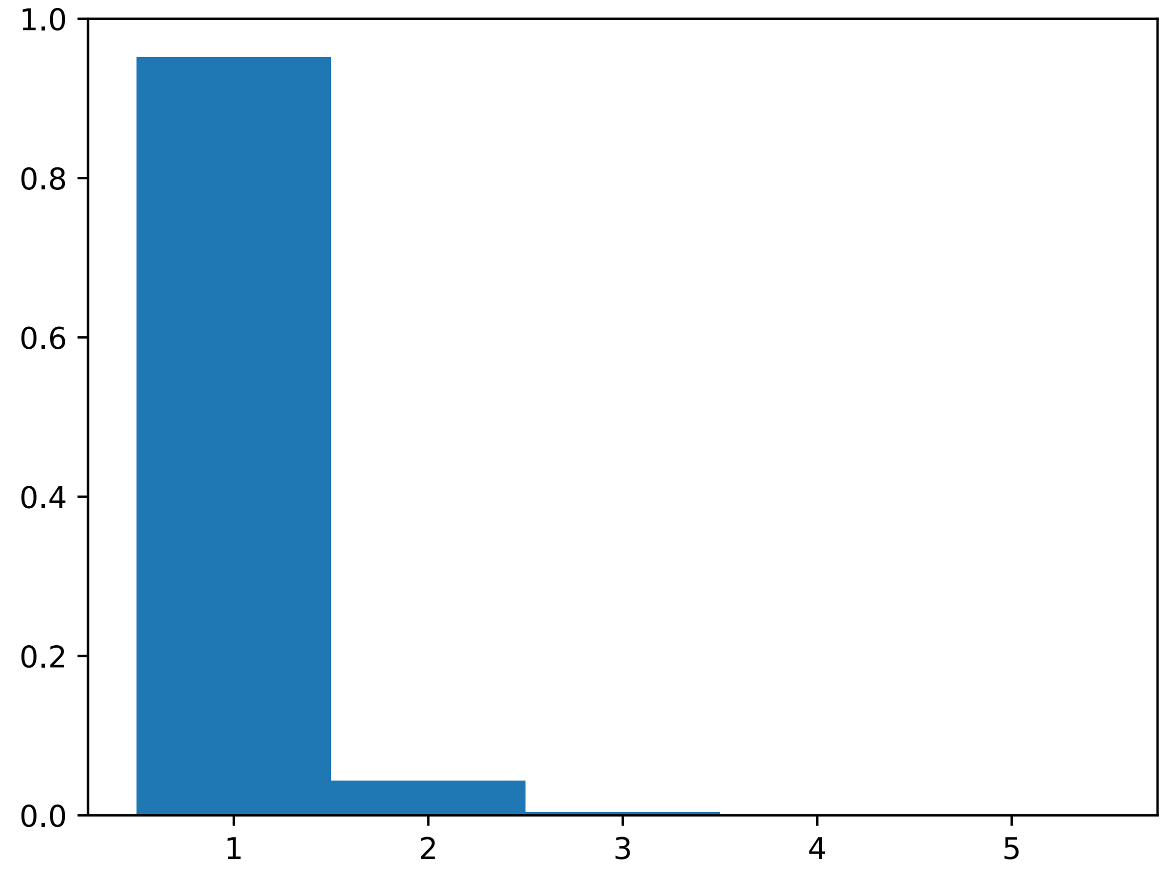
Clustering

- Soft spatial rule.
  - search radius **R = 3.6 cells**
- ~strict temporal rule
  - time window **1.5 ns**

➡ first guess parameters, to be optimised, included in GNN

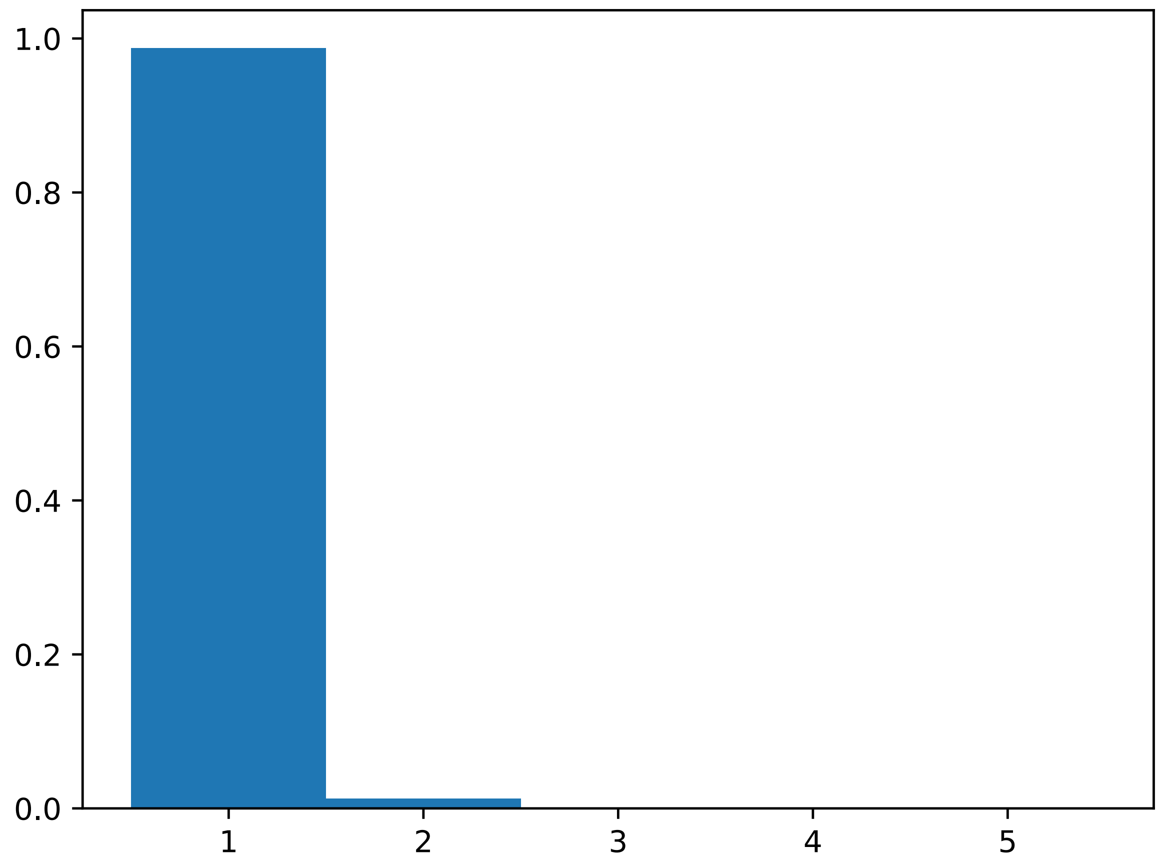


Prompt n^0 multiplicity per signal cluster



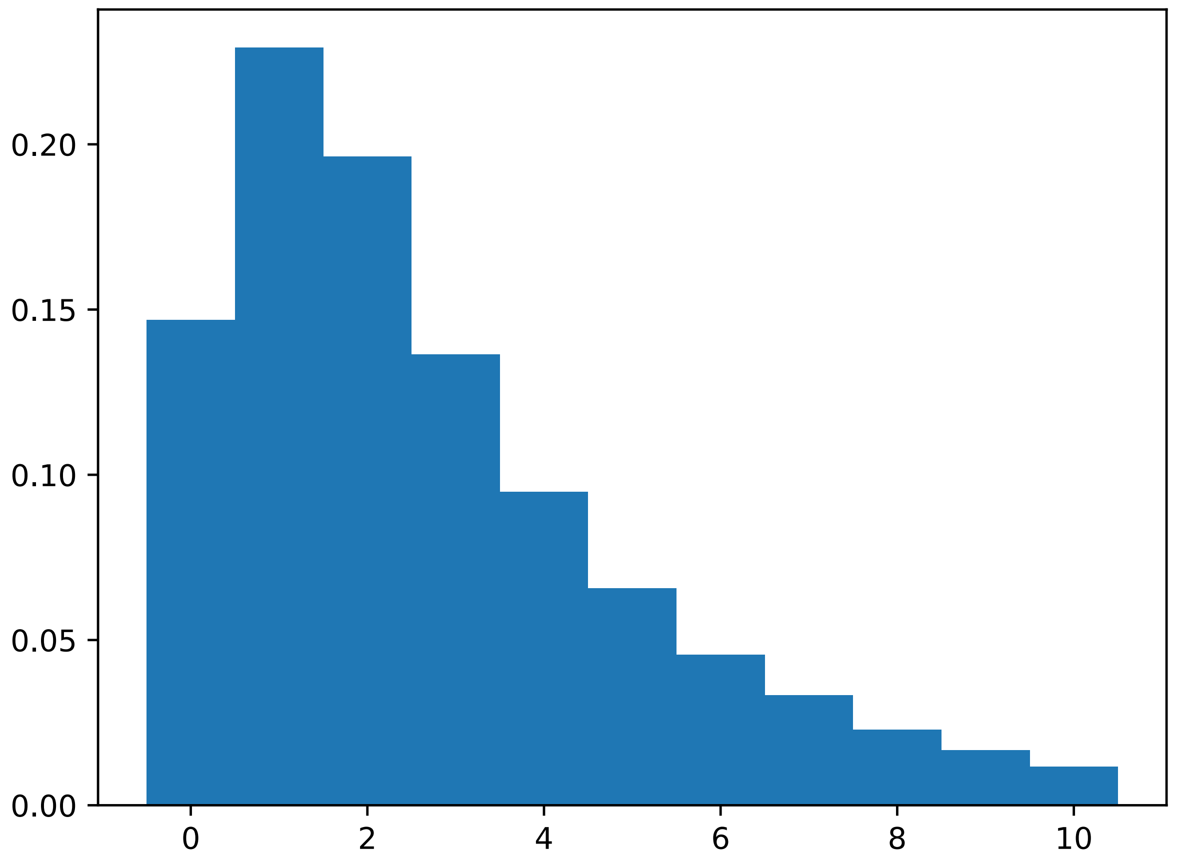
- isolation >95%

Cluster multiplicity per prompt n^0



- prompt n^0 splits in secondary clusters at level of < 2%

Background multiplicity per signal cluster



- significant background contribution => make use of ML

GNN Model

Training objective

- **Cluster** level:
  - predict **neutron class** score
  - reconstruct expected **neutron energy**

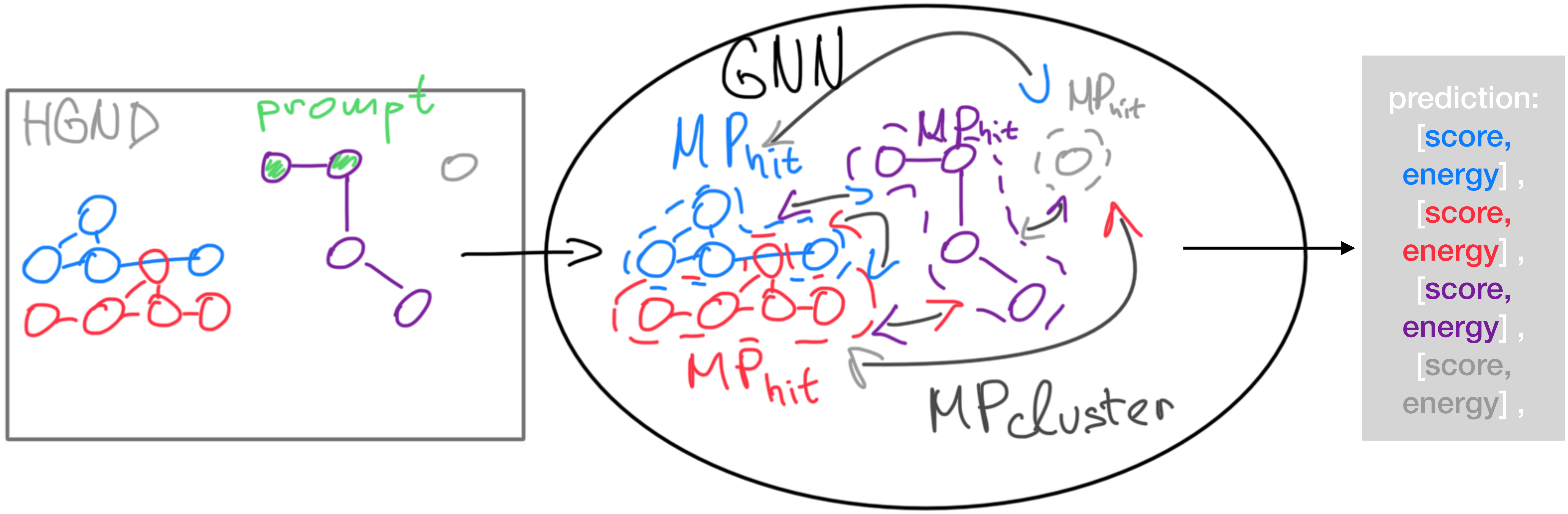
Loss function

- Binary Cross Entropy for classification
- Mean Squared Error for energy regression

$$Loss = BCE_{cluster} + MSE_{cluster}$$

Heteregenious GNN architecture

- *MP_{hit}*. EdgeConv+GraphSage layers *hit -> hit* within clusters
- GraphConv layer to aggregate *hit nodes -> virtual cluster* node
- *$MP_{cluster}$*. FC EdgeConv layer. *cluster -> cluster*
- Cluster output**: class score, predicted energy**

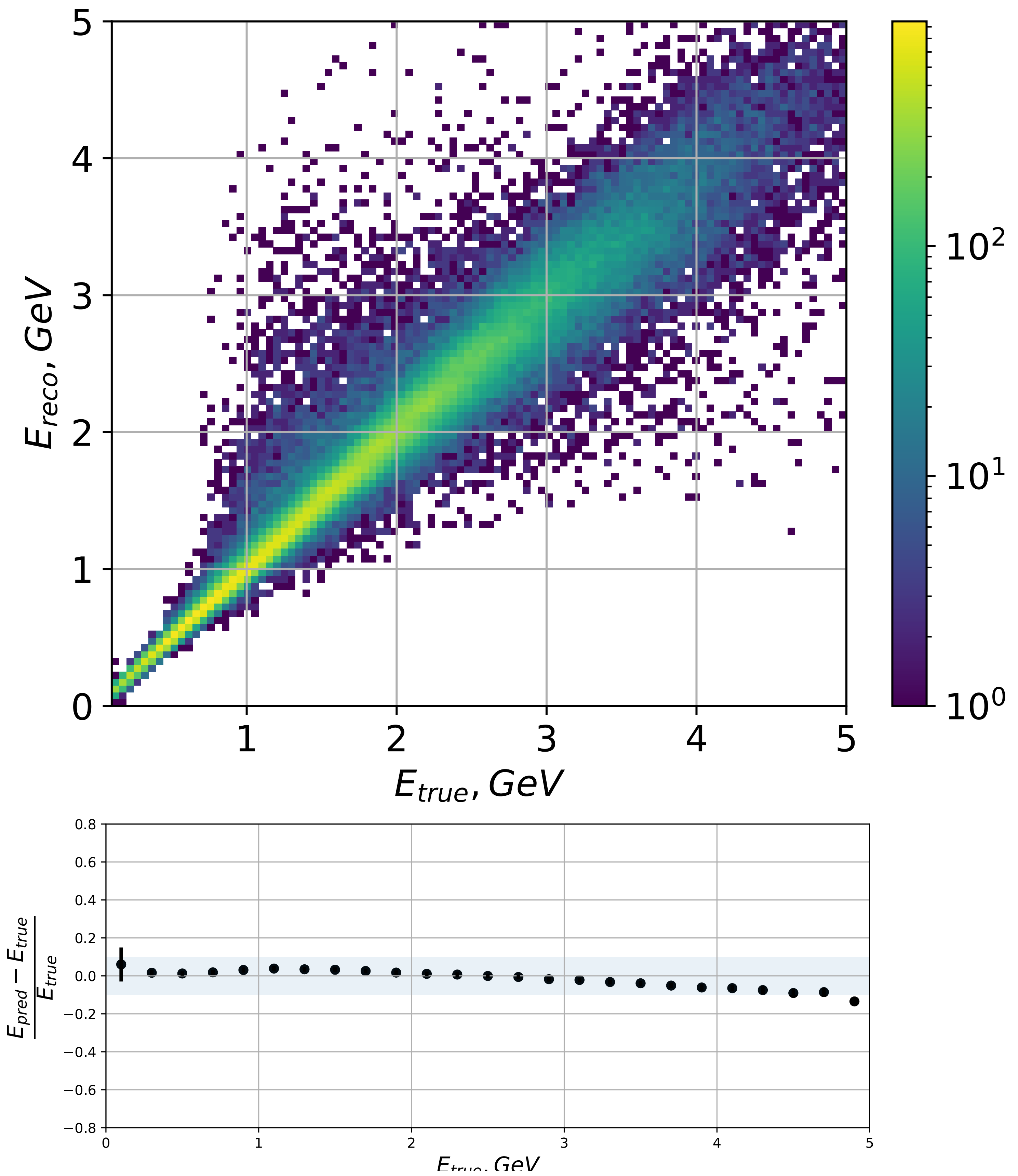


PyTorch Geometric library

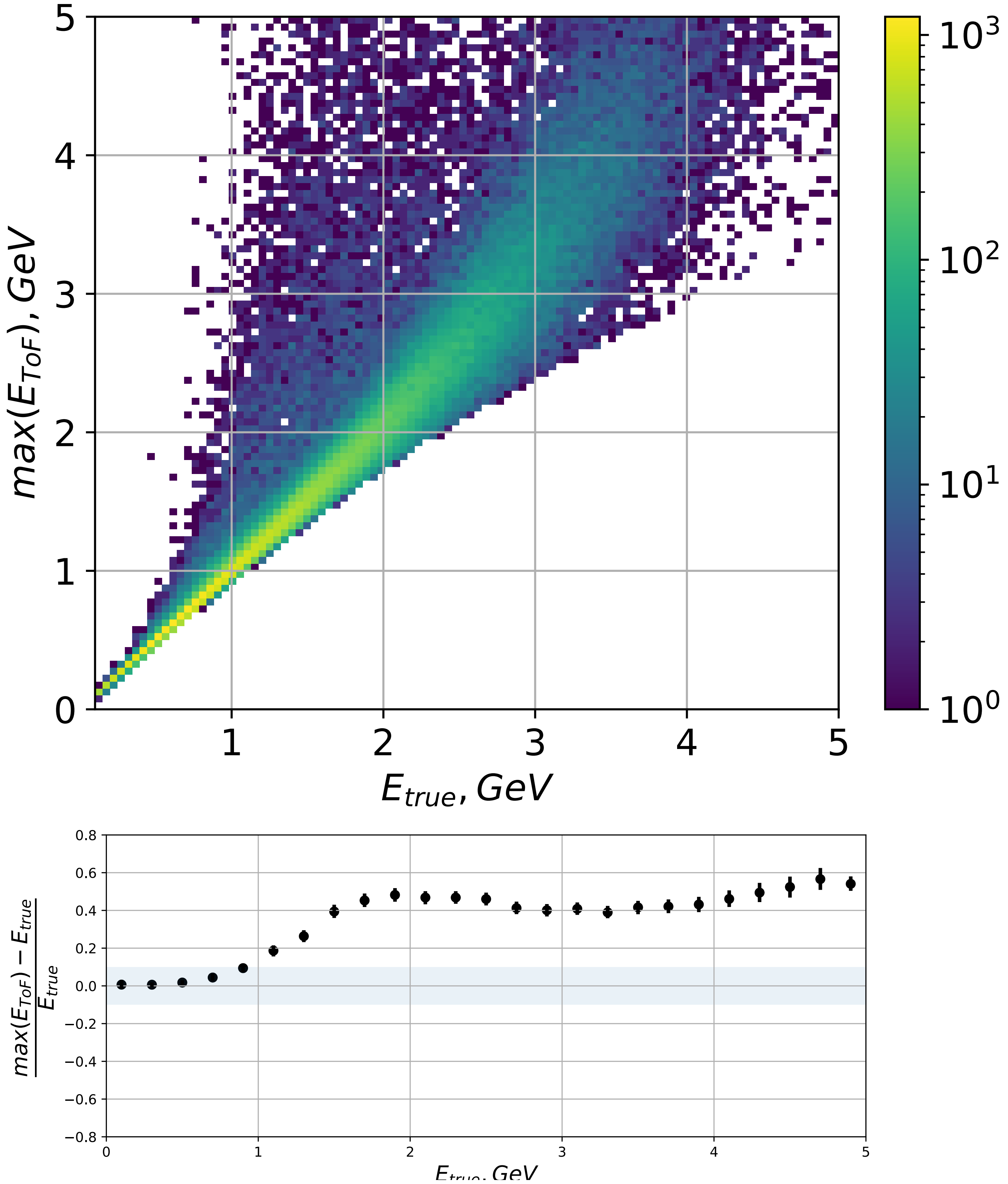
Cluster Reconstruction Performance

- Overall good cluster classification performance. **ROCAUC≈0.96**
- **Energy resolution ≈13%** — estimated on integrated relative error for true neutron clusters
    - **Linearity within 10%** for the most part of energy spectrum. Model compensates ToF overestimation

GNN energy regression

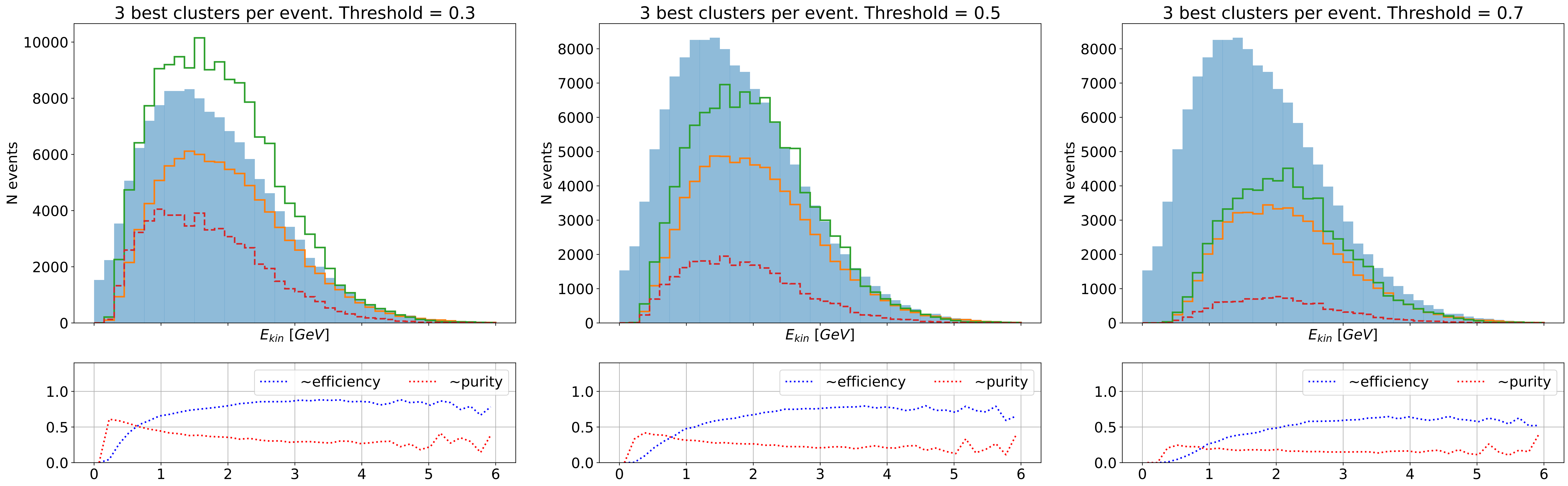


Time-of-flight reference



Neutron Energy Spectra

Examples of resulting neutron energy spectra



$$Efficiency = \frac{E_{true}}{E_{all\ signals}}$$

$$Purity \approx \frac{E_{fake}}{E_{predicted}}$$

- Energy dependent reconstruction performance
- Trade between purity and efficiency
- Optimal reconstruction scenario will be optimised on end-to-end physics performance simulation

Summary & Outlook

- Graph Neural Network-based neutron reconstruction algorithm in the highly granular time-of-flight detector is presented

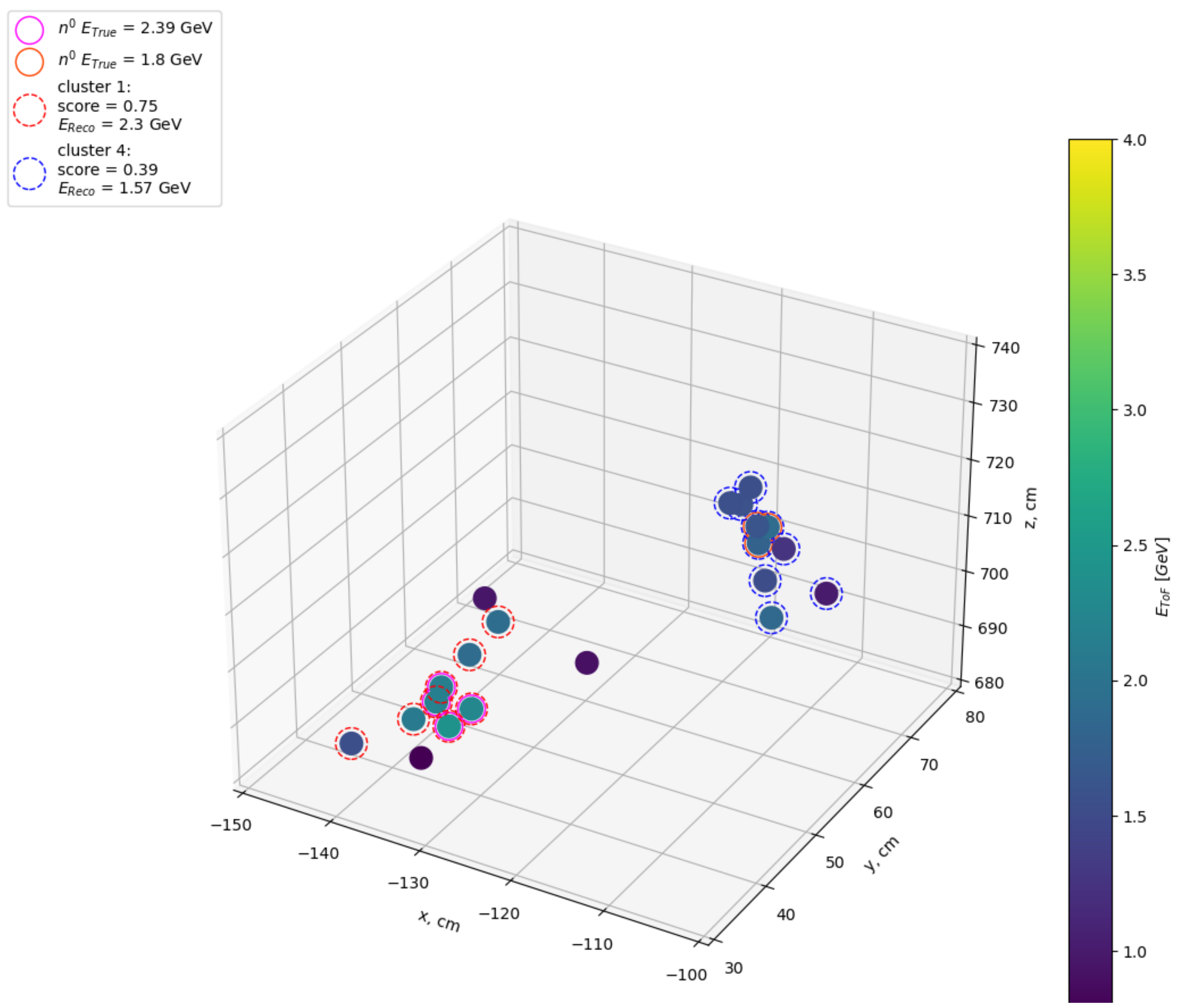
- Further steps for GNN model development:
  - Implementation of differentiable clustering
  - Detailed study of background contributions

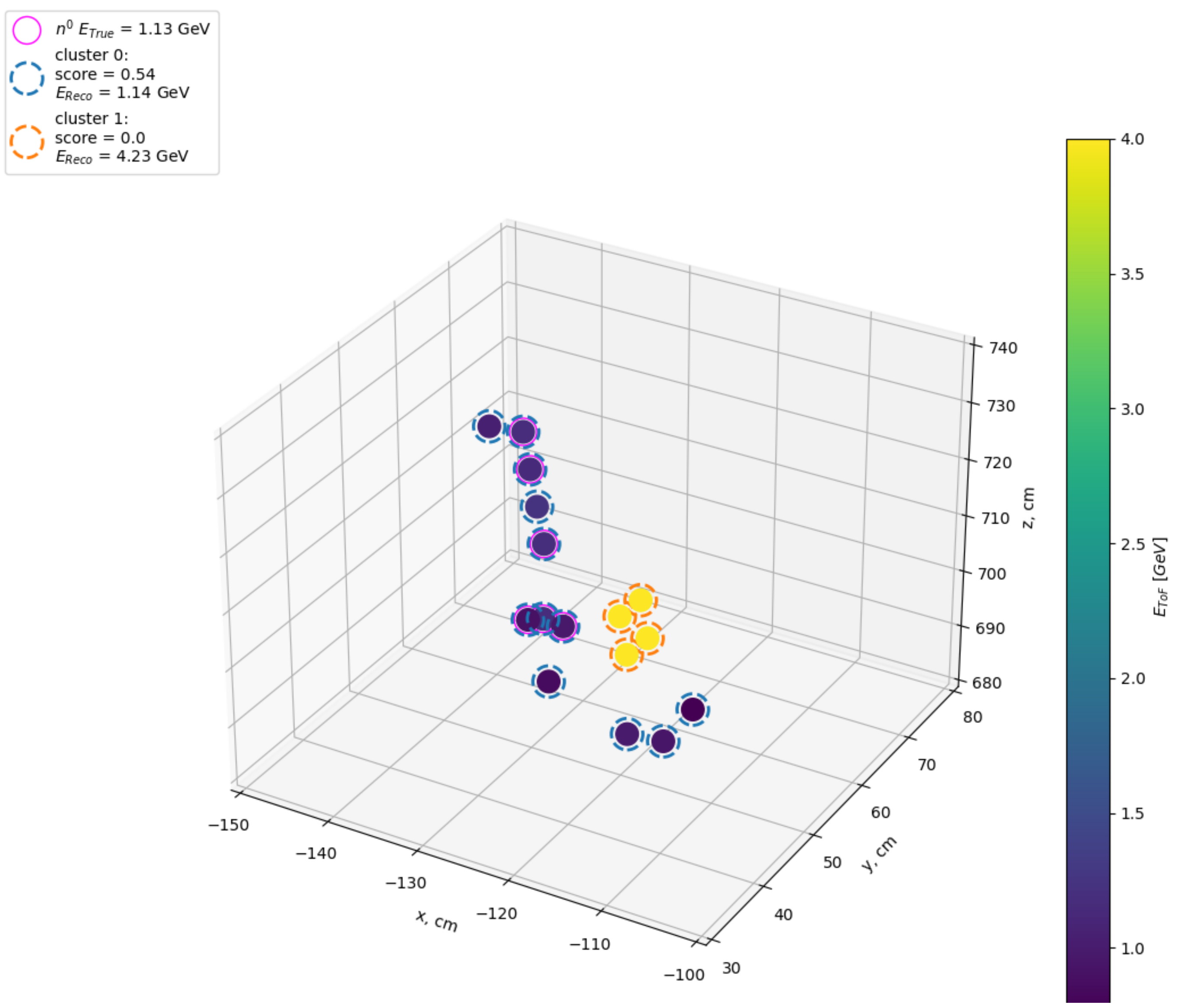
  ➡ Model architecture development

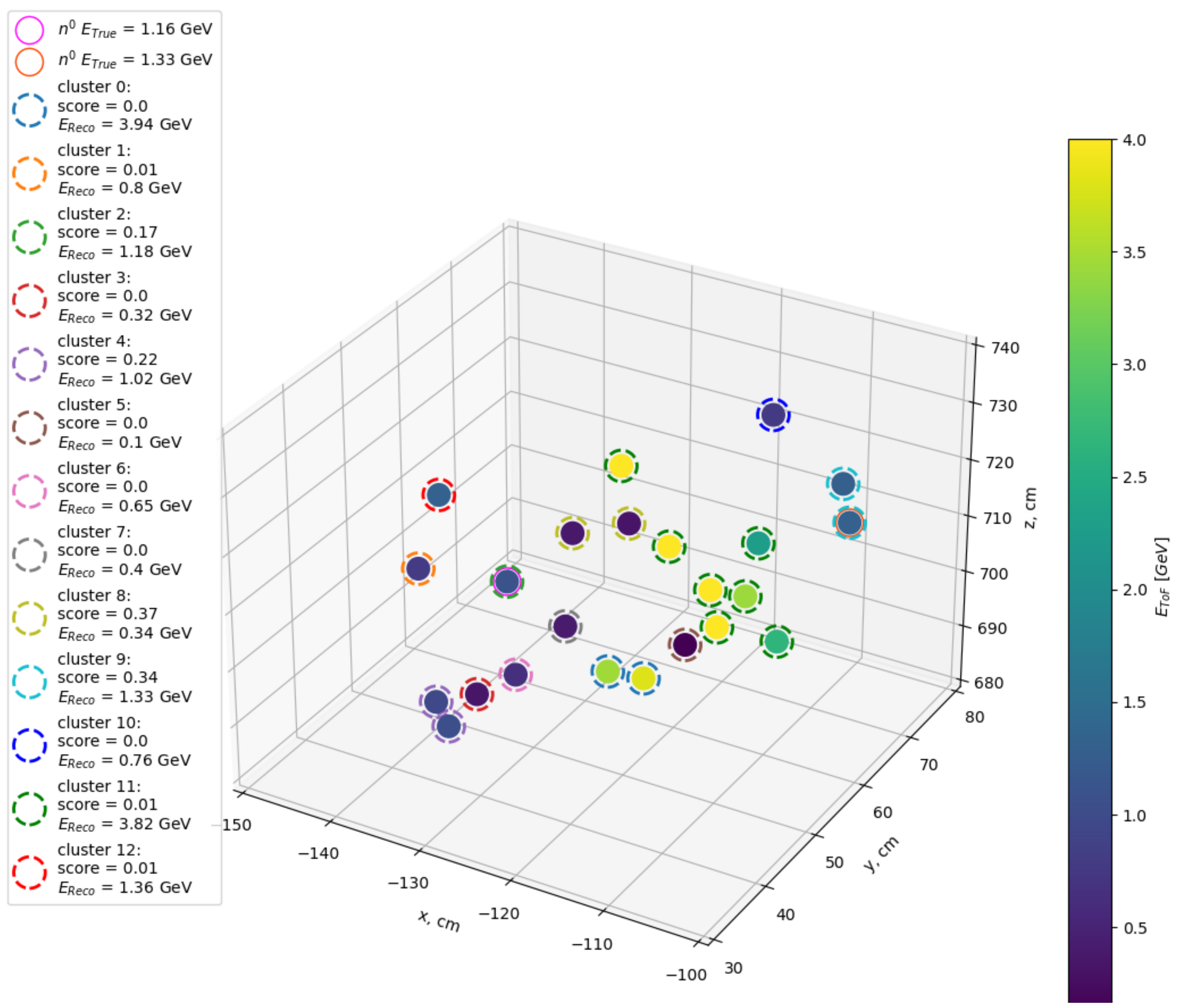
- Final physics performance and optimal reconstruction procedure will be defined using parametrised simulations

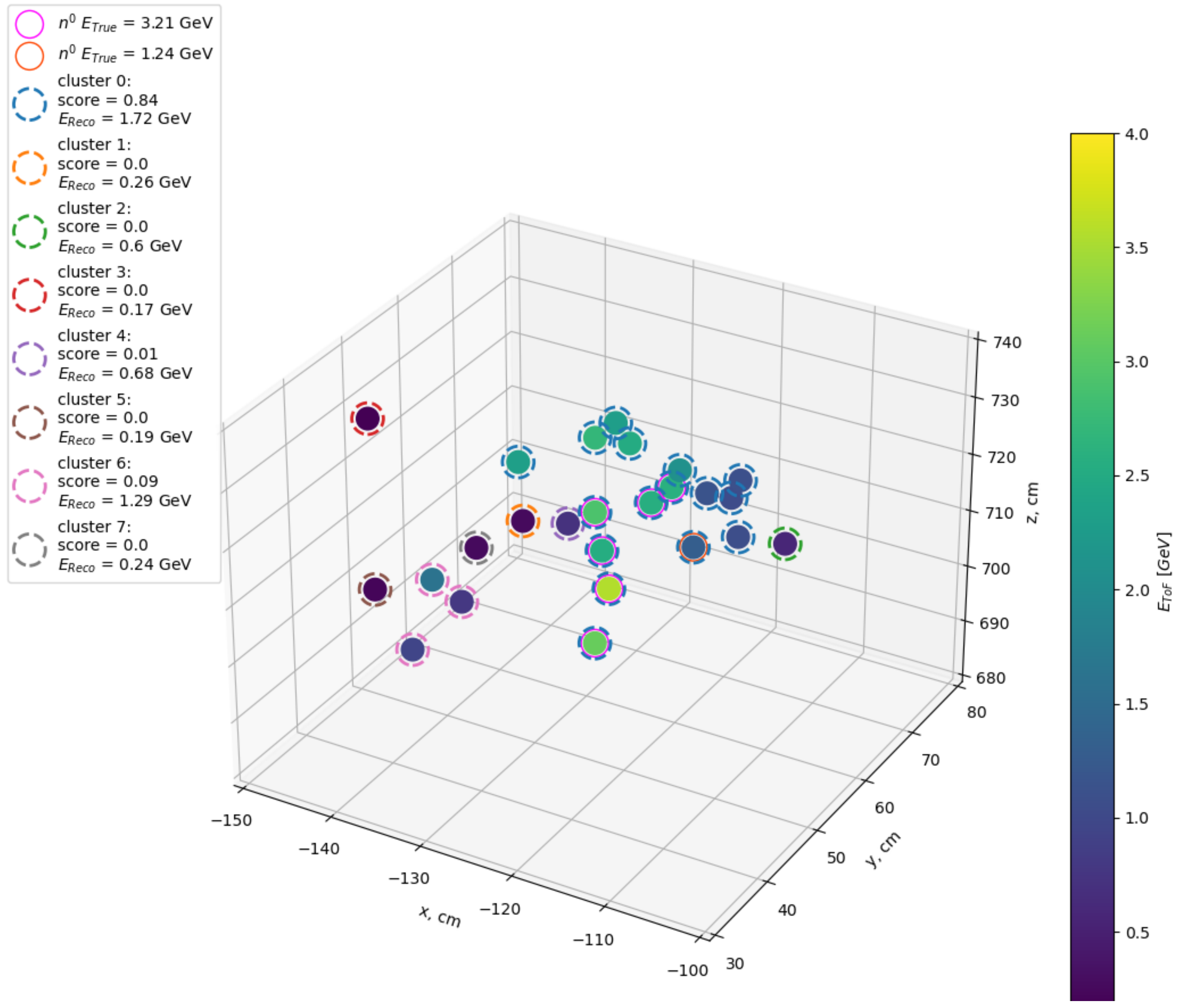
  ➡ Generative model is under development

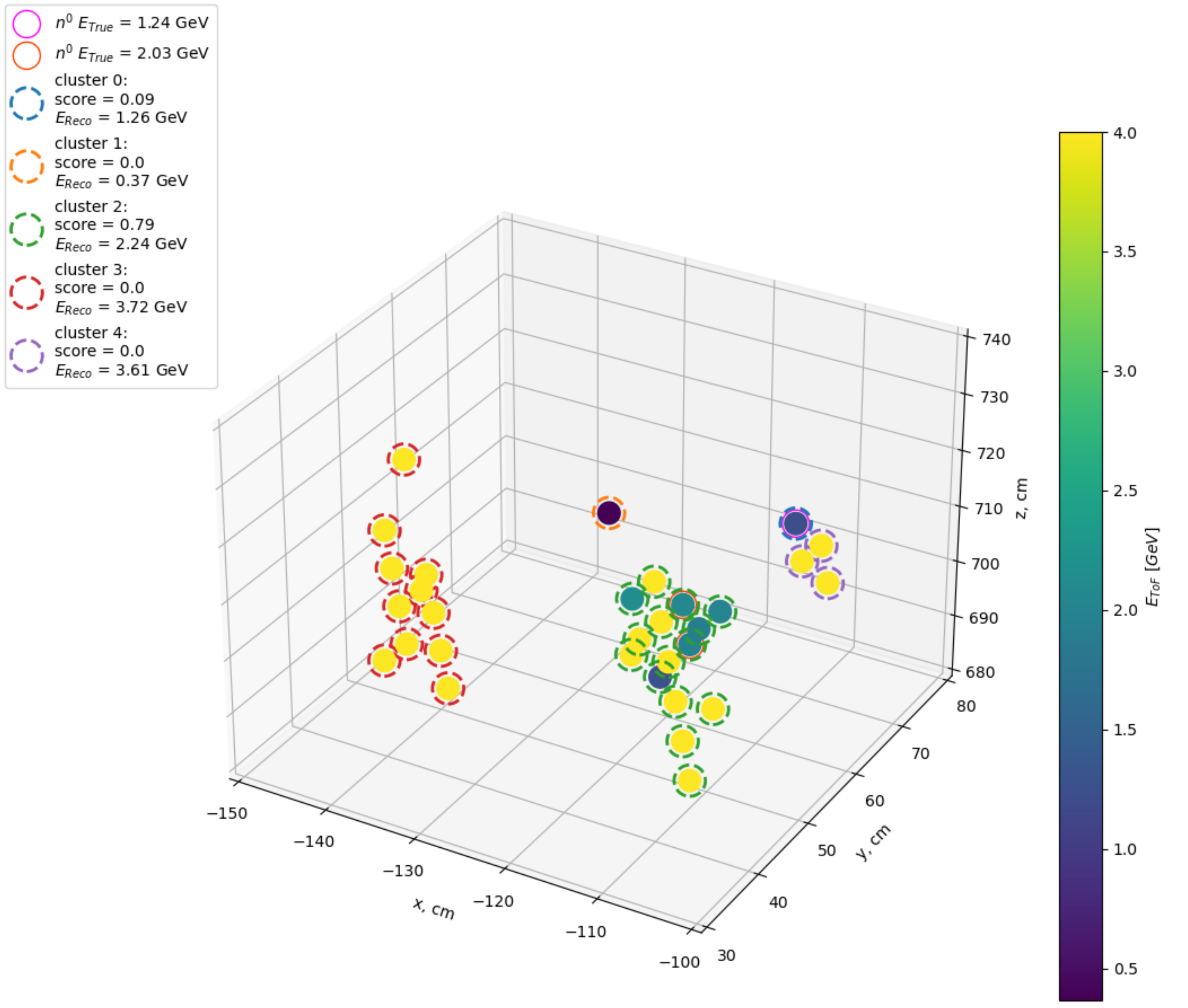
Event Displays

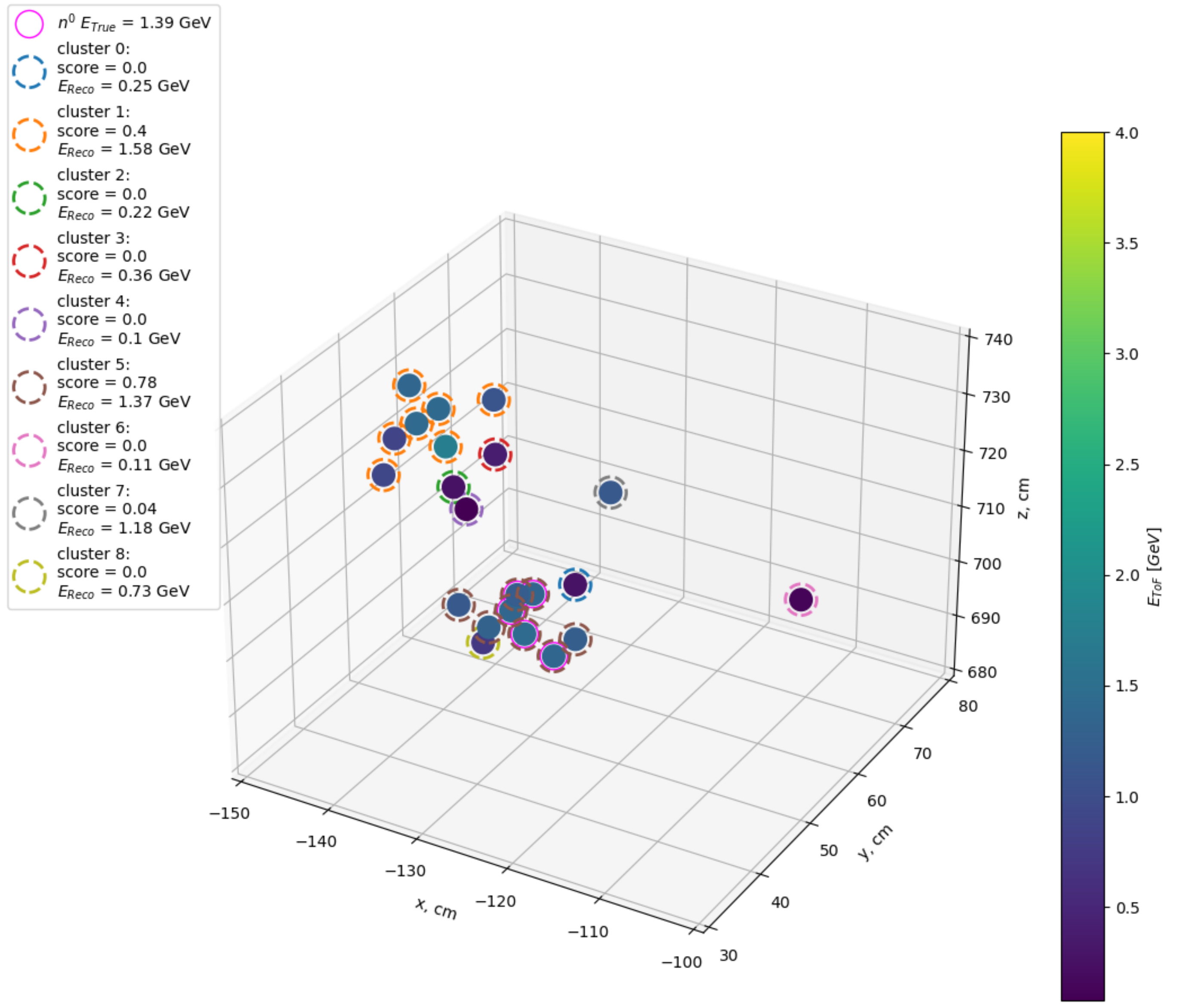










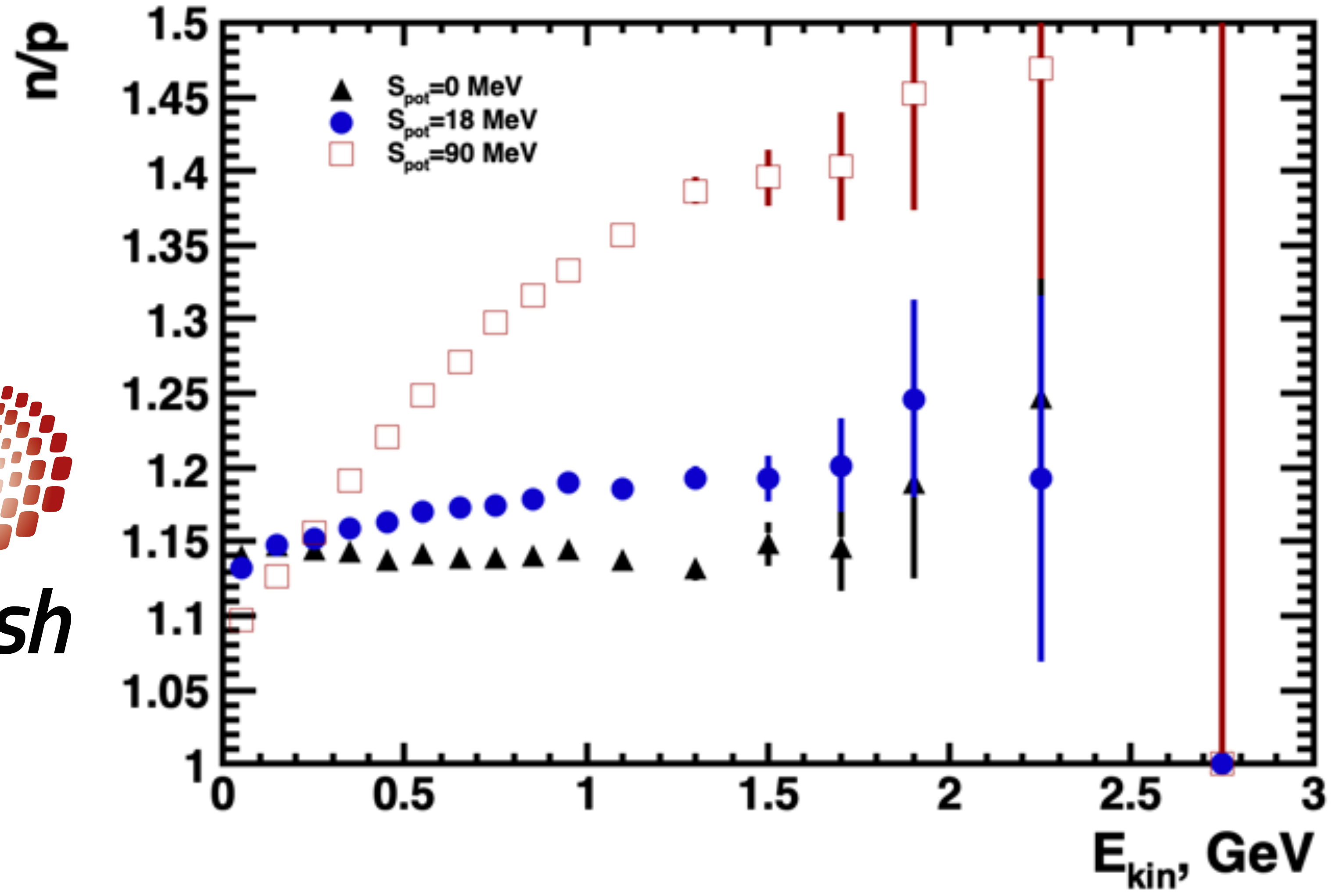


Physics performance toy-test

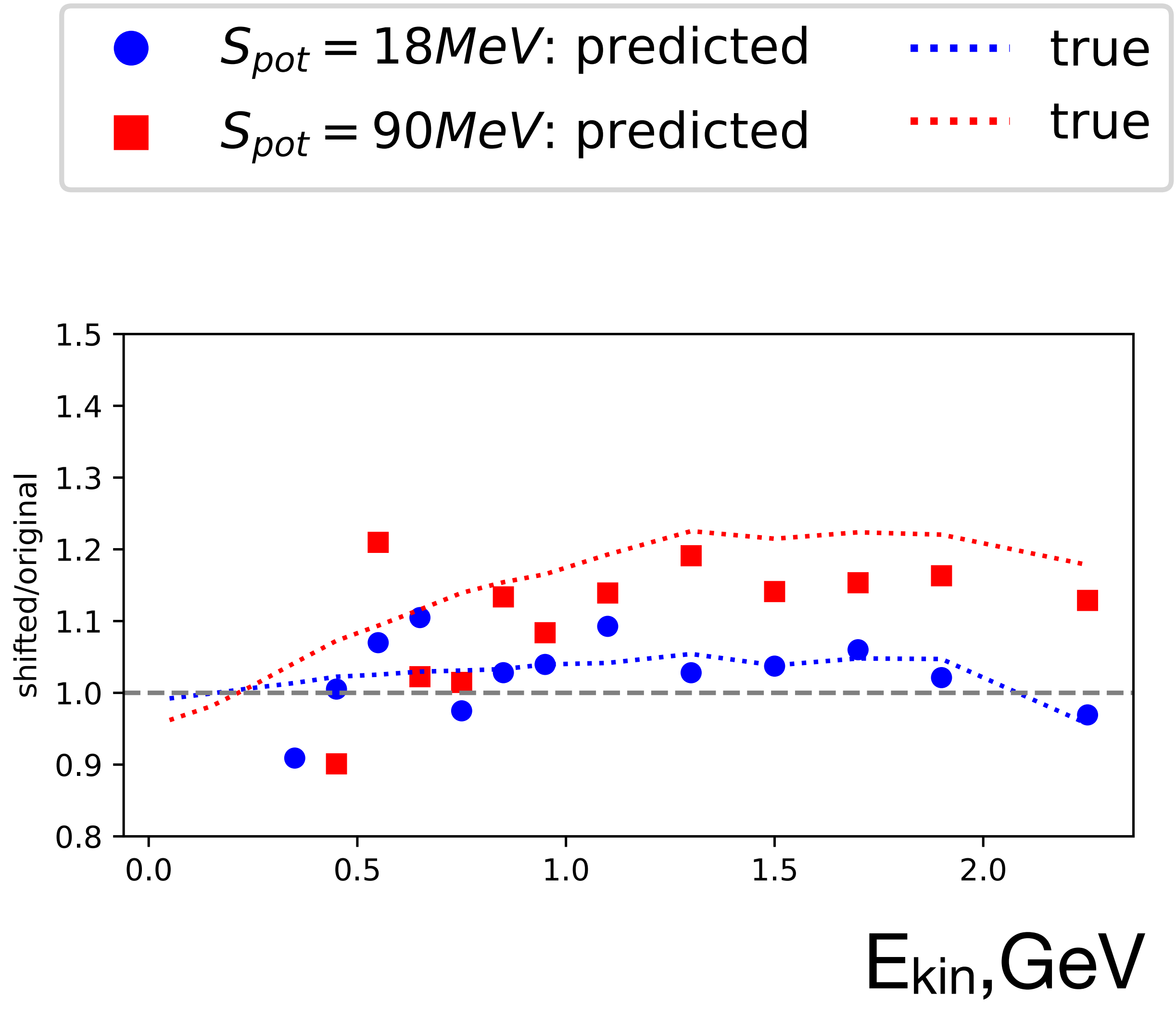
Resample test HGND dataset to get different neutron spectra:

SMASH simulations Xe+Cs @ 3.8A GeV:
500k events for 3 symmetry potential (S_{pot}) values

Neutron to proton ratio vs E_{kin}. All reaction particles.
Centrality selection: |y| < 0.5



smash



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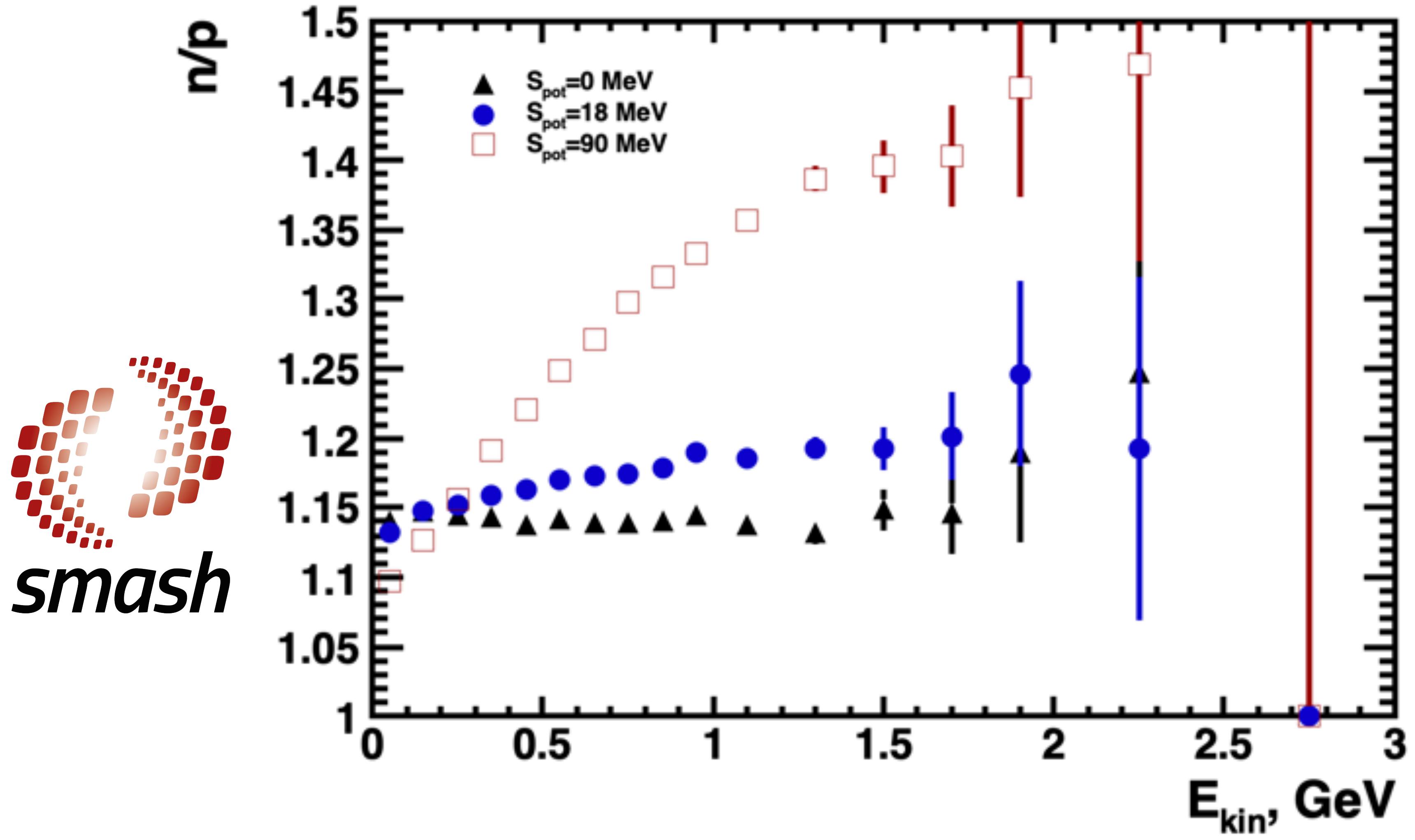

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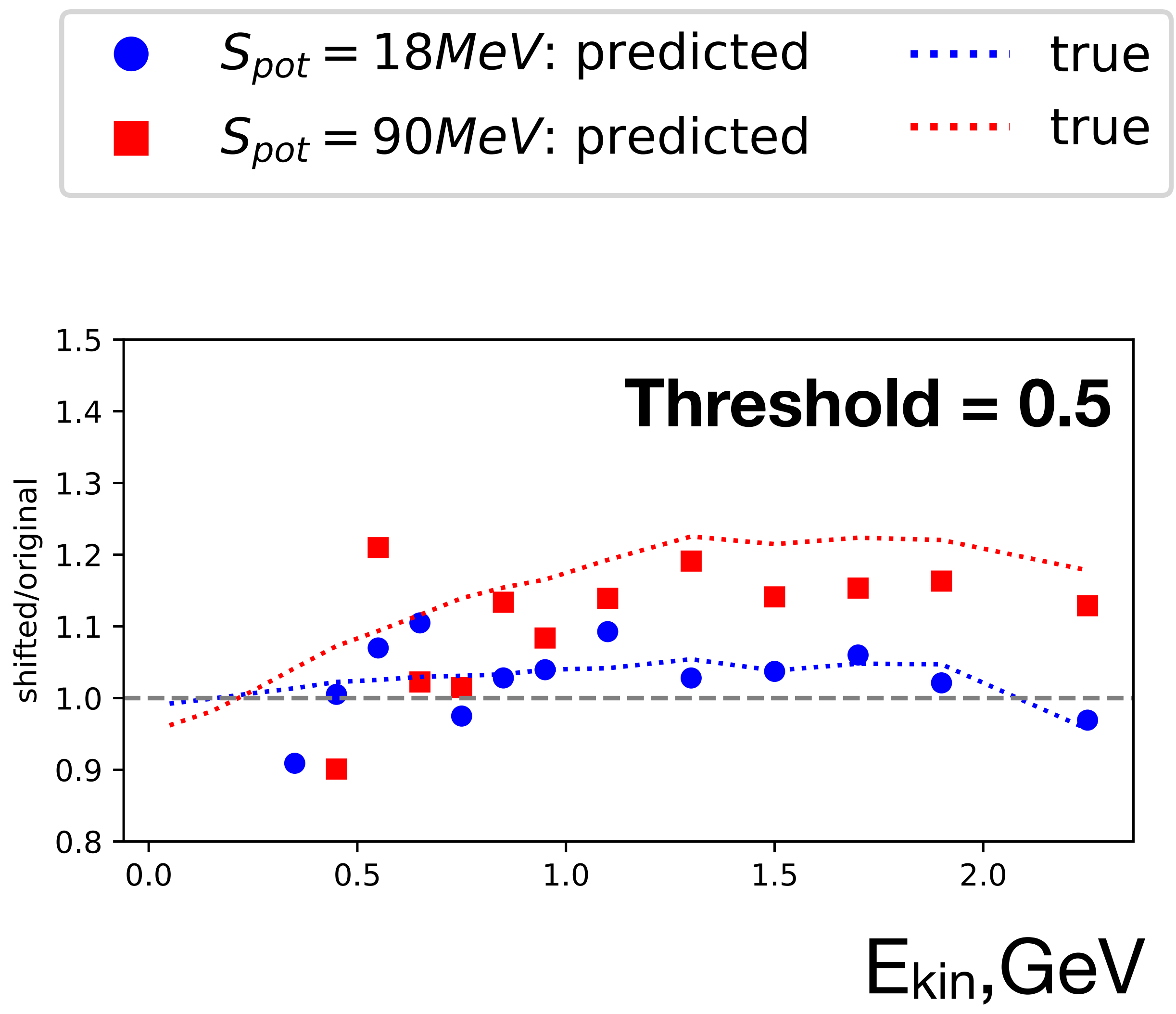
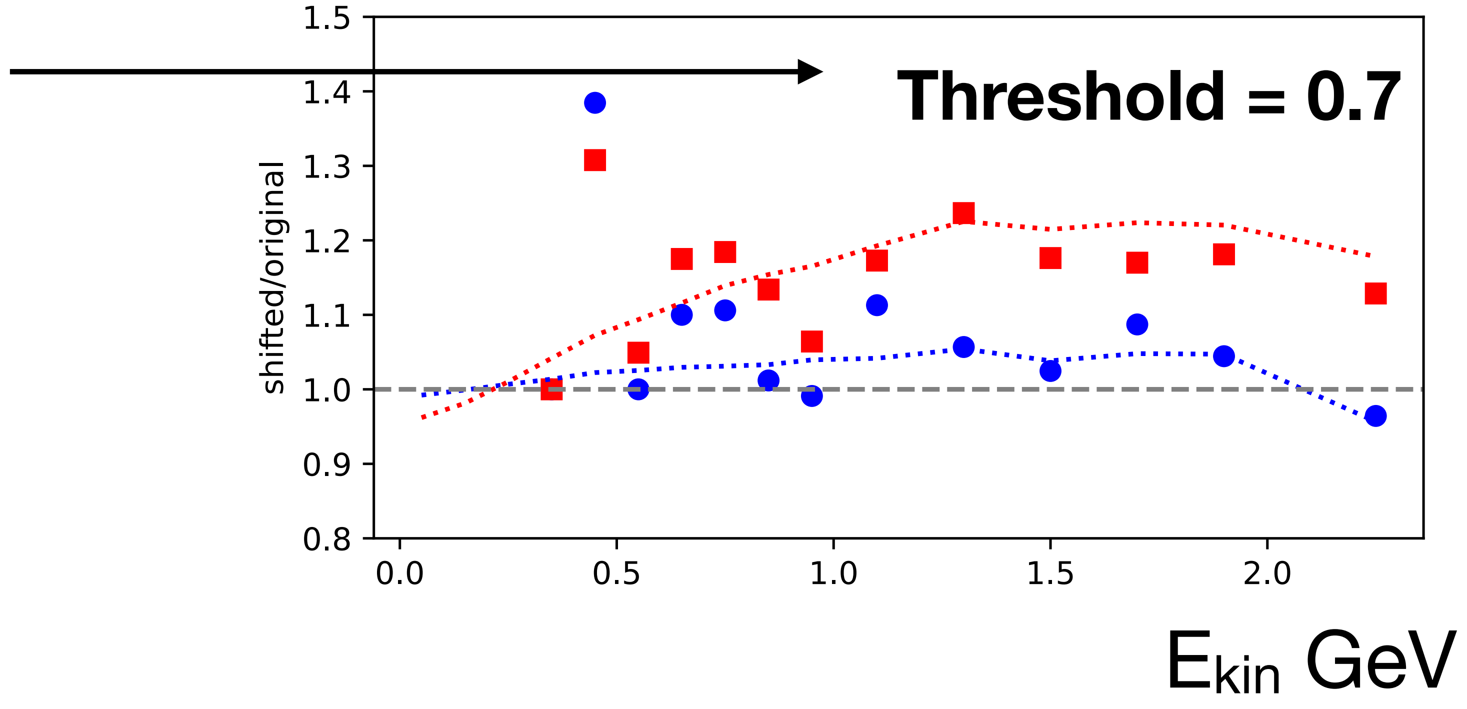
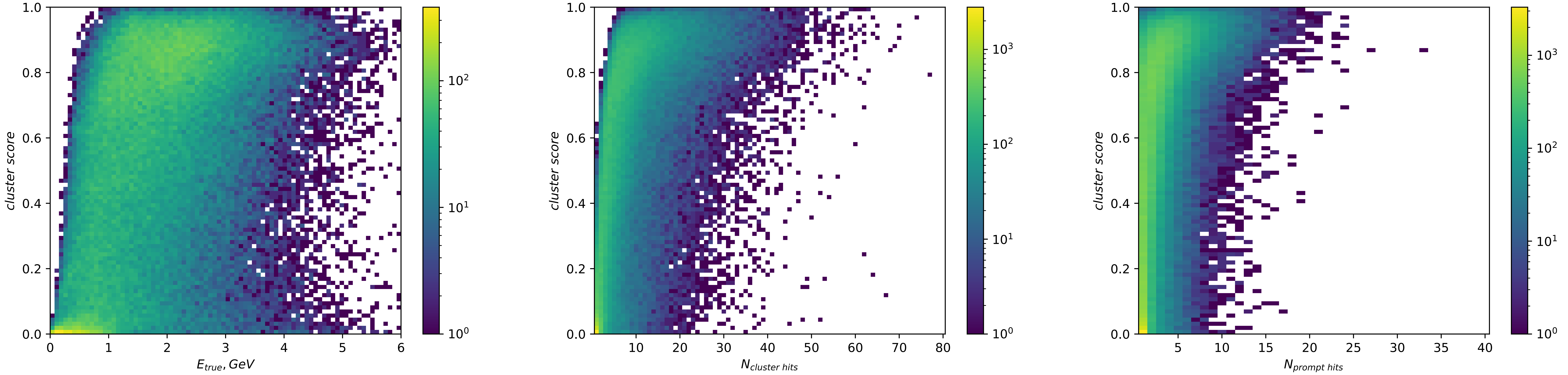


more strict neutron selection

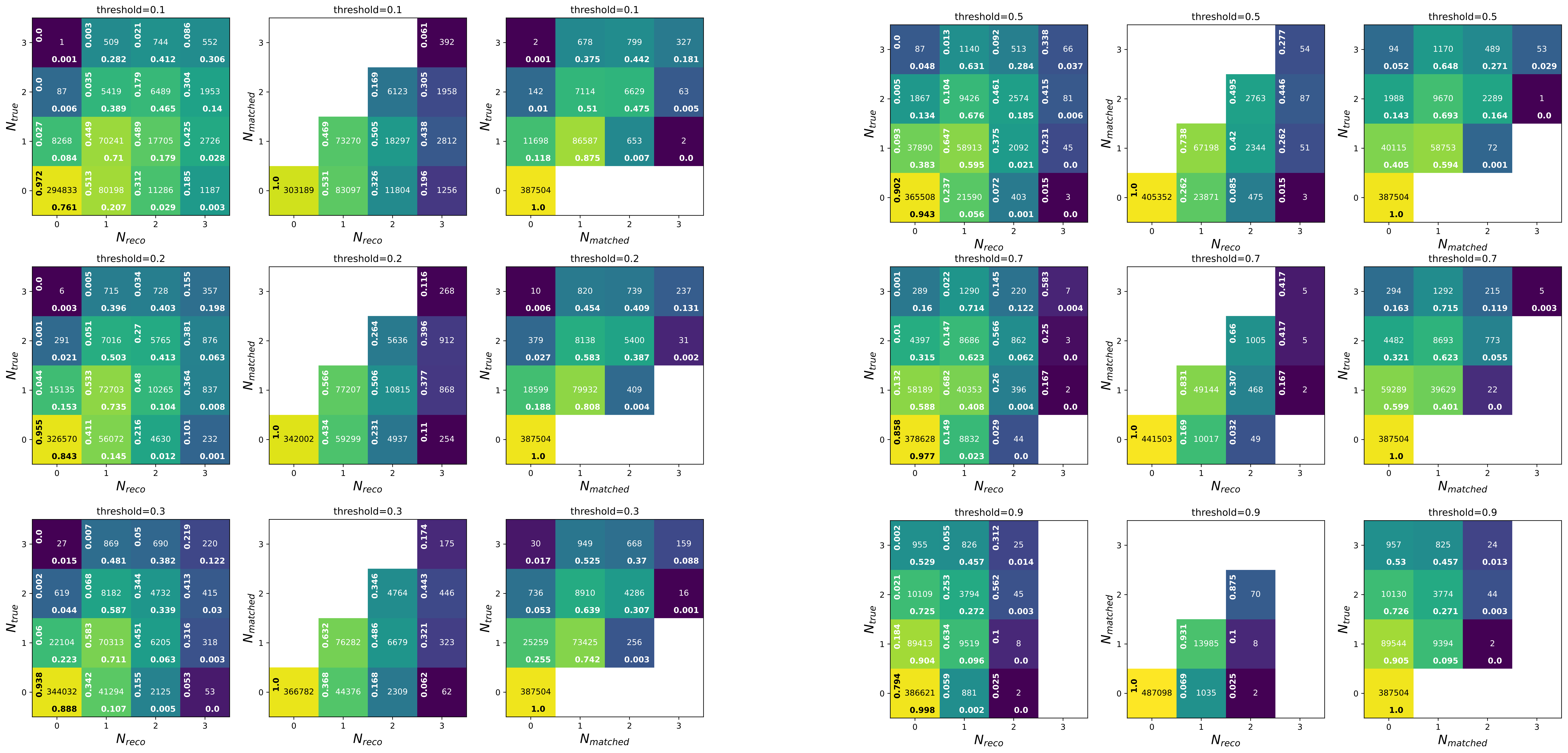


- Qualitatively, it’s possible to separate different symmetry potential at ~1GeV+ with relatively strict selection criteria
- Detailed understanding of background contributions is essential

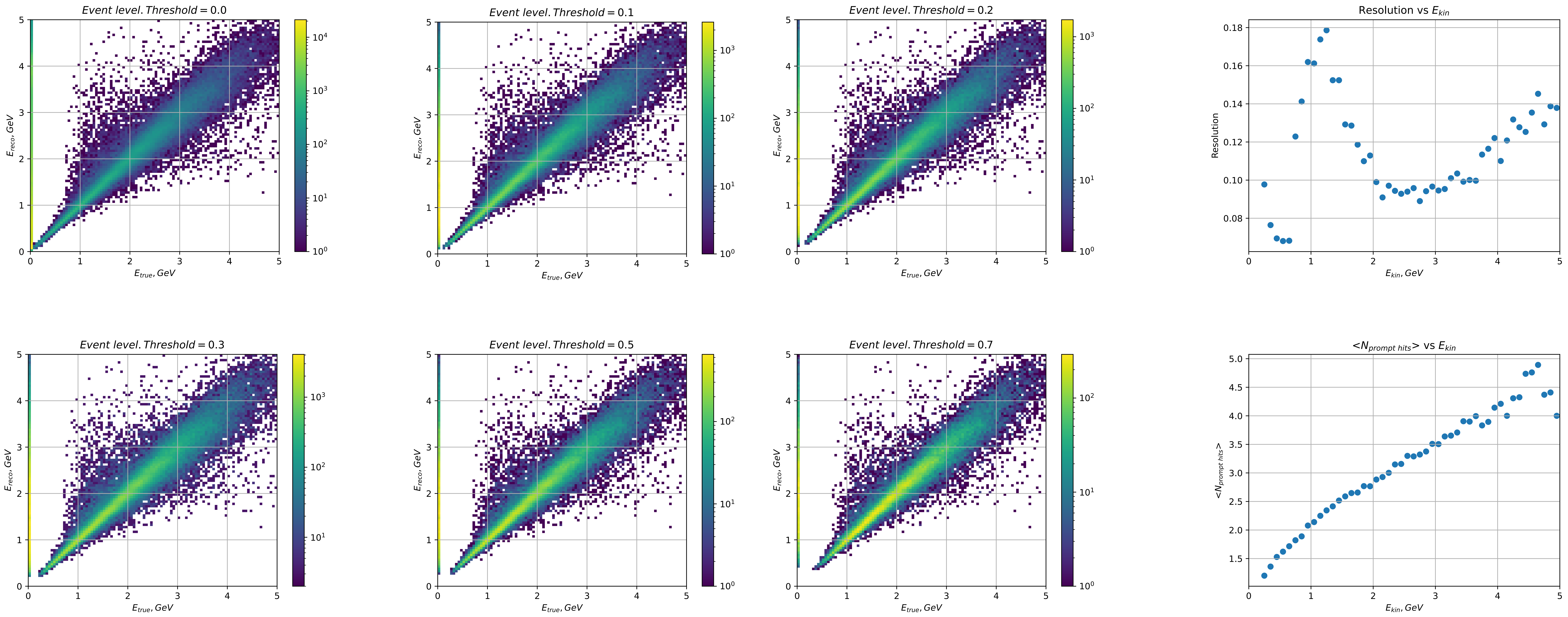
Score for different clusters



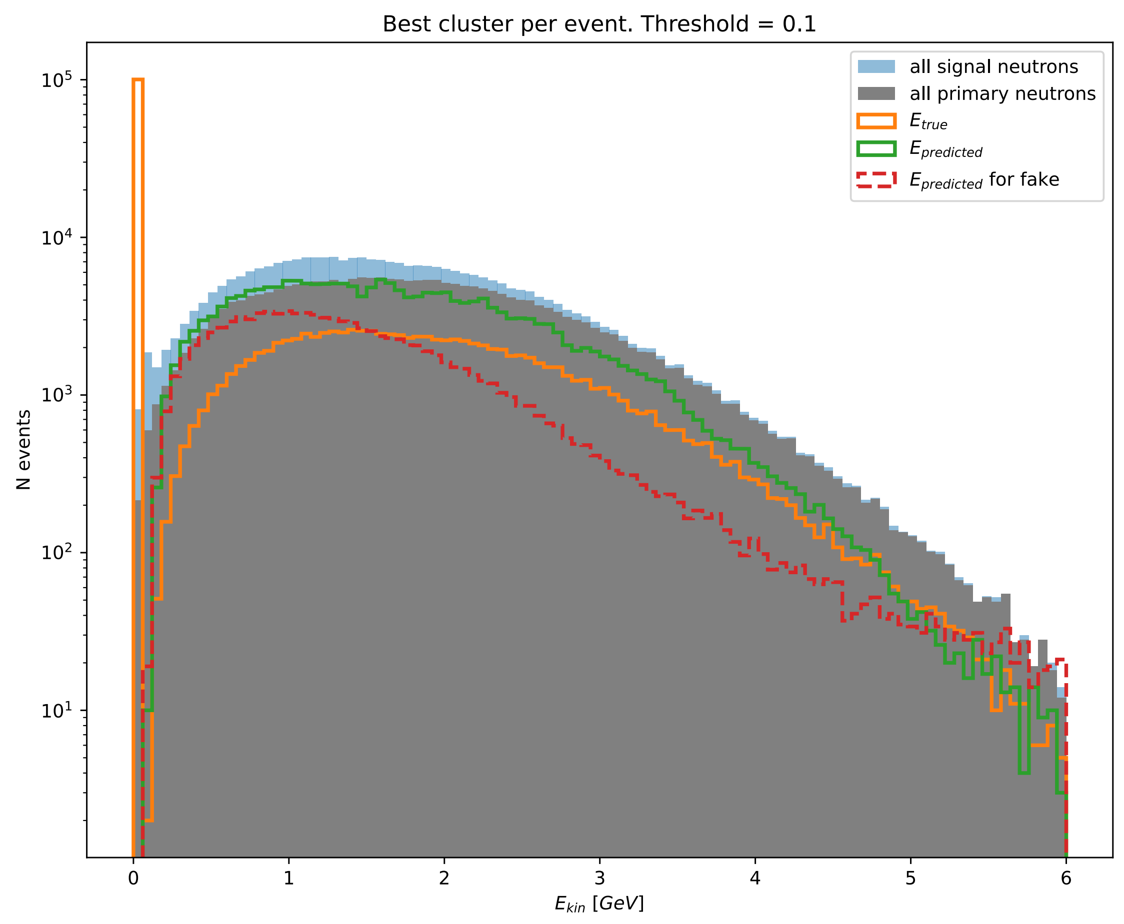
Multiplicity Reconstruction

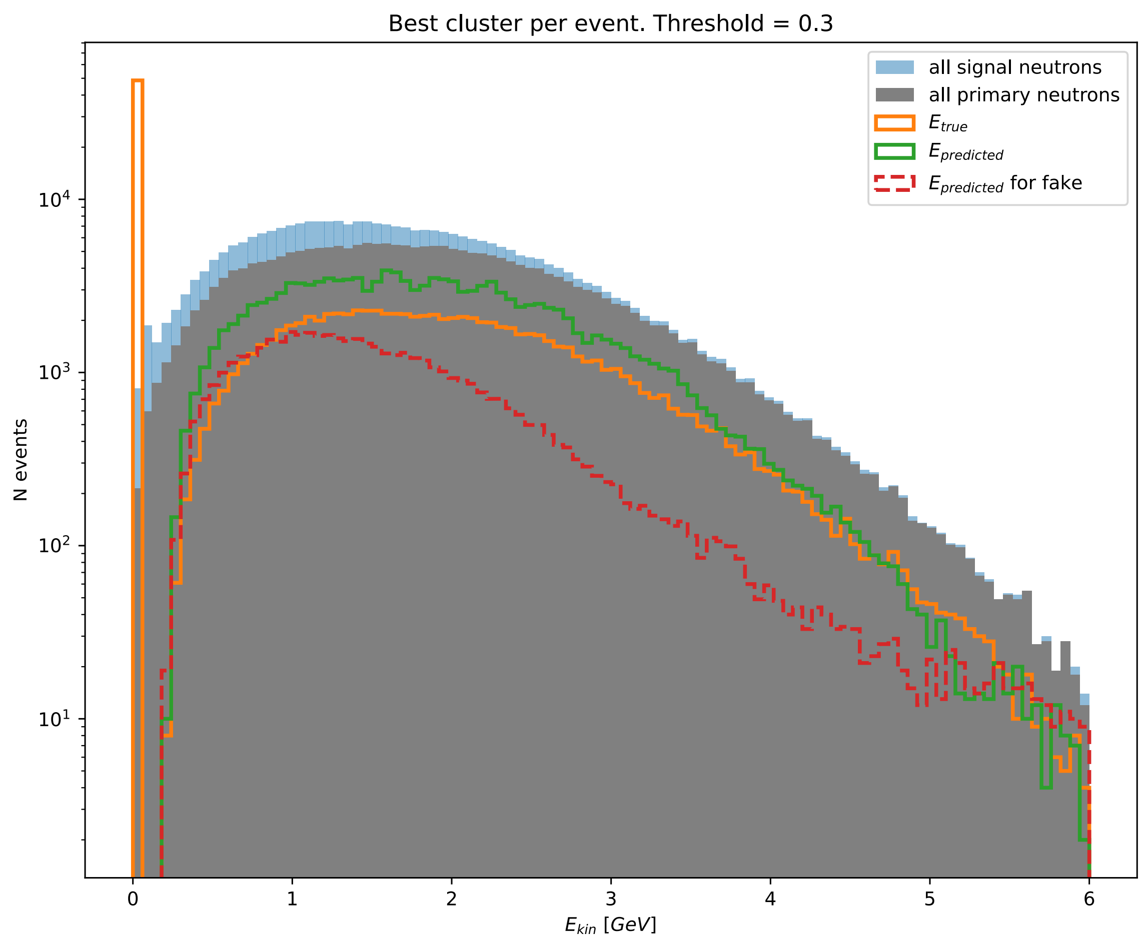


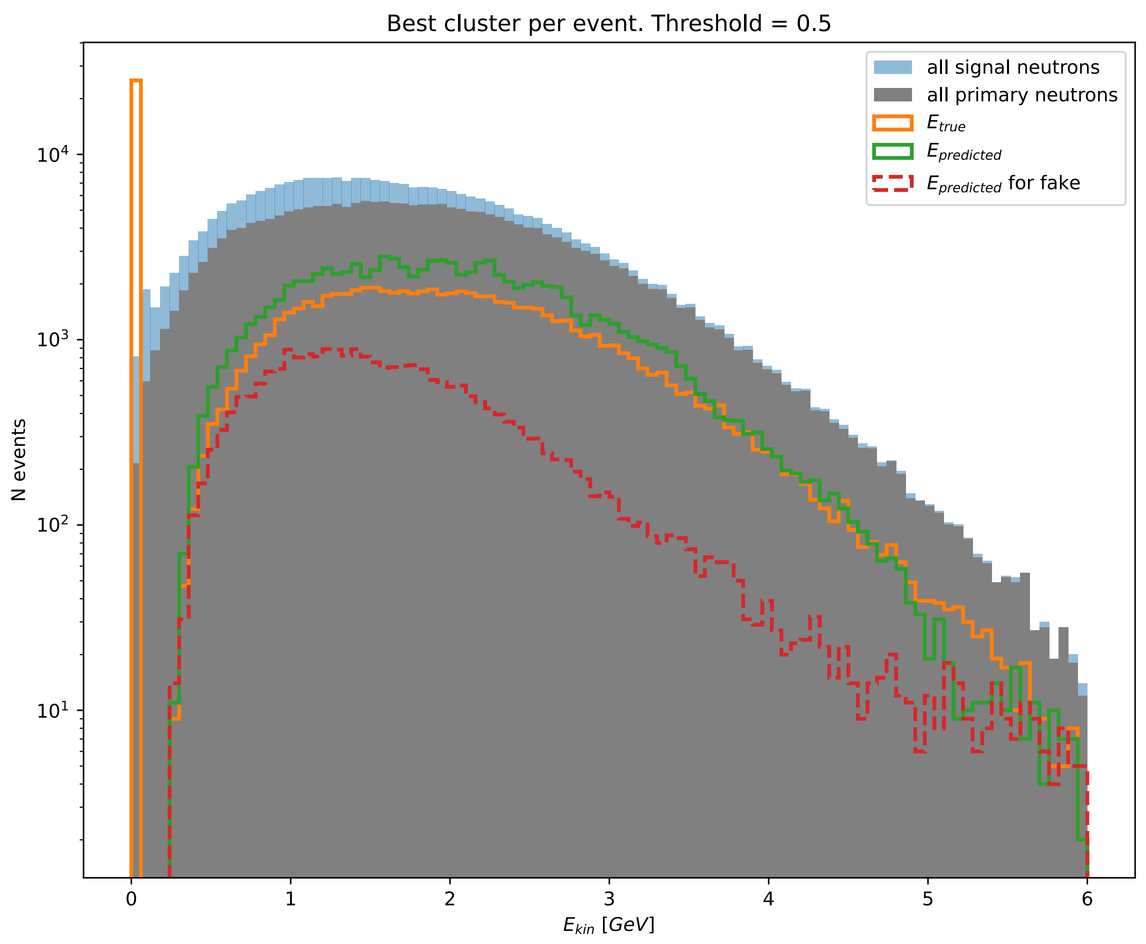
Energy Reconstruction

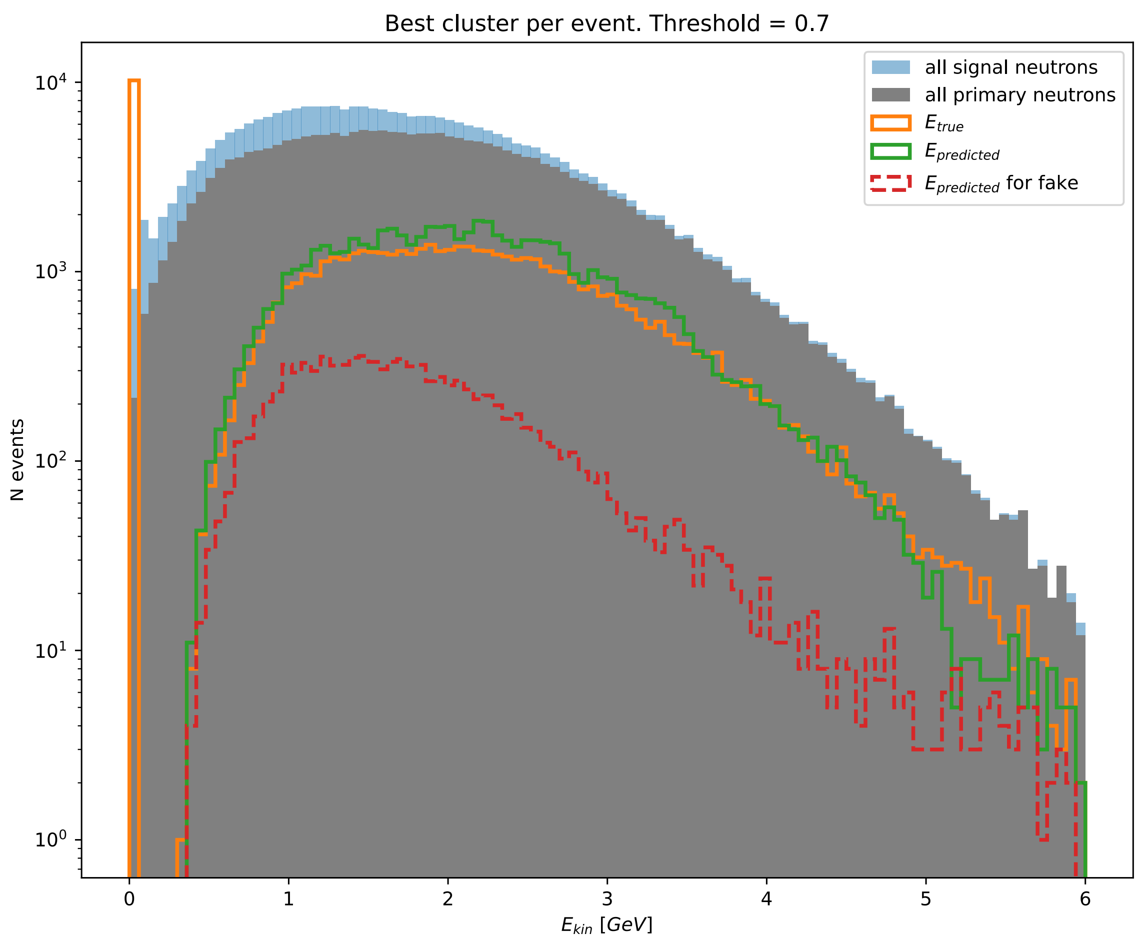


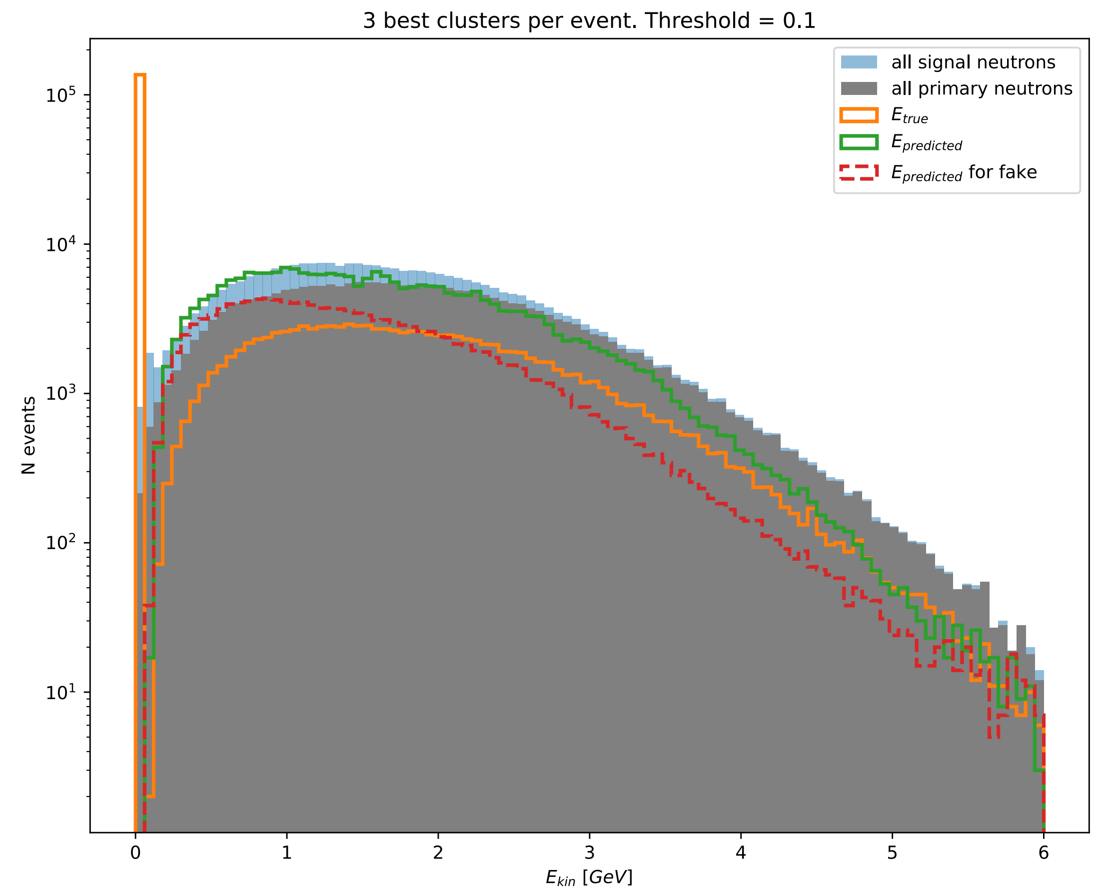
Spectra Reconstruction

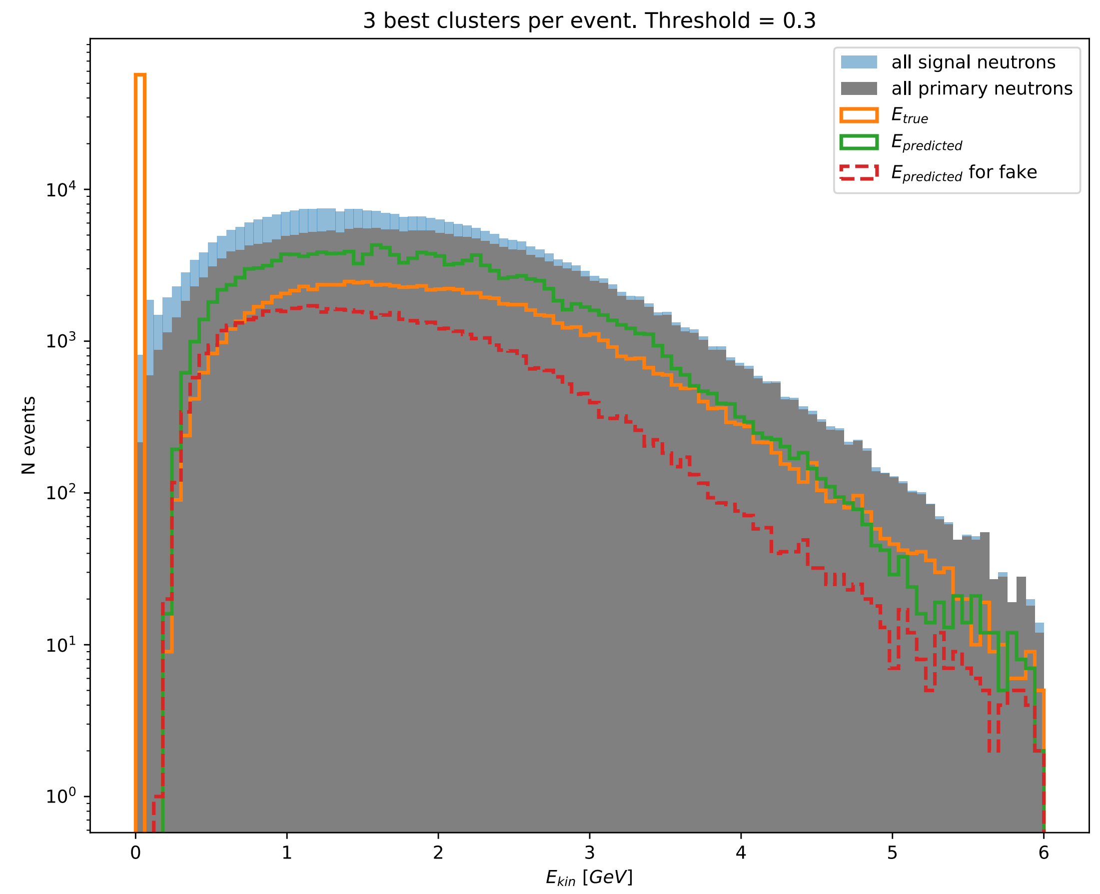


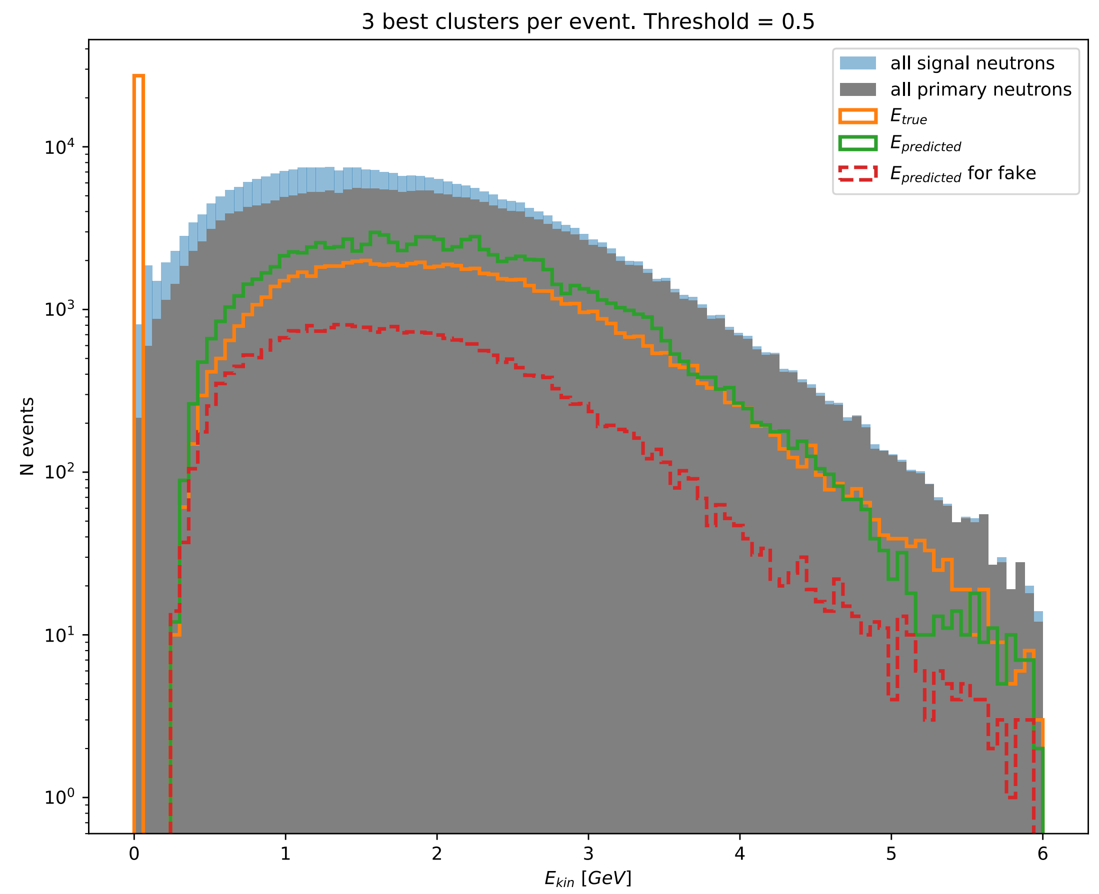


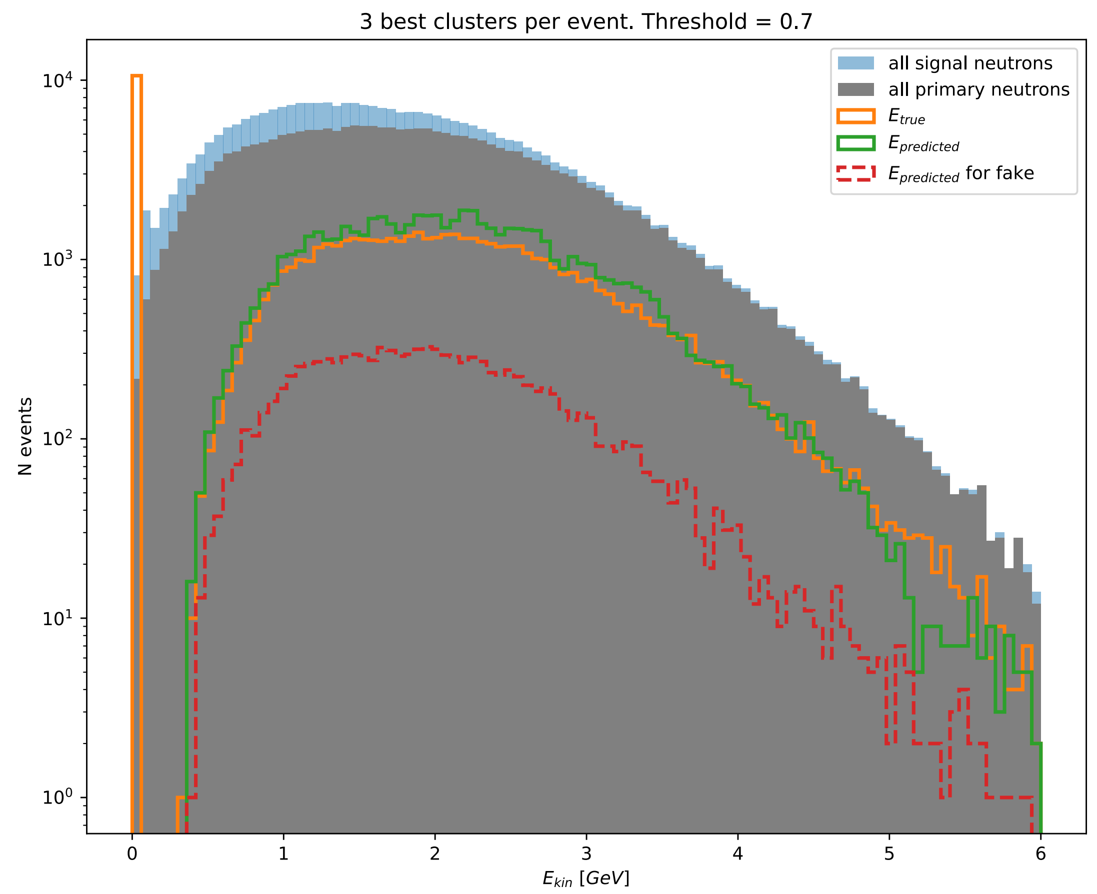




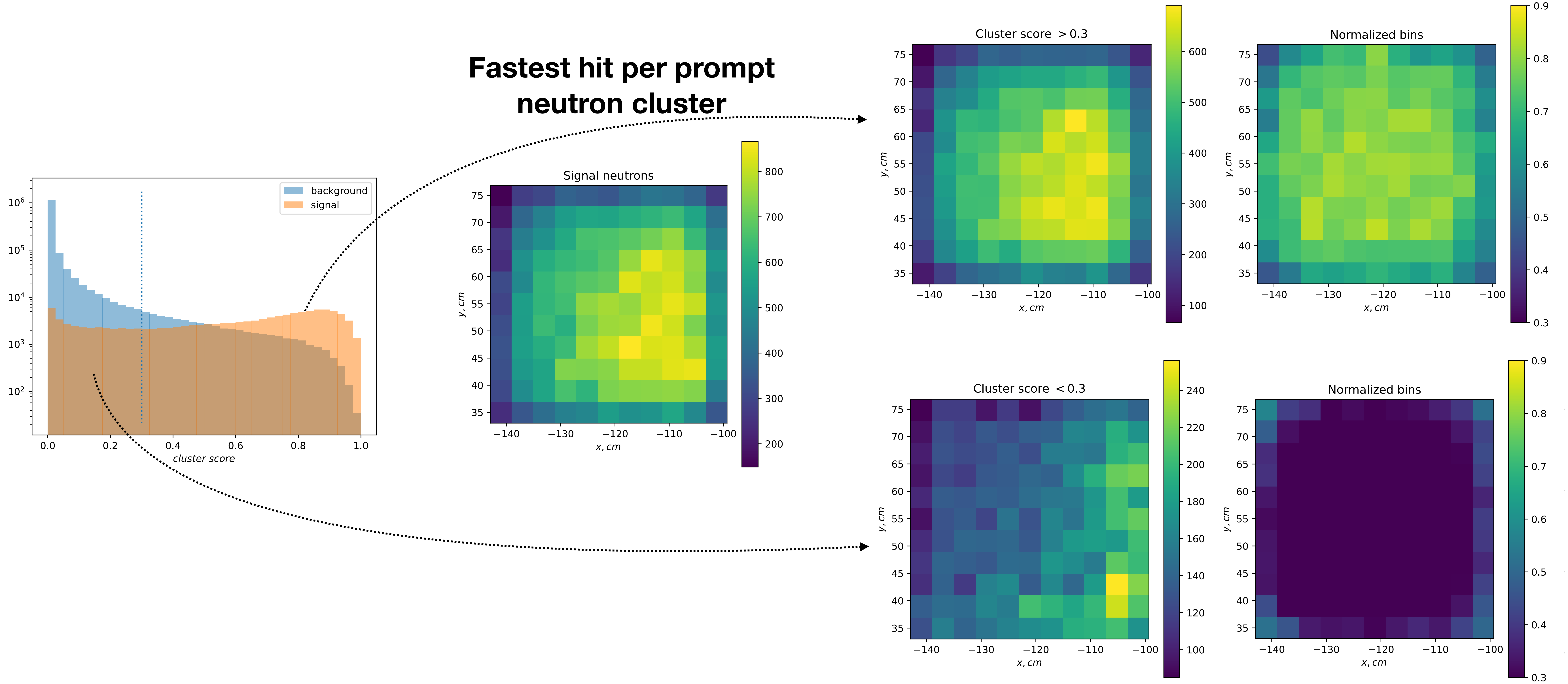








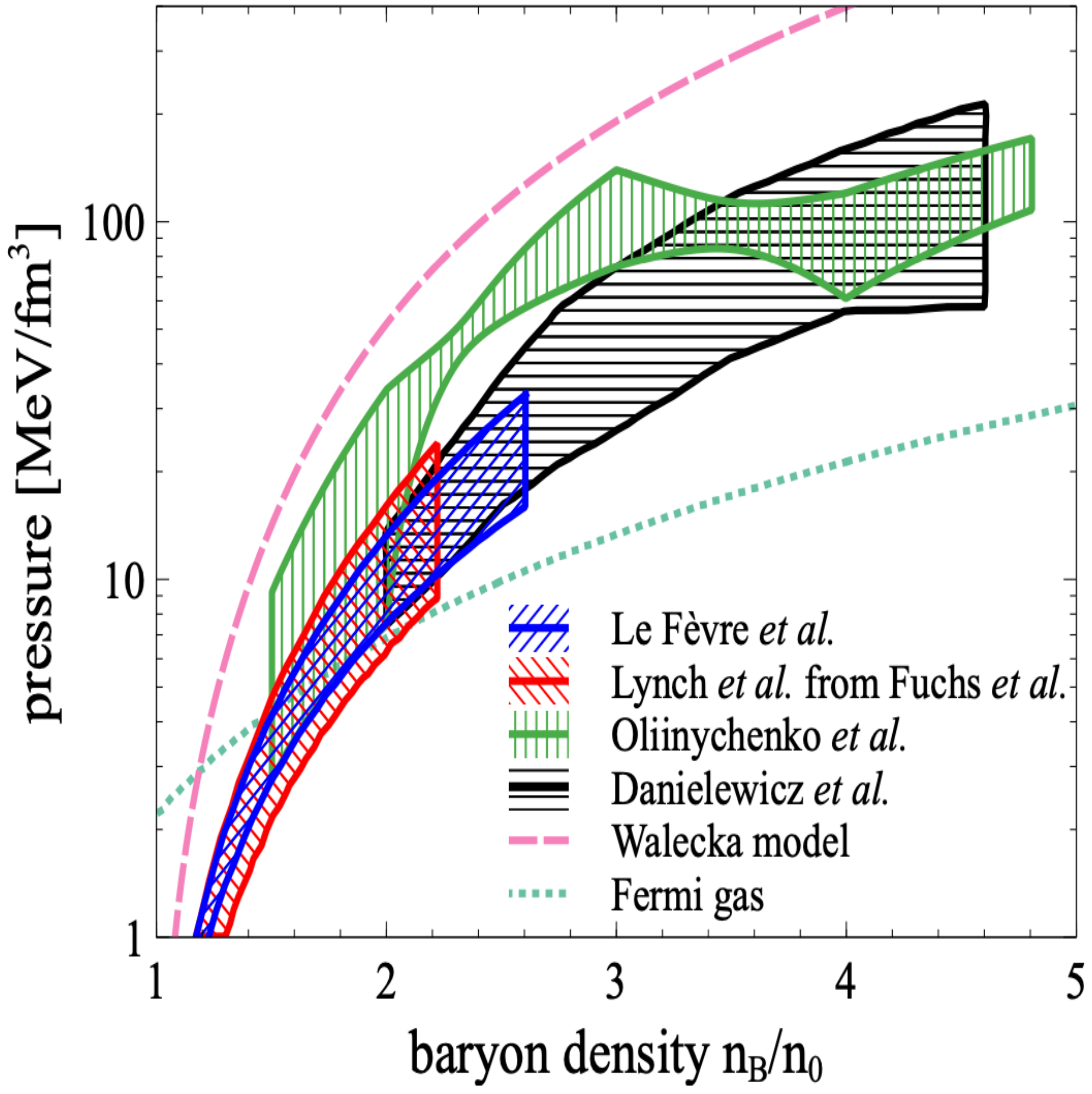
Efficiency in the XY-plane



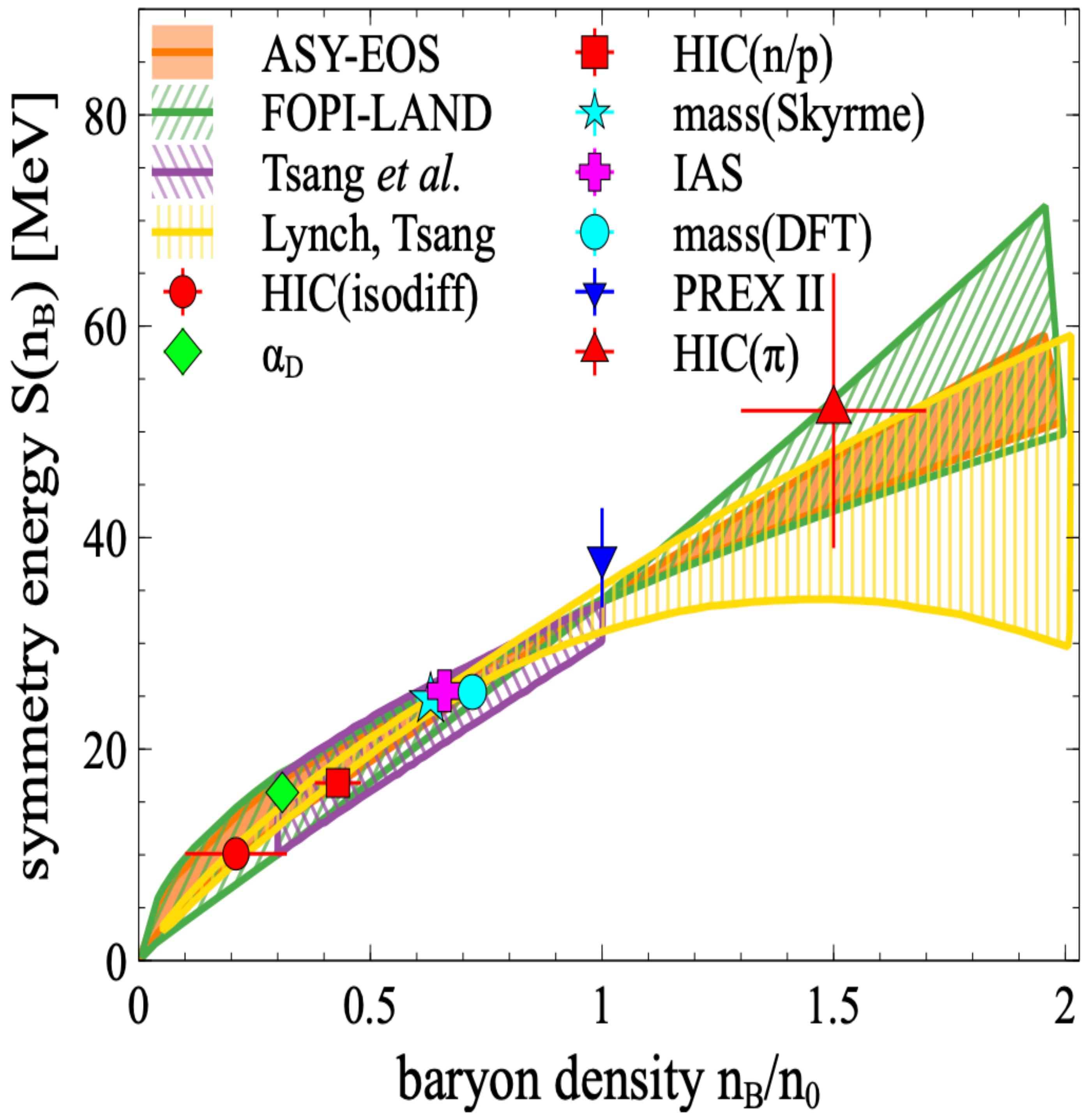
EOS for high baryon density matter

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**

- Symmetric matter is extensively studied
- **Symmetry energy** contribution lacks experimental data at energies above 800A MeV
  - Neutron-rich matter like a neutron star requires measurement of symmetric energy parameters

➡ reconstruction of **neutron** flow and yields

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

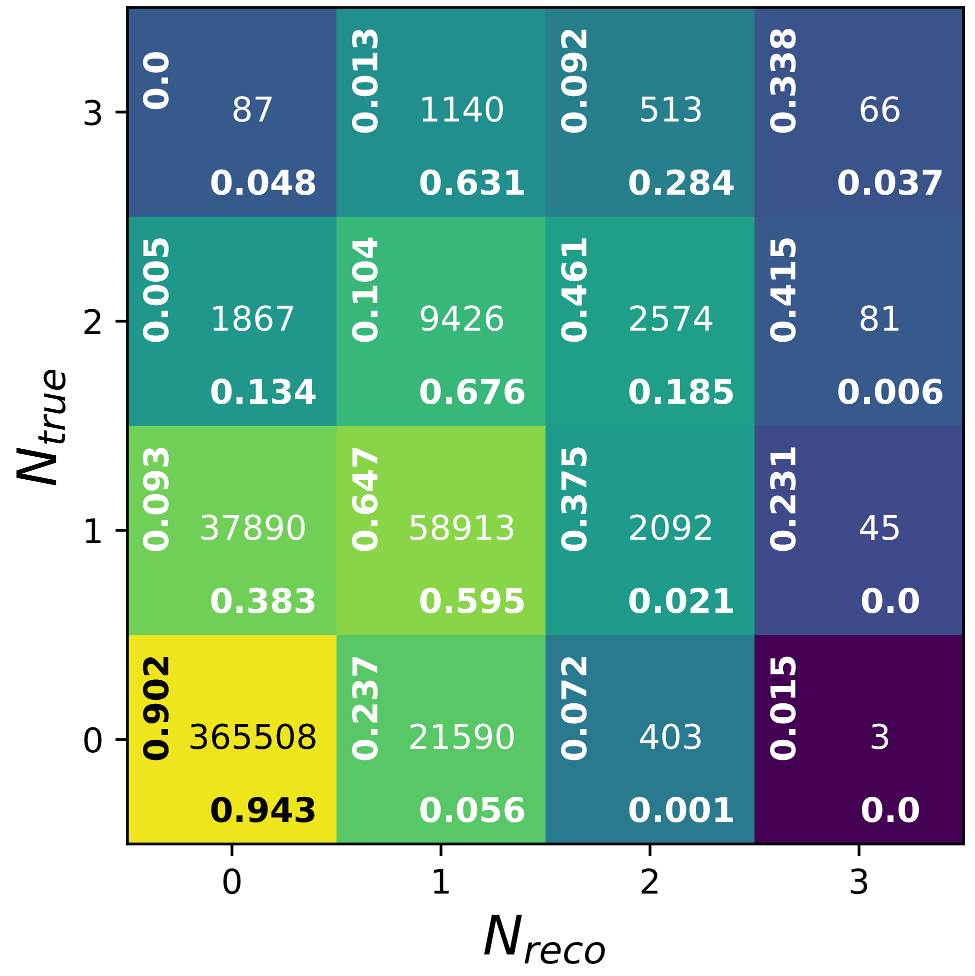
Multiplicity Reconstruction

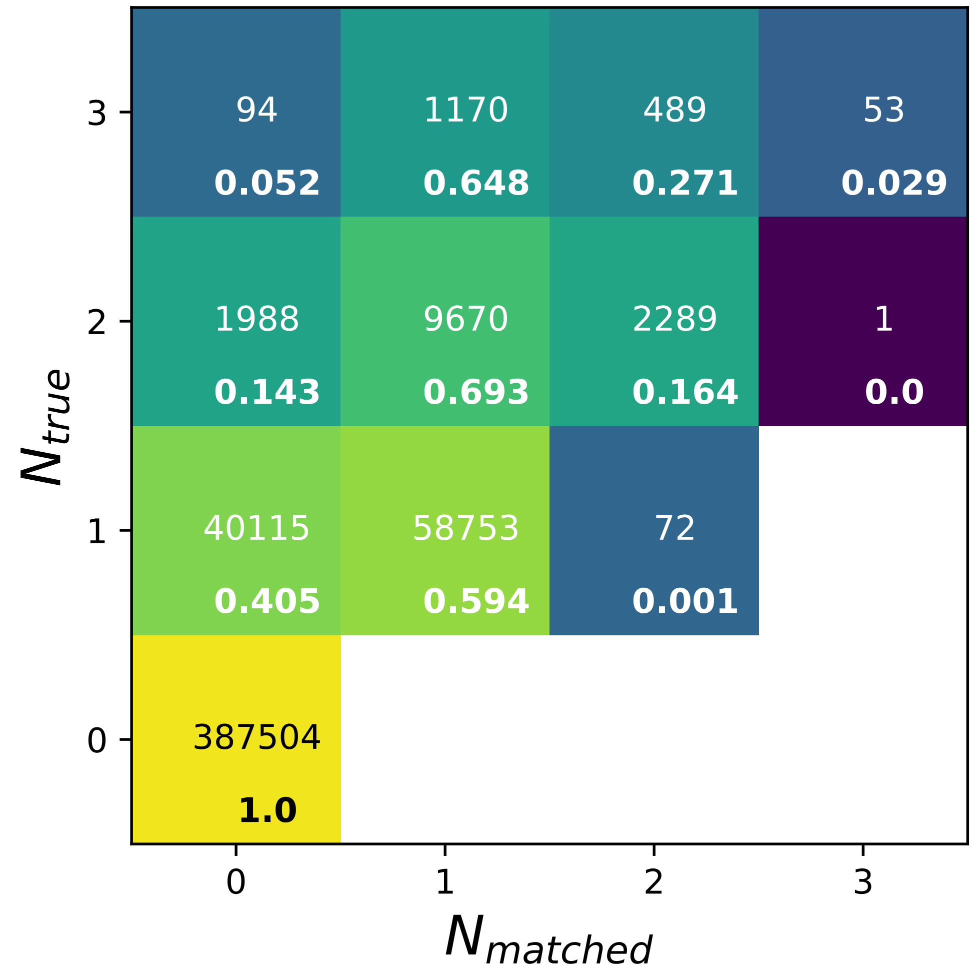
- Test dataset
  - 502198 events
- Selection:
  - E_{true} > 0.1 GeV
  - E_{reco} > 0.1 GeV

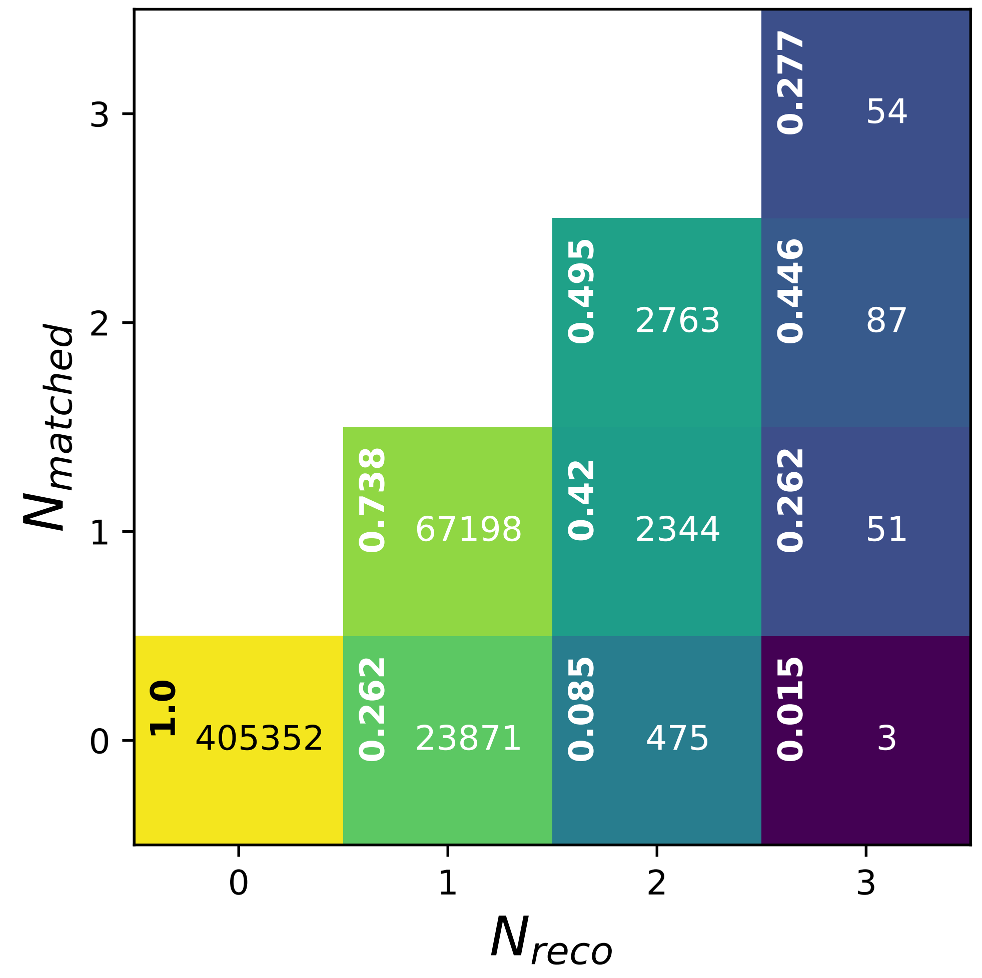
- 4 multiplicity classes:
  - [0, 1, 2, 3 and more]
- Fixed cluster score threshold = 0.5

- horizontal normalisation is related to efficiency
  - efficiency decreases for higher true multiplicities and higher score threshold
- vertical normalisation is related to purity
  - high score threshold allows to separate up to 3 ‘good’ neutron clusters

Matched neutron - reconstructed cluster corresponds to MC-truth neutron cluster.

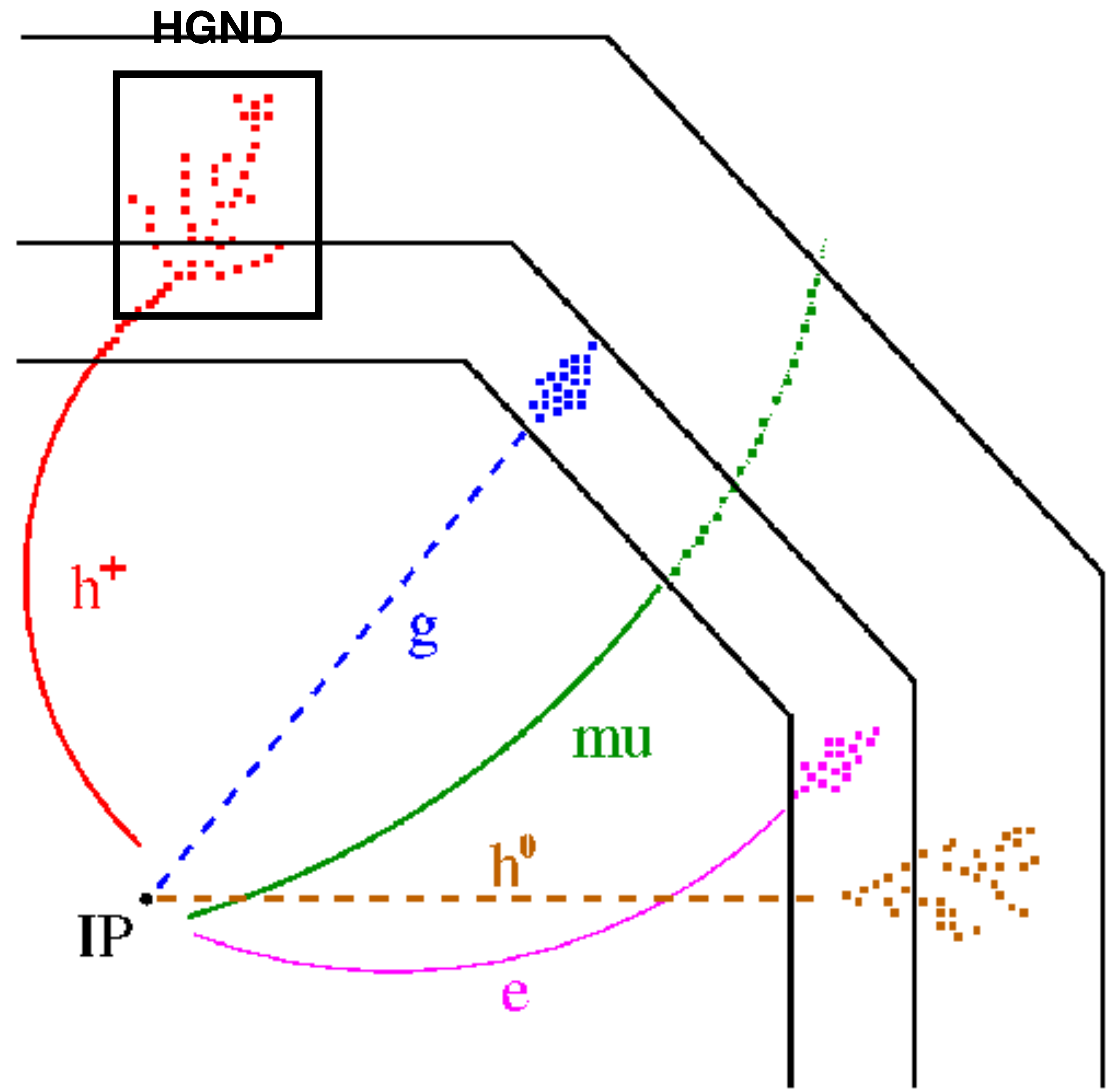






Tracking Outlook

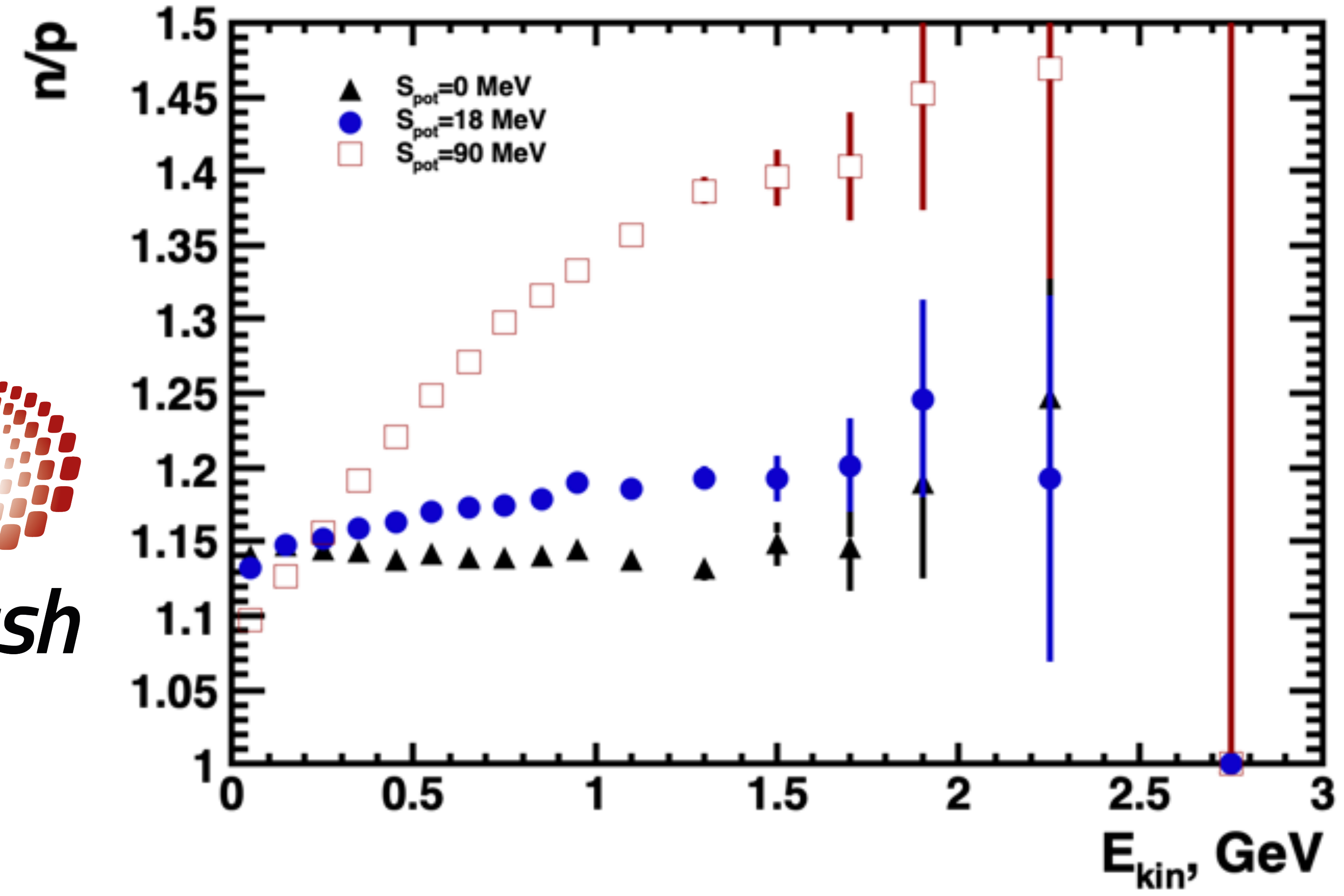
- BM@N has a dedicated tracking system to reconstruct charged particles
  - Tracks may be projected to the HGND upstream surface
  - ➡ Additional source of information to reject clusters from charged particles



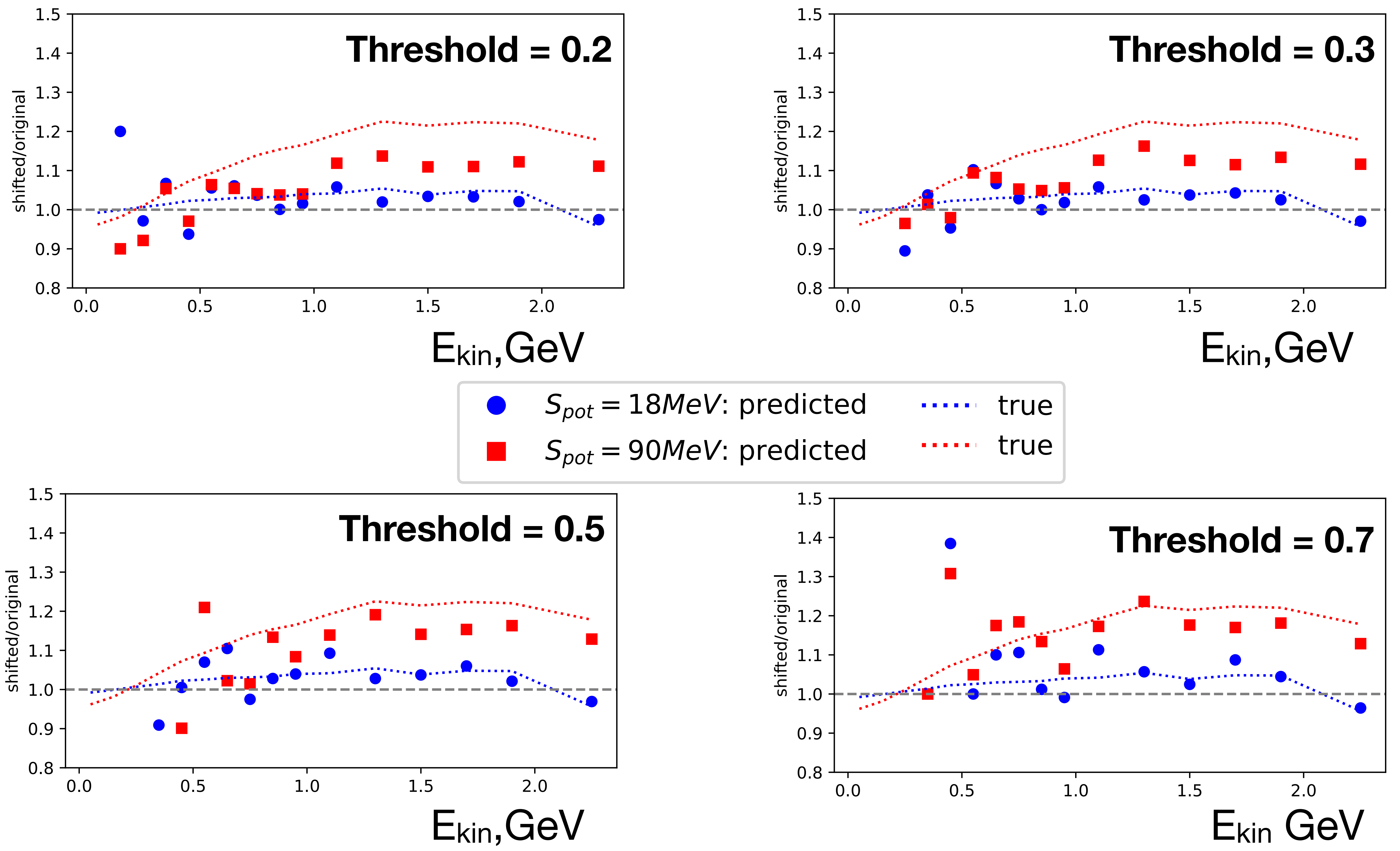
Physics performance toy-test

SMASH simulations Xe+Cs @ 3.8A GeV:
500k events for 3 symmetry potential (S_{pot}) values

Neutron to proton ratio vs E_{kin}.
All reaction particles.
Centrality selection: |y| < 0.5



Resample test HGND dataset to get different neutron spectra:



- Qualitatively, it's possible to separate different symmetry potential at ~1GeV+ with relatively strict selection criteria
- Detailed understanding of background contributions is essential

Event Level Performance

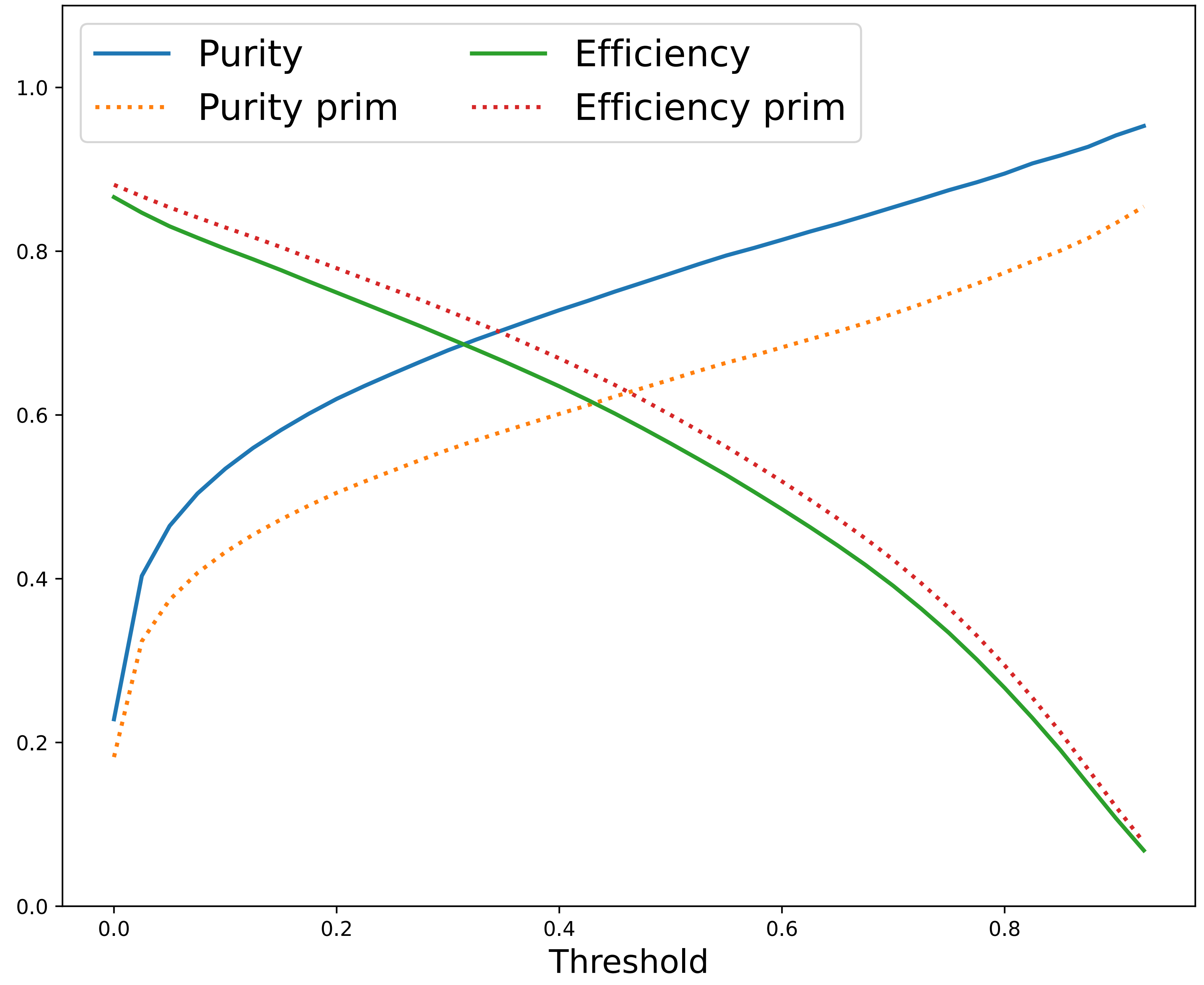
Single neutron reconstruction approach:

- Select best cluster in event by cluster score
- Varying threshold for event score and calculate neutron reconstruction efficiency and purity

$$Purity = \frac{N_{reco\ true}}{N_{reco\ all}}$$

$$Efficiency = \frac{N_{reco\ true}}{N_{neutrons}}$$

Event classification performance vs score threshold



- At selected threshold 0.5 Efficiency ≈ 0.57, Purity ≈ 0.77

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
- Multi-parameter task ⇒ may benefit from **ML-based methods**