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Jet Quenching: A Fresh Look at the Energy Loss Scenario

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Abstract: The popular energy loss scenario explaining the observed suppression of hadrons produced *via* in-medium hadronization relies upon poorly justified assumptions. First, one assumes that hadronization and energy loss are continuing through the whole medium and ends far outside. Second, the standard prescription for incorporating energy loss induced by multiple interactions in the medium is to make a shift of the variable in the fragmentation function. This implies that the hadronization starts only at the medium surface. In this note we challenge the latter assumption. We calculate the upper bound for the modification of the fragmentation function *via* the medium driven DGLAP evolution. The effects are found to be too week to explain available data and quite different from what is predicted by the standard energy loss scenario.

Keywords: Heavy ions, QCD, energy loss, suppression, perturbative.

1. RADIATIVE ENERGY LOSS, VACUUM AND MEDIUM-INDUCED

It was proposed by Gyulassy and Plümer [1] that suppression of high-p_T hadron production in heavy ion collisions may serve as a sensitive probe, called jet quenching, for the created dense medium. Indeed, a very strong effect has been detected in the experiments at RHIC [2, 3].

Such a probe may be effective only if the theoretical description of the effect is reliable and is tested somewhere else. However, the current interpretation of the observed effect is still controversial. The most popular model relates the observed suppression to the energy loss induced by final state interaction (FSI) of high-p_T partons in the dense medium. This model is based on a assumptions which have never been proven. In this note we examine and challenge one of them, the way how the induced energy loss is implemented into the medium-modified fragmentation function.

We calculate the upper bound for this modification assuming a constant and maximal rate of induced energy loss in the medium. In this case the influence of the medium is equivalent to a shift in the scale of the fragmentation function. Relying on the DGLAP evolution we calculated the fragmentation function in the medium and found modifications which are far too weak in comparison with the results of the energy loss scenario.

To test theoretical models in a more certain situation, a dedicated measurement with the HERMES spectrometer of hadron attenuation in DIS on nuclei was proposed in [4, 5]. The medium properties and jet kinematics are known in DIS much better than in heavy ion collisions. The results of the HERMES experiment are in good agreement with the predictions [4, 5] based on a dynamical model for hadronization. At the same time, the postdictions of the energy loss scenario failed to explain the data for ratios at large $z_h > 0.5$ [6].

1.1. Vacuum Energy Loss

A parton experiencing a kick of strength p_T shakes off a part of its color field up to transverse momenta $k_T \sim p_T$. The spectrum of radiated gluons was calculated by Gunion and Bertsch in Born approximation [7],

$$x\frac{dn_g}{dx d^2k_T} = \frac{3\alpha_s}{\pi^2}\frac{p_T^2}{k_T^2(\vec{k}_T - \vec{p}_T)^2}, \quad (1)$$

where x is the fraction of the parton momentum carried by the gluon. In this process the color current flows between the fragmentation regions of the colliding particles and radiates gluons through the whole rapidity interval forming a plateau. However, this happens only if $p_T \neq 0$, i.e. a color current which switches from the forward to backward direction along the same line does not radiate. This is different from an electromagnetic current. Such a property is a manifestation of nonabeliance and is important for further applications.

The gluon radiation does not happen instantaneously. The Weitzäcker-Williams gluons accompanying the parton are considered as a part of the parton, unless the coherence between them breaks down. Then one may say that those incoherent gluons are radiated carrying away a fraction of the parton energy. This does not happen instantaneously, but takes time called coherence time,

$$t_c = \frac{2Ex(1-x)}{k_T^2 + x^2\mu^2}, \quad (2)$$

where μ and E are the parton mass and energy. In other words, one may say that the amplitudes for radiation of two

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identical gluons add up coherently if they are radiated within the time interval $\Delta t < t_c$.

Thus, gluons with different transverse momenta and energies are emitted at different times and this process takes long time proportional to the initial parton energy. This looks like a delayed result of the initial hard kick to the parton. No medium is needed, this process takes place in vacuum. During this time interval the parton is gradually losing energy with the rate which we label as vacuum, $(dE/dt)_{vac}$.

How much energy is radiated in vacuum over time interval t? One should count only the gluons whose radiation time $t_c < t$, therefore,

$$\Delta E_{vac} = E\int d^2k\int_0^1 dx x\frac{dn}{dxd^2k}\Theta(t-t_c) = \frac{3\alpha_s}{2\pi}tQ^2 , \qquad (3)$$

where we use the spectrum Eq. (1) in the approximation of small x and k_T. The scale of the original hard reaction, Q^2, plays role of the upper cut off in the k_T distribution, like the momentum transfer p_T in (1).

According to (3), the rate of energy loss is constant,

$$\left(\frac{dE}{dt}\right)_{vac} = -\frac{3\alpha_s}{2\pi}Q^2 . \qquad (4)$$

This is a nontrivial result. Indeed, the rate of gluon radiation, $dn_g/dt \propto 1/t$, inversely decreases with time. Gluons are radiated with different energies, why is this process tuned to produce a constant rate of energy loss?

It is easy to understand this result, Eq. (4), just from consideration of the dimensions. The key observation is that this function is invariant relative longitudinal Lorentz boosts. For a massless parton, available dimensional qualities are E, t and Q^2. One might also think about Λ_{QCD}, but in perturbative calculations it comes only under log, so does not bring any dimension. Apparently, one cannot construct any Lorentz invariant combination of energy and time, only Q^2 is suitable. Therefore, up to the constant coefficient, relation (4) is unavoidable.

Thus, the rate of energy loss is independent of time like in the string model. This is a very nontrivial result: emission of gluons with different energies and transverse momenta is arranged in a way that amount of energy radiated per unit of time is constant. This was first derived in QED by Niedermayer [8] who also calculated the pre-factor, $\gamma_{QED} = \frac{1}{2\pi}\alpha_{em}$. Correspondingly, in QCD $\gamma_{QCD} = \frac{2}{3\pi}\alpha_s$.

The result Eq. (4) is quite intuitive: the stronger is the kick to the parton, the more gluons it shakes off, the larger is the rate of energy loss. This is why the rate Eq. (4) is proportional to Q^2.

1.2. Medium-Induced Energy Loss

If the hard reaction occurred inside a medium (e.g. in DIS on nuclei or in a dense matter created in heavy ion collision), the parton may experience few additional kicks while it is propagating and hadronizing inside the medium. Within a cold nuclear medium these kicks should be quite soft, but should be harder in a dense matter produced in heavy ion collisions. In both cases, however, they are much weaker than the original kick, and may be treated as a small distortion.

The extra loss of energy caused by these multiple kicks is usually called induced energy loss. Its rate also can be found basing on Lorentz invariance and dimension counting. In this case we acquire a new dimensional parameter, the density ρ of the medium. This gives a possibility to construct a new Lorentz invariant quantity, a product of time and density,

$$\left(\frac{dE}{dt}\right)_{ind} = -\kappa\rho t. \qquad (5)$$

This is a unique combination, since the Q^2 dependent vacuum term cancels in the difference $dE/dt - (dE/dt)_{vac}$. Of course, the factor κ may depend on Q^2.

Thus, the rate of energy loss inside the medium rises linearly with time (or length), why? Because the effective scale responsible for gluon radiation is increased by the transverse momentum gained by the parton traveling through the medium, i.e. $Q^2(t) = Q^2 + k_T^2(t)$. The transverse momentum accumulated in multiple interactions in the medium performs Brownian motion, therefore $k_T^2(t) \propto t$. Then, according to (4), the intensity of gluon radiation also rises with time as a sum of $(dE/dt)_{vac} + (dE/dt)_{ind}$ given by Eqs. (4) and (5) respectively. This is illustrated in Fig. (**1**) where we plotted schematically the time dependence of the rate of energy loss consists of the vacuum and induced parts.

The contribution of radiation induced by multiple interactions rises linearly with time up to the surface of the medium where it reaches the maximal value $-(dE/dt)_{ind}^{max} = \delta\rho L$ (here we assume ρ homogeneous, for the sake of simplicity). Then the accumulated transverse momentum remains unchanged, correspondingly, the rate of induced energy loss does not vary any more, since radiation of long-l_c gluons induced by multiple interactions in the medium is continuing. This goes well along with the Landau-Pomeranchuk principle [9], namely, gluons radiated at long times, i.e. having a long coherence time, do not resolve the structure of the interaction at the early stage. The radiation only "keeps memory" about the full kick to the parton, but does not resolve whether it was a single kick or a series of smaller kicks with the same accumulated strength.

Thus, the full amount of induced energy loss along a path of length l reads,

$$\Delta E_{ind}(l) = \kappa 2\rho l^2\,\Theta(L-l) + \kappa\rho L\left(\ell - \frac{1}{2}L\right)\Theta(l-L). \qquad (6)$$

Indeed, direct calculations in QCD by BDMPS [10] confirmed the quadratic l-dependence inside the medium

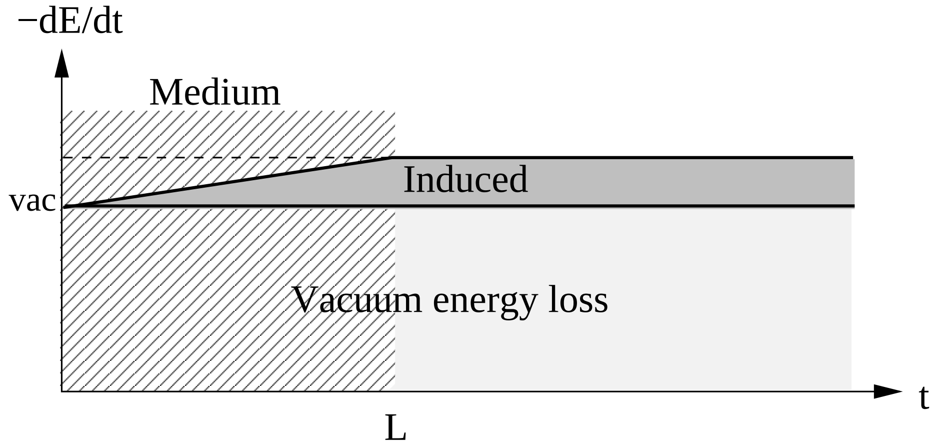

Fig. (1). The rate of energy loss as function of time. The horizontal thick line presents the time independent rate of vacuum energy loss. The induced energy loss generated by multiple collisions in the nucleus is shown by grey. This rate linearly rises with time within the medium and the stays unchanged outside.

with the pre-factor $\kappa = \frac{8}{3\pi}\alpha_s^2 G(x)$, where $G(x)$ is the gluon density at $x = (rE)^{-1}$, and r is the color screening radius for the medium.

Besides dimension counting, the L^2 dependence is easily understood intuitively. The random multiple kick acquired by the parton propagating through the medium add up quadratically to a total kick whose strength linearly rises with L (Brownian motion in the transverse momentum plane). Therefore, according to (4) the rate of energy loss also rises linearly with L, like in (5), and the full lost energy is proportional to L^2.

2. MODIFIED FRAGMENTATION FUNCTION

2.1. The Poor Man's Recipe

The hadronization process is characterized by the fragmentation function $D_i^h(z_h, Q^2)$ which is the probability for parton i to produce hadron h carrying fraction z_h of the initial parton light-cone momentum. According to QCD factorization this function is expected to be process independent and only controlled by the hard scale Q^2 of the reaction.

The standard energy loss scenario (see [11] and references therein) provides a prescription for medium-modification of $D_i^h(z_h, Q^2)$. The basic assumption of this approach is that the parton keeps radiating gluons and hadronizes outside the medium. This assumption having no good justification was already examined in [4, 5, 13-17] and found incorrect, at least in some instances[1]. Nevertheless, here we accept this assumption, but challenge another rudiment of the energy loss scenario. It is assumed in the standard energy loss scenario that induced energy loss precedes hadronization which starts from the surface of the medium. The corresponding recipe for modification of the fragmentation function explicitly employs this assumption (see e.g. [11] and references therein),

$$\tilde{D}_i^h(z_h, Q^2) = \int_0^1 \frac{d\varepsilon}{1-\varepsilon} W(\varepsilon) D_i^h\left(\frac{z_h}{1-\varepsilon}, Q^2\right), \tag{7}$$

where $W(\varepsilon)$ is the normalized probability to lose energy ε for induced radiation. According to this prescription, the induced energy loss reduces the initial energy available for hadronization, i.e. makes a shift in the argument of the fragmentation function, $z_h \Rightarrow z_h/(1-\varepsilon)$.

Energy loss is caused by hadronization, the former cannot precede the latter. This is an artificial and incorrect separation to the two stages: energy loss without hadronization followed by hadronization without energy loss.

One may wonder, why the medium surface, $t = L$ in Fig. (**1**) is chosen to start hadronization? If it started somewhat earlier or later, that would lead to dramatic variations in the predicted suppression. Apparently, this brings a sizeable ambiguity into the energy loss scenario.

Hadronization is initiated by the hard reaction and starts right away, deep inside the medium. The following multiple interactions in the medium affect the hadronization process, since they induce additional radiation. To solve the problem of modification of the fragmentation function due to multiple interactions one needs a detailed knowledge of the hadronization dynamics [4, 5, 13]. The results are of course quite model dependent.

2.2. Medium Induced DGLAP Evolution

This problem can be simplified and solved exactly, namely, let us assume that the rate of induced energy loss does not rise linearly within the medium, but reaches its maximal value $(dE/dt)_{ind}^{max}$ immediately after the hard reaction and then remains constant, as is shown by dashed line in Fig. (**1**). In this case the modification of the fragmentation function is rather obvious: the scale imposed by the hard reaction at the origin of hadronization must be increased,

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[1] We are interested in the time scale for the perturbative stage of hadronization when the parton is radiating gluons and losing energy. This stage cannot last long if $1 - z_h = 1$ and must end up early *via* color neutralization [12, 13, 16]. Only production of small-z_h hadrons takes long time as considered in [18].

$$\tilde{D}_i^h(z_h,Q^2)=D_i^h(z_h,Q^2+\Delta p_T^2), \tag{8}$$

where Δp_T^2 is the broadening of the transverse momentum of the parton propagating through the medium. The scale modification Eq. (8) is the only source of modification of the fragmentation function. Of course, this result of scaling violation includes the effect of induced energy loss, but there is no need to know how much energy is lost within the medium. Moreover, below we demonstrate that the standard procedure of modification of the fragmentation function *via* energy loss consideration is incorrect.

The fragmentation functions cannot be calculated perturbatively, but their variation with Q^2 is given by the DGLAP evolution and is calculable [19-21]. This is actually, what we need. Thus, the medium-modified fragmentation function reads,

$$\tilde{D}^h{}_i(z_h,Q^2)=D_i^h(z_h,Q^2)+\frac{\Delta p_T^2}{Q^2}\sum_j\int\limits_{z_h}^1\frac{dx}{x}P_{ji}[x,\alpha_s(Q^2)] \\ D_j^h(z_h/x,Q^2), \tag{9}$$

where $P_{ji}[x,\alpha_s(Q^2)]$ are the splitting functions calculated perturbatively.

The results of the DGLAP analysis of data for jet production were parametrized in [22] in the form suitable for practical implications. Then the ratio of medium to free fragmentation functions gets the simple form,

$$R(z_h,Q^2)\equiv\frac{\tilde{D}_i^h(z_h,Q^2)}{D_i^h(z_h,Q^2)}\approx\left[\frac{(1-z_h)^{\lambda_1}}{z_h^{\lambda_2}}\right]^{\frac{\Delta p_T^2}{Q^2\ln(Q^2/\Lambda^2)}}. \tag{10}$$

Here for pion production by light quarks the factor in the exponent corresponding to the NLO fragmentation function [22] reads,

$$\lambda_1(Q^2)=0.64+0.15\bar{s}-0.51\bar{s}^2 \\ \lambda_2(Q^2)=0.3+0.04\bar{s}+0.38\bar{s}^2 \tag{11}$$

with parameters fixed in [22],

$$\bar{s}=\ln\left[\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right], \tag{12}$$

where $Q_0^2=2\,GeV^2$, $\Lambda=213\,MeV$.

Broadening of p_T for a parton propagating through a medium was studied in [23] in the dipole approach. In terms of the universal dipole cross section, the broadening of a parton traveling in a medium reads [23, 24],

$$\Delta p_T^2=2T_A\frac{\partial\sigma_{\bar{q}q}(r,x)}{\partial r^2}=2T_AC(x,Q^2), \tag{13}$$

Here the thickness function T is given by an integral of the medium density along the parton trajectory, $T=\int dz\rho(z)$. Factor $C(x,Q^2)$ is fixed at the scale $r^2=1/Q^2$ characteristic for the problem under consideration. For small $r^2\sim1/Q^2$ this factor reads, $C(x,Q^2)=\frac{\pi^2}{3}G(x,Q^2)$, where $G(x,r^2)=xg(x,r^2)$ is the gluon density. For cold nuclear medium one can rely on the dipole cross section fitted to data for $F_2(x,Q^2)$ at small x [25]. Factor $C(x,Q^2)$ was calculated this way in [23].

In the case of nuclear target (DIS, high-p_T hadrons, ect.) the ratio should be averaged over impact parameter,

$$R_{A/p}(z_h,Q^2)=\frac{Q^2\ln(Q^2/\Lambda^2)}{2AC\ln[(1-z_h)^{\lambda_1}/z_h^{\lambda_2}]} \\ \int d^2b\left\{\left[\frac{(1-z_h)^{\lambda_1}}{z_h^{\lambda_2}}\right]^{\frac{2CT_A(b)}{Q^2\ln(Q^2/\Lambda^2)}}-1\right\}. \tag{14}$$

Here $T_A(b)=\int_{-\infty}^{\infty}dz\rho_A(b,z)$ is the nuclear thickness function, integral of the nuclear density along the parton direction.

We performed calculations for lead in order to enhance nuclear effects, and used the Woods-Saxon density. The results are depicted in Fig. (**2**) as function of z_h for different scales. The found nuclear effects are far too weak to explain the nuclear suppression observed in the HERMES experiment [26]. Moreover, Eq. (10) predicts an approximate z_h-scaling. The only source of a weak energy dependence is the slow rise of Δp_T^2, Eq. (13), with energy as is calculated in [23]. This is also in strict contradiction with the results of HERMES [26].

This is not a surprise, however, that the effects of induced energy loss alone cannot explain data. It was demonstrated in [4, 5, 13] that the hadronization time is short at the kinematics of the HERMES experiment, and the colorless dipole (pre-hadron) is mostly produced within the nucleus. This leads to a substantial nuclear suppression. One needs data at much higher energies to compare with Eqs. (10), (14). Indeed, EMC data [27] for inclusive hadron production in DIS at $E=145\,GeV$ demonstrate no nuclear suppression in a good accord with Fig. (**2**). Note, however, that even at this high energy the assumption of long production time fails at large $z_h\to1$ where no date are available so far.

In the case of high-p_T hadron production in heavy ion collisions, the scale $Q^2\sim p_T^2$ is quite large, but factor $1/Q^2$ in the exponent in (10) might be compensated by a high density of the created matter. Even if this happens, the scale increases with p_T leading to disappearance of hadron suppression at large p_T. This expectation is in strict contradiction with RHIC data [2, 3], and for a good reason: the time of perturbative hadronization is too short and is getting even shorter at higher p_T, $l_p\propto1/p_T$ [13].

2.3. Sudakov Suppression

Notice, that at $z_h\to1$ the ratio Eq. (10) can be represented as

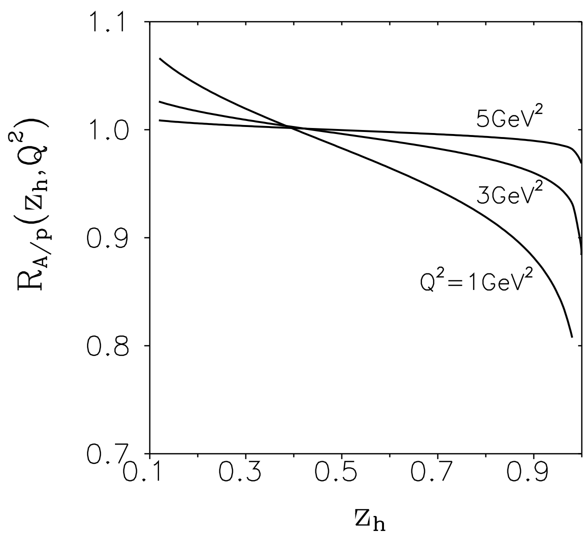

Fig. (2). Ratio of the medium-modified fragmentation function to the vacuum one for lead target at different scales Q^2.

$$R(z_h,Q^2)|_{z_h\to 1} \approx (1-z_h)^{\xi\langle n\rangle}, \qquad (15)$$

where $\langle n\rangle = \sigma_{\bar{q}q}(r^2 = 1/Q^2)\langle T_A(6)\rangle$ is the mean number of collisions in the medium; $\xi = 9\alpha_s\lambda_1/2\pi$. This result confirms the conjecture of Ref. [28] that in a large rapidity gap process (we do have such a process at $z_h \to 1$) every collision in the medium adds a Sudakov suppression factor. In our case this factor equals to $(1-z_h)^{\xi}$. This suppression is weaker than one found in [28], since that was for soft reactions.

3. CONCLUSIONS

The standard energy loss scenario for jet quenching relies upon two poorly justified assumptions: (i) the perturbative stage of hadronization, gluon bremsstrahlung, lasts longer than it takes to get out of the medium; (ii) gluon radiation induced by multiple interactions in the medium precedes the hadronization which start outside the medium. So, the induced energy loss results in a simple shift of the argument of the fragmentation function.

While the first assumption (i) was already challenged in [4, 5, 13], in this note we consider the second conjecture (ii) and find it quite incorrect. Our key observation is the following: as far as induced energy loss results from p_T broadening, its rate proportional to $\langle \Delta p_T^2\rangle$ linearly rises with the length of the path in the medium and reaches its maximum at the surface. The induced energy loss does not stop after wards, but is continuing in vacuum with a constant rate, as is illustrated in Fig. (**1**).

We found an upper bound for the effect of induced energy loss by means of replacement the linearly rising rate by a constant one at the maximal value reached at the medium surface. Then the hadronization pattern becomes identical to one in vacuum, but with an increased scale, $Q^2 \Rightarrow Q^2 + \Delta p_T^2$. Such a shift in the scale can be easily incorporated *via* DGLAP evolution. Although induced energy loss is not presented explicitly, it is an essential part of the DGLAP evolution and is responsible for the modification of the fragmentation function. This way of calculation, however, does not rely upon any *ad hoc* recipe.

We calculated the modified fragmentation function, Eq. (14), and found that the related nuclear effects are too weak to explain the nuclear suppression observed in DIS by the HERMES experiment. Besides, the predicted strong scale dependence is not supported by data on high- p_T hadron production in heavy ion collision. We conclude that the trouble in both cases is related to failure of the first assumption (i) mentioned above.

The prominent feature of the medium suppression Eqs. (10) - (15) is its scaling in z_h. This is in contrast to the standard energy loss scenario which predicts a strong variation of $R(z_h)$ with energy, since the shift of the argument of the fragmentation function, $\Delta z_h = \Delta E/E$ vanishes at high energies.

Notice that in the situations when the parton indeed hadronizes outside of the medium (e.g. DIS at small x_{Bj}) our upper bound for the medium induced modification of the fragmentation function, Eqs. (9)-(14), is close to reality. Indeed, if the coherence length, Eq. (2), of a radiated gluon is long, $l_c \gg R_A$, the probability of radiation of such a gluon is insensitive to the details of multiple interactions, but depends only on the strength of the total accumulated kick got by the parton from the original hard reaction and following collisions in the medium, all together . This is the heart of the Landau-Pomeranchuk suppression.

ACKNOWLEDGMENTS

This work was supported in part by Fondecyt (Chile) grants 1090236, 1090291 and 1100287, by DFG (Germany) grant PI182/3-1, and by Conicyt-DFG grant No. 084-2009.

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Received: April 24, 2010 Revised: July 19, 2010 Accepted: October 08, 2010