Fractional energy losses in the black disk regime and BRAHMS effect

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Abstract
We argue that in the small x processes, in the black disc QCD regime (BDR) a very forward parton propagating through the nuclear matter should loose a significant and increasing with energy and atomic number fraction of its initial energy as a result of dominance of inelastic interactions, causality and energy-momentum conservation. We evaluate energy losses of forward partons in the kinematics close to BDR and find them to lead to the significant suppression of the forward jet production in the central NA collisions at collider energies with a moderate suppression of recoiling jet at central rapidities. We find our expectations to be in agreement with the recent RHIC data.

1 Introduction

It is well understood now that one of distinctive properties of hard processes in pQCD is the fast increase with energy of cross sections of hard inelastic processes and their significant value. Thus the interactions of the leading partons carrying finite fraction η of projectile momentum and produced in the sufficiently small x hard processes should be highly inelastic. Dominance of inelastic processes leads to the specific pattern of absorption for a parton propagating through the nuclear medium which is the main subject of this talk. For a more detailed discussion and extensive references see [1].

The difference between geometry of collisions dominated in the hard and soft QCD processes should disappear in the limit of complete absorption-black disc regime (BDR) i.e. at $x \leq x_{BDR}(Q^2)$ where Q^2 is the scale of hard processes and $x = (Q^2/\eta s)$. Decomposition of amplitude of DIS over powers of $1/Q^2$ disappears and therefore QCD factorization theorem is violated and at smaller $x \ll x_{BDR}$ hard partons are completely absorbed. With increase of Q leading partons leave kinematics of BDR and at sufficiently large Q conventional LT approximation will be restored. In this kinematics concept of fractional energy losses would become useful. Thus propagation of parton carrying significant fraction of projectile momentum differs strongly from that for the propagation of a parton in the center in rapidity where the elastic rescatterings of a parton dominates. Such a parton looses a finite energy [2] while propagating a distance L: $\Delta E \approx 0.02 GeV L^2/Fm^2$.

In contrast in the deep inelastic processes for example DIS off a proton the fraction of initial photon energy lost by incident parton is $\sim 10\%$ within DGLAP approximations, cf. dis-

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cussion in section 2. Numbers are probably similar within the NLO BFKL approximation corresponding to the rapidity interval between the leading particle and next rung in the ladder of about two. (It is equal to zero within the LO BFKL approximation which systematically neglects the loss of energy by energetic particles.)

In the regime where $x \approx x_{BDR}$ the contrast between the different patterns of energy losses becomes dramatic. A parton with energy E propagating sufficiently large distance L through the nuclear media should loose energy:

$$\Delta E/E = c(L/L_0) \tag{1}$$

with $c \approx 0.1$ in small x processes, and $L_0 \sim$ 3fm the mean free path for the interaction of a parton in BDR and $c(L/L_0) \to 1$ for $x \ll x_{BDR}$. This energy loss exceeds by orders of magnitude the losses in the large x regime.

Another subtle effect characteristic for a quantum field theory has been found long before the advent of QCD: eikonal interactions of energetic particle are cancelled out as the consequence of causality. This cancellation including additional suppression of eikonal diagrams due to energy-momentum conservation is valid for the exchanges by pQCD ladders with vacuum quantum numbers in the crossed channel. The cancellation of the contribution of eikonal diagrams has been demonstrated also for the exchanges by color octet ladders as the consequence of bootstrip condition for the reggeized gluon. Thus sufficiently energetic parton may experience only one inelastic collision. To produce n inelastic collisions wave function of energetic parton should develop component containing at least n constituents. This effect leads to the additional depletion of the spectrum of leading partons in the kinematics close to BDR where inelastic interactions of the energetic parton is important part of unitarization of amplitudes of hard processes.

Since the number of inelastic collisions is controlled by the number of scattering centres at given impact parameter the effect of the suppression of the yield of leading partons should be largest at the central impact parameters. We evaluate energy losses of leading parton in small x regime of QCD and show that blackening of pQCD interaction leads to dominance of peripheral collisions in the production of the leading hadrons/jets in high energy hadron - nucleus interactions and to a significant, increasing with energy and atomic number loss of finite fraction of leading parton energy in the central collisions. Inclusive cross section is $\propto A^{1/3}$ deep in the BDR region with suppression of the recoil jets depending on x of jet. One of characteristic features of BDR regime is that there is no suppression of recoil jet in the peripheral collisions. At moderately small x which are reached at RHIC, suppression of recoil jet should depend on its rapidity and be maximal if both jets carry a significant fraction of the projectile energy. We will show that this prediction is supported by the recent RHIC data on leading hadron production in dA collisions.

It is instructive to compare the kinematics of partons involved in the production of leading hadrons at RHIC with that for small x phenomena at HERA. Taking for example the STAR highest rapidity (y=4) and $\langle p_T \rangle = 1.3\,GeV/c$ bin [3] we find that $x_N \geq 0.7$ for the incoming parton. Hence, minimal x_g resolved by such a parton are $\sim 4p_T^2/(x_N s_{NN}) \sim (2 \div 3) \cdot 10^{-4}$. This is very close to the kinematics reached at HERA. The analyses of the HERA data within the dipole model approximation show that the partial amplitude for the quark interaction reaches at HERA strength up to 1/2 of the maximal strength, see review in Ref. [4]. In the case of heavy nuclei one gets an enhancement factor $\sim 0.5A^{1/3}$ so the quark interaction with heavy nuclei should be close to BDR for $p_t^2 \leq 1.5GeV^2$ and $x_{projectile} \sim 0.5$. In the LHC kinematics BDR will cover much larger p_t^2 range, see for example Fig. 17 in Ref. [4].

Suppression of the forward spectra in the deuteron-gold collisions in the kinematics rather close to the BDR was reported by several RHIC experiments. The suppression factor is significantly larger than expected suppression due to the leading twist nuclear shadowing. Suppression was observed in the kinematics where the hadron production in pp collisions is in a reasonable agreement with the recent pQCD calculations based on the NLO DGLAP approximation [5]. Very recently STAR [3] has reported new results for the π^0 ratios for $y \sim 4$ and $p_t \leq 2.0\,GeV$. They observed a larger suppression factor $\sim 1/3$, which is consistent with a linear extrapolation of the suppression factor for negatively charged hadrons, h^- measured at smaller rapidities to $y = 4$ taking into account the 2/3 factor due to the isospin effects [6]. The STAR experiment also reported the first observation of the correlations between the forward π^0 production with the production of the hadrons at the central rapidities $|\eta_h| \leq 0.75$. Such correlations provide a new information about the mechanism of the suppression of the inclusive spectrum.

2 Energy losses of forward parton in the vicinity of black disk regime

The amplitude with color octet quantum numbers decreases with energy due to the gluon reggeization in pQCD as:

$$A_g \propto \alpha_s^2 s^{\beta(t)}\,(i + \tan(\pi\beta(t)/2)) \tag{2}$$

where $\beta(t)$ is the gluon Regge trajectory with $\beta(t=0) < 1$. Infrared divergences of $\beta(t)$ are regulated by hadron wave functions. At the same time the amplitude due to exchange by a ladder with the vacuum quantum numbers in the crossed channel rapidly grows with energy:

$$A \propto \alpha_s^2 s^{(1+\lambda(t))}\,(i + \tan((\pi/2)\lambda(t))) \tag{3}$$

where $\lambda(t=0) \approx 0.2$. (For the simplicity we restrict ourselves here by the phenomenological fit to the theoretical formulae and to the HERA data on structure functions of a proton.) Hence such amplitudes (modeled at moderately small x as the two gluon exchange ladder) fastly exceed single gluon exchange term and at larger energies achieve maximum values permitted by probability conservation.

Single inelastic collision of the parton produced in a hard high energy NN collision off another nucleon is described by the imaginary part of the two gluon ladder with the vacuum quantum numbers. By definition, the inelastic cross section is calculable in terms of the probability of inelastic interaction, $P_{inel}(b)$ of a parton with a target at a given impact parameter b:

$$\sigma_{inel} = \int d^2b P_{inel}(b,s,Q^2) \tag{4}$$

Since σ_{inel} is calculable in QCD above equation helps to calculate $P_{inel}(b,s,Q^2)$. The probability of inelastic interaction of a quark is cf. discussion in [4]:

$$P_{inel}(b,x,Q^2) = \frac{\pi^2}{3}\alpha_s(k_t^2)\frac{\Lambda}{k_t^2}xG_A(x,Q^2,b), \tag{5}$$

where $x \approx 4k_t^2/s_{qN}, Q^2 \approx 4k_t^2, \Lambda \sim 2\text{GeV}^2$ (for the gluon case $P_{inel}(b)$ is 9/4 times larger). We use gluon density of the nucleus in impact parameter space, $G_A(x, Q^2, b)$ ($\int d^2bG_A(x, Q^2, b) = G_A(x, Q^2)$) . Above equation for the probability of inelastic interaction is valid only for the onset of BDR when $P_{inel}(b, s, Q^2) < 1$ (which is the unitarity limit for $P_{inel}(b, s, Q^2)$).

If $P_{inel}(b, x, Q^2)$ as given by Eq.5 approaches one or exceeds one it means that average number of inelastic interactions, $N(b)$ becomes larger than one. Denoting as $G_{cr}(x, Q^2, b)$ for which $P_{inel}(b)$ reaches one we can evaluate $N(b, x, Q^2)$ as

$$N(b, x, Q^2) = G_A(x, Q^2, b)/G_{cr}(x, Q^2, b). \tag{6}$$

As soon as P_{inel} becomes close to one, we can easily evaluate lower boundary for the energy losses arising from the single inelastic interaction of a parton. This boundary follows from the general properties of the parton ladder. Really, the loss of finite fraction of incident parton energy ϵ arises from the processes of parton fragmentation into mass M which does not increase with energy. For binary collision $M^2 = \frac{k_t^2}{\epsilon(1-\epsilon)}$. For the contribution of small $\epsilon \leq 1/4$

$$\epsilon \approx k_t^2/M^2 \tag{7}$$

Here k_t is transverse momentum of incident parton after inelastic collision. The spectrum over the masses in the single ladder approximation (NLO DGLAP and BFKL approximations) is as follows

$$d\sigma \propto \int dM^2/M^2(s/M^2)^\lambda \theta(M^2 - 4k_t^2), \tag{8}$$

where we accounted for the high energy behavior of the two gluon ladder amplitude Eq.(3). We effectively take into account the energy momentum conservation i.e. NLO effects. Consequently the *average* energy loss (for the contribution of relatively small energy losses ($\epsilon \leq \gamma \sim 1/4$) where approximation of Eq.(7) is valid):

$$\epsilon_N \equiv \langle \epsilon \rangle = \frac{\int_0^\gamma \epsilon d\epsilon/\epsilon^{1-\lambda}}{\int_0^\gamma d\epsilon/\epsilon^{1-\lambda}} = \gamma \frac{\lambda}{1-\lambda}. \tag{9}$$

For the realistic case $\gamma = 1/4, \lambda = 0.2$ this calculation gives the fractional energy loss of 6%. This is lower limit since we neglect here a significant contribution of larger ϵ (it will be calculated elsewhere).

In the kinematics of onset of BDR absorption at central impact parameters is due to $N(b) > 1$ inelastic collisions (interaction with several ladders). The energy of initial parton is shared before collisions at least between N constituents in the wave function of the incident parton to satisfy causality and energy-momentum conservation. This quantum field theory effect which is absent in the framework of eikonal approximation can be interpreted as an additional energy loss [4]:

$$\epsilon_A(b) \approx N(b)\epsilon_N. \tag{10}$$

Here ϵ_N is the energy lost due to exchange by one ladder - Eq. (9). Above we do not subtract scattering off nucleon since our interest in the paper is in energy losses specific for nuclear processes in the regime when interaction with a single nucleon is still far from the BDR. If collision energies are far from BDR, the energy losses estimated above should be multiplied by small probability of secondary interactions. Inclusion of enhanced "pomeron" diagrams will not change our conclusions based on the necessity to account for the energy-momentum conservation law.

Yields of leading hadrons carrying fraction of projectile momentum $\geq x_F$ are rapidly decreasing with x_N as $\propto (1-x_F)^n$. For pion production $n \sim 5 \div 6$. Obviously for large x_F average values of x of the parton of the projectile involved in the production of the pion are even larger, leading to strong amplification of the suppression due to the energy losses. The spectrum of leading pions is given in pQCD by the convolution of the quark structure function, $\propto (1-x)^n, n \sim 3.5$ and the fragmentation function $\propto (1-z)^m, m \sim 1.5 \div 2$ leading to a very steep dependence on x_F, $\propto (1-x_F)^{n+m+1}$. As a result for the STAR kinematics $x \sim 0.7$ and $z \sim 0.8$ correspondingly energy losses of 10% lead to a suppression roughly by a factor $[(0.9-x_F)/(1-x_F)]^6$. For $x_F = 1/2$ this corresponds to suppression by a factor of four. In particular, introducing the energy loss of $\sim 6\%$ in the NLO calculation of the pion production is sufficient [6] to reproduce the suppression observed at y=3. Similar estimate shows that average losses of $\sim 8 \div 10\%$ reproduce the suppression of the inclusive yield observed by STAR [3]. This value is of the same magnitude as the above estimate. Also, Eq.(10) leads to much stronger suppression for production at central impact parameters than in peripheral collisions.

In the kinematics of LHC the same $k_t(BDR)$ would be reached at x_N which are smaller by a factor $s_{RHIC}/s_{LHC} \sim 10^{-3}$, while for the same x_N one expects much larger values of $k_t(BDR)$ (see e.g. Fig.17 in [4]). Thus in the kinematics of LHC the regime of large energy losses should extend to smaller x_N.

There are two effects associated with the interaction of partons in the BDR - one is an increase of the transverse momenta of the partons and another is the loss of the fraction of the longitudinal momentum [8]. The net result is that distribution of the leading hadrons should drop much stronger with x_F than in the Color Glass Condensate (CGC) models [9] where only k_t broadening, change of the resolution scale and suppression of coalescence of partons in the final state but not the absorption and related energy losses were taken into account. At the same time, the k_t distribution for fixed x_F should be broader. Note here that the leading particle yield due to the scattering with $k_t \gg k_{BDR}$ is not suppressed and may give a significant contribution at smaller k_t via fragmentation processes. This discussion shows that selection in the final state of the leading hadron ($x_F \geq 0.3 \div 0.5$ at RHIC) with moderately large k_t should strongly enhance the relative contribution of the peripheral collisions where BDR effects are much smaller. These expectations are consistent [1] with the STAR data [3].

At extremely high energies where kinematics of the BDR will be achieved for a broad range of the projectile's parton light-cone fractions and virtualities, QCD predicts dominance of scattering off the nuclear edge leading to inclusive pion production cross section $\propto A^{1/3}$for a large enough x_N and a wide range of p_t. With increase of incident energy the range of p_t for fixed x_N would increase. Also the suppression for a given p_t would be extended to smaller x_N.

3 Interaction of leading partons with opaque nuclear medium

At high energies leading partons with light cone momentum x_N, p_t are formed before nucleus and can be considered as plane wave if

$$(x_N s/m_N)(1/M^2) \gg 2R_A. \tag{11}$$

Here M is the mass of parton pair (and bremstrahlung gluon) produced in the hard collision. If sufficiently small x are resolved, the BDR regime would be reached:

$$4p_t^2/x_N s \leq x(BDR). \tag{12}$$

In the BDR interaction at impact parameters $b \leq R_A$ is strongly absorptive as the medium is opaque. As a result, interaction of leading parton lead to a hole of radius R_A in the wave function describing incident parton. Correspondingly, propagation of parton at large impact parameters leads to elastic scattering - an analogue of the Fraunhofer diffraction of light off the black screen. However since the parton belongs to a nucleon, the diffraction for impact parameters larger than $R_A + r_{str}$ (where r_{str} is the radius of the strong interaction) will lead to the proton in the final state - elastic p A scattering. Only for impact parameters $R_A + r_{str} > b > R_A$ the parton may survive to emerge in the final state and fragment into the leading hadron. Cross section of such diffraction is $2\pi R_A r_{str}$. Another contribution is due to the propagation of the parton through the media. This contribution is suppressed due to fractional energy losses which increase with the increase of energy, leading to gradual decrease of the relative contribution of the inelastic mechanism.

Thus we predict that in the kinematics when BDR is achieved in pA but not in pN scattering, the hadron inclusive cross section should be given by the sum of two terms - scattering from the nucleus edge which has the same momentum dependence as the elementary cross section and scattering off the opaque media which occurs with large energy losses:

$$\frac{d\sigma(d + A \to h + X)/dx_h d^2p_t}{d\sigma(d + p \to h + X)/dx_h d^2p_t} = c_1 A^{1/3} + c_2(A) A^{2/3} \tag{13}$$

The coefficient c_1 is essentially given by the geometry of the nucleus edge - cross section for a projectile nucleon to be involved in an inelastic interaction with a single nucleon of the target. Coefficient $c_2(A)$ includes a factor due to large energy losses and hence it decreases with increase of the incident energy for fixed x_h, p_t. Deep in the BDR the factor $c_2(A)$ would be small enough, so that the periphery term would dominate.

It is worth to compare outlined pattern of interaction in the BDR with the expectations of the CGC models for small x hard processes in the kinematics where transverse momenta of partons significantly larger than that characteristic for BDR. These models employ the LO BFKL approximation with saturation model used as initial condition of evolution in $\ln(x_o/x)$. In these models the dependence on atomic number is hidden in the "saturation scale" and in the blackness of interaction at this scale. In this model partons interact with maximal strength at small impact parameters without significant loss of energy. Note that leading parton looses significant fraction of incident energy in the NLO BFKL approximation but not in LO BFKL. As a result the cross section is dominated by the scattering at small impact parameters and depends on A at energies of RHIC approximately as $A^{5/6}$ [7]. Also, the process which dominates in this model at central impact parameters is the scattering off the mean field leading (in difference from BDR where DGLAP approximation dominates in the peripheral processes in the kinematics of RHIC) to events without balancing jets. With increase of jet transverse momenta interaction becomes less opaque, leading to a graduate decrease of the probability of inelastic collisions and hence to the dominance of the volume term.

A natural way to distinguish between these possibilities is to study correlations between production of forward high p_t hadrons and production of hadrons at central rapidities. First such study was undertaken by the STAR experiment [3]. In the pp case the rate of recoiled jets at $y \sim 0$ was found to be compatible with pQCD calculations. This suggests that the mechanism for pion production in the STAR kinematics is predominantly perturbative so that it is legitimate to discuss the propagation of a parton through the nucleus leading to pion production.

Our analysis indicates that the dA correlation data [3] for production of the balancing hadron for the trigger with $\langle p_T \rangle \sim 1.3\, GeV/c$ occurs with the same strength as in pp scattering, corresponding to $< x_A >\sim 0.01$. Lack of the suppression of the pQCD mechanism for these x_A puts an upper limit on the x range where coherent effects may suppress the pQCD contribution. Since the analysis of [6] find that the pQCD contribution is dominated by $x_A \geq 0.01$, we can conclude that the main contribution both to inclusive and the correlated cross section originates from pQCD hard collisions at large impact parameters.

To ensure a suppression of the pion yield at central impact parameters for the discussed kinematics one needs a mechanism which is related to the propagation of the projectile parton which is generating a pion in a hard interaction with the $x \sim 0.01$ parton. For example, the rate of suppression observed by BRAHMS would require fractional energy losses $\sim 3\%$ both in the initial and final state [6]. Similar losses would produce a suppression of the pion yield in STAR kinematics comparable with the inclusive data. Modeling performed in [1] indicates that for the central impact parameters the fractional energy losses should be at least a factor of 1.5 larger. Note here that such losses are sufficient only because the kinematics of the elementary process is close to the limit of the phase space. At the same time, this estimate assumes that fluctuations in the energy losses should not be large. For example, processes with energy losses comparable to the initial energy (like in the case of high energy electron propagation through the media) would not generate necessary suppression provided overall losses are of the order of few percent. Note also that the second jet in the STAR kinematics has much smaller longitudinal momentum and hence is far from the BDR. Therefore in the STAR kinematics one does not expect the suppression of the correlation with production of the second jet. However a strong suppression is expected for production of two balancing forward jets since both of them are interacting in the BDR.

Hence the data are qualitatively consistent with the scenario described in the introduction that leading partons of the projectile (with $x \approx 0.7$) interact at central impact parameters with the small x nuclear gluon fields with the strength close to the BDR and do not contribute to the inclusive π^0 yield.

We also performed analysis of interplay of soft and hard QCD phenomena for correlations between forward and central hadron production based on the geometry of deuteron-gold collisions. This allowed us to determine average number of wounded nucleons, N_w, for the π^0 trigger. We find $N_w \sim 3$, which is much smaller than $N_w \sim 13$ for central impact parameters.

This strongly suggests dominance of the peripheral collisions in π^0 production rather than the central collisions as in the mechanism of [7]. The seeming suppression of the recoil reported by [3] is due to soft interactions and does not indicate suppression of the pQCD mechanism of the production of the recoil jets relative to other mechanisms.

Thus RHIC data are consistent with the pattern of energy losses in central collisions described above. Further analyses along the lines suggested in [1] would allow to diminish model dependence of comparison between the hard components of the interaction in pp and dAu cases, quantitative study of the suppression on the number of wounded nucleons, which also will provide a probe of the color transparency effects as well as effects of large gluon fields.

We want to stress that the discussed mechanism of energy losses is operational only for propagation of partons with transverse momenta $\leq$ than that typical for the BDR. At the same time pion production with transverse momenta significantly larger than that typical for BDR should be dominated by the scattering at central impact parameters. With increase of energy from RHIC to LHC energy losses at large x_N should strongly increase, while substantial losses $\geq 10\%$ should persist for rapidities $|y| \geq 2$. This effect should lead to suppression of the production of the recoil jets at the rapidity intervals where no suppression is present at RHIC. It may also lead to higher densities in the central collisions as compared to the current estimates. In the forward direction we expect a significantly larger suppression than already large suppression found in [9] where fractional energy losses were neglected. Fractional energy losses result in modification of the form of the QCD factorization theorem at LHC energies. Similar effects will be present in the central pp collisions at LHC. They would amplify the correlations between the hadron production in the fragmentation and central regions discussed in Ref. [4].

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