

Jet-Hadron Correlations in $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au and $p+p$ Collisions

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Azimuthal angular correlations of charged hadrons with respect to the axis of a reconstructed (trigger) jet in Au+Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR are presented. The trigger jet population in Au+Au collisions is biased towards jets that have not interacted with the medium,

allowing easier matching of jet energies between Au+Au and $p+p$ collisions while enhancing medium effects on the recoil jet. The associated hadron yield of the recoil jet is significantly suppressed at high transverse momentum (p_T^{assoc}) and enhanced at low p_T^{assoc} in Au+Au collisions, which is indicative of medium-induced parton energy loss in ultrarelativistic heavy-ion collisions.

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High-energy collisions of heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory produce an energy density for which a strongly-coupled medium of deconfined quarks and gluons is expected to form [1–4]. The properties of this medium can be studied using partons with large transverse momenta (p_T) resulting from hard scatterings in the initial stages of the collision. The scattered partons recoil and fragment into back-to-back clusters of hadrons, known as jets.

Jets in $p+p$ collisions are well-described by pQCD theory [5] and can be used as a reference for studies of medium-induced jet modification. Comparisons are also frequently made between jets in Au+Au and $d+Au$ in order to separate initial and final state effects [6, 7]. Suppression of high- p_T hadrons in single-particle measurements [8–11] and of particle yields on the recoil side (“awayside”) of high- p_T triggered “dihadron” correlations [12–18] has been observed in more-central Au+Au collisions relative to $p+p$ and $d+Au$ collisions. This suppression of jet fragments is often attributed to partonic energy loss due to interactions with the medium [19]. However, these single- and two-particle methods do not allow direct access to the original parton kinematics. Furthermore, due to the steeply falling parton energy spectrum, the trigger hadron population in dihadron correlations is dominated by fragments from lower-energy partons.

Due to recent advances in jet-finding techniques in heavy-ion collisions [20] it is now possible to study triggered correlations with respect to the axis of a reconstructed jet, instead of using the dihadron correlation technique in which a high- p_T hadron is used as a proxy for the jet axis. Jet reconstruction allows more direct access to the original parton energy and makes it possible to select a sample of higher-energy partons, thus increasing the kinematic reach of these correlation measurements.

Conceptually, models of partonic energy loss fall into two general categories: (1) radiative/collisional energy loss models [19, 21–25], in which partons lose energy and are scattered as they traverse the medium (radiative energy loss is expected to dominate for light partons), and (2) calculations within a gauge/gravity duality framework, specifically in a strongly-coupled $\mathcal{N} = 4$ supersymmetric Yang-Mills theory [26–28], in which light partons either emerge from the medium nearly unmodified or deposit all their energy into the medium. In this analysis, azimuthal angular correlations of mid-rapidity charged hadrons are studied with respect to a reconstructed mid-

rapidity (trigger) jet. In the radiative energy loss model the correlations should exhibit a difference in the widths and/or yields of the jet peaks in Au+Au compared to $p+p$, while in AdS/CFT models little or no jet shape modification is expected (although jet suppression would be observed in the awayside associated particle yields and in single-particle inclusive measurements). The effects of medium-induced partonic energy loss, or “jet-quenching,” can be studied by comparing the shapes and associated hadron yields of jets in Au+Au with those in $p+p$ collisions.

The data used in this analysis were collected by the STAR detector at RHIC for $p+p$ and Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV in 2006 and 2007, respectively. Charged tracks are reconstructed in the Time Projection Chamber (TPC) [29] and the transverse energy (E_T) of neutral hadrons is measured in the Barrel Electromagnetic Calorimeter (BEMC) towers (with size $\Delta\phi \times \Delta\eta = 0.05 \times 0.05$) [30]. A 100% hadronic correction scheme (in which the total momentum of all charged tracks which point towards a BEMC tower is subtracted from the energy of that tower) is applied to account for charged hadron energy deposition in the BEMC. BEMC towers associated with electrons are rejected.

Events are selected by an online high tower (HT) trigger, which imposed thresholds on E_T of about 5.4 GeV to be deposited in at least one BEMC tower. A common offline software HT threshold of $E_T > 6$ GeV is imposed (after hadronic correction). In Au+Au only the 20% most central events are analyzed, where event centrality is determined by the uncorrected charged particle multiplicity in the TPC within pseudorapidity $|\eta| < 0.5$. Events are required to have a primary vertex position along the beam axis within 25 cm of the center of the TPC. Tracks are required to have $p_T > 0.2$ GeV/ c , at least 20 points measured in the TPC (out of a maximum of 45), a distance of closest approach to the collision vertex of less than 1 cm, and $|\eta| < 1$. Events containing tracks with $p_T > 30$ GeV/ c are not considered in this analysis because of poor momentum resolution. Particle distributions are corrected for single particle tracking efficiency and for detector pair acceptance by event mixing (in relative azimuthal angle $\Delta\phi$ only).

Jets are reconstructed from charged tracks in the TPC and neutral towers in the BEMC using the anti- k_T algorithm from the FastJet package [31] with a resolution parameter $R = 0.4$. The reconstructed jet axis is required to be within $|\eta| < 1 - R$. Only tracks with $p_T > 2$ GeV/ c and towers with $E_T > 2$ GeV are used

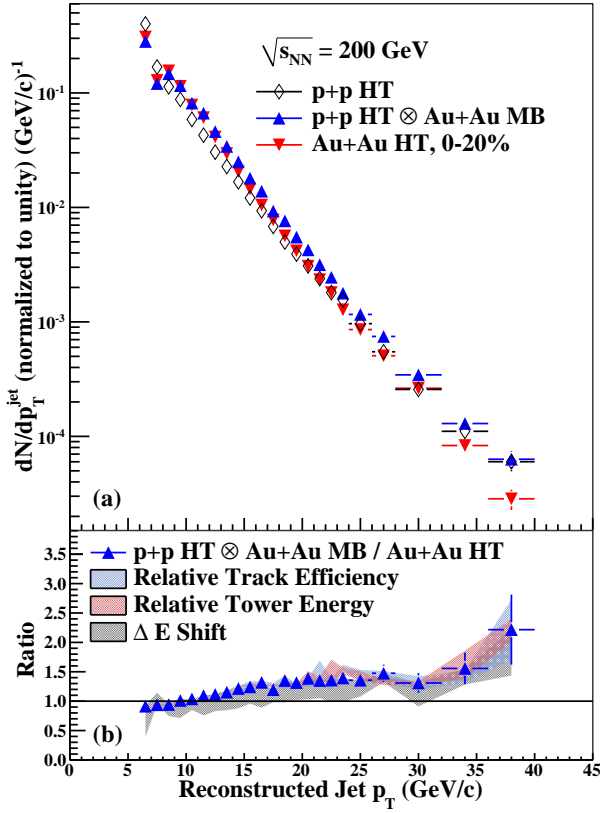


FIG. 1. (Color online.) (a) $p_T^{\text{jet,rec}}$ spectra of HT trigger jets in $p+p$ and Au+Au, and of $p+p$ HT trigger jets embedded in Au+Au MB events. (b) The ratio of $dN/dp_T^{\text{jet,rec,Au+Au}}$ to $dN/dp_T^{\text{jet,rec,p+p emb}}$. Uncertainties due to the relative tracking efficiency, relative tower energy, and ΔE shift are shown as shaded bands. Note that $p_T^{\text{jet,rec}}$ is calculated only from tracks and towers with $p_T > 2$ GeV/ c .

in the jet reconstruction in order to control the effects of background fluctuations. Furthermore, the reconstructed jet must include as one of its constituents a BEMC tower that fired the HT trigger. While in most jet reconstruction analyses it is necessary to subtract an average background energy from the reconstructed jet p_T [32], the 2 GeV cut on tracks and towers makes this subtraction unnecessary here. Instead, background fluctuations are handled using an embedding procedure described later.

Jet-hadron correlations are defined as distributions in $\Delta\phi = \phi_{\text{jet}} - \phi_{\text{assoc}}$, where ϕ_{jet} denotes the azimuthal angle of the axis of a reconstructed (trigger) jet and the associated particles are all charged hadrons, measured as TPC tracks, in the event. To obtain the associated particle yields (Y) and widths (σ) of the jet peaks, the raw correlation functions are fit with the functional form:

$$\frac{Y_{\text{NS}}}{\sqrt{2\pi\sigma_{\text{NS}}^2}} e^{-(\Delta\phi)^2/2\sigma_{\text{NS}}^2} + \frac{Y_{\text{AS}}}{\sqrt{2\pi\sigma_{\text{AS}}^2}} e^{-(\Delta\phi-\pi)^2/2\sigma_{\text{AS}}^2} \quad (1)$$

$$+ B \left(1 + 2v_2^{\text{assoc}}v_2^{\text{jet}} \cos(2\Delta\phi) + 2v_3^{\text{assoc}}v_3^{\text{jet}} \cos(3\Delta\phi) \right),$$

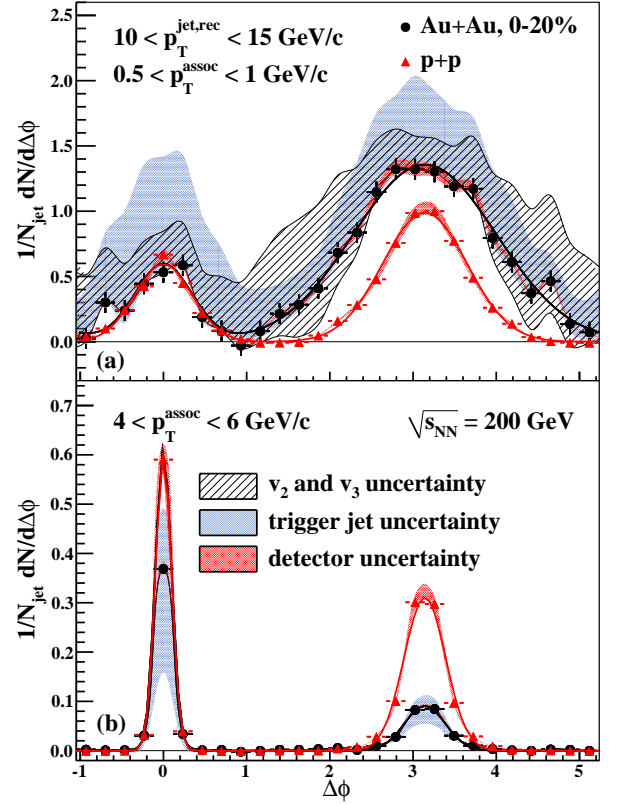


FIG. 2. (Color online.) Jet-hadron correlations are shown after background subtraction for $10 < p_T^{\text{jet,rec}} < 15$ GeV/ c and for two ranges in p_T^{assoc} : (a) $0.5 < p_T^{\text{assoc}} < 1$ GeV/ c and (b) $4 < p_T^{\text{assoc}} < 6$ GeV/ c . The data points from Au+Au and $p+p$ collisions are shown with Gaussian fits to the jet peaks and systematic uncertainty bands due to: tracking efficiency, the shape of the combinatoric background, and the trigger jet energy scale defined by the ΔE and ΣD_{AA} shifts.

which includes two Gaussians representing the trigger/nearside (NS) and away-side (AS) jet peaks, and a background term modulated by $v_2^{\text{assoc}}v_2^{\text{jet}}$ and $v_3^{\text{assoc}}v_3^{\text{jet}}$.

The elliptic anisotropy of the background is assumed to factorize into the product of the single-particle anisotropy of the associated particles due to elliptic flow (v_2^{assoc}) and the correlation of the jet axis with the 2nd-harmonic event plane [33] (v_2^{jet}). The possibility that there is a correlation between the jet axis and the 3rd-harmonic event plane [34] (which can give rise to a v_3^{jet} component and thus a non-zero $v_3^{\text{assoc}}v_3^{\text{jet}}$ term) is also taken into account. The values of $v_2^{\text{assoc}}v_2^{\text{jet}}$ and $v_3^{\text{assoc}}v_3^{\text{jet}}$ are discussed later.

The Gaussian yields of the jet peaks, Y , are integrated over a given bin in the transverse momentum of the associated hadrons (p_T^{assoc}), and the reconstructed jet p_T ($p_T^{\text{jet,rec}}$), as well as over the $\Delta\eta$ acceptance.

The effects of medium-induced modification can be quantified by the widths of the jet peaks, σ , as well as D_{AA} and ΣD_{AA} , defined in Eqns. (2) and (3) respectively. D_{AA} measures the transverse-momentum differ-

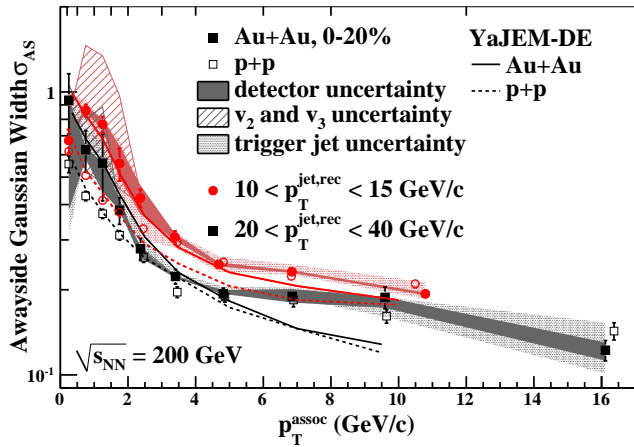


FIG. 3. (Color online.) The Gaussian widths of the awayside jet peaks (σ_{AS}) in Au+Au (solid symbols) and $p+p$ (open symbols) are shown for two ranges of $p_T^{\text{jet,rec}}$: 10 – 15 GeV/ c (red circles) and 20 – 40 GeV/ c (black squares). The results for 15 – 20 GeV/ c (not shown) are similar. The boundaries of the p_T^{assoc} bins are shown along the upper axis. YaJEM-DE model calculations (solid and dashed lines) are from [35].

ence between Au+Au and $p+p$ (in a given p_T^{assoc} bin with mean $\langle p_T^{\text{assoc}} \rangle$):

$$D_{AA}(p_T^{\text{assoc}}) \equiv Y_{\text{Au+Au}}(p_T^{\text{assoc}}) \cdot \langle p_T^{\text{assoc}} \rangle_{\text{Au+Au}} - Y_{p+p}(p_T^{\text{assoc}}) \cdot \langle p_T^{\text{assoc}} \rangle_{p+p}. \quad (2)$$

ΣD_{AA} measures the energy balance over the entire p_T^{assoc} range:

$$\Sigma D_{AA} \equiv \sum_{p_T^{\text{assoc}} \text{ bins}} D_{AA}(p_T^{\text{assoc}}). \quad (3)$$

If jets in Au+Au and $p+p$ have identical fragmentation patterns, then $D_{AA} = 0$ for all p_T^{assoc} . Deviations from $D_{AA} = 0$ are indicative of jet modification.

In order to make meaningful quantitative comparisons between jets in Au+Au and $p+p$, it is necessary to compare jets with similar energies in the two collision systems. While the reconstructed jet p_T is not directly related to the original parton energy (especially in this analysis because $p_T^{\text{jet,rec}}$ is calculated only from tracks and towers with $p_T > 2$ GeV/ c), jets in Au+Au with a given $p_T^{\text{jet,rec,Au+Au}}$ are matched to similar $p+p$ jets using the following procedure: The effect of the background associated with heavy-ion collisions on the trigger jet energy is assessed through embedding $p+p$ HT events in Au+Au minimum bias (MB) events (with the same centrality and high-multiplicity bias as the Au+Au HT events). Under the assumption that Au+Au HT trigger jets are similar to $p+p$ HT trigger jets in a Au+Au collision background, the correspondence between the $p+p$ jet energy ($p_T^{\text{jet,rec,p+p}}$) and the Au+Au jet energy ($p_T^{\text{jet,rec,p+p emb}} \simeq p_T^{\text{jet,rec,Au+Au}}$) can be determined through this embedding. Figure 1 compares the $p_T^{\text{jet,rec,p+p emb}}$ spectrum

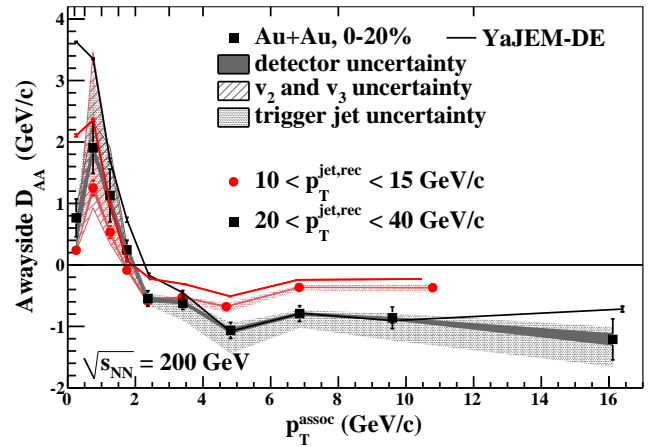


FIG. 4. (Color online.) The awayside momentum difference D_{AA} is shown for two ranges of $p_T^{\text{jet,rec}}$: 10 – 15 GeV/ c (red circles) and 20 – 40 GeV/ c (black squares). The results for 15 – 20 GeV/ c (not shown) are similar. The boundaries of the p_T^{assoc} bins are shown along the upper axis. YaJEM-DE model calculations (solid lines) are from [35].

to the $p_T^{\text{jet,rec,Au+Au}}$ spectrum measured in Au+Au HT events. For a given range in $p_T^{\text{jet,rec,p+p}}$ the corresponding $p_T^{\text{jet,rec,Au+Au}}$ distribution is obtained. When comparing Au+Au jets to equivalent $p+p$ jets in this analysis, the Au+Au signal is weighted according to this distribution. This procedure largely accounts for the effects of background fluctuations in Au+Au events; the possibility of additional discrepancies between the reconstructed jet energies in Au+Au and $p+p$ will be included within systematic uncertainties described below.

The performance of the TPC and BEMC can vary in different collision systems and over time. These variations are accounted for in the relative tracking efficiency between Au+Au and $p+p$ ($90\% \pm 7\%$ for $p_T > 2$ GeV/ c), the relative tower efficiency ($98\% \pm 2\%$), and the relative tower energy scale ($100\% \pm 2\%$). These variations in detector performance were included, and their systematic uncertainties were assessed, in the $p+p$ HT \otimes Au+Au MB embedding. The effects of the relative tracking efficiency uncertainty and the tower energy scale uncertainty on the $p_T^{\text{jet,rec}}$ spectrum are shown in Fig. 1(b). The embedding also accounted for jet v_2 and its associated uncertainty (discussed later) by weighting the distribution of the $p+p$ HT jets with respect to the event planes of the Au+Au MB events; different hadronic correction schemes were also investigated. The effects of the tower efficiency and jet v_2 on the jet energy scale are found to be negligible, as is the effect of the hadronic correction scheme on the final results.

In order to analyze the jet correlation signal in Au+Au collisions it is necessary to subtract the large combinatoric background in heavy-ion collisions. The background levels are estimated by fitting the functional form in (1)

$p_T^{\text{jet,rec}}$ (GeV/c)	ΣD_{AA} (GeV/c)	Detector Uncertainties	v_2 and v_3 Uncertainties	Jet Energy Scale Uncertainties
10 – 15	-0.6 ± 0.2	$+0.2$ -0.2	$+3.7$ -0.5	$+2.3$ -0.0
15 – 20	-1.8 ± 0.3	$+0.3$ -0.3	$+1.0$ -0.0	$+1.9$ -0.0
20 – 40	-1.0 ± 0.8	$+0.1$ -0.8	$+1.2$ -0.1	$+0.3$ -0.0

TABLE I. Awayside ΣD_{AA} values are shown with their statistical uncertainties as well as uncertainties due to detector effects, the shape of the combinatoric background, and the trigger jet energy scale (given by the ΔE and ΣD_{AA} shifts).

to the raw $\Delta\phi$ distributions in Au+Au and $p+p$, with the flow terms constrained to zero for the latter. The shape of the Au+Au background is not well-constrained because v_2^{jet} and v_3^{jet} have not yet been measured experimentally. Therefore the uncertainties are investigated using two diametrically opposed assumptions. To assess the effect of the uncertainty in the shape of the background, the assumption is made that Au+Au HT trigger jets undergo no medium modification. Then to assess the effect of the uncertainty in the jet energy scale, the assumption is made that Au+Au HT trigger jets are maximally modified, which is the case when $v_2^{\text{jet}} = v_3^{\text{jet}} = 0$.

First, it is assumed that the Au+Au HT trigger jets undergo no modification and are equivalent to $p+p$ HT trigger jets (at all p_T^{assoc}). It is expected, based on jet quenching model studies [36], that the combination of the constituent p_T cut and the HT trigger requirement biases the jet population towards unmodified jets. When fitting the $\Delta\phi$ distributions with the functional form in (1) the nearside yields and widths in Au+Au are fixed to the values measured in $p+p$, $v_2^{\text{assoc}}v_2^{\text{jet}}$ is fixed to a reasonable mean value and $v_3^{\text{assoc}}v_3^{\text{jet}}$ is left as a free parameter. The mean v_2^{assoc} is estimated to be the average of $v_2\{\text{FTPC}\}(p_T^{\text{assoc}})$ and $v_2\{4\}(p_T^{\text{assoc}})$, while v_2^{jet} is estimated to be $v_2\{\text{FTPC}\}(6 \text{ GeV}/c)$, where $v_2\{\text{FTPC}\}$ and $v_2\{4\}$ are parameterized as functions of p_T from STAR minimum bias data in [37]. Here, $v_2\{\text{FTPC}\}$ is estimated with respect to the event plane determined in the Forward Time Projection Chambers ($2.4 < |\eta| < 4.2$) [38] and $v_2\{4\}$ is determined using the 4-particle cumulant method [39]. The $v_3^{\text{assoc}}v_3^{\text{jet}}$ values that result from the fits are reasonable when compared to measurements from PHENIX [40]. The systematic uncertainties are determined by fixing $v_2^{\text{assoc}}v_2^{\text{jet}}$ to maximum and minimum values while letting $v_3^{\text{assoc}}v_3^{\text{jet}}$ float to force the Au+Au nearside yields to match $p+p$. The lower and upper limits on v_2^{assoc} are estimated to be $v_2\{4\}(p_T^{\text{assoc}})$ and $v_2\{\text{FTPC}\}(p_T^{\text{assoc}})$. The lower and upper bounds on v_2^{jet} are conservatively estimated to be 70% and 130% of $v_2\{\text{FTPC}\}(6 \text{ GeV}/c)$, respectively. Additionally, it is observed in Fig. 1 that the shape of the jet energy spectrum in Au+Au does not quite match the spectrum of $p+p$ HT jets embedded in Au+Au MB events, even after accounting for detector effects. The spectrum shape mismatch is attributed to an incomplete understanding of the back-

ground. The difference in spectra shapes is encompassed by a $\Delta E = +1 \text{ GeV}/c$ shift in the Au+Au trigger jet p_T , as shown in Fig. 1.

The second assumption is that the Au+Au HT trigger jets are maximally modified compared to $p+p$ HT trigger jets. The background conditions that allow maximum increases in the nearside widths and yields are $v_2^{\text{assoc}}v_2^{\text{jet}} = 0$ and $v_3^{\text{assoc}}v_3^{\text{jet}} = 0$. Under this assumption, $\Sigma D_{AA} = 0$ when the parent parton energies are correctly matched, even though $p_T^{\text{jet,rec,Au+Au}} \neq p_T^{\text{jet,rec,p+p}}$ because $p_T^{\text{jet,rec}}$ is calculated only from charged tracks and neutral towers with $p_T > 2 \text{ GeV}/c$. The shift in the Au+Au trigger jet energy necessary to force ΣD_{AA} to zero defines another systematic uncertainty estimate. Figure 2 shows background-subtracted $\Delta\phi$ distributions with systematic uncertainties due to the two opposing assumptions described above.

The nearside jet is expected to have a surface bias [41] which makes it more likely that the recoil parton will travel a significant distance through the medium, therefore enhancing partonic energy loss effects and quenching on the awayside. The awayside Gaussian widths (σ_{AS}), D_{AA} , and ΣD_{AA} are reported here for different ranges in $p_T^{\text{jet,rec}}$. The awayside widths, shown in Fig. 3, at high p_T^{assoc} are the same in $p+p$ and Au+Au on average, indicating that jets containing high- p_T fragments are not largely deflected by the presence of the medium. The widths at low p_T^{assoc} are indicative of broadening. However, as the low- p_T^{assoc} widths are anticorrelated with the magnitude of $v_3^{\text{assoc}}v_3^{\text{jet}}$, measurements of v_n^{jet} are necessary before quantitative conclusions are drawn. The awayside D_{AA} , shown in Fig. 4, exhibits suppression of high- p_T^{assoc} hadrons and enhancement of low- p_T^{assoc} jet fragments in Au+Au, indicating that the jets in Au+Au are significantly softer than those in $p+p$ collisions. The ΣD_{AA} values, shown in Table I, indicate that the high- p_T^{assoc} suppression is balanced in large part by the low- p_T^{assoc} enhancement.

Theoretical calculations from YaJEM-DE [42], a Monte Carlo model of in-medium shower evolution, are also shown for σ_{AS} and D_{AA} in Figs. 3 and 4 [35]. This model incorporates both radiative and elastic energy loss, and describes many high- p_T observables from RHIC. After the intrinsic transverse momentum imbalance, k_T , of the initial hard scattering was tuned to provide the best fit to the $p+p$ baseline yields ($Y_{AS,p+p}$), this model of

jet-medium interactions largely reproduces several of the quantitative and qualitative features observed in data. At high p_T^{assoc} the Au+Au and $p+p$ widths match and the jet yields are suppressed, while the missing energy appears as an enhancement and broadening of the soft jet fragments.

To conclude, jet-hadron correlations, which are azimuthal angular correlations triggered by reconstructed jets, are used for the first time to investigate the modification of the properties of partons that traverse the medium created in heavy-ion collisions. The trigger/nearside jet sample is highly biased towards jets that have not interacted with the medium, which may enhance the effects of jet-quenching on the recoil/awayside jet. While the widths of the awayside jet peaks are suggestive of medium-induced broadening, they are highly dependent on the shape of the subtracted background; measurements of v_2^{jet} and v_3^{jet} are needed before additional quantitative conclusions about broadening can be made. It is observed that the suppression of the high- p_T associated particle yield is in large part balanced by low- p_T^{assoc} enhancement. The redistribution of energy from high- p_T fragments to low- p_T fragments that remain correlated with the jet axis is quantitatively consistent with the YaJEM-DE model of in-medium shower modification, and in general, qualitatively consistent with radiative/collisional energy loss models.

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