Impact of temperature dependence of the energy loss on jet quenching observables

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Summary. — The quenching of jets (particles with $p_T \gg T, \Lambda_{QCD}$) in ultra-relativistic heavy-ion collisions has been one of the main prediction and discovery at RHIC. We have studied, by a simple jet quenching modeling, the correlation between different observables like the nuclear modification factor $R_{AA}(p_T)$, the elliptic flow $v_2$ and the ratio of quark to gluon suppression $R_{AA}(\text{quark})/R_{AA}(\text{gluon})$. We show that the relation among these observables is strongly affected by the temperature dependence of the energy loss. In particular the large $v_2$ and the nearly equal $R_{AA}(p_T)$ of quarks and gluons can be accounted for only if the energy loss occurs mainly around the temperature $T_c$ and the flavour conversion is significant. Finally we point out that the efficiency in the conversion of the space eccentricity into the momentum one ($v_2$) results to be quite smaller respect to the one coming from elastic scatterings in a fluid with a viscosity to entropy density ratio $4\pi\eta/s \approx 1$.

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1. – Introduction

The experiments at the Relativistic Heavy Ion Collider (RHIC) have given clear indications of the formation of Quark gluon plasma (QGP). One way to probe the QGP is to exploit the high energy jets ($p_T \gg T, \Lambda_{QCD}$) produced by the hard collisions at the initial stage. They are internal probes propagating through the fireball and interacting with the medium losing energy, hence carrying information on its properties as proposed long ago in Ref.s [1]. This energy loss can be quantified by the suppression of observed hadron spectra at high transverse momenta $p_T$, namely $R_{AA}(p_T)$ [2]. Although the observation of the jet suppression cannot be questioned there are several fundamental questions that still remain open. To investigate them we have constructed a model to study two observables beyond the $R_{AA}(p_T)$. One is the elliptic flow $v_2(p_T)$, that gives a measure of the angular dependence of quenching, and the other is $R_{AA}(q)/R_{AA}(g)$ that determines the flavor dependence of the suppression. We suggest that the study of the
correlation between $v_2(p_T)$ and $R_{AA}(q)/R_{AA}(g)$ carry information on the temperature dependence of the quenching and on the mechanism of parton flavor conversion. We find that an energy loss that increases as $T \to T_c$, the $q \leftrightarrow g$ in-medium conversion and an expansion-cooling of the fireball according to a lattice QCD EoS improve the agreement with the experimental data. Even if the $T$ dependence that has to be considered in the present modeling including only path-length energy loss appear to be too extreme.

2. – Modelling the jet quenching

In the model the density profile of the bulk is given by the standard Glauber model while the hard parton distributions in momenta space are calculated in the next-to-leading-order (NLO) pQCD scheme. For the hadronization the Albino-Kramer-Kniehl (AKK) fragmentation functions have been employed. For further details see Ref. [3]. With regard to the jets energy loss we have employed various schemes, however to make a connection to the large amount of effort to evaluate gluon radiation in a pQCD frame, we have used also the Gyulassy-Levai-Vitev (GLV) formula at first order in the opacity expansion [4, 5]:

$$
\Delta E(\rho, \tau, \mu) / \Delta \tau = \frac{9\pi}{4} C_R \alpha_s^2 \rho(x, y, \tau) \tau \log \left( \frac{2E}{\mu^2 \tau} \right)
$$

where $C_R$ is the Casimir factor equal to 4/3 for quarks and 3 for gluons, $\alpha_s$ is the strong coupling, $\rho(x, y, z)$ is the local density, $\tau$ the proper time, $E$ is the energy of the jet and $\mu = gT$ is the screening mass. There are corrections to Eq.(1) coming from higher order that can be approximately accounted for by a rescaling $Z$ factor of the energy loss. However this is not really relevant for the objectives of the present work because we will renormalize the energy loss in order to have the measured amount of suppression $R_{AA}(p_T)$ for central collisions. Usually in the GLV, as well as in other approaches, the temperature evolution of the strong coupling $\alpha_s$ is discarded. We will consider the impact of such a dependence to understand the amount of $T$ dependence coming simply from the asymptotic freedom. In the right panel of Fig.1 we show by dot-dashed and dashed lines the temperature dependence of the energy loss for the GLV with a dependence of the coupling(GLV-$\alpha_s(T)$) and with a constant coupling $\alpha_s = 0.27$ (GLVc). Furthermore we show two other opposite cases for $\Delta E/\Delta \tau$: the thick line that shifts the energy loss to lower temperature (hence low density $\rho$ or entropy density $s$) as suggested in [6, 7] and the other (thin line) that gives a dominance of quenching at high $T$, considered here just for comparison respect to the opposite case. We have applied our modelling of the jet quenching to Au+Au collisions at 200 AGeV and in the left panel of Fig.1 we can see that, once the $R_{AA}(p_T)$ at $0-5\%$ is fixed, the dependence on centrality is correctly predicted with a GLV formula for both constant and T-dependent $\alpha_s$. Hence looking at $R_{AA}$ one is not able to clearly discriminate the temperature dependence of the quenching and not even the details of the density profile [3].

3. – Angular and Flavor dependence of the Quenching

Generally, jet quenching modeling has not been able to simultaneously describe $R_{AA}$ and the elliptic flow $v_2$. In particular, experimental data relative to $v_2$ are considerably
larger than theoretical prediction. We have explored the relation between the temperature dependence of quenching and the value of the elliptic flow and in the left panel of Fig.2 we can see that even if the amount of total quenching has been fixed to the experimental value of $R_{AA}(p_T)$ the amount of elliptic flow is strongly dependent on the temperature dependence of the $E_{\text{loss}}$.

This correlation is due to the fact that at variance with $R_{AA}(p_T)$ the $v_2(p_T)$ has a longer formation time because the jets have to explore the shape of the fireball to

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**Fig. 1.** – Left panel: Nuclear Modification Factor as a function of the number of participant in $Au + Au$ at 200 AGeV [8]. Right panel: Temperature dependence of the energy loss for a parton with transverse momentum $p_T$ equal to 10 GeV. Dashed and dot-dashed lines represent the GLV energy loss with constant and $T$ dependent $\alpha_s$ coupling (see text). The thick line is the case in which the energy loss takes place only closer to the phase transition and the thin line represents an opposite case in which the energy loss take place only at high temperature $T$.

**Fig. 2.** – Left panel: Elliptic Flow for pions ($b=7.5$ fm) coming from quark and gluon fragmentation for the different $T$ dependence of the energy loss as shown in the right panel of Fig.1. The shaded area shows the experimental data [8, 9]. Right panel: Ratio of quark to gluon $R_{AA}$ for the different $T$ dependence of the energy loss as shown in the right panel of Fig.1. The shaded area approximatively shows the value expected for the ratio according to experimental observations and using the AKK fragmentation function.
realize its asymmetry. Therefore it seems to be quite likely that experiments are telling us that quenching does not take place mainly at the very early time (temperature) of the collision but mainly at later times close to the phase transition. This would mean that the quenching is not proportional to the density (or entropy density) but a decreasing function of it with a maximum at \( T \sim T_c \). This is what is essentially discussed also in Refs.\([6, 7]\) where however it was implicitly assumed that the amount of quenching of quarks and gluons are equal among them and to the hadronic one. Here we have modified such assumptions showing that the temperature (or entropy density) dependence of \( E_{\text{loss}} \) modifies not only the \( v_2(pT) \) but also the relative amount of quenching of quarks and gluons.

### 3.1. Quark to Gluon Modification Factor

Due to its SU(3) Lie algebra the energy loss of gluons is \( \frac{9}{4} \) larger than the quark one. For this reason sometimes it is assumed that the ratio between the quark and gluon suppression \( (R_{AA}(q)/R_{AA}(g)) \) is equal to \( \frac{9}{4} \). From this one would think that the (anti-)protons are more suppressed respect to pions because they come more from gluon fragmentation than from quarks fragmentation respect to pions, at least according to the AKK fragmentation function we employ. The data at RHIC however have shown that even outside the region where coalescence should be dominant \([10, 11]\) the protons and the antiprotons appear to be less suppressed than the pions and \( \rho^0 \) \([12, 13]\). Again we can see that going beyond the simple amount of quenching given by \( R_{AA}(p_T) \) both the azimuthal dependence and the flavor dependence of the quenching appear to be in disagreement with the data. We call this open issues the "azimuthal" and the "flavor" puzzle respectively. We will show that even if \( R_{AA} \) for central collisions is fixed to be \( \sim 0.2 \) the \( R_{AA}(q)/R_{AA}(g) \) is significantly affected by the temperature dependence of \( E_{\text{loss}} \).

In the right panel of Fig. 2 we show the ratio of the \( R_{AA}(q)/R_{AA}(g) \) for four different temperature dependences of the energy loss \( E_{\text{loss}} \), as in Fig. 1 (right). We can see that the standard GLVc energy loss does not give the expected ratio \( \frac{9}{4} \) for \( R_{AA}(q)/R_{AA}(g) \) but a lower value, around 1.8, which represents already a non negligible deviation from 2.25. We can however see that if the energy loss would be strongly \( T \) dependent and dominant in the \( T \sim T_c \) region \( R_{AA}(q)/R_{AA}(g) \) can increase up to about 2.2 on the contrary, if it is dominant in the high temperature region (thin solid line) the \( R_{AA}(g)/R_{AA}(g) \) can become as small as 1.5.

To understand this behavior is useful to consider the left panel of Fig. 3 where the transverse momentum distribution of initial parton and those obtained if all partons lose the same amount of energy (3 GeV and 4 GeV in the dotted and dot-dashed line, respectively) are shown. The effect of the quenching in this oversimplified case is to shift the spectra by a quantity equal to the amount of energy loss in a way indicated by the black arrow. Because of the rapid falling distribution the spectra after quenching are in these cases one order of magnitude smaller respect to the initial one. Therefore the 10\% of the spectrum without quenching, indicated by the thin line, is comparable to the spectrum in the case of \( E_{\text{loss}} = 3-4 \) GeV. This means that if there are particles that lose a very small quantity of energy, like in the case of quenching at high temperature, they strongly influenced the final spectra for both quarks and gluons and damping the difference between the \( R_{AA} \) of quarks and gluons. For energy loss dominated by low temperature all particles lose energy and this increases the difference between the respective \( R_{AA} \). A similar effect could come not only from the \( T \)-dependence of \( E_{\text{loss}} \) but from a core-corona effect \([14]\). For further explanations see Ref. \([3]\).
4. – Correlation between \( R_{AA}(q)/R_{AA}(g) \) and elliptic flow

We have seen (Fig. 2, left and right panel) that an energy loss predominant at low \( T \) move \( v_2 \) toward observed data but move also the ratio \( R_{AA}(q)/R_{AA}(g) \) away from experimental indications. This is evident if one looks at the upper symbols of Fig. 3 (right) where \( R_{AA}(q)/R_{AA}(g) \) vs \( v_2 \) is shown. To solve the "flavor puzzle" inelastic collisions that cause a change of the flavor has been invoked [15, 16, 17]. Such a process would at the end produce a net conversion of quarks into gluons. Hence a decrease of gluon suppression respect to the original suppression and an increase of the quark one. In Ref.[15] it has been calculated the conversion rate of a quark jet to a gluon jet and vice versa due to two-body scatterings. An enhancement factor \( K_c = 4 - 6 \) that accounts for non-perturbative effect is needed to produce a nearly equal suppression of quarks and gluons. We have included such a mechanism in our model. The results are the lower symbols in the right panel of Fig 3. We can see that the \( q \leftrightarrow g \) conversion does not affect the \( v_2 \) and allows to get closer to the experimental observed value, i.e. a \( v_2 \sim 0.1 \) and an \( R_{AA}(q)/R_{AA}(g) \leq 1 \) (to account for the \( R_{AA}(p + \bar{p}) > R_{AA}(\pi^+ + \pi^-) \) with AKK fragmentation function).

5. – Impact of the Equation of State

As a last point, we have observed that if the quenching is predominant near the phase transition the question of the correct equation of state arises. In fact the free gas approximation is no longer a reasonable approximation just close to \( T_c \). We have made some explorative studies on the impact that a more correct equation of state (EoS) can have on the correlation between \( R_{AA}(q)/R_{AA}(g) \) and \( v_2(p_T) \). Making a fit to the lattice QCD data [18] we have obtained the following relation between density and temperature

\[
\frac{T}{T_0} = \left( \frac{\rho}{\rho_0} \right)^{\beta(T)}
\]
where $\beta(T) = 1/3 - a(T_c/T)^n$ with $T \geq T_c$, $a = 0.15$ and $n = 1.89$ and of course for $T >> T_c$ one gets $\beta \sim 1/3$. In order to estimate the impact of this correction we have performed a simulation for the $\Delta E_{\text{loss}}(T)$ behavior represented by the thick solid line in the left panel of Fig.1 which is similar to the delayed energy loss proposed by Pantuev [6] as a solution for the observed large elliptic flow. We consider only this case because it is of course the one that is much more affected by the modification implied by Eq.(2). The results are given by open symbols in the right panel of Fig.3. Respect to the free gas expansion cooling the system spends more time at $T \sim T_c$. This reflects in a further enhancement of both $v_2(p_T)$ and efficiency of the $q \leftrightarrow g$ conversion moving the two observables closer to experimental data (shaded area in Fig.3 (right))

As a last point we want to mention the issue of the efficiency of conversion of initial spatial asymmetry $\epsilon$ into a $v_2$, namely the $v_2/\epsilon$. In the left panel of Fig.4 we show the different values of $v_2/\epsilon$ that one obtains through the simple path-length mechanism studied with our modeling, noticing that it is at maximum $v_2/\epsilon \leq 0.25$. In the right panel of Fig. 4 we show the $v_2/\epsilon$ coming from elastic scattering in a cascade approach for a fluid at finite shear viscosity to entropy density $4\pi\eta/s = 1$ [20]. Even if at slightly lower $p_T$ the $v_2/\epsilon$ in this case is about a factor of two larger. This seems to indicate that a proper treatment of elastic energy loss can give an important contribution at least at intermediate $p_T \sim 4 - 6$ GeV where presently the experimental data on $v_2$ are available.

6. Conclusions

We have pointed out the impact of peculiar temperature dependences of the energy loss on the elliptic flow and on the ratio between the quark and gluon suppression and their correlation. Moreover we have spot the relevance that the $EoS$ may have in case of $E_{\text{loss}}$ dominant in the $T \sim T_c$ region. In any case our study, although already revealing several interesting indications, is mainly explorative and it can be considered as a benchmark. A more quantitative analysis should be performed with more sophisticated
models that include the energy loss fluctuations, realistic gain and loss processes, elastic energy loss and a more accurate description of the bulk. Furthermore it should be explored if mass dependent formation time can affected the correlation between $v_2$ and $R_{AA}(g)/R_{AA}(a)$ [21]. Obviously, it is also important to study how the longer lifetime and higher temperatures which will be reached at LHC energies could affect the observed correlations.

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