Correlated Emission of Hadrons from Recombination of Correlated Partons

R. J. Fries,[1] S. A. Bass,[2,3] and B. Müller[2]

[1]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[2]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*
[3]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

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We discuss different sources of hadron correlations in relativistic heavy ion collisions. We show that correlations among partons in a quasithermal medium can lead to the correlated emission of hadrons by quark recombination and argue that this mechanism offers a plausible explanation for the dihadron correlations in the few GeV/c momentum range observed in Au + Au collisions at the BNL Relativistic Heavy Ion Collider.

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The recombination of thermalized quarks has recently been proposed as the dominant mechanism for the production of hadrons with transverse momenta of a few GeV/c in Au + Au collisions at the BNL Relativistic Heavy Ion Collider (RHIC) [1–5]. While the concept of recombination of deconfined quarks is not new [6], the RHIC data have provided compelling evidence for the presence of this hadronization mechanism. Quark recombination explains the enhancement of baryon emission, compared with meson emission, in the range of intermediate transverse momenta (roughly from 2 to 5 GeV/c), and it provides naturally for the observed hadron species dependence of the elliptic flow in the same momentum region in terms of a universal elliptic flow curve for the constituent quarks [7].

However, quark recombination from a collectively flowing, deconfined thermal quark plasma appears to be at odds with the observation of "jetlike" correlations of hadrons observed in the same transverse momentum range [8,9]. Data show an enhancement of hadron emission in a narrow angular cone around the direction of a trigger hadron. Can such correlations be reconciled with the claim that hadrons in this momentum range are mostly created by recombination of quarks?

Obviously, the observation is incompatible with any model which assumes that no correlations exist among the quarks before recombination. Such correlations require deviations from a global thermal equilibrium in the quark phase. One mechanism is already well established: a strong, but anisotropic and locally varying, collective flow produces correlations among hadrons after recombination. Indeed, the hadronic elliptic flow correlation is known to be larger than the elliptic flow of the quarks before recombination [1,2], because the parameter v_2 characterizing the magnitude of elliptic flow for a hadron is proportional to the number of its constituent quarks.

One would generally expect that correlations among the quarks, when present before their recombination into hadrons, will be amplified by the hadronization process. Here, we argue that two-body correlations among the partons of a quark-gluon plasma are to be expected. Energetic partons produced in the collision lose a significant amount of energy through collisions with thermal partons on their way out of the dense medium. The dissipated energy and momentum are absorbed by the surrounding medium, increasing its temperature slightly and setting it into motion in the direction of the energetic parton. This "wake effect" produces correlations among medium partons (S) and the originally energetic parton (H). If the parton loses enough energy to become indistinguishable from the thermal medium, all that remains is a narrowly directed, "jetty" flow pattern within the medium. Such soft partons can either recombine with each other upon hadronization (denoted by SS for a meson), or a soft parton can recombine with a hard jet parton (SH) [4,10], or a jet parton can fragment outside the medium (F) to form a hadron.

Recently, the STAR collaboration presented experimental evidence that jet cones are not isolated from the surrounding medium, but strongly influence each other [11]. They found that hadrons correlated with the jet participate in the longitudinal expansion of the medium. We will not attempt here to give a quantitative description of how the correlations in the parton phase arise. Rather we will show how such correlations between partons can translate into hadron correlations in a hadronization scenario with recombination and fragmentation. We will focus on dimeson production by the three processes depicted in Fig. 1: the recombination of four thermal partons into two mesons (SS-SS), jet correlations by double fragmentation (F-F) and fragmentation accompanied by a soft-hard recombination between a jet fragment and a thermal parton (F-SH). There are three additional possibilities, SH-SH, SH-SS and F-SS. However, they do not involve any new aspects and they are not considered further here. Baryons can be classified analogously as SSS, SSH, etc.

We start by discussing recombination from a thermal, but correlated, ensemble of quarks (SS-SS), following the formalism described by Fries *et al.* [2]. We denote the yield of pairs of hadrons A, B with N_{AB}. The creation of two mesons from four partons can be expressed as a convolution of the meson Wigner functions Φ_A, Φ_B and the Wigner

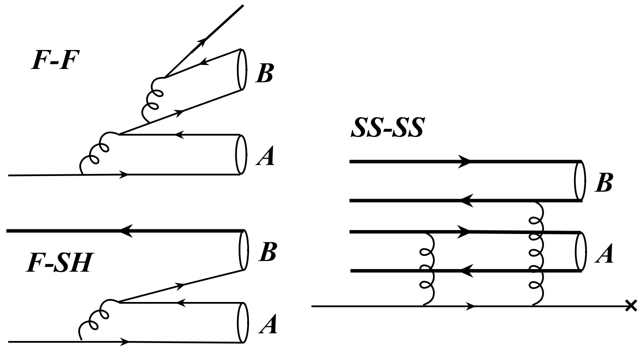

FIG. 1. Schematic pictures of the processes F-F, F-SH and SS-SS for producing two mesons A, B. Thick lines are medium quarks. Possible correlations are indicated by curly lines.

function W_{1234} of the four partons, integrated over the hadronization hypersurface Σ,

$$\frac{E_A E_B d^6 N_{AB}}{d^3 P_A d^3 P_B} = C_{AB} \int_\Sigma d\sigma_A d\sigma_B \Phi_A \otimes \Phi_B \otimes W_{1234}, \quad (1)$$

where $C_{AB} = C_A C_B$ is a degeneracy factor. The generalization to the case where A, B, or both are baryons is straightforward. In the absence of correlations the n-parton Wigner function $W_{1\ldots n}$ is approximated by a product of classical one-parton phase space distributions w_i. This approximation yields satisfactory results for inclusive hadron spectra. However, it should not come as a surprise that it is not sufficient to describe hadron correlations. For this reason, we go one step further and include two-parton correlations in the form

$$W_{1234} \approx w_1 w_2 w_3 w_4 \left(1 + \sum_{i<j} C_{ij}\right). \quad (2)$$

Here C_{ij} is the correlation function between partons i and j. It is not necessary to restrict the form of the C_{ij} other than that they shall not rapidly vary in momentum, can be localized around a certain direction and are confined to a subvolume V_c of the fireball.

We want to discuss a simple example here that convinces the reader that such parton correlations are indeed suitable to explain the jet pattern at RHIC. We evaluate the azimuthal correlations between hadrons emitted around midrapidity in Au + Au collisions. We choose an ansatz for the parton correlations that is inspired by the picture of jet-induced hot spots in the medium and exhibits cones in rapidity y and azimuthal angle ϕ

$$C_{ij} = c_0 S_0 f_0 e^{-(\phi_i - \phi_j)^2/(2\phi_0^2)} e^{-(y_i - y_j)^2/(2y_0^2)} + c_\pi S_\pi f_\pi e^{-(\phi_i - \phi_j + \pi)^2/(2\phi_\pi^2)} e^{-(y_i - y_j)^2/(2y_\pi^2)}. \quad (3)$$

Here $\phi_{0,\pi}$ and $y_{0,\pi}$ are the widths of the Gaussians in azimuth and rapidity, respectively. The two terms correspond to correlations initiated by an energetic parton ($\phi = 0$) and its recoil partner ($\phi = \pi$), normalized by c_0 and c_π. The functions $f_{0,\pi}(p_{Ti}, p_{Tj})$ describe the transverse momentum dependence of the correlations and $S_{0,\pi}(\sigma_i, \sigma_j)$ parametrize the spatial localization of the parton correlations on the hypersurface Σ. For simplification we assume that $S_{0,\pi} = 1$, if $\sigma_i, \sigma_j \in V_c$ and $S_{0,\pi} = 0$ otherwise. Here, we restrict the discussion to near side correlations ($c_\pi = 0$) and refrain from exploring the P_T dependence, because of the present lack of data, which would allow us to constrain the function $f_0(p_{Ti}, p_{Tj})$. Since we work with fixed P_T windows here, for which experimental data exist, we shall simply set $f_0 \equiv 1$, absorbing all numerical factors into the parameter c_0. We also assume that $c_0 \ll 1$, allowing us to neglect terms of higher power in the correlations, such as c_0^2, $c_0 v_2$, or v_2^2.

Following [2] we integrate over the spatial coordinates (assuming $V_{\text{hadron}} \ll V_c \ll V_\Sigma$) and the quark momenta transverse to the hadron momentum. Note that, unlike for single inclusive hadron spectra, the width of the hadron wave function in the azimuthal direction could, in principle, interfere with the correlation width ϕ_0. For simplicity, we neglect such effects here. We also use the narrow wave function approximation (see [2]), which was shown to provide a good description of the measured spectra and elliptic flow. For the thermal parton distributions w_i we use Boltzmann distributions with temperature T, radial flow rapidity η_T, and a boost invariant hadronization hypersurface Σ at fixed proper time τ [2].

The dimeson spectrum for the SS-SS process is

$$\frac{E_A E_B d^6 N_{AB}}{d^3 P_A d^3 P_B} = (1 + 2\hat{c}_0 + 4\hat{c}_0 e^{-(\Delta\phi)^2/(2\phi_0^2)}) \times \prod_{A,B} h_i(P_{Ti})[1 + 2v_{2i}(P_{Ti}) \cos(2\phi_i)], \quad (4)$$

where we introduced the abbreviation

$$h_i(P_T) = C_i \frac{\tau A_T}{(2\pi)^3} M_T I_0\left(\frac{P_T \sinh\eta_T}{T}\right) \times K_1\left(\frac{(m_1^T + m_2^T)\cosh\eta_T}{T}\right) \quad (5)$$

with $m_j^T = \sqrt{m_j^2 + P_T^2/4}$. m_j are the quark masses and M_T is the transverse mass of the meson. This quantity is related to the single inclusive meson spectrum at midrapidity which, including elliptic flow and two-parton correlations, is given by [2] $h_i(P_T)(1 + \hat{c}_0)[1 + 2v_2 \cos(2\phi)]$. The effect of the space-time correlation volume V_c has been approximated in (4) by a rescaling of the normalization constant $\hat{c}_0 = c_0 V_c/(\tau A_T)$.

We note that the amplification factor $Q = 4$ in front of the Gaussian term counts the number of possible correlations of a quark in meson A with a quark in meson B. Likewise the term $2\hat{c}_0$ accounts for the correlations of quarks inside the same meson. It is easy to see that in general for a pair of hadrons with n_A and n_B valence quarks the amplification factor is $Q = n_A n_B$, i.e., 6 for a meson-baryon pair and 9 for a baryon-baryon pair. This result confirms our expectation that correlations within the partonic medium are amplified in the recombination process, similar to elliptic flow.

The experiments at RHIC measure the associated particle yield per trigger hadron A. After subtracting the uncorrelated background and using the notation $\Delta\phi = |\phi_A - \phi_B|$, the relevant observable is defined as

$$Y_{AB}(\Delta\phi) = N_A^{-1}\left(\frac{dN_{AB}}{d(\Delta\phi)} - \frac{d(N_A N_B)}{d(\Delta\phi)}\right). \quad (6)$$

The particle yields are integrated over the kinematic windows of the hadrons A and B with the exception of the relative angle $\Delta\phi$. The P_T spectra of associated particles have recently been studied in [12] in a recombination picture. Neglecting quadratic terms of correlation coefficients, the background subtraction cancels the term proportional to $1 + 2\hat{c}_0$ in Eq. (4) and leads to the result

$$N_A Y_{AB}(\Delta\phi) = Q\hat{c}_0 e^{-(\Delta\phi)/(2\phi_0^2)} N_A N_B/(2\pi), \quad (7)$$

where $N_i = 2\pi \int dy_i dP_{Ti} P_{Ti} h_i(P_{Ti})$ is the total particle number for species i in the kinematic window. The effect of a possible correlation in rapidity—not discussed here—can be absorbed into the normalization $\hat{c}_0$. The uncorrelated background up to first order in the coefficients $\hat{c}_0$, v_2 is given by $(2\pi)^{-1} N_A N_B[1 + 2\hat{c}_0 + 2\bar{v}_{2A}\bar{v}_{2B}\cos(2\Delta\phi)]$, where $\bar{v}_{2i}$ is the average elliptic flow of hadron species i in the kinematic window.

Dihadron production through fragmentation from a jet (F-F) is described by dihadron fragmentation functions. These have recently been discussed by Majumder and Wang [13]. We assume that they can be factorized into single hadron fragmentation functions $D_{a/h}$ with an appropriate scaling of the momentum variable. Since the formalism is strictly collinear, we introduce a Gaussian smearing in relative azimuthal angle and rapidity of the two hadron momenta. Integrating over rapidities we obtain for hadrons emitted around midrapidity

$$\frac{d(N_A Y_{AB})}{dP_{TA} dP_{TB}} = \frac{2\pi I}{\sqrt{2\pi\phi_0^2}} e^{-(\Delta\phi)^2/(2\phi_0^2)} \sum_a \int_{z_0}^{z_1} \frac{dz_A}{z_A(1-z_A)} \times g_a\left(\frac{P_{TA}}{z_A} + \Delta E\right) D_{a/A}(z_A) D_{a/B}\left(\frac{z_A P_{TB}}{(1-z_A)P_{TA}}\right). \quad (8)$$

Here $g_a(p) = E_p d^3N_a/d^3p$ is the invariant spectrum of the fragmenting parton a. The factor I contains the integration over the correlated hadron rapidities y_A and y_B in their respective windows around midrapidity, assuming that the parton spectra g_a are slowly varying. Of course, the width ϕ_0 for this mechanism does not generally coincide with that introduced for correlations among the thermal partons. The kinematic limits are $z_0 = 2P_{TA}/\sqrt{s}$ and $z_1 = P_{TA}/(P_{TA} + P_{TB})$. ΔE denotes the average energy loss of parton a before fragmentation.

For the F-SH process we adopt the following simple model for dimeson production. Suppose a hard parton a with initial momentum p_a dresses itself with a pair $b\bar{b}$ (where b is any flavor). The pair $a\bar{b}$ hadronizes into a meson A. The remaining parton b can pick up a soft parton c from the medium and recombine into another meson B. It is clear that this is only the simplest possible realization of F-SH. We assume that the production of A from a can be described by a fragmentation function $D_{a/A}$. The phase space distribution of the leftover parton b, which picks up the remaining momentum, is then fixed. Together with the thermal distribution of c it can be used to describe the recombination of meson B. After some algebra the correlation of A and B can be written as

$$\frac{d(N_A Y_{AB})}{dP_{TA} dP_{TB}} = \hat{v} \frac{16\pi I C_B M_{TB}}{\sqrt{2\pi\phi_0^2} P_{TB}} g_a(p_a) e^{-(\Delta\phi)^2/(2\phi_0^2)} \times I_0\left(\frac{P_{TB}\sinh\eta_T}{2T}\right) K_1\left(\frac{m_c^T \cosh\eta_T}{T}\right) \times D_{a/A}\left(\frac{P_{TA}}{P_{TA} + P_{TB}/2}\right) + (A \leftrightarrow B) \quad (9)$$

with $p_a = P_{TA} + P_{TB}/2 + \Delta E$. The normalization constant $\hat{v} < 1$ arises from restricting the integration over Σ to a subspace given by the jet cone. Details of these calculations will be provided in a forthcoming publication.

Figure 2 shows numerical examples of the different contributions. We use windows of $1.7\ \mathrm{GeV}/c \le P_{TB} \le 2.5\ \mathrm{GeV}/c$ for associated particles and $2.5\ \mathrm{GeV}/c \le P_{TA} \le 4.0\ \mathrm{GeV}/c$ for trigger particles and $|y| < 0.35$ as in [8]. Our calculation includes charged pions and kaons as well as protons and antiprotons. The parameters of the thermal parton phase are taken from [2]. We use the minijet distributions from [14] and Kniehl-Kramer-Pötter fragmentation functions [15]. The adjustable parameters in our model are the azimuthal width ϕ_0, which is chosen to be 0.2 for all processes, the correlation strength $\hat{c}_0$, and $\hat{v}$.

Figure 2 compares the background subtracted associated yield Y_{AB}, integrated over $0 \le \Delta\phi \le 0.94$ as a function of centrality for meson (left) and baryon (right) triggers. The following scenarios are calculated: (i) F-F process only, (ii) F-F and soft recombination (i.e. SS-SS and SS-SSS for meson triggers, SSS-SS and SSS-SSS for baryon triggers) with no correlations in the parton phase ($\hat{c}_0 = 0$), and (iii) the same with $\hat{c}_0 = 0.08$. The insert shows the total yield with uncorrelated background for (iii).

The F-F mechanism (squares) produces strong near side correlations, which are larger for baryon triggers. However, the trigger yields from this process are small in the considered window, thus adding trigger particles from recombination dilutes the signal dramatically (solid dia-

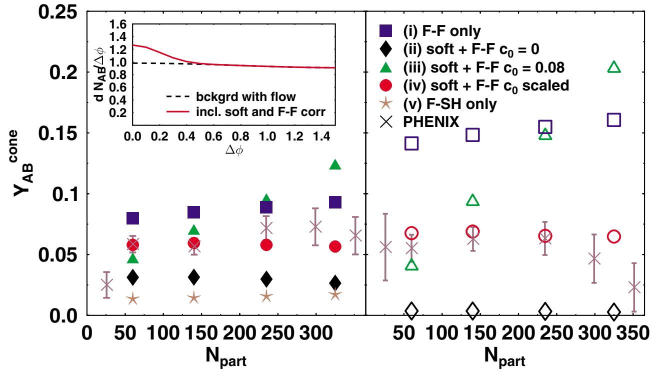

FIG. 2 (color online). $Y_{AB}^{\rm cone} = \int_0^{0.94} d(\Delta\phi) Y_{AB}(\Delta\phi)$ for meson (left panel) and baryon triggers (right panel) as a function of centrality. "Soft" means contributions from SS-SS and SS-SSS for meson triggers and from SSS-SS and SSS-SSS for baryon triggers. Data shown is from PHENIX [9] with statistical errors only. Inset: Associated yield as a function of $\Delta\phi$ before background subtraction at impact parameter $b = 8$ fm.

monds). This effect is even more pronounced for baryons (open diamonds). Switching on soft correlations strongly increases the hadron correlations (triangles). Note that a constant value of $\hat{c}_0$ corresponds to a correlation volume V_c scaling with $N_{\rm part}$, which is not realistic. We also (iv) show the result for $\hat{c}_0 = 0.08 \times 100/N_{\rm part}$ (circles), which corresponds to a correlation column V_c independent of centrality. In this case Y_{AB} varies only weakly and describes the PHENIX data [9] quite well.

We also (v) show F-SH correlations for π-π with $\hat{v} = 0.5$ (stars). The yields in this case are so small that the contribution is negligible compared with soft recombination and fragmentation. It was already pointed out in [2] that with the parton parametrization found by fitting the single inclusive spectra, soft-hard processes are subdominant. Groups using other parametrizations have come to different conclusions [4,5].

Apparently the behavior of baryon and meson triggered yields relative to each other depends on the relative strength of the recombination and fragmentation contributions. Our results show that in a realistic case (F-F and soft recombination with a fixed correlation volume) the associated particle yields for meson and baryon triggers can be of equal magnitude. More experimental information is needed, including measurements in $p + p$, identification of the associated particle and more P_T bins, to better constrain parton correlations.

In summary, we have shown that correlations among partons in a quark-gluon plasma naturally translate into correlations between hadrons formed by recombination of quarks. We found that correlations are even enhanced by an amplification factor $Q = n_A n_B$ similar to the scaling of elliptic flow. The interaction of hard partons with the medium has been discussed as one plausible origin of such parton correlations. We presented a numerical example to demonstrate that two-parton correlations of order $\approx 10\%$ will be sufficient to explain the hadron correlations measured by PHENIX. We conclude that the existence of localized angular correlations among hadrons are not in contradiction with the recombination scenario. We have also shown that experimental data favors a correlation volume that is independent of centrality. At this point, however, it is not possible to determine V_c and the intrinsic strength of the parton correlations c_0 separately.

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