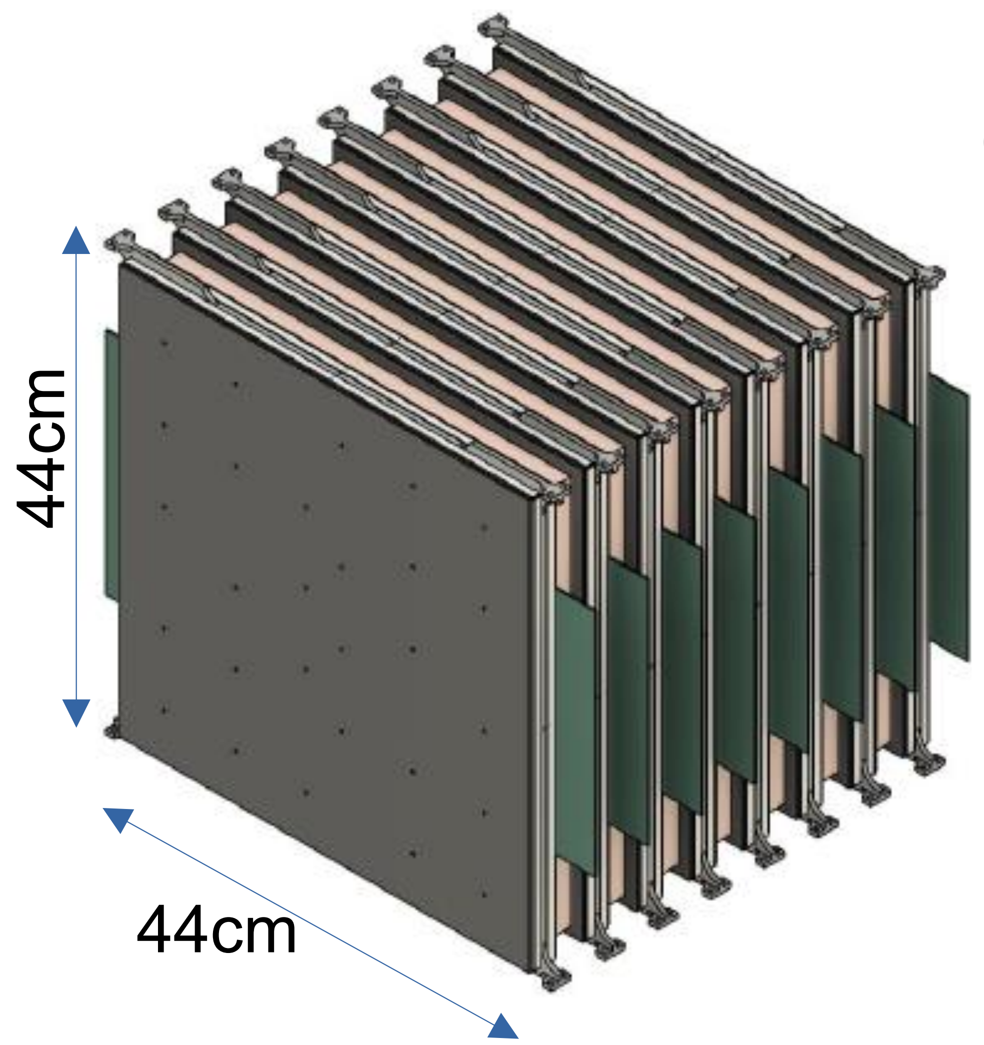
ML-based neutron reconstruction in the HGND

Analysis and Detector Meeting of the BM@N Experiment at NICA,

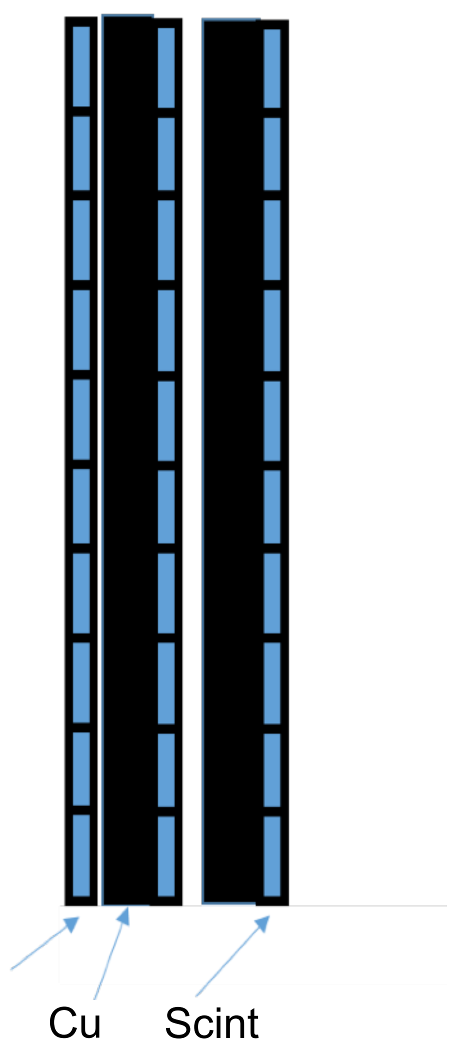
Vladimir Bocharnikov, HSE University
on behalf of the HGND group

5.03.2025

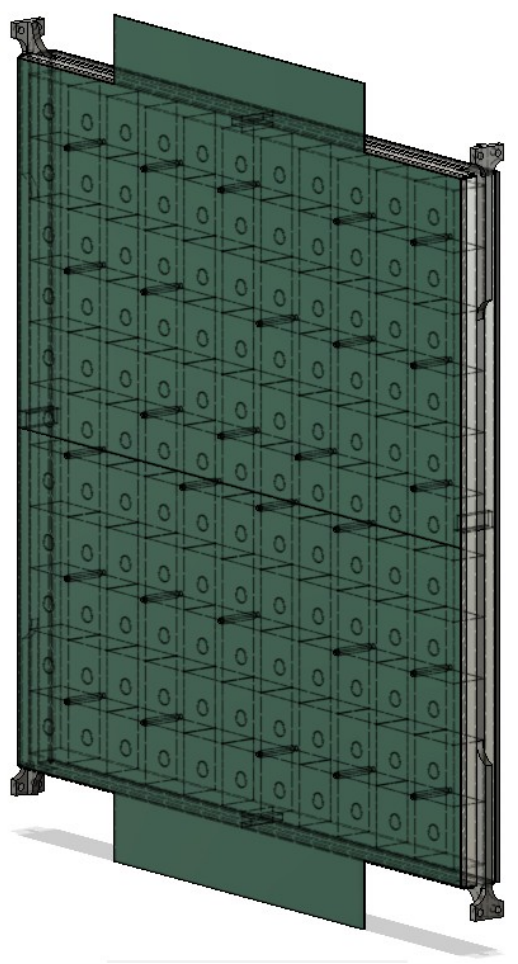
Highly granular time-of-flight neutron detector (HGND)

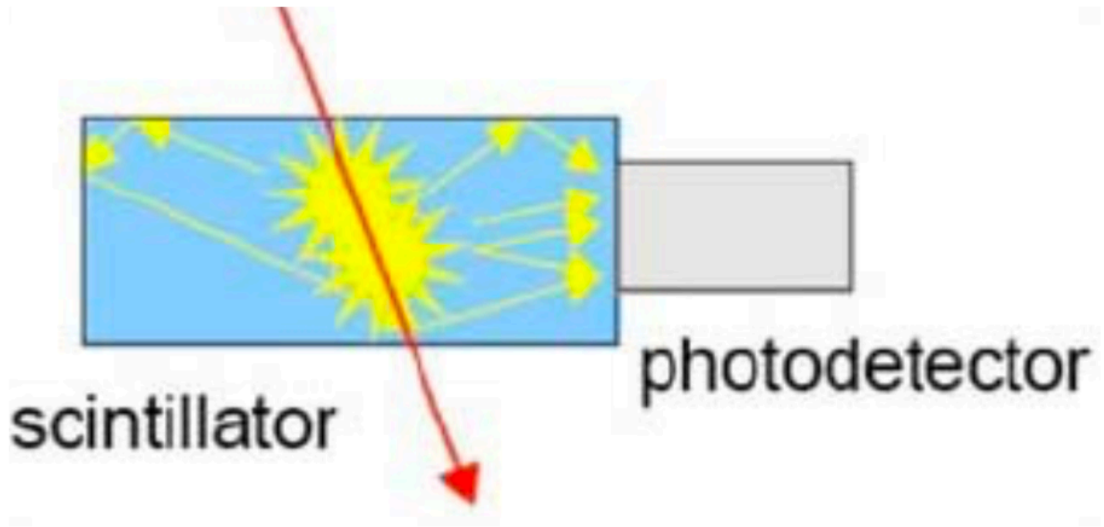


Longitudinal structure



Active layer

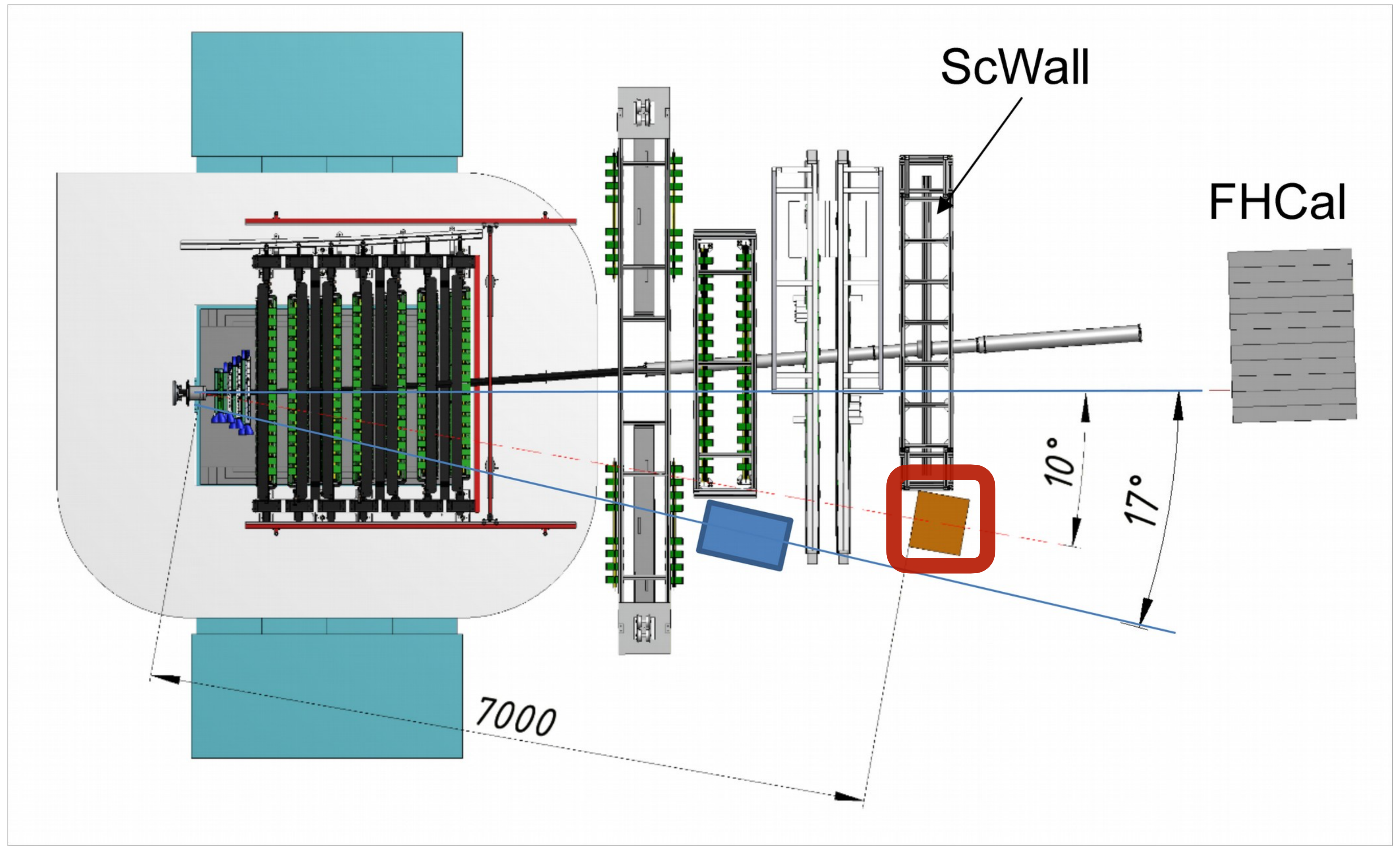


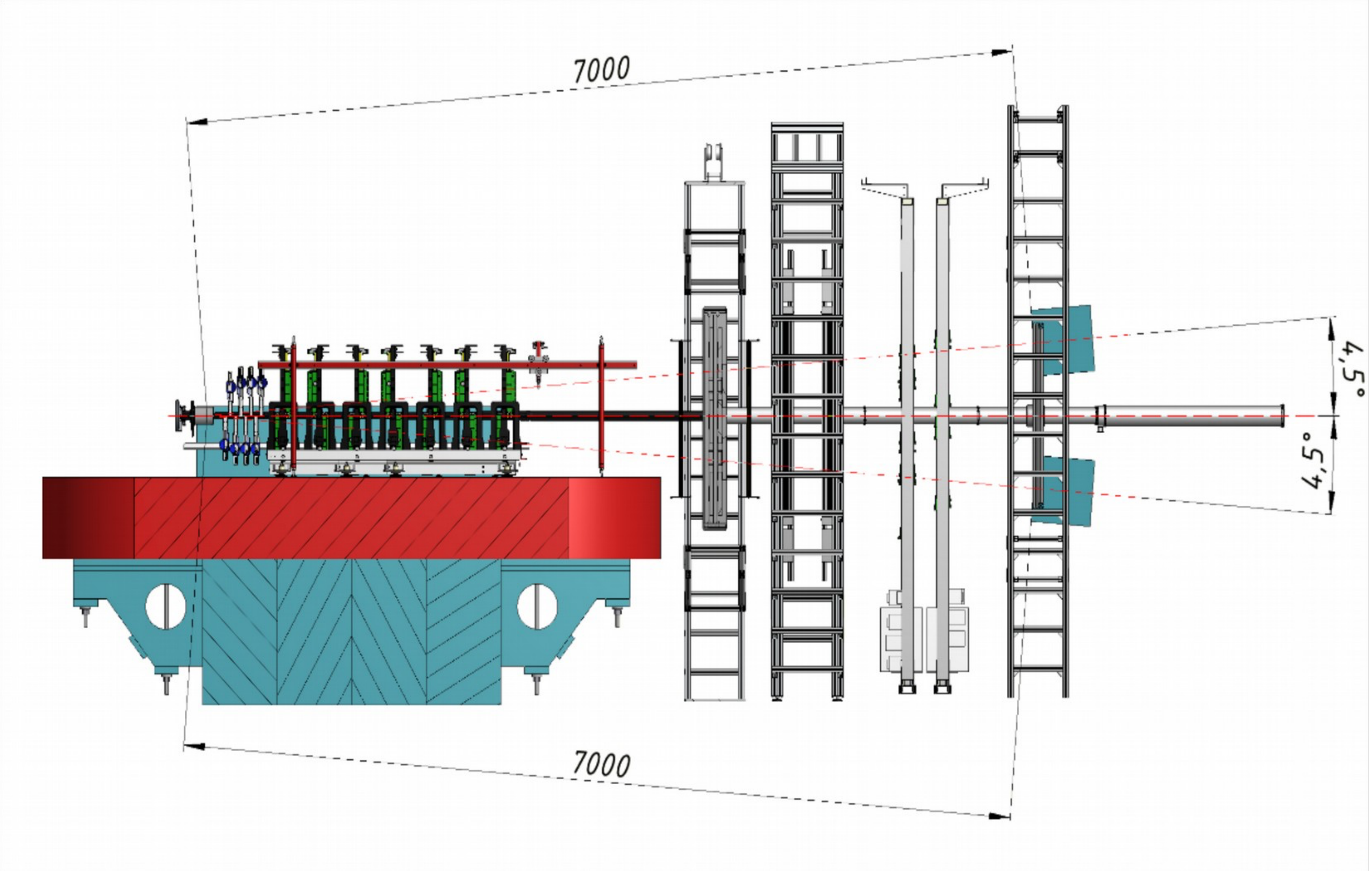


- (2x) 8 layers: *3cm Cu (absorber)* + *2.5cm Scintillator + 0.5cm PCB; 1st layer — 'veto' before absorber*
  ➡Total length: ~0.5m, **~1.5 λ_{in}**
  ➡ neutron detection efficiency ~60% @ 1 GeV
  - Transverse size: **44x44 cm²**
  - *11x11 scintillator cell grid*

- scintillator cells:
  - size: 4x4x2.5 cm³,
  - **total number of cells: 968 (x2)**
  - individual readout by SiPM
  - expected time resolution per cell: ~150 ps
- Alternative **"No absorber" configuration**:
  - Only 1 absorber after 'veto' layer
  - 16 active layers

Detector Setup and Simulations





- HGND sub-detectors are located at **10º to the beam** axis at **~7m from the target**
- Monte-Carlo event simulations: **3 AGeV Bi+Bi** DCM-QGSM-SMM model + Geant4
- 2 HGND configurations are compared:
  - **“Standard”** vs **“No absorber”**
  - **~0.2M events** per configuration

Hit Level Information

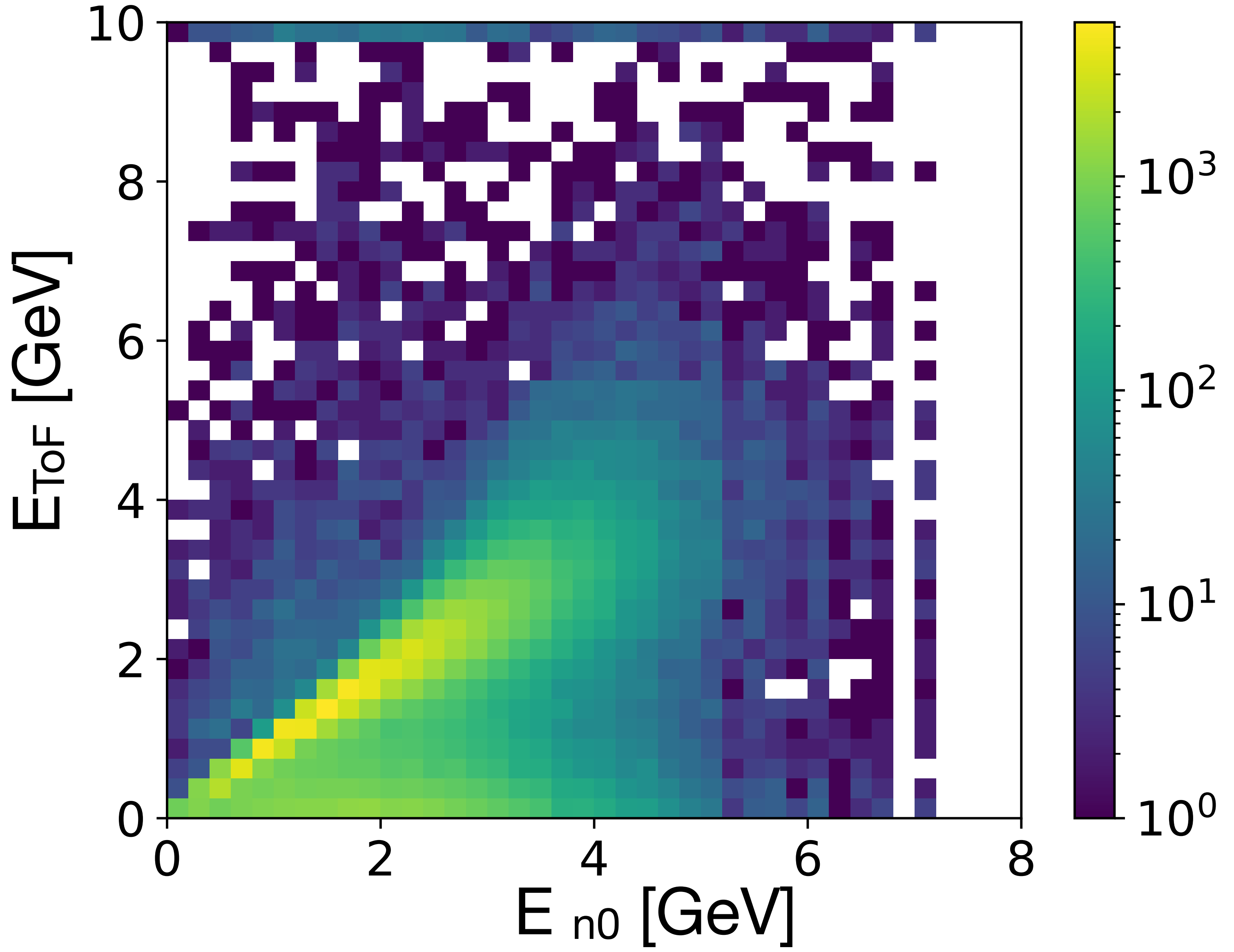
E_{dep} > 3 MeV ~ 0.5 MIP

ToF energy for n^0 hypothesis:

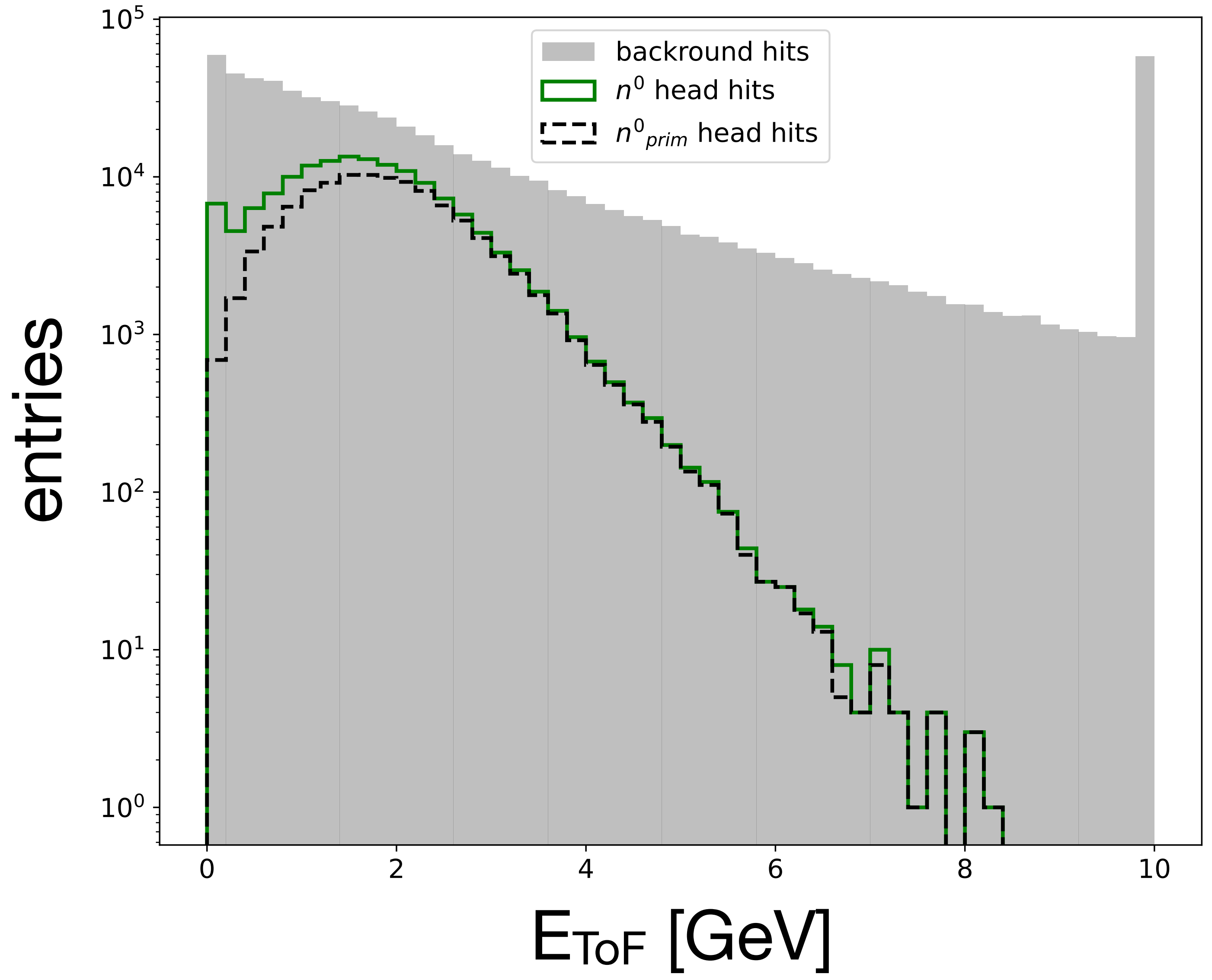
$$E_{ToF} = m_n\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

- $t_{hit}+\mathcal{N}(0,\sigma = 150ps)$
- hits with E_{ToF}>10GeV are set to 10 GeV
- 'Head' hits — prompt neutron deposition with $\delta(E_{ToF}) < 0.3$
  - other hits - background
- Primary neutrons are selected by MotherID=-1

ToF energy for primary neutron hits



Hit E_{ToF} distributions

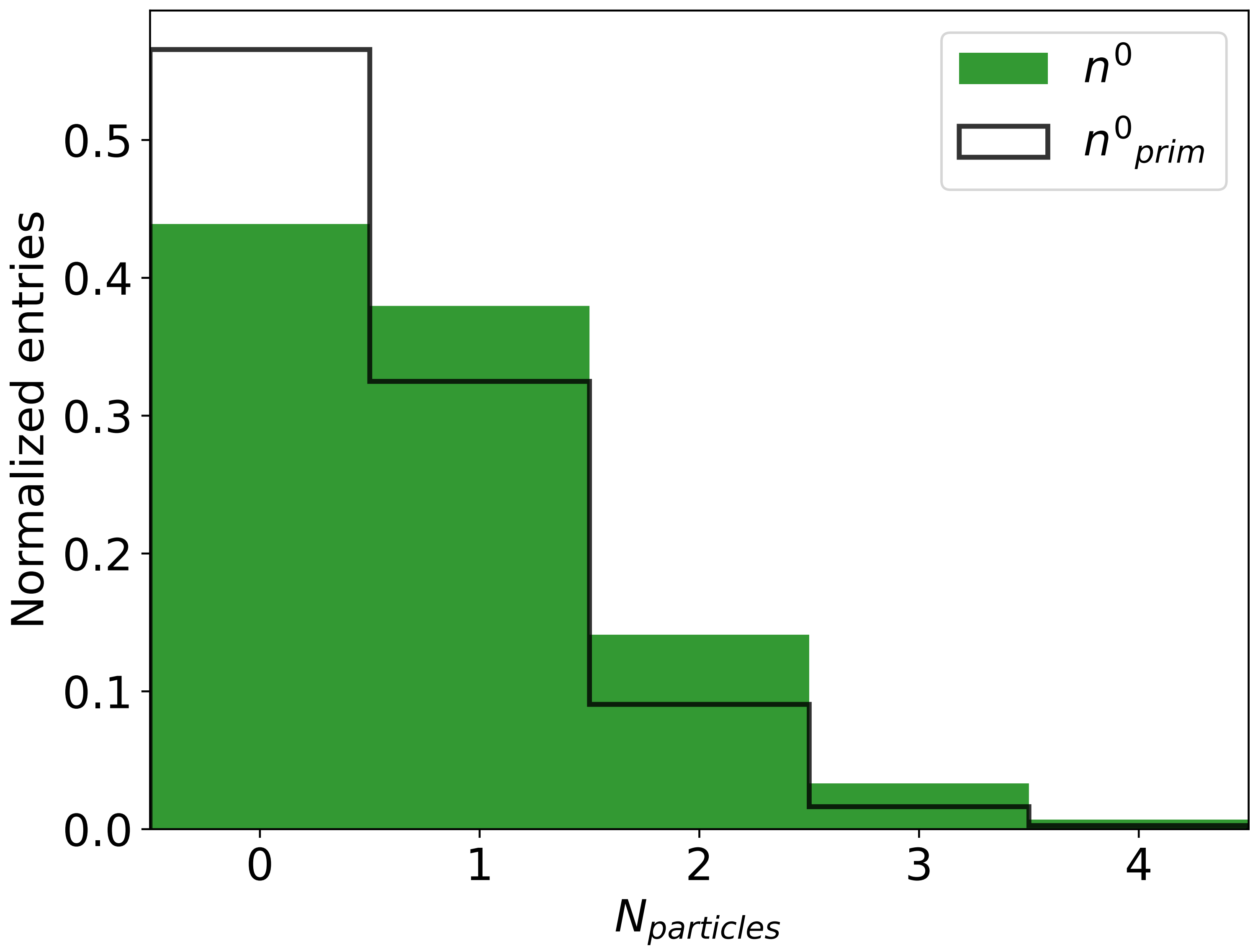


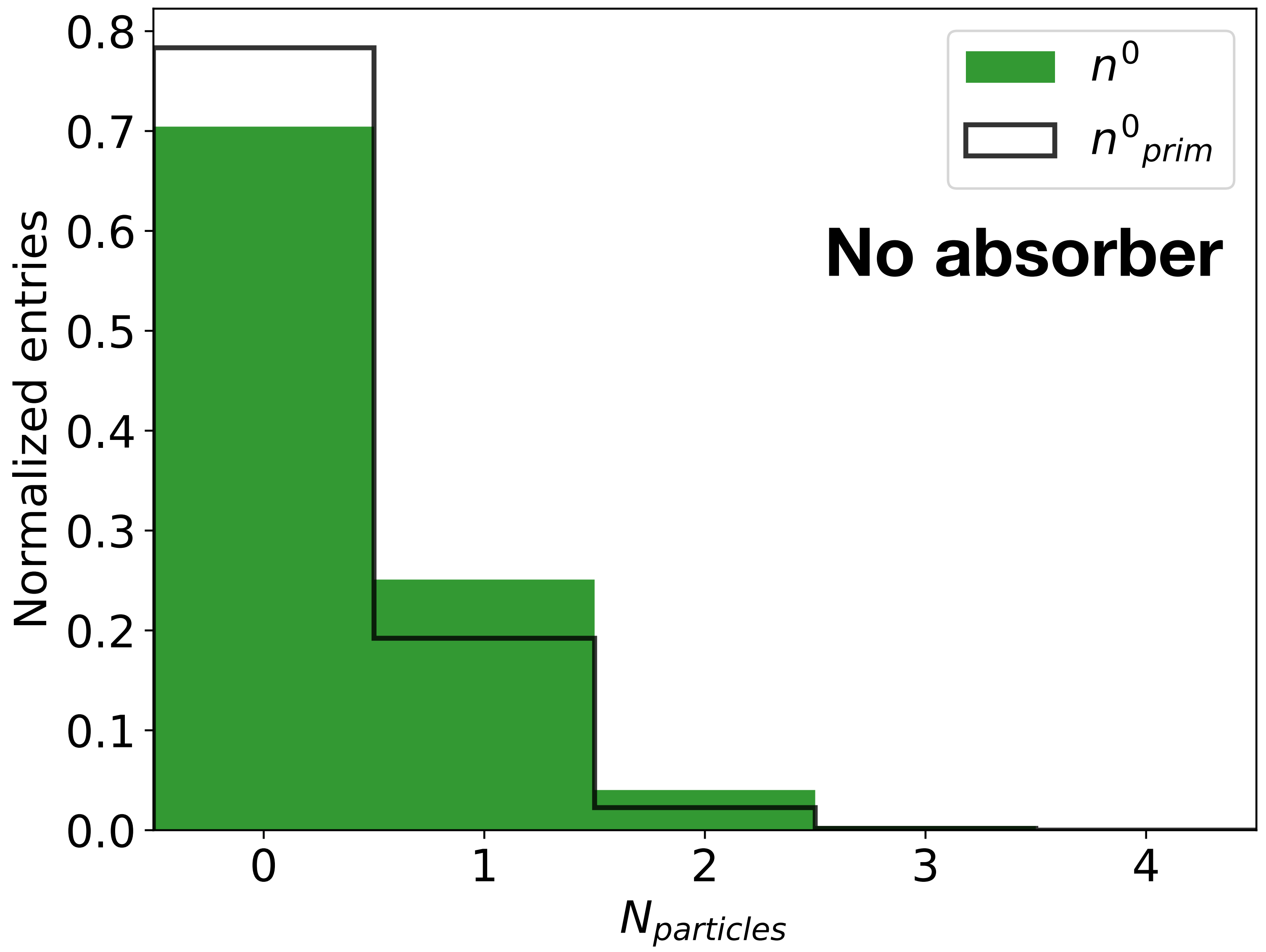
Neutron Multiplicity

Multiplicity counts require existence of 'Head' hit with $\delta(E_{ToF}) < 0.3$

Distributions normalised to number of events with energy deposition

Signal neutron multiplicity





- Significant contribution of events with N_{n0}>1
- signal/background ≈ 0.5 on event level

- Fraction of events with N_{n0}>1 < 2%
- signal/background ≈ 20-30% on event level

Graph Neural Networks (GNN)

Why Graph Neural Networks:

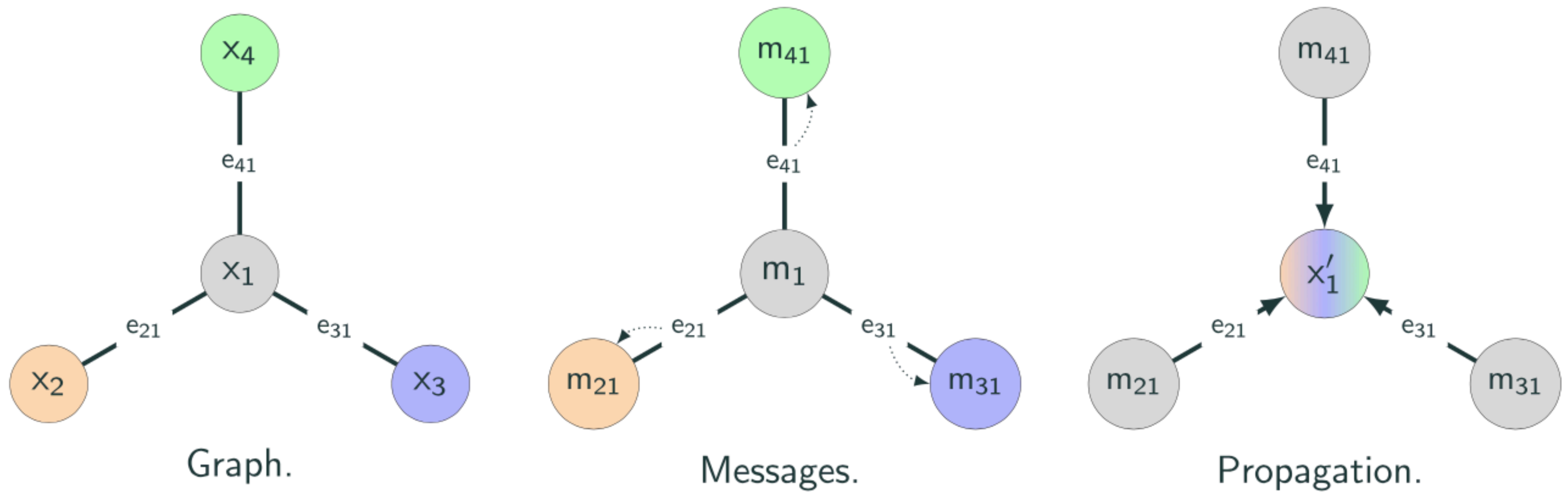
- Natural vector event representation
  - Detector cell hits as graph nodes
- Easily applied to sparse data with variable input size
  - Typically we have signal only in small fraction of sensors
- Captures event structures
- Increasing number of successful implementations in HEP

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.

GNN Model

Graph construction:

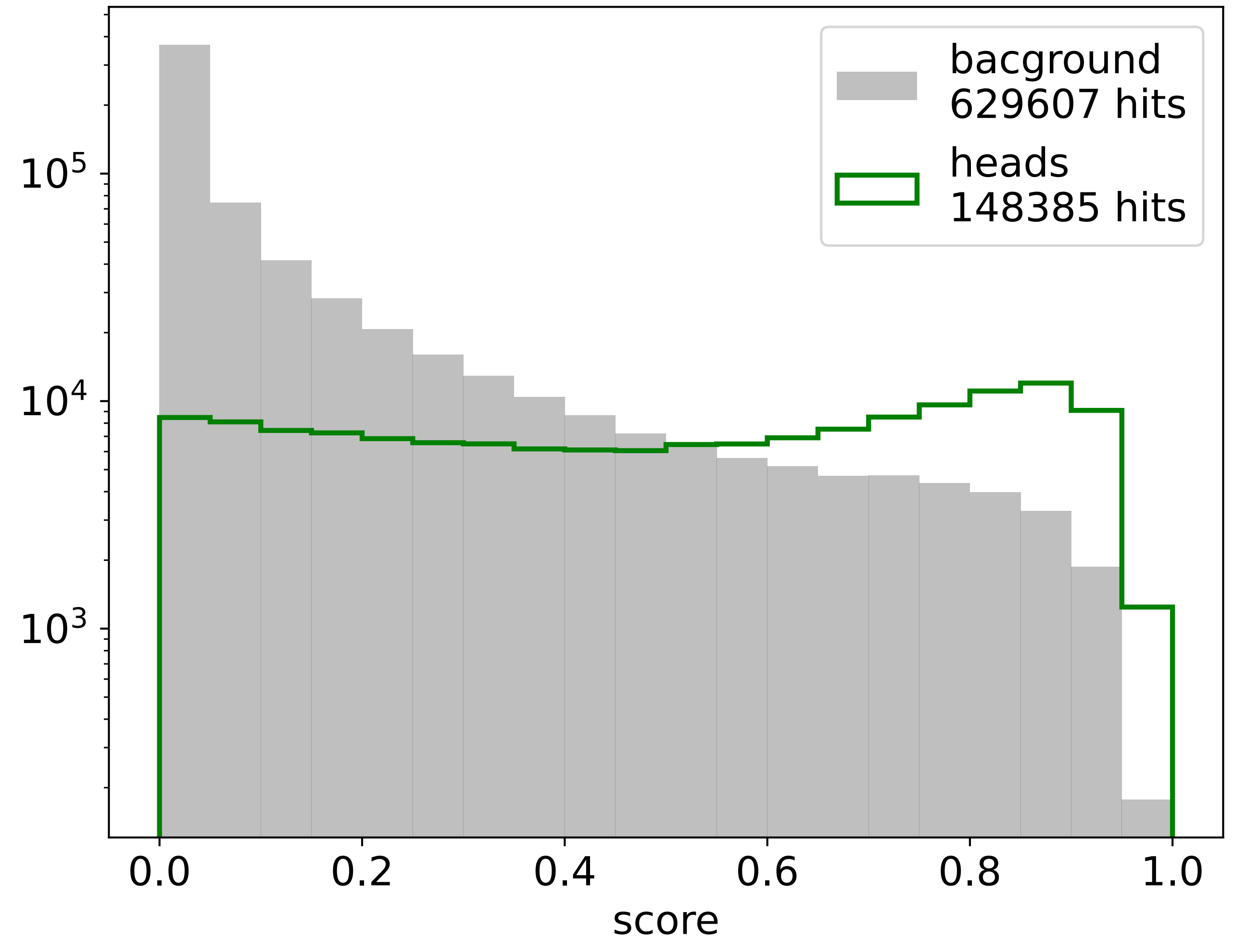
- Nodes — hits. Observables per hit:
  - hit coordinates; Edep > 3 MeV ~ 0.5 MIP; hit time, E_{ToF}
- Edges — fully connected graphs
- 176292 graphs with absorber
- 217792 graphs - no absorber
- Constructed event graphs are split 50/50% to train and test procedure

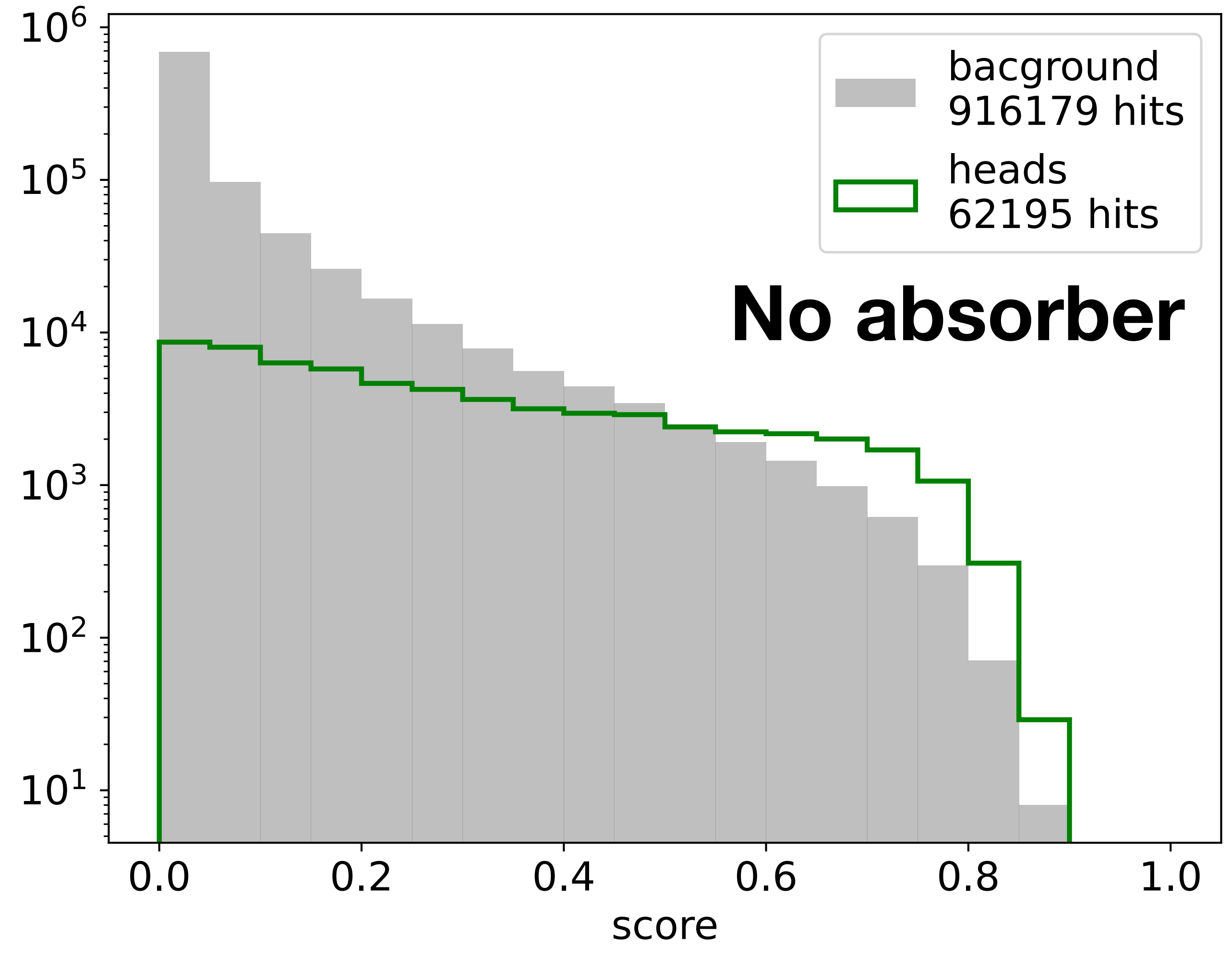
Training objective

- Neutron 'head' class* for each hit
  - * All neutrons with 'head' hit considered as signal
  - Binary cross entropy loss function

PyTorch Geometric library

Predicted 'head' score





Event Classification Performance

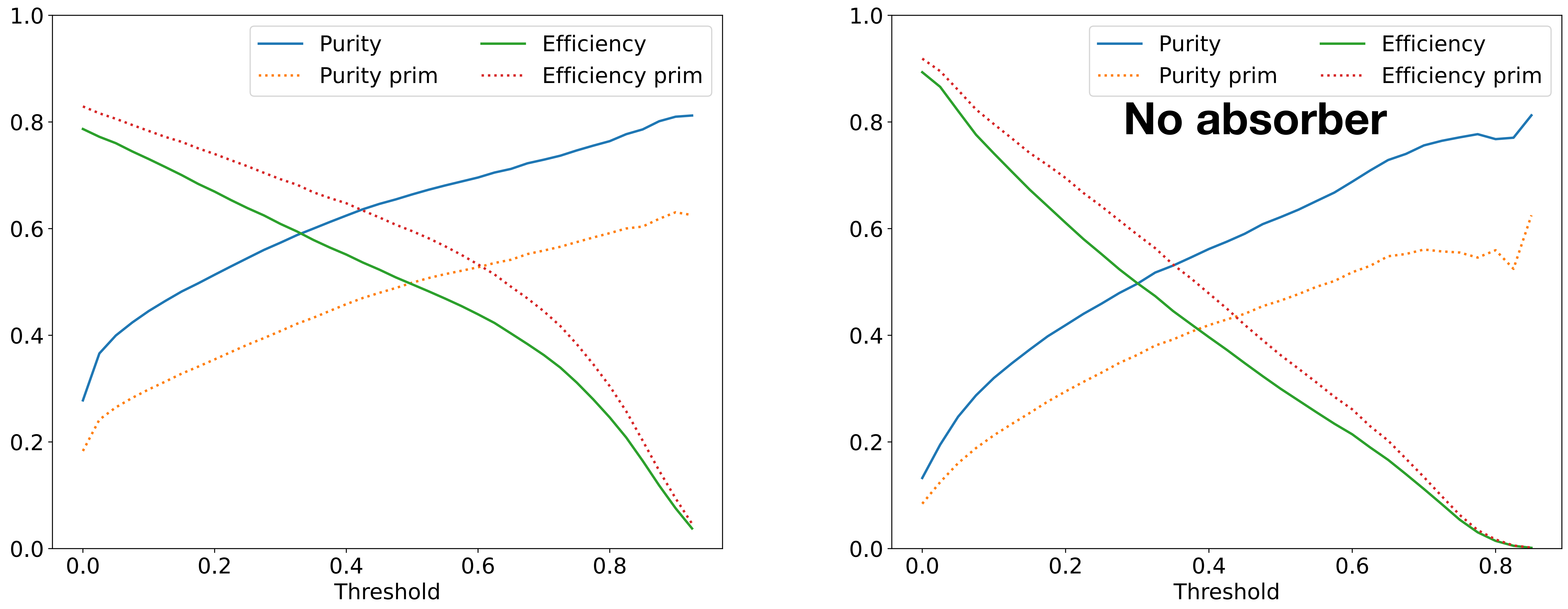
Simplified single neutron reconstruction approach:

- Max aggregation for predicted head score to get single prediction per event
- 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

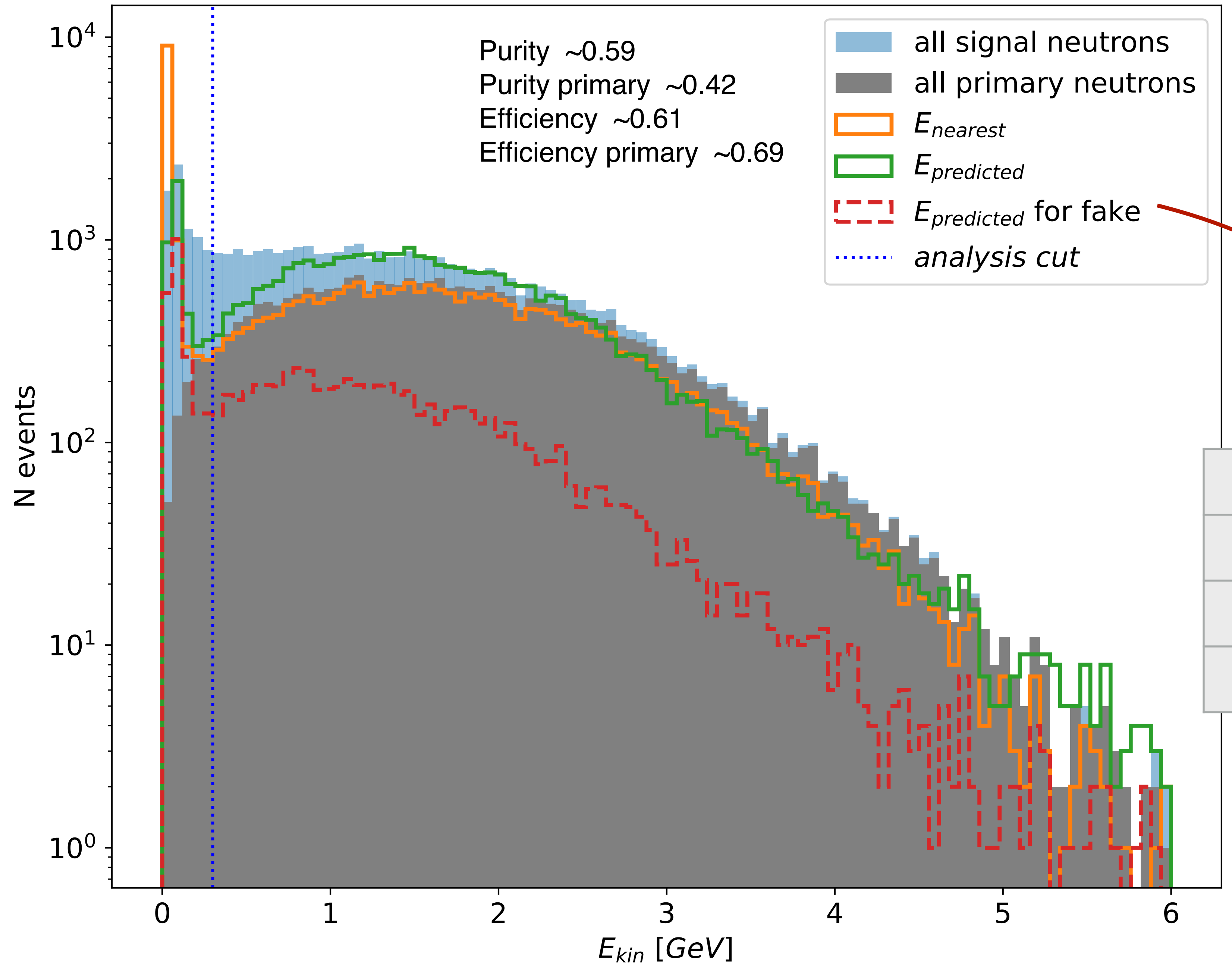


- 5-10% lower performance for “No absorber” configuration

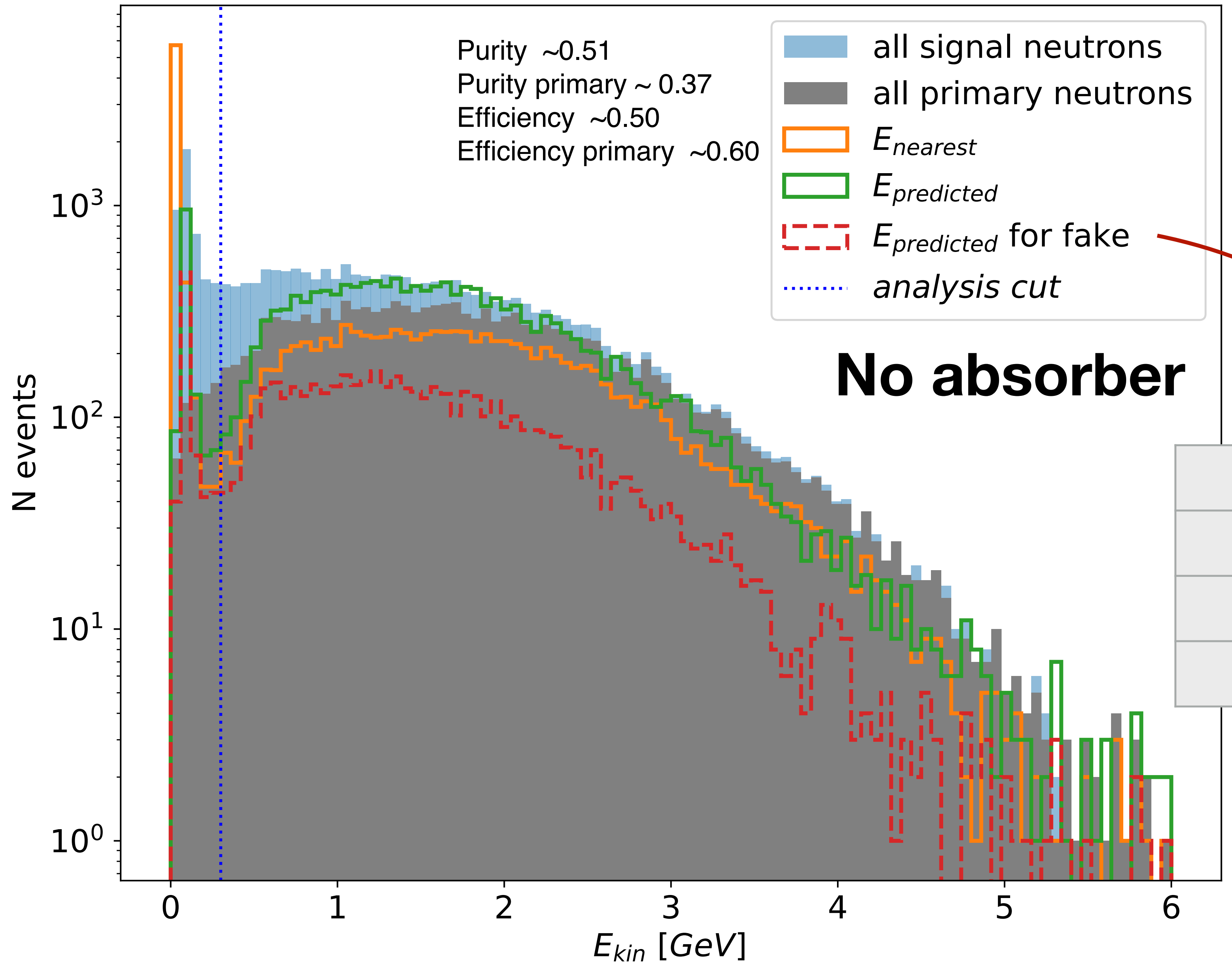
➡ to be confirmed at higher statistics

Neutron Energy Spectra

Example of resulting neutron energy spectra at fixed score threshold at 0.3



bg neutrons	~31%
protons	~23%
gamma	~17%
pions	~15%



protons	~37%
bg neutrons	~16%
pions	~18%
gamma	~13%

- ~0.3 GeV cut on reconstructed energy is planned to suppress backround suppression
- problematic region <1GeV for ‘no absorber’ configuration

Summary

- Two HGND configurations are compared using preliminary ML-based neutron reconstruction procedure
  - At comparable statistics of ~0.2M Bi+Bi collisions at 3 AGeV sligtly lower performance for ‘no absorber’ configuration
    - main reason - lower signal over background ratio
    - to be confirmed at higher statistics

Backup

Hit Level Information

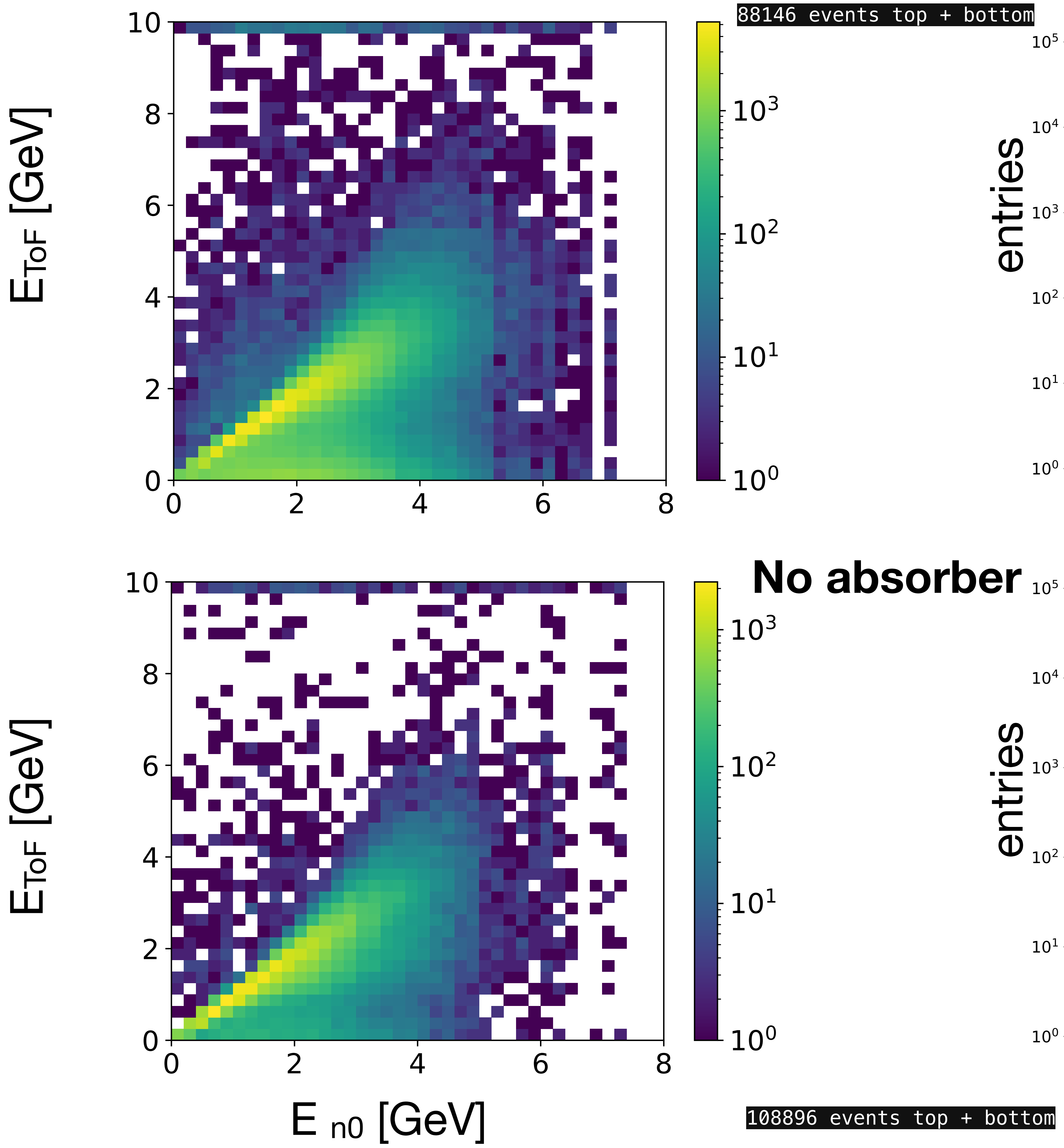
E_{dep} > 3 MeV ~ 0.5 MIP

ToF energy for *n^0* hypothesis:

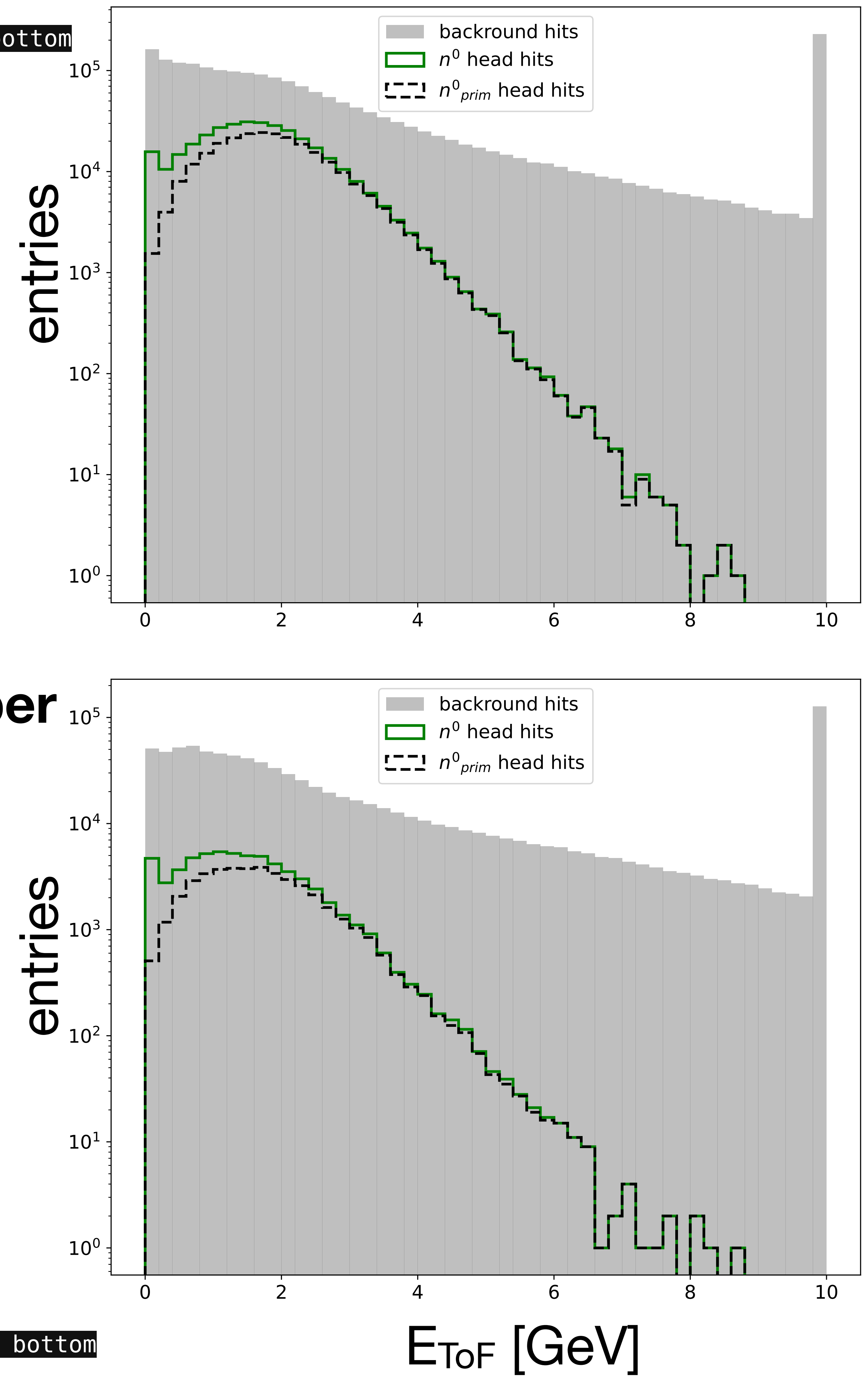
$$E_{ToF} = m_n\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

- $t_{hit} + \mathcal{N}(0, \sigma = 150\text{ps})$
- hits with E_{ToF}>10GeV are set to 10 GeV
- 'Head' hits — prompt neutron deposition with $\delta(E_{ToF}) < 0.3$
  - other hits - background
- Primary neutrons are selected by MotherID=-1

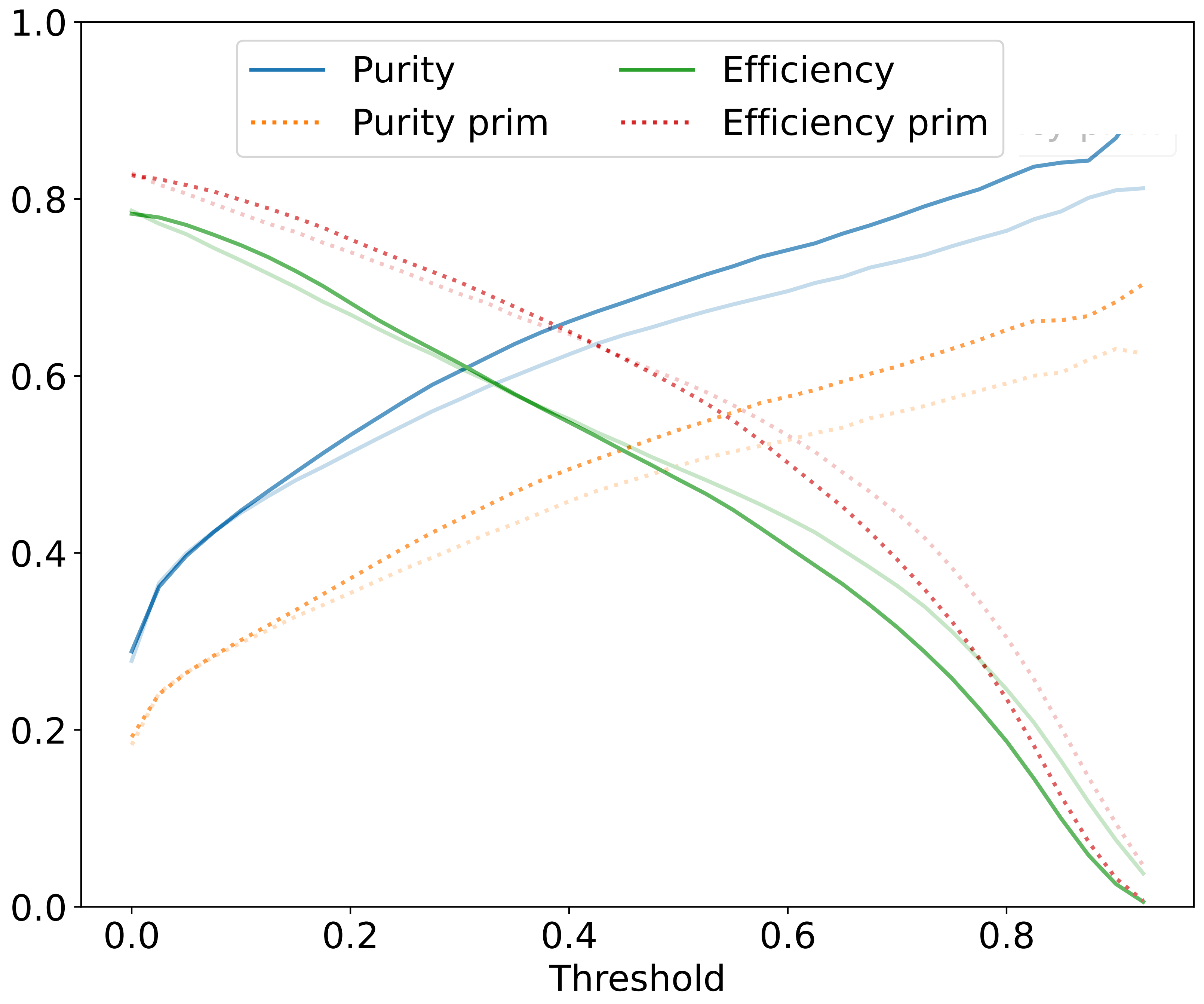
ToF energy for primary neutron hits

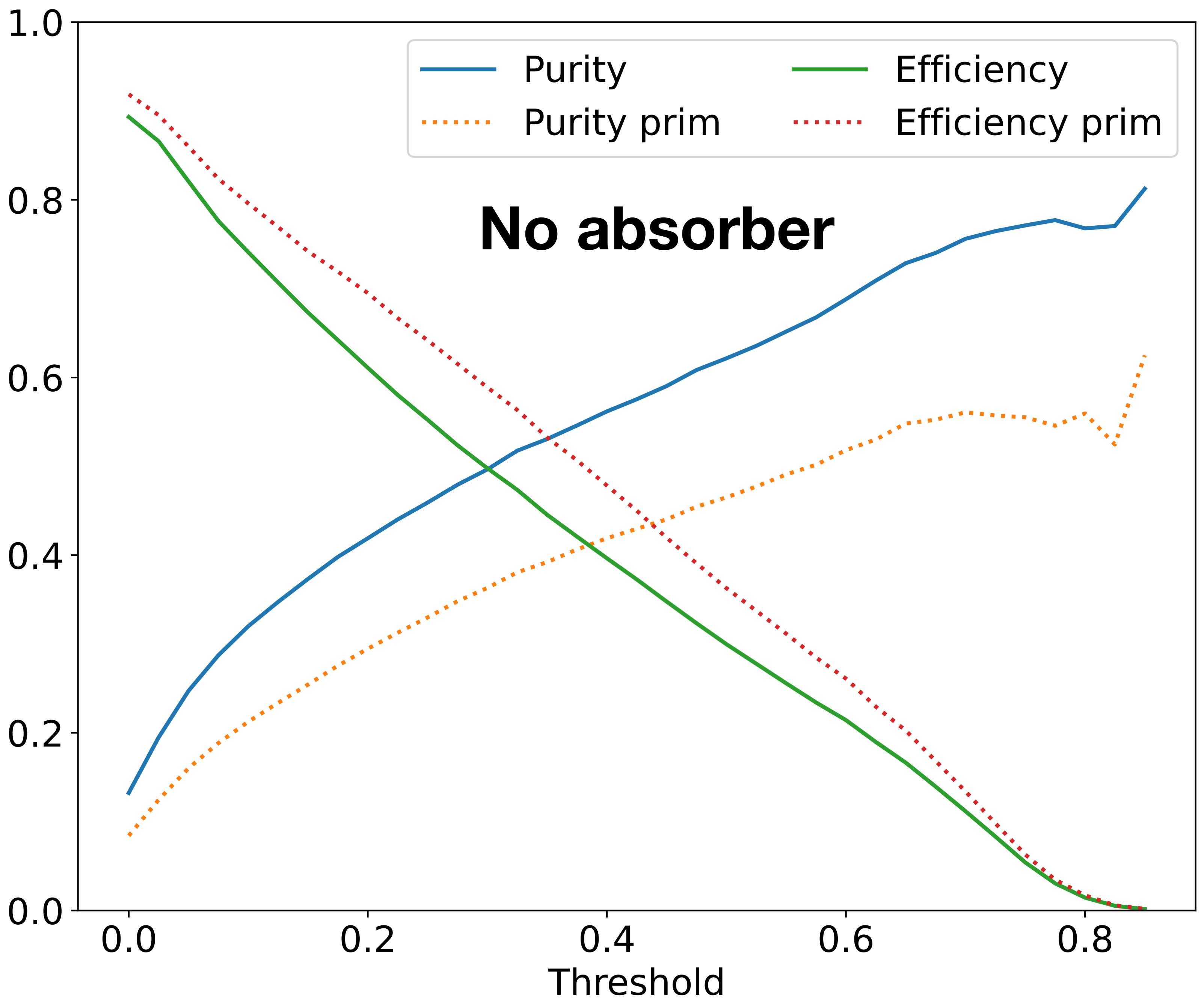


Hit E_{ToF} distributions



Purity & efficiency ~x2 statistics

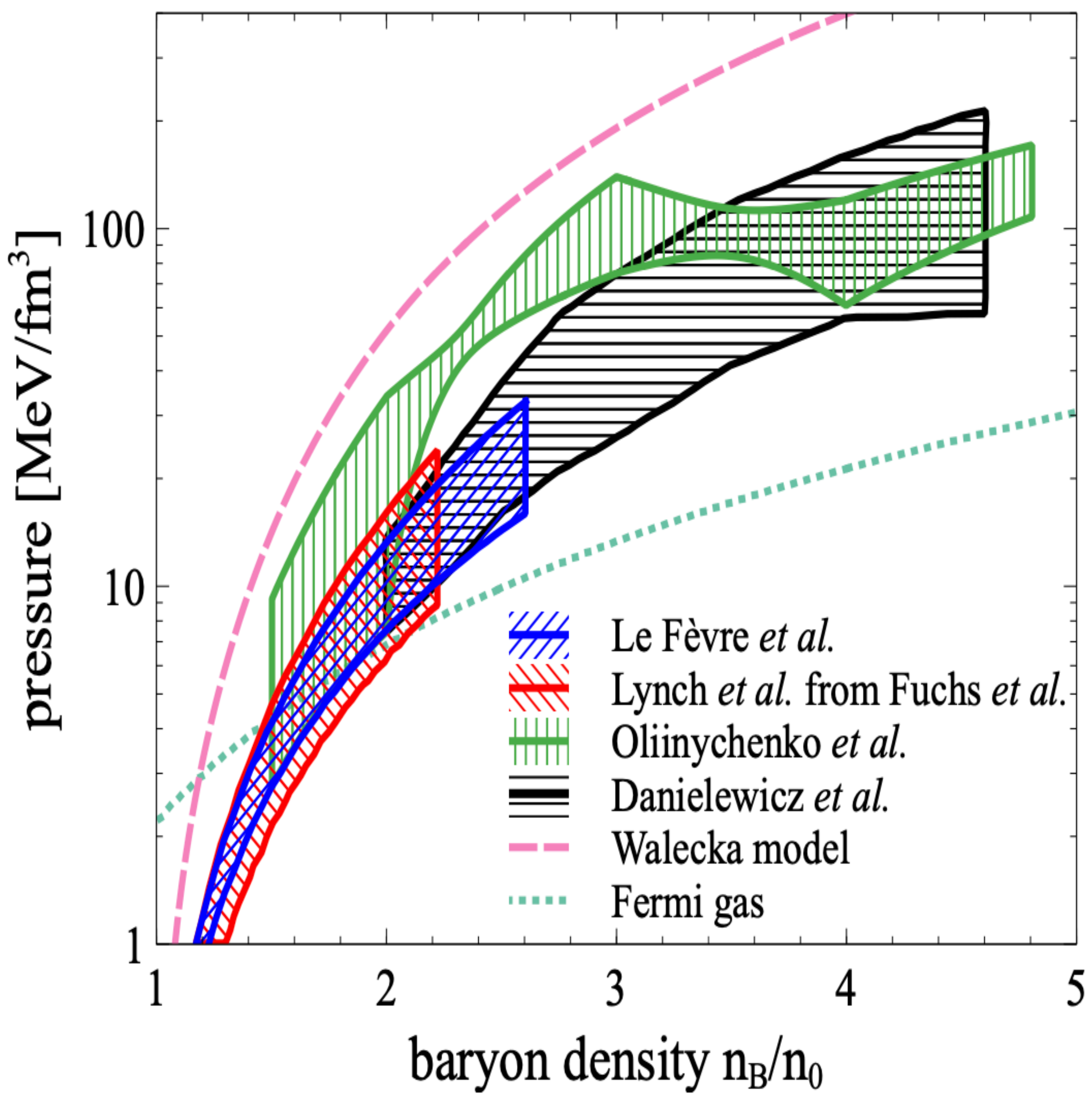




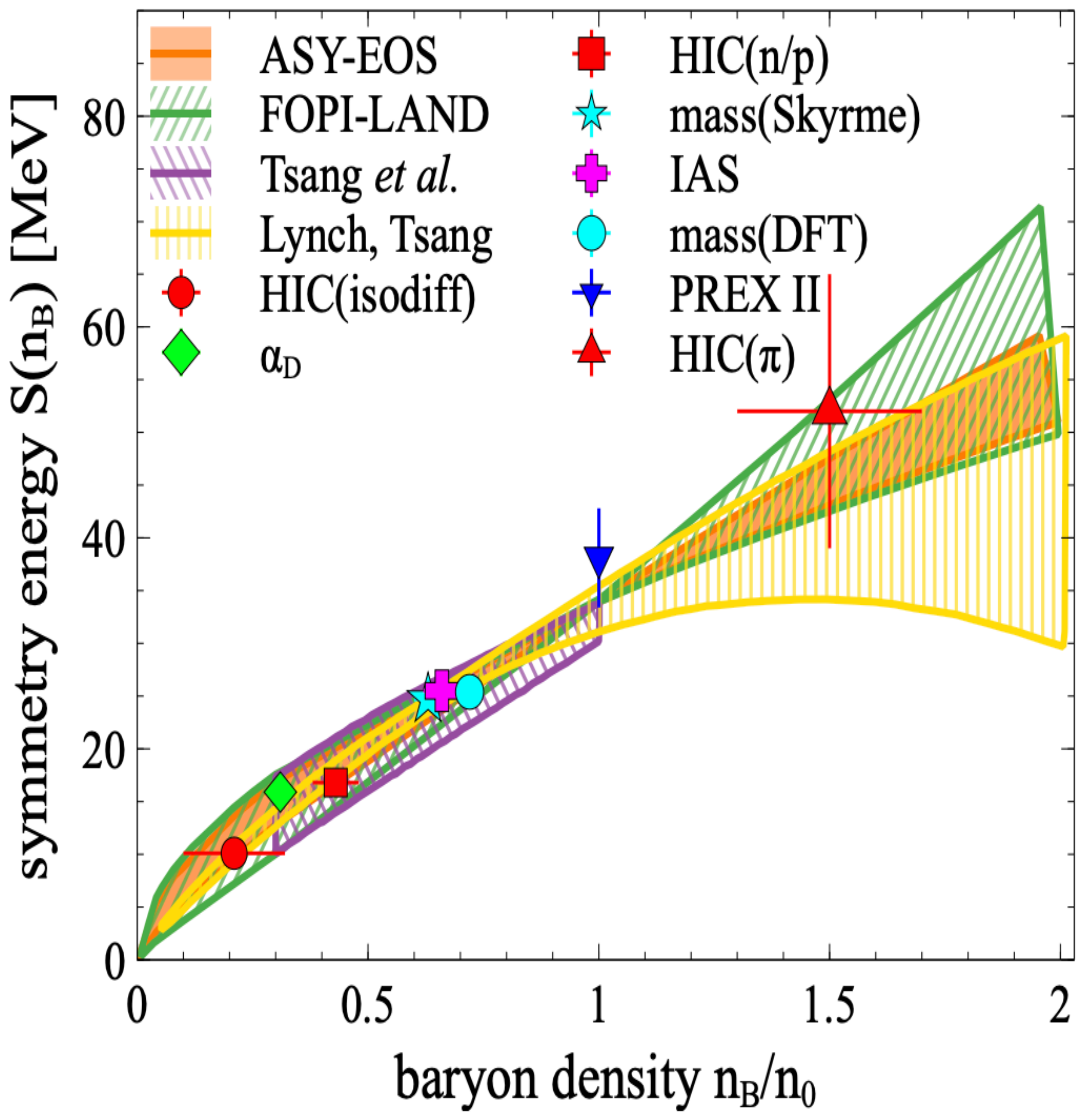
EOS for high baryon density matter

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

GNN Model

Graph construction:

- Nodes — hits. Observables per hit:
  - hit coordinates; Edep > 3 MeV ~ 0.5 MIP; E_{ToF}
  - additional global event node connected to each hit node
- **139004** graphs
- Constructed event graphs are split 50/50% to train and test procedure

Heterogenius GNN Model:

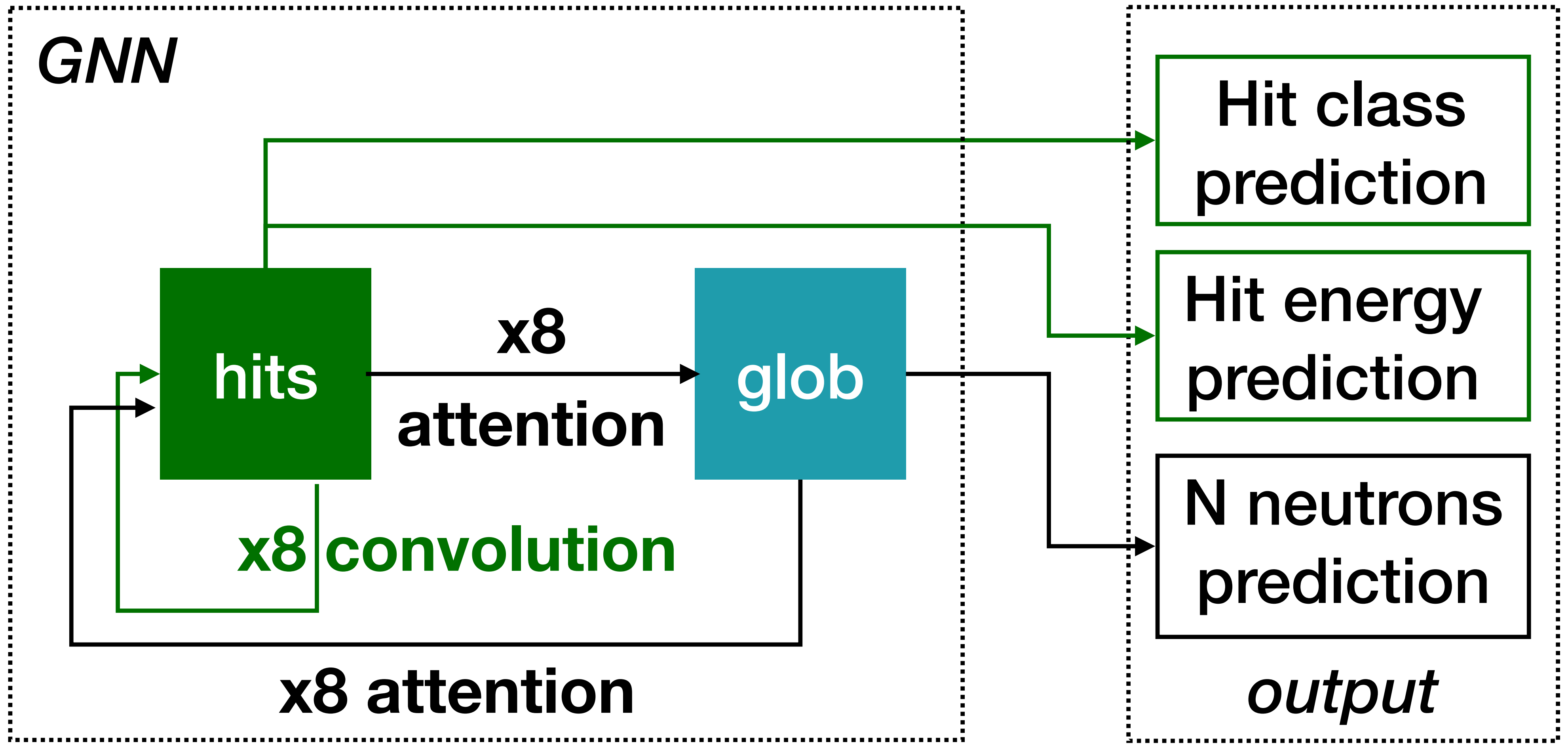
- <u>Graph convolution</u> layers between hit nodes. Hidden state size: 512
- <u>Graph attention</u> layers between hit and global node. Hidden state size: 512

PyTorch Geometric library

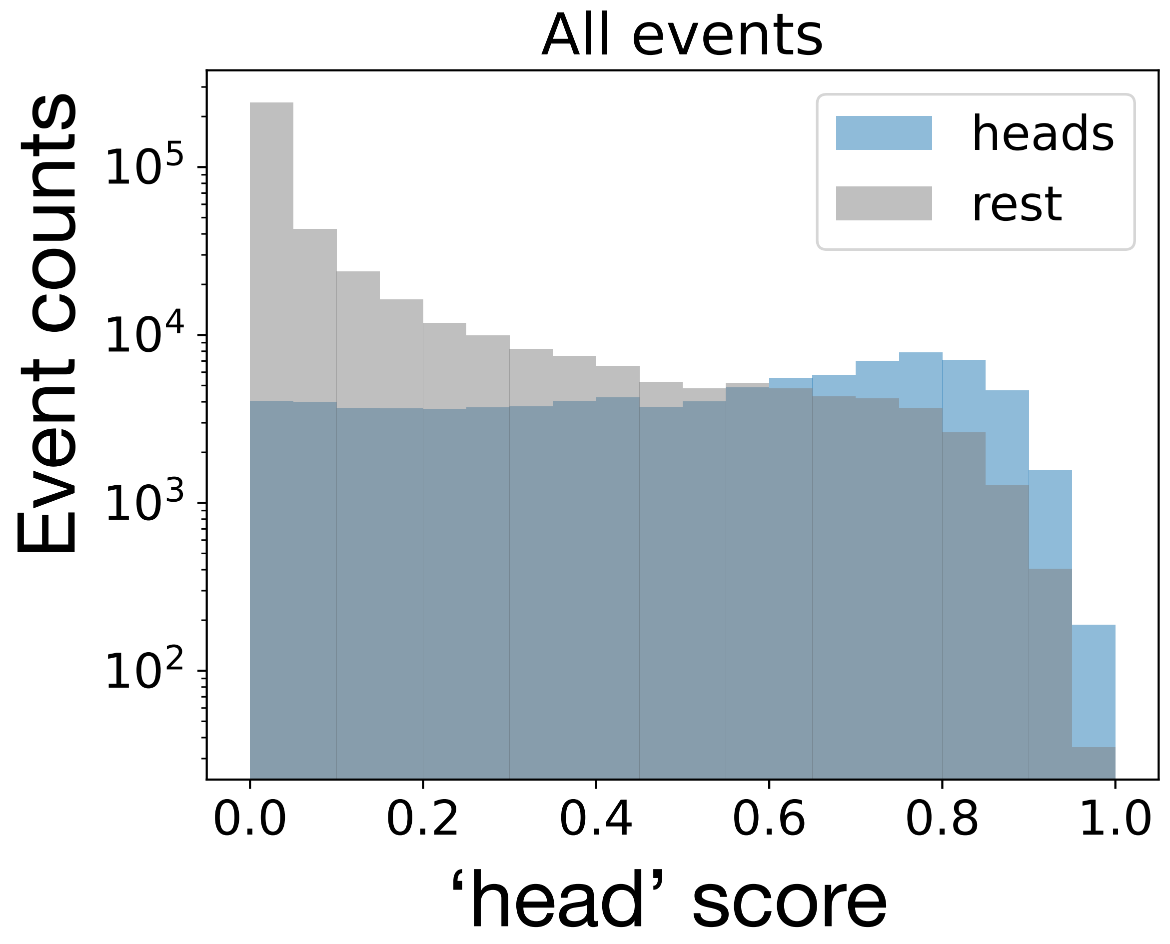
Output

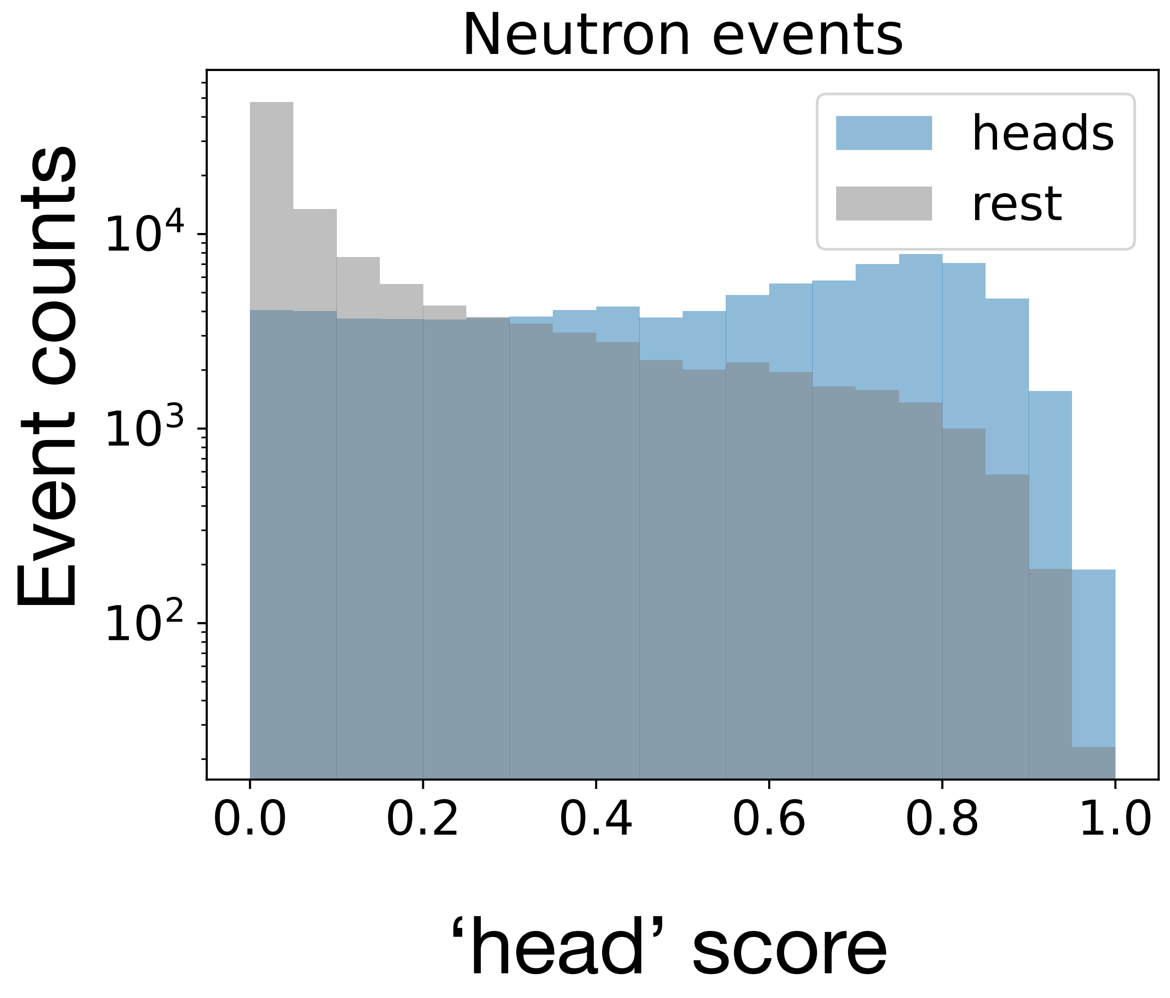
Simultaneous training for 3 tasks:

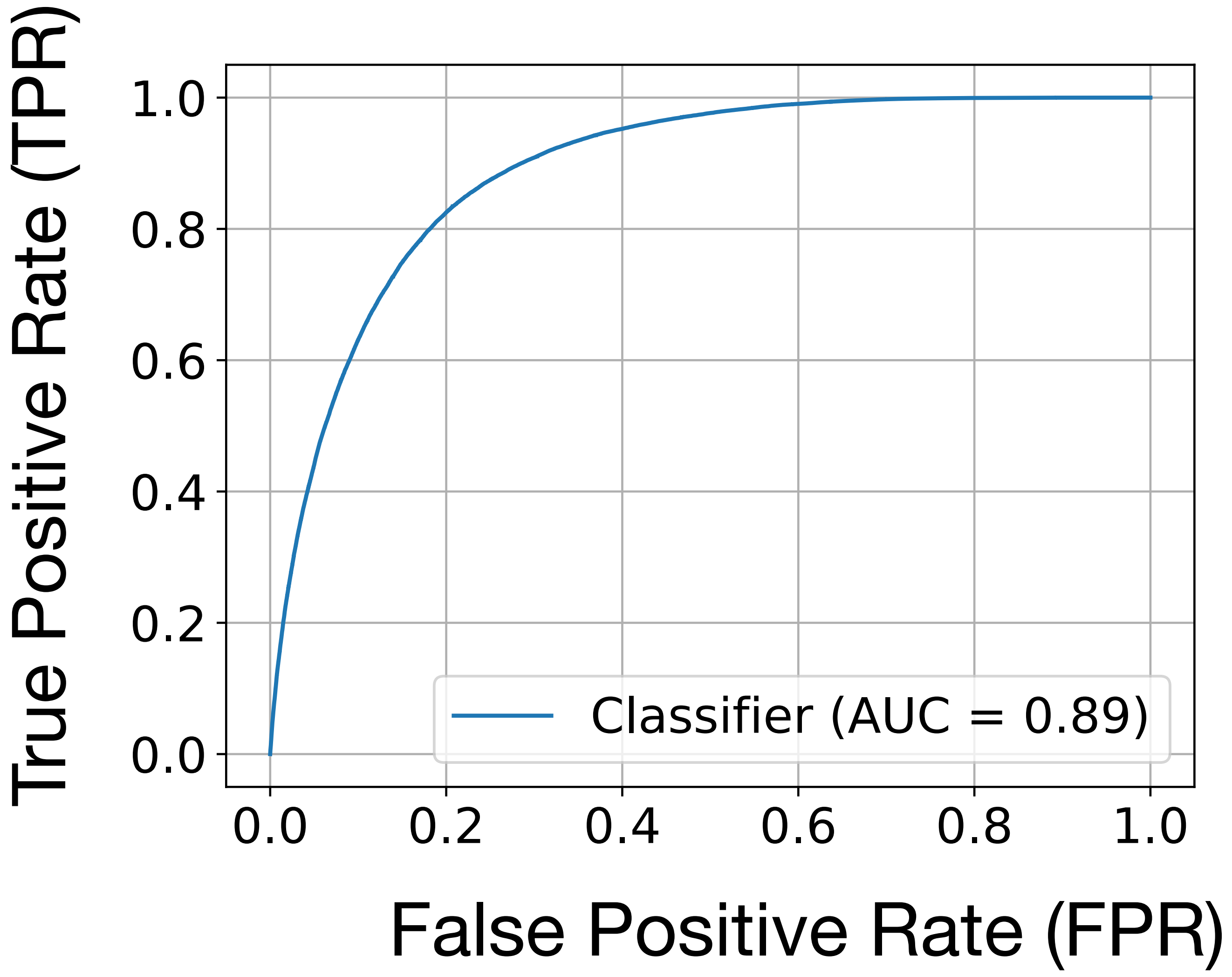
- Neutron 'head' class for each hit
  - Binary cross entropy loss function
- Neutron energy prediction for each hit
  - MSE loss function (only on MC truth 'heads')
- Number of neutrons in event (0 to 3)
  - Cross entropy loss function



Neutron Head Prediction



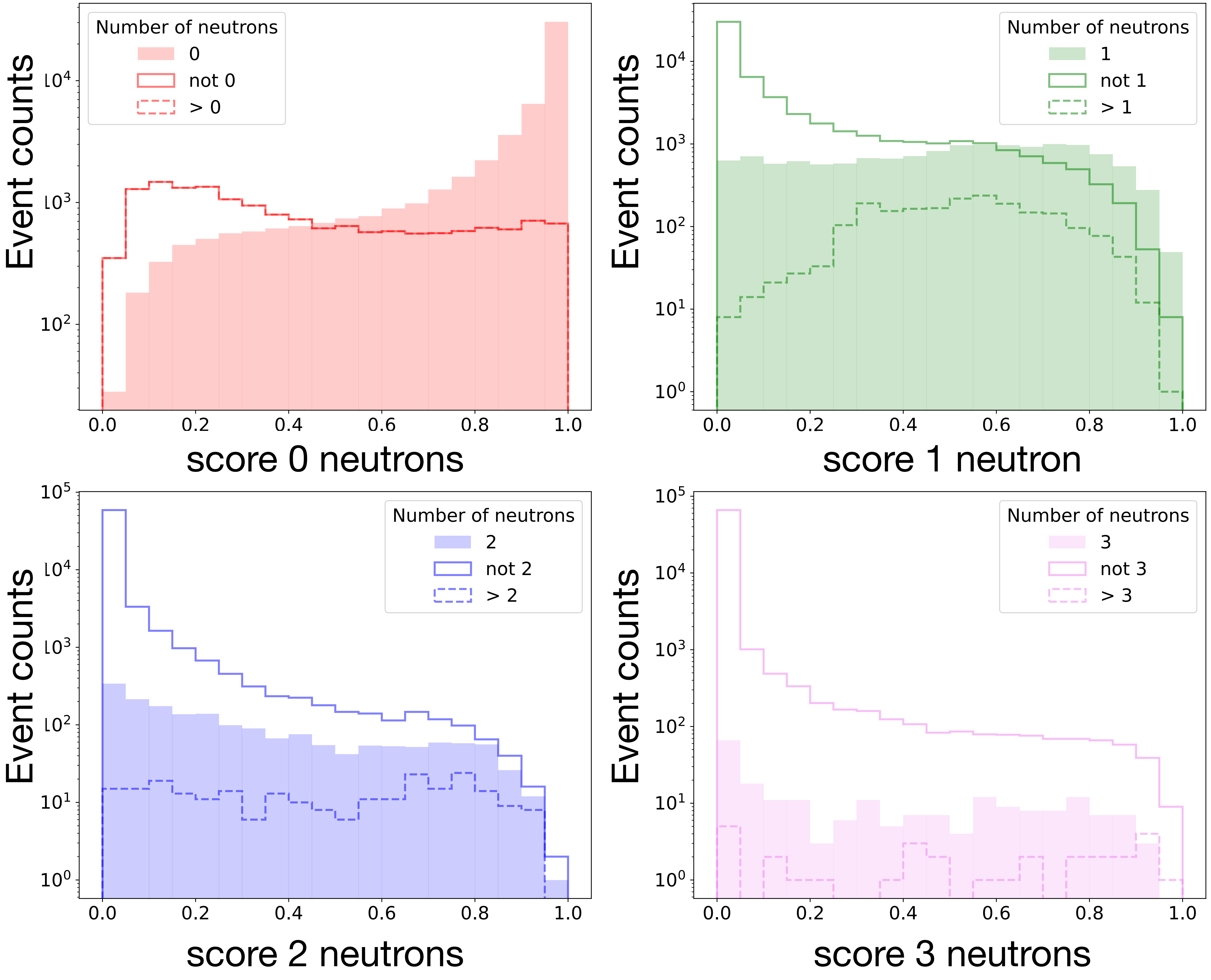




$$TPR = \frac{TP}{TP + FN} \qquad FPR = \frac{FP}{TN + FP}$$

- Overall good hit classification performance
- Requires additional clustering algorithms to be used in neutron reconstruction

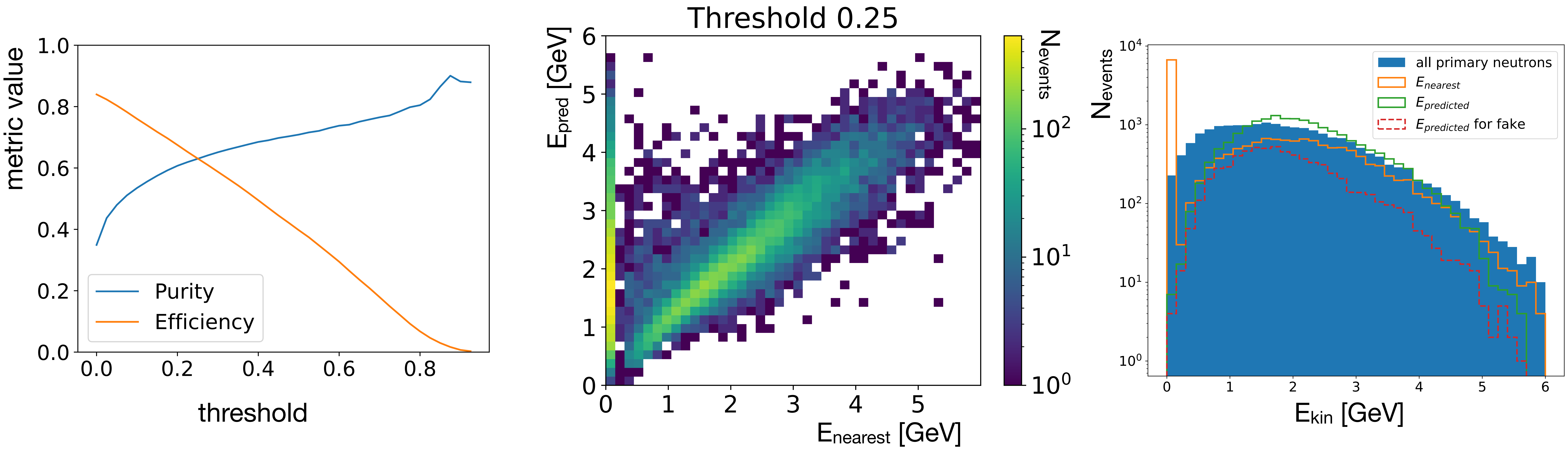
Neutron Multiplicity Prediction



- Good separation of neutron events as a binary problem
- Higher multiplicities require more sophisticated algorithms
  - Multiplicity prediction -> unsupervised clustering

Simple Clustering Algorithm

- Gaussian Mixture clustering approach to find best neutron cluster
  - Variables: hit coordinates, time, E_{ToF}, 'head' score (6D Gaussian)
  - N components = 1 to 3 for each event
    - For N > 1 select component with max(mean 'head' score)
  - $E_{nearest}$ — closest neutron energy to prediction (mean E_{ToF} per cluster)



Dataset

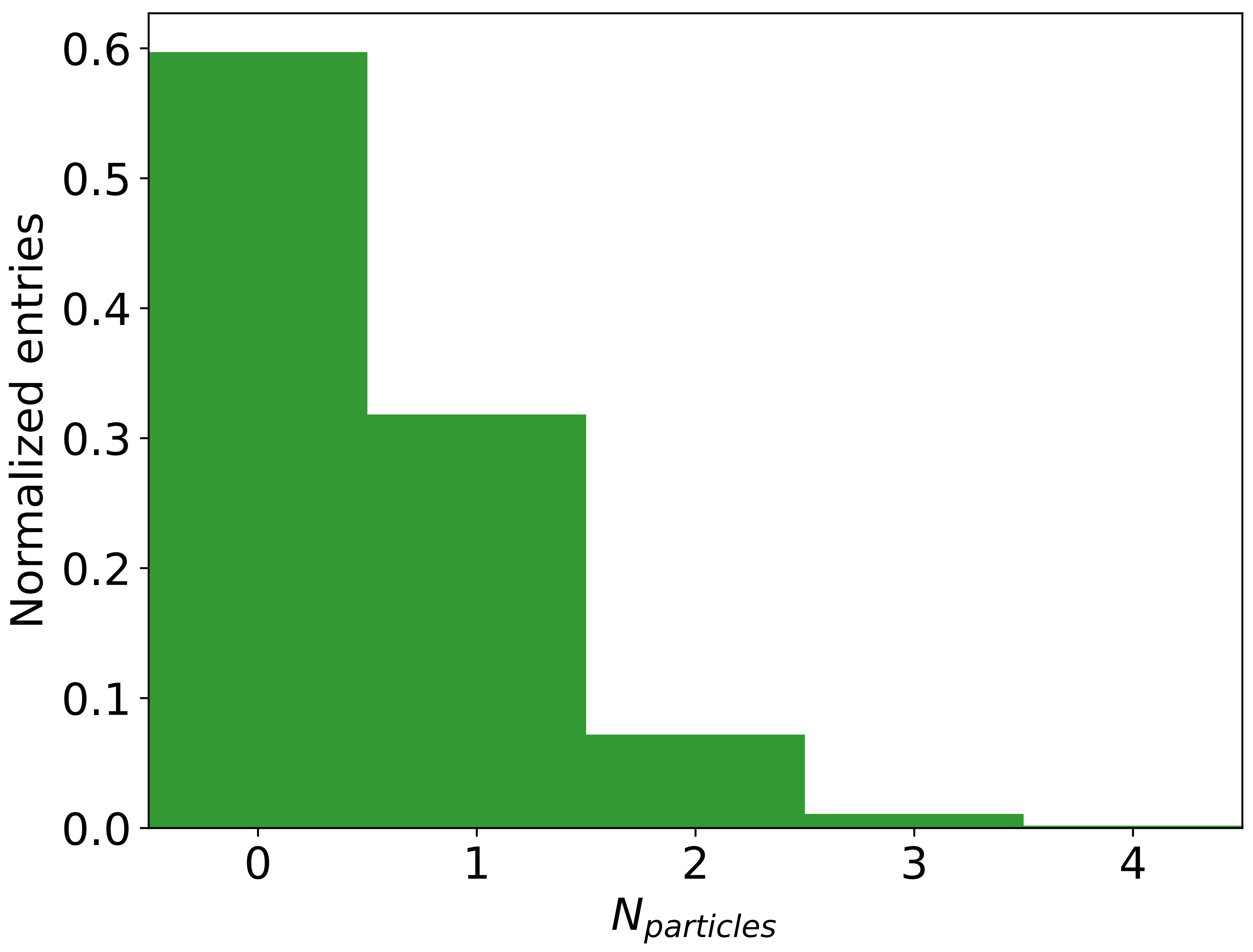
- Each hit caused by a primary neutron (MotherID=-1) is linked to corresponding MC particle
- Multiplicity counts require existence of 'Head' hit — with $\delta(E_{ToF}) < 0.3$

ToF energy for n^0 hypothesis:

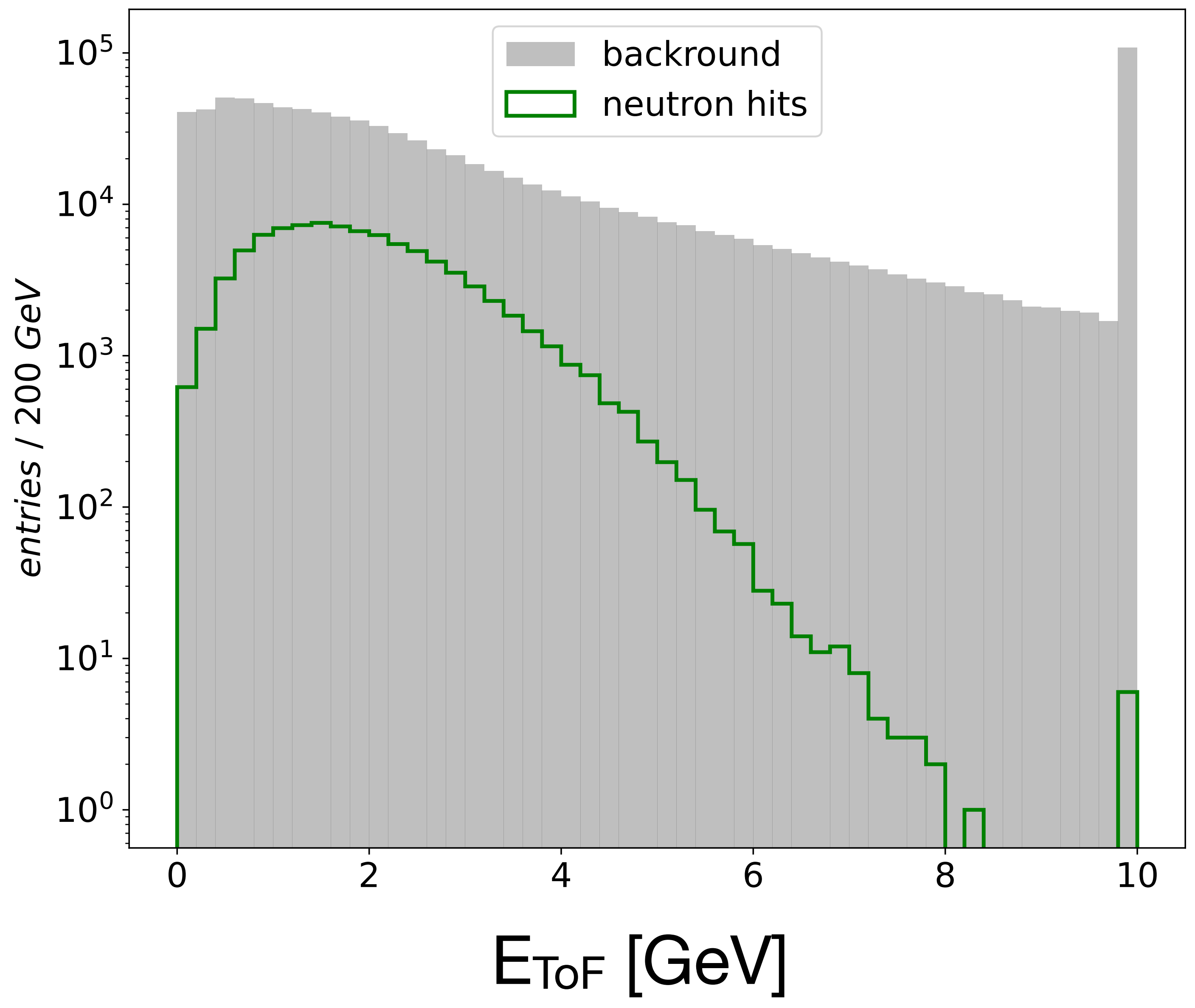
$$E_{ToF} = m_n\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

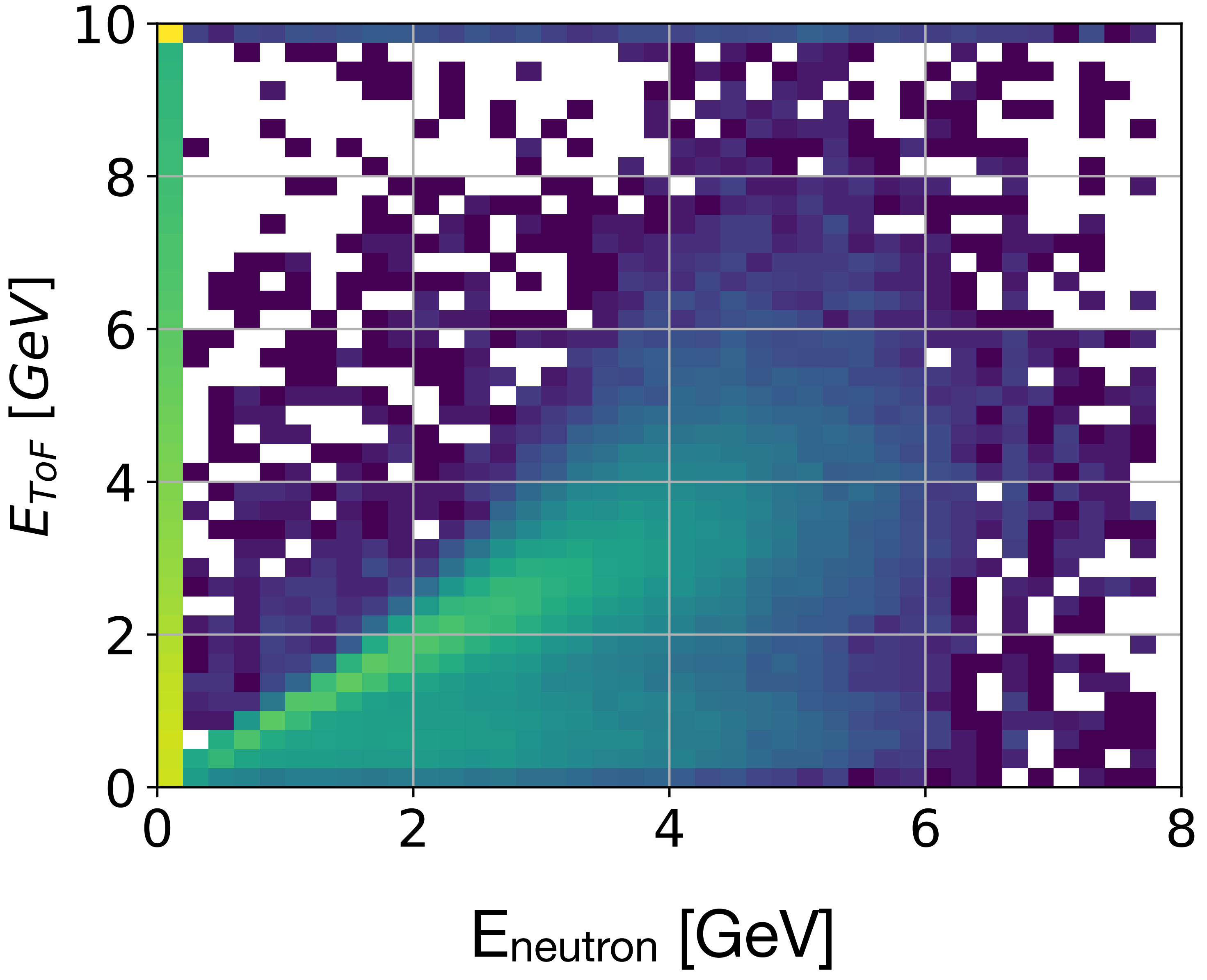
- $t_{hit} + \mathcal{N}(0, \sigma = 150\text{ps}) < 40\text{ns}$
- hits with E_{ToF}>10GeV are set to 10 GeV

Primary neutron multiplicity



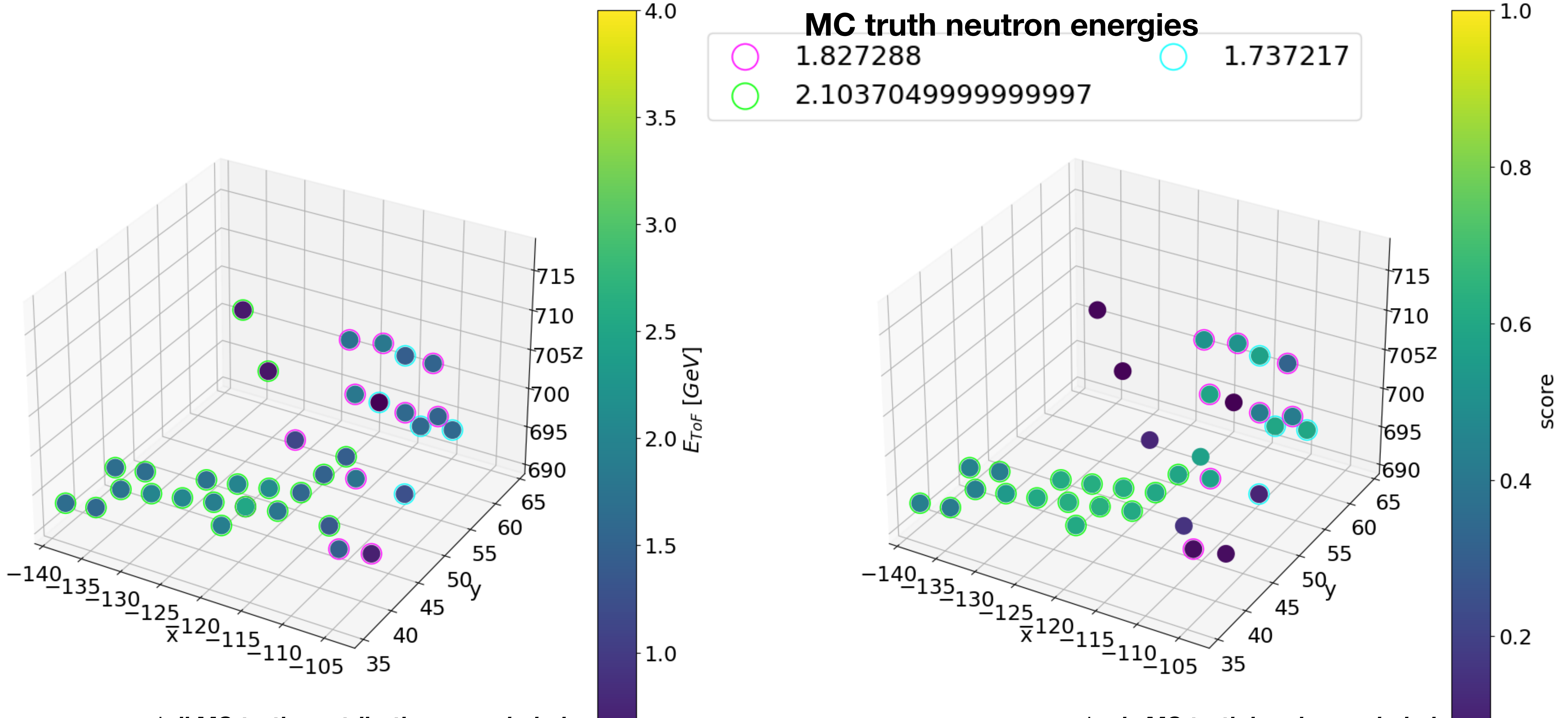
Hit E_{ToF} distribution





Reconstruction example

```
0 neutron score: 0.3053866344417157
1 neutron score: 0.669092359665289
2 neutron score: 0.1657184230945527
3 neutron score: 0.022741372617821658
1gm scores:  [0.45783916]
2gm scores:  [0.26996891 0.59203222]
3gm scores:  [0.34623281 0.59203222 0.21912647]
1 cluster prediction: [1.74045778]
2 cluster prediction: [1.48013984 1.92639919]
3 cluster prediction: [1.53982338 1.92639918 1.44035095]
```



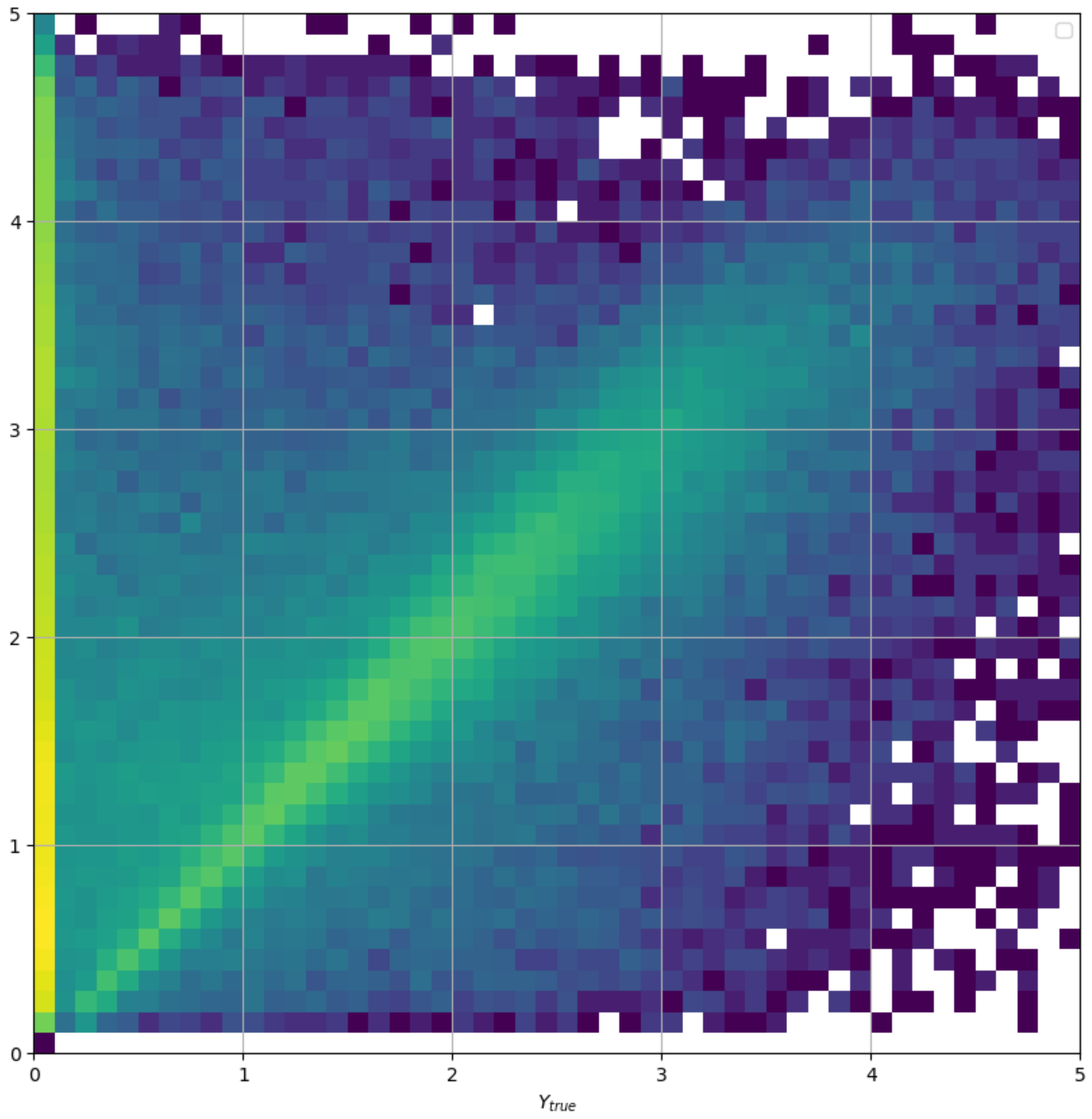
*all MC truth contributions are circled

*only MC truth heads are circled

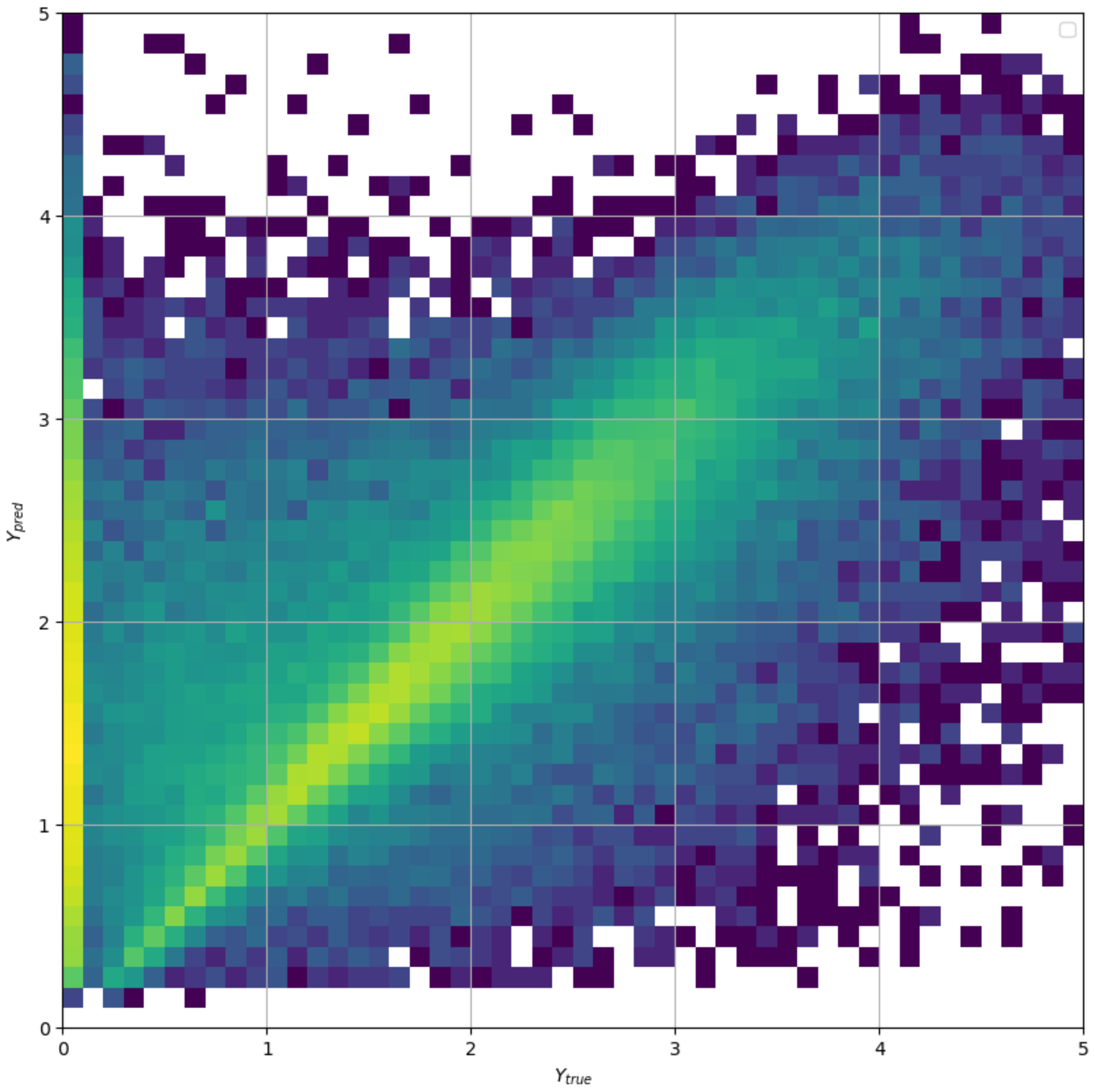
- Delayed depositions have lower 'head' score
- Same neutron produce similar score for 'heads'
- Gaussian Mixture approach potentially can be extended to reconstruct neutron with multiplicities > 1
- Combination with 'classic' cluster algorithm is foreseen

Neutron reconstruction

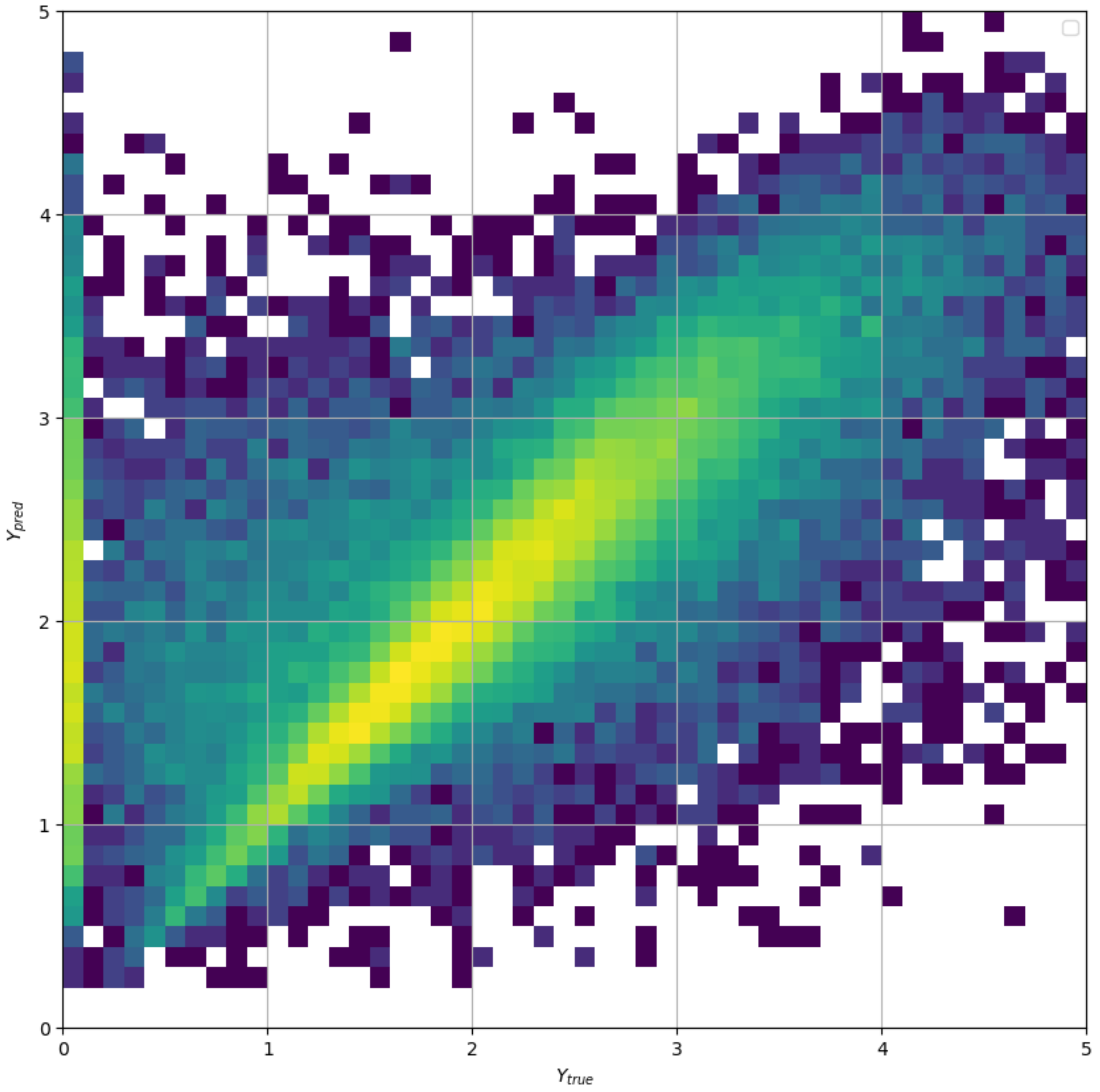
threshold = 0



threshold = 0.5

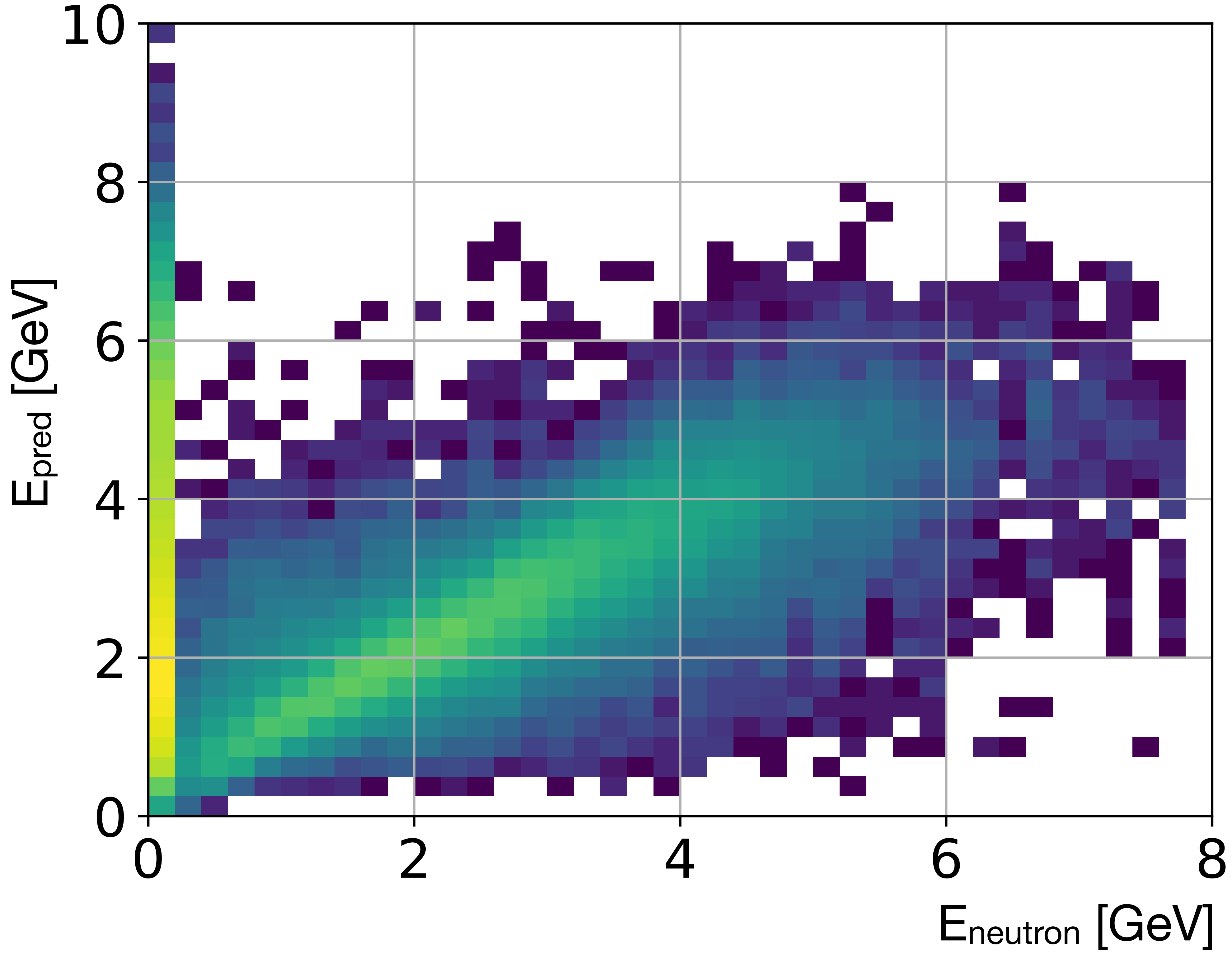


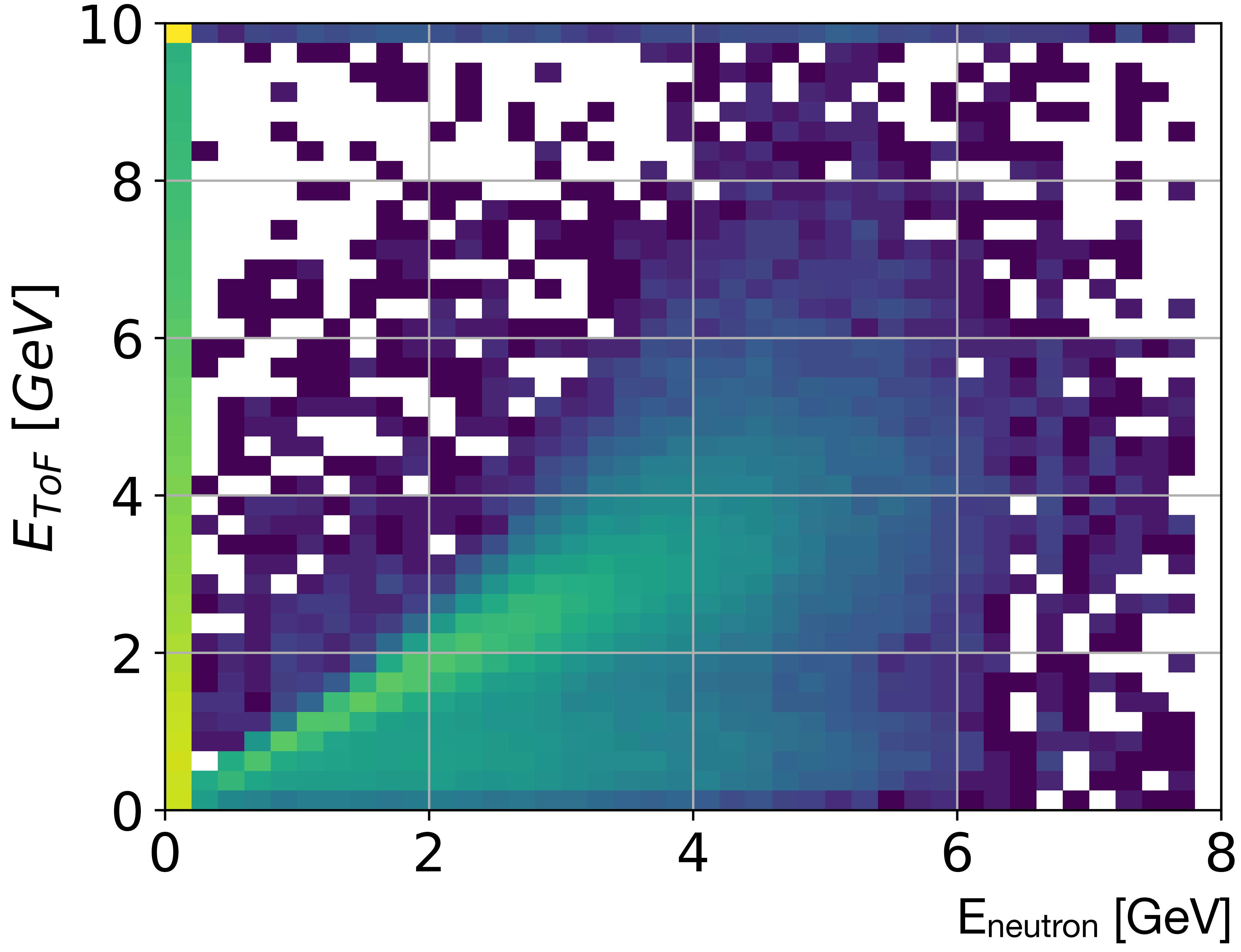
threshold = 0.8



- Background contribution reconstructed energy is distributed similarly to signal neutrons

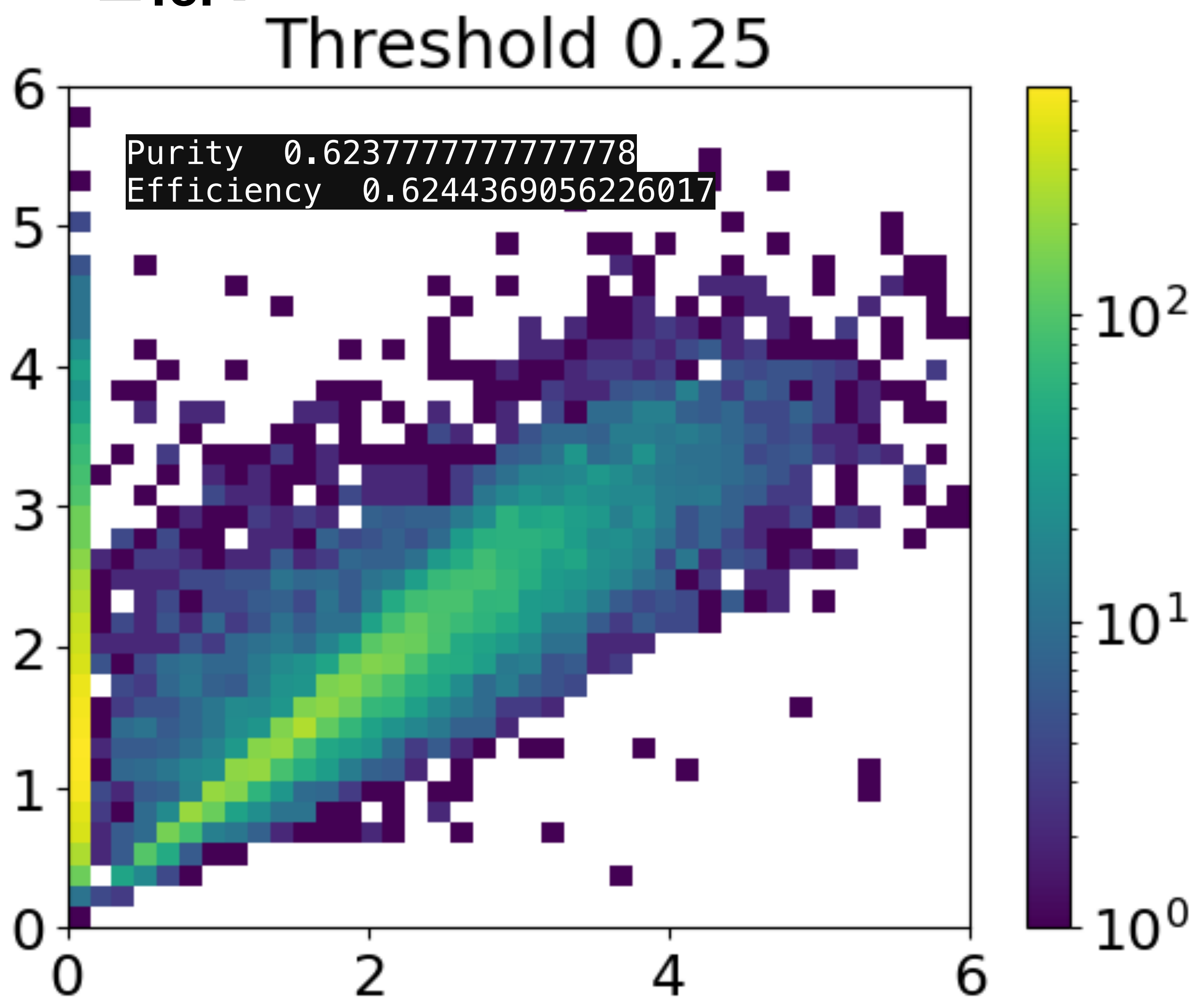
Energy prediction



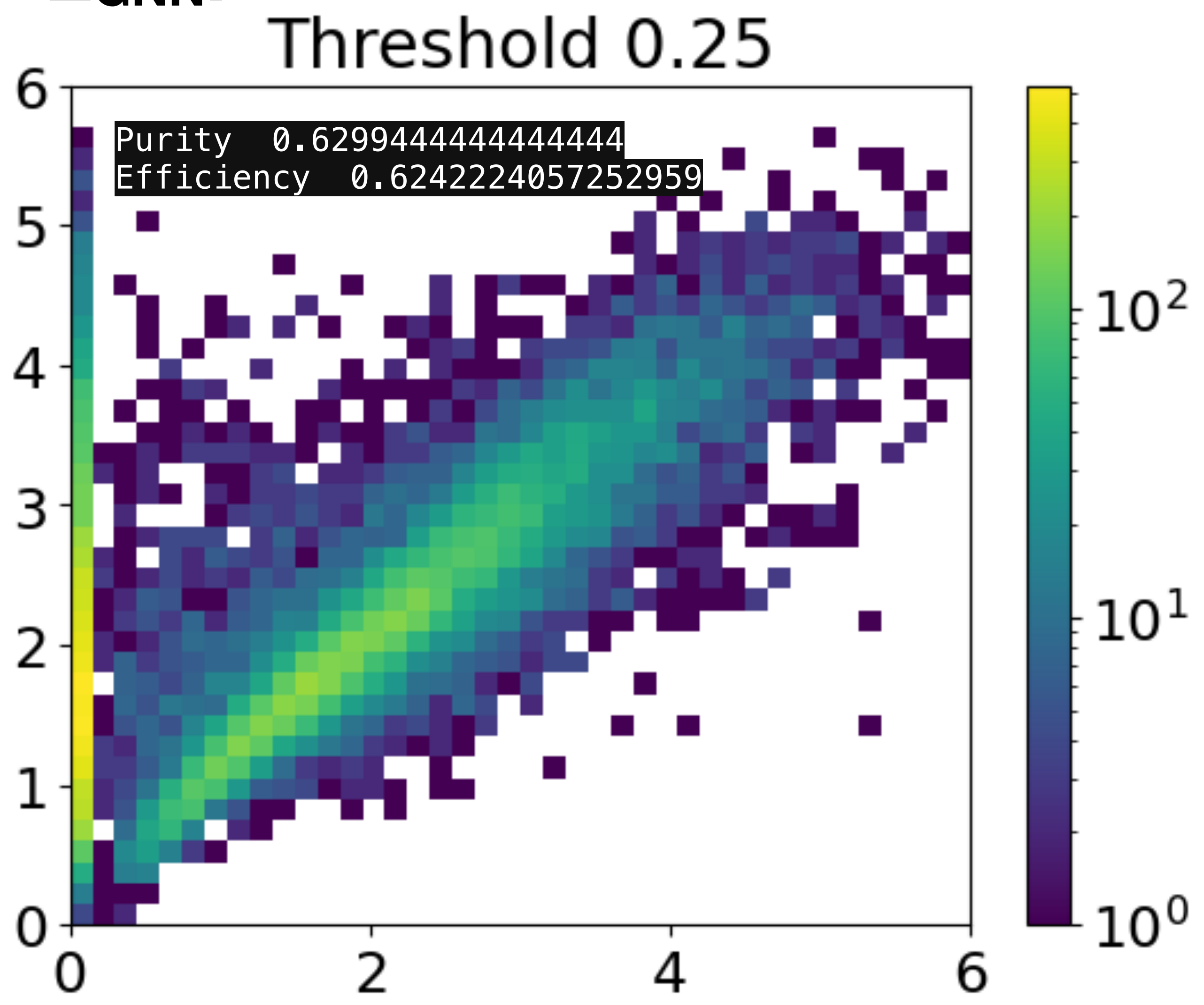


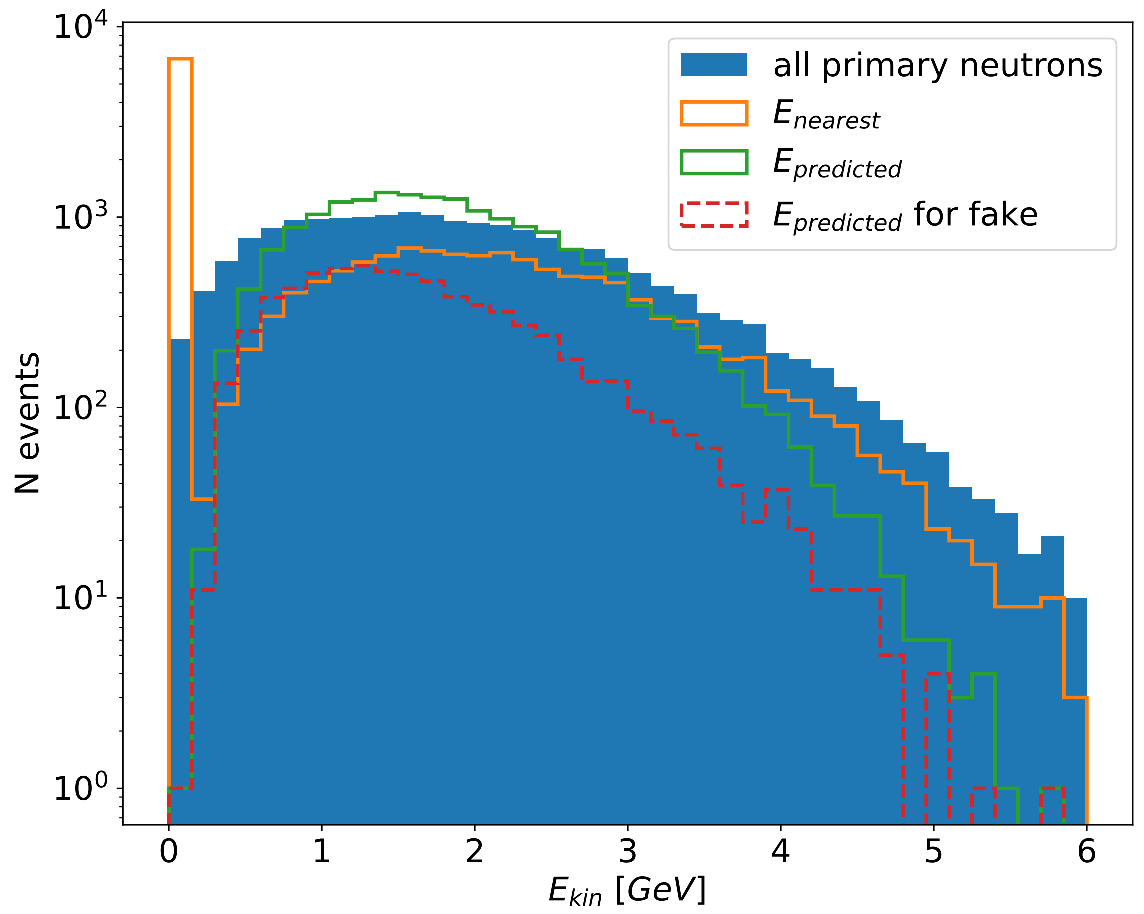
Energy correction

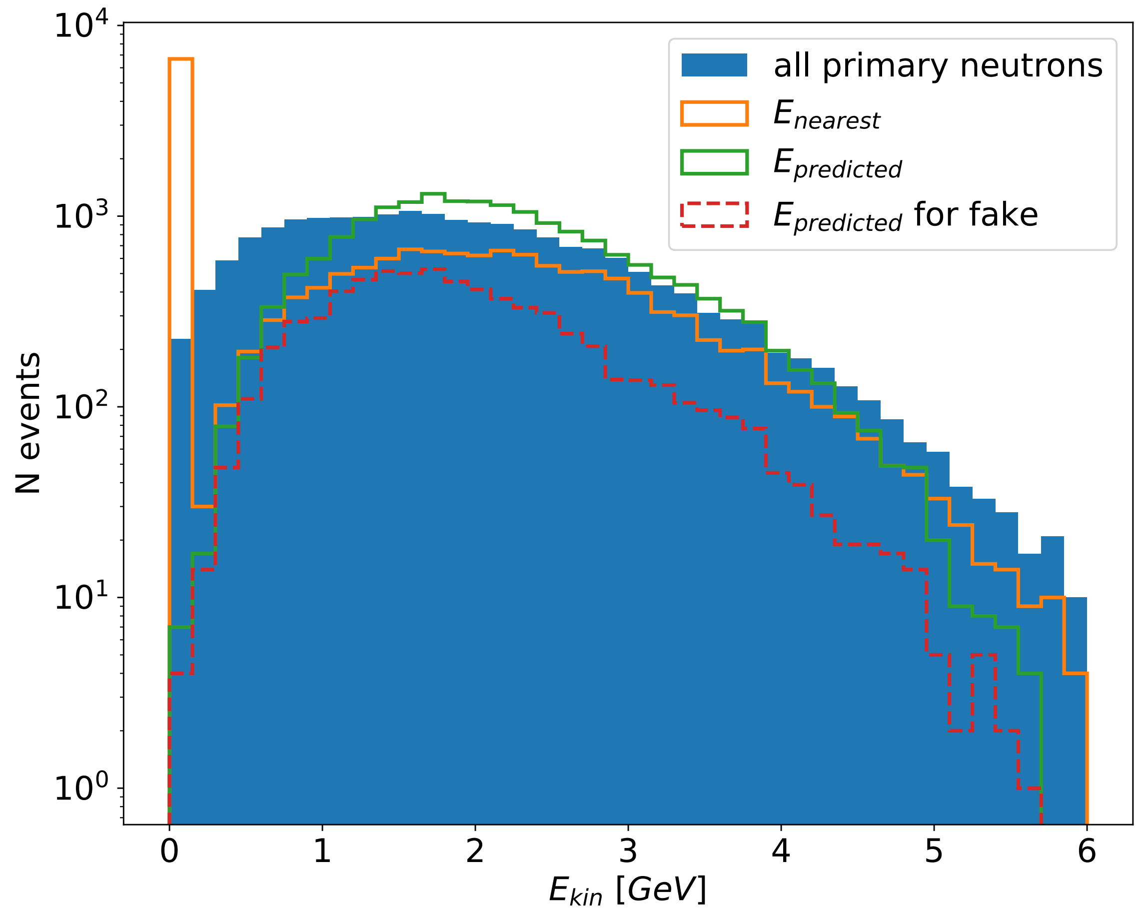
E_{ToF}:

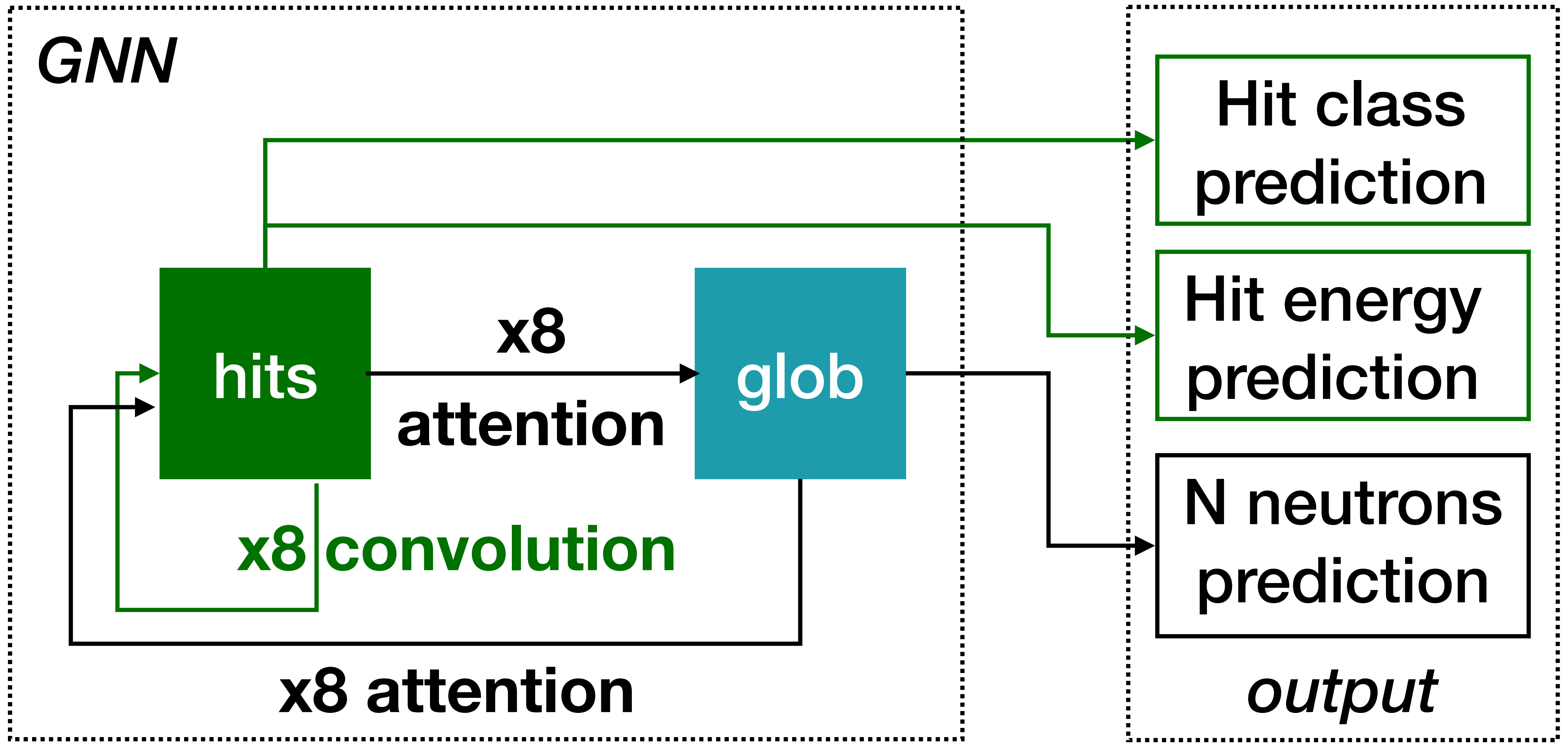


E_{GNN}:









$E_{neutron}$ [GeV]

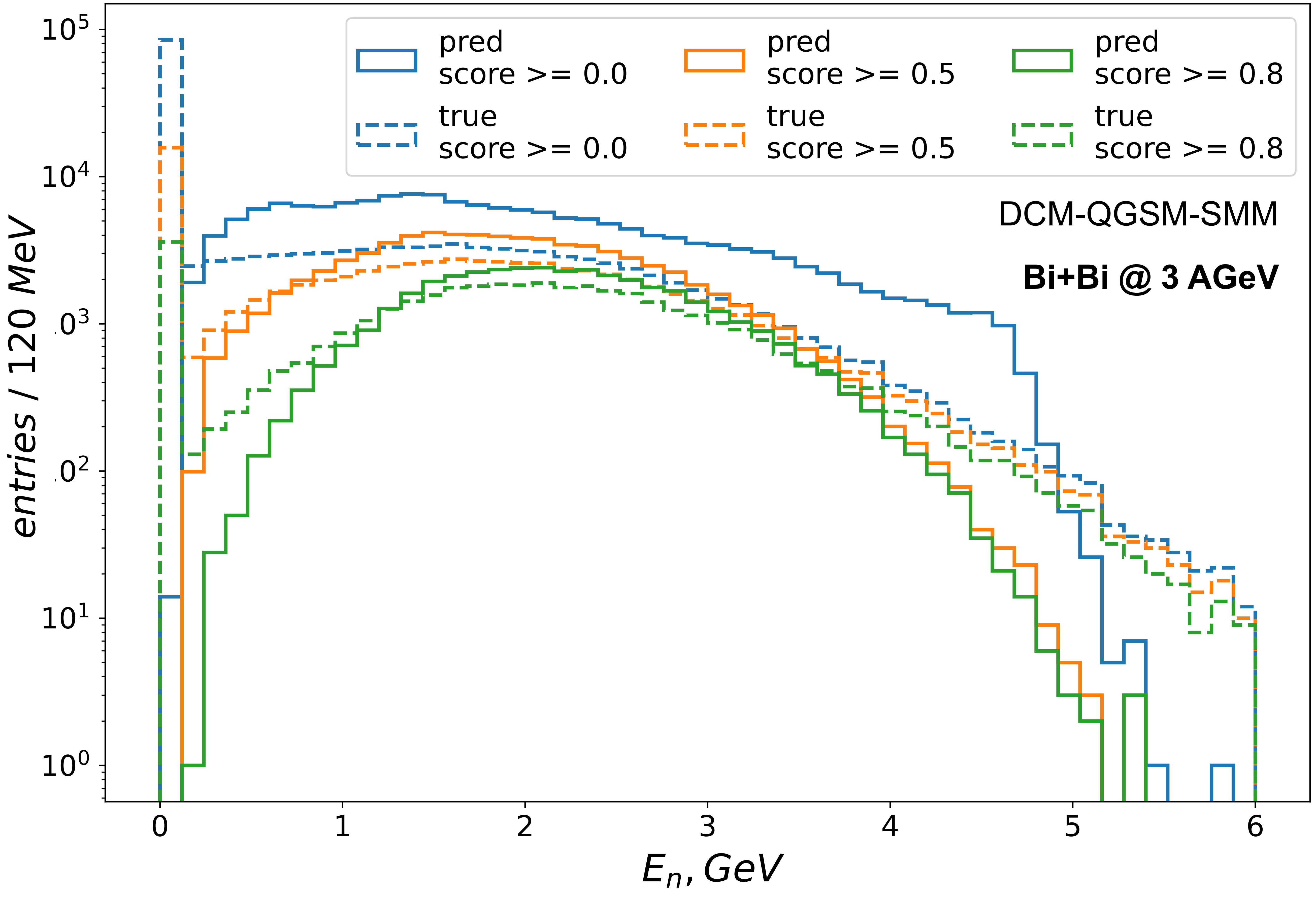
Neutron energy spectrum

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

Previous analysis iteration