Quenching of high $p_\perp$ hadrons by (pre-)hadronic FSI at RHIC

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Abstract. Recently we have conjectured that (in-)elastic collisions of (pre-)hadronic high momentum states with the bulk of hadrons in the late fireball might substantially account for the attenuation of the high transverse momentum hadrons at RHIC. The potential hadronic attenuation has therefore to be addressed in further detail before definite conclusions on possible QCD effects in a deconfined QGP phase can be drawn with respect to the materializing jets. From our transport studies we find that the interactions of fully formed hadrons are practically negligible in central Au+Au collisions at $\sqrt{s} = 200$ GeV for $p_\perp \geq 6$ GeV/c, but have some importance for the shape of the ratio $R_{AA}$ at lower $p_\perp (\leq 6$ GeV/c). However, a significant part of the large suppression seen experimentally is attributed to inelastic interactions of ‘leading’ jet-like pre-hadrons with the dense hadronic environment. In addition, we also show within this scenario first (preliminary) results of near-side and far-side correlations of high $p_\perp$ particles from central Au+Au collisions at $\sqrt{s} = 200$ GeV. It turns out that the near-side correlations are unaltered – in accordance with experiment – whereas the far-side correlations are suppressed by $\sim 60\%$. Since the experimental observation is a nearly complete disappearance of the far-side jet there should be some additional and earlier partonic interactions in the dense and possibly colored medium.

1. Motivation and Concepts

Within the standard picture of ‘jet quenching’ in a quark gluon plasma (QGP) the later materialization of the partonic jets are assumed to take place outside the fireball without any further interactions with the late stage dense hadronic environment. Hence, measurements of jets seem to offer a direct access to probe the early stage when the deconfined matter is very dense. In fact, the PHENIX [1] and STAR [2] collaborations have reported a large relative suppression of hadron spectra for transverse momenta $p_\perp$ above $\sim 3 – 4$ GeV/c which might point towards the creation of a QGP, since this suppression is not observed in d+Au interactions at the same bombarding energy per nucleon [3, 4].

On the other hand, it is not clear presently to which extent this suppression might be due to ordinary hadronic final state interactions (FSI) [5], too. We have recently proposed a scenario that (in-)elastic collisions of (pre-)hadronic high momentum states with the bulk of hadrons in the late fireball can also contribute significantly to the
The first idea is that most of the (pre-)hadrons stemming from a jet might still materialize in the dense system for transverse momenta up to 10 GeV/c. Indeed, the time for color neutralization of the leading particle due to gluon emission can be very small [6]. The late hadronic final state interactions with the bulk of comovers then have a clear and nonvanishing effect in suppressing the spectrum [5]. This comes about because (in-)elastic reactions of the (pre-)hadrons with hadrons of the bulk system at the relevant energy scale $\sqrt{s}$ of a few GeV are strong and cannot be described by pQCD methods. For a single collision the momentum degradation can be calculated via the folding equation [5]

$$f_j(p_\perp) = \sum_i \int d^2p_0^\perp f^0_i(p_0^\perp) g^X_{ij}(p_0^\perp, p_\perp).$$  (1)

In (1) $g^X_{ij}(p_0^\perp, p_\perp)$ indicates the probability that from a given particle $i$ with transverse momentum $p_0^\perp$ one gets a particle $j$ with transverse momentum $p_\perp$, if the collision is taken with a target $X$ at rest. The folding matrix can be modeled via the FRITIOF scheme; typical examples are depicted in Fig. 2. Such (in-)elastic collisions are very efficient for energy degradation since many hadrons with lower energies are produced. On the average 1 to 2 such interactions can account already quantitatively for the attenuation of high $p_\perp$ hadrons at RHIC [5].

Hence, the hadronic attenuation has therefore to be addressed in more detail before conclusions on possible QCD effects in a deconfined QGP phase on the materializing jets can be drawn. For a quantitative analysis (cf. [7]) we employ the HSD transport approach [8].

The initial conditions for the production and also subsequent propagation of hadrons with moderate to high transverse momentum ($> 1.5$ GeV/c) are incorporated by a superposition of $p + p$ collisions described via PYTHIA [9], which serve as the
Figure 2. The folding matrices $g$ in (1) according to (in)elastic scattering on a $\rho$ for a final $\pi^+$ meson as a function of the resulting transverse momentum $p_T$ (left). Here a fixed value of the initial transverse momentum $p_T^0 = 5$ GeV/c has been assumed. The r.h.s. shows the folding matrices $g$ as a function of the initial transverse momentum $p_T^0$ for a given final transverse momentum $p_T = 5$ GeV/c (right). Pions, kaons and protons/neutrons are separated by line colour, while their charge state (negative (long dashed), neutral (solid), positive (dashed)) is indicated by the line style. Neutral anti–particles are displayed by a thin line.

Figure 3. The invariant cross sections for the production of neutral pions and charged hadrons in $p+p$ collisions ($\sqrt{s} = 200$ GeV) at midrapidity as a function of transverse momentum $p_T$. The Pythia (v6.2) calculations (solid lines) are compared to the experimental data from RHIC.

basic input and have been adjusted to the experimental data for $pp$ reactions (cf. Fig. 3). Before coming to the actual results we briefly explain the concept of 'leading' and 'secondary' hadrons in the transport approach (see Fig. 4 for an illustration). In a high energy nucleon-nucleon collision two (or more) color-neutral strings are assumed to be formed. The string ends are defined by the space-time coordinates of the constituents. These constituent quarks (or diquarks or antiquarks) are denoted as 'leading' quarks that constitute the 'leading' pre-hadrons. The time that is needed for the fragmentation of the strings and for the hadronization of the fragments is denoted as formation time $\tau_f \approx 0.8$ fm. Due to time dilatation the formation time $t_f$
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Figure 4. Left panel: Sketch of a nucleon–nucleon collision. Particles containing a string end (di–)quarks are denoted by “leading” (pre–)hadrons and may interact immediately (with a reduced cross section), while the “secondary” hadrons are delayed by a formation time $\tau_f$. Right panel: The ratio of ‘leading particles’ to ‘all produced particles’ in N+N collisions at midrapidity for different particle classes as a function of the transverse momentum $p_T$ within the PYTHIA description.

in any reference frame is then proportional to the Lorentz $\gamma$-factor. We assume that hadrons, whose constituent quarks and antiquarks are created from the vacuum in the string fragmentation, do not interact with the surrounding nuclear medium within their formation time $t_f$. On the other hand, for the leading pre-hadrons, i.e. those involving quarks (antiquarks) from the struck nucleons, we adopt a reduced effective cross section $\sigma_{\text{lead}}$ during the formation time $t_f$ and the full hadronic cross section later on. As it turns out [7], hadrons with transverse momenta larger than $\sim 6$ GeV/c predominantly stem from the string ends and therefore can, in principle, interact directly with the reduced cross section $\sigma_{\text{lead}}$. In addition, when turning to Au+Au collisions, the formation of secondary hadrons is not only controlled by the formation time $t_f$, but also by the energy density in the local rest frame, i.e., hadrons are not allowed to be formed if the energy density is above 1 GeV/fm$^3$. The interaction of the leading and energetic (pre-)hadrons with the soft hadronic and bulk matter is thus explicitly modeled to occur only for local energy densities below that cut.

Especially the interactions of leading (pre–)hadrons are important to understand the attenuation of hadrons with high (longitudinal) momentum in ordinary cold nuclear matter. The studies in Ref. [10] (see also [6]) have shown that the dominant final state interactions of the hadrons with maximum momentum – as measured by the HERMES Collaboration [11] – are compatible with the concepts described above.

As a last prerequisite we note that a phenomenological broadening of the average transverse momentum squared $\langle k_T^2 \rangle$ of the partons in the nuclear medium prior to the 'hard' scattering vertex is incorporated via an increasing width

$$\langle k_T^2 \rangle = \langle k_T^2 \rangle_{pp}(1 + \alpha N_{\text{prev}})$$

in the string fragmentation function for a given number of previous collisions $N_{\text{prev}}$. This modelling mimics the so called ‘Cronin effect’ observed in $p + A$ collisions. The parameter $\alpha \approx 0.25 - 0.4$ is fixed [7] in comparison to the experimental data for d+Au collisions at $\sqrt{s} = 200$ GeV [3, 4].
2. Results of Transport calculations for Au+Au collisions

Fig. 5 shows our results for most central (5% centrality) Au+Au collisions at √s = 200 GeV for the nuclear modification factor

\[ R_{\text{AA}}(p_\perp) = \frac{1/N_{\text{event}}}{(N_{\text{coll}})/\sigma_{\text{inelas}}} \frac{d^2N_{\text{AA}}/dydp_\perp}{d^2\sigma_{\text{pp}}/dydp_\perp}. \]  

We emphasize, that the Cronin enhancement is visible at all momenta, but does not show up to be responsible for the peak structure in the enhancement around 2 GeV/c. As demonstrated in Ref. [7] the direct pions show a reduced attenuation, the kaon reduction is slightly larger for lower \( p_\perp \), while the vector meson absorption is much stronger. Hadron formation time effects do play a substantial role in the few GeV/c region since heavier hadrons are formed earlier than light pions in the cms frame at fixed transverse momentum due to the lower Lorentz boost. The interactions of formed hadrons after a formation time \( t_f \) are not able to explain the attenuation observed experimentally for transverse momenta \( p_\perp \geq 6 \text{ GeV/c} \). However, the shape of the ratio \( R_{\text{AA}} \) in transverse momentum \( p_\perp \) reflects the presence of final state interactions of formed hadrons in the 1...5 GeV/c range [7]. Such a behaviour for moderate transverse momentum has also been demonstrated in an exploratory UrQMD simulation in Ref. [12].

As pointed out before, the suppression seen in the calculation for larger transverse momentum hadrons is due to the interactions of the leading (pre-)hadrons with target/projectile nucleons and the bulk of low momentum hadrons. For the most central collisions, still, the experimentally observed suppression can not fully be described by the (pre-)hadronic attenuation of the leading particles. The ratio \( R_{\text{AA}} \) decreases to a value of about 0.35−0.04 for central collisions, whereas the data range between 0.2−0.25. Our calculations, though, turn out to be in a better agreement with the data for more peripheral reactions than for the most central Au+Au collisions [7].

As an interlude, we turn briefly to an alternative model for the leading pre-hadron cross section since the notion of a fractional constant cross section might be questionable [6] and alternative assumptions should be tested. To this aim we have adopted a time-dependent cross section for leading pre-hadrons of the kind

\[ \sigma_{\text{lead}}(\sqrt{s}, \tau) = \frac{\tau - \tau_0}{\tau_f} \sigma_{\text{had}}(\sqrt{s}) \]  

for \( \tau - \tau_0 \leq \tau_f \), where \( \tau_0 \) denotes the actual production time and \( \tau_f \) its formation time in the calculational frame. The full hadronic cross section is adopted for \( \tau \geq \tau_0 \). The numerical results of this assumption are shown for the ratio \( R_{\text{AA}} \) (3) in Fig. 6 in case of 5% central Au+Au collisions. Within this scenario the attenuation is less than 40% up to \( p_\perp \sim 10 \text{ GeV/c} \) and thus provides a noticable but not dominant contribution. Since the trend of high \( p_\perp \) hadron suppression is better described via the standard picture of leading (pre-)hadron cross sections, as also employed for the attenuation of maximum momentum particles in nuclei at HERMES [10], we now return to this default description.

In Fig. 7 we show the rapidity dependence of the suppression factor \( R \) averaged over the \( p_\perp \) range 3...6 GeV/c in d+Au and Au+Au collisions. While our results for Au+Au show a slight increase at higher rapidities, one observes a noticable asymmetry with respect to midrapidity in the d+Au case. This is due to the fact, that all...
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Figure 5. The suppression factor $R_{AA}(3)$ of charged hadrons at 0−5% central Au+Au collisions ($\sqrt{s} = 200$ GeV) at midrapidity; experimental data are from Refs. 1, 2. The hatched band denotes our calculations including the 'Cronin' effect, while the solid line results from transport calculations without employing any initial state Cronin enhancement.

Figure 6. Same as fig. 5 but with a leading cross section according to eq. (4) for the perturbative high $p_{\perp}$ particles.

hadronic particles in d+Au reactions are shifted to the rapidity of the Au nucleus as also observed for the dominant soft particles [7].

Gating on particles with momenta $p_{\perp} \geq 4$ GeV/c in the transport calculation, only 1/3 of these final hadrons have suffered one or more interactions during their propagation to the vacuum, whereas the other 2/3 escape without any interaction (in case of a central collision as depicted in Fig. 5). This observation implies, since more than 3/4 of the high $p_{\perp}$ hadrons are strongly absorbed, that the final high $p_T$ hadrons seen experimentally essentially stem from pre–hadrons that originate from a
diffuse 'surface region' of the expanding fireball. The latter pre–hadrons then evolve (or fragment) to the final hadrons dominantly in the vacuum and are accompanied by secondary hadrons, which - due to their large formation time - also hadronize in the vacuum.

In Fig. 8 we show the angular correlation of high $p_{\perp}$ particles ($p_{\perp,\text{trig}} = 4 \ldots 6\text{GeV}/c$, $p_{\perp} = 2\text{GeV} \ldots p_{\perp,\text{trig}}$, $|y| < 0.7$) for 5% central Au+Au collisions at $\sqrt{s} = 200\text{GeV}$ (solid line) as well as $pp$ reactions (dashed line) in comparison to the data from STAR for $pp$ collisions [13]. Thus, when gating on high $p_{\perp}$ hadrons (in the vacuum) the 'near–side' correlations are close to the 'near–side' correlations observed for jet fragmentation in the vacuum. This is in agreement with the experimental observation [13]. Furthermore, for the far-side correlations we get a $\sim 60\%$ reduction, but not a complete disappearance of the far-side jet as indicated by the experimental data [13].

3. Summary, Conclusions and some Remarks

Summarizing, we point out that (pre-) hadronic final state interactions are able to approximately reproduce the high $p_{\perp}$ suppression effects observed in Au+Au collisions at RHIC. This finding is important, since the same dynamics also describe the hadron formation and attenuation in deep–inelastic lepton scattering off nuclei at HERMES [10] appreciably well. In particular, it has been demonstrated, that the centrality dependence of the modification factor $R_{AA}$ 3 in Au+Au collisions at $\sqrt{s} = 200\text{GeV}$ is well described for peripheral and mid–central collisions on the basis of leading pre-hadron interactions [7]. On the other hand, the attenuation in central Au+Au collisions is noticeably underestimated. A similar situation also holds for an analysis of the far-side correlations, which show a substantial, but not fully complete suppression in central collisions as indicated by the experimental data. From these observations one should conclude that there are some additional (and earlier) interactions of partons in a possibly colored medium that have not been accounted for in our present HSD
transport studies. However, in any case, the final hadronic stage is rather opaque for high transverse momentum and jet-like (pre-)hadrons.

We note additionally, that the elliptic flow $v_2$ for high transverse momentum particles is underestimated by at least a factor of 3 in our transport calculations [7]. Moreover, also the experimental observation of having more protons than $\pi^+$ at moderate transverse momenta can not be explained within the present approach. This, however, is true also for the various parton jet–quenching models.

We close in pointing out that further experimental studies on the suppression of high momentum hadrons from d+Au and Au+Au collisions down to $\sqrt{s} = 20$ GeV will be necessary to clearly separate initial state Cronin effects from final state attenuation and to disentangle the role of partons in a colored partonic medium from those of interacting pre-hadrons in a color-neutral hot and dense fireball.

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