Letter of intent:

**Please specify an acronym, a project title and the name(s) of the project leader(s)**

*Chart\_HF*

*Accessing initial conditions of ultra-relativistic collisions and QGP properties through open and hidden heavy flavor*

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**In the sections below, please provide details on** *(2 pages max.):*

**1. Research objectives**

Heavy flavor (HF) quarks (charm and beauty) have been identified in recent years as a reliable mean to study the properties of the Quark Gluon Plasma (QGP), which is created in ultra-relativistic heavy ion collisions at the LHC. Due to their large masses, heavy quarks are produced early in the collision (t<0.1 fm/c) and traverse the full evolution of the medium, making them a powerful probe of both the initial state and the QGP properties. Additionally, the elementary production processes can be calculated reliably. Heavy quarks with large transverse momentum, which do not come to equilibrium, are unique probes to study the parton energy loss mechanism in the QGP, and its dependence on the parton type and mass (gluon vs. quark and light vs. heavy quarks, respectively).

The study of open heavy flavor has been very exciting also thanks to at least two surprising findings: the in medium interaction is largely non-perturbative and their hadronization (especially for baryons) have recently shown in both AA, and even more surprisingly, in pp collision at TeV scale a breaking of the universality of fragmentation function (at least at pT<10 GeV). Furthermore, new exotic mesons (XYZ) have been discovered and represent a new challenge to expand our understanding of QCD interactions.

The objective of this collaboration is to combine the capabilities of leading EU researchers in the field to develop a rigorous and comprehensive theoretical framework to describe in QCD matter, from the initial production of heavy quarks when the nuclei first collide, their subsequent diffusion through the QGP and their hadronization into heavy-flavor particles. This framework will be embedded into realistic numerical simulations that enable quantitative comparisons to experimental data from the HI-LHC.

A main motivation for the present project is that the research endeavor on HF at the LHC has significantly developed in the last decade and is now entering a precision era. The reason is threefold: in 2023-24 for the first time it has become possible to calculate the transport diffusion coefficients D\_s (encoding the coupling strength between heavy quarks and the QGP) on lattice for the full (non-quenched) QCD; the modeling through transport model have become highly realistic including event-by-event fluctuations, the experimental data with Run 3 are being able to generate high precision data in both high and the low pT region. The last being the most appropriate region for a solid determination of the transport coefficient and its comparison to phenomenological studies. In fact, the present network matches the investment for the main upgrades of CERN-LHC infrastructure and a prime scientific goals in heavy-ion physics of the upcoming runs 3-5 are centered around the exploration of the QGP via both, hidden and open heavy flavour. Furthermore, a similar activity (HEFTY) is currently funded by DOE for strengthening the collaboration among USA theoretical groups working on this same topic; the funding of the present project will permit to avoid a significant gap between EU wrt USA research groups. Certainly, in the EU the different competences of small university groups need to be gathered within a strong and efficient collaboration to efficiently address the current challenges. These groups necessitate dedicated funding to form interdisciplinary collaborations.

We aim to: a) quantify the QGP's coupling strength to heavy quarks via transport coefficients; b) elucidate the complex mechanisms of heavy quark hadronization in pp,pA and AA collisions wrt e+e- and ep collisions; c) explore heavy flavor as a novel window into the Glasma (very early stage of ultra-relativistic collisions) and pre-equilibrium dynamics.

As mentioned, the first novel data with unprecedented precision down to very low p\_T presented at QM2025 have already challenged several existing modeling and estimates of the Ds transport coefficient and seem to point to new lower values of the HF thermalization time. It is clear that these and the further data (also on new observables) from Run 3-5 ask for a new wave of predictions in a region of momenta poorly explored. Also a collaborative network is necessary to develop and share a suite of theoretical tools, including Langevin and Boltzmann transport models coupled to realistic hydrodynamic simulations and hadronic rescattering. Moreover, we are in the stage of precision where Bayesian inference methods and/or ML-based model comparison have to be employed to constrain Ds(T) as a function of temperature, significantly reducing the current uncertainties.

The tools developed for the above goal will allow to establish a solid basis for the other two main objectives of the project: understanding of the evolution of in-medium hadronization mechanism with system size and the development of the emerging direction to use HF as a probe of the **very early-time dynamics**, especially the **Glasma**—a pre-equilibrium, strongly correlated state described by classical color fields (CGC framework). In both these cases a key strategy will be to move from PbPb collisions and explore for the first time lighter systems down to ArAr and OO collisions and pA. In fact, for hadronization this will supply the new opportunity of a varying medium which appears essentially to study its role in the hadronization process. Furthermore, the system scan size at LHC will allow short-lived plasma to have HF non fully thermalized that may keep more significant signals to probe the Glasma phase. Therefore, the objectives are thought to have a perfect match with the HI-LHC infrastructure program. Angular correlations and flow-like signals in small AA systems as well as in pPb and high-multiplicity pp will be analyzed to look for evidence of initial-state collectivity. A network collaboration is particularly necessary to a theoretical modeling that should include Glasma+transport simulations to understand the initial momentum broadening and early time diffusion.

**Hidden heavy flavour -** Hidden heavy flavour hadrons, the quarkonia, are a complementary hard probe to the open heavy flavour hadrons. Experiments, which show a strong low pt enhancement of J/psi at the LHC, which is absent at RHIC, point already to the capacity of these mesons as messengers of the QGP. Hadronic interactions cannot produce such an enhancement.

There are several key quantities to which hidden heavy flavour mesons are sensitive:

a) They are sensitive to the initial QCD process in which they are produced (flavor excitation, gluon splitting, hard processes) and theory predicts that the dependence is different for bottomonia than for quarkonia. Their measurement together with the angular correlations of DDbar mesons may hence elucidate the initial distribution.

b) The LHC data suggest that quarkonia are formed before the plasma constituents hadronizes. This allows us to understand how tightly bound color neutral objects like a J/psi may survive the passage through the QGP as well as to study how the interaction between the heavy quark and antiquark is screened in a QGP.

At present the study of hidden heavy flavour particles is plagued by the low experimental statistics, a situation which will improve soon when the run 3 data are analyzed.

On the theoretical side, one should pursue further developments on non-relativistic effective field theory and studies of quarkonium suppression developing tools alternative to Bayesian ones; phenomenological models have been advanced to describe the time evolution of correlated heavy quarks pairs through the QGP medium, based on the result obtained in pp collisions at the same energy. It is, however, evident that the theory has to be developed further, especially if one wants to understand the time evolution of the color degrees of freedom, the transition from singlet and octet states by interactions with the environment. Initially, before the formation of a QGP, the heavy quark pair is surrounded by strongly fluctuating chromoelectric gluon fields, which may cause very frequent singlet-octet transition. Later, when the QGP is formed, the correlated pair presents an open quantum system, which can be described by a Linblad equation. The time evolution of such an open heavy quantum system depends on different time scales which are presently studied. However, there are still many steps necessary until the Linblad equation can be transformed into a kinetic equation, which can be used for the study of heavy-ion reactions. Therefore, in parallel, phenomenological studies are necessary to explore how the data agree with the underlying assumptions of these models, to explore qualitatively the importance of the different processes which may take place between creation and the registration of hidden heavy flavour hadrons in the detector.

The network unites the European groups, which led these studies in the last years to advance with a common effort to address the questions mentioned above, knowing that only a common effort, which unites the expertise of the different groups may yield a comprehensive understanding of the heavy flavour physics and of what heavy flavour observables tell us about the QGP.

Finally, we remark that the prime scientific goals in heavy-ion physics of the upcoming Runs 3-5 at HI-LHC are centered around the exploration of the QGP via both hidden and open heavy flavour, hence are expected in the next years very detailed data that the theory has to follow.

**2.** **Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)**

The study of the quark gluon plasma (QGP) and the initial condition with open and hidden heavy hadrons is one of the prime objectives of the heavy-ion experiments at CERN. The properties of the QGP can only indirectly be determined by comparison of the observables with transport theory results. Therefore theory has to provide the means to achieve this goal. The tasks to solve are to identify the initial heavy quark production, to understand how (correlated) heavy quarks move through the quark gluon plasma and a comprehension of the formation of open and hidden heavy hadrons. These
 theoretical studies are of central importance for the TA CERN considering also the main upgrades for the HI-LHC of ALICE and, partially, also of CMS and LHCb has been focused on the heavy flavor physics. To a lesser extent this is also true for the TA FAIR where the creation of heavy flavor hadrons is also one of the main objectives. These theoretical studies will also be performed in close connection with the TA ECT\* traditionally the place for exchanges of ideas and for the discussion of ongoing theory projects.

**3. Estimated budget request**

**400 000 Euro**

**3 years of postdoc (200 000 Euro), thematically center around topics, discussed above, to make a common and collective approach possible.**

**2 network workshops to discuss, synchronize and exchange the ideas and the work progress. They are also the events where the graduate student and postdocs involved in the project meet, get acquainted with each other and form collaborative work (60 000 Euro)

1 network at the ECT\* for a broader community including the concerned experimental
Groups and colleagues outside of Europe (15 000 Euro)

Partial support for 2 PhD projects, common between the laboratories of the network (40 000 Euro)**

**Mutual visits (short term for senior scientist, longer term for PhD students) 85 000 Euro**

**4. Participating and partner institutions**

1. Barcelona Univ. (Escobedo, Torres-Rincon)
2. Belgrade Univ. (Djordjevic)
3. CNRS/IN2P3/SUBATECH (Aichelin, Boguslavski, Gossiaux, Werner)
4. Frankfurt Univ. (Greiner)
5. GSI (Bratkovskaya)
6. INFN-LNS (Greco, Plumari) or Catania Univ.
7. INFN-CT (Ruggieri)
8. INFN-Firenze (Lombardo)
9. INFN-Torino (Beraudo, Nardi)
10. Jyväskylä Univ. (Eskola, Lappi, Mäntysaari, Niemi)
11. TU Munich (Brambilla, Vairo)
12. TU Wien (Ipp, Muller)
13. Wigner RCP - Budapest (Barnafoldi)