ePIC Barrel HCAL energy calibration using Machine Learning

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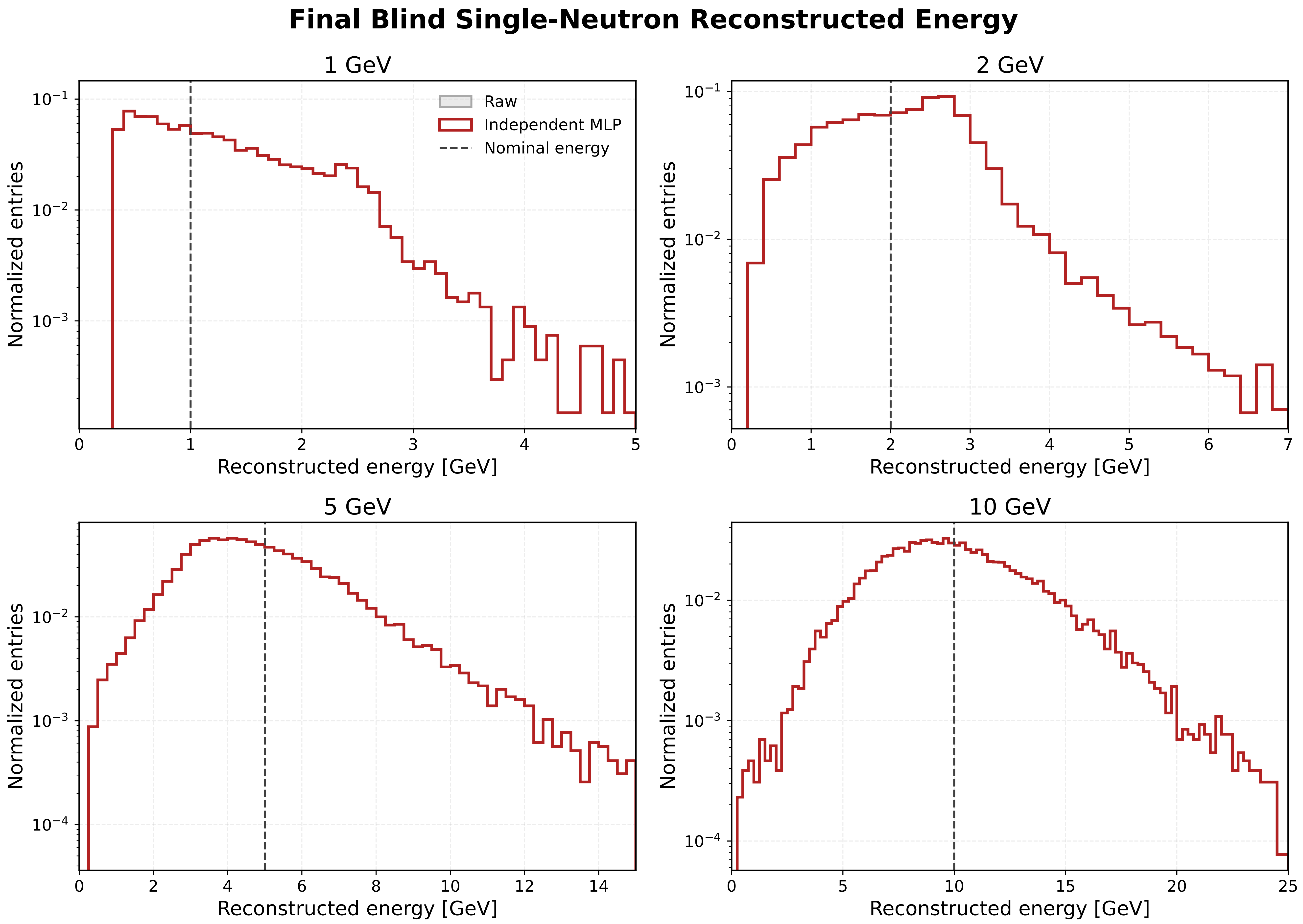
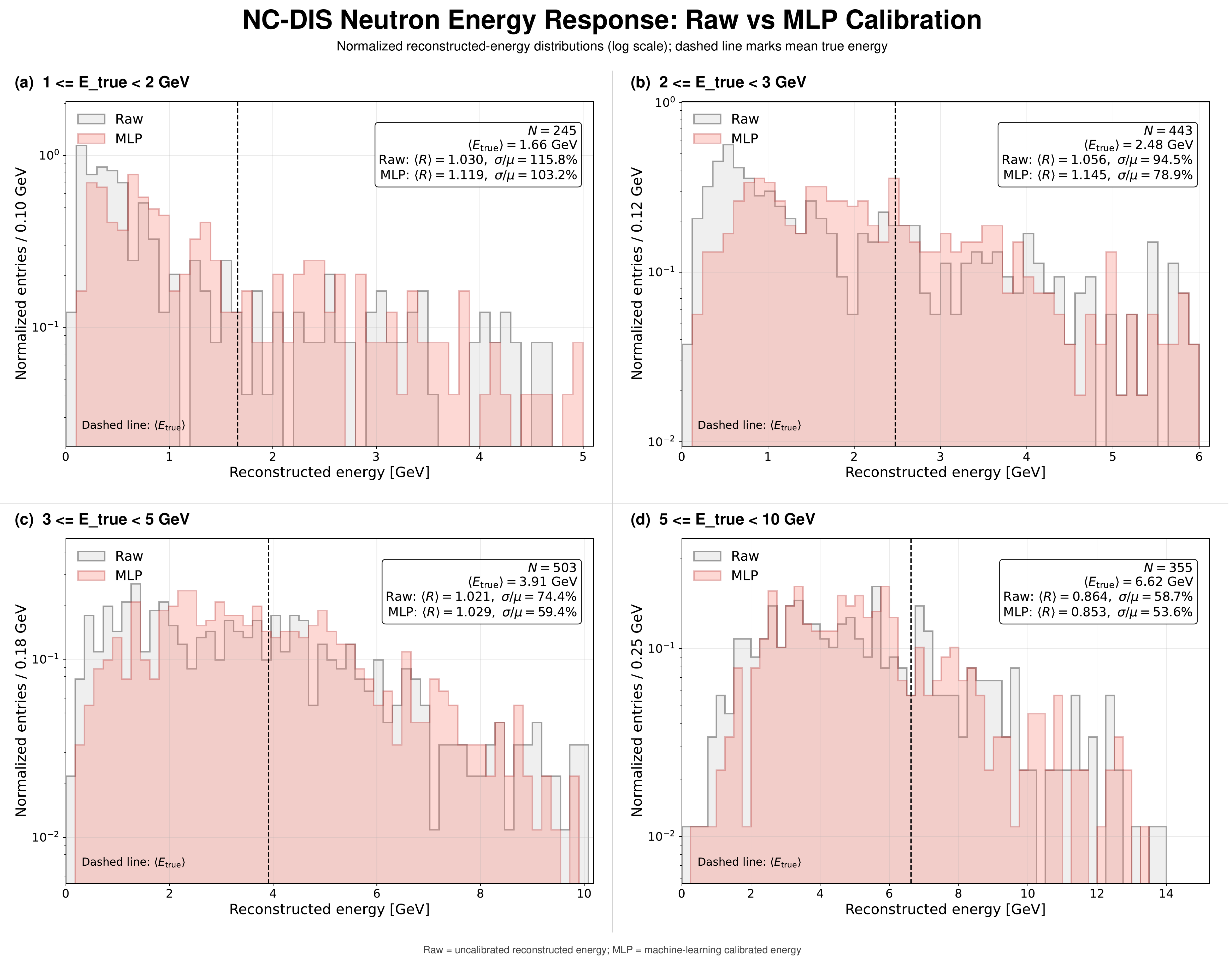
Single neutrons Reconstructed Energy

- 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



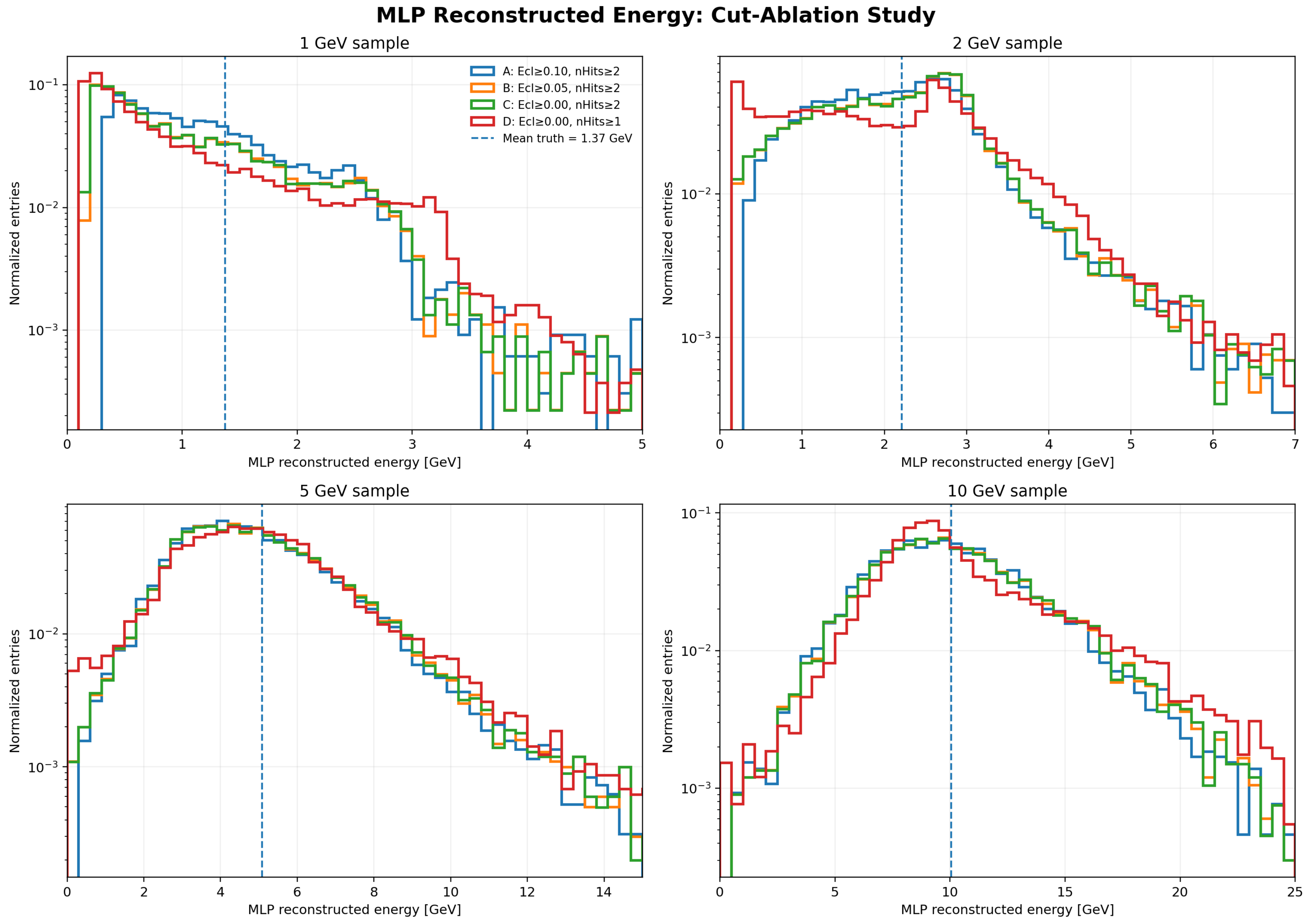
NC-DIS reconstructed energy (ML)

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



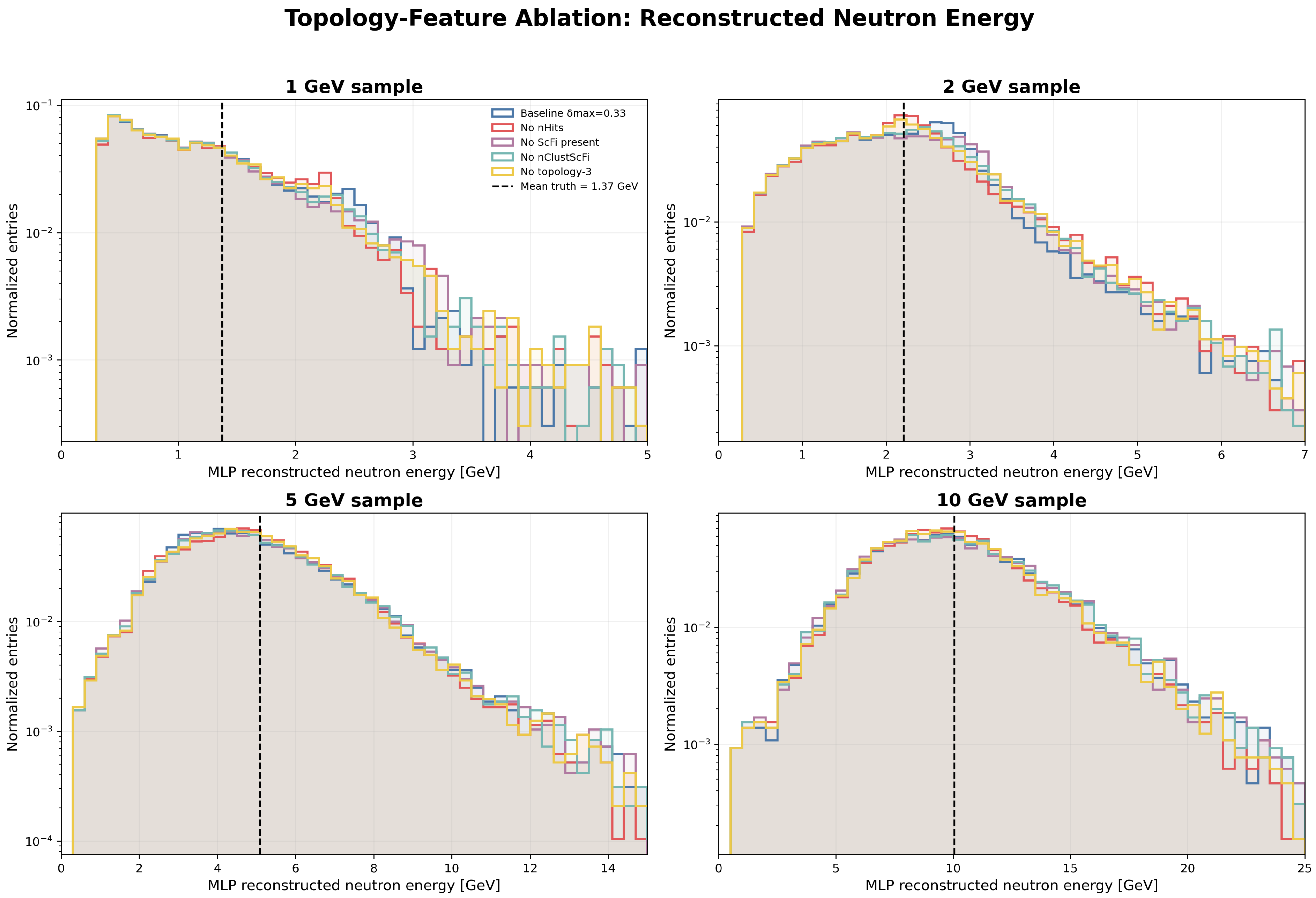
Selection Cuts Do Not Create the Low-Energy Structure

- Tested the reconstruction after removing individual selection requirements
- The 1–2 GeV structure remains in all cases
- The observed peak is therefore not caused by one analysis cut



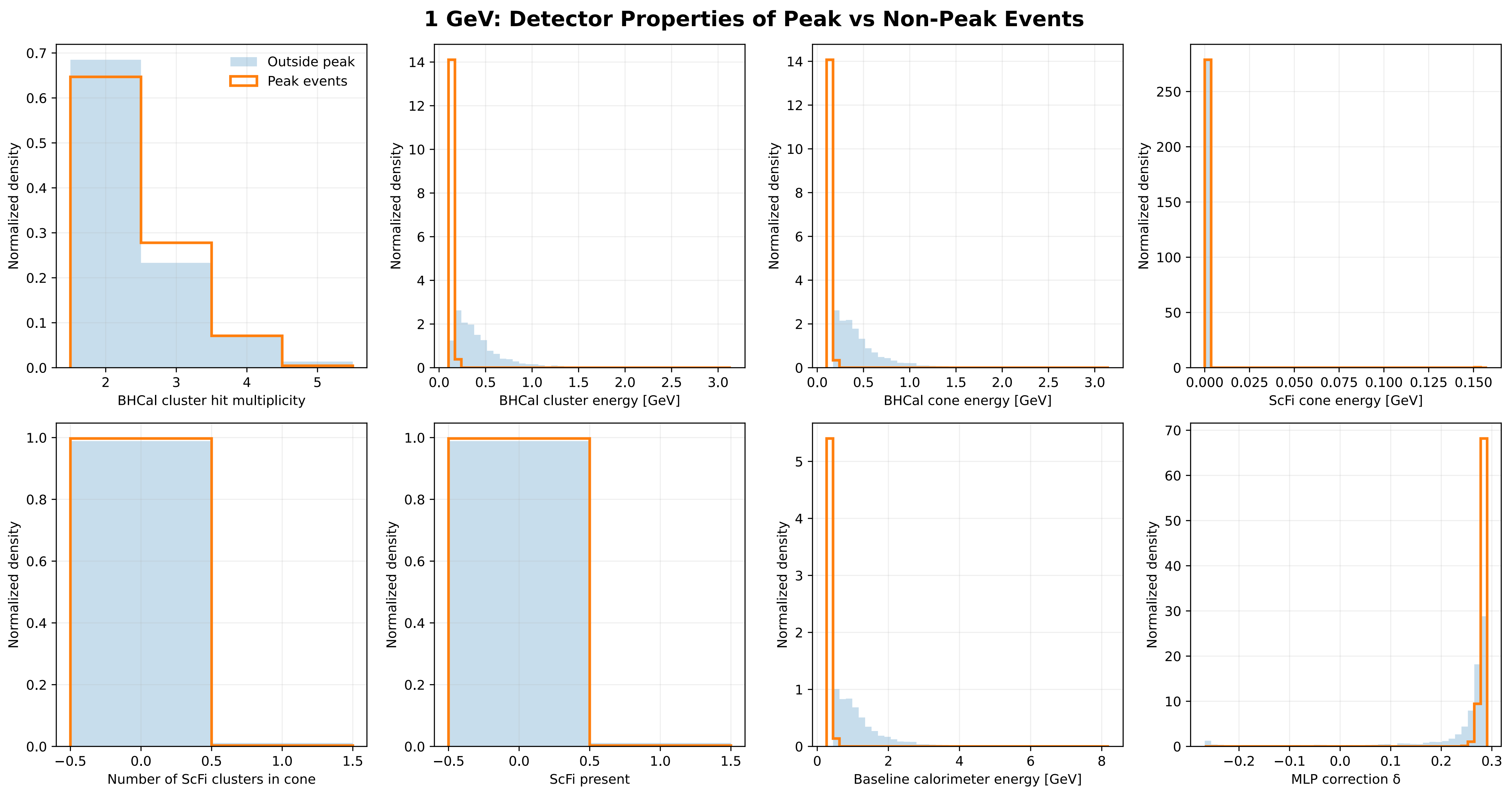
Topology Features Are Not the Origin of the Peak

- Removed BHCal hit and ScFi topology information
- Reconstructed-energy shapes change only slightly
- Topology inputs are not driving the low-energy structure



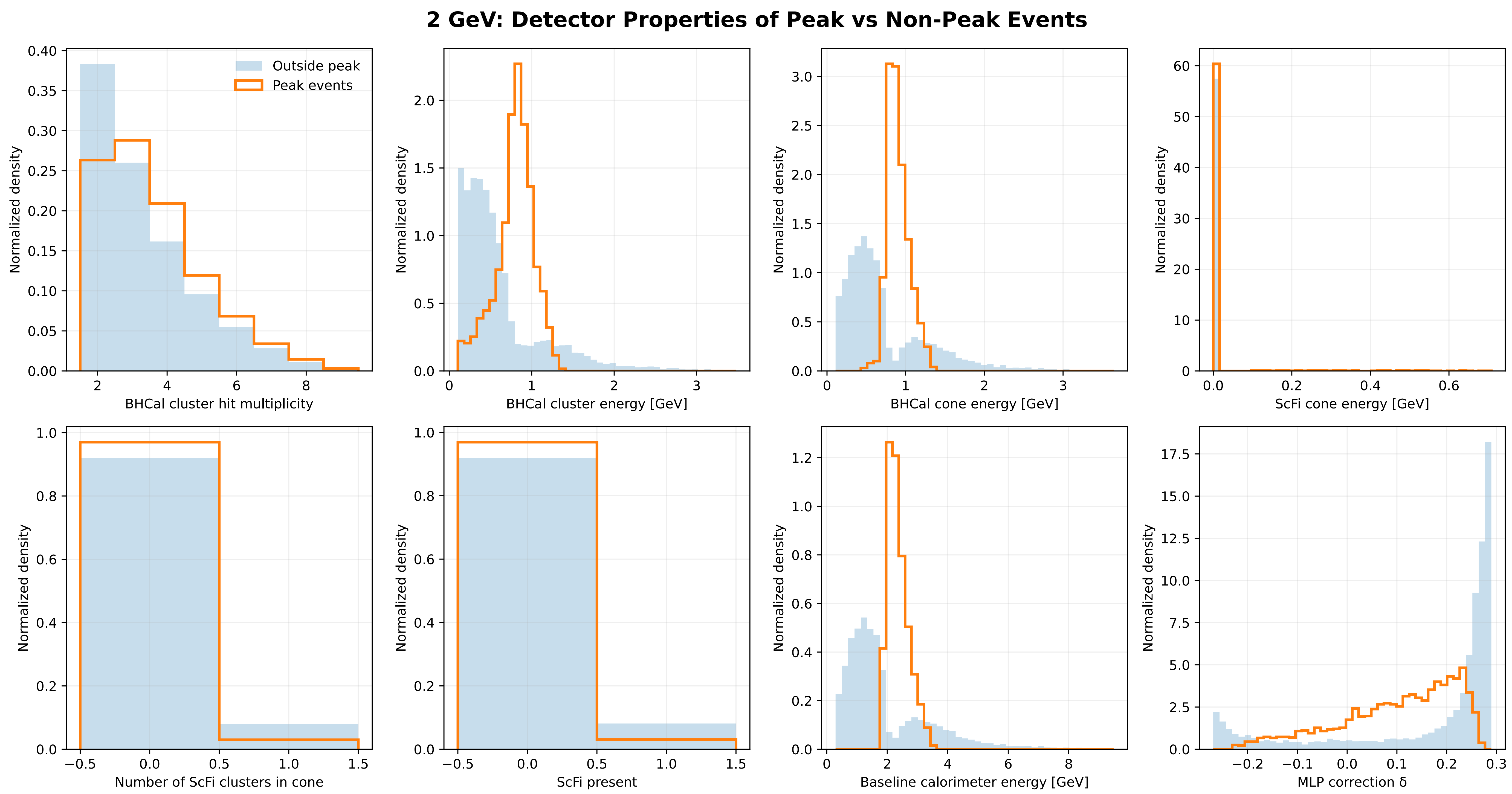
1 GeV Peak Events Have Sparse Detector Response

- Compare detector properties for peak and non-peak events
- Peak events correspond to very small calorimeter activity
- Sparse showers are a major feature of the 1 GeV population



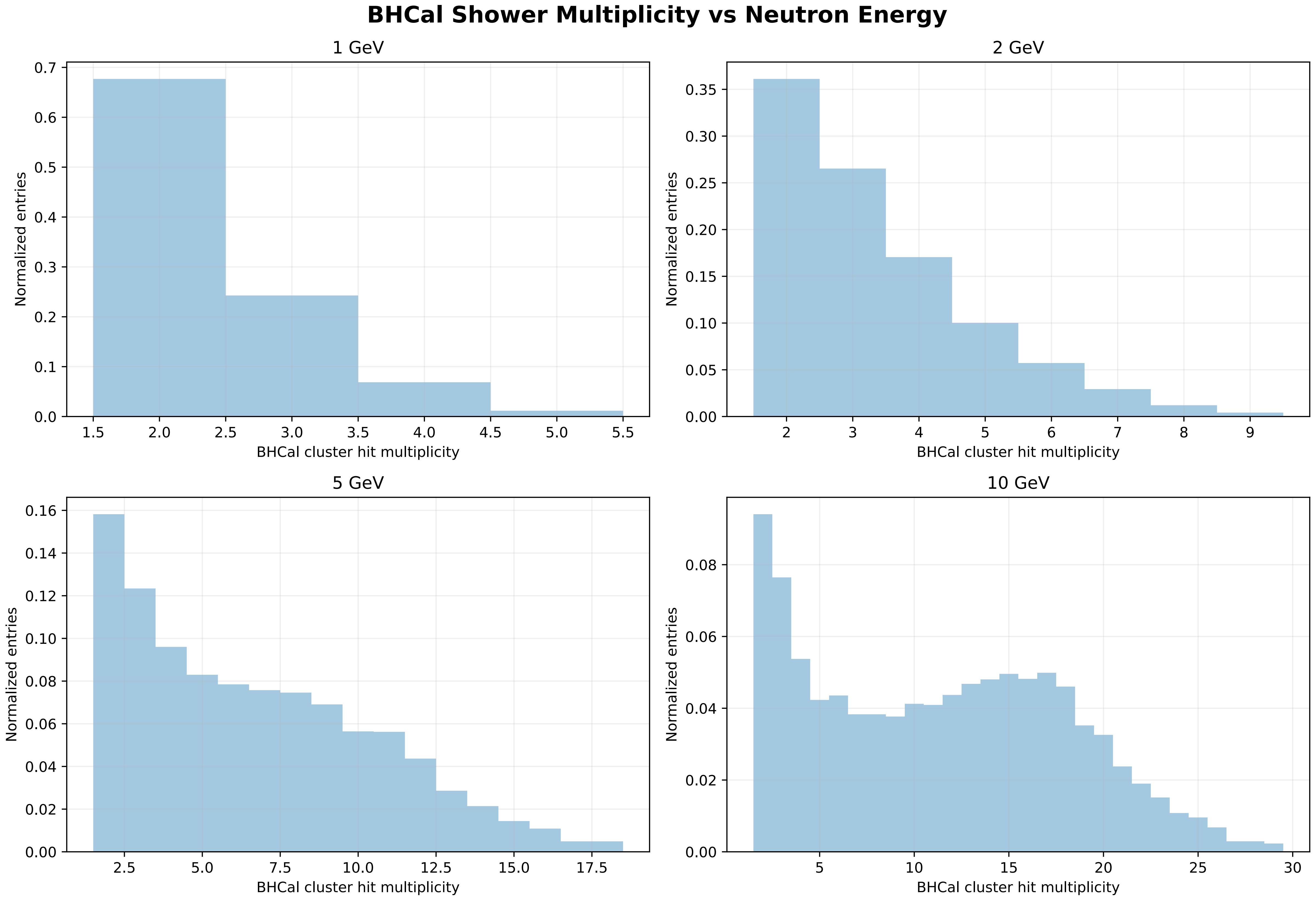
2 GeV Events Show the Same Trend with More Shower Activity

- The same peak/non-peak comparison was repeated at 2 GeV
  - Shower information is richer than at 1 GeV
- A low-response event population is still clearly present



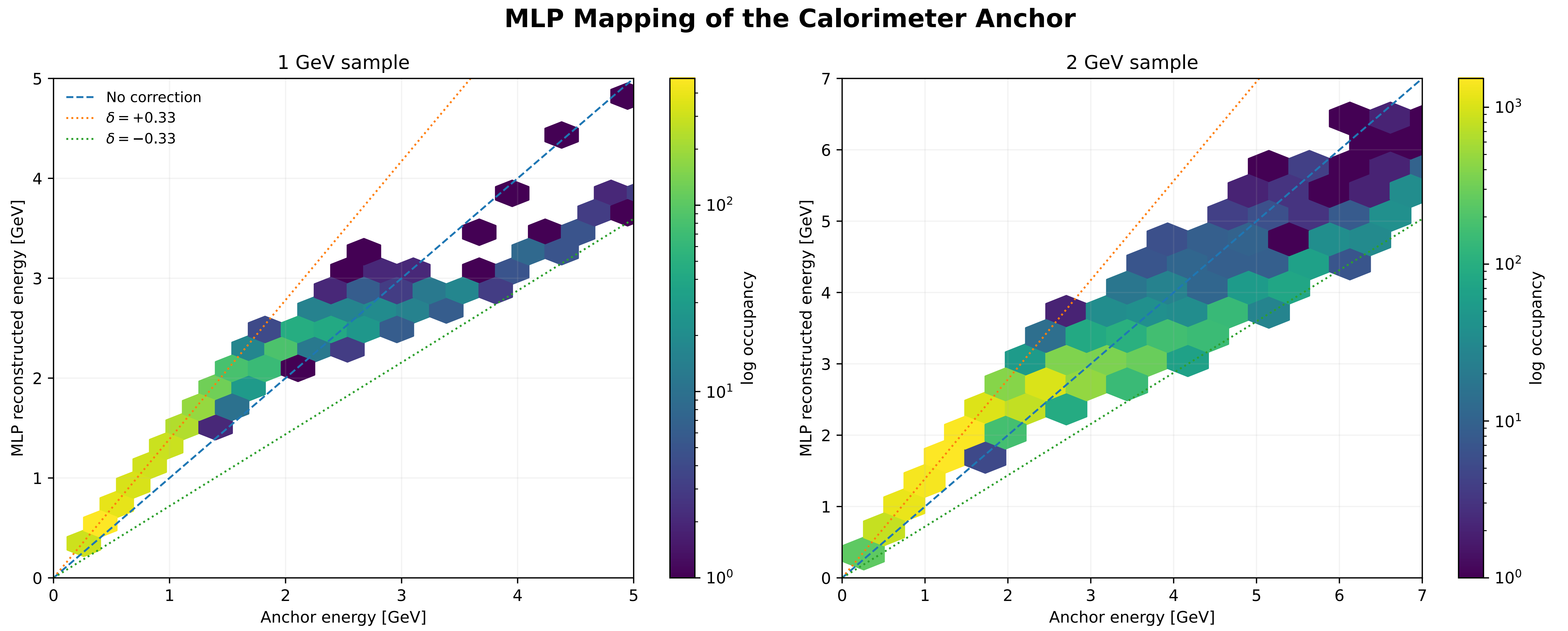
BHCal Shower Multiplicity Increases with Neutron Energy

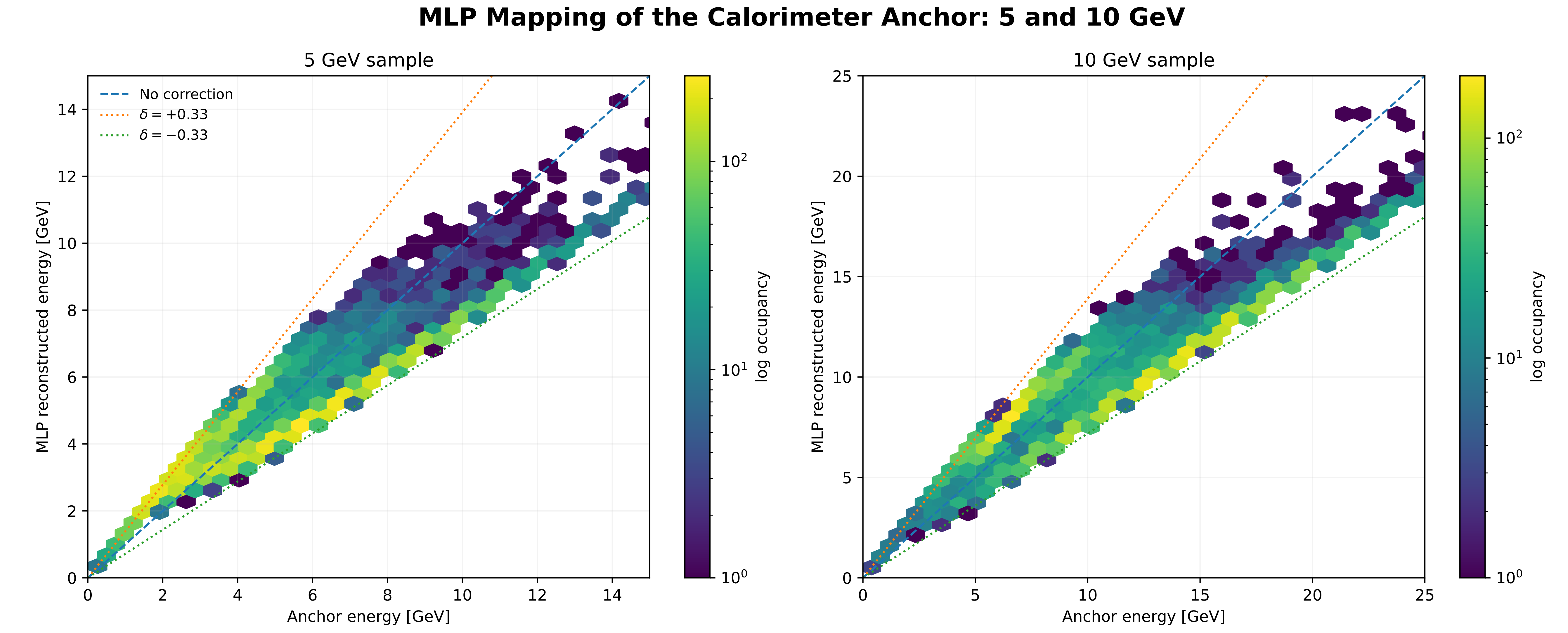
- 1–2 GeV showers contain only a few BHCal hits
- Hit multiplicity increases strongly with energy
  - Sparse low-energy showers provide limited information to the MLP



MLP Mapping of the Calorimeter Energy Anchor

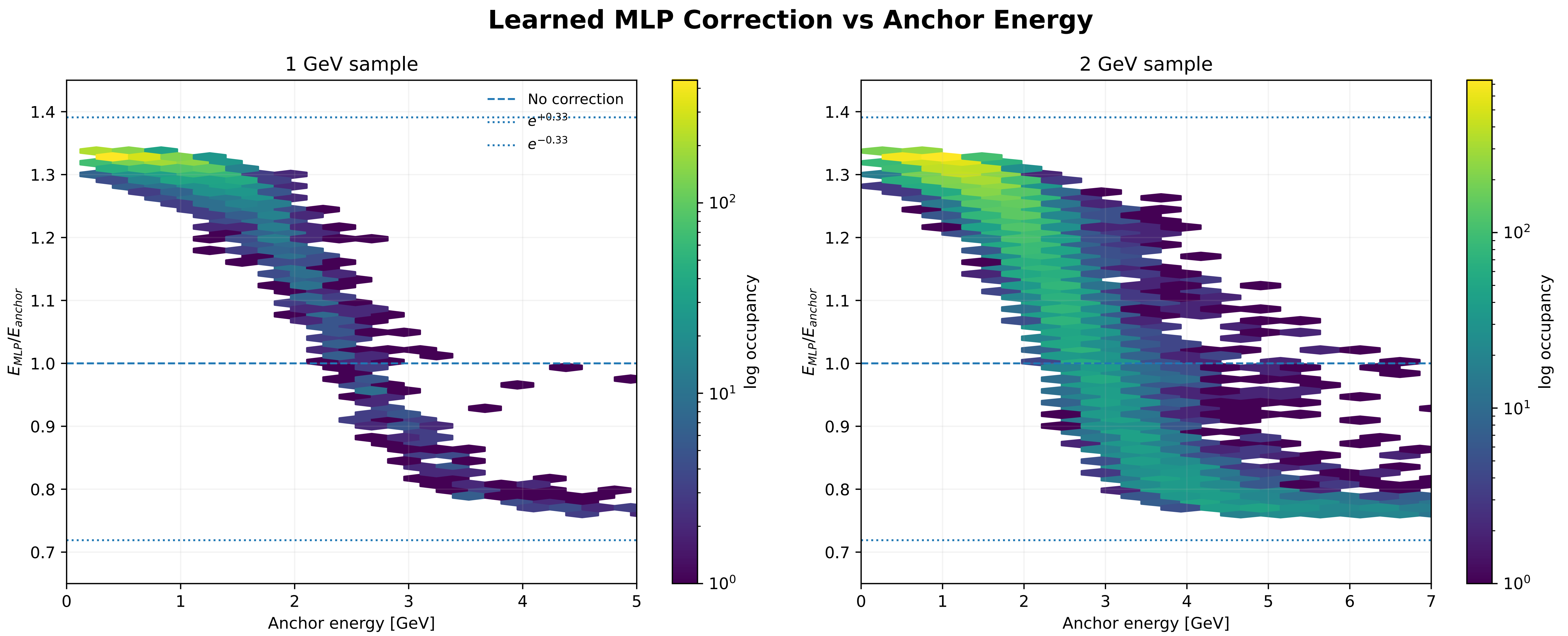
- The MLP learns a correction around the calorimeter anchor
- Under-response and over-response events are treated differently
- The mapping is broadest and most difficult at low energy





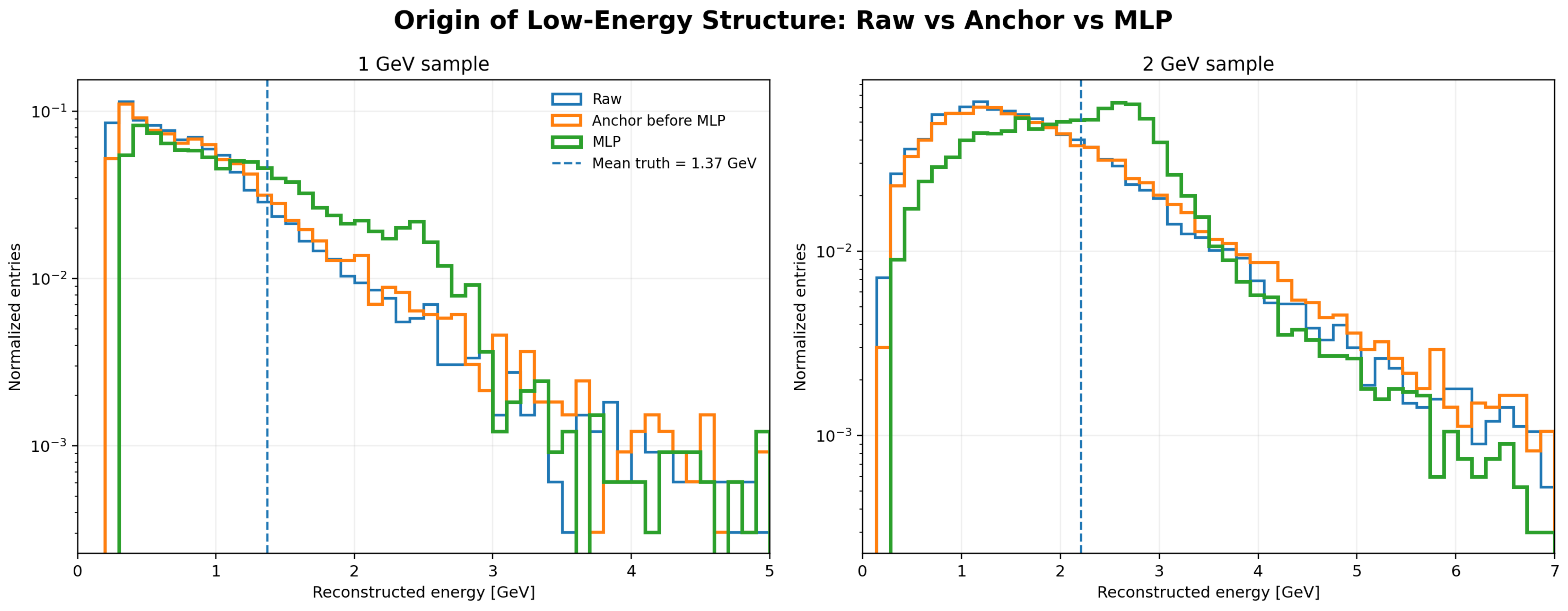
Large Corrections Are Required for Under-Responding Events

- Small anchor response receives a positive MLP correction
- Large response receives little or negative correction
- The required correction is especially large for low-energy neutrons



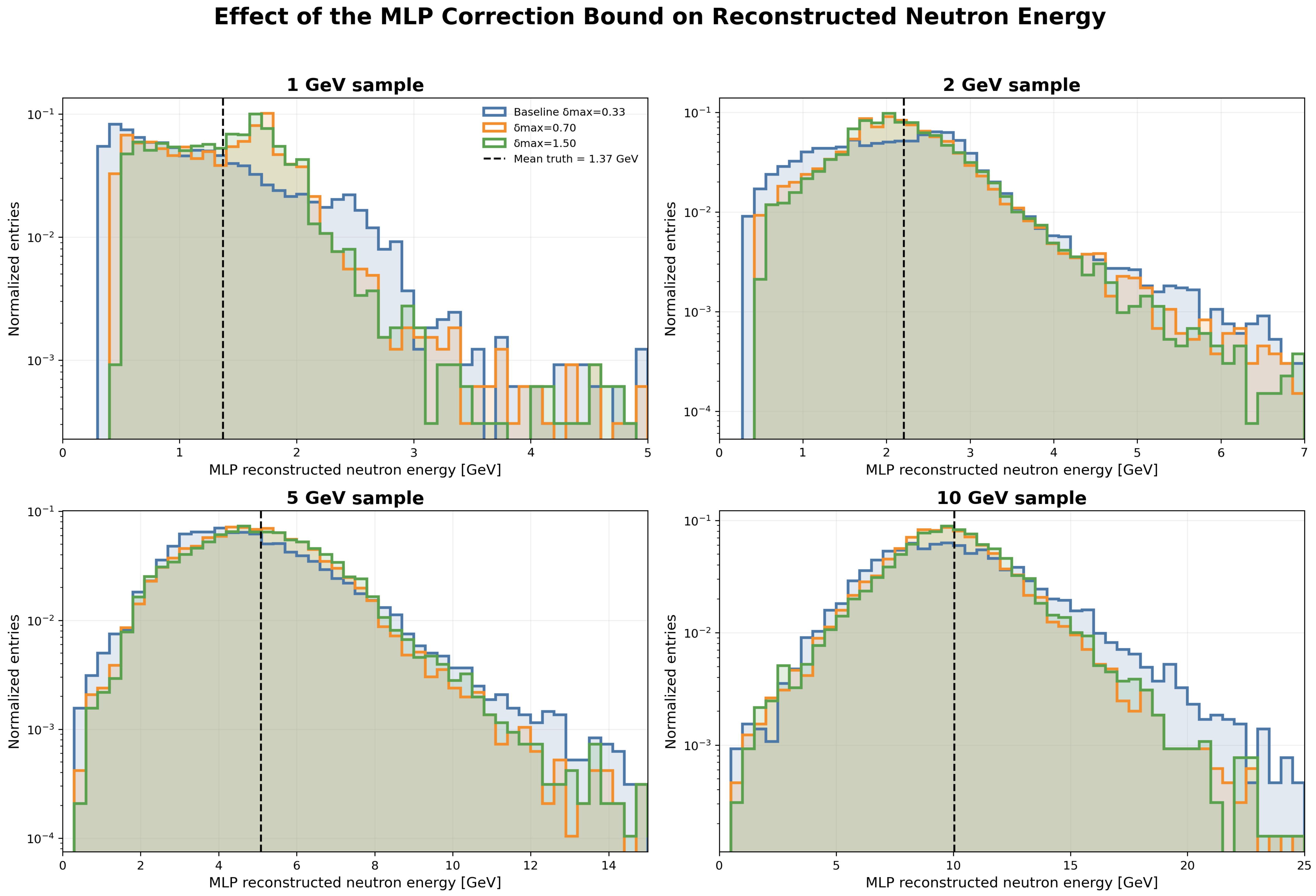
The Low-Energy Structure Exists Before the Final MLP Correction

- The low-response population is already visible in the detector-based energy
- The MLP moves this population but does not create it
- This identifies the detector response as the underlying origin



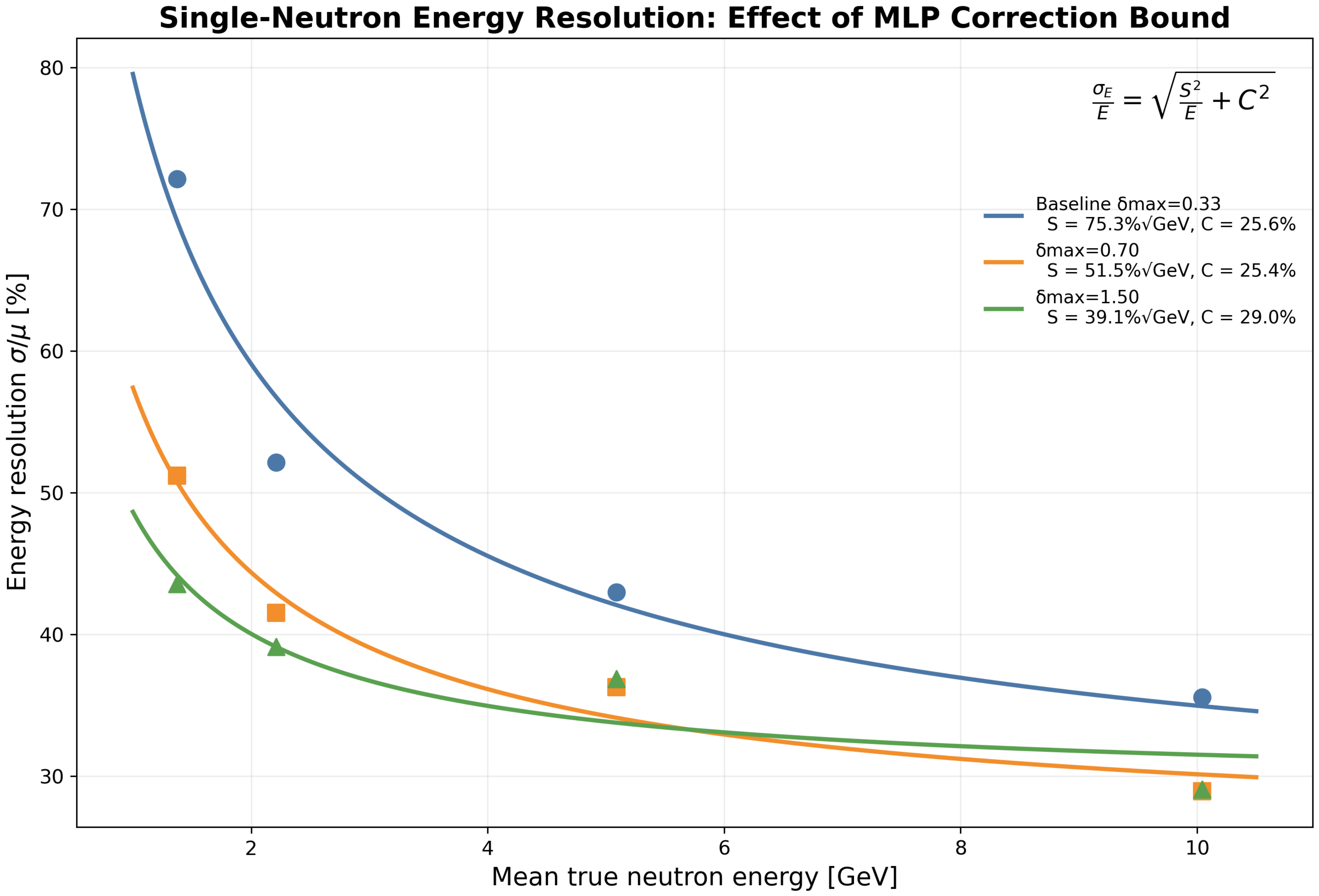
Relaxing the MLP Correction Bound Recovers Low-Energy Events

- Original model used a restricted correction range
  - Larger bounds strongly modify the 1–2 GeV response
  - The effect becomes much smaller at 5 and 10 GeV



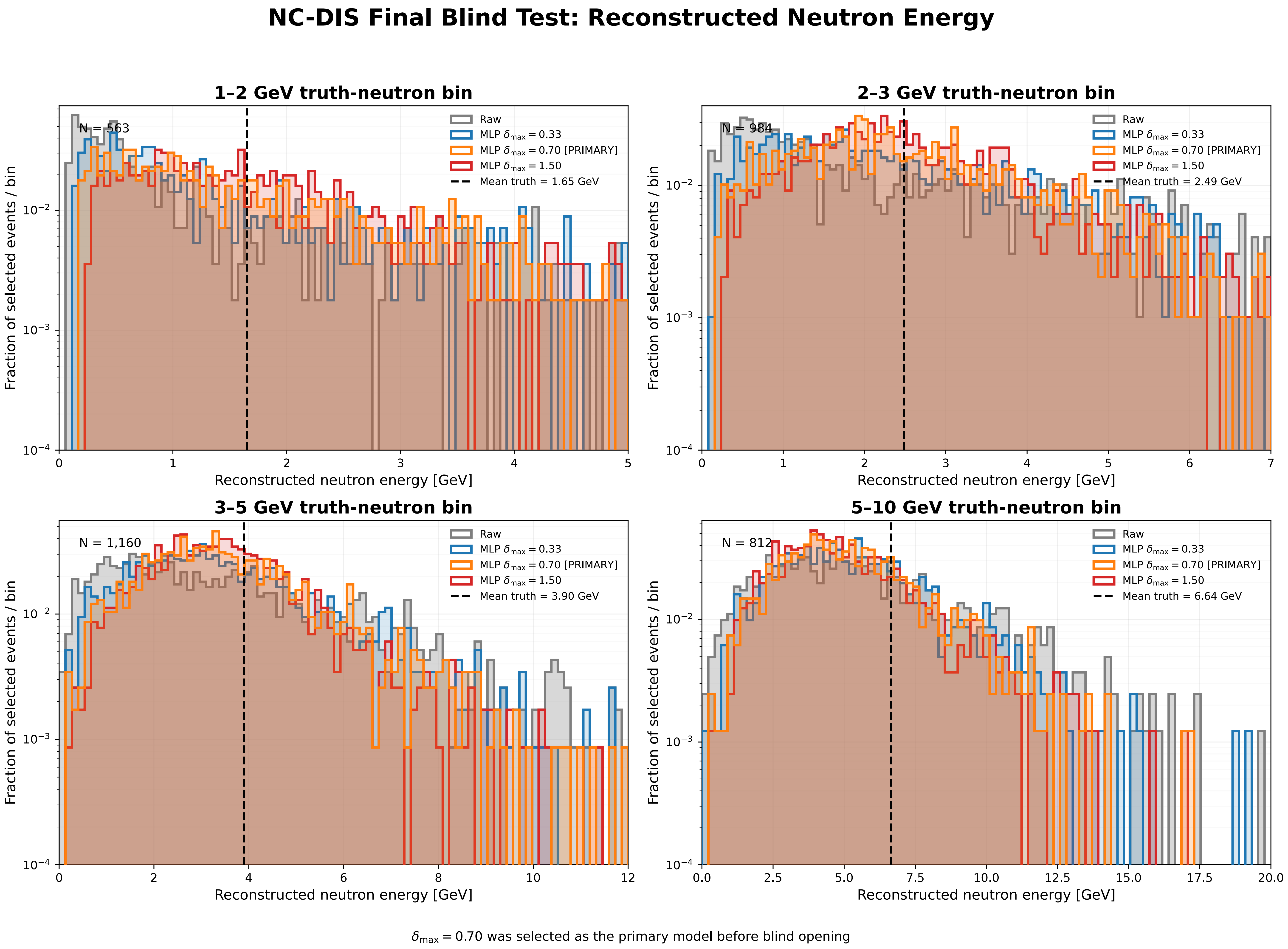
Relaxing the Correction Bound Improves Single-Neutron Resolution

- Resolution improves strongly when the correction range is increased
  - The largest gain occurs at low energy
- The stochastic contribution is substantially reduced



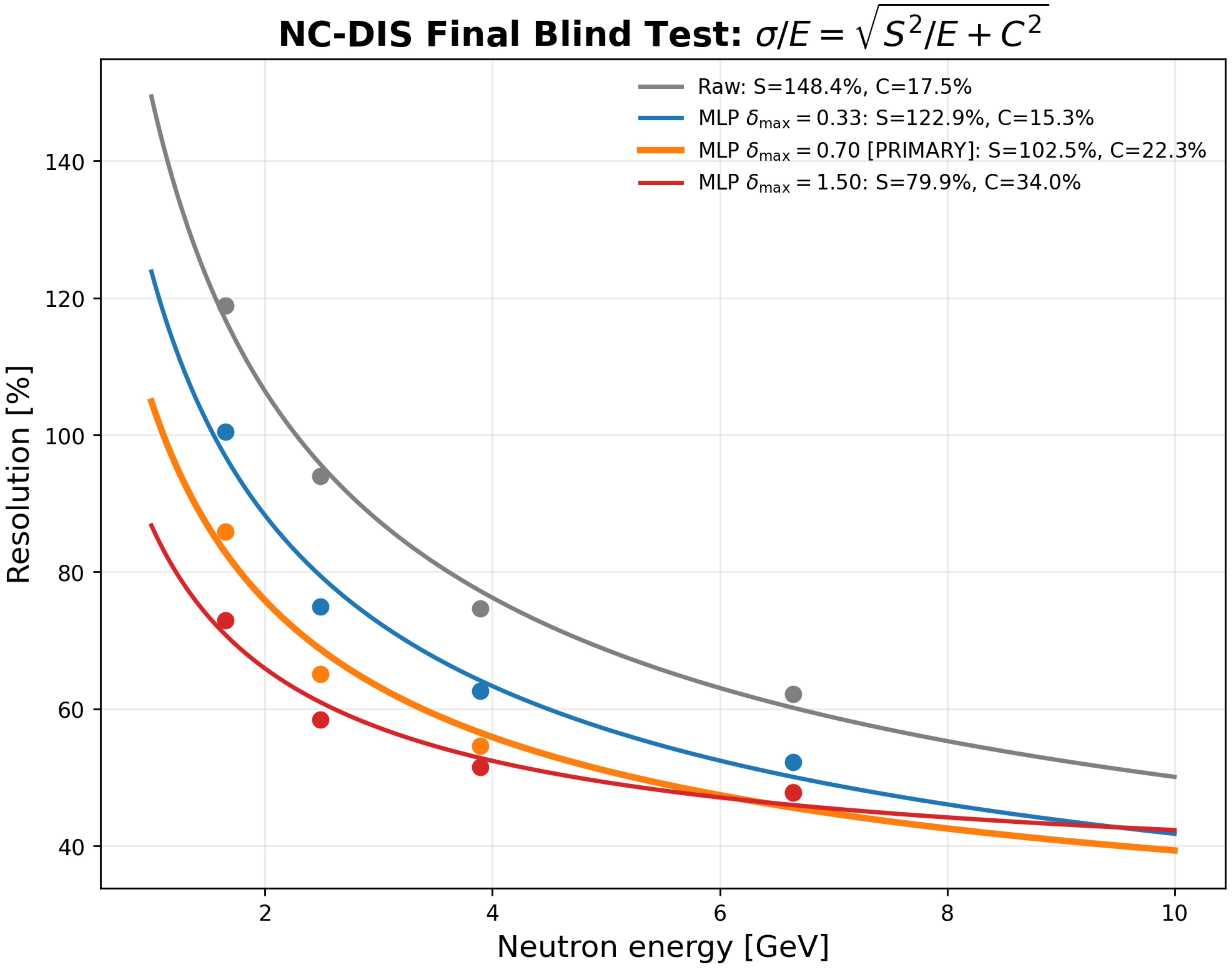
NC-DIS Blind Test Confirms the Low-Energy Behavior

- Final blind NC-DIS events are shown in four truth-energy bins: **1–2, 2–3, 3–5, and 5–10 GeV**.
- The raw reconstructed-energy distributions are very broad, with the strongest low-energy under-response in the **1–2 GeV bin**.
- Increasing the allowed MLP correction from **delta_max = 0.33 to 0.70 and 1.50** progressively moves under-responding events toward higher reconstructed energy.
- The effect of increasing the correction range is strongest at low energy and becomes much smaller in the higher-energy bins.
- **delta_max = 0.70 was selected as the primary NC-DIS model before opening the final blind sample**, so the blind result was not used for model selection.
- The blind distributions therefore confirm that the low-energy behavior observed during development persists in an independent sample

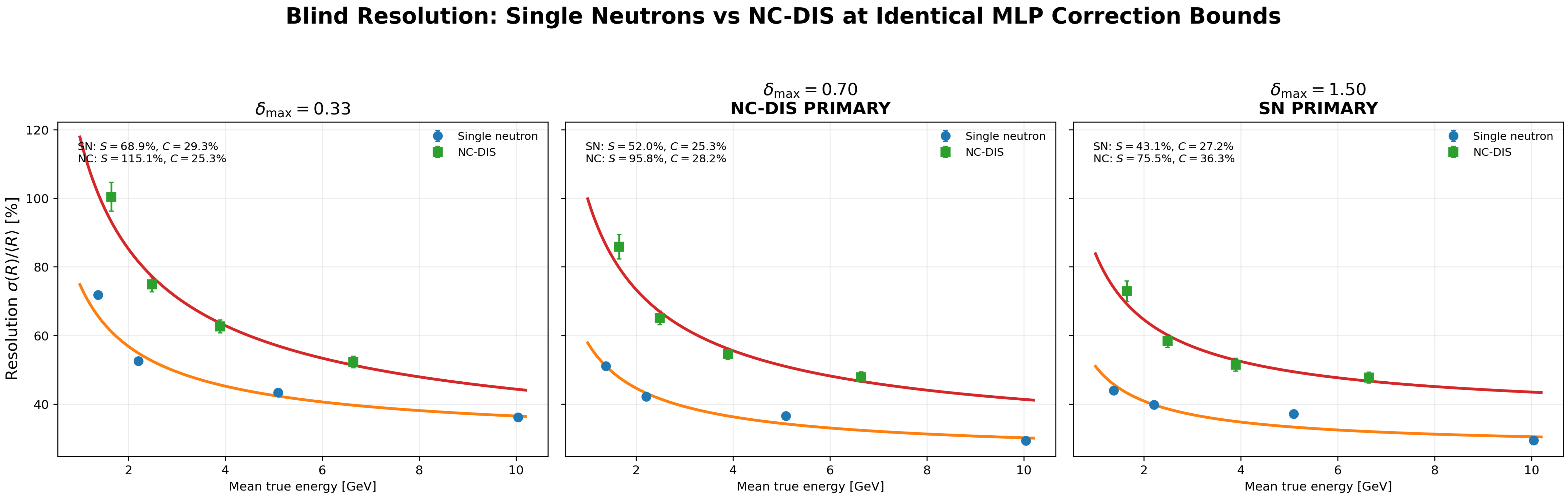


NC-DIS Resolution Improves but Remains Detector-Limited

- All MLP models improve on the raw resolution
- Increasing the correction range reduces the stochastic component
- A substantial resolution term remains even after calibration



NC-DIS Is Harder Than Isolated Neutrons at the Same MLP Bound



- This comparison uses the **same MLP correction bound in both samples**, so the difference mainly reflects the event environment rather than a different allowed correction range.

For **delta_max = 0.33**, the stochastic term is about **68.9% for single neutrons** and **115.1% for NC-DIS**.
For **delta_max = 0.70**, it improves to about **52.0% for single neutrons** and **95.8% for NC-DIS**.
For **delta_max = 1.50**, it further improves to about **43.1% for single neutrons** and **75.5% for NC-DIS**.

- Increasing `delta_max` therefore improves the stochastic resolution in **both** samples, especially at low energy.

However, at every identical correction bound, **NC-DIS remains substantially broader than the isolated single-neutron sample**.
This shows that the poor NC-DIS resolution is **not explained only by the MLP correction limit**; additional fluctuations from the realistic DIS environment also contribute.

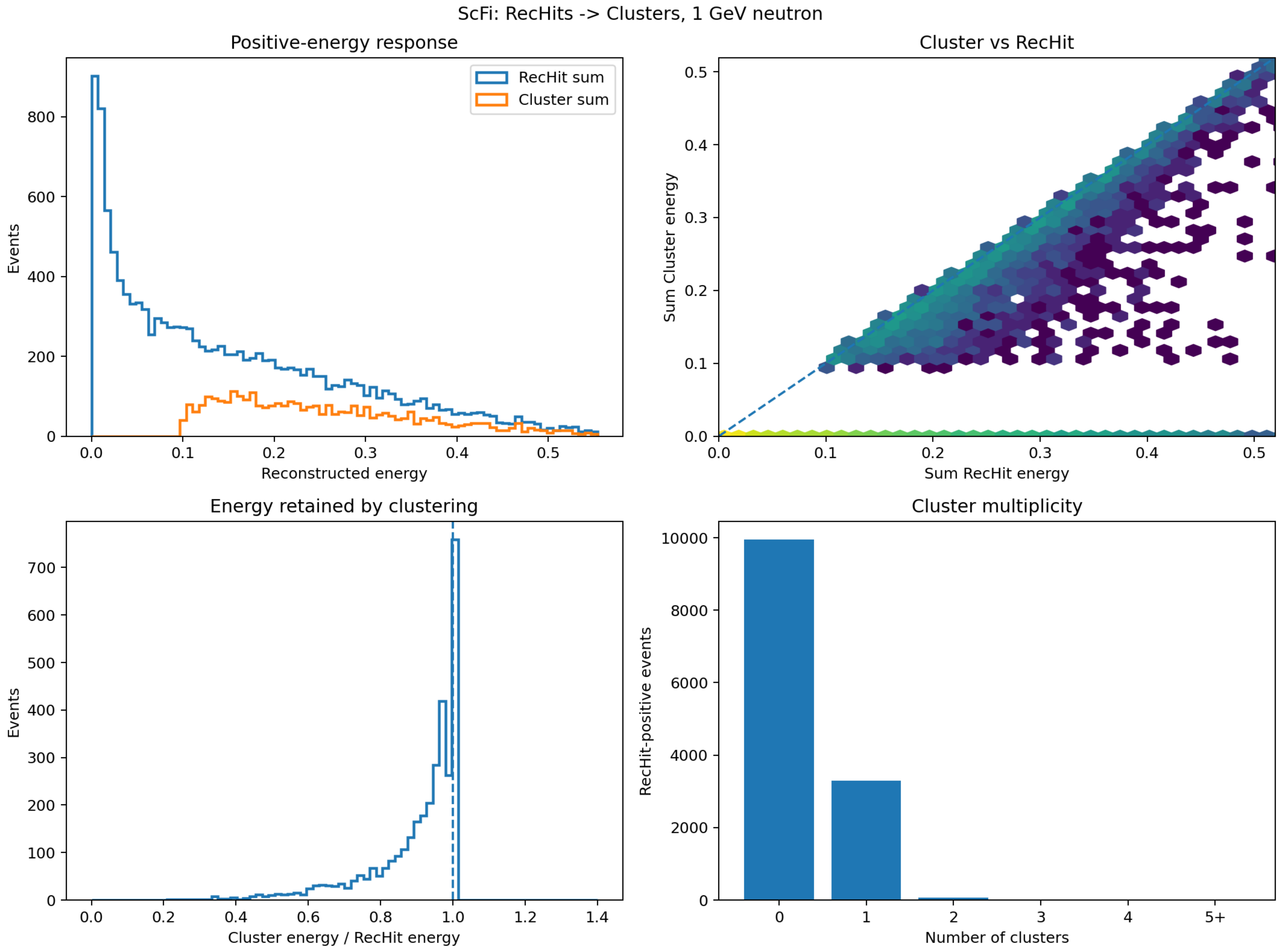
Note: The correction bound explains part of the low-energy problem, but it does not explain the full NC-DIS resolution yet.

Single neutron simulation for bHCAL

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

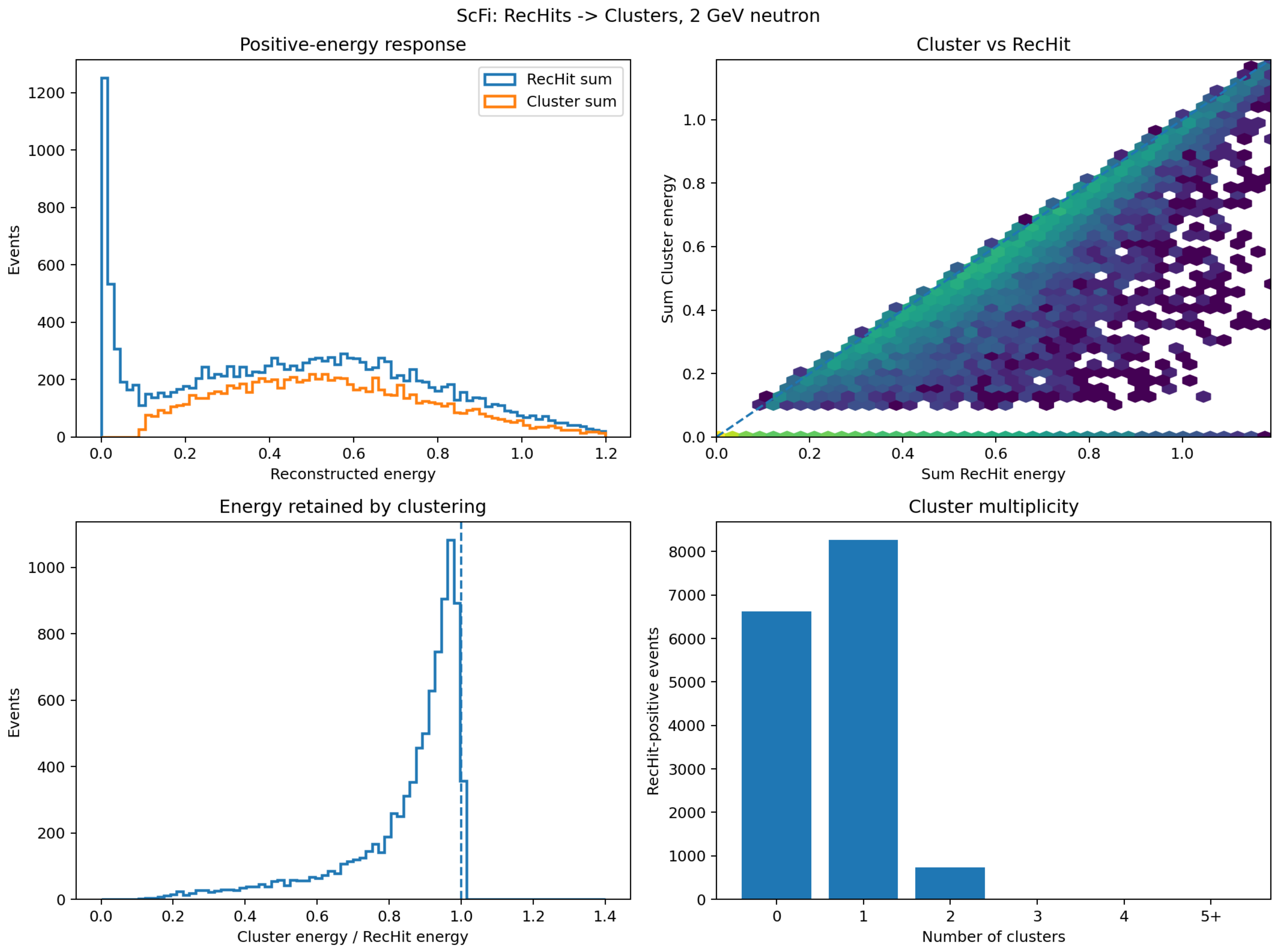
ScFi Clustering at 1 GeV

- Many 1 GeV events have very small ScFi deposits
- A large fraction forms zero or only one cluster
  - Low-energy ScFi information is therefore limited



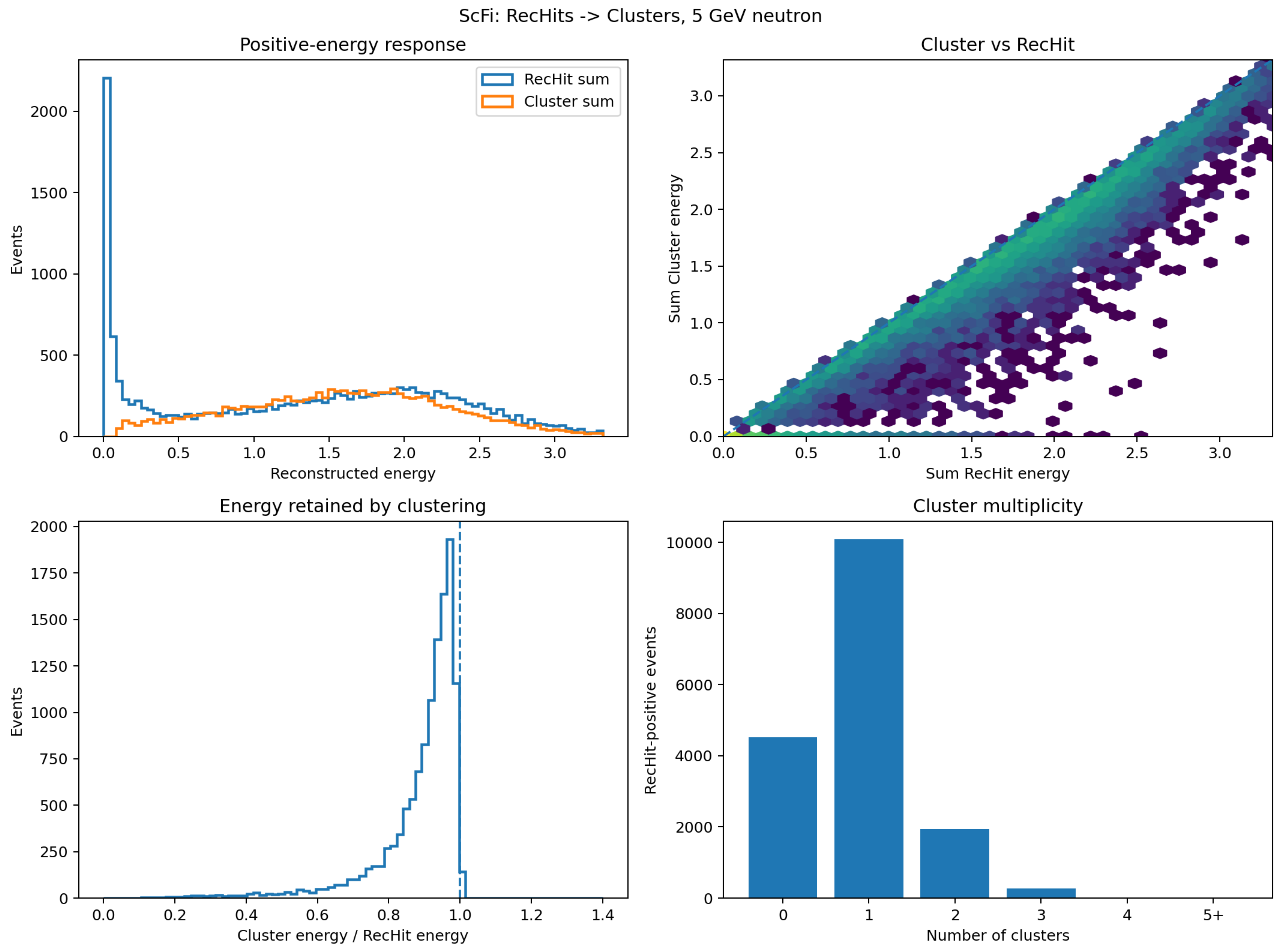
ScFi Clustering at 2 GeV

- More ScFi activity appears at 2 GeV
  - Cluster formation becomes more efficient
  - Some low-energy deposits are still not retained in clusters



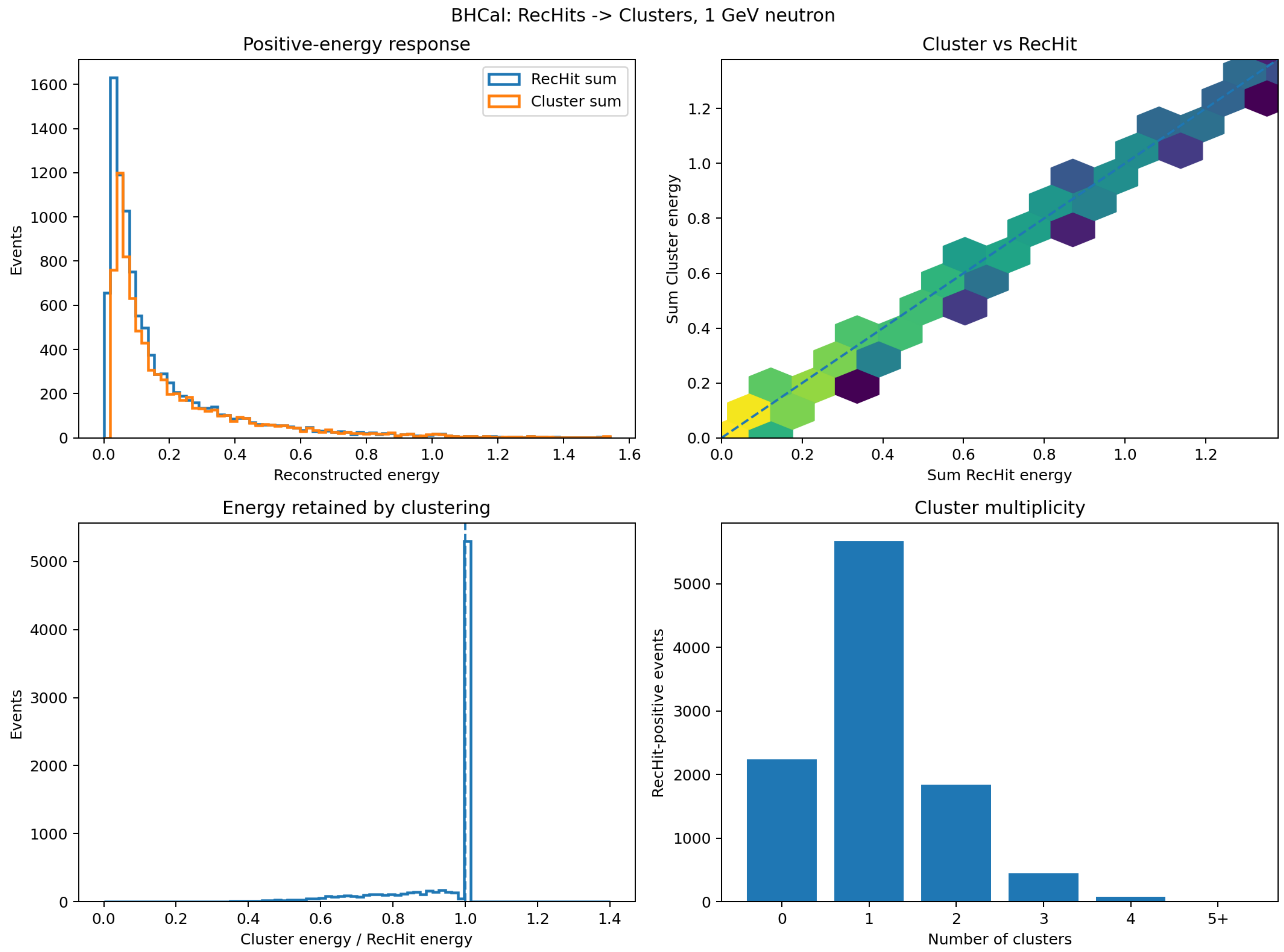
ScFi Clustering Improves at Higher Energy

• Higher-energy showers produce more usable ScFi signal
• Cluster energy follows RecHit energy more closely
• This explains why reconstruction becomes easier with energy



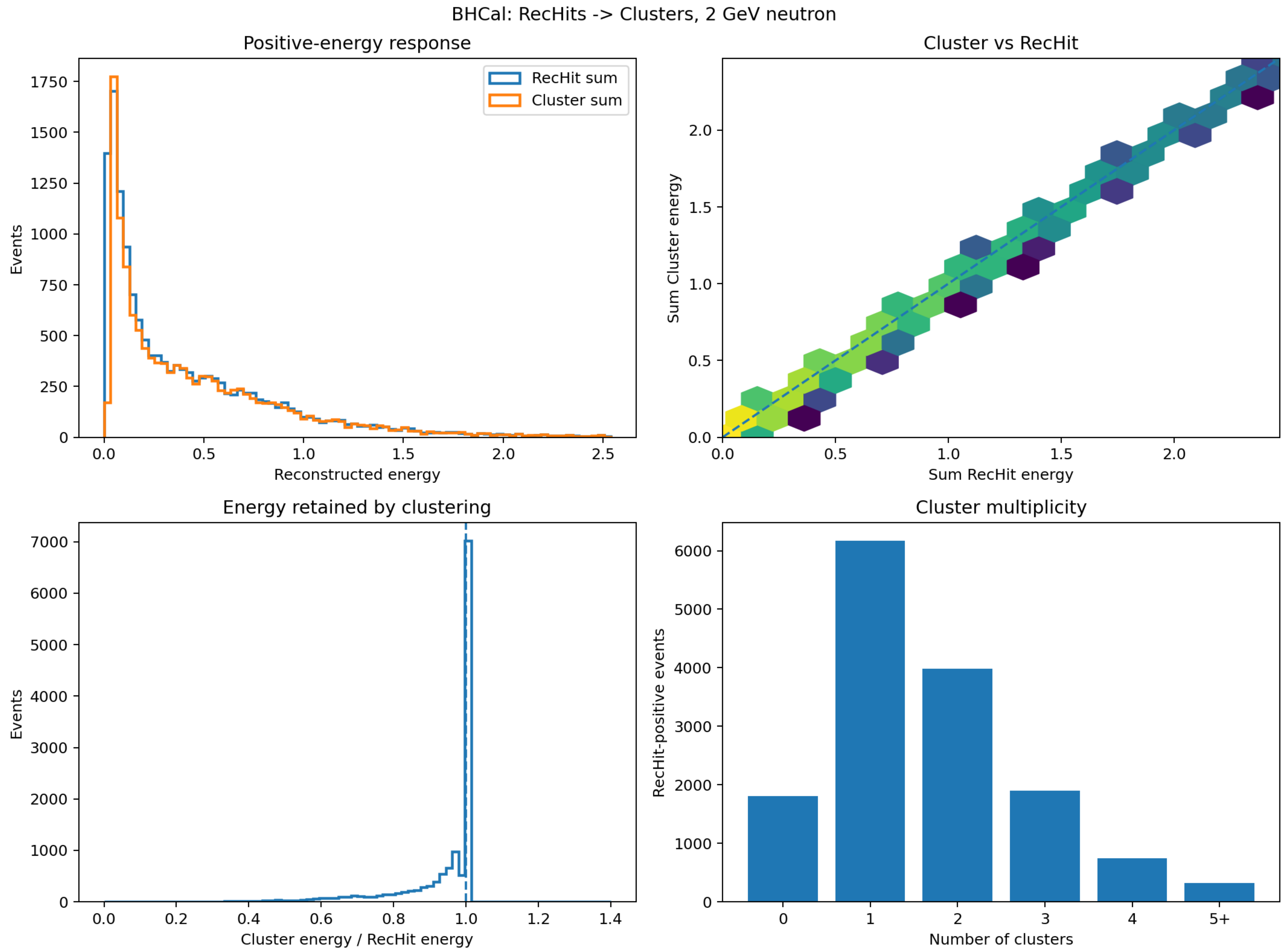
BHCal Clustering at 1 GeV

- BHCal provides the dominant information at low energy
- Most responding events form only a small number of clusters
  - Sparse showers remain the main limitation



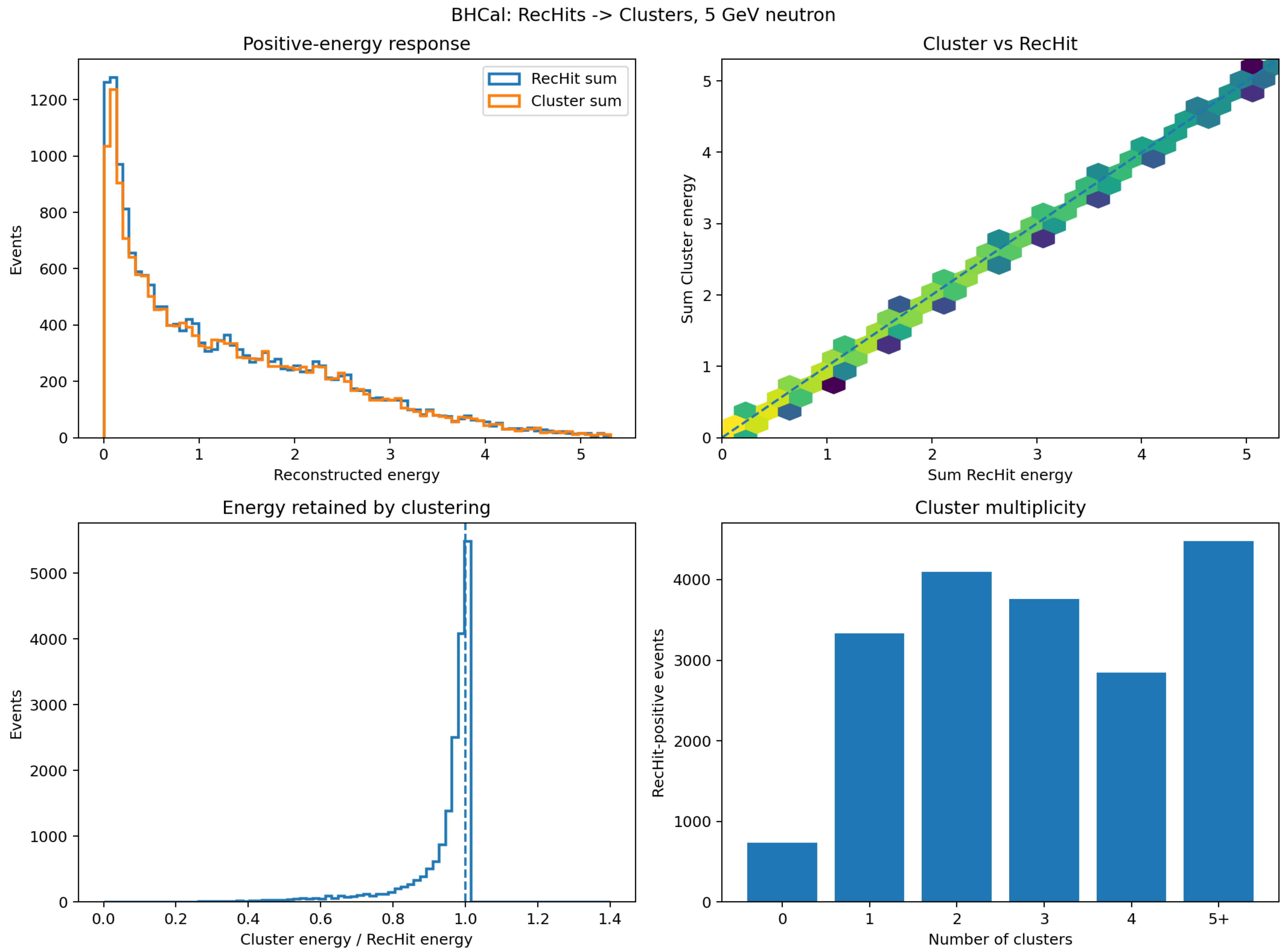
BHCal Clustering at 2 GeV

- Cluster energy follows the RecHit energy more closely
- Shower multiplicity begins to increase
- Reconstruction becomes more stable than at 1 GeV

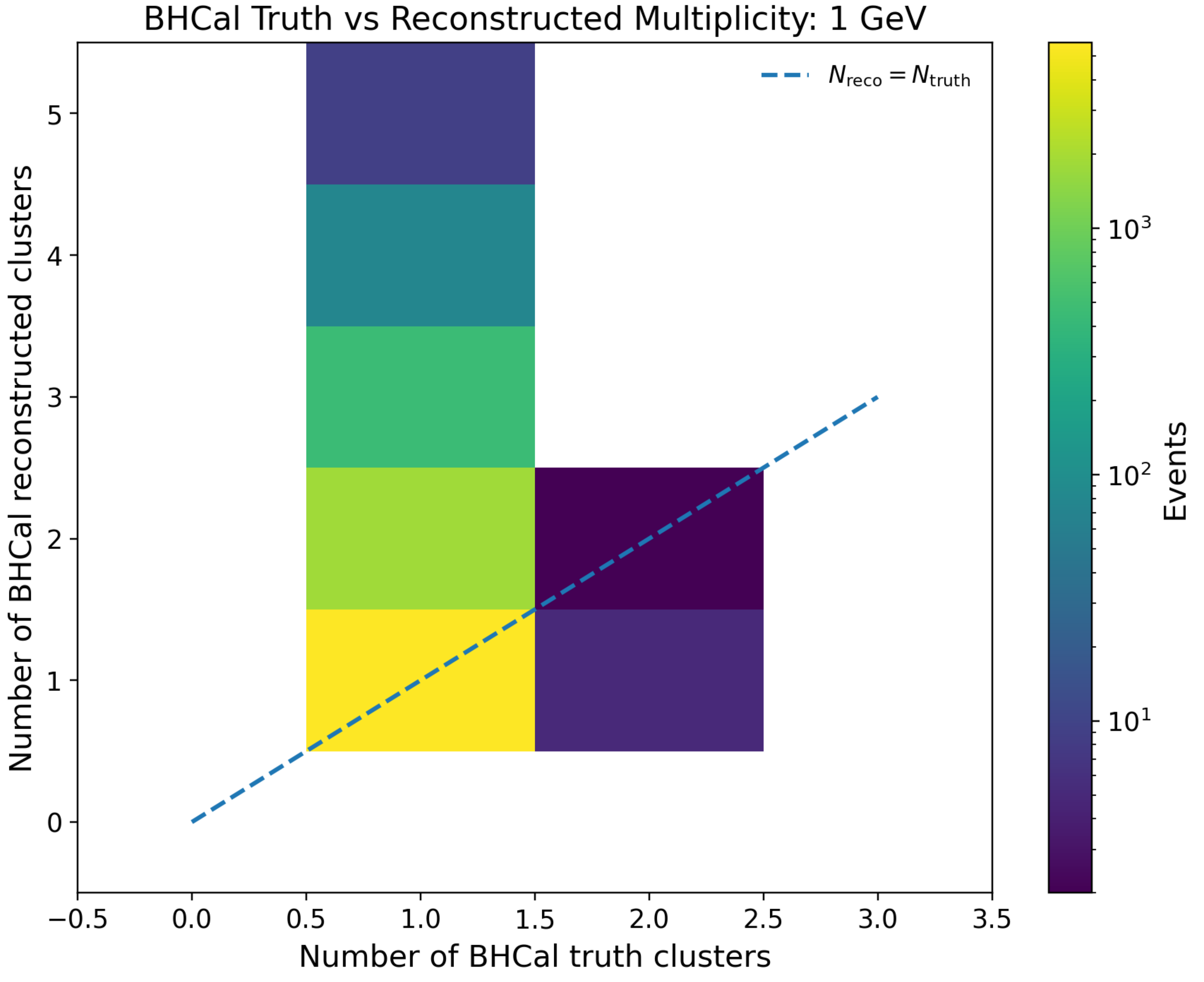


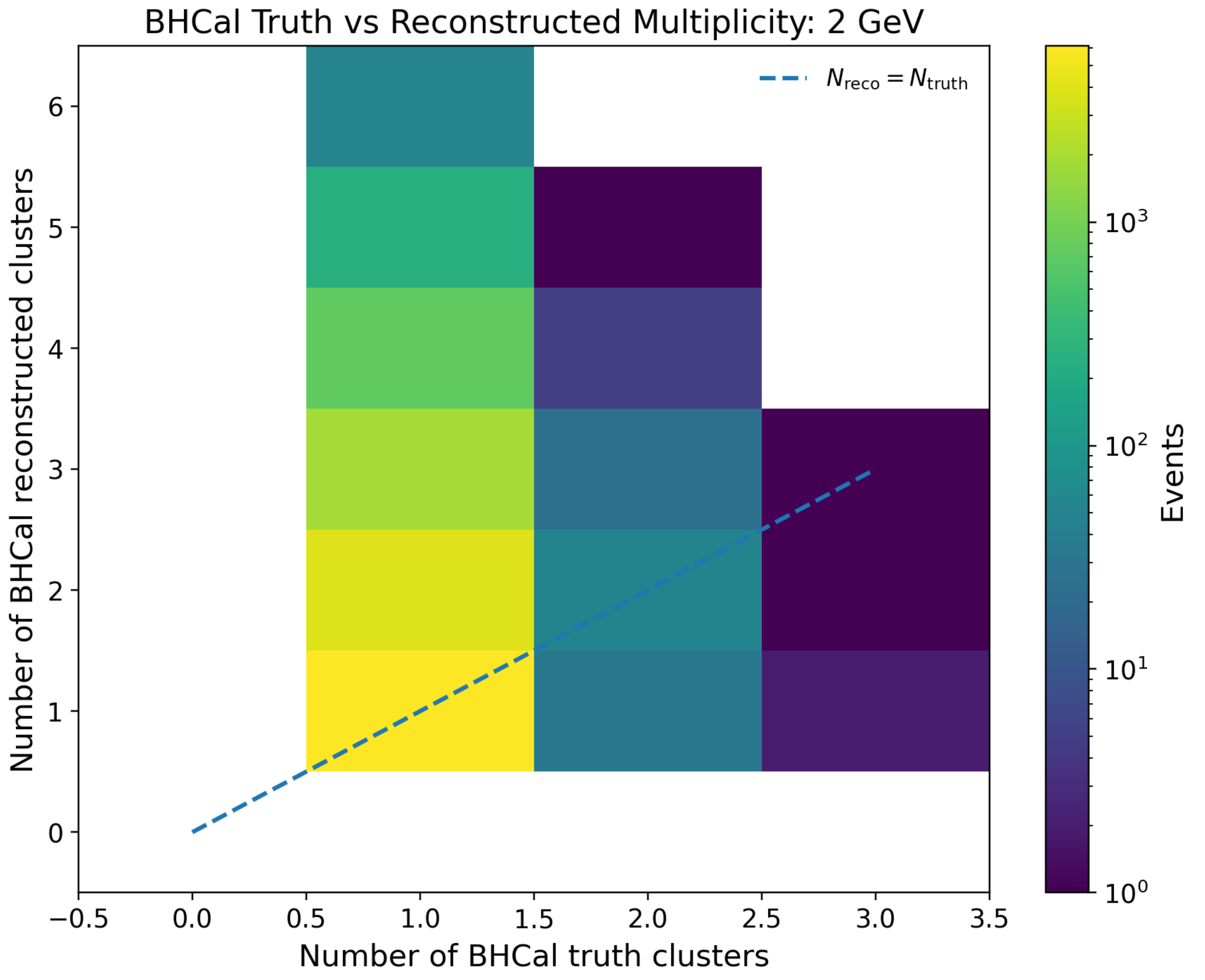
BHCal Clustering at Higher Energy

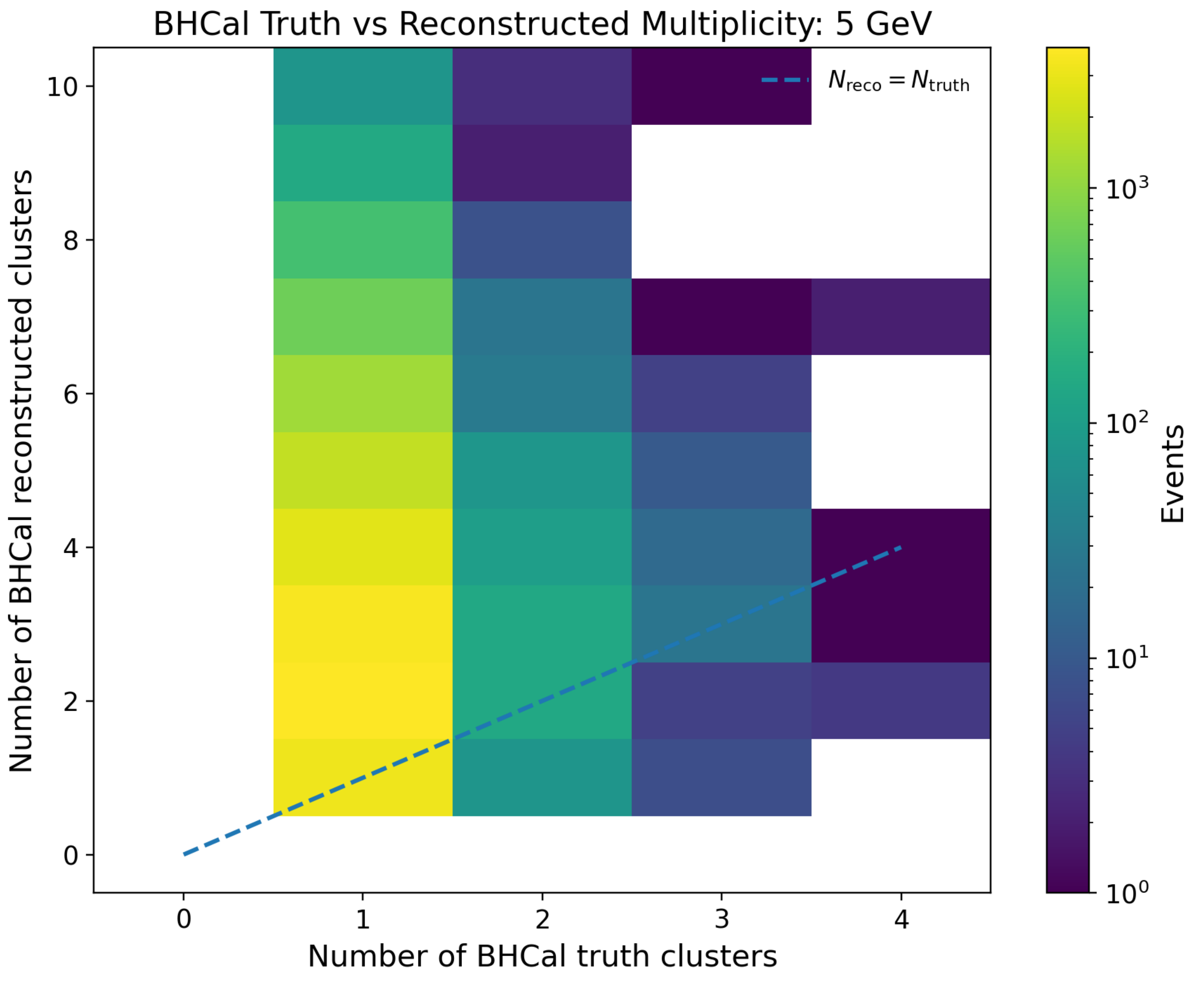
- More developed hadronic showers are reconstructed
  - RecHit and cluster energies show stronger correlation
- Richer shower information improves calibration performance



BHCal Truth vs Reconstructed Cluster Multiplicity

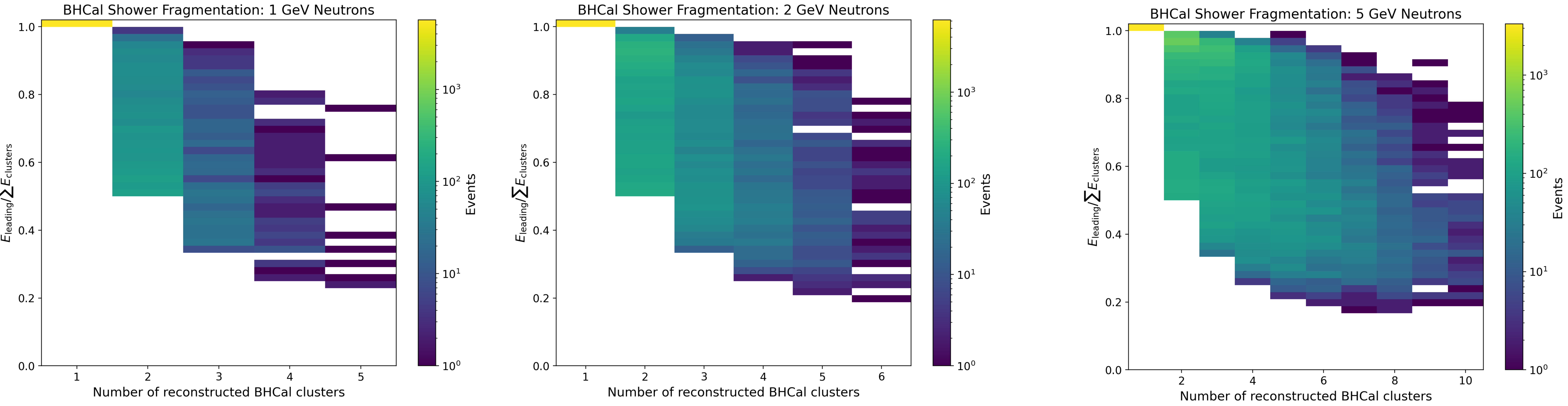






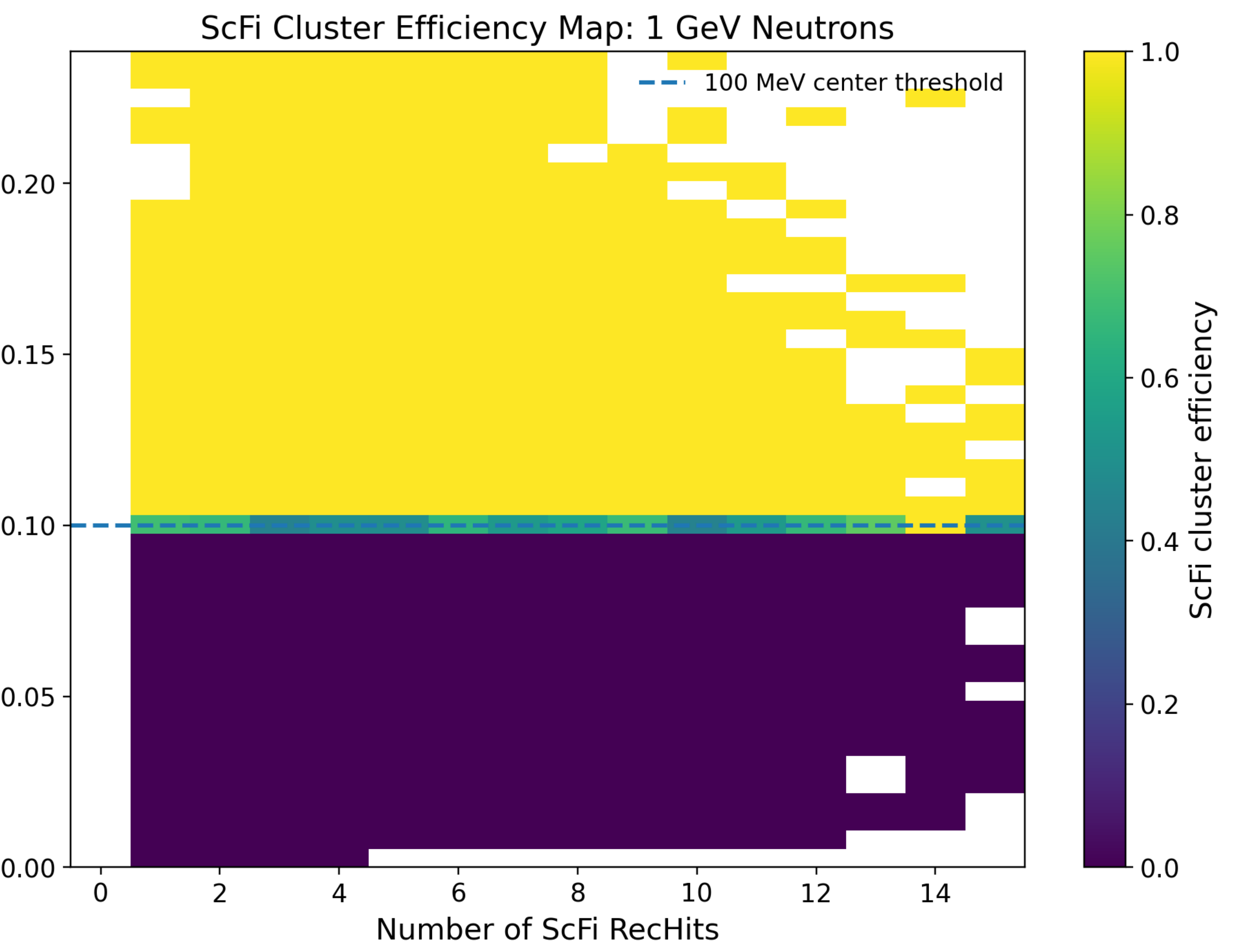
- The dashed line shows the ideal case: **number of reconstructed clusters = number of truth clusters**.
- Many events lie **above the diagonal**, meaning one truth shower is reconstructed as several BHCal clusters.
- This cluster splitting is already visible at 1 GeV and becomes broader as neutron energy increases.
- Therefore, reconstructed cluster multiplicity is not a direct one-to-one measure of the underlying truth shower multiplicity.

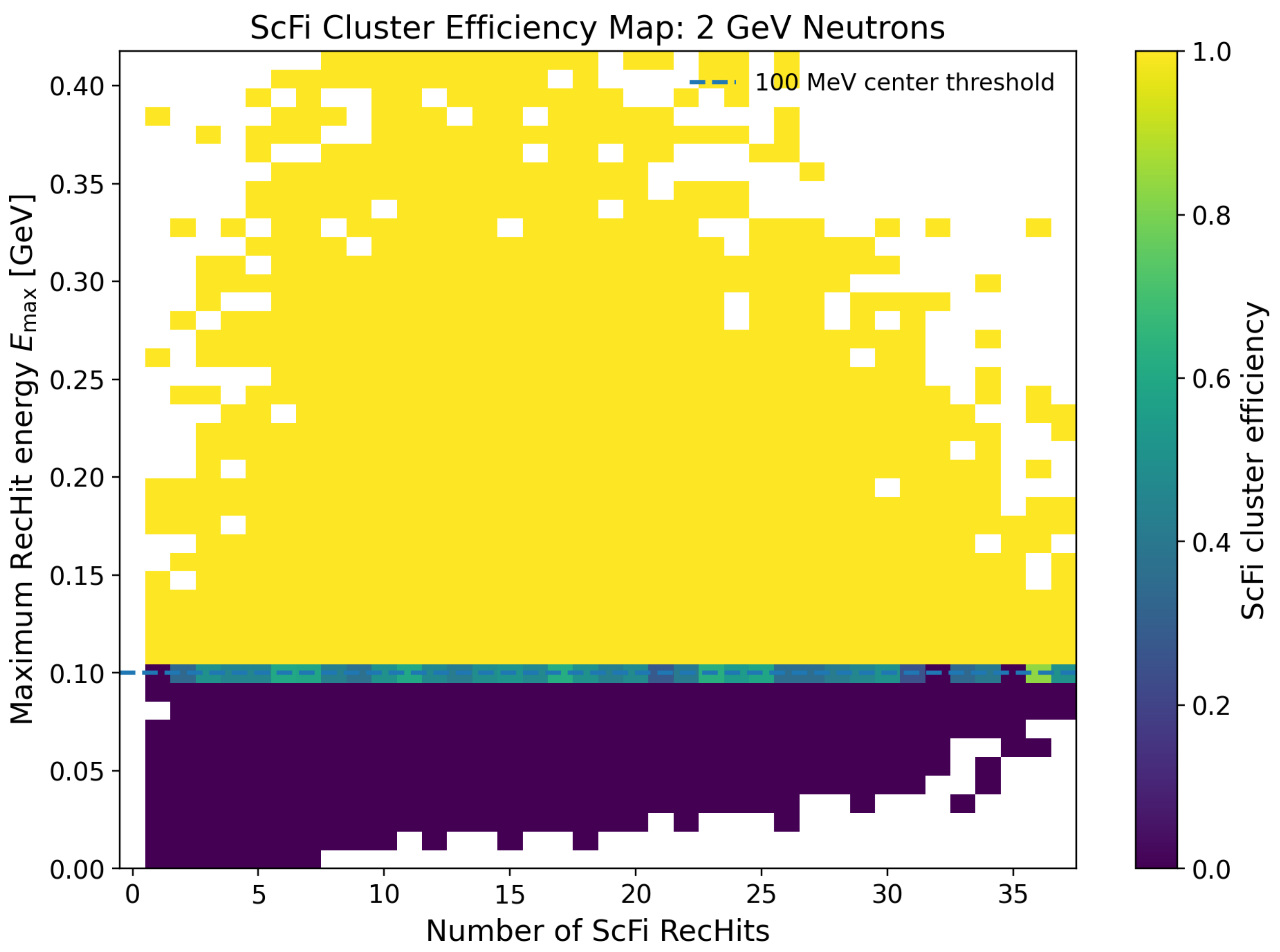
BHCal Shower Energy Becomes More Fragmented at Higher Multiplicity

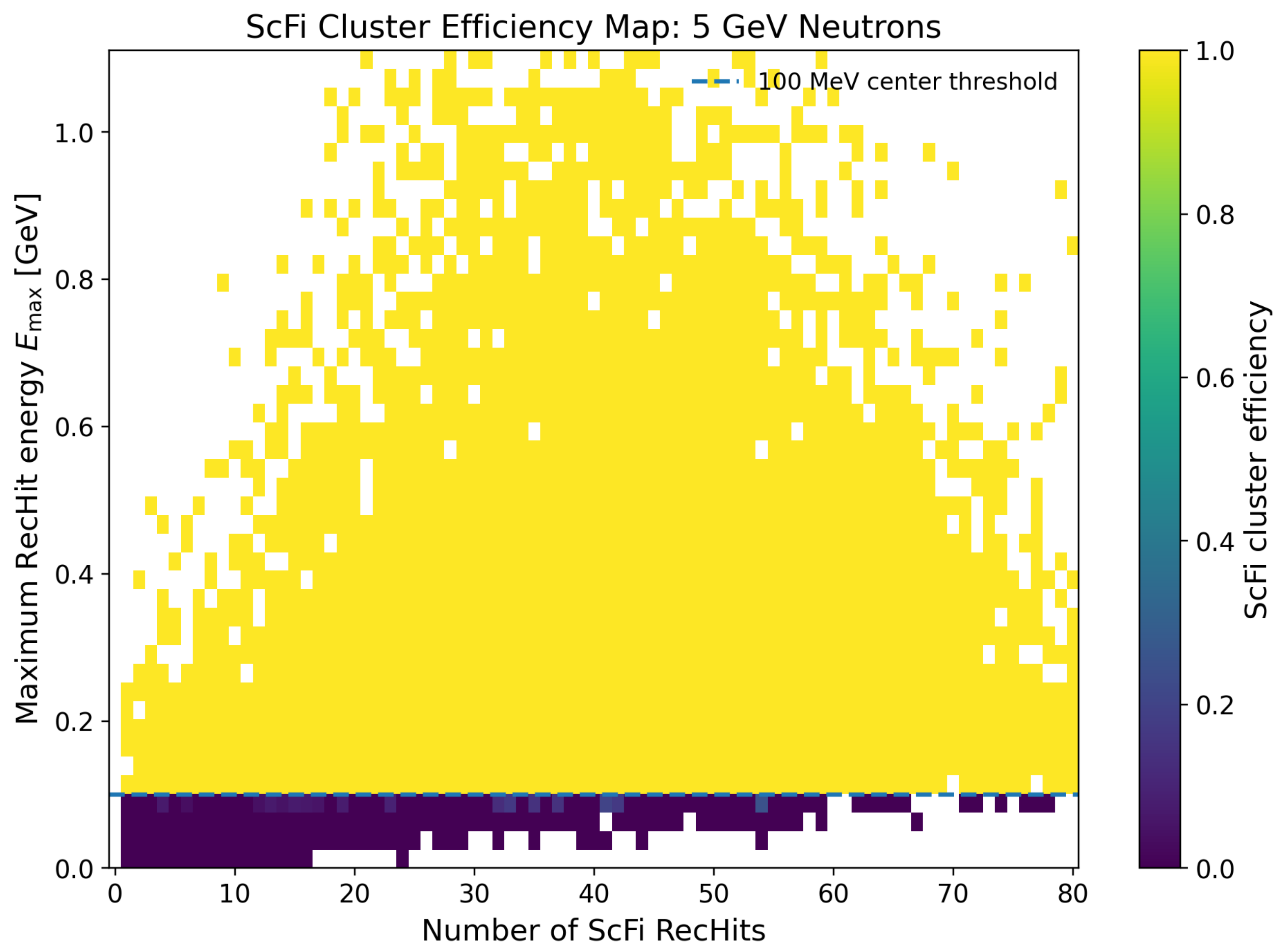


- With one reconstructed cluster, the leading cluster contains essentially **all of the shower energy**.
- As cluster multiplicity increases, the leading-cluster energy fraction decreases.
- The remaining energy is therefore distributed among additional reconstructed clusters.
- Higher-energy neutrons populate larger cluster multiplicities and show more developed shower fragmentation.
- Using only the leading BHCal cluster can therefore miss part of the reconstructed neutron energy.

ScFi Cluster Formation Is Controlled by the 100 MeV Seed Threshold

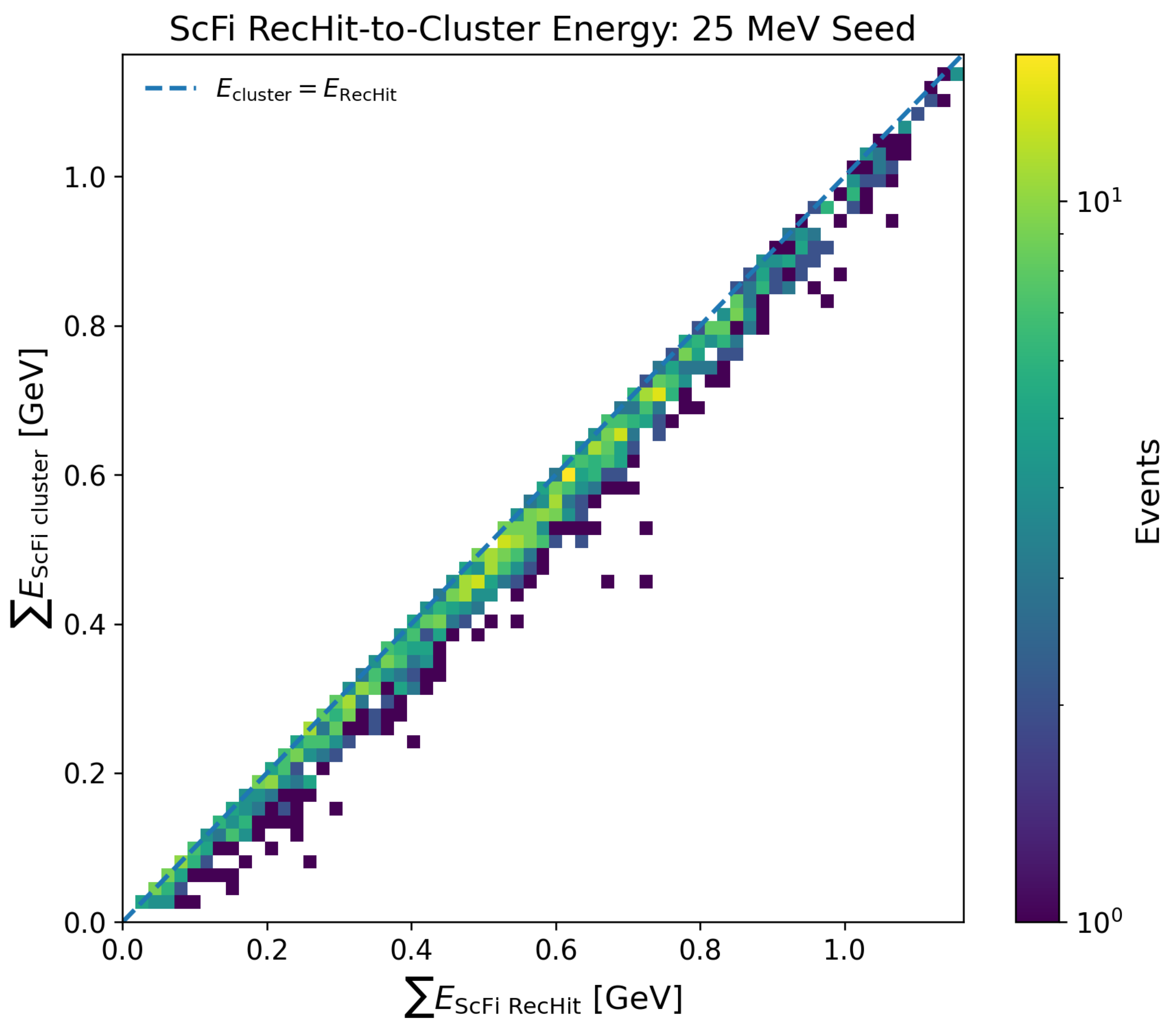


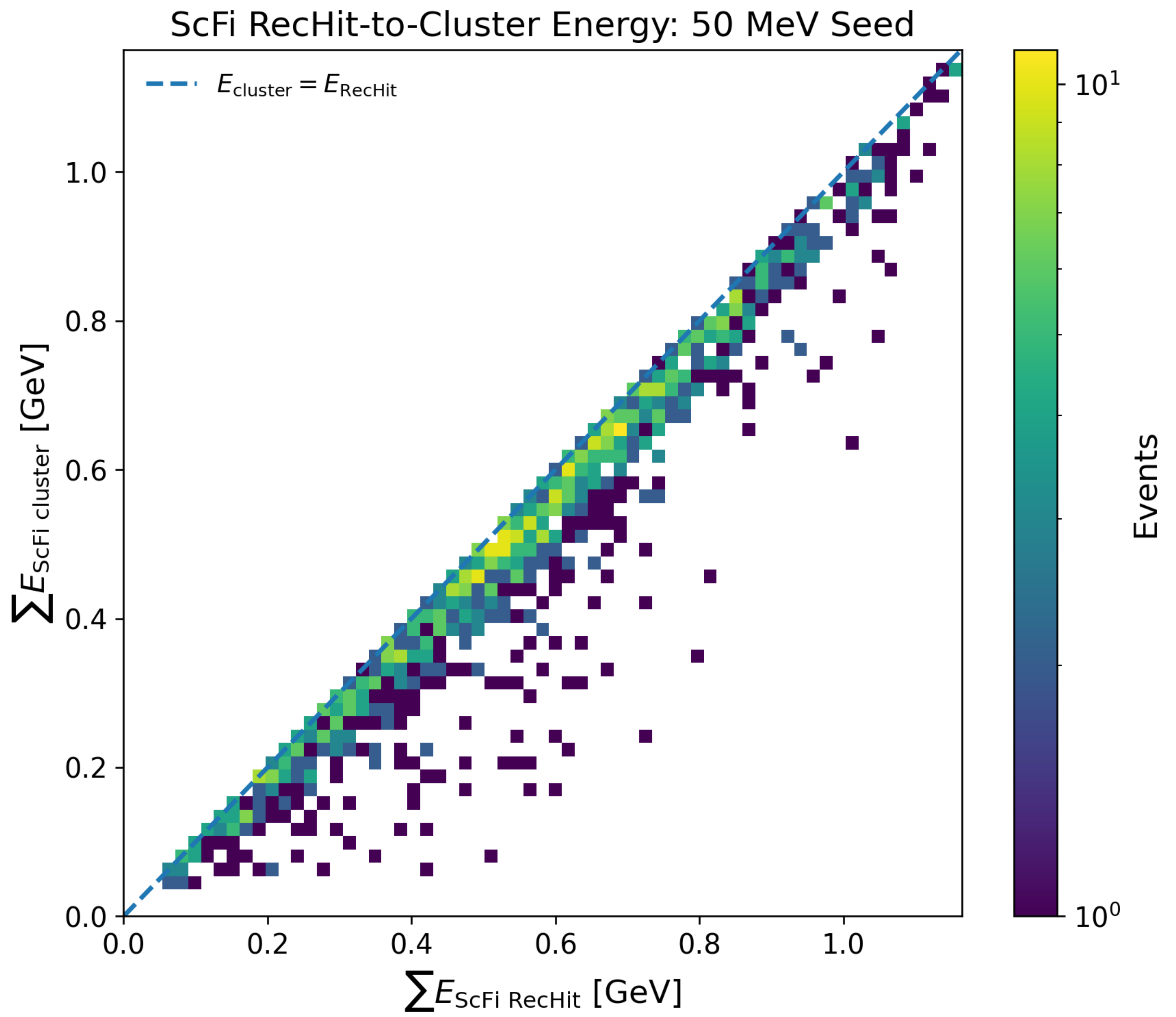


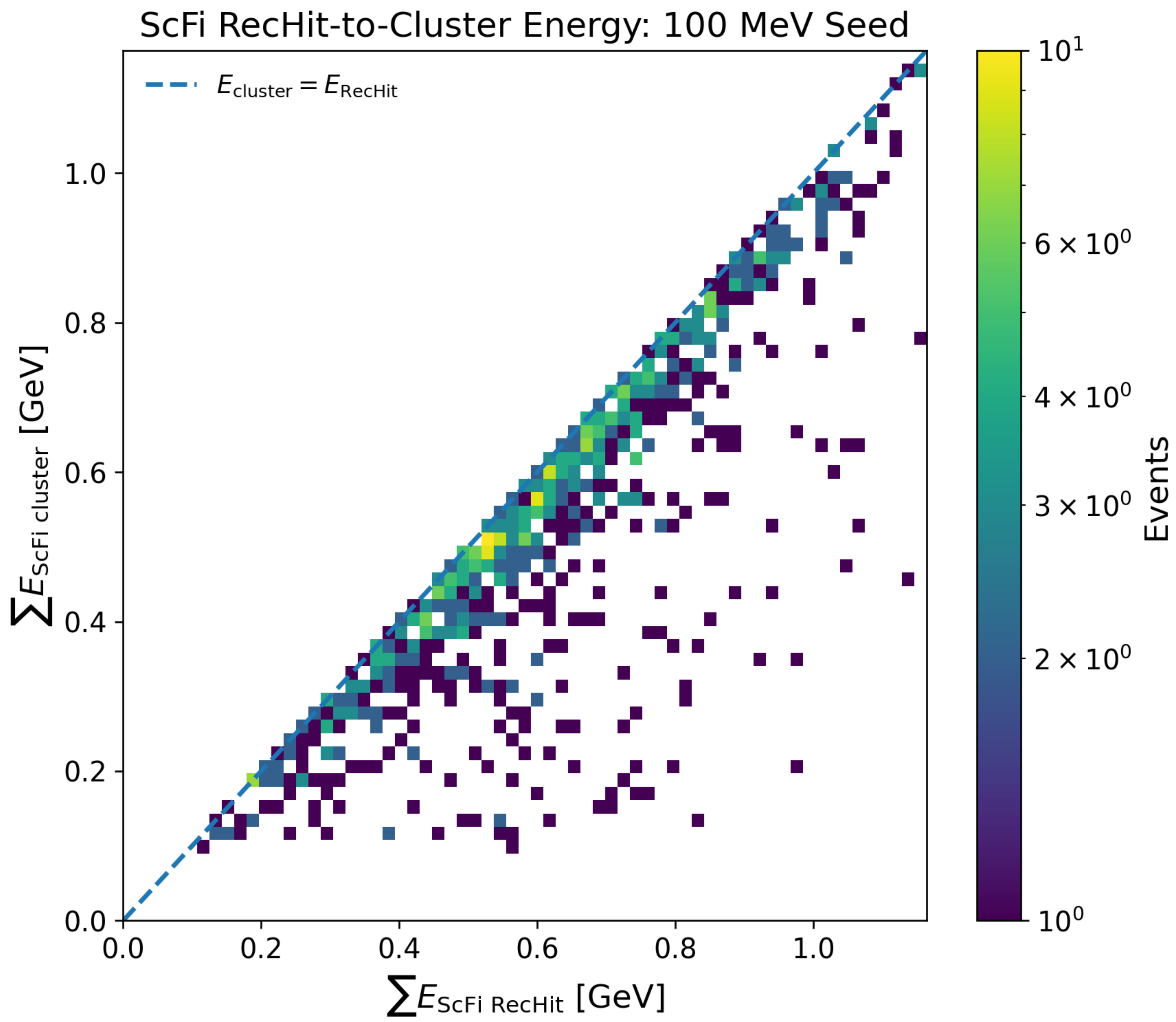


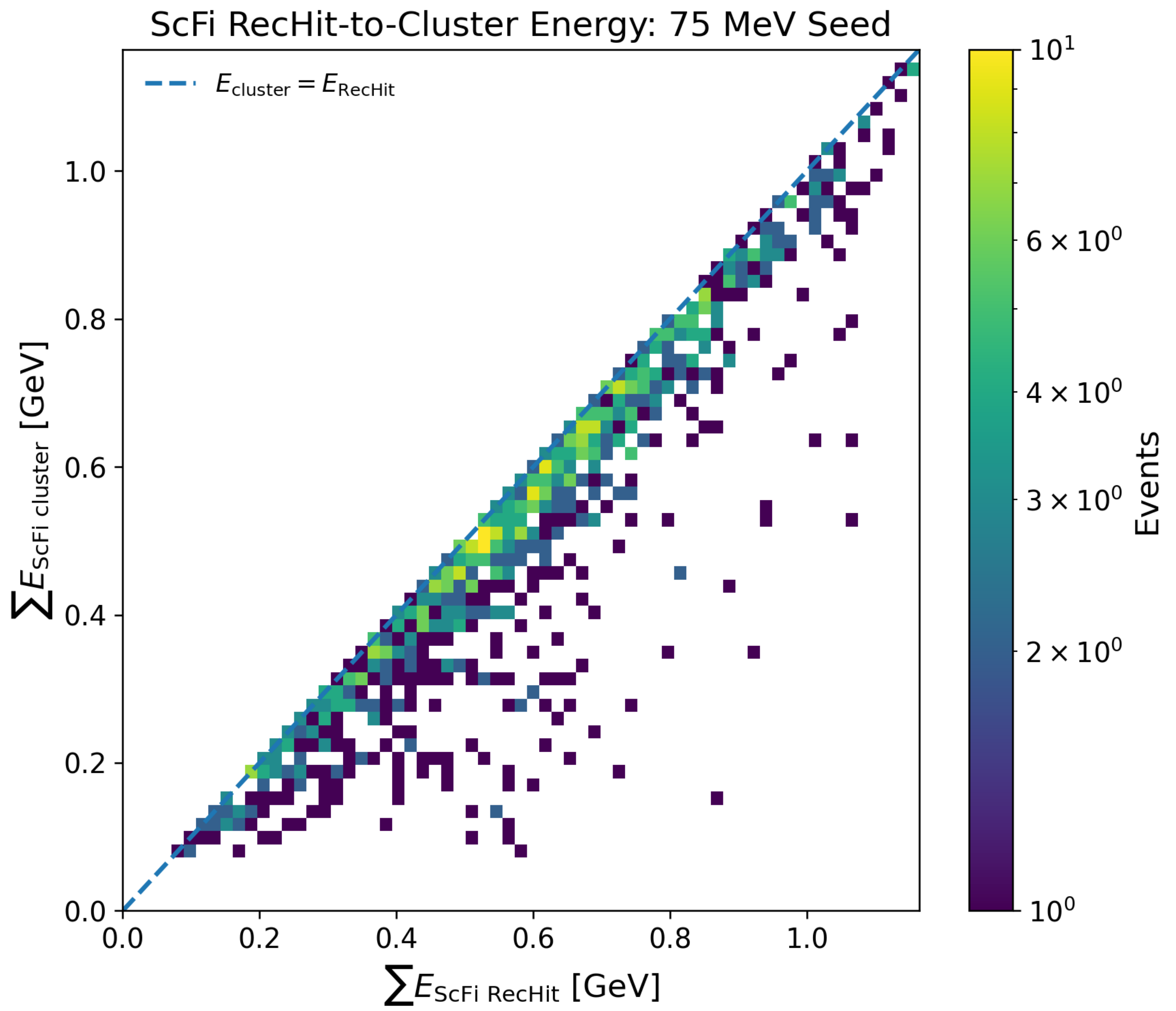
- The horizontal axis is the **number of ScFi RecHits**, while the vertical axis is the **largest RecHit energy** in the shower.
- The dashed line marks the **100 MeV cluster-center threshold**.
- Below this threshold, ScFi cluster efficiency is nearly zero even when several RecHits are present.
- Once at least one RecHit exceeds 100 MeV, the cluster efficiency becomes nearly 100%.
- Low-energy neutrons are most affected because many of their ScFi deposits remain below this threshold.

ScFi Cluster Energy Depends on the Seed Threshold



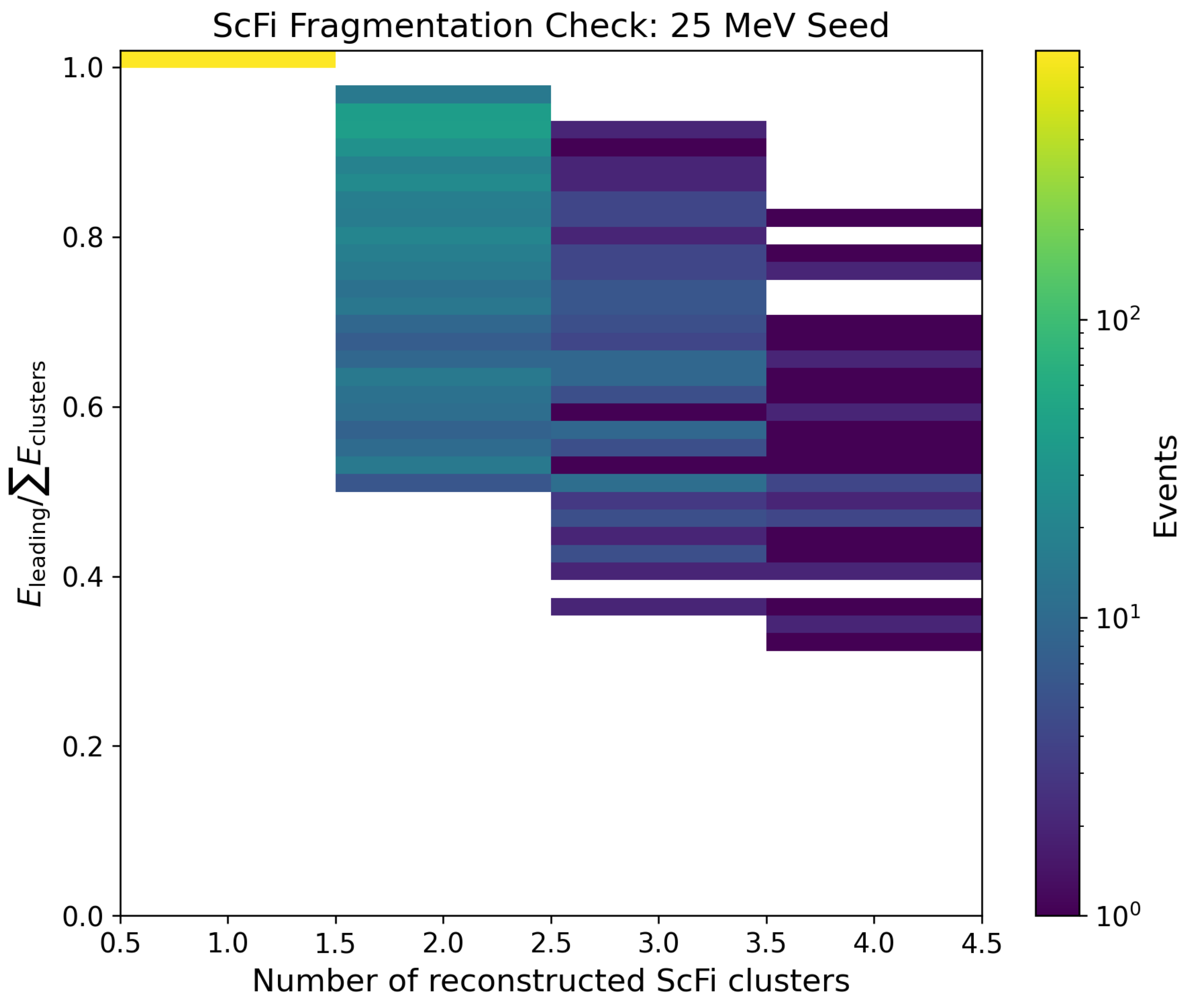


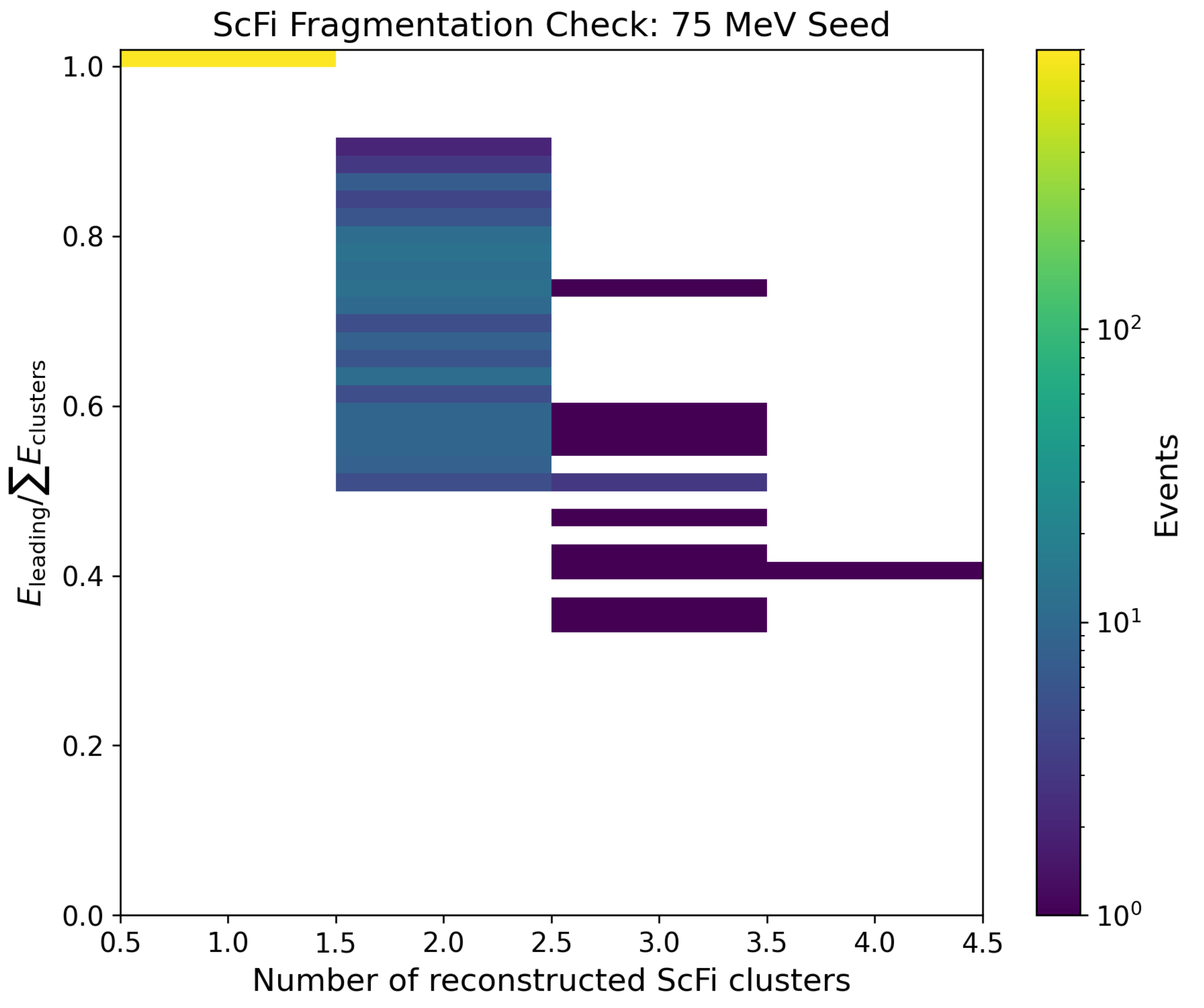




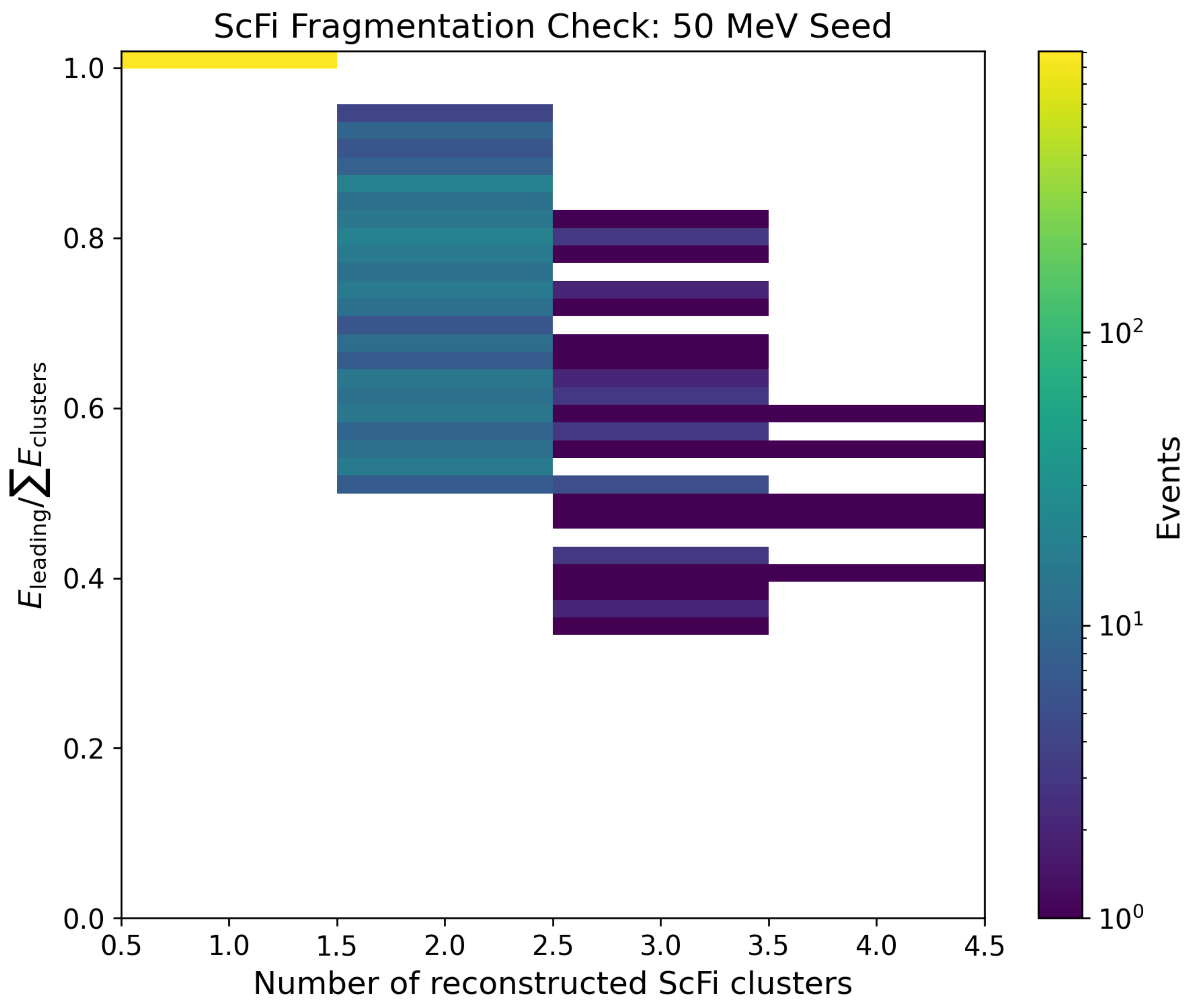
- Seed threshold changes how much RecHit energy enters clusters
  - Higher thresholds can lose small energy deposits
- This effect is important for low-energy neutrons

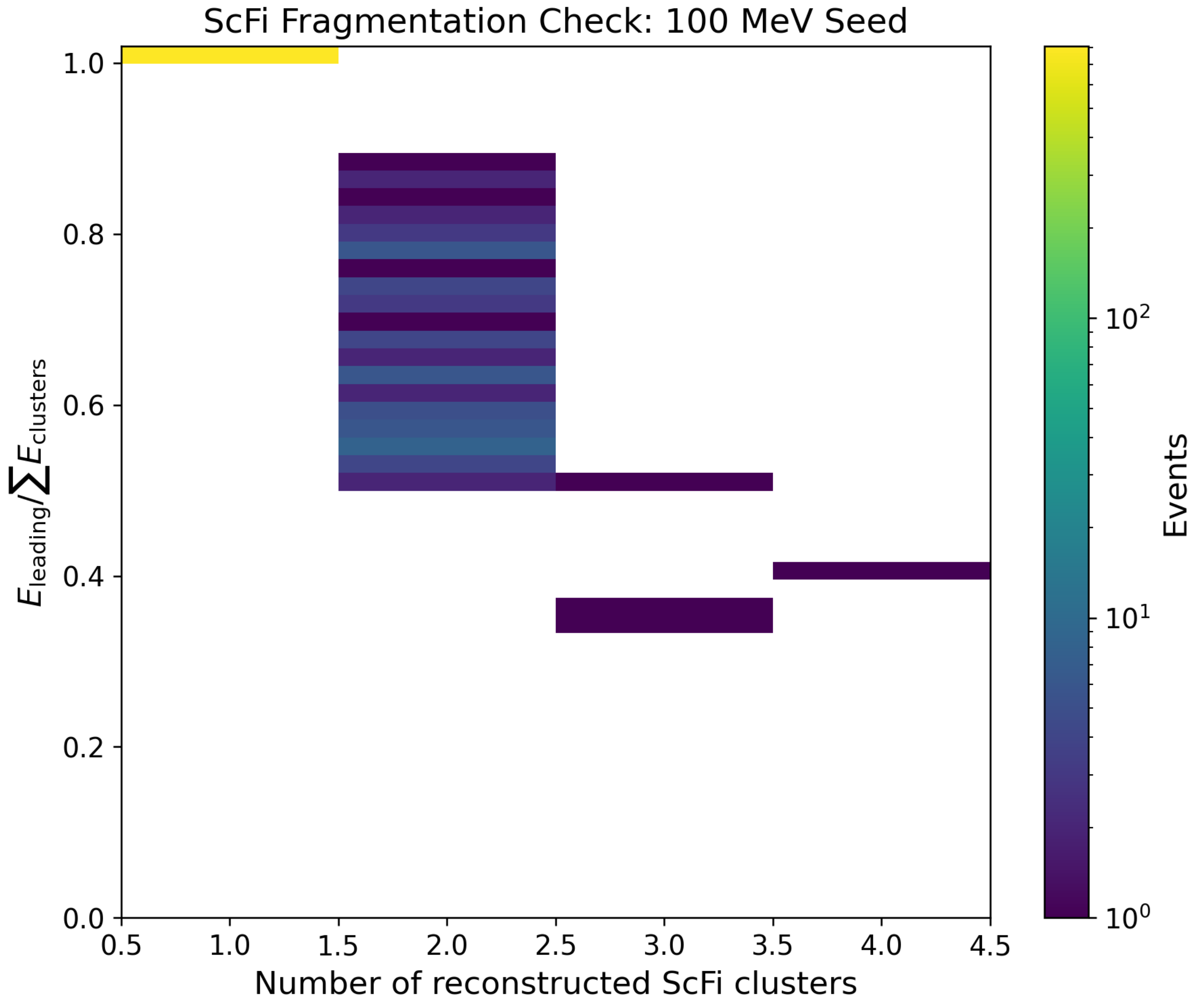
ScFi Seed Threshold Controls Energy Recovery and Fragmentation





- Lower thresholds recover more small deposits
- They can also produce additional cluster fragmentation
- An optimized threshold must balance both effects





Summary

• The 1–2 GeV low-response population originates in the calorimeter response, not in the MLP.

• Removing cuts or topology features does not eliminate the structure.

• The original MLP correction bound was too restrictive for strongly under-responding events.

• Relaxing the bound improves resolution, while NC-DIS remains still broader because of the realistic event environment.

Thank you for your attention!!!