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Latent Generative Models for Calo Simulation with VQ-VAE

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Simulation of calorimeter response is important for modern high energy physics experiments. With increasingly large and high granularity design of calorimeters, the computational cost of conventional MC-based simulation of each particle-material interaction is becoming a major bottleneck.

We propose a new generative model based on a two-stage generative model which is similar to recently latent diffusion models. The first stage model aims only to compress the calorimeter response into a regularized latent space based on Vector Quantized Variational Autoencoders (VQ-VAE). The second stage model handles generative sampling in the latent representation, conditional on phase space parameters such as pT. This second stage can be trained independently of the first, and we demonstrate prior models based on RNNs and diffusion.

For the Calo Challenge Dataset 1, our demonstration model achieves a speedup of more than 10^4 over GEANT4. The modeling of energy deposition and shower shape is comparable to other approaches such as CaloFlow, with substantially fewer parameters and a factor of ~2 speedup.

For Datasets 2, we have designed a fully convolutional architecture, employing novel operations which maintain equivariance w.r.t. the cylindrical geometry of the data. This combined with the two-stage modeling approach shows promising generation quality with substantially faster training and approximately 2x faster inference time relative to CaloScore.

In addition to cylindrical convolution and two-stage VQ-VAE training, we also introduce a novel, self-supervised proxy model that can be used as a perceptual loss function to help with training any AutoEncoder-based model. While some challenges remain in achieving ultra high fidelity suitable for certain physics applications, we present several innovative techniques that may help solve the puzzle of fast and accurate calorimeter simulation.

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