# Anisotropic flow of the fireball fed by hard partons

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In nuclear collisions at highest accessible Large Hadron Collider (LHC) energies, often more than one dijet pairs deposit momentum into the deconfined expanding medium. With the help of 3+1 dimensional relativistic hydrodynamic simulation we show that this leads to measurable contribution to the anisotropy of collective transverse expansion. Hard partons generate streams in plasma which merge if they come close to each other. This mechanism correlates the resulting contribution to flow anisotropy with the fireball geometry and causes an increase of the elliptic flow in noncentral collisions.

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### I. INTRODUCTION

Study of the properties of the hottest matter ever created in laboratory is in the focus of the heavy-ion program at the Large Hadron Collider (LHC). From data on jet quenching we know that the created matter is in a deconfined state. Currently, the focus is on studying the properties of such deconfined strongly interacting matter. Comparisons of hydrodynamic simulations with the measured data aim at extracting the transport coefficients, mainly the viscosity.

Due to transverse expansion of the created hot matter, hadronic transverse momentum spectra show a blueshift. The blueshift varies azimuthally. This indicates the modulation of the transverse expansion velocity as a function of the azimuthal angle. Such a modulation appears naturally in noncentral collisions due to azimuthally asymmetric shape of the initial overlap region. However, a more detailed analysis reveals azimuthal anisotropies in every event, which are causally linked to to fluctuations in the initial state [1-6]. As these fluctuations are propagated within the (weakly) viscous relativistic fluid, dedicated simulation could put relevant limits on the transport properties of the deconfined matter [2]. This is the standard approach which is being used in present investigations: by selecting a set of initial conditions and tuning the values of viscosities one tries to find such a setting of hydrodynamic simulations which reproduces as many features of data as possible. The data today are very rich with a few orders of azimuthal anisotropies for identified species, and many kinds of correlations, with everything measured in various centrality classes [7–11].

In this paper we point out another source of spectral azimuthal anisotropy. It cannot be put into the family of models where initial conditions are exclusively responsible for the anisotropy. At the LHC, jets are no longer such a rare probe. They are produced in initial hard scattering, together with copious minijets, and propagate through the deconfined medium. It is known that quark-gluon plasma quenches a large part—if not all—of the energy and momentum of the hard partons which might become jets. The momentum deposition from the partons into the medium induces collective effects [12–21] and owing to momentum conservation there must be net flow. Recently in Ref. [22] the response of the medium to one very energetic dijet was simulated in 3+1 dimensional (3+1D) hydrodynamics. In Ref. [23] the generation of elliptic and triangular flow due to hard partons within a 2+1D model was simulated. The introduction of jets, however, breaks longitudinal boost invariance which is implicitly assumed in a 2+1D simulation. The influence of jets on the evolution in central collisions was investigated in a 1+1D approach also in [24,25]. Here we present results from our three-dimensional ideal hydrodynamic simulation with a realistic multiplicity distribution of hard partons.

In Ref. [26] it was shown with a help of a toy model that if there are a few pairs of minijets within one event, the wakes which they deposit may influence each other and so lead to elliptic flow anisotropy correlated with the reaction plane. Later in Ref. [27] we have shown that the concept of two merging wakes that follow as one stream is reproduced in ideal hydrodynamics in a static medium. Here we apply these ideas in three-dimensional simulations of an expanding fireball motivated by realistic collision dynamics.

We present results on first- to fourth-order flow anisotropies in central and noncentral collisions. Hard partons depositing momentum themselves are capable of generating  $v_2$  of the order 0.015 in ultracentral collisions at the LHC. It is important that in noncentral collisions their contribution is correlated with fireball geometry. We show that they contribute considerably to the observed anisotropy of hadronic spectra.

Higher harmonics of azimuthal anisotropy from a hydrodynamically expanding fireball complemented with jets were recently calculated also within the HYDJET++ model [28]. However, that model consists of two *independent* parts: the soft production is modeled by parametrisation of hadron emission while the hard part is simulated by separate Monte Carlo model. In contrast to that, we focus on the *interplay* of the fluid and the jets. We study how the fluid behaves when it is stimulated by jets in addition to expansion due to pressure gradients.

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#### **II. DESCRIPTION OF THE MODEL**

We perform event-by-event hydrodynamic simulations. Our model is three-dimensional, based on ideal hydrodynamics, and uses the SHASTA algorithm [29,30] to deal with shock fronts. For each event the initial conditions are first constructed smooth according to the optical Glauber prescription. The transverse profile of the energy density at impact parameter b is characterized by

$$W(x, y; b) = (1 - \alpha)n_w(x, y; b) + \alpha n_{bin}(x, y; b), \quad (1)$$

where  $n_w$  and  $n_{\text{bin}}$  are the numbers of wounded nucleons and binary collisions at given transverse position (x, y), and the coefficient  $\alpha$  is set to 0.16. The nucleon-nucleon cross section for the Glauber calculation at  $\sqrt{s_{NN}} = 5.5$  TeV is set to 62 mb. By choosing a smooth transverse profile with no event-byevent fluctuations we can later be sure that any anisotropic flow in addition to the event-averaged one is due to the contribution of hard partons. We can thus better estimate their contribution. For the 3+1D hydrodynamic simulation, the initial profile in space-time rapidity  $\eta_s = \frac{1}{2} \ln[(t + z)/(t - z)]$  is given by

$$H(\eta_s) = \exp\left(-\frac{\left(|\eta_s| - \eta_{\text{flat}}/2\right)^2}{2\sigma_\eta^2}\right) \theta\left(|\eta_s| - \eta_{\text{flat}}/2\right). \quad (2)$$

We chose  $\eta_{\text{flat}} = 10$  [31] and  $\sigma_{\eta} = 0.5$ . The initial energy density then follows the distribution

$$\epsilon(x, y, \eta_s; b) = \epsilon_0 \frac{W(x, y; b)}{W(0, 0; 0)} H(\eta_s).$$
(3)

We choose  $\epsilon_0 = 60 \text{ GeV}/\text{fm}^3$  for the initial longitudinal proper time  $\tau = 0.55 \text{ fm}/c$ .

For the hydrodynamic evolution we have taken latticeinspired equation of state from [32].

Momentum feeding from hard partons into the medium is implemented via source terms in the energy-momentum conservation equation

$$\partial_{\mu}T^{\mu\nu} = J^{\nu}, \qquad (4)$$

where the source term  $J^{\nu}$  stands for the rate of energymomentum loss of the hard parton [19,20]

$$J^{\nu} = -\sum_{i} \int_{\tau_{i,i}}^{\tau_{f,i}} d\tau \, \frac{dP_{i}^{\nu}}{d\tau} \, \delta^{(4)} \big( x^{\mu} - x_{\text{jet},i}^{\mu} \big), \tag{5}$$

where  $P_i^{\mu}$  and  $x_{jet,i}^{\nu}$  denote momentum and position of the *i*th hard parton, respectively. The sign in front of the summation reflects the fact that the change of momentum of the medium is opposite to the momentum change of the hard parton. Integration runs over the whole lifetime of *i*th parton until its energy is fully quenched, and the summation goes over all hard partons of the event. The microscopic picture of how momentum is transferred from the parton into the medium is being investigated [17,33] but is not yet fully understood at an applicable level. We thus introduce the spatial region over which the momentum is initially distributed in a noncovariant

implementation of the source term,

$$J^{\nu} = -\sum_{i} \frac{1}{\left(2\pi \sigma_{i}^{2}\right)^{\frac{3}{2}}} \exp\left(-\frac{(\vec{x} - \vec{x}_{\text{jet},i})^{2}}{2\sigma_{i}^{2}}\right) \left(\frac{dE_{i}}{dt}, \frac{dP_{i}}{dt}\right)$$
(6)

with  $\sigma = 0.3$  fm. Partons are assumed to have mass 0.3 GeV when momentum loss is determined from the energy loss.

Parton energy loss depends on the density of the medium. The exact form of this dependence is not known yet [34,35]. Here we assume that it scales with entropy density *s* [36]. The scaling relation is thus

$$\frac{dE}{dx} = \frac{dE}{dx}\Big|_{0} \frac{s}{s_0},\tag{7}$$

with  $s_0$  corresponding to energy density 20.0 GeV/fm<sup>3</sup> (T = 324 MeV and s = 78.2/fm<sup>3</sup>). For  $dE/dx|_0$  we usually choose values 4 and 7 GeV/fm.

For the production of hard partons we take the parametrization of gluon cross section per nucleon-nucleon pair in nucleusnucleus collisions,

$$E\frac{d\sigma_{NN}}{d^3p} = \frac{1}{2\pi} \frac{1}{p_t} \frac{d\sigma_{NN}}{dp_t \, dy} = \frac{B}{(1+p_t/p_0)^n},\tag{8}$$

where for the energy  $\sqrt{s_{NN}} = 5.5$  TeV we have B = 14.7 mb/GeV<sup>2</sup>,  $p_0 = 6$  GeV, and n = 9.5. The distribution of hard parton pairs in the transverse plane scales with the number of binary collisions. The pairs have balanced transverse momentum. For the presented results we generated dijet pairs with  $p_t$  above 3 GeV.

We chose to make simulations for the collision energy of  $\sqrt{s_{NN}} = 5.5$  TeV for which one of us published the educated guess that the effects of momentum deposition on flow anisotropy should be measurable [26]. This can also be regarded as a prediction for a future LHC run.

Freeze-out is handled by the Cooper-Frye prescription [37] on the hypersurface given by T = 150 MeV. We use the THERMINATOR2 package [38] to generate hadrons on the obtained hypersurface and evaluate results.

### **III. SIMULATIONS AND RESULTS**

For Pb+Pb collision at full LHC energy  $\sqrt{s_{NN}} = 5.5$  TeV we simulate sets of events in three centrality classes. In order to establish the effect on anisotropic flow due to hard partons we analyze two central classes of events: one corresponding to 0–2.5 % of centrality distribution and one where we strictly set the impact parameter b = 0 fm. In order to see the contribution of our mechanism in noncentral collisions, we also simulate a set of 30–40 % centrality class.

For each setting we generate 100 hydrodynamic events. On top of that we run on each obtained hypersurface five times the THERMINATOR2 freeze-out procedure and thus we quintuple the number of events in the analysis. Resonance decays are included. We obtain the anisotropic flow parameters  $v_1$ ,  $v_2$ ,  $v_3$ ,  $v_4$  for charged hadrons by the two-particle cumulant method. Recall that we analyze hadrons coming from the bulk freeze-out of hot matter with collective flow influenced by hard partons. All anisotropies in hadronic distributions are due to anisotropic collective expansion.



FIG. 1. (Color online) Parameters  $v_n$  from collisions at b = 0 for charged hadrons. Different symbols represent energy loss of hard parton  $dE/dx|_0 = 4$  GeV/fm (red –), 7 GeV/fm (black  $\Box$ ), scenario with only hot spots in initial conditions (purple ×), scenario with smooth initial conditions (blue \*).

We first investigate the size of generated anisotropy of momentum distribution in ultracentral collisions (b = 0). Results are shown in Fig. 1. Two values for the energy



FIG. 2. (Color online) Anisotropy parameters  $v_n$  from centrality class 0–2.5 % for charged hadrons as functions of  $p_t$ . The energy loss of hard partons is given by  $dE/dx|_0 = 4 \text{ GeV}/\text{fm}$ . Red  $\triangle$ :  $v_2$ ; black  $\circ$ :  $v_3$ ; blue  $\nabla$ :  $v_4$ .

loss are tested:  $dE/dx|_0 = 4$  GeV/fm and 7 GeV/fm. As a benchmark test we also evaluate the  $v_n$ 's from simulation with no hard partons and no fluctuations and show that they are consistent with 0. The results are also compared with simulations where hot spots were superimposed on the smooth energy density profile. There are as many hot spots as there would be hard partons. These are regions where we deposit the same amount of energy that a hard parton would carry if it were produced there. In contrast to hard partons, in hot spots the energy is included in the initial conditions and not released over finite time interval. Also, in a hot-spots scenario no momentum is deposited. The comparison in Fig. 1 shows that momentum deposition is important. Fluctuations in the initial conditions by themselves are not able to generate the same flow anisotropies as wakes with streams induced by hard partons.

It is somewhat puzzling why there is no difference in results between the two scenarios which differ in the value of the energy loss. Choosing a higher value of dE/dx causes the partons to lose their momentum faster, but it is the same total



FIG. 3. (Color online) Anisotropy parameters  $v_n$  for charged hadrons integrated over  $p_t$  for different centralities. The energy loss of hard partons is given by  $dE/dx|_0 = 4 \text{ GeV/fm}$ .



FIG. 4. (Color online) Anisotropy parameters  $v_2$  and  $v_3$  for charged hadrons as functions of  $p_t$  from collisions within centrality class 30–40%. The energy loss of hard partons is given by  $dE/dx|_0 = 4 \text{ GeV/fm}.$ 

amount of momentum that is deposited into the fluid. In fact, most of them have rather low  $p_t$  and thus are quenched early.

The CMS Collaboration has found a strong dependence of  $v_2$  and  $v_3$  on centrality even for central collisions [11]. Although here we only want to get an educated estimate on the size of the effect that our mechanism can generate, it is tempting now to see how our  $v_n$ 's would change if we go to centrality class 0–2.5 %. The results are shown in Fig. 2 for charged particles. In Fig. 3 we present the integarted  $v_n$ 's as functions of centrality. We see that going from b = 0 fm to 0–2.5% centrality there is no dramatic increase in  $v_n$ 's. If such effect is present in data, it must be caused by a different mechanism.

In simulations of noncentral events we clearly establish that the flow anisotropy generated by hard partons is correlated with the reaction plane. This is a consequence of the mechanism

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where two streams of the fluid in the wakes merge when they are close. Then they continue flowing in the direction given by momenta of the two streams [26,27]. The proof of validity of this mechanism is presented in Fig. 4. We show  $v_2$  and  $v_3$  of charged hadrons as calculated from an ensemble of 500 events with hard partons depositing momentum. They are compared with  $v_2$  and  $v_3$  being only due to the event-averaged almond shape of the initial hot matter. Obviously,  $v_3$  must vanish then, and it indeed does. If the contribution of hard partons had random direction, we would not expect an increase of  $v_2$ . However,  $v_2$  increases by more than factor of 1.5.

Note also the increase of other orders of the anisotropy presented in Fig. 3 for integrated  $v_n$ 's.

## **IV. CONCLUSIONS**

Our results show that the interplay of many minijetinduced streams in a single nuclear collision at the LHC yields considerable contribution to azimuthal anisotropies of hadron distributions. The present simple nonviscous model with smooth initial conditions should merely be used for an educated estimate of the influence. It is certainly not capable of reproducing data, since this requires inclusion of many fine details. Among them the most prominent are shear and bulk viscosities and a tuned model of fluctuating initial conditions. How to disentangle various mechanisms that generate all kinds of azimuthal anisotropies must be investigated, with the help of many features of data that are currently being measured.

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