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Nuclear suppression at large x

Jan Nemchik
Czech Technical University in Prague, FNSPE, Břehová 7, 11519 Prague, Czech Republic &
Institute of Experimental Physics SAS, Watsonova 47, 04001 Košice, Slovakia
E-mail: nemcik@saske.sk

Michal Šumbera*
Nuclear Physics Institute ASCR, 25068 Řež/Prague, Czech Republic
E-mail: sumbera@ujf.cas.cz

We discuss a common feature of all known reactions on nuclear targets - a significant suppression of the relative production yields at large x. Interpretation of this effect based on energy conservation restrictions in initial state parton multiple interactions in nuclear matter is presented. We describe several applications of this interpretation using the light-cone dipole approach-based calculations. We demonstrate that the same mechanism of large-x suppression is important also at lower energies where coherent nuclear effects are not expected. This allows to exclude from the interpretation of observed phenomena the models based on the Color Glass Condensate.

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*Speaker.

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1. Introduction

The main aim of the recent measurements of high-p_T hadrons produced in the beam fragmentation region in the deuteron-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) is to reach the smallest values of Bjorken x in the nucleus. This allows to observe the coherence effects which should usually lead to nuclear suppression. Such a suppression of high-p_T hadrons has been indeed found by the BRAHMS [1, 2] and STAR [3] Collaborations.

Natural interpretation of the observed suppression based on the coherence effects was performed in [4] within a model based on color glass condensate (CGC). However, such an approach misses a global applicability for any energy and leads to problems with explanation of nuclear suppression at lower energies and for different reactions. For example, a similar suppression like at RHIC was measured also at much lower energy in $p+Pb$ collisions at SPS corresponding to c.m.s. energy $\sqrt{s} = 17.3\,\mathrm{GeV}$ where no effects of coherence are possible. The observed rise of the nuclear suppression with Feynman x_F by the NA49 Collaboration [5] is in accord with the same pattern seen in the RHIC energy range.

The same pattern of increasing suppression with x_F is also demonstrated by the E772 experiment at Fermilab [6] for the Drell-Yan (DY) process. Quite strong and universal nuclear suppression at large x_F is also confirmed by the collection of data from [7] for production of different species of particles in $p+A$ collisions. These examples and another reactions treated in ref. [8] confirm our expectation that this common feature should be attributed to all know reactions on nuclear targets. This allows to expect naturally that the same mechanism should cause the observed suppression at large x_F independently of the energy and type of the reaction.

Such a common mechanism of nuclear suppression was proposed in refs. [8, 9, 10] (see also [11, 12]). It is not related to coherence and can be applied to any reaction at forward rapidities and at any energy. Then the large-x_F nuclear suppression can be treated, alternatively, as a Sudakov suppression, 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 also demonstrated in [8] that the nuclear suppression at large x_F caused by the initial state multiple interactions is a leading twist effect leading to breakdown of QCD factorization.

Natural interpretation of suppression comes from energy conservation restrictions. Projectile parton propagating through a nucleus experiences multiple interactions. As a result it losses gradually energy leading at large x_F to a reduction of the probability to give a major fraction of the initial energy to one particle produced on a nucleus compared to a proton target. For this reason, the nuclear ratio should be suppressed below one at large x_F. Such an interpretation based on the energy conservation leads also to x_F scaling of the nuclear suppression as was analyzed in [10].

Besides, as an another consequence of energy conservation restrictions, observed nuclear effects occur also at midrapidities [13], i.e. at large $x_T = 2\,p_T/\sqrt{s}$, where p_T is transverse momentum of the produced particles. In spite of the Cronin effect at moderate p_T, the main consequence of QCD factorization is that the nuclear ratio should approach one at large p_T. However, initial state multiple interactions and energy sharing lead to a suppression pattern similar to that occurring at large x_F. Thus, at large x_T the nuclear ratio should fall below one. Moreover, we predict also x_T-scaling of this effect similarly to x_F-scaling at forward rapidities.

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The onset of nuclear suppression at midrapidities at large x_T manifests itself also through data on production of neutral pions in $d+Au$ collisions measured by the PHENIX Collaboration [13]. The same Collaboration [14] also demonstrated a strong nuclear effects at large p_T for direct photon production in $Au+Au$ collisions.

In this paper using a novel mechanism from refs. [8, 9] based on energy conservation in initial state multiple interactions we analyze and quantify the nuclear suppression at large x_F and large x_T for a variety of processes occurring in $p(d)+A$ and $A+B$ collisions:

- production of leading hadrons with small p_T,
- high-p_T hadron production at forward rapidities in p(d)+A collisions,
- production of hadrons at SPS energies vs. NA49 data,
- Drell-Yan production at Fermilab energy at large x_F,
- high-p_T hadron production at midrapidities,
- direct photon production at large p_T in Au+Au collisions.

2. Survival probability of large rapidity gaps

Energy conservation restrictions lead to a feature common to all reactions; namely, when the final particle is produced with $x_F \to 1$ ($x_T \to 1$), insufficient energy is left to produce anything else. In another words, gluon radiation during propagation of the projectile hadron or its debris is forbidden by energy conservation. As a class, such events are usually called LRG processes. 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 Δy, becomes

$$S(\Delta y) = e^{-\langle n_G(\Delta y)\rangle} \; , \tag{2.1}$$

where $n_G(\Delta y)$ is the mean number of gluons that would be radiated within Δy if energy conservation were not an issue.

The mean number $\langle n_G(\Delta y)\rangle$ of gluons radiated in the rapidity interval Δy is related to the height of the plateau in the gluon spectrum, $\langle n_G(\Delta y)\rangle = \Delta y\, dn_G/dy$. Then, the Sudakov factor acquires the simple form,

$$S(x_F) = (1-x_F)^{dn_G/dy} \; . \tag{2.2}$$

The height of the gluon plateau was estimated in ref. [15] as,

$$\frac{dn_G}{dy} = \frac{3\alpha_s}{\pi} \ln\left(\frac{m_\rho^2}{\Lambda_{QCD}^2}\right) \; . \tag{2.3}$$

For further calculations we take $\alpha_s = 0.4$ (see discussion in ref. [8]), which gives with high accuracy $dn_G/dy = 1$, i.e. the Sudakov factor,

$$S(x_F) = 1 - x_F \; . \tag{2.4}$$

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One can formulate nuclear suppression at $x_F \to 1$ ($x_T \to 1$) 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 [16]. Then the survival probability at impact parameter **b** reads,

$$W^{hA}_{LRG}(\mathbf{b}) = \exp\left[-\sigma^{hN}_{in}\, T_A(\mathbf{b})\right] \sum_{n=1}^{A} \frac{1}{n!} \left[\sigma^{hN}_{in}\, T_A(\mathbf{b})\right]^n S(x_F)^{n-1} , \tag{2.5}$$

where $T_A(\mathbf{b})$ is the nuclear thickness function.

3. Production of leading hadrons with small p_T

The left panel of Fig. 1 shows the collection of data from [7] for production of different species of particles in $p+A$ collisions exhibiting quite a strong and universal suppression at large x_F. Moreover, these data covering the laboratory energy range from 70 to 400 GeV demonstrate with a reasonable accuracy the x_F scaling of nuclear effects.

Relating the observed suppression to the dynamics discussed in the previous section, the nuclear effects can be calculated using Eq. (2.5) summing over the number of collisions and integrating over the impact parameter. Then, the nucleus-to-nucleon ratio normalized to the number of nucleon A reads

$$R_{A/N}(x_F) \,=\, \frac{1}{(1-x_F)\,\sigma_{eff} A} \int d^2\mathbf{b}\, e^{-\sigma_{eff}\, T_A(\mathbf{b})} \left\{ e^{(1-x_F)\sigma_{eff} T_A(\mathbf{b})} - 1 \right\}. \tag{3.1}$$

In the Glauber model $\sigma_{eff} = \sigma^{NN}_{in}$. However, Gribov's inelastic shadowing corrections substantially reduce σ_{eff} [17, 18].

To compare with data, the nuclear effects are parametrized as $R_{A/N} \propto A^{\alpha}$, where the exponent α varies with A. We used $A = 40$, for which the Gribov corrections evaluated in [18] lead to $\sigma_{eff} \sim 20\,\text{mb}$. Then a simple expression Eq. (3.1) explains the observed x_F scaling and describes rather well the data.

4. High-p_T hadron production at forward rapidities

Assuming large values of hadron transverse momenta, 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,

$$\frac{d^2\sigma}{d^2p_T\, d\eta} = \sum_q \int_{z_{min}}^{1} dz\, f_{q/d(p)}(x_1, q_T^2)\, \frac{d^2\sigma[qA(p)]}{d^2q_T\, d\eta}\bigg|_{\mathbf{q}_T = \mathbf{p}_T/z} \frac{D_{h/q}(z)}{z^2}, \tag{4.1}$$

where $x_1 = \frac{q_T}{\sqrt{s}} e^{\eta}$ is the light-cone momentum fraction of the projectile taken away by the quark. The quark distribution functions in the nucleon have the form using the lowest order parametrization of Gluck, Reya and Vogt [19]. We used proper fragmentation functions using parametrization from [20].

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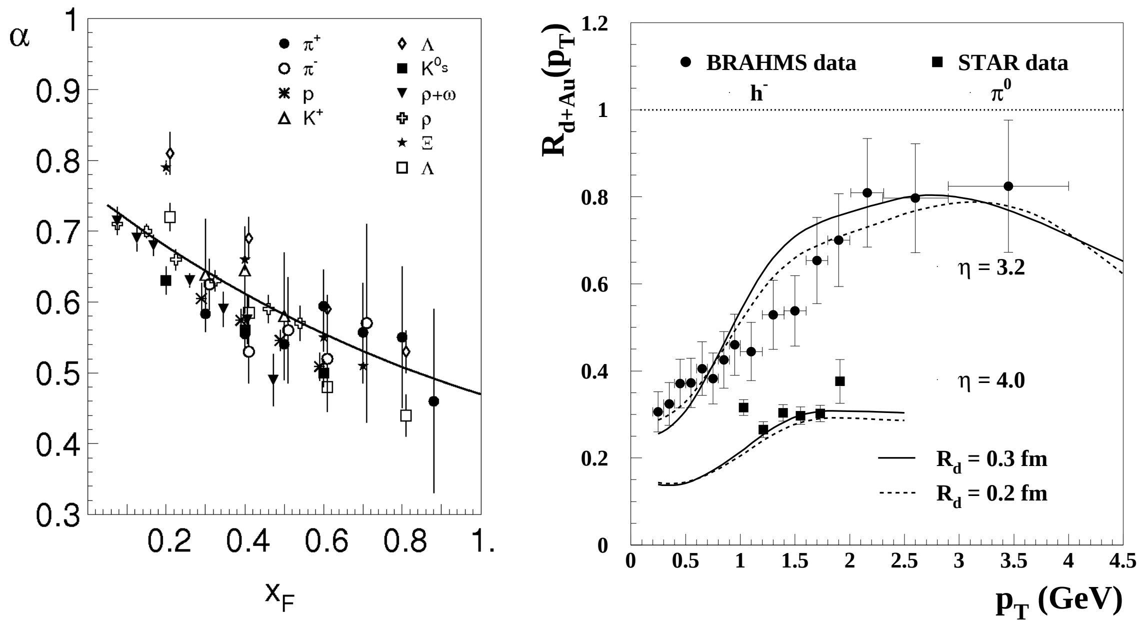

Figure 1: (Left) Exponent describing the A dependence ($\propto A^{\alpha}$) of the nucleus-to-proton ratio for production of different hadrons as a function of x_F. (Right) Ratio of negative hadron and neutral pion production rates in $d-Au$ and pp collisions as function of p_T at pseudorapidity $\eta = 3.2$ and $\eta = 4.0$ vs. data from the BRAHMS [1] and STAR Collaborations [3], respectively.

The cross section of quark scattering on the target $d\sigma[qA(p)]/d^2q_T d\eta$ in Eq. (3.1) is calculated in the light-cone dipole approach [21, 22]. In our calculations, we separate the contributions characterized by different initial transverse momenta and sum over different mechanisms of high-p_T production. Details can be found in [8].

Interaction with a nuclear target does not obey factorization, since the effective projectile quark distribution correlates with the target. The main source of suppression at large p_T concerns initial state multiple interactions in nuclear matter leading to energy conservation restrictions valid at any energy.

The quark distribution in the nucleus can be then evaluated 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 [16]. It has the following form:

$$f^A_{q/N}(x_1, q_T^2, \mathbf{b}) = \sum_{n=0}^{\infty} v_n(\mathbf{b})\, f^n_{q/N}(x_1, q_T^2)\,, \tag{4.2}$$

where the coefficients v_n are dependent on nuclear impact parameter $\mathbf{b}$,

$$v_n(\mathbf{b}) = \frac{\left[\sigma_{eff}\, T_A(\mathbf{b})\right]^n}{\left[1 + \sigma_{eff}\, T_A(\mathbf{b})\right]^{n+1}}\,. \tag{4.3}$$

Here the effective cross section $\sigma_{eff} = \left\langle \sigma^2_{\bar{q}q}(r_T)\right\rangle / \left\langle \sigma_{\bar{q}q}(r_T)\right\rangle$ has been evaluated in [8].

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The valence quark distribution functions $f^n_{q/N}(x_1,q_T^2)$ in Eq. (4.2) are also given by the GRV parametrization [19] but contain extra suppression factors, $S(x_1)^n = (1-x_1)^n$ (2.4), corresponding to an n-fold inelastic collision,

$$f^n_{q/N}(x_1,q_T^2) = C_n\, f_{q/N}(x_1,q_T^2)\, S(x_1)^n\,, \tag{4.4}$$

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

In 2004 the BRAHMS Collaboration [1] found a substantial nuclear suppression for high-p_T negative hadrons produced at pseudorapidity $\eta = 3.2$. Two years later, the STAR Collaboration [3] has observed even stronger suppression for neutral pions at $\eta = 4.0$ as one sees from the right panel of Fig. 1. Because the data cover rather small $x_2 \sim 10^{-3}$, the interpretation of such a suppression has been tempted to be a result of saturation [23, 24] or the CGC [25], expected in some models [4]. However, as a demonstration of an alternative interpretation of a strong onset of nuclear effects at large η, the right panel of Fig. 1 clearly shows a good agreement of our model based on energy conservation with corresponding data.

Much stronger nuclear effects at $\eta = 4$ can be simply explained by the stronger energy conservation restrictions leading to much smaller survival probability of LRG in multiple quark interactions at larger η-values [8, 10].

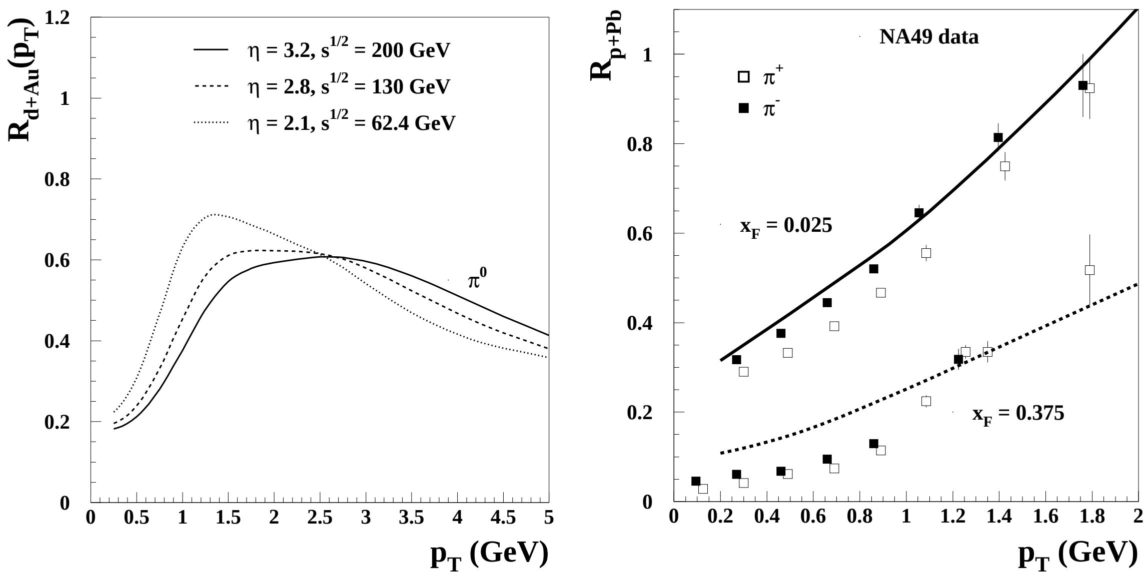

Figure 2: (Left) Theoretical predictions for an approximate $\exp(\eta)/\sqrt{s}$- scaling of the ratio $R_{d+Au}(p_T)$ for π^0 production rates in $d-Au$ and pp collisions. (Right) Ratio, $R_{p+Pb}(p_T)$, for $\pi^\pm$ production rates in $p-Pb$ and pp collisions as a function of p_T at two fixed values of Feynman $x_F = 0.025$ and 0.375 vs. the NA49 data [5].

Energy conservation restrictions in multiple parton rescatterings should lead also to x_F scaling of nuclear effects [8, 9, 10] since a corresponding parton energy loss is proportional to initial energy. We expect approximately the same effect of nuclear suppression at different energies and pseudorapidities corresponding to the same values of x_F. Such a behavior is demonstrated in the left panel of Fig. 2, where we present p_T dependence of nuclear attenuation factor $R_{d+Au}(p_T)$ for

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π^0 production in the RHIC kinematic range at different c.m.s. energies and η keeping the same value of x_F.

5. Nuclear suppression at small energy vs. NA49 data

The main attribute of a novel mechanism of nuclear suppression at forward rapidities proposed in [8] is its applicability and validity at any energy. The right panel of Fig. 2 clearly manifests that the pion production in $p+Pb$ collisions at SPS at low energy of 158 GeV in lab. frame exhibits the same pattern of nuclear suppression as that in the RHIC kinematic range. Such a suppression and its rise with x_F can not be explained within CGC picture whose validity is confined to the region of $x_1 < 0.01$ hardly accessible at SPS. The model predictions for nuclear suppression have been performed employing the dipole formalism for calculation of nuclear broadening using the standard convolution expression based on QCD factorization from [26]. Initial state multiple interactions leading to breakdown of QCD factorization are included as described in sect. 4 and presented also in [8]. One can see a reasonable agreement of our calculations with NA49 data [5].

6. Drell-Yan production at large x_F

The DY reaction is also known to be considerably suppressed at large x_F (x_1) [27] as one can see from Fig. 3. The origin of this suppression does not follow from the effects of coherence or shadowing since the corresponding data was obtained by the E772 Collaboration [6] at Fermilab at rather low energy of 800 GeV in the lab. frame.

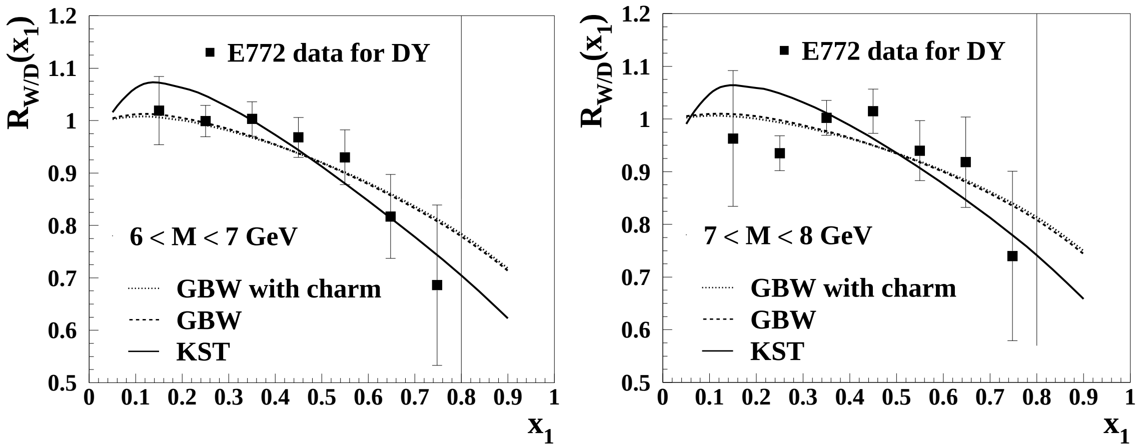

Figure 3: Normalized ratio of Drell-Yan cross sections on Tungsten and Deuterium as a function of x_1 for two different intervals of the dilepton effective mass. Solid, dashed and dotted curves correspond to different parametrizations of the dipole cross section: KST [33], GBW [34] without and with inclusion of charm quark [35], respectively.

Treating the DY process in the rest frame of the nucleus this process looks like radiation of a heavy photon/dilepton by a valence quark [28]. The coherence length in this case is related to the mean lifetime of a fluctuation $q \to q\bar{l}l$ and reads [28, 27],

$$l_c = \frac{2E_q\,\alpha(1-\alpha)}{(1-\alpha)\,M^2+\alpha^2\,m_q^2+p_T^2} = \frac{1}{m_N\,x_2}\,\frac{(1-\alpha)\,M^2}{(1-\alpha)\,M^2+m_q^2\,\alpha^2+p_T^2}\ , \tag{6.1}$$

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where M is the effective mass of the dilepton; $\vec{p}_T$ and α are the transverse momentum and the fraction of the light-cone momentum of the quark carried by the dilepton; and $E_q = x_q s/2m_N$ and m_q are the energy and mass of the projectile valence quark. The fraction of the proton momentum x_q carried by the valence quark in this reference frame is not equal to x_1, but $\alpha x_q = x_1$. At large $x_1 \to 1$, also $\alpha \to 1$, i.e. the coherence length Eq. (6.1) vanishes in this limit, no shadowing is possible and nuclear suppression can not be explained by the CGC based models.

Alternative interpretation of nuclear suppression at large x_1 is based again on energy conservation restrictions in multiple quark rescatterings using results discussed above in sect. 2 (see also [8, 9, 10]). Model calculations have been performed using expressions for the production cross sections in the color dipole approach [29, 30]. For the differential cross section for the photon radiation in a quark-nucleus collision we adopt [31] the light-cone Green function formalism [32] which naturally incorporates effects of quantum coherence. Fig. 3 shows our calculations for several parametrizations of the dipole cross section: KST [33], GBW [34] without and with inclusion of charm quark [35]. The difference between corresponding curves can be treated as a measure of the theoretical uncertainty. Model predictions are in a reasonable agreement with data from the E772 experiment [6].

7. High-p_T hadron production at midrapidities

Another consequence of energy conservation restrictions in multiple parton rescatterings is that nuclear effects should occur also at midrapidities, i.e. at large $x_T = 2\,p_T/\sqrt{s}$. However, the corresponding values of p_T should be high enough to keep variable x_T on the same level as Feynman x_F at forward rapidities. Such an expectation is confirmed by the recent data from the PHENIX Collaboration [13] showing an evidence for nuclear suppression at large $p_T > 8 \div 10\,\mathrm{GeV}$ (see the left panel of Fig. 4).

At $\eta = 0$ the small-p_T region is dominated by production and fragmentation of gluons. On the other hand, the region of very large p_T is dominated by production and fragmentation of valence quarks. Consequently, any value of the hadron transverse momentum differs only in the relative contributions of valence quarks and gluons.

In comparison with reactions at forward rapidities (large x_F) where mostly valence quarks dominate, here one should include also gluons in our calculations. Details can be found in ref. [26]. Correspondingly, the cross section for hadron production, Eq. (4.1), is extended also for gluons with corresponding distribution function, parton scattering cross section and the fragmentation function.

Including multiple parton rescatterings, the gluon distribution in the nucleus is given by the same formula as for quarks (see Eq. (4.2), except σ_{eff} in Eq. (4.2), which should be multiplied by the Casimir factor $9/4$.

If the effects of energy conservation in multiple parton rescatterings are not taken into account the p_T dependence of $R_{d+Au}(p_T)$ is described by the thin dashed line. One can see from the left panel of Fig. 4 that our calculations at moderate p_T are not in a bad agreement with data and a small suppression at large p_T is given by the isospin effects. After inclusion of energy sharing in multiple parton rescatterings the model predictions presented by the thin solid line underestimate the data at moderate p_T. However, at larger p_T quite a strong onset of nuclear effects is not in disagreement with corresponding experimental points.

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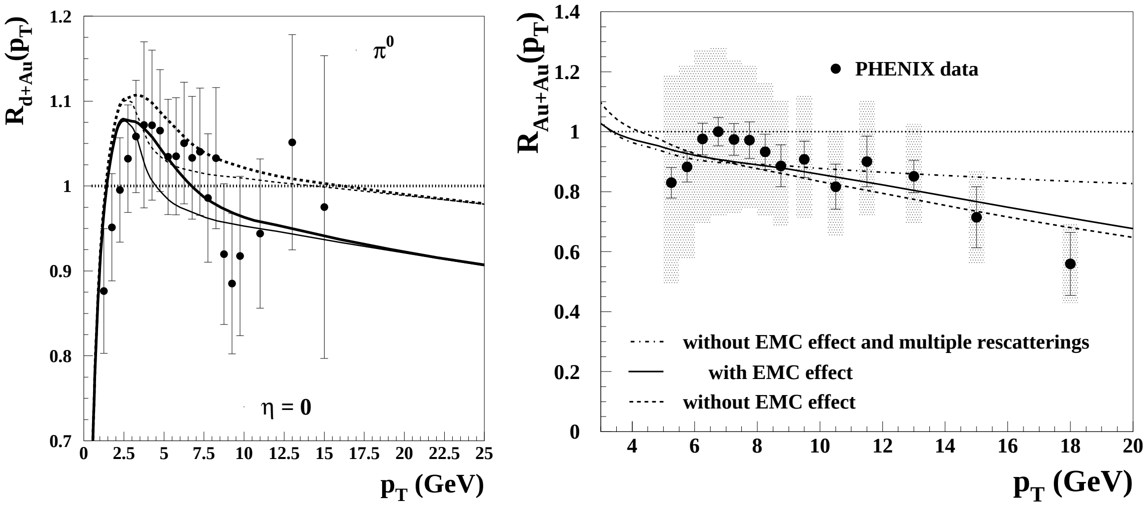

Figure 4: (Left) Nuclear attenuation factor $R_{d+Au}(p_T)$ as a function of p_T for production of π^0 mesons at $\sqrt{s} = 200\,\text{GeV}$ and $\eta = 0$ vs. data from PHENIX Collaboration [13]. (Right) Nuclear modification factor for direct photon production in $Au - Au$ collisions as a function of p_T.

Calculations in the RHIC energy range at midrapidities are most complicated since this is the transition region between the regimes of long (small p_T) and short (large p_T) coherence lengths. Instead of too complicated rigorous light-cone Green function formalism [36, 37, 38, 39] we preset corrections for finite coherence length using the linear interpolation performed by means of the so-called nuclear longitudinal form factor [26]. Such a situation is described by the thick solid and dashed lines reflecting the cases with and without inclusion of energy conservation in multiple parton rescatterings, respectively. It brings the model predictions to a better agreement with data at moderate p_T.

Finally we would like to emphasize again that nuclear suppression at large $p_T > 10\,\text{GeV}$ observed by the PHENIX experiment [13] can not be explained as a result of CGC because data cover rather large $x_2 \sim 0.05 - 0.1$ where no effects of quantum coherence are possible.

The minimum bias data from the PHENIX Collaboration [13] (see the left panel of Fig. 4) are not very precise and do not allow to make a definite conclusion about the onset of nuclear effects at large $p_T \gtrsim 8 \div 10\,\text{GeV}$. However, the same data distributed over different centralities in spite of large error bars demonstrate more decisively that the nuclear suppression $R_{d+Au} < 1$ at $p_T \gtrsim 9 \div 10\,\text{GeV}$ for centrality $0 - 20\%$. This gives a crucial signal to expect a suppression also for minimum bias events even according to worst scenario when more peripheral collisions do not contribute to overall nuclear suppression (i.e. $R_{d+Au} \to 1$ at centralities $\gtrsim 20\%$). More precise data at midrapidities and large p_T are needed in the RHIC energy range for a clear manifestation of breakdown of QCD factorization, $R_{p+Au} < 1$.

8. Direct photon production in Au+Au collisions

Data from the PHENIX Collaboration [14] represent another demonstration of a strong suppression in production of direct photons in $Au + Au$ collisions. Expressions for production cross sections have been derived employing the dipole formalism [32, 29, 30, 22, 40]. Model predictions

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for the ratio R_{Au+Au} as a function of p_T are compared with the PHENIX data [14] in the right panel of Fig. 4. If energy conservation restrictions in initial state multiple parton interactions are not taken into account the model calculations depicted by the dash-dotted line overestimate the data at large $p_T \gtrsim 13\,\mathrm{GeV}$. The onset of isospin effects gives a value $R_{Au+Au} \to 0.8$ in accord with our calculations. Inclusion of the energy conservation in multiple parton rescatterings leads to stronger nuclear effects at large p_T as it is demonstrated by the dashed line. It brings a better agreement of the model with data. Finally, the solid line additionally includes also a small correction for the EMC effect [41].

9. Summary and conclusions

In this paper we analyze a significant nuclear suppression at forward rapidities (large x_F) and at midrapidities (large x_T) for variety of processes. The new results are the following :

- QCD factorization fails at the kinematic limits, $x_F \to 1$, $x_T \to 1$. Nuclear targets cause a suppression of partons with $x \to 1$, due to energy sharing problems.
- Suppression of high-p_T hadrons at large forward rapidity observed by the BRAHMS and STAR Collaborations is well explained by the energy conservation restrictions in multiple parton rescatterings.
- We predict x_F (x_T) scaling of nuclear effects, i.e. the same suppression at different energies and rapidities corresponding to the same value of x_F (x_T).
- The same formalism explains well the nuclear suppression and its rise with x_F at low energy of 158 GeV in the lab. frame in accord with NA49 data [5].
- Suppression of Drell-Yan pairs at large x_F observed by E772 Collaboration [6] is again well explained by the same mechanism based on the energy sharing problems in initial state interactions.
- As a consequence of energy conservation restrictions in multiple parton rescatterings we predict that nuclear effects occur also at midrapidities, i.e. at large $x_T = 2\,p_T/\sqrt{s}$. Model calculations describe well the PHENIX data [13] for production of high-p_T hadrons at $\eta = 0$.
- With the same input we find a strong nuclear suppression for the large-p_T direct photon production in $Au + Au$ collisions in a good agreement with the PHENIX data [14].
- Study of nuclear effects at small energies and 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 saturation models or the models based on CGC from interpretation of observed nuclear suppression.

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References

[1] BRAHMS Collaboration, I. Arsene et al., *Phys. Rev. Lett.* **93**, 242303 (2004).

[2] BRAHMS Collaboration, Hongyan Yang et al., *J. Phys.* **G34**, S619 (2007).

[3] STAR Collaboration, J. Adams et al., emphPhys. Rev. Lett. **97**, 152302 (2006).

[4] D. Kharzeev, Y.V. Kovchegov and K. Tuchin, *Phys. Lett.* **B599**, 23 (2004).

[5] NA49 Collaboration, B. Boimska, *Ph.D. Dissertation* (Warsaw 2004), **CERN-THESIS-2004-035**.

[6] E772 Collaboration, D.M. Alde at al., *Phys. Rev. Lett* **64**, 2479 (1990).

[7] D.S. Barton et al., *Phys. Rev.* **D27**, 2580 (1983); W.M. Geist, *Nucl. Phys.* **A525**, 149c (1991); A. Beretvas et al., *ibid.* **34**, 53 (1986); M. Binkley et al., *Phys. Rev. Lett.* **37**, 571 (1976); R. Bailey et al., *Z. Phys.* **C22**, 125 (1984); P. Skubic et al., *Phys. Rev.* **D18**, 3115 (1978).

[8] B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, I. Schmidt and M.B. Johnson, *Phys. Rev.* **C72**, 054606 (2005).

[9] B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, I. Schmidt and M.B. Johnson, *Nucl. Phys.* (Proc. Suppl.)**B146**, 171 (2005).

[10] J. Nemchik, V. Petracek, I.K. Potashnikova and M. Sumbera, *Phys. Rev.* **C78**, 025213 (2008).

[11] J. Nemchik and I. Potashnikova, *Forward Physics in Proton-Nucleus and Nucleus-Nucleus Collisions*; invited talk at the 6th International Conference on Perspectives in Hadronic Physics (Hadron 08), Trieste, Italy, 12-16 May 2008; *AIP Conf. Proc.* **1056**, 207 (2008); *e-Print:* arXiv:**0807.1605** [hep-ph].

[12] J. Nemchik and M. Šumbera, *Nuclear Effects in High-pT Hadron Production at Large x*; in Proc. of the XXXVIII International Symposium on Multiparticle Dynamics (ISMD-08), 15-20 Sep. 2008, DESY, Hamburg; ed. J. Bartels, K. Borras, G. Gustafson, H. Jung, K. Kutak, S. Levonian and J. Mnich, p.354; *e-Print:* arXiv:**0902.0377** [hep-ph].

[13] PHENIX Collaboration, S.S. Adler et al., *Phys. Rev. Lett.* **98**, 172302 (2007).

[14] PHENIX Collaboration, T. Isobe et al., talk at Quark Matter 2006, Shanghai, China, 14-20 Nov. 2006; *J. Phys.* **G34**, S1015 (2007).

[15] J.F. Gunion and G. Bertsch, *Phys. Rev.* **D25**, 746 (1982).

[16] A.V. Abramovsky, V.N. Gribov and O.V. Kancheli, *Yad. Fiz.* **18**, 595 (1973).

[17] B.Z. Kopeliovich, *Phys. Rev.* **C68**, 044906 (2003).

[18] B.Z. Kopeliovich, I.K. Potashnikova and I.A. Schmidt, *Phys. Rev.* **C73**, 034901 (2006).

[19] M. Gluck, E. Reya and A. Vogt, *Z. Phys.* **C67**, 433 (1995).

[20] D. de Florian, R. Sassot and M. Stratmann, *Phys. Rev.* **D75**, 114010 (2007); *Phys. Rev.* **D76**, 074033 (2007).

[21] A.B. Zamolodchikov, B.Z. Kopeliovich and L.I. Lapidus, *Pis'ma Zh. Eksp. Teor. Fiz.* **33**, 612 (1981); *Sov. Phys. JETP Lett.* **33**, 595 (1981).

[22] M.B. Johnson, B.Z. Kopeliovich and A.V. Tarasov, *Phys. Rev.* **C63**, 035203 (2001).

[23] L.V. Gribov, E.M. Levin and M.G. Ryskin, *Nucl. Phys.* **B188**, 555 (1981); *Phys. Rep.* **100**, 1 (1983).

[24] A.H. Mueller, *Eur. Phys. J.* **A1**, 19 (1998).

PoS(High-pT physics09)042

[25] L. McLerran and R. Venugopalan, *Phys. Rev.* **D49**, 2233 (1994); *Phys. rev.* **D49**, 3352 (1994).

[26] B.Z. Kopeliovich, J. Nemchik, A. Schäfer and A.V. Tarasov, *Phys. Rev. Lett.* **88**, 232303 (2002).

[27] M.B. Johnson et al., *Phys. Rev. Lett.* **86**. 4483 (2001); *Phys. Rev.* **C65**, 025203 (2002).

[28] B.Z. Kopeliovich, *Soft Component of Hard Reactions and Nuclear Shadowing (DIS, Drell-Yan reaction, heavy quark production)*; in Proc. of the Workshop 'Dynamical Properties of Hadrons in Nuclear Matter', Hirschegg 1995, ed. H. Feldmeier and W. Noerenberg, p. 102; *e-Print:* arXiv:**hep-ph/9609385**.

[29] B.Z. Kopeliovich, J. Raufeisen and A.V. Tarasov, *Phys. Lett.* **B503**, 91 (2001).

[30] B.Z. Kopeliovich, J. Raufeisen, A.V. Tarasov and M.B. Johnson, *Phys. Rev.* **C67**, 014903 (2003).

[31] B.Z. Kopeliovich, J. Nemchik and I.A. Schmidt, *Production of Drell-Yan pairs in proton-nucleus collisions*; paper in preparation.

[32] B.Z. Kopeliovich, A. Schäfer and A.V. Tarasov, *Phys. Rev.* **C59**, 1609 (1999).

[33] B.Z. Kopeliovich, A. Schäfer and A.V. Tarasov, *Phys. Rev.* **D62**, 054022 (2000).

[34] K. Golec-Biernat and M. Wüsthoff, *Phys. Rev.* **D59**, 014017 (1999); *Phys. Rev.* **D60**, 114023 (1999).

[35] H. Kowalski, L. Motyka and G. Watt, *Phys. Rev.* **D74**, 074016 (2006).

[36] B.Z. Kopeliovich, J. Nemchik, A. Schäfer and A.V. Tarasov, *Phys. Rev.* **C88**, 035201 (2002).

[37] B.Z. Kopeliovich, J. Raufeisen and A.V. Tarasov, *Phys. Rev.* **C62**, 035204 (2000).

[38] J. Nemchik, *Nuclear shadowing in the light-cone dipole approach*, Talk given at Workshop on High P(T) Physics at LHC (LHC07), Jyvaskyla, Finland, 23-27 Mar 2007. Published in *PoS* **LHC07**, 028 (2007); *e-Print:* arXiv:**0803.1744** [hep-ph].

[39] B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova and I. Schmidt, *J. Phys.* **G35**, 115010 (2008).

[40] B.Z. Kopeliovich, J. Nemchik and I.A. Schmidt, *Direct photons in heavy ion collisions*; paper in preparation.

[41] K.J. Eskola, V.J. Kolhinen and C.A. Salgado, *Eur. Phys. J.* **C9**, 61 (1999).

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