Medium Modification of Jet Fragmentation in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV Measured in Direct Photon-Hadron Correlations

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The jet fragmentation function is measured with direct photon-hadron correlations in $p + p$ and Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The p_T of the photon is an excellent approximation to the initial p_T of the jet and the ratio $z_T = p_T^h/p_T^\gamma$ is used as a proxy for the jet fragmentation function. A statistical subtraction is used to extract the direct photon-hadron yields in Au + Au collisions while a photon isolation cut is applied in $p + p$. I_{AA}, the ratio of hadron yield opposite the photon in Au + Au to that in

$p + p$, indicates modification of the jet fragmentation function. Suppression, most likely due to energy loss in the medium, is seen at high z_T. The associated hadron yield at low z_T is enhanced at large angles. Such a trend is expected from redistribution of the lost energy into increased production of low-momentum particles.

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Experiments at the Relativistic Heavy Ion Collider have observed the formation of a quark-gluon plasma, reported as a fundamentally new state of matter [1–4]. High momentum quarks and gluons (partons) lose energy as they traverse this matter, resulting in the observed suppression of high transverse momentum (high p_T) hadrons in central heavy-ion collisions [5–10].

Direct photons, however, escape the medium unmodified [11], since they do not interact via the strong force. This makes them an ideal probe with which to calibrate the energy of an initial hard scattering. At leading order, direct photons are predominantly produced via the quantum-chromodynamics analog of Compton scattering, $q + g \rightarrow q + \gamma$. In the limit of negligible initial transverse momentum, the final state quark and photon are emitted back to back in azimuth with the photon balancing the transverse momentum of the jet arising from the quark. Determining the initial momentum of the parton is key to measuring the fragmentation function of the quark jet. This initial momentum is provided by the measured energy of the unmodified direct photon, via direct photon-hadron correlations [12]. A study of direct photon-hadron correlations in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV has provided a measurement of the quark fragmentation function in agreement with measurements from e^+e^- collisions [13]. In Au + Au collisions, the contributions from next-to-leading-order processes, such as fragmentation photons and medium induced photon production, are expected to be small ($\approx 10\%$) at high p_T [14].

Parton energy loss in the medium can be observed as a modification to the jet fragmentation function in heavy ion collisions. The fragmentation function is defined as $D(z) = (1/N_{\rm jet})(dN(z)/dz)$, where $z = p^h/p^{\rm jet}$; $p^{\rm jet}$ is the initial jet momentum, and p^h is the momentum of a hadronic jet fragment. Experimentally, this is accessible using direct photon-hadron correlations, where $p_T^\gamma \approx p_T^{\rm jet}$. This balance is only approximate due to the transverse momentum, k_T, of the colliding partons inside nucleons, which on average introduces a transverse momentum imbalance and acoplanarity to the photon and its opposing jet. The measured value of k_T is ~ 3 GeV/c in both $p + p$ and $d +$ Au collisions with no measured difference in k_T smearing [15,16]. Furthermore, the good agreement between $p + p$ and e^+e^- measurements indicates that any difference seen between $p + p$ and Au + Au is not due to k_T smearing.

Several energy loss models [14,17] predicting direct photon-hadron correlations only track the medium induced parton splitting of the leading parton. Other models follow the lost energy, leading to an increase in low momentum (soft) particle production. In particular, Borghini and Weidemann [18] use the modified leading log approximation (BW-MLLA) and local parton hadron duality to first reproduce the measured fragmentation function in e^+e^- data. Modeling the energy loss in the medium as an increased parton splitting probability, they calculate the suppression of high p_T jet fragments, as well as the redistribution of energy to lower p_T fragments and resulting enhancement at low z. The resulting $R_{\rm AA}$ reproduces the PHENIX π^0 measurement for 0%–10% central events. The yet-another-jet-energy-loss model (YaJEM) [19] traces the energy lost via gluon radiation and redistribution to soft particle production, predicting a suppression of particles at high z and an enhancement at low z. This calculation has been done specifically for $\gamma_{\rm dir}$-h, making it directly comparable to this data. The predicted low-z_T enhancement has not yet been observed within the statistical and systematic limitations of previously published data [20,21].

In this Letter, we report fragmentation functions measured in Au + Au and $p + p$ collisions determined from the yield of hadrons recoiling opposite to direct photons (i.e., the "away side"). The extraction of a purely direct-photon sample is complicated by the presence of photons from meson decays (dominantly $\pi^0 \rightarrow \gamma\gamma$), which must be removed from the inclusive photon-hadron correlations. PHENIX has previously established the extraction of direct photon-hadron correlations via a statistical subtraction procedure in Au + Au collisions [20] and via an isolation cut in $p + p$ collisions [13], wherein higher-order sources of photons were shown to be negligible.

This analysis includes 3.9 billion minimum bias Au + Au events collected by PHENIX in 2007 and 2.9 billion in 2010, after quality cuts. The $p + p$ data set comprises 0.5 billion photon-triggered events collected in 2005 and 2006, corresponding to total recorded integrated luminosities of 3.8 (2005) and 10.7 (2006) pb^{-1}, respectively. Details on the $p + p$ measurement were previously presented in [13]. The kinematic reach and improved statistical precision of both data sets allow us to extend previous measurements [20,21], reaching a low momentum fraction, $z \approx 0.1$, where interplay between the medium and the deposited energy may be important [9].

The Au + Au minimum bias events are triggered by particles firing the beam-beam counters, which are arrays of Čerenkov counters covering $3.1 < |\eta| < 3.9$ and 2π in azimuth. The beam-beam counters are also used to determine the collision centrality and the collision vertex position along the beam direction. The 0%–40% most central collisions are presented here. Photons and hadrons are measured in two central spectrometers spanning $\pi/2$ in azimuth and ± 0.35 units of pseudorapidity each [22]. The photons are measured in one of two electromagnetic calorimeters [23] and charged hadrons are measured by reconstructing tracks in the drift chambers and pad chambers [24].

Inclusive photon-hadron correlations are determined from the distribution of photon-hadron pairs as a function of their azimuthal angular separation, $\Delta\phi$. The distribution of real pairs is divided by photon-hadron pairs in mixed events to correct for the PHENIX acceptance.

The conditional, or per trigger, associated yield is extracted after subtraction of photon-hadron pairs from the bulk underlying event [15]. In heavy-ion collisions, such particles are expected to be correlated to one another through the bulk anisotropy of the event, which is conventionally characterized by the Fourier coefficients v_n. Neglecting higher order terms, and using previously measured v_2 [25] for associated hadrons, inclusive and decay photons, this bulk is removed from the per-trigger yields according to:

$$\frac{1}{N^t}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{1}{N^t}\frac{N^{\rm pair}_{\rm real}}{\epsilon^a \int d\Delta\phi}\left\{\frac{dN^{\rm pair}_{\rm real}/d\Delta\phi}{dN^{\rm pair}_{\rm mix}/d\Delta\phi} - b_0[1 + 2\langle v_2^t v_2^a\rangle \cos(2\Delta\phi)]\right\}, \quad (1)$$

where the subscripts t and a refer to trigger and associated particle, ϵ^a is the detection efficiency for the associated particle, and b_0 indicates the level of background pairs. An absolute background normalization is used to fix the background level, b_0, as described in [26], which makes up more than 95% of the total yield at low pair p_T, and $\sim$25% at high p_T. The $\langle v_2^t v_2^a\rangle$ term modulates the background rate by less than 1% as a function of $\Delta\phi$, to account for correlations arising from flow of the bulk. In $p+p$ collisions, the underlying event is subtracted assuming the yield of photon-hadron coincidences is zero at the minimum point in the correlation as a function of $\Delta\phi$. The lowest three points outside the isolation cut region are averaged; as there is no flow in $p+p$ collisions, the background is assumed to be flat in $\Delta\phi$. A GEANT simulation of the detector determined the acceptance and efficiency for the measured charged hadrons, ϵ^a, starting at $\sim$35% at low p_T and plateauing at $\sim$45%. The uncertainty on ϵ^a leads to an 8.8% overall and 8.0% normalization uncertainty on the yields for the Au + Au and $p+p$ data, respectively.

The potential effect of ignoring v_3 in the background subtraction in Au + Au is studied by extrapolating the PHENIX hadron v_3 measurements [25]. Including a modulation of the background by this v_3 in addition to the v_2 results in a change in the away-side yield on the order of a few percent, depending on $\Delta\phi$ and p_T. The resulting background shape uncertainty is minimal for the highest hadron p_T selections used here due to the low level of combinatorial background. The v_3 effect is included as an additional systematic uncertainty on the background subtraction.

In Au + Au, a statistical subtraction determines the direct (i.e., nondecay) photon-hadron correlations from the measured inclusive photon-hadron correlations. Using the measured associated hadron yield per inclusive photon, $Y_{\rm inc} = 1/N_{\rm inc} dN^{h-\gamma_{\rm inc}}/d\Delta\phi$, and per decay photon, $Y_{\rm dec}$, the associated yield per direct photon, $Y_{\rm dir}$, is determined by [20]:

$$Y_{\rm dir} = \frac{R_\gamma Y_{\rm inc} - Y_{\rm dec}}{R_\gamma - 1}, \quad (2)$$

where R_γ is the ratio of inclusive photons to decay photons, which was reported by PHENIX in [11]. R_γ ranges from $\sim$1.4 to $\sim$2.3, as the photon p_T increases, for the centrality and momentum ranges used here.

To measure the decay photon contribution, π^0-h correlations are constructed following the same method as above using π^0s as the trigger. The π^0s are reconstructed from photon pairs whose invariant mass is within the window of 0.12–0.16 GeV$/c^2$. The π^0-h correlations are translated into decay photon-hadron correlations according to a Monte Carlo study of the probability that a π^0 with a given p_T produces a decay photon within a certain p_T bin. This procedure is explained in detail in [20].

In $p+p$ collisions, $\gamma_{\rm dir}$-h yields were measured using an isolation cut, and removing decay photons from the inclusive sample on an event-by-event basis [13]. In the analysis, photons which combine with another photon in the event to produce a mass within the π^0 or η mass windows were rejected. Next, an isolation cut was applied, requiring that the transverse electromagnetic energy and charged track momentum within a cone of 0.3 rad around the photon be less than 10% of the photon energy. Finally, a statistical subtraction similar to that in the Au + Au analysis eliminated contributions from decay photons, which appeared isolated or whose decay partner was lost due to finite detector acceptance or efficiency. By first eliminating photons from other sources event by event, the signal to background ratio is improved and final uncertainties are reduced. The $p+p$ results using the isolation cut agree with a statistical subtraction analysis in $p+p$, but have smaller uncertainties.

In order to study the jet fragmentation function, $D(z)$, associated hadron yields are determined as a function of $z_T = p_T^h/p_T^\gamma$, the ratio of the associated hadron transverse momentum, p_T^h, to the trigger photon transverse momentum, p_T^γ. Here $z_T \approx z$, since direct photon triggers balance the opposing jet. To focus on the low z_T region, one can express the fragmentation function as a function of the variable, $\xi = \ln(1/z_T)$. To extend the accessible z_T range,

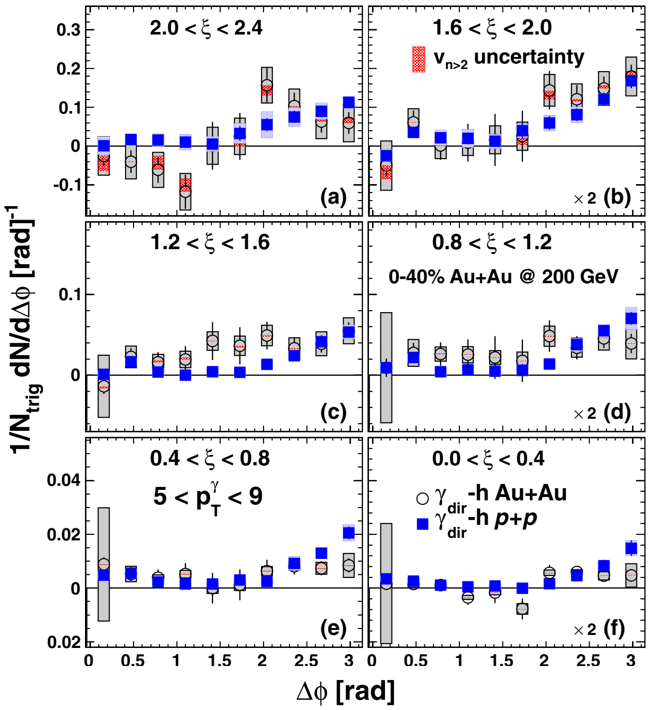

FIG. 1 (color online). $\Delta\phi$ distributions for (a) $2.0 < \xi < 2.4$, (b) $1.6 < \xi < 2.0$, (c) $1.2 < \xi < 1.6$, (d) $0.8 < \xi < 1.2$, (e) $0.4 < \xi < 0.8$, and (f) $0.0 < \xi < 0.4$ for direct photons (circles) for the 0%–40% most central Au + Au collisions and the $p + p$ reference (squares) in all panels. The data shown in panels (b), (d), and (f) are multiplied by a factor of 2 as indicated.

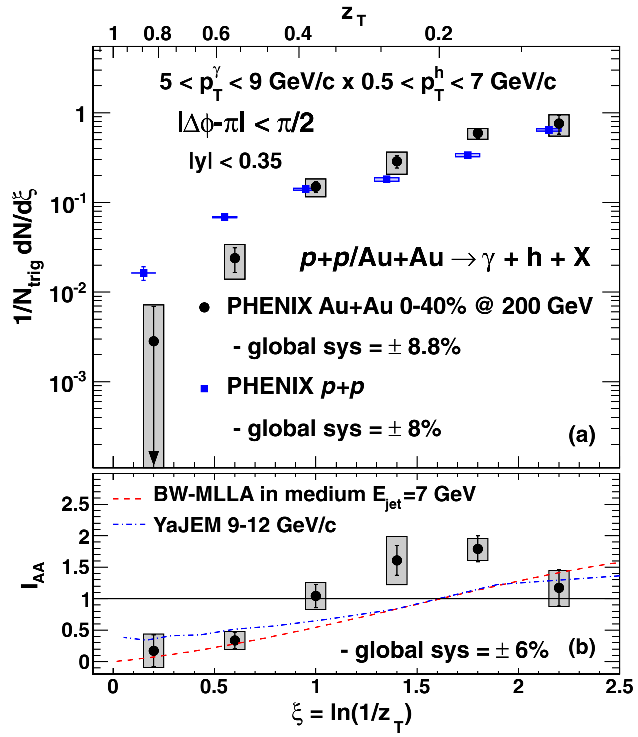

FIG. 2 (color online). Panel (a) shows per trigger yield as a function of ξ for $p + p$ collisions (squares) and 0%–40% most central Au + Au collisions (circles). The points are shifted for clarity. For reference, the dependence on z_T is also indicated. Panel (b) shows I_{AA}, the ratio of Au + Au to $p + p$ fragmentation functions. Also shown are predictions from BW-MLLA [18] (dashed line), calculated at $E_{jet} = 7$ GeV with $f_{med} = 0.8$ selected for 0%–10% central Au + Au and from YaJEM-DE [27,28] (dot-dashed curve) for 0%–40% centrality and trigger photons from 9–12 GeV/c, both for the full away side ($|\Delta\phi - \pi| < \pi/2$).

hadrons from $0.5 < p_T < 7.0$ GeV/c are used in combination with a single $5 < p_T^\gamma < 9$ GeV/c photon bin.

Figure 1 shows azimuthal pair angle distributions for the extracted direct γ-h correlations in 0%–40% central Au + Au collisions as well as comparison with the direct γ-h correlations in $p + p$. The systematic uncertainties arise from the absolute normalization procedure, v_2 estimation, and R_γ. The estimated uncertainty from higher flow moments is shown separately and is only significant for the highest ξ pairs.

Unlike on the away side, on the trigger side ($|\Delta\phi| < \pi/2$) the direct γ-h correlations in Au + Au show an integrated yield consistent with zero when considering systematic uncertainties, which are dominated by the lowest $\Delta\phi$ point, indicating that the statistical subtraction method indeed yields direct photons and that the yield of fragmentation photons in Au + Au is negligible within uncertainties.

On the away side the associated particle yield is visible, and there is significant variation when comparing the correlations in Au + Au to $p + p$. To further quantify this variation, the yields are integrated over $\Delta\phi$ for $|\pi - \Delta\phi| < \pi/2$, as a function of ξ, to obtain the effective fragmentation function. Figure 2(a) shows the integrated away-side yields in Au + Au and $p + p$ as circles and squares, respectively. The statistical error bars include the point-to-point uncorrelated systematic uncertainty from the background subtraction, while the boxes around the points show the correlated uncertainties. For reference, the dependence on z_T is also indicated as the upper scale axis label.

To study medium modification of the jet fragmentation function, we take a ratio of the ξ distribution in Au + Au to $p + p$. This ratio, known as I_{AA}, is shown in Fig. 2(b) and can be written as $I_{AA} = Y^{\mathrm{Au+Au}}/Y^{p+p}$. Much of the global scale uncertainty cancels in this ratio, but there is a remaining 6% uncertainty. In the absence of modification, I_{AA} would equal 1. The data instead indicate suppression at low ξ and enhancement at higher ξ. Including all systematic uncertainties the χ^2/DOF value for the highest four points compared to the hypothesis that $I_{AA} = 1$ is 17.6/4, corresponding to a probability that I_{AA} is 1.0 for $\xi > 0.8$ of less than 0.1%.

The dashed curve in Fig. 2(b) shows I_{AA} calculated at $E_{jet} = 7$ GeV using the BW-MLLA model in medium and in vacuum. The vacuum calculation agrees well with the

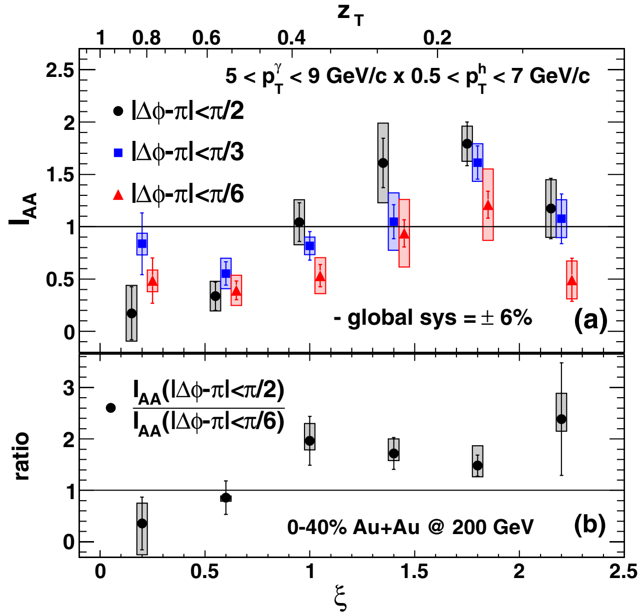

FIG. 3 (color online). Panel (a) shows the I_{AA} for the full away side ($|\Delta\phi - \pi| < \pi/2$) (circles) and for two restricted away-side integration ranges, $|\Delta\phi - \pi| < \pi/3$ (squares) and $|\Delta\phi - \pi| < \pi/6$ (triangles). The points are shifted for clarity. Panel (b) shows the ratio of the I_{AA} for $|\Delta\phi - \pi| < \pi/2$ to $|\Delta\phi - \pi| < \pi/6$.

measured ξ distribution in e^+e^-, and the in-medium conditions reproduce the measured π^0 R_{AA} at high-p_T for 0%–10% central Au + Au events [18]. The dot-dashed curve shows I_{AA} predicted by YaJEM-DE [27] for trigger photons from 9–12 GeV/c for the same centrality range (0%–40%) as the present data [28]. Both models, which include all away-side jet fragments, show suppression at low ξ due to parton energy loss in Au + Au collisions and increasing I_{AA} with increasing ξ, as observed in the data. In both cases, this is due to the lost energy being redistributed into enhanced production of lower momentum particles. We note that the energies in the available calculations do not exactly match the momentum range of the trigger photons in the data. However, large deviations in the trend of these calculations as a function of jet energy are not expected.

The large uncertainties and clear modification to the $\Delta\phi$ distributions in Au + Au make it difficult to choose an away-side integration range that unambiguously encompasses the opposing jet. As shown in Fig. 3(a), I_{AA} was determined in three integration ranges in order to better understand the $\Delta\phi$ dependence of the observed modification and the angular distribution of particles on the away side. Reducing the integration range from $|\Delta\phi - \pi| < \pi/2$ reduces the observed enhancement and shifts the effect to higher ξ. If the integration range is restricted to $|\Delta\phi - \pi| < \pi/6$, the enhancement for $\xi > 1.0$ becomes negligible, while still showing significant suppression for $\xi < 0.8$.

The systematic and statistical uncertainties shown in Fig. 3(a) are partially correlated due to the overlap in integration ranges. Therefore, to better quantify the significance of the angular range of the enhancement, we can look at the ratio of I_{AA}'s, where such correlations cancel. Figure 3(b) shows the ratio of the full away-side integration range to the $|\Delta\phi - \pi| < \pi/6$ case. From this ratio it is clear that there is a significant variation in observed I_{AA} as a function of the integration range. The average ratio for $\xi > 0.8$ is $1.9 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})$, indicating that the enhancement in I_{AA} seen at large ξ is predominantly at large angles ($|\Delta\phi - \pi| > \pi/6$). Related measurements using full jet reconstruction at the Large Hadron Collider at much higher jet energies, do not show a broadening in the angular distribution of jets with respect to trigger photons [29], but do show evidence for the broadening of the jets themselves [30], which would result in a modification to the observed fragmentation function in the present analysis.

In summary, we have presented evidence for medium modification of jet fragmentation, measured via comparison of direct photon-hadron correlations in $\sqrt{s_{NN}} = 200$ GeV Au + Au and $p + p$ collisions. The ratio of Au + Au to $p + p$ yields indicates that particles are depleted at low ξ or high momentum fraction, z_T, due to the energy loss of quarks traversing the medium. The ratio exhibits an increasing trend toward high ξ, exceeding one at $\xi \geq 1.0$. Restricting the away-side azimuthal integration range reduces the enhancement at high ξ significantly. This suggests that the medium enhances production of soft particles in parton fragmentation, relative to $p + p$, preferentially at large angles.

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