Jet/Fireball Edge should be observable!

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Shock/sound propagation from the quenched jets have well-defined front, separating the fireball into regions which are and are not affected. While even for the most robust jet quenching observed this increases local temperature and flow of ambient matter by only few percent at most, strong radial flow increases the contrast between the two regions so that the difference should be well seen in particle spectra at some $p_t$, perhaps even on event-by-event basis. We further show that the effect comes mostly from certain ellipse-shaped 1-d curve, the intercept of three 3-d surfaces, the Mach cone history, the timelike and spacelike freezeout surfaces. We further suggest that this “edge” is already seen in an event released by ATLAS collaboration.

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I. INTRODUCTION OF THE IDEA

Observation of jets at RHIC are limited to the transverse energy in the range 20-30 GeV, which is quite difficult because of large and strongly fluctuating background. Therefore most of the studies has been based on the two and three-hadron correlation functions. Furthermore, for hadrons mostly studies their transverse momenta are in the range of several GeV, where contributions from hard jets and the tail of hydrodynamical flow is hard to separate uniquely. With the “Little Bang” arriving at LHC in November 2010, the situation has changed since at LHC much higher energy jets are available, for which triggering on jets works well. The first glimpse of what is to come has been spectacularly demonstrated by ATLAS collaboration in their first heavy ion paper [1] devoted to jet quenching. Now the trigger jets have the transverse energy $E_\perp > 100\, \text{GeV}$: excellent calorimeter of ATLAS make standard jet finding algorithms to work well. The distribution over lost energy were found to be very sensitive to centrality, and for central collisions significant part of jet energy is lost, in some events completely.

In the present paper we turn to discussion of perturbations of the “Little Bang” by the energy deposited by jets. As evidenced by the enhanced radial and elliptic flows [2], overall hydrodynamical picture seem to work at LHC as well as at RHIC. Once the energy is deposited into the medium by the jet, it will result in shock/sound perturbations in the shape of the Mach cone [3,4], similar e.g. to lightning and thunder. The present paper points out that very strong radial flow allows one to significantly simplify the problem, by focussing only the overlap of the Mach (lifeline) 3d surface with the time-like and the space-like freezeout surfaces.

The main idea to be presented is based on two very simple geometrical observations:

(i) whatever complicated distortions of the Mach cone in exploding matter may appear, the observed spectra come mostly from its intersection with the fireball space-time boundary known as a freezeout surface.

(ii) Furthermore, because of the Hubble-like nature of the radial flow, the effect is strongly peaked at the intersection of all three surfaces, the Mach surface $\sigma_M$, the timelike and spacelike freezeout surfaces, denoted by $\sigma_T, \sigma_s$ respectively.

Since each 3-d surface is one equation in 4-d space-time, the intersection of three of them are (two) 4-3=1-d lines, $\epsilon_C, \epsilon_T$, to be specified below. It is those lines
which we call the jet/ﬁreball edges: its size will also be estimated and compared with the data. Hydrodynamical causality would require that only a patch of matter inside it is affected by the jet, while that outside it is unperturbed. We will show below that the contrast between those two regions can be experimentally observable.

The geometry of the problem is schematically explained in Fig.1. Its upper part is a snapshot at some time and some longitudinal coordinate, taken to be zero \( z = 0 \), of the hydrodynamical perturbation in the transverse plane. In inﬁnite homogeneous matter two back-to-back jets depositing energy into the medium create two cones tangent to a sphere, shown by the continuous lines. The shock/sound speed is assumed to be roughly constant, about half of the speed of light. If matter is present only outside the ﬁreball, approximated by the (dashed) sphere, only the part inside it actually exists. The intersection of this sphere with the affected matter happens at 4 points, indicated as \( A, B \) for a companion jet \( C \) and \( A', B' \) for a trigger jet \( T \). The so called “trigger bias” leads to a trigger jet passing less matter than the companion jet: thus the picture is left-right asymmetric. (We assume central collisions and a jet with transverse companion jet: thus the picture is left-right asymmetric. The balance “bias” leads to a trigger jet passing less matter than the companion jet.)

The lower plot of Fig.1 shows this picture in 3d, still at the same \( z = 0 \) but now including the so called longitudinal proper time \( t = \sqrt{t_{lab}^2 - z^2} \), where \( t_{lab} \) is the laboratory time. This time runs upward, and the upper ellipse schematically represent the time-like part of the freezeout surface, \( \sigma_t \), approximated by the constant time surface, \( t = t_f \). The lower ellipse is the “initiation time surface”, and the conical surface connecting them is our approximation to the space-like part of the freezeout surface, \( \sigma_s \). Inside the region hydrodynamics is assumed to be valid, as usual, whole outside secondaries freestream to the detector. The points \( A, B, A', B' \) have the same meaning as in the upper plot, which can be seen as corresponding to its \( \sigma_s \) face. Since we only show the 3d picture (\( z = 0 \)) three surfaces we speak about are 2-dimensional, and their overlap is 3-3=0 dimensional, reduced to 4 points \( A, B, A', B' \).

For obvious reason we do not show 4-d plot, but this is not needed. Adding the longitudinal \( z \) direction is simple, it will promote the edge into two ellipses, one having points \( A, B \) on it and one having \( A', B' \). Those will be called the edges \( \epsilon_c, \epsilon_T \) of the companion and trigger jets, respectively. Since trigger-bias force the companion jet to deposit much larger amount of energy, the former one has much larger chance to become visible.

II. FURTHER DETAILS

The general expression for a spectrum is thermal spectrum boosted by the flow \( u^a \) and integrated over the 3d freezeout surface (the Cooper-Fry formula)

\[
\frac{dN}{dp} = \int_{\sigma_t,\sigma_s} d\Sigma_{\mu \nu} u^\mu \exp \left[ -\frac{p \cdot u^\nu}{T} \right]
\]

Let us ﬁrst quantify the second part of the idea (ii), that the intercept with both surfaces \( \sigma_t, \sigma_s \) is the most visible one. (We will only show it for \( \sigma_t \) part, similar argument holds for the \( \sigma_s \) part as well.)

Focusing on the exponent and using (for simplicity) nonrelativistic approximation for the ﬂow \( u_0 = \text{cosh} y_\perp \approx 1, u_r = \text{sinh} y_\perp \approx y_\perp \) and Hubble parameterization for the radial ﬂow near the surface of the ﬁreball as \( y_\perp(r, \tau) \approx H(R - \delta r) \) one can simplify the relevant exponential factor into

\[
\exp \left( -\frac{p_t H}{R} \frac{\delta r}{R} \right)
\]

The ﬁrst ratio, \( p_t / T \) should be taken as large as possible, remaining at the same time in the validity region of the hydrodynamical description of the spectra. Let us say take \( p_t / T = 2 \) GeV for RHIC and 3 GeV for LHC. The second factor \( RH \), the maximal value of the transverse rapidity of the ﬂow, is about 0.7 and 0.8, respectively. Let the freezeout temperature be \( T_f = 0.12 \) GeV. One ﬁnds \( \exp(-\delta r / R) \) for RHIC and even \( \exp(-20 \delta r / R) \) for LHC, which means that only a small vicinity of the rim \( \delta r / R = 0.1 - 0.05 \) is “experimentally visible”.

The Mach surface \( \sigma_M \) surrounds the matter which is affected by the jet. Let us provide a simple (upper limit) estimate of how different this matter is from the unperturbed ambient matter. Using mid-rapidity ALICE multiplicity \( dN_{ch} / d\eta \approx 1584 \) of the charged particles, we multiply it by 3/2 to include neutrals and get \( dN / d\eta \approx 2400 \). Since the rapidity width of the region affected by a jet has \( \Delta \eta \sim 1 \), this multiplicity can be directly compared with the “extra particles” originated from the jet. At deposited \( E_\perp \sim 100 \) GeV this number is about \( N_{\text{extra}} \sim 200 \), provided they are equilibrated with flowing medium completely, an increase of about 8%. Since multiplicity scales as \( T^3 \), the increase of the temperature (if homogeneous) is about \( \delta T / T \sim 2.7\% \) only, which does not look like much. And yet, this effect is so much ampliﬁed by the radial ﬂow that it should be easily observable, in a specially tuned region of the spectra.

At the freezeout the matter density is roughly constant (e.g. twice larger multiplicity at LHC relative to RHIC leads to twice large HBT volume, as shown by ALICE [14]). So, \( N_{\text{extra}} \) particles need about 8% of extra volume. Assuming that longitudinal expansion is still rapidity-independent, it means increasing the transverse area, or increasing the freezeout radius by the square root of it, or 4% in our example. The Hubble law of expansion then tell us that it will increase ﬂow velocity linearly with \( r \), or also by 4%. The boost exponent however can easily increase the contrast to be as large as 100%, for example

\[
\exp\left( \frac{p_t u_{\perp}}{T_f} \frac{\delta r}{u_t} \right) \sim \exp(20 * 0.04) \sim 2.2
\]
(using the same parameters as in the example above).

So far our discussion is completely geometrical in nature: all we have used above is that jets move with a speed of light and shock/sound with a speed $c_s$ (although depending on the density/temperature, but the same for all events in the same centrality bin). Note that neither jet energy nor its fraction deposited are important. The difference between RHIC and LHC collisions only come from a somewhat different multiplicity and timing.

So far, we have ignored many complications. The speed of the shock/sound is not in fact constant and depend on the amplitude a bit and also has a dip near the QCD phase transition: this should somewhat deform the Mach cone. Another issue (see below) is the interaction between the wave and the flow.

So far we have ignored the dynamics of jet quenching itself, on which the magnitude of the observed signal depends. Let us thus briefly mention the evolution of current views on the quenching mechanism. The very first measurements at RHIC have provided the magnitude of the attenuation of the hadron spectra, known as the $R_{AA}(p_t)$. Although the magnitude of suppression is quite large, up to factor 5, perturbative models were able to reproduced it. However next RHIC discoveries put pQCD explanations into doubt. Single leptons, originating from $c, b$ quark decays, show equally small $R_{AA}^b$, which is hard to explain perturbatively. Another issue, pointed out in \[5\], is large angular asymmetry of the jet quenching incompatible with models for which $-dE/dx$ is proportional to the matter density. The value of $v_2(p_t > 6\, GeV) = < \cos(2\phi) >$ is wrong by a factor 2. (Note high $p_t$: it should not be confused with the elliptic flow!) One possible solution \[5\] to this puzzle is a nontrivial dependence of quenching rate on matter density, with enhancement in the near-$T_c$ region. Another solution came from the strong coupling (AdS/CFT) framework, which predicts the energy loss \[9\]

$$\frac{dE}{dx} \sim T^4 x^2,$$

with an extra peak at the very end near the stopping point. While this result may look similar to the perturbative BDMC result \[1\] $\frac{dE}{dx} \sim T^3 x$, the timing predicted by those two regimes are in fact completely different. Strong coupling scenario \[2, 3\] effectively shifts most of the jet quenching to its latest moments, and therefore $v_2$ in the denominator of the second term, which leads to analytic solution $Z_s = e_s t f \sin(t f / R)$ which by the time of final freezeout is greater than $H_s$ by about factor $Z_s / H_s \approx 1.4$. The shape of the jet edge is thus approximately an ellipse with the ratio of radii $Z_s / H_s$.

What happens if the jet stops inside the fireball? The upper plot in Fig.1 gets modified, the cone gets “rounded” by a sphere centered at the stopping point. Its intersection with the two other freezeout surfaces can still be defined, as above.

Crude estimate of the azimuthal angle of the edge is given by $\Delta \phi = \pm \frac{H_s}{R}$, the distance shock/sound travel
after the jet left the fireball to the final fireball radius. It is of the order of one radian numerically: but specific values depend both on the length of the jet path inside the matter and on the wave speed. The shock speed for QGP-to-QGP case we worked out for different compression factors: there is no place here to present this calculation, and we just say that in the range of compression factors of interest shock rapidity remains close to 1/2.

IV. EXPERIMENTAL SIGNATURES

As argued above, each jet which deposit certain amount of energy into hydrodynamical process effectively heats up matter insider the Mach surface, which results in extra radial flow in certain angular sector. We have argued that one should look at $p_t = 2 - 3$ GeV, a window where hydrodynamical effects are still dominant and the “contrast” is the largest. We expect to find sharp jump between the inside of this sector and the outside. Furthermore, there should be extra peaks near the edge itself, corresponding to the “frozen sound pulse”. In principle, this should happen both for companion and trigger jets, although with larger magnitude in the former case.

This statement is of course statistical, and should be studied for a sample of events with close energy deposition. However, the predicted contrast is large enough to be perhaps seen in single events. One event display shown in ATLAS paper is reproduced in our Fig. 2: note that tracks $p_t$ and calorimeter energy cuts are in the range we propose. Indeed, tracks and calorimeter energy distributions are very peculiar. First of all, they are wide and not jet-like, as has been observed in pp collisions. Second, the distributions are not Gaussian-like but flat, with clear sharp edges beyond which there is no signal. We suggest that this is the manifestation of the “edge” phenomenon discussed. Last but not least, there are symmetrically placed small peaks near both edges: those presumably are due to “frozen sound waves”. If one accounts for longitudinal (first order velocity) $\delta u$ in exponent of (2.1), their azimuthal angle is slightly larger than that of the geometric edge discussed above. Although this display shows only one event, being projected onto the azimuthal angle, in fact the edge and near-edge enhancement should make an ellipse in the $\phi, \eta$ plan, as we discussed above.

In summary, we suggest that events in which large energy is deposited by jets should develop sharp “edges” in angular distribution of particles, best seen for $p_t = 2 - 3$ GeV, which are of geometric nature and thus nearly independent on the jet energy. We expect them to become a new experimental tool, as they should be noticeable even on event-by-event basis.

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