Nuclear Effects in High-p_T Hadron Production at Large x

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Abstract

We demonstrate that strong suppression of the relative production rate $(d + Au)/(p + p)$ observed at forward rapidities in inclusive high-p_T hadron production 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 Collaborations data at large x_1. We predict similar suppression pattern also for regions where effects of parton saturation are not expected thus ruling out applicability of the models based on Color Glass Condensate.

1 Introduction

High-p_T hadron spectra at large forward rapidities are promising tool to study nuclear effects. Strong nuclear suppression of the spectra observed by the BRAHMS [1, 2] and STAR [3] Collaboration in deuteron-gold collisions at the Relativistic Heavy Ion Collider (RHIC) was tempting to call in the parton saturation [4, 5] or the Color Glass Condensate (CGC) [6] motivated phenomenology [7] as its most natural interpretation.

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 these effects is the fragmentation region of the light projectile nucleus 1 colliding with the heavy one 2. At large x_1 (i.e. at large Feynman x_F) one can simultaneously reach the smallest values of the light-front momentum fraction variable in nuclei $x_2 = x_1 - x_F$.

However, observed nuclear effects occur not only at forward rapidities [1–3] but, quite unexpectedly, also at midrapidities [8]. In this case they can not be explained in terms of CGC because at large p_T the data cover region of not too small $x_2 \gtrsim 0.01$ where effects of coherence are very unlikely.

It was shown in [9, 10] that a considerable nuclear suppression for any large x_1 reaction comes from the energy conservation applied to multiple rescatterings of the projectile partons. It was also demonstrated [9] that such a 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 multiple parton rescatterings leads also to approximate x_1 (x_F)-scaling [9, 10]: similar nuclear effects occur also at smaller energies where the onset of coherence effects is expected to be much weaker.

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In this article we present another consequence of x_1-scaling and namely that the similar nuclear effects can be important also at midrapidities provided that the corresponding p_T-values are high enough to keep the same value of x_1 as that at forward rapidities.

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

Let us recall that in the limit $x_1 \to 1$ 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 acquires a very simple form: $S(x_1) = 1 - x_1$ [9].

Suppression at $x_1 \to 1$ 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,

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

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,

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

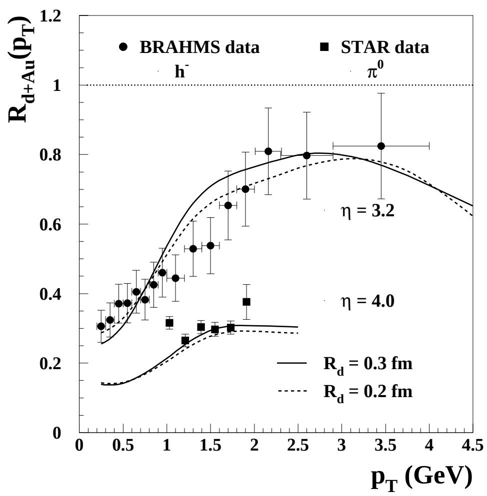
where $x_1 = \frac{q_T}{\sqrt{s}}\, e^{\eta}$. The quark distribution functions in the nucleon have the form adopted the lowest order (LO) parametrization from [12]. Fragmentation functions have been taken from [13]. Summed over multiple interactions, the quark distribution in the nucleus reads,

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

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

The cross section for 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 the contributions characterized by different initial transverse momenta and sum over different mechanisms of high-p_T hadron production. Details can be found in [9].

At midrapidities in the RHIC kinematic range, at small and moderate p_T, one should also take into account production and fragmentation of gluons. Details of calculation can be found in [16]. Consequently, the cross section for hadron production, Eq. (2), should be supplemented by the gluon term 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 $9/4$.



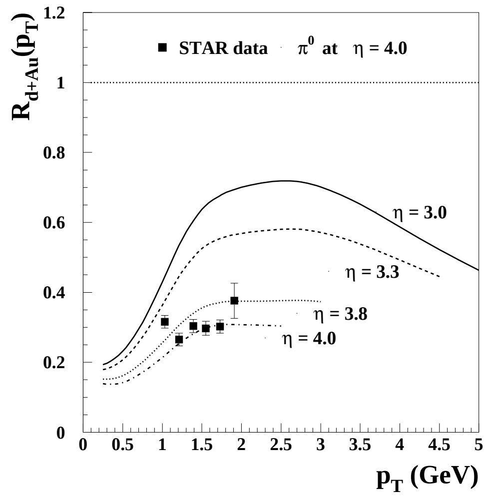


Fig. 1: Left panel: Ratio of negative hadron and neutral pion production rates in $d + Au$ and $p + p$ collisions as function of p_T at $\eta = 3.2$ and $\eta = 4.0$ vs. data from the BRAHMS [1] and STAR Collaborations [3], respectively. Right panel: Model predictions for nuclear attenuation factor $R_{d+Au}(p_T)$ as a function of p_T for production of π^0 mesons at $\sqrt{s} = 200\,\mathrm{GeV}$ and at different values of η from 3.0 to 4.0.

3 Comparison with data

In 2004 the BRAHMS Collaboration [1] found a significant nuclear suppression in production of negative hadrons at $\eta = 3.2$. Their measurements are plotted in the left panel of Fig. 1. Much stronger onset of nuclear effects was observed later on by the STAR Collaboration [3] for π^0 production at pseudorapidity $\eta = 4.0$ (left panel of Fig. 1). A huge difference in nuclear effects for 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].

To demonstrate different onsets of nuclear effects as a function of pseudorapidity we present in the right panel of Fig. 1 predictions for nuclear suppression factor at different fixed values of η. Changing the value of η from 3.0 to 4.0, one can see a huge rise of nuclear suppression by a factor of 2 [10].

Fig. 2 clearly demonstrates x_1 (x_F)-scaling of nuclear suppression, i.e. approximately the same nuclear effects at different energies, $\sqrt{s} = 200, 130$ and $62.4\,\mathrm{GeV}$ accessible at RHIC, and pseudorapidities corresponding to the same values of x_1.

Let us note that observed x_1-scaling enables to predict similar nuclear effects also at midrapidities. However, in this case hadron transverse momenta should be high enough so that x_1 are as large as those at forward rapidities. This expectations seems to be confirmed by the recent PHENIX Collaboration $d + Au$ data at midrapidities [8] (see the left panel of Fig. 3).

If the effects of multiple parton rescatterings are not taken into account the p_T-dependence of the ratio $R_{d+Au}(p_T)$ is given by the thin dashed line shown in the left panel of Fig. 3. The model predictions with inclusion of multiple parton rescatterings are presented by the thin solid line. Obviously at moderate $3 \lesssim p_T \lesssim 7$ GeV our calculations underestimate the data. Nevertheless, quite a strong onset of nuclear suppression at large p_T is not in a disagreement with the corresponding experimental data points. At $p_T = 25$ GeV we expect $R_{d+Au}(p_T) \sim 0.9$.

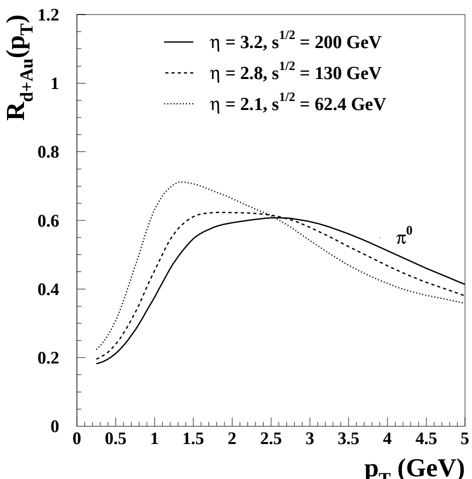


Fig. 2: Predictions for an approximate $\exp(\eta)/\sqrt{s}$-scaling of the ratio $R_{d+Au}(p_T)$ for π^0 production rates in $d + Au$ and $p + p$ collisions.

Let us note that midrapidity calculations in the RHIC energy range are most complicated since this is the transition region between the regimes with (small p_T) and without (large p_T) onset of the coherence effects. One can deal with this situation relying on the light-cone Green function formalism [17–19]. However, in this case the integrations involved become too complicated. Therefore, we present in the same Fig. 3 also corrections for finite coherence length by the linear interpolation performed by means of the so-called nuclear longitudinal form factor following the procedure from [16]. Such a situation is described by the thick solid and dashed lines reflecting the cases with and without inclusion of the multiple parton rescatterings, respectively. It brings the model predictions to a better agreement with data at moderate p_T.

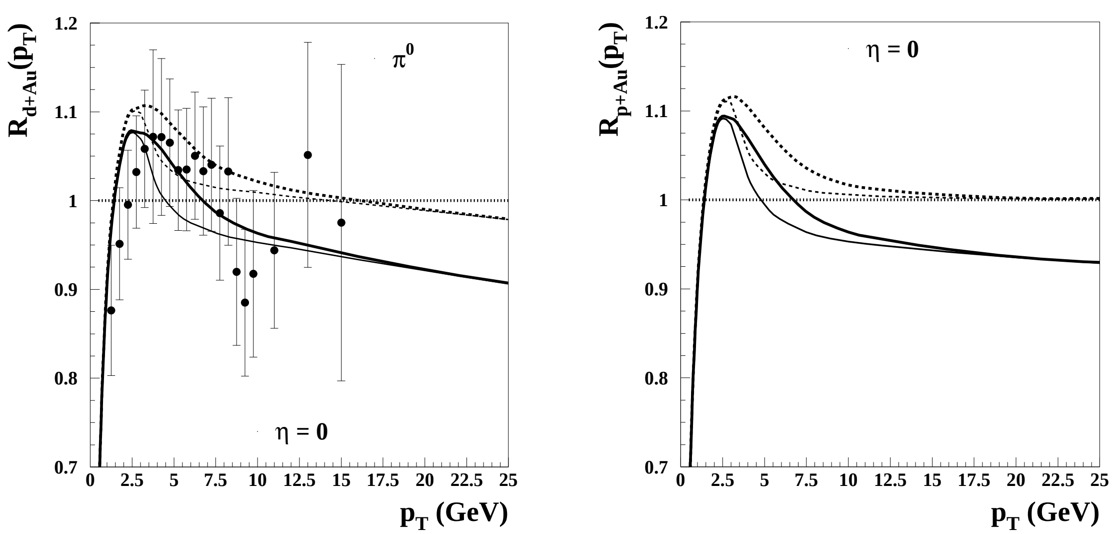


Fig. 3: (Left) Ratio $R_{d+Au}(p_T)$ as a function of p_T for production of π^0 mesons at $\sqrt{s} = 200$ GeV and $\eta = 0$ vs. data from the PHENIX Collaboration [8]. Thin solid and dashed lines represent the predictions calculated in the limit of long coherence length. Thick solid and dashed lines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

In order to minimize the isospin effects it is more convenient to study the nuclear effects in $p+Au$ collisions. Therefore, we present in the right panel of Fig. 3 also model predictions for R_{p+Au} as a function of p_T. At $p_T = 25\,\mathrm{GeV}$ we predict $R_{p+Au} \sim 0.93$.

4 Summary and conclusions

In this article we have analyzed implications of the x_1 (x_F)-scaling of nuclear suppression for production of high-p_T hadrons in $p(d)+Au$ collisions at RHIC. Using this scaling we predict considerable nuclear suppression at large x_1 at several very different kinematic regions: **i)** at large forward rapidities, **ii)** at smaller rapidities and smaller energies, **iii)** at midrapidity but at very large p_T.

Using a simple formula Eq. (3) based on Glauber multiple interaction theory and the AGK cutting rules, we have calculated hadron production at midrapidity and found an unexpectedly strong nuclear suppression at large p_T. This observation is not in a contradiction with the recent PHENIX Collaboration measurements [8].

To avoid the isospin effects, we have also studied large-p_T π^0 production in $p+Au$ collisions. With the same input parameters, we predict quite a strong nuclear suppression factor, $R_{p+Au} = 0.93$ at $p_T = 25\,\mathrm{GeV}$.

As a final remark let us note that in the RHIC kinematic region, investigation of hadron production in $p(d)+Au$ collisions at midrapidities is very important because at large p_T the data cover rather large $x_2 \sim 0.05 - 0.1$ where no effects of coherence are possible. It allows to exclude the models based on CGC from interpretation of observed nuclear suppression.

Acknowledgments

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