Hard probes of QCD matter at RHIC and the beginning of the LHC

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Abstract. With the Large Hadron Collider, nuclear collisions have reached the TeV scale for the first time. This large jump in energy from its predecessor, the Relativistic Heavy Ion Collider, indicates that a new discovery regime is open in QCD at high temperatures and densities. Indeed, the first data are already showing the potential of the LHC to go far beyond our present knowledge in the field. In particular new observables, reconstructed jets, are fully available and data have already been published. These new tools promise to provide an unprecedented characterization of the properties of the medium produced. I will review all new opportunities at the LHC in the hard-QCD sector, especially the case of jets, from a theoretical perspective. I will comment on the latest developments, the relation of the present data from RHIC and the LHC, the limitations of the present formalisms and how these limitations are being overcome.

1. Introduction
The celebration of the centennial of the publication of Rutherford’s paper describing the discovery of the atomic nucleus [1] marks also the starting point of hard processes as a tool to study the structure of matter at the most fundamental level. Indeed, most of the events in the experimental set-up of fast $\alpha$ particles colliding against gold nuclei were small-angle scatterings, however, the most interesting were those rare events in which the $\alpha$ particle exchanged a large momentum with the nucleus, emerging at large angles in the laboratory frame. The large momentum exchange allowed the smallest possible distance, then the atomic nucleus, to be probed.

Today, the use of hard probes is a pillar of new discoveries in particle physics. Events with large momentum exchanges trigger the search for signals of the smaller possible distances in the quest of the fundamental constituents of matter. The LHC is the newest version of the experimental setup initiated by Rutherford and collaborators one hundred years ago.

Interestingly, hard processes are excellent probes of the properties of nuclear matter under extreme conditions of temperatures and densities. The atomic nucleus discovered by Rutherford is nowadays known to be formed of hadrons, composed of quarks and gluons subject to the property of confinement. The confinement conditions can be overcome by producing a high temperature or high density medium [2, 3, 4, 5, 6, 7] and the study of the properties of this fundamental state of matter is the main goal of the high energy nuclear collisions program at RHIC and the LHC, as it was previously at the CERN SPS.

The QCD medium produced in high energy nuclear collisions at RHIC or LHC has a temperature of several hundreds of MeV. This medium is probed by hard processes with scales
ranging from a few GeV to the TeV scale. This variety of scales provides the most diverse tool to study the properties of nuclear matter under extreme conditions of temperature and density. A good example of how hard processes can help in determining the properties of the hot and dense medium created in high energy nuclear collisions is jet quenching, the modification of the structure of jets by interaction with the surrounding matter [8, 9, 10, 11, 12]. The hard cross section can be written in a form in which the long- and the short-distance contributions are factorized

\[
\frac{d\sigma^{AB\rightarrow h}}{dp_T} \sim f_i^A(x_1, Q^2) \otimes f_j^B(x_2, Q^2) \otimes \sigma^{ij\rightarrow k}(x_1, x_2, zp_T, Q^2) \otimes D_{k\rightarrow h}(z, Q^2).
\]

Here, along with the short distance parton-parton scattering cross section, \(\sigma(x_1, x_2, zp_T, Q^2)\), long distance terms describing the structure of the colliding objects \(A\) and \(B\), the parton distribution functions (PDFs), \(f_i(x, Q^2)\), and the hadronization of the quark or gluon \(k\) into the final hadron \(h\) appear. These two types of long-distance terms, which encode the non-perturbative contributions from the large sizes (in QCD scales) of both the colliding and the produced hadrons, provide the tools to study QCD matter with hard processes. One can imagine that if a hard process takes place inside the QCD medium, the long distance part of (1) describing the hadronization of the original quark \(k\) into a final hadron \(h\), \(D_{k\rightarrow h}(z)\), will be modified and studying this modification leads to a better knowledge of the properties of the medium. This idealized picture implies, in particular, that the (possible) modifications of the other type of long-distance terms, the PDFs are under control and that the factorization formula (1) applies.

The factor of almost 30 jump in energy from RHIC to the LHC is unprecedented in any collider over its precessor. The LHC will have access to unknown regimes of QCD characterized by small values of the Bjorken-\(x\) in the nuclear wave function and large virtualities. For these qualitatively new regimes of QCD new theory developments are needed, which can be summarized as follows

- The LHC explores new regimes of small-\(x\) in nuclear partonic structure for which little information is available. This implies large theoretical uncertainties for some of the observables which will need to be pinned down by a parallel proton-nucleus program [13, 14]. Some of the new theory developments associated would be:
  - A better knowledge of the nuclear PDFs in DGLAP analyses. This is a standard procedure but essential in any phenomenological study of hard processes in nuclear collisions as the nPDFs are important ingredients in Eq. (1).
  - Study of non-linear evolution and saturation of partonic densities. The linear regime of QCD evolution characterized by parton splittings should cease to be valid at high enough energies, where the occupation numbers in the partonic structure of the hadron/nucleus become large and non-linear effects start to play a role. Proton-nucleus collisions at the LHC are the best experimental option for these studies before a lepton-ion collider becomes available. In fact, a precise knowledge of the initial state is essential for a correct interpretation of the nucleus-nucleus data, e.g. for the determination of viscosity.

- The LHC explores new regimes of large-\(Q\) with jets and other hard probes. The present interest on these hard processes lies in the fact that they are excellent probes of the matter produced. Theoretical developments will be needed for a correct interpretation of the results:
  - A new theory of jets in the medium. The in-medium parton shower is not known from first principles, limiting the potential of this observable as a valid tool to pin down the properties of the produced medium. In vacuum a good description of jets is possible in a parton shower language, in which a highly virtual quark or gluon produced in the
hard scattering emits gluons to become on-shell. The equivalent for the medium needs to be developed. The interpretation of data needs a controlled theoretical framework.

– New probes are also possible at the LHC energies as abundant heavy quarks, the production of electroweak bosons, including the case of Z+jets, different quarkonia states, etc..

In the following we review the status and new opportunities of some selected hard processes of relevance at RHIC and the LHC.

2. Quarkonia suppression

Quarkonia suppression is a conceptually simple and potentially powerful tool to characterize the properties of the produced QCD matter. An intuitive idea can be formulated in terms of the potential between a quark and an antiquark which, in the case of a hot deconfined medium is screened: if such a medium is created in a nuclear collision bound states are disfavored during the plasma phase and the production of charmonia or bottomonia states suppressed [15]. The interpretation of the corresponding data has been confusing, however, in the last twenty years. The suppression has indeed been observed already in the pioneering experiments at the CERN-SPS of fixed-target S+U [16] and Pb+Pb [17] or In+In collisions [18], it was also observed at RHIC in Au+Au [19, 20] and Cu+Cu collisions [21] and recently also at the LHC not only for the J/Ψ [22, 23, 24] but also for excited quarkonia states [25]. One of the main problems for the interpretation of the data is the subtraction of the cold nuclear matter background. The suppression of both the J/Ψ, the Υ and other excited states has also been observed in proton-nucleus (or deuteron-gold) collisions in magnitude similar to the one in nucleus-nucleus collisions [26, 27, 28, 29, 30]. The theoretical description of this cold nuclear matter effects is not under good theoretical control and several mechanisms of J/Ψ-suppression are proposed. The most canonical one assumes a modification of the J/Ψ yield due to nuclear PDFs and a modification of the hadronization modeled by a probabilistic Glauber model — see e.g. [31, 32]. This factorization is not proved but used as a working hypothesis.

In this situation, the long-standing problem of the suppression of quarkonia states in nuclear collisions needs of a systematic study of the production in different systems (p+p, p+A, A+A) and energies as well as a systematic study of the different quarkonia states. Indeed, the excited states are predicted [33] to be more easily destroyed in hot matter than the ground states J/Ψ and Υ — a fact which is in qualitative agreement with the findings in [25] but whose quantitative understanding would need a better control over the cold nuclear matter effects. With the data accumulated in the last 20 years and the new data from both RHIC and, especially, the LHC a clear picture of this interesting observable should emerge in the near future.

3. Jet quenching

A quark or gluon produced at high transverse momentum in an elementary QCD collision is associated with a large phase space available for extra gluon radiation. This extra radiation is emitted at small angles and can be experimentally identified in the form of jets. The theoretical control on the jet production and evolution is very good in the absence of a medium, this is, in fact, an essential requirement in the searches for new physics at the LHC. In a parton shower approach, the large virtuality of the original quark or gluon is reduced during evolution by radiating (mainly) gluons with a probability controlled by the Altarelli-Parisi splitting functions. The corresponding evolution equations of the fragmentation functions are known in different approximations.

The case of the medium is not as well understood. Assuming that the evolution of the final state jet can be factorized from the initial state in a way similar to the vacuum, several different effect could appear: (1) **collisional energy loss**, due to elastic scatterings of the fast partons
with the medium; (2) medium-induced gluon radiation also known as radiative energy loss; (3) a modification of the colour flow within the jet due to exchanges with the medium [34]; (4) a modification of the ordering variable, or, in general, the evolution equations; etc..

RHIC phenomenology has been dominated by the energy loss mechanisms, this is because the corresponding jet quenching measurements were performed with inclusive particle measurements (one- or two-particle correlations) which measures the effects on the most energetic (leading) particle in the jet. A rather successful formalism (see e.g. Refs. [35, 36, 37, 38] for recent reviews) based on the medium-induced gluon radiation is able to reproduce the corresponding data with two main unsolved issues

(i) Heavy flavour suppression: Basically all formalisms predict that heavy quarks will lose less energy than light quarks [39, 40, 41]. The exact difference depend on the details of the formalism but experimental data on the suppression of non-photonic electrons point to a stronger suppression [42, 43]

(ii) Sizable discrepancies between theoretical implementations: The underlying physical hypothesis in the computations of the medium-induced gluon radiation are basically common to all formalisms but the actual approximations made translate into sizable differences in the output medium parameters [44].

3.1. Jet quenching with inclusive particles

The simplest observable of jets in nuclear collisions is the measurement of the one-particle inclusive production at high transverse momentum. The effect of the surrounding matter can be identified by the suppression of the signal, with respect to the proton-proton collisions, due to energy loss. The nuclear modification ratio

\[ R_{AA} = \frac{d\sigma^{AA}/dydk_T}{N_{coll}d\sigma^{pp}/dydk_T} \]  

is normally employed to single-out the medium effects, where \( N_{coll} \) is a normalization factor computed in the Glauber model to allow the comparison with the proton-proton cross section. The suppression of high-\( p_T \) hadrons is one of the first, and also one of the main, observations at RHIC [45, 46, 47, 48]. Several theoretical approaches have been used to reproduce the data, the most successful ones being those based on radiative energy loss as explained above. In Fig. 1 we plot the description of the data in one of these approaches [49] for both the one- and two-particle inclusive distributions (back-to-back signals for the second). The description of the data is good. A quality analysis returns a value \( K = 4.1 \pm 0.6 \) when the transport coefficient is parametrized as \( \hat{q} = 2K \epsilon^{3/4} \), \( \epsilon \) being the local energy density of the medium in a hydrodynamical approach. In the case of an ideal quark-gluon plasma, a free gas of quarks and gluons, \( K \sim 1 \) — see e.g. [51] — indicating that the properties of the medium do not naively correspond to this simplified scenario. As mentioned above, however, despite the successful description of the data two main open issues need to be solved for which LHC data will be most helpful.

LHC collaborations have also measured \( R_{AA} \) for inclusive particles at high-\( p_T \) both for light hadrons [52, 53] and, interestingly, for charmed mesons [54]. The suppression for light hadrons turns out to be similar, though slightly larger, than the one at RHIC for moderate values of \( p_T \). Models tested at RHIC can reproduce the data reasonably well, including the positive slope which indicates \( R_{AA} \to 1 \) for large transverse momenta. Concerning the D-meson suppression, with large error bars it also indicates a similar, although slightly smaller, suppression than the corresponding one for light hadrons. This was expected from calculations of medium-induced gluon radiation [55]. So, there seems to be a compatibility of the well-tested approaches used in RHIC phenomenology with the new data from the LHC. More quantitative analyses should be performed now, with all available data, also when the medium density distributions from hydrodynamical analyses become available as input.
3.2. Reconstructed jets in nuclear collisions

Although the results from the previous section are extremely interesting for the characterization of the medium properties, the use of inclusive quantities present also limitations which are difficult to overcome. In particular, in a scenario of very dense medium, surface effects could affect the extraction of the medium parameters and different approaches are difficult to distinguish. A powerful tool to overcome these limitations is the reconstruction of jets in nuclear collisions. In the ideal situation, if the whole energy of the jet can be reconstructed, the modifications that the medium induce in its structure give a direct information about the splitting process as well as other mechanisms which could be present.

Jet reconstruction is one of the main issues in hadronic colliders, and essential for physics searches. In the case of the nuclear collisions, the size of the underlying event, with a very large multiplicity, makes the identification of the jets more difficult. The first data on identified jets has been performed at RHIC [56, 57] and the first published data appeared very recently from the LHC [58, 59]. The analysis of the ATLAS and CMS collaborations present some surprising results. They can be summarized as follows:

(i) Reconstructed jets from ATLAS are suppressed from central to peripheral collisions ($R_{CP} \sim 0.5$ and basically flat). This indicates that the sample of studied jets are still biased to some extent.

(ii) When the back-to-back jet signals are studied, the energy imbalance from the most energetic jet to the one in the opposite direction is larger in central Pb+Pb than in p+p collisions. This indicates a large energy loss of jets in the produced matter.

(iii) CMS data indicate that this lost energy is dominantly carried away by soft particles (less than 2 GeV) at large angles. This contrasts with the vacuum where the particles are harder at large angles due to angular ordering.

(iv) The di-jet azimuthal asymmetry is very similar in Pb+Pb collisions and in p+p collisions. So, no strong change with respect to the vacuum jets is observed: the effect is not dominantly driven by e.g. emission of hard particles which would change the direction of the jets.

(v) The fragmentation functions of the leading and the subleading jets do not present any change from Pb+Pb or p+p collisions. So, the fragmentation function is vacuum-like.

Notice that the experimental fragmentation function (FF) is built by dividing the particles’ transverse...
Some of these properties were not, a priori, expected from theoretical estimates. In particular, the usual, and quite generic, relation between broadening and energy loss, \( \Delta E \sim \langle k_t^2 \rangle L/\alpha_s \), seems difficult to reconcile with those observations at least naively. However, a note of caution needs to be made here as a complete picture of the underlying mechanism of jet quenching needs a controlled analysis of several factors: e.g. the amount of jets which are lost; the effect of the background subtraction [60]; the actual theoretical implementations which are compared with the data, etc. One can imagine, for example, a simplified scenario in which two different jet quenching mechanisms are at work and one of them is removed from the sample because it produces e.g. a too hard spectrum. With all these caveats, we can still try to extract some consequences. The properties above indicate that the effects in the measured jets are not compatible with a hard radiation at large angles, which would modify, in particular, the di-jet azimuthal asymmetry or, with a strong modification of the radiation pattern inside the cone, would modify the fragmentation functions. A naive interpretation of the data would then indicate that mechanisms in which the jet broadening and the energy loss do not follow the traditional relation \( \Delta E \sim \langle k_t^2 \rangle L/\alpha_s \) are favoured in the particular sample of jets measured.

3.3. Towards a new theory of jets in the medium

The limitations in the theoretical implementation of jet quenching as well as the quality of the new data becoming available, especially from LHC, calls for a new theory of jets in the medium. An essential ingredient that any description of the jet development should contain is a correct treatment of the multi-parton emissions. The traditional way of assuming an independent gluon emission approximation is probably good enough to estimate the energy loss and, hence, for the phenomenology of inclusive particle suppression. The description of a final state with a large number of gluons emitted needs, on the other hand, the inclusion of quantum interferences among different emitters which are known to be essential in the vacuum. As a first step towards this goal, recent developments consider emission out of a quark-antiquark antenna [61, 62, 63, 64, 65, 66]. The setup captures the main physical ingredients in the vacuum, in particular, the presence of angular ordering due to colour coherence effects. In the case of a medium the situation is radically changed. Several regimes have been identified, and interestingly, a new contribution emerges in which a vacuum-like radiation, but antiangular ordered [61] can be identified. This new contribution is especially interesting because its features are completely different from all known medium-induced gluon radiation presented in the previous sections. This becomes more clear in the soft limit where the sum of the vacuum plus the medium-induced gluon radiation off a \( q\bar{q} \) antenna with opening angle \( \theta_{q\bar{q}} \) in a singlet state is simply

\[
dN_{q\gamma'}^\text{tot} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta} \left[ \Theta(\cos \theta - \cos \theta_{q\bar{q}}) - \Delta_{\text{med}} \Theta(\cos \theta_{q\bar{q}} - \cos \theta) \right].
\] (3)

Here the first term is just the vacuum angular-ordered contribution and the second term is the new medium contribution which has been called antiangular ordering [61]. In particular, and in contrast to previous results, a soft divergence appears also for the medium-induced part due to the vacuum-like spectrum. The parameter of the medium controlling the amount of antiangular ordering is the dipole scattering amplitude

\[
\Delta_{\text{med}} = 1 - \frac{1}{N_c^2 - 1} \langle \text{Tr} \ U_p(L, 0) U_p^\dagger(L, 0) \rangle,
\] (4)

momentum by the jet's total energy, while the theoretical predictions before the data appeared typically divided the transverse momentum of the particle by the energy of the parton originating the jet. In the second case (not possible in experimental conditions unless the whole energy of the jet is reconstructed) a suppression of the FF is predicted, in agreement with the suppression found in inclusive particle measurements as the ones in Fig. 1.
which, by unitarity, is bounded by 1. In the case of an opaque medium, $\Delta_{\text{med}} \to 1$, a total decoherence is then achieved in which the total spectrum is $|62|$

$$dN_{q,\gamma}^{\text{tot}}|_{\text{opaque}} = \alpha_s C_F \omega \sin \theta \, d\theta = dN_{q,\gamma}^{\text{tot}}|_{\text{opaque}}$$

The last equality means that another property of the spectrum is the memory loss: the radiated gluons do not keep information about the original pair being in a singlet or an octet state. Interestingly, these new properties survive the soft limit and the spectrum retains a form similar to (3) for sizable values of the gluon energy.

These new results indicate that the medium-induced gluon radiation off a single emitter, considered up to now in all phenomenological approaches and also implemented in some Monte Carlo codes $|67, 68, 69, 70, 71|$, would not be enough for a correct interpretation of the experimental data. Non-trivial structures appear when considering more than one emitter, the realistic situation in a jet shower, as already known from the vacuum.

The features of the radiation are, on the other hand, in good qualitative agreement with the experimental data on jets presented in the previous sections: The spectrum (3) presents vacuum-like radiation outside the cone delimited by the pair angle, in particular with a soft divergency, so, soft, vacuum-like, radiation is expected at relatively large angles while the radiation inside remains unchanged and just as in vacuum. These are qualitative behaviours which should be contrasted with data in a more quantitative analysis once the correct implementation of the multi-gluon emission is known.

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