Azimuthal Angle Correlations for Rapidity Separated Hadron Pairs in d + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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We report on two-particle azimuthal angle correlations between charged hadrons at forward/backward (deuteron/gold going direction) rapidity and charged hadrons at mid-rapidity in deuteron-gold ($d + Au$) and proton-proton ($p + p$) collisions at $\sqrt{s_{NN}} = 200$ GeV. Jet structures are observed in the correlations which we quantify in terms of the conditional yield and angular width of away-side partners. The kinematic region studied here samples partons in the gold nucleus carrying nucleon momentum fraction $x \sim 0.1$ to $\sim 0.01$. Within this range, we find no $x$ dependence of the jet structure in $d + Au$ collisions.

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Observations in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at the Relativistic Heavy Ion Collider (RHIC) reveal a significant suppression of hadron production at forward rapidity (deuteron-going direction) relative to $p + p$ reactions scaled up by the equivalent number of nucleon-nucleon collisions ($N_{\text{coll}}$) \cite{1, 2, 3}. This suppression is observed for hadrons with momentum transverse to the beam direction over the range $p_T \approx 1.5 - 4$ GeV/c. In contrast, measurements at mid-rapidity \cite{4, 5, 6} and backward rapidity \cite{7, 8, 9} show a modest enhancement of the particle yield relative to $N_{\text{coll}}$ scaling over the same $p_T$ range. Particle production at forward rapidity is sensitive to partons in the gold nucleus which carry a small nucleon momentum fraction (small Bjorken $x$). The suppression has generated significant theoretical interest including different calculational frameworks for understanding the data \cite{10, 11, 12, 13}.

One such framework, the Color Glass Condensate (CGC), attempts to describe the data in terms of gluon saturation \cite{14}. At small $x$ the probability of emitting an extra gluon is large and the number of gluons grows in a limited transverse area. When the transverse density becomes large, partons start to overlap and gluon-gluon fusion processes start to dominate the parton evolution in the hadronic wave functions. As a result the gluon density becomes saturated. Since the nonlinear growth of the gluon density depends on the transverse size of the system, the effects of gluon saturation are expected to set in earlier (at higher Bjorken $x$) for heavy nuclei accelerated at ultra-relativistic energies than for free nucleons.

In the leading order pQCD framework, a quark or gluon jet with large transverse momentum produced in a hard scattering process (high momentum transfer or large $Q^2$) must be momentum balanced by another quark or gluon jet in the opposite direction but with almost the same transverse momentum. Thus the azimuthal angle correlation between particles from the pair of jets (referred to as di-jets) is characterized by two peak structures separated by 180 degrees. In CGC calculations, the momentum to balance a jet may come from a large multiplicity of gluons in the saturation regime, and thus no single partner jet may appear on the opposite side \cite{15}. This effect is analogous to the nuclear Mössbauer effect, and is often referred to as the appearance of mono-jets. Alternative calculations, describing the suppression of single hadrons at forward rapidity in $d + Au$ reactions in terms of leading twist pQCD effects, predict no such mono-jet feature \cite{16}.

We want to probe this high gluon density regime in $d + Au$ collisions with relatively high transverse momentum particles at forward rapidity. Such particles are likely to result from hard-scattering collisions involving small $x$ partons in the gold nucleus. At small $x$ the gluon density increases rapidly with $Q^2$ and saturation effects may be relevant for $x \approx 0.01$ at modest $p_T$. CGC calculations \cite{12} predict significant suppression of the conditional yield and widening of away-side jet azimuthal correlations between rapidity-separated jet azimuthal angles, suggesting that one of those hadrons is at forward rapidity.

In this Letter we report on measurements of two-particle azimuthal angle correlations between unidentified charged hadrons in $p + p$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. In our analysis, the two particles are referred to as the trigger and associated particles. The trigger particle is at forward ($1.4 < \eta < 2.0$) or backward ($-2.0 < \eta < -1.4$) rapidity and the associated particle is at mid-rapidity, $|\eta| < 0.35$. The particles are separated by an average pseudorapidity gap $< \Delta \eta > \sim 1.5$. The criteria for trigger particles, associated particles and event selection are described elsewhere \cite{17, 18, 19, 20}. The two-particle azimuthal angle correlation technique has been used extensively by RHIC experiments and is described in detail elsewhere \cite{21, 22, 23, 24, 25, 26}. In this technique the azimuthal correlation function is formed from the angular difference, $\Delta \phi = \phi_{\text{assoc}} - \phi_{\text{trig}}$, between each trigger and associated particle pair. Two jet peaks are normally observed in such correlation functions: the near-side peak ($\Delta \phi \sim 0$) in which the two particles come from the same jet, and the away-side peak ($\Delta \phi \sim \pi$) in which they come from the back-to-back jets. In addition to these peaks the correlation functions usually also have a $\Delta \phi$ independent combinatoric background contribution which is due to trigger-associated pairs from different jets or from non-jet processes.

We can construct separate correlation functions that are sensitive to partons in the gold nucleus with different Bjorken $x$ ranges. By choosing trigger particles with $1.0 < p_T < 5.0$ GeV/c at forward (backward) rapidity, we sample partons in gold nuclei with $x \sim 0.01 (0.1)$. At $x \sim 0.1$, we do not expect to be sensitive to any saturation effects, but we may be sensitive at $x \sim 0.01$ \cite{19}. The comparison in $d + Au$ reactions between these two cases, as well as with the $p + p$ case, may give insights into possible saturation effects on jet production and other mechanisms for forward rapidity single particle suppression. It should be noted that the prediction of mono-jets in \cite{12} assumes one particle at pseudorapidity $\eta = 3.8$ and one at mid-rapidity, thus demonstrating sensitivity at even lower $x_{Au} \sim 10^{-4}$ which is outside the range presented in this analysis.

Data for this analysis were collected by the PHENIX experiment \cite{21} in the 2003 RHIC $p + p$ and $d + Au$ running period. In the case of $d + Au$ collisions, we divide the data into two centrality (impact parameter) classes based on the number of hits in the backward-rapidity PHENIX Beam-Beam Counter (BBC, $-3.9 < \eta < -3.0$). Central (peripheral) collisions comprise 0 - 40% (40 - 88%) of the minimum bias cross section respectively. Using a Glauber model \cite{22} and a simulation of the BBC, we determine $< N_{\text{coll}} > = 4.7 \pm 0.4$ for peripheral collisions and $< N_{\text{coll}} > = 13.0 \pm 0.9$ for central collisions.

The trigger particles are measured in the PHENIX
muon spectrometers \[20\]. In this analysis we only select trigger particles from \(1.4 < |\eta| < 2.0\) to obtain homogenous acceptance in transverse momentum from \(1 < p_T < 5\) GeV/c and to reduce beam correlated backgrounds. We identify hadrons, as opposed to muons, in the muon spectrometers by comparing their momentum and penetration depth. This hadron identification method is described elsewhere \[14\]. It is notable that there is no peak near \(\Delta \phi\) in all cases corresponding to the away-side jet. It is notable that there is no peak near \(\Delta \phi\) in analysis that was published in \[16\].

Figure 1 show the correlation functions for central forward and backward pseudorapidity since the collision +
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For comparison we have also included measurements where trigger particles and associated particles are both measured in the PHENIX central spectrometers \[20\] which cover \(|\eta|<0.35\) and in this analysis have \(0.5 < p_T < 2.5\) GeV/c. Standard track selection criteria \[14\] are applied.

We define the azimuthal angle correlation function as:

\[
CF = \frac{dN(\Delta \phi)/d(\Delta \phi)}{acc(\Delta \phi)} \quad (1)
\]

where \(dN(\Delta \phi)/d(\Delta \phi)\) is the measured two-particle distribution and \(acc(\Delta \phi)\) is the two-particle acceptance obtained by an event mixing technique in which we mix trigger particles with associated particles from different events within the same centrality and collision vertex category. This correction is necessary because the PHENIX central arm detector is not azimuthally symmetric and the pair acceptance varies as a function of \(\Delta \phi\).

In Figure 1 we show the correlation functions for trigger particles with \(p_T = 2 - 5\) GeV/c and associated particles with \(p_T = 0.5 - 1.0\) GeV/c. The top panel is for \(p+p\) collisions where we have combined the results from forward and backward pseudorapidity since the collision system is symmetric. The middle and bottom panels of Figure 1 show the correlation functions for central \(d+Au\) collisions. The middle panel is for the trigger particle at forward rapidity and the bottom panel is for the trigger particle at backward rapidity. A clear peak is seen near \(\Delta \phi = \pi\) in all cases corresponding to the away-side jet. It is notable that there is no peak near \(\Delta \phi = 0\), as expected, because the rapidity gap between the two particles is larger than the width of the near side jet.

After constructing the correlation functions in various bins in \(p_T^{assoc}\), \(p_T^{trig}\) and \(\eta^{trig}\) we used two methods to determine the unnormalized number of trigger-associated particle pairs, \(N_{pair}\), above a constant background. In the first method, we define

\[
N_{pair} = \sum_{\Delta \phi = \pi - 1}^{\pi + 1} CF(\Delta \phi) - \sum_{\Delta \phi = -1}^{\pi + 1} CF(\Delta \phi), \quad (2)
\]

where the first term is the integral of the correlation function in the area of the correlation peak \((\pi - 1 < \Delta \phi < \pi + 1)\) and the second term is the integral away from the peak \((-1 < \Delta \phi < 1)\). In the second method we fit the correlation function with a Gaussian distribution centered at \(\Delta \phi = \pi\) plus a constant background. The values of \(N_{pair}\) obtained by each method are found to be consistent and the small differences are included in our systematic errors. The solid lines in Figure 1 show the resulting fits and the Gaussian width parameters \((\sigma)\) over the signal region \((\pi - 1 < \Delta \phi < \pi + 1)\) are quoted.

The conditional yield (per trigger particle) is defined to be

\[
CY = \frac{N_{pair}/\varepsilon^{assoc}}{N_{trig}}, \quad (3)
\]

where \(\varepsilon^{assoc} \approx 0.15 \pm 0.015\) is the efficiency times acceptance for associated particles and \(N_{trig}\) is the number of trigger particles used to generate the correlation function. \(\varepsilon^{assoc}\) is obtained for each colliding system, centrality class, and transverse momentum bin by a GEANT based simulation of the PHENIX detector \[14\].
There may even be some evidence of slight enhancement in the gold nucleus. The errors on each points are statistical errors. The black bar around 0.1 on the left of the plot indicates a 10% systematic error for all the data points due to the determination of associated particle efficiency. There is an additional +0.037 systematic error on the mid-rapidity p + p point from jet yield extraction, which is shown as the arrow on that point (similar analysis as [16]).

It is interesting to plot the conditional yields as a function of $\eta_{\text{trig}}$. Changing $\eta_{\text{trig}}$ from $-2.0$ to $2.0$ effectively changes the range of Bjorken $x$ of sampled partons in gold nuclei from $0.1_{-0.04}^{+0.06}$ to $0.01_{-0.007}^{+0.02}$. Results are shown in Figure 2. The first observation is that there is no difference beyond statistical fluctuations in the conditional yields for $p + p$, $d + Au$ peripheral, or $d + Au$ central collisions at any trigger particle pseudorapidity.

We further quantified any nuclear modification in the conditional yield by defining the following ratio:

$$I_{dAu} = \frac{CY_{d+Au}}{CY_{p+p}}$$

Figure 2 shows the ratio $I_{dAu}$ as a function of $p_T^{assoc}$ for central and peripheral $d + Au$ collisions, two different $p_T^{\text{trig}}$ ranges, and for forward and backward rapidity trigger particles. In the plot, the shaded bands on each of the data points are the systematic errors which are the differences in $N_{\text{pair}}$ obtained from the two methods described above and are independent from point-to-point. There is also a point-by-point correlated ~2% systematic uncertainty in the centrality dependence of $\varepsilon_{\text{assoc}}$ determined by embedding Monte Carlo tracks into real events. The size of this uncertainty is comparable to the width of the $I_{dAu} = 1$ line.

Our measurement of the nuclear modification of the conditional yield indicates that $I_{dAu}$ with the trigger particle at forward rapidity (sampling low-$x$ partons in the gold nucleus) and backward rapidity (sampling high-$x$ partons in the gold nucleus) are both consistent with one. There may even be some evidence of slight enhancement for the case with trigger particles at forward pseudorapidity in central $d + Au$ collisions. We note that if mono-jets were a major contributor to our trigger particle sample in our $x$ range, we would have expected a decrease in the conditional yield for $d + Au$ central collisions when the trigger particle is at forward pseudorapidity. Our measurement is inconsistent with any large nuclear suppression (i.e. mono-jets) of the jet structure in this kinematic range. However, we note that in these modest $p_T$ ranges, there may be contributions from both “hard” (large $Q^2$) processes and “soft” coherent (small $Q^2$) processes. In $d + Au$ collisions “soft” particle production is shifted away from forward rapidity towards backward rapidity [21]. Thus, the fraction of hadrons at forward rapidity from “hard” processes may be increased in central $d + Au$ reactions, which may offer an explanation for the modest enhancement seen in the conditional yield for this case and could also mask off small mono-jet signals.

We have also compared the Gaussian widths of the

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**Figure 2:** Conditional yields are shown as a function of trigger particle pseudorapidity. The data points at mid-rapidity for $d + Au$ collisions are from [14]. To increase visibility, we artificially shift the data points belonging to the same $\eta_{\text{trig}}$ bin. The errors on each points are statistical errors. The black bar around 0.1 on the left of the plot indicates a 10% common systematic error for all the data points due to the determination of associated particle efficiency. There is an additional +0.037 systematic error on the mid-rapidity $p + p$ point from jet yield extraction, which is shown as the arrow on that point (similar analysis as [16]).

**Figure 3:** $I_{dAu}$ vs. $p_T^{assoc}$ for different centrality, $p_T^{\text{trig}}$ and $\eta_{\text{trig}}$ bins. To increase visibility, we artificially shift the data points belonging to the same $p_T^{assoc}$ bin.

**Figure 4:** The ratio of correlation peak widths between $d + Au$ and $p + p$ collisions. Only statistic error is shown. To increase visibility, we artificially shift the data points belonging to the same $p_T^{assoc}$ bin.
correlation peaks in $d + Au$ collisions to the widths in $p + p$ collisions. The ratios of the $d + Au$ widths to the $p + p$ widths are plotted in Figure 4 as a function of $p_T^{\text{assoc}}$. There may be a hint of a slight $p_T^{\text{assoc}}$ dependence in the ratio, but overall there is no significant difference in the width in $d + Au$ collisions for different $\eta^{\text{trig}}$.

In conclusion, we have measured the two-particle azimuthal angle correlations in two centrality categories of $d + Au$ collisions and in $p + p$ collisions. We measured trigger particles at forward, backward and mid-rapidity and correlated them with associated particles at mid-rapidity. The associated particle conditional yields in central $d + Au$ collisions are consistent with the conditional yield in $p + p$ collisions. These conditional yields also do not change as we vary the trigger particle pseudo-rapidity over the range $|\eta| < 2.0$. We have also compared the widths of the away-side jet peaks in $d + Au$ and in $p + p$ collisions, and find no evidence for large $\eta^{\text{trig}}$-dependent modification.

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