Preprint SINP MSU 2004-14/753

Fast simulation of flow effects in central and semi-central heavy ion collisions at LHC

I.P. Lokhtin and A.M. Snigirev

M.V.Lomonosov Moscow State University, D.V.Skobeltsyn Institute of Nuclear Physics
119992, Vorobievy Gory, Moscow, Russia
E-mail: Igor.Lokhtin@cern.ch

Abstract

The simple method for simulation of "thermal" hadron spectra in ultrarelativistic heavy ion collisions including longitudinal, transverse and elliptic flow is developed. The model is realized as fast Monte-Carlo event generator.

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 is transverse and elliptic flow observables.

In particular, the experimentally observed growth of the mean transverse momentum with increasing mass in most central nuclear collisions at SPS [2, 3] and RHIC [4, 5] energies is naturally and simply explained with the hydrodynamical model [6], where the change of momentum $\Delta p_T(\mathbf{r})$ of a hadron of mass m due to transverse motion of a fluid element at the point $\mathbf{r}$ can be written as $\Delta p_T(\mathbf{r}) = m \sinh Y_T(\mathbf{r})$, where Y_T is the collective transverse rapidity.

Moreover, a strong interest in azimuthal correlation measurements in ultrarelativistic heavy ion collisions has recently gained impetus. Recent anisotropic flow data from SPS [7] and RHIC [8, 9, 10] can be described well by hydrodynamical models for semi-central collisions and transverse momentum, p_T, up to ~ 2 GeV/c (the coefficient of elliptic flow v_2, which is defined as the coefficient of the second harmonic of the particle azimuthal distribution with respect to the reaction plane, appears to be monotonously growing with increasing p_T [11] in this case). On the other hand, the majority of microscopical Monte-Carlo models underestimate the flow effects (see however [12]). Measurements of v_2 present one of the effective tools to test various models. In particular, the saturation and gradual decrease of v_2 for $p_T > 2$ GeV/c, predicted as a signature of strong partonic energy loss in a QGP, is supported by the recent RHIC data [8, 9] extending up to $p_T \simeq 10$ GeV/c. The interpolation between the low-p_T relativistic hydrodynamics region and the high-p_T pQCD-computable region was evaluated in [13].

The initial gluon densities in Pb−Pb reactions at $\sqrt{s_{\rm NN}} = 5.5$ TeV at the Large Hadron Collider (LHC) are expected to be significantly higher than at RHIC, implying much stronger QGP effects. The probing experimental capabilities of LHC detectors together with physics and software validation of various Monte-Carlo tools and cross-comparisons among different codes are important tasks in the light of coming LHC Heavy Ion Program [14]. A number of Monte-Carlo generators is available at the moment to generate heavy ion events at LHC energies: HIJING [15], FRITIOF [16], LUCIAE [17], DPMJET-III [18], PSM [19], NEXUS [20], etc. However, flow effects in almost of such models are lacking or implemented insufficiently. Besides, running these codes at LHC energies consumes much computing efforts. On the other hand, macroscopic hydrodynamical models basically reproduce the bulk of hadron spectra observed at SPS and RHIC, and can be in principle used to estimation of particle flow effects at LHC, may be extending this approach to even some higher p_T values. Of course, for more detailed simulation, one has to take into account the interplay between hydro flow and semi-hard particle flow due to parton energy loss, secondary scatterings, etc.

2 "Thermal" model and fast Monte-Carlo generation

We suggest simple hydrodynamical Monte-Carlo code [21, 22] giving final hadron spectrum as a superposition of a thermal distribution and a collective flow [23, 24, 25, 11],

$$E\frac{d^3N}{d^3p} = \int_\sigma f(x,p)\; p^\mu d\sigma_\mu \quad , \tag{1}$$

where the invariant distribution function $f(x,p)$ is taken in the Bose-Einstein form for particles of integer spin and in the Fermi-Dirac form for particles of half-integer spin (p_μ is the 4-momentum of hadron, and $E = p_0$ is its energy). Integration is performed over the hypersurface σ at the "freeze-out" temperature $T = T_f$. The formation of the cylindrically symmetric hot matter expanding preferably along the cylinder axis is expected in the case of relativistic heavy ion collisions; as to the transverse motion, it can be taken into account as a correction [26]. In this case, the variables τ, r, η and Φ ($r = \sqrt{x^2+y^2}$, $\tau = \sqrt{t^2-z^2}$, $\eta = \frac{1}{2}\ln\frac{t+z}{t-z}$, $\tan\Phi = y/x$) are commonly used instead of the Cartesian coordinates t, x, y, z. We consider charged and neutral pions, kaons and nucleons only, and kaons and nucleons are supposed to be thermally suppressed by their heavier mass. In addition, the linear transverse velocity profile specification

$$u^r = \sinh Y_T = \frac{dR}{d\tau}\frac{r}{R}$$

(which follows from a solution of the nonrelativistic continuity equation with uniform density) and longitudinal velocity specification in accordance with one-dimensional scaling solution $Y_L = \eta$ are assumed (Y_T and Y_L are, respectively, the transverse and the longitudinal rapidity of collective motion, while R is the effective transverse radius of the system).

The following procedure were applied to simulate "thermal" hadron spectra in heavy ion AA collisions at given impact parameter b.

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

$$f(E^*) \propto E^*\sqrt{E^{*2}-m^2}\exp\left(-E^*/T_f\right), \qquad -1 < \cos\theta^* < 1, \qquad 0 < \phi^* < 2\pi \quad , \tag{2}$$

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 phase space and the character of motion of the fluid:

$$\begin{aligned} &f(r) = 2r/R_f^2 \;(0 < r < R_f), \qquad -\eta_{\rm max} < \eta < \eta_{\rm max}, \qquad 0 < \Phi < 2\pi, \\ &u_r = \frac{r}{R_f}\sinh Y_T^{\rm max}, \qquad u_t = \sqrt{1+u_r^2}\cosh\eta, \qquad u_z = \sqrt{1+u_r^2}\sinh\eta \quad , \end{aligned} \tag{3}$$

where R_f is the effective final transverse radius of the system, which is fixed here by specifying the mean charged multiplicity per unit rapidity interval, $< dN/dy^h >$, in the final state;

$\eta_{\max} = Y_L^{\max}$ and $Y_T^{\max}$ are maximum longitudinal and transverse collective rapidities.

3. Further, boost of the hadron 4-momentum in the c.m. frame of the event was performed:

$$
\begin{aligned}
p_x &= p^* \sin\theta^* \cos\phi^* + u_r \cos\Phi \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right] \\
p_y &= p^* \sin\theta^* \sin\phi^* + u_r \sin\Phi \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right] \\
p_z &= p^* \cos\theta^* + u_z \left[E^* + \frac{(u^i p^{*i})}{u_t + 1} \right] \\
E &= E^* u_t + (u^i p^{*i}),
\end{aligned}
\qquad (4)
$$

where

$$
(u^i p^{*i}) = u_r p^* \sin\theta^* \cos(\Phi - \phi^*) + u_z p^* \cos\theta^* \; . \qquad (5)
$$

Anisotropic flow is introduced here under simple assumption that the spatial ellipticity of "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, $\epsilon_0 = b/2R_A$ (R_A is nucleus radius). This "scaling" enables one to avoid introducing additional parameters and, at the same time, leads to an azimuthal anisotropy of generated particles due to dependence of effective final radius $R_f(b)$ on the angle Φ [27]:

$$
R_f(b) = R_f(b=0) \; \min\{\sqrt{1 - \epsilon_0^2 \; \sin^2\Phi} + \epsilon_0 \; \cos\Phi, \; \sqrt{1 - \epsilon_0^2 \; \sin^2\Phi} - \epsilon_0 \; \cos\Phi\}. \qquad (6)
$$

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

We also set the Poisson multiplicity distribution and assume that the mean multiplicity of particles is proportional to the nuclear overlap function [27]. For estimated "freeze-out" parameters – temperature $T_f = 140$ MeV, collective longitudinal rapidity $Y_L^{max} = 5$ and collective transverse rapidity $Y_T^{max} = 1$ – we get average hadron transverse momentum $< p_T^h >= 0.55$ GeV/c and following particle ratios:

$$
\pi^{\pm} : K^{\pm} : p^{\pm} = 24 : 6 : 1, \qquad \pi^{\pm} : \pi^0 = 2 : 1, \qquad K^{\pm} : K^0 = 1 : 1, \qquad p : n = 1 : 1 \; .
$$

The model has been realized as fast Monte-Carlo event generator, and corresponding Fortran routine is available by the web [28]. The following input parameters should be specified by user to set hadron event configuration: beam and target nucleus atomic number; type of event centrality generation (options "fixed impact parameter" or "impact parameter is generated with standard Glauber geometry between minimum and maximum values" are foreseen); baseline mean charged particle multiplicity per unit rapidity at mid-rapidity, $< dN^{\pm}/dy^h >$ ($y^h = 0$), in central Pb-Pb collisions (total multiplicity for other centralities and atomic numbers will be calculated automatically). Since the output particle information is stored in common block LUJETS of JETSET routine [29], main users program should be compiled with JETSET Fortran routine with extended size (up to 150000) of LUJETS arrays.

3 Conclusions

The simple model to simulate flow effects in heavy ion collisions at LHC energies has been developed. This model is realized as fast Monte-Carlo event generator, and corresponding Fortran routine is available by the web.

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

- Internal parameters of the routine for flow 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 heavy ion collisions is expected to be applicable for central and semi-central collisions. The result obtained for very peripheral collisions ($b \sim 2R_A$) can be not adequate.

- Hydro flow mechanism in heavy ion collisions is valid for restricted kinematic range: mid-rapidity, low and intermediate p_T. The model is not applicable for very forward rapidity ($|y| \gtrsim 3$) and very high p_T ($\gg 2-5$ GeV/c).

Acknowledgments.
We would like to thank S.V. Petrushanko, C. Roland and L.I. Sarycheva for useful discussions.

References

[1] Proceedings of 16th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions "Quark Matter'2002" (Nantes, France, July 18-24, 2002), Nucl. Phys. **A 715** (2003).

[2] N. Xu *et al.* (NA44 Coll.), Nucl. Phys. **A 610** (1996) 175.

[3] H. Appelshauser *et al.* (NA49 Coll.), Eur. Phys. J. **C 2** (1998) 661.

[4] O. Barannikova *et al.* (STAR Coll.), Nucl. Phys. **A 715** (2003) 458.

[5] T. Chujo *et al.* (PHENIX Coll.), Nucl. Phys. **A 715** (2003) 151; S. Adler *et al* (PHENIX Coll.), [arXiv:nucl-ex/0307022].

[6] I.L. Rozental and Yu.A. Tarasov, Phys. Usp. **36** (1993) 572.

[7] H. Appelshauser *et al.* (NA49 Coll.), Phys. Rev. Lett **80** (1998) 4136; C. Alt *et al.* (STAR Coll.), Phys. Rev. **C 68** (2003) 034903.

[8] K.H. Ackermann *et al.* (STAR Coll.), Phys. Rev. Lett. **86** (2001) 402; C. Adler *et al.* (STAR Coll.), Phys. Rev. Lett. **87** (2001) 182303; Phys. Rev. Lett. **90** (2003) 032301; R.J.M. Snellings *et al.* (STAR Coll.) Nucl. Phys. **A 698** (2002) 193.

[9] R.A. Lacey *et al.* (PHENIX Coll.), Nucl. Phys. **A 698** (2002) 559.

[10] I.C. Park *et al.* (PHOBOS Coll.), Nucl. Phys. **A 698** (2002) 564; B.B. Back *et al.* (PHOBOS Coll.), Phys. Rev. Lett. **89** (2002) 222301; Nucl. Phys. **A 715** (2003) 611.

[11] P.F. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. **C 62** (2000) 054909; P.F. Kolb *et al.*, Phys. Lett. **B 500** (2001) 232; Nucl. Phys. **A 696** (2001) 175.

[12] E.E. Zabrodin, C. Fuchs, L.V. Bravina, and A. Faessler, Phys. Lett. **B 508** (2001) 184.

[13] M. Gyulassy, I. Vitev, and X.-N. Wang, Phys. Rev. Lett. **86** (2001) 2537.

[14] CERN Workshop on Monte Carlo tools for the LHC, http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html .

[15] M. Gyulassy and X.-N. Wang, Phys. Rev. **D 44** (1991) 3501; Comput. Phys. Commun. **83** (1994) 307.

[16] Hong Pi, Comput. Phys. Commun. **71** (1992) 173; B. Andersson, G. Gustafson, and Hong Pi, Z. Phys. **C 57** (1993) 485.

[17] An Tai and Ben-Hao Sa, Comput. Phys. Commun. **116** (199) 353.

[18] S. Roesler, R. Engel, and J. Ranft, [arXiv: hep-ph/0012252].

[19] N.S. Amelin, N. Armesto, C. Pajars, and D. Sousa, Eur. Phys. J. **C 22** (2001) 149.

[20] K. Werner, H.J. Drescher, S. Ostapchenko, and T. Pierog, [arXiv: hep-ph/0209198].

[21] N.A. Kruglov, I.P. Lokhtin, L.I. Sarycheva, and A.M. Snigirev, Z. Phys. **C 76** (1997) 99.

[22] I.P. Lokhtin, L.I. Sarycheva, and A.M. Snigirev, Phys. Lett. **B 537** (2002) 261; Nucl. Phys. **A 715** (2003) 633.

[23] E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. **C 48** (1993) 2462.

[24] S. Muroya, H. Nakamura, and M. Namiki, Progr. Theor. Phys. Suppl. **120** (1995) 209.

[25] I.P. Lokhtin and A.M. Snigirev, Phys. Lett. **B 378** (1996) 247.

[26] J.D. Bjorken, Phys. Rev. **D 27** (1983) 140.

[27] I.P. Lokhtin and A.M. Snigirev, Eur. Phys. J **C 16** (2000) 527.

[28] HYDRO fast event generator, http://cern.ch/lokhtin/hydro .

[29] T. Sjöstrand, Comput. Phys. Commun. **82** (1994) 74.