Physics of Large-x Nuclear Suppression

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Abstract

We discuss a common feature of all known reactions on nuclear targets - a significant suppression at large $x$. Simple interpretation of this effect is based on energy conservation restrictions in initial state parton rescatterings. Using the light-cone dipole approach this mechanism is shown to control variety of processes on nuclear targets: high-$p_T$ particle production at different rapidities as well as direct and virtual (Drell-Yan) photon production. We demonstrate universality and wide applicability of this mechanism allowing to describe large-$x$ effects also at SPS and FNAL energies too low for the onset of coherent effects or shadowing.

1. Introduction

Recent measurements of high-$p_T$ hadrons produced in the beam fragmentation region in $d+Au$ collisions at RHIC \cite{1,2,3} allow to reach the smallest values of Bjorken $x$ in the nucleus and thus to reach maximal coherence effects leading eventually to nuclear suppression. Observed suppression is usually interpreted within the models based on color glass condensate (CGC). However, such an interpretation misses a global applicability. For example, a similar suppression like at RHIC was measured also in $p+Pb$ collisions at SPS where no effects of coherence are possible.

The rise of the suppression with Feynman $x_F$ for hadrons produced in $p+Pb$ collisions at SPS \cite{4} or for the Drell-Yan (DY) pairs at FNAL \cite{5} has a similar pattern as seen at RHIC. All these examples and another reactions treated in \cite{6} favor the same large-$x$ mechanism independently of the energy and type of reaction.

Such a common mechanism was proposed in \cite{6,7} where large-$x_F$ nuclear suppression was shown to be caused by the energy conservation in multiple parton rescatterings. This mechanism is a leading twist effect giving rise to the breakdown of QCD factorization and exhibits also the $x_F$-scaling \cite{7}.

Another consequence of this treatment discussed in this paper is the manifestation of nuclear effects also at midrapidities, i.e. at large $x_T = 2p_T/\sqrt{s}$. We expect a suppression pattern similar to that at large $x_F$ and the nucleus-to-nucleon ratio below one. Similarly to $x_F$-scaling at forward rapidities $x_T$-scaling of this effect is predicted.

In this paper we further exploit proposed model \cite{6,7} to analyze and quantify the nuclear suppression at large $x$ for a variety of processes occurring in $p(d)+A$ and $A+B$ collisions.

2. Sudakov suppression, production cross section

In any hard reaction in the limit $x \to 1$ gluon radiation is forbidden by the energy conservation. Then the probability to have a large rapidity gap (LRG) $\Delta y = -\ln S(x)$ between the leading
parton and rest of the system, where the Sudakov suppression factor \( S(x) = 1 - x \) \[6\].

Suppression at \( x \to 1 \) can thus be formulated in terms of multiple interactions of projectile partons with the nucleus. Each of multiple interactions produces an extra suppression factor \( S(x) \) and corresponding weight factors are given by the AGK cutting rules \[8\]. Then, in terms of the nuclear thickness function \( T_A(b) \) and the effective cross section \( \sigma_{\text{eff}} \) \[6\], the cross sections of hard reaction on a nuclear target \( A \) at impact parameter \( b \) and on a nucleon \( N \) are related as \[9\],

\[
\frac{d^2\sigma_A}{dx db} = \frac{d\sigma_N}{dx} \frac{1}{\sigma_{\text{eff}}} e^{-\sigma_{\text{eff}} T_A(b)} \sum_{n=1}^{\infty} \frac{1}{n!} (\sigma_{\text{eff}} T_A(b))^n S(x)^{n-1} = \frac{d\sigma_N}{dx} T_A(b) e^{-[1-S(x)]\sigma_{\text{eff}} T_A(b)}. \tag{1}
\]

Employing factorization, the hadron production cross section in \( d + A \) (\( p + p \)) collisions reads,

\[
\frac{d^2\sigma(p A \to h X)}{d^2p_T d\eta} = \int x_0 dx \int_{z_{\min}}^{1} \frac{dz}{z^2} \left\{ \sum_q f_{q(d/p)}(x, q_T^2) \left[ \frac{d^2\sigma(q A(N) \to q X)}{d^2q_T d\eta} D_{h/q}(z, q_T^2) + \left( \frac{d^2\sigma(g A(N) \to g X)}{d^2q_T d\eta} D_{h/g}(z, q_T^2) \right) \right] \right\} + f_{g(d/p)}(x, q_T^2) \frac{d^2\sigma(g A(N) \to g X)}{d^2q_T d\eta} D_{h/g}(z, q_T^2) \tag{2}
\]

where \( \eta \) is pseudorapidity, \( x_h = p_T / \sqrt{s} \), \( z_{\min} = x_h / x \) and \( q_T = p_T / z \) is the parton transverse momentum. The parton cross sections of \( d^2\sigma(q A(N) + A(N))d^2q_T d\eta \) in Eq. (2) are calculated in the light-cone (LC) dipole approach \[6\], \[8\], \[10\]. For parton distribution functions we use the parametrization from \[11\]. Fragmentation functions were taken from \[12\].

As first shown in \[6\], \[7\], the effective projectile quark (gluon) distribution correlates with the target and corresponding quark (gluon) distribution in the nucleus reads

\[
f_{q(\bar{q})/N}(x, q_T^2) = C \, f_{q(\bar{q})/N}(x, q_T^2) \int d^2b \left[ e^{-x \sigma_{\text{eff}} T_A(b)} - e^{-\sigma_{\text{eff}} T_A(b)} \right] \tag{3}
\]

For the quark part the normalization factor \( C \) in Eq. (3) is fixed by the Gottfried sum rule.

3. Hadron production at forward rapidities

In 2004 the BRAHMS Collaboration \[1\] observed a significant nuclear suppression of \( h^- \) at \( \eta = 3.2 \). Much stronger nuclear effects was found later on by the STAR Collaboration \[3\] for \( p^0 \) production at \( \eta = 4.0 \). All these data are consistent with model calculations \[6\], \[7\]. A strong rise of suppression with \( \eta \) reflects much smaller survival probability \( S(x) \) of a LRG at larger \( x \).

Since parton energy loss is proportional to the initial energy the energy conservation restrictions in multiple parton rescatterings should also lead to \( x \)-scaling of the nuclear effects \[6\] . A similarity of suppression at different energies and pseudorapidities was demonstrated in \[6\], \[7\].

4. Hadron production at midrapidities

Another manifestation of the energy conservation in multiple parton rescatterings occurs at midrapidities. Here the corresponding values of \( p_T \) should be high enough to keep \( x_F = 2 p_T / \sqrt{s} \) on the same level as \( x_F \) at the forward rapidities. This is supported by data from the PHENIX Collaboration \[13\] showing an evidence for suppression at large \( p_T \geq 8 \text{ GeV/c} \) (see Fig. \[1\]).

If effects of energy conservation are not included the \( p_T \) dependence of \( R_{d+Au} \) described by the dashed lines exhibits only a small suppression at large \( p_T \) given by the isotopic effects (see Fig. \[1\]). After inclusion of energy sharing in parton rescatterings we predict \( R_{d+Au} < 1 \) at large \( p_T \) presented by the solid lines. More precise data are needed for a clear manifestation of breakdown of QCD factorization.
5. Direct photon production in Au+Au collisions at RHIC

Direct photons in Au + Au collisions are also suppressed at large \( p_T \) as was demonstrated by the PHENIX Collaboration [14]. Model predictions for the ratio \( R_{Au+Au} \) as a function of \( p_T \) are compared with data in Fig. 2. Expressions for production cross sections have been adopted from [15, 16]. If the energy conservation in parton rescatterings is not taken into account model calculations depicted by the dashed line gives a value \( R_{Au+Au} \rightarrow 0.8 \) in accord with onset of isotopic effects. Inclusion of the energy conservation leads to strong nuclear effects at large \( p_T \) as is demonstrated by thick and thin solid lines.

6. Nuclear suppression at SPS and FNAL energies

The left panel of Fig. 3 clearly manifests that pions from \( p + Pb \) collisions at SPS energy exhibit the same suppression pattern as that in the RHIC kinematic range. Model predictions employ the dipole formalism for calculation of nuclear broadening using standard convolution expression based on QCD factorization [10]. Initial state multiple interactions leading to breakdown of QCD factorization are included as described in Sect. 2. One can see a reasonable agreement of our calculations with NA49 data [4].
The DY reaction is also known to be considerably suppressed at large \( x_F \) (\( x_1 \)) \[17\] (see the right panel of Fig. 3). Using the same mechanism as discussed in Sect. 2, one can explain a strong suppression at large \( x_1 \). The differential cross section for the photon radiation in a quark-nucleus collision is calculated \[18\] using the LC Green function formalism \[15\]. The right panel of Fig. 3 demonstrates a good agreement of our calculations with E772 data \[5\].

7. Summary

Unified approach to large-\( x \) nuclear suppression based on the energy conservation restrictions in multiple parton rescatterings was presented. QCD factorization fails at the kinematic limit, \( x \to 1 \). Universal suppression driven by Sudakov factor \( S(x) \) brings in the \( x \)-scaling of nuclear effects. The same formalism explains well available data from RHIC on suppression of high-\( p_T \) hadrons and photons at different rapidities. This common mechanism explains also a suppression at low SPS and FNAL energies where no coherence effects are possible.

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