IRIS-HEP Summer Fellow Project Proposal

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Project: Beam-Induced Background Simulations at Muon Colliders

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Duration: July 2025 - September 2025 (12 weeks)

Project Description

Beam-induced backgrounds (BIB) at muon colliders arise predominantly from muon decays along the beamline, producing high fluxes of secondary particles—especially electrons, photons, and neutrons—that impact detector occupancy, trigger strategies, radiation damage, and the overall physics performance.

Current BIB simulations, based on Monte Carlo tools like FLUKA and machine lattice descriptions, typically model only ~10% of a bunch crossing and simplify the process by randomly mixing decay products and assuming planar symmetries. These approximations are not necessarily true and can introduce errors, such as ignoring Φ-asymmetries caused by magnets near the interaction point, which propagate during the data extrapolation and lead to inaccurate predictions of occupancies, timing structures, and radiation profiles.

A more accurate treatment requires preserving parent muon information, grouping decay products accordingly before symmetry-breaking effects occur, and propagating them based on their true initial conditions. Such improvements are essential for optimizing the machine-detector interface (MDI), nozzle design, and timing strategies at future muon colliders.

Project Goals

- Understand and modify the current simulation pipeline to develop a data-handling framework to track parent muon identity through BIB simulations.
- Implement event grouping: sample and inject decay products in correlated groups corresponding to individual initial muons.
- Generate a training dataset by processing the modified BIB samples into structured variables describing each event, including information such as the distance of decay from the interaction point, decay angles, number of secondary particles, their types, positions, and momenta.
- Train a generative neural network (GenNN) to learn the complex high-dimensional probability distribution (PDF) of decay products for a single muon. This distribution spans millions of effective degrees of freedom, capturing the detailed structure of secondary particle production.
- Use the trained GenNN to bootstrap larger samples of BIB events by generating statistically accurate synthetic events, preserving correlations among particles and avoiding artifacts from limited Monte Carlo statistics.

- Validate the GenNN-generated datasets by comparing key observables against independent simulations.
- Deliver software tools for future BIB production campaigns using the improved methodology, along with technical documentation and reproducibility pipelines.

Time Frame	**Objective #1**	**Objective #2**	**Objective #3**	**Objective #4**
Weeks 1-4	Work with Dr. Daniele Calzolari to understand the BIB simulation.	Plan modifications to propagate parent muon information throughout pipeline.	Modify the simulation to group decay products by their parent muon and implement correlated event sampling.	Validate that grouped events preserve full kinematic and particle identity information correctly
Weeks 5-8	Generate a structured training dataset including relevant features.	Clean, normalize, and organize the dataset to prepare it for training the generative model.	Design, implement, and train a GenNN to learn the high dimensional PDF of muon decay events.	Monitor training, validate initial generation quality, and tune hyperparameter s as needed.
Weeks 9-12	Use the trained GenNN to generate large synthetic BIB samples, bootstrapping statistics from the learned distributions.	Analyze generated samples for preservation of correlations and compare distributions to independent datasets.	Finalize software tools, write full project documentation and report, and prepare presentation materials.	

References:

- A. Butter and T. Plehn, *Generative Networks for LHC Events,* arXiv 2008.08558 [hep-ph].
- A. Cho, *The Dream Machine,* Science.
- C. Curatolo *et al.,* Simulation of Beam Induced Background at Muon Collider and Study of its properties, American Physical Society April Meeting 2021.
- D. Ally, L. Carpenter, T. Holmes, L. Lee, and P. Wagenknecht, *Strategies for Beam-Induced Background Reduction at Muon Colliders.* arXIv 2203.06773 [physics.ins-det].
- D. Calzolari, *10 TeV Muon Collider: MDI - Machine-Detector and Beam Induced Background,* IMCC Annual Meeting 2024.