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## Measurement of jet-medium interactions via direct photon-hadron correlations in Au + Au and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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We present direct photon-hadron correlations in 200 GeV/A Au + Au,  $d + Au$ , and  $p + p$  collisions, for direct photon  $p_T$  from 5–12 GeV/ $c$ , collected by the PHENIX Collaboration in the years from 2006 to 2011. We observe no significant modification of jet fragmentation in  $d + Au$  collisions, indicating that cold nuclear matter effects are small or absent. Hadrons carrying a large fraction of the quark’s momentum are suppressed in Au + Au compared to  $p + p$  and  $d + Au$ . As the momentum fraction decreases, the yield of hadrons in Au + Au increases to an excess over the yield in  $p + p$  collisions. The excess is at large angles and at low hadron  $p_T$  and

is most pronounced for hadrons associated with lower momentum direct photons. Comparison to theoretical calculations suggests that the hadron excess arises from medium response to energy deposited by jets.

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## I. INTRODUCTION

Collisions of heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) produce matter that is sufficiently hot and dense to form a plasma of quarks and gluons [1]. Bound hadronic states cannot exist in a quark gluon plasma, as the temperatures far exceed the transition temperature calculated by lattice quantum chromodynamics (QCD) [2]. Experimental measurements and theoretical analyses have shown that this plasma exhibits remarkable properties, including opacity to traversing quarks and gluons [3,4]. However, the exact mechanism for energy loss by these partons in quark-gluon plasma and the transport of the deposited energy within the plasma is not yet understood.

Experimental probes to address these questions include high momentum hadrons, reconstructed jets, and correlations among particles arising from hard partonic scatterings [1] occurring in the initial stages of the collision. Direct photons are produced dominantly via the QCD analog of Compton scattering,  $q + g \rightarrow q + \gamma$ , at leading order, and do not interact via the strong force as they traverse the plasma. In the limit of negligible initial partonic 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. Consequently, measuring the correlation of high momentum direct photons with opposing hadrons allows investigation of quark-gluon plasma effects upon transiting quarks and their fragmentation into hadrons.

Correlations of direct photons with hadrons and jets have been measured by the PHENIX [5,6] and STAR [7] Collaborations at RHIC, and by the CMS and ATLAS Collaborations at the Large Hadron Collider [8–14]. Using the photon energy to tag the initial energy of the quark showed that quarks lose a substantial amount of energy while traversing the plasma [6,15]. The photon tag also allows construction of the quark fragmentation function  $D(z)$ , where  $z = p^{\text{hadron}}/p^{\text{parton}}$ . Here,  $z$  represents the fraction of the quark's original longitudinal momentum carried by the hadrons. In photon-hadron ( $\gamma$ -h) correlations,  $z$  can be approximated by  $z_T = p_T^{\text{hadron}}/p_T^\gamma$ . Comparison of  $\gamma$ -h correlations in heavy ion collisions to those in  $p + p$  collisions quantifies the plasma's impact on parton fragmentation.  $\gamma$ -h correlations in  $p + A$  or  $d + A$  collisions will reflect any cold nuclear matter modification of jet fragmentation. The CMS Collaboration also studied jets correlated to neutral  $Z$  bosons [16].

At RHIC, the fragmentation function is substantially modified in central Au + Au collisions [6,17]. High  $z$  fragments are suppressed, as expected from energy loss. Low  $z$  fragments are enhanced at large angles with respect to the jet core, i.e., with respect to the original quark direction. CMS and ATLAS have measured jet fragmentation functions using reconstructed jets to tag the parton energy. These studies, conducted with jet energies of  $\approx 100$  GeV, show enhancement

of low  $p_T$  (i.e., low  $z$ ) jet fragments in central Pb + Pb collisions [18,19]. In addition, CMS has shown that the energy lost by the quark is approximately balanced by hadrons with approximately 2 GeV  $p_T$  [20] in the intrajet region. This is in qualitative agreement with the RHIC result, even though the initial quark energy differs by an order of magnitude.

There has been considerable theoretical effort to describe jet-medium interactions. Several mechanisms for parton energy loss were compared by the JET Collaboration [21]. The medium response to deposited energy is now under study by several groups [22–25]. The deposited energy may be totally equilibrated in the plasma, but alternatively the deposited energy may kick up a wake in the expanding plasma [22,26]. Different descriptions of plasma-modified gluon splitting result in different fragmentation functions, and can be tested by comparing the predictions to direct photon-hadron ( $\gamma_{\text{dir}}$ -h) correlations.

The previously published analysis of  $\gamma_{\text{dir}}$ -h correlations showed an enhancement in soft particle production at large angles. However, due to limited statistics, it was not possible to investigate how the fragmentation function depends on the parton energy or the medium scale. In this paper, we explore this question by looking at the direct photon  $p_T$  dependence of the fragmentation function modification. We investigate whether enhancement over the fragmentation function in  $p + p$  collisions depends on the fragment  $z_T$  or on the fragment  $p_T$ . That is, does it depend on the jet structure or does it reflect the distribution of particles in the medium? We also present first results on  $\gamma_{\text{dir}}$ -h correlations in  $d + Au$  collisions to investigate possible cold-nuclear-matter effects on the fragmentation function. Fragmentation function modification is quantified here by the nuclear modification factor,  $I_{AA}$ , which is a ratio of the fragmentation function in Au + Au collisions to that in  $p + p$  collisions.

## II. DATASET AND ANALYSIS

In 2011, PHENIX collected data from Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. After event selection and quality cuts,  $4.4 \times 10^9$  minimum-bias (MB) events were analyzed. These are combined with the previously reported  $3.9 \times 10^9$  MB Au + Au events from 2007 and  $2.9 \times 10^9$  from 2010 [6]. The high momentum photon triggered  $d + Au$  data set at  $\sqrt{s_{NN}} = 200$  GeV was collected in 2008, and  $3 \times 10^9$  events are analyzed. The  $p + p$  comparison data are from 2005 and 2006 [15].

The measurements in this paper use the PHENIX central spectrometers [27]. Two-particle correlations are constructed by pairing photons or  $\pi^0$ 's measured in the electromagnetic calorimeter (EMCal) [28] with charged hadrons reconstructed in the drift chambers and pad chambers [29]. The acceptance in pseudorapidity is  $|\eta| < 0.35$ , while each spectrometer arm covers  $90^\circ$  in azimuth. Beam-beam counters [30], located at

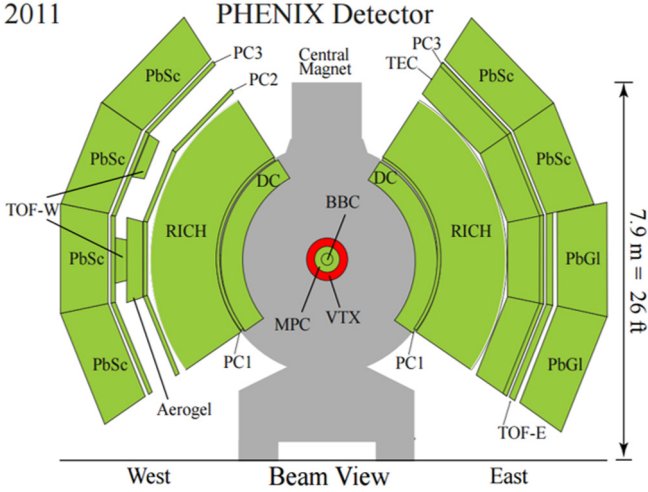


FIG. 1. Side view of the PHENIX central arm spectrometers in 2011.

1.44 m from the center of the interaction region, cover the pseudorapidity range from 3.0 to 3.9 and full azimuthal angle. They are used to determine the collision centralities and vertex positions. Figure 1 shows the detector configuration in 2011.

Photons and  $\pi^0$ 's are measured in the EMCal. There are four sectors of lead-scintillator (PbSc) sampling calorimeters in the west arm, while the east arm has two sectors of lead-scintillator and two lead-glass (PbGl) Čerenkov calorimeters. The PbSc and PbGl calorimeters have energy resolutions of  $\sigma_E/\sqrt{E} = 8.1\%/\sqrt{E} \oplus 2.1\%$  and  $5.9\%/\sqrt{E} \oplus 0.8\%$ , respectively. Photons are selected via an electromagnetic shower shape cut [31] on energy clusters. The high granularity of the EMCal,  $\delta\eta \times \delta\phi = 0.011 \times 0.011$  for PbSc and  $0.008 \times 0.008$  for PbGl, allows for  $\pi^0$  reconstruction via the  $\pi^0 \rightarrow \gamma\gamma$  channel (invariant mass = 120–160 MeV/ $c^2$ ) up to  $p_T = 15$  GeV, beyond which shower merging becomes significant. A charged track veto is applied to remove possible hadron or electron contamination in the photon sample, reducing auto-correlations in the measurement. The EMCal system is also used to trigger on  $d + \text{Au}$  events with high  $p_T$  photons.

Two-particle correlations are constructed as a function of  $\Delta\phi$ , the azimuthal angle between photon or  $\pi^0$  triggers and associated hadron partners. Pairs arise from jet correlations superimposed on a combinatorial background from the underlying event. In  $p + p$  and  $d + \text{Au}$  collisions where the event multiplicity is low, we treat this background as flat in  $\Delta\phi$  and subtract it, normalizing the level via the zero-yield-at-minimum (ZYAM) procedure [32]. In Au + Au collisions, the background has an azimuthal asymmetry quantified in the flow parameters  $v_n$ , which are used to modulate the subtracted background, as described in Eq. (1). Only  $v_2$  is included in the subtraction, while higher-order effects are included as an additional systematic uncertainty on the final results.

We report jet pairs as conditional (or per-trigger) yields of hadrons. Detector acceptance corrections are determined using mixed events with similar centrality and collision vertex. For Au + Au collisions, the background level  $b_0$  is estimated using an absolute normalization [32], determined from the

uncorrelated single-photon and single-hadron production rates. The final invariant yield of associated hadrons is obtained by dividing the background-subtracted correlated hadron yields by the number of triggers  $N_t$  and correcting for the associate charged hadron efficiency  $\epsilon^a$ , determined by a GEANT detector simulation:

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

where  $v_2^t$  and  $v_2^a$  are the elliptic flow magnitudes independently measured for the trigger and associated particles, respectively [6]. These modulate the angular distribution of the background. Lastly,  $N^{\text{pair}}$  denotes the number of trigger-associate pairs. The subscript “real” refers to a trigger-associate particle pair that came from the same event, and the subscript “mix” refers to trigger-associate pairs that come from different events and are used to correct for correlations due to detector effects.

In both Au + Au and  $d + \text{Au}$  analyses, photons with transverse momentum of 5 to 15 GeV/ $c$  are selected as triggers. To extract yields of hadrons associated with direct photons, the background from decay photon correlations with hadrons must be subtracted. In Au + Au collisions, where the multiplicity is high, this is achieved via a statistical subtraction procedure. If  $N_{\text{inc}}$ ,  $N_{\text{dec}}$ , and  $N_{\text{dir}}$  are the inclusive, decay, and direct photon yields, respectively, then  $N_{\text{dir}} = N_{\text{inc}} - N_{\text{dec}}$ . It follows that the conditional yield of hadrons  $Y$  for different photon trigger samples is

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

where  $R_\gamma \equiv N_{\text{inc}}/N_{\text{dec}}$  and is measured independently [33].

The decay photon background is estimated using measured  $\pi^0$ -hadron ( $\pi^0$ -h) correlations and a Monte Carlo pair-by-pair mapping procedure. The simulation calculates the probability distribution for decay photon-hadron ( $\gamma_{\text{dec}}$ -h) pairs in a certain photon  $p_T$  range as a function of the parent  $\pi^0$   $p_T$ .  $\gamma_{\text{dec}}$ -h correlations are constructed via a weighted sum over all individual  $\pi^0$ -hadron pairs, where the weighting factor reflects the kinematic probability for a  $\pi^0$  at a given  $p_T$  to decay into a photon in the selected  $p_T$  range. The  $\gamma_{\text{dec}}$ -h per-trigger yield can be described by the following equation:

$$Y_{\text{dec}} = \frac{\int \rho(p_T \pi^0 \rightarrow p_T \gamma) \epsilon^{-1}(p_T \pi^0) N_{\pi^0-h} d p_T \pi^0}{\int \rho(p_T \pi^0 \rightarrow p_T \gamma) \epsilon^{-1}(p_T \pi^0) N_{\pi^0} d p_T \pi^0}, \quad (3)$$

where  $\rho$  gives the probability that a  $\pi^0$  decays to a photon with  $p_T \gamma$ , and  $\epsilon$  is the  $\pi^0$  reconstruction efficiency, which can be determined by scaling the raw  $\pi^0$  spectra to a power law fit to published data [34].  $N_{\pi^0-h}$  and  $N_{\pi^0}$  are the number of  $\pi^0$ -h pairs and number of  $\pi^0$ 's, respectively. When reconstructing the  $\pi^0$ , a strict cut on the asymmetry of the energy of the two photons is applied to reduce the combinatorial background from low energy photons. The probability weighting function, determined from Monte Carlo simulation, takes into account

the actual EMCal response, including energy and position resolution and detector acceptance.

With the  $\pi^0$  to decay photon  $p_T$  map,  $\rho$ , the inclusive photon sample can be separated into a meson decay component and a direct component. Of the meson decay component, 20% of the decay yield is from non- $\pi^0$  decays as calculated from previous PHENIX results [35]. To construct  $\gamma_{\text{dec-h}}$  yields with trigger photon  $p_T$  of 5–15 GeV/ $c$ , hadron correlations with  $\pi^0$  of  $4 \leq p_T \leq 17$  GeV/ $c$  are utilized. The slightly wider  $p_T$  range is chosen to account for decay kinematics, as well as  $p_T$  smearing from the EMCal energy and position resolution. An additional cutoff correction accounts for the small  $\gamma_{\text{dec-h}}$  yield in the trigger  $p_T$  range 5–15 GeV/ $c$  from  $\pi^0$  with  $p_T \geq 17$  GeV/ $c$ . The merging of decay photons from high  $p_T$   $\pi^0$  is not accounted for in the Monte Carlo mapping simulation. Instead, the efficiency to detect photons from a high momentum parent meson is calculated via GEANT simulation of the full detector response. This loss is included in the probability function as an additional correction. The opening angle of photon pairs that merge is small, thus they are removed from the measured inclusive photon sample by the shower shape cut.

In  $d + \text{Au}$  collisions, where the underlying event background is much smaller, it is possible to improve the signal to background for direct photons. This is done event by event using a photon isolation cut and by removing all photons identified (tagged) as resulting from a  $\pi^0$  decay [15]. First, all photons with  $p_T \geq 0.5$  GeV/ $c$  are paired. Those pairs with invariant mass between 120–160 MeV/ $c^2$  are tagged as decay photons and removed from the inclusive sample. Next, an isolation criterion is applied to the remaining photons to further reduce the background of decay photons, as well as contamination from fragmentation photons. The isolation cut requires that the energy in a cone around the trigger photon be less than 10% of the photon energy in  $p + p$  collisions. In the  $d + \text{Au}$  analysis, the cut is modified slightly to include the effect of the modest underlying event. The underlying event is evaluated separately for each  $d + \text{Au}$  centrality class, resulting in an isolation criterion:

$$\sum_{\Delta R < R_{\text{max}}} E < (E_\gamma * 0.1 + \langle E_{bg} \rangle), \quad (4)$$

where  $E$  is the measured energy in the isolation cone,  $E_\gamma$  is the photon energy,  $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$  is the distance between the trigger photon and other particles in the event and  $\langle E_{bg} \rangle$  is the average energy inside the cone in the underlying event. The cone size ( $R_{\text{max}}$ ) used in this analysis is 0.4.

To account for the  $d + \text{Au}$  underlying event, the ZYAM procedure [32] is applied to the angular correlation functions for each centrality class. As an isolation cut distorts the near-side yield, the minimum point is determined within the restricted  $\Delta\phi$  range of 0.9–1.6 rad. The zero-point yield is determined by integrating in a 0.03 rad range around the minimum point. The hadron conditional yield reported here is corrected for the PHENIX hadron acceptance. The ZYAM subtracted inclusive and decay yields for each centrality are combined using a weighted sum based on the number of each type of trigger to obtain the MB yields.

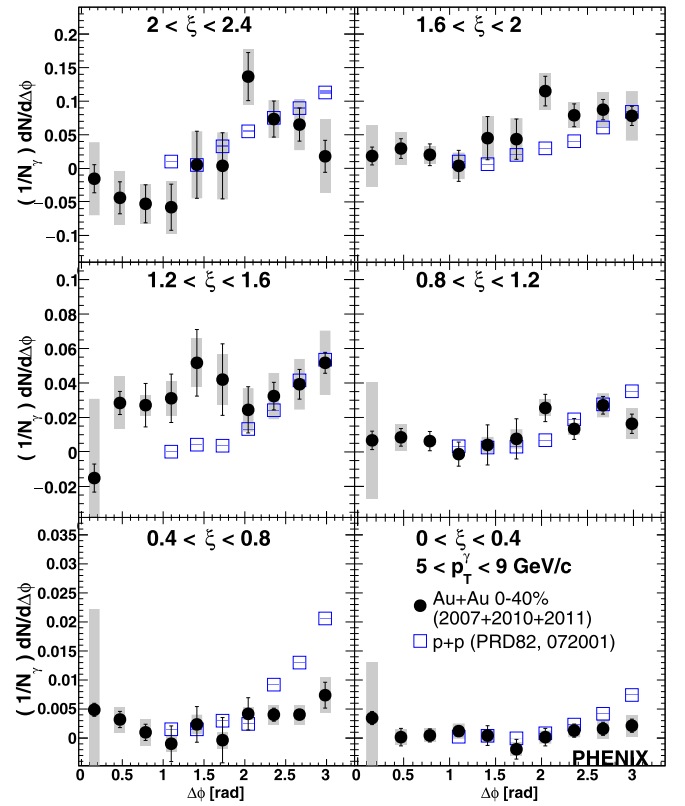


FIG. 2. Per-trigger yield of hadrons associated with direct photons in Au + Au collisions (closed [black] circles) for direct photon  $p_T$  5–9 GeV/ $c$ , compared with  $p + p$  baseline (open [blue] squares), in various  $\xi$  bins.

Some decay photons are missed by the  $\pi^0$  tagging procedure and slip through the isolation cut to be counted as direct photons. Such falsely isolated  $\gamma_{\text{dec-h}}$  correlations are corrected via a statistical subtraction, similar to Eq. (2). If we define  $N_{\text{inc-tag}}^{\text{iso}}$  as the yield of isolated photons after removing those isolated photon tagged as decay photons,  $N_{\text{dec}}^{\text{miss,iso}}$  as those decay photons that are isolated but not tagged as decay photons, and  $N_{\text{dir}}^{\text{iso}}$  as isolated direct photons, then  $N_{\text{dir}}^{\text{iso}} = N_{\text{inc-tag}}^{\text{iso}} - N_{\text{dec}}^{\text{miss,iso}}$ . It follows that the condition of yield of hadrons for direct, isolated photons is

$$Y_{\text{dir}}^{\text{iso}} = \frac{R_\gamma^{\text{eff}} Y_{\text{inc-tag}}^{\text{iso}} - Y_{\text{dec}}^{\text{miss,iso}}}{R_\gamma^{\text{eff}} - 1}, \quad (5)$$

where

$$R_\gamma^{\text{eff}} = \frac{N_{\text{inc}}^{\text{iso}}}{N_{\text{dec}}^{\text{iso}}} = \frac{R_\gamma}{(1 - \epsilon_{\text{dec}}^{\text{tag}})(1 - \epsilon_{\text{dec}}^{\text{iso}})} \frac{N_{\text{inc-tag}}^{\text{iso}}}{N_{\text{inc}}}, \quad (6)$$

where  $\epsilon_{\text{dec}}^{\text{iso}}$  is the isolation cut efficiency and  $\epsilon_{\text{dec}}^{\text{tag}}$  is the tagging efficiency. More detail on the subtraction procedures and cuts can be found in Refs. [5,15].

In the Au + Au analysis, there are four main sources of systematic uncertainties. The systematic uncertainty coming from the statistical subtraction method is due to the statistical and systematic uncertainties on the value of  $R_\gamma$ . There are also uncertainties when extracting the jet

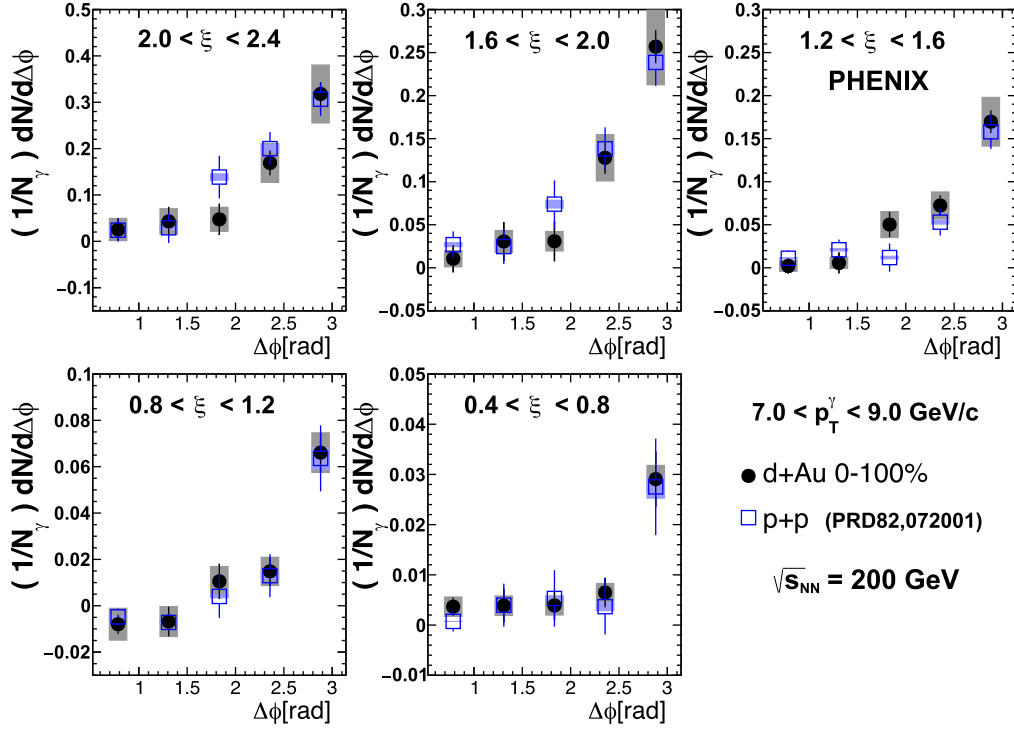


FIG. 3. Per-trigger yield of hadrons associated with direct photons in  $d + Au$  collisions (closed [black] circles) for direct photon  $p_T$  7–9 GeV/ $c$ , compared with  $p + p$  baseline (open [blue] squares), in various  $\xi$  bins.

functions due to uncertainties on the value of the elliptic flow modulation magnitude,  $v_2$ . This analysis uses published values and uncertainties from PHENIX [6]. The absolute normalization method to determine the underlying event background level and the determination of the decay photon  $p_T$  mapping are also significant contributors to the overall systematic uncertainties. The uncertainties, along with their  $p_T$  and centrality dependence, are propagated into the final jet functions and per-trigger hadron yields. The systematic uncertainty on the hadron efficiency determination comes in as a global scale uncertainty on the correlated hadron yields.

In MB  $d + Au$  collisions,  $v_2$  is small. However, the systematic uncertainties on  $\gamma$ -h correlations include those arising from the ZYAM procedure used to determine the combinatorial background. There is also an uncertainty arising from the  $\pi^0$  tagging and isolation cuts, which is included in the quoted systematic uncertainty.

### III. RESULTS

In this paper, we aim to quantify the modification of the jet fragmentation function  $D(z)$  in  $Au + Au$  and  $d + Au$  collisions, compared to the  $p + p$  baseline. The jet fragmentation function describes the probability of an outgoing parton yielding a hadron with momentum fraction  $z = p^{\text{hadron}}/p^{\text{parton}}$ . Assuming that the initial state  $k_T$  of partons in a nucleon has a negligible effect, then  $z_T = p_T^{\text{hadron}}/p_T^{\text{parton}}$  can be used to approximate  $z$ . To focus on the low  $z_T$  region, where modification is anticipated, we use the variable  $\xi = \ln(1/z_T)$ .

Figure 2 shows azimuthal angular distributions of hadrons associated with direct photons of  $5 < p_T < 9$  GeV/ $c$ , in the 0–40% most central  $Au + Au$  collisions, separated into bins of  $\xi$ . These distributions are a combination of the 2007, 2010, and 2011 data sets. The  $Au + Au$  results are shown as closed [black] circles, with shaded boxes representing systematic uncertainties on the measurement. The  $p + p$   $\gamma_{\text{dir}}$ -h results are shown in open [blue] squares. The  $p + p$  baseline measurement combines data collected in 2005 and 2006 [6,15]. It should be noted that the isolation cut in the  $p + p$  analysis makes the near-side yield not measurable. Consequently, the  $p + p$  points with  $\Delta\phi < 1$  are not shown in these distributions.

On the near side, i.e.,  $\Delta\phi < \pi/2$ , the  $Au + Au$   $\gamma_{\text{dir}}$ -h yields are consistent with zero, indicating that the statistical subtraction is properly carried out and next-to-leading-order effects are negligible. On the away side, i.e.,  $\Delta\phi > \pi/2$ , an enhancement in the  $Au + Au$  data compared to  $p + p$  is observed in the higher  $\xi$  bins. As noted before, this corresponds to low  $z$ , where the observed hadrons carry a small fraction of the scattered parton's original momentum. In the low  $\xi$  bins, the  $Au + Au$  per-trigger yield is suppressed, as expected if the parton loses energy in the medium.

Figure 3 shows the  $\Delta\phi$  distributions of isolated  $\gamma_{\text{dir}}$ -h yields in  $d + Au$  and  $p + p$  collisions, for direct photon  $p_T$  7–9 GeV/ $c$ . The  $d + Au$  and  $p + p$  results are consistent in all the measured  $\xi$  bins.

Figure 4(a) shows the fragmentation functions for all three systems as a function of  $\xi$ . These are calculated by integrating the per-trigger yield of hadrons in the azimuthal angle region



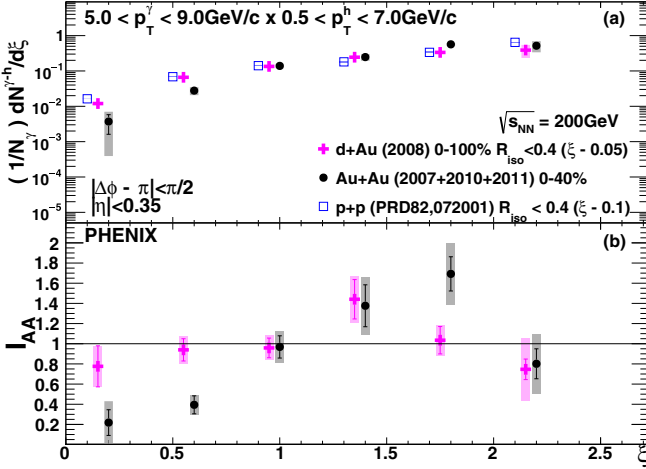


FIG. 4. (a) Integrated away-side  $\gamma_{dir}$ -h per-trigger yields of Au + Au (closed [black] circles), d + Au ([purple] crosses) and p + p (open [blue] squares), as a function of  $\xi$ . The p + p and d + Au points have been shifted to the left for clear viewing, as indicated in the legend. (b)  $I_{AA}$  (closed [black] circles) and  $I_{dA}$  ([purple] crosses).

$|\Delta\phi - \pi| < \pi/2$  rad. Data points for Au + Au are plotted on the  $\xi$  axis at the middle of each  $\xi$  bin: 0.2, 0.6, 1.0, 1.4, 1.8, 2.2. The p + p and d + Au points have been shifted to the left in  $\xi$  for viewing clarity.

As noted in the Introduction,  $I_{AA} = Y_{AA}/Y_{pp}$  is a nuclear-modification factor, which quantifies the difference between the fragmentation functions in Au + Au and p + p. In the absence of any medium modifications,  $I_{AA}$  should equal 1.

Figure 4(b) shows  $I_{AA}$  for direct photons of  $5 < p_T^{\gamma} < 9$  GeV/c. In Au + Au collisions, there is a clear suppression at low  $\xi$  and enhancement at high  $\xi$ . The d + Au nuclear modification factor,  $I_{dA}$ , is also shown as closed [purple] crosses in Fig. 4(b).  $I_{dA}$  is consistent with unity across all  $\xi$  ranges, indicating that there is no significant modification of the jet fragmentation function in d + Au collisions.

The statistics from the combined Au + Au runs allow for a differential measurement as a function of direct photon  $p_T$  (i.e., as a function of the approximate jet energy). Figure 5 shows  $I_{AA}$  as a function of  $\xi$  for three direct photon  $p_T$  ranges. While the associated hadron yields are smaller than those in p + p at low  $\xi$ , the appearance of extra particles at higher  $\xi$  is observed for direct photons with  $p_T$  of 5–7 GeV/c. A qualitatively similar increase of  $I_{AA}$  with  $\xi$  is visible for the 7–9 GeV/c direct photon  $p_T$  range.

To investigate where the energy deposited in the plasma goes, we study the dependence of  $I_{AA}$  on the integration range in azimuthal opening angle. The hadron yields are also integrated in two narrower angular ranges on the away side:  $|\Delta\phi - \pi| < \pi/3$  rad and  $|\Delta\phi - \pi| < \pi/6$  rad. The resulting  $I_{AA}$  values are shown in Fig. 6 for all three direct photon  $p_T$  bins. The enhancement over p + p is largest for the 5–7 GeV/c direct photon momentum range, and for the full away-side integration range. The suppression pattern is similar for the different integration regions, suggesting that the jet core is suppressed, and the enhancement exists at large angles. The angular distributions support the observation from Fig. 2 that

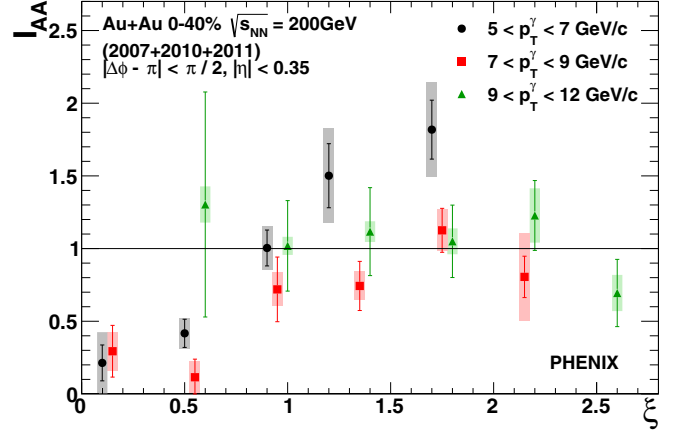


FIG. 5.  $I_{AA}$  vs  $\xi$  for direct photon  $p_T^{\gamma}$  of 5–7 GeV/c (closed [black] circles), 7–9 GeV/c (closed [red] squares), and 9–12 GeV/c (closed [green] triangles).

particle yields are enhanced at large angles with respect to the away-side jet axis in the  $1.6 < \xi < 2.0$  bin.

Whether or not  $I_{AA}$  becomes significantly larger than unity (what we have been referring to as enhancement) there is a tendency for  $I_{AA}$  to increase with increasing  $\xi$ . To quantify this, we calculate the weighted averages of  $I_{AA}$  values above and below  $\xi = 1.2$ . The ratio for each integration range is plotted in Fig. 7, as a function of the direct photon  $p_T$ . The enhancement is largest for softer jets and for the full away-side integration range, implying that jets with lower energy are broadened more than higher energy jets.

#### IV. DISCUSSION

To determine whether  $I_{dA}$  indicates any cold nuclear matter effects, the  $\chi^2$  per degree of freedom values were calculated

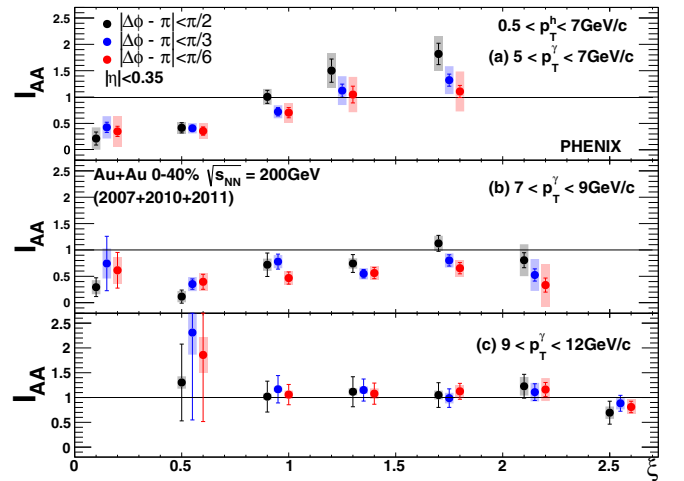


FIG. 6.  $I_{AA}$  as a function of  $\xi$  for direct photon  $p_T^{\gamma}$  of (a) 5–7, (b) 7–9, and (c) 9–12 GeV/c. Three away-side integration ranges are chosen to calculate the per-trigger yield and the corresponding  $I_{AA}$ :  $|\Delta\phi - \pi| < \pi/2$  (closed [black] circles),  $|\Delta\phi - \pi| < \pi/3$  (closed [blue] squares), and  $|\Delta\phi - \pi| < \pi/6$  (closed [red] triangles).

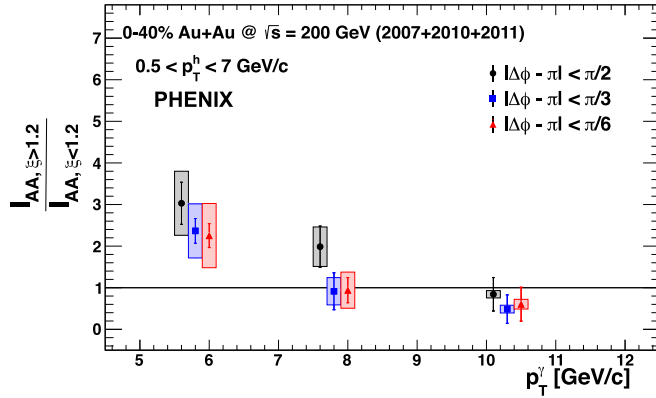


FIG. 7. Ratios of  $I_{AA}$  as a function of direct photon  $p_T$  for three different away-side integration ranges.

under the assumption of no modification and are determined to be 7.4/5, 4.0/5, 10.0/5 for direct photon  $p_T$  bins 5–7, 7–9, and 9–12 GeV/c, respectively. The result indicates that  $I_{dA}$  is consistent with unity and therefore the jet fragmentation function is not significantly modified in  $d + Au$  collisions, within the current uncertainties. This suggests that any possible cold nuclear matter effect is small.

We next compare our Au + Au results to predictions from the coupled linear Boltzmann transport and hydrodynamic (CoLBT-hydro) model [26] in Fig. 8, which shows  $I_{AA}$  as a function of  $\xi$  for the three direct photon  $p_T$  bins; the  $z_T$  axis is displayed on the top. The solid lines are from the CoLBT model calculated in the same kinematic ranges as the data. The model calculation shows the same trends with  $\xi$  as the data. CoLBT has a kinetic description of the leading parton propagation, including a hydrodynamical picture for the medium evolution. In this calculation, both the propagating jet shower parton and the thermal parton are recorded, along with their further interactions with the medium. Consequently, the medium response to deposited energy is modeled. The model clearly shows that as the direct photon  $p_T$  increases, the transition where  $I_{AA}$  exceeds 1 occurs at increasing  $\xi$ . According to this calculation, the enhancement at large  $\xi$  arises from jet-induced medium excitations, and that the enhancement occurs at low  $z_T$  reflects the thermal nature of the produced soft particles.

Figure 8(b) shows a Borghini Wiedemann-modified leading logarithmic approximation (BW-MLLA) calculation (dashed [red] curve) in which it is assumed that the lost energy is redistributed, resulting in an enhanced production of soft particles [36]. The calculation for jets with energy of 7 GeV in

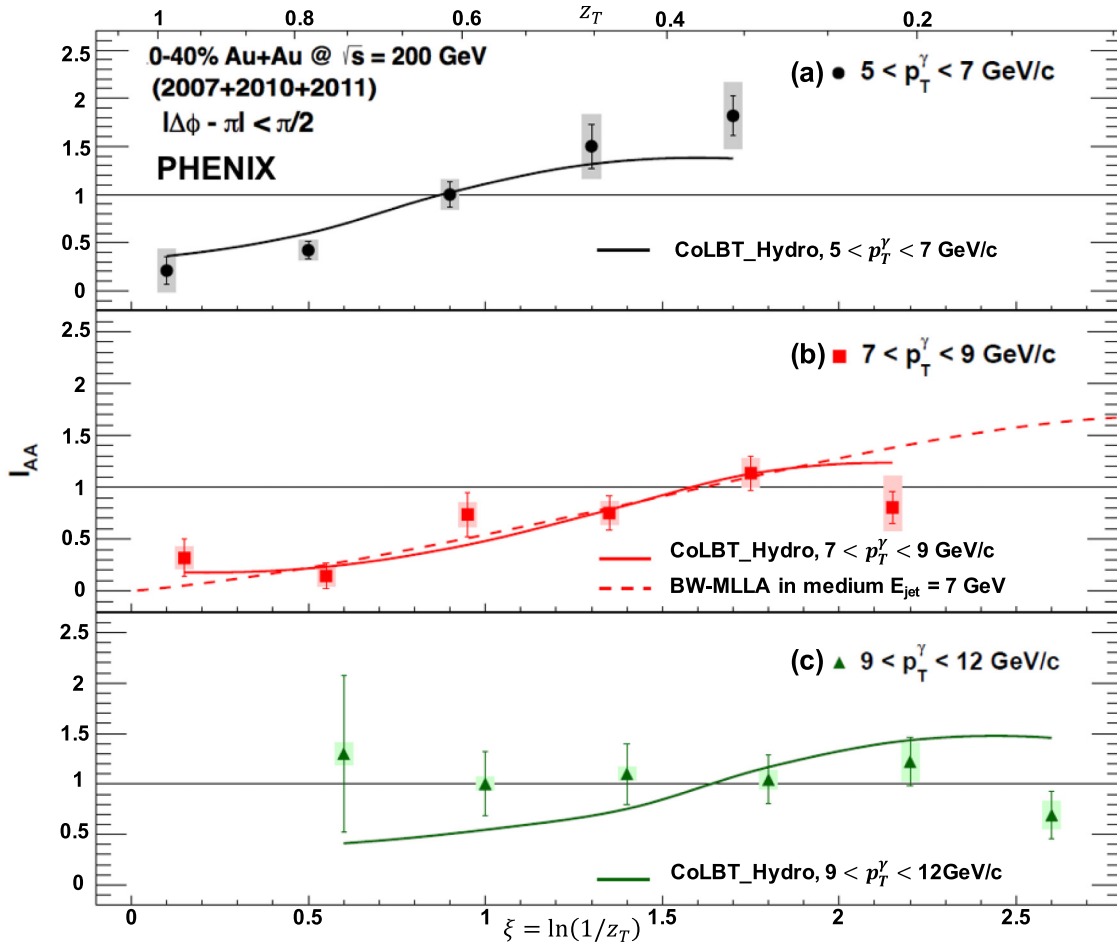


FIG. 8. Measured  $I_{AA}$  for direct photon  $p_T$  of (a) 5–7, (b) 7–9, and (c) 9–12 GeV/c, as a function of  $\xi$ , are compared with theoretical model calculations.

the medium is in relatively good agreement with the measured results. The model comparisons suggest that the enhancement of soft hadrons associated with the away-side jet should scale with the  $p_T$  of the hadrons. A modified fragmentation function could be expected to produce a change at fixed  $z_T$ . This is not consistent with either the data or the CoLBT model.

## V. SUMMARY

We have presented direct photon-hadron correlations in  $\sqrt{s_{NN}} = 200$  GeV Au + Au,  $d + Au$ , and  $p + p$  collisions, for photon  $p_T$  from 5–12 GeV/ $c$ . As the dominant source of correlations is QCD Compton scattering, we use the photon energy as a proxy for the opposing quark's energy to study the jet fragmentation function. Combining data sets from three years of data taking at RHIC allows study of the conditional hadron yields opposite to the direct photons as a function of  $z_T$  and the photon  $p_T$ . This is the first time such a differential study of direct photon-hadron correlations has been performed at RHIC.

We observe no significant modification of the jet fragmentation in  $d + Au$  collisions, indicating that cold nuclear matter effects are small or absent. We find that hadrons carrying a large fraction of the quark's momentum are suppressed in Au + Au compared to  $p + p$  and  $d + Au$ . This is expected from energy loss of partons in quark gluon plasma. As the momentum fraction decreases, the yield of hadrons in Au + Au increases, eventually showing an excess over the jet fragment yield in  $p + p$  collisions. The excess is seen primarily at large angles and is most pronounced for hadrons associated to lower momentum direct photons.

To address whether the excess is a result of medium modification of the jet fragmentation function or the excess indicates the presence of “extra” particles from the medium, we compared to theoretical calculations. The calculations suggest that the observed excess arises from medium response to the deposited energy. Furthermore, the excess particles appear at low  $z_T$ , corresponding to low associate hadron  $p_T$ . This can be seen in each direct photon  $p_T$  bin.

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