RHIC results from LHC perspectives

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RHIC data opens new ways of characterizing the medium created in a heavy ion collision by measuring particles with high transverse momentum. In addition to the observation of the predicted jet quenching, the new data on particle correlations indicate that a strong modification of the jet-like shapes is driven by the dynamical properties of the medium. I will review the lessons we are learning from RHIC and outline some new directions which could become of primary importance at the LHC.

1. Introduction

Quarks or gluons produced at high transverse momentum in elementary collisions build up their hadronic wave function by emitting partons, mostly gluons, reducing their large virtuality ($Q \sim p_t$) to a typical hadronic scale. These emitted particles form QCD parton showers which can be experimentally observed as jets. The properties of these objects can be computed by resumming the relevant logarithms originated by the large difference in the scales of the problem. A well-known example of these resummations are the DGLAP evolution equations describing the virtuality dependence of the fragmentation functions (for a general introduction on these topics see e.g. [1]). In Monte Carlo event generators the virtuality evolution of the created particles is a major issue and several solutions are proposed to match these parton showers with known results at a fixed order in perturbation theory. Jets being spatially extended objects (or equivalently, sensitive to different scales) provide optimal conditions for the characterization of the medium created in a nucleus-nucleus collisions. The main predictions for high-p_t measurements in a nuclear environment are the suppression of the inclusive particle yields due to the additional medium energy-loss and the broadening of the associated jets [2–7]. Indeed, the strong suppression of high-p_t particles [8] is one of the main observations made at RHIC which now extends to particles up to $p_t \sim 20$ GeV [9]. The situation for the jet broadening is, however, not as clear, due basically to the limited range of virtualities studied in present experiments. The future LHC will largely improve this limitation thanks to a logarithmically extended range of virtualities.

On the theory side, there is a wide consensus that the dominant mechanism of *jet quenching* is the medium-induced gluon radiation [2–7]. The way the inclusive gluon spectrum can be translated into a medium-modified parton shower has not been fully solved theoretically and in most cases the independent gluon emission approximation leading to a Poisson distribution is employed. This formalism reproduces successfully

[7,10] the observed suppression of hadrons with $p_t \sim 5...20$ GeV. The main outcome of these analyses is meant to be the density of the produced medium. In the following we will briefly introduce the formalism, its main successes and weakness and comment on how present experimental data can be described and the new possibilities open at both RHIC and the LHC.

2. The formalism

The vacuum. Parton branching is an essential property of QCD processes involving large virtualities. It is present in the initial or final state radiation leading to the scale evolution of the parton distributions or fragmentation functions respectively and is well reproduced by DGLAP evolution equations. An equivalent integral formulation for the evolution with the virtuality t of these quantities

$$f(x,t)=\Delta(t)f(x,t_0)+\int_{t_0}^{t}\frac{dt'}{t'}\frac{\Delta(t)}{\Delta(t')}\int\frac{dz}{z}\frac{\alpha_S}{2\pi}P(z)f(x/z,t'), \tag{1}$$

provides a simple probabilistic interpretation in terms of the non-branching probabilities (*Sudakov form factors*)

$$\Delta(t)\equiv\exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\frac{\alpha_S}{2\pi}P(z)\right], \tag{2}$$

where $P(z)$ are the QCD splitting functions. These equations resum the relevant divergences of the vacuum radiation spectrum $\omega dI^{\rm vac}/d\omega dk_t^2 \sim 1/k_t^2$ of gluons with energy ω and transverse momentum k_t, being $z=\omega/E$ and E the energy of the parent parton.

The medium. Eqs. (1) and (2) describe the process in which a parton reduces its energy and virtuality by radiating other partons (gluons in general) with a fraction of momentum z. The description of the experimental data given by this general formalism is one of the most precise tests of QCD. The counterpart for the branching of a parton traversing a medium has not yet reach the same degree of refinement. In the following we will restrict to the case of final state radiation. In most current approximations, one simply neglects the virtuality ordering of the process, resumming the energy loss of subsequent branchings by a simple Poisson distribution [11–13]

$$P_E(\epsilon)=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\prod_{i=1}^{n}\int d\omega_i\frac{dI^{\rm med}(\omega_i)}{d\omega}\right]\delta\left(\epsilon-\sum_{i=1}^{n}\frac{\omega_i}{E}\right)\exp\left[-\int d\omega\frac{dI^{\rm med}}{d\omega}\right]. \tag{3}$$

These *quenching weights* [11,12] give the probability of an additional energy loss, $\Delta E=\epsilon\,E$, for a known medium-induced gluon radiation spectrum $\omega dI^{\rm med}/d\omega$ [2–5,12]. Assuming that the hadronization takes place outside the medium, the medium-modified fragmentation functions are computed by the convolution of (3) with the vacuum fragmentation functions [14,13,15]. Neglecting the evolution is a reasonable approximation for moderate values of p_t in which the correction due to energy loss is expected to dominate over the milder (logarithmic) evolution in virtuality [15].

2.1. The medium-induced gluon radiation spectrum

The general description of a high-energy parton propagation is in terms of Wilson lines [16,4,7], averaged in the allowed configurations of a medium. Several prescriptions for these medium averages exist, but most of them are based in a model of the medium as a collection of static scattering centers with no correlations between them [17]. In this framework, at high-energy, the effect of the each individual scattering reduces to induce color rotations and to transfer transverse momentum. For large number of scatterings (*multiple soft scattering*) a saddle point approximation of the scattering amplitudes defines the single parameter of the model, the transport coefficient $\hat{q}$, with the meaning of the average transverse momentum transferred to the gluon per mean free path.

The spectra of gluons computed in this framework can be found in [2–7,12] An interesting property is that, contrary to the vacuum case, the medium-induced spectrum is infrared and collinear finite due to formation time effects [12,18]. The functional dependences in ω and k_t away from the regions affected by formation time are, however, stronger than the vacuum ones. In particular the k_t dependence is that of a typical elastic scattering $dI^{\rm med}/dk_t^2 \sim 1/k_t^4$, – in other words, this corrections appear as higher-twist – and, also, the energy spectrum of radiated gluons is softer than in the vacuum.

The angular dependence of the radiation is affected by formation time effects in a peculiar way. Recalling that $t_{\rm form} \sim \omega/k_t^2$ the typical transverse momentum for a static medium

$$k_t^2 \simeq \int^{t_{\rm form}} d\xi \hat{q}(\xi) = \hat{q} t_{\rm form} \quad \Longrightarrow \quad k_t^2 \sim \sqrt{\omega \hat{q}} \tag{4}$$

defines a typical emission angle $\sin\theta \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$. Radiation is then suppressed for $\omega \lesssim \hat{q}^{1/3}$ [12]. For a very opaque medium (large $\hat{q}$) the typical radiation angle is large for small ω and reaches its maximum at the end of the phase space for $\omega \lesssim \hat{q}^{1/3}$. These estimations are independent on the length of traversed medium[1]

3. Inclusive particle suppression

Due to the different coupling to the emitted gluon, the quark energy loss is known to be smaller by a factor $C_F/N_C = 4/9$ than the gluon energy loss. Massive quarks are also known to lose less energy due to the *dead cone effect* [2] [19–22]. This translates into a quantified identity dependence of the nuclear modification factor R_{AA}, defined as the suppression with respect to the scaling with the number of collisions.

Experimental data on light-meson suppression for central AuAu collisions at RHIC are used in Fig. 1 to find the best value of the time averaged transport coefficient [23,24]. However, when the values of $\hat{q}$ exceed ~5 GeV^2/fm, R_{AA} is dominated by geometry and the sensitivity to the actual value of $\hat{q}$ is reduced (see Fig. 1). This surface emission [23–25] is originated by the steeply falling perturbative partonic spectrum which due to

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[1] Alternatively to the multiple soft scattering approximation, an expansion in scattering centers is often used [5,6]. In this case the emission angle decreases proportional to the length of traversed medium, implying more collinear radiation for larger in-medium pathlength.

[2] This name refers, originally, to the suppression of collinear emission in the vacuum due to mass terms. In the medium, the larger massive quark formation time leads to a *filling* of the already suppressed collinear region [20]. However, this small effect don't affect the discussion here.

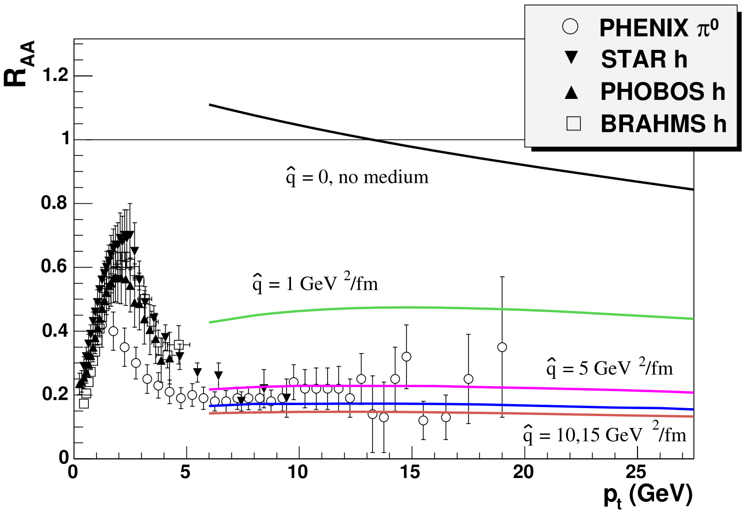

Figure 1. Nuclear modification factor R_{AA} for charged hadrons in central AuAu collisions at $\sqrt{s}$=200 GeV [23]. All data from Ref. [8] except preliminary PHENIX data from [9].

triggering in high-p_t particles select those which lose small amounts of energy. This is an intrinsic limitation of inclusive particle production for a precise measurement of the energy loss.

One way of improving the determination of the transport coefficient is by changing the identity of the parent parton, in particular via heavy quarks. Experimentally, a measurement of identified heavy mesons in nucleus-nucleus collisions has not been possible yet. A way out is to detect the weak decays of these mesons into electrons, whose spectrum is, at RHIC energies, expected to be the dominant contribution, once the photonic background is subtracted. In Fig. 3 the suppression factor for the electrons coming from decays of charm and beauty is computed [28] using the value of $\hat{q}$ obtained to fit the R_{AA} for light mesons. The total contribution of $c + b \to (e^- + e^+)$ is also computed in the FONLL approximation [29]. Interestingly the mass effects are found to be small for the charm quark and their suppression almost identical to that of light quarks [30]. Preliminary data presented at this conference [26,27] find a strong reduction of the non-photonic electron yields, compatible with that from the decays of charm quarks in Fig. 3. This could indicate a enlarged contribution of the charm spectrum as compared with the theoretical expectations given by FONLL [32], but probably compatible with proton-proton measurements [33]. Notice, that in this case, the mass dependence of the medium-induced gluon radiation cannot be access with this measurement and the identification of beauty mesons will be needed [30]. These theoretical uncertainties (see also [31]), as well as the experimental discrepancies reported at the conference [26,27] must be solved before a firm conclusion can be drawn.

4. Jets in heavy ion collisions?

The potential of high-p_t measurements as a tool to characterize the medium properties is not reduced to inclusive particles. The additional induced radiation modifies the

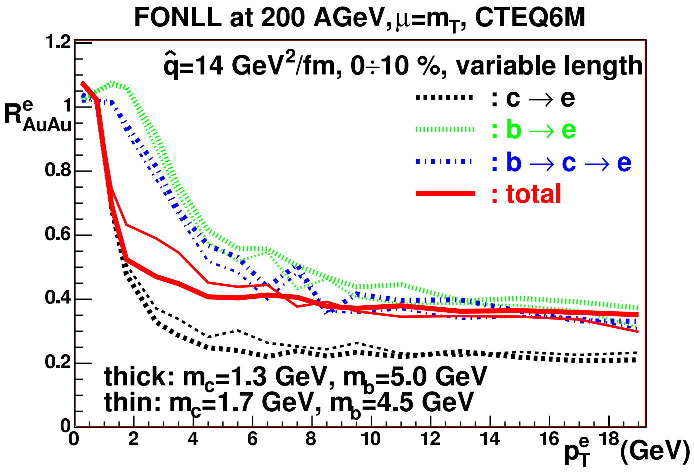

Figure 2. R_{AA} for electrons coming from the decay of charm quarks (black line) beauty (blue and green lines) and total (red) assuming the relative normalization of b and c as given by the FONLL approximation. The bands for each curve correspond to the uncertainty on the heavy quark masses.

structure of the branching process – which carries the signature of the medium – and can be measured as in-medium modification of jet properties. A main issue in jet reconstruction (even in more elementary collisions) is the energy calibration. The amount of energy deposited into a jet cone of radius $R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$ is affected by two opposite effects, namely the out-of-cone fluctuations (which increase with the cone radius) and the background fluctuations (which decrease with the cone radius). At RHIC an energy background of 20 GeV (50 GeV) is expected for jet radius R=0.3 (0.5) respectively for central AuAu collisions. The corresponding figures for the LHC are estimated to be $E^{\rm bg} \sim 100$ GeV (250 GeV). A proper subtraction of these large backgrounds remains the main challenge of jet measurements in heavy ion collisions. At the LHC [34], the different collaborations ALICE, CMS and ATLAS study different methods of background subtraction using moderate jet radius R = 0.3...0.5. From a theoretical point of view, it is, then, essential to identify jet observables in which the medium modification is not largely affected by the background.

In [18] the first study of this type of observables was performed. In particular a small broadening in the energy distributions inside a jet was found when computing the fraction $\rho(R)$ of the total jet energy deposited within a subcone of radius R. Physically, this means that the gluons emitted at larger angles are softer and unable to redistribute a sizable amount of energy. As a consequence, the additional out-of-cone fluctuations are not enhanced dramatically. This general result is independent on imposing small-p_t cuts to the observed associated radiation. If the jet energy distribution is not modified by medium-effects the different structure of the radiation should manifest in the multiplicity distributions. Indeed, a large broadening is seen in Fig. 4 for the additional number of medium-induced gluons as a function of their transverse momentum with respect to

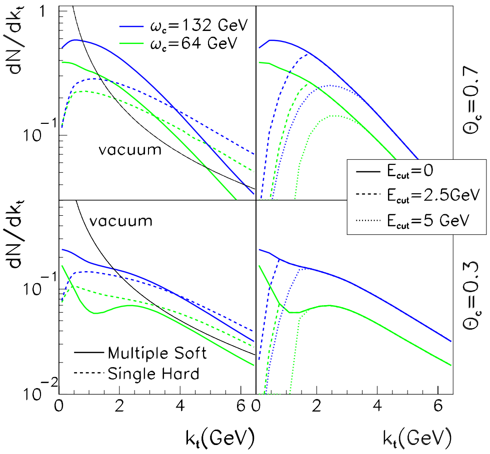

Figure 3. The gluon multiplicity distribution inside a cone size $R = \Theta_c$ as a function of the transverse momentum k_t with respect to the jet axis. In the two right panels the sensitivity to infrared cuts is shown to be small.

the jet axis. By imposing different cuts to the energy spectrum the sensitivity of this observable to background subtraction is shown to be small. It is worth noting that even though the present calculations lack of several physical mechanisms as hadronization etc, the main conclusions are independent on the actual realization of the model and are based solely on the general properties of the medium-induced gluon radiation; in particular the non-divergency of the spectrum in the infrared and collinear limits. These properties are given by formation time effects and kinematics.

4.1. Particle correlations: RHIC

At RHIC, where a complete jet reconstruction has not been possible, jet-like structures are measured by two-particle correlations. In this situation, the background subtraction is a complicated issue which makes the interpretation of the experimental data difficult in some cases. One clear step forward is the first measurement, presented in this conference, of correlations of particles with p_t above any significant background, namely $8 < p_t^{\rm trig} < 15$ GeV and $p_t^{\rm assoc} > 6$ GeV [35]. The results of this analysis indicates that the near-side peak is not suppressed, the away side is suppressed as much as R_{AA} and there is no evidence of broadening in any of them. Moreover, the distributions in $p_t^{\rm assoc}/p_t^{\rm trig}$ do not present any centrality dependence or difference with the ones in proton-proton. In the most natural interpretation, the observed particles come from vacuum fragmentation of parent partons which suffered small medium energy-loss. Two competing trigger-bias effects lead to this picture: on the one hand, the higher-p_t trigger particle is produced close to the surface, as explained previously, due to the large slope of the perturbative spectrum; on the other hand, for the same reason, the opposite jet is only observed in the case it suffers small energy loss, i.e. for small in-medium pathlengths. As a result, only those pairs produced close and *tangential* to the surface can be observed [25,36]. Calculations including the quenching weights defined in (3) with realist geometry confirm this picture [36]. From the point of view of the formalism, this measurement is able to constrain the probability of no-interaction in (3). Moreover, a small energy loss must show up as moderate energy ($\omega \lesssim \hat{q}^{1/3} \sim \mathcal{O}(1\text{ GeV})$) particles correlated with the pair. It would be interesting to measure this associated radiation by three-particle correlations provided the background subtraction is experimentally under control.

Removing the small-p_t cut-off. At RHIC a series of measurements try to reconstruct the spectrum of associated particles with small or moderate p_t. The most spectacular findings are in the away-side jet with the possibility of a two-peak structure [37,38]. This associated radiation was also found to be softer than in the vacuum [38]. The interpretation of these data is still not clear, and different mechanisms have been recently proposed [39] which couple dynamical medium properties to the jet structure. Let us simply mention here that these findings do not disagree with qualitative expectations from the medium-induced gluon radiation which, as explained, predicts softer spectra of associated particles and large angle emission for gluons with $p_t \sim \omega \lesssim \hat{q}^{1/3}$. A complete implementation of these effects is still missing; this leads us to our last subject:

5. Limitations and future developments

The formalism described in previous sections provide a nice description of experimental data. It presents, however, limitations related with both its range of applicability and the potential to study important dynamical properties of the medium. I will present here two lines of future research which, from my point of view, could improve the present limitations and be of primary importance for the LHC.

5.1. Improving the model of the medium

Hydrodynamical models [40] have revealed to be in nice agreement with experimental data from RHIC at small transverse momenta. They provide a consistent picture of the medium created in nucleus-nucleus collisions by means of the energy-momentum tensor

$$T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p g^{\mu\nu} \tag{5}$$

and an equation of state $p = p(\epsilon, t, \mu_B)$. If $T^{\mu\nu}$ is the fundamental object which describes the medium, it must determine $\hat{q}$. Theoretically, this relation should appear in the medium-averages of the Wilson lines describing the propagation of the high energy particles in the medium. In an exploratory study [41] we have proposed a modification of the scattering potential to take into account flow-induced gluon radiation. One observable consequence is the presence of asymmetric jet-shapes in the $\eta \times \phi$ plane with an elongation in the direction of the local flow (see Fig. 4). Preliminary data from the STAR collaboration shows an enhancement and elongation in the η-direction of the particle multiplicities associated to a high-p_t trigger [42] in qualitative agreement with the presence of a strong coupling of the medium-induced gluon radiation to the longitudinal flow. Similar effects are expected due to the transverse flow. To estimate them we generalize [41] the relation [43] $\hat{q} = c\epsilon^{3/4}(p)$ – where $\epsilon(p)$ is the equation of state – to $\hat{q} = c\epsilon^{3/4}(T^{n_\perp n_\perp})$, which can be written as a sum of a (symmetric) non-flow plus a (asymmetric) flow components $\hat{q} = \hat{q}_{nf} + \hat{q}_f(\mathbf{r})$. The presence of the flow component produces an additional energy loss, translating into additional suppression of inclusive yields, which affects the estima-

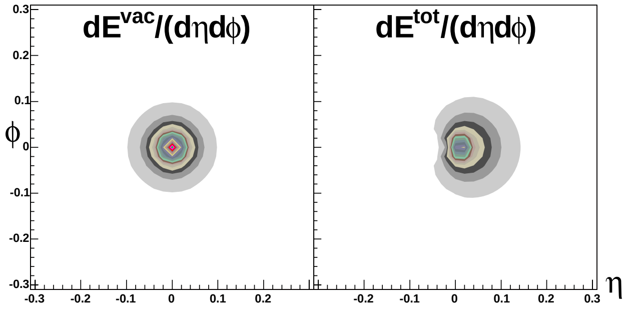

Figure 4. Jet energy distributions in the $\eta \times \phi$ plane for a 100 GeV jet for a non-flowing (left panel) and flowing (right panel) medium.

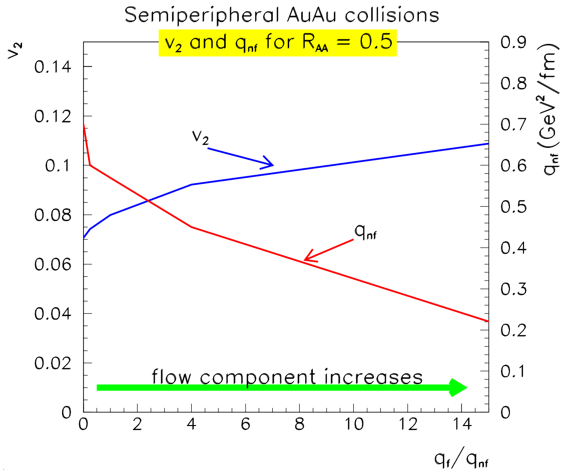

Figure 5. Dependence of v_2 and non-flow component for the same $R_{AA} = 0.5$ in semiperipheral AuAu collisions.

tion of the medium densities (non-flow component) as shown in Fig. 5. The asymmetric dependence of $\hat{q}_f$ on the azimuthal angle enhances moderately the value of v_2 as well.

5.2. Improving the shower evolution

In order to go beyond the independent gluon emission approximation given by the Poisson distribution (3) both energy constrains and the possibility of secondary branchings must be included. In the vacuum, the shower evolution as given by Sudakov form factors (2) provide a good description of the experimental data. For the medium, only a couple of attempts in this direction are available. On one hand, in a formal derivation [6] the medium effects are computed as higher-twist terms in a generalization of the DGLAP equations for the nuclear fragmentation functions in DIS. In this approach modified splitting functions are obtained which encode the main properties of the radiation as LPM suppression, etc. The generalization of this formalism to describe other jet properties has not been worked out yet. On the other hand, in an attempt to describe the associated radiation, an enhancement by a constant factor of the singular part of the vacuum splitting functions is proposed in [44]. In this simple approach a good description of R_{AA} is obtained together with a softening of the associated multiplicity spectrum.

6. Final comments

The value of the transport coefficient. The large value of $\hat{q}$ obtained by fits to the experimental data reported in previous sections deserves some interpretation. In [43] the transport coefficient for an ideal QGP gas was computed to be $\hat{q} = c\,\epsilon^{3/4}$ with $c_{QGP}^{\rm ideal} \simeq 2$. Assuming a Bjorken expanding medium the time averaged transport coefficient $\hat{q} = 5...15$ GeV^2/fm translates into a proportionality factor $c > 5\,c_{QGP}^{\rm ideal}$ [23]. This disagreement opens two interesting possibilities: recalling that $\hat{q}$ is not only proportional to the density of scattering centers but also to the individual scattering cross sections, the first possibility is that the propagating particles couple to the medium with cross sections at least five times larger than the pertubative ones – this interpretation goes in the line of strong non-perturbative effects in the medium [45,46]; a second possibility is that the presence of flow fields, which contribute to the energy loss as explained in previous section, affects the above estimates. Following this idea, in an recent work [47] the proportionality factor $c \sim 2$ is recovered when the flow field contribution to $\hat{q}$ as proposed in [41] is included.

In summary, RHIC has shown the potential of the high-p_t particles to characterize the medium properties with a quantified probe. The dialectic between experiment and theory opens a large window for new developments in which the interplay between the soft bulk and the hard part of the spectra will be exploited. We have outlined some of the main directions in which the formalism should be improved for a more complete characterization of the dynamical medium created in high energy heavy ion collisions. The qualitative new regimes of large virtuality accessible at the LHC will be an ideal situation for these studies.

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