

A model of jet quenching in ultrarelativistic heavy ion collisions and high- p_T hadron spectra at RHIC

I.P. Lokhtin^a, A.M. Snigirev^b

M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, 119992, Vorobievy Gory, Moscow, Russia

Received: 20 June 2005 / Revised version: 11 October 2005 /

Published online: 24 November 2005 – © Springer-Verlag / Società Italiana di Fisica 2005

Abstract. The method to simulate the rescattering and energy loss of hard partons in ultrarelativistic heavy ion collisions has been developed. The model is a fast Monte Carlo tool introduced to modify a standard PYTHIA jet event. The full heavy ion event is obtained as a superposition of a soft hydro-type state and hard multi-jets. The model is applied to the analysis of the jet quenching pattern at RHIC.

1 Introduction

One of the important tools for studying the properties of the quark–gluon plasma (QGP) in ultrarelativistic heavy ion collisions is the analysis of a QCD jet production. The medium-induced energy loss of energetic partons, “jet quenching”, should be very different in the cold nuclear matter and QGP, resulting in many observable phenomena [1]. Recent RHIC data on high- p_T particle production [2] (the suppression of hadron spectra and azimuthal back-to-back two-particle correlations, strong elliptic flow) are in agreement with the jet quenching hypothesis [3]. At LHC, a new regime of heavy ion physics will be reached at $\sqrt{s_{NN}} = 5.5A$ TeV, where hard and semi-hard particle production can stand out against the underlying soft events. The initial gluon densities in Pb + Pb reactions at LHC are expected to be significantly higher than those at RHIC, implying a stronger partonic energy loss, observable in various new channels [4].

In most of the available Monte Carlo heavy ion event generators the medium-induced partonic rescattering and energy loss are either ignored or implemented insufficiently [5]. Thus, in order to analyze RHIC data on high- p_T hadron production, test the sensitivity of LHC observables to the QGP formation, and study the corresponding experimental capabilities of detectors, the development of adequate and fast Monte Carlo models for jet quenching simulation is necessary.

In this paper we present the model of jet quenching and discuss its validation basing on RHIC data for high- p_T hadron spectra. In Sect. 2 we give the physics frameworks of the model. Section 3 describes the event-by-event simulation procedure. In Sect. 4 the generalization of the model to the case of “full” heavy ion event (superposition of soft hydro-type state and hard multi-jets) is fulfilled. In Sect. 5

the efficiency of the model is demonstrated by means of the numerical analysis of hadron spectra at RHIC.

2 Physics frameworks of the model

The detailed description of the physics frameworks of the developed model can be found in a number of our previous papers [6–10]. Our approach is based on an accumulating energy loss, the gluon radiation being associated with each parton scattering in the expanding medium, and includes the interference effect using the modified radiation spectrum dE/dl as a function of decreasing temperature T . The basic kinetic integral equation for the energy loss ΔE as a function of the initial energy E and path length L has the form

$$\Delta E(L, E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l, E)}{dl},$$
$$\frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp(-l/\lambda(l)), \quad (1)$$

where l is the current transverse coordinate of a parton, dP/dl is the scattering probability density, dE/dl is the energy loss per unit length, $\lambda = 1/(\sigma\rho)$ is the in-medium mean free path, $\rho \propto T^3$ is the medium density at the temperature T , and σ is the integral cross section for parton interaction in the medium.

The collisional energy loss due to elastic scattering with high-momentum transfer has been originally estimated by Bjorken in [11] and recalculated later in [12] taking also into account the low-momentum transfer loss resulting mainly from the interactions with plasma collective modes. Since the latter process does not contribute much to the total collisional loss in comparison with high-momentum scattering (due to the absence of a large factor $\sim \ln(E/\mu_D)$)

^a e-mail: igor@lav01.sinp.msu.ru

^b e-mail: snigirev@lav01.sinp.msu.ru

where μ_D is the Debye screening mass) and in numerical estimates it can be effectively “absorbed” by means of redefinition of minimum momentum transfer $t_{\min} \sim \mu_D^2$, we used the collisional part associated with high-momentum transfer only [7],

$$\frac{dE}{dl}^{\text{col}} = \frac{1}{4T\lambda\sigma} \int_{\mu_D^2}^{t_{\max}} dt \frac{d\sigma}{dt} t, \quad (2)$$

and the dominant contribution to the differential cross section

$$\frac{d\sigma}{dt} \cong C \frac{2\pi\alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_p^2},$$

$$\alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{\text{QCD}}^2)} \quad (3)$$

for scattering of a hard parton with energy E and mass m_p off the “thermal” parton with energy (or effective mass) $m_0 \sim 3T \ll E$. Here $C = 9/4, 1, 4/9$ for gg, gq and qq scatterings respectively; α_s is the QCD running coupling constant for N_f active quark flavors, and Λ_{QCD} is the QCD scale parameter, which is of the order of the critical temperature, $\Lambda_{\text{QCD}} \simeq T_c \simeq 200$ MeV. The integrated cross section σ is regularized by the Debye screening mass squared $\mu_D^2(T) \simeq 4\pi\alpha_s T^2(1 + N_f/6)$. The maximum momentum transfer is $t_{\max} = [s - (m_p + m_0)^2][s - (m_p - m_0)^2]/s$ where $s = 2m_0E + m_0^2 + m_p^2$.

There are several calculations of the inclusive energy distribution of medium-induced gluon radiation using Feynman multiple scattering diagrams. The relation between these approaches and their basic parameters has been discussed in detail in the recent write-up of the working group “Jet Physics” for the CERN Yellow Report [4]. We restrict ourselves to using the BDMS formalism [13]. In the BDMS frameworks, the strength of multiple scattering is characterized by the transport coefficient $\hat{q} = \mu_D^2/\lambda_g$ (λ_g is the gluon mean free path), which is related to the elastic scattering cross section σ (3). In our simulations this strength is in fact regulated mainly by the initial QGP temperature T_0 . Then the energy spectrum of coherent medium-induced gluon radiation and the corresponding dominant part of radiative energy loss of massless parton have the form [13]

$$\frac{dE}{dl}^{\text{rad}} = \frac{2\alpha_s(\mu_D^2)C_R}{\pi L} \times \int_{\omega_{\min}}^E d\omega \left[1 - y + \frac{y^2}{2} \right] \ln |\cos(\omega_1\tau_1)|, \quad (4)$$

$$\omega_1 = \sqrt{i \left(1 - y + \frac{C_R}{3} y^2 \right) \bar{\kappa} \ln \frac{16}{\bar{\kappa}}}, \quad (5)$$

with

$$\bar{\kappa} = \frac{\mu_D^2 \lambda_g}{\omega(1-y)},$$

where $\tau_1 = L/(2\lambda_g)$, $y = \omega/E$ is the fraction of the hard parton energy carried away by the radiated gluon, and $C_R = 4/3$ is the quark color factor. A similar expression for the gluon jet can be obtained by setting $C_R = 3$ and properly by changing the factor in the square brackets in (4) [13]. The integration (4) is carried out over all energies from $\omega_{\min} = E_{\text{LPM}} = \mu_D^2 \lambda_g$, the minimum radiated gluon energy in the coherent LPM regime, up to initial parton energy E . Note that we do not consider here possible effects of double parton scattering [14, 15] and thermal gluon absorption [16], which can be included in the model in the future.

The simplest generalization of the formula for a heavy quark of mass m_q can be done by using the “dead-cone” approximation [17]:

$$\left. \frac{dE}{dl d\omega} \right|_{m_q \neq 0} = \frac{1}{(1 + (\beta\omega)^{3/2})^2} \left. \frac{dE}{dl d\omega} \right|_{m_q = 0},$$

$$\beta = \left(\frac{\lambda}{\mu_D^2} \right)^{1/3} \left(\frac{m_q}{E} \right)^{4/3}. \quad (6)$$

One should mention the more recent developments on heavy quark energy loss calculations available in the literature [18–20], which can be also considered as further model improvements.

The medium is treated as a boost-invariant longitudinally expanding quark–gluon fluid, and partons as being produced on a hyper-surface of equal proper times τ [21]. In order to simplify numerical calculations we omit here the transverse expansion and viscosity of the fluid using the well-known scaling solution obtained by Bjorken [21] for a temperature and density of QGP at $T > T_c \simeq 200$ MeV:

$$\varepsilon(\tau)\tau^{4/3} = \varepsilon_0\tau_0^{4/3}, \quad T(\tau)\tau^{1/3} = T_0\tau_0^{1/3}, \quad \rho(\tau)\tau = \rho_0\tau_0. \quad (7)$$

The internal model parameters are the initial conditions for the QGP formation expected for central Au+Au (Pb+Pb) collisions at RHIC (LHC): τ_0, T_0 and N_f . For non-central collisions and for other beam atomic numbers we suggest the proportionality of the initial energy density ε_0 to the ratio of nuclear overlap function and effective transverse area of nuclear overlapping [7].

Note that using other scenarios of QGP space-time evolution for the Monte Carlo implementation of the model is also envisaged. In fact, the influence of the transverse flow, as well as that of the mixed phase at $T = T_c$, on the intensity of jet rescattering (which is a strongly increasing function of T) has been found to be inessential for high initial temperatures $T_0 \gg T_c$. On the contrary, the presence of QGP viscosity slows down the cooling rate, which implies a jet parton spending more time in the hottest regions of the medium. As a result the rescattering intensity increases, i.e., in fact the effective temperature of the medium gets higher as compared with the perfect QGP case. We also do not take into account here the probability of jet rescattering in nuclear matter, because the intensity of this process and the corresponding contribution to the total energy loss are not significant due to the much smaller energy density in a “cold” nucleus.

Another important element of the model is the angular spectrum of in-medium gluon radiation. Since the detailed calculation of the angular spectrum of emitted gluons is rather sophisticated and model-dependent [6,13,15,22–24], the simple parameterization of the gluon angular distribution over the emission angle θ was used:

$$\frac{dN^g}{d\theta} \propto \sin \theta \exp\left(-\frac{(\theta - \theta_0)^2}{2\theta_0^2}\right), \quad (8)$$

where $\theta_0 \sim 5^\circ$ is the typical angle of the coherent gluon radiation as estimated in [6]. Other parameterizations are also envisaged.

3 Simulation procedure

The model has been constructed as the fast Monte Carlo event generator PYQUEN (PYthia QUENched), and the corresponding Fortran routine PYQUEN is available via Internet [25]. The routine is implemented as a modification of the standard PYTHIA_6.2.* jet event [26].

The following event-by-event Monte Carlo simulation procedure is applied.

- Generation of the initial parton spectra with PYTHIA (fragmentation *off*).
- Generation of the jet production vertex at the impact parameter b according to the distribution

$$\frac{dN^{\text{jet}}}{d\psi dr}(b) = \frac{T_A(r_1)T_A(r_2)}{T_{AA}(b)},$$

$$T_{AA}(b) = \int_0^{2\pi} d\psi \int_0^{r_{\max}} r dr T_A(r_1)T_A(r_2), \quad (9)$$

where $r_{1,2}(b, r, \psi)$ are the distances between the nucleus centers and the jet production vertex $V(r \cos \psi, r \sin \psi)$; $r_{\max}(b, \psi) \leq R_A$ is the maximum possible transverse distance r from the nuclear collision axis to V ; R_A is the radius of the nucleus A ; $T_A(\mathbf{r}) = A \int \rho_A(\mathbf{r}, z) dz$ is the nuclear thickness function with the nucleon density distribution $\rho_A(\mathbf{r}, z)$; $T_{AA}(b)$ is the nuclear overlap function (see [7] for detailed nuclear geometry explanation).

- Calculation of the scattering cross section $\sigma = \int dt d\sigma/dt$ (3).
- Generation of the displacement between the i th and $(i+1)$ th scatterings, $l_i = (\tau_{i+1} - \tau_i)$:

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1}) \exp\left(-\int_0^{l_i} \lambda^{-1}(\tau_i + s) ds\right),$$

$$\lambda^{-1}(\tau) = \sigma(\tau)\rho(\tau), \quad (10)$$

and calculation of the corresponding transverse distance, $l_i p_T/E$.

- Reducing the parton energy by collisional and radiative loss per each i th scattering:

$$\Delta E_{\text{tot},i} = \Delta E_{\text{col},i} + \Delta E_{\text{rad},i}, \quad (11)$$

where the collisional part is calculated in the high-momentum transfer approximation (3),

$$\Delta E_{\text{col},i} = \frac{t_i}{2m_0}, \quad (12)$$

and the energy of a radiated gluon, $\omega_i = \Delta E_{\text{rad},i}$, is generated according to (4) and (6):

$$\left.\frac{dI}{d\omega}\right|_{m_q=0} = \frac{2\alpha_s(\mu_D^2)\lambda C_R}{\pi L\omega} \left[1 - y + \frac{y^2}{2}\right] \ln |\cos(\omega_1 \tau_1)|,$$

$$\left.\frac{dI}{d\omega}\right|_{m_q \neq 0} = \frac{1}{(1 + (\beta\omega)^{3/2})^2} \left.\frac{dI}{d\omega}\right|_{m_q=0}. \quad (13)$$

- Calculation of the parton transverse momentum kick due to elastic scattering i :

$$\Delta k_{t,i}^2 = \left(E - \frac{t_i}{2m_{0i}}\right)^2 - \left(p - \frac{E}{p} \frac{t_i}{2m_{0i}} - \frac{t_i}{2p}\right)^2 - m_p^2. \quad (14)$$

- Formation of the additional (in-medium emitted) gluon with the energy ω_i and the emission angle θ_i relative to the parent parton determined according to the parameterization (8).
- Halting the rescattering if
 - (a) the parton escapes the dense zone, or
 - (b) QGP cools down to $T_c = 200$ MeV, or
 - (c) the parton loses so much energy that its $p_T(\tau)$ drops below $2T(\tau)$.
- At the end of each event, adding new (in-medium emitted) gluons to the PYTHIA parton list and rearrangement of partons to update string formation.
- Formation of the final state particles by PYTHIA (fragmentation *on*).

4 Extension of the model to simulate full heavy ion event

The full heavy ion event is simulated as a superposition of soft hydro-type state and hard multi-jets. The simple approximation [27,28] of the hadronic liquid at the “freeze-out” stage has been used to treat the soft part of the event giving the final hadron spectrum as a superposition of thermal distribution and collective flow [29–31].

(1) The 4-momentum p_μ^* of a hadron of mass m was generated at random in the rest frame of a liquid element in accordance with the isotropic Boltzmann distribution

$$f(E^*) \propto E^* \sqrt{E^{*2} - m^2} \exp(-E^*/T_f), \quad (15)$$

$$-1 < \cos \theta^* < 1, \quad 0 < \phi^* < 2\pi,$$

where $E^* = \sqrt{p^{*2} + m^2}$ is the energy of the hadron, and the polar angle θ^* and the azimuthal angle ϕ^* specify the direction of its motion in the rest frame of the liquid element.

(2) The spatial position of a liquid element and its local

4-velocity u_μ were generated at random in accordance with the phase space and the character of the motion of the fluid:

$$\begin{aligned}
 f(r) &= 2r/R_f^2 \quad (0 < r < R_f), \\
 f(\eta) &\propto \exp[-(\eta - Y_L^{\max})^2/2(Y_L^{\max})^2], \\
 0 &< \Phi < 2\pi, \\
 u_r &= \sinh Y_T^{\max} \frac{r}{\sqrt{R_f(b)R_f(b=0)}}, \\
 u_t &= \sqrt{1 + u_r^2} \cosh \eta, \\
 u_z &= \sqrt{1 + u_r^2} \sinh \eta,
 \end{aligned} \tag{16}$$

where R_f is the final transverse radius of the system in a given direction. Freeze-out parameters of the model are the kinetic freeze-out temperature T_f and the maximum longitudinal, Y_L^{\max} , and transverse, Y_T^{\max} , collective flow rapidities.

(3) Further, a boost of the hadron 4-momentum in the CM frame of the event was calculated:

$$\begin{aligned}
 p_x &= p^* \sin \theta^* \cos \phi^* + u_r \cos \Phi \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right], \\
 p_y &= p^* \sin \theta^* \sin \phi^* + u_r \sin \Phi \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right], \\
 p_z &= p^* \cos \theta^* + u_z \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right], \\
 E &= E^* u_t + (u^i p^{*i}),
 \end{aligned} \tag{17}$$

where

$$(u^i p^{*i}) = u_r p^* \sin \theta^* \cos(\Phi - \phi^*) + u_z p^* \cos \theta^*. \tag{18}$$

Anisotropic flow is introduced here under the simple assumption that the spatial ellipticity of the “freeze-out” region, $\epsilon = \langle y^2 - x^2 \rangle / \langle y^2 + x^2 \rangle$, is directly related to the ellipticity of the system formed in the region of the initial overlap of nuclei, $\epsilon_0 = b/2R_A$. This “scaling” enables one to avoid introducing additional parameters and, at the same time, leads to an azimuthal anisotropy of the generated particles due to the dependence of the transverse radius $R_f(b)$ on the angle Φ [28]:

$$\begin{aligned}
 R_f(b) &= R_f(b=0) \\
 &\times \min \left\{ \sqrt{1 - \epsilon_0^2 \sin^2 \Phi} + \epsilon_0 \cos \Phi, \right. \\
 &\quad \left. \sqrt{1 - \epsilon_0^2 \sin^2 \Phi} - \epsilon_0 \cos \Phi \right\}.
 \end{aligned} \tag{19}$$

Obtained in such a way the azimuthal distribution of the particles is described well by the elliptic form for the domain of reasonable impact parameter values.

The mean total particle multiplicity in central Au + Au (Pb + Pb) collisions at RHIC (LHC) is the input parameter

of the model (instead of $R_f(b=0)$ we put R_A here for simplicity), the total multiplicity for other centralities and atomic numbers being assumed to be proportional to the number of nucleons-participants. We also set the Poisson multiplicity distribution and the following particle ratios:

$$\begin{aligned}
 \pi^\pm : K^\pm : p^\pm &= 24 : 6 : 1, \quad \pi^\pm : \pi^0 = 2 : 1, \\
 K^\pm : K^0 &= 1 : 1, \quad p : n = 1 : 1.
 \end{aligned}$$

The hard part of the event includes PYTHIA/PYQUEN hadronic jets generated according to the binomial distribution. The mean number of jets produced in AA events at a given b is proportional to the number of binary nucleon-nucleon sub-collisions and determined as

$$\overline{N_{AA}^{\text{jet}}}(b, \sqrt{s}) = T_{AA}(b) \int_{p_T^{\min}} dp_T^2 \int dy \frac{d\sigma_{pp}^{\text{hard}}(p_T, \sqrt{s})}{dp_T^2 dy}, \tag{20}$$

where $d\sigma_{pp}^{\text{hard}}(p_T, \sqrt{s})/dp_T^2 dy$ is the cross section of the corresponding hard process in pp collisions (at the same CMS energy, \sqrt{s} , of colliding beams) with the minimum transverse momentum transfer p_T^{\min} . The latter is another input parameter of the model. In the frameworks of our approximation, partons produced in (semi) hard processes with the momentum transfer less than p_T^{\min} are considered as being “thermalized”, so their hadronization products are included in the soft part of the event “automatically”.

Note that we can expect some adequate results only for central and semi-central collisions, but not for very peripheral collisions ($b \sim 2R_A$) where the hydro-type description is not applicable. Besides, the very forward rapidity region (where other dynamical effects can be important) is beyond our treatment here.

The jet quenching model extended in such a way has been constructed as a fast Monte Carlo event generator, and the corresponding Fortran code is also available via Internet [32].

Let us recall in the end of this section that ideologically our approximation is similar to the model of Hirano and Nara [33]. The difference is that we concentrate here on the detailed simulation of the parton multiple scattering in a QCD-medium (the scattering-by-scattering generation of parton path length and energy loss in an expanding QGP, taking into account the collisional loss, the Lund string fragmentation model both for hard partons and in-medium emitted gluons, etc.), while the treatment of the hydrodynamic part in [33] is much more detailed than in our simple (and therefore fast) simulation procedure.

5 Validation of the model at RHIC, $\sqrt{s} = 200A$ GeV

In order to demonstrate the efficiency of the model, the jet quenching pattern in Au + Au collisions at RHIC was considered. The comparison of calculated and experimentally measured pseudorapidity η and transverse momentum p_T spectra of hadrons together with their dependence of

event centrality allows for the optimization of the model and specification of the main model parameters.

The PHOBOS data on η -spectra of charged hadrons [34] have been analyzed to fix the particle density in the mid-rapidity region and the maximum particle longitudinal flow rapidity, $Y_L^{\max} = 3.5$. For the calculation of the (multi) jet production cross section, we used the factor $K = 2$ taking into account higher order corrections of perturbative QCD. The rest of the model parameters have been obtained by fitting the PHENIX data on p_T -spectra of neutral pions [35]: the kinetic freeze-out temperature $T_f = 100$ MeV, maximum transverse flow rapidity $Y_T^{\max} = 1.25$ and minimum transverse momentum transfer of “non-thermalized” hard process $p_T^{\min} = 2.8$ GeV/ c . It was found that the nuclear modification of the hardest domain of the p_T -spectrum ($\gtrsim 5$ GeV/ c) is determined in our case only by the intensity of the medium-induced parton rescattering. This fact allows us to extract from the data the initial conditions of the QGP formation independently on other input parameters: the initial temperature $T_0 = 500$ MeV, the formation time $\tau_0 = 0.4$ fm/ c and the number of active quark flavors $N_f = 2$. We will see below that setting the model parameters as it was described above makes it possible to reproduce the main features of the jet quenching pattern at RHIC: the p_T -dependence of the nuclear modification factor R_{AA} and two-particle azimuthal correlation function $C(\Delta\varphi)$.

Figure 1 shows the η -distribution of charged hadrons in Au + Au collisions for different centrality sets. The good fit of the PHOBOS data [34] is achieved excepting very forward rapidities. The p_T -distributions of π^0 -mesons obtained at PHENIX [35] is also well reproduced by our calculations, even for relatively peripheral collisions (Fig. 2).

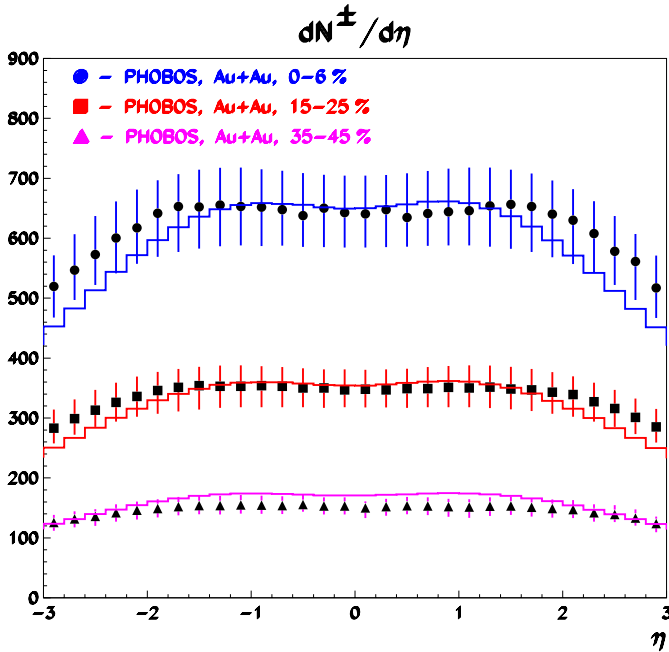


Fig. 1. The pseudorapidity distribution of charged hadrons in Au + Au collisions for three centrality sets. The points are PHOBOS data [34], histograms are the model calculations

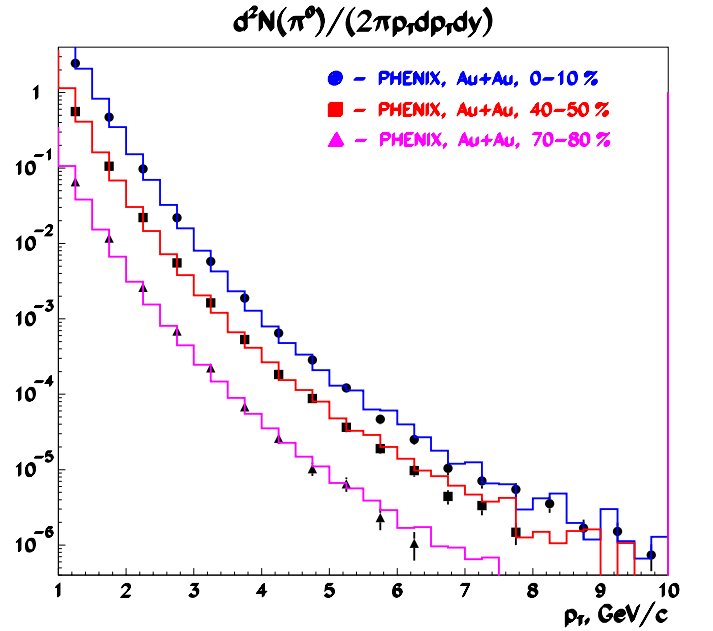


Fig. 2. The transverse momentum distribution of neutral pions in Au + Au collisions for three centrality sets. The points are PHENIX data [35], histograms are the model calculations

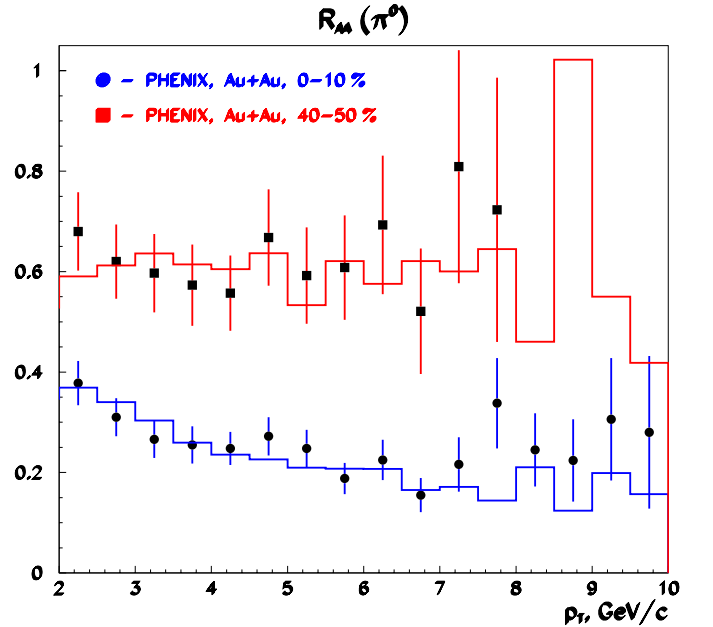


Fig. 3. The nuclear modification factor R_{AA} (21) for neutral pions in Au + Au collisions for two centrality sets. The points are PHENIX data [35], histograms are the model calculations

Figure 3 shows the nuclear modification factor R_{AA} for neutral pions, which is defined as the ratio of particle yields in AA and pp collisions normalized on the number of binary nucleon–nucleon sub-collisions:

$$R_{AA} = \frac{d\sigma_{AA}^{\pi^0}/dp_T}{T_{AA}(b)\sigma_{in}d\sigma_{pp}^{\pi^0}/dp_T}, \quad (21)$$

where $\sigma_{in} = 42$ mb is the inelastic non-diffractive pp cross section at $\sqrt{s} = 200$ GeV. In the absence of medium-

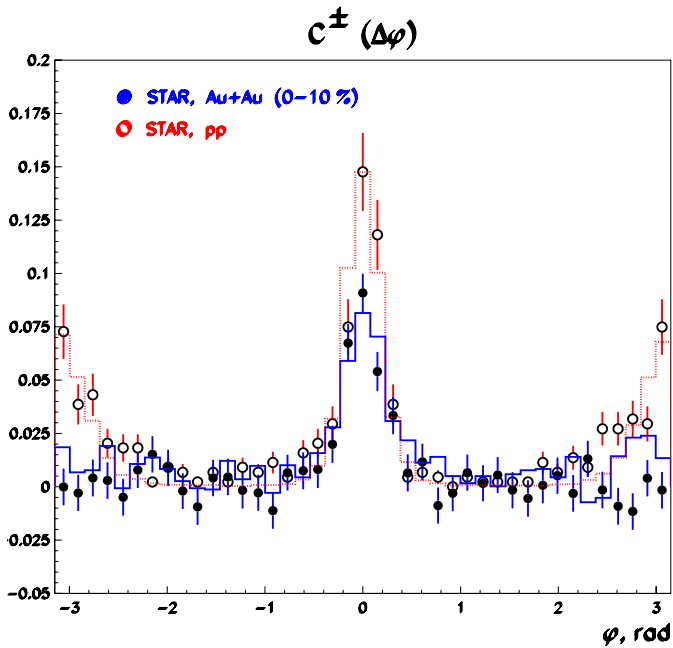


Fig. 4. The azimuthal two-particle correlation function for pp and for central Au + Au collisions. The points are STAR data [35], dashed and solid histograms are the model calculations for pp and Au + Au events respectively

induced effects in the mid-rapidity region it should be $R_{AA} = 1$ for high enough p_T ($\gtrsim 2$ GeV/ c). Such a value of $R_{AA} \sim 1$ has been observed thus for d + Au and peripheral Au + Au collisions, but not for central and semi-central Au + Au events, where $R_{AA} < 1$ up to maximum measured transverse momenta $p_T \sim 10$ GeV/ c . One can see from Fig. 3 that our model calculations reproduce p_T - and centrality dependences of R_{AA} [35] quite well.

Another important tool to verify jet quenching is the two-particle azimuthal correlation function $C(\Delta\varphi)$ – the distribution over an azimuthal angle of high- p_T hadrons in the event with 2 GeV/ $c < p_T < p_T^{\text{trig}}$ relative to that for the hardest “trigger” particle with $p_T^{\text{trig}} > 4$ GeV/ c . Figure 4 presents $C(\Delta\varphi)$ in pp and in central Au + Au collisions (data from STAR [36]). Clear peaks in pp collisions at $\Delta\varphi = 0$ and $\Delta\varphi = \pi$ indicate a typical dijet event topology. Note that almost the same pattern has been observed in d + Au and peripheral Au + Au collisions. However, for most central Au + Au collisions the peak near π disappears. This can be interpreted as the observation of monojet events due to the “absorption” of one of the jets in a dense medium. Such an event configuration corresponds to the situation when the dijet production vertex is close to the surface of the nuclear overlap region: then one partonic jet can escape the medium almost without re-interactions and then go to detectors, while the second jet loses most of its initial energy due to the large number of rescatterings and therefore becomes unobservable [37]. Figure 4 demonstrates that the measured suppression of azimuthal back-to-back correlations is well reproduced by our model (the same procedure of uncorrelated background subtraction as in [36] was applied).

We leave beyond the scope of this paper the analysis of such important RHIC observables as the azimuthal anisotropy and particle ratios. Since these observables are very sensitive to the soft physics, in order to study them a more careful treatment of low- p_T particle production than our simple approach is needed (the detailed description of the space-time structure of the freeze-out region, resonance decays, etc.) For example, our model can reproduce the experimentally measured [38, 39] p_T -dependence of the coefficient of azimuthal anisotropy v_2 (the second harmonic of the Fourier decomposition of particle azimuthal distribution) qualitatively, giving rapid hydrodynamical growth up to $p_T \sim 3$ GeV/ c with the subsequent saturation. However, the model calculations significantly underestimate the data at $p_T < 2$ GeV/ c . A solution of the baryon-to-meson ratio “puzzle” [40, 41] is also beyond our consideration here. Further development of our model with special emphasis on the more detailed description of low- p_T particle production is planned for the future.

6 Conclusions

The model of jet quenching in ultrarelativistic heavy ion collisions has been developed. It includes the generation of the hard parton production vertex according to the realistic nuclear geometry, rescattering-by-rescattering simulation of the parton path length in dense matter, radiative and collisional energy loss per rescattering, final hadronization with the Lund string fragmentation model for hard partons and in-medium emitted gluons. The model is the fast Monte Carlo tool implemented to modify a standard PYTHIA jet event. The model has been generalized to the case of the “full” heavy ion event (the superposition of soft, hydro-type state and hard multi-jets) using a simple and fast simulation procedure for soft particle production.

The efficiency of the model is demonstrated basing on the numerical analysis of high- p_T hadron production in Au + Au collisions at RHIC. The good fit of the experimental data on the η - and p_T -spectra of hadrons for different event centralities is achieved. The model is capable of reproducing the main features of the jet quenching pattern at RHIC: the p_T -dependence of the nuclear modification factor R_{AA} , and the suppression of azimuthal back-to-back correlations. The further development of the model focusing on a more detailed description of low- p_T particle production is planned for the future.

Acknowledgements. Discussions with A.I. Demianov, Yu.L. Dokshitzer, A. Morsch, S.V. Petrushanko, C. Roland, L.I. Sarycheva, J. Schukraft, C.Yu. Teplov, I.N. Vardanyan, I. Vitev, B. Wyslouch, B.G. Zakharov and G.M. Zinovjev are gratefully acknowledged. This work is supported by grant N 04-02-16333 of Russian Foundation for Basic Research.

References

1. R. Baier, D. Schiff, B.G. Zakharov, *Annual Rev. Nucl. Part. Sci.* **50**, 37 (2000)
2. Proceedings of 16th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions Quark Matter 2002 (Nantes, France, 18–24 June, 2002), *Nucl. Phys. A* **715**, (2003); Proceedings of 17th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions Quark Matter 2004 (Oakland, California, 11–17 January, 2004), *J. Phys. G* **30**, (2004)
3. X.-N. Wang, *Phys. Lett. B* **579**, 299 (2004)
4. A. Accardi et al., Jet physics, in *Hard probes in heavy ion collisions at the LHC*, edited by M. Mangano, H. Satz, U. Wiedemann, CERN Report 2004-09, hep-ph/0310274
5. CERN Workshop on Monte Carlo tools for the LHC, 2003, <http://mlm.home.cern.ch/mlm/mcworkshop03/mcworkshop.html>
6. I.P. Lokhtin, A.M. Snigirev, *Phys. Lett. B* **440**, 163 (1998)
7. I.P. Lokhtin, A.M. Snigirev, *Eur. Phys. J. C* **16**, 527 (2000)
8. I.P. Lokhtin, A.M. Snigirev, *Eur. Phys. J. C* **21**, 155 (2001)
9. I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva, A.M. Snigirev, *Phys. At. Nucl.* **65**, 943 (2002)
10. I.P. Lokhtin, A.M. Snigirev, *Phys. Lett. B* **567**, 39 (2003)
11. J.D. Bjorken, Fermilab publication Pub-82/29-THY (1982)
12. S. Mrówczyński, *Phys. Lett. B* **269**, 383 (1991); M.H. Thoma, *Phys. Lett. B* **273**, 128 (1991)
13. R. Baier, Yu.L. Dokshitzer, A.H. Mueller, D. Schiff, *Phys. Rev. C* **60**, 064902 (1999); *C* **64**, 057902 (2001)
14. X.-N. Wang, X.-F. Guo, *Nucl. Phys. A* **696**, 788 (2001)
15. I. Vitev, hep-ph/0503221
16. E. Wang, X.-N. Wang, *Phys. Rev. Lett.* **87**, 142301 (2001)
17. Yu.L. Dokshitzer, D. Kharzeev, *Phys. Lett. B* **519**, 199 (2001)
18. M. Djordjevic, M. Gyulassy, *Nucl. Phys. A* **733**, 265 (2004)
19. N. Armesto, C.A. Salgado, U.A. Wiedemann, *Phys. Rev. D* **69**, 114003 (2004)
20. B.-W. Zhang, E. Wang, X.-N. Wang, *Phys. Rev. Lett.* **93**, 072301 (2004)
21. J.D. Bjorken, *Phys. Rev. D* **27**, 140 (1983)
22. B.G. Zakharov, *JETP Lett.* **70**, 176 (1999)
23. U.A. Wiedemann, M. Gyulassy, *Nucl. Phys. B* **560**, 345 (1999); U.A. Wiedemann, *Nucl. Phys. B* **588**, 303 (2000); *A* **690**, 731 (2001)
24. M. Gyulassy, P. Levai, I. Vitev, *Nucl. Phys. B* **571**, 197 (2000); *Phys. Rev. Lett.* **85**, 5335 (2000); *Nucl. Phys. B* **594**, 371 (2001)
25. <http://cern.ch/lokhtin/pyquen>
26. T. Sjostrand, *Comp. Phys. Com.* **135**, 238 (2001)
27. N.A. Kruglov, I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, *Z. Phys. C* **76**, 99 (1997)
28. I.P. Lokhtin, L.I. Sarycheva, A.M. Snigirev, *Phys. Lett. B* **537**, 261 (2002)
29. E. Schnedermann, J. Sollfrank, U. Heinz, *Phys. Rev. C* **48**, 2462 (1993)
30. S. Muroya, H. Nakamura, M. Namiki, *Progr. Theor. Phys. Suppl.* **120**, 209 (1995)
31. P.F. Kolb, J. Sollfrank, U. Heinz, *Phys. Rev. C* **62**, 054909 (2000); P.F. Kolb et al., *Phys. Lett. B* **500**, 232 (2001); *Nucl. Phys. A* **696**, 175 (2001)
32. HYDJET fast event generator, <http://cern.ch/lokhtin/hydro/hydjet.html>
33. T. Hirano, T. Nara, *Nucl. Phys. A* **743**, 305 (2004); *Phys. Rev. C* **69**, 034908 (2004); *C* **66**, 041901 (2002)
34. B.B. Back et al. (PHOBOS Collab.), *Phys. Rev. Lett.* **91**, 052303 (2003)
35. S.S. Adler et al. (PHENIX Collab.), *Phys. Rev. Lett.* **91**, 072301 (2003)
36. C. Adler et al. (STAR Collaboration), *Phys. Rev. Lett.* **89**, 202301 (2002)
37. M. Plumer, M. Gyulassy, X.-N. Wang, *Nucl. Phys. A* **590**, 511 (1995)
38. S.S. Adler et al. (PHENIX Collab.), *Phys. Rev. Lett.* **91**, 182301 (2003); nucl-ex/0411040
39. J. Adams et al. (STAR Collaboration), *Phys. Rev. Lett.* **93**, 252301 (2004); nucl-ex/0409033
40. S.S. Adler et al. (PHENIX Collab.), *Phys. Rev. C* **69**, 034909 (2004)
41. J. Adams et al. (STAR Collaboration), *Phys. Rev. Lett.* **92**, 112301 (2004)