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IN ULTRARELATIVISTIC
HEAVY ION COLLISIONS**

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Abstract

The method for simulation of medium-induced rescattering and energy loss of hard partons in ultrarelativistic heavy ion collisions is developed. The model is realized as fast Monte-Carlo tool implemented to modify standard PYTHIA jet event.

И.П.Лохтин и А.М.Снигирев

**Быстрое моделирование подавления струй
в ультрарелятивистских соударениях тяжелых ионов**

Препринт НИИЯФ МГУ 2004-13/752

Аннотация

Разработан метод моделирования индуцированных средой перерасcеяния и потерь энергии партонов в ультрарелятивистских соударениях тяжелых ионов. Модель реализована в виде Монте-Карло программы, позволяющей модифицировать стандартные события генератора PYTHIA.

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1 Introduction

The experimental investigation of ultra-relativistic nuclear collisions offers a unique possibility of studying the properties of strongly interacting matter at high energy density. In that regime, hadronic matter is expected to become deconfined, and a gas of asymptotically free quarks and gluons is formed, the so-called quark-gluon plasma (QGP), in which the colour interactions between partons are screened owing to collective effects [1]. One of the important tools to study QGP properties in heavy ion collisions is a QCD jet production. Medium-induced energy loss of energetic partons, the so-called jet quenching, has been proposed to be very different in cold nuclear matter and in QGP, resulting in many challenging observable phenomena [2]. Recent RHIC data on suppression of inclusive high- p_T charge and neutral hadron production from STAR [3], PHENIX [4], PHOBOS [5] and BRAHMS [6] are in agreement with the jet quenching hypothesis [7]. However direct event-by-event reconstruction of jets and their characteristics is not available in RHIC experiments at the moment, while the assumption that integrated yield of all high- p_T particles originates only from jet fragmentation is not obvious.

At LHC a new regime of heavy ion physics will be reached at $\sqrt{s_{NN}} = 5.5$ TeV where hard and semi-hard QCD multi-particle production can dominate over underlying soft events. The initial gluon densities in Pb–Pb reactions at LHC are expected to be significantly higher than at RHIC, implying stronger partonic energy loss which can be observable in various new channels [8]. Thus in order to test a sensitivity of accessible at LHC observables to jet quenching, and to study corresponding experimental capabilities of real detectors, the development of fast Monte-Carlo tools is necessary.

2 Physics frameworks of the model

The detailed description of physics frameworks of the developed model can be found in a number of our previous papers [9, 10, 11, 12, 13]. The approach relies on an accumulative energy losses, when gluon radiation is associated with each scattering in expanding medium together including the interference effect by 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 initial energy E and path length L has the form

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

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 in-medium mean free path, $\rho \propto T^3$ is the medium density at the temperature T , σ is the integral cross section of parton interaction in the medium.

The collisional energy loss due to elastic scattering with high-momentum transfer have been originally estimated by Bjorken in [14], and recalculated later in [15] taking also into account the loss with low-momentum transfer dominated by the interactions with plasma collective modes. Since latter process contributes to the total collisional loss without the large factor $\sim \ln(E/\mu_D)$ (μ_D is the Debye screening mass) in comparison with high-momentum scattering and it can be effectively “absorbed” by the redefinition of minimal momentum transfer $t \sim \mu_D^2$ under the numerical estimates, we used the collisional part with high-momentum transfer only [10],

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

and the dominant contribution to the differential cross section

$$\frac{d\sigma}{dt} \cong C \frac{2\pi\alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_q^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f) \ln(t/\Lambda_{QCD}^2)} \quad (3)$$

for scattering of a parton with energy E off the “thermal” partons 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, $\Lambda_{QCD} \simeq T_c \simeq 200$ 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 $t_{\max} = [s - (m_p + m_0)^2][s - (m_p - m_0)^2]/s$ where $s = 2m_0E + m_0^2 + m_p^2$, m_p is the hard parton mass.

There are several calculations of the inclusive energy distribution of medium-induced gluon radiation from Feynman multiple scattering diagrams. The relation between these approaches and their main parameters have been discussed in details in the recent writeup of the working group “Jet Physics” for the CERN Yellow Report [8]. We restrict to ourself here by using BDMS formalism [16]. In the BDMS framework 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 in fact is regulated mainly by the initial

QGP temperature T_0 . Then the energy spectrum of coherent medium-induced gluon radiation and the corresponding dominated part of radiative energy loss of massless parton has the form [16]:

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

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

where $\tau_1 = L/(2\lambda_g)$, $y = \omega/E$ is the fraction of the hard parton energy carried 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 substituting $C_R = 3$ and a proper change of the factor in the square bracket in (4), see ref. [16]. The integral (4) is carried out over all energies from $\omega_{\min} = E_{LPM} = \mu_D^2 \lambda_g$, the minimal radiated gluon energy in the coherent LPM regime, up to initial jet energy E .

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

$$\frac{dE}{dx} \Big|_{m_q \neq 0} = \frac{1}{(1 + (l\omega)^{3/2})^2} \frac{dE}{dx} \Big|_{m_q = 0}, \quad l = \left(\frac{\lambda}{\mu_D^2} \right)^{1/3} \left(\frac{m_q}{E} \right)^{4/3}, \quad (6)$$

but note there are exist more recent developments on heavy quark energy loss in the literature [18, 19].

The medium was treated as a boost-invariant longitudinally expanding quark-gluon fluid, and partons as being produced on a hyper-surface of equal proper times τ [20]. In order to simplify numerical calculations in original version of the model we omit the transverse expansion and viscosity of the fluid using the well-known scaling Bjorken’s solution [20] for temperature and density of QGP at $T > T_c \simeq 200$ MeV:

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

For certainty we used the initial conditions for the gluon-dominated plasma formation expected for central Pb–Pb collisions at LHC [21]:

$$\tau_0 \simeq 0.1 \text{ fm}/c, \quad T_0 \simeq 1 \text{ GeV}, \quad \rho_g \approx 1.95T^3.$$

Then 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 [10].

Note, however, that using other initial parameters and scenarios of QGP space-time evolution for Monte-Carlo realization of the model is possible (by changing some internal parameters of the routine). In fact, the influence of the transverse flow, as well as 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 leads to a jet parton spending more time in the hottest regions of the medium. As a result the rescattering intensity goes up, i.e., in fact an effective temperature of the medium gets lifted 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 corresponding contribution to total energy loss are not significant due to much smaller energy density in a “cold” nuclei.

Another important set of the model is the angular spectrum of in-medium gluon radiation. Since the full treatment of angular spectrum of emitted gluons is rather sophisticated and model-dependent [9, 16, 22, 23, 24], simple parameterizations of gluon angular distribution over 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 coherent gluon radiation estimated in work [9]. Other parameterizations are also possible.

3 Monte-Carlo simulation procedure

The model has been realized as fast Monte-Carlo event generator, and corresponding Fortran routine PYQUEN.F is available by the web [25]. The following input parameters should be specified by user to fix QGP properties: beam and target nucleus atomic number and type of event centrality selection (options “fixed impact parameter” or “minimum bias events” are foreseen). Since the routine is implemented as a modification of standard PYTHIA6.2 jet event [26], the main user program should be compiled with this version of PYTHIA.

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

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

the distribution

$$\frac{dN^{\text{jet}}}{d\psi dr}(b) = \frac{T_A(r_1)T_A(r_2)}{2\pi \int_0^{r_{max}} d\psi \int_0^{r_{max}} r dr T_A(r_1)T_A(r_2)},$$

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 the V ; R_A is the radius of the nucleus A ; $T_A(r_{1,2})$ is the nuclear thickness function (see ref. [10] for detailed nuclear geometry explanations).

- Generating scattering cross section $d\sigma/dt$ (3).
- Generating transverse distance between scatterings, $l_i = (\tau_{i+1} - \tau_i)E/p_T$:

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

- Reducing parton energy by collisional (2) and radiative (4), (6) loss per scattering i :

$$\Delta E_{\text{tot},i} = \Delta E_{\text{col},i} + \Delta E_{\text{rad},i}.$$

- Calculating parton transverse momentum kick due to elastic scattering i :

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

- Halting parton rescattering if 1) parton escapes from dense zone, or 2) QGP cools down to $T_c = 200$ MeV, or 3) parton loses so much energy that its $p_T(\tau)$ drops below $2T(\tau)$.
- In the end of each event adding new (in-medium emitted) gluons into PYTHIA parton list and rearrangements of partons to update string formation are performed.
- Formation of final hadrons by PYTHIA (fragmentation *on*).

As the example, let us compare hadron p_T -spectra obtained with jet quenching (PYTHIA+ PYQUEN) and without one (PYTHIA only). Fig.1 shows this spectrum for $\sqrt{s_{pp}} = 5.5$ TeV and QGP parameters selected for central Pb–Pb collisions, the events being triggered by having at least one jet with $E_T > 100$ GeV in the final state. As it could be expected, energy loss of hard partons results in the high- p_T suppression of the spectrum, while the intensive gluon emission of soft and semi-hard gluons governs the low- p_T enhancement.

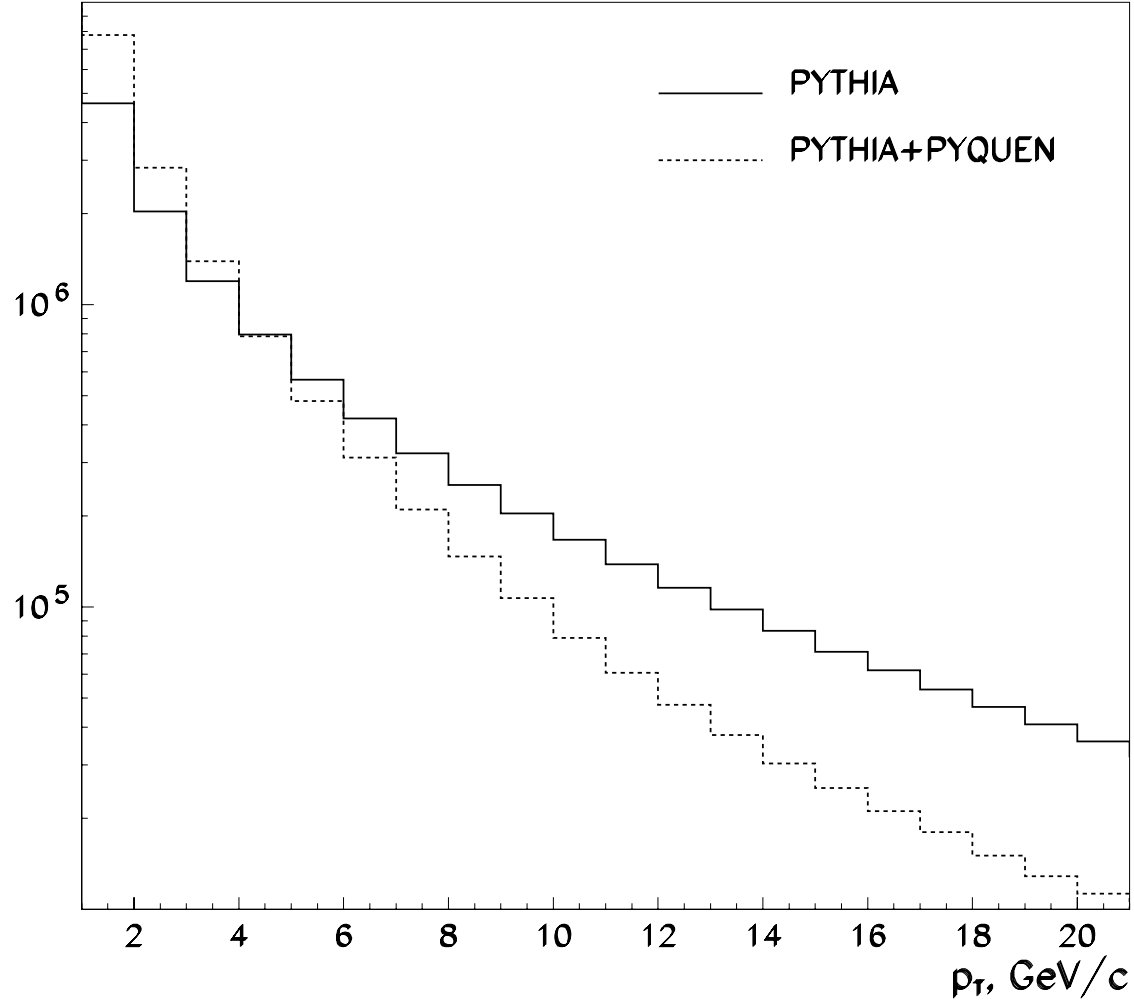


Рис. 1: The hadron p_T -spectrum at $\sqrt{s_{pp}} = 5.5$ TeV obtained with jet quenching (PYTHIA+PYQUEN, dashed histogram) and without one (PYTHIA, solid histogram). QGP parameters were selected for central Pb–Pb collisions. Events were triggered having at least one jet with $E_T > 100$ GeV in the final state.

4 Conclusions

The method to simulate rescattering and energy loss of hard partons in ultrarelativistic heavy ion collisions has been developed. The model is realized as fast Monte-Carlo tool implemented to modify standard PYTHIA jet event. Corresponding Fortran routine is available by the web.

To conclude, let us discuss the physics validity of the model application.

- Internal parameters of the routine for initial conditions and space-time evolution of quark-gluon plasma were selected as an estimation for LHC heavy ion beam energies. The result for other beam energy ranges, obtained without additional internal parameters adjusting, is not expected to be reasonable.
- Hydro-type description of expanding quark-gluon plasma used by the model can be applicable for central and semi-central collisions. The result obtained for very peripheral collisions ($b \sim 2R_A$) can be not adequate.
- Physics model for medium-induced gluon radiation is valid for relatively high transverse momenta of jet partons ($\gg 1 \text{ GeV}/c$). Thus setting reasonably high value of minimum p_T in initial hard parton sub-processes in PYTHIA is preferable.

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