Neutral Pion Suppression at Forward Rapidities in d+Au Collisions at STAR

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Abstract. Measurements of the inclusive yields of π^0 mesons in p+p and d+Au collisions at center of mass energy $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ and pseudorapidity $\langle\eta\rangle = 4.00$ (d beam direction) are reported. The yield for p+p collisions is in general agreement with perturbative QCD calculations. The d+Au yield is in agreement with a calculation which models the Au nucleus as a Color Glass Condensate for forward particle production. The nuclear modification factor derived from the inclusive yields is qualitatively consistent with models which suppress the gluon density in nuclei.

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In contrast to the nucleon, very little is known about the density of gluons in nuclei [1]. For protons, the gluon parton distribution function (PDF) is constrained primarily by scaling violations in deeply-inelastic lepton scattering (DIS) measured at the HERA collider [2]. The data are accurately described by QCD evolution equations that allow the determination of the gluon PDF. As the momentum fraction of the parton (x_{Bj}) decreases, the gluon PDF is found to increase. At sufficiently low x_{Bj}, the increase in gluon splitting is expected to become balanced by gluon-gluon recombination, resulting in gluon saturation. In nuclei, the density of gluons per unit transverse area is expected to be larger than in nucleons, and so is a natural environment in which to establish if, and under which conditions, gluon saturation occurs. Quantifying if gluon saturation occurs at RHIC energies is important because most of the matter created in heavy ion collisions is expected to evolve from an initial state produced by the collisions of low-x_{Bj} gluon fields in the nuclei [3]. Fixed target nuclear DIS experiments are restricted in the kinematics available and have determined the nuclear gluon PDF for $x_{Bj} \gtrsim 0.02$ [1]. In a conventional pQCD description of d(p)+A collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, inclusive forward hadroproduction probes the nuclear gluon density over a broad distribution of x_{Bj} peaked around 0.02 and extending well below $x_{Bj} \approx 0.005$ [4].

Using factorization in a perturbative QCD (pQCD) framework, the PDF's and fragmentation functions (FF's) measured in electromagnetic processes can be used in the description of hadronic scattering processes. In p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$, factorized leading twist pQCD calculations have been shown to quantitatively describe inclusive π^0 production over a broad rapidity window [5, 6]. In pQCD, forward π production in p+p collisions probes low-x_{Bj} gluons (g) in one proton using the valence quarks (q) of the other. Recently, the yield of forward negatively charged hadrons (h^-) in the d-beam direction of d+Au collisions was found to be reduced when normalized to p+p collisions [7]. The reduction is especially significant since isospin effects are expected to suppress h^- production in p+p collisions, but not in d+Au collisions [4].

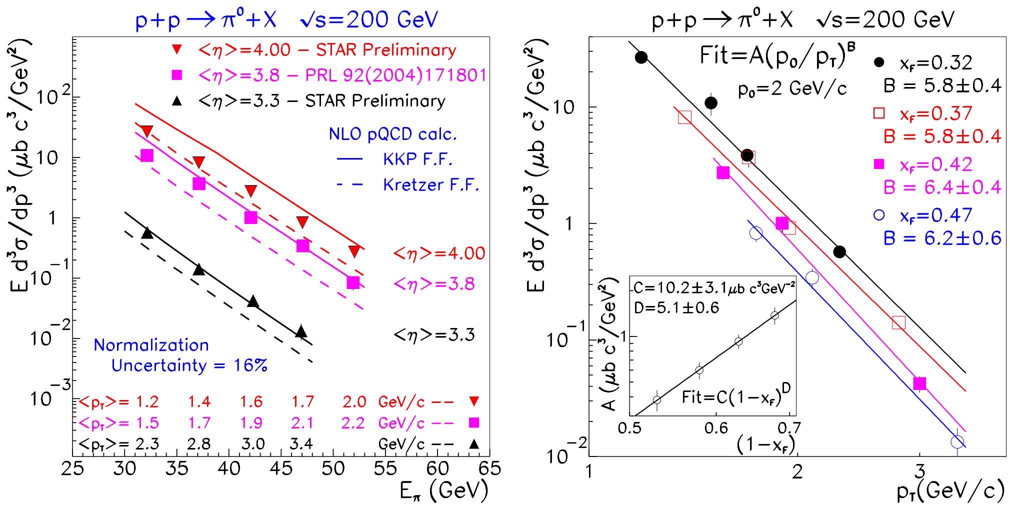

FIGURE 1. Inclusive π^0 production cross section for p+p collisions. The error bars, often smaller than the points, combine the statistical and point-to-point systematic errors. (Left) Versus pion energy (E_π) at fixed pseudorapidity (η). The curves are NLO pQCD calculations using two sets of fragmentation functions (FF). (Right) Versus transverse momentum (p_T) at fixed Feynman-x (x_F). Curves here and in the inset are fits to the data of the form shown on the plots. (Inset) Versus $(1-x_F)$ at $p_T = 2\,\text{GeV/c}$.

Many models attempt to describe forward hadroproduction from nuclear targets. Saturation models [8] include a QCD based theory called the Color Glass Condensate (CGC) [9, 10]. Another approach models quarks scattering coherently from multiple nucleons, leading to an effective shift in the x_{Bj} probed [11]. Shadowing models suppress the nuclear gluon PDF in a standard factorization framework [12]. Parton recombination models modify the fragmentation of a quark passing through many gluons [13]. Other descriptions include factorization breaking in heavy nuclei [14]. More data are needed to constrain the mechanisms for forward hadroproduction in nuclear collisions.

In this paper we present the inclusive yields of high energy π^0 mesons at $\langle\eta\rangle = 4.00$ ($\eta = -\ln[\tan(\theta/2)]$) in p+p and d+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. The results are compared with theoretical predictions. The η dependence of the normalized cross section ratio is also presented. Analysis of the azimuthal correlations of the forward π^0 with coincident hadrons at midrapidity is presented elsewhere [15].

A forward π^0 detector (FPD) was installed at the Solenoidal Tracker At RHIC (STAR) to detect high energy π^0 mesons with $3.3 < \eta < 4.1$. In the 2002 run, p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ were studied with a prototype FPD [5]. In the 2003 run, p+p collisions were studied with the complete FPD and exploratory measurements were performed for d+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. Details of the FPD performance can be found in Ref. [16]. The luminosity was determined by measuring the transverse size of the colliding beams and the number of colliding ions, giving a normalization error of $\approx 11\%$.

The cross sections for $p + p \to \pi^0 + X$ at $\langle\eta\rangle = 3.3$, 3.8, and 4.00 are presented in Fig. 1 (left) [5, 16]. The E_π-dependent systematic error at $\langle\eta\rangle = 4.00$ is $10-20\%$, dominated by the energy calibration of the FPD. The absolute η uncertainty contributes 11% to the normalization error [16]. The curves are NLO pQCD calculations using the KKP and Kretzer sets of FF's differing primarily in the gluon-to-pion FF, D_g^π. At

$\eta = 3.3$ and 3.8, the data are consistent with KKP. As p_T decreases further, the data begin to undershoot KKP and approach consistency with Kretzer. This is consistent with the trend seen at midrapidity [6]. At low p_T, the dominant contribution to π^0 production becomes gg scattering, making D_g^π the dominant FF [17]. In Fig. 1 (right), the cross section is shown versus p_T at fixed Feynman-x ($x_F \approx 2E_\pi/\sqrt{s}$), and versus $(1-x_F)$ at $p_T = 2\,\mathrm{GeV/c}$ (inset). As was reported at the CERN ISR [18], the forward rapidity yields are rapidly changing functions of both x_F and p_T.

The cross section for $d+Au \rightarrow \pi^0 + X$ at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ and $\langle\eta\rangle = 4.00$ is presented in Fig. 2 (left). The E_π-dependent systematic error is $\approx 20\%$, dominated by the background correction because, on average, 0.5 more photons are observed in d+Au than in p+p collisions per event with $> 30\,\mathrm{GeV}$ detected in the FPD. The curves are LO calculations from Ref. [10], using CTEQ5 PDF's and KKP FF's convoluted with a dipole-nucleus cross section which models parton scattering from a CGC in the Au nucleus. The "MV" and "No DGLAP" curves neglect QCD evolution of the Au wave function and the PDF/FF, respectively. The difference in the slopes with and without evolution is greater than the slope change from LO to NLO for $p+p \rightarrow \pi^0 + X$ at $\eta = 3.8$. The calculations in Fig. 2 are normalized by a p_T-independent K-factor of 0.8. This is smaller than the K-factor used to normalize the theory to the $d+Au \rightarrow h^-$ yield at the nominal value of $\eta = 3.2$, in the same direction as the renormalization needed to scale the NLO calculations with KKP FF to $p+p \rightarrow \pi^0$ data at $\eta = 4.00$. Note from Fig. 1 that a change of $\Delta\eta \approx 0.05$ at these kinematics results in $\Delta\sigma/\sigma \approx 35\%$ at fixed x_F. The slope of the π^0 yield is consistent with the calculation where the PDF and FF evolve à la DGLAP, and includes small-x_{Bj} evolution of the Au wave function.

Nuclear effects on particle production are quantified by the nuclear modification factor, R^Y_{dAu}, which can be defined for minimum-bias events by the ratio,

$$R^Y_{\mathrm{dAu}} = \frac{\sigma^{pp}_{\mathrm{inel}}}{\langle N_{\mathrm{bin}}\rangle \sigma^{dAu}_{\mathrm{hadr}}} \frac{Ed^3\sigma/dp^3(d+Au \rightarrow Y+X)}{Ed^3\sigma/dp^3(p+p \rightarrow Y+X)}. \tag{1}$$

We adopt $\sigma^{pp}_{\mathrm{inel}} = 42\,\mathrm{mb}$ for the inelastic p+p cross section, while the non-elastic d+Au cross section, $\sigma^{dAu}_{\mathrm{hadr}} = 2.21 \pm 0.09\,\mathrm{b}$, and the mean number of binary collisions, $\langle N_{\mathrm{bin}}\rangle = 7.5 \pm 0.4$, are determined by a Glauber model calculation [19]. Normalization systematic errors mostly cancel in the ratio. At $\eta \approx 0$, $R^{h^\pm}_{\mathrm{dAu}} \gtrsim 1$, with a Cronin peak at $p_T > 2\,\mathrm{GeV/c}$ [19]. In contrast, at $\langle\eta\rangle = 4.00$, $R^{\pi^0}_{\mathrm{dAu}} \ll 1$, as seen in Fig. 2 (right). The decrease of R_{dAu} with η is qualitatively consistent with models that suppress the nuclear gluon density [9, 11, 12, 13]. $R^{\pi^0}_{\mathrm{dAu}}$ is significantly smaller than a linear extrapolation of $R^{h^-}_{\mathrm{dAu}}$ to $\eta = 4$, consistent with expectations of isospin suppression of $p+p \rightarrow h^- + X$ [4].

In summary, inclusive yields of forward π^0 mesons from p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ are consistent with NLO pQCD calculations. The cross sections show rapid variation with both x_F and p_T. The d+Au yield is consistent with a model which treats the Au nucleus as a CGC for forward particle production. Comparisons with other models will be interesting to perform. Normalizing to equal numbers of binary collisions, the d+Au yield is significantly smaller than the p+p yield. The η dependence of the reduction is consistent with models which suppress the gluon density in nuclei, in addition to exhibiting isospin effects at these kinematics. Additional measurements

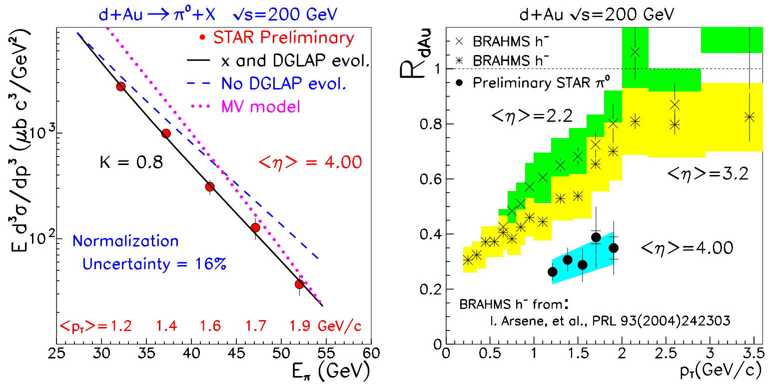

FIGURE 2. (Left) Inclusive π^0 production cross section for d+Au collisions, displayed as in Fig. 1. The curves are from models which treat the Au nucleus as a CGC, normalized with a p_T-independent K-factor. (Right) Nuclear modification factor for minimum-bias d+Au collisions versus p_T. The solid circles are data for π^0 mesons. The inner error bars are statistical, the outer combine these with the point-to-point systematic errors, and the shaded band is the normalization error. The x's and stars are data for h^- at smaller η. These error bars are statistical, while the shaded boxes are the point-to-point systematic errors.

at different centralities and with other final states will help elucidate the cause of the suppression. In addition, both di-hadron correlation data and quantitative theoretical understanding thereof are needed to facilitate tests of a possible CGC.

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