Particle Production in p(d)A Collisions

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Abstract. We discuss particle production in $p(d)A$ collisions in the saturation/Color Glass Condensate physics framework. We describe how predictions of saturation physics can be tested by studying energy/rapidity dependence of particle spectra in p(d)A collisions. We concentrate on the nuclear modification factor R^{pA} for gluon production. We show that at moderately high energy/rapidity the nuclear modification factor R^{pA} exhibits Cronin enhancement. As the energy/rapidity increases, R^{pA} decreases. At sufficiently high energy/rapidity R^{pA} becomes less than 1 for all values of p_T indicating the onset of suppression of gluon production due to quantum small-x evolution effects. These predictions were confirmed by RHIC data.

Keywords: saturation, Color Glass Condensate, particle production, BFKL evolution, shadowing
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INTRODUCTION

This talk is based on work done in collaboration with Dima Kharzeev and Kirill Tuchin [1, 2].

We will discuss single inclusive particle production in $p(d)A$ collisions calculated in the framework of saturation/Color Glass Condensate physics. In $p(d)A$ collisions, due to absence of final state interactions, predictions of saturation physics can be tested directly. Single gluon production cross section in pA collisions was found in [3] in the quasi-classical approximation and the effects of quantum small-x evolution were included in it in [4]. Concentrating on the resulting nuclear modification factor R^{pA} we will argue that the quasi-classical gluon production cross section calculated in [3] leads to Cronin enhancement [1, 5]. This regime is probably relevant for mid-rapidity particle production in dAu collisions at RHIC. At higher (forward) rapidities the effects of small-x evolution would lead to suppression of R^{pA} and disappearance of Cronin effect [6, 1, 7]. The suppression predicted in [6, 1, 7] was observed experimentally in [8, 9], confirming the expectation of saturation/Color Glass physics: it may also be regarded as experimental evidence of BFKL evolution. We will demonstrate that a quantitative saturation-inspired model from [2] describes the data of [8] rather well.

SINGLE GLUON PRODUCTION IN PA COLLISIONS

We start by discussing single inclusive particle production cross section and transverse momentum spectra in dAu collisions. The gluon production cross section in pA in the quasi-classical approximation was constructed in [3] yielding

$$\frac{d\sigma^{pA}}{d^2k\,dy} = \int d^2b\,d^2x\,d^2y\,\frac{1}{(2\pi)^2}\,\frac{\alpha_s C_F}{\pi^2}\,\frac{\underline{x}\cdot\underline{y}}{\underline{x}^2\underline{y}^2}\,e^{-i\underline{k}\cdot(\underline{x}-\underline{y})}$$
$$\times\left[1-e^{-\underline{x}^2 Q_{s0}^2\ln(1/x_T\Lambda)/4}-e^{-\underline{y}^2 Q_{s0}^2\ln(1/y_T\Lambda)/4}+e^{-(\underline{x}-\underline{y})^2 Q_{s0}^2\ln(1/|\underline{x}-\underline{y}|\Lambda)/4}\right], \qquad (1)$$

where $\underline{k}$ and y are the produced gluon's transverse momentum and rapidity, $\underline{b}$ is the proton's impact factor, Q_{s0} is the saturation scale in McLerran-Venugopalan model and $\underline{x}$, $\underline{y}$ are two-dimensional gluon transverse position vectors which are integrated over.

Eq. (1) can be used to construct the nuclear modifi cation factor [1]

$$R^{pA}(\underline{k},y) = \frac{\frac{d\sigma^{pA}}{d^2k\,dy}}{A\,\frac{d\sigma^{pp}}{d^2k\,dy}}. \qquad (2)$$

The ratio $R^{pA}(k_T)$ is plotted in Fig. 1 for $\Lambda = 0.2\,Q_{s0}$. It clearly exhibits an enhancement at high-k_T characteristic of Cronin effect. Similar conclusions have been reached by other authors [5]. Note that the position and height of the Cronin peak are increasing functions of the centrality of pA collisions [1].

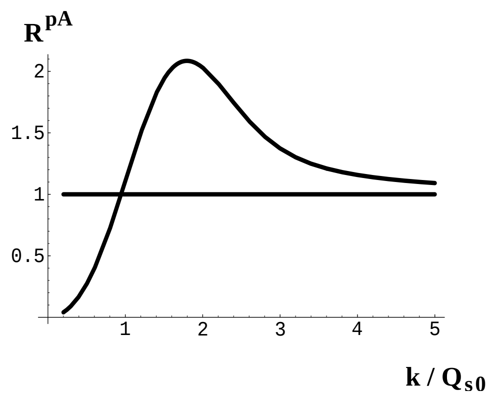

FIGURE 1. Nuclear modification factor R^{pA} plotted as a function of k_T/Q_{s0} for gluon production in the quasi-classical McLerran-Venugopalan model as found in [3]. The cutoff is $\Lambda = 0.2\,Q_s$.

Before including quantum evolution into Eq. (1), let us fi rst note that Eq. (1), even though it includes multiple rescatterings, can still be written in k_T-factorized form (!) [4, 1]

$$\frac{d\sigma^{pA}}{d^2k\,dy} = \frac{2\,\alpha_s}{C_F}\,\frac{1}{\underline{k}^2}\int d^2q\,\phi_p(\underline{q},0)\,\phi_A(\underline{k}-\underline{q},0), \qquad (3)$$

with the unintegrated "gluon distributions" given by

$$\phi_A(x,\underline{k}^2) = \frac{C_F}{\alpha_s\,(2\pi)^3}\int d^2b\,d^2r\,e^{-i\underline{k}\cdot\underline{r}}\,\nabla_r^2\,N_G(\underline{r},\underline{b},y=\ln 1/x), \qquad (4)$$

and

$$\phi_p(x,\underline{k}^2) = \frac{C_F}{\alpha_s\,(2\pi)^3}\int d^2b\,d^2r\,e^{-i\underline{k}\cdot\underline{r}}\,\nabla_r^2\,n_G(\underline{r},\underline{b},y=\ln 1/x). \qquad (5)$$

Here $N_G(\underline{r},\underline{b},y=\ln 1/x)$ and $n_G(\underline{r},\underline{b},y=\ln 1/x)$ are forward scattering amplitudes of a gluon dipole of size r located at impact parameter $\underline{b}$ on a nucleus and a proton correspondingly. Eq. (1) is reproduced by using $N_G(\underline{r},\underline{b},0) = 1-e^{-\underline{r}^2 Q_{s0}^2 \ln(1/r_T\Lambda)/4}$ and $n_G(\underline{r},\underline{b},0) = \underline{r}^2\Lambda^2\ln(1/r_T\Lambda)$ [1].

As was shown in [4], Eq. (3) makes inclusion of quantum small-x evolution straightforward. A tedious analysis shows that the inclusion of evolution preserves k_T-factorization of Eq. (3) yielding the full answer for inclusive cross section [4]

$$\frac{d\sigma^{pA}}{d^2k\,dy} = \frac{2\,\alpha_s}{C_F}\,\frac{1}{\underline{k}^2}\int d^2q\,\phi_p(\underline{q},Y-y)\,\phi_A(\underline{k}-\underline{q},y), \tag{6}$$

where Y is the full rapidity interval between the proton and the nucleus. The gluon distribution functions in Eq. (6) are still given by Eqs. (4) and (5), but now with n_G given by the solution of the BFKL equation and with N_G given by the solution of the non-linear evolution equation.

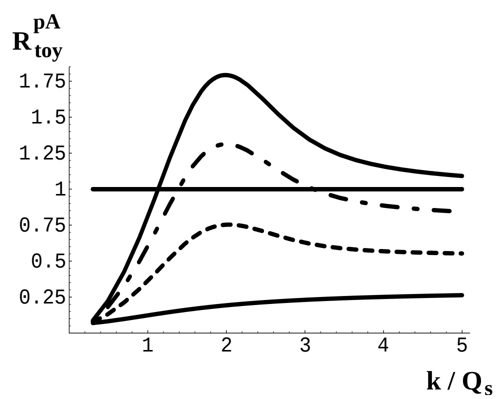

FIGURE 2. R^{pA} plotted as a function of k_T/Q_s for (i) McLerran-Venugopalan model, which is valid for moderate energies/rapidities (upper solid line); (ii) our toy model for very high energies/rapidities from [1] (lower solid line); (iii) an interpolation to intermediate energies/rapidities (dash-dotted and dashed lines).

The analysis of nuclear modification factor resulting from Eq. (6) was carried out in [6, 1, 7]. The result is that $R^{pA} \sim A^{-1/6}$ at very large y for all p_T. Note that R^{pA} will become a decreasing function of centrality at high energies/rapidities.

Our conclusions regarding the variation of R^{pA} with energy/ centrality are summarized in Fig. 2. The top solid curve in Fig. 2 is the same as in the quasi-classical approximation shown in Fig. 1. It corresponds to moderately high energy/rapidity. As energy/rapidity increases R^{pA} decreases (dash-dotted and dashed lines) and the Cronin peak flattens, eventually approaching a flat curve (lower solid line) which has suppression at all p_T. Similar conclusions have been reached in [7].

THE DATA

The data on the nuclear modification function R^{dAu} for $d+Au$ collisions reported by BRAHMS collaboration [8] is shown in Fig. 3, along with predictions of a saturation-inspired model constructed in [2], which includes valence quark contribution as well. As one can see from Fig. 3, the onset of suppression at higher rapidities, predicted by CGC approach, is confirmed by RHIC data.

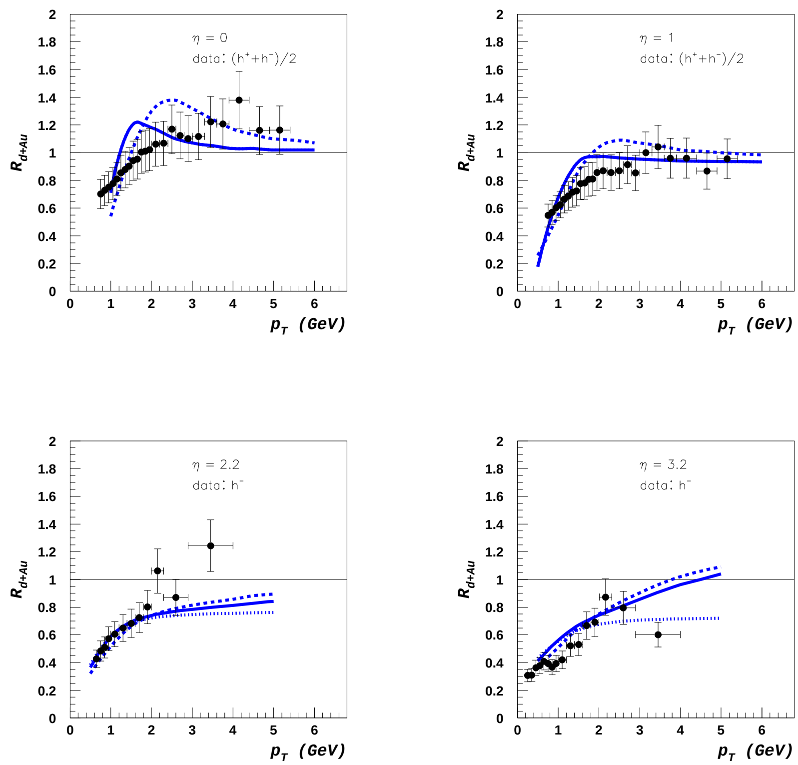

FIGURE 3. Nuclear modification factor R_{dAu} of charged particles for different rapidities. The fit uses the model described in [2]. Data is from [8].

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