Origin of the "ridge" phenomenon induced by jets in heavy ion collisions

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We argue that "ridge" in two-particle correlation function associated with hard trigger at BNL Relativistic Heavy Ion Collider (RHIC) heavy ion collisions is naturally explained by an interrelation of jet quenching and hydrodynamical transverse flow. The excess particles forming the ridge are produced by QCD bremsstrahlung along the beam (and thus have wide rapidity distribution) and then boosted by transverse flow. Nontrivial correlation between directions of the jet and the radial flow is provided by jet quenching: our straightforward and basically parameter-independent calculation reproduces the angular shape, width, and other properties of the ridge.

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Introduction. Two of the most important discoveries made in the first years of heavy ion collision experiments at the BNL Relativistic Heavy Ion Collider (RHIC) are (i) robust radial and elliptic flows that are well described hydrodynamically [1] and (ii) strong jet quenching. In the past years the interaction between jets and the medium has become a hot subject. Strong modification of the away-side jets seem to be well described by hydrodynamical "conical flow" [2].

This article is about another phenomenon observed in jet-related two-particle correlations, known as "ridge" and found by the STAR Collaboration. It was originally observed in fluctuation analysis [3] revealing "mini-jets" and then related to few-GeV jets (for a recent summary, see Ref. [4]). Its main features are (i) a peak at relative azimuthal angle $\phi = \phi_1 - \phi_2 = 0$ with a width of about 1 radian, about twice that of the jet; (ii) a wide distribution in (pseudo)rapidity η; (iii) a spectrum of secondaries slightly harder than a bulk one but much softer than that for a jet; and (iv) a composition very different from jets, in particular, a large fraction of baryons/anti-baryons.

We do not go into a review of the various ideas proposed to explain the ridge. We simply report our calculations aimed at testing one specific idea, originating from the paper of Voloshin [5], who pointed out that one can get information about the location of the hard collision point by correlating it with the transverse flow. To our knowledge, the present article is the first attempt to make quantitative estimates based on it, with results we consider very encouraging.

Angular correlation between jet and flow. As is well known, radiative QCD processes lead to the production of four cones of radiation. Two of them—the "jets"—are better known and studied more than the two others produced along the beams. While they are similar in multiplicity and other features to the two jets (because the appearance and disappearance of the same color current produces similar radiation), the hadrons originating from them cannot be separated from "bulk" multiple production in pp collisions. Indeed, they have similarly wide rapidity distributions and similar transverse momenta p_t with respect to the beam direction, so their presence may only be seen via overall multiplicity increase in jet-containing events, relative to "soft" ones.

In heavy ion collisions the situation is different: as we show below, the "longitudinal cone" products can be naturally separated from the "bulk." The reason for that is their specific production locations in the transverse plane—the gray circle in Fig. 1 (top panel)—which tend to be closer to the nuclear edge than to the center, due to jet quenching. Collective transverse flow boost them strongly in the radial direction, making their azimuthal directions be well aligned along $\vec{r}$ (especially if one selects the right window of $p_t \sim 2$ GeV, see below). The next step, explaining why this effect is observable, is a correlation between the radial direction and that of the triggered jet.

The geometry of the phenomenon and the notations used is explained in Fig. 1 (top panel), depicting the transverse plane at the moment of a collision. For simplicity we discuss only central collisions, for which there is perfect axial symmetry and the elliptic flow is absent. The point at which hard collision takes place is denoted by $\vec{r}$ and the (azimuthal) angle at which the triggered jet is emitted is called ϕ_1. At the moment of production obviously there is no correlation between directions of $\vec{r}$ and ϕ_1. However, this correlation appears for *observed* jets because of the jet quenching phenomenon. Indeed, to be detected the jet has to travel through matter for the distance (depicted L at the figure) at which quenching takes place, the probability of which we call $P_{\text{quench}}(L)$. Because obviously the distance depends on both r, ϕ_1 and the nuclear radius R,

$$L(r, \phi_1) = \sqrt{R^2 - r^2 * \sin^2(\phi_1)} - r\cos(\phi_1); \qquad (1)$$

this generates the correlation between them to be explored.

Because it is the main point of the phenomenon, let us discuss this in detail. If a jet is produced at small r close to the nuclear center (where the probability of production $P_{\text{prod}}(r)$ obviously has its maximum) there is no correlation, because L in this case is about the same $\approx R$ in all directions. If the jet is produced near the nuclear surface $R - r \ll R$, there is some angular correlation, but a weak one: in this case the jet may be emitted in the whole half-plane $-\pi/2 < \phi_1 < \pi/2$. The correlation reducing the ϕ_1 distribution to a more narrow peak appears only when jets originate at a certain depth inside

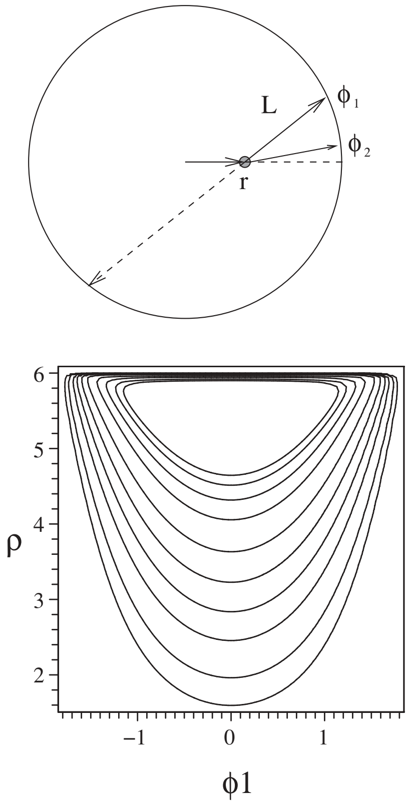

FIG. 1. (Top) Schematic view of the transverse plane for central heavy ion collisions. The small circle at coordinate $\vec{r}$ is the place where hard collision takes place, in which a pair of jets (triggered one shown by a solid line, unobserved by the dashed one) are produced. The distance traveled by the triggered jet inside the nucleus is L, which depends on $\vec{r}$ and jet direction angle ϕ_1. (Bottom) Jet distribution over point of origin-direction ($\rho = r - \phi_1$ plane): the contours are for values 0.96, 0.8, 0.6, 0.4, 0.2, 0.1, 0.05, 0.025, and 0.01 of the maximum, for $l_{\rm abs} = 0.5$ fm.

the nuclei: and the question to be addressed is whether it is strong enough to explain the observed effect.

Although we have used different variants of distributions in the study, it has been found to be enough to use the simplest models of the production/quenching, as the results are found to be insensitive to any details. For central collisions of two homogeneous balls of radius R, with a sharp edge, at position r one has collision of two columns of matter with a length $\sqrt{R^2 - r^2}$, and thus "collision scaling" means

$$P_{\rm prod}(r) \sim (R^2 - r^2). \quad (2)$$

The probability of quenching can be written as a simple exponential damping with distance,

$$P_{\rm quench}(L) \sim \exp\left(-\frac{L(r, \phi_1)}{l_{\rm abs}}\right), \quad (3)$$

where $l_{\rm abs}$ is the quenching length. The resulting distribution $P_{\rm prod} P_{\rm quench}$ in the $r - \phi_1$ plane is shown in Fig. 1 (bottom panel). We have also calculated the double distribution for nuclei that are not sharp spheres: in this case the sharp cut at the top of the bottom panel of Fig. 1 gets smooth. We also calculated distributions for quenching probablity, which is the exponential of the *square* of the path, which also changes the shape of the contour plot Fig. 1 (bottom panel). What remains the same is the angular width of the ϕ_1 distribution, of about one radian. This width eventually becomes the observed width of the ridge, shown in Fig. 2.

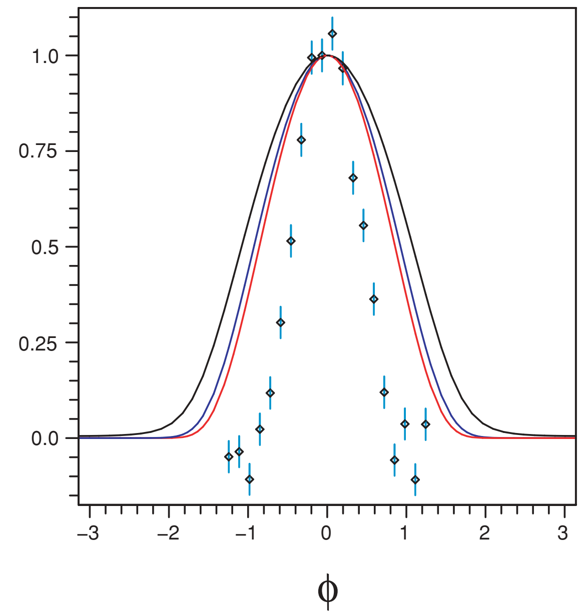

FIG. 2. (Color online) Calculated correlation function $C(p_t = 2.25$ GeV, $\phi)$ as a function of the angle between two observed particles. Three curves (top to bottom) correspond to absorption length $l_{\rm abs} = 1, 0.5, 0.25$ fm. Points are preliminary STAR data [4] on the ridge shape as a function of ϕ, with the jet component subtracted. All curves and data are for AuAu collisions at $\sqrt{s} = 200$ GeV and the central collision bin 0–10%. All curved data are normalized to one at angle zero, for comparison.

The next step in the calculation is to address the effect of the radial flow on spectra of secondaries. As usual, those are determined from the Boltzmann thermal distribution at the kinetic freezeout temperature T_f, boosted by the flow velocity to

$$\frac{dN}{dydp_t^2} \sim \exp\left(-\frac{u_\mu p_\mu}{T_f}\right) \quad (4)$$

Here the nonzero components of the flow velocity are written as $u_0 = 1/\sqrt{1 - v^2}$, $u_r = v/\sqrt{1 - v^2}$ (because we focus on the transverse flow). Because we discuss anisotropy, we can focuson the second term in the exponent, containing the angle ϕ_2 between the particle 2 and theflow direction:

$$F(p_t, v, \phi_2) \sim \exp\left(\frac{vp_t \cos(\phi_2)}{\sqrt{1 - v^2}T_f}\right). \quad (5)$$

(For more precise expression of spectra from an expanding fireball see Eq. (8): two exponents correpond to asymptotics of two Bessel functions there.) To get a feeling of the degree of collimation, let us estimate the combination of parameters entering this exponent. We take $p_t \approx 2.25$ GeV (the lowest p_t used by STAR in ridge studies to be discussed below) and $T_f \approx 100$ MeV. At the edge of the fireball $v \approx 0.7$ and thus the distribution $F \approx \exp(-11\phi_2^2)$, which is extremely well collimated, with a width much less than that of the observed ridge. At the opposite limit, at the center $r = 0$, there is no radial flow, $v = 0$, and the ϕ_2 distribution is isotropic.

Thus the remaining task to be performed is the averaging over both the jet origination point r and the angle ϕ_1, with the weights given by the distributions discussed above. Furthermore, the experimentally observable angle is neither ϕ_2 nor ϕ_1 but the angle $\phi = \phi_1 - \phi_2$ between particles 1 and 2, and so the correlation function is

$$C(p_t, \phi) = \int P_{\text{prod}}(r) P_{\text{quench}}(r, \phi_1) \times F(p_t, v(r), \phi_1 - \phi) r\, dr\, d\phi_1. \quad (6)$$

The only remaining input needed is the "Hubble law" for the radial flow, which we use in the form[1]

$$v(r) = r/(10\,\text{fm}). \quad (7)$$

In Fig. 2 we show the resulting angular distributions: the main result is that the peak survives the averaging. Furthermore, for the sufficiently small absorption lengths l_{abs} shown, the result is only weakly dependent on it. (However, for weak quenching $l_{\text{abs}} > 3$ fm the width of the ϕ distribution grows catastrophically and the ridge correlation disappears entirely.)

While comparing these distributions to STAR data (points with error bars in Fig. 2) one finds that the model is *not* quantitatively accurate: the width we found is larger than the one observed. (The points go to negative values at the wings, which suggests that some oversubtraction takes place: it may be that the width is, in fact, a bit different.) By making more complicated models for quenching one probably can recover better agreement: all we conclude for now is that the mechanism of ridge formation basically works.

Other observables. **Spectra** of particles belonging to a ridge are very different from those of the jet: their effective logarithmic slope is about twice smaller than that for jets. On the other hand, they are much closer to the spectrum of the "bulk" represented by inclusive spectra (see Ref. [4]).

Relatively small differences between spectra or secondaries originated from the ridge and bulk (inclusive) are, however, of great interest because they reveal (via flow magnitude) different distributions of their points of origin. As we will see shortly, they are thus sensitive to jet absorbtion length l_{abs} and potentially can tell us its magnitude.

The ridge is a small perturbation on top of the overall flow of thousands of particles and is thus simply carried by the flow. Because we are now interested in more fine detail, we must treat flow less schematically than we did above. Excellent fits to inclusive data of all secondaries have been provided, e.g., by the expression from Ref. [6]

$$\frac{dN}{dp_t^2} \sim \int_0^R dr\, r n(r) m_t I_0\left(\frac{p_t \sinh(y_t)}{T}\right) K_1\left(\frac{m_t \cosh(y_t)}{T}\right), \quad (8)$$

[1]This expression is supposed to give the final velocity that is obtained by the volume element which started hydro expansion at the point r. It should not be confused with a solution of hydro equations at some intermediate time moment.

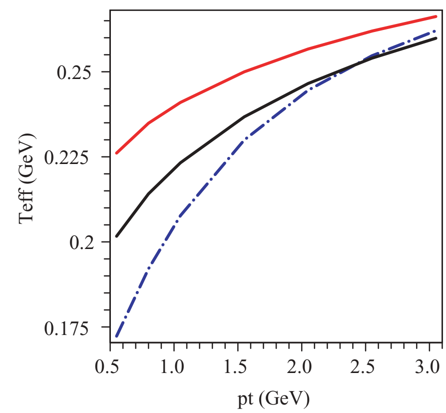

FIG. 3. (Color online) The effective temperature T_{eff} (m_t slope) versus transverse momentum p_t, both in GeV. Two solid curves (upper red and lower black) are for ridge spectra, with the absorption parameter $l_{\text{abs}} = .5$ and 1 fm, respectively. The dash-dotted (blue) line is not for the ridge but rather is for the inclusive spectrum, shown for comparison.

where $m_t^2 = p_t^2 + m^2$, $n(r)$ is the particle density distribution, T is the kinetic freeze-out temperature, and the transverse rapidity is related to transverse flow velocity $y_t = \tanh^{-1} v_t$, which is assumed to have a Hubble-like flow profile

$$v_t(r) = v_{\max}\left(\frac{r}{R}\right)^n, \quad (9)$$

with n close to 1. For fits and parameters see STAR publications such as Ref. [7]. We use a bit rounded values: $n = 1$, $T = 90$ MeV, and $v_{\max} = .84$.

The difference between ridge and bulk particles come from different distributions $n(r)$: most notably jet quenching makes the middle of the fireball "black" for ridge emission, as detailed above. As their origin is more biased toward the nuclear surface, they pick up a larger flow. We have calculated spectra for both ridge and bulk components: the difference is visible if one plots the "local slopes,"

$$T_{\text{eff}}^{-1} = -\frac{d}{dm_t}\log\left(\frac{dN}{dp_t^2}\right), \quad (10)$$

rather than the spectra themselves. The results[2] are shown in Fig. 3. Although freeze-out T is constant, the slopes grow with p_t because effectively we pick up particles closer and closer to the edge. The maximal value of the slope is thus "blue shifted," $T_{\text{eff}} = T * \exp(y_t^{\max}) \approx 300$ MeV. Ridge spectra are generally above the inclusive one, and the smaller the absorption length is, the larger the difference.

STAR data reported in Ref. [4] also show that effective slopes for ridge spectra are indeed *larger* than those for inclusive spectra. Unfortunately those data are for larger $p_t = 2$–4 GeV, for which hydro description is not adequate,

[2]We ignored the particle mass and so they are strictly speaking for pions, but corrections for inclusive spectra of all secondaries are small at the p_t range shown.

and thus direct comparison is not yet possible.[3] The effective inclusive slope in this region is well known, $T_{\rm eff}^{\rm bulk} = 355.5 \pm 5$ MeV, while that for the ridge is $T_{\rm eff}^{\rm ridge} \approx 400 \pm 20$ MeV with much larger statistical errors.

Another important conclusion from Fig. 3 is that the spectra are completely independent of the jet momentum, which confirms that the ridge is not physically related to a jet itself. This fact is consistent with our model, because different jets have the same "collision scaling" distribution in the transverse plane.

Particle composition of the ridge particle is also very different from that of the jet. The fraction of baryons is much larger. This is naturally explained by the fact that the ridge is seen in the region of $p_t \sim 2$ GeV, which constitutes the tail of the (boosted) Boltzmann distribution in which mass dependence is small. The same very phenomenon was observed in the bulk and was explained by hydrodynamics [1]. Indeed, around $p_t \sim 2$ GeV the p/π^+ ratio crosses 1, and if the hydro-induced tail would dominate the spectrum at arbitrary large p_t (which it does not) the ratio would eventually be mass independent and reach 2, the number of spin components.

Outlook: three-particle correlations. The next step in the data analysis is obviously adding one more particle correlated with the jet. Depending on whether the second particle is included in the trigger condition or not, those can be called $(2+1)$ or $(1+2)$ correlations.

The latter case is basically the same as $(1+1)$ in terms of geometry and trigger bias. In this case one would like to check whether the ridge extends longitudinally on both sides from a jet in each event. The alternative mechanism suggested in Ref. [8]—a longitudinal extension of a jet due to *longitudinal* flow—can thus be finally confirmed or rejected. So far, the only observation *against* it is that the ridge was never seen near the away-side jet, which their model seems to predict to be even larger than the observed ridge at the trigger side.

[3]Note, in particular, that those slopes are even above the maximum one for the hydro model we use, which is a sign of hard processes playing some role at such p_t.

The $(2+1)$ case, with two hard particles in the trigger, is completely symmetric if two momenta are about the same, and therefore its trigger bias is completely different from the one discussed above. Indeed, it is determined by quenching along the sum of the paths of both jets,

$$L + \bar{L} = 2\sqrt{R^2 - r^2 * \sin^2(\phi_1)}, \qquad (11)$$

where $\bar{L}$ is the path of the companion jet shown in Fig. 1 by the dashed line. Its exponent now favors the flow vector $\vec{r}$ to be *orthogonal* to both jets, $\phi_1 = \pm\pi/2$. The favorite configuration is when two jets are emitted "tangentially" to flow: therefore, we predict that now one should find the ridge at a completely different location! In rapidity it is expected to be symmetric around the di-jet center-of-mass, the mean of the rapidities of both jets.

Summary. In short, the proposed mechanism works as follows. The particles forming the ridge originate from glue radiated in the hard collision along the beam direction and thus having wide rapidity distribution. Their angular collimation in azimuthal angle is created by transverse radial flow. The most nontrivial point is the correlation between the direction of the flow and the jet direction, which is induced by the jet quenching: as we show, it survives the averaging over positions and jet directions. We conclude that this mechanism is in good correspondence with many aspects of the data on the ridge phenomenon at hand. Further experimentation, especially measurements of difference in slopes between the ridge and bulk particles, can provide an estimate for the jet absorption length. Three-particle correlations will further elucidate whether this mechanism is indeed responsible for this phenomenon.

Note added in proof. After the paper was submitted, a qualitative discussion of the same model was made in Ref. [9]. We also became aware of a different model for the ridge that is proposed in Ref. [10].

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[1] D. Teaney, J. Lauret, and E. V. Shuryak, Phys. Rev. Lett. **86**, 4783 (2001); "A hydrodynamic description of heavy ion collisions at the SPS and RHIC," arXiv:nucl-th/0110037; P. F. Kolb and U. W. Heinz, "Hydrodynamic description of ultrarelativistic heavy-ion collisions," in Quark Gluon Plasma 3', edited by R. C. Hwa and X. N. Wang (World Scientific, Singapore), pp. 634–714. arXiv:nucl-th/0305084.

[2] J. Casalderrey-Solana, E. V. Shuryak, and D. Teaney, J. Phys. Conf. Ser. **27**, 22 (2005) [Nucl. Phys. **A774**, 577 (2006)]; L. M. Satarov, H. Stoecker, and I. N. Mishustin, Phys. Lett. **B627**, 64 (2005).

[3] J. Adams *et al.* (STAR Collaboration), J. Phys. G **32**, L37 (2006).

[4] J. Putschke, J. Phys. G **34**, S679 (2007); arXiv:nucl-ex/0701074; Talk at Quark Matter 2006 (for STAR Collaboration), Shanghai, Nov. 2006.

[5] S. A. Voloshin, Phys. Lett. **B632**, 490 (2006).

[6] E. Schnedermann, J. Sollfrank, and U. W. Heinz, Phys. Rev. C **48**, 2462 (1993).

[7] J. Adams *et al.*, Phys. Rev. Lett. **92**, 112301 (2004).

[8] N. Armesto, C. A. Salgado, and U. A. Wiedemann, Phys. Rev. Lett. **93**, 242301 (2004).

[9] N. Borghini and U. A. Wiedemann, arXiv:0707.0564 [hep-ph].

[10] A. Majumder, B. Muller, and S. A. Bass, Phys. Rev. Lett. **99**, 042301 (2007); arXiv:hep-ph/0611135.