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Searching for Gluon Saturation in d+Au Collisions at PHENIX

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Measurements using the PHENIX forward detectors in high energy deuteron-gold collisions make it possible to study cold nuclear matter effects in nucleon structure at low x. The gold nuclei are Lorentz contracted leading to further enhancement in the nuclear parton densities. The high gluon densities make it possible to probe for saturation effects and to search for experimental evidence in support of a new effective field theory, the Color Glass Condensate, describing the limit of high parton densities in QCD. Past RHIC experiments have shown a suppression in nuclear modification factors (R_{dA}, R_{cp}) for $\sqrt{s_{NN}} = 200$ GeV d+Au collisions in the forward (deuteron) direction. Multiple theories exist that can explain the observed suppression (including saturation), but a conclusive measurement discriminating between the different mechanisms has yet to be carried out. Two new forward electromagnetic calorimeters (Muon Piston Calorimeters or MPCs, $-3.7 < \eta < -3.1$, $3.1 < \eta < 3.9$) may provide the PHENIX experiment with the capability to determine if gluon saturation is the reason for the observed suppression. With the calorimeters, one can measure forward di-hadron correlations, which have been predicted to show dramatic effects due to gluon saturation. In particular, azimuthal correlations of di-hadron pairs at different pseudorapidities will be shown; the forward pseudorapidity correlations are especially interesting because it is expected that they provide a test of gluon saturation down to $x \approx 10^{-3}$ in the Au nucleus. The analysis presented is based on the high integrated luminosity data sample of d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV taken at RHIC in 2008.

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1. Introduction

Deuteron-gold collisions at RHIC provide a heavy-ion collision system wherein one can explore nuclear effects on initial-state parton densities in the absence of quark-gluon plasma effects. RHIC experiments have shown a suppression in nuclear modification factors (R_{dA}, R_{cp}) for $\sqrt{s_{NN}} = 200$ GeV d+Au collisions in the forward (deuteron) direction and enhancement in the backward (gold) direction [1, 2, 3]. One explanation for the observed suppression of forward particle production in d+Au relative to p+p is that an increase in parton densities in the Lorentz-contracted Au nucleus has caused the onset of gluon saturation, or color glass condensate (CGC) [4]. CGC is a model for how the ostensibly divergent gluon density saturates at small parton momentum fraction x because the high gluon density leads to the balance between gluon splitting and recombination. It predicts a modification to the conventional $2 \rightarrow 2$ hard-scattering picture; one parton from the deuteron interacts with many low x gluons in the Au nucleus, resulting in a suppression of forward jet production. Other theories exist that also can explain the observed suppression such as initial state energy loss [5, 6], and non-leading twist shadowing [7]. Hence, more detailed measurements are needed to elucidate the mechanism responsible for the suppression.

One promising set of measurements are forward azimuthal angle di-hadron correlation functions, which directly probe di-jet production by the appearance of a $2 \rightarrow 2$ back-to-back peak at $\Delta\phi = \pi$. These measurements more precisely determine the momentum fraction of the interacting partons than do single hadron probes (such as R_{dA}), and they provide direct access to the jet structure rather than including all particle production mechanisms. By performing several correlation measurements with particles at different rapidities, we can systematically scan different x ranges and thus understand of the effects in an x dependent manner; this is paramount to understand if the suppression originates from gluon saturation, as it is an x-dependent phenomena. Signatures of gluon saturation include suppression of the signal in the correlation function as well as broadened widths produced from scattering off of multiple gluons [4, 8].

Previous PHENIX correlation studies in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions indicate no modification [9, 10], including a measurement where one particle's pseudorapidity was between 1.4 and 2.0. However, recent PHENIX results for rapidity separated pairs ($\langle\eta_1\rangle = 0$, $\langle\eta_2\rangle = 3.4$) show a suppression in the di-jet yield and indicate nuclear modification of di-jets in the forward region [11].

In these proceedings we present a new two-particle azimuthal angle correlation measurement wherein both particles are at forward rapidities. This tests the gluon saturation hypothesis by probing the lowest x accessible in PHENIX. The analysis presented is based on the ≈ 80 nb^{-1} integrated luminosity data sample of d+Au collisions taken at RHIC in 2008.

2. Apparatus

The correlation measurements use the PHENIX forward $PbWO_4$ electromagnetic calorimeter $3.1 < \eta < 3.9$ (called the Muon Piston Calorimeter or MPC) which was installed in 2006. The MPC covers the full 2π azimuthal angle; the towers have lateral dimensions of 2.2 $cm \times$ 2.2 cm. The MPC rests 220 cm from the nominal interaction point [12].

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For the measurements of interest, the MPC is used to identify pions via the $\pi^0 \rightarrow \gamma\gamma$ decay channel. In any electromagnetic calorimeter, if the momentum of a π^0 is sufficiently high, the energy from both decay photons will be reconstructed as a single cluster. For the MPC, this merging effect begins at $p_{tot} \approx 15\ GeV/c$ and is dominant by $25\ GeV/c$. In order to reach high p_T in the forward direction, we are forced to use the single clusters as an identification technique for π^0s. When using the single clusters, Pythia studies show that the π^0 constitutes nearly $80-85\%$ of all high energy clusters[1]. We thus detect pions in two ways: **1)** identify single clusters above $p_{tot} = 15\ GeV/c$ and **2)** reconstruct the invariant mass of all cluster pairs below $20\ GeV/c$. Sample invariant mass distributions are shown in Fig. 1 for the two cluster reconstruction.

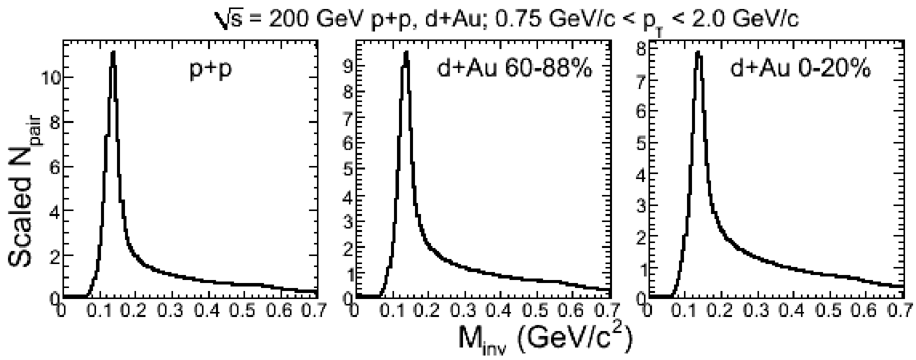


Figure 1: North MPC invariant mass distributions of photon pairs $0.75\ GeV/c < p_T < 2.0\ GeV/c$ for p+p, d+Au 60-88%, and d+Au 0-20% centrality bins.

3. Measurement

The correlation function, $CF(\Delta\phi)$, is the $\Delta\phi$ distribution of the two particles corrected for the nonuniform detector acceptance [13]. Acceptance-corrected $\Delta\phi$ correlation functions from this analysis (cluster/π^0) are shown in Fig. 2. The π^0s are defined as cluster pairs in the invariant mass window of 0.08 to 0.18 GeV/c^2; both single clusters and π^0s have $\langle\eta\rangle = 3.4$. The correlation functions shown have a range of $[0, \pi]$ and have the mirror image displayed from $[\pi, 2\pi]$. The di-cluster invariant mass distribution (see Fig. 1) has a π^0 peak which sits on top of a combinatorial background. The background contributions to the correlation functions are subtracted off by measuring the correlations outside the π^0 mass window. The systematic error bars (hollow boxes) shown in Figs. 2, 3 are from this subtraction.

The correlation functions are modeled as a Gaussian di-jet signal on top of a constant background. For $\Delta\eta \approx 1$ or less, a peak at $\Delta\phi = 0$ appears corresponding to particles from the same jet. The peak at $\Delta\phi = \pi$ is from the back-to-back jets in the $2 \rightarrow 2$ hard scattering. For correlation functions in Fig. 2, data points near $\Delta\phi = 0$ have been excluded because the acceptance for pairs in the MPC at $\Delta\phi = 0$ is exceedingly small; corrections for this region are ongoing.

The higher p_T particle in the pair is termed the trigger particle; the lower is called the associate particle. Two relevant quantities for comparison of d+Au with p+p data are the width of the

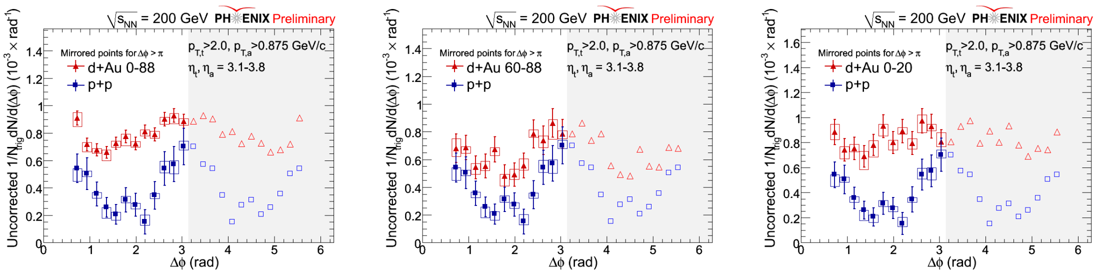
[1]The study was documented in an internal PHENIX document.

Gaussian peak at $\Delta\phi = \pi$ and the conditional (or per-trigger) yield, CY. The conditional yield is the efficiency-corrected signal pair-yield of particles produced per trigger particle detected, or

$$CY = \frac{\int_0^{2\pi} d(\Delta\phi)(CF(\Delta\phi) - bg(\Delta\phi))}{N_{trig} \times \varepsilon} \tag{3.1}$$

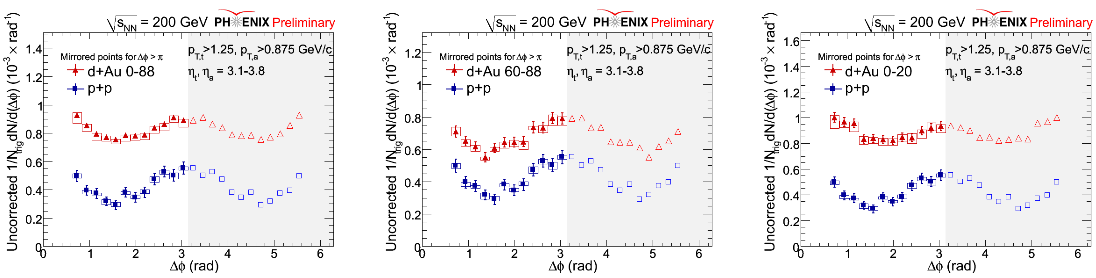
where N_{trig} is the number of trigger particles, ε is the detection efficiency of the associate particle, and $bg(\Delta\phi)$ is the constant combinatorial background. The ratio of the CYs for d+Au and p+p is called I_{dA}; $I_{dA} < 1$ indicates a suppression in the yield of di-jets.

The correlation functions in Fig. 2 are shown as per-trigger correlation functions but do not have the efficiency corrections applied. Because the same MPC detector configuration was used in d+Au as in p+p, the relative efficiency corrections will be small; hence it is qualitatively meaningful to compare the signal size in d+Au to p+p, as the ratio is essentially I_{dA}. The determination of the constant background is complicated by the large width of the peaks, and a careful treatment is necessary to extract the correct physics result.



(a) (b) (c)

Figure 2: Forward ($\langle\eta_{1,2}\rangle = 3.4$) per-trigger $\Delta\phi$ correlation functions for high energy clusters ($p_T > 2$ GeV/c) and π^0s ($0.875\ GeV/c < p_T < 2.0\ GeV/c$) for **(a)** d+Au minimum bias, **(b)** d+Au 60-88% centrality bin, **(c)** d+Au 0-20% centrality bin. In each plot the p+p correlation functions are also shown as a reference.



(a) (b) (c)

Figure 3: Forward ($\langle\eta_{1,2}\rangle = 3.4$) per-trigger $\Delta\phi$ correlation functions for high energy clusters ($p_T > 1.25$ GeV/c) and π^0s ($0.875\ GeV/c < p_T < 2.0\ GeV/c$) for **(a)** d+Au minimum bias, **(b)** d+Au 60-88% centrality bin, **(c)** d+Au 0-20% centrality bin. In each plot the p+p correlation functions are also shown as a reference.

4. Discussion

In Fig. 2, we show the forward correlation functions for d+Au collisions in **(a)** the minimum bias sample, **(b)** peripheral collisions, and **(c)** the most central collisions. In all the plots the p+p correlation functions are plotted as a reference for comparison. One sees an apparent disappearance of the peak at $\Delta\phi = \pi$ for central d+Au collisions, while in peripheral collisions the peak appears similar to p+p. Thus we see an apparent suppression in the ratio of conditional yields for small impact parameter. Additionally, it appears that there is an azimuthal broadening to the peak. These observations are purely qualitative at this point; accurate quantification of the yields and widths requires careful background subtraction which is ongoing.

There also seems to be a p_T dependence to the suppression phenomenon as well; lower p_T correlations seem to show less of a difference between p+p and d+Au central collisions than the higher p_T correlations, as seen in Fig. 3.

The color glass condensate predicts the disappearance of the away-side peak, and thus, this measurement seems to be a strong experimental signature for gluon saturation. It is our hope that by combining the single particle probes with the two-particle correlation functions a complete picture will emerge as to the mechanisms responsible for the interesting suppression seen in the forward direction.

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