Study of Nuclear Suppression at Large Forward Rapidities in d-Au Collisions at Relativistic and Ultrarelativistic Energies

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We study a strong suppression of the relative production rate \((d−Au)/(p−p)\) for inclusive high-\(p_T\) hadrons of different species at large forward rapidities (large Feynman \(x_F\)). The model predictions calculated in the light-cone dipole approach are in a good agreement with the recent measurements by the BRAHMS and STAR Collaborations at the BNL Relativistic Heavy Ion Collider. We predict a similar suppression at large \(p_T\) and large \(x_F\) also at lower energies, where no effect of coherence is possible. It allows to exclude the saturation models or the models based on Color Glass Condensate from interpretation of nuclear effects.

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I. INTRODUCTION

In the proton(deuteron)-nucleus collisions, investigated at the Relativistic Heavy Ion Collider (RHIC), recent measurements of high-\(p_T\) particle spectra at large forward rapidities performed recently by the BRAHMS \cite{1,2} and STAR \cite{3} Collaborations show a strong nuclear suppression. The basic explanation for such an effect has been based on an idea that in this kinematic region corresponding to the beam fragmentation region at large Feynman \(x_F\) one can reach the smallest values of the light-front momentum fraction variable \(x_2\) in nuclei. It allows to access the strongest coherence effects such as those associated with shadowing or the Color Glass Condensate (CGC).

It was shown in \cite{4,5} that a considerable nuclear suppression for any reaction at large \(x_F\) (small \(x_2\)) is caused by another effects, which can be easily misinterpreted as coherence. Such a suppression, for example, can be treated in terms of the Sudakov form factor reflecting the energy conservation. It is governed by the probability to produce no particles at large \(x_F\) → 1.

Nuclear suppression at large \(x_F\) can be also interpreted alternatively, as a consequence of a reduced survival probability for large rapidity gap (LRG) processes in nuclei, an enhanced resolution of higher Fock states by nuclei, or an effective energy loss that rises linearly with energy. It was demonstrated in refs. \cite{4,5} that it is a leading twist effect, violating QCD factorization.

The BRAHMS Collaboration \cite{1} in 2004 for the first time found a substantial nuclear suppression for high-\(p_T\) negative hadrons produced at large pseudorapidity \(\eta = 3.2\) (see Fig. 1). Because the data cover rather small \(x_2 \sim 10^{-3}\), the interpretation of such a suppression has been tempted to be as a result of saturation \cite{6,7} or the CGC \cite{8}, expected in some models \cite{9}.

Alternative interpretation of the nuclear effects occurring in the BRAHMS data \cite{1} is based on energy conservation implemented into multiple soft rescatterings of the projectile quark in nuclear matter \cite{4,5}. Moreover, new data for neutral pions from the STAR Collaboration have been recently appeared at the same c.m. energy, \(\sqrt{s} = 200\) GeV but at still larger pseudorapidity \(\eta = 4.0\) demonstrating a huge nuclear suppression, which is more than a factor of 2 larger than at \(\eta = 3.2\) manifested by the BRAHMS data. Although a minor part of this difference can be explained by the isospin effects, i.e. by a difference in production of \(h^-\) and \(\pi^0\) particles on deuteron target, there is still a large room for investigation of this huge suppression. It provides a good possibility to test our interpretation of such an effect. This represents one of the main goal of the present paper.

Another very interesting effect following from our interpretation of nuclear effects at large \(x_F\) and supported by available data is the \(x_F\) scaling of nuclear suppression. It is in contradiction with \(x_2\) scaling, which is expected if the scaling represents the net effect of quantum coherence. The detailed analysis of this \(x_F\) scaling can be found in \cite{4,5} collecting the data for production of different species of leading hadrons with small \(p_T\) in \(p−A\) collisions at different energies covering the laboratory energy range from 70 GeV to 400 GeV. Similar \(x_F\) scaling of the nuclear effects is observed from data on \(J/\Psi\) and \(\Psi'\) production measured by the E866 Collaboration at Fermilab \cite{10} compared to lower-energy data \cite{11}. Besides, recent measurements of nuclear suppression for \(J/\Psi\) production in \(d−Au\) collisions by the PHENIX Collaboration \cite{12} at RHIC are consistent with \(x_F\) scaling and exhibit a dramatic violation of \(x_2\) scaling when compared with the E866 data \cite{10}.

According to \(x_F\) scaling \cite{4,5}, we expect similar nuclear effects at forward rapidities also at lower energies when the onset of coherence effects is much weaker. It gives much less room for explanation of a strong nu-
clear suppression in terms of CGC. Because new data of high-$p_T$ hadron production at forward rapidities are expected also at smaller c.m. energies $\sqrt{s} = 130$ GeV and 62.4 GeV, corresponding predictions for nuclear effects at large $p_T$ will play an important role for further verification of various phenomenological models based on the CGC.

Besides, new data from the BRAHMS Collaboration for different species of high-$p_T$ hadrons produced at $\eta = 3.0$ have been recently appeared. It allows to provide another probe of our model in investigation of significant nuclear suppression at forward rapidities. This coincides with the further goal of the present paper.

The paper is organized as follows. In Sect. II we present shortly a formulation of nuclear suppression in terms of Sudakov suppression factors adopted for multiple parton interactions with the nucleus. Here we also mention about three different mechanisms of high-$p_T$ particle production. In the next Sect. III we calculate the predictions for the ratio of particle production rate in $d-A$ and $p-p$ collisions as a function of $p_T$ at large forward rapidities corresponding to BRAHMS and STAR experiments at RHIC. We analyze much stronger nuclear suppression obtained recently by the STAR Collaboration at $\eta = 4.0$ in comparison with the well known results from the BRAHMS experiment at $\eta = 3.2$. We demonstrate that the model calculations without any free parameter are in a good agreement with data from the both collaborations. Finally we perform predictions for nuclear suppression at large forward rapidities also at lower energies, where no effect of coherence is possible. It allows to exclude the models based on CGC from explanation of a strong nuclear suppression. We also demonstrate an approximate $\exp(\eta) / \sqrt{s}$ ($x_F$) scaling of nuclear effects in the energy and pseudorapidity range accessible by the BRAHMS and STAR Collaborations. The results of the paper are summarized and discussed in Sect. IV.

II. HIGH-$p_T$ HADRON PRODUCTION AT FORWARD RAPIDITIES: SUDAKOV SUPPRESSION, PRODUCTION CROSS SECTION

Any hard reaction in the limit $x_F \to 1$ can be treated as LRG process, where gluon radiation is forbidden by energy conservation. If a large-$x_F$ particle is produced, the rapidity interval to be kept empty is $\Delta y = -\ln(1 - x_F)$. Assuming as usual an uncorrelated Poisson distribution for radiated gluons, the Sudakov suppression factor, i.e. the probability to have a rapidity gap $\Delta y$, was developed in ref. [3] and has a very simple form,

$$S(x_F) = 1 - x_F .$$

Nuclear suppression at $x_F \to 1$ can be formulated as a survival probability of the LRG in multiple interactions with the nucleus. Every additional inelastic interaction contributes an extra suppression factor $S(x_F)$. The probability of an $n$-fold inelastic collision is related to the Glauber model coefficients via the Abramovsky-Gribov-Kancheli (AGK) cutting rules [13]. Correspondingly, the survival probability at impact parameter $\bar{b}$ reads,

$$W_{L_{RG}}^A(b) = \exp[-q_{in}^A T_A(b)]$$

$$\times \sum_{n=1}^A \left[ q_{in}^A T_A(b) \right]^n S(x_F)^{n-1} ,$$

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

Assuming large values of hadron transverse momenta, the cross section of hadron production in $dA(pp)$ 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,

$$\frac{d^2 \sigma}{d^2 p_T \, d\eta} = \int_{z_{min}}^1 dz \, f_{q/d(p)}(x_1, q_T^2)$$

$$\times \frac{d^2 \sigma[qA(p)]}{d^2 q_T \, dq_T} |_{q_T = \bar{p}_T / z} D_{h/q}(z),$$

where $x_1 = q_T e^n / \sqrt{s}$. The quark distribution functions in the nucleon have the form using the lowest order parametrization of Gluck, Reya and Vogt [14]. For fragmentation functions we use parametrization from [15].

The main source of suppression at large $p_T$ concerns to multiple quark rescatterings in nuclear matter. The quark distribution in the nucleus can be defined performing summation over multiple interactions and using the probability of an $n$-fold inelastic collision related to the Glauber model coefficients with Gribov’s corrections via AGK cutting rules [13]. It has the following form:

$$f_{q/N}(x, q_T^2, \bar{b}, z) = \sum_{n=0}^A v_n(\bar{b}, z) f_{q/N}(x, q_T^2)^n ,$$

where the coefficients $v_n$ reads

$$v_n(\bar{b}, z) = \left[ \frac{\sigma_{eff} T(b, z)}{1 + \sigma_{eff} T(b, z)} \right]^{n+1} .$$

The effective cross section $\sigma_{eff}$ was evaluated in [4].

The valence quark distribution functions $f_{q/N}(x, q_T^2)$ in Eq. (4) are also given by the GRV parametrization [14] but contain extra suppression factors, $S(x)^n = (1 - x)^n$ [14], corresponding to an $n$-fold inelastic collision,

$$f_{q/N}^n(x, q_T^2) = C_n f_{q/N}(x, q_T^2) S(x)^n ,$$

where the normalization factors $C_n$ are fixed by the Gottfried sum rule.

The cross section of quark scattering on the target $d \sigma[qA(p)]/d^2 q_T \, dq_T$ in Eq. (3) is calculated in the light-cone dipole approach [16, 17]. Performing calculations,
we separate the contributions characterized by different initial transverse momenta of the projectile partons and sum over different mechanisms of high-$p_T$ production.

**Quark-diquark break up of the proton.** Here we consider proton breakup remaining the diquark intact, $p \rightarrow \bar{q}q + q$. We treat the diquark $\{\bar{q}q\}$ as point-like and integrate over its momentum. The corresponding $k_T$ distribution of the projectile valence quark, after propagation through the nucleus at impact parameter $b$, is calculated using the dipole technique developed in refs. [18, 19] (see also [2]). This contribution dominates the low transverse momentum region $k_T \lesssim 1$ GeV.

**Diquark break up $\bar{q}q \rightarrow qq$.** At larger $k_T$ the interaction resolves the diquark, so its break-up should be included. In this case the valence quark has much larger primordial transverse momentum. Its contribution is calculated in accordance with [18, 19] (see also [4]).

**Hard gluon radiation $q \rightarrow Gq$.** At large $k_T$ the dipole approach should recover the parton model [20], where high momentum transfer processes occur (in leading order) as binary collisions with the transverse momentum of each final parton of order $k_T$. Therefore, one should explicitly include in the dipole description radiation of a gluon with large transverse momentum that approximately equilibrates $k_T$, i.e. the process $qN \rightarrow qGX$. We employ the nonperturbative quark-gluon wave function developed in [10], which corresponds to small gluonic spots in the nucleon [21, 22]. Details of calculation of the quark scattering cross section can be found in [4].

### III. COMPARISON WITH DATA

Several years ago the BRAHMS collaboration performed measurements of nuclear effects at pseudorapidity $\eta = 3.2$ for production of negative hadrons with transverse momentum up to $p_T \approx 3.5$ GeV. Instead of the usual Cronin enhancement a suppression was found, as one can see from Fig. IV. Rather strong nuclear suppression of data at small $p_T$ has been analysed and interpreted in details in refs. [4, 5] and such an analysis does not need to be repeated here. On the other hand we will concentrate on a study of nuclear effects at large $p_T$.

Note that the dominance of valence quarks in the projectile proton leads to an isospin-biased ratio. Namely, high-$p_T$ negative hadrons close to the kinematic limit are produced mainly from $d$, rather than $u$, quarks. Therefore, more negative hadrons are produced by deuterons than by protons, and this causes an enhancement of the ratio plotted in Fig. IV by a factor of 3/2. We take care of this by using proper fragmentation functions from [13].

Although the nuclear effects under discussion are not sensitive to $p_T$ dependence of the cross section for hadron production in $p-p$ collisions, the model has been already successfully confronted with $p-p$ data from the BRAHMS experiment [1] at $\eta = 3.2$ in refs. [4, 5].

As the next step, very important for verification of our model, we calculate nuclear effects employing the dipole formalism and the mechanisms described shortly in the previous section (see also [4]). The results are compared with the BRAHMS data for the minimum-bias ratio $R_{d+Au}(p_T)$ [1] in Fig. IV. One can see that calculations are in a rather good agreement with data.

In the same Fig. IV we show also the STAR data for $\pi^0$ production presented as the ratio $R_{d+Au}(p_T)$ at pseudorapidity $\eta = 4.0$ [3]. Data demonstrate that suppression is much stronger than at $\eta = 3.2$ observed by the BRAHMS Collaboration [1]. A part of this difference can be explained by an isospin-biased ratio followed from the dominance of valence quarks in the projectile proton (deuteron). Whereas more negative hadrons are produced by deuterons than by protons, for positive hadrons the situation is opposite.

For production of negative hadrons, it leads to an enhancement of the ratio $R_{d+Au}(p_T)$ by a factor of 3/2 in comparison with $R_{p+Au}(p_T)$. However, for production of positive hadrons one arrives to a suppression by a factor of 3/4. As a result, for $\pi^0$ mesons one gets for $R_{d+Au}(p_T)$ a small overall suppression factor = 5/6, which is smaller than a factor of 3/2 for negative hadrons. However, such a difference following from the isospin effects can explain only a minor part from a huge difference in nuclear suppressions experimentally observed at $\eta = 3.2$ and 4.0 by the BRAHMS [1] and STAR [2] Collaborations, respectively.

If one supposes to interpret the nuclear effects of high-
As a demonstration of the valence quark domination in the projectile particle leading to an enhancement in production of negative hadrons by deuterons, we present in the same Fig. 3 also the model predictions for $\pi^-$ production at $\eta = 3.0$. Much smaller nuclear suppression clearly confirms the isospin asymmetry of leading particle production at large forward rapidities and large $p_T$ in $d-Au$ collisions.

Energy conservation applied to multiple parton rescatterings in nuclear medium leads to $x_F$ scaling of nuclear effects $^{1,2}$. We expect approximately the same nuclear effects at different energies and pseudorapidities corresponding to the same values of $x_F$. Such a situation is demonstrated in Fig. 4 where we present $p_T$ dependence of nuclear attenuation factor $R_{d+Au}(p_T)$ for $\pi^0$ mesons at different c.m. energies $\sqrt{s} = 200, 130$ and 62.4 GeV and such corresponding values of $\eta$, which keep the same value of $x_F$. Such a $x_F$ scaling can be verified and investigated in the future by the BRAHMS or STAR Collaborations in the energy and pseudorapidity range accessible at RHIC also for production of other species of hadrons.

IV. SUMMARY AND CONCLUSIONS

In the present paper we analyze a significant nuclear suppression in production of different species of particles...
at large pseudorapidities (large \( x_F \)) in \( d - Au \) collisions investigated at present mainly by the BRAHMS \[1, 2\] and STAR \[3\] Collaborations.

The new results of this paper are the following:

- Using the simple formula \((6)\) adopted from ref. \[4\] and based on Glauber-Gribov multiple interaction theory and the AGK cutting rules, we calculated high-\( p_T \) hadron production at large \( x_F \) and found a substantial suppression. This parameter-free calculation agrees with recent measurements performed by the BRAHMS \[1\] and STAR \[3\] Collaborations at forward rapidities in deuteron-gold collisions at RHIC. Our simple explanation is based on just energy conservation reflecting a small survival probability of LRG in multiple quark rescatterings.

- With the same input, we explain for the first time very strong nuclear suppression for \( \pi^0 \) production at \( \eta = 4.0 \) measured recently by the STAR Collaboration \[3\]. This suppression is more than a factor of 2 larger than at \( \eta = 3.2 \) (see Fig. \[1\]) investigated by the BRAHMS Collaboration \[1\] for \( h^- \) production and no other models with a reasonable alternative description are known.

- In order to exclude differences affected by isospin effects in production of different species of particles, we performed also model predictions for nuclear suppression at large \( p_T \) as a function of pseudorapidity changing from 3.0 to 4.0 (see Fig. \[2\]). Predicted a huge rise of nuclear suppression with \( \eta \) about a factor of 2 follows from much smaller survival probability of LRG in multiple quark rescatterings.

- Using proper fragmentation functions from ref. \[15\] we performed model calculations of nuclear suppression at large \( p_T \) and \( \eta = 3.0 \) for \( \pi^+ \) and \( K^+ \) production in a good agreement with the latest data from the BRAHMS Collaboration \[2\] (see Fig. \[3\]).

- As a consequence of \( x_F \) scaling, we predict approximately the same nuclear effects at different energies and pseudorapidities corresponding to the same values of \( x_F \) (see Fig. \[4\]). Such a \( x_F \) scaling can be verified in the future by the BRAHMS or STAR Collaborations mainly at lower energies, where no effect of coherence is possible. It allows to exclude the saturation models or the models based on CGC from explanation of nuclear suppression.

- According to \( x_F \) scaling we expect similar nuclear effects also at midrapidities in the RHIC energy range. However, the corresponding values of \( p_T \) for the produced hadrons should be much higher than at forward rapidities to keep the same value of \( x_F \), where the nuclear suppression is studied. In this kinematic region, investigation of nuclear suppression in production of different hadrons in \( p(d) - Au \) collisions is also very important because at large \( p_T \) the data cover rather large \( x_2 \sim 0.05 - 0.1 \) where no effect of coherence is possible. It gives another possibility to exclude the models based on CGC.

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