Cronin Effect at Different Rapidities at RHIC

G G Barnaföldi†‡, G Papp‡, P Lévai†, G Fai¶
† RMKI KFKI, P.O. Box 49, Budapest, H-1525, Hungary
‡ Eötvös University, Pázmány P. 1/A, Budapest, H-1117, Hungary
¶ CNR, Kent State University, Kent, OH 44242, USA
E-mail: bgergely@rmki.kfki.hu

Abstract. Calculations of the nuclear modification factor, \( R_{dAu} \), for \( \pi^0 \) production in \( dAu \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 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 \( p_T \) \cite{1}. This effect was explained by jet energy loss in hot dense matter (see Ref. \cite{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 \cite{3} (the “Cronin effect” in \( pA \) collisions at FERMILAB energies \cite{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. \cite{6}). However, new data with centrality dependence in midrapidity \( dAu \) collisions \cite{7} could provide more detailed information about the interplay between nuclear multiscattering \cite{8} and (standard) nuclear shadowing \cite{9}. Analysis of recent data at forward rapidities \cite{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 \( 2 < p_T < 10 \text{ GeV} \) at different centralities. In parallel, we consider available data at forward rapidities in \( dAu \) collisions \cite{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 \cite{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 \([14]\):

\[
E_\pi \frac{d\sigma_{\pi}^{dAu}}{d^3p} = \int d^2b \int d^2r \ t_{Au}(|b - r|) \ t_{Au} |\frac{1}{s} \sum_{abc} \int_{vw/ze}^{1-(1-v)/ze} \frac{d\hat{v}}{\hat{v}(1-\hat{v})} \times \int_{vw\hat{v}/ze}^{1} \frac{d\hat{\omega}}{\hat{\omega}} \int_{1}^{1} dz_c \int d^2k_{Ta} \int d^2k_{Tb} \ f_{a/d}(x_a, k_{Ta}, Q^2) \ f_{b/A}(x_b, k_{Tb}, Q^2) \times \left[ \frac{d\tilde{\sigma}}{d\tilde{v}}(1 - \tilde{v}) + \frac{\alpha_s(Q_r)}{\pi} K_{ab,c}(\tilde{s}, \tilde{v}, \tilde{w}, Q, Q_r, \tilde{Q}) \right] D_c^z(z_c, \tilde{Q}^2) \right].
\]

(1)

In our next-to-leading order (NLO) calculation \([11]\), \( d\tilde{\sigma}/d\tilde{v} \) represents the Born cross section of the partonic subprocess, and \( K_{ab,c}(\tilde{s}, \tilde{v}, \tilde{w}, Q, Q_r, \tilde{Q}) \) 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:

\[
f_{a/p}(x_a, Q^2) = f_{a/p}(x_a, Q^2) \cdot g_{a/p}(k_{Ta}) .
\]

(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, \( g_{a/p}(k_T) \), 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:

\[
\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + \Delta(b) \quad \text{where} \quad \Delta(b) = C \cdot h_{pA}(b) .
\]

(3)

Pion production in \( pp \) collisions at RHIC energy indicates the value \( \langle k_T^2 \rangle_{pp} = 2.5 \text{ GeV}^2 \)
\([14] [15]\). 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 \( C = 0.35 \text{ GeV}^2 \)
\([16]\), which implies a total broadening \( \Delta \sim 1 \text{ GeV}^2 \). 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, \( f_{b/A}(x_b, k_{Tb}, Q^2) \), 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), \( D_c^z(z_c, \tilde{Q}^2) \), 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:

\[
R_{dAu} = \frac{1}{N_{bin}} \frac{E_\pi d\sigma_{\pi}^{dAu}/d^3p}{E_\pi d\sigma_{\pi}^{pp}/d^3p} = \frac{E_\pi d\sigma_{\pi}^{dAu(\text{with nuclear effects})}/d^3p}{E_\pi d\sigma_{\pi}^{dAu(\text{no nuclear effects})}/d^3p} .
\]

(4)
2. Results on \(dAu\) collisions at \(\eta = 0\) in different centrality bins

In Fig. 1 we display the measured \(R_{dAu}^\pi\) 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](image_url)

Figure 1. Theoretical results on \(R_{dAu}^\pi\) 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 \(R_{dAu}^\pi\) (\(solid\) \(lines\)). Our results indicate the validity of pQCD description for \(dAu\) collisions at high \(\eta\).
Figure 2. Theoretical pQCD results on $R_{p_{T}}^{\pi^{0}}$ 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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