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Transition in Yield and Azimuthal Shape Modification in Dihadron Correlations in Relativistic Heavy Ion Collisions

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Hard-scattered parton probes produced in collisions of large nuclei indicate large partonic energy loss, possibly with collective produced-medium response to the lost energy. We present measurements of π^0 trigger particles at transverse momenta $p_T^t = 4$–$12\ \mathrm{GeV}/c$ and associated charged hadrons ($p_T^a = 0.5$–$7\ \mathrm{GeV}/c$) vs relative azimuthal angle $\Delta\phi$ in Au + Au and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The Au + Au distribution at low p_T^a, whose shape has been interpreted as a medium effect, is modified for $p_T^t < 7\ \mathrm{GeV}/c$. At higher p_T^t, the data are consistent with unmodified or very weakly modified shapes, even for the lowest measured p_T^a, which quantitatively challenges some medium response models. The associated yield of hadrons opposing the trigger particle in Au + Au relative to $p + p$ (I_{AA}) is suppressed at high p_T ($I_{AA} \approx 0.35$–0.5), but less than for inclusive suppression ($R_{AA} \approx 0.2$).

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Angular correlations between the hadronic fragments of energetic partons are an essential tool for understanding the hot dense matter produced in relativistic heavy ion collisions [1–6]. It is expected that fast partons dissipate a large portion of their energy while traversing this medium, and that correlations between the hadronic fragments of these partons reflect the influence of the energy loss and its deposition into the medium. It has already been observed in dihadron correlations from central Au + Au collisions that both the shape of the relative azimuthal angular distribution and the yield of jetlike fragment pairs can depart significantly from those of $p + p$ collisions [1,5]. The underlying mechanisms for jet modification are not yet fully understood, but partonic energy loss by QCD radiative processes and collisions with medium constituents, as well as the evolution of the lost energy, should contribute to the modification of single and pair yields of hadrons associated with jets.

In the moderate p_T^t, p_T^a range ($\sim$2–5 GeV/c), a pronounced away-side peak broadening [2] and shape modification [3,5] have been observed. The modified shape has been interpreted in some models as a medium response to the energy deposited by partons. These include large-angle gluon radiation [7,8], Čerenkov gluon radiation [9], and Mach-shock or wave excitations [10,11]. Alternative explanations include fluctuating background correlations [12,13] and jets deflected by the medium [14].

Previous measurements [4,5] at p_T^t, $p_T^a \gtrsim 5\ \mathrm{GeV}/c$ have shown that away-side correlations exhibit suppressed jet peaks with shapes similar to those observed in $p + p$ collisions. The resemblance to $p + p$ at the highest momenta p_T^t and p_T^a may be indicative of selective sensitivity to parton pairs that are emitted tangentially near the medium surface and thus suffer minimal energy loss, or alternatively, that some energetic partons lose significant energy in medium, but the effect from such cases is only visible at very low p_T^a. However, these high-p_T results ($p_T \gtrsim 5\ \mathrm{GeV}/c$) are averaged over broad momentum ranges to cope with statistical limitations. Moreover, correlations of unidentified hadrons may include effects from enhanced baryon-to-meson ratios in heavy ion collisions [15]. The use of π^0 trigger particles in narrow p_T bins allows a simpler determination of medium properties.

The results presented here are based on minimum-bias Au + Au and photon-triggered [16] $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV collected with the PHENIX detector in 2006 and 2007. The event centrality in Au + Au is determined by categorizing the integrated charge seen by the beam-beam counters [17] by upper percentile. After the application of event quality cuts, 3.24×10^6 level-1 "photon" triggered $p + p$ events and 1.78×10^9 minimum-bias Au + Au events were used in this analysis.

Neutral pion triggers are reconstructed from photon clusters measured by lead-glass and lead-scintillator electromagnetic calorimeters in the two central arms of PHENIX, covering $|\eta| < 0.35$ and $2 \times 90°$ in azimuth [18]. Neutral pions are identified in each event through 2γ decay by pairing all photons satisfying a minimum energy threshold cut and requiring the reconstructed mass to lie near the π^0 mass peak. More restrictive cuts are used in more central events and for lower-p_T $\pi^0 s$ to reduce the rate of random associations and preserve a π^0 identification signal-to-background ratio (S/B) larger than 4:1 for central Au + Au and 20:1 in $p + p$. A systematic uncertainty of $<1\%$–6%, depending on S/B, is included for the π^0 signal extraction.

Charged hadron partners are reconstructed in the central arms using the drift chambers (DC) with hit association requirements in two layers of multiwire proportional chambers with pad readout (PC1 and PC3), achieving a momentum resolution of $0.7\% \oplus 1.1\% p$ (GeV/c). Only tracks with full and unambiguous DC and PC1 hit information are used. Projections of these tracks are required to match a PC3 hit within a $\pm 2\sigma$ proximity window to reduce background from conversion and decay products.

All trigger-partner pairs satisfying the identification requirements within an event are measured. These pairs are corrected for the PHENIX acceptance through a process of event mixing, and then background pairs which are correlated through the reaction plane are subtracted. The conditional jet pair multiplicity per trigger particle is thus determined by:

$$\frac{1}{N^t}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N^a}{2\pi\epsilon^a}\left[\frac{dN^{\rm pair}_{\rm same}/d\Delta\phi}{dN^{\rm pair}_{\rm mix}/d\Delta\phi} - \xi(1 + 2\langle v_2^t v_2^a\rangle \times \cos(2\Delta\phi))\right], \tag{1}$$

where N^t (N^a) is the number of trigger (associated) particles [5]. The background modulation accounts for quadrupole anisotropy only, and is assumed to factorize such that $\langle v_2^t v_2^a\rangle \approx \langle v_2^t\rangle\langle v_2^a\rangle$ [3]. The elliptic flow coefficients, v_2, are taken from recent PHENIX measurements of neutral pions [19] and charged hadrons [20]. The background level, ξ, is determined in Au + Au collisions using the absolute background subtraction method [21]. A pedestal subtraction employing the zero-yield-at-minimum (ZYAM) method is used in $p + p$. In certain cases, e.g., very broad jets, the ZYAM method could lead to an oversubtraction by removing signal pairs. The effect is typically small in $p + p$ where an additional 6% global scale uncertainty is applied. Charged hadron acceptance and efficiency corrections, ϵ^a, are calculated via full detector simulations [5].

Figure 1 shows the resulting per-trigger jet pair yields for selected trigger-partner combinations in $p + p$ and the 20% most central Au + Au collisions. On the near side, the widths in central Au + Au are comparable to $p + p$ over the full p_T^t and p_T^a ranges, while the yields are slightly enhanced at low p_T, matching $p + p$ as p_T increases. On the opposing side, qualitatively one observes that for low p_T^t and low p_T^a the Au + Au jet peaks are strongly broadened and non-Gaussian. In contrast, at high p_T^t and high p_T^a the yield is substantially suppressed, but the shape appears consistent with the measurement in the $p + p$ case (as has been previously reported in much broader p_T ranges for unidentified charged hadron triggers [4,5]). Here we quantify the trends in the shape and yield between these two extremes.

First, we have performed a fit to the away-side distribution over the range $|\Delta\phi - \pi| < \pi/2$ to a simple Gaussian distribution. Figure 2 shows the results. In $p + p$ collisions, the away-side width narrows at higher trigger and partner momentum as expected from the angular ordering of jet fragmentation. For $p_T^t > 7$ GeV/c, the widths are consistent within uncertainties between $p + p$ and Au + Au at all p_T^a. There is no evidence of large jet broadening from in-medium scattering [14] or from initial state effects [22], expected for surviving partons produced in the interior rather than the surface of the medium. However, it is also possible that for high p_T^t the broadening is modest for the leading parton and its fragmentation products and the

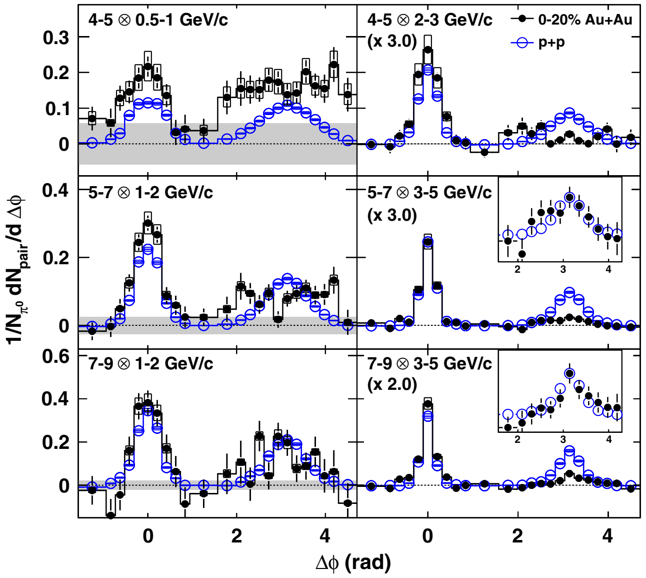

FIG. 1 (color online). Per-trigger jet pair yield vs $\Delta\phi$ for selected π^0 trigger and $h^\pm$ partner p_T combinations ($p_T^t \otimes p_T^a$) in Au + Au and $p + p$ collisions. Depicted Au + Au systematic uncertainties include point-to-point correlated background level and modulation uncertainties (gray bands and open boxes, respectively). For shape comparison insets show away-side distributions scaled to match at $\Delta\phi = \pi$.

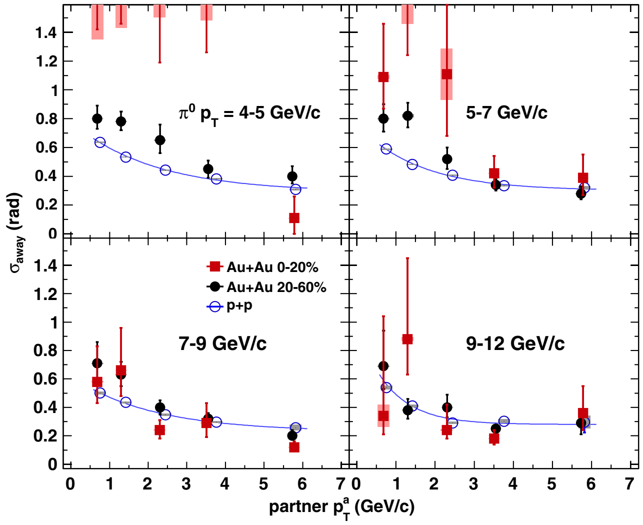

FIG. 2 (color online). Away-side jet widths from a Gaussian fit by $h^{\pm}$ partner momentum for various π^0 trigger momenta in $p + p$, midcentral 20%–60% Au + Au, and central 0%–20% Au + Au collisions. For comparison, an interpolation of the $p + p$ is depicted (curve). In cases where the best fit $\sigma_{\text{away}} > \pi/2$ radians, the point is off the plot.

radiated energy results in only very low p_T^a hadrons (mostly with $p_T^a < 0.5$ GeV/c).

For $p_T^t < 7$ GeV/c, the away-side widths are significantly wider than in $p + p$, except at the highest p_T^a. Note that for $p_T^t < 7$ GeV/c and low p_T^a, the best fit σ_{away} values are larger than $\pi/2$ radians. These trends in shape are further quantified with the use of a χ^2 test to examine the hypothesis that the central Au + Au jet shape on the near and away side is the same as the $p + p$ jet shape. For $p_T^t > 7$ GeV/c, agreement is found for all p_T^a. However, for p_T^t at 5–7 (4–5) GeV/c, the agreement worsens sharply for $p_T^a < 3(4)$ GeV/c as the away-side jet becomes increasingly broad. For example, the p values for agreement between the $p + p$ and Au + Au shapes for $p_T^a = 1 - 2$ GeV/c are very small ($<10^{-4}$) for $p_T^t =$ 4–5 and 5–7 GeV/c, but indicate reasonable agreement (0.33 and 0.16) for $p_T^t =$ 7–9 and 9–12 GeV/c, respectively. The statistical precision of the experimental data does not allow conclusion of a sharp transition in the shape; however, there is a clear indication of a trend towards either much smaller modification or unmodifed jet shapes for higher p_T^t at all p_T^a. To confirm this finding, we compared the away-side distributions in Au + Au central events for p_T^t5–7 GeV/c with p_T^t7–9 GeV/c for p_T^a1–2 GeV/c (see Fig. 1) and find the probability that they have a common shape is small (p-value $<$0.07).

The lack of large away-side shape modification for $p_T^t >$ 7 GeV/c and $p_T^a < 3$ GeV/c is surprising as medium response effects are not generally expected to decrease at larger p_T^t. In descriptions where the medium-induced energy loss (ΔE) is nearly proportional to the initial parton energy (E) [23], and where the lost energy produces a medium response, a larger medium modification is expected for higher momentum partons. Within our statistical precision, no evidence for this is seen; rather, the opposite is found. However, should $\Delta E/E$ fall steeply with increasing parton p_T, an increased contribution from partons which have lost little energy could make an observation of the medium response more difficult. In alternative models of fluctuating background correlations [12,13], the modification is predicted to diminish at higher trigger p_T as the background contribution drops, in agreement with observations.

In addition to the shape modification measurement, the away-side integrated yield is determined. Away-side jet yield modification in central collisions, shown in Fig. 3, is measured by I_{AA} (the ratio of conditional jet pair yields integrated over a particular range in $\Delta\phi$ in Au + Au to $p + p$). The I_{AA} uncertainties include uncorrelated errors (σ_{stat}), point-to-point correlated errors from the background subtraction (σ_{syst}), and a normalization uncertainty from the single particle efficiency determination.

Away-side I_{AA} values for $p_T^t > 7$ GeV/c tend to fall with p_T^a for both the full away-side region ($|\Delta\phi - \pi| < \pi/2$) and for a narrower "head" selection ($|\Delta\phi - \pi| < \pi/6$) until $p_T^a \approx$ 2–3 GeV/c, above which they become roughly constant. The yield enhancement at $p_T^t >$ 7 GeV/c and $p_T^a < 2$ GeV/c is modest and occurs without significant shape modification (Fig. 2). When p_T^t is decreased, the away-side I_{AA} differs between the two angular selections as the shape becomes modified.

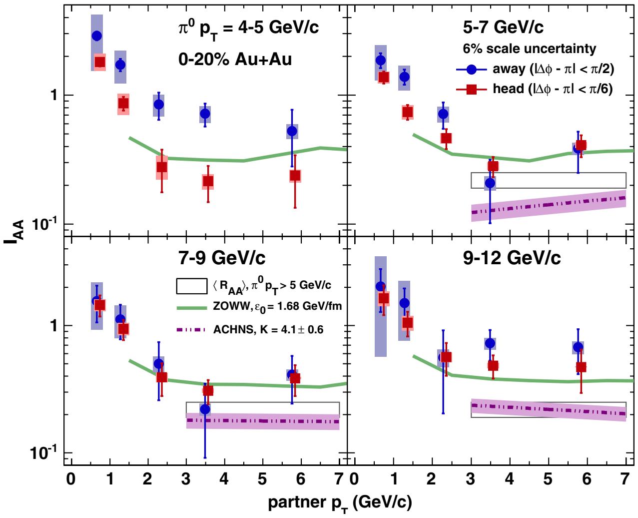

FIG. 3 (color online). Away-side I_{AA} for a narrow head $|\Delta\phi - \pi| < \pi/6$ selection and the entire away side, $|\Delta\phi - \pi| < \pi/2$ vs $h^{\pm}$ partner momentum for various π^0 trigger momenta. Calculations from two different predictions are shown for the head region in applicable p_T ranges. A point-to-point uncorrelated 6% normalization uncertainty applies to all measurements. For comparison, π^0 R_{AA} [24] bands are included where $p_T^t >$ 5 GeV/c.

TABLE I. Average away-side $I_{AA}^{\rm head}$ above 2 GeV/c for various π^0 trigger momenta in central and midcentral collisions where $|\Delta\phi - \pi| < \pi/6$. Note: a 6% scale uncertainty applies to all I_{AA} values.

	Central 0%–20%			Central 20%–60%		
p_T^t	$I_{AA}^{\rm head}$	$\pm\sigma_{\rm stat}$	$\pm\sigma_{\rm syst}$	$I_{AA}^{\rm head}$	$\pm\sigma_{\rm stat}$	$\pm\sigma_{\rm syst}$
5–7	0.35	0.04	0.03	0.55	0.02	0.04
7–9	0.34	0.05	0.03	0.64	0.04	0.02
9–12	0.50	0.08	0.02	0.73	0.06	0.02

Average away-side I_{AA} values from weighted averages of the head region data in Fig. 3 for $p_T^t(p_T^a) > 5(2)$ GeV/c are listed in Table I. The fits, which are not shown, cover the momentum range where shape modification is weak or nonexistent. The away-side I_{AA} values for both centrality selections tend to rise as p_T^t increases. Reference [4] measured a constant away-side I_{AA} for z_T ($= p_T^a/p_T^t$) above 0.4 for triggers at 8–16 GeV/c, but such a single point spanning a broad momentum range fails to provide information on the p_T^t evolution of I_{AA} for comparison with the present results.

Figure 3 also shows the π^0 R_{AA} for $p_T > 5$ GeV/c [24]. The comparison reveals that I_{AA} is consistently higher than R_{AA}. This feature probably results from a few competing effects. Selection of a high p_T trigger π^0 is expected to bias the hard scattering towards the medium surface. Thus, away-side partons have a long average path length through the medium and consequently lose more energy. However, this does not require that I_{AA} be lower than R_{AA}. The away-side conditional spectrum falls less steeply than the inclusive hadron spectrum and so the same spectral shift will more strongly reduce R_{AA}.

Figure 3 also shows I_{AA} calculations from the ACHNS [25] and ZOWW [26] models. Each calculation includes the combination of a parton energy loss formalism and a modeling of medium geometry. The ACHNS calculation, which employs a hydrodynamic evolution model of the medium and an energy loss prescription based on quenching parameters constrained by other data [4,24], predicts $I_{AA} \lesssim R_{AA}$. The ZOWW calculation, which utilizes a simple spherical nuclear geometry and is similarly constrained by other data [4,24], predicts $I_{AA} > R_{AA}$ in agreement with these data. It would be instructive to recalculate these I_{AA} predictions with a common medium geometry (as was done for R_{AA} in Reference [27]) to disentangle the model differences. Additionally, a full assessment including all R_{AA} and I_{AA} measurements, including direct photon trigger data [28,29], is warranted.

In summary, $\pi^0 - h^\pm$ correlations over a very broad range in trigger and partner p_T have been measured. We observe an away-side modification for moderate p_T triggers ($p_T^t < 7$ GeV/c) and low p_T partners ($p_T^a < 3$ GeV/c) as has been observed in unidentified dihadron correlations. However, this modification is reduced or absent for triggers above 7 GeV/c for any partner p_T. At large momenta, i.e., triggers above 5 GeV/c and partners above 2 GeV/c, away-side modification factor I_{AA} is above the inclusive π^0 modification factor R_{AA} ($p_T > 5$ GeV/c).

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