Cold nuclear matter physics at forward rapidities from $d+Au$ collisions in PHENIX

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Abstract. We present measurements by the PHENIX experiment at RHIC of di-hadron pair production in $d+Au$ collisions where the particles in the pair are varied across a wide range of pseudorapidity, out to $\eta = 3.8$. With di-hadrons, varying the $p_T$ and rapidity of the particles in the di-hadron pair allows studying any effects as a function of partonic $x$ in the nucleus. These di-hadron measurements might probe down to parton momentum fractions $x \sim 10^{-3}$ in the gold nucleus, where the interesting possibility of observing gluon saturation effects at RHIC is the greatest. Our measurements show that the correlated yield of back-to-back pairs in $d+Au$ collisions is suppressed by up to an order of magnitude relative to $p+p$ collisions, and increases with greater nuclear path thickness and with a selection for lower $x$ in the Au nucleus.

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1. Introduction

Deuteron-gold collisions at RHIC provide a means to explore nuclear effects on the initial-state parton densities in the nucleus, which is vitally important for understanding the baseline production in heavy-ion collisions. RHIC experiments have shown that single inclusive hadron yields in the forward (deuteron) rapidity direction for $\sqrt{s_{NN}} = 200$ GeV $d+Au$ collisions are suppressed relative to $p+p$ collisions [1, 2, 3]. The mechanism for the suppression has not been firmly established. Many effects have been proposed for this suppression, such as gluon saturation [4, 5], initial state energy loss [6, 7], parton recombination [8], multi-parton interactions [9], and leading and higher-twist shadowing [10, 11].

One set of measurements that might help to distinguish between the competing models is forward azimuthally correlated di-hadron correlation functions, which directly probe di-jet production through their $2 \rightarrow 2$ back-to-back peak at $\Delta \phi = \pi$. This technique has been used extensively at RHIC and is described in detail elsewhere [12, 13, 14]. The di-hadron results presented here were obtained from $p+p$ and $d+Au$ runs in 2008 with the PHENIX detector and include a new electromagnetic calorimeter, the Muon Piston Calorimeter (MPC), with an acceptance of $3.1 < \eta < 3.8$ in pseudorapidity and

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0 < \phi < 2\pi. Di-hadron measurements can probe more precise ranges of parton x in a gold nucleus than do single hadron probes (e.g., \( R_{dA} \)). At forward rapidities, a single hadron probe will cover a very broad range of x, \( 10^{-3} < x_{Au} < 0.5 \), thus mixing together the shadowing, anti-shadowing, and even EMC effects [10]. Azimuthally correlated di-hadron measurements also enhance the di-jet fraction in the event selection, since one selects only the back-to-back hadrons.

**Figure 1.** Background-subtracted mid-forward rapidity \( \pi^0-\pi^0 \) (top) and forward-forward cluster-\( \pi^0 \) (bottom) per-trigger correlation functions, for \( p+p \) (open points), \( d+Au \) peripheral (60-88%, triangles), and \( d+Au \) central collisions (0-20%, solid points) at \( \sqrt{s_{NN}} = 200 \) GeV. The trigger \( p_T \) ranges from 1.1 to 7 GeV/c and the associated \( \pi^0 \)'s have \( p_T = 0.5 - 0.75 \) GeV/c. Systematic errors of up to 30% on the near side (|\( \Delta \phi \)| < 0.5) have not been shown. The subtracted pedestals, \( b_0 \), are shown for each case.

By performing several correlation measurements with particles at different \( p_T \) and rapidities, one can systematically scan different x ranges with an observable that is enhanced for the leading-order perturbative QCD component. Probing the x dependence of the effect is an important test since most models predict that any effects should be stronger at smaller x. Particles at higher pseudorapidities are produced from smaller x, so measuring hadrons from more forward rapidities should probe smaller x.

**2. PHENIX MPC \( d+Au \) di-Hadron Correlations**

For this analysis, back-to-back \( \pi^0-\pi^0 \) or hadron-\( \pi^0 \) pairs are measured with one particle at mid-rapidity, and the other at forward rapidity. Back-to-back cluster-\( \pi^0 \) pairs are also measured where both are in the forward rapidity region. The clusters are reconstructed from the energy deposit of photons in the MPC, and are estimated to be at least 80%
Forward di-hadron measurements in $d+Au$ collisions with PHENIX

A dominated by $\pi^0$'s, with the remainder coming from single photons from decays of $\eta$'s and from direct photons. Further details of the analysis are available in [14].

As shown in figure 1 the away-side peak for $d+Au$ central collisions appears significantly suppressed compared to $p+p$ collisions and peripheral $d+Au$ collisions. This effect is large for the mid-forward di-hadron correlations and becomes even larger for the forward-forward correlations. Within large errors, the Gaussian widths of the away-side correlation peak for the mid-forward di-hadron correlations remain the same between $p+p$ and central $d+Au$. For the forward-forward case, uncertainties in the pedestal level from the underlying event and the strong suppression of the away-side peak make extracting the width unreliable. For this case, the away side peak width in central $d+Au$ collisions is allowed to vary up to twice as much as in $p+p$ when accounting for this systematic uncertainty.

![Figure 2](image.png)

Figure 2. $J_{dA}$ versus $x_{Au}^{frag}$ for peripheral (60-88%, in red) and central (0-20%, in blue) $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, and compared to the EPS09 LO $R_{Au}^{Au}(x_{Au})$ curves at a scale $Q^2 = 4$ GeV$^2$ [16].

The observed suppression is quantified by studying the relative yield, $J_{dA}$ [15], of correlated back-to-back hadron pairs in $d+Au$ collision compared to $p+p$ collisions scaled with the average number of binary nucleon collisions $\langle N_{coll} \rangle$,

$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair}}{\sigma_{dA}^{pp} / \sigma_{pp}}. \tag{1}$$

This is simply the analog of the usual nuclear modification factor $R_{dA}$ but for hadron pairs. The $\sigma$ are the $p+p$ or $d+Au$ inelastic cross-sections, while $\sigma^{pair}$ is the cross-section for di-hadron pair production. The $J_{dA}$ is calculated using the correlated away side peak after subtracting the pedestal $b_0$. $J_{dA}$ decreases with increasing number of binary collisions, $\langle N_{coll} \rangle$, 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 mid-forward pairs. The observed suppression of $J_{dA}$ versus nuclear
Forward di-hadron measurements in d+Au collisions with PHENIX

thickness, $p_T$ and $\eta$ points to large cold nuclear matter effects arising at low parton momentum fractions $x$ in the nucleus probed by the deuteron. This trend is seen more clearly in Fig. 2 where $J_{dA}$ is plotted versus $x_{Au}^{\text{frag}} = (\langle p_{T1} \rangle e^{-(\eta_1)} + \langle p_{T2} \rangle e^{-(\eta_2)})/\sqrt{s_{NN}}$ for all pair selections in $\eta$ and $p_T$. In the case of 2→2 leading order (LO) processes, the variable $x_{Au}^{\text{frag}}$ is lower than $x_{Au}$ by the mean fragmentation fraction, $\langle z \rangle$, of the struck parton in the Au nucleus. Since $x_{Au}^{\text{frag}}$ is an entirely experimental defined quantity, it should be reproducible in any theoretical framework.

3. Discussion

In a leading order pQCD picture, the variable $J_{dA}$ is

$$J_{dA} = \frac{\sigma_{dA}^{\text{pair}} / \sigma_{dA}}{\langle N_{\text{coll}} \rangle} \sim \frac{f_A^a(x_A^a) \otimes f_A^b(x_A^b) \otimes \hat{\sigma}_A^{ab\rightarrow cd} \otimes D(z_c, z_d) \otimes \sigma_{pp}^{\text{pair}} / \sigma_{pp}}{\langle N_{\text{coll}} \rangle} f_p^a(x_p^a) \otimes f_p^b(x_p^b) \otimes \hat{\sigma}_p^{ab\rightarrow cd} \otimes D(z_c, z_d)$$

(2)

for partons a+b going to outgoing jets c+d, which then fragment to hadrons with longitudinal fractions $z_c, z_d$. In the above convolutions over p+p and d+Au, most of the terms are expected to be roughly similar between p+p and d+Au except for the nuclear gluon pdf. Naively, $J_{dA}$ might be largely dominated by the modification to the nuclear gluon parton distribution function (pdf’s), since most of the events with di-hadrons at forward rapidities consist of a high-$x$ parton from the deuteron and a low-$x$ gluon from the gold nucleus. Assuming this to be true then $J_{dA} \sim R_g^{Au} = G_A(x, Q^2) / A G_p(x, Q^2)$.

In figure 2 the $J_{dA}$ values are overlaid with the EPS09 $R_g^{Au}$ curves [16]. The $J_{dA}$ values for the peripheral bins are above the best fit EPS09, while the central bins are below. The EPS09 curves are taken largely from nuclear deep inelastic scattering and represent an averaged value of $R_g^{Au}$ over all centralities. The $J_{dA}$ values for the most central bin at the lowest $x$ are well below the EPS09 curves. This is qualitatively consistent with the expectations for the Color-Glass Condensate [4], which posits an extreme form of shadowing due to the onset of gluon saturation.

If nature is kind and this data can be interpreted in terms of a simple LO pQCD picture, it may be possible to extract $R_g^{Au}$, which is extremely important for understanding the quark gluon plasma since it forms the baseline for production in heavy ion collisions. In addition, if the large suppression of $J_{dA}$ observed in central d+Au collisions is from gluon saturation, it may be possible to study the dependence of that saturation on the thickness of the nucleus. One possible test of whether these ideas are correct would be to use extractions of $R_g^{Au}$ from this data to predict $J/\Psi$ data in d+Au collisions from PHENIX.

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Forward di-hadron measurements in $d+Au$ collisions with PHENIX

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\[
J_{dA} \times 10^{-3} \frac{\text{d}N}{\text{d}X_{\text{Au}}} \times 10^{-2}
\]

- d+Au 60-88 \(p_T^{fwd}\)
  - 0.5-0.75 GeV/c
  - 0.75-1.0 GeV/c
  - 1.0-1.5 GeV/c
- d+Au 0-20 \(p_T^{fwd}\)
  - 0.5-0.75 GeV/c
  - 0.75-1.0 GeV/c
  - 1.0-1.5 GeV/c