

PARTON RESCATTERINGS IN LARGE- x NUCLEAR SUPPRESSION AT RHIC

J. Nemchik^{1,2} and M. Šumbera^{3†}

- (1) *Institute of Experimental Physics SAS, Watsonova 47, 04001 Košice, Slovakia*
(2) *Czech Technical University in Prague, FNSPE, Břehová 7, 11519 Prague, Czech Republic*
(3) *Nuclear Physics Institute AS CR, 25068 Řež/Prague, Czech Republic*

† *speaker, E-mail: sumbera@ujf.cas.cz*

Abstract

We demonstrate that strong suppression of the relative production rate $(d+Au)/(p+p)$ of inclusive high- p_T hadrons at forward rapidities observed at RHIC is due to parton multiple rescatterings in nuclear matter. The light-cone dipole approach-based calculations are in a good agreement with BRAHMS and STAR data. They also indicate a significant nuclear suppression at midrapidities with a weak onset of the coherence effects. This prediction is supported by the preliminary $d+Au$ data from the PHENIX Collaboration. Moreover, since similar suppression pattern is also expected to show up at lower energies where effects of parton saturation are not expected, we are able to exclude from the interpretation of observed phenomena models based on the Color Glass Condensate.

1 Introduction

Spectra of high- p_T hadrons produced in nuclear collisions at large forward rapidities are promising tool to study partonic degrees of freedom in nuclei. Strong nuclear suppression of the spectra observed by the BRAHMS [1, 2] and STAR [3] Collaborations in deuteron-gold collisions at the Relativistic Heavy Ion Collider (RHIC) was a tempting invitation for the parton saturation [4, 5] or the Color Glass Condensate (CGC) [6] motivated phenomenology [7] as its most natural explanation.

According to these models the parton coherence phenomena may reveal itself already at RHIC energies showing up first in the wave function of heavy nuclei. Kinematically most favorable region to access the strongest coherence effects is the fragmentation region of the light nucleus 1 colliding with the heavy one 2. At large x_1 (large Feynman x_F at forward rapidities) one can reach the smallest values of the light-front momentum fraction variable $x_2 = x_1 - x_F$ ($2 \times 10^{-4} \lesssim x_2 \lesssim 10^{-3}$ in the RHIC kinematic range).

Quite unexpectedly, the same nuclear effects occur not only at forward rapidities [1, 2, 3] but also in the large p_T region at midrapidity [8] where effects of coherence are not important. The covered interval of $x_2 \gtrsim 0.01$ goes too far beyond the region where the CGC is valid.

In [9, 10] it was shown that for any large- x_1 reaction considerable nuclear suppression comes from the energy conservation at the level of projectile partons undergoing multiple rescatterings in nuclear medium. It was also demonstrated [9] that large- x_1 suppression is a leading twist effect, violating QCD factorization, a basic ingredient of the CGC-based models.

Analysis of nuclear suppression based on the multiple parton rescatterings leads also to a new type of scaling: the same nuclear effect are expected at different energies and rapidities corresponding to the same value of x_1 (x_F at forward rapidities) [9, 10]. The most straight

forward prediction of the x_1 -scaling is that similar nuclear effects must also show up at lower c.m. energy $\sqrt{s}$. Here the onset of coherence effects is much weaker and so there is much less room for explanation of strong nuclear suppression in terms of the CGC.

Another consequence of this scaling is that in the RHIC energy range similar nuclear effects must also show up at midrapidities provided that the corresponding values of p_T of produced hadrons reach the same value of x_1 as at forward rapidities. This prediction is confirmed by the preliminary data on neutral pion production in $d + Au$ collisions measured recently by the PHENIX experiment [8] showing an evidence for the nuclear suppression at rather large $p_T > 8$ GeV. This and new 2008 $d + Au$ high-statistic data may provide another test of our approach.

2 High- p_T hadron production: Sudakov suppression, production cross section

Let us recall that in the limit $x_1 \rightarrow 1$ ($x_F \rightarrow 1$ at forward rapidities) gluon radiation in any pQCD-driven hard scattering is forbidden by the energy conservation. For uncorrelated Poisson distribution of radiated gluons, the Sudakov suppression factor, i.e. the probability to have a rapidity gap $\Delta y = -\ln(1 - x_1)$ between leading parton and rest of the system, has a very simple form: $S(x_1) = 1 - x_1$ [9].

Suppression at $x_1 \rightarrow 1$ can thus be formulated as a survival probability of the large rapidity gap (LRG) process in multiple interactions of projectile valence quarks with the nucleus. Every additional inelastic interaction of the quarks contributes an extra suppression factor $S(x_1)$. The probability of an n -fold inelastic collision is related to the Glauber model coefficients via the Abramovsky-Gribov-Kancheli (AGK) cutting rules [11]. Correspondingly, the survival probability at impact parameter $\vec{b}$ reads

$$W_{LRG}^{hA}(b) = \exp[-\sigma_{in}^{hN} T_A(b)] \sum_{n=1}^A \frac{1}{n!} \left[\sigma_{in}^{hN} T_A(b) \right]^n S(x_1)^{n-1}, \quad (1)$$

where $T_A(b)$ is the nuclear thickness function.

At large p_T , the cross section of hadron production in $d + A$ ($p + p$) collisions is given by a convolution of the distribution function for the projectile valence quark with the quark scattering cross section and the fragmentation function

$$\frac{d^2\sigma}{d^2p_T d\eta} = \sum_q \int_{z_{min}}^1 dz f_{q/d(p)}(x_1, q_T^2) \frac{d^2\sigma[qA(p)]}{d^2q_T d\eta} \Big|_{\vec{q}_T=\vec{p}_T/z} \frac{D_{h/q}(z)}{z^2}, \quad (2)$$

where $x_1 = \frac{q_T}{\sqrt{s}} e^\eta$. For the quark distribution functions in the nucleon we use the lowest order parametrization from [12]. Fragmentation functions were taken from [13].

As first shown in [9, 10] the effective projectile quark distribution correlates with the target. So interaction with the nuclear target does not obey the factorization. Main source of suppression at large p_T comes from multiple soft rescatterings of the quark in nuclear matter. Summed over multiple interactions, the quark distribution in the nucleus reads

$$f_{q/N}^{(A)}(x_1, q_T^2) = C f_{q/N}(x_1, q_T^2) \frac{\int d^2b \left[e^{-x_1 \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)} \right]}{(1 - x_1) \int d^2b \left[1 - e^{-\sigma_{eff} T_A(b)} \right]}, \quad (3)$$

where effective cross section $\sigma_{eff} = \sigma_{eff}(p_T, s) = \frac{\langle \sigma_{qq}^2(r_T) \rangle}{\langle \sigma_{qq}(r_T) \rangle}$ has been evaluated in [9]. The normalization factor C in Eq. (3) is fixed by the Gottfried sum rule.

The cross section of quark scattering on the target $d\sigma[qA(p)]/d^2q_T d\eta$ in Eq. (2) is calculated in the light-cone dipole approach [14, 15]. We separate contributions with different initial transverse momenta and sum over different mechanisms of high- p_T hadron production. Details can be found in [9].

Let us note that in the RHIC energy range and at midrapidity correct description of hadrons with small and moderate p_T can be achieved only if the above calculations incorporate production and fragmentation of gluons[16]. Consequently, the cross section for hadron production, Eq. (2), should be extended also for gluons with corresponding distribution function, parton scattering cross section and the fragmentation function. Including multiple parton interactions, the gluon distribution in the nucleus is given by the same formula as for quarks (see Eq. (3)), except σ_{eff} , which should be multiplied by the Casimir factor $9/4$.

3 Comparison with data

In 2004 the BRAHMS Collaboration [1] observed a significant nuclear suppression of negative hadrons produced at $\eta = 3.2$. Much stronger onset of nuclear effects was observed later on by the STAR Collaboration [3] for π^0 production at pseudorapidity $\eta = 4.0$. Both measurements are plotted in the left panel of Fig. 1. A huge difference in nuclear suppression factor at different η is due to the energy conservation and reflects much smaller survival probability of the LRG in multiple parton interactions at larger x_1 [9, 10].

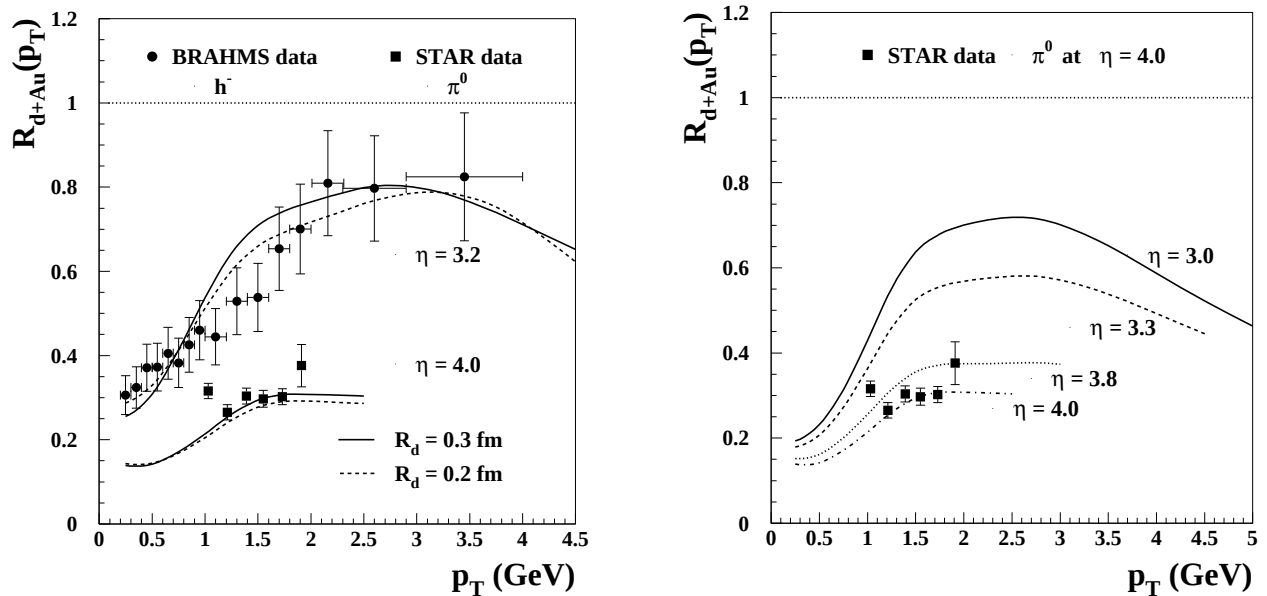


Figure 1: (Left) Ratio of negative hadron and neutral pion production rates in $d + Au$ and $p + p$ collisions as function of p_T at $\eta = 3.2$ and $\eta = 4.0$. Data are from the BRAHMS [1] and STAR Collaborations [3], respectively. (Right) Model predictions for the ratio $R_{d+Au}(p_T)$ for production of π^0 mesons at $\sqrt{s} = 200$ GeV and different values of η changing from 3 to 4.

To demonstrate different onsets of nuclear effects with increasing pseudorapidity we present in the right panel of Fig. 1 our calculations for the nuclear suppression factor at different fixed values of η . Changing the value of η from 3.0 to 4.0 leads to a rise of $R_{d+Au}(p_T)$ by a factor of 2 [10].

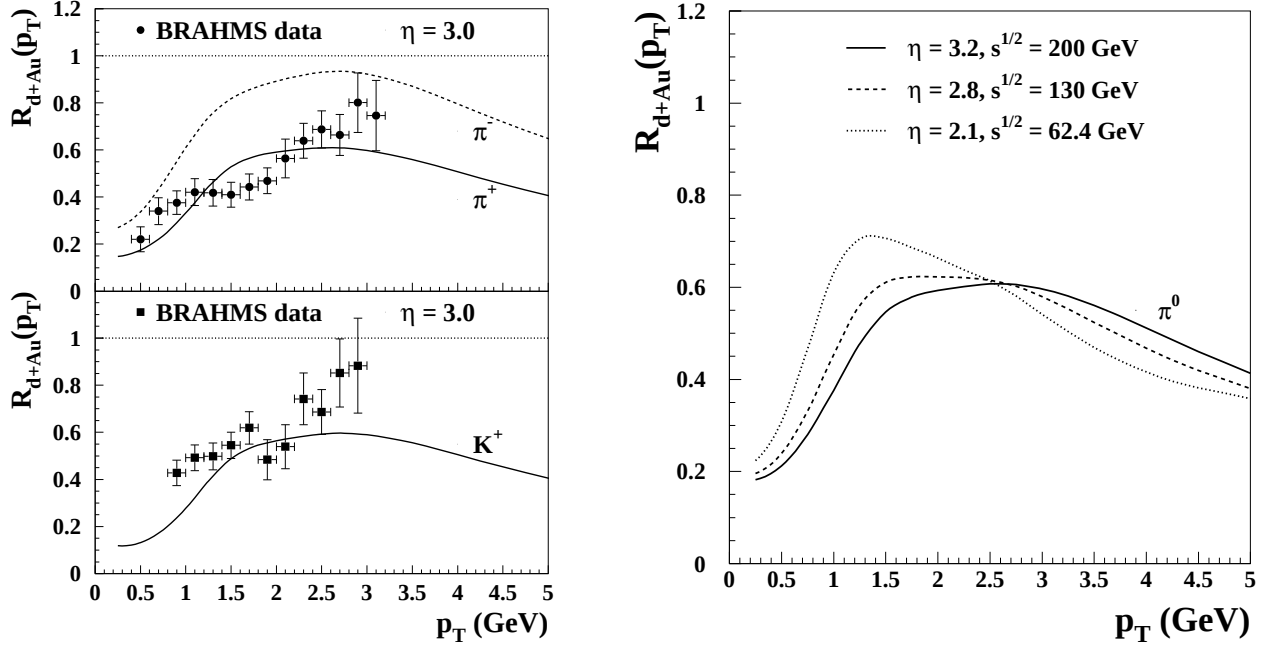


Figure 2: (Left) Ratio, $R_{d+Au}(p_T)$ for identified particles produced in $d + Au$ and $p + p$ collisions at $\eta = 3$. The data are from the BRAHMS Collaboration [2]. (Right) Predictions for the ratio $R_{d+Au}(p_T)$ for π^0 at different η and $\sqrt{s}$ having the same $\exp(\eta)/\sqrt{s}$.

The BRAHMS Collaboration has recently reported a new measurements [2] on production of positively charged pions and kaons at $\eta = 3.0$ in $d + Au$ collisions confirming suppression pattern they found in 2004 for the negative particles[1]. Their recent data are plotted on the left panel of Fig. 2 together with our model predictions.

The calculations of $R_{d+Au}(p_T)$ of neutral pions at $\sqrt{s} = 200, 130$ and 62.4 GeV shown on the right panel of Fig. 2 reveal approximate $x_1(x_F)$ -scaling at RHIC energy range, i.e. the same nuclear effects at values of η and $\sqrt{s}$ corresponding to the same value of x_1 .

Generalization of the x_1 -scaling from the forward region to midrapidity is studied on Fig. 3. The only difference to the previous analysis is that the same value of x_1 at midrapidity as that in the forward region requires substantially higher hadron transverse momenta. On the left panel of Fig. 3 our predictions for the nuclear suppression factor of π^0 produced in $d + Au$ collisions at midrapidities are confronted with the recent data of the PHENIX Collaboration[8].

Here the thin dashed line corresponds to the case when multiple parton rescatterings are not taken into account. The calculations with inclusion of multiple parton rescatterings are presented by the thin solid line. At moderate $p_T \in (3, 7)$ GeV the model underestimates the data. However, quite a strong onset of nuclear suppression at large p_T is not in a disagreement with corresponding experimental points. At $p_T = 25$ GeV we expect $R_{d+Au}(p_T) \sim 0.9$.

Due to the transition between the regimes with (small p_T) and without (large p_T) onset of coherence effects in the RHIC energy range calculations at $\eta = 0$ are very complicated. One can deal with this situation relying on the light-cone Green function formalism [17, 18, 19] but the integrations involved become too complicated. To simplify the situation we have used instead corrections for finite coherence length. Following the procedure described in[16] we have used linear interpolation performed by the means of so-called nuclear longitudinal form factor. Such a situation is shown by the thick solid and dashed lines on Fig. 3 corresponding to the case with and without inclusion of the multiple parton rescatterings, respectively. One can see that this correction brings the model predictions to a better agreement with the data

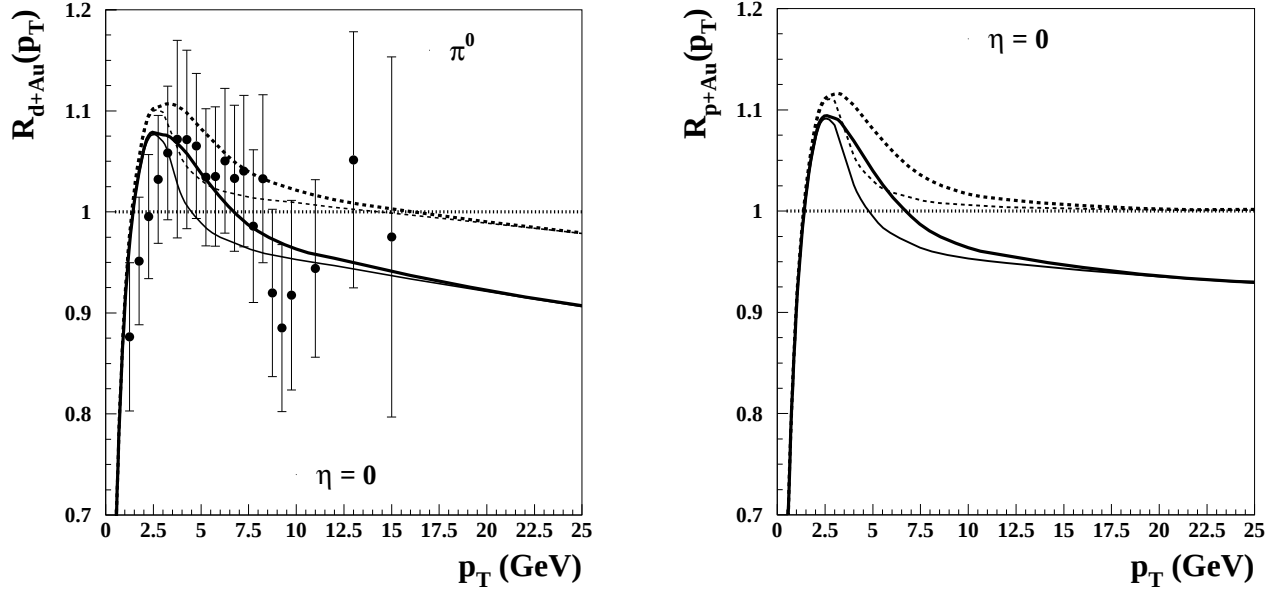


Figure 3: (Left) Ratio $R_{d+Au}(p_T)$ as a function of p_T for production of π^0 mesons at $\sqrt{s} = 200$ GeV and $\eta = 0$ vs. data from the PHENIX Collaboration [8]. Thin solid and dashed lines represent the predictions calculated in the limit of long coherence length. Thick solid and dashed lines include corrections for the finite coherence length. (Right) The same as Fig. in the left panel but for the ratio $R_{p+Au}(p_T)$.

at moderate p_T .

On the right panel of Fig. 3 we also present model predictions for the ratio R_{p+Au} as a function of p_T . Compared to $d + Au$ system study of nuclear effects in $p + Au$ minimizes the isospin effects. At $p_T = 25$ GeV we predict $R_{p+Au} \sim 0.93$.

4 Summary and conclusions

In the present paper we have analyzed consequences of the x_1 (x_F)-scaling of the nuclear suppression factor $R_{p(d)+Au}$ of high- p_T hadrons at RHIC.

The new results are:

- According to the x_1 -scaling, considerable nuclear suppression at large x_1 is expected for different kinematic regions :
 - **production of high- p_T hadrons at forward rapidities.**
 - **production of high- p_T hadrons at smaller rapidities and smaller energies.**
 - **productions of hadrons with very large p_T at midrapidity.**
- Using simple formula (3) adopted from [9] and based on the Glauber multiple interaction theory and the AGK cutting rules, we have calculated high- p_T hadron production at midrapidity and found quite a strong nuclear suppression. This observation does not contradict to the recent measurements of the PHENIX Collaboration [8].
- In order to avoid the isospin effects, we have also studied large- p_T neutral pion production in $p + Au$ collisions. With the same input, we predict (see the right panel of Fig. 3) for the first time quite a strong nuclear suppression, $R_{p+Au} = 0.93$ at $p_T = 25$ GeV.
- In the RHIC kinematic region, investigation of large- x hadron production in $p(d) + Au$ collisions at midrapidities represents the baseline for verification of different phenomeno-

logical models. important. At high- p_T the data cover region of $x_2 \sim 0.05 - 0.1$ where effects of coherence are negligible allowing to exclude the CGC-based models from interpretation of observed nuclear suppression.

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