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# Cronin Effect at Different Rapidities at RHIC

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**Abstract.** Calculations of the nuclear modification factor, $R_{dAu}$, for $\pi^0$ production in $dAu$ collisions at $\sqrt{s}_{NN} = 200$ GeV are presented. The applied pQCD-improved parton model incorporates intrinsic $k_T$. Nuclear multiscattering and nuclear shadowing are considered in the $Au$ nucleus. Theoretical results are displayed for midrapidity and high pseudorapidity, $\eta$, and compared to preliminary PHENIX and BRAHMS data.

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## Introduction

Midrapidity $AuAu$ experiments at RHIC energies display strong suppression in $\pi$ spectra at high $p_T$ [1]. This effect was explained by jet energy loss in hot dense matter (see Ref. [2]). To investigate whether initial state effects play a role in this suppression, $dAu$ experiments were carried out. Instead of suppression, an enhancement has been seen in minimum bias data [3] (the "Cronin effect" in $pA$ collisions at FERMILAB energies [4, 5]). This result indicates the absence of extra shadowing (gluon saturation), related to proposed wave-function modifications in the fast moving $Au$ nucleus (see Ref. [6]). However, new data with centrality dependence in midrapidity $dAu$ collisions [7] could provide more detailed information about the interplay between nuclear multiscattering [8] and (standard) nuclear shadowing [9]. Analysis of recent data at forward rapidities [10] can give more insight into the $\eta$-dependence of nuclear effects.

Here we display the results of our NLO pQCD calculations on pion production at $2 < p_T < 10$ GeV at different centralities. In parallel, we consider available data at forward rapidities in $dAu$ collisions [10], and investigate them theoretically.

## 1. Calculational method in a nutshell

We perform calculations on $\pi^0$ production in $dAu$ collisions using a pQCD-improved parton model extended by a Glauber-type collision geometry [11, 12, 13]. Introducing nuclear thickness function, $t_{Au}$, with a Woods−Saxon formula for $Au$ and $t_d$ with a sharp sphere for $d$, the invariant cross section is obtained as [14]:

$$
\begin{aligned}
E_\pi \frac{\mathrm{d}\sigma_\pi^{dAu}}{\mathrm{d}^3p} &= \int \mathrm{d}^2b \, \mathrm{d}^2r \; t_d(r) \; t_{Au}(|\mathbf{b}-\mathbf{r}|) \; \frac{1}{s} \sum_{abc} \int_{vw/z_c}^{1-(1-v)/z_c} \frac{\mathrm{d}\hat{v}}{\hat{v}(1-\hat{v})} \times \\
&\times \int_{vw/\hat{v}z_c}^{1} \frac{\mathrm{d}\hat{w}}{\hat{w}} \int^1 \mathrm{d}z_c \int \mathrm{d}^2\mathbf{k}_{Ta} \int \mathrm{d}^2\mathbf{k}_{Tb} \; f_{a/d}(x_a, \mathbf{k}_{Ta}, Q^2) \; f_{b/A}(x_b, \mathbf{k}_{Tb}, Q^2) \times \\
&\times \left[ \frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\hat{v}} \delta(1-\hat{w}) + \frac{\alpha_s(Q_r)}{\pi} K_{ab,c}(\hat{s}, \hat{v}, \hat{w}, Q, Q_r, \tilde{Q}) \right] \frac{D_c^\pi(z_c, \tilde{Q}^2)}{\pi z_c^2} \; . \qquad (1)
\end{aligned}
$$

In our next-to-leading order (NLO) calculation [11], $\mathrm{d}\widehat{\sigma}/\mathrm{d}\hat{v}$ represents the Born cross section of the partonic subprocess, and $K_{ab,c}(\hat{s}, \hat{v}, \hat{w}, Q, Q_r, \tilde{Q})$ is the corresponding higher order correction term [11, 12, 13]. We fix the factorization and renormalization scales and connect them to the momentum of the intermediate jet, $Q = Q_r = (4/3)p_q$ (where $p_q = p_T/z_c$), reproducing $pp$ data at RHIC with high precision at high $p_T$ [14].

The approximate form of the 3-dimensional parton distribution function (PDF) is:

$$
f_{a/p}(x_a, \mathbf{k}_{Ta}, Q^2) \;\; = \;\; f_{a/p}(x_a, Q^2) \cdot g_{a/p}(\mathbf{k}_{Ta}) \; . \qquad (2)
$$

Here, the function $f_{a/p}(x_a, Q^2)$ represents the standard NLO PDF as a function of momentum fraction of the incoming parton, $x_a$, at scale $Q$ (we use MRST(cg)). The partonic transverse-momentum distribution is defined phenomenologically as a 2-dimensional Gaussian, $g_{a/p}(\mathbf{k}_T)$, and characterized by an "intrinsic $k_T$" width [11, 15].

Nuclear multiscattering is accounted for through broadening of the incoming parton's $k_T$-distribution function, namely an increase in the width of the Gaussian:

$$
\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + \Delta(b) \quad \text{where} \quad \Delta(b) = C \cdot h_{pA}(b) \; . \qquad (3)
$$

Pion production in $pp$ collisions at RHIC energy indicates the value $\langle k_T^2 \rangle_{pp} = 2.5$ GeV$^2$ [14, 15]. Considering the multiscattering part, $h_{pA}(b)$ describes the number of *effective* $NN$ collisions (or *effective* collision length for partons) at impact parameter $b$, which impart an average transverse momentum squared, $C$ [15]. At SPS energies the effectivity function $h_{pA}(b)$ was written in terms of the number of collisions suffered by the incoming proton in the target nucleus. For this energy region we have found a limited number of semihard collisions, $\nu_m - 1 = 4$ and the value $C = 0.35$ GeV$^2$ [16], which implies a total broadening $\Delta \sim 1$ GeV$^2$. We will assume these values at RHIC energies, although the precise energy and rapidity dependence of $\nu_m$ and $C$ is not yet verified.

The nuclear PDF, $f_{b/A}(x_b, \mathbf{k}_{Tb}, Q^2)$, incorporates the shadowing parametrization used in HIJING [9]. Extra gluon saturation (CGC) [6] would require a further suppression factor to be introduced. The experimental data will decide if such an extra suppression factor is necessary.

Fragmentation function (NLO KKP), $D_c^\pi(z_c, \tilde{Q}^2)$, in eq. (1) is responsible for the hadronization of parton $c$ into a pion with momentum fraction $z_c$ at scale $\tilde{Q} = (4/3)p_T$.

We present results on the nuclear modification factor, defined as follows:

$$
R_{dAu} = \frac{1}{N_{bin}} \frac{E_\pi \mathrm{d}\sigma_\pi^{dAu}/\mathrm{d}^3p}{E_\pi \mathrm{d}\sigma_\pi^{pp}/\mathrm{d}^3p} = \frac{E_\pi \mathrm{d}\sigma_\pi^{dAu}(\text{with nuclear effects})/\mathrm{d}^3p}{E_\pi \mathrm{d}\sigma_\pi^{dAu}(\text{no nuclear effects})/\mathrm{d}^3p} \; . \qquad (4)
$$

## 2. Results on $dAu$ collisions at $\eta = 0$ in different centrality bins

In Fig. 1 we display the measured $R^{\pi}_{dAu}$ for $\pi^0$ production at $\sqrt{s}_{NN} = 200$ GeV at different centralities: $0 - 20\%$, $20 - 40\%$, $40 - 60\%$ and $60 - 88\%$ [7]. The first three centrality bins (up to 60 %) are similar to each other, only a slight decrease can be seen.

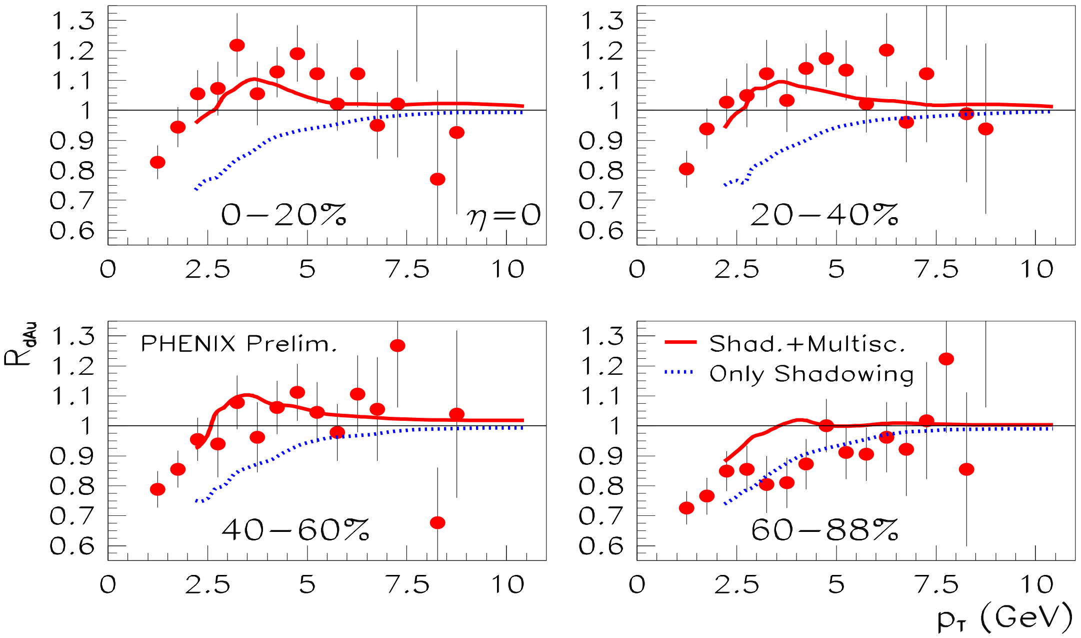

**Figure 1.** Theoretical results on $R^{\pi}_{dAu}$ at $\eta = 0$, compared to PHENIX data on $\pi^0$ [7].

Our theoretical pQCD results on $\pi^0$, containing multiscattering and shadowing (*solid lines*), show similar tendency and overlap with the preliminary PHENIX data. We predicted this behavior in Ref. [14]. These data indicate the plateau of the applied Woods – Saxon density profile of the $Au$ nucleus and the applicability of a $b$-independent shadowing in the model. The difference between data and theory in the most peripheral case requires further study. To indicate the importance of nuclear multiscattering in $dAu$ collisions we also show results containing only shadowing (*dotted lines*).

## 3. Minimum bias results in $dAu$ collisions at forward rapidities

Figure 2 summarizes BRAHMS data on charged-hadron production at forward pseudorapidities [10], CGC result at $\eta = 3.2$ in the low-$p_T$ region [6] (*dashed line*), and our pQCD results on $\pi^0$ at $p_T > 2$ GeV. We concentrate on the high-$p_T$ region, where no CGC result was available. The increasing strength of conventional nuclear shadowing with increasing pseudorapidity is indicated by pQCD results containing only this shadowing (*dotted lines*, $C = 0$). Including nuclear multiscattering (Cronin effect) we obtain reasonable agreement between data and our pQCD calculations on $R^{\pi}_{dAu}$ (*solid lines*). Our results indicate the validity of pQCD description for $dAu$ collisions at high $\eta$.

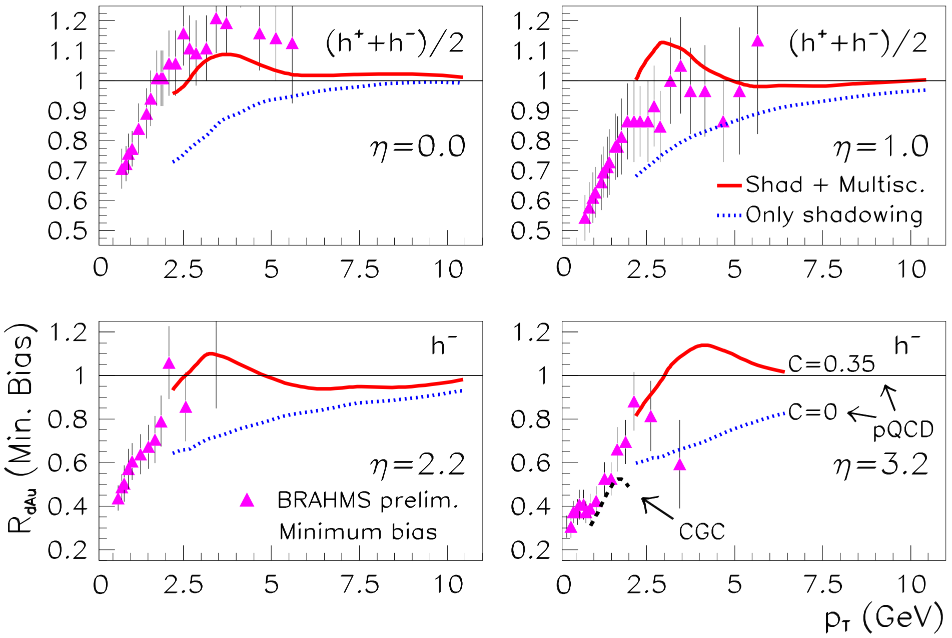

**Figure 2.** Theoretical pQCD results on $R^{\pi}_{dAu}$ for $\pi^0$ at $\eta = 0$, 1, 2.2 and 3.2, compared to BRAHMS data on charged particles [10]. The CGC result is from Ref. [6].

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