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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 $R_{AA}(quark)/R_{AA}(gluon)$. 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 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 efficency in the conversion of the space eccentricity into the momentum one (v_2) results to be quite smaller with respect to the one coming from elastic scatterings in a fluid with a viscosity-to-entropy density ratio $4\pi\eta/s = 1$.

PACS 12.38.Mh – Quark-gluon plasma.
PACS 25.75.-q – Relativistic heavy-ion collisions.
PACS 25.75.Ld – Collective flow.

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. [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 increase 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-lenth energy loss appear to be too extreme.

2. – Modeling 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]:

$$(1) \qquad \frac{\Delta E(\rho, \tau, \mu)}{\Delta \tau} = \frac{9\pi}{4} C_R \alpha_s^3 \rho(x,y,\tau)\, \tau \log\left(\frac{2E}{\mu^2 \tau}\right),$$

where C_R is the Casimir factor equal to $4/3$ for quarks and 3 for gluons, α_s is the strong coupling, $\rho(x,y,z)$ is the local density, τ 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 α_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 ρ 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 with 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 α_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
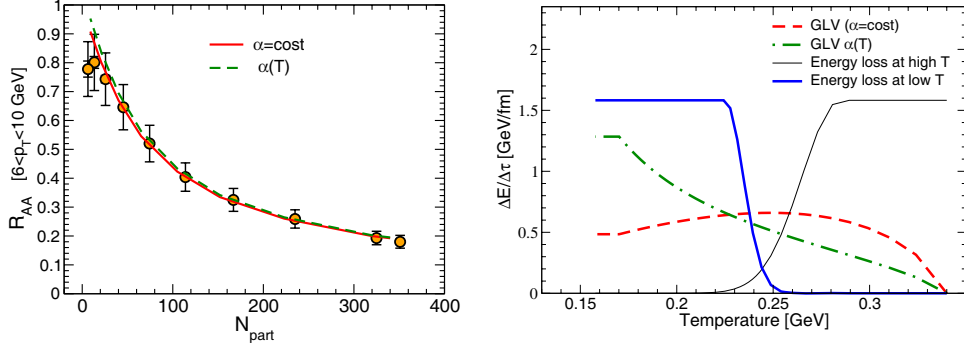
Fig. 1. – Left panel: nuclear modification factor as a function of the number of participants in Au + Au at 200 AGeV [8]. Right panel: temperature dependence of the energy loss for a parton with transverse momentum p_T equal to 10 GeV. Dashed and dot-dashed lines represent the GLV energy loss with constant and T-dependent α_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 takes place only at high temperature T.

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_{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 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
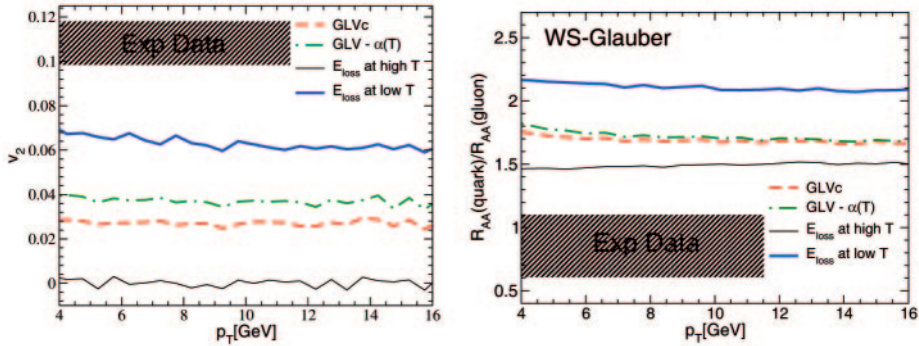

Fig. 2. – Left panel: elliptic flow for pions ($b = 7.5$ fm) coming from quark and gluon fragmentation for the different T-dependence of the energy loss as shown in the right panel of fig. 1. The shaded area shows the experimental data [8,9]. Right panel: ratio of quark to gluon R_{AA} for the different 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.

that the quenching is not proportional to the density (or entropy density) but it is 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 amounts of quenching of quarks and gluons are equal to each other as well as to the hadronic one. Here we have modified such assumptions showing that the temperature (or entropy density) dependence of E_{loss} modifies not only the $v_2(p_T)$ 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 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 9/4. From this, one would think that the (anti-)protons are more suppressed with respect to pions because they come more from gluon fragmentation than from quarks fragmentation with 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 ρ^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 ~ 0.2 the $R_{AA}(q)/R_{AA}(g)$ is significantly affected by the temperature dependence of E_{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_{loss}, as in fig. 1 (right). We can see that the standard GLVc energy loss does not give the expected ratio 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 $R_{AA}(q)/R_{AA}(g)$ can become as small as 1.5.

To understand this behavior it 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 quenchig are in these cases one order of magnitude smaller with 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 $E_{loss} = 3$–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 influence 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_{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 moves v_2 toward observed data but moves also the ratio $R_{AA}(q)/R_{AA}(g)$ away from
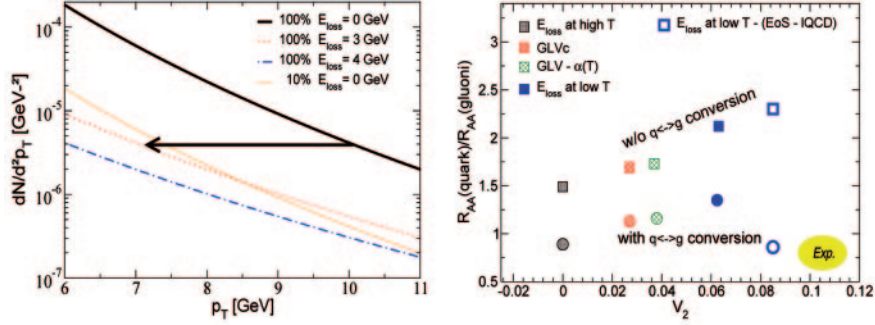
Fig. 3. – Left panel: spectra for partons that lose a fixed amount of energy (see text). Right panel: correlation between the $R_{AA}(q)/R_{AA}(g)$ and the elliptic flow of pions with transverse momentum in the range $6 < p_T$ (GeV) < 10. The squares refer to calculation without jet conversion while the circles are the values obtained including jet conversion with a $K_c = 6$ factor.

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 [15-17]. Such a process would at the end produce a net conversion of quarks into gluons. Hence a decrease of gluon suppression with 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:

$$\frac{T}{T_0} = \left(\frac{\rho}{\rho_0}\right)^{\beta(T)},$$

(2)

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 $T \gg T_c$ one gets $\beta \sim 1/3$. In order to estimate the impact of this correction we have performed a simulation for the $\Delta E_{loss}(T)$ behavior represented by the thick solid line in the right 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
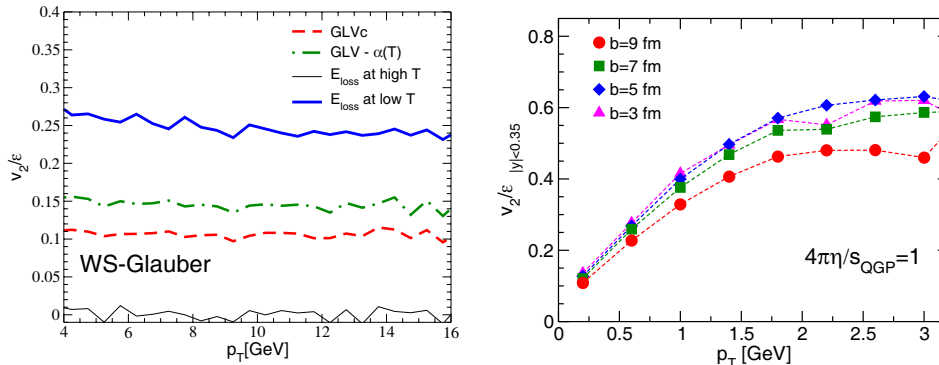
Fig. 4. – Left panel: ratio between the elliptic flow and the eccentricity v_2/ϵ as a function of the transverse momentum p_T of pions produced in collision with impact parameter equal to 7.5 fm for different temperature dependence of the energy loss, as shown in the right panel of fig. 1. Right panel: v_2/ϵ as a transverse momentum function estimated in a parton cascade approach ref. [19] at different impact parameters.

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. With 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 efficency 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 asimmetry ϵ into a v_2, namely the v_2/ϵ. In the left panel of fig. 4 we show the different values of v_2/ϵ 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/ϵ coming from elastic scattering in a cascade approach for a fluid at finite shear viscosity to entropy density $4\pi\eta/s = 1$ [19]. Even if at slightly lower p_T the v_2/ϵ 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 spotted the relevance that the EoS may have in case of E_{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 the mass-dependent formation time can affect the correlation between v_2 and $R_{AA}(q)/R_{AA}(g)$ [20]. 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.

REFERENCES

[1] GYULASSY M. and PLUMER M., *Phys. Lett. B*, **243** (1990) 432; WANG X. N. and GYULASSY M., *Phys. Rev. Lett.*, **68** (1992) 1480.
[2] ADAMS J. *et al.*, *Nucl. Phys. A*, **757** (2005) 102; ADCOX K. *et al.*, *Nucl. Phys. A*, **757** (2005) 184.
[3] SCARDINA F., DI TORO M. and GRECO V., *Phys. Rev. C*, **82** (2010) 054901.
[4] GYULASSY M., VITEV I. and WANG X. N., *Phys. Rev. Lett.*, **86** (2001) 2537.
[5] GYULASSY M., VITEV I. and ZHANG B. W., arXiv:nucl-th/0302077; WANG X. N., *Nucl. Phys. A*, **750** (2005) 98.
[6] PANTUEV V. S., *JETP Lett.*, **85** (2007) 104.
[7] LIAO J. and SHURYAK E., *Phys. Rev. Lett.*, **102** (2009) 202302.
[8] ADLER S. S. *et al.* (PHENIX COLLABORATION), *Phys. Rev. C*, **76** (2007) 034904; *Phys. Rev. Lett.*, **101** (2008) 232301.
[9] AFANASIEV S. *et al.* (PHENIX COLLABORATION), *Phys. Rev. C*, **80** (2009) 054907.
[10] FRIES R. J., GRECO V. and SORENSEN P., *Ann. Rev. Nucl. Part. Sci.*, **58** (2008) 177.
[11] GRECO V., *Eur. Phys. J. ST*, **155** (2008) 45; GRECO V., KO C. M. and LEVAI P., *Phys. Rev. Lett.*, **90** (2003) 202302; *Phys. Rev. C*, **68** (2003) 034904.
[12] SICKLES A., *Nucl. Phys. A*, **830** (2009) 131c.
[13] XU Y. *et al.*, *Nucl. Phys. A*, **830** (2009) 701c; RUAN L. *et al.*, *SQM2009 Proceedings*, nucl-ex/1001.3347.
[14] BECATTINI F. and MAMMINEM J., *Phys. Lett. B*, **673** (2009) 19.
[15] LIU W., KO C. M. and ZHANG B. W., *Phys. Rev. C*, **75** (2007) 051901.
[16] LIU W. and FRIES R. J., *Phys. Rev. C*, **77** (2008) 054902.
[17] LIU W. and FRIES R. J., *Phys. Rev. C*, **78** (2008) 037902.
[18] KARSCH F. *et al.*, *Nucl. Phys. A*, **698** (2002) 198; KATZ SD. *et al.*, arXiv:hep-ph/0511166.
[19] GRECO V., COLONNA M., DI TORO M. and FERINI G., *Nucl. Phys. A*, **834** (2010) 273C; *Prog. Part. Nucl. Phys.*, **62** (2009) 562, arXiv:0811.3170v1 [hep-ph].
[20] MARKERT C. R., BELLWIED R. and VITEV I., *Phys. Lett. B*, **669** (2008) 92.