Modeling the jet quenching, thermal resonance production and hydrodynamical flow in relativistic heavy ion collisions

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Abstract.

The event topology in relativistic heavy ion collisions is determined by various multi-particle production mechanisms. The simultaneous model treatment of different collective nuclear effects at high energies (such as a hard multi-parton fragmentation in hot QCD-matter, thermal resonance production, hydrodynamical flows, etc.) is actual but rather complicated task. We discuss the simulation of the above effects by means of Monte-Carlo model HYDJET++.

1. Introduction

Ongoing and future experimental studies of relativistic heavy ion collisions in a wide range of beam energies require the development of new Monte-Carlo (MC) event generators and improvement of existing ones. A realistic MC event generator should include a maximum possible number of observable physical effects which are important to determine the event topology: from the bulk properties of soft hadroproduction (domain of low transverse momenta \( p_T < 1 \div 2 \text{ GeV}/c \)) such as thermal resonance production and collective flows, to hard multi-parton fragmentation in hot and dense QCD-matter, which reveals itself in the spectra of high-\( p_T \) particles and hadronic jets. HYDJET++ event generator [1] includes detailed treatment of soft hadroproduction as well as hard multi-parton production, and takes into account medium-induced parton rescattering and energy loss. The heavy ion event in HYDJET++ is the superposition of two independent components: the soft, hydro-type state and the hard state resulting from multi-parton fragmentation. Note that a conceptually similar approximation has been developed in [2, 3]. HYDJET++ model is the development and continuation of HYDJET event generator [4], and it contains the important additional features for the soft component: resonance decays and more detailed treatment of thermal and chemical freeze-out hypersurfaces [5, 6]. The details on physics model and simulation procedure can be found in HYDJET++ manual [1], the main features of the model being listed only very briefly below.
2. HYDJET++ model

The model for the hard multi-parton part of HYDJET++ event is the same as that for HYDJET event generator, and it is based on PYQUEN partonic energy loss model [3]. The approach to the description of multiple scattering of hard partons in the dense QCD-matter (such as quark-gluon plasma) is based on the accumulative energy loss via the gluon radiation being associated with each parton scattering in the expanding quark-gluon fluid and includes the interference effect (for the emission of gluons with a finite formation time) using the modified radiation spectrum \( dE/dl \) as a function of decreasing temperature \( T \). The model takes into account radiative and collisional energy loss of hard partons in longitudinally expanding quark-gluon fluid, as well as realistic nuclear geometry. The event generator for single hard nucleon-nucleon sub-collision PYQUEN was constructed as a modification of the jet event obtained with the generator of hadron-hadron interactions PYTHIA 6.4 [7]. The event-by-event simulation procedure in PYQUEN includes 1) generation of initial parton spectra with PYTHIA and production vertexes at given impact parameter; 2) rescattering-by-rescattering simulation of the parton path in a dense zone and its radiative and collisional energy loss; 3) final hadronization according to the Lund string model for hard partons and in-medium emitted gluons. Then the PYQUEN multi-jets generated according to the binomial distribution are included in the hard part of the event. The mean number of jets produced in an AA event is the product of the number of binary NN sub-collisions at a given impact parameter and the integral cross section of the hard process in \( NN \) collisions with the minimum transverse momentum transfer \( p_T^{\text{min}} \). In order to take into account the effect of nuclear shadowing on parton distribution functions, the impact parameter dependent parameterization obtained in the framework of Glauber-Gribov theory [8] is used.

The soft part of HYDJET++ event is the “thermal” hadronic state generated on the chemical and thermal freeze-out hypersurfaces obtained from the parametrization of relativistic hydrodynamics with preset freeze-out conditions (the adapted C++ code FAST MC [5, 6]). Hadron multiplicities are calculated using the effective thermal volume approximation and Poisson multiplicity distribution around its mean value, which is supposed to be proportional to the number of participating nucleons at a given impact parameter of AA collision. The fast soft hadron simulation procedure includes 1) generation of the 4-momentum of a hadron in the rest frame of a liquid element in accordance with the equilibrium distribution function; 2) generation of the spatial position of a liquid element and its local 4-velocity in accordance with phase space and the character of motion of the fluid; 3) the standard von Neumann rejection/acceptance procedure to account for the difference between the true and generated probabilities; 4) boost of the hadron 4-momentum in the center of mass frame of the event; 5) the two- and three-body decays of resonances with branching ratios taken from the SHARE particle decay table [9]. The high generation speed in HYDJET++ is achieved due to almost 100% generation efficiency of the “soft” part because of the nearly uniform residual invariant weights which appear in the freeze-out momentum and coordinate simulation.

Note that although HYDJET++ is optimized for very high energies of RHIC and LHC colliders (c.m.s. energies of heavy ion beams \( \sqrt{s} = 200 \) and 2760 ÷ 5500 GeV per nucleon pair respectively), it can also be used for studying the particle production in a wider energy range down to \( \sqrt{s} \sim 10 \) GeV per nucleon pair at future facilities FAIR and NICA. As one moves from very high to moderately high energies, the contribution of the hard part of the event becomes smaller, while the soft part turns into just a multi-parameter fit to the data.

3. Some applications of HYDJET++ at RHIC and LHC

It was demonstrated in [1] that HYDJET++ model can describe the bulk properties of hadronic state created in \( \text{Au+Au} \) collisions at RHIC at \( \sqrt{s} = 200 A \) GeV (hadron spectra and ratios, radial and elliptic flow, femtosopic momentum correlations), as well as the high-\( p_T \) hadron spectra. A number of input parameters of the model can be fixed from fitting the RHIC data to various
physical observables. For example, the thermodynamical potentials and the chemical freeze-out temperature \( T_{ch} = 0.165 \) GeV have been fixed in HYDJET++ from fitting the RHIC data to hadron ratios near mid-rapidity in central Au+Au collisions. The slopes of transverse mass \( m_T \) hadron spectra (\( \pi^+, K^+ \) and \( p \) with \( m_T < 0.7 \) GeV/\( c^2 \)) near mid-rapidity at different centralities spectra allow the thermal freeze-out temperature \( T_{th} = 0.1 \) GeV and the maximal radial flow rapidity in central collisions \( \rho_{max}(b = 0) = 1.1 \) to be fixed. The space-time parameters of thermal freeze-out region can be fixed by means of fitting the three-dimensional correlation functions measured for \( \pi^+\pi^+ \) pairs and extracting the correlation radii \( R_{side}, R_{out} \) and \( R_{long} \). Rapidity spectra of charged hadrons at different centralities allow us to fix the particle densities in the mid-rapidity region and the maximum longitudinal flow rapidity \( \eta_{max} = 3.3 \). Since mean “soft” and “hard” hadron multiplicities depend on the centrality in different ways, the relative contribution of soft and hard parts to the total event multiplicity can be fixed through the centrality dependence of \( dN/d\eta \). High transverse momentum hadron spectra (\( p_T > 2 \div 4 \) GeV/\( c \)) are sensitive to parton production and jet quenching effect, therefore fitting the measured high-\( p_T \) tail allows the extraction of PYQEN energy loss model parameters. The momentum and azimuthal anisotropy parameters are estimated for different centrality sets by fitting the measured transverse momentum dependence of the elliptic flow coefficient, \( v_2(p_T) \).

![Figure 1](image_url)  

**Figure 1.** The pseudorapidity (left) and the transverse momentum (right) spectra of \( J/\psi \)-mesons in Au+Au collisions at \( \sqrt{s} = 200A \) GeV for 0 \( \div \) 20% centrality. The points are PHENIX data [12], histograms are the HYDJET++ calculations for \( \gamma_c = 7 \) and \( T_{th}(J/\psi) = T_{ch} = 0.165 \) GeV (solid – total, dotted – soft component, dashed – hard component).

Thermal charm hadron production was implemented in HYDJET++ recently. \( D, J/\psi \) and \( \Lambda_c \) hadrons are generated within the statistical hadronization model [10][11]. Momentum spectra of charm hadrons are computed according to the thermal distribution, and the multiplicities \( N_c \) (\( C = D, J/\psi, \Lambda_c \)) are calculated through the corresponding thermal numbers \( N_{c th} \) as

\[
N_c = \gamma_c N_{c th},
\]

where \( \gamma_c \) is the charm enhancement factor (or charm fugacity), and \( N_c \) is the number of charm quarks in a hadron \( C \). The fugacity \( \gamma_c \) can be treated as a free parameter of the model or calculated through the number of charm quark pairs obtained from perturbative QCD. HYDJET++ fits measured by PHENIX \( J/\psi \) yields in central Au+Au collisions [12] with \( \gamma_c = 7 \). If we assume that thermal freeze-out for \( J/\psi \)-mesons happens at the same temperature as for light hadrons, \( T_{th} = 0.1 \) GeV (\( \eta_{max} = 3.3, \rho_{max} = 1.1 \)), then simulated \( y- \) and \( p_T- \)spectra are much wider than the data. However if we assume that thermal freeze-out for \( J/\psi \)-mesons occurs at the same temperature as chemical freeze-out, \( T_{th}(J/\psi) = T_{ch} = 0.165 \) GeV, then simulated
spectra are capable of fitting the PHENIX data for the values of maximal longitudinal and radial flow rapidities $\eta_{ch}^{z_{\text{max}}} = 1.1$ and $\eta_{ch}^{x_{\text{max}}} = 0.5$ respectively (see Fig. [1]).

The heavy ion collision energy at LHC will be a factor of $\sim 15 \div 30$ larger then that in RHIC, thereby allows one to probe new frontiers of super-high temperature and (almost) net-baryon free QCD. It is expected that at such ultra-high energies the role of hard and semi-hard particle production may be significant even for the bulk properties of created matter. In particular, the spectacular predictions of HYDJET++ are possible reducing the femtoscopic correlation radii [13] and elliptic flow [14] in heavy ion collisions as one moves from RHIC to LHC energies due to the significant contribution of (semi)hard component to the space-time structure of the hadron emission source.

4. Summary
Among other heavy ion event generators, Monte-Carlo model HYDJET++ focuses on the detailed simulation of jet quenching effect basing on the partonic energy loss model PYQUEN, and also reproducing the main features of nuclear collective dynamics by the parametrization of relativistic hydrodynamics with preset freeze-out conditions (including resonance decays, and separate treatment of thermal and chemical freeze-out hypersurfaces). Thus the final hadronic state in HYDJET++ represents the superposition of two independent components: medium-modified hard multi-parton fragmentation and soft hydro-type part. HYDJET++ is capable of reproducing the bulk properties of heavy ion collisions at RHIC (hadron spectra and ratios, radial and elliptic flow, femtoscopic momentum correlations), as well as hard probes (high-$p_T$ hadron and $J/\psi$ spectra). The simulations for LHC (and also at lower energies of future facilities FAIR and NICA) are in progress.

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