Probing the Low-x Structure of the Nucleus with the PHENIX Detector

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One of the fundamental goals of the PHENIX experiment is to understand the structure of cold nuclear matter, since this serves as the initial state for heavy-ion collisions. Knowing the initial state is vital for interpreting measurements from heavy-ion collisions. Moreover, the structure of the cold nucleus by itself is interesting since it is a test-bed for our understanding of QCD. In particular there is the possibility of novel QCD effects such as gluon saturation at low-x in the nucleus. At RHIC we can probe the behavior of gluons at low-x by measuring the pair cross-section of di-hadrons from di-jets in d+Au collisions. Our results show a systematic decrease in the pair cross-section as one goes to smaller impact parameters of the nucleus, and also as one goes to lower Bjorken x. There is a possibility that these interesting effects come from gluon recombination at low x in the Au nucleus.

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 to understanding the baseline production for Quark-Gluon Plasma studies 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→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 $0 < \phi < 2\pi$.

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.

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 π^0-π^0 or hadron-π^0 pairs are measured with one particle at mid-rapidity, and the other at forward rapidity. Back-to-back cluster-π^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% dominated by π^0's, with the remainder coming from single photons from decays of η's and from direct photons. Further details of the analysis are available in [14].

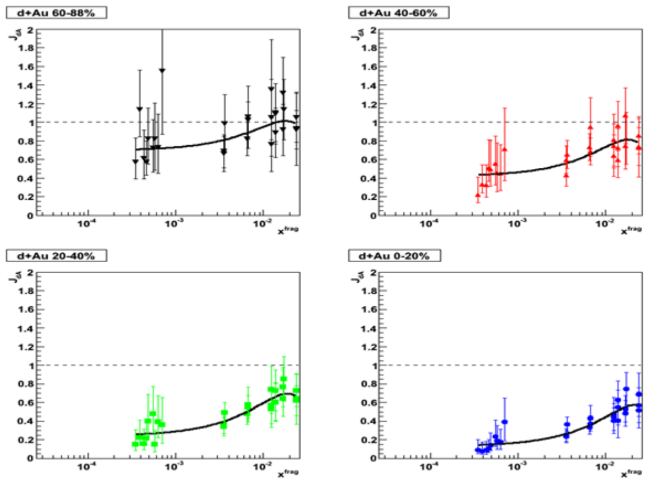

Figure 1: $J_{\rm dA}$ vs x_{Au}^{frag} for 4 different centrality bins. The points are fit with the same parametric function as those used for the EPS09 set of nuclear pdf's [16].

From the pairs we extract the relative yield, $J_{\rm dA}$, of correlated back-to-back hadrons in d+Au collisions compared to p+p collisions scaled with the average number of binary nucleon collisions $\langle N_{coll}\rangle$, where

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

and is explained in detail in [15]. $J_{\rm dA}$ is simply the analog of the usual nuclear modification factor $R_{\rm dA}$ but for hadron pairs. The $\sigma_{dA,pp}$ are the p+p or d+Au inelastic cross-sections, while $\sigma_{dA,pp}^{pair}$ are the cross-sections for di-hadron pair production, and is used as a proxy for di-jets in PHENIX.

In Fig. 1, we have plotted the values of $J_{\rm dA}$ versus x_{Au}^{frag} for four different d+Au centrality selections. x_{Au}^{frag} is defined as

$$x_{Au}^{frag} = (\langle p_{T1}\rangle e^{-\langle\eta_1\rangle} + \langle p_{T2}\rangle e^{-\langle\eta_2\rangle})/\sqrt{s_{NN}}$$

and can be directly measured experimentally. x_{Au}^{frag} should be correlated with the Bjorken x that is probed in the nucleus, assuming that a normal leading order (LO) perturbative QCD framework applies for this data. In the case of 2→2 LO processes, the variable x_{Au}^{frag} is lower than x_{Au} by the mean fragmentation fraction, $\langle z\rangle$, of the struck parton in the Au nucleus. From the plot, one can see that $J_{\rm dA}$ decreases with increasing centrality, or equivalently with increasing nuclear thickness. The suppression also increases as one goes to lower x_{Au}^{frag} in the nucleus probed by the deuteron.

In Fig. 2, the $J_{\rm dA}$ values for three different x_{Au}^{frag} are plotted versus $\langle N_{\rm coll}\rangle$, the mean number of binary collisions, in the four centrality classes depicted in Fig. 1. One can clearly see from this plot a systematic decrease of $J_{\rm dA}$ with greater $\langle N_{\rm coll}\rangle$, as well as with decreasing x. The decrease is approximately linear.

3 Discussion

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

$$J_{dA} = \frac{\sigma_{dA}^{pair}/\sigma_{dA}}{\langle N_{coll}\rangle\, \sigma_{pp}^{pair}/\sigma_{pp}} \approx \frac{f_d^a(x_d^a) \otimes f_{Au}^b(x_{Au}^b) \otimes \hat{\sigma}^{ab\to cd} \otimes \mathcal{D}(z_c, z_d)}{\langle N_{coll}\rangle\, f_p^a(x_p^a) \otimes f_p^b(x_p^b) \otimes \hat{\sigma}^{ab\to cd} \otimes \mathcal{D}(z_c, z_d)} \tag{1}$$

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 the parton distribution functions (f), the parton-parton cross-section $\hat{\sigma}$, and fragmentation functions $\mathcal{D}$, most of the terms are expected to be roughly similar between p+p and d+Au except for the nuclear gluon parton distribution (pdf).

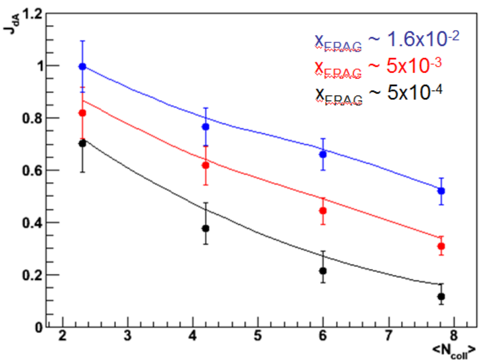

Figure 2: $J_{\rm dA}$ vs $\langle N_{\rm coll}\rangle$, the mean number of binary collisions, for different x_{Au}^{frag} values.

Naively, $J_{\rm dA}$ might be largely dominated by the modification to the nuclear gluon pdf, 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, one can then associate $J_{\rm dA}$ with the relative modification of the nuclear gluon distribution, R_g^{Au}, i.e.,

$$J_{\rm dA} \sim R_g^{Au} = G_{Au}(x, Q^2)/A\, G_p(x, Q^2)$$

One can then interpret Fig. 2 as a systematic decrease in the gluon distribution when one goes to the thicker parts of the nucleus, perhaps due to recombination of the gluons, and that the recombination creates a proportional decrease in the number of gluons with increasing number of nucleons along a line in the nucleus. This is schematically illustrated in Fig. 3. This decrease is stronger at lower x, which one might expect since the transverse size of the gluons are larger for lower x.

If nature is kind and this data can be interpreted in terms of a simple LO pQCD picture, then this data may provide valuable information on how gluons recombine in the nucleus as a function of the thickness of the nucleus and Bjorken x of the gluon. Furthermore, it may be possible to extract R_g^{Au}, which is extremely important for understanding the quark gluon plasma since it forms the main ingredient for production in heavy ion collisions.

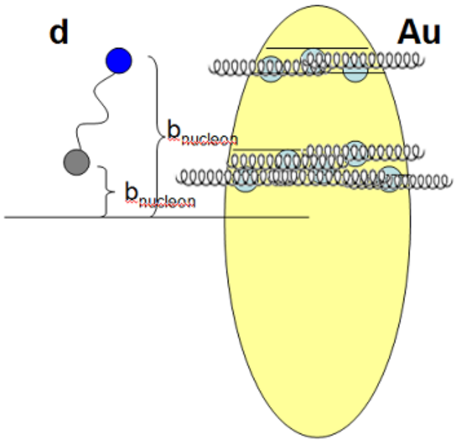

Figure 3: Schematic illustration depicting the increasing overlapping of gluons with smaller impact parameter.

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