# JetQCD: Multi-Differential Jet Studies of QCD Matter

## A Community Framework for QGP Structure and Evolution

**Main objectives:**

This proposal aims to deploy multi-differential jet observables as precision tools to probe the microscopic structure and space-time evolution of the Quark–Gluon Plasma (QGP). These observables — sensitive to a range of kinematic scales — provide a tomographic view of QGP dynamics beyond inclusive measurements. The initiative will:

- Validate, and disseminate jet observables that access distinct stages of a heavy-ion collision, from early-time formation to late-time QGP evolution;
- Develop reproducible workflows and modular analysis tools to support community-wide adoption;
- Strengthen theory–experiment collaboration by sharing benchmarks and open-access simulation frameworks.

**Scientific Motivation:**

Jets have emerged as precision probes of the Quark–Gluon Plasma (QGP), the hot and dense state of QCD matter produced in ultra-relativistic heavy-ion collisions. While inclusive jet observables have provided key insights into parton energy loss and medium transport properties, they integrate over the full collision history, making it difficult to access the space–time evolution of the QGP. To move beyond this limitation, a new generation of multi-differential jet substructure observables has been developed, offering unprecedented sensitivity to the medium's microscopic structure and dynamics at different stages of its evolution. Among these, formation-time observables (e.g., the first unclustering step in a tau-reclustered tree) provide access to the temporal ordering of emissions and potential constraints on the lifetime of the QGP. Heavy-flavour–tagged systems, such as charm–anti-charm ($c\bar{c}$) antennas, introduce additional control on formation-time and color coherence effects. Energy–Energy Correlators (EECs) resolve angular and momentum flow patterns that are sensitive to medium-induced radiation and recoil. Boosted objects offer access to delayed QGP interaction timescales due to their boosted topologies.

This proposal aims to consolidate and systematise these developments by creating a shared computational and interpretative framework for multi-differential jet observables. Through close collaboration between theory, Monte Carlo developers, and experimental groups from ATLAS, CMS, and ALICE, the project will provide open-access tools and datasets that promote reproducibility, training, and long-term reusability. While primarily based on current PbPb and pp data, this effort will also inform strategic planning for future heavy-ion runs.

**Summary of Tasks:**

1) *Differential Probes of QGP via Jet Substructure*:

This task focuses on the systematic exploration of multi-differential jet observables that are sensitive to the temporal evolution of the QGP and its momentum scales. Specific observables include: (i) hadronic decay of W-boson events; (ii) Formation-time variables obtained via re-clustering jet tools and/or associated with heavy-quarks; (iii) Energy–Energy Correlators. As additional jet substructure, the hardest kT splitting within the jet tree will also be included as it offers better analytical control for perturbative calculations.

Monte Carlo event samples, particularly from JEWEL and tuned to LHC and RHIC conditions, will be used for PbPb studies. For pp collisions, workflows will be developed using CMS Open Data (e.g., for EECs) to ensure compatibility with open-access analysis practices. All implementations will be released as modular, containerised software packages, with full documentation and example workflows for reproducibility.

2) *Bayesian Inference with Jet Observables:*
This task aims to develop a modular Bayesian inference pipeline for comparing jet substructure observables with predictions from state-of-the-art models such as JEWEL, Hybrid, and JetMed. The goal is to establish probabilistic constraints on model parameters and assess the discriminating power of different observables. A simulation library and inference interface will be released to the community, enabling wide-scale model–data comparisons and guiding future developments in jet quenching theory.

**Contribution to Transnational and Virtual Access:**
The project directly supports Virtual Access (VA) and contributes to Transnational Access (TA) by delivering:
- Containerised software tools and documented workflows for computing jet substructure observables;
- Analysis pipelines using CERN Open Data (e.g., EECs in pp);
- Open-access simulation library including JEWEL, Hybrid, and JetMed events, tuned to current PbPb conditions;
- Public code environments and notebooks to facilitate training, reproducibility, and re-use.

It will also enable researchers at institutions without high-performance computing facilities to conduct QGP analyses using harmonised tools and validated benchmarks. It also promotes broader collaboration between theorists and experimentalists through shared analysis frameworks as well as support to early-career researchers through documented platforms.