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JETS AND THEIR ROLE IN MODIFICATION OF v_4/v_2^2 RATIO*

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Formation and evolution of the v_2 and v_4 flow pattern in Pb + Pb collisions at $\sqrt{s} = 2.76$ ATeV and in Au + Au collisions at $\sqrt{s} = 200$ AGeV are analyzed for charged hadrons within the framework of HYDJET++ Monte Carlo model. The model contains both hydrodynamic part and jets, thus allowing for a study of the interplay between the soft and hard processes. It is found that jets are terminating the rise of the elliptic flow with increasing transverse momentum. The final state interactions play a minor role in modification of the $v_4/(v_2)^2$ ratio. In contrast, jets increase this ratio. While jets together with the eccentricity fluctuations are sufficient to describe the RHIC data, the high value of the ratio at LHC is still underpredicted.

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1. Introduction

Collective flow of particles in the transverse plane of a heavy-ion reaction at ultrarelativistic energies is considered to be one of the most prominent tools to investigate the creation and evolution of the quark-gluon plasma (QGP). Therefore, this phenomenon is extensively studied by both experimentalists and theoreticians. The modern analysis of the flow utilizes the Fourier expansion [1] of the particle distribution in the azimuthal plane in the form

$$\frac{dN}{d\phi} = a_0 \left[1 + 2 \sum_{n=1}^{\infty} v_n \cos(n\phi) \right] , \tag{1}$$

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where ϕ is the azimuthal angle between the momentum of the particle and the reaction plane, and v_n are the flow harmonics. In the present analysis, we will concentrate on first two even harmonics, elliptic flow v_2 and hexadecapole flow v_4. Hydrodynamic models are quite successful in description of the elliptic flow in heavy-ion collisions at RHIC and LHC energies. Also, the hexadecapole flow was shown to be completely determined via the v_2 within the ideal hydro approach, $v_4 = 0.5(v_2)^2$ [2]. In stark contrast, experiments show that the ratio $v_4/(v_2)^2$ is about 0.8–1.0 at RHIC [3, 4] and rises to 1.5–2.0 at LHC [5]. It was argued in [6] that the observed high value of this ratio was mostly caused by elliptic flow fluctuations. Namely, if the experimental results for v_2 and v_4 are averaged over *e.g.* large centrality interval, or rapidity, or transverse momentum before computing the ratio $v_4/(v_2)^2$, then the calculated ratio must be significantly larger than the predicted value 0.5. For instance, for the centrality bins with width 5% or 10% the scale factor is estimated to decrease slightly from $K = 1.56$ in semicentral (10–20%) to $K = 1.38$ in semipripheral (40–50%) Au + Au collisions [7]. Still the reduced experimental values appear to be higher than the ideal hydro estimates. Inclusion of viscosity cannot help us to resolve the discrepancy [7]. The aim of our present paper is to show that the jets, traditionally linked to hard processes with high $p_{\rm T}$, can also be accounted for the increase of the ratio $v_4/(v_2)^2$ even in the range of small transverse momenta. For the analysis of heavy-ion reactions at energies of RHIC and LHC we are employing the HYDJET++ model [8]. This model has been already used [9, 10] to study the influence of resonance decays and jets on the fulfillment of number-of-constituent-quark scaling (NCQ) at high energies. Its basic features are described below.

2. The model

The Monte Carlo event generator HYDJET++ [8] allows for fast realistic simulation of spectra of secondary hadrons produced in the course of heavy-ion collisions at energies between $\sqrt{s} = 200$ AGeV and $\sqrt{s} = 5.5$ ATeV. This model is created as a result of merging of two MC generators: the FASTMC [11, 12] that describes the evolution of a soft hydro-type state, and the HYDJET model [13] dealing with propagation of hard partons through hot and dense partonic medium. The soft physics in the HYDJET++ is represented by a parametrization of relativistic hydrodynamics with given freeze-out conditions. A separation of the chemical and thermal freeze-out is implemented, *i.e.* after the chemical freeze-out the fireball continues to expand hydrodynamically, and then it cools down and breaks into individual hadrons at certain thermal freeze-out hypersurface. Knowing the effective volume of the source, one is able to calculate the mean multiplicity of secondary hadrons produced at the space-like freeze-out hypersurface. The very rich table of *ca.* 360 baryon and meson resonances with the decay modes and branching ratios is taken from the SHARE particle decay table [14].

The hard part of the HYDJET++ takes into account various energy losses, both radiative and collisional ones, experienced by a parton traversing the quark-gluon plasma. The generation of hard nucleon–nucleon collisions is realized by means of the PYQUEN [13] routine that employs the initial spectra of partons simulated by the PYTHIA [15] generator of hadronic interactions. Note, that for calculations at LHC energy we use the upgraded HYDJET++ that implemented the tuned Perugia version [16]. After the generation of the partonic spectra and production vertexes at a given impact parameter the PYQUEN propagates the partons in a dense medium and calculates its free path between the successive collisions, as well as the radiative and collisional energy losses. Then, the hard partons and in-medium emitted gluons are hadronized according to Lund string model [17]. Finally, the minijets generated around its mean number in the PYQUEN according to the binomial distribution are added to the hard part of the spectra. Further details of the model can be found in Refs. [8, 11, 12, 13].

3. Results and conclusions

For the further investigations we generated *ca.* 60 000 minimum bias Au + Au collisions at $\sqrt{s} = 200$ AGeV and *ca.* 50 000 minimum bias Pb + Pb collisions at $\sqrt{s} = 2.76$ ATeV. The transverse momentum dependencies of the second and forth flow harmonics for four selected centralities are shown in Fig. 1 (a), (b) for RHIC and LHC energies, respectively. For both harmonics at both energies the initial rise of the signal is accompanied by a falloff at certain threshold energy. In the HYDJET++ such a behavior originates

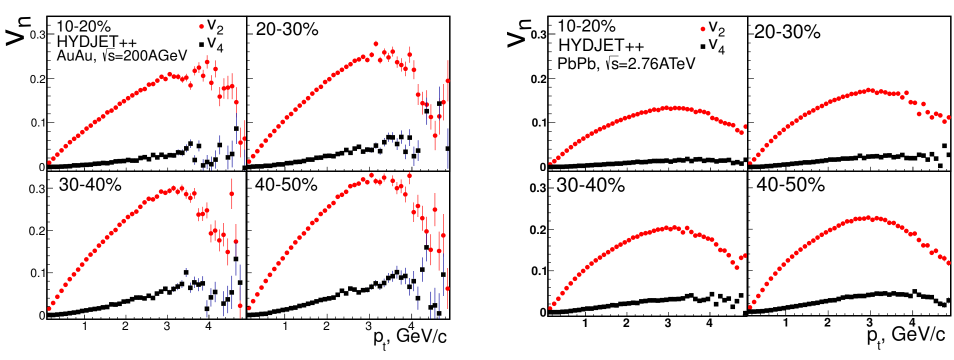

Fig. 1. (Color online) Left: v_2 (circles) and v_4 (squares) of charged hadrons in Au + Au collisions at $\sqrt{s} = 200$ AGeV at four different centralities. Right: The same as the left but for Pb + Pb collisions at $\sqrt{s} = 2.76$ ATeV.

from the interplay between the soft hydro-like processes and jets. Indeed, the particle spectrum at $p_{\rm T} \leq 2.5$ GeV$/c$ is dominated by the hadrons from the soft processes. Therefore, both final v_2 and final v_4 should be very close here to those given by hydrodynamics. The particle spectrum at $p_{\rm T} \geq 3.0$ GeV$/c$, however, is dominated by the hadrons from jets that carry very weak v_2 and v_4. For this reason, both even components of the anisotropic flow rapidly drop. Note, that at RHIC the model predict too strong elliptic flow for $p_{\rm T} \geq 2$ GeV$/c$. This means that jets alone cannot be responsible for the flow falloff at intermediate $p_{\rm T}$. Other mechanisms are needed. At LHC the jets are strong enough and the model results are much closer to the data.

The separate contributions to the elliptic and hexadecapole flows coming from the soft and hard processes in semi-central interval $\sigma/\sigma_{\rm geo} = 20$–30% are presented for both energies in question in Fig. 2 (a), (b). To reveal the role of final state interactions the hydro-flow created by the hadrons, directly produced on the freeze-out surface, is shown in both figures as well. We see that decays of resonances can change the hydrodynamic elliptic flow by 2–3% at RHIC and even less at LHC. The v_2 carried by the jet particles is almost zero at $p_{\rm T} \leq 2$ GeV$/c$ and slowly increases up to 3–5% with rising transverse momentum due to well-known effect of jet quenching. Similar tendencies in the behavior of hydro and jet parts are observed for the v_4, although its strength is much weaker compared to the v_2 one.

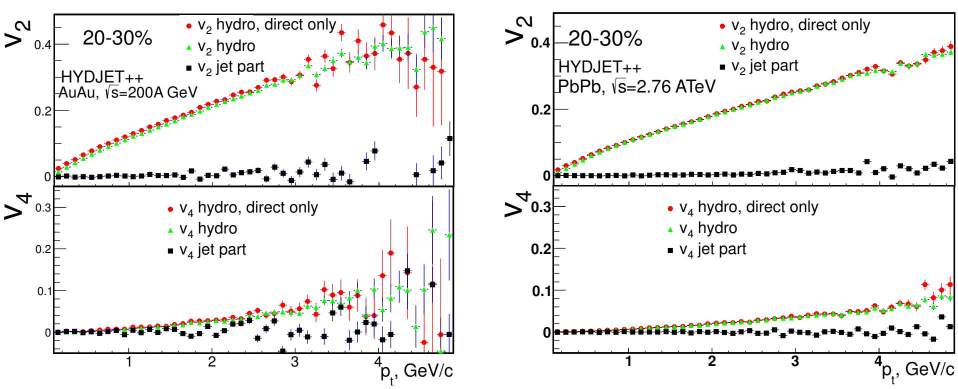

Fig. 2. (Color online) Left: Contributions to the v_2 (upper plot) and v_4 (bottom plot) at RHIC coming from direct particles (circles), hydro + final state interactions (triangles) and jets solely (squares). Calculations are done for centrality 20–30%. Right: The same as the left but for LHC energy.

Finally, the ratio $v_4/(v_2)^2$ as a function of transverse momentum is displayed in Fig. 3. It is worth noting that even for pure hydrodynamic part the final state interactions increase this ratio from ideal $R = 0.5$ to $R \approx 0.6$. When added, jets increase the ratio further to $R \approx 0.7$ at RHIC and $R \approx 0.75$–0.85 at LHC. The first result matches the reduced experimental data $v_4/(v_2)^2 = 0.65 \pm 0.05$ [7] quite well. As to LHC, the measured value of the signal is rather high, $v_4/(v_2)^2 \approx 1.8$ [5], therefore, the reduced result should be about $R = 1.2$. We see that up to 30% of the signal is somehow missing. On the other hand, the $v_4/(v_2)^2$ given by ideal hydrodynamics is rather insensitive to p_{T}, whereas both the experimental data and the hydro + jets analysis show increase of this ratio with rising transverse momentum.

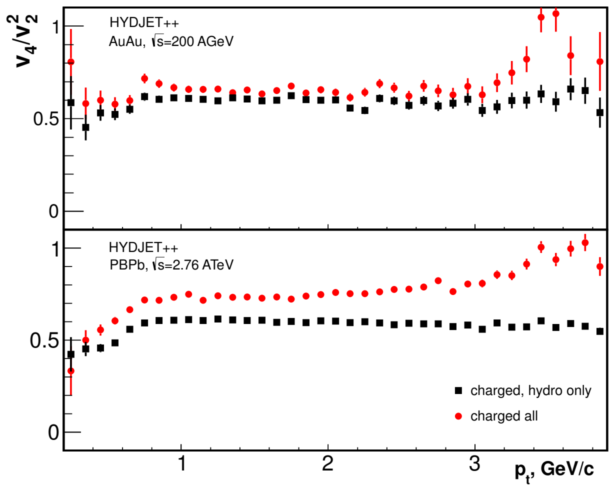

Fig. 3. (Color online) Ratio $v_4/(v_2)^2$ as a function of p_{T} obtained for charged particles from hydro-part (squares) and from all processes (circles) in heavy-ion collisions at RHIC (upper plot) and LHC (bottom plot) energies.

In conclusion, we studied the ratio $R = v_4/(v_2)^2$ for charged hadrons produced in heavy-ion collisions at $\sqrt{s} = 200$ AGeV and 2.76 ATeV within the HYDJET++ model, that combines parametrized hydrodynamics with hard processes. Jets are found to increase R. Together with the eccentricity fluctuations jet contribution is enough to explain quantitatively the data at RHIC energy. At LHC energy the observed enhancement of R is too strong despite of the fact that the shape of the signal, particularly the rise of the high-p_{T} tail, is well reproduced in the model calculations.

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