HSF-India Trainee Project Proposal

Trainee Information

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- **Home Institution:** Adani University
- **Project Duration:** July 13, 2026 – October 16, 2026
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Project Title

Exploring Diffusion Models for Hadronic Physics Simulation

Project Description and Goals

This project aims to investigate the use of generative diffusion models for simulating hadronic interactions in high-energy particle collisions. Accurate modeling of hadronic showers is one of the main computational bottlenecks in detector simulation frameworks such as Geant4, due to the complexity and stochastic nature of the underlying physics. Recent studies have demonstrated the potential of generative AI techniques, in particular conditional normalizing flows, to learn and reproduce key features of hadronic interactions from Geant4-simulated data. While these methods show encouraging performance, certain regions of phase space, particularly at low energies, remain challenging to model accurately.

The primary goal of this project is to explore the potential of diffusion-based generative models for modeling hadronic shower development, and to investigate whether they can complement existing generative approaches, particularly in challenging regions of phase space such as the low-pT regime. In particular, the project will focus on training conditional diffusion models on simulated hadronic interaction data and evaluating their ability to reproduce key physics observables and distributions. If successful, this approach could provide a foundation for GPU-native surrogate models of hadronic physics, enabling faster and more scalable simulation workflows for the LHC and future experiments.

Proposed Schedule

The project development is structured into six two-week phases, focusing on progressive milestones from initial architecture design to comprehensive physics validation.

Phase	**Timeline Focus**	**Key Objectives & Milestones**
Phase 1	Weeks 1 - 2	Set up the working environment, secure access to initial Geant4 baseline datasets, and perform preliminary data exploration and preprocessing.
Phase 2	Weeks 3 - 4	Design the initial conditional diffusion model architecture specifically targeted at hadronic shower generation and establish the baseline structure.
Phase 3	Weeks 5 - 6	Develop custom training loops, implement initial model training on high-energy physics datasets, and focus on loss optimization.
Phase 4	Weeks 7 - 8	Evaluate preliminary generation results and fine-tune hyperparameters to better model challenging phase space regions (e.g., the low-pT regime).

Phase	Timeline Focus	Key Objectives & Milestones
Phase 5	Weeks 9 - 10	Conduct rigorous physics validation by benchmarking the diffusion surrogate model's output against standard Geant4 observables and distributions.
Phase 6	Weeks 11 - 12	Finalize code documentation, consolidate findings into a final project report, and outline abstracts for prospective external submissions.