

## An alternative model of jet suppression at RHIC energies

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### Abstract

We propose a simple Glauber-type mechanism for suppression of jet production up to transverse momenta of about 10 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. 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+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  $p_T \approx 2 \text{ GeV}/c$  with respect to this expectation and rather seem to scale with the number of participating nucleons [1, 2, 3, 4, 5]. This suppression is most frequently interpreted [6, 7, 8, 9, 10, 11] as due to loss of energy of high- $p_T$  partons in quark-gluon plasma (QGP). Such a mechanism affects the fragmentation of jet into final-state hadrons but does not influence jet production. A slight attenuation of jet production may be due to shadowing [12] but even both 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  $2 \leq p_T \leq 10 \text{ GeV}/c$ . 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 nucleon in a nucleus at rest is  $\lambda \approx 2.5 \text{ fm}$ . In the centre of mass frame of a nuclear collision at RHIC, the mean free path of an incident participating nucleon is Lorentz contracted to about  $0.025 \text{ fm}$ , whereas in the SPS energy region it is  $0.25 \text{ fm}$ . At RHIC, the time interval between two successive nucleon-nucleon collisions is thus  $\Delta t \approx 0.025 \text{ fm}/c$ . From uncertainty relation, a process with longitudinal momentum transfer  $\Delta p_L$  and energy transfer  $\Delta E$  is materialized within the space interval  $\Delta z$  and time interval  $\Delta t$ , provided that

$$\Delta p_L > \frac{\hbar}{\Delta z}, \quad \Delta E > \frac{\hbar}{\Delta t}. \quad (1)$$

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

$$\Delta p_L \approx p_T \geq 8 \text{ GeV}/c, \quad (2)$$

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  $\Delta p_L$  larger than 12 or perhaps even 15 GeV/ $c$ . This lead us to label those processes with  $p_T$  in the region 2–8 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 Eqs. (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 interaction by colour 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 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 localised. Hard processes, however, come from interactions of hard partons which are well localised 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 nucleons. In this simple model we ignore the possible influence of 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 hadronic spectra. In order to calculate them we would have to use fragmentation function which depends on medium in which the jets fragment. We defer this to further work.

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

$$\sigma_a = \sigma_a(p_T) = \sigma_0 \left( \frac{1}{1 + (p_T/p_{T0})^2} \right)^2 \quad (3)$$

where  $p_{T0} \approx 8$  GeV/ $c$  and  $\sigma_0$  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  $p_{T0}$  and for low  $p_T$  the absorptive cross-section goes to  $\sigma_0$ . A motivation for the specific choice of  $p_T$ -dependence of  $\sigma_a$  comes

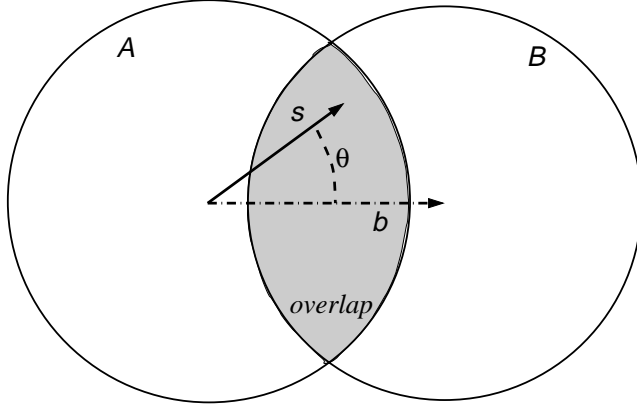


Figure 1: Geometry of non-central collisions.

from the modification of Coulomb scattering in Born approximation caused by Debye screening, see also [13].

In order to simplify 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  $b$

$$Y_{AB}(p_T, b) = \frac{\frac{d\sigma_{AB}}{dp_T^2 db^2}}{\frac{d\sigma_{AB}}{db^2}}. \quad (4)$$

For normalisation we will use the corresponding yield in proton-proton collisions

$$Y_{pp}(p_T) = \frac{\frac{d\sigma_{pp}}{dp_T^2}}{\sigma_{pp}}. \quad (5)$$

We want to determine

$$\frac{Y_{AB}(p_T, b)}{Y_{pp}(p_T)} = \int_{\text{overlap}} s ds d\theta \int_{-L_A}^{L_A} dz_A \rho_A \int_{-L_B}^{L_B} dz_B \rho_B \sigma_{nn} F(b, s, \theta, z_A, z_B), \quad (6)$$

where

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

For simplicity we work here in approximation with nuclei as spheres with constant densities  $\rho_A$  and  $\rho_B$ . The first integration in (6) runs over the overlapping region in non-central collision, see Fig. 1. The use of coordinates  $s$  and  $\theta$  is also explained in that Figure. For the non-diffractive nucleon-nucleon cross-section we take the value  $\sigma_{nn} = 4 \text{ fm}^2$  and  $\sigma_a(p_T)$  is given by eq. (3). Finally,  $2L_A$  and  $2L_B$  are lengths of colliding tubes

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

in the notation of Fig. 1. The coordinates  $z_A$  and  $z_B$  in eqs. (6) and (7) specify 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  $0.138 \text{ fm}^{-3}$  for  $\rho_A$  and  $\rho_B$ , in order to proceed in a consistent way.

The number of participating nucleons  $n_{\text{part}}$  and the number of binary collisions  $n_{\text{coll}}$  at a given value of  $b$  are calculated in the standard way

$$n_{\text{part}} = \int_{\text{overlap}} s ds d\theta (2\rho_A L_A(s) + 2\rho_B L_B(b, s, \theta)), \quad (9)$$

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

Results can be obtained from direct evaluation of eqs. (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 jet production with the number of participants. This regime corresponds to a constant curve in Fig. 2 and is realized as  $p_T \rightarrow 0$ . For increasing  $p_T$  the scaling with number of binary collisions is recovered. This is seen in Fig. 3: for  $p_T > p_{T0}$  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 come to the regime of scaling with number of binary collisions faster. This is indeed seen in Fig. 4.

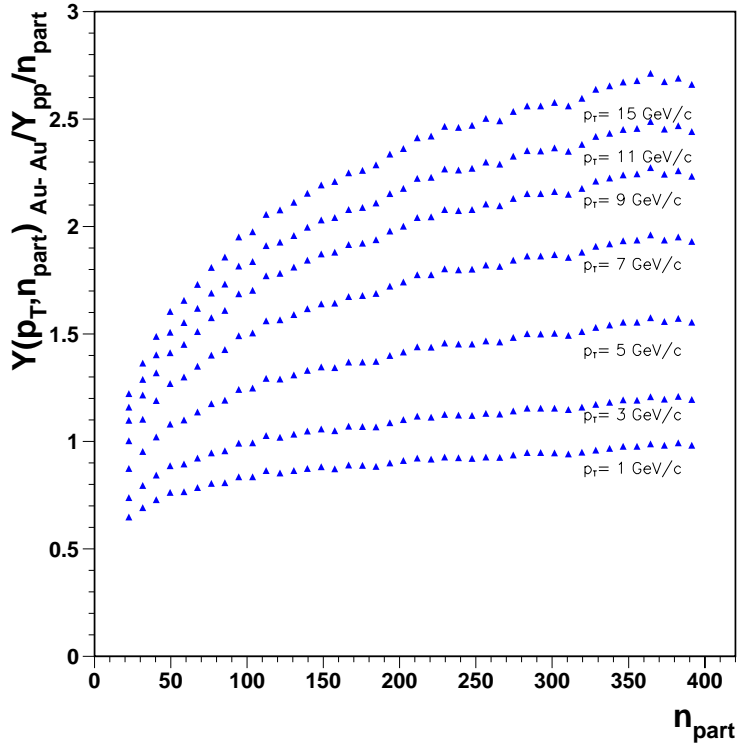


Figure 2: The ratio  $Y_{\text{Au+Au}}(p_T, b)/[n_{\text{part}}(b) Y_{pp}(p_T)]$  plotted as a function of  $n_{\text{part}}(b)$  for  $p_T = 1 \text{ GeV}/c$ ,  $p_T = 3 \text{ GeV}/c$ ,  $p_T = 5 \text{ GeV}/c$ ,  $p_T = 7 \text{ GeV}/c$  and  $p_T = 9 \text{ GeV}/c$  in Au+Au interactions at RHIC.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

The described mechanism also leads to suppression of *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 cannot be directly compared with measured spectra of high- $p_T$  hadrons.

Before concluding let us add a few comments:

- i) Suppression of hard processes in p+A interactions based on shadowing

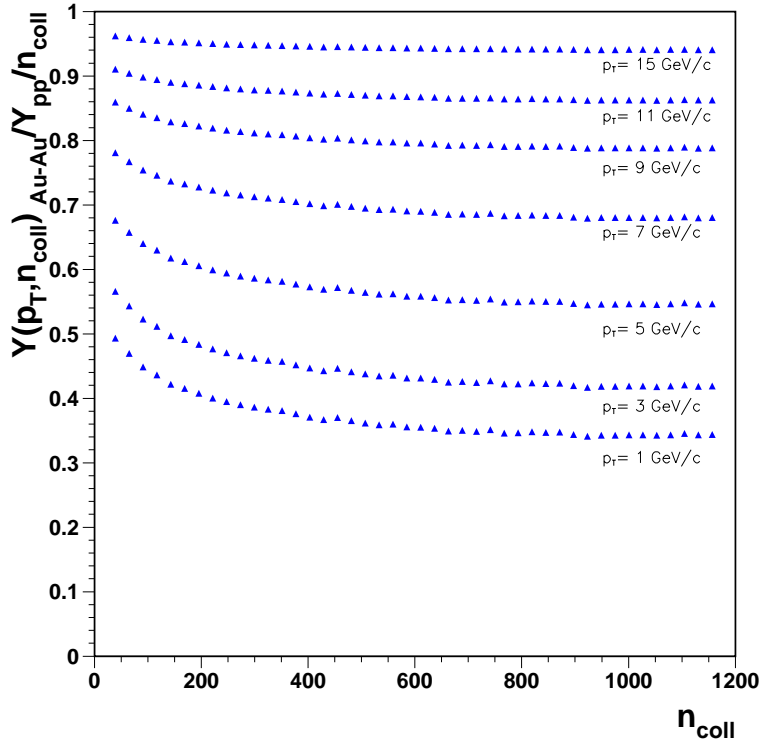


Figure 3: The ratio  $Y_{\text{Au+Au}}(p_T, b)/[n_{\text{coll}}(b) Y_{pp}(p_T)]$  plotted as a function of  $n_{\text{coll}}(b)$  for  $p_T = 1$  GeV/c,  $p_T = 3$  GeV/c,  $p_T = 5$  GeV/c,  $p_T = 7$  GeV/c and  $p_T = 9$  GeV/c in Au+Au interactions at RHIC. Parameters are given in the text,  $\sigma_0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

and incident parton energy loss in nuclear matter has been discussed in [16, 17, 18]. In this approach the shadowing is understood as destructive interference derived from the space-time properties of nuclear interaction which is of a similar origin as the suppression considered in our model. The effect of 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 can be added in the future.

- ii) We want to stress that the model described above cannot explain the disappearance of opposite-side jet. If fully confirmed, this effect will

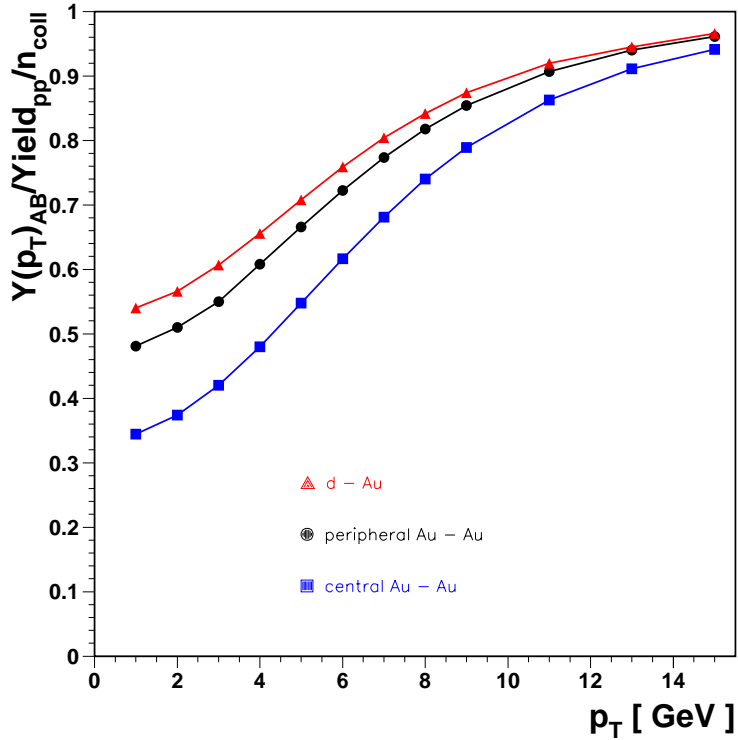


Figure 4: The ratio  $Y_{AB}(p_T)/[n_{\text{coll}} Y_{pp}(p_T)]$  as a function of  $p_T$ . Results are shown for three different colliding systems at RHIC: central Au+Au collisions (0-5% of the total cross section), peripheral (60-80%) Au+Au collisions, and d+Au collisions. We set  $\sigma_0 = 8$  mb.

give evidence in favour of jet suppression by hard parton energy loss in quark-gluon plasma. Jet suppression by QGP is not included in our model, but it can be added later.

- iii) 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.
- iv) For SPS energy region, the value of  $p_{T0}$  is about 0.8 GeV/c. Hence, the production of particles with  $p_T \leq 0.8$  GeV/c is suppressed and scales



rather with  $n_{\text{part}}$  than with  $n_{\text{coll}}$ , in accord with the venerable wounded nucleon model [15] and with the data [20].

We conclude that nuclear absorption can attenuate production of medium- $p_T$  hadrons. Their yield then scales roughly with the number of participants.

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