Anisotropic flow from hard partons in ultra-relativistic nuclear collisions

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Anisotropies of hadronic distribution in nuclear collisions are used for determination of properties of the nuclear matter. At the LHC it is important to account for the contribution to the flow due to momentum transferred from hard partons to the quark-gluon plasma.

In ultrarelativistic nuclear collisions, hadron momentum distributions are azimuthally anisotropic and parametrised with the help of Fourier expansion with amplitudes of individual modes usually denoted as v_n's. If spectra are summed over a large number of events, symmetry constraints dictate all odd amplitudes to vanish. In individual events, however, these constraints are not realised, because the event shapes fluctuate.

In general, the mechanism behind the modification of hadronic spectra is the blue-shift. Transverse expansion of the fireball enhances production of hadrons with higher p_t. If the normalisation and the slope of p_t spectrum depend on azimuthal angle, this indicates different transverse expansion velocity in different directions. Expansion is caused by pressure gradients in the initial state. We thus have a link between the initial state of the fireball and the observed hadronic spectra. (In fact, here we propose a mechanism which can break this link.)

The link is described by relativistic hydrodynamics. The scheme is based on fundamental conservation laws complemented by the equation of state. In non-ideal hydrodynamics it also involves transport coefficients, e.g. shear and bulk viscosity. The goal is to tune them so that hydrodynamic modelling yields results in accord with the observations.

Unfortunately, there are some problems. The initial conditions are unknown. They are set by energy depositions in early partonic interactions. Various models predict energy and momentum density profiles with different levels of spikiness. One can get the same result on flow anisotropies with different initial conditions if one re-tunes the transport coefficients [1]. This hinders the determination of viscosities from comparisons to data. The extracted values would depend on the assumptions that are made about *unknown* initial conditions.

This problem might be settled with the help of flow anisotropy fluctuations [2]. Simulations indicate that the values of v_n's in individual events follow to large extent the corresponding spatial anisotropies of the initial state [3, 4]. The departure from this proportionality has also been studied [4, 5]. The mechanism proposed in the present paper would break this proportionality since it produces flow anisotropy *during* the hydrodynamic evolution *without* the need for any anisotropy in the initial state.

We point out [6] that in nuclear collisions at LHC energies there is more than one dijet pair per event. (We might have to lower the threshold for what we count as hard parton; here we use $p_t > 3$ GeV/c.) They deposit most—if not all—of their energy and momentum into the plasma and are fully quenched. Since momentum must be conserved, the wakes behind the partons must stream and carry it. Such streams would generate anisotropy of collective expansion in every individual event. This leads to elliptic anisotropy even after a summation over large number of events. Indeed, isotropically produced jets generate elliptic anisotropy. The important detail is the possibility that the induced streams can interact and merge.

Suppose that two dijet pairs are produced in a non-central collision. The elliptic flow due to spatial deformation is directed parallel to the reaction plane. If both pairs are aligned with this plane, then all streams contribute to positive v_2, see Fig. 1 (left). On the other hand, if the jets are oriented under large angle with respect to the reaction plane, then the two streams directed inwards can meet, merge into one, and continue in a direction given by the sum of their two momenta. They do not contribute to the collective flow in their original direction. The chance of merger is higher in the latter case than in the former one since there the jets pass each other within a narrower path. Perpendicularly to the reaction plane the fireball is wider so the streams parallel to the reaction plane can well proceed without bothering each other. In addition to this mechanism, Fig. 1 (right) also suggests that contribution to triangular flow is created by the merger of two streams.

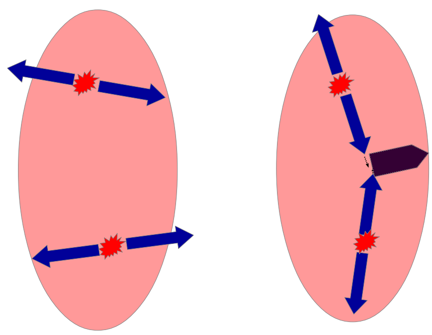

Figure 1: Transverse cross-section through the fireball with two dijet pairs produced. Reaction plane is horizontal. Left: two dijets both emitted in the direction of the reaction plane both contribute positively to the elliptic flow, which is dominant in the same direction. Right: if hard partons are produced off the reaction plane, some of their streams can come together and merge.

This picture is supported by our simulations. We developed 3+1D ideal hydrodynamic simulation code [7, 8] using the SHASTA scheme to handle shocks. We include force term J^μ

$$\partial_\mu T^{\mu\nu} = J^\nu \tag{1}$$

which represents the dragging of the fluid by hard partons [9]

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

where the sum goes through all hard partons in the system and the width σ_i was set to 0.3.

We first checked that indeed the streams are induced behind the partons and that they flow even after the partons are fully quenched (as was also observed in [9]). In a simulation with static medium we could see that the streams merge when they meet. Then, until their energy is spread over a larger volume, they continue flowing in common direction [7].

The mechanism has been included into more realistic simulation of nuclear collisions. In these studies it was not our aim to reach the complete description of data. We rather wanted to gain realistic estimate of the influence of our mechanism on the observed anisotropies. Therefore, we started our simulations always with smooth initial conditions calculated within the optical Glauber model. Any fluctuation on top of non-zero event-averaged flow harmonics is then

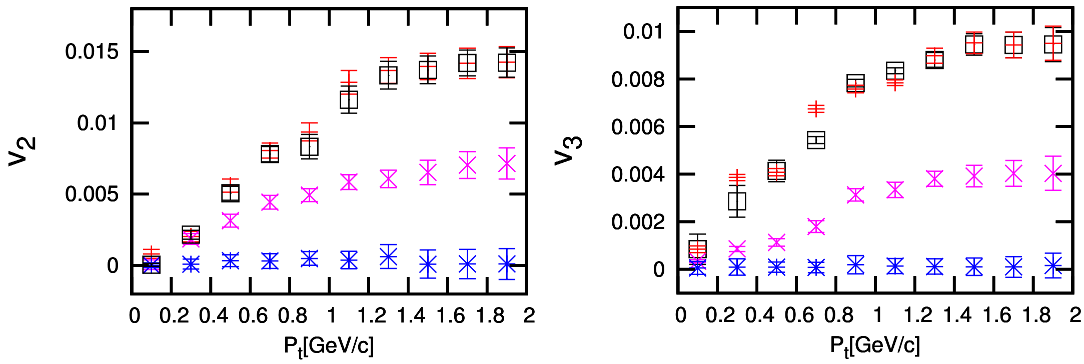

Figure 2: Anisotropy coefficients from central collisions. Two simulations with hard partons with different energy loss. One simulation with only energy and no momentum deposition (hot spots). One simulation with smooth initial conditions.

clearly a consequence of hard partons inducing flow anisotropies. We start our simulation with uniform profile in longitudinal rapidity stretched over 10 units and cut by half-Gaussian tails at both ends. This feature represents the approximate boost-invariance at highest LHC energies. Note that the use of 3+1D hydrodynamic model, which makes our simulation distinct from those reported in [10, 11], is important because the hard partons injected into plasma break the boost invariance and thus the possibility to reduce the dimensionality of the hydrodynamic model.

At the beginning of each event simulation we generate the positions and directions of the hard parton pairs. Their number fluctuates according to Poissonian and their p_T's follow from [6]

$$E\frac{d\sigma_{NN}}{d^3p} = \frac{1}{2\pi}\,\frac{1}{p_T}\,\frac{d\sigma_{NN}}{dp_T\,dy} = \frac{B}{(1+p_T/p_0)^n} \tag{3}$$

with $B = 14.7$ mb/GeV^2, $p_0 = 6$ GeV and $n = 9.5$. Momenta in a pair are back-to-back. The initial positions are generated from the distribution of the binary collisions calculated within optical Glauber model.

In an expanding fireball we assume that the energy loss of a parton scales with the entropy density as $dE/dx = dE/dx|_0\,(s/s_0)$ where $s_0 = 78.2/\mathrm{fm}^3$ (corresponds to energy density 20 GeV/fm^3). Hydrodynamic description of the collision is finished at the freeze-out hypersurface specified by temperature 150 MeV. Generation of final state hadrons is done with the help of THERMINATOR2 [12] Monte Carlo model.

In Fig. 2 we show the v_n's calculated in central collisions. To study the effect of momentum deposition we simulated 100 evolutions for every setting and generated 5 THERMINATOR2 events for each of them. For the momentum loss we made simulations with $dE/dx|_0$ set to 4 GeV/fm and 7 GeV/fm and they lead to the same momentum anisotropies. Their magnitude indicates that the effect is important and should be included in realistic simulations. Finally, we also simulated events where we put in hot spots with the same energy on top of the smooth initial conditions instead of hard partons. They deposit only energy and no momentum, and the generated flow anisotropies are about half of those initiated by hard partons.

Simulations of non-central collisions clearly show that the contribution enhances the observed anisotropies. In Fig. 3 we see about 50% addition to v_2 as compared to the case with smooth initial conditions. Triangular anisotropy is absent in the initial conditions and thus any v_3 is exclusively due to hard partons.

The presented results clearly demonstrate the necessity to include this mechanism into realistic hydrodynamic simulations which aim at extracting the properties of quark matter. For the alignment of the studied effect with the geometry of the fireball it is crucial to include more than one dijet pair into the simulation, unlike done in [13]. The interplay of many generated streams appears important.

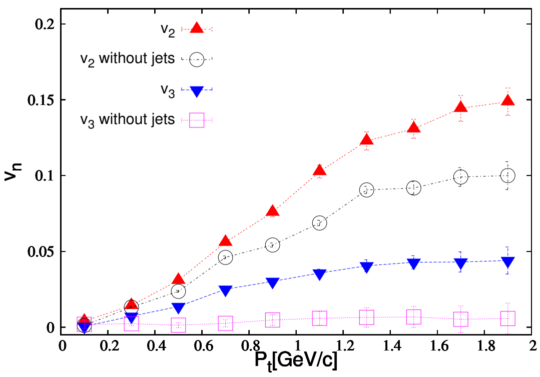

Figure 3: Coefficients v_2 and v_3 from 30–40% centrality events. Results of simulations with hard partons are compared with results from smooth initial conditions.

Acknowledgments

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