3-years PhD at Subatech (France, Nantes) starting fall 2024

Open quantum system approach for medium-induced gluon radiation in a dense QCD medium

Keywords: Quark gluon plasma, theory, jets, open quantum systems

1 Scientific context and motivations

In 2022, the Large Hadron Collider (LHC) at CERN has started its third run of operations, at a center of mass energy of 13.6 TeV. Besides the emblematic studies of the Higgs boson and the search of new physics beyond the Standard Model, another goal of this experimental program is the study of the quark-gluon plasma (QGP), a new phase of nuclear matter that exists at high temperature or density, and in which the quarks and gluons are deconfined (while they are confined inside the hadrons in ordinary conditions). This state of matter existed in the Early Universe for a few microseconds only, and is now re-created in the laboratory in high-energy nucleus-nucleus collisions. However, this plasma has only a very short lifetime, of order 10 fermi/c (about 10^{-23} seconds), before it cools down and hadronises into a myriad of hadrons, that are eventually measured by the detectors. In practice, it is quite challenging to extract the properties of the ephemeral plasma phase from the measured distribution of particles in the final state.

To probe the properties of the quark-gluon plasma, a very useful class of observables refers to the propagation of energetic jets. A jet is a collimated spray of particles generated via successive parton branchings, starting with a virtual quark or gluon produced by the collision. When such a jet is produced in the dense environment of a nucleus-nucleus collision, its interactions with the surrounding medium lead to a modification of its properties, phenomenon known as jet quenching. As QCD is asymptotically free, the large energy of these objects enables one to rely on first principles perturbative QCD techniques to compute their physical properties, which are well understood in *pp* collisions and can thus serve to benchmark their modifications in nucleus-nucleus collisions.

However, despite a lot of theoretical efforts in the recent years, quantitative extractions of QGP physical properties from jet quenching observables are still lacking, in contrast to the extraction of QGP transport coefficients from bulk observables matched by hydrodynamical calculations. This is mainly due to large theoretical uncertainties in the simulation of the decay of a highly virtual particle in a dense medium. A highly virtual particle produced in the vacuum radiates predominantly soft and collinear gluon (Bremsstrahlung process), but this phenomenon is affected by its interactions with the plasma constituents and the emission of medium-induced gluons. As this process is the building block of the entire jet evolution, reducing the theoretical uncertainties on jet observables demands a precise understanding of the competing effects between Bremsstrahlung and medium-induced radiations…

2 Objectives and methodology

In order to address the question of reducing the theoretical uncertainties affecting jet observables, the general purpose of this PhD is to formulate the problem of the radiation of a virtual particle in a dense QCD medium in a open quantum system approach. Such a formulation turned out to be very fruitful for the propagation of heavy quarks in the quark-gluon plasma, but has never been considered so far for a virtual parton sourcing a jet. The suggested methodology is as follows

1. *Establish the quantum evolution equation (or master equation) of a highly virtual quark or gluon coupled to a large system representing the dense quark-gluon plasma.*

   This first requires re-formulating the well-known problem of the radiation spectrum of on-shell partons in a quark-gluon plasma using open quantum system techniques. Similar formulations already exist for the evolution of heavy quarks or the transverse momentum broadening of on-shell particles. Then, one of the main challenge will be to implement the virtuality of the evolving parton in this framework.

2. *Numerically solve the quantum master equation.*

   Unless simplified models of the interaction between the off-shell parton and the surrounding medium are used, the quantum master equation cannot be solved analytically. An important aspect of the PhD project will be to write a numerical code to solve this equation and to benchmark it with known analytic approximations. State of the art techniques for the resolution of the associated Linblad equation will be used.

3. *Quantitatively clarify the interplay between Bremsstrahlung and medium-induced radiations.*

   In particular, the expected outcome of the calculation is the determination of the phase-space for Bremsstrahlung emissions in a dense QCD medium with improved precision with respect to the parametric estimations used so far in Monte-Carlo event generators. The entire framework developed by the PhD student can then be used to benchmark Monte-Carlo event generators developed in the theory group of Subatech and reduce their theory uncertainties.

3 The candidate

We are primarily looking for students with a master degree in theoretical physics (nuclear and/or particles), educated on different aspects of QCD and having already acquired a basic knowledge in numerical physics. Candidates with good knowledge of open quantum systems are encouraged to apply as well, even if they have a less extended background in QCD. In addition to disciplinary knowledge mentioned above, the expected soft skills we expect from the candidate are: ability to carry out long and complex tasks by implementing control processes, spirit of initiative, imagination and curiosity.

4 The PhD advisors and the local context

The PhD will be performed under the joined supervision of Paul Caucal (caucal@subatech.in2p3.fr) and Pol Bernard Gossiaux (gossiaux@subatech.in2p3.fr) who can be contacted for further information and questions on the application process. The PhD will take place inside the theory group of Subatech[1] (presently 10 permanent researchers, 4 post docs, 6 PhD students). Subatech is a joint research unit comprising 3 research organizations: CNRS-IN2P3, IMT-Atlantique

[1] http://www-subatech.in2p3.fr/fr/recherche/equipes/theorie/presentation

and Nantes Université. The 3-years position will be financed by IMT-Atlantique[2] and attached to the 3MG graduate school.[3]

5 The recruitment process

The recruitment process will run from mi-April 2024 until a suitable candidate has been found. First interviews are expected early May. Application files must be submitted on the following website : https://theses.doctorat-bretagneloire.fr/3mg/campagne-2024, under the tab "Laboratoire de physique subatomique et des technologies associées". The application file should at least contain the following documents :

- A Curriculum Vitae
- A cover letter outlining your professional project in relation with the PhD subject
- Transcripts of grades from "Bac+3" to "Bac+5" or equivalent (for results from a Master's degree or equivalent, please attach any documents in your possession).

The application can be completed with any document considered relevant by the candidate. Candidates selected for the interview will be required to provide 2 letters of reference, including one from the master's internship tutor.

[2]https://www.imt-atlantique.fr/fr
[3]https://ed-3mg.doctorat-paysdelaloire.fr/