ePIC Barrel HCAL energy calibration using Machine Learning

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Neutron Energy Calibration Strategy and Event Selection

- **MC:** Truth neutron information is used only for candidate matching and the energy target.
- **Data application:** Neutron candidates are reconstructed from BHCal clusters; the calibration uses only detector-level BHCal/ScFi shower variables. No truth information enters the MLP inference.

PDG = 2112 (*TRAINING SAMPLE PREPARATION*)

$1 < E_{\text{true}} < 10$ GeV,

$|\eta_{\text{true}}| < 1$,

$|\eta_{\text{BHCal cluster}}| < 1$,

$\Delta R(\text{truth neutron}, \text{BHCal candidate}) < 0.30$,

one closest BHCal candidate per truth neutron,

$n_{\text{Hits}}^{\text{BHCal cluster}} \geq 2$,

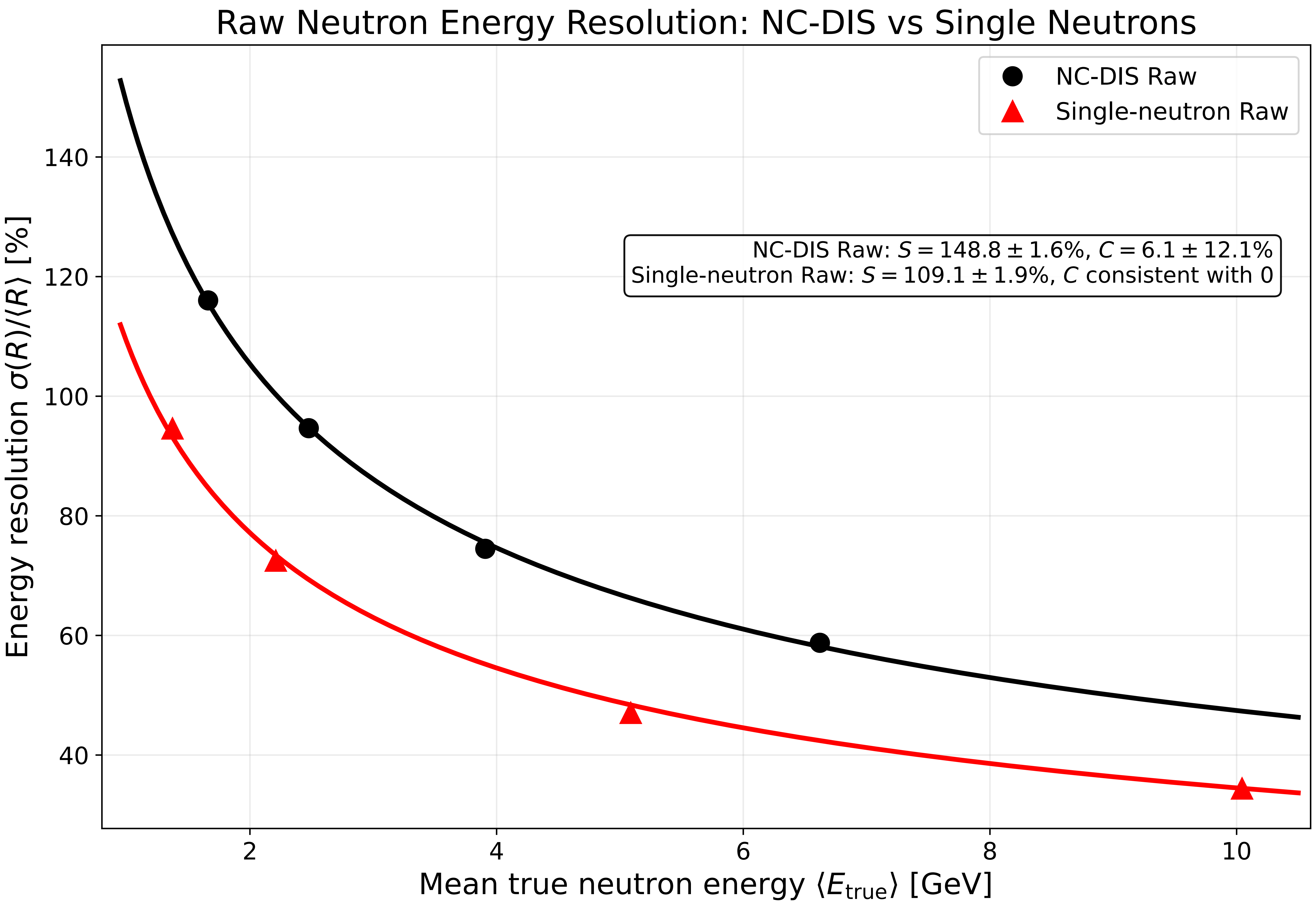
$E_{\text{BHCal cluster}} \geq 0.10$ GeV .

$$E_{\text{raw}} = E_{\text{BHCal}}^{R<0.30} + E_{\text{ScFiECAL}}^{R<0.30}$$

$$E_{NN} = f(x_1, x_2, x_3, \ldots\ldots x_N)$$

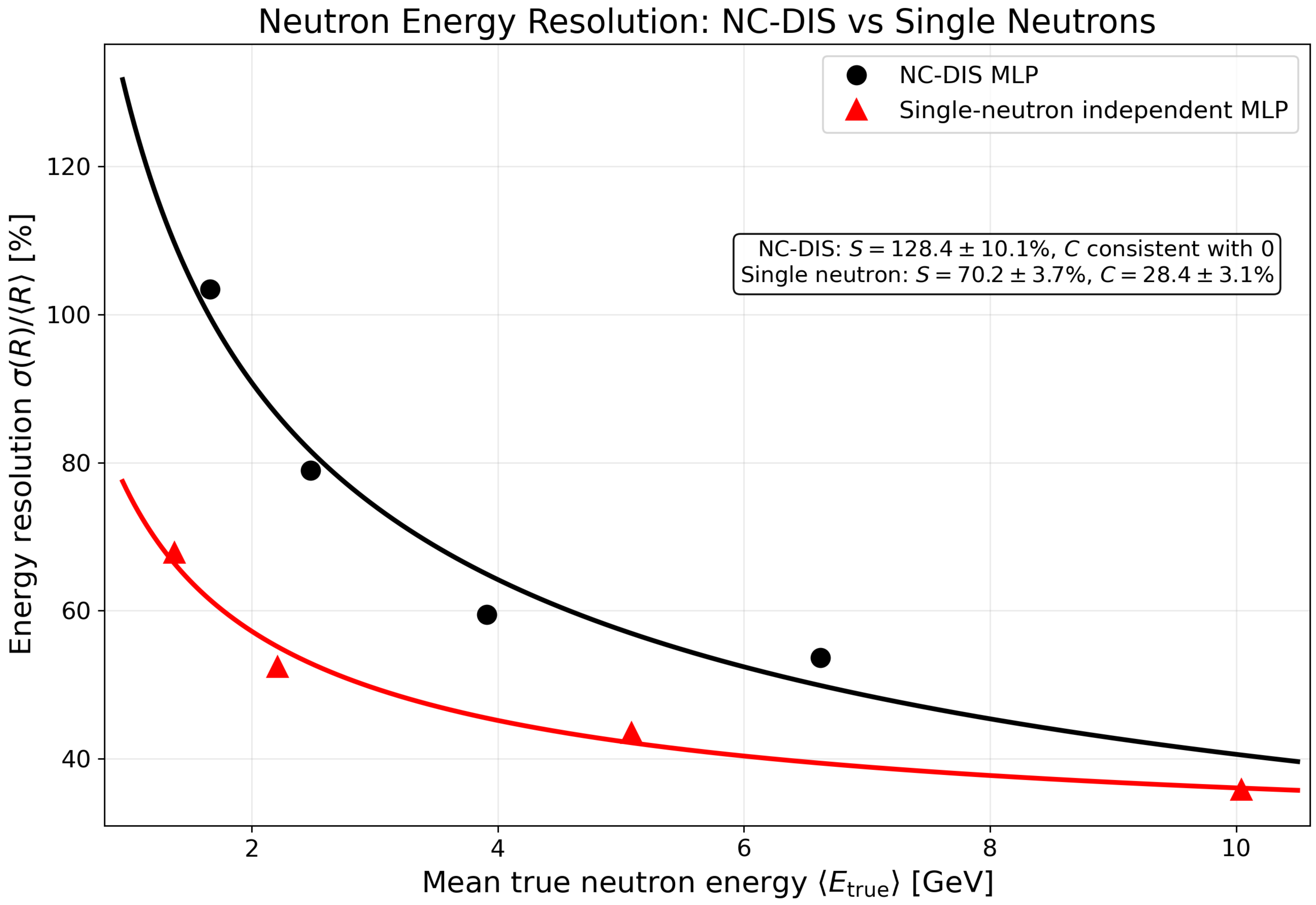
Raw resolution of NC-DIS remains broader than that of single neutrons

- Resolution improves with neutron energy
- NC-DIS is broader than single-neutron simulation
- Largest difference appears at low energy
- Realistic DIS environment adds response fluctuations



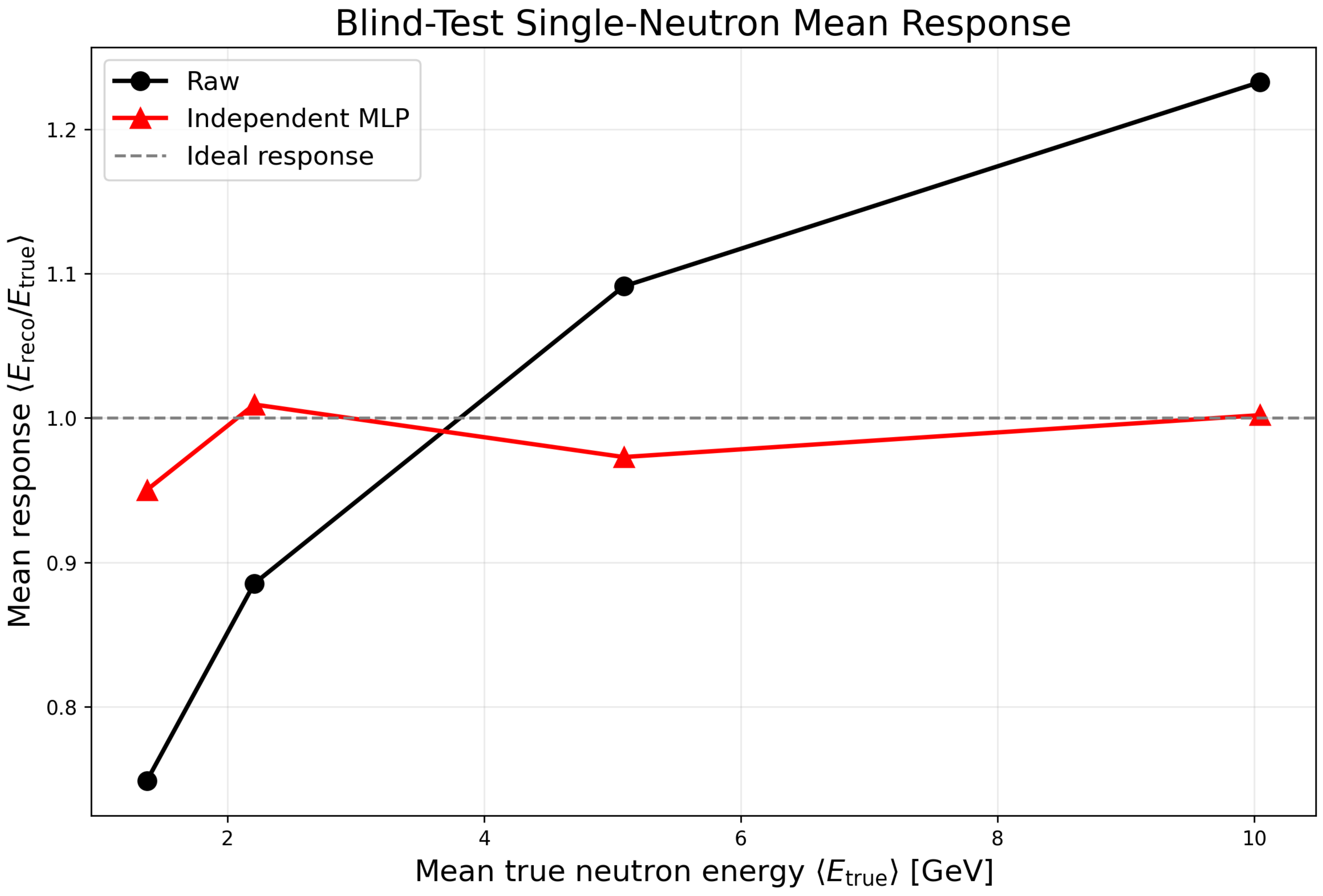
MLP Resolution: NC-DIS Remains Broader Than Single Neutrons

- MLP resolution improves with increasing neutron energy in both samples
- NC-DIS remains significantly broader than isolated single neutrons
- Stochastic term: 128.4% (NC-DIS) vs 70.2% (single neutron)
- Largest performance gap occurs at low–intermediate neutron energy



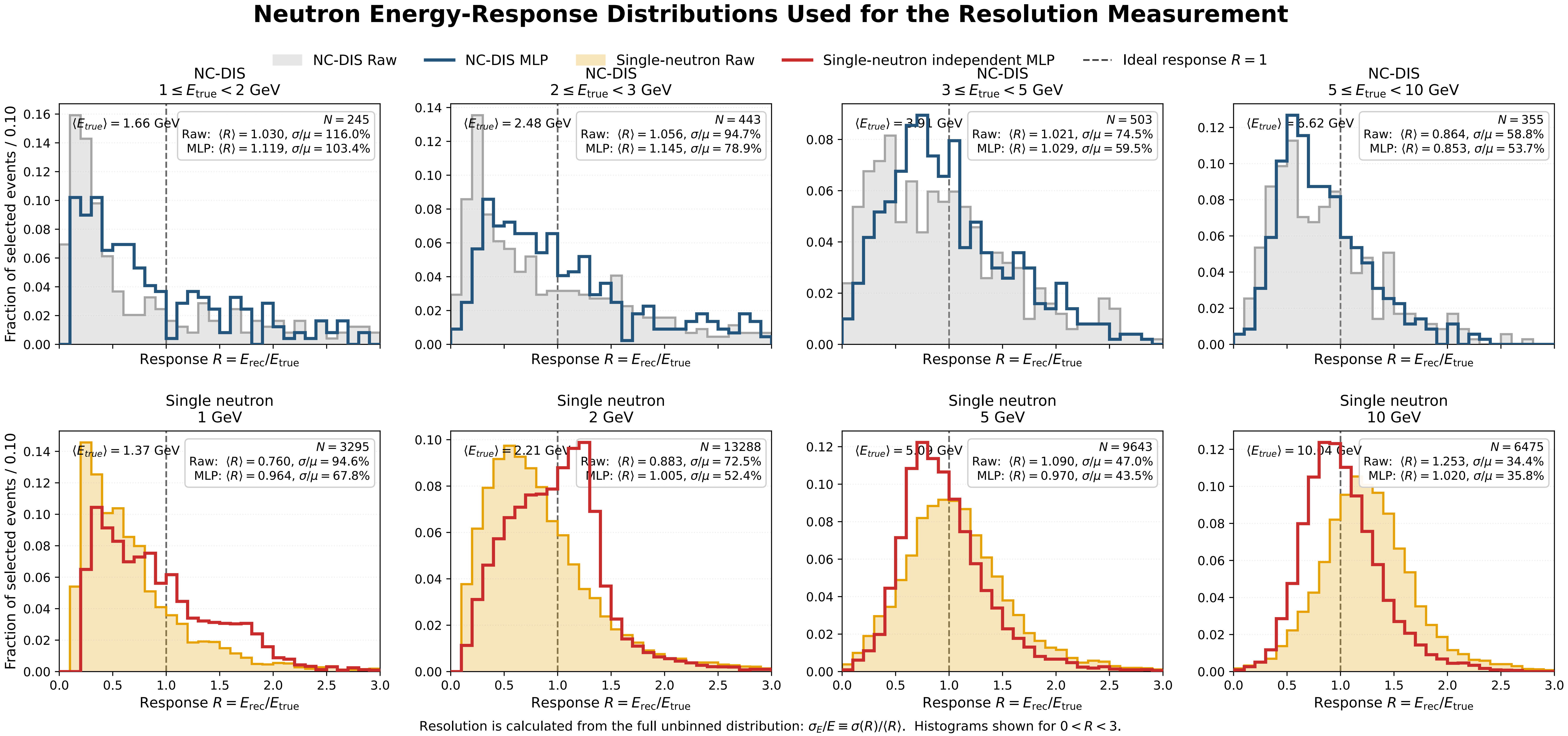
Blind-Test Single-Neutron Mean Response

- Ideal response: Ereco/Etrue =1
- Raw response strongly depends on energy
- MLP response stays close to unity
- Energy-dependent bias is largely corrected



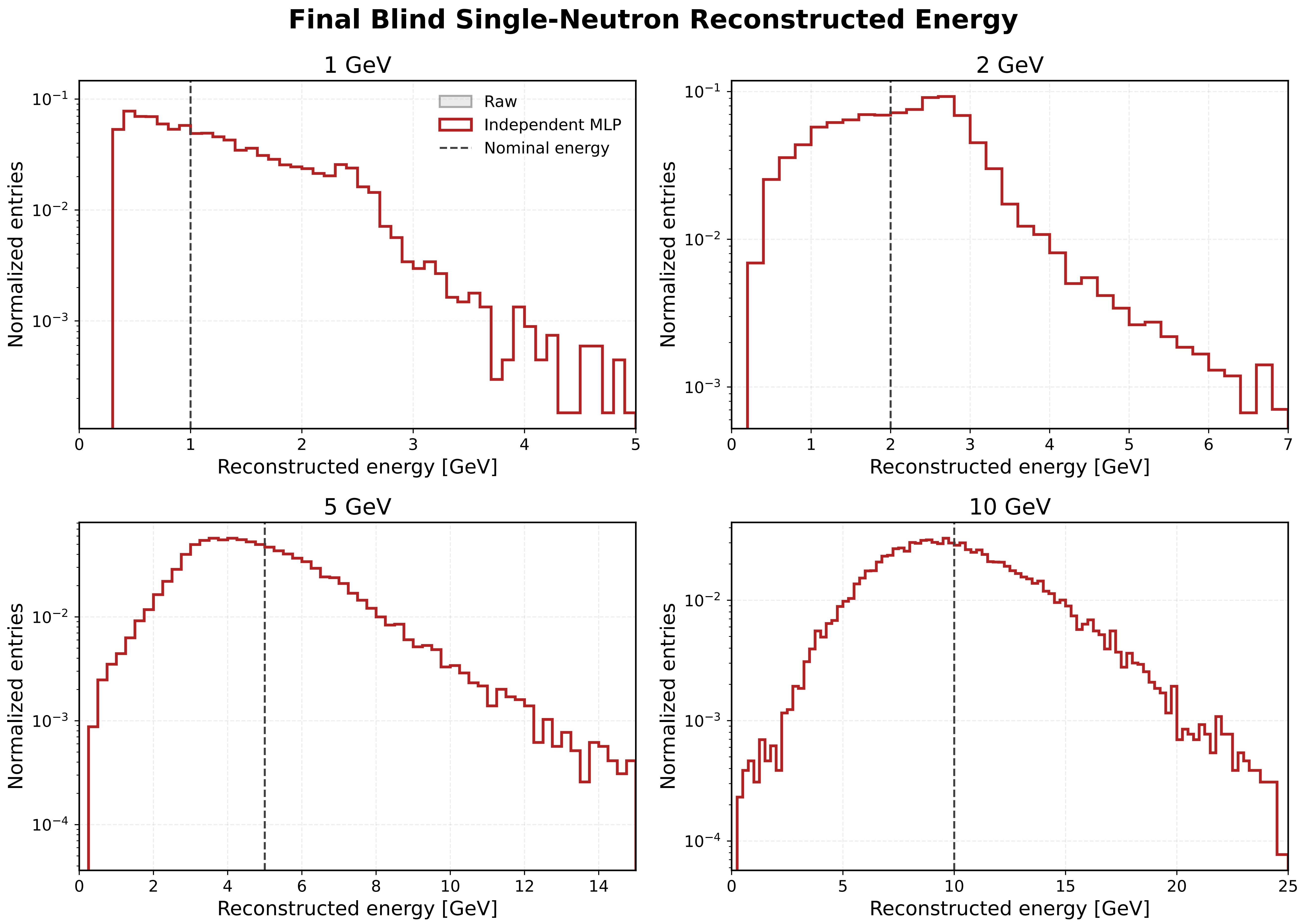
Neutron Response Distributions

- Response defined as R=Ereco /Etrue
- Dashed line marks ideal response R=1
- Low-energy distributions are very broad
- MLP generally narrows and recenters the response



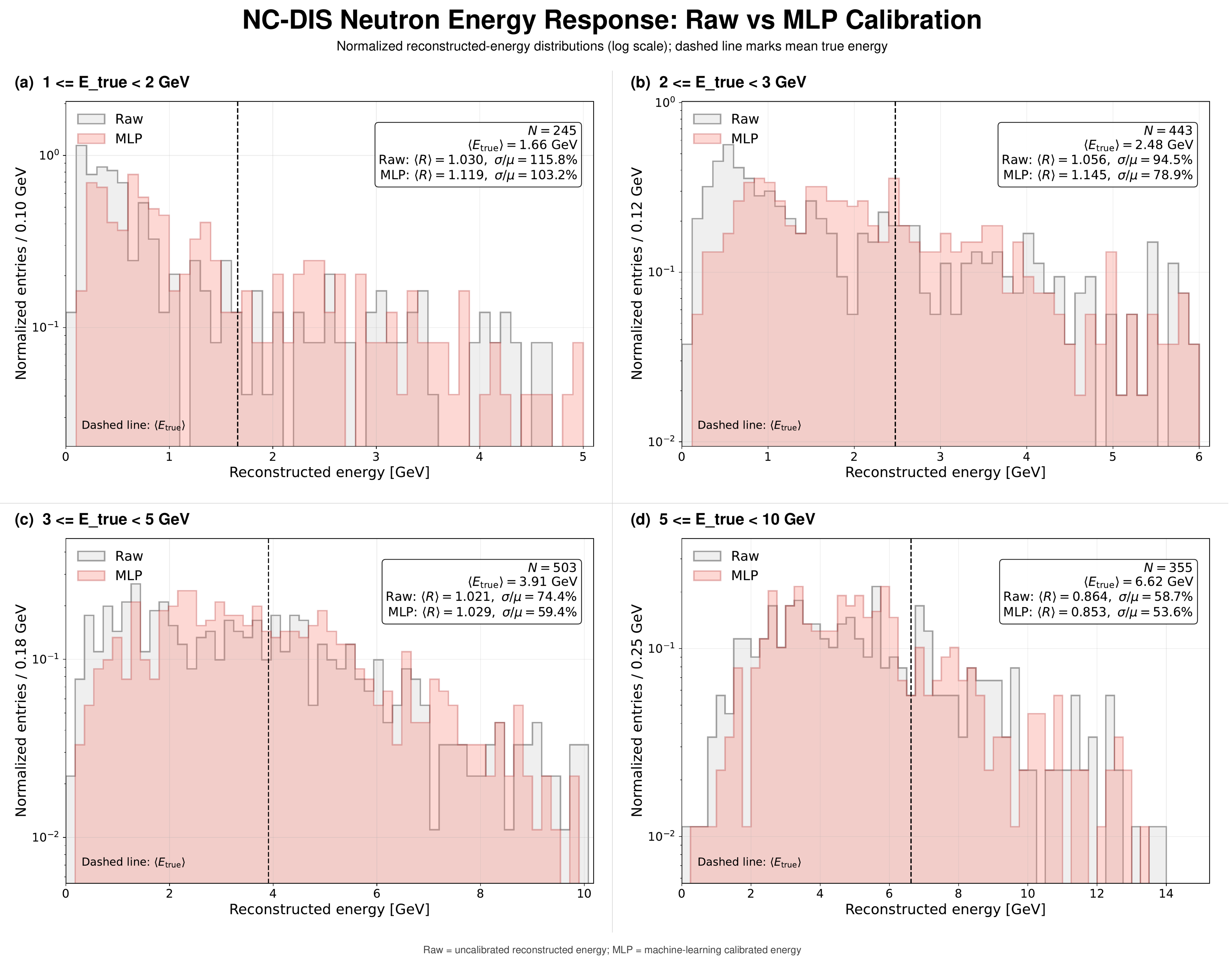
Single neutrons Reconstructed Energy

- Clear improvement at 1 and 2 GeV
- 5 GeV shows smaller but visible improvement
- 10 GeV mainly shows energy-scale correction
- MLP performance depends strongly on energy



NC-DIS reconstructed energy (ML)

- NC-DIS distributions are significantly broader
- MLP improves mean response
- MLP also reduces the spread
- Long tails remain after calibration

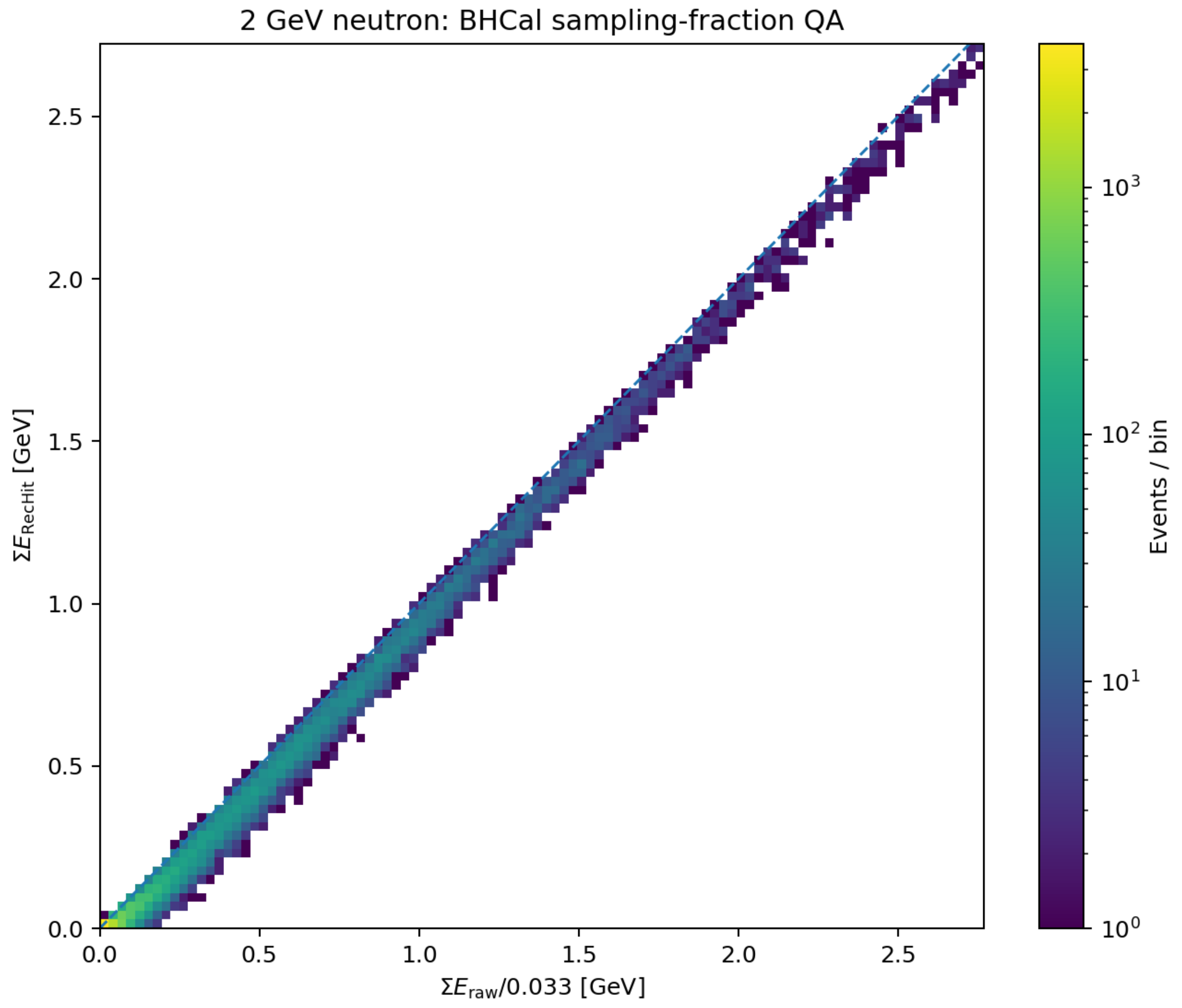


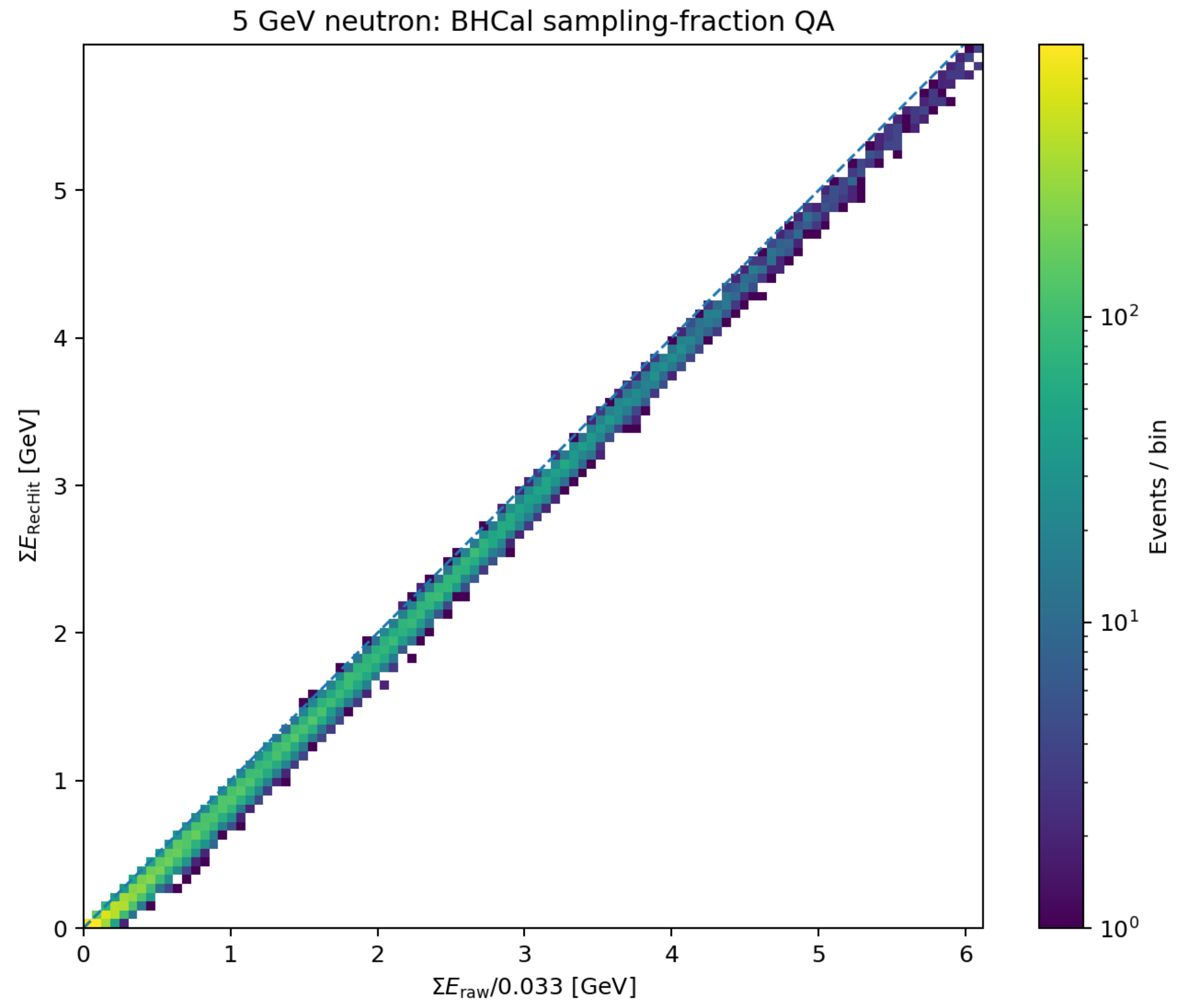
Single neutron simulation for bHCAL

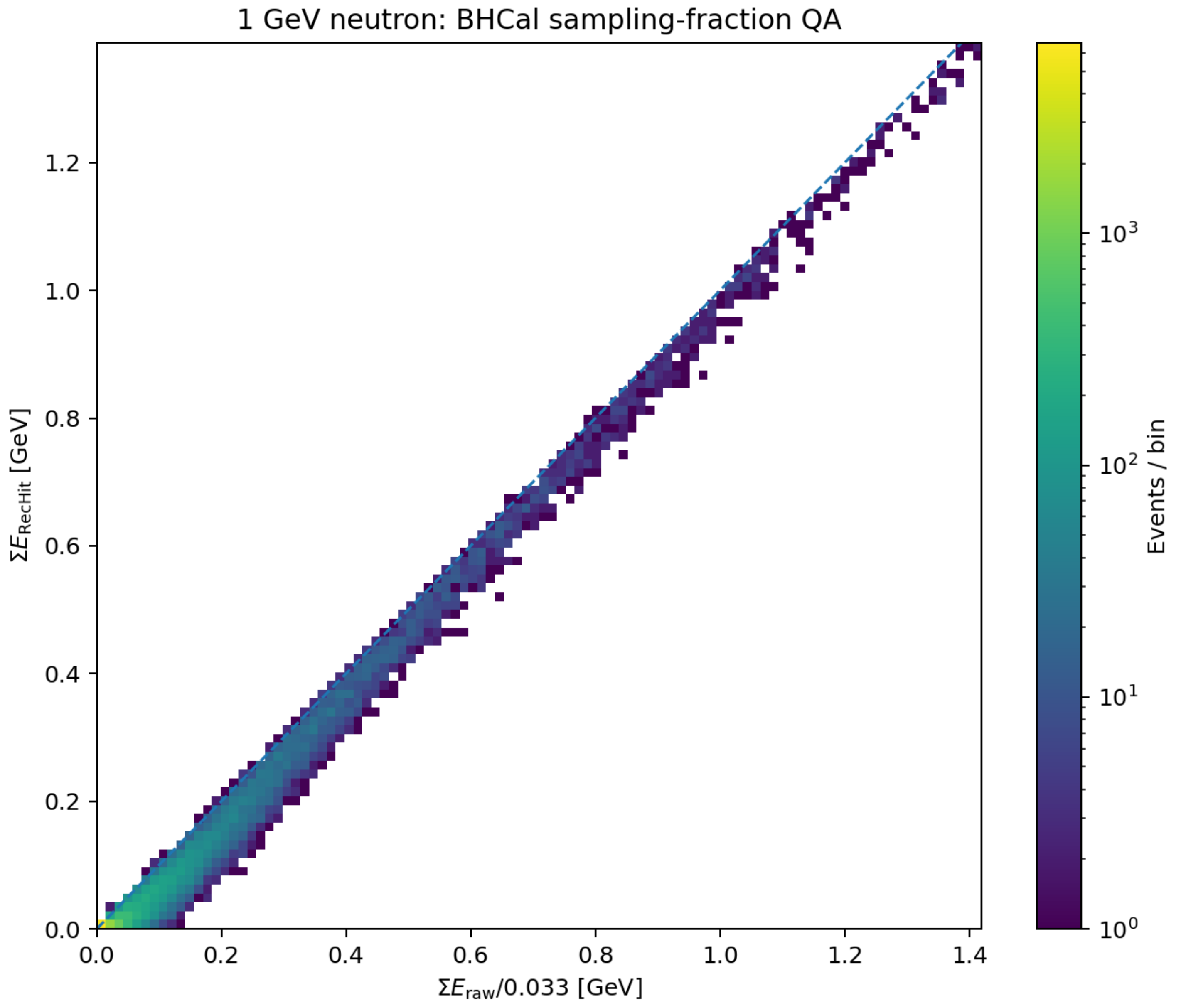
- Software versions used
  - **ePIC detector geometry:** `epic-26.05.0`
  - **npsim:** `1.4.6`
  - **EICrecon:** `1.37.1`

Sampling-fraction QA

- Strong diagonal correlation
- Same behavior at 1, 2, and 5 GeV
- Sampling conversion is stable
- Not the dominant source of broad resolution

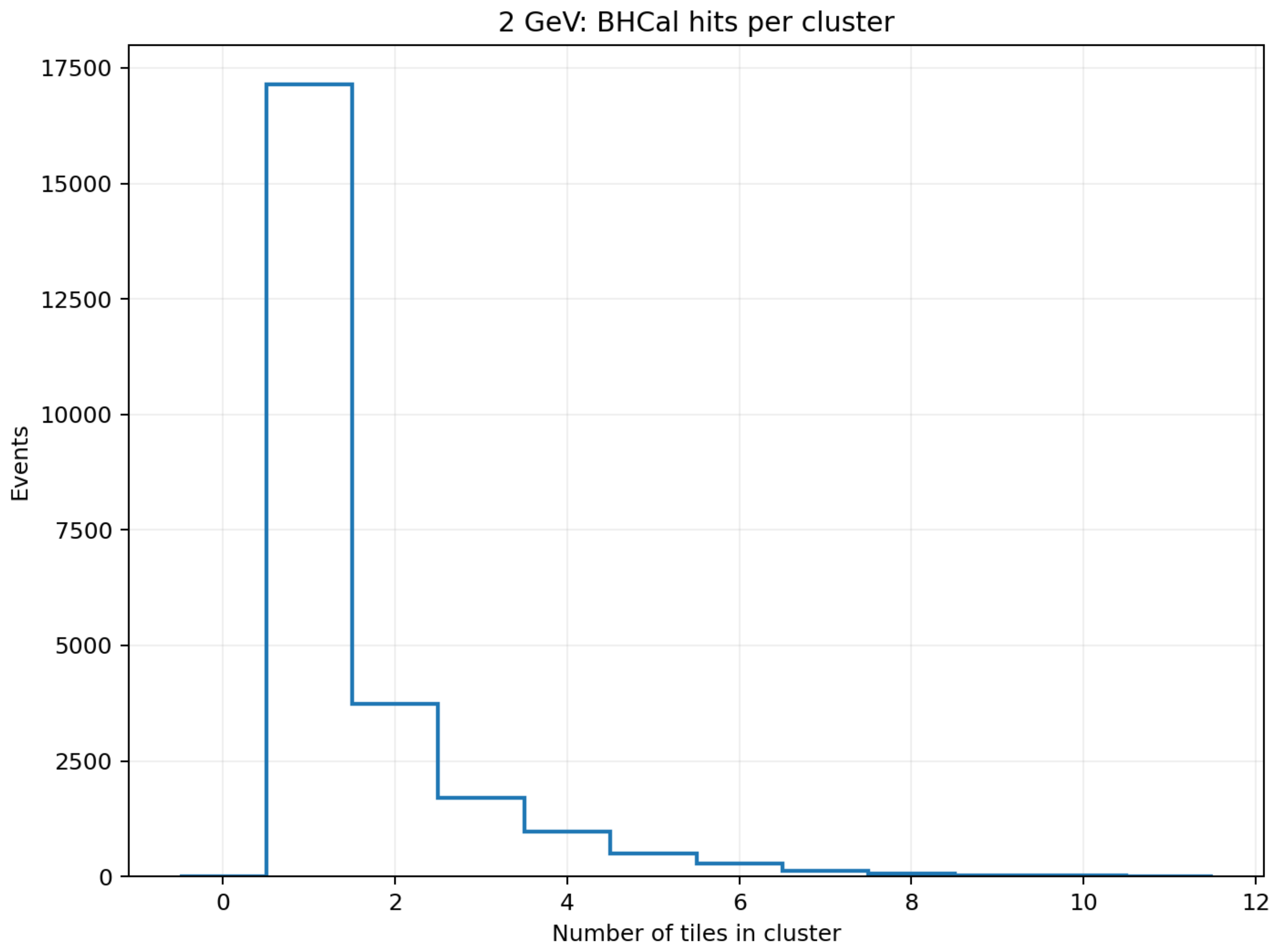


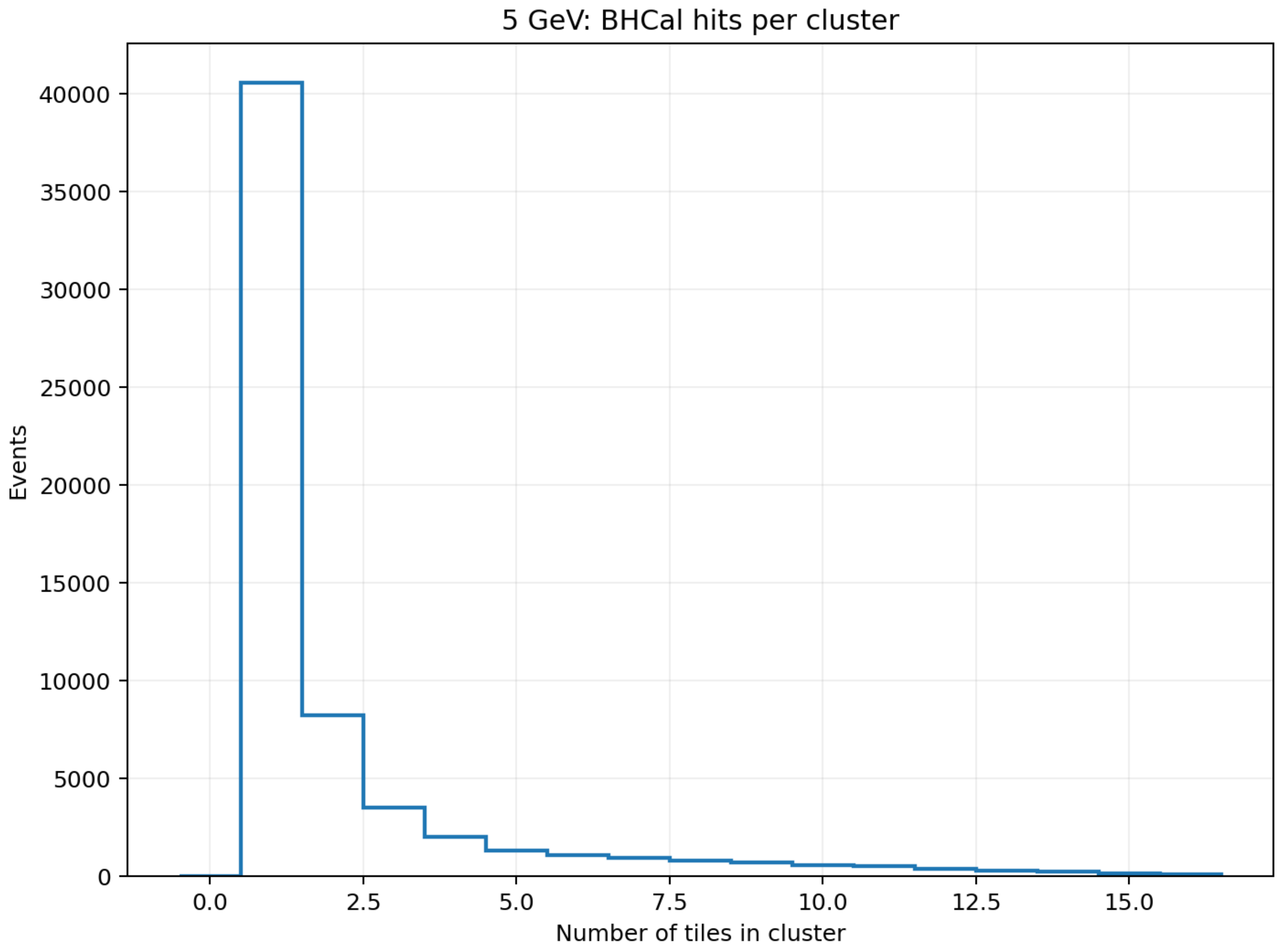


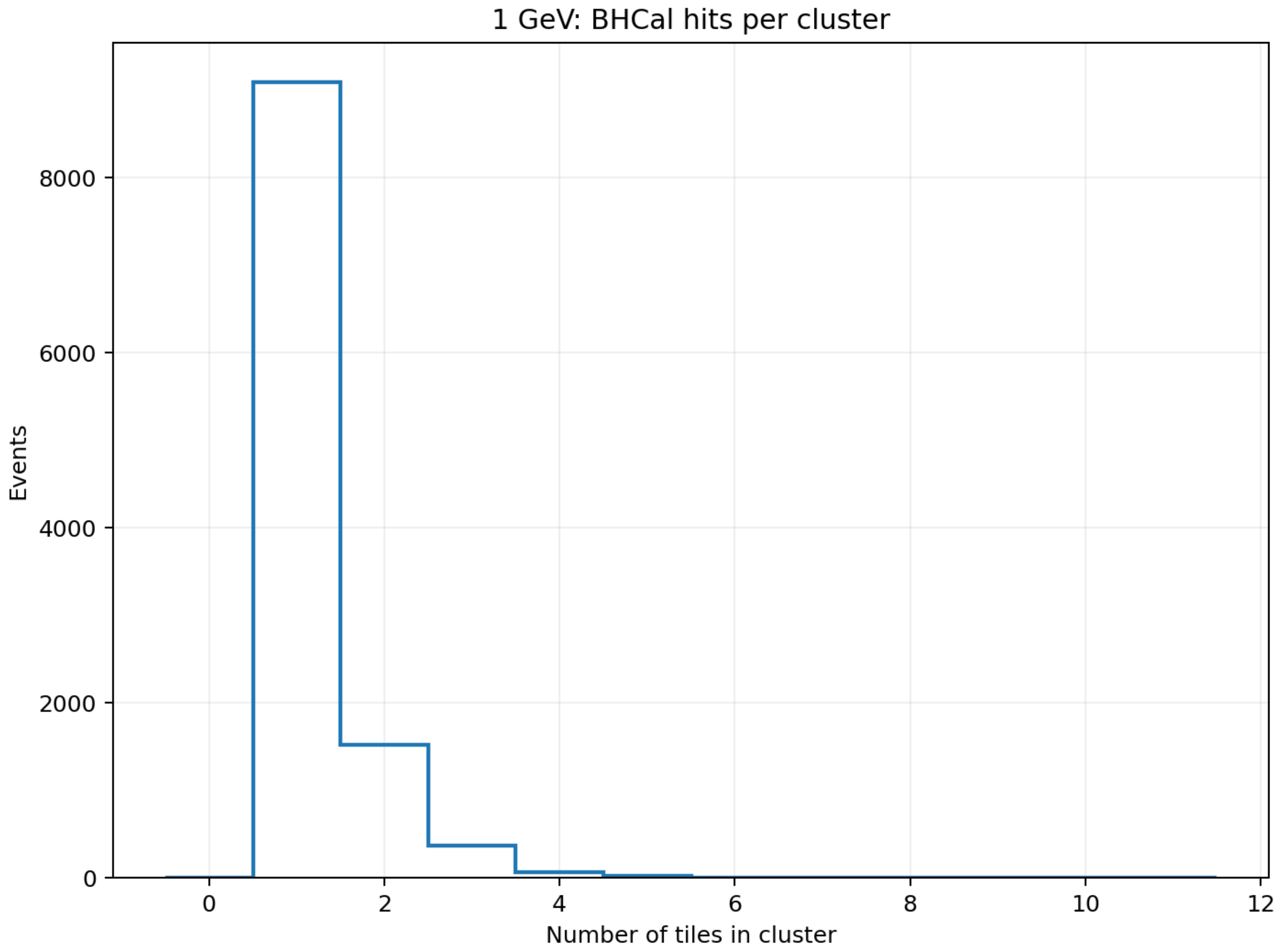


Hits per Cluster

- Low-energy showers contain few hit tiles
- Hit multiplicity increases with energy
- Large event-to-event shower-size variation
- Shower size carries useful calibration information

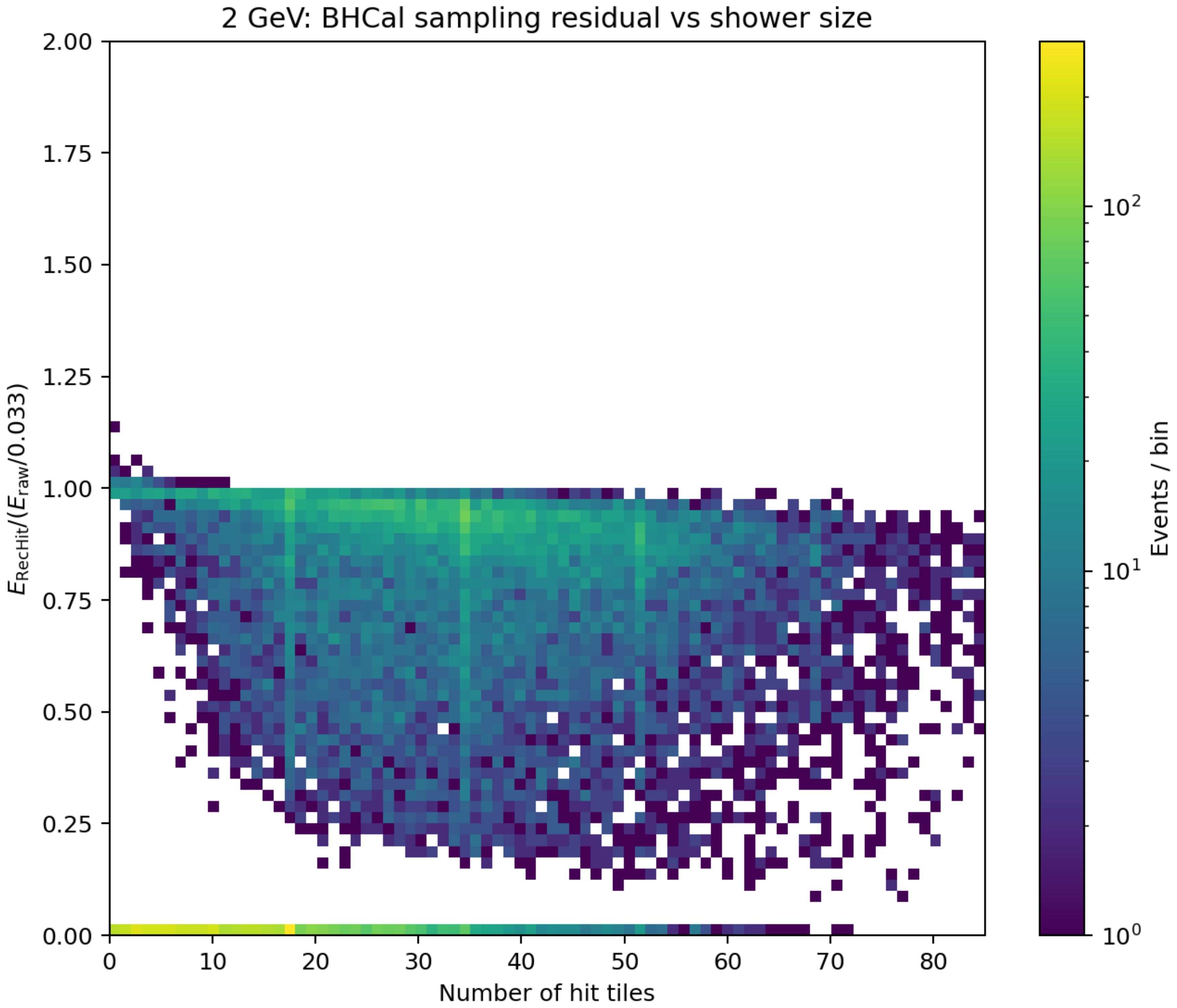


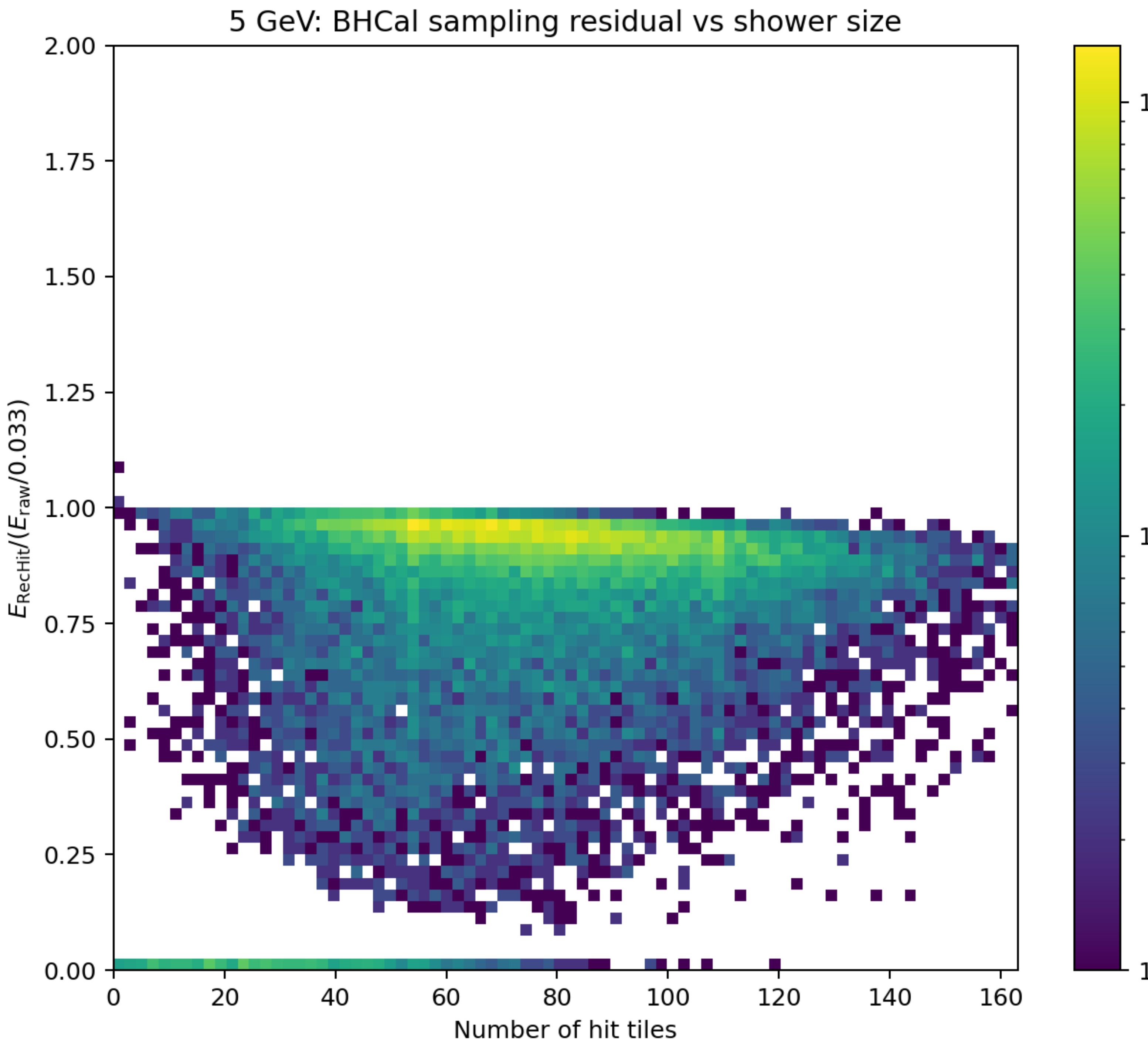


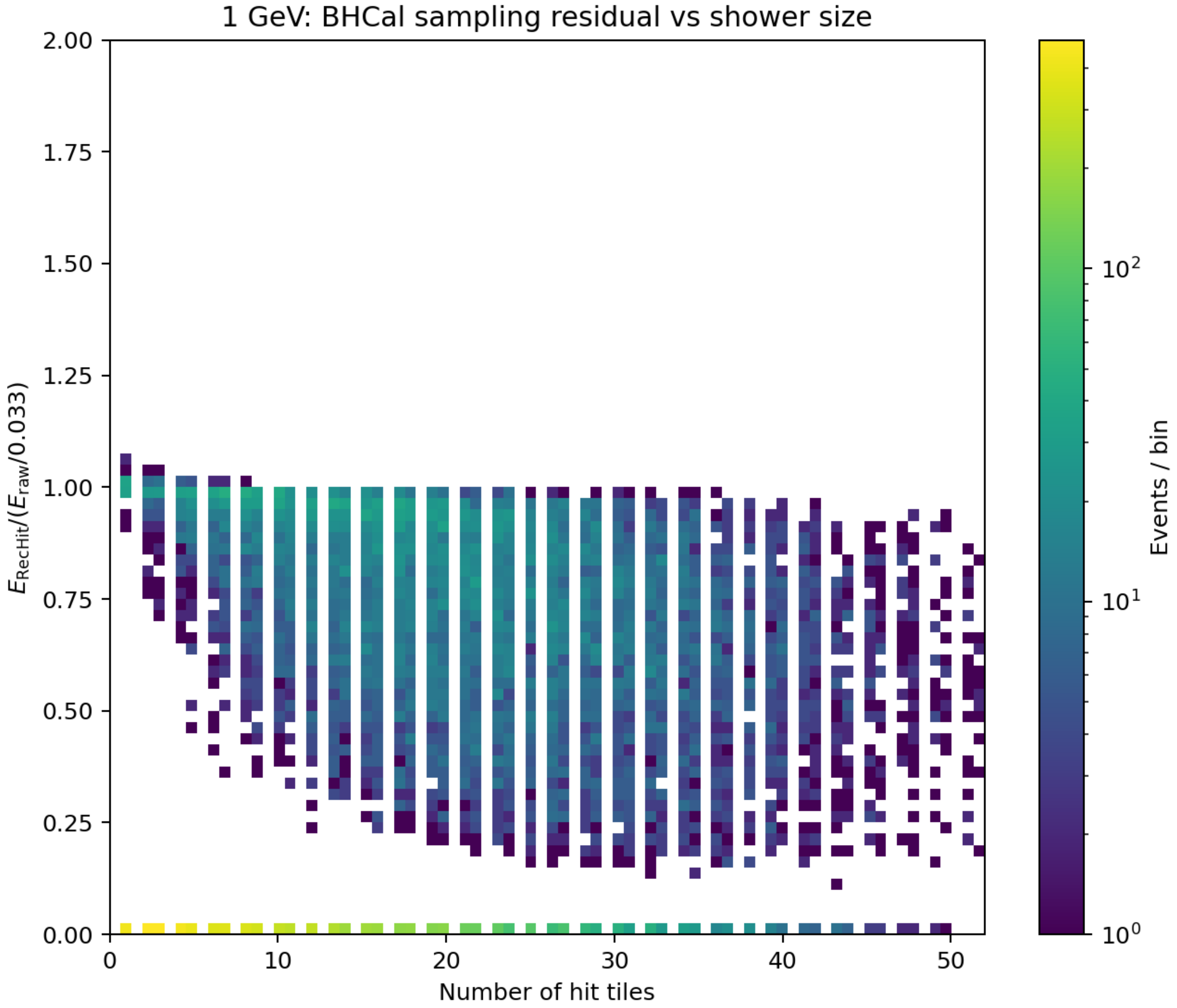


Sampling residual vs shower size

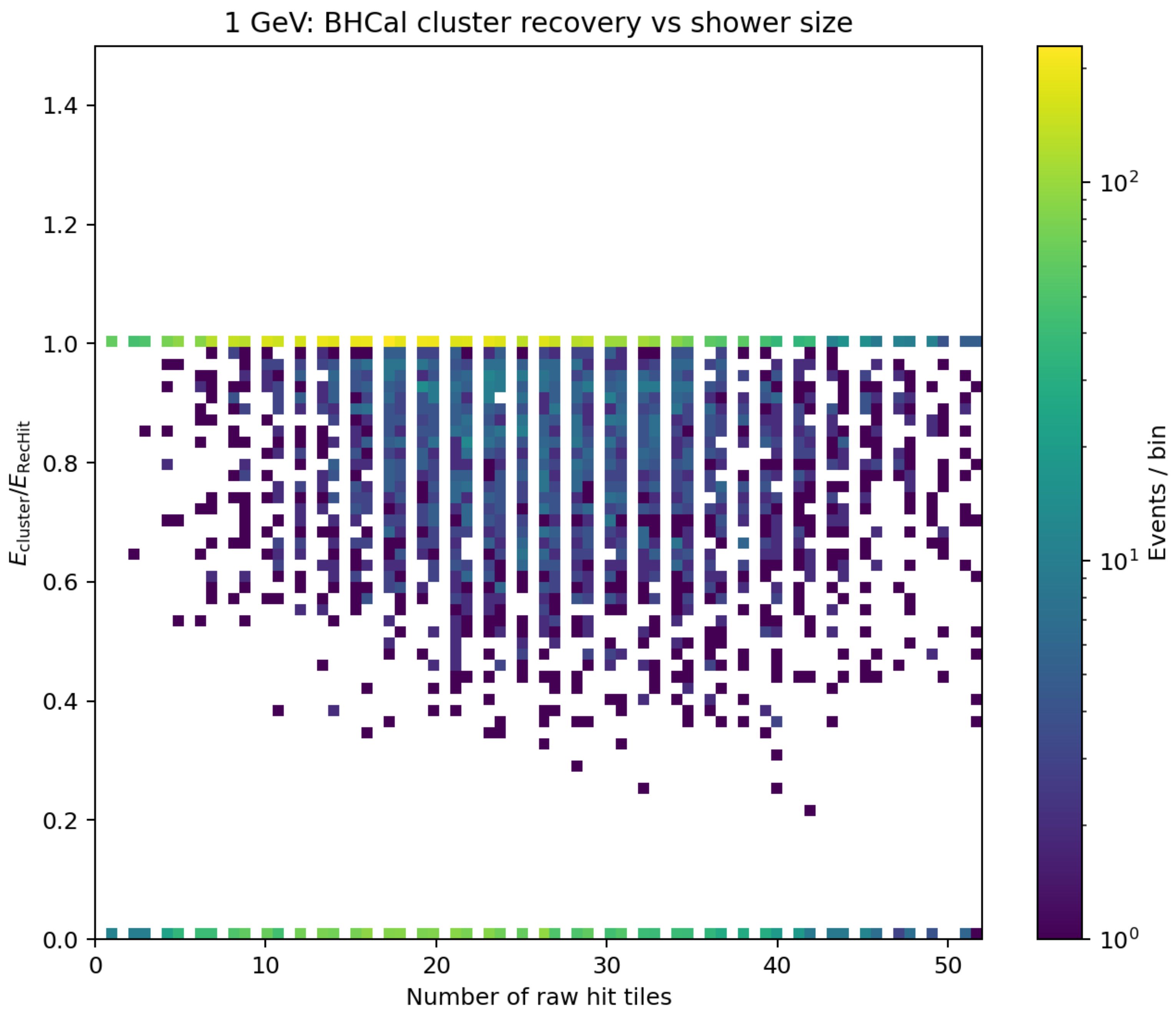
- Recovered fraction varies event by event
- Large spread at fixed shower size
- Spread persists across neutron energies
- Response depends on shower topology

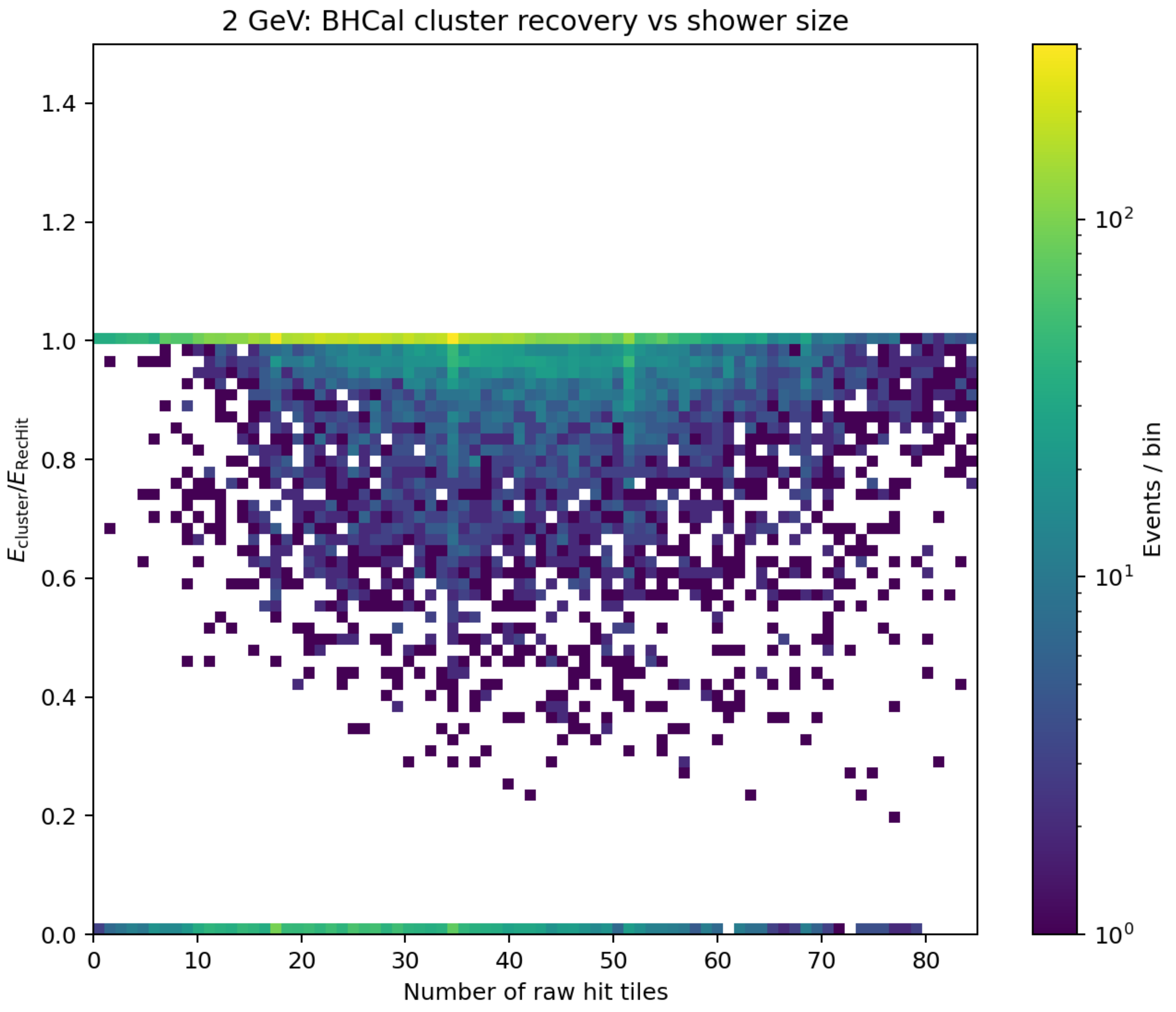


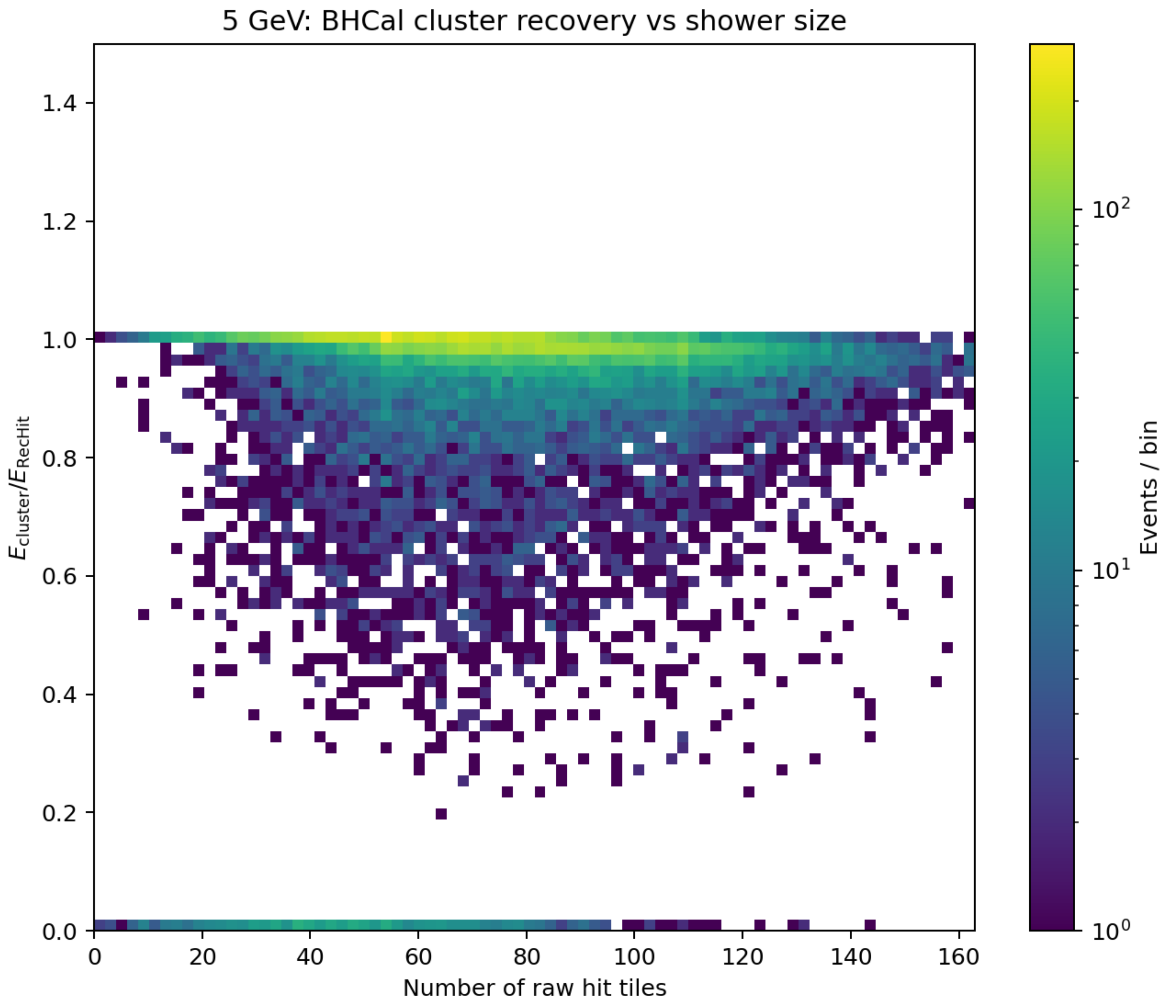




Cluster Recovery

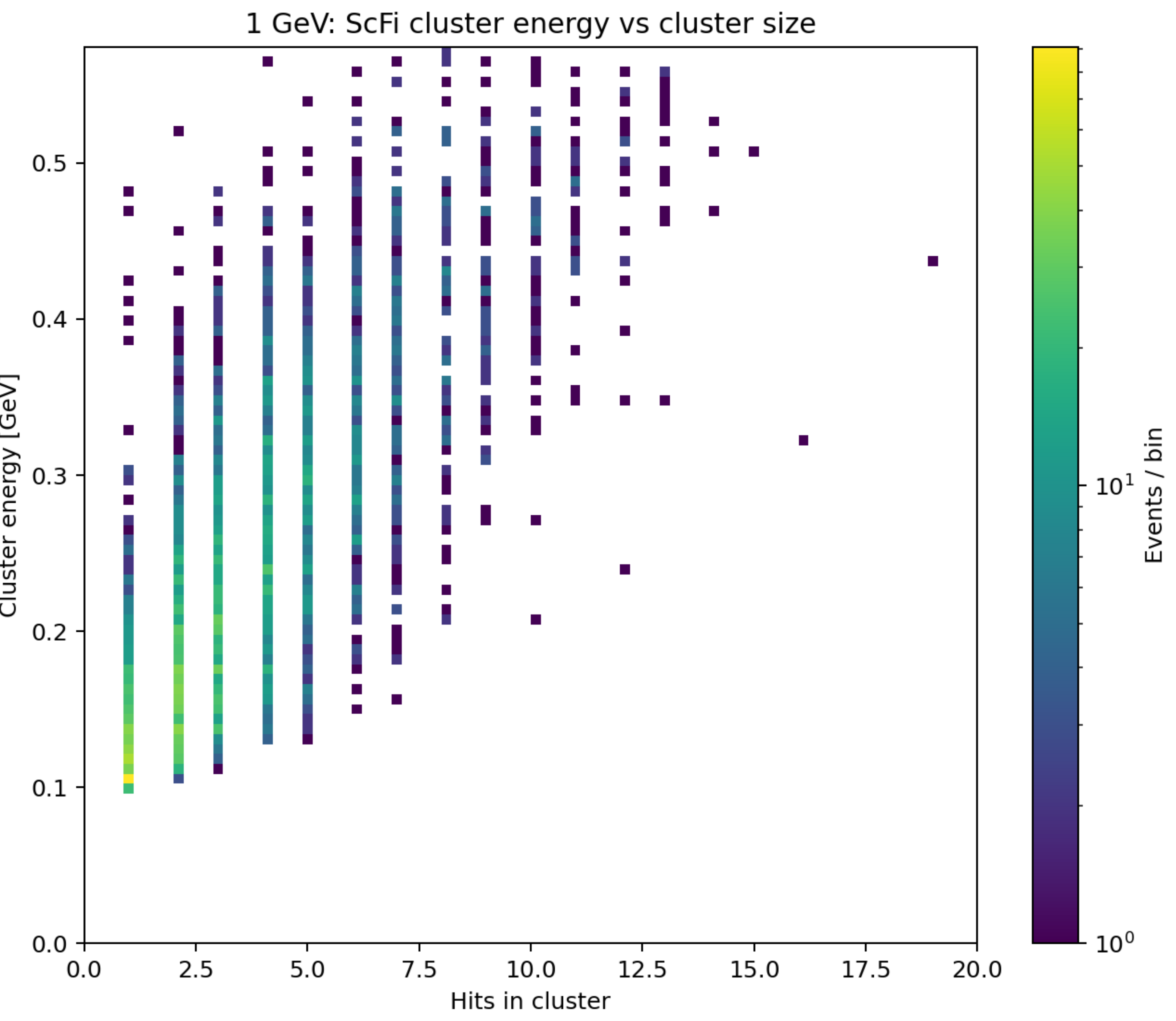


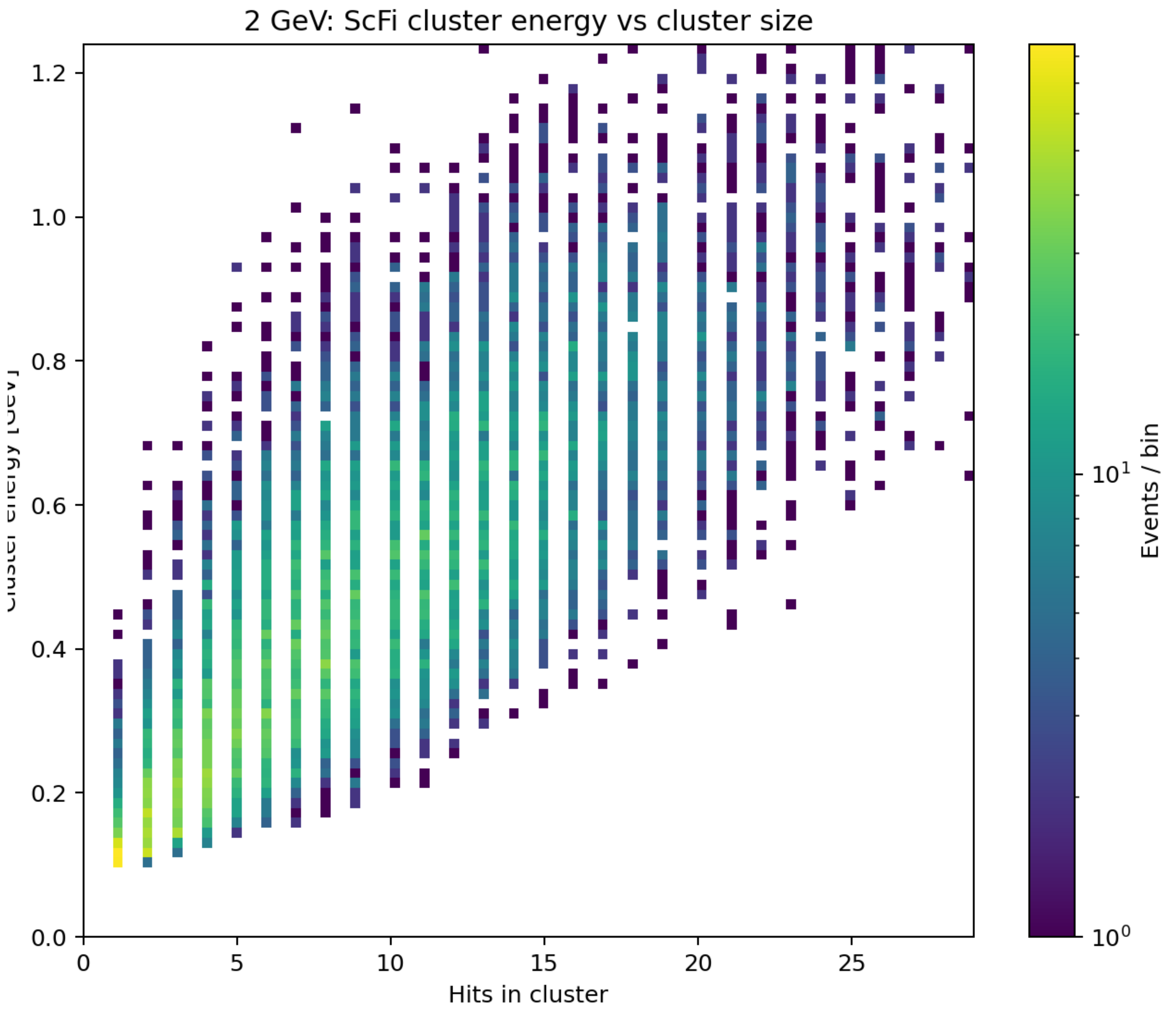


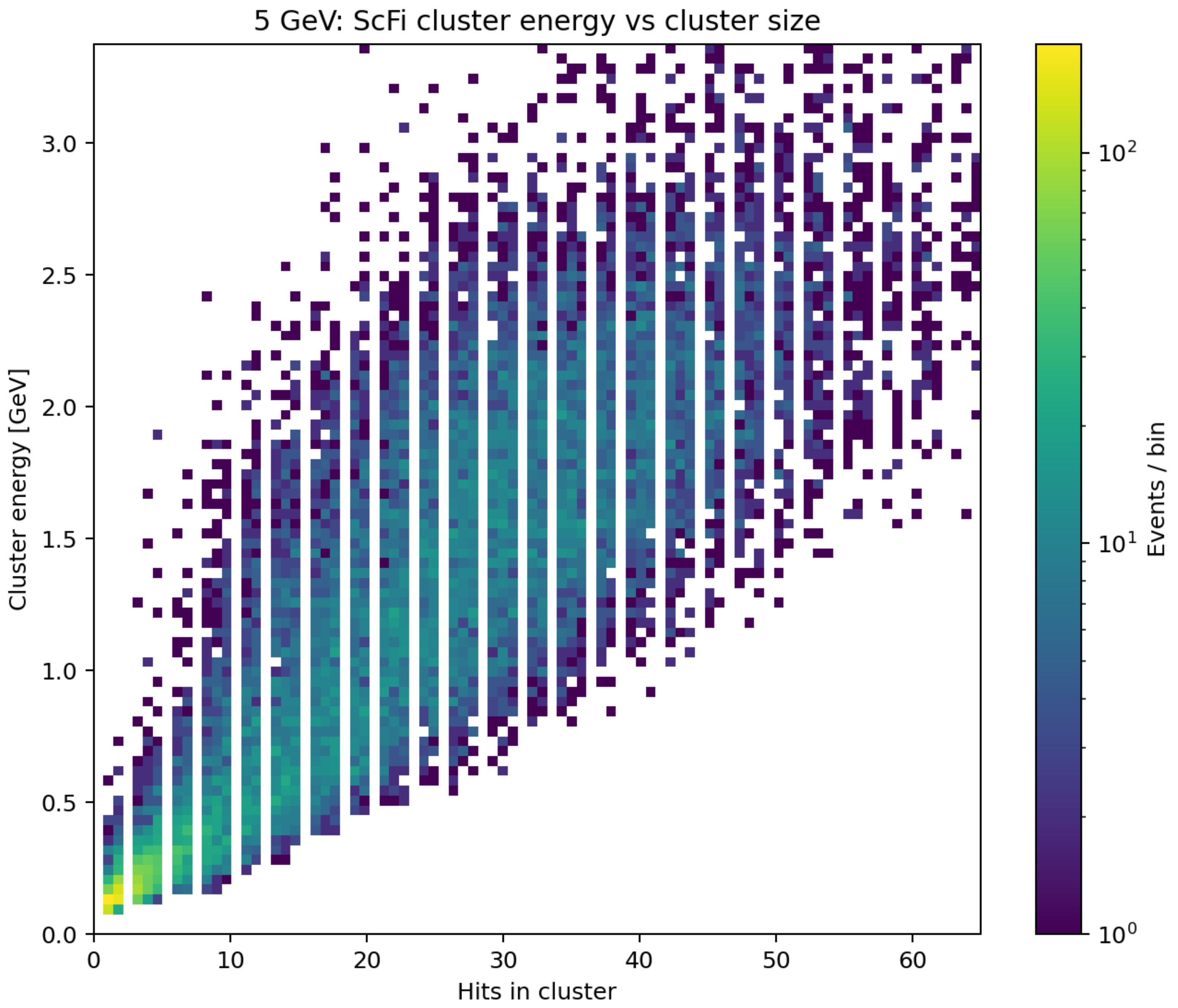


- Many events recover nearly all hit energy
- Significant partial-recovery population remains
- Larger showers show wider fluctuations
- Clustering contributes to response tails

ScFi Shower Topology

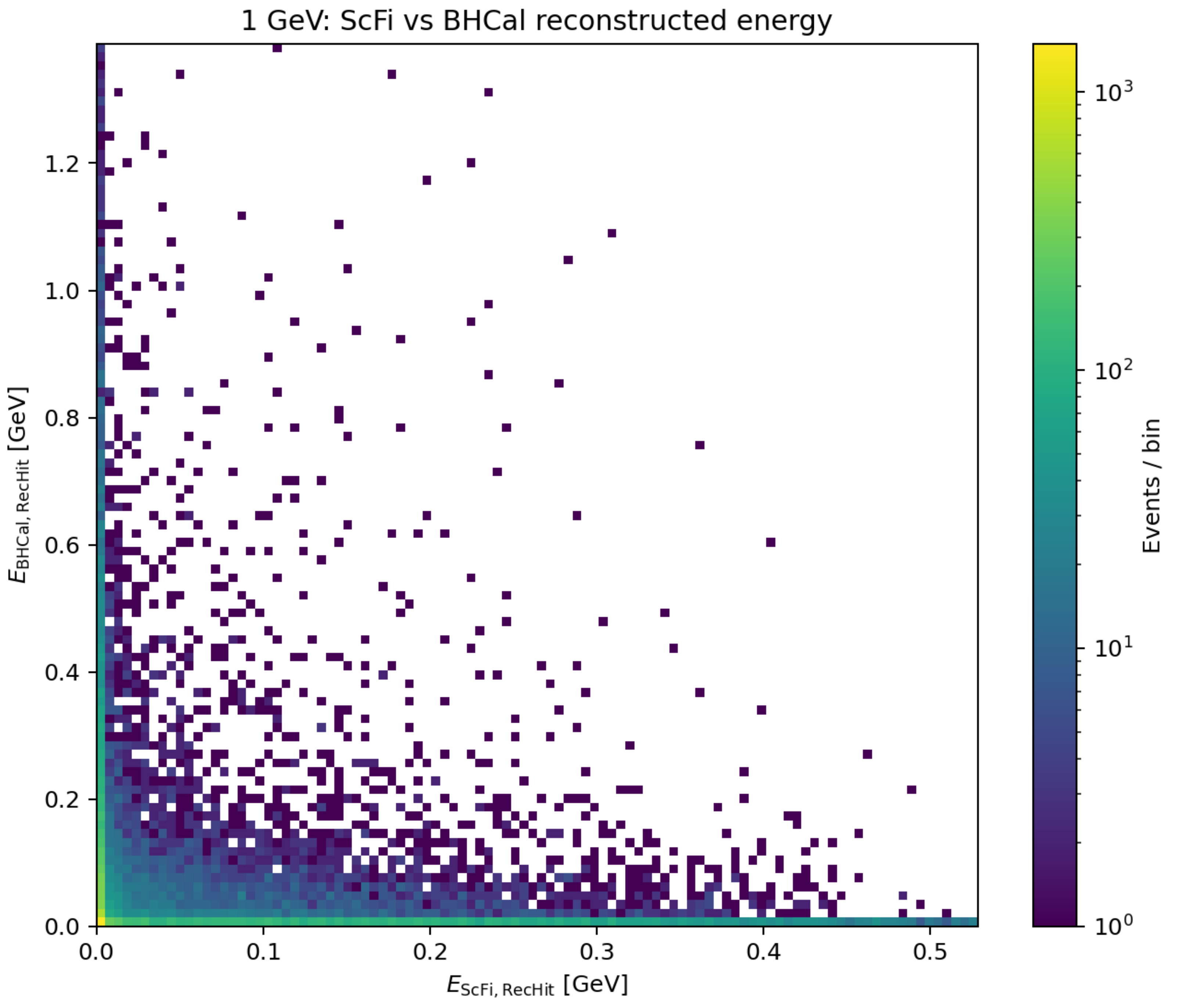


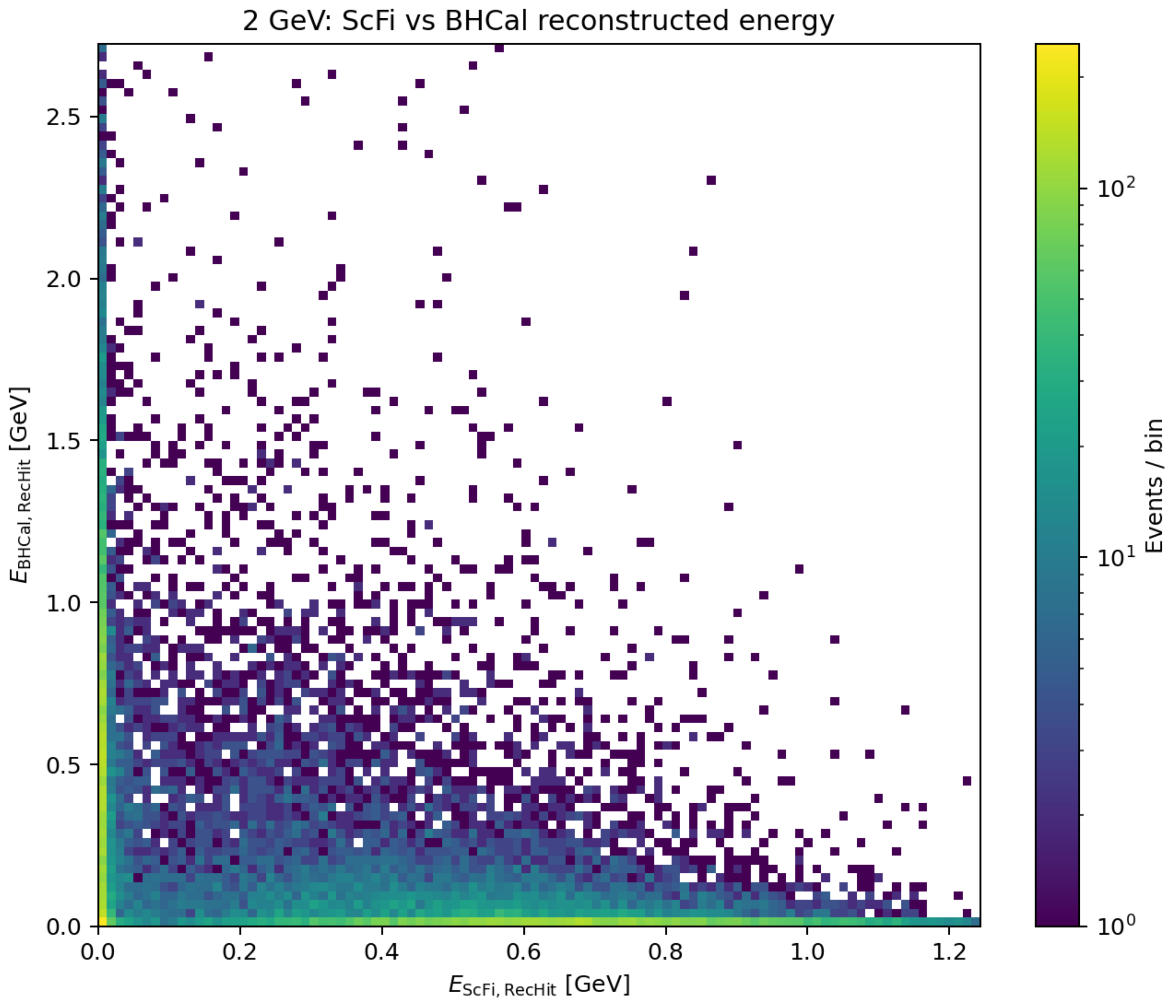


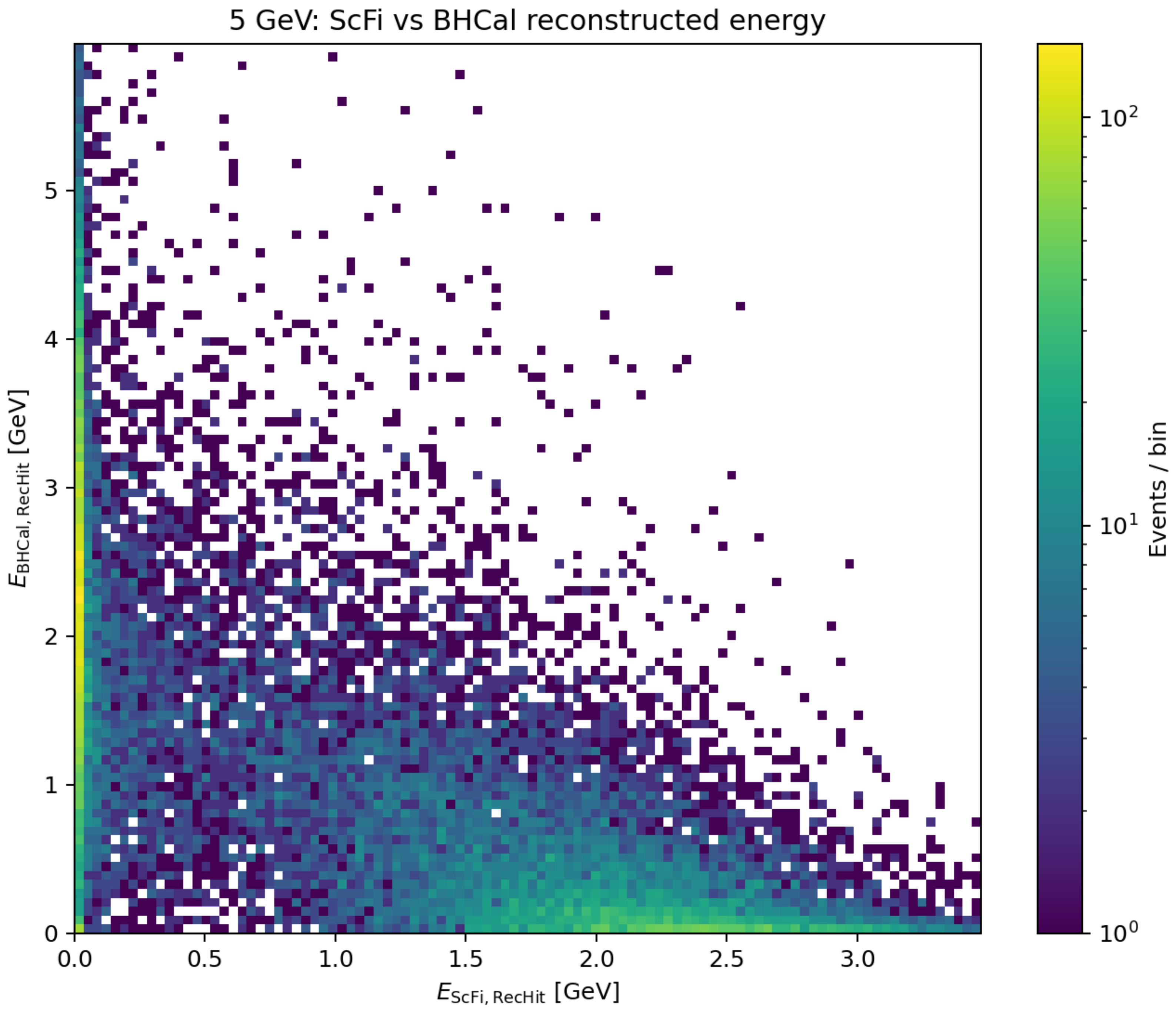


- ScFi energy increases with hit multiplicity
- Correlation broadens with neutron energy
- Same trend seen at 1, 2, and 5 GeV
- ScFi topology provides additional MLP information

BHCal vs ScFi Reconstructed Energy

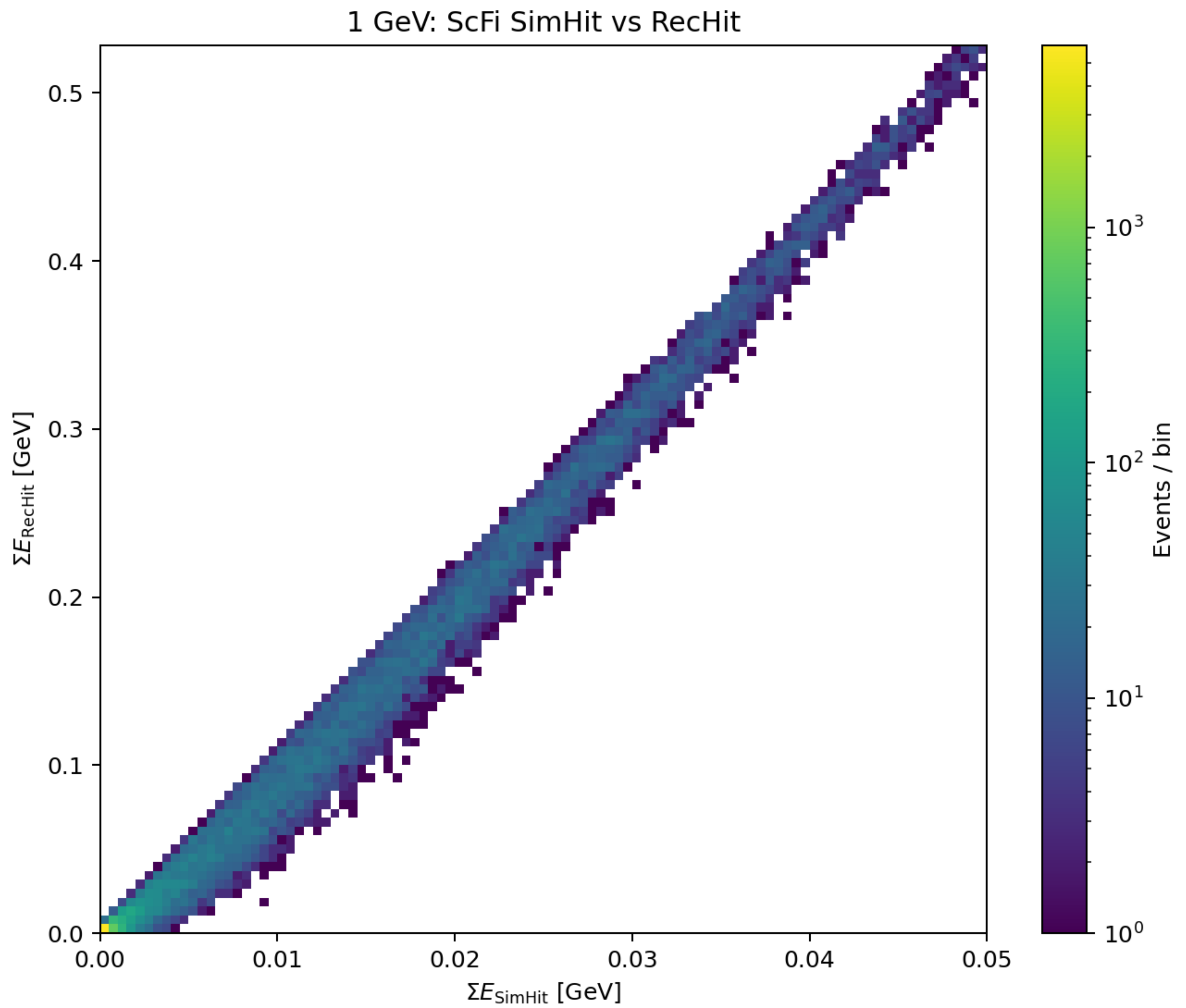


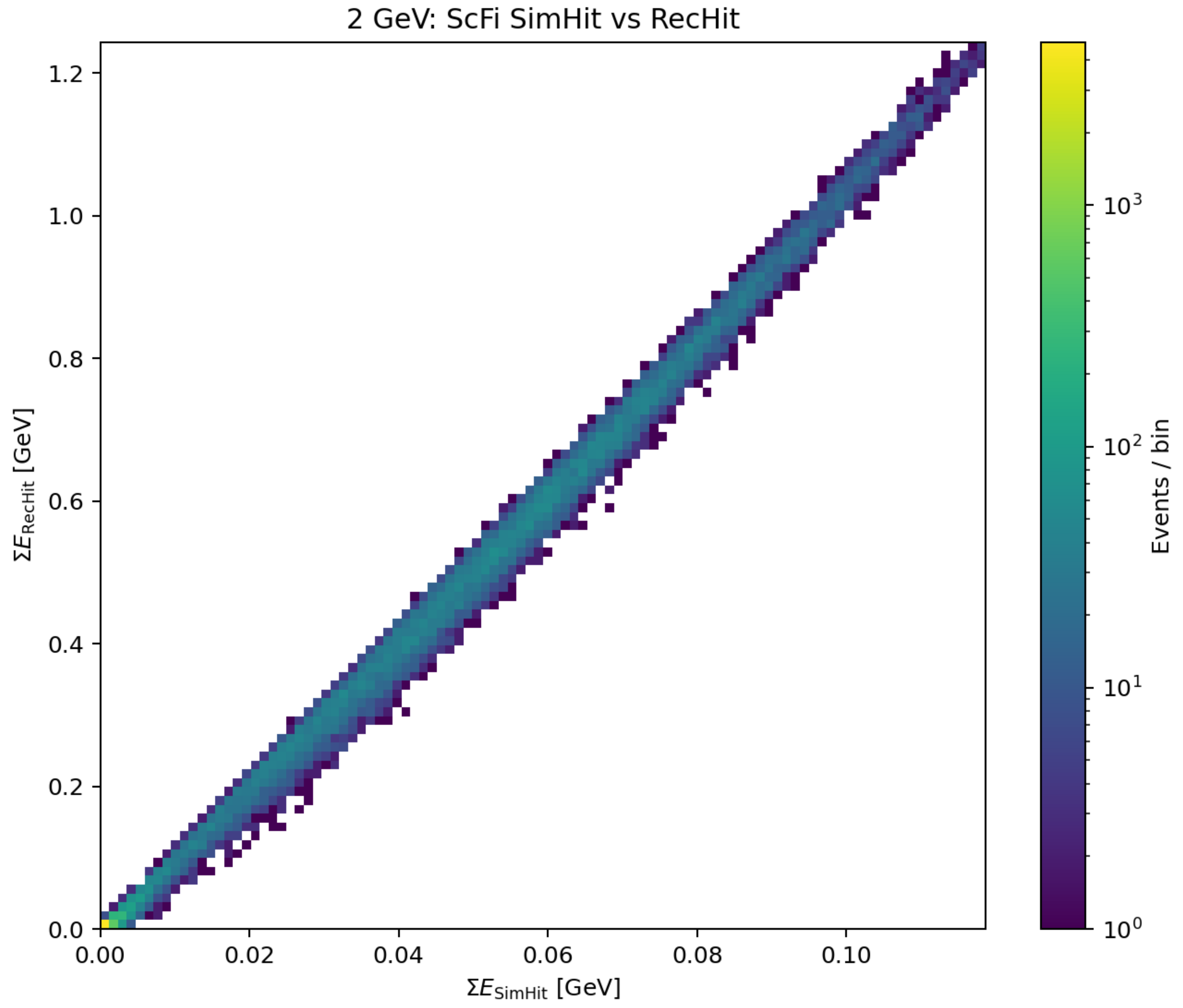


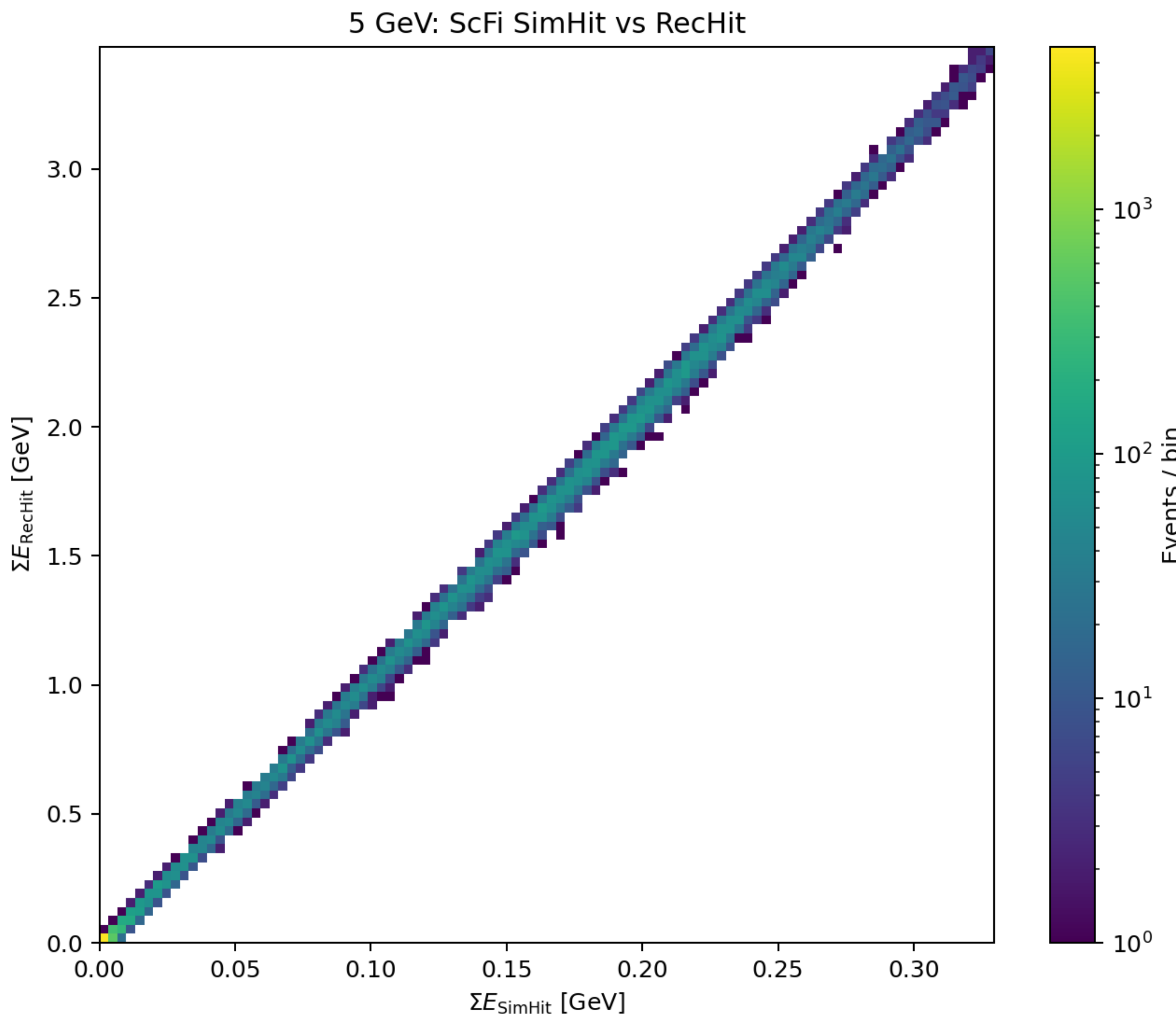


- BHCal and ScFi are not one-to-one correlated
- Energy sharing varies strongly event by event
- Phase space broadens at higher energy
- Combining both detectors improves calibration potential

ScFi SimHit vs RecHit



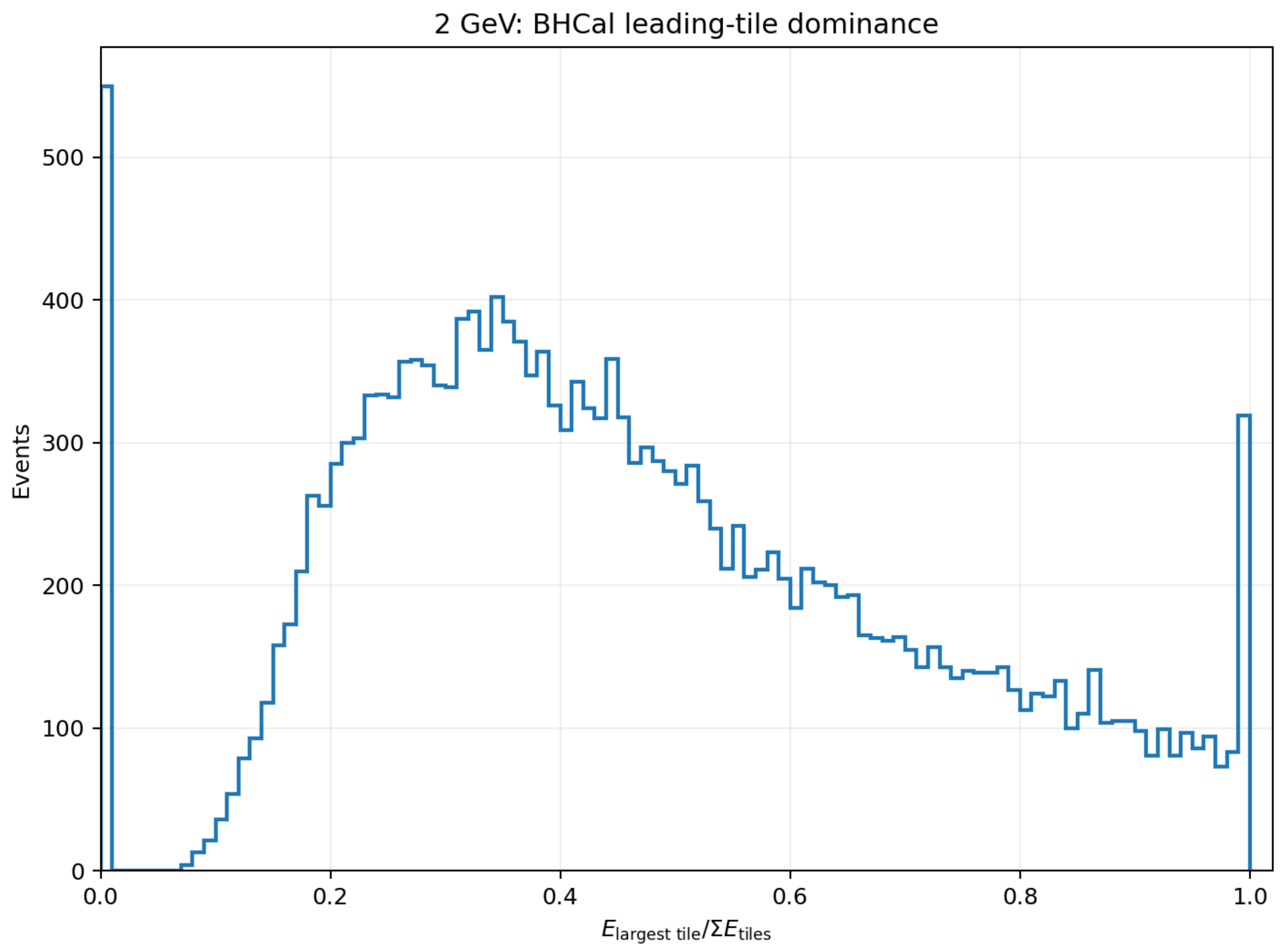


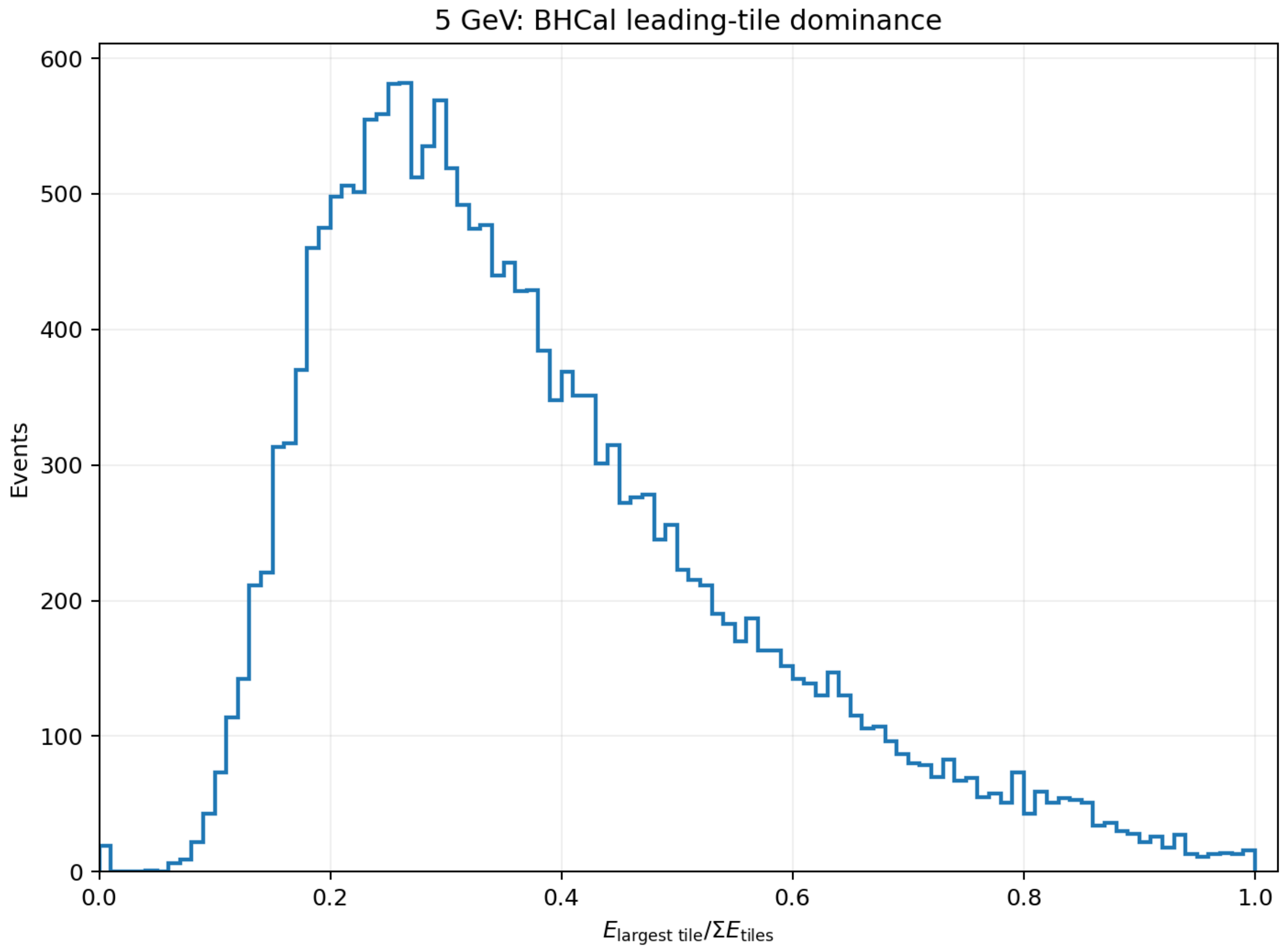


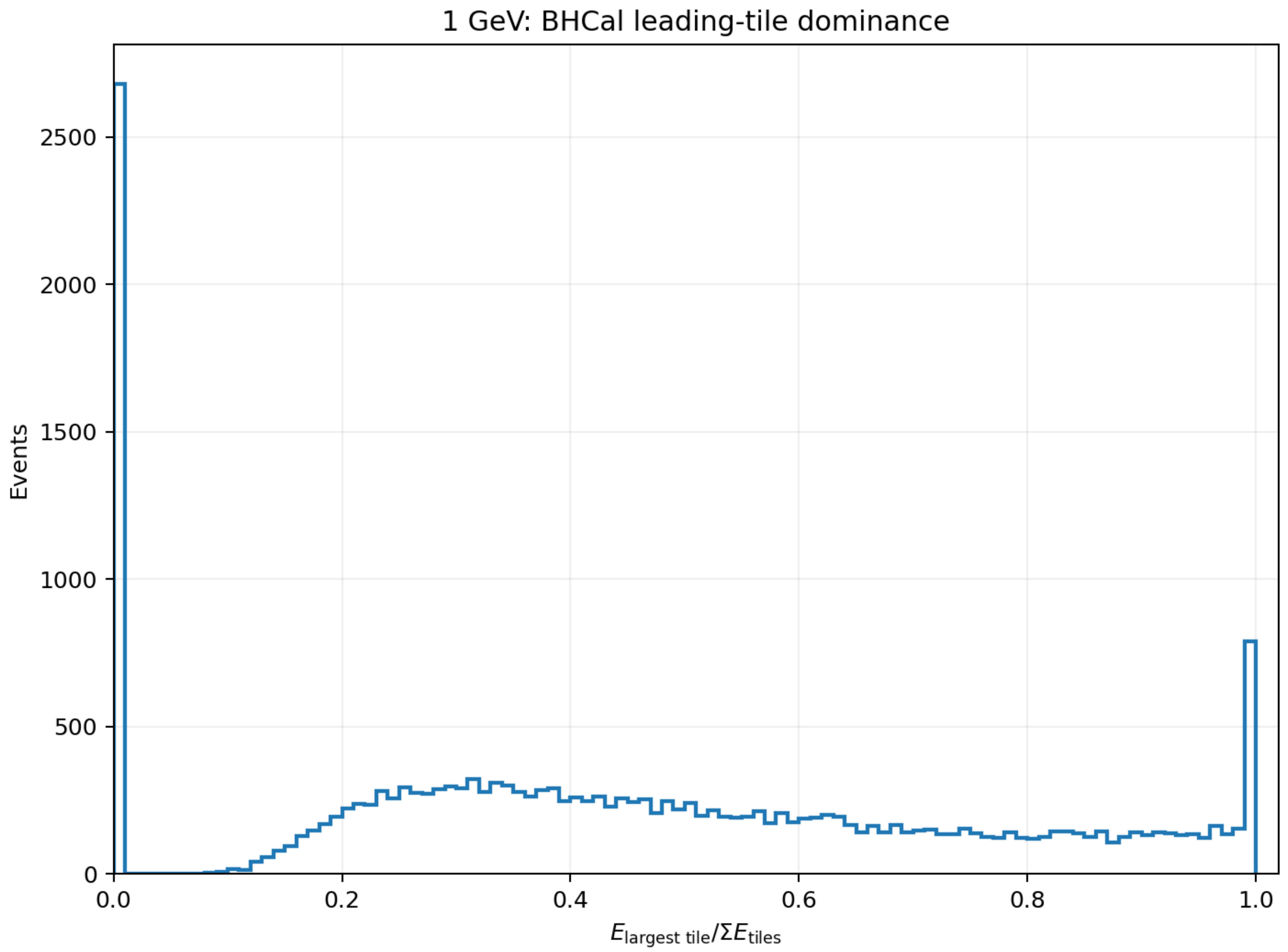
- Very narrow linear correlation
- Stable from 1 to 5 GeV
- SimHit-to-RecHit conversion behaves well

Leading tile fraction

- Neutron energy is distributed across many tiles
- Leading-tile fraction has a broad distribution
- Shower structure changes with neutron energy
- Total energy alone misses shower-topology information



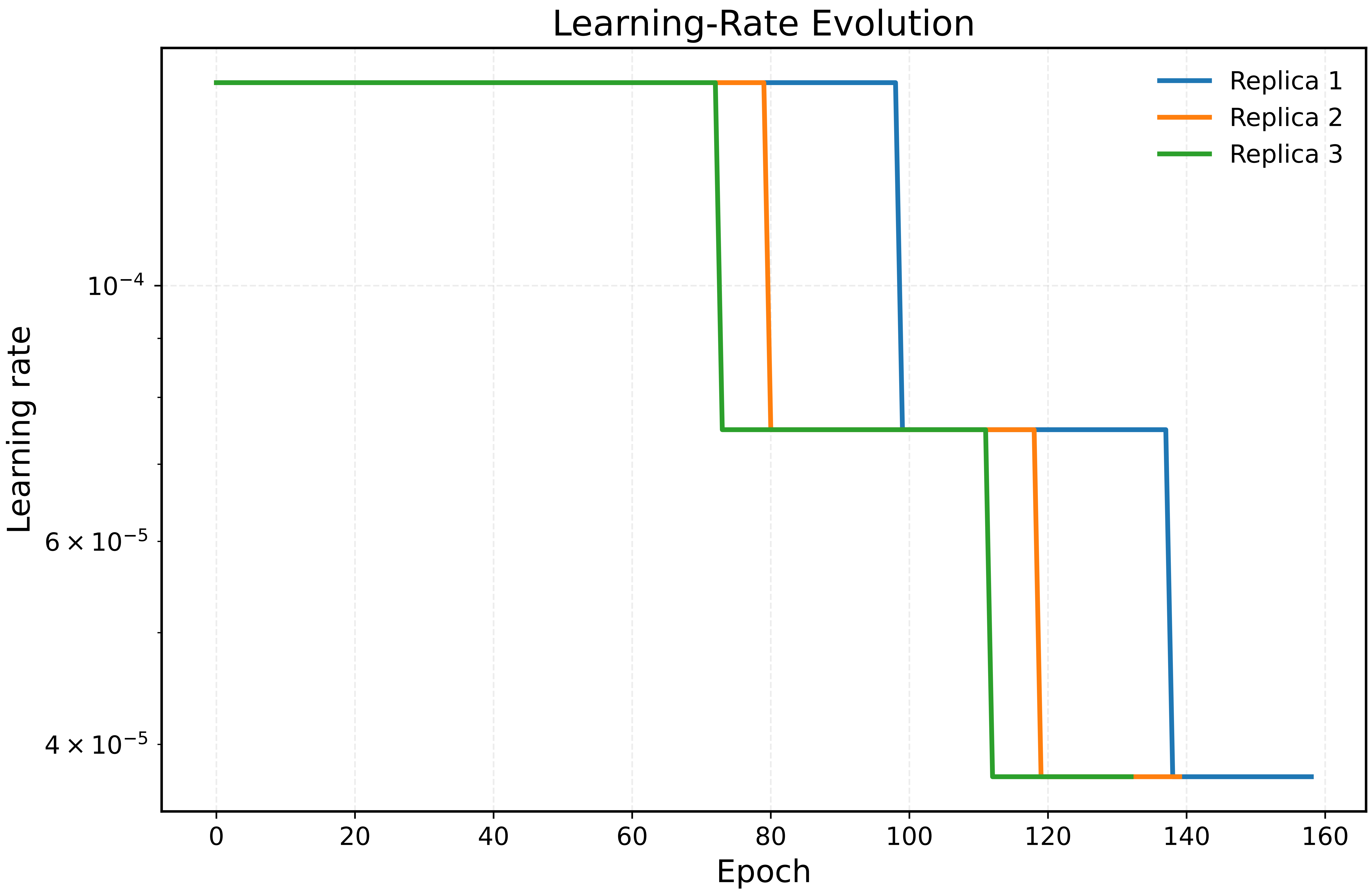




Learning-Rate Evolution

Replicas:same network architecture, same training/validation data, same hyperparameters, but different random initialization.

- **All three replicas begin with the same initial learning rate.**
- **The learning rate is reduced stepwise as the training improvement begins to plateau.**
- **Replica 3 reaches the first reduction earliest, followed by Replica 2 and Replica 1.**
- **Smaller learning rates allow finer optimization after the initial rapid learning stage.**
- **Different reduction times are expected because each random-seed replica converges at a slightly different rate.**



Summary

◆MLP uses detector-level observables only
◆Mean response and resolution are improved
◆Shower topology drives important fluctuations
◆Next: isolate the NC-DIS vs single-neutron difference

Thank you for your attention!!