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Effective denoising diffusion probabilistic models for fast and high fidelity whole-event simulation in high-energy heavy-ion experiment

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AI generative models, such as generative adversarial networks (GANs), variational auto-encoders, and normalizing flows, have been widely used and studied as efficient alternatives for traditional scientific simulations, such as Geant4. However, they have several drawbacks such as training instability and unable to cover the entire data distribution especially for the region where data are rare. This is particularly challenging for whole-event full-detector simulations in the high-energy heavy-ion experiments, such as sPHENIX at RHIC and LHC experiments, where thousands of particles are produced per event and interact through the detector. AI-based surrogate models need to reproduce short-range and long-range patterns, and their energy spread, all of which stems from the evolution of the quark-gluon plasma produced in the collisions and its detector response.

Here, we investigate the effectiveness of denoising diffusion probabilistic models (DDPM) as an AI-based generative surrogate model for sPHENIX experiment that include both the heavy ion event generation and its response in the whole calorimeter stack. DDPM, a new type of AI generative model, underpins the recent generative AI success such as Stable Diffusion and Mid-Journey. For photographic images and arts, it can outperform previous generative models in image quality, data diversity and training stability. We study its performance in sPHENIX data compared with a popular rival –GANs. Our results show that both DDPM and GAN can reproduce the data distribution where the examples are abundant (low to medium tower energies). But DDPM significantly outperforms GANs in overall distribution distance and high-tower energy regions, where events are rare. The results are consistent between both central and peripheral centrality heavy ion collision events.

Significance

This work represents the first use of the diffusion model in the full detector full event simulation of heavy ion experiments. Our approach is self-supervising and data-driven that results in faithful reproduction of the full calorimeter detector data. Compared with traditional Geant4-based simulation, this approach leads to two orders of magnitude faster speed gain.

References

Experiment context, if any

This exploratory work uses sPHENIX simulation software and simulation data for demonstration. However, this work is developed independently of the sPHENIX collaboration.

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