Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

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We study dependence of jet quenching on matter density, using "tomography" of the fireball provided by RHIC data on azimuthal anisotropy v_2 of high p_t hadron yield at different centralities. Slicing the fireball into shells with constant (entropy) density, we derive a "layer-wise geometrical limit" $v_2^{\max}$ which is indeed above the data $v_2 < v_2^{\max}$. Interestingly, the limit is reached only if quenching is dominated by shells with the entropy density exactly in the near-T_c region. We show two models that simultaneously describe the high p_t v_2 and $R_{A\text{-}A}$ data and conclude that such a description can be achieved only if the jet quenching is few times stronger in the near-T_c region relative to QGP at $T > T_c$. One possible reason for such enhancement may be recent indications that the near-T_c region is a magnetic plasma of relatively light color-magnetic monopoles.

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Introduction.—Recent experiments at the Relativistic Heavy Ion Collider (RHIC) are dedicated to study possible new forms of QCD matter, with increasing energy density. In such collisions the produced matter equilibrates as quark-gluon plasma (QGP)[1] and then cools down through the near-T_c (M) phase (M for mixed, median, magnetic [2]) into the usual hadronic phase (H). To probe the created matter in an externally controllable way, like using x ray for medical diagnosis is impossible. However, high energy jets are internal probes: propagating through the fireball, they interact—and thus obtain important information about the medium—as proposed long ago in Refs. [3–5]. In heavy ion collisions this energy loss can be manifested in the suppression of observed hadron spectra at high transverse momenta p_t, as well as in the suppression of back-to-back di-hadron correlations with a high-p_t trigger, when compared with p-p and d-A collisions. The "jet quenching" phenomenon is one of the major discoveries by the RHIC experimental program [6].

The suppression is quantified by comparison of the inclusive spectra $d^2N^{A\text{-}A}/dp_td\eta$ in ion-ion (A-A) collision to a nucleon-nucleon (p-p) reference $d^2\sigma^{N\text{-}N}/dp_td\eta$ via the Nuclear Modification Factor $R_{A\text{-}A}(p_t)$:

$$R_{A\text{-}A}(p_t) \equiv \frac{d^2N^{A\text{-}A}/dp_td\eta}{T_{A\text{-}A}d^2\sigma^{N\text{-}N}/dp_td\eta} \qquad (1)$$

with $T_{A\text{-}A}$ the nuclear overlap function which scales up a single N-N cross section to A-A according to the expected number of binary N-N collisions *without* modification. Thus a $R_{A\text{-}A}$ smaller (larger) than unity means suppression (enhancement) due to medium effect. At RHIC this ratio at large $p_t > 6$ GeV has been measured to be a constant, about 0.2 for the most central Au-Au collisions. Accurate calibration of hard processes in p-p and d-Au collisions, as well as with hard photon measurements (which show no quenching) [6] resulted in quite accurate knowledge of jet production geometry, for any impact parameter b (or centrality bins, often characterized by the number of nucleon participants N_{part} in a collision event). While quenching is firmly established as a final state effect, many efforts to understand its microscopic mechanism are not yet conclusive. Those include pQCD gluon radiation with Landau-Pomeranchuk-Migdal (LPM) effect [7], synchrotronlike radiation on coherent fields [8,9], elastic scattering loss [10], etc. The fate of deposited energy discussed in Refs. [11,12] led to predictions of "conical flow" correlated with experimentally observed conical structures in correlations involving 2 or 3 particles, for reviews see e.g., [13,14].

Jet tomography and the geometric limit.—In noncentral collisions the overlap region of two colliding nuclei has an almondlike shape: thus jets penetrating the fireball in different directions lose different amount of energy according to their varying paths. Their yield distribution $d^2N/dp_td\phi$ in azimuthal angle ϕ (with respect to the reaction plane) for high p_t hadrons thus provides a "tomography" of the fireball [15–17]. We will focus on the second Fourier coefficient

$$v_2(p_t, b) \equiv \frac{\int_0^{2\pi} d\phi \cos(2\phi)[d^2N/dp_td\phi]}{\int_0^{2\pi} d\phi[d^2N/dp_td\phi]} \qquad (2)$$

depending on impact parameter b for large $p_t > 6$ GeV where hard processes dominate and dependence on p_t is weak [18].

Unexpectedly, measured $v_2(p_t, b)$ happen to be considerably larger than what jet quenching models predicted. The aim of our work is to provide simultaneous description of both $R_{A\text{-}A}$ and v_2 at high p_t based on theoretically known geometry of jet production and bulk matter evolution. One important concept of the analysis is the so-called *geometric limit*, first suggested by one of us in [17]: the observed asymmetry should be less than some value $v_2(\text{large}\, p_t, b) < v_2^{\max}(b)$ provided by the geometry of the overlap region of two colliding nuclei. The idea [17] was that for very strong quenching only jets emitted from the surface of the almond can be observed. Two other assumptions were made, namely: (i) quenching is proportional to matter density; (ii) colliding nuclei were approximated by homogeneous sharp-edge spheres. However, even early experimental data showed that v_2 is actually well *above* this bound. Subsequent studies by Drees, *et al.* [19] relaxed the second assumption, with realistic nuclear shapes, which only made contradiction with data even stronger (see, e.g., their Fig. 3d).

The main lesson from those studies is that quenching is *not* proportional to the matter density, but a nontrivial function of it. Assuming some form of this function, one can then calculate both observables $v_2(b)$ and $R_{A\text{-}A}$.

Layer-wise geometrical limit.—Systematically slicing the (expanding) fireball into shells with the entropy density $s_a < s \le s_b$, we calculate what $R_{A\text{-}A}(b)$ and $v_2(b)$ would result with such a single shell being the sole source of quenching by a Glauber simulation of Au-Au collisions and jet production as in [17,19]. With the quenching function $\kappa(s)$ assumed to be concentrated at this slice $\kappa_{ab}\theta(s - s_a)\theta(s_b - s)$, the distribution in survival probability f can be calculated and directly leads to evaluation of $R_{A\text{-}A}$:

$$f = e^{-\int_{\text{path}} \kappa[s(l)]\, s(l)\, l\, dl}, \qquad R_{A\text{-}A} = \langle f^{n-2} \rangle, \qquad n \approx 8.10. \tag{3}$$

The extra l in the path corresponds to radiative LPM theory [7]. The power index n comes from the π_0 p_t spectrum in p-p collisions, see detailed discussions in [18]. For each density shell the absorption coefficient κ_{ab} (in unit fm) is then fixed by $R_{A\text{-}A}$ data [18] parameterized by $R_{A\text{-}A}(p_T > 5\ \text{GeV}) = [1 - 8.3 \times 10^{-3} N_{\text{part}}^{0.58}]^{n-2}$. Then we calculate v_2, by sampling half of the jets travelling in x directions $\pm 5°$ and the other half in y direction and extracting the difference in the respective $R_{A\text{-}A}^{x(y)}$ [18]. For the Glauber initial condition we follow hydro calculations (see e.g., [20]) to scale entropy density with local participant density, and for bulk evolution we use 1D Bjorken dilution which is appropriate till time $\sim$10 fm/c (see e.g., [21]). Jet production points are simulated according to binary collision density. We have 24 entropy shells, (0,1],(1,2],...,(23,24] (in/fm^{-3} units).

The resulting v_2 for three impact parameters $b = 5$, 7, 10 fm (bottom-to-top) are shown in Fig. 1(a). (i) Note that certain entropy shells produce v_2 much larger than the old geometric limits of Refs. [17,19], corresponding to surface emission (small s at the left side of the plot). (ii) The existence of the maximum $v_2^{\max}(b)$ leads to *layer-wise geometrical limit*: its dependence on centrality is shown in Fig. 1(b) by filled big blue diamonds. (iii) Interestingly enough, the entropy shells where the maxima occur (for all centralities) correspond to the same interval $s =$ 4–8 fm^{-3}, which is in fact quite special: it corresponds *exactly* to the vicinity of the QCD phase transition (see e.g., [22]). These curves reflect not only the geometry of the respective entropy shells, but also their placement relative to the jet production points.

After these studies of single shells, we turn to the compiled high-p_t RHIC data on $v_2(b)$, shown in Fig. 1(b). We include only data for "hard" hadrons with $p_t > 6$ GeV from PHENIX (open green boxes) and STAR (open magenta stars) collaborations. Comparing these data points to our *layer-wise geometric limit* (filled big blue diamonds), we do observe that all the data points are (within error bars) indeed below this proposed bound. We also show $v_2(b)$ lines which would come out if all jet quenching would be due to two other single entropy shells, with

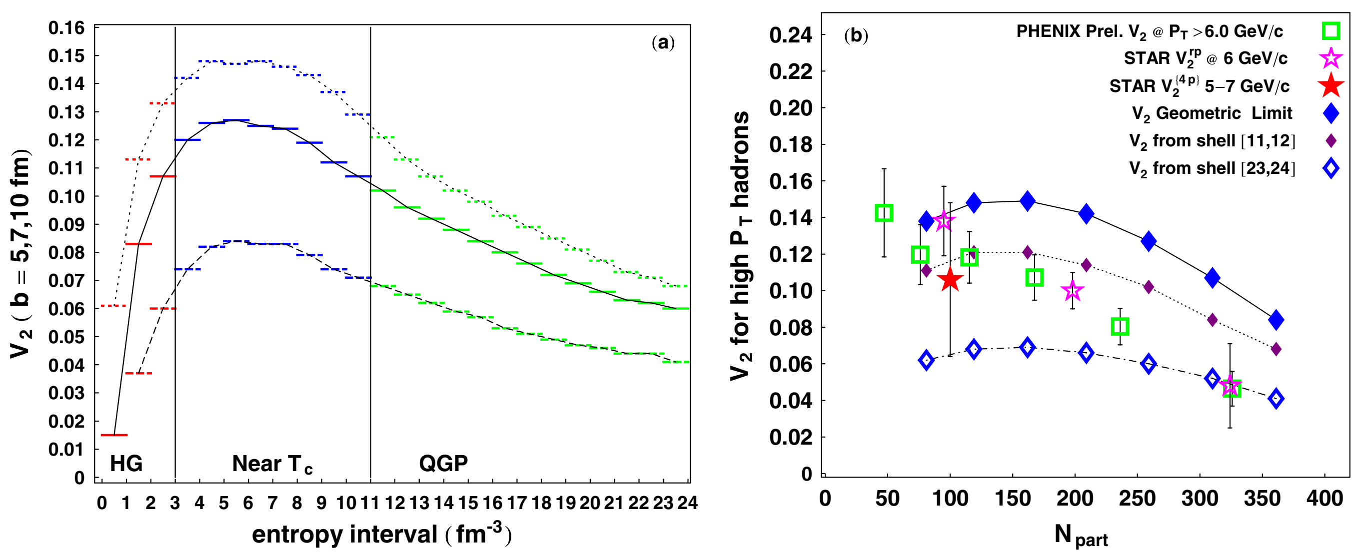

FIG. 1 (color online). (a) The v_2 obtained for each entropy shell at $b = 5$ fm (dashed line), 7 fm (solid line), and 10 fm (dotted line); (b) $v_2^{\max}$ for high p_T hadrons calculated at different N_{part} as compared with available RHIC data from [18,29,30].

$s = (11, 12]$ fm^{-3} (filled small purple diamonds) and $s = (23, 24]$ fm^{-3} (open blue diamonds). Those correspond to the QGP phase, near and far from the transition region: the values of $v_2(b)$ from those shells are significantly smaller than the maximal. Now we qualitatively understand the experimental trend: going from the more central to the more peripheral collisions, quenching geometry shifts from quenching at high density shells (QGP), to the near-T_c region at $N_p \sim 100$ (approaching the upper limit). For extremely peripheral collisions we expect v_2 to decrease again, reflecting geometry of the low entropy density shells (the hadronic phase).

Modelling tomography of jet quenching.—We now turn from individual shells to realistic models, describing the combined effect of all of them.

Model A.—A two-phase scenario model, in which we assume the quenching function $\kappa(s)$ with two parameters: one in the near-T_c region and the other for the QGP phase, i.e.,

$$\kappa(s) = \kappa_R[1\theta(s - s_1^c)\theta(s_2^c - s) + \lambda\theta(s - s_2^c)], \quad (4)$$

with $s_1^c = 3/\text{fm}^{-3}$ and $s_2^c = 11/\text{fm}^{-3}$ bracketing the near-T_c region. The parameter κ_R is globally fitted from $R_{A\text{-}A}(N_{\text{part}})$ (for each given λ), while λ characterizes the relative quenching strength between the near-T_c region and the QGP, with its best value to be determined from a global fitting for $v_2(N_{\text{part}})$.

Model B.—A scenario featuring peaked quenching strength at T_c, which assumes

$$\kappa(s) = \kappa_R[e^{-(s-s_c/s_w^c)^2}\theta(s - s_1^c) + \xi\theta(s - s_1^c)] \quad (5)$$

with $s^c = 7/\text{fm}^{-3}$ and $s_w^c = 2/\text{fm}^{-3}$ spanning the near-T_c region according to lattice results [22].

Schematic sketches of the two models' κ are shown in Fig. 2 (left) and χ^2/(degrees of freedom) from fitting the v_2 data (both the PHENIX and the STAR points), with a variety of choices of λ (model A)/ξ (model B), are shown in Fig. 2 (right). The plots suggest that current v_2 data favors the relative quenching strength $\lambda = 0.4$ for model A and $\xi = 0.2$ for model B, both favoring a scenario that in relativistic heavy ion collisions the jets are quenched about 2–5 times stronger in the near-T_c region than the higher-T QGP phase.

We also plot in Fig. 3 the $v_2(N_{\text{part}})$ obtained with the above optimal parameters: model A with $\kappa_R = 0.00435$ fm and $\lambda = 0.4$, model B with $\kappa_R = 0.00745$ fm and $\xi = 0.2$. Both of them describe current data very well and predict rapid dropping of v_2 at the very peripheral end $N_p \ll 100$.

Conclusions and discussion.—We started with the calculation of the "layer-wise geometric limit" for models describing jet quenching

$$v_2(b) < v_2^{\max}(b) \quad (6)$$

where the r.h.s. is shown by the filled big blue diamonds in Fig. 1(b) and corresponds to particular density shells. Unlike previously proposed bounds, this one is indeed

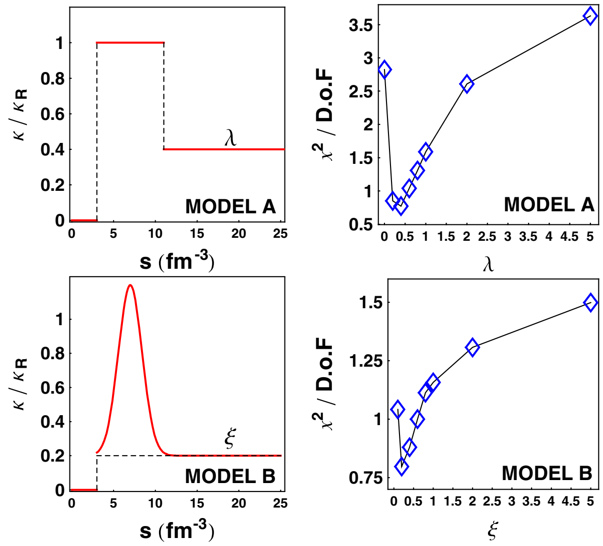

FIG. 2 (color online). (left) Schematic demonstration of the quenching functions of our model A and model B; (right) The χ^2/(degrees of freedom) when fitting the v_2 data with different values of parameters λ (ξ) in our model A (B), see text.

satisfied by all available data (for large enough p_t, within error bars). The limit can be reached only when the jet quenching is overwhelmingly dominated by the matter shells with the entropy density $s = 4 - 8$ fm^{-3} since only those have the right geometrical properties: the data points suggest this seems indeed to be the case for the Au-Au collisions at RHIC at $N_p \sim 100$.

While previous models [17,19] failed to reproduce the high p_t v_2 and $R_{A\text{-}A}$ simultaneously, we now presented two models which can do so. The key is the nontrivial dependence of quenching on the (entropy) density. We concluded that the angular dependence of jet quenching indicates its strong enhancement near the QCD phase transition, about several times stronger than in the QGP.

Why can it be so? Perhaps a near-T_c peak in jet quenching should not be too surprising, as we already saw similar

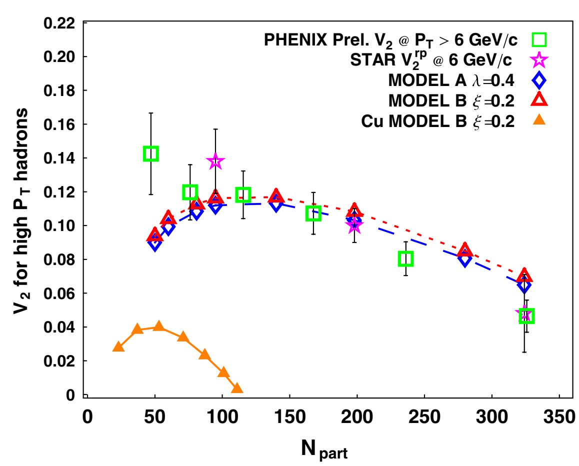

FIG. 3 (color online). Comparison between v_2 experimental data and v_2 calculated from our models, see text.

peaks or sharp valleys around T_c for other properties of QGP, from trace anomaly, specific heat and speed of sound [22] to shear and bulk viscosities [23]. Recently the jet quenching strength was found to be inversely related to shear viscosity in weakly coupled QGP [24]—such relation if naively extrapolated and combined with the minimum of shear viscosity at T_c would also point to a near-T_c peak of jet quenching. It was also proposed in [25] that switching on quenching only after a *global* time $\tau_q \sim 2$ fm one can obtain better values of the asymmetry: such effect is incorporated by near-Tc dominance in a much more plausible manner via *local* density evolution.

A microscopic explanation may be provided by a recent magnetic scenario for the near-T_c QCD plasma, in which this narrow T region is treated as a magnetic plasma of light monopoles [2]. In the same region quarks and gluons are a few times heavier and thus get less energy for the same momentum transfer. When a fast electric charge (the jet) penetrates such plasma, its strong transverse magnetic field easily accelerates the abundant light monopoles into an overheated magnetic "coil" behind it via the dual Faraday effect, leading to substantial energy loss of the jet [26].

It will be interesting to extend the present study to different colliding nuclei A and beam energy $\sqrt{s}$: the data are becoming available (see e.g., [27]) and the phenomena are rich as the jet production, the bulk evolution, and the p-p reference all scale differently with A and $\sqrt{s}$. In Fig. 3 we have included the prediction for high p_t v_2 of Cu-Cu 200 GeV collisions from our model B fixed by Au-Au (orange filled triangle), to be tested by data. More dedicated studies (including different initial scaling, different path length dependence, etc) will be reported in [28].

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Note added.—After the Letter was submitted, PHENIX run7 preliminary data were released [29]. They are now included in Figs. 1(a) and 3 (squares): as one can see they agree with our model well. As also shown in [29], most other models of quenching give v_2 2-3 times smaller than data.

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