

# How do Jets Affect the Collective Flow of the Quark-Gluon Plasma?



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## Abstract

In this work we study how highly energetic jets affect the hydrodynamic evolution of the quark-gluon plasma on an event-by-event basis. This is done by introducing a source term into the energy-momentum conservation equations that describe the evolution of inviscid hydrodynamics. The source is parametrized in terms of the direction of the jet in the medium and its energy loss rate. The influence of jets on the QGP collective flow is systematically investigated using the Fourier coefficients of the azimuthal flow distribution computed at RHIC energies.

## I Motivation

The experimental data, for RHIC and LHC energies, show that the spectra of hadrons for nucleus-nucleus collisions, in the region where  $p_t > 5\text{GeV}$ , is strongly suppressed in comparison to the spectra observed in proton-proton collisions [1]. This is the so called jet quenching effect. Once the jets lose a considerable fraction of their energy-momentum in the medium, created, for instance, in Au+Au collisions, it would be interesting to study the influence of this extra flow on the spectra, particularly, on the Fourier components of the azimuthal distribution of particles. In this work, we suppose that the energy-momentum lost by the jet is instantly thermalized by the medium. In this case, the effects of jets, in a hydrodynamic model, can be included through a source term in the energy-momentum continuity equation [2]. In the next section, we show how the source term (the jet) is implemented. In Section III, we show the results and, finally, in Section IV, we present our conclusion and perspectives.

## II Formalism

The energy-momentum continuity equation, for an ideal fluid, is given by

$$D_\nu T^{\mu\nu} = J^\mu, \quad (1)$$

where

$$T^{\mu\nu} = \omega u^\mu u^\nu - p g^{\mu\nu} \quad (2)$$

is the energy-momentum tensor,  $\omega$  is the enthalpy,  $p$  is the pressure and  $g^{\mu\nu}$  is the metric tensor. The quantity  $J^\mu$  is an arbitrary 4-current density (the source).

For the sake of simplicity (see [2]), let us consider massless partons traveling transversely along the mid-rapidity transverse plane. In this case, the 4-current density  $J^\mu$ , which describes the energy loss of these partons in the medium, is light-like (massless particles have light-like 4-momentum). Thus, the trajectory of the  $n^{\text{th}}$ -parton can be parameterized in the following way

$$(\vec{r}_{jet})_n = (\vec{r}_0)_n + \lambda_n(\tau) \hat{q}_n, \quad (3)$$

where

$$\hat{q}_n = (q_x, q_y)_n \quad (4)$$

is the unity vector that indicates the parton direction along the transverse plane and  $\lambda_n(\tau)$  is a function of time. For light-like partons, one finds

$$\left| \frac{d}{d\tau} (\vec{r}_{jet})_n \right| = \frac{d\lambda_n}{d\tau} = 1. \quad (5)$$

In the situation described above, the 4-current density can be parameterized by

$$(J^\mu) = \sum_n \frac{dE_n}{d\tau} h(\vec{r} - (\vec{r}_{jet}(\tau))_n) f(\eta, \tau) (1, \hat{q}_n, 0) \quad (6)$$

where

$$\int h(\vec{r} - (\vec{r}_{jet}(\tau))_n) f(\eta, \tau) \sqrt{-g} dx dy d\eta = 1, \quad (7)$$

and  $dE_n/d\tau$  is the energy loss rate of the  $n^{\text{th}}$ -parton. Observe that

$$\frac{dE_n}{d\tau} = \frac{dE_n}{d\lambda_n} \frac{d\lambda_n}{d\tau} = \frac{dE_n}{d\lambda_n}. \quad (8)$$

Motivated by (8), the following parameterization seems to be quite reasonable

$$\frac{dE_n}{d\lambda_n} = \frac{s(\vec{r}_{jet})_n}{s_0} \frac{dE}{d\lambda} \Big|_0, \quad (9)$$

where the quantities  $s_0$  and  $dE/d\lambda|_0$  are the entropy density reference and the energy loss rate parameter.

In this work, for the sake of simplicity, we computed the hydrodynamic expansion in two dimensions, using, for the longitudinal direction, the boost invariance ansatz. In order to solve the transverse equations, we applied the so called smooth particles hydrodynamics approach [3], which is suitable tool to deal with irregular distributions of matter. From now on, we will replace the term light-like parton by jet. Thus, a di-jet configuration means two light-like partons traveling in opposite directions.

## III Results

The procedure to compute the observables on an event-by-event basis, including the jet parametrization, is the following: (i) the initial conditions are computed, in this work by using the Monte Carlo Glauber generator [4]; (ii) the initial position of the di-jet is randomly chosen (one di-jet per event), according to the hot spots positions (see Fig 1). Hot spots with high energy density have a greater probability of emitting a di-jet. Consequently, jets are mainly produced in the inner region; (iii) the hydrodynamic evolution is computed through the SPH method; (iv) the final spectra is computed by using the Cooper-Frye prescription [5]. In our model we have not implemented the decay of particles. All the results presented in this poster correspond to the direct pions.

We show in Fig. 1 the hydrodynamic evolution of the energy density distribution for a random event, at mid-rapidity, for Au+Au collisions at 200AGeV. The initial conditions were obtained by using the Monte Carlo Glauber generator. The yellow arrows (see the graph for  $\tau=1\text{fm}$ ) indicate the direction of the jets in this event. It is clearly seen that two Mach cones are formed, despite the fact that the fluctuation tends to deform the cones.

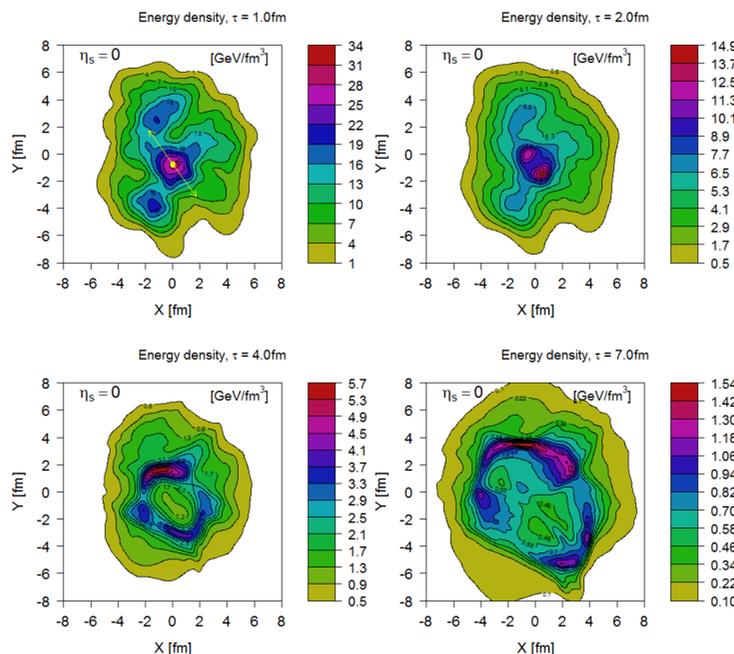


Fig. 1: Hydrodynamic evolution of the energy density distribution for a random event, at mid-rapidity, for Au+Au collisions at 200AGeV. The initial conditions were obtained by using the Monte Carlo Glauber generator. The yellow arrows (see the graph for  $\tau=1\text{fm}$ ) indicate the direction of the jets in this event ( $dE/d\lambda|_0 = 28\text{ GeV/fm}$ ).

In Fig. 2, we show the average energy deposited in the medium,  $\langle \Delta E \rangle$ , by the di-jet configuration, as a function of the energy loss rate  $dE/d\lambda|_0$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV. The percentages close to the symbols correspond to the fraction  $\langle \Delta E \rangle / \langle E \rangle$  where  $\langle E \rangle$  is average initial energy in this centrality window. An interesting result in this graph is that the fluctuation does not change  $\langle \Delta E \rangle$  significantly.

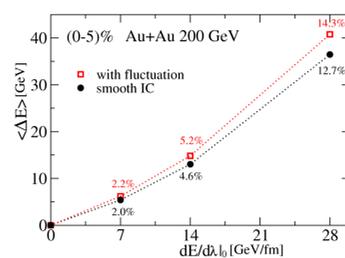


Fig. 2: Average energy deposited in the medium,  $\langle \Delta E \rangle$ , by the di-jet configuration, as a function of the energy loss rate  $dE/d\lambda|_0$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV. The closed circles correspond to the Glauber smooth IC (initial conditions) and the open squares to the fluctuating IC.

What do we expect to observe in the particle spectra if the jets deposit a considerable fraction of their energy-momentum in the medium, as showed in Fig. 2? First of all, considering that jets enhance the transverse velocity of the fluid, we expect an enhancement of the number of particles in the region of high  $p_t$ . Moreover, in central collisions, where the distribution of matter is symmetric, it is expected an enhancement of the elliptic flow, as a consequence of the preferred direction given by the di-jet configuration. In the case of non-central collisions, the analysis is more complicated, as a consequence of the asymmetry of the initial conditions. In this case, we expect a rotation of the event plane, with respect to the standard procedure (without jets).

We show in Fig. 3, the pion distribution as a function of  $p_t$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV. Two kinds of initial conditions are considered: smooth IC (left) and fluctuating IC (right). 30 events including jets are used. We see that the effect of the jet in the medium is to increase the high- $p_t$  component of the spectra as expected, making the curve more concave and following the trend of the data.

In Fig. 4, it is shown the Fourier harmonics  $v_2$ ,  $v_3$  and  $v_4$  of pions, as a function of  $p_t$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV. As expected, there is an enhancement, in the high- $p_t$  region, of the Fourier components when jets lose energy-momentum in the medium. This behavior is observed in both cases: smooth IC (left) and fluctuating IC (right).

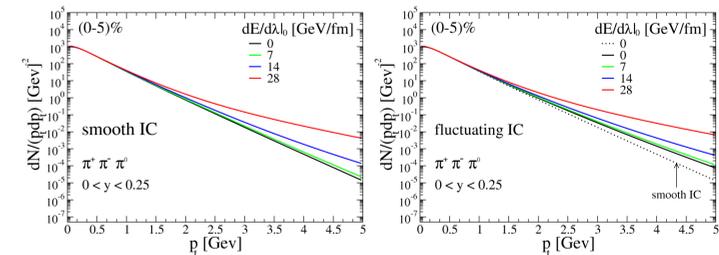


Fig. 3: Pion distribution as a function of  $p_t$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV. Two kinds of initial conditions are considered: smooth Glauber IC (left) and fluctuating Glauber IC (right).

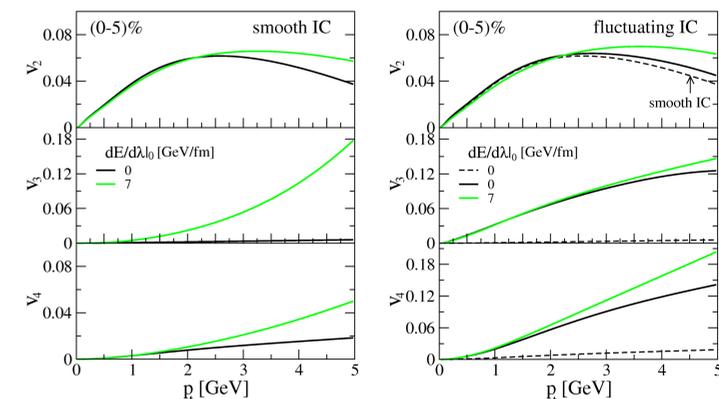


Fig. 4: Fourier harmonics  $v_2$ ,  $v_3$  and  $v_4$  of pions, as a function of  $p_t$ , in the (0-5)% centrality window, for Au+Au collisions at 200AGeV.

Finally, in Fig. 5, we show the elliptic flow parameter  $v_2$  as a function of  $p_t$ , in the (15-25)% centrality window, for Au+Au collisions at 200AGeV. The plots on the left correspond to two distinct di-jet configurations:  $\phi_{jet}=0^\circ$ , along the event plane, and  $\phi_{jet}=45^\circ$ . The configuration  $\phi_{jet}=90^\circ$ , perpendicular to the event plane, is shown in the plot on the right (top). It is interesting to see that the di-jet transverse to the event plane tends to diminish the elliptic flow and the di-jets along the event plane tend to enhance this parameter. On average, the result is an enhancement of  $v_2$  in the high- $p_t$  region, similar to the central case (see the right bottom plot). The changes in the elliptic flow observed in non-central collisions are connected with the rotation of the event plane caused by the jets.

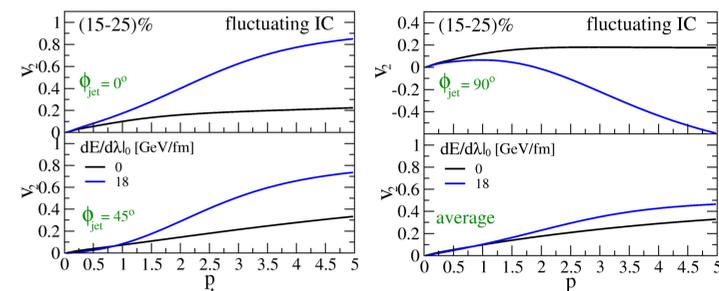


Fig. 5: Elliptic flow parameter  $v_2$  as a function of  $p_t$ , in the (15-25)% centrality window, for Au+Au collisions at 200AGeV. The plots on the left correspond to two distinct di-jet configurations:  $\phi_{jet}=0^\circ$ , along the event plane, and  $\phi_{jet}=45^\circ$ . The configuration  $\phi_{jet}=90^\circ$ , perpendicular to the event plane, is shown on the plot on the right (top). Finally, the plot on the right (bottom) shows the elliptic flow parameter averaged over a set of di-jet configurations.

## IV Conclusion and Perspectives

The effects of di-jets in the medium are strong enough to change the Fourier coefficients of the azimuthal distribution of particles, especially in the region of high- $p_t$ . In particular, it can change the angle of the event plane in non-central collisions. Moreover, the distribution of particles as a function of  $p_t$  is enhanced at high  $p_t$ , due to the effects of jets, in comparison to the standard case (without jets but using fluctuating IC).

The perspectives for this work include the study of the influence of mini-jets in the medium, which means to include more than one di-jet per event. In addition, it would be interesting to extend this study to LHC energies.

## References

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