Correlated emission of hadrons from recombination of correlated partons

R. J. Fries,1 S. A. Bass,2,3 and B. Müller2

1School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455
2Department of Physics, Duke University, Durham, NC 27708
3RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973

(Dated: August 1, 2004)

We discuss different sources of hadron correlations in relativistic heavy ion collisions. We show that correlations among partons in a quasi-thermal 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 RHIC.

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 Relativistic Heavy Ion Collider (RHIC)1,2,3,4,5. While the concept of recombination of deconfined quarks is not new6, 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 quarks7.

However, the model of quark recombination from a collectively flowing, deconfined thermal quark plasma appears to be at odds with the observation of “jet-like” correlations of hadrons observed in the same transverse momentum range of 2 to 5 GeV/c8,9. Triggering on a hadron, e.g., with transverse momentum 2.5 GeV/c < pT < 4 GeV/c, the data shows an enhancement of hadron emission in a narrow angular cone around the direction of the trigger hadron in a momentum window below 2.5 GeV/c. 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 recombination10, because the parameter v2 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 a certain amount of two-body correlations among the partons of a quark-gluon plasma produced in a relativistic heavy-ion collision is to be expected. Energetic partons produced in such a collision lose a significant amount of energy through collisions with thermal partons on their way out of the dense medium, but do not completely thermalize before they form hadrons. 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 thermal 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), 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 that jets and the medium strongly influence each other11. 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 three processes: 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). These processes are schematically depicted in Fig. 1. Obviously, there are three additional possibilities for producing two mesons in this recombination–fragmentation picture, SH-SH, SH-SS and F-SS, and even more if baryons are involved. However they do not involve any essentially new aspects and we will not consider them further here.

We start by discussing recombination from a thermal,
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.

but correlated ensemble of quarks (SS-SS), following the formalism described by Fries et al. [2]. The creation of a pair of mesons $A$, $B$ from four partons can be expressed as a convolution of the meson Wigner functions $\Phi_A$, $\Phi_B$ and the Wigner function $W_{1234}$ of the four partons, integrated over the hadronization hypersurface $\Sigma$:

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

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

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

(2)

Here $C_{ij}$ is the correlation function between partons $i$ and $j$. We shall not make special assumptions about the origin of the correlations among partons, except that they do not rapidly vary in momentum, can be localized around a certain direction and are confined to a subvolume $V_c$ of the fireball. This is compatible with correlations being induced by the interaction of an energetic parton with the thermalized medium, as discussed above as a likely source for partonic correlations.

As an example we are going to evaluate the azimuthal correlations between mesons emitted around midrapidity in Au+Au collisions at RHIC. We assume that momentum correlations of partons are restricted to a cone in rapidity $y$ and azimuthal angle $\phi$. Hence we choose the correlation functions to be of the form

$$C_{ij} = c_0 S_0 f_0 e^{-\left(\phi_i - \phi_j\right)^2/(2\sigma_0^2)} e^{-\left(y_i - y_j\right)^2/(2\sigma_T^2)}$$

$$+ c_\pi S_\pi f_\pi e^{-\left(\phi_i - \phi_j + \pi\right)^2/(2\sigma_\pi^2)} e^{-\left(y_i - y_j\right)^2/(2\sigma_T^2)}. $$

(3)

Here $\phi_{0,\pi}$ and $y_{0,\pi}$ are the widths of the Gaussians in azimuth and rapidity, respectively. The two terms of the sum correspond to correlations initiated by an energetic parton ($\phi = 0$) and its recoil partner ($\phi = \pi$). $c_0$ and $c_\pi$ give the strength of the short and far side correlations, while the functions $f_{0,\pi}(p_{T_i}, p_{T_j})$ describe the transverse momentum dependence of the correlations. The functions $S_{0,\pi}(\sigma_i, \sigma_j)$ parametrize the spatial localization of the parton correlations on the hypersurface $\Sigma$. As indicated above, we assume that $S_{0,\pi} = 1$, if $\sigma_i, \sigma_j \in V_c$ and $S_{0,\pi} = 0$ otherwise.

In this letter we restrict the discussion to near side correlations ($c_\pi = 0$). We also refrain from exploring the $p_T$ dependence, because of the present lack of data, which would allow us to constrain the function $f_0(p_{T_i}, p_{T_j})$. 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 $c_\pi^2$, $c_0 v_2$ 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 $\phi_0$. 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 $\eta_T$ and a boost invariant hadronization hypersurface $\Sigma$ at fixed proper time $\tau$.

The dimeson spectrum for the SS-SS process is

$$\frac{d^6 N_{AB}}{d^3 P_T d^3 P_T d\phi_1 d\phi_2} = \left(1 + 2\hat{c}_0 + 4\hat{c}_0 e^{-\left(\Delta \phi^2/(2\phi_0^2)\right)}\right)$$

$$\times \prod_{A,B} h_i(P_{T_i}) \left(1 + 2v_2(P_{T_i}) \cos(2\phi_i)\right),$$

(4)

where we introduced the abbreviation

$$h_i(P_T) = C_i \frac{\tau A_T}{(2\pi)^3} M_T I_0 \left(\frac{P_T \sinh \eta_T}{T}\right)$$

$$\times K_1 \left(\frac{m_i^2 + m_j^2}{2T} \cosh \eta_T\right),$$

(5)

with $m_j^2 = \sqrt{m_j^2 + P_T^2}/4$. $m_j$ 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

$$h_i(P_T)(1 + \hat{c}_0)(1 + 2v_2 \cos(2\phi)).$$

The effect of the space-time correlation volume $V_c$ has been approximated in [2] 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 \( 2\tilde{c}_0 \) accounts for the correlations of quarks inside the same meson. It is then easy to see that the amplification factor is \( Q = 6 \) for a meson-baryon pair and \( Q = 9 \) for a baryon-baryon pair. This result confirms our expectation that correlations within the partonic medium are amplified in the recombination process, similar to the amplification of the elliptic flow \( v_2 \) by the number of valence quarks.

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

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

The particle yields are integrated over the kinematic windows of the hadrons \( A \) and \( B \) with 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 \( 1 + 2\tilde{c}_0 \) in Eq. (4) and leads to the result

\[
N_A Y_{AB}(\Delta \phi) = Q\tilde{c}_0 e^{-(\Delta \phi)/(2\tilde{c}_0^2)} N_A N_B/(2\pi), \tag{7}
\]

were \( N_i = 2\pi \int dy_i dp_{T_i} P_{T_i} n_i(p_{T_i}) \) 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 \( \tilde{c}_0 \). The uncorrelated background up to first order in the coefficients \( \tilde{c}_0 \), \( v_2 \) is given by \((2\pi)^{-1} N_A N_B [1 + 2\tilde{c}_0 + 2v_2 A v_2 B \cos(2\Delta \phi)]\), where \( v_2 \) 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 \( D_{a/b} \) 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

\[
\frac{d(N_A Y_{AB}(\Delta \phi))}{dP_{TA} dP_{TB}} = 2\pi \int_0^{\pi/2} d\phi_0^a \int_0^{\pi/2} d\phi_0^b e^{-(\Delta \phi)^2/(2\tilde{c}_0^2)} e^{-(\Delta \phi_0^a)^2/(2\tilde{c}_0^2)} e^{-(\Delta \phi_0^b)^2/(2\tilde{c}_0^2)} \int_{\eta_T}^{\eta_T} d\eta_T \frac{P_{TA}}{P_{TB}} \hat{g}_a(p_a) \tag{8}
\]

Here \( g_a(p) = E_p d^3 N_a/d^3 p \) 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 \( \phi_0 \) for this mechanism does not generally coincide with that introduced for correlations among the thermal partons. The kinematic limits are \( z_0 = 2 P_{TA}/\sqrt{s} \) and \( z_1 = P_{TB}/(P_{TA} + P_{TB}) \). \( \Delta \phi \) 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) and that the pair \( b\bar{b} \) hadronizes into a meson \( A \). Instead of further fragmentation 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 \( A \) can be described by a fragmentation function \( D_{a/A} \) and we approximate the correlated emission by a product ansatz, where one of the parton distributions entering recombination is coming from a jet. Eventually we arrive at

\[
\frac{d(N_A Y_{AB}(\Delta \phi))}{dP_{TA} dP_{TB}} = 2\pi \int d\phi_0^a 8 C_B M_{TB} \hat{g}_a(p_a) \times \frac{P_{TB} \sinh \eta_T}{2 T} \times K_1 \left( \frac{m^2}{T} \cosh \eta_T \right) D_{a/A} \left( \frac{P_{TA}}{P_{TA} + P_{TB}/2} \right) \tag{9}
\]

with \( p_a = P_{TA} + P_{TB}/2 \). The normalization constant \( \hat{v} \) arises from restricting the integration over \( \Sigma \) to a subspace given by the jet cone. Our notation implies that the fragmented hadron \( A \) is the trigger hadron, but the process where \( B \) is the trigger has to be taken into account as well. Details of these calculations will be provided in a forthcoming publication.

Fig. 2 shows numerical examples of the different contributions. We use windows of 1.7 GeV/c \( \leq P_{TB} \leq 2.5 \)
GeV/c for associated particles and 2.5 GeV/c ≤ p_{TA} ≤ 4.0 GeV/c for trigger particles and |y| < 0.35 as in [3]. 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 KKP fragmentation functions [13]. The adjustable parameters in our model are the azimuthal width \( \phi_0 \), which is chosen to be 0.2 for all processes, the correlation strength \( c_0 \), and \( \hat{c} \).

Fig. 2 compares the background subtracted associated yield \( Y_{AB} \), integrated over \( 0 \leq \Delta \phi \leq 0.94 \) as a function of centrality for the following scenarios: (i) F-F process only, (ii) FF-FF and SS-SS with no soft correlations \((c_0 = 0)\), and (iii) the same with \( c_0 = 0.08 \). The left panel is for meson triggers, the right panel for baryon triggers. The insert shows the uncorrelated background due to the associated yield from the SS-SS process and independent fragmentation as well as the signal for a near side correlation from SS-SS and F-F for \( \hat{c} = 0.08 \).

As seen in the figure, 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 (full diamonds). This effect is even more pronounced for baryons (open diamonds). Switching on SS-SS correlations strongly increases the hadron correlations (triangles). Note that a constant value of \( c_0 \) corresponds to a correlation volume \( V_c \) scaling with \( N_{\text{part}} \), which is not likely realistic. We also show the result for a more realistic fixed \( V_c \) corresponding to \( \hat{c} = 0.08 \times 100/N_{\text{part}} \) (circles), which makes \( Y_{AB} \) vary weakly with centrality.

We also show F-SH correlations for \( \pi - \pi \) and \( \hat{c} = 0.5 \) (stars). The yields in this case are so small that the contribution is negligible compared with SS-SS and F-F. It was already pointed out in [2] that with the parton parametrization found by fitting the single inclusive spectra, soft-hard processes are subdominant. Other groups using different parametrizations have come to different conclusions [1, 2].

The PHENIX preliminary results do not show clearly identifiable near-side jet cones above background for baryon triggers [3], which suggests that one must be cautious with the interpretation of the \( \Delta \phi \)-integrated associated yields in this case. In our model the relative behavior of baryon and meson triggers depends on the relative strength of the SS-SS and F-F contributions. Double fragmentation (F-F) would predict a larger associated yield for baryons triggers than for meson triggers. For the most realistic case (F-F and SS-SS with \( \hat{c} \approx 0.08 \) and fixed correlation volume) meson and baryon triggers result in dihadron correlations of approximately equal magnitude. More experimental information is needed, including measurements of \( p-p \) collisions, to determine which scenario describes the data best.

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 with an amplification factor similar to the one obtained for elliptic flow. Preliminary data from the PHENIX collaboration are consistent with hadron production by quark recombination if two-parton correlations of order 10% within a fixed correlation volume are assumed to be present in the deconfined phase. We conclude that the existence of localized angular correlations among hadrons are not in contradiction to the recombination scenario, since a plausible mechanism for the formation of such parton correlations — passage of hard partons through the dense matter — exists in nuclear collisions at RHIC.

The authors want to thank B. Jacak, R. Lacey and A. Sickles for illuminating discussions. This work was supported in part by RIKEN, Brookhaven National Laboratory and DOE grants DE-AC02-98CH10886, DE-FG02-96ER40945 and DE-FG02-03ER41239.

References: