ENERGY LOSS OF HIGH $p_{\perp}$ HADRONS
BY FINAL HADRONIC STATE

K. GALLMEISTER, C. GREINER AND Z. XU

Institut für Theoretische Physik, Universität Giessen
Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

Abstract

In the context of the ‘jet quenching’ phenomena typically materialization of the jet is assumed to take place in vacuum outside the reaction zone. On the other hand quantum mechanical estimates give a hadronization time on the order of only a few fm/c for jets materializing into hadrons with transverse momenta of $p_{\perp} \leq 10 \text{ GeV}$, which thus should well take place inside the fireball. Typical (in-)elastic collisions of these high $p_{\perp}$ particles with the bulk of hadrons of the fireball have a rather low invariant mass and are thus nonperturbative. An analysis within an opacity expansion in the number of collisions by means of the FRITIOF collision scheme for various hadrons will be presented. It shows that late hadronic collisions can substantially account for the modification of the high $p_{\perp}$-spectrum observed for central collisions at RHIC.

1 Introduction: Qualitative estimates

As one of the very interesting first results, RHIC experiments have established a significant suppression of moderately high $p_{\perp}$ hadrons produced in central A+A collisions compared to rescaled peripheral collisions or rescaled (and extrapolated) p+p collisions [1]. The results are a clear hint for nuclear medium effect(s) at work.

The most popular explanation is the onset of the occurrence of so called ‘jet quenching’ [2]. It is the idea that a high energetic parton moving through a color dense (and then deconfined) medium will lose considerable energy most dominantly by gluon radiation, and so its final fragmentation will give rise to a leading hadron with considerable lower energy. A recent and much involved calculation based on the GLV formalism for a finite number of colored collisions (and including the Cronin effect as well as a slight modification of the gluon distribution due to shadowing) provide a good agreement with the data. Still, though, a phenomenological opacity parameter has to be adjusted [3]. It has
also been suggested that simple incoherent scattering in the further partonic

evolution of the fireball should be of relevance [4]. Contrary, also the proposal

was made that the observed spectra for central collisions show a significant

scaling being a manifestation of a direct remnant of the initial gluons

which were liberated from gluon saturated nuclear distribution functions [5].

Here, any possible final state interactions which might or should alter the

distributions are completely discarded.

A major concern, and which lead to the present study, is that it is typically

assumed in all these descriptions that the partons somehow exits the collision

region before finally fragmenting into a ‘jet’ of hadrons. The potential magni-

tude of the hadronization time (or, to be more precise, the time to build

up the hadronic wavefunction) is based on a relativistic and simple quantum

mechanical estimate for (a) light or (b) heavy quarks [6]

\[
(a) \quad t_{Q}^{hadr} \approx E R^2 \quad \leftrightarrow \quad (b) \quad t_{Q}^{hadr} \approx \frac{E}{m_Q} R .
\]

Taking (a) with the average radius of the pion \( R_\pi \approx 0.5 \) fm or (b) substituting

\( m_Q \) by \( m_\rho \) for a \( \rho \)-meson and taking \( R_\rho \approx 0.8 \) fm, one has for the formation
time a crude understanding given as

\[
t_F \approx 1 - 1.2 \left( \frac{E}{GeV} \right) \times fm/c . \tag{1}
\]

Hence, for leading hadrons with moderately high \( p_\perp \leq 10 GeV \) original point-

like jet-partons have established already a complete nonperturbative, transver-
sal wavefunction after traveling a distance in length of smaller or equal than

10 fm. Accordingly, the jets should, to a large fraction, materialize into

hadrons still inside the expanding fireball, which has a transversal size of

\( R \approx 8 fm + 0.5 \times ct \), where \( t \) denotes the local proper time of the expanding

system.

The state becoming the leading hadron will interact as a (pre-)meson with

the surrounding low momentum mesons with a cross section of roughly

\( \sigma(t) = \sigma_0 \times \left( t/t_F \right) \) as long as it is not completely being build up [3]. \( \sigma_0 \approx 10 - 15 mb \)
denotes the total cross section of two mesons. The density of hadrons in the

late fireball changes from about 1 \( fm^{-3} \) to 0.1 \( fm^{-3} \). The mean free path of the

fast hadron is then estimated to be \( \lambda \approx 1 - 10 \) fm, meaning a few collisions

\( L/\lambda = 0, 1, 2, 3 \ldots \) The system is potentially rather opaque!

Looking at the available energy for an individual collision (compare Fig. 1),
even for a value of \( p_\perp = 10 GeV \), one gets a \( \sqrt{s} < 2 \) GeV, if the target is a

pion at rest, and only with a \( \rho \) as target, one has an invariant mass of above

2.5 GeV for particles with a transverse momentum larger than 3 GeV.
Fig. 1: The CMS energy for three targets at rest ($\pi, K, \rho$, depicted by the labels near the curves) and three types of projectiles ($\pi, K, n/p$, indicated by the solid, dashed and long dashed lines) as function of the momentum of the projectile.

Hence, for the considered transverse momentum region, one has either elastic scattering, resonance scattering or also inelastic scattering resulting in a few final hadrons. In the following we treat the collision with the FRITIOF Monte-Carlo scheme with a $\rho$-meson as characteristic target hadron being at rest. To also stress some model dependence, we later compare with elastic scattering on either a $\rho$ or a $\pi$ as target particles, where the scattering is taken simply as isotropic [7].

2 Energy loss by (multiple) final state hadronic interactions

The energy loss for one single interaction of a leading hadron $i$ with momentum $p_{\bot 0}$ on a low transverse momentum target (taken as $\approx 0$, and both hadrons being located at the same space-time rapidity and momentum rapidity in a Bjorken-type picture), going into a hadron $j$ with (lower) momentum $p_{\bot}$ can be written as

$$f_j(p_{\bot}) = \sum_i \int dp_{\bot 0} \ f^0_i(p_{\bot 0}) \ g_{ij}(p_{\bot 0}, p_{\bot}),$$

while $f^0_i(p_{\bot 0})$ is the initial distribution, $g_{ij}(p_{\bot 0}, p_{\bot})$ is a folding matrix and $f_j(p_{\bot})$ is the resulting distribution. $i, j$ stand for the particles $\pi^0, \pi^\pm, K^0, \bar{K}^0, K^\pm, p, \bar{p}, n$ and $\bar{n}$. The folding matrix $g_{ij}$ depends on the model employed for the collision (for further details we refer to [7]).
For the initial distribution $f_0^i$ of individual hadrons $i$ at moderately high $p_\perp$ when entering the final hadronic stage we have no direct information. All various ideas, as mentioned at the beginning, might contribute and already steepen the spectrum. In order to see the possible effect of the late hadronic interactions, we use individual distributions generated by PYTHIA v6.2. The parameters were first adjusted to UA1-results of $p\bar{p}$-collisions. Isospin averaged N-N-collision were then calculated (for details we refer to [7]). With the appropriate scaling of binary collisions ($N_{coll} = 2.4$ for $80\ldots92\%$, $12.6$ for $60\ldots80\%$ and $945$ for $0\ldots5\%$ centrality), the calculations are in perfect agreement with the preliminary PHENIX data for charged hadrons  and for neutral pions in the case of peripheral collisions, as can be seen from Figs 2 and 3.

Moreover, one can see a dramatic effect when employing on average one single final inelastic collision modelled via the FRITIOF scheme. In case of the charged hadrons, one single collision already would slightly overestimate the suppression. On the other hand one collision is just right to perfectly explain quantitatively the modification of the momentum distribution of the $\pi_0$! (We have only shown the modifications for $p_\perp > 2$ GeV, as the spectrum below should be dominated by soft physics and hydrodynamical expansion.)
Hence, any potential energy loss by final state hadronic reactions is in the same range as considered for the jets in deconfined matter. In Fig. 4 we show calculations for various number of collisions now at a $\sqrt{s_{NN}} = 200$ GeV up to $p_T = 10$ GeV. The three employed models (for treating the collisions) do give more or less similar predictions. The spectrum steepens considerably for a larger effective opacity $< L/\lambda >$. On the other hand at some stage the complete evolution of all hadronic particles has to be incorporated to see in full detail the dynamical interplay among ‘soft’ and ‘hard’ hadrons. The spectrum can not become more steepe than exponential as then the system has thermalized also in the high $p_T$ hadronic degrees of freedom.

In summary, we have motivated that (pre-)hadrons stemming from a jet should still materialize in the dense system for momenta up to 10 GeV. The late hadronic interactions have a clear and nonvanishing effect in suppressing the spectrum. On the average one single such interaction should already be enough to explain quantitatively the RHIC results. Our finding, however, signals a warning which has to be addressed in future studies very accurately. ‘Omnes viae Romam ducunt’: Various different roads at present can account for the possible explanation of the modification in the spectra for central collisions. Deductions for possible QCD effects of a deconfined QGP phase on the materializing jets have to disentangle from the here investigated final state interactions, before definite conclusions on the importance of a potential dense partonic phase, or any other effect, can quantitatively be drawn.
Fig. 4: Resulting $p_\perp$-spectrum of charged hadrons at midrapidity for $\sqrt{s_{NN}} = 200$ GeV and for $<L/\lambda> \equiv 0, 1, 2, 3$ collisions. Hadronic collisions are treated in three different ways (compare text).

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