Novel QCD phenomena in pA collisions at LHC

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Abstract
We discuss novel QCD phenomena in pA collisions at LHC energies such as the possibility to investigate the behaviour of hard processes at $x$ as low as $10^{-7}$, signals for onset of the black body limit in the hard processes and in the nucleon fragmentation, multijet production.

1. Physics motivations
The proton-ion collisions at LHC will be qualitatively different from those at fixed target energies\textsuperscript{1}. In the soft interactions two prime effects are a strong increase of the mean number of “wounded” nucleons - from about 6 to about 20 in pA central collisions (due to increase of $\sigma_{\text{inel}}(NN)$) and a 50\% increase of the average impact parameters in pp collisions (as manifested in the shrinkage with increase with energy of the diffractive peak in the elastic pp collisions) making it possible for a proton to interact often simultaneously with nucleons which have essentially the same longitudinal coordinate but different impact parameters. At the same time geometry of pA collisions at LHC should be more close to that in the classical mechanics because increase of cross sections combined with the suppression of the inelastic diffraction in pp scattering, leads to the suppression of fluctuations in the value of effective $NN$ cross section (and hence the suppression of inelastic shadowing corrections in pA scattering), to a very strong suppression of inelastic diffraction in pA collisions as compared to the fixed target FNAL energies\textsuperscript{2}. In the hard interactions the prime effect is a strong increase of the gluon densities at small $x$ both in projectile and ion. Gluon densities can be measured at LHC up to ultra small $x \propto 10^{-6-7}$ where PQCD will be probed in a new domain\textsuperscript{3}. As a consequence of blackening of the interaction of proton partons with nuclear partons at small $x_A$ one should expect disappearance in the proton fragmentation region of hadrons with small transverse momenta, and hence a strong suppression of nonperturbative QCD effects\textsuperscript{3,4}. Thus the high transverse momentum proton fragmentation region is a natural place to search for unusual QCD phases which should live long time because of the Lorentz dilatation of time. In spite of a small coupling constant, gluon densities of heavy ions become larger in a wide range of $x$ and $Q^2$ and impact parameters than that permitted by the conservation of probability within the leading twist approximation\textsuperscript{1,2,5}. Thus a decrease of the strong coupling constant with virtuality would be insufficient to support applicability of PQCD to the hard small $x$ processes in the kinematical domain where gluon fields may appear strong enough for nonperturbative QCD vacuum to become unstable and where equations of QCD may need to be modified. The possibility for novel QCD regime and therefore new phenomena are maximized in this QCD regime.\textsuperscript{3} At the same time interpretation of these novel effects would be much more definitive in pA collisions than in the heavy ion collisions.

New classes of strong-interaction phenomena which occur within the short-distance, near-the-light-cone space-time region and which could be associated with perturbative QCD or with interface of perturbative and nonperturbative QCD are much more probable in pA collisions than in pp collisions. The densities of partons, and of energy-momentum, may be high enough to “burn away” the nonperturbative QCD vacuum structure in a cylinder of a radius $\sim 1 fm$ and length $\sim 2 R_A$, leaving behind only .

\textsuperscript{1} An extensive discussion of the novel pA physics at LHC was presented in\cite{1}. Here we summarize few key points of this analysis and extend it to consider effects of the small x high field regime.

\textsuperscript{2} A similar phenomenon of the suppression of small transverse momenta for another quantity, the nuclear light cone wave function at small $x$, is discussed in the saturation models\cite{6,7}.

\textsuperscript{3} It is important to distinguish between parton densities which are defined within the leading twist approximation only\cite{2} and may increase with energy forever and physical quantities - cross sections/structure functions - whose increase with energy at given impact parameter is restricted by the probability conservation.
a dense partonic fluid governed by new QCD dynamics with small $\alpha_s$ but effective short-distance large couplings. If there is a large enhancement of hard-collision, gluon-induced processes, then there should be an enhancement of hard multiparton collisions, heavy-flavor production \[1\]. The study of the $x$, $p_t^2$ and $A$-dependence of multiparton interactions, of the forward charm and beauty hadron production (in the direction of the fragmenting proton) should be especially incisive to address these questions.

Estimates of the kinematical region for the new QCD dynamics in proton (nucleus)-heavy nucleus collisions based on the LO formulae for the dipole cross section and the conservation of probability indicate \[3\] that for the central impact parameters for $A \sim 200$ and $Q^2 \sim 25 GeV^2$ for quarks $x_A \leq 5 \cdot 10^{-5}$ and for gluons $x_A \leq 10^{-3}$.

2. Measurements of nuclear parton densities at ultra small $x$

One of the fundamental issues in high energy QCD is the dynamics of the hard interactions in the small $x$ kinematics. Depending on the resolution scale ($Q^2$) one investigates here either the leading twist effects or the regime of strong color fields. Since the cross-sections for hard processes increase roughly linearly with $A$ (except for very small $x$ and relatively small $Q^2$ where the counting rates are high anyway), even short runs with nuclear beams will produce data samples sufficient to measure parton distributions with statistical accuracy better than 1% practically down to the smallest $x$ which is kinematically allowed: $x \sim 10^{-7}$ for quarks and $x \sim 10^{-6}$ for gluons \[7\]. The systematic errors for the ratios of nuclear and nucleon structure functions are also expected to be small since most of these errors cancel in the ratios of the cross-sections, cf \[8\].

There are several processes which could be used to probe the small $x$ dynamics in $pA$ collisions. They include the Drell-Yan pair production, study of dijets, jet + photon, charm production, diffractive exclusive production of three jets \[15\], multijet events. It is worth emphasizing that for these measurements it is necessary to detect jets, leptons and photons at rapidities close enough to the nucleon rapidity. In this $y$-range, the accompanying soft hadron multiplicities are relatively small, leading to a soft particle background comparable to that in $pp$ scattering. In fact, for $|y_{max} - y| \leq (2 - 4)$ the background level is likely to be significantly smaller than in $pp$ collisions due to suppression of the leading particle production in $pA$ scattering (for a thorough discussion of these reactions see \[1\]).

The measurements of the dimuon production appear to be more feasible experimentally for the forward angles than studies of the hadron production due to small energy losses for muons. In the kinematics where the leading twist dominates one can study both the quark small $x$ distributions (from the cross section at relatively small transverse momenta: $p_t^2(\mu^+\mu^-) \ll M^2(\mu^+\mu^-)$, and the gluon distribution (from the measurements of the cross section at $p_t(\mu^+\mu^-) \sim M(\mu^+\mu^-)$ \[16\]). Note also that for the forward region a dimuon background from the charm production is likely to be rather small since muons in average carry only 1/3 of the energy in the charm decays.

3. Signals for onset of the black body limit

A fast increase with energy of structure functions of heavy nuclei contradicts to the probability conservation for a wide range of parton momenta and virtualities for the LHC energy range. On the contrary the rapid, power-like growth of structure function of a nucleon observed at HERA may continue forever because of the diffuse edge of a nucleon \[9\]. At present new QCD dynamics of the regime of high parton densities where multiparton interactions are inhibited remains a subject of lively debates. PreQCD black body regime for the structure functions of heavy nuclei \[10\], QCD black body regime for hard processes off heavy nuclei \[9\], saturation of parton densities at given impact parameter \[8\], color glass condensate regime \[4\], turbulence and related scaling laws are possible options. For the estimates of the pattern of the novel phenomena we shall use in this text the formulae of black body regime because they are generic enough for the expectations of the onset of new QCD dynamics within the existing theoretical
The space time picture of the black body limit in the proton-nucleus collisions at least two orders of magnitude in proton. Hence in the LHC kinematics the region where novel QCD phenomena are important will extend due to enhancement of the high twist effects as the whole picture of interactions can qualitatively change. Leaving a lot of room for the violation of leading twist approximation. It maybe more serious than merely however the leading twist taming being large is still insufficient to restore the probability conservation in the gluon and quark channels and significant up to very large allows to evaluate taming due to the leading twist nuclear shadowing which turns out to be large both effects. Recently extensive studies of hard diffraction were performed at HERA, for review see [14]. This leads to a qualitative change in the picture of the proton-nucleus interactions for the partons before the target and interacts with the target in a black regime releasing the fluctuation, e.g. a Drell-Yan pair. This leads to a large amplification of the multiparton hard collisions expected in QCD at small x; see e.g. [8, 11]. Eikonal approximation [11], constraints from the probability conservation [12, 13] indicate that new QCD dynamics should reveal itself at significantly larger x than in the proton and in more striking effects. Recently extensive studies of hard diffraction were performed at HERA, for review see [14]. This allows to evaluate taming due to the leading twist nuclear shadowing which turns out to be large both in the gluon and quark channels and significant up to very large $Q^2$. - for the recent discussion see [8]. However the leading twist taming being large is still insufficient to restore the probability conservation leaving a lot of room for the violation of leading twist approximation. It maybe more serious than merely due to enhancement of the high twist effects as the whole picture of interactions can qualitatively change. Really, the common wisdom is that smallness of $\alpha_s$ guarantees that bare particle is free within a hadron but this remarkable property which confirmed experimentally in many hard processes is violated in small x phenomena. One may think about this phenomenon in term of an effective violation of the asymptotic freedom in this limit. It is expected to occur in heavy nuclei at x at least ten times larger than in the proton. Hence in the LHC kinematics the region where novel QCD phenomena are important will extend at least two orders of magnitude in $x_A$ for a large range of virtualities.

The space time picture of the black body limit in the proton-nucleus collisions can be seen best in the rest frame for the nucleus. A parton belonging to the proton emits a hard gluon (virtual photon) long before the target and interacts with the target in a black regime releasing the fluctuation, e.g. a Drell-Yan pair. This leads to a qualitative change in the picture of the proton-nucleus interactions for the partons with $x_p, p_t$ satisfying the condition that

$$x_A = \frac{4p_t^2}{x_p s_{NN}}$$

is in the black body kinematics for the resolution scale $p_t \leq p_t^{b.b.l.}(x_A)$. Here $p_t^{b.b.l.}(x_A)$ is maximum $p_t$ for which the black body approximation is applicable. In the kinematics of LHC $Q^2 \approx 4(p_t^{b.b.l.})^2$ can be estimated by using formulae derived in [12]. At minimal $x_A$ it may appear as large as $(p_t^{b.b.l.}(x_A))^2 = 15 GeV^2$. All the partons with such $x_p$ will obtain $p_t(jet) \sim p_t^{b.b.l.}(x_A)$ leading to the multijet production. The black body regime will extend down in $x_p$ with increase of the incident energy. For LHC for $p_t \leq 3 GeV/c$ this regime may cover the whole region of $x_p \geq 0.01$ where of the order ten partons resides. Hence in this limit most of the final states will correspond to multiparton collisions. For $p_t \leq 2 GeV/c$ the region extends to $x_p \geq 0.001$. At LHC collisions of such partons correspond to the central rapidities. Dynamics of conversion of the high $p_t$ partons with similar rapidities to hadrons is certainly a collective effect which requires a special consideration.

Inclusive observables For the calculation of the total cross sections the logic similar to the one used in the consideration of $\gamma^* - \text{nucleus scattering}$ [8] should be applicable. In particular for the case of

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4In the black regime highly virtual probe interacts at the same time with several high $k_t$ partons from the wave function of a hadron [8]. This is qualitatively different from the asymptotic freedom limit where interaction with only one highly virtual parton are important. Hence the interacting parton is far from being free when probed by a hard probe of a large coherence length $l_c = 1/2m_N x$. 

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the total cross section of the dimuon production can be evaluated as:

\[
\frac{d\sigma}{dx_A dx_p} (p + A \rightarrow \mu^+ \mu^- + X) = \frac{4\pi\alpha^2}{9} K(x_A, x_p, M^2) \frac{F_{2p}(x_p, Q^2)}{M^2} \cdot \frac{1}{6\pi^2} M^2 \cdot 2\pi R_A^2 \ln(x_0/x_A),
\]

(2)

for large but not too large dimuon masses, \(M^2\). In particular we estimate \(M^2(\text{bbl}) = 10^{-7} \approx 60\text{GeV}^2\). Here \(K\)-factor has the same origin as in the leading twist case, but it should be smaller since it originates from the gluon emissions only from the parton belonging to the proton, \(R_A\) is the nuclear radius, and \(x_0\) is maximal \(x_0\) for which the black body limit is valid. Hence the expected \(M^2\) dependence of the dimuon production is qualitatively different in this case than in the case of \(pp\) scattering where scattering at large impact parameters may mask the black body limit contribution. Also the \(x_A\) dependence in this limit becomes pretty weak.

The study of the \(p_t\) distribution of the dimuons may provide also a signal for the onset of the black body regime. Similar to the case of \(p_t\) distribution of leading partons in the deep inelastic scattering \([9]\), one should expect a broadening of the \(p_t\) distribution of the dimuons in the black body limit as compared to the DGLAP expectations, see \([17]\) for a calculation of this effect in the color glass condensate model.

With further decrease of \(x_A\) formulae of black limit will probably overestimate cross section because the interaction with heavy nucleus of sea quarks and gluons in the proton would become black also.

The onset of the black body limit will lead also to gross changes in the hadron production: much stronger drop with \(x_F\) of the spectrum in the proton fragmentation region accompanied by a gross \(p_t\) broadening of the spectrum as well as the enhancement of the hadron production at smaller rapidities, see discussion in section 4.3.

It is worth emphasizing here that onset of the black body limit for ultra small \(x_A\) will pose limits on using the forward kinematics for the measurements of the parton densities at larger \(x_A\). Indeed as soon as one tries to use large enough \(x_p\) for the nuclear parton density measurements one would have to take into account that collisions of these partons with nuclear partons are always accompanied by a significant \(p_t\) broadening associated with the interaction with “black component” of the nucleus wave function. As a minimum this would lead to a significant \(p_t\) broadening of the \(p_t\) distribution of the produced hard system. One can also question the validity of the leading twist expansion for the cross sections integrated over the transverse momentum of the produced system. To investigate these phenomena an ability to do measurements at fixed \(x_A\) and different \(x_p\) would be very important.

4. Mapping of the three dimensional nucleon parton structure

The systematic studies of hard inclusive processes during the last two decades have led to a pretty good understanding of the single parton densities in nucleons. However very little is known about multi-parton correlations in nucleons which can provide critical new insights into the dynamics of the strong interactions, and allow to discriminate between different models of nucleons. Such correlations may be generated, for example, by the fluctuations of the transverse size of the color field in the nucleon leading, via color screening, to correlated fluctuations of the densities of gluons and quarks.

A related source of correlations is QCD evolution, since a selection of a parton with a given \(x, Q^2\) may lead to a local (in transverse plane) enhancement of the parton density at different \(x\) values. Also, practically nothing is known about possible correlations between the transverse size of a particular configuration in the nucleon and the longitudinal distribution of partons in this configuration.

4.1 Multi-jet production and double parton distributions

It was recognized already more than two decades ago \([18]\) that the increase of parton densities at small \(x\) leads to a strong increase of the probability of nucleon-nucleon collisions where two or more partons of each projectile experience pair-wise independent hard interactions. Although the production of multijets
through the double parton scattering mechanism was investigated in several experiments \cite{19, 20} at pp, p\bar{p} colliders, the interpretation of the data was hampered by the need to model both the longitudinal and the transverse partonic correlations at the same time. The studies of proton-nucleus collisions at LHC will provide a feasible opportunity to study separately the longitudinal and transverse partonic correlations in the nucleon as well as to check the validity of the underlying picture of multiple collisions.

The simplest case of a multiparton process is the double parton collision. Since the momentum scale $p_t$ of a hard interaction corresponds to much smaller transverse distances $\sim 1/p_t$ in the coordinate space than the hadronic radius, in a double parton collision the two interaction regions are well separated in the transverse space. Also in the c.m. frame pairs of partons from the colliding hadrons are located in pancakes of thickness $\leq (1/x_1 + 1/x_2)/p_{c.m.}$. So two hard collisions occur practically simultaneously as soon as $x_1, x_2$ are not too small and hence there is no cross talk between two hard collisions. A consequence is that the different parton processes add incoherently in the cross section. The double parton scattering cross section, being proportional to the square of the elementary parton-parton cross section, is therefore characterized by a scale factor with dimension of the inverse of a length squared. The dimensional quantity is provided by the nonperturbative input to the process, namely by the multiparton section, is therefore characterized by a scale factor with dimension of the inverse of a length squared. The parton scattering cross section, being proportional to the square of the elementary parton-parton cross section, is therefore characterized by a scale factor with dimension of the inverse of a length squared. The dimensional quantity is provided by the nonperturbative input to the process, namely by the multiparton distributions. In fact, because of the localization of the interactions in transverse space, the two pairs of colliding partons are aligned, in such a way that the transverse distance between the interacting partons of the target hadron is practically the same as the transverse distance between the partons of the projectile.

The double parton distribution is therefore a function of two momentum fractions and of their transverse distance, and it can be written as

$$Q^2, Q'^2,$$

though to make the expressions more compact we will not write explicitly this $Q^2$ dependence. Hence the double parton scattering cross section for the two “two \rightarrow two” parton processes $\alpha$ and $\beta$ in an inelastic interaction between hadrons $a$ and $b$ can be written as:

$$\sigma_D(\alpha, \beta) = \frac{m}{2} \int \Gamma_a(x_1, x_2; b) \sigma_\alpha(x_1, x'_1) \sigma_\beta(x_2, x'_2) \Gamma_b(x'_1, x'_2; b) dx_1 dx'_1 dx_2 dx'_2 d^2b \quad (3)$$

where $m = 1$ for indistinguishable parton processes and $m = 2$ for distinguishable parton processes. Note that though the factorization approximation of Eq.(3) is generally accepted in the analyses of the multijet processes and appears natural based on the geometry of the process no formal proof exists in the literature. As we will show below the study of the A-dependence of this process will allow to perform a stringent test of this approximation.

Here to simplify the discussion we neglect small non-additive effects in the parton densities, which is a reasonable approximation for $0.02 \leq x \leq 0.5$. In this case we have to take into account only $b$-space correlations of partons in individual nucleons.

One has therefore two different contributions to the double parton scattering cross section: $\sigma_D = \sigma_D^A + \sigma_D^P$. The first one, $\sigma_D^P$, interaction with two partons of the same nucleon in the nucleus, is the same as for the nucleon target (the only difference being the enhancement of the parton flux) and the corresponding cross section is

$$\sigma_D^A = \sigma_D \int d^2 BT(B) = A\sigma_D,$$

where

$$T(B) = \int_{-\infty}^{\infty} dz \rho_A(r), \int T(B)d^2B = A \quad (5)$$

is the nuclear thickness, as a function of the impact parameter of the hadron-nucleus collision $B$.

The contribution to the term in $\Gamma_A(x'_1, x'_2, b)$ due to the partons originated from different nucleons of the target, $\sigma_D^N$, can be calculated solely from the geometry of the process by observing that the nuclear density does not change within a transverse scale $\langle b \rangle \ll R_A$. It rapidly increases with $A \propto \int T^2(B)d^2B$. Using information from the CDF double scattering experiment\cite{20} on the mean transverse separation of
partons in a nucleon, one finds that the contribution of the second term should dominate in the case of proton - heavy nucleus collisions: \( \sigma_1^2 / \sigma_1^2 \approx 0.68 (A/12)^{0.39} \). Hence one expects a stronger than \( A \) increase of the multijet production in \( pA \) collisions at LHC. Measurements with a set of nuclei would to measure the double parton distributions in nucleons and also to check the validity of the QCD factorization for such processes which appears natural but which so far was not derived in pQCD. An important application of the discussed process would be to investigate transverse correlations between the nuclear partons in the shadowing region. This would require a selection of both partons from the nucleus in the shadowing region, \( x_A \leq x_{sh} \sim 10^{-2} \).5

As we already mentioned in section 3, partons with sufficiently large \( x_p \) satisfying Eq.1 are expected to interact with a probability of the order one with small \( x \) partons of nucleus. As a result a hard collision of the partons with sufficiently large \( x_p \) and \( x_A \geq 0.01 \) will be accompanied by production of a minijet/minijets at the black body kinematics with \( p_t \sim p_t^{b.b.l.}(x_A) \). Most of sufficiently fast partons of the protons will generate minijets leading to a strong suppression of cross section of the events with only two jets.

Detectors with sufficiently large rapidity acceptance would allow to detect events originating from the triple parton collisions at \( x_A \geq x_{sh} \) and large enough \( p_t \) where \( p_t \) broadening related to the blackbody limit effects are sufficiently small. This provide stringent tests of the dynamics of the hard interactions and provide additional information on two parton correlations as well as unique information on triple parton correlations.

Other opportunities with multi-jets include

- Probing correlations between partons in the nucleus at high densities, i.e. for \( x_1 A, x_2 A \ll 10^{-3} \), which would provide qualitatively new information about the dynamics of nuclear shadowing and the presence of possible new condensates of partons.
- Studying the accompanying soft hadron production (cf. the discussion in Section 4.2), which would allow measurement of the transverse size of a proton configuration containing partons \( x_1, x_2 \). In particular, the production of 4 jets with two jets at large \( x \) in the proton fragmentation region \( x_1 + x_2 \geq 0.5 \) may provide another way to look for point-like configurations in nucleons, see [1] and [2] for discussion of some other options.

4.2 Proton-ion collisions probe transverse nucleon structure

As we discussed in [15], one supposes that in some subclass of events the distribution of constituents in the initial proton may be unusually local in the transverse (impact parameter) plane when the proton collides with the ion. If this is so, its effective cross-section per nucleon will be greatly reduced, perhaps all the way to the perturbative-QCD level. If the effective cross-section of such a point-like configuration goes below 20mb, there will be an appreciable probability that it can penetrate through the center of a \( Pb \) ion and survive. This would lead to a highly enhanced yield of diffractive production of the products of the point-like configuration in collisions with heavy ions.

Not only might the properties of the final-state collision products depend upon the nature of the transverse structure of the proton primary at arrival at the collision point, but even the conventional parton distributions may also be affected. For example, let us consider, a nucleon as a quark and small diquark connected by a narrow QCD flux-tube. It should be clear that if the flux-tube is at right angles to the collision axis at arrival, then the valence partons will have comparable longitudinal momentum or \( x \). On the other hand, if the flux tube is parallel to the direction of motion, then one of the valence systems will have very large \( x \), and the other very small. This happens because in this case the internal longitudinal momenta of the valence systems, in the rest frame of the projectile proton, are in opposite directions. Therefore the smallness of the configuration is correlated with the joint \( x \)-distribution of its constituents.

5 The A-dependence of the ratio of \( \sigma_2/\sigma_1 \) in the kinematics where only one of the nuclear partons has \( x_A \leq x_{sh} \) is practically the same as for the case when both nuclear partons have \( x \geq x_{sh} \).
This kind of nonfactorization may be determined by the study of the perturbative-QCD processes of dilepton, direct-photon, or dijet production as a function of the centrality of the collision, multiplicity of soft hadrons, as well as a function of the atomic number. Naturally such studies would require also experimental investigation of the production of the soft hadrons as a function of impact parameter at LHC energies where it may differ quite strongly from the one observed at fixed target energies.

One possible kinematics where a strong correlation is expected is when a parton with large $x (x \geq 0.6)$ is selected in the proton. The presence of such a parton requires three quarks to exchange rather large momenta. Hence one may expect that these configurations have a smaller transverse size and therefore interact with the target with a smaller effective cross-section $\sigma_{\text{eff}}(x)$. Suggestions for such a dependence of the size on $x$ are widely discussed in the literature. Using as a guide a geometric (eikonal type) picture of $pA$ interactions and neglecting (for simplicity) shadowing effects for nuclear parton densities one can estimate the number of wounded nucleons $\nu(x, A)$ in events with a hard trigger (Drell-Yan pair, $\gamma$-jet, dijet,...) as a function of $\sigma_{\text{eff}}$ [22]:

$$\nu(x, A) = 1 + \sigma_{\text{eff}}(x) \frac{A - 1}{A^2} \int T^2(b) \, d^2b,$$

where the nuclear density per unit area $T(b)$ is defined in Eq. (4.1). At LHC for average inelastic $pPb$ collisions and $\sigma_{\text{eff}} \sim \sigma_{\text{inel}}(pp)$ Eq. [22] leads to $\nu \approx 10$. This is somewhat larger than the average number of wounded nucleons in $pA$ collisions, due to the selection of more central impact parameters in events with a hard trigger.

A decrease of the effective cross-section for large $x$, say, by a factor of 2, would result in a comparable drop of the number of particles produced at central rapidities as well as in a smaller number of nucleons produced in the fragmentation of the nucleus. in the nucleus fragmentation region.

### 4.3 $A$-dependence of the particle production

**Particle production in the proton fragmentation region** The $A$-dependence of hadron production in the proton fragmentation region remains one of the least understood aspects of hadron-nucleus interactions. Practically all available data are inclusive and correspond to the energies where the cross section of inelastic $NN$ scattering is about three times smaller than at LHC. They indicate that the cross-section is dominated by the production of leading particles at large impact parameters, where the projectile interacts with only one or two nucleons of the nucleus. As a result very little information is available about hadron production at the central impact parameters which are most crucial for the study, for example of $AA$ collisions. Theoretical predictions for this region are also rather uncertain.

In eikonal type models, where the energy is split between several soft interactions, one may expect a very strong decrease of the yield of the leading particles. The dependence is expected to be exponential with path length in the nucleus; their mean energy is attenuated exponentially. On the other hand, if the valence partons of the projectile do not lose a significant amount of their initial momentum, as suggested by the models motivated by perturbative QCD, see review in [23], the spectrum of leading particles may approach a finite limit for large $A$ and central impact parameters [24]. Indeed in this case the leading partons will acquire significant transverse momenta and will not be able to coalesce back into leading baryons and mesons as it seemingly happens in the nucleon-nucleon collisions. As a result they will fragment practically independently leading to much softer distributions in the longitudinal momentum for mesons and especially for baryons [24].

We discussed above that the strength of the interaction of fast partons in the nucleon ($x_p \geq 10^{-2}$ for LHC) with heavy nuclei at the central impact parameters may approach the black body limit and

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6The impact-parameter dependence is accessible in the proton - nucleus collisions via a study of nuclear fragmentation into a number of channels, for an extensive discussion see [1].
that under this scenario all these partons will acquire large transverse momenta $\sim p_{t,b.l.}(x_A)$.\footnote{Hence in the black body limit $p_t$ broadening of the partons should be much larger than at low energies where $p_t$ broadening is consistent with the QCD multiple rescattering model\cite{34}, see \cite{25} for the discussion of the matching of these two regimes.} This would lead to a very significant $p_t$ broadening of the spectrum of leading hadrons \cite{27}. Probably the most feasible way to study this effect will be to measure the $p_t$ distribution of the leading neutrons for the collisions at the central impact parameters, which will closely follow the $p_t$ distribution of leading quarks \cite{27}. It is worth emphasizing that a strong $p_t$ broadening which should increase with increase of $x_F$ clearly distinguishes this mechanism of the suppression of the leading hadron spectrum from the soft physics effect of the increase of the total $pp$ cross-section by nearly a factor of three from fixed target energies.

**Particle production in the central region** The Gribov-Glauber model including inelastic screening effects, but neglecting the final state interactions between the hadrons produced in different Pomeron exchanges, as well as neglecting the interactions of these hadrons with the nuclear target, leads to a prediction that at high energies and rapidities $y$, such that $|y_p - y| \gg 1$, the inclusive spectrum of produced hadrons should be proportional to that in the inclusive cross-section of $hN$ scattering:

$$
\frac{d\sigma^{pA\rightarrow hN}(y,p_T)}{dy\,d^2p_T} = A \frac{d\sigma^{pN\rightarrow hN}(y,p_T)}{dy\,d^2p_T}. \quad (7)
$$

Since $\sigma_{inel}(pA)/\sigma_{inel}(pN) \propto A^{2/3}$, Eq. (7) implies that the multiplicity of particles produced in the inelastic $pA$ collisions should increase with $A$, roughly as $A^{1/3}$. Data at fixed target energies do not contradict this relation, but the energy is too low for an unambiguous interpretation. Effects of splitting the energy between multiple soft $NN$ interactions are much larger in the nucleus-nucleus collisions than in proton-nucleus collisions so checking whether similar formula is valid for AA collisions would require energies much higher than those available at RHIC.

The opposite extreme is to assume that interactions of partons in the black body regime become important in a large range of $x_p \geq 10^{-2}$. In this case multiple scatterings between the partons, their independent fragmentation together with associated QCD radiation (gluon bremsstrahlung) may produce the major part of the total entropy and transverse energy and will lead to enhancement of the production of hadrons at central rapidities as compared to the the expectations of the Gribov-Glauber model.

**Particle production in the ion fragmentation region** For the rapidities close to the nucleus rapidity, there are indications of the contribution of slow hadron re-interactions, which lead to an increase of the multiplicity of nucleons with momenta $1.0 \geq p_N \geq 0.3$ GeV, as compared with expectations neglecting final state re-interactions (a factor of $\sim 2$ for heavy nuclei) \cite{28}. As we have discussed above, it is doubtful that the Gribov-Glauber picture is correct at LHC energies, so one may expect significant deviations from the expectations based on Eq.(7). It is likely that color quark system with rapidities close to $y_A$ will be excited along the cylinder of the radius $\sim 1$ fm and length $R_A$. This may result in unusual properties of the hadron production in the nucleus fragmentation region including production of exotic multiquark, multigluon... states.

It must be emphasized that a quantitative understanding of the physics of particle production in $pA$ collisions in this phase-space region is a prerequisite for the understanding the corresponding phenomenology in $AA$ collisions.

In conclusion, studies of proton-nucleus scattering at LHC will allow to study strong interactions in the high field domain over extended region of rapidities. New phenomena will be especially prominent in the proton fragmentation region, though they will also extend to the central region and to the nucleus fragmentation region.
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