Azimuthal asymmetry at large p_t seem to be too large for a pure "jet quenching"

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We discuss a simple generic model of "jet quenching" in which matter absorption is defined by one parameter. We show that as absorption grows, the azimuthal asymmetry parameter v_2 grows as well, reaching the finite limit v_2^* which has a simple geometric interpretation. We show that this limit is still below the experimental values for $6>p_t>2$ GeV, according to preliminary data from the STAR experiment at RHIC. We thus conclude that jet quenching models alone cannot account for the observed phenomenon, and speculate about alternative scenarios.

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Azimuthal asymmetry for noncentral heavy ion collisions has been predicted [1] to be larger at RHIC then at lower energies. In hydrodynamic models this happens due to the stronger push by the high pressure of the Quark-gluon plasma (QGP) well above the phase transition region, which is expected to be produced at RHIC. In contrast to that, models based on string picture of hadron production (e.g., RQMD and UrQMD event generators) or on mini-jet scenarios (e.g., HIJING) have predicted its decrease. The issue has been settled already by the first data from RHIC, by the STAR collaboration [2], who have found large asymmetry consistent with hydrodynamic predictions. Detailed studies [3,4] have provided significant details, such as the asymmetry parameter

$$v_2=\langle\cos(2\phi)\rangle \tag{1}$$

(where ϕ is the angle between the impact parameter and momentum of a secondary hadron in the transverse plane) as a function of centrality, particle type and its p_t. Data from the STAR and PHENIX experiments for a rather wide range of momenta $p_t<2$ GeV agree well with these predictions for all secondaries. This is probably the most direct signature of QGP plasma formation observed at RHIC.

In this paper we, however, discuss a different question, related to (much less certain experimentally) such asymmetry at higher transverse momenta $6>p_t>2$ GeV. According to the latest STAR data [5] (which are still unpublished and are thus considered preliminary, although reported at many meetings), $v_2(p_t)$ for all charged secondaries seem to be about constant for each centrality. This means a different regime seems to be established in this region of p_t, and the original intention of this paper was to compare these data with a simple geometric model for jet quenching by relating the asymmetry to the strength of the jet quenching itself. However, after playing with different versions of the model, from more complex to a most generic one to be reported in this paper, I concluded that the intended fit is simply impossible.

A jet quenching idea has been discussed for a long time, see, e.g., Ref. [6], and it has been naturally related to the azimuthal asymmetry for noncentral collisions. If a high-p_t jet is loosing energy in matter, jet emission is dominated by the surface of the almond and the correlation between the position and the emission direction appears, thus the observed azimuthal asymmetry.

A relation between this phenomenon and data has been discussed in Ref. [7], where it was concluded that a combination of jet quenching and hydrodynamical expansion can approximately describe them.[1] Later STAR data have shown at high $p_t=2$–6, an approximately p_t-independent v_2, which disagree with a decreasing trend expected from jet quenching. Qualitative discussion of many possible scenarios that can have such a behavior has been made in Ref. [8], including the interplay of jet quenching, hydrodynamical expansion, and "baryon junction dynamics." We return to this discussion at the end of the paper.

The present work ignores such details as the p_t dependence of v_2 and focuses instead on its measured values: we demonstrate that by looking at the pure geometric aspect of the problem one can show that those are too high for *any* jet quenching model (without hydro).

The most generic model we use can be described as follows. First, the distribution of originating points for outgoing jets is simulated: this is done using the usual assumption of parton model and the simplest model of nuclei as two homogeneous colliding spheres. (Diffuse boundary only makes effects smaller.)

The second step is the calculation of the chances for the parton to escape the absorption in matter, as it goes out of the almond. The absorption rate is characterized by one (and the only) free parameter of the model. Its magnitude determines the strength of jet quenching itself [the fraction of escaping partons $f(p_t,b)$], with the predicted azimuthal asymmetry, $v_2(b)$.

As high-p_t partons move with the speed of light, we ignore a possible change of shape due to a geometrical expansion of the "almond" during this time. (If anything, this will reduce the asymmetry, as expansion reduces spatial asymmetry.)

Naturally, in the absence of an absorption there is no azimuthal asymmetry, $v_2(\kappa=0)=0$, while increasing absorp-

[1]Although no curves for jet quenching alone are shown, the text implies that it is indeed insufficient by itself, in agreement with the (more general) argument we will give below.

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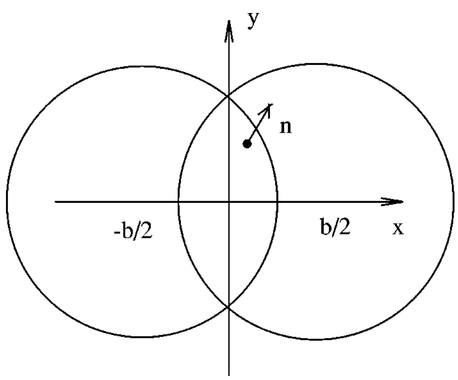

FIG. 1. A frontal view of two colliding nuclei, with definition of the axis. The black dot (x,y) inside the almond is the origin of the parton, which propagates in the direction of the unit vector $\vec{n}$.

tion leads to increasing v_2. Interestingly, in the limit of very strong absorption the asymmetry reaches a finite limit, denoted by asterisk below,

$$v_2(b,\kappa\to\infty)\to v_2^*(b). \tag{2}$$

The reason for this is that in this case all the emitted partons/hadrons originate from the thin surface of the almond (see below). Even in this case, however, partons have half solid angle open for them: thus $v_2^*(b)$ has a direct geometric interpretation. The main result of this paper is that, after evaluating $v_2(b)$ values for the experimental conditions and comparing them with data, we have found that even the limiting ones, $v_2^*(b)$, are below the data.

Let us now provide more details about the model itself. In Fig. 1 we show the geometry of the collision and the definition of two longitudinal lengths $L_\pm(x,y)$ for a hard collision at point (x,y). For hard spheres

$$L_\pm(x,y)=2[R^2-y^2-(x\pm b/2)^2]^{1/2}. \tag{3}$$

The probability of production of a parton in hard collisions at position x,y is simply proportional to the product of longitudinal lengths $P(x,y)=\alpha L_+(x,y)L_-(x,y)$. Vanishing of each of these factors defines the boundary of the initial almond in the transverse plane. Figure 1 shows the sketch of the initial distribution in transverse, x-y, plane. One characterizes it by the standard spatial anisotropy

$$s_2(b)=\langle y^2-x^2\rangle/\langle y^2+x^2\rangle, \tag{4}$$

where the angular brackets indicate average over all outgoing jets, with the weight given by the parton model as described above. The distribution depends on impact parameter b, indicated in the left-hand side. In Table I below we will make integration over b with geometric weight $2\pi b db$ over bins of centrality, within limits defined by upper and lower percentages of the total cross section.

The probability to escape depends not only on the point of jet origin but also on the optical depth of matter along the outgoing line $(x+sn_x,y+sn_y)$, which we calculate as follows:

TABLE I. The limiting momentum/spatial asymmetry for three different centrality selections of STAR collaboration, given as v_2 versus the percentage of total AuAu cross section. The quantity $\langle f\rangle$ is the escape probability (5) averaged over produced jets in the collisions, with all directions and origin points.

Centrality %	$\langle f\rangle$	v_2^*/s_2	v_2^*	v_2^{STAR}
0–11	0.018	0.32	0.042	0.12±0.02
11–34	0.027	0.35	0.12	0.16±0.02
34–85	0.046	0.31	0.16	0.22±0.02

$$f=\exp\left[-\kappa\int_0^\infty ds(L_-L_+)(x+sn_x,y+sn_y)\right]. \tag{5}$$

The parameter κ (dimension fm^{-3}) includes both the density of the material and the absorption rate. Figure 2 shows how the efficiency of the parton quenching and the v_2 parameter depend on it in the whole dynamical range. The dependence of jet quenching and v_2 on the absorption strength is shown in Fig. 2(b). It displays the saturation of v_2 as well as the tendency toward the surface emission at large absorption, mentioned in the beginning.

The main outcome of simulations is summarized in Table I, in which we compare the high absorption limit v_2 calculated from the model with STAR preliminary data[2] [5] at $p_t>3.5$ GeV. As one can easily see, even in the high absorption limit the model fails to reproduce data, being systematically below the present preliminary data. The difference is especially striking for the most central bin, in which the observed v_2 nearly matches the asymmetry s_2 of the original almond.

(Although the result is described as that in the high absorption limit, it actually corresponds to the calculation in which absorption was large but finite, $\kappa=0.2$ fm^{-3}, with the actual quenching factors f also given in the table.)

Let us now summarize the main result of this paper. The dynamical range of "jet quenching" scenarios is approximately confined in the region

$$0<v_2^*/s_2<1/3, \tag{6}$$

while the preliminary STAR data give larger values $v_2/s_2=0.5$–1 and therefore these cannot be explained by models of this kind alone, irraspective of the magnitude of jet quenching used. The generic model used can, of course, be modified in many ways, but it seems unlikely that jet quenching by matter absorption in whatever form is able to explain these data by itself.

Assuming these preliminary STAR data are correct, let us consider what their explanation can be. The main shortcom-

[2]The error bars are calculated by the author, based on three STAR points at the largest p_t bins, for each centrality. As at this point the data still have preliminary status, the reader should be warned that the error bars may be modified and the systematic errors be better understood and included. Now it is not possible to quantify the problem we discuss any better.

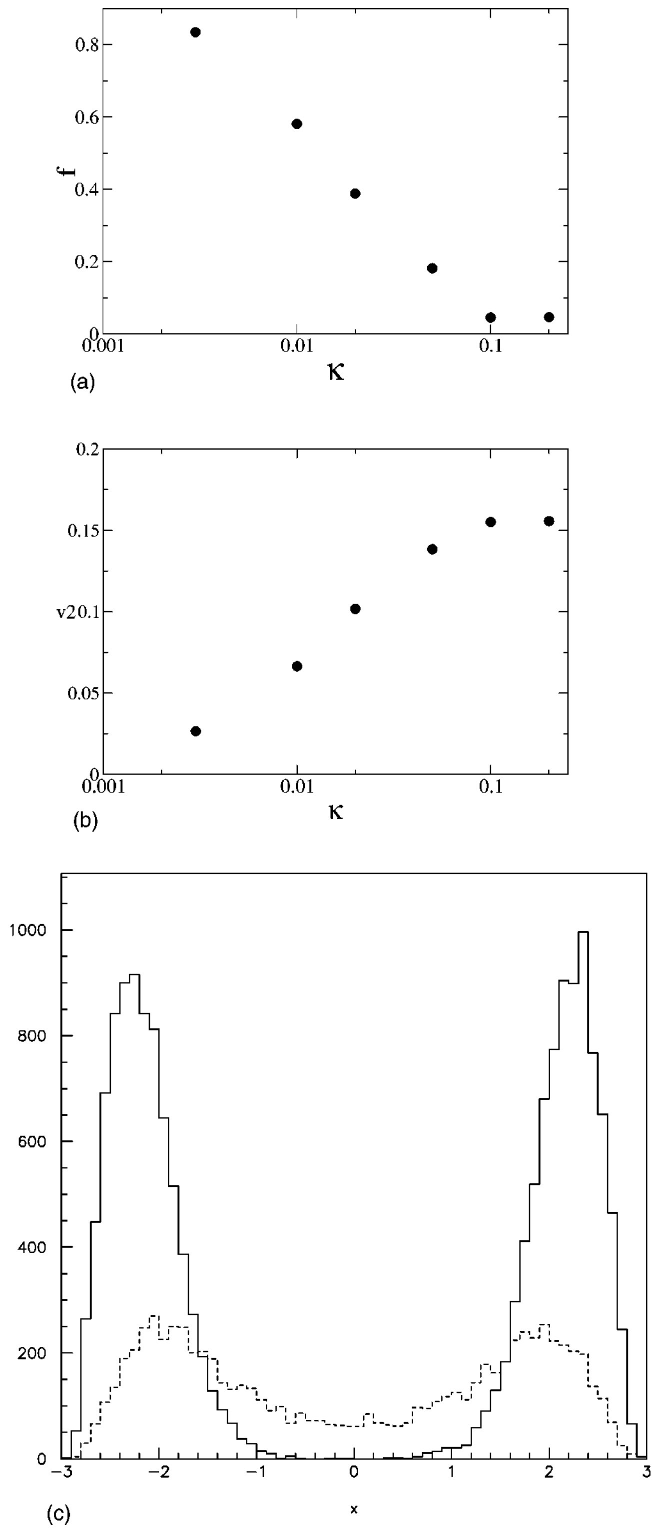

FIG. 2. Dependence of (a) the strength of jet quenching, the fraction of escaping partons $f(\kappa)$ and (b) the corresponding asymmetry parameter $v_2(\kappa)$ on the absorption strength parameter κ, in units of fm^{-3}. Figure (c) shows the (unnormalized) distribution over initial position x of the escaped partons, for the cut $|y| < 2$ fm. The solid and dashed lines are for $\kappa = 0.2$ and 0.05 fm^{-3}, respectively. All three figures correspond to the most peripheral centrality bin, 34%–81%.

ing of the model comes from the idea that secondaries in this region of p_t originate *only* from jets, obtaining azimuthal asymmetry *only* from geometrical asymmetry of the almond. The interplay between jet quenching and hydro expansion, quantitatively discussed in Ref. [8], only reduces the effect due to the reduction of geometrical asymmetry with time.

The resolution of this puzzle can only be obtained if a significant fraction of secondaries originate from a source other than jets. A general discussion in Ref. [8] has mentioned a possibility that v_2 for baryons and pions can be very different, with the former getting a contribution from *baryon junctions* and/or *collective flow*, as the sources complementary to jets. We also believe that it is likely to be the explanation, although we are quite sceptical about the role of the baryon junctions.[3]

Collective hydro expansion is not just a simple and general concept, it is basically the only known mechanism capable of generating very large values of the azimuthal anisotropy. (Let us remind the reader why is it so. Due to different hydro motion in different directions, spectra have the ϕ-dependent p_t slopes, resulting in asymmetry, v_2, linearly increasing with p_t.) However, the issue is far from being simple, and a significant role of hydro component in the high-p_t tails of spectra, at $p_t \sim 4$–6 GeV, is a very nontrivial thing. These tails of the particle spectra are six orders of magnitude below the majority of the particles, way below where a macroscopic language is routinely used. More work is needed in order to understand whether such approaches can at all be used in this region. In connection with that, let me mention a very interesting paper by Molnar and Gyulassy [9] in which v_2 has been generated kinetically in some model with very large cross section, way above perturbative predictions. Although it is far from being clear that the extreme assumptions made in these calculations are realistic, it has been able to yield a collective flow and sufficient values of the v_2.

Experimentally it is quite obvious what one should do: as soon as statistics will allow, one needs to study v_2 at such p_t for *any identified secondaries*. Particles that are seen via decays, e.g., Λ and K_s and especially ϕ can be identified at rather high momenta and are thus most interesting. Since jets decay into pions much more than into strange mesons such as ϕ and especially into baryons, one should expect the corresponding fractions of jet-originated and hydro-originated secondaries to be very different for all of them. The observed constancy of v_2 with p_t for all charge secondaries is likely to be just a result of occasional cancellation between rising hydro-based and decreasing jet-based components.

Note added in proof. After the paper was submitted to Phys. Rev. C, STAR data used have passed necessary procedures and are no longer preliminary. The final data have been submitted to Phys. Rev. Lett. for publication [10]. Systematic

[3]Recent STAR data on spectra of ϕ mesons have provided one more argument against it. These data show that ϕ has p_t slopes consistent with hydro predictions [4] with the slope not very different from the nucleon's: so it is the mass, not the baryon, that which matters here.

effects due to two-body correlations have been studied by comparison between two-particle and four-particle cumulants. When the latter values for v_2 are used, the discrepancy with the maximal model values at strong jet quenching v_2^* nearly disappears. Another significant fact reported in this STAR publication is the first direct observation of jet component in the two-body correlations. More recent STAR data at 200 GeV/*N* have been presented at the recent Quark Matter 2002 conference. Due to much higher statistics, those extend to larger $p_t = 6-12$ GeV, but display about the same v_2. Good agreement between the measured values of v_2 and the theoretical high quenching limit v_2^* has been shown in the summary talk there by S. A. Voloshin: it seems to suggest that geometrical interpretation of azymuthal asymmetry suggested in this paper seem to be correct, after all.

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