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

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Fast parton probes produced by hard scattering and embedded within collisions of large nuclei have shown that partons suffer large energy loss and that the produced medium may respond collectively to the lost energy. We present measurements of neutral pion trigger particles at transverse momenta \( p_T \) = 4–12 GeV/c and associated charged hadrons (\( p_T^a \) = 0.5–7 GeV/c) as a function of relative azimuthal angle \( \Delta \phi \) at midrapidity in Au+Au and p+p collisions at \( \sqrt{s_{NN}} \) = 200 GeV. These data lead to two major observations. First, the relative angular distribution of low momentum hadrons, whose shape modification has been interpreted as a medium response to parton energy loss, is found to be modified for \( p_T^a < 7 \) GeV/c. At higher \( p_T^a \), the data are consistent with unmodified or very weakly modified shapes, even for the lowest measured \( p_T^a \). This observation presents a quantitative challenge to medium response scenarios. Second, the associated yield of hadrons opposite to the trigger particle in Au+Au relative to that in p+p (\( I_{AA} \)) is found to be suppressed at large momentum (\( I_{AA} \approx 0.35–0.5 \)), but less than the single particle nuclear modification factor (\( R_{AA} \approx 0.2 \)).

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 \([1,5]\). 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 jet-like 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 \( p_T^a \), \( p_T^p \) range (\( \sim 2 – 5 \) GeV/c), a pronounced away-side peak broadening \([2,5]\) and shape modification \([2,5]\) 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 \([8]\), 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 \( p_T^a > 5 \) 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 \( p_T^p \) 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 are only visible at very low \( p_T^a \). However, these high-\( p_T \) results \( (p_T > 5 \) GeV/c) are averaged over broad momentum ranges to cope with statistical limitations.

The results presented here are based on minimum-bias Au+Au and photon-triggered \([15]\) 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 \([16]\) by upper percentile. After the application of event quality cuts, 3.24 million level-1 “photon” triggered p+p events and 1.78 billion 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 \( \mid \eta \mid < 0.35 \) and 2×90° in azimuth \([17]\).
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 π⁰ mass peak. More restrictive cuts are used in more central events and for lower-p_T π⁰s to reduce the rate of random associations and preserve a π⁰ 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 π⁰ signal extraction.

Charged hadron partners are reconstructed in the central arms using the drift chambers (DC) with hit association requirements in two layers of multi-wire proportional chambers with pad readout (PC1 and PC3), achieving a momentum resolution of 0.7% ± 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 ±2σ 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:

\[
\frac{1}{N^t} \frac{dN^{\text{pair}}}{d\Delta \phi} = \frac{N^a}{2\pi \epsilon^t} \left[ \frac{dN_{\text{pair sum}}^{\text{pair}}}{d\Delta \phi} \right] \left[ \frac{dN_{\text{pair mix}}^{\text{pair}}}{d\Delta \phi} \right] - \xi \left[ 1 + 2\langle v^2 \rangle \cos(2\Delta \phi) \right],
\]

where \( N^t \) (\( N^a \)) is the number of trigger (associated) particles. The background modulation accounts for quadrupole anisotropy only, and is assumed to factorize such that \( \langle v^2 \rangle \approx \langle v^2 \rangle \). The elliptic flow coefficients, \( v_2 \), are taken from recent PHENIX measurements of neutral pions and charged hadrons. The background level, \( \xi \), is determined in Au+Au collisions using the absolute background subtraction method. 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 over-subtraction 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, \( \epsilon^t \), are calculated via full detector simulations.

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 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 and low p_T the Au+Au jet peaks are strongly broadened and non-Gaussian. In contrast, at high p_T and high p_T 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). 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 > 7 GeV/c, the widths are consistent within uncertainties between p+p and Au+Au at all p_T. There is no evidence of large jet broadening from in-medium scattering or from initial state effects, 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 the broadening is modest for the leading parton and its fragmentation products and the radiated energy results in only very low p_T hadrons (mostly with p_T < 0.5 GeV/c).

For p_T < 7 GeV/c, the away-side widths are significantly wider than in p+p, except at the highest p_T. Note that for p_T < 7 GeV/c and low p_T, the best fit \( \sigma_{\text{away}} \) values are larger than \( \pi/2 \) radians. These trends in shape are further quantified with the use of a \( \chi^2 \) 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 $p_T^p > 7 \text{ GeV/c}$, agreement is found for all $p_T^p$. However, for $p_T^p$ at 5–7 (4–5) GeV/c, the agreement worsens sharply for $p_T^p < 3$ (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 $p_T^p = 1$–2 GeV/c are very small ($< 10^{-4}$) for $p_T^p = 4$–5 and 5–7 GeV/c, but indicate reasonable agreement (0.33 and 0.16) for $p_T^p = 7$–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 unmodified jet shapes for higher $p_T^p$ at all $p_T^p$. To confirm this finding, we compared the away-side distributions in Au+Au central events for $p_T^p = 5$–7 GeV/c with $p_T^p = 7$–9 GeV/c for $p_T^p = 1$–2 GeV/c (see Fig. 1) and find the probability that they have a common source is small (p-value $< 0.07$).

The lack of large away-side shape modification for $p_T^p > 7 \text{ GeV/c}$ and $p_T^p < 3 \text{ GeV/c}$ is surprising as medium response effects are not generally expected to decrease at larger $p_T^p$. In descriptions where the medium-induced energy loss ($\Delta E$) is nearly proportional to the initial parton energy ($E$) \cite{12,13}, 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 \cite{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 ($\sigma_{\text{stat}}$), point-to-point correlated errors from the background subtraction ($\sigma_{\text{syst}}$), and a normalization uncertainty from the single particle efficiency determination.

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

Average away-side $I_{AA}$ values from weighted averages of the “head” region data in Fig. 3 for $p_T^p(p_T^p) > 5(2)$ GeV/c are listed in Table 1 for both central and midcentral collisions. The fits, which are not shown, cover the

![Figure 2](image1.png)

**FIG. 2:** (Color online) Away-side jet widths from a Gaussian fit by $h^0$ partner momentum for various $\pi^0$ trigger momenta in p+p (open circles), midcentral 20–60% Au+Au (solid circles), and central 0–20% Au+Au collisions (squares). 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.

![Figure 3](image2.png)

**FIG. 3:** (Color online) Away-side $I_{AA}$ for a narrow “head” $|\Delta \phi - \pi| < \pi/6$ selection (solid squares) and the entire away-side, $|\Delta \phi - \pi| < \pi/2$ (solid circles) vs. $h^0$ partner momentum for various $\pi^0$ 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 (mainly due to efficiency corrections) applies to all measurements. For comparison, $\pi^0 R_{AA}$ \cite{22} bands are included where $p_T^p > 5 \text{ GeV/c}$. 

The lack of large away-side shape modification for $p_T^p > 7 \text{ GeV/c}$ and $p_T^p < 3 \text{ GeV/c}$ is surprising as medium response effects are not generally expected to decrease at larger $p_T^p$. In descriptions where the medium-induced energy loss ($\Delta E$) is nearly proportional to the initial parton energy ($E$) \cite{12,13}, 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 \cite{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 ($\sigma_{\text{stat}}$), point-to-point correlated errors from the background subtraction ($\sigma_{\text{syst}}$), and a normalization uncertainty from the single particle efficiency determination.

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

Average away-side $I_{AA}$ values from weighted averages of the “head” region data in Fig. 3 for $p_T^p(p_T^p) > 5(2)$ GeV/c are listed in Table 1 for both central and midcentral collisions. The fits, which are not shown, cover the
TABLE I: Average away-side \( I_{AA}^{\text{head}} \) above 2 GeV/c for various \( \pi^0 \) trigger momenta in central and midcentral collisions where \( |\Delta \phi - \pi| < \pi/6 \). Note: a 6% scale uncertainty applies to all \( I_{AA} \) values.

\[
\begin{array}{ccccccc}
\text{Cent} 0-20\% & \text{Cent} 20-60\% \\
\hline
p_T^t & I_{AA}^{\text{head}} & \pm \sigma_{\text{stat}} & \pm \sigma_{\text{sys}} & p_T^t & I_{AA}^{\text{head}} & \pm \sigma_{\text{stat}} & \pm \sigma_{\text{sys}} \\
\hline
5-7 & 0.35 & 0.04 & 0.03 & 0.55 & 0.02 & 0.04 \\
7-9 & 0.34 & 0.05 & 0.03 & 0.55 & 0.04 & 0.02 \\
9-12 & 0.50 & 0.08 & 0.02 & 0.73 & 0.06 & 0.02 \\
\end{array}
\]

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 \( z_T (= p_T^t/p_T^t) \) 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.

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 \( \pi^0 \) 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 the \( \pi^0 \) \( R_{AA} \) for \( p_T > 5 \) GeV/c [23]. The comparison 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 [1,23], predicts \( I_{AA} \lesssim R_{AA} \). The ZOWW calculation, which utilizes a simple spherical nuclear geometry and is similarly constrained by other data [4,23], predicts \( I_{AA} > R_{AA} \) in agreement with other data. It would be instructive to re-calculate these \( I_{AA} \) predictions with a common medium geometry (as was done for \( R_{AA} \) in Reference [26]) to disentangle the model differences. Additionally, a full assessment including all \( R_{AA} \) and \( I_{AA} \) measurements, including direct photon trigger data [27,28], is warranted.

In summary, \( \pi^0 \), \( A \), and \( p_T^t \) 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 (\( p_T^t < 3 \) 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 \( p_T \) and challenges descriptions where more (initially) energetic partons lose more energy and should produce a larger medium response. 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 \( \pi^0 \) modification factor \( R_{AA} \) (\( p_T > 5 \) GeV/c).

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