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An alternative model of jet suppression at RHIC energies

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Abstract. We propose a simple Glauber-type mechanism for the suppression of jet production up to transverse momenta of about $10\,\mathrm{GeV}/c$ at RHIC. For processes in this kinematic region, the formation time is smaller than the interval between two successive hard partonic collisions and the subsequent collision influences the jet production. The number of jets then roughly scales with the number of participants. Proportionality to the number of binary collisions is recovered for very high transverse momenta. The model predicts suppression of jet production in $d+\mathrm{Au}$ collisions at RHIC.

It was expected that the yields of high-p_{T} hadrons from nuclear collisions at RHIC would scale with the number of nucleon–nucleon interactions at the given value of the impact parameter. The observed spectra are suppressed above $p_{\mathrm{T}} \approx 2\,\mathrm{GeV}/c$ with respect to this expectation [1–5]. This suppression is most frequently interpreted [6–11] as due to loss of energy of high-p_{T} partons in a quark–gluon plasma (QGP). Such a mechanism affects the fragmentation of a jet into final-state hadrons but does not influence the jet production. A slight attenuation of jet production may be due to shadowing [12], but even these effects together are unable to reproduce the strong observed suppression.

In this paper we propose a mechanism which leads to attenuated production of jets with $2 \le p_{\mathrm{T}} \le 10\,\mathrm{GeV}/c$. We will label this kinematic region as "medium" p_{T} in order to distinguish it from really hard jets at higher energies. Owing to the reduced production of jets, hadronic yields will be suppressed as well.

We start with the estimate of the formation time of medium-p_{T} jets at RHIC energies, following [13]. Our estimate is based on a simple Glauber approach which we take as justified for hard constituent partons. The mean free path of a nucleon in a nucleus at rest is $\lambda \approx 2.5\,\mathrm{fm}$. In the center of mass frame of a nuclear collision at RHIC, the mean free path of an incident participating nucleon is Lorentz contracted to about $0.025\,\mathrm{fm}$, whereas in the SPS energy region it is $0.25\,\mathrm{fm}$. At RHIC, the time interval between two successive nucleon–nucleon collisions is thus $\Delta t \approx 0.025\,\mathrm{fm}/c$. From the uncertainty relation, a process with longitudinal momentum transfer Δp_{L} and energy transfer ΔE is materialized within the space interval Δz and time interval Δt, provided that

$$\Delta p_{\mathrm{L}} > \frac{\hbar}{\Delta z}\,, \quad \Delta E > \frac{\hbar}{\Delta t}\,. \tag{1}$$

According to our argument, processes which do not satisfy this condition suffer from interference due to subsequent interactions with the following incident nucleons or hard partons. The limiting values for RHIC and SPS are $\Delta p_{\mathrm{L}} \approx 8\,\mathrm{GeV}/c$ and $\Delta p_{\mathrm{L}} \approx 0.8\,\mathrm{GeV}/c$, respectively. Since the p_{T} of jets comes mainly from the transfer of the longitudinal momentum of partons to the transverse one, the condition

$$\Delta p_{\mathrm{L}} \approx p_{\mathrm{T}} \ge 8\,\mathrm{GeV}/c\,, \tag{2}$$

has to be satisfied if the process is to be finished before the next nucleon comes to the space-time region where the process develops. Equations (1) and (2) are approximations which fully exploit the uncertainty relation, so we expect that at RHIC truly hard processes are those with Δp_{L} larger than 12 or perhaps even $15\,\mathrm{GeV}/c$. This leads us to label those processes with p_{T} in the region 2–$8\,\mathrm{GeV}/c$ as "medium- p_{T}" ones.

When two jets are produced in a collision of two nucleons and a third nucleon arrives at the production place such that (1) and (2) are not satisfied, we will assume that the process of jet formation can be attenuated. A possible mechanism causing this effect is the screening of the interaction by color fields of the third nucleon.

We use the original "Glauber language" and formulate our mechanism in terms of nucleon–nucleon collisions. At RHIC energies one could object that softer parton fields of the incident nucleons spread longitudinally more than the naively calculated Lorentz-contracted nucleon size. They overlap and it is hard to talk about individual nucleons as they are hardly localized. Hard processes, however, come from interactions of hard partons which are well localized within the Lorentz-contracted nucleons. In addition, in order to make our picture consistent, we will assume that hard processes, during their formation time, can only be influenced by other *hard* partons which can be localized within the nucleons. In this simple model we ignore the possible influence of the softer partons.

Now, we shall describe our qualitative model of medium-p_T jet suppression at RHIC energies. In this paper we remain at the level of jets and do not calculate the hadronic spectra. In order to calculate these we would have to use a fragmentation function which depends on the medium in which the jets fragment. We defer this to further work.

Technically, our Glauber model is constructed in analogy with nuclear absorption of J/ψ in heavy-ion collisions [14]. The cross-section for the destruction of jets in the stage of formation by an incident nucleon is parametrized as

$$\sigma_a = \sigma_a(p_\mathrm{T}) = \sigma_0 \left(\frac{1}{1+(p_\mathrm{T}/p_{\mathrm{T}0})^2} \right)^2 , \qquad (3)$$

where $p_{\mathrm{T}0} \approx 8\,\mathrm{GeV}/c$ and σ_0 is of the order of a few mb. The parametrization has been chosen in such a way that the suppression disappears for truly hard jets when p_T is larger than $p_{\mathrm{T}0}$ and for low p_T the absorptive cross-section goes to σ_0. A motivation for the specific choice of p_T-dependence of σ_a comes from the modification of Coulomb scattering in the Born approximation caused by Debye screening; see also [13].

In order to simplify the further notation we introduce a shorthand for the yield of jets with transverse momenta equal to p_T produced in a collision of nuclei $A+B$ at a given value of the impact parameter b:

$$Y_{AB}(p_\mathrm{T}, b) = \frac{\dfrac{\mathrm{d}\sigma_{AB}}{\mathrm{d}p_\mathrm{T}^2\,\mathrm{d}b^2}}{\dfrac{\mathrm{d}\sigma_{AB}}{\mathrm{d}b^2}} . \qquad (4)$$

For normalization we will use the corresponding yield in proton–proton collisions:

$$Y_{pp}(p_\mathrm{T}) = \frac{\dfrac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_\mathrm{T}^2}}{\sigma_{pp}} . \qquad (5)$$

We want to determine

$$\frac{Y_{AB}(p_\mathrm{T}, b)}{Y_{pp}(p_\mathrm{T})} = \int_\mathrm{overlap} s\,\mathrm{d}s\,\mathrm{d}\theta \int_{-L_A}^{L_A} \mathrm{d}z_A\,\rho_A \int_{-L_B}^{L_B} \mathrm{d}z_B\,\rho_B \times \sigma_{nn}\, F(b,s,\theta,z_A,z_B) , \qquad (6)$$

where

$$F(b,s,\theta,z_A,z_B) = \exp\left[-\sigma_a \rho_A (z_A + L_A)\right] \exp\left[-\sigma_a \rho_B (z_B + L_B)\right] . \qquad (7)$$

For simplicity we work here in an approximation with nuclei as spheres with constant densities ρ_A and ρ_B. The first integration in (6) runs over the overlapping region in a non-central collision; see Fig. 1. The use of coordinates s and θ is also explained in that figure. For the non-diffractive nucleon–nucleon cross-section we take the value $\sigma_{nn} = 4\,\mathrm{fm}^2$ and $\sigma_a(p_\mathrm{T})$ is given by (3). Finally, $2L_A$ and $2L_B$ are the lengths of the colliding tubes

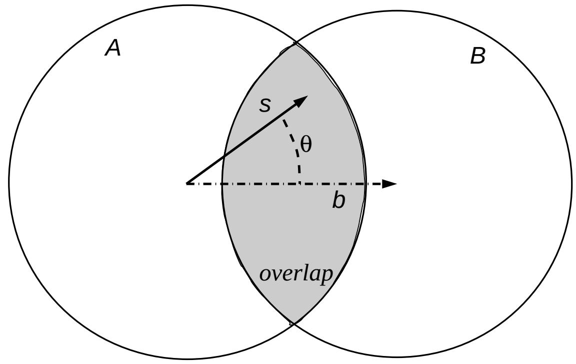

Fig. 1. Geometry of non-central collisions

$$2L_A(s) = 2\sqrt{R_A^2 - s^2} ,$$
$$2L_B(b,s,\theta) = 2\sqrt{R_B^2 - b^2 - s^2 + 2bs\cos\theta} , \qquad (8)$$

in the notation of Fig. 1. The coordinates z_A and z_B in (6) and (7) specify the positions of those nucleons whose collision led to the production of two jets. Note that the calculation can be formulated without accounting for Lorentz contraction of the nuclei when determining the values of L_A and L_B. In such a case, we have to use the standard nuclear density $0.138\,\mathrm{fm}^{-3}$ for ρ_A and ρ_B, in order to proceed in a consistent way.

The number of participating nucleons n_part and the number of binary collisions n_coll at a given value of b are calculated in the standard way:

$$n_\mathrm{part} = \int_\mathrm{overlap} s\,\mathrm{d}s\,\mathrm{d}\theta \; \left(2\rho_A\, L_A(s) + 2\rho_B\, L_B(b,s,\theta)\right) , \qquad (9)$$

$$n_\mathrm{coll} = \int_\mathrm{overlap} s\,\mathrm{d}s\,\mathrm{d}\theta\, \sigma_{nn}\, \rho_A\, \rho_B\, L_A(s)\, L_B(b,s,\theta) . \qquad (10)$$

Results can be obtained from a direct evaluation of (6), (9) and (10), or from a simulation of the described model. We chose the latter method. In Fig. 2 we test the scaling of the jet production with the number of participants. This regime corresponds to a constant curve in Fig. 2 and is realized as $p_\mathrm{T} \to 0$. For increasing p_T the scaling with the number of binary collisions is recovered. This is seen in Fig. 3: for $p_\mathrm{T} > p_{\mathrm{T}0}$ the curves are close to the asymptotic value of 1.

Scaling with the number of participants at low p_T comes from the fact that most of the jets produced in the volume are suppressed by nuclear absorption and only those originating from the rear parts of the colliding nuclei survive. In this way, the jet production is close to the surface effect. With growing impact parameter the volume decreases faster than the surface, and so production from the surface makes up a bigger part of the total yield. Thus peripheral collisions should faster come to the regime of scaling with the number of binary collisions. This is indeed seen in Fig. 4.

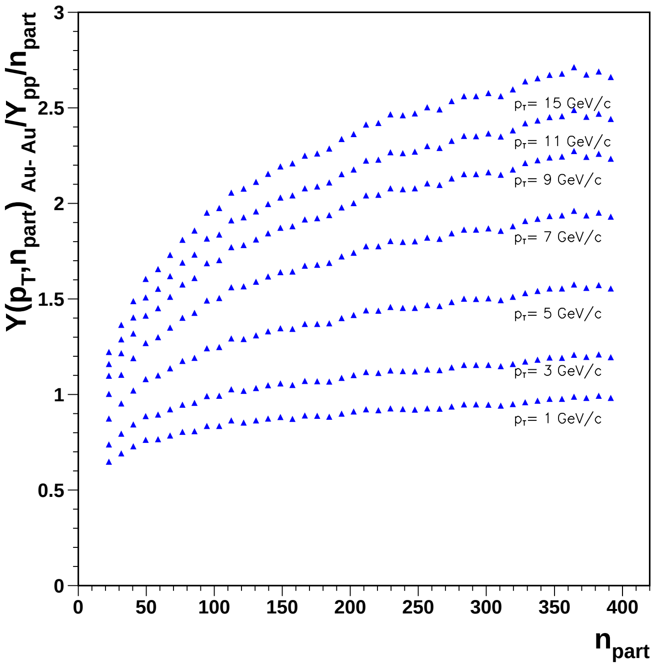

Fig. 2. The ratio $Y_{\mathrm{Au+Au}}(p_{\mathrm{T}}, b)/[n_{\mathrm{part}}(b)\, Y_{pp}(p_{\mathrm{T}})]$ plotted as a function of $n_{\mathrm{part}}(b)$ for $p_{\mathrm{T}} = 1\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 3\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 5\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 7\,\mathrm{GeV}/c$ and $p_{\mathrm{T}} = 9\,\mathrm{GeV}/c$ in Au + Au interactions at RHIC. Parameters are given in the text; $\sigma_0 = 8\,\mathrm{mb}$

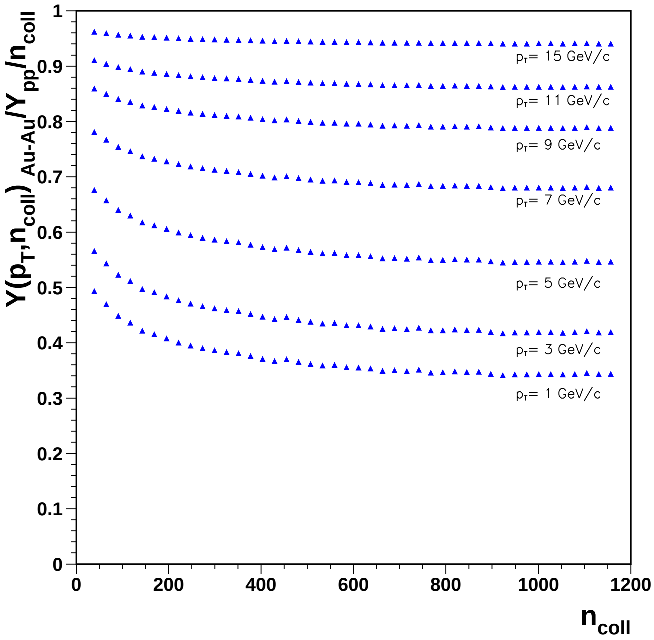

Fig. 3. The ratio $Y_{\mathrm{Au+Au}}(p_{\mathrm{T}}, b)/[n_{\mathrm{coll}}(b)\, Y_{pp}(p_{\mathrm{T}})]$ plotted as a function of $n_{\mathrm{coll}}(b)$ for $p_{\mathrm{T}} = 1\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 3\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 5\,\mathrm{GeV}/c$, $p_{\mathrm{T}} = 7\,\mathrm{GeV}/c$ and $p_{\mathrm{T}} = 9\,\mathrm{GeV}/c$ in Au + Au interactions at RHIC. Parameters are given in the text; $\sigma_0 = 8\,\mathrm{mb}$

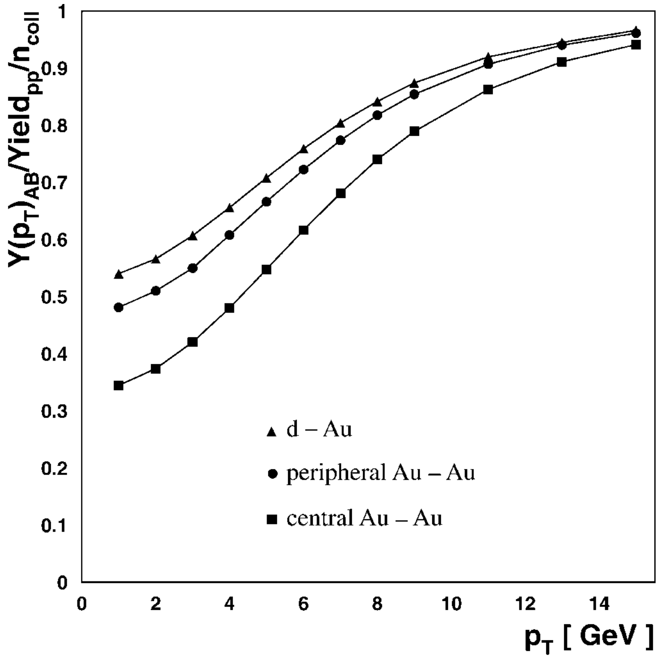

Fig. 4. The ratio $Y_{AB}(p_{\mathrm{T}})/[n_{\mathrm{coll}}\, Y_{pp}(p_{\mathrm{T}})]$ as a function of p_{T}. Results are shown for three different colliding systems at RHIC: central Au + Au collisions (0–5% of the total cross-section), peripheral (60–80%) Au + Au collisions, and d + Au collisions. We set $\sigma_0 = 8\,\mathrm{mb}$

The described mechanism also leads to suppression of the *jet* production in proton–nucleus or deuteron–nucleus collisions. Our prediction for d + Au is shown in Fig. 4. Data from this collision system should be available soon.

We should stress again that in this paper we only calculate how the jet production is suppressed and do not include fragmentation into hadrons. Our results thus show qualitative features which will be seen in the hard hadronic spectra, but which cannot be directly compared with the measured spectra of high-p_{T} hadrons.

Before concluding let us add a few comments.

(1) Suppression of hard processes in $p + A$ interactions based on shadowing and incident parton energy loss in nuclear matter has been discussed in [16–18]. In this approach the shadowing is understood as destructive interference derived from the space-time properties of the nuclear interaction which is of a similar origin as the suppression considered in our model. The effect of the incident parton energy loss while traversing nuclear matter before the hard collision which leads to jet production is not included in the present version of the model, but it can be added in the future.

(2) We want to stress that the model described above cannot explain the disappearance of the opposite-side jet. If fully confirmed, this effect will give evidence in favor of jet suppression by hard parton energy loss in a quark–gluon plasma. Jet suppression by QGP is not included in our model, but it can be added later.

(3) As shown in [19], nuclear absorption in $p + A$ and $A + B$ interactions leads to very similar results as gluon depletion due to energy loss of gluons in nuclear matter. Since absorption, as shown in Figs. 2 and 3, can convert the “volume” effect to the “surface” one, it is likely that gluon energy loss in nuclear matter could lead to similar results.

(4) For the SPS energy region, the value of p_{T0} is about $0.8\,\mathrm{GeV}/c$. Hence, the production of particles with $p_{\mathrm{T}} \leq$

$0.8\,\mathrm{GeV}/c$ is suppressed and scales rather with n_{part} than with n_{coll}, in accord with the venerable wounded nucleon model [15] and with the data [20].

We conclude that nuclear absorption can attenuate the production of medium-p_{T} hadrons. Their yield then scales roughly with the number of participants.

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Note added in proof: After having submitted the first version of this article we have learned that jet quenching in Au–Au data at the RHIC has been obtained by Kharzeev, Levin and McLerran [21] by parton saturation [22–24] and that they have also predicted jet quenching in d–Au interactions; see also [25].

The approach of [21,25] may seem at first sight as quite different from what we have proposed above, but in fact the two are rather similar. In [21,25] jets are quenched because due to parton saturation not all gluons in the nucleus can independently scatter off the gluons in the other nucleus. In our approach gluon–gluon scattering at low $p_{\mathrm{T}}^2 \approx Q^2 \leq Q_s^2 \approx p_0^2$ is less efficient due to the space-time limitations imposed upon the interaction. Perhaps the two approaches are two ways of describing similar effects.

We have also realized that G. Papp et al. [26] have shown that the ability of a proton to give rise to multiple hard collisions in pA interactions even in the CERN SPS energy range decreases with the number of interactions in a nucleus.

We have also learned about the interesting centrality scaling [27,28] in the pion p_{T}-spectra at RHIC, which is becoming a challenge for model builders.