System Size and Energy Dependence of Jet-Induced Hadron Pair Correlation Shapes in Cu + Cu and Au + Au Collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV

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We present azimuthal angle correlations of intermediate transverse momentum (1–4 GeV/c) hadrons from dijets in Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The away-side dijet induced azimuthal correlation is broadened, non-Gaussian, and peaked away from $\Delta\phi = \pi$ in central and semicentral collisions in all the systems. The broadening and peak location are found to depend upon the number of participants in the collision, but not on the collision energy or beam nuclei. These results are consistent with sound or shock wave models, but pose challenges to Cherenkov gluon radiation models.

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Heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) produce QCD matter at enormous energy density [1], exceeding that required for a phase transition to partonic, rather than hadronic, matter. The produced matter exhibits collective motion [2] and is opaque to scattered quarks and gluons. The opacity is observed via suppression of high momentum hadrons and intermediate energy dijets [3], and provides clear evidence of large energy loss by partons (quarks or gluons) traversing the medium. A key question is how the hot, dense medium transports the deposited energy.

As partons fragment into back-to-back jets of hadrons, angular correlations of the hadrons are used to study medium effects upon hard scattered parton pairs. Hadron pairs from the same parton appear at $\Delta\phi \sim 0$ (the near side), while those with one hadron from each parton in the hard scattered pair appear at $\Delta\phi \sim \pi$ (the away side). For brevity, we refer to these dijet induced dihadron azimuthal correlations as "dijet correlations."

Of great interest are intermediate transverse momentum (p_T) hadrons, as they can arise from intermediate energy jets or involve partons from the medium [4,5]. Their correlations can provide information about energy loss mechanisms, dissipation of the radiated energy in the medium, and collective modes induced by the deposited energy. Theoretical ideas include Mach cones from density waves induced by supersonic partons [4], comoving radiated gluons producing "wakes" in the medium [5], ultrarelativistic partons creating Cherenkov gluon radiation [6], and medium-induced gluon radiation at large emission angles [7,8]. They all imply significant modifications of dijet correlations in the away side, when the parton path through the medium is long. In particular, some of these theoretical models [4,6,7] imply a transition from the peaked distribution at $\Delta\phi \sim \pi$ characteristic of $p + p$ and $p + A$ collisions to a distribution with a peak away from $\Delta\phi \sim \pi$ in head-on Au + Au collisions.

Low p_T (≥ 0.15 GeV/c) hadrons associated with high p_T hadrons (≥ 4 GeV/c) have modified away-side dijet correlations and softened p_T distributions relative to those in $p + p$ collisions, suggesting that at least some of the lost energy is thermalized in the medium [9]. At intermediate p_T, a strong non-Gaussian shape modification of the dijet away-side correlation [10] indicates the possible existence of a local minimum at $\Delta\phi = \pi$. This Letter shows how the away-side jet modification depends on the size of the produced medium, and not on the collision energy or beam species. We report dijet correlations measured by the PHENIX experiment at RHIC.

The data were collected in the years 2005 (Cu + Cu at $\sqrt{s_{NN}} = 200$ and 62.4 GeV), 2004 (Au + Au at $\sqrt{s_{NN}} = 200$ and 62.4 GeV), and 2003 (d + Au at $\sqrt{s_{NN}} = 200$ GeV). Charged hadrons are tracked using the drift chambers and pad chambers of the PHENIX central arm spectrometers at midrapidity in the same way as described in [10]. The number of events in the Au + Au data at 200 GeV used here is 30 times higher than that in [10]. Collision centrality and number of participant nucleons

($N_{\rm part}$) are determined using the beam-beam counters (BBCs) and zero degree calorimeters [11].

Relative azimuthal distributions $Y_{\rm same}(\Delta\phi)$ between "trigger" hadrons with $2.5 < p_T < 4$ GeV/c and "associated" hadrons with $1 < p_T < 2.5$ GeV/c are formed. We correct for the nonuniform azimuthal acceptance of the PHENIX central arms by using the mixed event pairs $Y_{\rm mixed}(\Delta\phi)$ from the same data sample [10]:

$$C(\Delta\phi) \equiv \frac{Y_{\rm same}(\Delta\phi)}{Y_{\rm mixed}(\Delta\phi)} \frac{\int Y_{\rm mixed}(\Delta\phi)d\Delta\phi}{\int Y_{\rm same}(\Delta\phi)d\Delta\phi}. \quad (1)$$

Extensive Monte Carlo simulations were performed to ensure that the true pair distribution shape is recovered.

In Au + Au and Cu + Cu collisions, hadrons have an azimuthal correlation with the reaction plane orientation $\Phi_{\rm RP}$ which is proportional to $1 + 2v_2\cos[2(\phi - \Phi_{\rm RP})]$. This generates a significant correlated background to our dijet source $J(\Delta\phi)$ of azimuthal correlations:

$$C(\Delta\phi) = b_0[1 + 2\langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trigg}\rangle\cos(2\Delta\phi)] + J(\Delta\phi). \quad (2)$$

The charged hadron $\langle v_2\rangle$ at midrapidity ($|\eta| < 0.35$), where "$\langle\rangle$" signifies an event average, was measured through a reaction plane analysis using the BBCs ($3 < |\eta| < 4$) [10,12]. The large rapidity gap between the BBCs and the central arms substantially reduces nonflow contributions to $\langle v_2\rangle$, in particular, dijet induced.

There also exists a much smaller fourth order azimuthal correlation with the reaction plane orientation. Its effect was studied with the Au + Au data at 200 GeV by including the corresponding $2\langle v_4^{\rm assoc}\rangle\langle v_4^{\rm trigg}\rangle\cos(4\Delta\phi)$ term in Eq. (2), where $\langle v_4\rangle$ has also been measured by the reaction plane analysis [12]. No significant v_4 systematic effects on the shape of the dijet correlations were found.

The background subtraction generates point-by-point ($\Delta\phi$ dependent) systematic errors from $\langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trigg}\rangle$ uncertainty and an overall ($\Delta\phi$ independent) systematic error from b_0 uncertainty. The sources of $\langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trigg}\rangle$ uncertainty are the $\langle v_2\rangle$ systematic error [10], dominated by the reaction plane resolution uncertainty, the $\langle v_2\rangle$ statistical error, and the systematic error from the $\langle v_2^{\rm assoc}v_2^{\rm trigg}\rangle \approx \langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trigg}\rangle$ factorization approximation made in Eq. (2). The latter is estimated to be 5% of the $\langle v_2\rangle$ product for the most central events, where it is the largest.

The b_0 uncertainty is estimated by using three independent methods to calculate b_0. The first method is independent of the measured $C(\Delta\phi)$. We calculate $b_0 = \xi\kappa\langle n_{\rm trigg}\rangle\langle n_{\rm assoc}\rangle/\langle n_{\rm same}\rangle$ with hadron production rates measured from all events within each centrality class and scaled by the same-event pair rate $\langle n_{\rm same}\rangle$. The pair-cut correction κ lowers the combinatoric pair multiplicity for pair loss due to proximity cuts in tracking detectors. A residual multiplicity correlation factor, $\xi = \langle n_{\rm trigg}n_{\rm assoc}\rangle/\langle n_{\rm trigg}\rangle\langle n_{\rm assoc}\rangle$, corrects for averaging production rates over events of different multiplicity within the same centrality class, estimated from Glauber $N_{\rm part}$ and $N_{\rm coll}$ distributions [11,13]. In the second method a functional form for $J(\Delta\phi)$ is added to the background, and the sum fitted to the measured correlation with b_0 as a free parameter. Motivated by the theoretical ideas discussed above, we use a function with a near-side Gaussian, and two symmetric away-side Gaussians:

$$J(\Delta\phi) = G(\Delta\phi) + G(\Delta\phi - \pi - D) + G(\Delta\phi - \pi + D). \quad (3)$$

While the choice of this functional form is not unique, it does provide a reasonable fit to the measured correlations, as shown by the dotted line in Fig. 1. The parameter D, or peak angle, is motivated by an attempt to describe the away-side dijet correlation in terms of its symmetry around $\Delta\phi \sim \pi$. We note that it also tends to absorb any non-Gaussian character of the dijet correlation. The third method, called zero yield at minimum (ZYAM), assumes that there is a region in $\Delta\phi$ where the dijet source of particle pairs is negligible. b_0 is varied until the background component in Eq. (2) matches the measured correlation $C(\Delta\phi)$ at some value of $\Delta\phi$.

As shown in Table I for the Au + Au data at 200 GeV, there are slight b_0 variations depending on which method is used to extract its value. However, the dijet correlation shape is essentially independent of these variations.

Figure 1 summarizes the ZYAM extraction of the dijet correlations using the central (0%–5%) Au + Au data at 200 GeV: the measured correlation is shown with squares, the background term with a full line, and the background subtracted dijet correlation with circles for values and boxes for the point-by-point systematic errors. The systematic errors are correlated since they depend on the same parameter—the $\langle v_2\rangle$ uncertainty. For clarity, $J(\Delta\phi)$ is

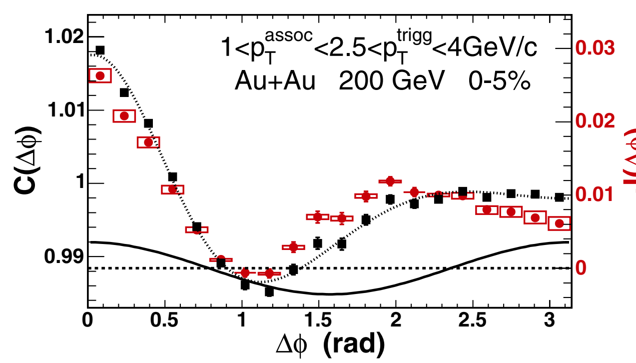

FIG. 1 (color online). The measured correlation $C(\Delta\phi)$ (squares) and the dijet correlation $J(\Delta\phi)$ (circles with boxes for point-to-point systematic errors) in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The full line shows the background term and the dotted line shows a $C(\Delta\phi)$ fit with Eqs. (2) and (3). The left axis shows the measured correlation amplitude and the right axis shows the dijet correlation amplitude.

TABLE I. b_0 values in Au + Au data at $\sqrt{s_{NN}} = 200$ GeV: ZYAM values (first row), variation of fit values from the ZYAM values (second row), variation of combinatorial (Comb.) values from the ZYAM values (third row).

Centrality	60%–90%	40%–60%	20%–40%	10%–20%	5%–10%	0%–5%
ZYAM b_0	0.861	0.942	0.960	0.971	0.982	0.988
Fit δb_0	−0.003	−0.003	−0.006	−0.028	−0.035	−0.022
Comb. δb_0	−0.086	−0.013	−0.004	+0.002	+0.001	+0.001

shifted up by b_0, shown with dashed line, and its amplitude is shown on the right axis. We note that, in this case, the measured correlation is flat near $\Delta\phi \sim \pi$, even before any background subtraction. Because of the cosine modulation of the background, a local minimum develops at $\Delta\phi \sim \pi$ in the dijet away-side correlation.

Figure 2 shows a central and a peripheral dijet correlation for each colliding system and energy. A remarkable away-side feature in central and semicentral collisions (<40%) is the peak location away from $\Delta\phi = \pi$, and the appearance of a local minimum at $\Delta\phi = \pi$. To quantify the significance of this minimum in the Au + Au data at 200 GeV, we have studied how much $\langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trig}\rangle$ would need to change for the away side to be flat. For the four most central bins (0%–5%, 5%–10%, 10%–20%, and 20%–40%) it would have to decrease by 85%(5.1σ), 41%(4.2σ), 20%(2.3σ), and 23%(2.7σ), respectively, where σ is the total $\langle v_2^{\rm assoc}\rangle\langle v_2^{\rm trig}\rangle$ uncertainty.

We quantify the away-side shape change and deviation from a Gaussian distribution by extracting the second and fourth central moments around $\Delta\phi \sim \pi$ ($\mu_n \equiv \langle(\Delta\phi - \pi)^n\rangle$, $n = 2, 4$), in the standard form of the following statistical quantities: the root mean square $\equiv \sqrt{\mu_2}$ and the kurtosis $\equiv \mu_4/\mu_2^2$. The away side is defined here as all $\Delta\phi$ values above the dijet function $J(\Delta\phi)$ minimum, typically 1 rad. We extract these statistics on only the away-side jet peaks in $J(\Delta\phi)$; possible jet-associated flat underlying distributions, which are highly sensitive to the uncertainty in b_0 and precluded by the ZYAM assumption, are not included.

The rms and kurtosis centrality dependence is shown in Fig. 3(a). The rms increases with centrality, indicating broadening of the away-side dijet correlation, while the kurtosis decreases from the value characteristic of a Gaussian shape (three), demonstrating a flattening of its shape beyond an increase in the Gaussian width.

The peak angle D centrality dependence, extracted by fitting dijet correlations with Eq. (3), is shown in Fig. 3(b). It is consistent with zero radians in d + Au and peripheral collisions, but rapidly grows to a value around 1 rad in central collisions. Some deviation from zero radians may be due to slight non-Gaussian shapes of the dijet correlations even without medium modification. This is seen in

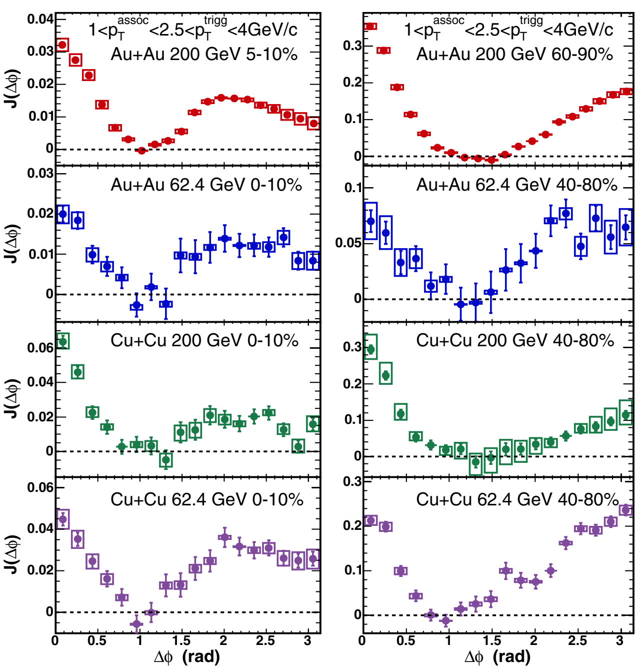

FIG. 2 (color online). Dijet correlations (circles with boxes for point-to-point systematic errors) in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. Left panels show central collisions, while right panels show peripheral collisions.

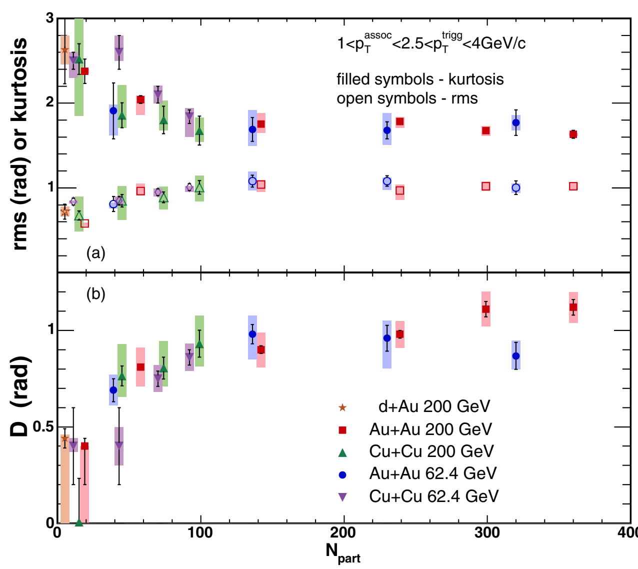

FIG. 3 (color online). Collision centrality, energy, and system size dependence of shape parameters: (a) kurtosis (filled symbols) and rms (open symbols); (b) peak angle D. Bars show statistical errors, shaded bands systematic errors.

TABLE II. Dependence of away-side shape parameters on associated hadron p_T in central (0%–20%) Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $3 < p_T^{\text{trigg}} < 5$ GeV/c. First error is statistical and second error is systematic.

p_T^{assoc}	D (rad)	rms (rad)	Kurtosis
1–1.5	$1.04 \pm 0.03 \pm 0.03$	$1.02 \pm 0.02 \pm 0.05$	$1.68 \pm 0.04 \pm 0.10$
1.5–2	$1.07 \pm 0.04 \pm 0.04$	$1.06 \pm 0.02 \pm 0.05$	$1.58 \pm 0.05 \pm 0.10$
2–2.5	$1.05 \pm 0.03 \pm 0.06$	$1.08 \pm 0.04 \pm 0.08$	$1.38 \pm 0.11 \pm 0.12$
2.5–3	$1.07 \pm 0.06 \pm 0.06$	$1.09 \pm 0.07 \pm 0.07$	$1.35 \pm 0.17 \pm 0.12$
3–5	$0.88 \pm 0.13 \pm 0.16$	$1.01 \pm 0.11 \pm 0.14$	$1.31 \pm 0.23 \pm 0.25$

the kurtosis values for d + Au and peripheral collisions, which have values somewhat lower than three. The systematic errors in Fig. 3 come primarily from the v_2 uncertainty for Cu + Cu and Au + Au and from the $J(\Delta\phi)$ minimum determination for d + Au.

No dependence of rms, kurtosis, or peak angle D on collision energy or species is observed, the away-side dijet shape exhibiting an N_{part} scaling also observed in the suppression of single hadron spectra [14].

Table II shows the dependence of the away-side shape parameters on the associated hadron p_T in the Au + Au data at 200 GeV for a 0%–20% centrality bin, $3 < p_T^{\text{trigg}} < 5$ GeV/c, and the following p_T^{assoc} bins: 1–1.5, 1.5–2, 2–2.5, 2.5–3, and 3–5 GeV/c. The peak angle D and the rms have no p_T dependence, while the kurtosis is consistent with a slow decrease with p_T.

Several phenomenological models for modification of the away-side jet have been proposed; all involve a strong response of the medium to the traversing jet. Bow shocks propagating as sound, or density, waves in the medium produce a peak located away from $\Delta\phi = \pi$ [4,15]. If the peak indeed arises from a sound wave, its location at 1 rad away from the nominal jet direction implies a speed of sound intermediate between that expected in a hadron gas and quark-gluon plasma [4]. A first order phase transition would cause a region with speed of sound identically zero. This region was postulated [4] to reflect sound waves and cause a second away-side peak located at about $\Delta\phi =$ 1.4 rad. No clear evidence for a distinct peak is seen in our data.

If the coupling among partons in the medium is strong, then the high momentum parton may induce non-sound-wave collective plasma excitations [5]. In the strong coupling limit the anti–de Sitter/conformal field theory (AdS/CFT) correspondence was applied to calculate the wake of directional emission from a heavy quark traversing the medium, where a peak angle is found at values slightly larger than in these data [16].

The peak may also arise from Cherenkov gluon radiation [6]. Such a mechanism should disappear for high energy gluons, implying that the peak angle D should gradually approach zero with increasing momentum of associated hadrons. Table II shows that this is not supported by the data. The medium may induce gluon radiation at large angles by mechanisms other than Cherenkov radiation [7,8]. Such models can reproduce the observed peak if the density of scattering centers is large and the gluon splitting sufficiently asymmetric [7]. However, the predicted radiation is very sensitive to the treatment of geometry, expansion, and radiative energy loss framework used. Our detailed measurements constrain the options.

An important issue is whether the density wave correlations survive the underlying medium expansion [4,17]. It was shown that the interplay of the longitudinal expansion and limited experimental η acceptance preserves, and even amplifies, the signal of directed collective excitations [15]. The creation of a shock wave consistent with our data requires that 75%–90% of the parton's lost energy be transferred to the collective mode [15].

We have presented azimuthal angle correlations of intermediate transverse momentum hadrons from dijets in Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The away-side dijet correlation is seen to be broadened, non-Gaussian, and peaked away from $\Delta\phi = \pi$ in central and semicentral collisions. The away-side shape depends on the number of participants in the collision, and not on the beam nuclei or energy. The general features of the observed shape can be qualitatively accounted for by a number of phenomenological models, all having in common a strong medium response to the energy deposited by the traversing parton. The systematic data presented here provide quantitative tests that could discriminate between these models.

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