Research statement of Leticia Cunqueiro

I would like to join the Sapienza physics department and its CMS group to do research on Quantum Chromodynamics (QCD) and on its high temperature limit using jet and jet substructure physics.

I have been awarded with a consolidator grant by the European Research Council (QCDHighDensity-QCD) to develop a five-year research project, which I will describe in the following pages. The grant will allow me to hire 2/3 postdocs and 3 PhD students to work on several fundamental problems of QCD.
My wish is to join Sapienza permanently, beyond the end of the ERC grant, and for that reason I have also sketched a "Beyond the ERC grant" section with several research topics that match the research lines of the Sapienza CMS group.

The ERC project

QCD is the only non-abelian Quantum Field Theory whose high-temperature phase can be accessed experimentally via high-energy heavy-ion collisions, allowing us to investigate how the macroscopic properties of nuclear matter arise from QCD interactions, i.e. interactions between quarks and gluons. With this proposal I aim to solve several fundamental and long-standing questions concerning the strong force and the evolution of the high-density phase of QCD, the Quark Gluon plasma (QGP) using jets and jet substructure measurements.
In the next few lines I will summarize what we have learnt about the QGP with jets in heavy-ion collisions at the LHC and what are in my view the outstanding open questions.

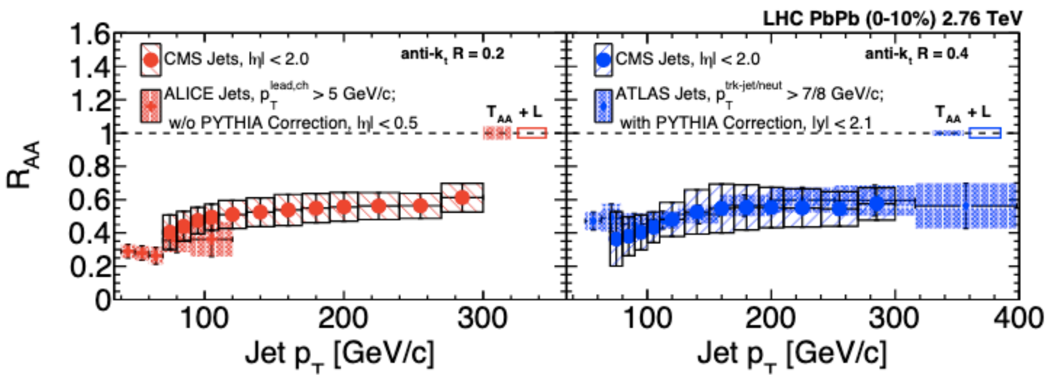

Fig.1: Jet suppression in heavy ion collisions [1].

The most striking fact about jets in heavy-ion collisions is that their measured rate is suppressed by more than a factor two relative to proton-proton collisions up to very high jet energies ~400 GeV, indicating that the medium is extremely opaque. This suppression is quantified by the nuclear modification factor R_{AA} in Fig.1 [1]. This strong suppression of the jet yields does not lead to an angular deflection of the jets, as measured by the azimuthal correlations between dijets, hadron-jet or Z/gamma-jet pairs [2], as shown in in Fig.2.
In the perturbative description of the interactions of jets and the dense QCD medium [3], energy loss and broadening of the jet shower are linked by the same parameter $\hat{q}$, the transport coefficient, but have

different parametric dependences on the medium length. So, in order to constrain experimentally the value of $\hat{q}$, simultaneous fits of the R_{AA} and azimuthal acoplanarity to the theory are desired. However, as I will argue later when describing Objective 1 of the ERC, current measurements of the azimuthal acoplanarity were done in a kinematic regime where no sensitivity to in-medium broadening exists. This can be solved experimentally as described in my Objective 1.

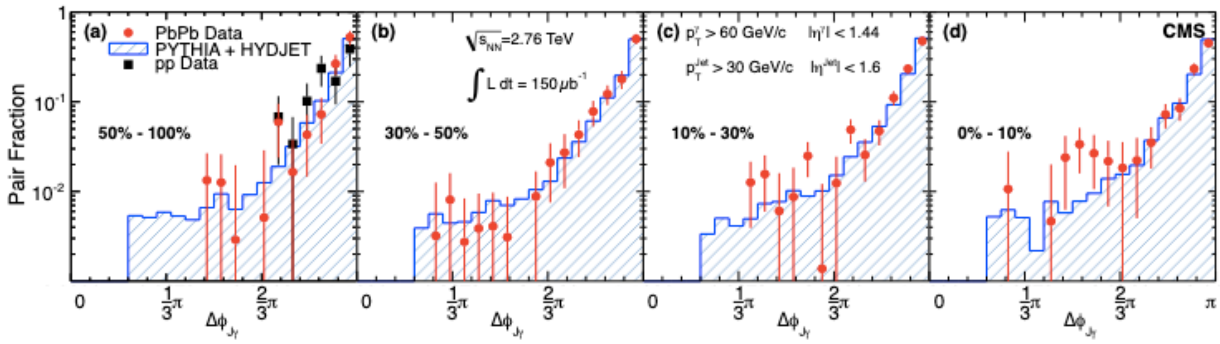

Fig.2: Azimuthal correlation between photons and jets with RUN1 CMS [3] showing no extra decorrelation induced by the medium.

Another fundamental open problem is the characterization of the degrees of freedom of the QGP and how they vary with the probing scale. Most of the measurements performed in the soft sector, such as the elliptic flow, indicate that the QGP is a strongly coupled liquid that can be described hydrodynamically [4]. However, when inspected at sufficiently short distances, the quasi-particle degrees of freedom must emerge. The searches of large-angle decorrelation at inter-jet and intra-jet level as a signature of point-like scatterers, pretty much like the Rutherford experiment that revealed the structure of the atom, are key elements of my research proposal, as it will be described in Objectives 1 and 2.

A subfield that has undergone a revolution in the last year is that of jet substructure in heavy-ion collisions. We have introduced new tools like grooming or iterative declustering [5] that allow to undo the clustering history and build and intrajet emission map, the Lund plane [6-7]. This plane is a very beautiful tool because it allows to visualize in a very direct way differences between the HI jet and the pp fragmentation. An example is the Lund plane that I measured for the first time in ALICE (Fig.3, right plot) showing a suppression of splittings with large opening angle (the yellow spot in the plot), which could be the first direct measurement of an important quantum effect in the medium, the color coherence [8].

The plot on the left of Fig. 3 shows a Lund plane with some lines representing different scales that govern the physics of the jet evolution in the presence of the medium. Among those, the vertical line at $\theta=1/\mathrm{sqrt}(\hat{q}L^3)$ represents the color coherence scale. To the left of that vertical line, the two splitting prongs are resolved by the medium and radiate independently. To the right of the plot, the splitting is not resolved and radiates coherently as a single color charge. The consequence of such a scale is that energy loss depends on jet substructure.

A precision scan of the Lund plane (and its projections like the momentum balance z_g [5]) to determine the coherence angle is part of my plan in ERC Objective 2. That will be achieved by measuring the Lund plane of jets recoiling from Z bosons or prompt photons for the first time. By comparing the Lund plane in PbPb and pp collisions, we will look for regions of the phase space with enhanced signal and the ultimate goal is to map those enhancements onto the relevant scales.

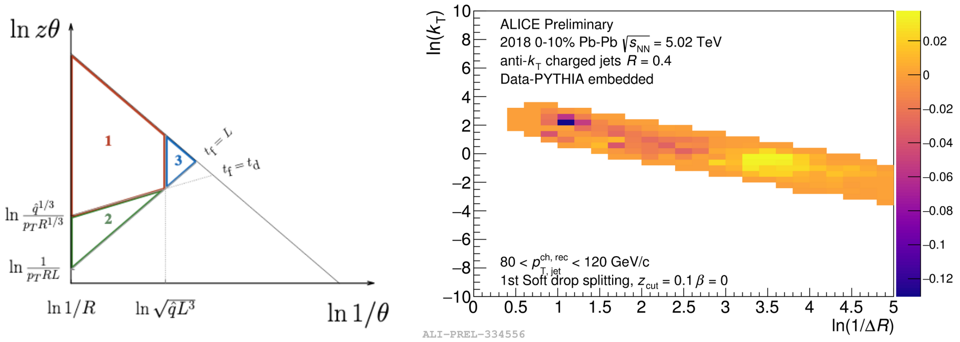

Fig.3: Left, Lund plane with some relevant scales; Right, Measured Lund plane at ALICE.

To prove that iterative declustering accesses partonic properties, I lead a measurement of the dead cone effect using the ALICE detector. For the first time at colliders, a direct exposure of such a fundamental property of QCD was done, based on a method I developed [9], see Fig.4. This brings in new possibilities that I plan to exploit in CMS to extract other fundamental properties of QCD at high densities such as the LPM interference effect [10][11][12].

So far at the LHC, all jet measurements are time-integrated and so will be all the extracted medium properties. The extracted $\hat{q}$ will be an effective transport coefficient integrated over the evolution of the medium, for instance. The possibility to introduce a notion of time in the substructure measurements will be discussed in Objective 4, but the final goal will be to build a yoctosecond chronometer [13]. The possibility to fix the time at which a dijet system starts interacting with the medium by exploting the delay time of the W/Z decay opens a new window to time-scan the medium and this will be the subject of research in Objective 5.

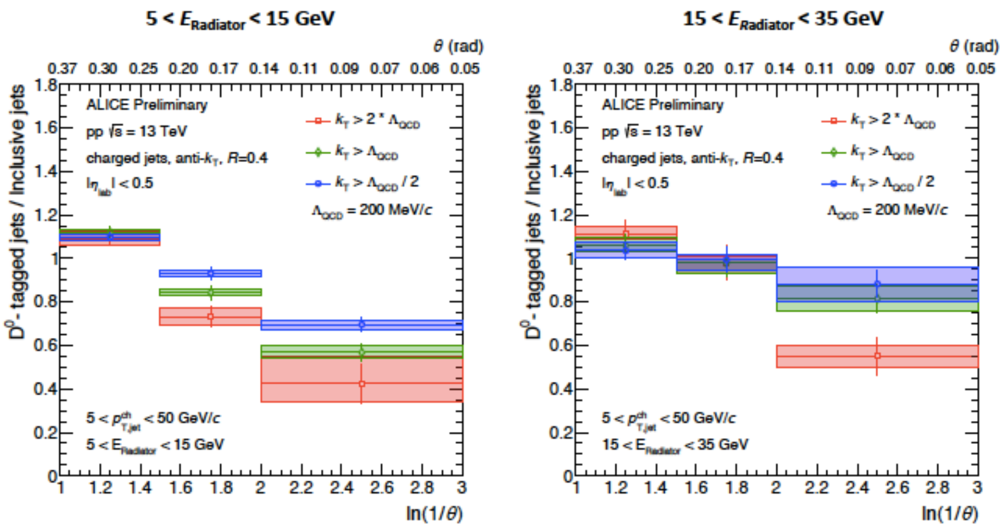

Fig.4: Dead cone exposed. Ratio of the distribution of the splitting angle in D^0-tagged and inclusive jets. A suppression is observed at the smallest angles. The suppression decreases as the energy of the fragmenting prong ($E_{Radiator}$) is higher.

Objective 1: The Rutherford scattering in the QGP: resolving quark and gluons using electroweak boson-jet angular correlations

Electromagnetic probes such as photons or Z-bosons do not interact strongly with the dense medium created in heavy-ion collisions [14]. Consequently, balancing pairs of photon and jets in heavy-ion collisions are a very clean probe to study jet quenching. The photon determines the transverse momentum of the balancing scattered parton, its direction and, to an extent, its flavour.
The parton and its shower constituents will interact with the medium and acquire transverse momentum, resulting in an induced extra decorrelation relative to the boson direction, as compared to proton-proton collisions:

- The bulk of the distribution is expected to be broader. A fundamental transport property of the medium, the transport coefficienct $\hat{q}$ [15], which is related to the QGP density, can be extracted by comparison to theoretical calculations.
- A scattering of the parton with the medium with a large deflection angle is a signature of scattering off partonic degrees of freedom in the medium, i.e. free quarks and gluons. This is the equivalent of the Rutherford experiment [16] where a large angle deflection of the incident probe upon an atom was a signature of a scattering against a proton. Finding an enhancement of large angle medium-induced deflections in heavy-ion collisions relative to proton-proton collisions, will unequivocally point to quark and gluon degrees of freedom in the otherwise strongly coupled quark gluon plasma.

Measurements of the angular distribution of jets relative to a reference axis have been reported for dijet, photon-jet, Z^0-jet and hadron-jet coincidences at RHIC and LHC [2]. These current measurements exhibit no significant evidence of in-medium modification of angular distributions, both at small and large angles to the reference axis. Moreover their statistical precision is limited.
Recent theoretical work [17] has shown that the azimuthal correlation is dominated by vacuum radiation (the reference distribution is already wide), thus medium-modifications are a small perturbation that is hard to disentangle. Experimentally, my goal is thus to supress the vacuum radiation, and this can be done by lowering the virtuality Q^2 of the trigger-jet system, by lowering the momentum of the boson and/or that of the balancing jet. I have worked out a background subtraction technique [18] and the physics case with simulations [19].

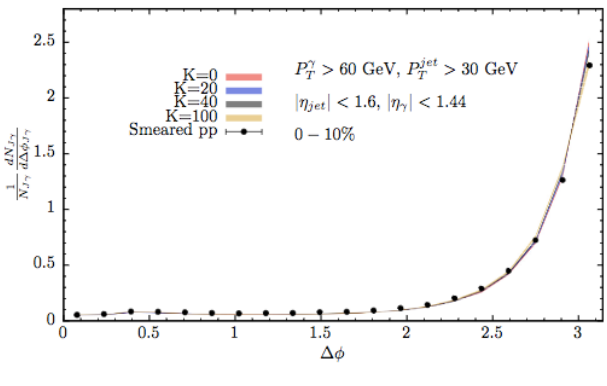

Fig.5: This plot shows CMS photon-jet azimuthal correlations in PbPb collisions compared to the vacuum reference (smeared pp) and several model lines [20] corresponding to different strengths of the medium-induced broadening (controlled by the parmeter K). Due to the selected kinematics, no sensitivity to medium-modifications is seen.

Objective 2, Probing the color coherence in the QPG: precision measurements of jet substructure in heavy-ion collisions

Jet substructure in heavy-ion collisions is a relatively new field and I have been instrumental to its development. There has been a lot of recent theoretical and experimental work trying to identify techniques such as grooming [21][22[23] or iterative declustering and observables such as the Lund plane and all its relevant projections to map the content of a jet splitting process. The possibility to access the full map of jet splittings via the Lund plane [7] allows to search for enriched or depleted regions of phase space as a result of medium interaction and recoil and to separate small-angle from large-angle and perturbative from non-perturbative components.
I regard the development and use of iterative declustering of jets in heavy-ion collisions as a conceptual revolution that allows to access a history of the branching process in the jet.

One of the main problems in extracting physics conclusions from the comparison of pp and Pb-Pb jet observables is that since jets in heavy-ion collisions are quenched (lose energy and their yield is strongly suppressed), a comparison at the same reconstructed jet energy is not conclusive since the kinematics of the partons originating the jets in the two systems are not equivalent – they are potentially harder in heavy-ion collisions. For this reason, my second objective consists on performing jet substructure measurements of jets recoiling from electroweak bosons, because the bosons are color-transparent (they do not interact with the QCD medium) and their energy is a good proxy for the jet energy.
The Rutherford scattering can be searched as a large transverse momentum deflection of the jet as a whole, this is the core of the searches in Objective 1, as well as an emission or splitting with large transverse momentum, which can be explored at the level of jet substructure. Consequently, one of the substructure measurements we will perform first, will be the transverse momentum k_T of the hardest splitting obtained via iterative declustering. A harder tail in PbPb collisions compared to pp, might be a signature of scattering off free quark and gluons in the heavy-ion strongly coupled medium [24]. Different grooming conditions will be studied such as the newly proposed dynamical grooming [25].

Objective 3: Is the dead cone filled in heavy-ion collisions due to medium-induced radiation?

The dead cone effect [26] is a fundamental property of QCD according to which gluon emission off a heavy quark Q is suppressed below critical angles $\theta_C \sim m_Q/E_Q$, where m_Q and E_Q are the mass and energy of the quark.
I developed a method to expose the dead cone effect at colliders using jet substructure [8] and carried the first measurement in pp collisions at ALICE (paper in preparation). I used the iterative declustering of D^0-tagged jets and it led to the first direct confirmation of such an important quantum effect (see my presentation at ICHEP 20'[27]).
In heavy-ion collisions, the theory has shown that, as a result of the LPM effect in medium, the dead cone is filled [12]. The LPM effect [10-11] is an interference phenomena, which leads to a specific dependence of the energy lost in medium by an energetic quark or gluon with the squared of the traversed medium length. This proportionality or the role of the LPM effect remains one of the fundamental points of the theory of jet quenching to be unveiled experimentally.

For this reason, the aim of this third objective is to apply the method I developed to heavy ion D^0-jets. Uncorrelated heavy-ion background populates the large angle corner of the phase space, so it is likely that the low-angle region remains clean of uncorrelated background and that the filling or darkening of the dead cone can be observed, ideally systematically as a function of the collision centrality. The main challenge of the analysis will be the strong smearing of the subjet energy by the underlying event background, in particular at low subjet energies, where mass effects matter.

Objective 4: Phenomenology using jet substructure: notion of branching time in the jet shower in heavy-ion collisions. Can we separate early from late splittings and draw a time-dependent picture of jet quenching?

In parallel to the substructure measurements of the Objective 2, interesting ideas can be explored phenomenologically and in collaboration with theory colleagues in the group.
A very interesting point is the notion of time. In vacuum, time is not a relevant scale in the description of the jet shower evolution. However, in heavy-ion collisions, a new ingredient appears, which is a medium of fixed lenght, so time matters. It matters whether the splitting is produced or decohered inside or outside the medium.
When filling the Lund plane, the branching time can be access via the kinematics of the splittings, $t_f=2\omega/k_T^2$, where ω and k_T are the energy and the relative transverse momentum of the subleading prong. Then a relevant question is whether the branching time from the splitting kinematics corresponds to an actual measurement of the splitting time.

Some of the planned studies are: the exploration of a time-ordered declustering, which is obtained with the generalized k_T algorithm but with power p=2 [28], the exploration of the correlation between the first splitting in the parton graph (directly from the parton shower from the MC) and the shortest formation-time splitting via declustering, for various Monte Carlo generators with different ordering prescriptions. Another interesting opportunity will be the implementation of color coherence in a Monte Carlo shower, for instance in the MC shower I developed for my PhD [29].
These activities will lead to phenomenology publications and will be in strong sinergy with the measurements.

Objective 5, the medium chronometer using hadronic decays of heavy resonances or can we time-resolve the early dynamics of the Universe?

The deconfined state of quarks and gluons in the first few fm/c of heavy-ion collisions (first μs of the early Universe) has only been probed so far with time-integrated probes. A very relevant question is whether we can find probes for which we can control the time when they interact with the medium.
Top quarks have recently been measured for the first time in heavy-ion collisions [30] and a new proposal exists to use the top quark at the HL-LHC, HE-LHC and finally FCC as one of the best tools to study the time evolution of the Quark Gluon Plasma [13].
The top quarks decay almost exclusively into a W boson and a b quark. The W decays into a color singlet $q\bar{q}$. The decay time of the top plus the decay time of the W boson, plus the time it takes the color singlet $q\bar{q}$ to be resolved by the medium (decoherence time, the same coherence mechanisms we discussed in Objective 2), sets a fixed time delay before the q and the $\bar{q}$ start interacting with the medium independently. So the idea consists essentially on exploiting the delay time induced by the top and the W boson to build a yoctosecond chronometer of the medium.

The W invariant mass is plotted as a function of the reconstructed top transverse momentum. The reconstructed W mass is sensitive to the medium-induced modifications to the jets, while the transverse momentum of the top sets the time delay before quenching starts.

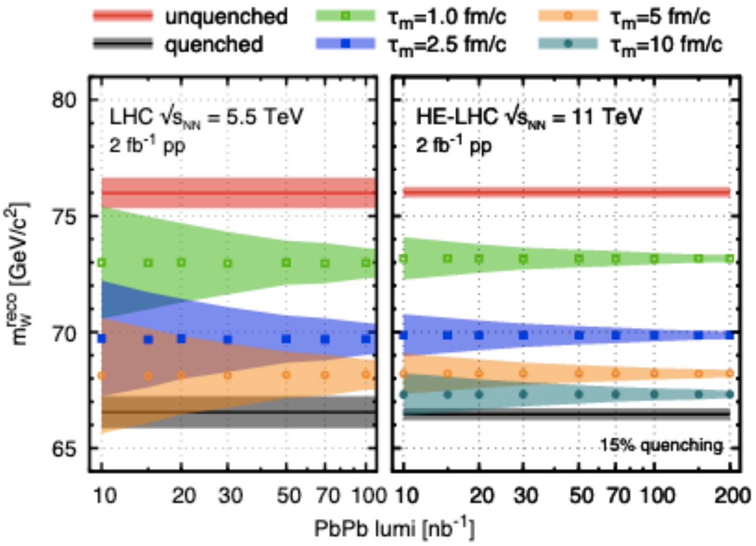

Fig.6 shows the predictions done by the authors, of the resolution of the chronometer [11] for the different forseen luminosities in PbPb collisions

My proposal is to **e**xploit the delay time of the Ws and Zs directly, without a top jet reconstruction, which will not be accessible during Run3, which is the time scale of this ERC grant.

The W/Z mass can be reconstructed by measuring large-R (resolution) jets, typically R=0.8, applying grooming in order to obtain two sufficiently hard subjets. Multijet background can be suppressed by calculating τ_2/τ_1, where τ_N is the N-Subjettiness [31], a jet substructure variable that quantifies the degree of N-prongness of the jet. By selecting small values of the ratio τ_2/τ_1, one can select very two-prong jets, which is what we are looking after, when exploring the boosted decay of a W/Z jet antenna. If the multijet background is not easily reducible, we will study the case where the pair of decay quarks are heavy quarks by considering only the large-R jets in the event whose grooming leads to two heavy-flavour-tagged subjets. The heavy-flavour tagging might be critical statistically and needs to be explored.

Beyond the ERC grant

My background and interests push me most naturally to do research on pQCD and precision tests of the the SM, with extensions to the physics of heavy ion collisions but I am also open to new areas and I wish to apply the experience, results and methods developed during the ERC grant to the strategic interest of the CMS Sapienza group.

The CMS Sapienza group has a strong involvement in the performance/calibration of key detectors like the electromagnetic calorimeter and in the construction of the MIP Timing Detector designed for the HL-LHC. The excellent timing resolution and PID capabilities of the latter will improve the performance in B-physics. The CMS group at Sapienza has a strong tradition on B physics already from the

BaBar period and this is a research area that I will be happy to join, contributing both to the hardware/ software developments and the physics analysis.
I am also interested in precision measurements of jet substructure and event shapes to extract the strong coupling constant and related Bayesian techniques.
Another example of analysis I would like to carry out is the Lund plane of top jets. The mass effects in the splitting phase space should be brutal for such a heavy object and it would be great to expose the dead cone in a very clear way. I am in general interested in top physics.
I am also interested in studying charm and beauty quarks using jet substructure. In particular, on disentangling heavy production mechanisms like gluon splitting, by measuring double-heavy flavour tagged jets [32].
Quantum computing and its applications to high energy physics and even to heavy ion collisions (for instance quantum jet algorithms) will open plenty of research areas to explore.

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