Effect of jets on $v_4/v_2^2$ ratio and constituent quark scaling in relativistic heavy-ion collisions

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The Monte Carlo HYDJET++ model, that combines parametrized hydrodynamics with jets, is employed to study formation of second $v_2$ and fourth $v_4$ components of the anisotropic flow in ultrarelativistic heavy-ion collisions at energies of the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), $\sqrt{s} = 200A$ GeV and $\sqrt{s} = 2.76A$ TeV, respectively. It is shown that the quenched jets contribute to the soft part of the $v_2(p_T)$ and $v_4(p_T)$ spectra. The jets increase the ratio $v_4/v_2^2$ thus leading to deviations of the ratio from the value of 0.5 predicted by the ideal hydrodynamics. Together with the event-by-event fluctuations, the influence of jets can explain quantitatively the ratio $v_4/v_2^2$ at $p_T \leq 2$ GeV/$c$ for both energies and qualitatively the rise of its high-$p_T$ tail at LHC. Jets are also responsible for violation of the number-of-constituent-quark (NCQ) scaling at LHC despite the fact that the scaling is fulfilled for the hydro part of particle spectra.

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I. INTRODUCTION

The transverse collective flow of particles is an important characteristic of ultrarelativistic heavy-ion collisions because the flow is able to carry information about the early stage of the reaction. Particularly, the collective flow is very sensitive to change of the equation of state (EOS), e.g., during the quark-hadron phase transition. The azimuthal distribution of particles can be cast [1, 2] in the form of Fourier series

$$E \frac{d^3 N}{dp^3} = \frac{1}{\pi} \frac{d^2 N}{dy^2} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi) \right]. \quad (1)$$

Here $\phi$, $p_t$, and $y$ are the azimuthal angle, the transverse momentum, and the rapidity of a particle, respectively. The unity in the parentheses represents the isotropic radial flow, whereas the sum of harmonics refers to anisotropic flow. The first two harmonics of the anisotropic flow, dubbed directed flow $v_1$ and elliptic flow $v_2$, have been extensively studied both experimentally and theoretically in the last 15 years (see, e.g., [3] and references therein), while the systematic study of higher harmonics began quite recently [4–7].

In the present paper we investigate the ratio $R = v_4/v_2^2$ in heavy-ion collisions at energies of the Relativistic Heavy Ion Collider (RHIC) ($\sqrt{s} = 200A$ GeV) and the Large Hadron Collider (LHC) ($\sqrt{s} = 2.76A$ TeV). Interest in the study was raised due to the obvious discrepancy between the theoretical estimates and the experimental measurements. On the one hand, the exact theoretical result for hydrodynamics provided $v_4/v_2^2 = 0.5$ for a thermal freeze-out distribution [8]. On the other hand, it was found soon in RHIC experiments [9, 10] that the measured ratio $R$ exceeded by factor 2 the theoretically predicted one. Both the STAR and the PHENIX Collaborations have reported that the $R$ is rather close to unity for all identified particles in a broad ranges of centrality, $10% \leq \sigma/\sigma_{\text{geo}} \leq 70%$, and transverse momentum, $p_T \geq 0.5$ GeV/$c$. For the smaller $p_T$ the ratio seems to exceed the value of 1. Note also that the PHENIX data are about 10–15% below the STAR ones.

In Ref. [11] it was argued that the experimentally measured $R$ can be larger than 0.5 even if the ratio $v_4/v_2^2$ was exactly equal to 0.5 in each event. Such a distortion can be caused by event-by-event fluctuations. Namely, if the ratio $v_4/v_2^2$ is estimated not on an event-by-event basis but rather on averaging of both $v_2$ and $v_4$ over the whole statistics, the event-by-event fluctuations will significantly increase the extracted value of the ratio. Calculations of $R$ at RHIC energies within both ideal and viscous hydrodynamics with different initial conditions [12] revealed that the ideal hydrodynamics provided better agreement with the data, although the STAR results remained underpredicted a bit. For LHC the hydrodynamic calculations have predicted similar behavior with slight increase at small transverse momenta [12].

The preliminary results obtained in Pb + Pb collisions at $\sqrt{s} = 2.76A$ TeV favor further increase of the $v_4/v_2^2$ ratio [5, 6]. Moreover, this ratio is not a constant at $p_T \geq 0.5$ GeV/$c$ but increases with rising transverse momentum. The first aim of the present paper is to study to what extent the hard processes, i.e., jets, can affect the ratio $R$ predicted by the hydrodynamic calculations.

The second aim of the paper is investigation of the fulfillment of the so-called number-of-constituent-quark (NCQ) scaling, observed initially for the partial elliptic of mesons and baryons at RHIC [13, 14]. Despite the general expectations, the measurements show that the NCQ scaling is broken at LHC energies [15]. Thus, it would
be interesting to elucidate the role of jets in the scaling violation. For these purposes we employ the HYDJET++ model [16], which couples the parametrized hydrodynamics to jets. The soft part of the HYDJET++ simulated event represents the thermalized hadronic state where particle multiplicities are determined under assumption of thermal equilibrium. Hadrons are produced on the hypersurface, represented by a parametrization of relativistic hydrodynamics with given freeze-out conditions. At the freeze-out stage the system breaks up into hadrons and their resonances. The table of baryon and meson resonances implemented in the model is quite extensive. This allows for better accounting of the influence of final-state interactions on the generated spectra. The hard part of the model accounts for jet quenching effect, i.e., radiation and collisional losses of partons traversing hot and dense media. The contribution of soft and hard processes to the total multiplicity of secondaries depends on both centrality of the collision and its energy and is tuned by model parameters to RHIC and LHC data.

The paper is organized as follows. A brief description of the HYDJET++ is given in Sec. II. Section III presents the results of calculations of both $v_2$ and $v_4$ for charged particles in both considered reactions. The even components of the anisotropic flow and their ratio $R = v_4/v_2^2$ are studied in the interval $10\% \leq \sigma/\sigma_{geo} \leq 50\%$ in four centrality bins. In Sec. IV the interplay between jets and decays of resonances, as well as the roles of resonance decays in better realization and the jets in violation of the number-of-constituent-quark scaling are discussed. Conclusions are drawn in Sec. V.

II. THE HYDJET++ EVENT GENERATOR

The Monte Carlo event generator HYDJET++ [16] was developed for fast but realistic simulation of hadron spectra in both central and non-central heavy-ion collisions at ultrarelativistic energies. It consists of two parts. The FASTMC [17, 18] event generator deals with the hydrodynamic evolution of the fireball. Therefore, it describes the soft parts of particle spectra with the transverse momenta $p_T \leq 2$ GeV/c. The hard processes are simulated by the HYDJET model [19] that propagates jets through hot and dense partonic medium. Both parts of the HYDJET++ generate particles independently.

To allow for really fast generation of the spectra the FASTMC employs a parametrized hydrodynamics with Bjorken-like or Hubble-like freeze-out surface parametrization. Since at ultrarelativistic energies the particle densities at the stage of chemical freeze-out are quite high, a separation of the chemical and thermal freeze-out is also implemented. The mean number of participating nucleons $N_{part}$ at a given impact parameter $b$ is calculated from the Glauber model of independent inelastic nucleon-nucleon collisions. After that the value of effective volume of the fireball $V_{eff}$, that is directly proportional to $N_{part}$, is generated. When the effective volume of the source is known, the mean multiplicity of secondaries produced at the spacelike freeze-out hypersurface is calculated. Parametrizations of the odd harmonics of the anisotropic flow are not implemented in the present version of HYDJET++, whereas the elliptic flow is generated by means of the hydro-inspired parametrization that depends on momentum and spatial anisotropy of the emitting source. The model utilizes a very extensive table of ca. 360 baryon and meson resonances and their antistates together with the decay modes and branching ratios taken from the SHARE particle decay table [20]. After the proper tuning of the free parameters, the HYDJET++ simultaneously reproduces the main characteristics of heavy-ion collisions at RHIC and at LHC, such as hadron spectra and ratios, radial and elliptic flow, and femtoscopic momentum correlations.

The multiple scattering of hard partons in the quark-gluon plasma (QGP) is generated by means of the HYDJET model. This approach takes into account accumulating energy loss, the gluon radiation, and collisional loss, experienced by a parton traversing the QGP. The shadowing effect [21] is implemented in the model as well. The PYQUEN routine [22] generates a single hard NN collision. The simulation procedure includes the generation of the initial parton spectra with PYTHIA [23] and production vertexes at a given impact parameter, rescattering-by-rescattering simulation of the parton path length in a dense medium, radiative and collisional energy losses, and final hadronization for hard partons and in-medium emitted gluons according to the Lund string model [24]. Then, the full hard part of the event includes PYQUEN multi-jets generated around its mean value according to the binomial distribution. The mean number of jets produced in $A + A$ events is a product of the number of binary NN sub-collisions at a given impact parameter and the integral cross section of the hard process in NN collisions with the minimal transverse momentum transfer, $p_T^{min}$. Further details of the model can be found in Refs. [16–19].

It is worth mentioning recent important modification of the HYDJET++. After the measurement of particle spectra in pp collisions at LHC it became clear that the set of model parameters employed by the PYTHIA 6.4 version had to be tuned. Several modifications have been proposed [25, 26]. The application of standard PYTHIA 6.4 in the HYDJET++ led to too early suppression of elliptic flow of charged particles at intermediate transverse momenta in lead-lead collisions and, therefore, to the prediction of a weaker $v_2$ [27, 28] compared to the data. Recently, the HYDJET++ was modified [29] to implement the Pro-Q20 tune of PYTHIA. In contrast to calculations of elliptic flow presented in [27, 28, 30], all simulations of Pb + Pb reactions at LHC energies in the present paper are performed with the upgraded HYDJET++.
produced by jets (dotted lines). (dashed lines), total hydrodynamic flow (solid lines), and flow show flow of directly produced particles in hydro-calculations on the surface in the hydrodynamic part, (ii) direct and secondary hadrons created after the decays of resonances, and (iii) hadrons produced in the course of jet fragmentation. Recall briefly the main features of the $v_2(p_T)$ behavior in HYDJET++. The elliptic flow rises up to its maximum at intermediate $p_T$ around $2.5–3$ GeV/$c$ and then rapidly drops. This falloff is observed in experimental data also. In the model its origin is traced to the interplay between the soft hydrolike processes and hard jets, as was studied in details in [27, 28]. The ideal hydrodynamics demonstrates continuous increase of the elliptic flow with rising transverse momentum. Because of the jet quenching the jets also develop an azimuthal anisotropy that increases with the $p_T$ too; however, this effect is quite weak and does not exceed few percent. The particle yield as a function of the transverse momentum drops more rapidly for hydroproduced hadrons than for hadrons from jets. Therefore, after a certain $p_T$ threshold jet particles start to dominate the particle spectrum, thus leading to a weakening of the combined elliptic flow. A similar tendency is observed in Fig. 1 and Fig. 2 for the $v_4$ also, but, because of the quite weak signal in the hydrodynamic part, the effect of the $v_4$ falloff is not as pronounced as that of the elliptic flow.

As shown in Fig. 1 decays of resonances can change the elliptic flow of directly produced hadrons with $p_T \leq 3$ GeV/$c$ by 1–2% at RHIC and by less than 1% at LHC; see Fig. 2. For the $v_4$ the difference between the two histograms is negligible; i.e., resonance decays play a minor role for soft parts of both $v_2(p_T)$ and $v_4(p_T)$ distributions. At $p_T \approx 2.5$ GeV/$c$ jets come into play and change dramatically the shapes of the elliptic and hexadecapole flows.

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**III. $v_2$ AND $v_4$ FROM HYDRODYNAMICS AND FROM JETS**

For the investigations of the second and the fourth flow harmonics, ca. 60 000 gold-gold and ca. 50 000 lead-lead minimum bias collisions have been generated at $\sqrt{s} = 200$ A GeV and $\sqrt{s} = 2.76$ A GeV, respectively. The transverse momentum dependencies of $v_2$ and $v_4$ obtained for the centralities 20–30% are shown in Fig. 1 for RHIC and in Fig. 2 for LHC energies.

Together with the resulting distributions for $v_2(p_T)$ and $v_4(p_T)$ we present separate contributions coming from (i) hadrons directly produced at the freeze-out hypersurface in the hydrodynamic part, (ii) direct and secondary hadrons created after the decays of resonances, and (iii) hadrons produced in the course of jet fragmentation. Recall briefly the main features of the $v_2(p_T)$ behavior in HYDJET++. The elliptic flow rises up to its maximum at intermediate $p_T$ around $2.5–3$ GeV/$c$ and then rapidly drops. This falloff is observed in experimental data also. In the model its origin is traced to the interplay between the soft hydrolike processes and hard jets, as was studied in details in [27, 28]. The ideal hydrodynamics demonstrates continuous increase of the elliptic flow with rising transverse momentum. Because of the jet quenching the jets also develop an azimuthal anisotropy that increases with the $p_T$ too; however, this effect is quite weak and does not exceed few percent. The particle yield as a function of the transverse momentum drops more rapidly for hydroproduced hadrons than for hadrons from jets. Therefore, after a certain $p_T$ threshold jet particles start to dominate the particle spectrum, thus leading to a weakening of the combined elliptic flow.

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It is worth discussing here details concerning the determination of the flow components in the experiment
and in the model. In the HYDJET++ simulations the elliptic flow is connected to the eccentricity of overlapped volume of colliding nuclei. No fluctuations in the location of nucleons within the overlapped zone are considered. Therefore, the flow is determined with respect to the position of true reaction plane. The next even component, \(v_4\), is not parametrized in the present version of the model; i.e., the hexadecapole flow comes out here merely due to the elliptic flow. Thus, it should also be settled by the position of the true reaction plane. Because of the absence of the fluctuations and non-flow effects, the ratio \(v_4/v_2^2\) obtained on an event-by-event basis equals that extracted by separate averaging of \(v_4\) and \(v_2\) over the whole simulated statistics.

In the experiment the situation is more complex. For instance, in the standard event plane (EP) method the event flow vector \(\vec{Q}_n\) for \(n\)-th harmonic is defined as (see [3] for details)

\[
\vec{Q}_n = (Q_{n,x}, Q_{n,y}) = \left( \sum_i w_i \cos (n\phi_i), \sum_i w_i \sin (n\phi_i) \right) = \left( Q_n \cos (n\Psi_n), Q_n \sin (n\Psi_n) \right). \tag{2}
\]

The quantities \(w_i\) and \(\phi_i\) are the weight and the azimuthal angle in the laboratory frame for the \(i\)th particle, respectively. From Eq. (2) it follows that the event plane angle \(\Psi_n\) can be expressed via the \(\arctan 2\) function, which takes into account the signs of both vector components to place the angle in the correct quadrant,

\[
\Psi_n = \arctan 2(Q_{n,y}/Q_{n,x})/n. \tag{3}
\]

The \(n\)th harmonic \(v_n\) of the anisotropic flow at given rapidity \(y\), transverse momentum \(p_T\), and centrality \(\sigma/\sigma_{\text{geo}}\) is determined with respect to the \(\Psi_n\) angle

\[
v_n(y, p_T, \sigma/\sigma_{\text{geo}}) = \langle \cos [n(\phi_i - \Psi_n)] \rangle \tag{4}
\]

by averaging \(\langle \ldots \rangle\) over all particles in all measured events. It is easy to see that the event plane angle for the elliptic flow \(\Psi_2\) does not necessarily coincide with that for the hexadecapole flow \(\Psi_4\). To compare our model results with the experimental ones we need, therefore, the data where the fourth harmonic is extracted with respect to the \(\Psi_2\) rather than the \(\Psi_4\) event plane angle.

To demonstrate the development of both \(v_2\) and \(v_4\) at different centralities, we display the flow harmonics for charged particles in heavy-ion collisions at RHIC and LHC energies in Figs. 3 and 4, respectively. The experimental data by the PHENIX (RHIC) and the ALICE (LHC) Collaborations are plotted onto the simulations as well. One can see here that HYDJET++ overestimates the elliptic flow of charged hadrons with transverse momenta 2 GeV/c \(\leq p_T \leq 4\) GeV/c in both reactions considered. This indicates that simplified combination of ideal hydrodynamics and jets is probably enough to simulate first two even harmonics of anisotropic flow at \(p_T \leq 2\) GeV/c, whereas at higher transverse momenta other mechanisms, e.g., coalescence, should be taken into account for better quantitative description of the flow behavior.

The elliptic flow produced by the jet hadrons with \(p_T \leq 2\) GeV/c is almost zero. Because of the jet quenching, the flow increases to \(-3\%\) with rising transverse momentum; however, the jets alone cannot provide strong flow signal, say \(v_2 \approx 10\%\), even at LHC energies. Since the \(v_4\) created by jets is also very small, it would be instructive to study how the admixture of jet hadrons can alter the \(v_4/v_2^2\) ratio.

The ratio \(R = v_4/v_2^2\) as a function of transverse momentum is presented in Figs. 5 and 6 for four different centralities in Au + Au collisions at RHIC and in Pb + Pb collisions at \(\sqrt{s} = 2.76\) A GeV. Experimental data are taken from [31].

FIG. 4: (Color online) The same as Fig. 3 but for Pb + Pb collisions at \(\sqrt{s} = 2.76\) A GeV. Experimental data are taken from [31].

FIG. 5: (Color online) Ratio \(v_4/(v_2)^2\) vs. \(p_T\) for charged particles in HYDJET++ calculations of Au + Au collisions at \(\sqrt{s} = 200\) A GeV at centrality \(\sigma/\sigma_{\text{geo}}\) (a) 10 -- 20\%, (b) 20 -- 30\%, (c) 30 -- 40\% and (d) 40 -- 50\%, respectively. Full circles denote the hydro+jet calculations, open circles show only hydro-part, and open squares indicate the rescaled experimental data (see text for details).
+ Pb collisions at LHC, respectively. The final result is compared here to the ratio obtained merely for hydro-like processes and to the experimental data. As was mentioned in [11], the measured ratio should be noticeably larger than 0.5. There are event-by-event fluctuations that increase \( R \) even if both flow harmonics are determined by means of the \( \Psi_2 \) event plane angle. The increase occurs because of the averaging of both \( v_2 \) and \( v_4 \) over the whole event sample before taking the ratio. These fluctuations are lacking in the HYDJET++ model. These fluctuations are lacking in the HYDJET++ model, and the transverse kinetic energy, \( KE_T \equiv m_T - m_0 \), of any hadron species are divided by the number of constituent quarks, i.e., \( n_q = 3 \) for a baryon and \( n_q = 2 \) for a meson, then the scaling in \( v_2(K E_T) \) holds up until \( K E_T/n_q \approx 1 \) GeV [32]. The observation of the NCQ scaling seems to favor the idea of the elliptic flow formation already on a partonic level. For instance, as pointed out in [33], the scaling is broken if hadrons are produced in the course of string fragmentation, whereas the process of quark coalescence leads to the scaling emergence. On the other hand, as was shown in Refs. [27, 28], the fulfillment of the NCQ scaling at ultrarelativistic energies depends strongly on the interplay between the decays of resonances and jets. Note that the breaking of the NCQ scaling at LHC was observed experimentally in [15, 34]. To demonstrate the importance of both resonance decays and jets for the formation of NCQ scaling we plot the reduced functions \( v_2^h/n_q(K E_T/n_q) \) for several hadronic species obtained in HYDJET++ simulations of heavy-ion collisions at RHIC (Fig. 7) and at LHC (Fig. 8) energies in centrality bin \( 20-30\% \). These distributions are then also normalized to the flow of protons, \( v_2^p/n_q : v_2^p/3 \), to see explicitly degree of the scaling fulfillment. The study is subdivided into three steps. The flow of hadrons.

IV. NUMBER-OF-CONSTITUENT-QUARK SCALING

The number-of-constituent-quark (NCQ) scaling in the development of elliptic flow was first observed in Au + Au collisions at RHIC [13, 14]. If the elliptic flow, \( v_2 \), and the transverse kinetic energy, \( KE_T \equiv m_T - m_0 \), of any hadron species are divided by the number of constituent quarks, i.e., \( n_q = 3 \) for a baryon and \( n_q = 2 \) for a meson, then the scaling in \( v_2(K E_T) \) holds up until \( KE_T/n_q \approx 1 \) GeV [32]. The observation of the NCQ scaling seems to favor the idea of the elliptic flow formation already on a partonic level. For instance, as pointed out in [33], the scaling is broken if hadrons are produced in the course of string fragmentation, whereas the process of quark coalescence leads to the scaling emergence. On the other hand, as was shown in Refs. [27, 28], the fulfillment of the NCQ scaling at ultrarelativistic energies depends strongly on the interplay between the decays of resonances and jets. Note that the breaking of the NCQ scaling at LHC was observed experimentally in [15, 34]. To demonstrate the importance of both resonance decays and jets for the formation of NCQ scaling we plot the reduced functions \( v_2^h/n_q(K E_T/n_q) \) for several hadronic species obtained in HYDJET++ simulations of heavy-ion collisions at RHIC (Fig. 7) and at LHC (Fig. 8) energies in centrality bin \( 20-30\% \). These distributions are then also normalized to the flow of protons, \( v_2^p/n_q : v_2^p/3 \), to see explicitly degree of the scaling fulfillment. The study is subdivided into three steps. The flow of hadrons.
FIG. 8: (Color online) The same as Fig. 7 but for Pb + Pb collisions at $\sqrt{s} = 2.76$ A TeV.

straight after the thermal freeze-out in hydrodynamic calculations is displayed in left windows. Central windows present this flow modified by the final state interactions, i.e., decays of resonances. Finally, right windows show the resulting flow of hadrons coming from all processes.

At RHIC energy, it looks like at given centrality the direct pions, protons and kaons are produced already obeying the scaling within the 5—10% accuracy limit; see Figs. 7(a) and 7(d). The scaling holds also after decays of resonances as demonstrated in Figs. 7(b) and 7(e). Its fulfillment becomes slightly worse when hadrons from jets are taken into account; however, the NCQ scaling remains valid within 10% accuracy at least for three main hadron species. The situation is drastically changed for the collisions at LHC. Here spectra of directly produced particles do not possess any scaling properties, as one can see in Figs. 8(a) and 8(d). After final-state interactions the scaling conditions for hadrons in hydrodynamic simulations are restored, as displayed in Figs. 8(b) and 8(e). Even $\phi$ mesons follow the unique trend. Why? Spectra of many light hadrons, especially pions and protons, are getting feed-down from heavy resonances, whereas the spectrum of $\phi$ remains unchanged. The resonance boost makes elliptic flows of light hadrons harder. As a result, the NCQ scaling is fulfilled in a broad range of $KE_T/n_q$ in the hydro sector of the model. In contrast, hard processes cause significant distortions of particle spectra and lead to violation of the scaling conditions; see Figs. 8(c) and 8(f), in accordance with experimental observations [15, 34].

V. CONCLUSIONS

Formation of elliptic $v_2$ and hexadecapole $v_4$ flows of hadrons in Au + Au collisions at $\sqrt{s} = 200$ A GeV and in Pb + Pb collisions at $\sqrt{s} = 2.76$ A TeV is studied within the HYDJET++ model. This model combines the parametrized hydrodynamics with hard processes (jets). Therefore, the main aim was to investigate the role of interplay between soft and hard processes for the development of flow. Several features have been observed. First, the jets are found to increase the ratio $R = v_4/v_2^2$ for both considered heavy-ion reactions. Second, jets lead to rise of the high-$p_T$ tail of the ratio $R$. Such a behavior is observed experimentally but cannot be reproduced by conventional hydro models relying on ideal or viscous hydrodynamics. Third, the resonance feed-down significantly enhances the flow of light hadrons and modifies their spectra toward the fulfillment of number-of-constituent-quark scaling. The flow of particles produced in jet fragmentation is quite weak, thus jets are working against the scaling. Due to interplay of resonance and jet contribution, the NCQ scaling works well only at certain energies, where jets are not abundant. Because jet influence increases with rising collision energy, just approximate NCQ scaling is observed at LHC despite the fact that the scaling holds for the pure hydrodynamic part of hadron spectra. At higher collision energies scaling performance should get worse.

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