Suppression of Back-to-Back Hadron Pairs at Forward Rapidity in d + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Back-to-back hadron pair yields in $d + \mathrm{Au}$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV were measured with the PHENIX detector at the Relativistic Heavy Ion Collider. Rapidity separated hadron pairs were detected with the trigger hadron at pseudorapidity $|\eta| < 0.35$ and the associated hadron at forward rapidity (deuteron direction, $3.0 < \eta < 3.8$). Pairs were also detected with both hadrons measured at forward rapidity; in this case, the yield of back-to-back hadron pairs in $d + \mathrm{Au}$ collisions with small impact parameters is observed to be suppressed by a factor of 10 relative to $p + p$ collisions. The kinematics of these pairs is expected to probe partons in the Au nucleus with a low fraction x of the nucleon momenta, where the gluon densities rise sharply. The observed suppression as a function of nuclear thickness, p_T, and η points to cold nuclear matter effects arising at high parton densities.

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Nuclear effects on quark and gluon densities of nucleons bound in nuclei can be studied in collisions of deuteron and gold nuclei at the Relativistic Heavy Ion Collider. At $\sqrt{s_{NN}} = 200$ GeV, the hadron yields in the forward-rapidity (deuteron-going) direction were observed to be suppressed for $d + \mathrm{Au}$ collisions relative to $p + p$ collisions [1–3]. However, the mechanism for the suppression was not firmly established and may indicate novel QCD effects in nuclei. Competing theoretical approaches include initial state energy loss [4,5], parton recombination [6], shadowing effects [7,8], and gluon saturation [9].

Back-to-back dijet yields were proposed as an additional observable to distinguish better between competing mechanisms. The color glass condensate (CGC) framework [10] predicts that quarks and gluons scattering at forward angles (large rapidity) will interact coherently off gluons at low x in the gold nucleus. As a result, the rate of observed recoiling jets is expected to be suppressed in $d + \mathrm{Au}$ collisions compared to $p + p$, and angular broadening of the back-to-back correlation of jets is predicted [11,12]. Dihadron correlation measurements were used [13,14] successfully in $d + \mathrm{Au}$ collisions to select dijet production based on the back-to-back peak at $\Delta\phi = \pi$ between trigger hadrons and their associated hadrons. Dihadron correlation measurements with varying kinematic constraints (transverse momentum p_T and rapidity) probe different x ranges in the nucleus. In particular, measurements at forward rapidity are thought to probe small x values in the Au nucleus.

In this Letter, we report results on the suppression in $d + \mathrm{Au}$ relative to $p + p$ collisions of inclusive π^0's and back-to-back cluster-π^0 pairs in the forward-rapidity region and for back-to-back π^0-π^0 or hadron-π^0 pairs separated in rapidity. The data were obtained from $p + p$ and $d + \mathrm{Au}$ runs in 2008 with the PHENIX detector and include a new electromagnetic calorimeter, the muon piston calorimeter (MPC), with an acceptance of $3.0 < \eta < 3.8$ in pseudorapidity and $0 < \phi < 2\pi$. The clusters are reconstructed from the energy deposit of photons in individual MPC towers. The MPC comprises 220 $PbWO_4$ towers of $20.2X_0$ depth, with lateral dimensions of $2.2 \times 2.2\ \mathrm{cm}^2$, and is located 220 cm along the beam axis from the nominal interaction point.

The $d + \mathrm{Au}$ sample is separated into four centrality classes—0–20% (most central), 20–40%, 40–60%, and 60–88% (most peripheral)—based on charge deposited in the backward (gold direction) beam-beam counter ($3.0 < -\eta < 3.9$). We determine the average number of binary collisions $\langle N_{\mathrm{coll}} \rangle$ from a Glauber model [3] and a simulation of the beam-beam counter; $\langle N_{\mathrm{coll}} \rangle$ values are 15.1 ± 1.0, 10.2 ± 0.70, 6.6 ± 0.44, and 3.2 ± 0.19, respectively.

The charged hadron ($h^{\pm}$) and π^0 analysis in the mid-rapidity region $|\eta| < 0.35$ is identical to that for previous measurements by PHENIX [15,16]. For the analysis in the forward-rapidity region, a fiducial cut is applied, ensuring that clusters are fully reconstructed within the MPC acceptance. Photon candidates are identified in the MPC by comparing cluster candidates to the expected shower profile for photons. The shower profile for photons is determined from the PHENIX GEANT3 [17] based detector simulation, PISA, which was tuned to reproduce MPC test beam data. For the pair analyses reported here, the associated particles in the MPC are π^0's, which are identified by reconstructing the mass of their decay photon pairs. The π^0 yield is obtained after subtraction of the combinatoric background of uncorrelated photon pairs. The shape of the background was determined from $p + p$ PYTHIA 6.4 [18] and $d + \mathrm{Au}$ HIJING [19] events that are

subsequently processed through PISA. The p_T-dependent systematic uncertainty on the associated π^0 yield extraction procedure is estimated to be 2–5% for $p + p$ and $d + \mathrm{Au}$.

The closeness of the MPC to the collision vertex and the high energy of particles emitted in the forward direction make it difficult to reconstruct photon pairs from π^0 decays at high p_T. For example, at $p_T = 1$ GeV/c, approximately 30% of the photon cluster pairs are merged and cannot be reconstructed separately in the MPC. To extend the p_T range and the pair yield, single electromagnetic clusters are used as trigger particles to construct cluster-π^0 dihadron pairs in the MPC. These trigger clusters are treated assuming that they are all π^0's. However, PYTHIA studies indicate that $\gtrsim 80\%$ of these trigger clusters are from π^0's, with the rest being dominantly single photons from asymmetric decays of η mesons or direct photons; thus, according to these studies, a relatively small contamination remains. The cluster energy was corrected to the true π^0 energy to account for the merging effects of the two photons from π^0 decay. These corrections were determined by embedding Monte Carlo generated π^0's into real data, as well as from PYTHIA tuned to match the data.

Figure 1 shows the azimuthal angle correlations between midrapidity and forward-rapidity π^0 pairs, per π^0 trigger detected at midrapidity, in $p + p$, peripheral $d + \mathrm{Au}$, and central $d + \mathrm{Au}$ collisions for varying trigger π^0 p_T. Figure 2 shows the same correlations for trigger clusters where the cluster-π^0 pairs are both detected at forward rapidity. The constant pedestal, b_0, was subtracted from the correlation function. The correlations were corrected for the forward π^0 detection efficiency and for the combinatoric background beneath the π^0 peaks in the photon-pair invariant mass spectra. This background is determined by measurement of the azimuthal correlations for photon-pair mass selections adjacent to the π^0 mass window and from studies of simulated jet events from PYTHIA events processed through PISA.

For the midrapidity/forward-rapidity correlations (Fig. 1), due to the large pseudorapidity gap of $\Delta\eta \sim 3.3$ between the hadrons, only an away-side peak ($\Delta\phi = \pi$) is seen. For the forward-forward correlations, a near-side peak ($\Delta\phi = 0$) is also present (see Fig. 2). The yields and widths of the correlated pairs are extracted by fits to an away-side Gaussian signal shape plus a constant background (b_0). The fit to the forward-forward correlations has an additional Gaussian signal for the near-side peak. The pedestal is determined from a fit in the midrapidity/forward-rapidity correlations and is consistent with the pedestal level found based on the assumption that the signal yield is 0 at the minimum of the correlation function—zero yield at minimum (ZYAM) [20]. In the forward-forward correlations, the ZYAM pedestal is used in the yield extraction. Additional systematic uncertainties of up to 30% (not shown in Fig. 2) are ascribed to the near-side peak due to corrections for resonance decays that contaminate the jet signal and due to the acceptance loss around the trigger particle of $\Delta\phi \times \Delta\eta \approx 0.5 \times 0.5$ rad, resulting from the minimum separation cut of one tower between cluster peaks in the MPC. The acceptance loss gives rise to the decrease observed for the near-side peak.

Figures 1 and 2 show that the away-side peak for $d + \mathrm{Au}$ central collisions is suppressed compared to $p + p$ collisions and peripheral $d + \mathrm{Au}$ collisions. This effect is large for the midrapidity/forward-rapidity correlations (Fig. 1) and becomes even larger when both particles are required to be in the forward-rapidity region (Fig. 2).

For the midrapidity/forward-rapidity correlations, within their large uncertainties, the Gaussian widths of the away-side correlation peak remain the same between $p + p$ and central $d + \mathrm{Au}$, and the broadening predicted in

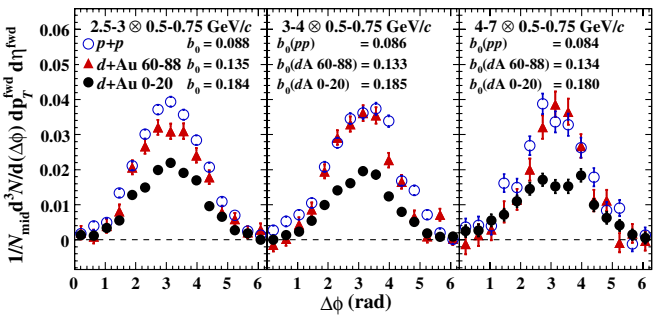

FIG. 1 (color online). Pedestal-subtracted π^0-π^0 per-trigger correlation functions for, as indicated, $p + p$, $d + \mathrm{Au}$ peripheral (60–88% centrality), and $d + \mathrm{Au}$ central (0–20% centrality) collisions at $\sqrt{s_{NN}} = 200$ GeV; the associated π^0's of $p_T = 0.5$–0.75 GeV/c are measured at forward rapidity ($3.0 < \eta < 3.8$), and the triggered π^0's are measured at midrapidity ($|\eta| < 0.35$) for the indicated p_T ranges. The subtracted pedestal values, b_0, are also indicated.

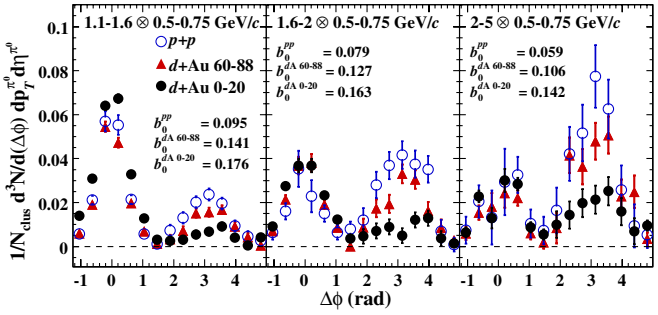

FIG. 2 (color online). Pedestal-subtracted cluster-π^0 per-trigger correlation functions measured at forward rapidity ($3.0 < \eta < 3.8$) for, as indicated, $p + p$, $d + \mathrm{Au}$ peripheral (60–88% centrality), and $d + \mathrm{Au}$ central (0–20% centrality) collisions at $\sqrt{s_{NN}} = 200$ GeV; the correlation functions are for associated π^0's of $p_T = 0.5$–0.75 GeV/c and trigger clusters over the indicated p_T ranges. Systematic uncertainties of up to 30% on the near side ($|\Delta\phi| < 0.5$) are not shown. The subtracted pedestal values, b_0, are also indicated.

the CGC framework in Ref. [11] is not observed. For example, in $d+\mathrm{Au}$ central collisions, $\sigma = 0.93 \pm 0.09^{\mathrm{stat}} \pm 0.139^{\mathrm{syst}}$ for $p_T^{\mathrm{fwd}} = 1.25\ \mathrm{GeV}/c$ and trigger particle momentum $2.5 < p_T^t < 3.0\ \mathrm{GeV}/c$, while $\sigma = 0.97 \pm 0.07^{\mathrm{stat}} \pm 0.08^{\mathrm{syst}}$ for $p+p$ collisions. For the forward-forward correlations, the measurement does not discern whether there is appreciable broadening between $d+\mathrm{Au}$ and $p+p$ collisions, as the ZYAM pedestal determination can bias the widths to smaller values.

The observed suppression is quantified by studying the relative yield, $J_{d\mathrm{A}}$ [21], of correlated back-to-back hadron pairs in $d+\mathrm{Au}$ collisions compared to $p+p$ collisions scaled with $\langle N_{\mathrm{coll}}\rangle$,

$$J_{d\mathrm{A}} = I_{d\mathrm{A}} \times R_{d\mathrm{A}}^t = \frac{1}{\langle N_{\mathrm{coll}}\rangle} \frac{\sigma_{d\mathrm{A}}^{\mathrm{pair}}/\sigma_{d\mathrm{A}}}{\sigma_{pp}^{\mathrm{pair}}/\sigma_{pp}}, \quad (1)$$

where $R_{d\mathrm{A}}^t = (1/\langle N_{\mathrm{coll}}\rangle)(\sigma_{d\mathrm{A}}^t/\sigma_{d\mathrm{A}})/(\sigma_{pp}^t/\sigma_{pp})$ is the usual nuclear modification factor for trigger particles t, and σ, σ^t, and σ^{pair} are the cross sections (or normalized yields) for the full event selection, trigger particle event selection, and dihadron pair event selection. $I_{d\mathrm{A}}$ is the ratio of conditional hadron yields, CY, for $d+\mathrm{Au}$ and $p+p$ collisions:

$$CY = \frac{\int d(\Delta\phi)[dN/d(\Delta\phi) - b_0]}{N^t \times \epsilon^a \times \Delta\eta^a \times \Delta p_T^a}, \quad (2)$$

with the acceptance corrected dihadron correlation function $dN/d(\Delta\phi)$, the number of trigger particles N^t, the detection efficiency for the associated particle ϵ^a, and the level of the uncorrelated pedestal in the correlation functions b_0. The integral is taken over the Gaussian fit of the away-side peak. The $J_{d\mathrm{A}}$ uncertainties include a systematic uncertainty from the ZYAM pedestal subtraction. In determining this uncertainty, it was assumed that changes between $d+\mathrm{Au}$ and $p+p$ in the Gaussian away-side width remain below a factor two. This upper limit is based on the small observed changes in width in the midrapidity/forward-rapidity correlations and the correlations studied previously with the PHENIX muon spectrometers [14]. The $J_{d\mathrm{A}}$ is calculated from the measured $I_{d\mathrm{A}}$ and $R_{d\mathrm{A}}^t$ for the forward-rapidity trigger correlations with the new π^0 $R_{d\mathrm{Au}} = R_{d\mathrm{Au}}^t$ determined in the MPC. For the midrapidity trigger correlations, published values for $R_{d\mathrm{A}}$ from the 2003 RHIC run [15,16] were used.

Figure 3 presents $J_{d\mathrm{A}}$ versus $\langle N_{\mathrm{coll}}\rangle$ for forward-rapidity π^0's paired with midrapidity hadrons and π^0's and for π^0's and clusters paired at forward rapidity. The $J_{d\mathrm{A}}$ decreases with an increasing number of binary collisions, $\langle N_{\mathrm{coll}}\rangle$, or equivalently with increasing nuclear thickness. The suppression also increases with decreasing particle p_T and is significantly larger for forward-forward hadron pairs than for midrapidity/forward-rapidity pairs. The observed suppression of $J_{d\mathrm{A}}$ versus nuclear thickness, p_T, and η points to large cold nuclear matter effects arising at high parton densities in the nucleus probed by the deuteron, consistent with predictions from CGC [12]. This trend is seen more clearly in Fig. 4, where $J_{d\mathrm{A}}$ is plotted versus

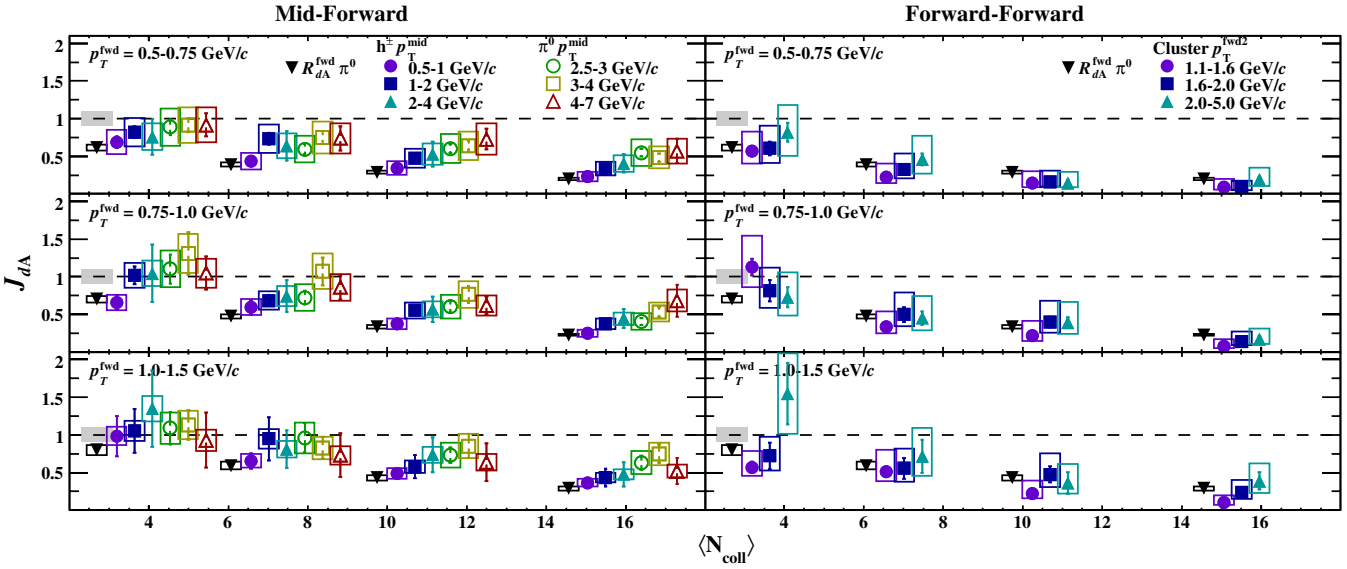

FIG. 3 (color online). Relative yield $J_{d\mathrm{A}}$ versus $\langle N_{\mathrm{coll}}\rangle$ for forward-rapidity ($3.0 < \eta < 3.8$) π^0's paired with (left) midrapidity ($|\eta| < 0.35$) hadrons and π^0's and (right) forward-rapidity ($3.0 < \eta < 3.8$) cluster-π^0 pairs for the indicated combinations of p_T ranges. Also plotted as inverted solid triangles are the values of the forward π^0 $R_{d\mathrm{A}}$. Around each data point, the vertical bars indicate statistical uncertainties, and the open boxes indicate point-to-point systematic uncertainties. The gray bar at the left in each panel represents a global systematic scale uncertainty of 9.7%. Additional centrality dependent systematic uncertainties of 7.5%, 5.1%, 4.1%, and 4.8% for the peripheral to central bins, respectively, are not shown. The $\langle N_{\mathrm{coll}}\rangle$ values within a centrality selection are offset from their actual values for visual clarity (see text for actual $\langle N_{\mathrm{coll}}\rangle$ values).

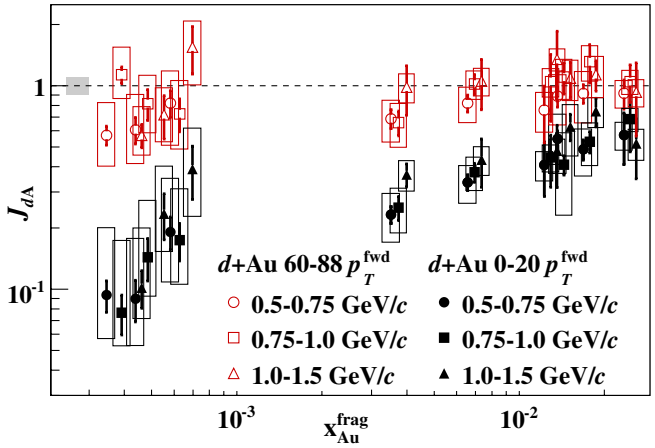

FIG. 4 (color online). J_{dA} versus x_{Au}^{frag} for peripheral (60–88%) and central (0–20%) d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The statistical error bars and systematic uncertainty boxes are the same as in Fig. 3. Above $x_{Au}^{frag} > 10^{-3}$, some data points were offset from their true x_{Au}^{frag} to avoid overlap. The leftmost point in each group of three is at the correct x_{Au}^{frag}.

$x_{Au}^{frag} = (\langle p_{T1}\rangle e^{-\langle\eta_1\rangle} + \langle p_{T2}\rangle e^{-\langle\eta_2\rangle})/\sqrt{s_{NN}}$ for all pair selections in η and p_T. In the case of $2 \rightarrow 2$ parton scattering, where two final state hadrons carry the full parton energy, $z = 1$, the variable x_{Au}^{frag} would be equal to $\langle x_{Au}\rangle$, which is the average momentum fraction of the struck parton in the Au nucleus.

Because the fragmentation hadrons on average carry a momentum fraction $\langle z\rangle < 1$, x_{Au}^{frag} will be smaller than $\langle x_{Au}\rangle$. Based on previous studies by PHENIX at midrapidity, the mean fragmentation $\langle z\rangle$ is expected to be between 0.5–0.75 [22]. In general, the theoretical extraction of x_{Au} from the measured p_T and η will differ from the leading-order QCD picture of $2 \rightarrow 2$ processes used above. Also, at modest p_T's, the interpretation of the measured correlation functions as high energy $2 \rightarrow 2$ parton scattering accessing low x may be limited by contributions from processes with small momentum transfer Q^2. Future theoretical analysis will be necessary to evaluate these and other contributions from different nuclear effects [4–10] on the observed large suppression in J_{dA}. These analyses could additionally be complicated by the presence of hadron pairs originating from multiparton interactions [23] that might not probe gluon structure at low x_{Au}.

In summary, measurements of the inclusive π^0 yield at forward rapidity, of the back-to-back correlated yield of cluster-π^0 pairs in the forward-rapidity region, and of the correlated yield of forward-rapidity π^0's with midrapidity π^0's or hadrons in $p + p$ and d + Au collisions at $\sqrt{s_{NN}} =$ 200 GeV were presented. The correlated yields of back-to-back pairs were analyzed for various kinematic selections in p_T and rapidity. The forward-central pair measurements show no increase in the azimuthal angular correlation width within experimental uncertainties. The correlated yield of back-to-back pairs in d + Au collisions is observed to be substantially suppressed relative to $p + p$ collisions with a suppression that is observed to increase with decreasing impact parameter selection and for pairs probing more forward rapidities.

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