Flow anisotropy due to momentum deposition in ultra-relativistic nuclear collisions

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Abstract. Minijets and jets are produced in large numbers in nuclear collisions at TeV energies, so that there are many of them in a single fireball. They deposit non-negligible amount of momentum and energy into the hydrodynamically expanding bulk and cause anisotropies of the expansion. Moreover, due to their multiple production in a single event the resulting anisotropies are correlated with the collision geometry and thus contribute positively also to event-averaged anisotropies in non-central collisions. Using simulations with three-dimensional ideal hydrodynamic model we demonstrate the importance of this effect. It must be taken into account if conclusions about the properties of the hot matter are to be drawn.

1 Introduction

One of the features of heavy-ion collisions at the LHC is the large portion of energy spent in production of hard partons. Some of them appear as jets, but a major part of hard and semi-hard partons never comes out of the fireball. Instead, they are fully stopped in the quark-gluon plasma. The energy as well as momentum of the partons is thus fully transformed into the fluid medium. It has been shown that this generates streams in the plasma which continue to move even after the (originally) hard partons have thermalised [1]. It is reasonable to expect that such streams would contribute to flow anisotropy of the created quark matter.

There is more than just one pair of hard partons per event at the LHC. Therefore, we can also expect more streams within the expanding plasma. If their number is not too large, then we can expect an increase of flow anisotropies of all orders. In addition to this, we also argue that this contribution to elliptic flow anisotropy is correlated with the geometry of the collision so that it actually increases the elliptic flow in non-central collisions. This can be explained with the help of the schematic drawings shown in Fig. 1. In non-central collisions the elliptic flow is caused by larger pressure gradients in the direction of the reaction plane. They result in faster expansion in that direction. If two dijets are both produced in the direction of the reaction plane, they both contribute positively to the elliptic flow.\(^1\) Jets are produced anisotropically, however. That means, that there will also be a pair of dijets produced

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\(^1\)For brevity, we will here refer to hard partons as to jets and back-to-back pairs of hard partons as dijets even if they have not yet formed the showers.
perpendicularly to the reaction plane. One would naively expect that they would then suppress the flow anisotropy. However, as it is sketched in Fig. 1, in this case the inward-flying jets are more likely to meet. Then the streams that they generate would merge, partially cancel each other and flow together in a new direction determined by their total momentum. Thus the resulting effect of the pair of dijets on the collective flow would be smaller than in the previous case, since a pair of dijets flying in the direction of the reaction plane is less likely to meet.

We will show below with the help of hydrodynamic simulations that these handwaving arguments are indeed true. We shall also show that the effect of the jets on flow anisotropies is significant.

2 The model

We have constructed a three-dimensional ideal hydrodynamic model which includes a source term in the energy-momentum conservation equation

\[ \partial_t T^{\mu \nu} = J^\nu. \]  

In fact, it might be better to call it a force term, since this is the real meaning of that term.

For the hydrodynamic evolution itself we chose the Equation of State [2] which combines the results of Lattice QCD at high temperatures with the construction from a hadron resonance gas at low temperatures. To handle large gradients and shocks, the model uses the SHASTA algorithm [3].

The initial conditions that we have chosen are smooth, with the initial energy density profile specified by the optical Glauber model. Intentionally, we have chosen this obsolete solution. The reason is that we shall be implementing a novel mechanism which should lead to flow anisotropies. Not having fluctuations in the initial state makes it easier to evaluate its impact. The initial energy density in the central point of the fireball produced in collisions with vanishing impact parameter was 60 GeV/fm³ and the time when hydrodynamics is started was set to \( \tau_0 = 0.55 \text{ fm/c} \).

The number of dijets fluctuates but on average we have about 10 pairs with \( p_t \) above 3 GeV/c in central Pb+Pb collision at \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \). The two jets of the pair are produced back-to-back in \( p_t \) but they generally have different rapidities. Their initial positions in transverse plane are given by the distribution of the binary nucleon-nucleon collisions. Transverse momenta of the jets follow the


\[ \frac{1}{2\pi p_t} \frac{d\sigma}{dp_t, dy} = \frac{B}{(1 + \frac{p_t}{p_0})^n} \]  

(2)

with \( B = 14.7 \, \text{mb/GeV}, p_0 = 6 \, \text{GeV}, n = 9.5. \)

The jets, as they traverse the quark-gluon plasma, lose their energy and momentum. It is assumed that this transfer scales with the entropy density of the medium

\[ \frac{dE}{dx} = \frac{dE}{dx}\bigg|_0 \frac{s}{s_0} \]  

(3)

where \( s_0 \) is the entropy density which corresponds to the energy density of 20 GeV/fm\(^3\) and the energy loss scale \( dE/dx|_0 \) has been varied in order to investigate its influence on the observable results.

The deposition of the energy and momentum has been smeared in space with the help of a Gaussian distribution with the width of 0.3 fm. We have checked that varying the width to 0.15 fm and 0.6 fm does not influence the results much.

Cooper-Frye freeze-out was handled with the help of THERMINATOR2 package [5]. Production and decays of resonances are included.

### 3 Results for non-central collisions

In order to confirm the hypothesis that the jets would enhance the elliptic flow in non-central collisions, we have performed simulations of Pb+Pb collisions within 30–40% centrality class [6]. The main results are summarised in Fig. 2. There we plot the elliptic flow coefficient \( v_2 \) and the triangular flow coefficient \( v_3 \) as functions of \( p_t \). They are both calculated for two scenarios. One is the simulation with jet energy loss included and the value of \( dE/dx|_0 \) set to 4 GeV/fm. For reference, we also show results from simulations with no jets. There, the elliptic flow results solely from the difference between the pressure gradients in-plane and out-of-plane in the initial conditions and there is no triangular flow. We see that the energy and momentum deposition enhances \( v_2 \) by about 50%.

This confirms our hypothesis: the flow anisotropy due to momentum deposition is correlated with the geometry of the collision via the effect described in the introductory section. Note that the jets also generate triangular anisotropy of the collective flow which otherwise would be absent in our simulations.

\[ \text{Figure 2. Elliptic flow and triangular flow in Pb+Pb collisions, centrality class 20–30\%, calculated with smooth fireball and no energy-momentum deposition from jets (circles and squares), as well as with energy-momentum deposition from jets (triangles).} \]
The cartoon argumentation used in the introduction might also illustrate a possible way of distinguishing our mechanism of generation of the flow anisotropy from the more conventional scenario where any anisotropy is just due to anisotropies in energy density distribution in the initial state of the collision. Recall that the combined second and third-order anisotropy would be parametrised as

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + 2v_2 \cos(2(\phi - \psi_2)) + 2v_3 \cos(3(\phi - \psi_3)) \right). \quad (4)$$

Figure 1 suggests that the triangular flow is connected with merging of streams, which is more likely for the jets flying out of the reaction plane. Then the third order reaction plane in an event is more likely to be directed together with the second order reaction plane.

In order to test this idea we have generated also a set of events where instead of jets we have included anisotropies into the initial conditions only. The same amount of energy and momentum has been put within localised “hot spots” which were superimposed over the smooth energy density profile. We then measured the correlation function of the difference $\psi_2 - \psi_3$, which is plotted in Fig. 3. Unfortunately, due to high computational cost we have only 500 events simulated for each of the two models, therefore the error bars are rather large and better statistics would be needed for a conclusive answer. However, the data are compatible with the hypothesis that momentum deposition from jets into plasma and the merging of streams lead to correlated $\psi_2$ and $\psi_3$, while such correlation is absent with the flow anisotropies caused only by initial conditions.

4 Results for central collisions

Experimental data suggest that hadronic distributions show anisotropies in azimuthal angle even in ultra-central heavy-ion collisions. We investigated to what extent they can be generated by the mechanism proposed here. To this end, we simulated the evolution of fireballs which are created at vanishing impact parameter and let the jets lose energy and momentum there. The results are shown in Fig. 4.

It is also interesting to explore whether or not the effect of jets can be mimicked just by including the corresponding anisotropies into the initial profile of the energy density. In order to answer this question we have produced two additional sets of simulations. First, on top of the smooth energy density profile we superimposed places with increased energy density, so that the energy of one such “hot spot” is equal to the energy of a dijet that would originate there. The results, also shown in Fig. 4, are clear: this mechanism can account for not even 50% of the anisotropies which are due to jets. One might argue, however, that in this simple hot spot scenario no momentum anisotropies...
are initiated, whereas jets deposit also momentum into the fluid. Therefore, we have made another set of initial conditions where the hot spots included not only additional energy, but also momentum. The included momentum was equal to the total momentum that would have been deposited by the jet. Nevertheless, neither this set of initial conditions did reproduce the results from the simulations with jets. We conclude that momentum deposition during the evolution of the fireball cannot be mimicked by an augmented set of initial conditions [7].

5 Conclusions

Momentum deposition from hard partons represents an important contribution to flow asymmetry in ultrarelativistic nuclear collisions. That asymmetry is often being used for the measurement of transport properties of quark-gluon plasma. In such a measurement, results of hydrodynamic simulations which depend on transport coefficients, are compared to data and the coefficients are tuned in order to reach an agreement. It is important to include jets in such calculations, if reliable quantitative results on the viscosities are to be obtained.
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References

[1] B. Betz et al., Phys. Rev. C 79, 034902 (2009)
[2] P. Petreczky, P. Huovinen, Nucl. Phys. A 897, 26 (2010)
[3] J. P. Boris, D. L. Book, J. Comp. Phys. 11, 38 (1973); C. R. DeVore, J. Comput. Phys. 92, 142 (1991)
[4] B. Tomášik and P. Lévai, J. Phys. G 38, 095101 (2011)
[5] M. Chojnacki et al., Comput. Phys. Commun. 183, 746 (2012)
[6] M. Schulc, B. Tomášik, Phys. Rev. C 90, 064910 (2014)
[7] M. Schulc, B. Tomášik, J. Phys. G 43, 125106 (2016)