Letter of Intent for H2020 - HORIZON-INFRA-2025-01-SERV-03

Multi-Differential Jet Studies of QCD Matter

A Community Framework for QGP Structure and Evolution

Scientific Case & 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 different kinematic scales — enable a tomographic view of QGP dynamics beyond inclusive measurements. The initiative will:

- Design, validate, and disseminate jet observables that access different QGP stages, from early-time formation to late-time QGP evolution;
- Provide reproducible workflows and analysis environments for these observables, enabling community-wide use;
- Support systematic comparisons across collision systems (PbPb, pPb, OO) through MC datasets;
- Foster collaboration between theory and experiment by sharing benchmarks, facilitating hybrid task teams, and hosting regular coordination workshops.

By establishing open-access tools, this effort will enable consistent, interpretable jet studies at the LHC and beyond. Virtual access will be provided to ensure reusability and integration with future programs.

Background:

The study of jets in heavy-ion collisions has become central to understanding the properties of the Quark–Gluon Plasma (QGP), a strongly coupled phase of QCD matter. While significant progress has been made by using inclusive observables, a growing effort now highlights the importance of accessing the spatial and temporal evolution of the QGP — a task that demands more refined analysis strategies. This shift has led to the development of multi-differential jet observables, which disentangle jet structure across angular, energy, and formation-time scales. Such observables provide a tomographic view of the QGP, allowing researchers to probe different stages of its evolution — from early-time energy loss onset, decoherence phenomena, and medium-induced transverse momentum broadening. However, realising their full potential requires coordinated development across theory and experiment, detector-agnostic implementations, and strategies to ensure reproducibility and cross-system interpretability.

The upcoming oxygen–oxygen (OO) run at the LHC has reignited interest in these questions. While limited in duration, it highlights the community's ambition to explore QGP formation and medium-like effects in intermediate-size systems. At the same time, it underscores the need for reusable, detector-agnostic tools that can be applied across PbPb, pPb, and lighter systems — not just to analyse existing data, but also to shape the strategy for future measurements.

This proposal addresses that need by assembling a collaborative working group focused on providing a shared infrastructure for multi-differential jet studies. It builds on existing theory–experiment synergies and aims to advance QGP analyses, ensuring consistency and long-term impact.

Main activities of the working group and deliverables:

1) *Multi-Differential Jet Observable*: A coordinated effort will develop and disseminate a suite of jet observables that resolve QCD dynamics across multiple differential variables, including jet substructure features. It will use grooming strategies, sequential de-clustering techniques and particle correlators. These studies will also explore the feasibility of boosted objects, such as top/W-boson–initiated jets, as time-delayed probes of the QGP. While boosted top quark measurements may remain statistically limited, W-tagged jets offer a promising path toward time-resolved QGP characterisation, particularly in intermediate size systems. Time sensitivity in the QGP can also be

accessed via formation time–based observables from jet trees, including heavy-quark–tagged cases. Observable definitions, implementation code, and usage examples will be delivered in modular open-source libraries. Deliverables include a report on the physics reach and implementation guidelines. Finally, developing a Bayesian inference tool to systematically compare models to data is an attractive extension and will be pursued if time and resources permit.
2) *System-Scaling Translation*: This activity will focus on the interpretability and robustness of multi-differential observables across different collision systems. Using both Monte Carlo models and background embedding techniques, this task will establish strategies to translate observable responses from PbPb to pPb and lighter-ion systems such as OO. The goal is to equip the community with theoretical benchmarks to interpret how jet observables evolve across the system size, temperature, and lifetime. The output includes a system-scaling methodology, and MC datasets for direct use in feasibility studies and model comparisons.
3) *Community Workshops*: Yearly workshops will be organised to track progress, knowledge exchange, and steer the activities of the working group. These events will naturally promote interaction between experimental and theoretical communities. Efforts will be made to ensure engagement from researchers across a wide range of countries and early-career scientists through funding support.
4) *Virtual Access*: All developed resources will be deployed through a Virtual Access platform using containerised environments and standardised metadata. Services will include interactive Jupyter notebooks, pre-processed Monte Carlo datasets, and documentation hubs. Interoperability with CERN Open Data and EOSC services will be prioritised to ensure long-term accessibility and integration. Whenever possible, all outputs will be readily made available to the user community.

Links to Research Infrastructures:
Our activities will exploit resources and data from CERN (LHC heavy-ion open data platforms). Activities will leverage computing resources from partner institutions, such as LIP and Rome University, to ensure long-term support.

Indicative Budget:
We estimate a total budget of 450k€ over 4 years, broken down as:
- Personnel: 6 postdoc years (yearly gross cost ~50k€, total~300k€) focused on software development and dataset preparation. These roles will build transferable skills in data science, HPC, and collaborative computing, relevant for careers within and beyond academia.
- Workshops & Training: 4 events at ~25k€ each (totalling 100k€) that includes support for early-career researchers.
- Travel and dissemination related to the activities of the working group: ~50k€. This was estimated for the equivalent of three months of travel per year.

Spokespersons and Lead Partner Institutions:
Liliana Apolinário (Laboratory of Instrumentation and Experimental Particle Physics - LIP, Portugal), Leticia Cunqueiro (Rome University - La Sapienza, Italy)

Participating Institutes/Researchers:
Charles University (Czech Republic) Martin Rybar, Martin Spousta (EXP-ATLAS)**; Czech Technical University (Czech Republic)** Jaroslav Bielcik, Barbara Trzeciak (EXP-ALICE)**; Nuclear Physics Institute of the Czech Academy of Sciences (Czech Republic)** Jana Bielcikova, Filip Krizek (EXP-ALICE)**; IPhT, CEA-Saclay (France)** Gregory Soyez (TH/PH)**; École Polytechnique Paris (France)** Carlota Andrés, Cyrille Marquet (TH/PH), Matthew Nguyen (EXP-CMS)**; La Sapienza Rome University (IT)** Leticia Cunqueiro (EXP-CMS)**; LIP (Portugal)** Liliana Apolinário, Guilherme Milhano, Andrey Sadofyev (TH/PH), Helena Santos (EXP-ATLAS); **Nikhef (The Netherlands)** Marco van Leeuwen, Marta Verweij (EXP-ALICE); **SUBATECH, Nantes (France)** François Arleo, Paul Caucal (TH/PH)**; U. Bergen (Norway)** Konrad Tywoniuk (TH/PH)**; U. Granada (Spain)** Alba Soto-Ontoso (TH/PH) **U. Oxford (UK)** Gavin Salam (TH/PH)**; U. Santiago de Compostela/IGFAE (Spain)** Néstor Armesto (TH/PH)**; CERN** Urs Wiedemann, João Barata (TH/PH), Andreas Morsch, Nima Zardoshti (EXP-ALICE)