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# Anisotropic flow in HYDJET++: interplay between soft and hard physics

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**Abstract.** The development of elliptic, $v_2$ and quadrangular, $v_4$, flow in the $\Psi_2$ plane is studied within the HYDrodynamics with JETs (HYDJET++) model in ultrarelativistic heavy-ion collisions at energies of RHIC and LHC. Despite the general expectations, jet influence on the ratio of flow harmonics is shown to be significant already at intermediate transverse momenta. Hard processes lead to increase of the $v_4/v_2^2$ ratio and violation of the number-of-constituent-quark (NCQ) scaling at LHC.

## 1 Introduction

The collective flow of hadrons in the transverse plane of heavy-ion collisions at ultrarelativistic energies is considered as a good probe of the earliest stage of the collisions [1, 2], when the partonic matter is extremely hot and dense, and the quark-gluon plasma (QGP) is formed [3]. For analysis of the flow features it is convenient to decompose the particle production in Fourier series in azimuthal angle $\phi$ [4]

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2\, v_n \cos\left[(n(\phi - \Psi_n)\right] . \quad (1)$$

Here $v_n$ represents the flow harmonic of $n$-th order, $v_n = \langle \cos\left[(n(\phi - \Psi_n)\right]\rangle$ with averaging over all particles in an event and over all events, and $\Psi_n$ determines the event plane of this harmonic.

The first two harmonics, dubbed directed, $v_1$, and elliptic, $v_2$, flow, have been studied very intensively in the last 15 years, whereas the systematic study of higher coefficients has started quite recently [5]. One of the topic of current interest is the interplay of the flow harmonics [2]. Another issue is the search for a link between the fluctuations in initial state of the system and the final components of the flow. This study was inspired by [6], where the authors revealed the role of initial triangular spatial fluctuations in the formation of triangular flow, $v_3$.

The next flow harmonic, quadrangular (or hexadecapole) flow, $v_4$, is probably the most investigated one among the higher harmonics. The idea that $v_4$ can be a valuable independent signal of the early stage of system evolution was put forward in [7]. In [8], however, the quadrangular flow was shown to be dependent on the elliptic flow, $v_4 = 0.5 v_2^2$ within the framework of ideal hydrodynamics. Experiments with Au+Au collisions at RHIC found that the ratio $R = v_4/v_2^2$ was at least two times

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larger [9, 10]. According to [11], there are event-by-event particle fluctuations that might be responsible for the rise of $R$, because of the averaging of both $v_2$ and $v_4$ over the whole sample of events *before* the calculation of the ratio instead of its event-by-event determination. In case of averaging the data should be corrected by factor ca. 0.64 for semicentral and ca. 0.72 for semiperipheral collisions [12], respectively. Also, the increase of $R$ at $p_T \geq 2\,\mathrm{GeV}/c$ was found at LHC. It is not reproduced by any of the hydrodynamic models available on the market.

Another interesting peculiarity in the behavior of elliptic flow is violation of the so-called number-of-constituent-quark (NCQ) scaling in Pb+Pb collisions at LHC [13]. The scaling was first found in Au+Au collisions at RHIC. It was expected to be fulfilled with better accuracy at LHC provided the elliptic flow was formed at partonic stage.

The influence of hard processes on the formation of flow harmonics was not considered yet. The main aim of our paper is, therefore, study of the interplay of soft processes, governed by ideal hydrodynamics, and jets. The two aforementioned phenomena are scrutinized within the HYDJET++ model, which couples parametrized ideal hydrodynamics with jets traversing hot and dense medium. Basic features of the model are briefly discussed below.

## 2 The HYDJET++ model

The event generator HYDJET++ (HYDrodynamics with JETs) [14] is designed for fast simulation of ultra-relativistic heavy-ion collisions at energies of RHIC and LHC. It is a superposition of two independent event generators: FASTMC [15], which employs the parametrized ideal hydrodynamics to simulate hadrons with transverse momenta below 2 GeV/$c$, and PYQUEN [16], which deals with the propagation and fragmentation of hard quark-gluon jets.

In the soft sector the mean number of interacting nucleons is determined according to the Glauber model of independent inelastic collisions. After that the effective volume of the overlapped zone is estimated. The chemical composition of hadronic matter is assumed to be fixed at the stage of chemical freeze-out. The model provides also options for both separate and simultaneous treatment of chemical and thermal freeze-out. Secondary hadrons are produced either on Bjorken-like or Hubble-like freeze-out hypersurfaces. The model benefits from the very extensive table of ca. 360 baryon and meson resonances taken from the SHARE model [17]. Two- and three-body decays are considered. The free parameters of the model are tuned to reproduce simultaneously hadron yields and ratios, femtoscopy correlations, and both elliptic and triangular flow in heavy-ion collisions at RHIC and at LHC energies.

In the hard sector the model propagates hard partons through hot and dense partonic medium. Simulation of an A+A collision is subdivided into $NN$ collisions, each governed by the PYQUEN routine [16]. At this stage the model deals with (i) generation by means of PYTHIA [18] of production vertexes and individual parton spectra for a given impact parameter, (ii) calculation of gluon radiation and collisional energy losses for a parton traversing dense and hot medium, (iii) estimation of cold nuclear matter effects, such as quark and gluon shadowing, and finally, (iv) hadronization of both quarks and gluons according to prescriptions of Lund model [19]. The mean number of multi-jets generated in a single A+A collision at a given impact parameter is a product of the number of binary collisions experienced by all partons and the integral cross section of the hard process in $NN$ collision with the minimum transverse momentum transfer, $p_T^{min}$. Further description of the model features can be found elsewhere [14–16].

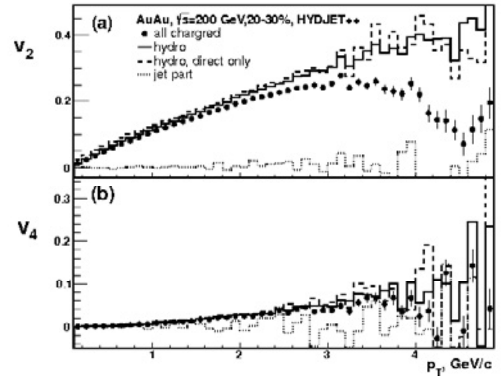


**Figure 1.** (a) $v_2(p_T)$ (full circles) and (b) $v_4(p_T)$ (full circles) for charged particles in HYDJET++ calculations of Au+Au collisions at $\sqrt{s} = 200$ AGeV at centrality $\sigma/\sigma_{\rm geo} = 20 - 30\%$. Dashed, solid and dotted lines show the $v_2$ of direct particles only, direct+resonance products and particles from jets, respectively.

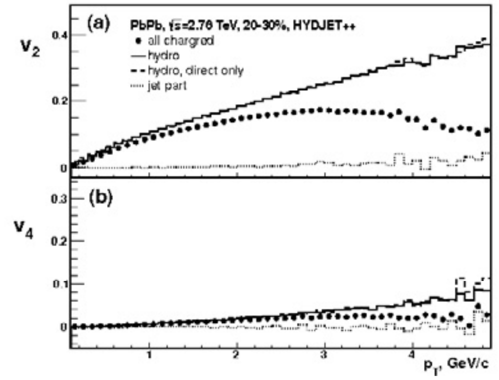


**Figure 2.** The same as Fig.1 but for Pb+Pb collisions at $\sqrt{s} = 2.76$ ATeV.

## 3 Second and fourth flow harmonics and their ratio

As was mentioned in Sect. 2, elliptic flow generated in the model is directly linked to the event eccentricity. Because of the absence of initial fluctuations in positions of nucleons, the generated flow is determined with respect to the reaction plane $\Phi_2$ rather than the event plane $\Psi_2$. When restored by the event plane (EP) method, the quadrangular flow $v_4$ is characterized by its own event plane $\Psi_4$. It should be correlated with the $\Psi_2$ plane. We have no original quadrangular eccentricities in the model, therefore, the $v_4$ in the simulations originates solely from the elliptic flow. Thus, it is also determined w.r.t. the event plane of the elliptic flow. For the correct comparison with the experiment, the data on $v_4\{\Psi_2\}$ and not $v_4\{\Psi_4\}$ should be selected in addition to the fluctuation's correction, discussed in Sect. 2.

At top RHIC energy $\sqrt{s} = 200$ AGeV ca. 60 000 gold-gold minimum bias collisions were generated, whereas at LHC energy $\sqrt{s} = 2.76$ ATeV the utilized statistics was ca. 50 000 lead-lead minimum bias events. To demonstrate the role of hard processes in the formation of the flow harmonics, we plot the transverse momentum distributions of $v_2$ and $v_4$ for RHIC and LHC in Fig. 1 and Fig. 2, respectively. The selected centrality is $\sigma/\sigma_{\rm geo} = 20 - 30\%$. The separate second and forth harmonics of directly produced hydro-particles, of direct particles and particles coming from the decay of resonances, and of particles decoupled from jets are shown together with the final elliptic and quadrangular flow. Because of the very weak flow of the jet particles, the resulting elliptic flow in the model stops to rise and then drops at certain $p_T$. The same is true for the quadrangular flow as well, although the magnitude of the signal is much weaker compared to the $v_2$. Note again, that the HYDJET++ assumes the ideal hydrodynamics, therefore, the saturation and falloff of the $v_2(p_T)$ is solely due to the hard processes [20, 21].

The ratio $R = v_4/v_2^2$ is shown for two centralities, $\sigma/\sigma_{geo} = 10 - 20\%$ and $\sigma/\sigma_{geo} = 40 - 50\%$, in Fig. 3 for RHIC and in Fig. 4 for LHC. Experimental data plotted onto the obtained results are required distributions $v_4\{\Psi_2\}/v_2^2\{\Psi_2\}$ measured by the ALICE Collaboration [22]. These date are reduced by factor 1.56 (10%-20%) and 1.38 (40%-50%) according to analysis of [12]. For the directly

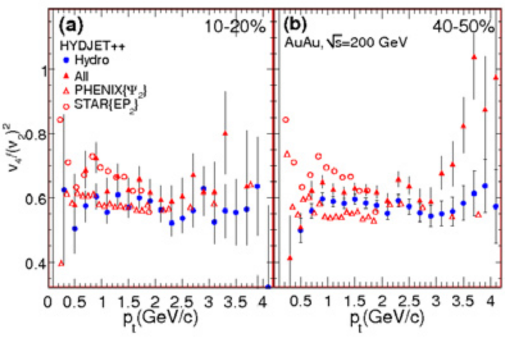


**Figure 3.** Ratio $v_4/(v_2)^2$ as a function of $p_T$ for charged particles in HYDJET++ hydro (full circles) and hydro+jets (full triangles) calculations of Au+Au collisions at $\sqrt{s}$ = 200 AGeV at centrality (a) 10% − 20% and (b) 40% − 50%. Open circles and open triangles denote data from [9] and [10], respectively.

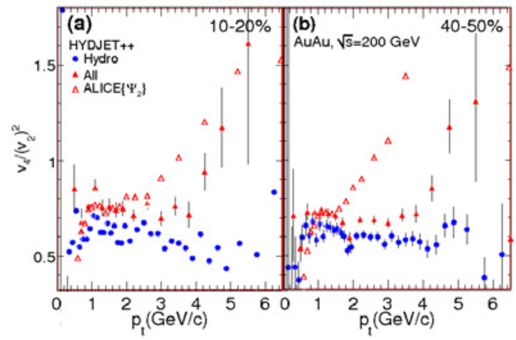


**Figure 4.** The same as Fig.3 but for Pb+Pb collisions at $\sqrt{s}$ = 2.76 AGeV. Data shown by open triangles are taken from [22].

produced particles in hydro part of the HYDJET++ the ratio $R$ equals to 0.5 [23]. Feed-down from resonances increases the ratio to 0.6, and jet contribution brings it to 0.65 (RHIC) and 0.7 (LHC). The most important feature is the rise of $R$ at $p_T \geq 2.5$ GeV/$c$ at LHC energy seen distinctly in Fig. 4. The hydrodynamic part of the simulations yields almost flat signal (see also [12] for calculations within ideal and viscous hydrodynamics), so only jets can account for the rising high-$p_T$ tail of the distribution [24, 25].

## 4 Number-of-constituent-quark scaling

The number-of-constituent-quark (NCQ) scaling postulates similarity of the distributions $v_2/n_q(KE_T/n_q)$ for different hadronic species. Here $KE_T \equiv m_T - m_0$ is the transverse kinetic energy, and $n_q$ is the number of constituent quarks in a hadron, i.e. two for a meson and three for a baryon. The NCQ scaling was first observed at RHIC in STAR and PHENIX experiments [26, 27] in a quite broad transverse energy range, 0.2 GeV $\leq KE_T \leq$ 0.7 GeV. Its origin is still unclear. One of the possible ideas is the formation of elliptic flow already at partonic level. As shown in [28], the coalescence of quarks leads to the NCQ emergence, whereas the string fragmentation breaks the scaling condition. However, if the elliptic flow is formed already at the partonic level, the NCQ scaling should certainly hold with even better accuracy at energies of LHC. This is not the case, because the LHC results of the ALICE collaboration [13, 29] reveal the opposite tendency. We would like to mention here that worsening of the NCQ scaling conditions at LHC was predicted within the HYDJET++ already in 2009 [20, 21].

To scrutinize the role of both soft and hard processes in the fulfillment of the NCQ scaling, Fig. 5 and Fig. 6 present the scaled elliptic flows $v_2^h/n_q(KE_T/n_q)$ of charged pions and kaons, as well as protons and lambdas, in heavy-ion collisions at RHIC and LHC, respectively. Centrality range $\sigma/\sigma_{\rm geo}$ = 20 − 30% has been selected. For convenience, these distributions are then normalized to the flow of protons. The obtained ratios are presented in bottom panels of the figures. Let us start with Au+Au collisions at RHIC, shown in Fig. 5. In hydrodynamic sector of the model the

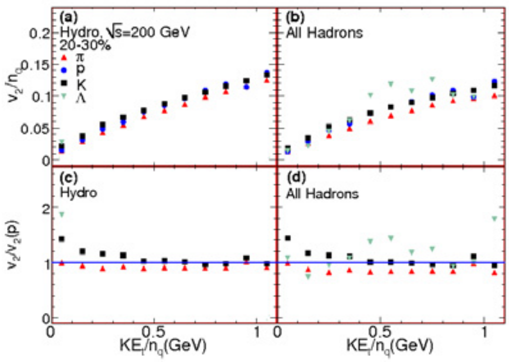


**Figure 5.** Elliptic flow vs. transverse energy obtained in HYDJET++ for hadrons in (a) hydrodynamic and (b) hydro+jet calculations of Au + Au collisions at $\sqrt{s}$ = 200 AGeV with centrality 20–30%. (c),(d) - the same as (a),(b) but normalized to the flow of protons.

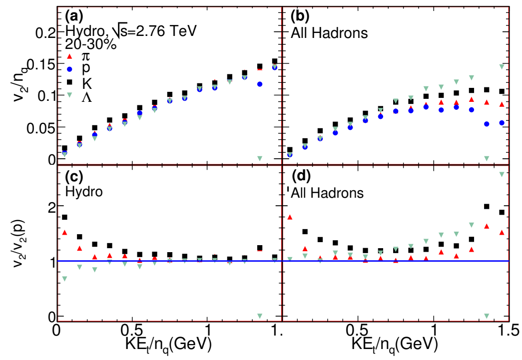


**Figure 6.** The same as Fig.6 but for Pb+Pb collisions at $\sqrt{s}$ = 2.76 ATeV.

scaling holds after the decays of resonances at least within the 5% accuracy limit within the range $0.3\,\mathrm{GeV}/c \leq KE_T/n_q \leq 1.0\,\mathrm{GeV}/c$. When hadrons fragmented from jets are taken into account, the scaling conditions get a bit worse. However, the scaling is still fulfilled within the 10% accuracy limit.

At LHC energy the NCQ scaling of hadrons, produced in soft processes, is similar to that at RHIC, see Fig. 6 left-upper panel. Here the difference in spectra caused by the mass hierarchy of the $v_2$ of directly produced particles is compensated by the final state interactions. Spectra of light hadrons are getting feed-down from the decays of heavy resonances. Such a boost increases the elliptic flow of light hadrons at intermediate transverse momenta and brings the $v_2/n_q$ distributions of different species closer to each other. But jets at LHC are much more influential compared to RHIC. Because of the jets, see Fig. 6(b,d), the NCQ scaling is fulfilled only approximately in Pb+Pb collisions at $\sqrt{s}$ = 2.76 ATeV. With further rise of the collision energy the scaling conditions will deteriorate.

## 5 Conclusions

The consequences of interplay between hard processes and hydrodynamics for the elliptic and quadrangular flow are studied within the HYDJET++ model. Gold-gold collisions at $\sqrt{s}$ = 200 AGeV and lead-lead collisions at $\sqrt{s}$ = 2.76 ATeV are considered at centralities from 10 – 20% to 40 – 50%. Besides the falloff of the $v_2(p_T)$ of hadrons at certain transverse momenta, the jets increase the ratio $R = v_4/v_2^2$ by 10 – 15% both at RHIC and at LHC. Jets are also account for the increase of the ratio $R$ at $p_T \geq 2.5\,\mathrm{GeV}/c$, in line with the experimental results. Note, that such a behavior is not found in both ideal and viscous hydrodynamic model calculations. Finally, jets appear to wash out the number-of-constituent-quark scaling of hadrons at LHC energy despite of the fact that the NCQ scaling is fulfilled for hadrons produced in soft processes, governed by ideal hydrodynamics with final state interactions.

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