JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Hubble law and anisotropic flow in heavy-ion collisions

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Abstract

In the present report, we considered simulations of heavy-ion collisions. Velocity field for different types of particles was calculated using the UrQMD model. Dependence of velocity on transverse distance was obtained. Anisotropic flow coefficients dependences on transverse momentum and rapidity calculated. Obtained results for different types of particles compared.

I. Introduction

Physics. Relativistic heavy-ion collisions allow us to observe strongly interacting matter under unusual conditions, like extremely high temperatures and densities. The extreme temperature and energy densities generated in heavy-ion collisions produce a state of matter called quark-gluon plasma, which represents fluid properties. The structure of velocity field must be understood to properly describe the fluid.

The general structure of the velocity field follows the so-called little bang pattern, which may be quantified by the velocity dependence allowing one to extract the so-called little Hubble constant:

$$\langle v/c \rangle = v_0/c + H\rho, \tag{1}$$

Where ρ is transverse distance, v – velocity, H – Hubble constant. [1]

The strong evidence of the existence of quark-gluon plasma is anisotropic flow. It represents momentum anisotropy of produced particles which arises from initial spatial anisotropy in non-central heavy-ion collisions.

Consider φ as the azimuthal angle of the transverse momentum vector of the particle, Ψ_{RP} as the angle of reaction plane. By using a Fourier series decomposition of the azimuthal distribution of produced particles,

$$\frac{dN}{d(\varphi - \Psi_{RP})} \sim 1 + \sum_{n=1}^{\infty} 2v_n cos\big(n(\varphi - \Psi_{RP})\big) \tag{2}$$

anisotropic flow is quantified with coefficients v_n. Coefficient $v_1$is referred as directed flow and v_2 as elliptic flow.

The UrQMD. There are different ways to investigate the properties of quark-gluon plasma. One of the models describing heavy-ion collisions is the Ultra-Relativistic Quantum Molecular Dynamics (UrQMD) model. This microscopic transport model describes the phenomenology of hadronic interactions at low and intermediate energies $\sqrt{s} < 5$ GeV) in terms of interactions between known hadrons and their resonances. At higher energies, $\sqrt{s} > 5$ GeV, the excitation of color strings and their subsequent fragmentation into hadrons dominates the multiple production of particles in the UrQMD model.[2]

The purpose of this paper is to determine the pattern of the velocity field and calculate flow coefficients for pions, protons, kaons and lambda hyperons separately.

II. Simulations parameters

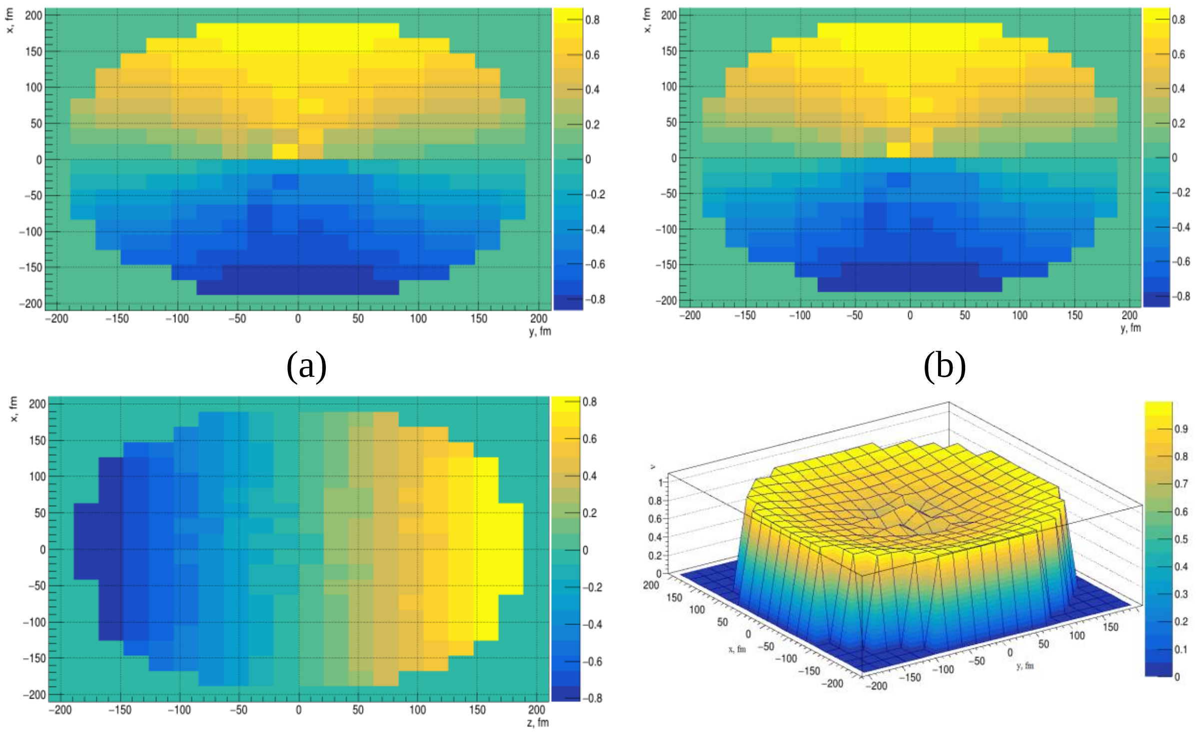
We focused on Au + Au collisions at energy $\sqrt{S_{NN}} = 11.5\,GeV$ and impact parameter from 0 up to 3 fm within UrQMD 3.4 model. The system was taken at the time 200 fm/c after the collision. To be more coincide with experiments, only particles with transverse momentum in the range 0.2 through 3.0 GeV/c and pseudorapidity in the range -1.2 through 1.2 were considered.

III. Hubble law

For investigation of the dependence of the velocity on transverse distance, the coordinate space was divided into $20 \times 20 \times 20$ cells of volume $dxdydz$ with $dx = dy = dz = 20$ fm. The velocity in given cell was defined as the following sum over all particles of a particular type in the cell and over all events:

$$\vec{v}(x,y,z) = \sum_i \sum_j \frac{\vec{P}_{ij}}{E_{ij}}, \tag{2}$$

where $\vec{P}_{ij}$ and E_{ij} are the momentum and energy of particle i in the collision j, respectively.



(a) (b)

(c) (d)

FIG. 1. Projection of the cell velocity for pions on x for (a) and y axis for (b) in XY plane; projection of of the cell velocity for pions on z axis in plane XZ for (c); magnitude of the cell velocity for pions in plane XY for (d).

Our observation is that the average cell velocity is directed away from the collision point; the magnitude of velocity becomes bigger with distance from this point (see Fig. 1, only pions shown). This means that the faster particles fly further from the center than the slower ones.

Using the field of velocity we calculated the dependence of average cell velocity on transverse distance $\rho = \sqrt{x^2 + y^2}$ and measured the Hubble constant for different types of particles (see Fig. 2).

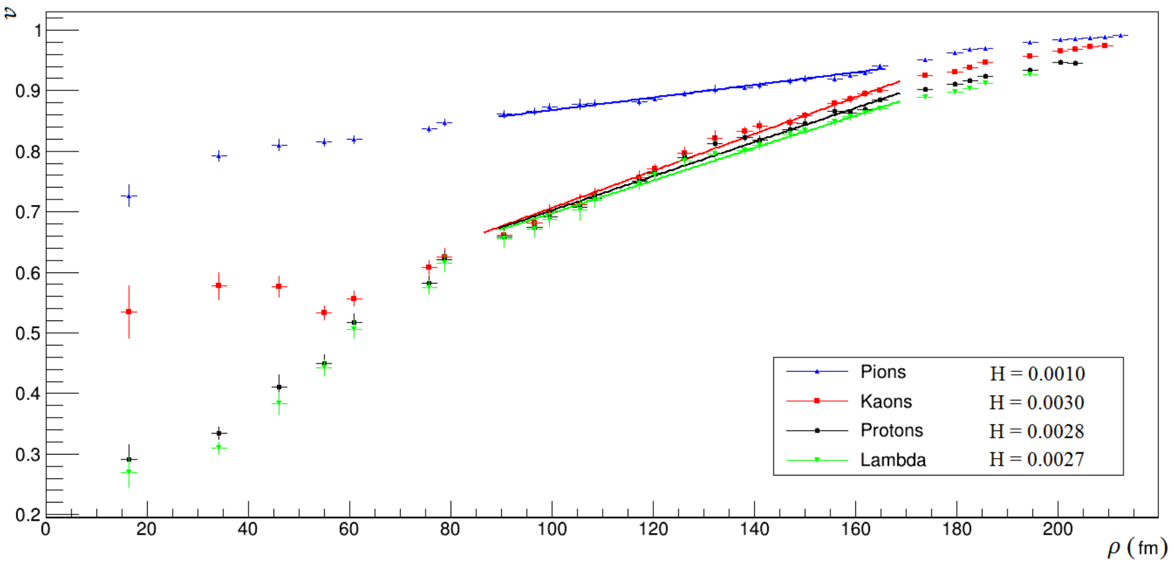


FIG. 2. The cell velocity dependence on the transverse distance.

As one can see, behavior of protons, kaons, and lambda hyperons is similar, but kaons have a maximum at smaller distances. Pions' behavior strongly differs from other particles, but still obeys the linear law. Only middle parts of the dependencies may be considered as linear, so the velocity fields need further investigation with larger statistics.

IV. Anisotropic flow

Anisotropic flow coefficients v_n are defined as $\langle \cos(n(\varphi - \Psi_{RP})) \rangle$, where $\langle \dots \rangle$ means average on all particles in all events. Thus v_1 and v_2 may be calculated as

$$v_n = \frac{\sum_i \sum_j \cos\left(n\left(\varphi_{ij} - \Psi_{RP_j}\right)\right)}{N}, \qquad (3)$$

where $n = 1, 2$; φ_{ij} is the azimuthal angle of the transverse momentum vector $\vec{p}_{ijT}$ of the particle i in the collision j, Ψ_{RP_j} is the angle of the reaction plane in the collision j, N is the total number of particles in all events.

In the UrQMD model, all collisions take place in the reaction plane. To be more coincide with experiments, we generated uniformly distributed Ψ_{RP_j} in each collision and rotated the initial plane, so that the angle between the initial plane and reaction plane in the collision j is Ψ_{RP_j}.

Calculated flow coefficients dependences on transverse momentum and rapidity are shown in figures 3 and 4 respectively.

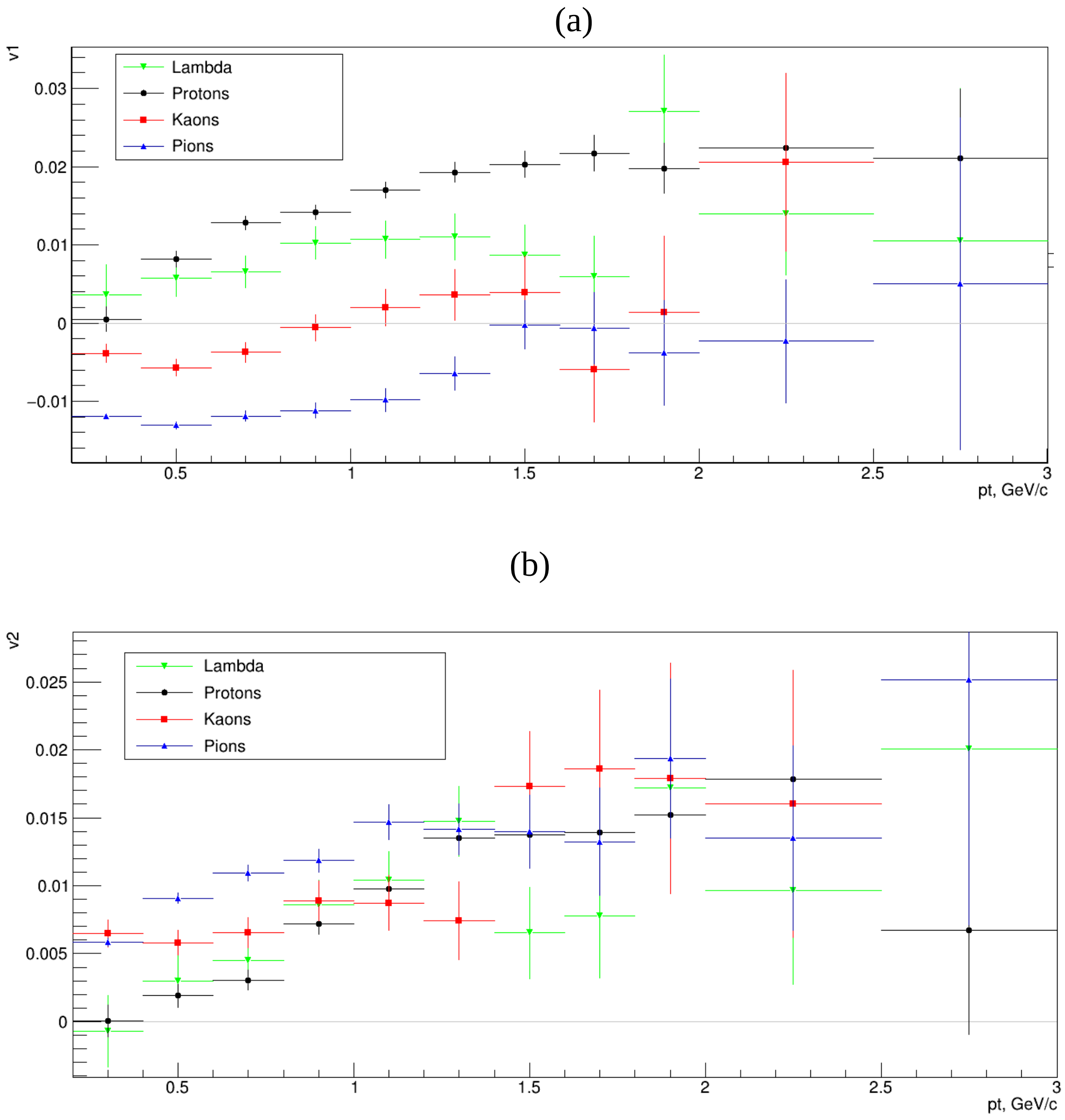


FIG. 3. The dependences of v_1 (a) and v_2 (b) coefficients on transverse momentum.

One can compare Figs. 2 and 3. For pions, protons and lambda the further the particles are from the center, the bigger the transverse momentum. Hence the dependence of flow coefficients on transverse distance should be close to dependence on p_T, which means they should decrease or increase simultaneously. This is valid in general for pions, protons and lambda with relatively small momentum. For kaons, further investigation is required because their dependence on distance is not as simple as for the other particles.

Despite the protons and lambda dependences for velocity being almost similar, their dependences for v_1 and v_2 are different, except for the dependence of v_2 on rapidity (see Fig. 3 and 4).

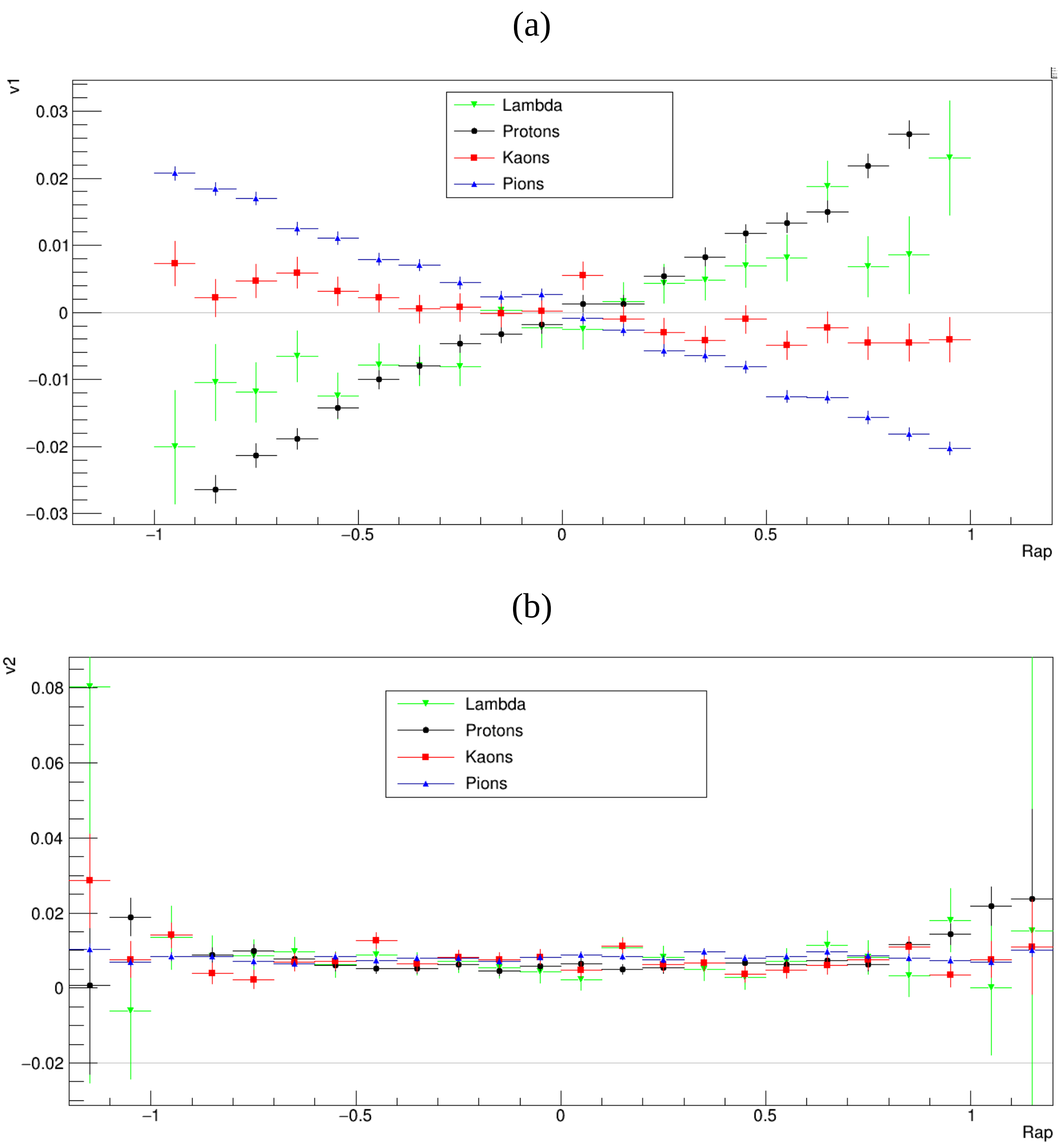


FIG. 4. The dependences of v_1 (a) and v_2 (b) coefficients on rapidity.

Conclusion

We obtained the structure of velocity field in heavy-ion collisions within the UrQMD model. Using the obtained results we calculated the dependences of velocity on transverse distance for different types of particles. They are almost similar for protons and lambda hyperons. Dependences for pions and kaons differ from them.

We calculated flow coefficients dependences on transverse momentum and rapidity for different particles. The dependences on transverse momentum for protons, lambda and kaons are in some way similar to the dependences of velocity on transverse distance. Only v_2 coefficients are similar for all particles.

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