Exploring the Frontier of 5D Calorimeter Reconstruction with HG-DREAM and IDEA Simulations

Applicant: Mengke Zhang
Mentors: Ariel Schwartzman, Michael Kagan, Rainer Bartoldus
Duration: June 2025 - September 2025 (12 Weeks)

Introduction

Calorimeters are a central focus of collider detector concepts as they are essential for the precision measurement of jets, electrons, and photons. The calorimeter is also one of the major components of a Higgs Factory Detector exhibiting the greatest variation among proposals which include two fundamentally different approaches: particle flow analysis (PFA) and dual readout (DRO). Recent advances in fast-timing electronics have enabled a novel calorimetry concept that emerged over the last five years: Imaging 5D Calorimetry in which fast-timing information at the level of 50ps can effectively segment high granularity fiber calorimeters in depth with a precision of a few centimeters. Such capability has the potential to unify PFA and DRO approaches into a new type of 5D Particle flow algorithm. In particular, precise timing of Cherenkov light detection, combined with ML/AI techniques, enables utilization of the full space-time structure of hadronic showers, improving the hadronic energy resolution [1,2].

Understanding the full potential of 5D Calorimetry, as well as deriving its requirements, requires simulation studies of jets. There are many questions that can be studied with such simulations. Examples include understanding the impact of segmentation, time resolution, combination of Cherenkov vs Scintillating images, the interplay with tracking, and eventually, the full combination of calorimetry energy deposits, fast-timing, and tracking into 5D PFA utilizing machine learning methods. This constitutes an exciting program of research for the particle physics community that will take place over the next several years.

In this proposal we aim at achieving a low-level understanding of 5D calorimetry and its performance for jets. We plan to utilize HG-DREAM and IDEA detector simulations to investigate the impact of key calorimeter design parameters such as time resolution, spatial segmentation, etc. impact performance.

Project Goal and Deliverables

Starting from HG-DREAM and/or IDEA full simulation datasets, **the first goal is to be able to characterize and understand the "baseline" jet energy resolution**. This means deriving the most basic DRO energy corrections, without timing, and fully understanding the jet energy response resolution. This includes understanding the stochastic and constant terms of the energy resolution, potential non-Gaussian effects, etc. One particular aspect that we would like to consider and that has not been studied in much detail in the past, is the characterization of jet performance for different final states. This is an aspect that is particularly relevant in e^+e^-

colliders because, due to the absence of underlying event particles as in proton-proton colliders, jet algorithms cluster all particles in the event. This means that busy final states such as the production of di-bosons decaying hadronically, can lead to misassociation of particles among jets. This effect therefore "competes" with intrinsic calorimeter energy resolution and might constitute a limit in resolution that we would like to study and quantify. **The first goal/deliverable of this project is therefore the development of software (and the corresponding analysis) to fully characterize the jet performance of a Higgs Factory dual DRO calorimeter concept separately in final states with two and four jets.** Having a solid "baseline" understanding of jet performance will be key to evaluate gains achieved by more advanced reconstruction.

The second goal of the project is to explore the new features of 5D fiber calorimeters and how they improve the jet energy resolution. The initial focus will be the addition of fast timing information. We will start by understanding the jet response as a function of timing features in the hadronic shower development and evolve these studies into a machine learning algorithm that can utilize the full space-time shower image as input. This algorithm can then be evaluated under different assumptions on time resolution and calorimeter segmentation to understand what are the major aspects that drive jet energy resolution performance. **For this study, we will consider "simple" machine learning methods** as we initially place the focus on the physics understanding over machine learning optimization which will come at a later stage.
For example, we will consider a regression algorithm to predict the jet energy out of the full set of inputs as an intermediate approach prior to PFA.

Timeline

Week 1-2: Study and understand the physics of 5D dual readout calorimeters and explore and become familiar with the HG-DREAM/IDEA simulation dataset.
Week 3-5: Study and understand jet energy resolution using the simulation dataset.
Week 6-7: Develop software algorithm for jet performance characterization.
Week 8-11: Develop ML algorithms to study impact of fast timing information on jet energy resolution.
Week 12: Wrapping up, preparing deliverables for final presentation.

References

[1] N. Akchurin, *et al*,. "High-granularity Dual-readout Calorimeter: Evolution of a Classic Prototype", 2024 https://arxiv.org/abs/2408.15430
[2] N. Akchurin, *et al.*, "On the Use of Neural Networks for Energy Reconstruction in High-granularity Calorimeters", JINST 16 P12036 2021 https://arxiv.org/abs/2107.10207