PROCEEDINGS OF SCIENCE

Triangular flow in relativistic heavy-ion collisions within HYDJET++

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The hadronic collective flow was found to be one of the most pronounced signatures of the Quark-Gluon Plasma (QGP), the hot and dense matter created in the collisions of relativistic heavy ions. The azimuthal distribution of detected hadrons can be expanded into a Fourier series over the azimuthal angle, the flow harmonics are then represented by the Fourier coefficients. In semi-peripheral and peripheral collisions, the anisotropic flow is dominated by elliptic flow, defined by the second Fourier coefficient v_2. On the other hand, the contribution of the third component v_3 becomes more pronounced in central collisions due to the spatial initial state fluctuations.

Study of the triangular flow, v_3 in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV was performed using HYDJET++ Monte Carlo model. HYDJET++ combines a parametrised hydrodynamics for soft physics with a microscopic jet quenching generator for hard and semi-hard scattering, giving a realistic prediction of the shape of distribution for different hadron species. The model also enables study of influence of final-state interactions on flow of created hadrons. The interplay between soft and hard processes, as well as the influence of the resonance decays on the triangular flow in AA collisions at RHIC and LHC were studied. Reasons for violation of number-of-constituent-quark scaling at LHC for triangular and elliptic flow will be also discussed.

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1. Anisotropic flow of particles

The invariant differential cross section can be expanded into a Fourier series w. r. t. the reaction plane Ψ_R as

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\varphi-n\Psi_R\right)\right) \tag{1.1}$$

where p_T stands for transverse momentum, y denotes rapidity and φ represents azimuthal angle of the particle [1]. The Fourier coefficients

$$v_n = \langle\cos\left(n\phi-n\Psi_R\right)\rangle \tag{1.2}$$

are taken as a sum over all hadrons in all events with similar geometry (i. e. described by the same value of the impact parameter). In semi-peripheral and peripheral relativistic collisions, the Fourier expansion is dominated by the second Fourier coefficient v_2 defining the elliptic flow. With increasing centrality of the collisions, the third Fourier coefficient v_3, which describes the triangular flow, grows in importance. Unlike to elliptic flow which is born from the asymmetry of the overlap region, the triangular flow originates in the spatial initial state fluctuations. Thus v_3 defined as Eq. 1.2 would always yield a zero value as the fluctuations would vanish in the sum. Hence we redefine the coefficients as

$$v_n = \langle\cos\left(n\phi-n\Psi_n\right)\rangle. \tag{1.3}$$

In this case, the chevrons denote a sum over all hadrons in single event thus preventing the loss of information on fluctuations. The participant planes Ψ_n in Eq. 1.3 are defined for each harmonic independently.

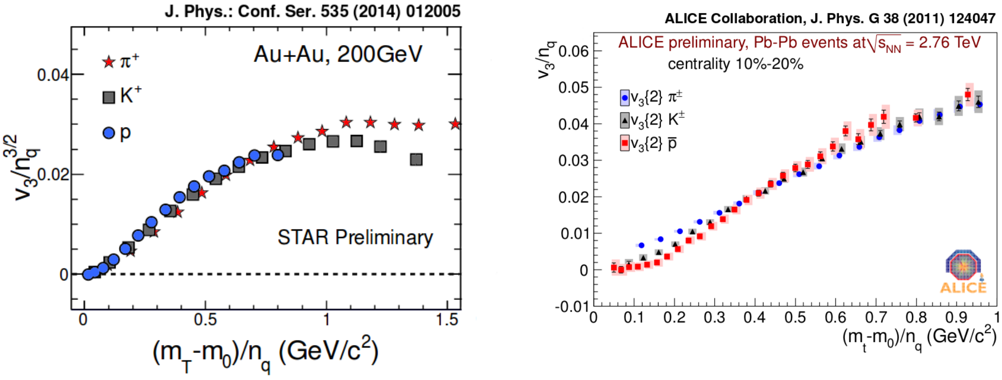
Flow measurements unveil information about the characteristics of medium created in collisions. Results for elliptic flow at RHIC suggest creation of ideal liquid with very low viscosity [2]. Triangular flow can provide new information in such measurements as it enables comparison of multiple parameters depending on viscosity [3].

At RHIC energies, number-of-constituent-quark scaling (NCQ) was found to be a prominent feature of elliptic flow [4], implying formation of flow at partonic level. Recent STAR measurements show scaling of triangular flow at RHIC energies as $v_3/n_q^{3/2}$ [5], see Fig. 1a. The ALICE experiment reported approximate scaling v_3/n_q [6] as shown in Fig. 1b.

2. HYDJET++

HYDJET++ [7] is a Monte Carlo heavy-ion event generator composed of two independent parts. The soft part of the model is represented by parametrized relativistic hydrodynamics, describing a transition from hot and dense lump of partonic substance to a freeze-out hypersurface on which the partons are generated. The hard part containing jets deals with binary collisions at given impact parameter b. Partons with transverse momenta $p_T > p_T^{min}$ are further evolved and let to interact with the medium.

The interplay of the two parts yields realistic shapes of flow distributions for charged hadrons, as shown in Fig. 2. The soft part of distributions is dominated by the hydro-driven soft component,



(a) (b)

Figure 1: (a) Number-of-constituent-quark scaling $v_3/n_q^{3/2}$ vs kE_T/n_q in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]. (b) v_3/n_q vs kE_T/n_q in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV at centrality 10-20% [6].

resulting in rise of the distribution and observed mass ordering. With higher p_T, the jets become gradually more prominent which causes the subsequent decrease in observed distributions.

The model can be toggled to keep full history of generated particles, enabling study of decays of resonances on observed flow distributions.

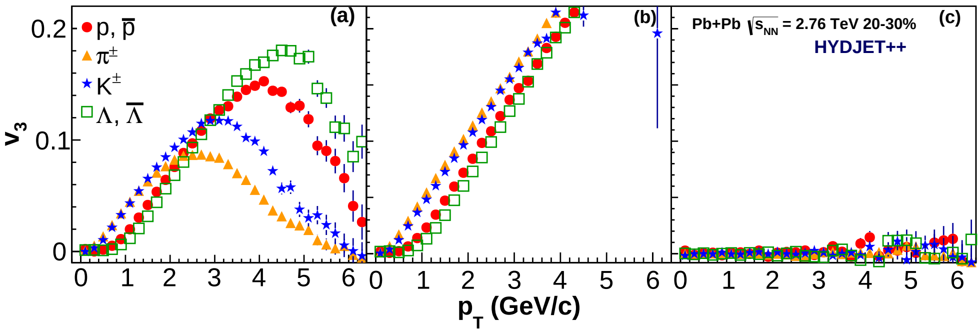


Figure 2: v_3 as a function of p_T in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV in HYDJET++. (a) The total distributions, (b) distributions for hydro part and (c) distributions for jet part are displayed for identified charged hadrons. The data show protons (red circles), charged pions (yellow triangles), charged kaons (blue stars) and lambdas (open green squares).

3. Triangular flow at LHC

Effects of final-state interactions on triangular flow in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV was studied using the HYDJET++ framework. HYDJET++ gives good qualitative description of LHC data [8, 9].

Preliminary results for NCQ scaling of triangular flow from ALICE suggest that the scaling of v_3 is broken asi it is in case of v_2 [6]. Scaling $v_3/n_q(kE_T/n_q)$ and its changing due to resonance decays has been studied in HYDJET++. According to our calculations, only approximate scaling is achieved as shown in Fig. 3. However, by comparing the scaling of direct distributions (a, d) and of total distributions including products of resonance decays (b, e), the decays of resonances drive the flow towards scaling fulfilment. Subplots (c, f) show total distributions obtained from the soft part of the model. In such case, the scaling is fulfilled. Our calculations suggest that the observed breaking of NCQ scaling is caused by jets.

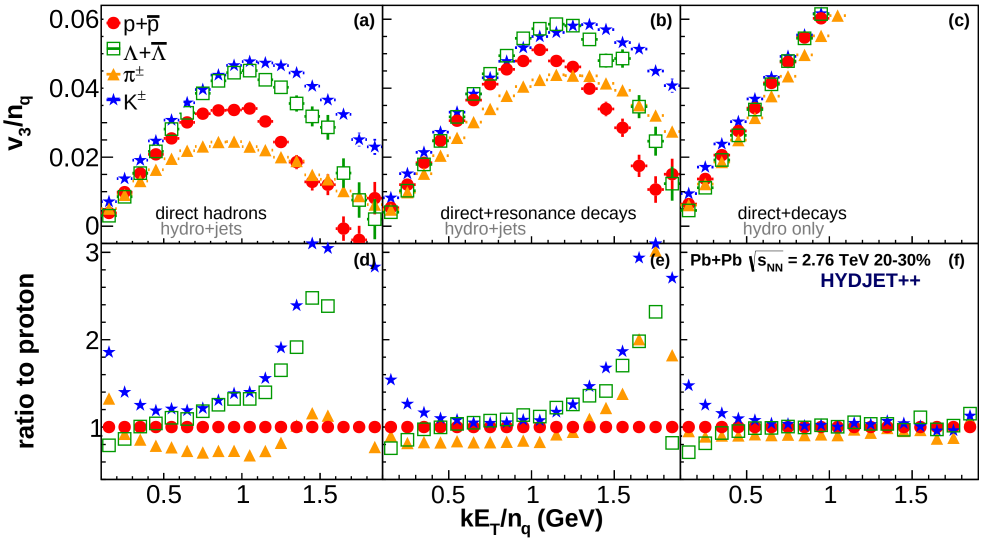


Figure 3: v_3/n_q vs kE_T/n_q in Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV in HYDJET++. (a) Direct hydro+jets , (b) total distribution (direct+from decays of resonances) in hydro+jets and (c) total distributions in hydro only for protons (red circles), lambdas (green open squares), charged kaons (blue stars) and charged pions (yellow triangles). Subplots (d), (e) and (f) show the respective three distributions divided by the corresponding proton distribution.

4. Triangular flow at RHIC

The triangular flow was equally investigated in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. While the $v_3(p_T)$ distributions of protons and pions generated in HYDJET++ are in agreement with recent STAR data [5], the distribution of kaons indicates significantly stronger triangular flow than observed by STAR. The same discrepancy is visible in the results of the NCQ scaling, see Fig. 4. The direct distributions (a, d) display no scaling behaviour. The total distributions (b, e), containing also hadrons from all decays, show scaling as $v_3/n_q^{3/2}(kE_T/n_q)$ in accordance with STAR data. To trace the origin of the observed scaling, we have plotted the distributions for hydro part only (c, f), containing both direct hadrons and hadrons coming from decays of resonances. Strong scaling is achieved in such scenario, hinting that in HYDJET++ the scaling is born from the decays of the resonances in the medium.

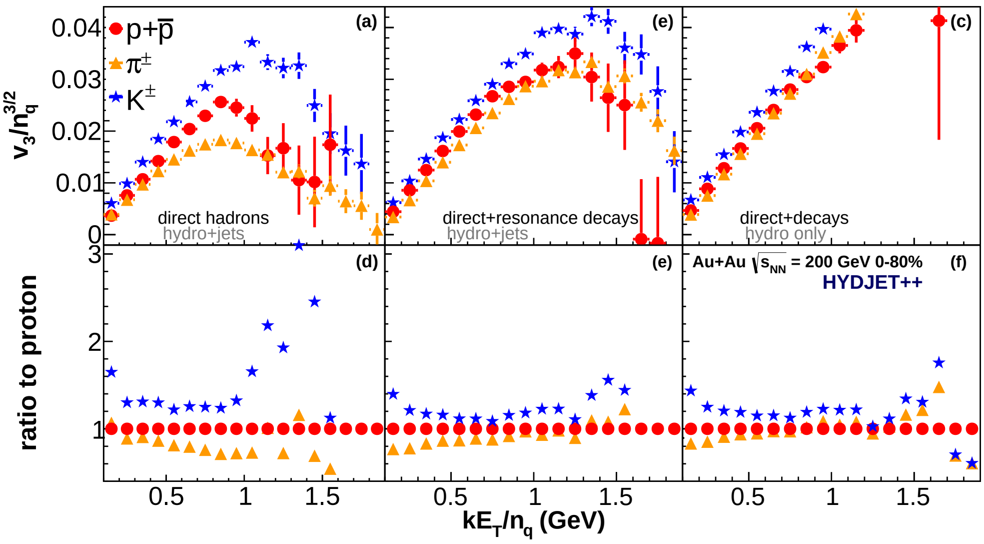


Figure 4: $v_3/n_q^{3/2}$ vs kE_T/n_q in Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV in HYDJET++. (a) Direct hydro+jets , (b) total distribution (direct+from decays of resonances) in hydro+jets and (c) total distributions in hydro only for protons (red circles), charged kaons (blue stars) and charged pions (yellow triangles). Subplots (d), (e) and (f) show the respective three distributions divided by the corresponding proton distribution.

5. Conclusions

HYDJET++ provides a good description of triangular flow in relativistic heavy-ion collisions. The final shape of distributions comes naturally from the interplay of hydrodynamics and jets. The model enables study of final-state-interaction effects on flow distributions.

Influence of resonance decays on triangular flow at LHC and at RHIC energies was investigated. Decays change significantly the shape of the distribution by increasing the amplitude in the maximum and by its shift to higher p_T region. Moreover, resonances also drive flow towards scaling behaviour. Scaling of v_3 is broken at LHC energies as it is in the case of v_2, this effect is attributed to the energetic jets.

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