Weekly Update

June 27, 2025

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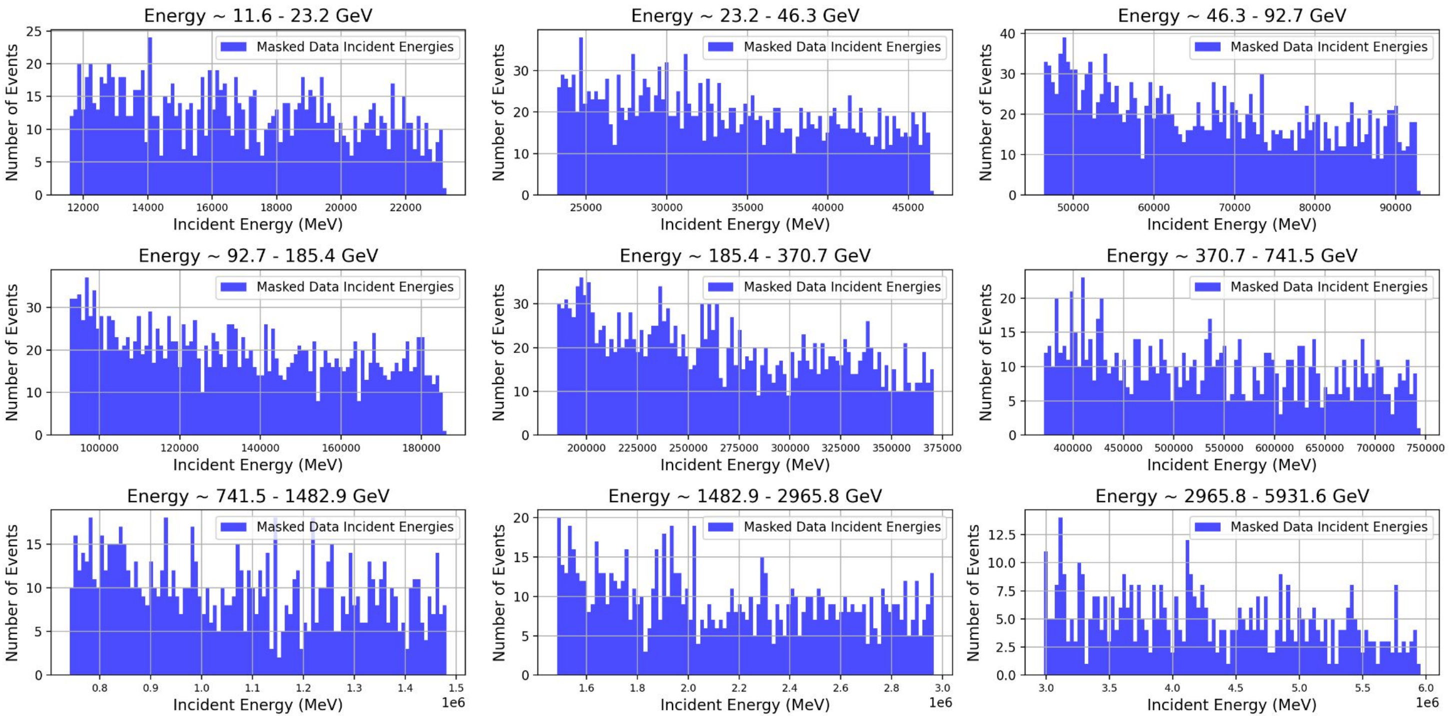
Science Week Abstract

The search for new physics and precision studies of the Higgs boson during the High-Luminosity Large Hadron Collider (HL-LHC) run will require fast and accurate particle-detector simulations. Traditional simulation methods are computationally intensive, with estimates reaching millions of CPU-years annually. To address this, we developed a quantum-assisted deep generative model that integrates quantum simulations with deep learning techniques. Our framework employs a variational autoencoder with a conditioned Restricted Boltzmann Machine (RBM) in the latent space, enabling sampling from D-Wave's Zephyr quantum annealer. This design enhances the modeling capacity of the latent space and allows for realistic, energy-conditioned electromagnetic shower generation. The model is trained on high-granularity ATLAS electromagnetic calorimeter datasets to generate energy-conditioned shower simulations. We validate the performance of our framework using metrics such as sparsity index, energy ratio, and deposited energy distributions, demonstrating promising agreement with ground-truth simulations. This approach achieves speed-ups of three to six orders of magnitude over traditional Geant4 simulations while preserving high fidelity, making it a powerful tool for simulation in high-energy physics.

Smearing Irregularities Fixed

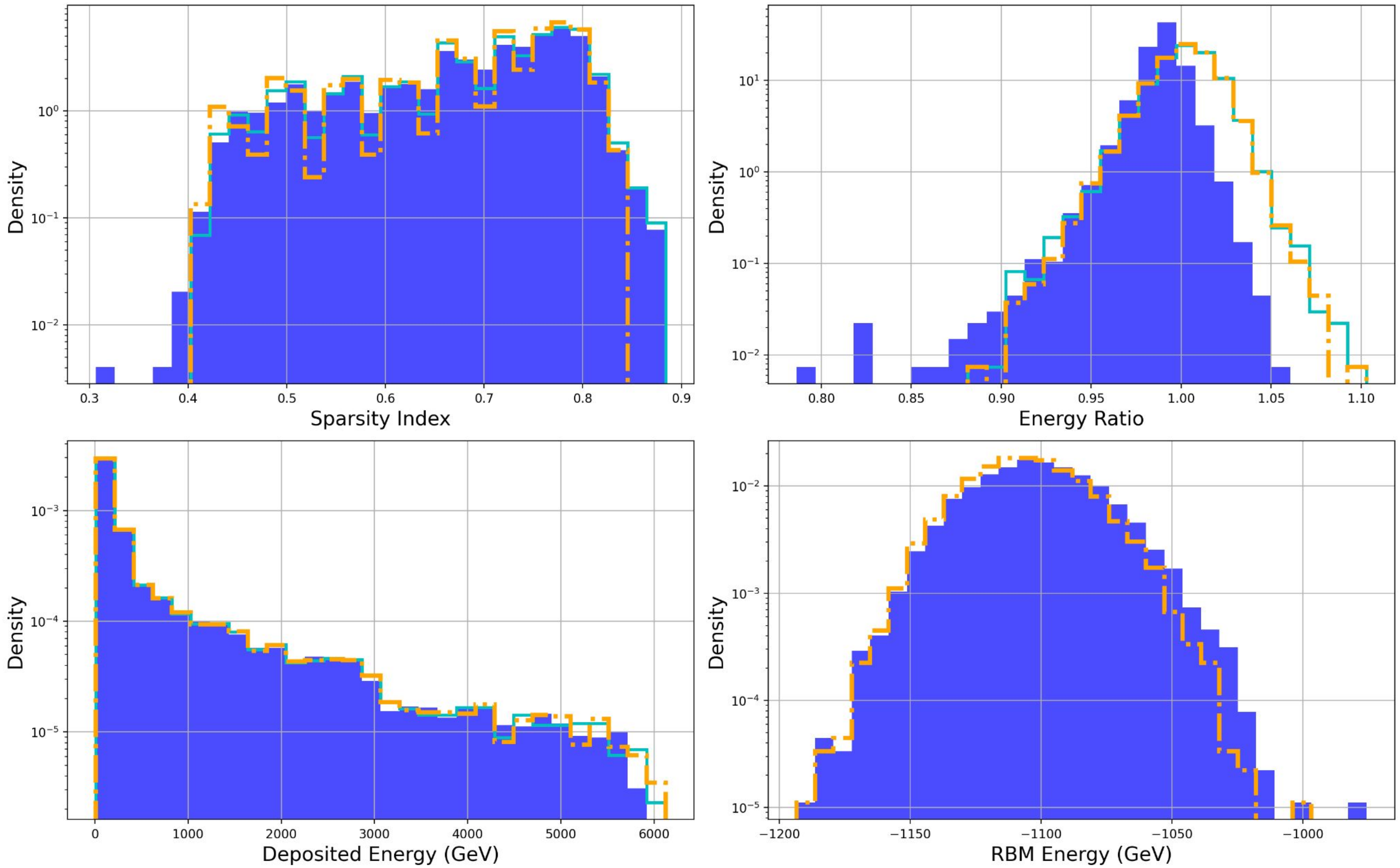
```
noise = torch.empty_like(incident_energies).uniform_(-0.5, 0.5)
perturbed_energies = 2**(torch.log2(incident_energies) + noise)
scale = perturbed_energies/incident_energies
```

- Fixed mistake with base e versus base 2

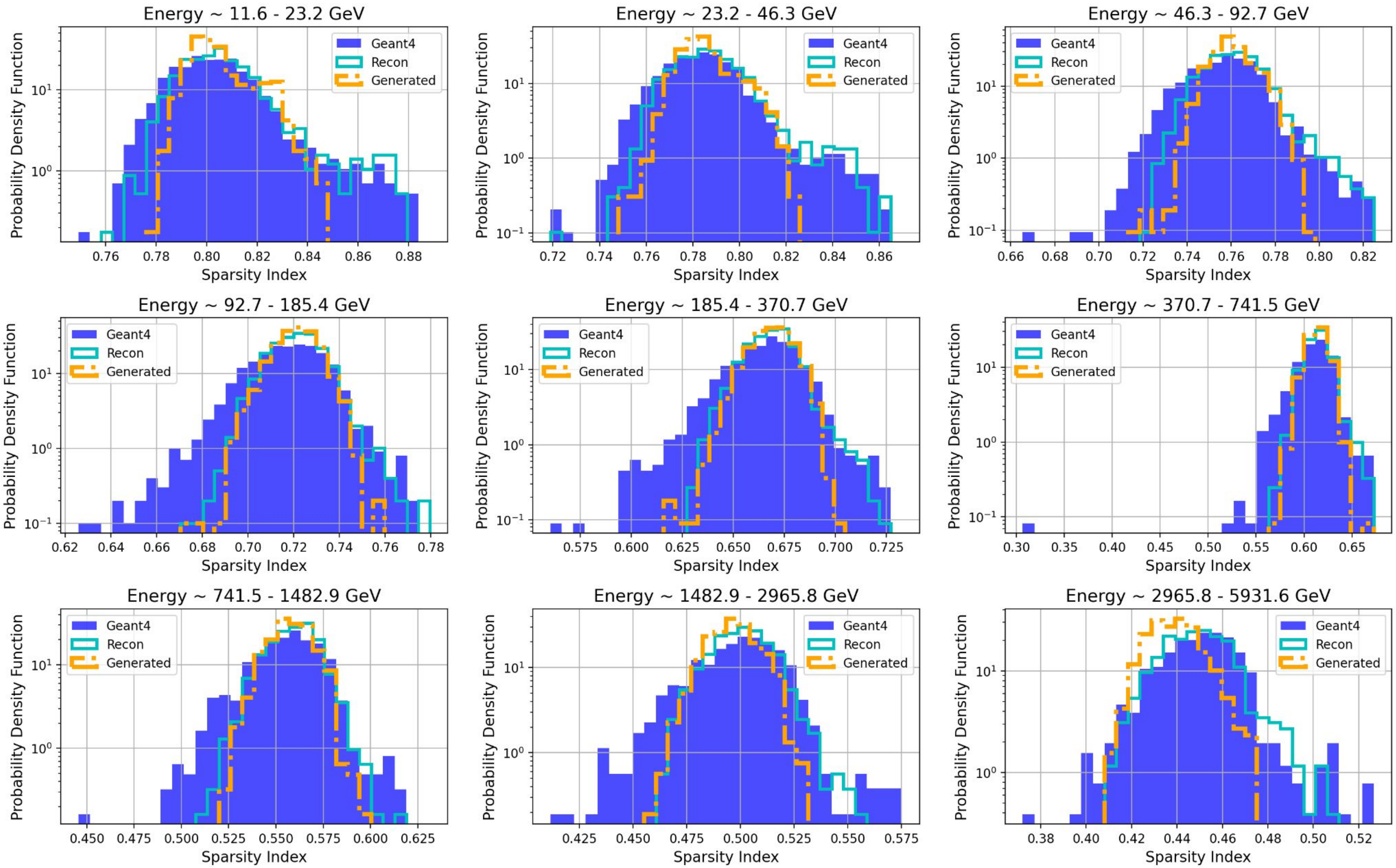


Model Results

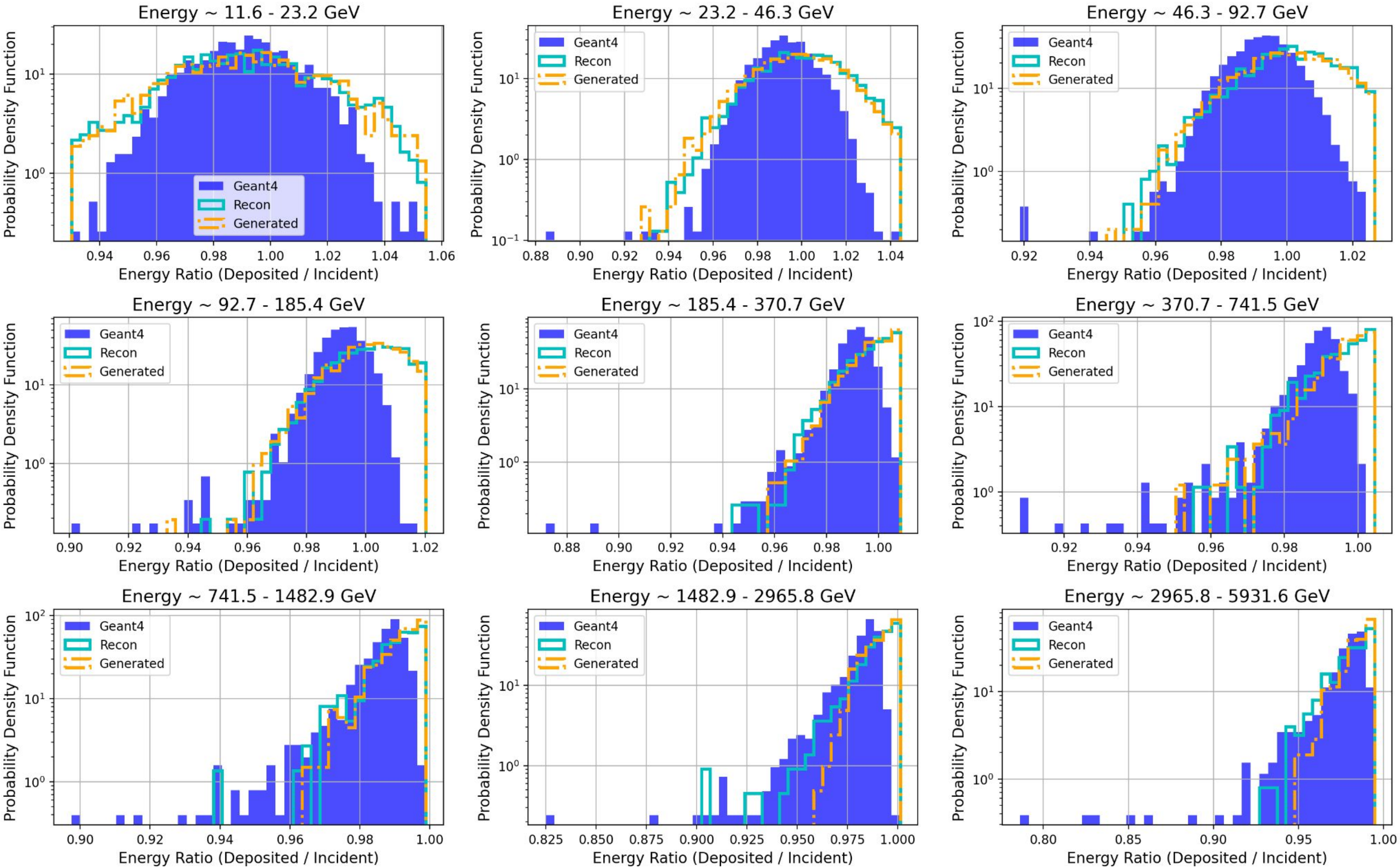
(Eta 0.40, Epoch 210)



Density
Sparsity Index
Density
Energy Ratio
Density
Deposited Energy (GeV)
Density
RBM Energy (GeV)



Energy ~ 11.6 - 23.2 GeV
Energy ~ 23.2 - 46.3 GeV
Energy ~ 46.3 - 92.7 GeV
Energy ~ 92.7 - 185.4 GeV
Energy ~ 185.4 - 370.7 GeV
Energy ~ 370.7 - 741.5 GeV
Energy ~ 741.5 - 1482.9 GeV
Energy ~ 1482.9 - 2965.8 GeV
Energy ~ 2965.8 - 5931.6 GeV
Geant4
Recon
Generated
Probability Density Function
Sparsity Index



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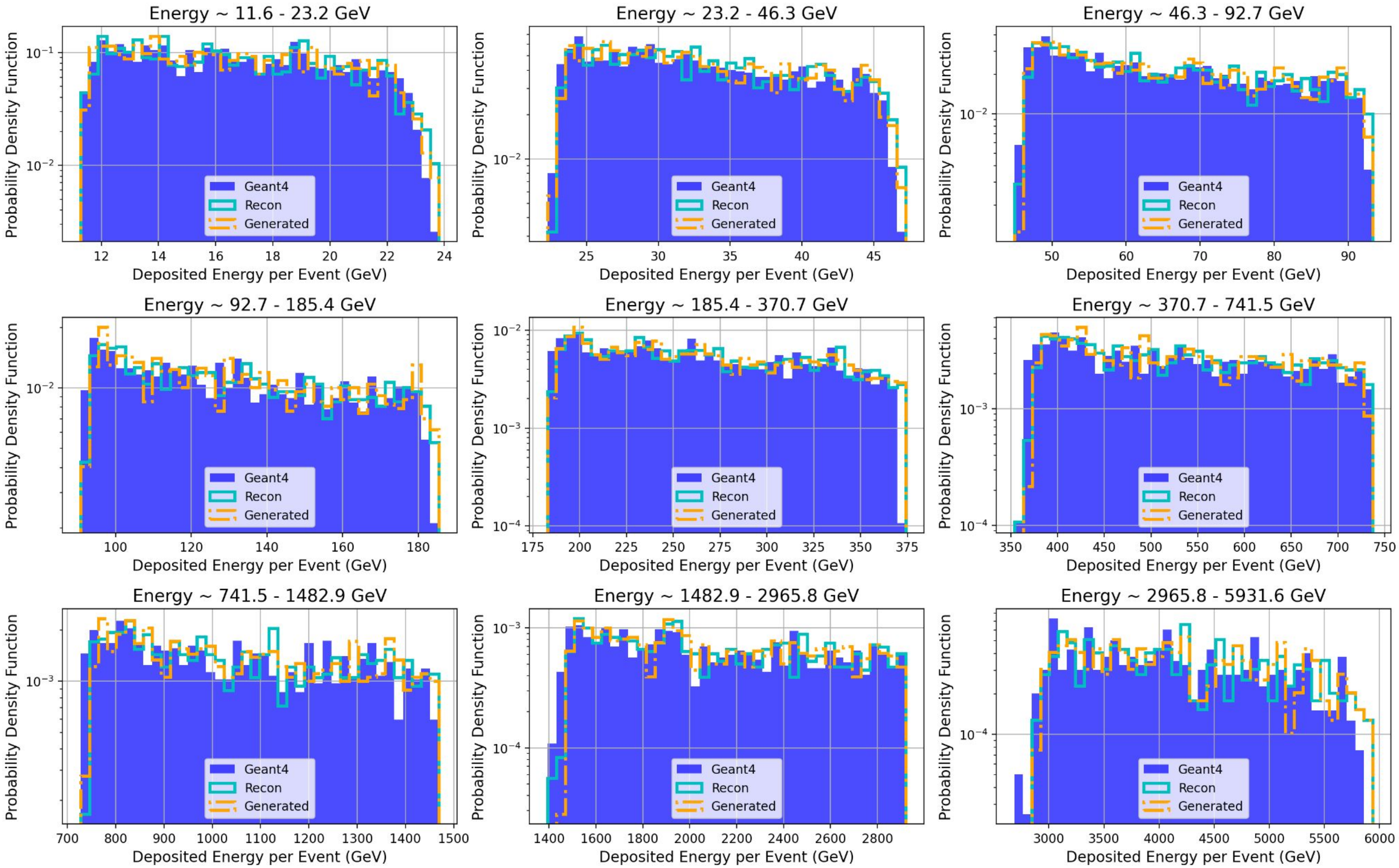
Probability Density Function
Energy Ratio (Deposited / Incident)
Geant4
Recon
Generated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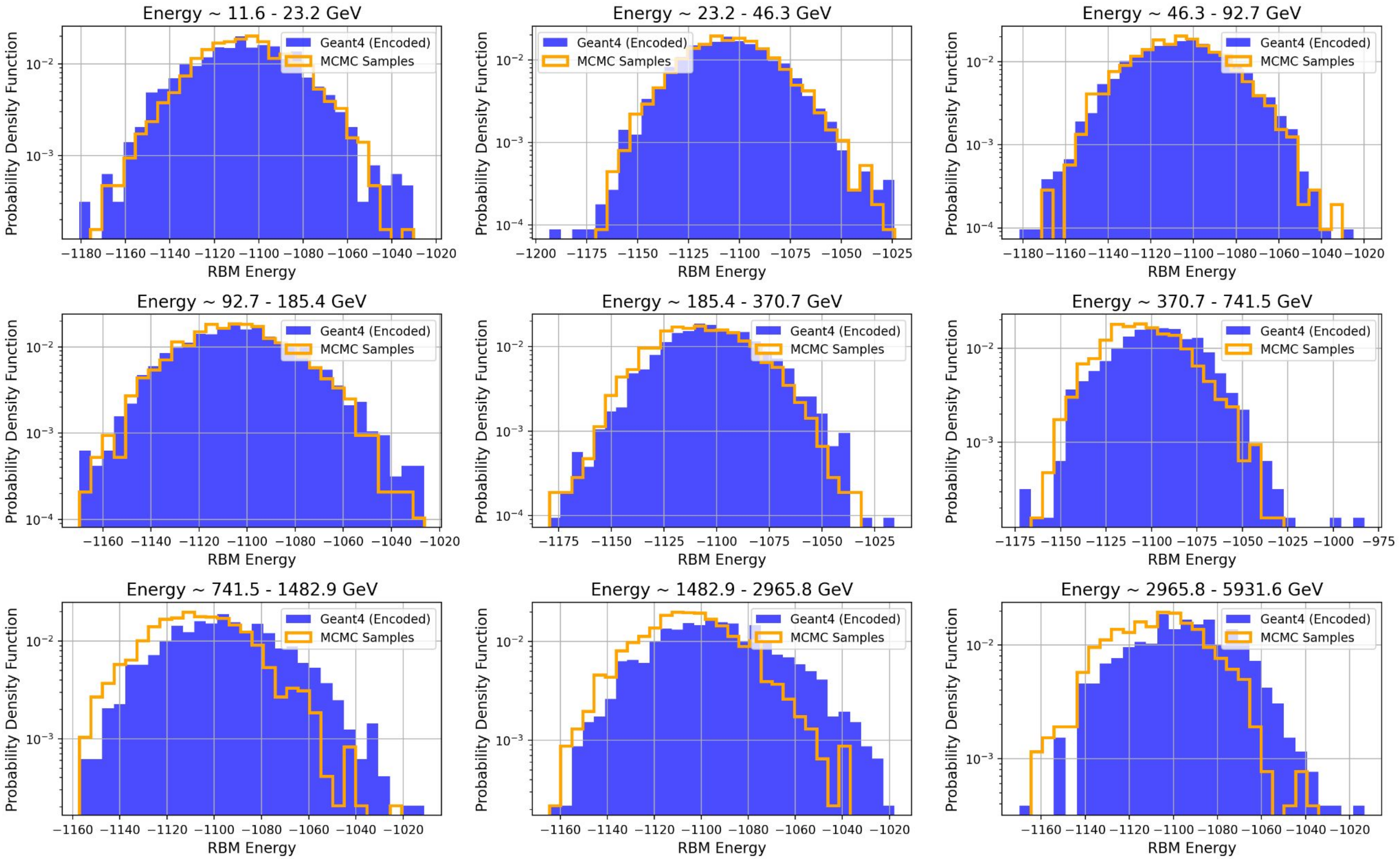
Probability Density Function
Deposited Energy per Event (GeV)
Geant4
Recon
Generated



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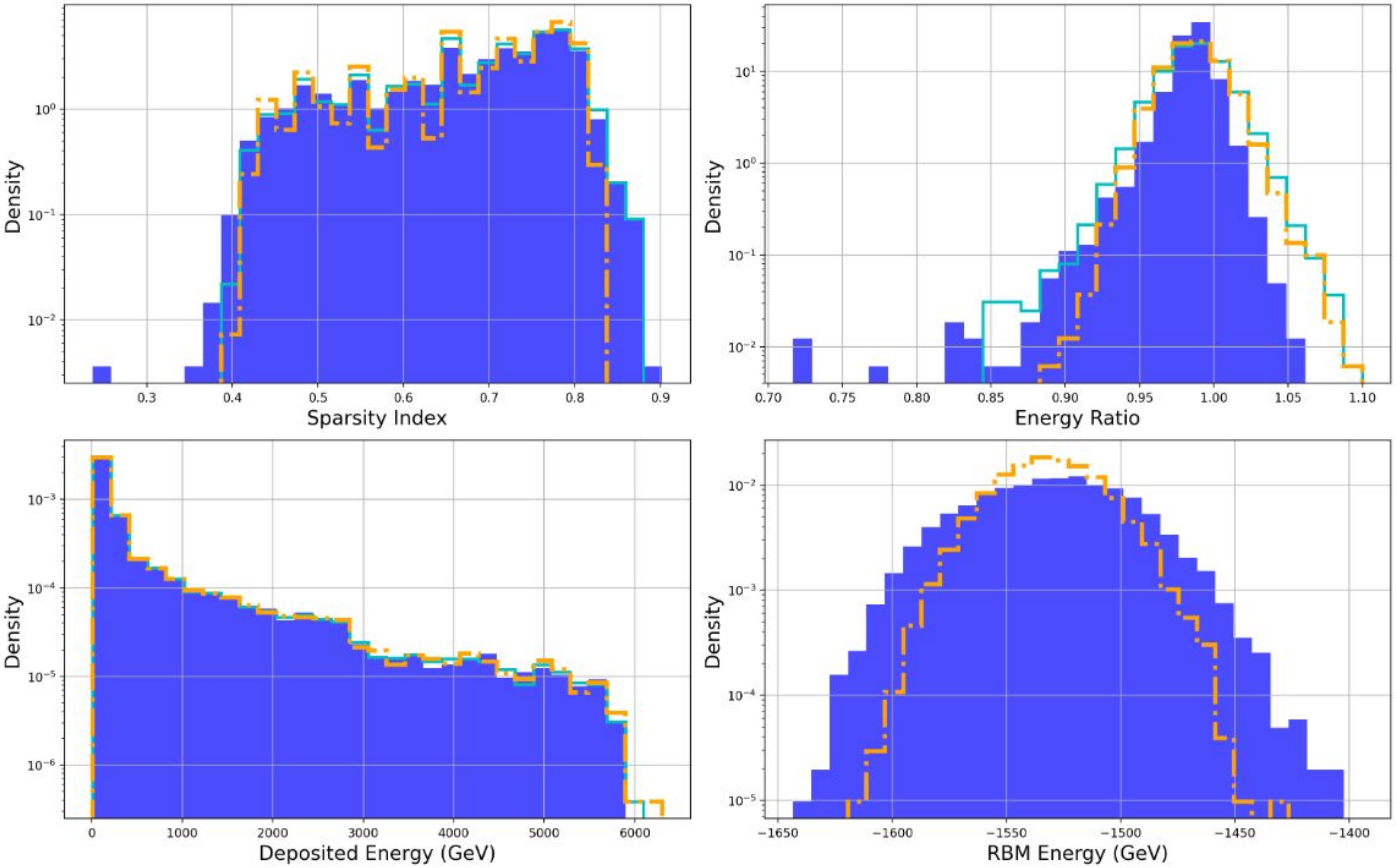
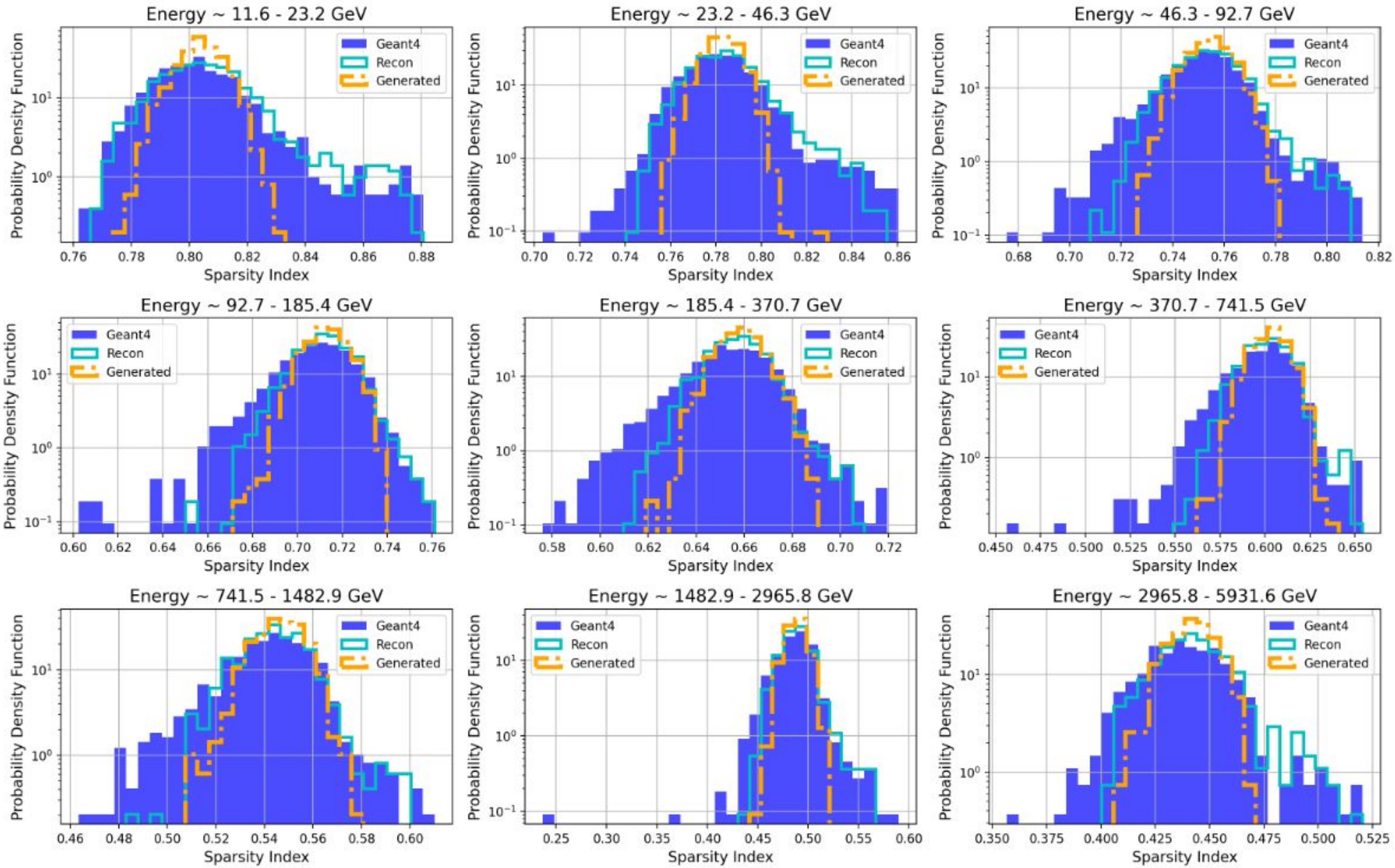
Geant4 (Encoded)
MCMC Samples
Probability Density Function
RBM Energy

(Eta 0.25, Epoch 220)



Density
Sparsity Index
Density
Energy Ratio
Density
Deposited Energy (GeV)
Density
RBM Energy (GeV)



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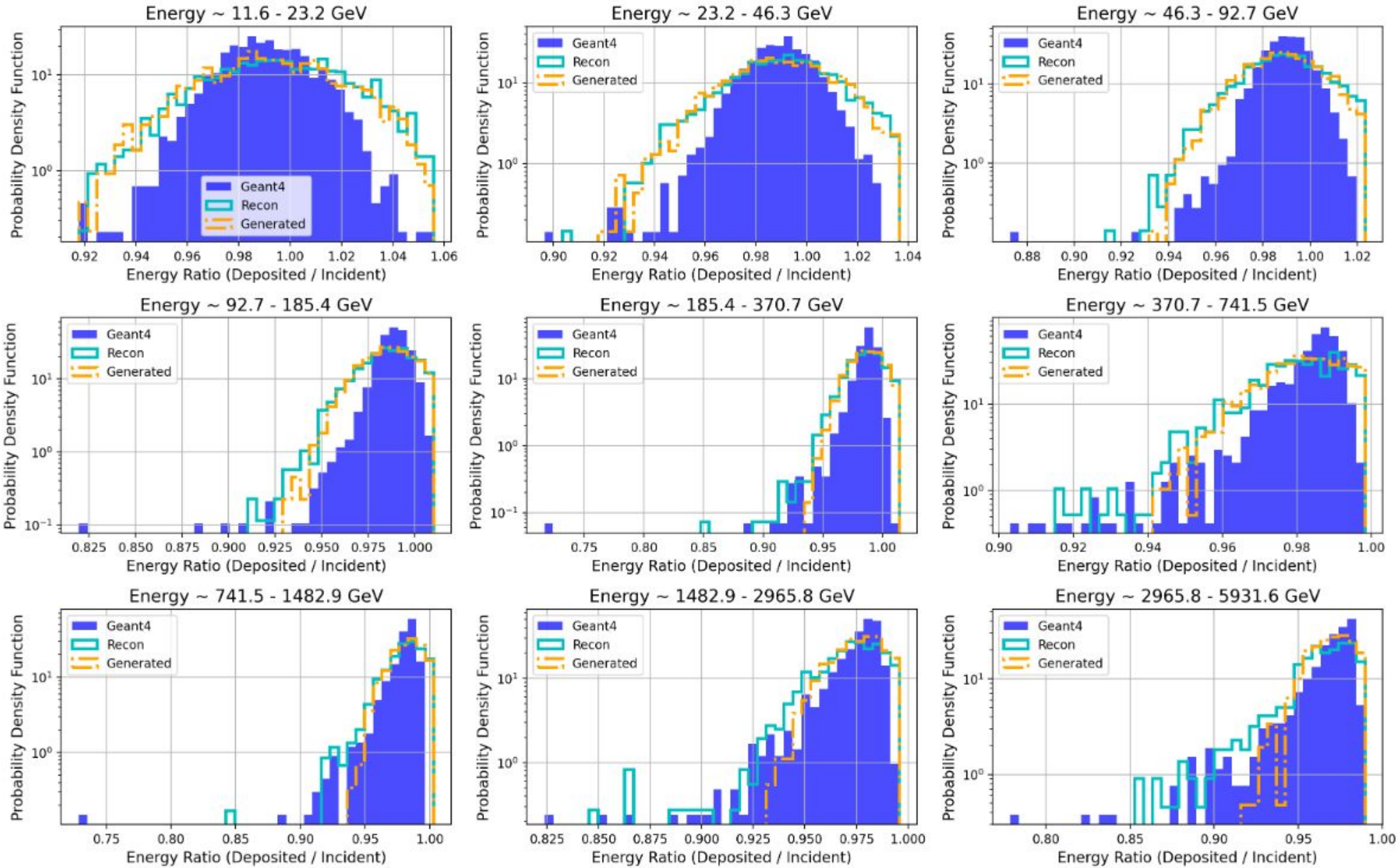
Sparsity Index



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Geant4
Recon
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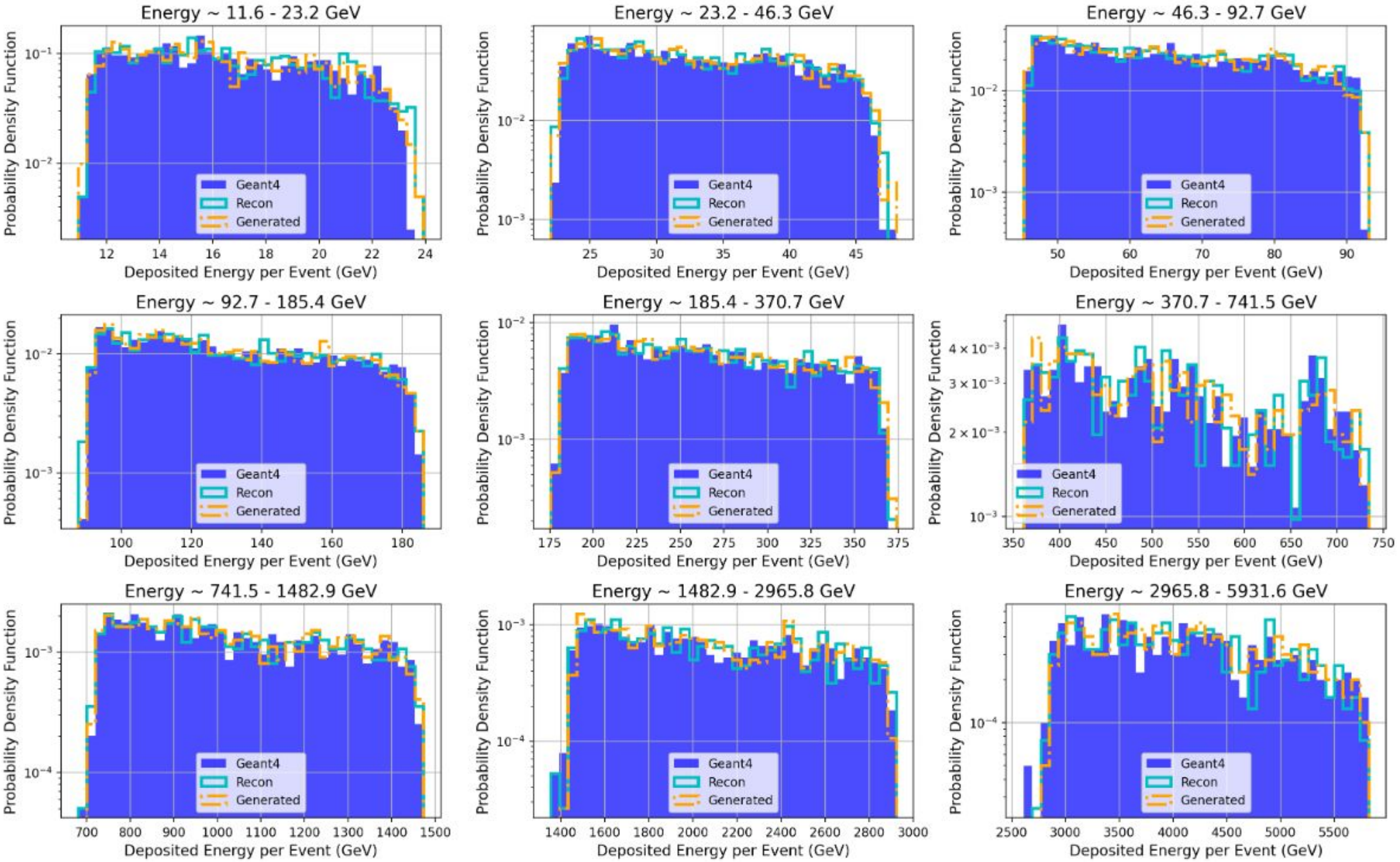
Probability Density Function
Energy Ratio (Deposited / Incident)



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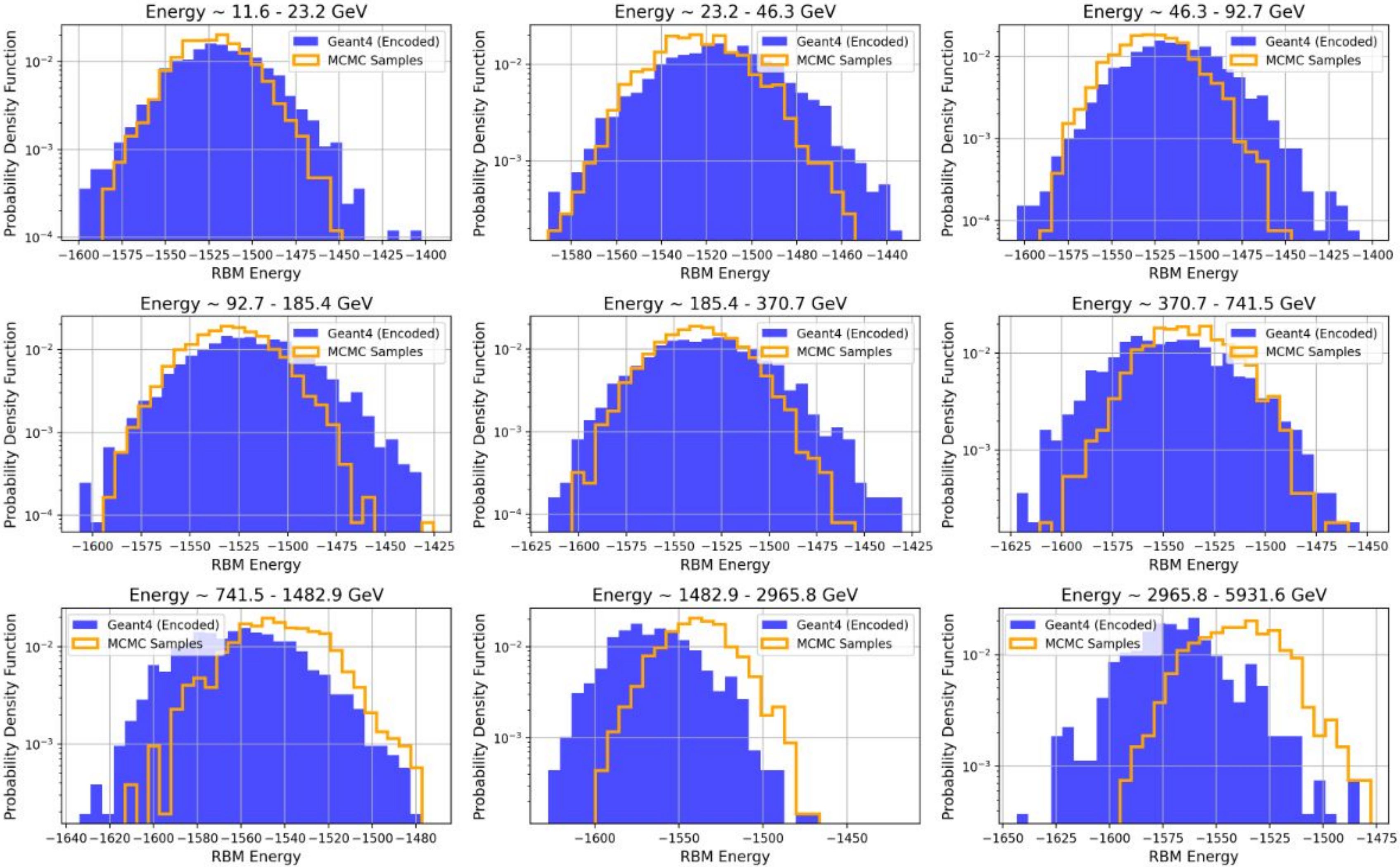

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RBM Energy

Insights from Latent Diffusion

- Their strategy: train VAE to learn latent representation, then train diffusion model on modelling latent space
    - Diffusion model is analogous to RBM in our case
- Training is separate: the VAE is trained by itself, with very minimal (1e-6) regularization
    - Supports idea to train RBM after VAE is fully trained
- Additional loss terms for the VAE
    - Perceptual loss term included in typical generative models for images (no good counterpart for particle showers)
    - Discriminator loss, specifically a PatchGAN discriminator
        - For us, patches could be layers or voxel patches?