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Anisotropic (v_1 and v_2) Flow in Relativistic Heavy-Ion Collisions at Energies between 4 GeV and 200 GeV

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Abstract. Basic features of directed and elliptic flows of identified hadrons in heavy-ion collisions at intermediate and high energies are considered within two transport string models, UrQMD and QGSM. Both models indicate changing of the sign of proton directed flow at midrapidity from antiflow to normal flow with decreasing energy of collisions. The origin of this effect is traced to hadron rescattering in baryon-rich remnants of the colliding nuclei. To distinguish the effect of rescattering from the flow softening caused by creation of quark-gluon plasma one has to compare heavy-ion and light-ion collisions at the same energy. Both directed and elliptic flows at midrapidity are formed within $t = 10 - 12\,\mathrm{fm}/c$. The differences in the development of elliptic flows of mesons and baryons are found at high energies. These differences can be explained by dissimilar freeze-out conditions, thus suggesting simultaneous study of particle collective flow and freeze-out.

1 Introduction

The expansion of hadrons, produced in relativistic heavy-ion collisions, in transverse and longitudinal directions was considered as a collective effect about four decades ago [1, 2] within the hydrodynamic model. This phenomenon is colloquially known nowadays as a collective flow. The flow was found to be very sensitive to the equation of state (EOS) of the expanding matter. Particularly, the flow should carry the fingerprints of the new state of matter - the quark-gluon plasma (QGP). Initially, the collective flow was decomposed into the bounce-off flow elongated within the reaction plane, and the squeeze-out flow, which was orthogonal to the reaction plane. Experimental observation of both types of the flow was reported by the Plastic Ball collaboration at Bevalac in [3]. Since then the analysis of the flow effects was concerning the in-plane flow and out-of-plane flow.

The situation was changed drastically some 20 years ago, when the method of Fourier series expansion was proposed [4]. According to it the invariant distribution is represented as

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right\}, \tag{1}$$

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where p_T is particle transverse momentum, y is rapidity, ϕ is the azimuthal angle between the particle $\vec{p_T}$ and the participant event plane, and Ψ_n is the azimuth of the event plane of n-th flow component. The flow harmonics

$$v_n = \langle \cos\left[n(\phi - \Psi_n)\right]\rangle \tag{2}$$

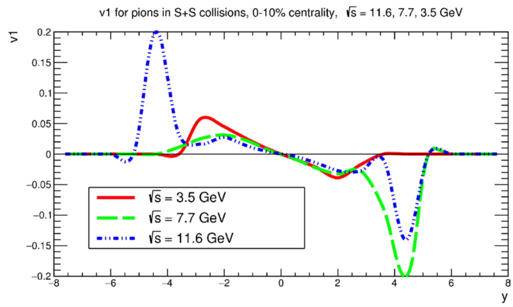
can be found after the averaging over all particles in a single event and all events in the data sample. The first coefficients of the flow are dubbed as *directed*, v_1, *elliptic*, v_2, *triangular*, v_3, *quadrangular*, v_4, flow, and so forth. Our present study focuses on properties of the directed and elliptic flows of charged and identified particles in heavy-ion collisions at energies between $E_{lab} = 11.6$ AGeV (AGS) and $\sqrt{s} = 200$ GeV (RHIC). Of special interest is the energy range of future collider NICA, 4GeV $\leq \sqrt{s} \leq$ 11GeV. We start with the discussion of basic features of directed flow.

2 Directed flow

This flow component appears to be qualitatively similar to the bounce-off flow, $\langle p_x/A\rangle$, because $v_1 = \langle p_x/p_T\rangle$, where p_x is the projection of particle momentum on the impact parameter axis. Experiments on heavy-ion collisions at bombarding energies below 1-2 AGeV revealed that (i) the proton flow had linear slope at midrapidity, $\partial p_x/\partial y(y = 0) \propto y$, (ii) the slope is positive, i.e. the product $p_x \cdot y > 0$, and (iii) it demonstrates the scaling behavior in terms of reduced variables $\tilde{p}_x = p_x/p_{max}$ and $\tilde{y} = y/y_{max}$ in the center of mass frame. Violation of the scaling of proton flow with increasing impact parameter of the collision and increasing bombarding energy was predicted in [5] and then studied in [6–10]. It should be noted that at c.m. energies above 12-15 GeV the directed flow of any hadrons has negative slope, which sometimes is very close to zero, at midrapidity (so-called antiflow) in semi-peripheral and peripheral collisions. Results of the beam energy scan (BES) at RHIC show that in Au+Au collisions at $\sqrt{s} = 7.7$ GeV the proton directed flow becomes positive for collisions with centrality $10\% \leq \sigma/\sigma_{geo} \leq 40\%$, whereas the v_1 of antibaryons and mesons demonstrate clearly antiflow [11]. Hydrodynamic models experience several difficulties to explain the different signs of directed flows of different hadron species, see, e.g. [12, 13]. However, this peculiarity has almost natural explanation within the framework of microscopic transport models, such as quark-gluon string model (QGSM) [14, 15]. Below we will use also another model, UrQMD [16, 17], in order to show that these features are general for string models, despite of the differences in mechanisms of string excitation and fragmentation.

Let us consider directed flow of pions as function of rapidity shown in Fig. 1 for S+S collisions with centrality 0 - 10% at $\sqrt{s} = 3.5$, 7.7, and 11.6 GeV, respectively. All spectra has negative slope at midrapidity. The absolute strength of $v_1^\pi|_{y=0}$ increases with decreasing c.m. energy. For the directed flow of protons in these reactions displayed in Fig. 2 the situation is different. Firstly, v_1^p in the fragmentation regions is always positive, whereas at midrapidity it is consistent with zero. With decreasing c.m. energy of collisions the fragmentation peaks become closer to each other, thus entering the midrapidity area. Directed flow of protons at energies $\sqrt{s} = 7.7$ GeV and below in (semi-)central collisions becomes positive. Different hadron species are produced with different abundances in the central and in the spectator areas of heavy-ion collisions. Their directed flows, therefore, will be also different.

Figure 3 presents the snapshots of collective velocities and particle partial densities of the rectangular cells with volumes $V = 3\,\mathrm{fm}^3$ in Au+Au collisions at $\sqrt{s} = 7.7$ GeV for protons, antiprotons and charged pions, respectively (upper row). The impact parameter is $b = 6$ fm, and the snapshots are taken at $t = 10\,\mathrm{fm}/c$ after beginning of the collisions. Cells which possess normal flow are shown in red, in case of antiflow their color is blue. Hadrons with



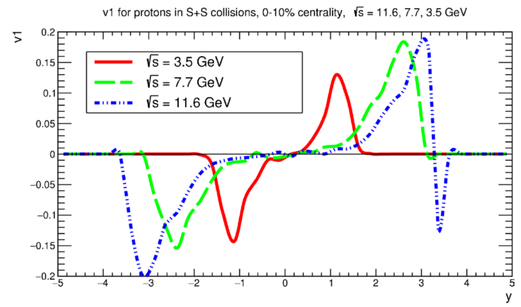


Figure 1. Directed flow of charged pions vs rapidity $y_{c.m.}$ in UrQMD calculations of S+S collisions with centrality 0-10% at $\sqrt{s}$ = 3.5 GeV (solid line), 7.7 GeV (dashed line), and 11.6 GeV (dash-dotted line).

Figure 2. The same as Fig 1 but for the directed flow of protons.

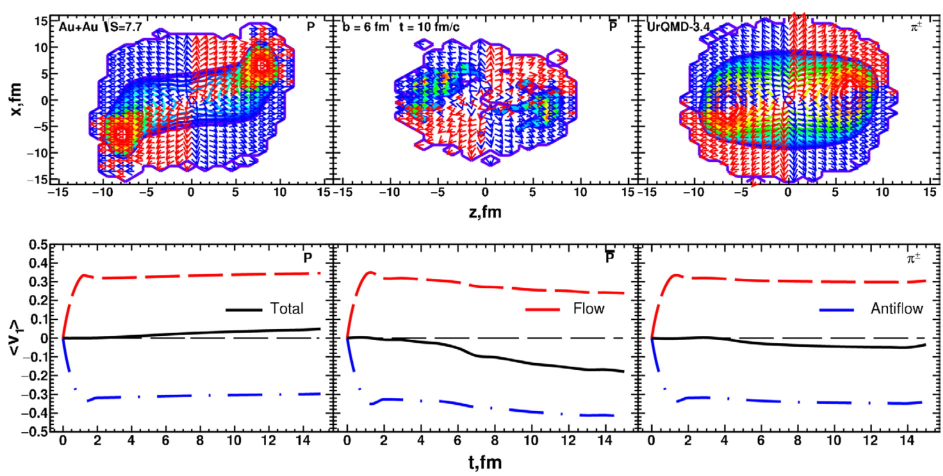


Figure 3. Upper row: The snapshot of hadron densities (contour plots) and collective velocities (arrows) of the cells with volume $V = 3\,\mathrm{fm}^3$ each for protons (left), antiprotons (middle), and charged pions (right) in UrQMD calculations of Au+Au collisions with $b = 6\,\mathrm{fm}$ at $\sqrt{s} = 7.7\,\mathrm{GeV}$ at $t = 10\,\mathrm{fm}/c$. Bottom row: The time development of total directed flow (solid line) and partial flows in normal (red dashed line) and antiflow (blue dash-dotted line) directions of protons (left), antiprotons (middle), and charged pions (right) in aforementioned reactions.

positive flow propagate in the direction of baryon-rich spectator matter, whereas the particles with antiflow are propagating through the dilute areas. The spectators absorb hadrons (especially, with small rapidity) and re-emit them after series of rescattering. These hadrons usually should get higher both p_T and p_x, and, therefore, larger rapidity. The resulting directed flow, which is a difference between the normal flow and antiflow, will be antiflow elongated at $y \approx 0$. Thus the effect of the v_1 softening due to hadron rescattering can be mixed up with the flow softening because of the QGP formation. To resolve the ambiguity one has to perform collisions of light ions at the same c.m. energy as well. In case of hadron rescattering the softening of the v_1 is stronger in light-ion collisions [6, 7, 18], whereas in case of the plasma formation the effect is opposite.

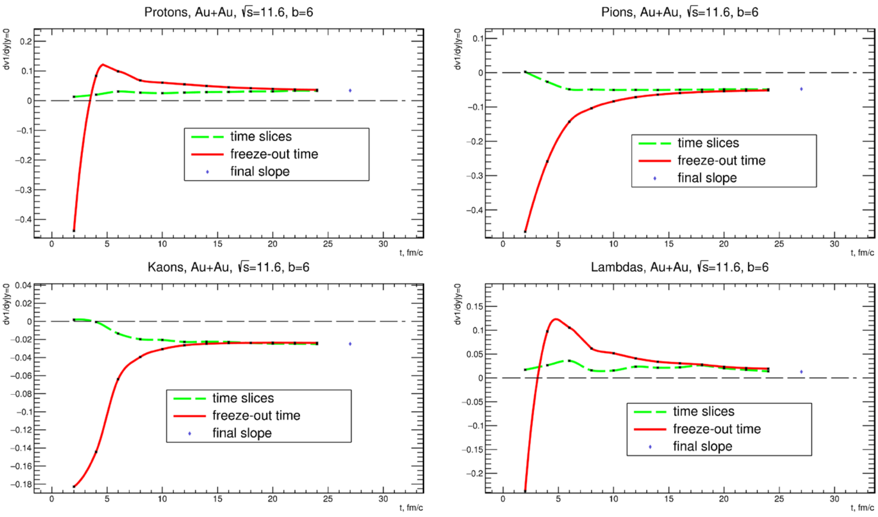


Figure 4. Time evolution of midrapidity directed flow (green dashed curves) of $p, \pi^{\pm}, K^{\pm}$, and Λ in UrQMD calculations of Au+Au collisions with $b = 6$ fm at $\sqrt{s} = 11.6$ GeV. Directed flow carried by the hadrons already frozen at a certain time is shown by red solid curve.

Time development of the directed flow of protons, antiprotons, and charged pions is also displayed in Fig. 3 (bottom row). Within first 4 fm/c resulting directed flow for all hadrons is close to zero, although the partial normal flow and antiflow are quickly developing. How long time does it take? It is assumed *a priori* that the evolution of the directed flow of hadrons takes place almost until the late freeze-out stage. In contrast, the elliptic flow stops to develop when the almond-shaped zone of overlapping nuclei restores the symmetry in the transverse plane. To check these statements, we have to compare the snapshots of the directed flow at different times with the final flow and also with the v_1 of hadrons frozen at different times. The last check is important because, unlike to hydrodynamic models, particles in microscopic calculations of heavy-ion collisions can leave the fireball freely, meaning the absence of sharp freeze-out. This comparison is shown in Fig. 4 for midrapidity v_1 of $p, \pi^{\pm}, K^{\pm}$, and Λ produced in Au+Au collisions with $b = 6$ fm at $\sqrt{s} = 11.6$ GeV. The snapshots are taken with time step $\Delta t = 1$ fm/c. This flow is compared with the v_1 of hadrons from the final spectrum frozen at $t = n \pm 0.25$ fm/c, where n is integer. We see that both distributions converge to each other and saturate at $t \geq 10$ fm/c for all hadron species considered.

3 Elliptic flow

Similar analysis is employed to study the time evolution of the elliptic flow of baryons and mesons. The parameters of Au+Au collisions are the same as for study of v_1 discussed above. Recall that elliptic flow is

$$v_2 = \langle \cos\left[2(\phi - \Psi_2)\right] \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \tag{3}$$

Results of the study are shown in Fig. 5. It is worth mentioning several features. Namely, (i) the partial v_2 of most abundant hadron species at midrapidity develops up to $t \approx 10 - 14$ fm/c, which almost coincides with the time development of directed flow. Then,

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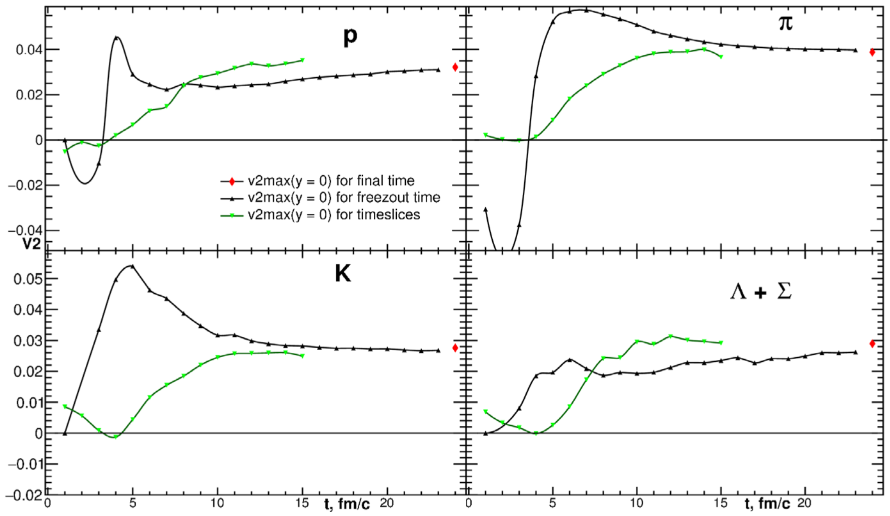

Figure 5. The same as Fig. 4 but for the elliptic flow of these hadrons.

(ii) hadrons frozen before 5 fm/c have the strongest elliptic flow, whereas the actual elliptic flow at early times is very weak. This behavior is also observed in QGSM calculations, see [18, 19]. It is closely connected to the continuous freeze-out picture attributed to transport string models. At low and intermediate energies the fraction of hadrons emitted from the surface of the fireball during the first two fm/c is very small. Also, baryons and mesons are emitted mainly from the central area, although the baryon source is larger a bit. At higher collision energies the situation is changed, as indicated in Fig. 6. Here Au+Au collisions at $\sqrt{s} = 130$ GeV with $b = 8$ fm are calculated within the QGSM.

The freeze-out distributions of charged pions, nucleons, and lambdas show that the substantial part of hadrons in ultrarelativistic collisions leaves the system within first 2 fm/c. The hadron spectrum is heavily dominated by pions. The latter have a second maximum at $t = 5$ fm/c, whereas the baryon distributions reveal quite broad peaks at $t = 10 - 12$ fm/c. The broadening of the peaks and their shift to later times are caused by rescattering. As a result, the elliptic flows carried by frozen mesons and baryons are different as also displayed in Fig. 6. Here pions emitted earlier demonstrate the strongest v_2, and the elliptic flow carried by pions at the late stages of the fireball expansion is significantly reduced. Baryons, in contrast, are getting stronger v_2 because of rescattering process. Their elliptic flow saturates when the system becomes dilute.

4 Conclusions

General features of directed and elliptic flows of hadrons produced in relativistic heavy-ion collisions are studied within two microscopic Monte Carlo models. The following conclusions can be drawn. Both models favor the reduction of proton directed flow at midrapidity in heavy-ion collisions with (i) increasing energy of collisions (from $\sqrt{s} = 4$ GeV) and (ii) increasing impact parameter of collisions. This effect, which is caused by hadronic rescattering in remnants of the nuclei, can mimic creation of the quark-gluon plasma. However, the so-called softening of the directed flow due to rescattering is stronger in light- and intermediate-ion collisions compared to the heavy-ones. In case of the QGP formation the effect should be

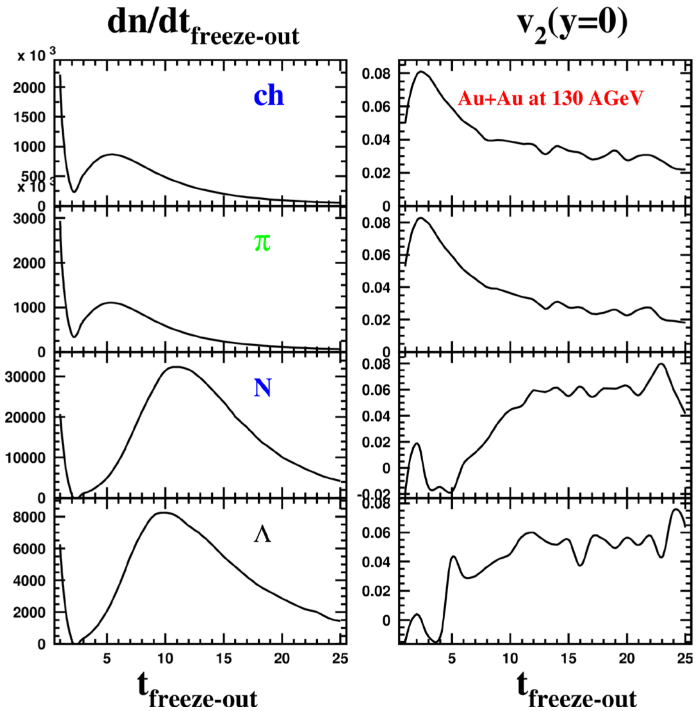

Figure 6. Left: Freeze-out spectra of charged particles, pions, nucleons and lambdas over the time of their last interactions in QGSM calculations of Au+Au collisions with $b = 8$ fm at $\sqrt{s} = 130$ GeV. Right: elliptic flow carried by hadrons frozen at a certain time.

opposite. Directed flows of mesons and antibaryons are negative (or close to zero) for light- and heavy-ion collisions in the considered energy range.

The time evolution of particle directed and elliptic flows at midrapidity takes about 10 - 15 fm/c for collisions from the energy range of NICA. Here particles frozen at $t \leq 4$ fm/c carry the weakest v_1 and v_2. At RHIC energies the situation for partial elliptic flows of hadrons is changed. Pions frozen earlier now carry the strongest v_2, although the original elliptic flow at that time is weak. Baryons, in contrast, acquire the strongest v_2 at the late stages of the system expansion due to hadronic rescattering. The flow development, therefore, should be studied together with the hadronic freeze-out.

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