Transverse momentum and centrality dependence of dihadron correlations in Au+Au collisions at $\sqrt{s_{_{\text{NN}}}} = 200$ GeV: Jet-quenching and the response of partonic matter

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Azimuthal angle ($\Delta \phi$) correlations are presented for charged hadrons from dijets for $0.4 < p_T < 10$ GeV/$c$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. With increasing $p_T$, the away-side distribution evolves from a broad to a concave shape, then to a convex shape. Comparisons to $p+p$ data suggest that the away-side can be divided into a partially suppressed “head” region centered at $\Delta \phi \sim \pi$, and an enhanced “shoulder” region centered at $\Delta \phi \sim \pi \pm 1.1$. The $p_T$ spectrum for the “head” region softens toward central collisions, consistent with the onset of jet quenching. The spectral slope for the “shoulder” region is independent of centrality and trigger $p_T$, which offers constraints on energy transport mechanisms and suggests that the “shoulder” region contains the medium response to energetic jets.

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High transverse momentum ($p_T$) partons are valuable probes of the high energy density matter created at the Relativistic Heavy-Ion Collider (RHIC). These partons lose a large fraction of their energy in the matter prior to forming hadrons, a phenomenon known as jet-quenching. Such energy loss is predicted to lead to strong suppression of both single- and correlated away-side dihadron yields at high $p_T$ [1], consistent with experimental findings [2, 3]. The exact mechanism for energy loss is not yet understood. Recent results of dihadron azimuthal angle ($\Delta \phi$) correlations have indicated strong modification of the away-side jet [3, 4, 5, 6]. For high $p_T$ hadron pairs, such modification is manifested by a partially suppressed away-side peak at $\Delta \phi \sim \pi$ [3]. This has been interpreted as evidence for the fragmentation of jets that survive their passage through the medium.

For intermediate $p_T$ charged hadron pairs, the away-side jet was observed to peak at $\Delta \phi \sim \pi \pm 1.1$ [3, 4], suggesting that the energy lost by high $p_T$ partons is transported to lower $p_T$ hadrons at angles away from $\Delta \phi \sim \pi$. The proposed mechanisms for such energy transport include medium deflection of hard [7] or shower partons [8, large-angle gluon radiation [9, 10], Cherenkov gluon radiation [11], and “Mach Shock” medium excitations [12].

In this letter we present a detailed “mapping” of the $p_T$ and centrality dependence of away-side jet shapes and yields. These measurements (1) allow a detailed investigation of the jet distributions centered around $\Delta \phi \sim \pi \pm 1.1$ and $\Delta \phi \sim \pi$, (2) provide new insight on the interplay between jet quenching and the response of the medium to the lost energy, and (3) provide new constraints for distinguishing the competing mechanisms for energy transport.

The results presented here are based on minimum-bias (MB) Au+Au and $p+p$ datasets as well as a “photon” level-1 triggered (PT) $p+p$ dataset [13] collected with the PHENIX detector [14] at $\sqrt{s_{NN}}=200$ GeV, during the 2004-2005 RHIC running periods. The collision vertex $z$ was required to be within $|z| < 30\text{cm}$ of the nominal crossing point. The event centrality was determined via the method in Ref. [14]. A total of 840 million Au+Au events were analyzed. Charged particles were reconstructed in the two central arms of PHENIX, each covering -0.35 to 0.35 in pseudo-rapidity and 90° in azimuth. The tracking system consists of the drift chambers and two layers of multi-wire proportional chambers with pad readout (PC1 and PC3), achieving a momentum resolution of $0.7\% \oplus 1.1\% p$ (GeV/$c$) [2].

Dihadron azimuthal angle correlations are obtained by correlating “trigger” (type A) hadrons with “partner” (type B) hadrons. The MB and PT $p+p$ datasets are used for trigger $p_T < 5$ GeV/$c$ and $p_T > 5$ GeV/$c$, respectively. To reduce background from decays and conversions, tracks are required to have a matching hit within a ±2.3σ window in PC3. For $p_T > 4$ GeV/$c$, additional matching hit at the electromagnetic calorimeter (EMC) was required to suppress background tracks that randomly associate with the PC3 [2]. For triggers with $p_T > 5$ GeV/$c$, a $p_T$-dependent energy cut in the EMC and a tight ±1.5σ matching cut at the PC3 were applied to reduce the background to < 10% [15]. This energy cut greatly reduces PT trigger bias effects. The PT $p+p$ results are consistent with the MB $p+p$ data for trigger $p_T > 5$ GeV/$c$.

The jet associated partner yield per trigger, $Y_{jet}(\Delta \phi)$, is obtained from the $\Delta \phi$ correlations as [4, 13]:

$$Y_{jet} = \left[ N^p(\Delta \phi) \right] \left[ N^m(\Delta \phi) - b_0 \left( 1 + 2v^A \nu^B \cos 2\Delta \phi \right) \right] \left[ N_A \varepsilon_B \right] \int d\Delta \phi N_m^{\Delta \phi}(\Delta \phi) \frac{2\pi N_A \varepsilon_B}{2\pi N_A \varepsilon_B} \tag{1}$$

where $N_A$ is the number of triggers, $\varepsilon_B$ is the single particle efficiency for partners in the full azimuth and $|\eta| < 0.35$: $N^p(\Delta \phi)$ and $N^m(\Delta \phi)$ are pair distributions.
from the same- and mixed-events, respectively. Mixed-event pairs are obtained by selecting partners from different events with similar centrality and vertex. The \( \varepsilon_B \) values include detector acceptance and reconstruction efficiency, with an uncertainty of \( \sim 10\% \) \(^2\). The harmonic term, \( 2v_2^A v_2^B \cos 2\Delta \phi \), reflects the elliptic flow modulation of the combinatoric pairs in Au+Au collisions \(^4\). Values for \( v_2^A \) and \( v_2^B \) for each centrality class are measured via the reaction plane (RP) method \(^7\) using the Beam-Beam Counters at \( 3 < |\eta| < 4 \). The systematic errors on \( v_2 \) are dominated by the RP resolution, and are estimated to be \( \sim 6\% \) for central and mid-central collisions, and \( \sim 10\% \) for the peripheral collisions \(^4\).

To fix the value of \( b_0 \), we followed the subtraction procedure of Refs. \(^4\), \(^18\) and assumed that \( Y_{\text{jet}} \) has zero yield at its minimum \( \Delta \phi_{\text{min}} \) (ZYAM). To estimate the possible over-subtraction at \( \Delta \phi_{\text{min}} \), we calculate \( b_0 \) values independently by fitting \( Y_{\text{jet}}(\Delta \phi) \) to a function consisting of one near-side and two symmetric away-side Gaussians. The fitting procedure is similar to that used in \(^3\), except that a region around \( \pi \) (\( |\Delta \phi - \pi| < 1 \)) is excluded to avoid “punch-through” jets around \( \pi \) (see Fig.1). This fits accounts for the overlap of the near- and away-side Gaussians at \( \Delta \phi_{\text{min}} \), and thus gives systematically lower \( b_0 \) values than that for ZYAM. We assign the differences as one-sided systematic errors on \( b_0 \). This over-subtraction error is only significant in central collisions and at \( p_T^{A,B} < 3 \text{ GeV}/c \).

The per-trigger yield distributions for \( p + p \) and 0-20% central Au+Au collisions are compared in Fig.1 for various combinations of trigger and partner \( p_T \) ranges \( (p_T^{A} \otimes p_T^{B}) \) as indicated. The \( p + p \) data show essentially Gaussian away-side peaks centered at \( \Delta \phi \sim \pi \) for all \( p_T^A \) and \( p_T^B \). In contrast, the Au+Au data show substantial shape modifications dependent on \( p_T^A \) and \( p_T^B \). For a fixed value of \( p_T^A \), Figs.1(a)-(d) reveal a striking evolution from a broad, roughly flat peak to a local minimum at \( \Delta \phi \sim \pi \) with side-peaks at \( \Delta \phi \sim \pi \pm 1.1 \). Interestingly, the location of the side-peaks in \( \Delta \phi \) is roughly constant with increasing \( p_T^B \) (see also Fig.2). Such \( p_T \) independence is compatible with the away-side jet modification expected from a medium-induced “Mach Shock” \(^{12}\) but disfavors models which incorporate large angle gluon radiation \(^9, 10\), Cherenkov gluon radiation \(^11\) or deflected jets \(^7\) \( ^5\).

For relatively high values of \( p_T^A \otimes p_T^B \), Figs.1(e)-(h) show that the away-side jet shape for Au+Au gradually becomes peaked as for \( p + p \), albeit suppressed. This “reappearance” of the away-side peak seems due to a reduction of the yield centered at \( \Delta \phi \sim \pi \pm 1.1 \) relative to that at \( \Delta \phi \sim \pi \), rather than a merging of the peaks centered at \( \Delta \phi \sim \pi \pm 1.1 \). This is consistent with the dominance of dijet fragmentation at large \( p_T^A \otimes p_T^B \), possibly due to jets that “punch-through” the medium \(^{19}\), or those emitted tangentially to the medium’s surface \(^{20}\).

The evolution of the away-side jet shape with \( p_T \) (cf. Fig.1) suggests separate contributions from a medium-induced component centered at \( \Delta \phi \sim \pi \pm 1.1 \) and a fragmentation component centered at \( \Delta \phi \sim \pi \). A model independent study of these contributions can be made by dividing the away-side jet function into equal-sized “head” \( (|\Delta \phi - \pi| < \pi/6, \text{HR}) \) and “shoulder” \( (\pi/6 < |\Delta \phi - \pi| < \pi/2, \text{SR}) \) regions, as indicated in Fig.1(c). We characterize the relative amplitudes of these two regions with the ratio, \( R_{\text{HS}} \),

\[
R_{\text{HS}} = \frac{\int_{\Delta \phi_{\text{HR}}} d\Delta \phi Y_{\text{jet}}(\Delta \phi) \phi^{\Delta \phi_{\text{HR}}}}{\int_{\Delta \phi_{\text{SR}}} d\Delta \phi Y_{\text{jet}}(\Delta \phi) \phi^{\Delta \phi_{\text{SR}}}} \tag{2}
\]

Since \( N_A \) in Eq.1 cancels in the ratio, \( R_{\text{HS}} \) is a pure pair variable and is symmetric w.r.t \( p_T^A \) and \( p_T^B \): \( R_{\text{HS}}(p_T^A, p_T^B) = R_{\text{HS}}(p_T^B, p_T^A) \). For concave and convex shapes, one expects \( R_{\text{HS}} < 1 \) and \( R_{\text{HS}} > 1 \), respectively.

Figure 2 summarizes the \( p_T^B \) dependence of \( R_{\text{HS}} \) for both \( p + p \) and central Au+Au collisions in four \( p_T^A \) bins. The ratios for \( p + p \) are always above one and increase with \( p_T^B^2 \). This reflects the narrowing of a peaked jet shape with increasing \( p_T^B \) \(^{13}\). In contrast, the ratios for Au+Au show a non-monotonic dependence on \( p_T^{A,B} \). They evolve from \( R_{\text{HS}} \sim 1 \) for \( p_T^A, p_T^B \lesssim 1 \text{ GeV}/c \) through \( R_{\text{HS}} < 1 \) for \( 1 < p_T^{A,B} \lesssim 4 \text{ GeV}/c \) followed by \( R_{\text{HS}} > 1 \) for \( p_T^{A,B} \gtrsim 5 \text{ GeV}/c \). These trends reflect the competition between medium-induced modification and jet fragmentation, and suggest that the latter dominates at \( p_T^{A,B} \gtrsim 5 \text{ GeV}/c \). The results shown in Fig.1 indicate that, relative to \( p + p \), the Au+Au yield is suppressed in
the HR but is enhanced in the SR. We quantify this suppression/enhancement via $I_{AA}$, the ratio of jet yield $Y_{jet}$ between Au+Au and $p+p$ collisions over a $\Delta \phi$ region, $W$, $I_{AA}^{W} = \frac{\int_{\Delta \phi \in W} d\Delta \phi Y_{jet}^{Au+Au}}{\int_{\Delta \phi \in W} d\Delta \phi Y_{jet}^{p+p}}$.

Figure 3 shows $I_{AA}$ as a function of $p_T$ for the HR and the HR+SR, respectively, in four $p_T$ bins. For triggers of $2 < p_T^A < 3$ GeV/c, $I_{AA}$ for HR+SR exceeds one at low $p_T^B$, but falls and crosses one at $\sim 3.5$ GeV/c. A similar trend is observed for the higher $p_T$ triggers, but the enhancement (at low $p_T^B$) is smaller and the suppression (at high $p_T^B$) is stronger. The $I_{AA}$ values in HR are lower relative to HR+SR for all $p_T^A,B$. For the low $p_T$ triggers, the suppression sets in around $1 < p_T^B < 3$ GeV/c, followed by a fall-off for $p_T^B > 4$ GeV/c. For higher $p_T$ triggers, a constant level of $\sim 0.2 - 0.3$ is observed above $\sim 2$ GeV/c similar to the suppression level of inclusive hadrons [2]. These results provide clear evidence for significant yield enhancement in the SR and suppression in the HR. The data suggest that the SR reflects the dissipative processes that redistribute the energy lost in the medium: The suppression for the HR is consistent with jet quenching. However, we note that the $I_{AA}$ values for the HR are upper limit estimates for the jet fragmentation component. This is because the HR yield includes possible contributions from the tails of the SR, as well as from bremsstrahlung gluon radiations [8].

To further explore the interplay between the HR and the SR, we focus on the intermediate $p_T$ region, $1 < p_T^B < 5$ GeV/c, where the medium-induced component dominates the away-side yield. We characterize the inverse local slope of the partner yield in this $p_T$ range via a truncated mean $p_T^A \cdot \langle p_T^B \rangle \equiv \langle p_T^B \rangle |_{1 < p_T^B < 5}$ GeV/c - 1 GeV/c. $\langle p_T^B \rangle$ is calculated from the jet yields used to make $I_{AA}$ in Fig. 3. Fig. 4 shows the $\langle p_T^B \rangle$ values for the HR, SR and a near-side region ($|\Delta \phi | < \pi/3$, NR), as a function of the number of participating nucleons, $N_{part}$. The $\langle p_T^B \rangle$ values for NR have a weak centrality dependence. Their overall levels for $N_{part} > 100$ are $0.533 \pm 0.024, 0.605 \pm 0.032$ and $0.698 \pm 0.040$ GeV/c for the $p_T^A$ ranges 2-3, 3-4 and 4-5 GeV/c, respectively [21]. This finding is consistent with the dominance of jet fragmentation on the near-side, i.e. a harder spectrum for partner hadrons is expected for higher $p_T$ trigger hadrons.

A very weak centrality dependence is observed for the SR for $N_{part} \gtrsim 100$. In this case, the values for $\langle p_T^B \rangle$ are lower ($\approx 0.45$ GeV/c) and do not depend on $p_T^A$. They are, however, larger than the values measured for inclusive charged hadrons (0.38 GeV/c shown by solid lines) [2]. The relatively sharp increase in $\langle p_T^B \rangle$ for $N_{part} \lesssim 100$ may reflect a significant jet fragmentation contribution in peripheral collisions. In contrast, the $\langle p_T^B \rangle$ values for the HR show a gradual decrease with $N_{part}$, starting close to that for the near-side jet, and approaches the value for the inclusive spectrum for $N_{part} \gtrsim 150$.

The different patterns observed for the yields in the HR and SR suggest a different origin for these yields. The suppression of the HR yield and the softening of its spectrum are consistent with a depletion of yield due to jet quenching. The observed HR yield could be comprised of contributions from “punch-through” jets, radiated gluons and feed-in from the SR. By contrast, the enhancement of the SR yield for $p_T^A,B < 4$ GeV/c suggests a remnant of the lost energy from quenched jets. However, the very weak dependence on $p_T$ and centrality (for $N_{part} \gtrsim 100$) for its peak location and mean $p_T$ may re-
consistent with jet quenching. The latter exhibits the regions of $\Delta \phi$ gives strong evidence for two distinct contributions from sus $N$ angle and jet spectra slope would depend on the diation [11] models, since both the deflection/radiation 

tions for "Mach Shock" in a near-ideal hydrodynamical medium [12, 22], and thus they can be used to constrain medium transport properties such as speed of sound and viscosity to entropy ratio.

In conclusion, we have observed strong medium modification of away-side shapes and yields for jet-induced pairs in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. The detailed dependence of these results on $p_T$ and centrality independent shape and mean $p_T$, possibly reflecting an intrinsic property of the medium response to energetic jets. These results provide strong constraints on competing mechanisms for the energy transport.

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FIG. 4: Truncated mean $\langle p_T \rangle$ in $1 < p_T < 5$ GeV/c versus $N_{\text{part}}$ for the near-side (diamonds), away-side shoulder (circles) and head (squares) regions for Au+Au (filled) and p+p (open) for three trigger $p_T$ bins. Solid lines represent measured values for inclusive charged hadrons [2]. Error bars represent the statistical errors. Shaded bars represent the sum of $N_{\text{part}}$-correlated elliptic flow and ZYAM error.

reflect an intrinsic property of the response of the medium to the energetic jets. These observations are inconsistent with simple deflected jet [7, 8] and Cherenkov gluon radiation [11] models, since both the deflection/radiation angle and jet spectra slope would depend on the $p_T^A$ or $p_T^B$. However, these results are consistent with expectations for "Mach Shock" in a near-ideal hydrodynamical medium [12, 22], and thus they can be used to constrain medium transport properties such as speed of sound and viscosity to entropy ratio.

In conclusion, we have observed strong medium modification of away-side shapes and yields for jet-induced pairs in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. The detailed dependence of these results on $p_T$ and centrality independent shape and mean $p_T$, possibly reflecting an intrinsic property of the medium response to energetic jets. These results provide strong constraints on competing mechanisms for the energy transport.

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