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# FLOW ANISOTROPIES DUE TO MOMENTUM DEPOSITION FROM HARD PARTONS*

Boris Tomášik[a,b], Martin Schulc[b,c]

[a]Univerzita Mateja Bela, Banská Bystrica, Slovakia
[b]FNSPE, Czech Technical University in Prague, Prague, Czech Republic
[c]ÚJV Řež a.s., Řež u Prahy, Czech Republic

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In nuclear collisions at the LHC, a large number of hard partons is created in the initial partonic interactions, so that it is reasonable to suppose that they do not thermalise immediately but deposit their energy and momentum later into the evolving hot quark–gluon fluid. We show that this mechanism leads to contribution to flow anisotropies at all orders which are non-negligible and should be taken into account in realistic simulations.

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Hot and dense strongly interacting matter which is produced in ultrarelativistic nuclear collisions like those at the LHC or RHIC, expands swiftly and soon decouples into individual hadrons. Ultimately, one wants to investigate its evolution since it potentially bears an imprint of the Equation of State (EoS) and transport coefficients, which one wants to infer.

When the distribution of produced hadrons in transverse plane is studied, it appears far from isotropic even in most central collisions. Customarily, one studies its Fourier decomposition in azimuthal angle

$$\frac{dN}{p_{\mathrm{t}}dp_{\mathrm{t}}d\phi} = \frac{dN}{p_{\mathrm{t}}dp_{\mathrm{t}}}\frac{1}{2\pi}\left[1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\phi-\psi_n\right)\right)\right] , \tag{1}$$

where $v_n$ and $\psi_n$ are parameters. Presently available statistics allows to determine the first six terms of such series even for individual events.

The anisotropy is caused by anisotropic expansion of the hot fireball. Due to transverse expansion, transverse momentum spectra of hadrons are blueshifted. This is because particles are produced by regions of the fireball which

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move transversely outwards in the direction towards the detector. Waves emitted by a source moving towards the detector are recorded with shorter wavelength than emitted in the rest frame of the source. When translated in terms of momenta, this leads to an enhancement of higher momenta. This mechanism connects the transverse expansion of the fireball with the shape of the transverse momentum spectrum and maps the anisotropies of the former onto the anisotropies of the latter. The largest among the anisotropies is the so-called elliptic flow. It is mainly caused by the second-order anisotropy in the expansion velocity in non-central collisions due to initial anisotropic geometry of the fireball.

A classical argument then connects direction-dependent transverse expansion velocities with inhomogeneities in pressure distributions within the fireball. Distribution of the energy density is established after the incoming partons interact and shows quantum fluctuations. This is in addition to any geometrical anisotropies which are due to non-zero impact parameter in the collision. The evolution from such an initial state is reasonably well described by hydrodynamic models. This is the point where EoS and transport coefficients enter the game. The resulting state of the expanded and cooled fireball depends on EoS and transport properties. Thus, by calculating hadronic spectra and their anisotropy, one hopes to be able to tune *e.g.* the viscosities until an agreement with data is reached.

There is a caveat, however, in this game. The initial conditions are not measured and can only be determined in various models. Unfortunately, they influence strongly the resulting anisotropies of the hadron distributions [1]. Thus without the knowledge of the initial conditions, the intended strategy for the extraction of transport properties seems jeopardised. Lucky enough, simulations with both ideal and viscous hydrodynamic models show that there is quite a linear relation between the initial state spatial anisotropy and the anisotropy of hadron distribution [2–4]. This is true for the second and third orders and breaks for higher orders [2]. This can be understood, since higher order terms are influenced by the interference of lower orders (so that *e.g.* $v_4$ gets contribution from the square of $\varepsilon_2$ — second-order spatial distribution anisotropy). The linear relation allows to map the event-by-event fluctuations of $v_2$ and $v_3$ onto the fluctuations of $\varepsilon_2$ and $\varepsilon_3$, and thus identify the model for the initial state which best agrees with the data.

Usually, it is assumed that there is no contribution to fluctuations during the hydrodynamic evolution. This may not be the case, however. Hydrodynamic simulation with the fluid energy and momentum density coupled to dynamically fluctuating order parameter field shows fluctuations in the energy density which can well cause flow anisotropies observable in data [5]. More precise quantitative impact of such a mechanism remains to be studied.

Here, we introduce another mechanism that can induce flow anisotropies. Hard partons from the initial scatterings do not thermalise immediately as they are produced, but fly into the hot and dense quark–gluon plasma. There, mostly they are fully quenched so that their momentum is transferred into the fluid and must show up in the flow pattern. Directions of these partons are distributed isotropically, but due to their finite number, there may be a contribution to flow anisotropy.

In addition to that, the energy in a collision at the LHC is so large that there may be pairs of hard partons which are close in rapidity and are directed so that they might come close to each other during the evolution of the collision. Even if they are fully quenched before they could actually meet, their momentum has been shown to be further carried by the generated streams in the fluid [6]. There is a good chance that such streams merge into one. In peripheral collisions, through this mechanism, the collective flow induced by hard partons tends to be directed in the reaction plane (which is spanned by the beam and the direction of the impact parameter).

Imagine (Fig. 1) the almond-shaped cross sectional area of a fireball in non-central collisions with two pairs of hard partons produced. If all four partons are directed parallel to the reaction plane, through the momentum loss, they will all positively contribute to the elliptic flow (Fig. 1, left). If, however, they are directed perpendicularly to the reaction plane, there is a chance that two of the streams will meet, merge and cancel flow in that direction (Fig. 1, right). The chance is bigger in this direction because here the fireball is narrower and the streams have less space to avoid each other.

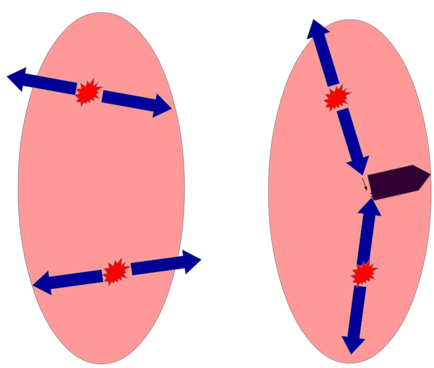

Fig. 1. Transverse cross section of the fireball in non-central collisions, with two dijet pairs produced. Reaction plane is horizontal.

We have set up a three-dimensional ideal hydrodynamic model and tested this scenario [7,8]. Note that a 3D simulation in this case is mandatory, since the presence of hard partons breaks the boost-invariance (and azimuthal symmetry). In order to estimate the effect on flow anisotropies due to hard partons, we formulated the model without any other fluctuations in the initial conditions. Thus, our initial energy density profile was determined from an optical Glauber model and the distribution in transverse plane was determined from a combination of wounded-nucleon and binary-collision density. The energy density in the central cell at the initial time of $\tau_0 = 0.5$ fm/$c$ was set to 60 GeV/fm$^3$. The initial profile in rapidity is flat over 10 units with Gaussian tails at the edges.

To implement the effect of energy and momentum deposition from hard partons into plasma, terms $J^\nu$ which represent forces are added into the energy and momentum conservation equation

$$\partial_\mu T^{\mu\nu} = J^\nu \,, \tag{2}$$

where $T^{\mu\nu}$ is energy-momentum tensor. The force field is parametrised with the help of Gaussians [6, 7]

$$J^\nu = \sum_i \frac{1}{\left(2\,\pi\,\sigma_i^2\right)^{\frac{3}{2}}} \exp\left(-\frac{\left(\vec{x}-\vec{x}_{\mathrm{jet},i}\right)^2}{2\,\sigma_i^2}\right)\left(\frac{dE_i}{dt}, \frac{d\vec{P}_i}{dt}\right) \,, \tag{3}$$

where the terms in the bracket stand for the rate of energy and momentum deposition, and the Gaussian ($\sigma = 0.3$ fm) distributes it around the trajectory of the parton until all its energy is used up. The actual energy loss scales with the entropy density as

$$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_0 \frac{s}{s_0} \tag{4}$$

with $s_0 = 78.2/\mathrm{fm}^3$ (corresponding to $\varepsilon_0 = 20$ GeV/fm$^3$) and $dE/dx|_0$ being a parameter that we tuned. The places of hard parton production are distributed according to binary collision density in the transverse plane and uniformly in rapidity. Their directions are azimuthally symmetric and the $p_{\mathrm{t}}$ spectrum follows from [9]

$$\frac{1}{2\pi}\,\frac{1}{p_{\mathrm{t}}}\,\frac{d\sigma_{NN}}{dp_{\mathrm{t}}\,dy} = \frac{B}{(1+p_{\mathrm{t}}/p_0)^n} \tag{5}$$

with $B = 14.7$ mb/GeV$^2$, $p_0 = 6$ GeV, and $n = 9.5$.

In Fig. 2, we show results obtained for collisions at vanishing impact parameter. There is no anisotropy in the case of no hard partons as we initiate the simulation with smooth azimuthally symmetric energy density profile. Momentum deposition *during* the evolution leads to measurable flow anisotropies. Interestingly, the effect of energy loss does not depend on the value of $dE/dx|_0$. Note that the total deposited momentum for both tested values is the same, only the rate of deposition is changed. Simulations with only hot spots added in the initial state, which contain the same amount of energy as hard partons, but no momentum, lead just to a half of the effect of parton energy loss.

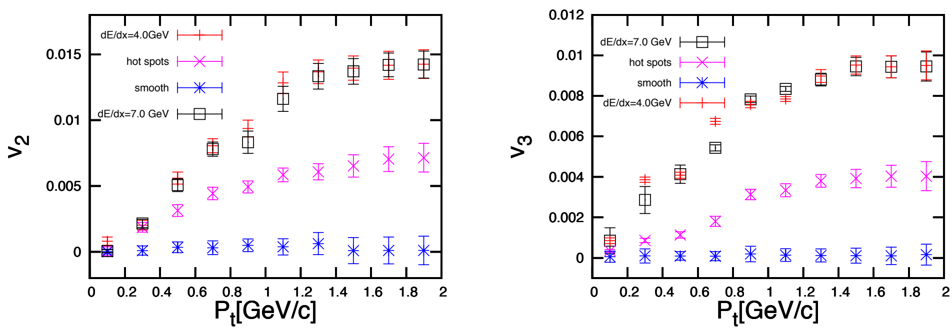


Fig. 2. Coefficients $v_2$ and $v_3$ from central collisions. Data calculated with two different values of hard parton energy loss, one simulation with only energy and no momentum deposition (hot spots). Shown are also reference simulation with the smooth initial conditions.

We should prove yet that the effect is correlated with event geometry so that in non-central collisions we indeed obtain positive contribution to the elliptic flow as argued above. To this end, events corresponding to impact parameter $b = 6$ fm (falls into the centrality class 30–40%) were simulated both with and without the hard partons contribution. Main results are summarised in Fig. 3, where we show $v_2$ and $v_3$ as functions of $p_\mathrm{t}$. In non-central collisions, elliptic flow is generated due to the anisotropic matter distribution from which the fluid evolves. Hard parton contribution increases the observed anisotropy by about 50%. As for $v_3$, it is not present in the case of smooth initial conditions and due to missing third-order spatial anisotropy, it is solely generated from the hard parton momentum deposition.

These results indicate that the contribution from hard parton momentum loss is significant and should be taken into account in hydrodynamic simulations that aim at the extraction of transport properties of the hot and dense nuclear matter.

An open question is why changing the rate of energy loss has no influence on the generated elliptic flow. We speculate that the reason may be that practically all of the energy and momentum is deposited very early in the densest period of fireball evolution. We want to investigate this question more closely in the future.

A realistic simulation, also to be accomplished in the future, must include viscosity effects and fluctuating initial conditions. There we plan to use a newly developed hydrodynamic model [10].

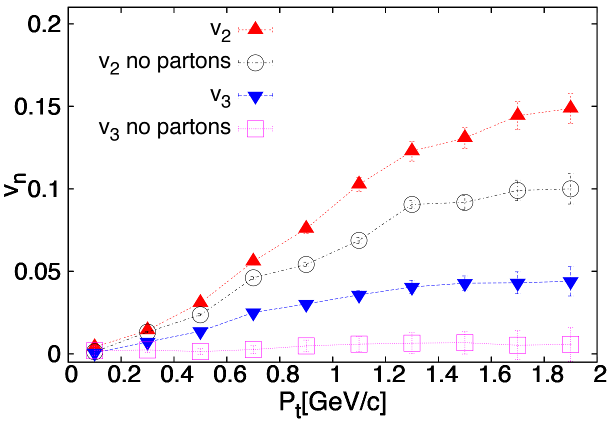


Fig. 3. Coefficients $v_2$ and $v_3$ from collisions at impact parameter $b = 6$ fm. We show results from simulations with only smooth initial energy density profile (legend: no partons) as well as with energy loss from hard partons included.

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