QCD - looking forward

L. Frankfurt
School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

M. Strikman
Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

Abstract

We outline theoretical ideas on the soft and hard dynamics of strong high-energy interactions and discuss promising directions for future high-energy experimental investigations including the ones which would allow one to reveal the three-dimensional structure of QCD bound states, investigate the onset of regime of large parton densities, and observe the violation of the DGLAP evolution equation. We emphasize that many qualitatively new phenomena should be present for the forward kinematics both in electron-nucleon(nucleus) collisions at HERA and in pp, pA collisions at LHC.

1 Introduction

Our current understanding of Nature - the Standard Model of Strong and Electroweak interactions - is formulated in terms of interactions of Abelian and non-Abelian gauge fields. All these Lagrangians lead to intricate phenomena in the situations where the coupling constant becomes large. One can even question whether these models are selfconsistent in the nonperturbative regime. The most pressing theoretical problems are the dynamics relevant for the confinement of quarks and gluons, the phenomenon of spontaneously broken continuous symmetries, the role of nearly massless quarks in QCD confinement, the possible existence of new forms of stable and metastable matter, kinetics of phase transitions, as well as the role of nonlinear chaotic phenomena in the large parton density regime. Obviously, experimental investigations of these problems in a non-Abelian gauge theory in perturbative and nonperturbative regimes in a Lab is feasible for QCD only. Hence the importance of QCD research for physics as a whole. Note also that the current analyses of the LEP data reviewed in the summary talk by J. Ellis make it quite probable that the Higgs meson is light enough to be discovered before the LHC, and supersymmetry particles are too heavy to be discovered at the LHC. In this case, QCD may provide the only avenue for discoveries of new phenomena at the LHC.
Recent HERA data observed a fast increase of parton distributions in DIS at small $x$ predicted by perturbative QCD. There are about 19 gluons in a proton at HERA energies and the gluon density of a proton increases with energy. Furthermore, HERA started investigating exclusive hard diffraction processes which are strikingly different from soft QCD diffraction, but are in line with the predictions based on the generalization of the QCD factorization theorem to exclusive DIS processes. Related experimental studies at FNAL of the diffractive dissociation of a pion into two high $p_t$ jets, of $J/\psi$ photo production off nuclear targets, and of $\Upsilon$ photo production off nuclear targets indicate the existence of a new QCD phenomenon: transparency of nuclear matter to the propagation of a fast spatially small wave package of quarks and gluons, cf. discussion and references in. Thus, one is tempted to look for ways to experimentally reach new hard-soft QCD regimes of large parton densities which may be manifested in a variety of Color Coherent Phenomena. The aim of this talk is to outline new and nontrivial QCD phenomena which can be discovered under the extreme conditions achievable in the kinematics of small $x$ processes in the LHC energy range and at HERA in both $ep$ and $eA$ modes.

Challenging Problems

• Does a spatially small color singlet object interact with a hadron target, $T$, at high energies with a small cross section, or can this cross section reach a maximum strength allowed by the geometric ($s$-channel) constraint of $\approx \pi r_T^2$, as hinted by the naive extrapolation of DGLAP calculations into the small $x$ region. What is the origin of the interaction strength fluctuations for large interaction strengths. How do two small objects interact at small $x$?

• What dynamics governs the states at high parton densities produced in hard and in soft collisions. How does one produce and investigate various new forms of hadron matter using well understood QCD phenomena.

• How can one extend the well understood methods of measuring the single parton densities to study multiparton correlations including correlations between longitudinal and transverse degrees of freedom. The ultimate goal would be to extract the three-dimensional image of the nucleon from appropriate data.

2 Perturbative QCD in the interactions of small dipoles with hadrons

\textsuperscript{a}The last problem is often referred to as the BFKL model of the Pomeron. This subject is discussed at length in the talk of A. Mueller and hence we will skip it in this talk.
2.1 Cross section of dipole-hadron interaction

A number of hard diffractive phenomena can be expressed through the interaction cross section of a small color dipole with a hadron target using the QCD factorization theorem. The LO expression for this cross section is

\[ \sigma_{\text{dipole}}(x, b) = \frac{\pi^2}{4} \frac{F^2}{b^2} \alpha_s(b^2/b^2) x G_T(x, b^2/b^2) \]  

(1)

In the case of a $q\bar{q}$ pair, $\vec{b}$ is the relative impact parameter between quark and antiquark: $(\vec{b} \cdot \vec{P}) = 0$; $x = \frac{\lambda}{s\sigma}$ and $F^2$ is the Casimir operator of $SU(3)_c$.

*Implications of eq. (1):

- Color screening property of eq. (1) - $\sigma(b)|_{b \to 0} \to 0$ in combination with the phenomenon of Lorentz slowing down of the space-time evolution for a fast particle interaction allows one to justify the applicability of the factorization theorem to hard diffractive phenomena initiated by a spatially small quark-gluon wave packet.

- Hard exclusive processes, like the production of vector mesons in DIS, are dominated by the interaction of $\gamma^*$ in small $q\bar{q}$ configurations. Hence these processes provide a new and effective method to measure the amplitude of small size quark-gluon configurations within wave functions of hadrons. Recently, the minimal Fock component of the light-cone wave function of a pion has been measured at FNAL in the process $\pi + A \to \text{jet}_1 + \text{jet}_2 + A$.

- Different quark-gluon configurations within a fast hadron interact with a target with different strengths. In particular, the cross section for colorless $q\bar{q}$ pair (the triplet representation of $SU(3)_c$ where $F^2 = 4/3$) is different from a colorless pair of gluons (the color octet representation of $SU(3)_c$ where $F^2 = 3$).

- The Color Transparency Phenomenon in hard diffractive processes is a reasonable approximation to the solution of the QCD evolution equation in the limit of fixed $x$ but $b \to 0$:

\[ \sigma_{q\bar{q}A}(x, b) \to A \sigma_{q\bar{q}N}(x, b). \]  

(2)

- Within the $x, Q^2$ range of applicability of the QCD evolution equation the cross section of a small dipole interaction with a hadron target rapidly increases when $x \to 0$ and its $A$ dependence becomes less steep as compared to that within the CT regime where $\sigma_{q\bar{q}A = A \sigma_{q\bar{q}N}}$. 

3
Data confirm this and several other striking QCD predictions in hard exclusive diffractive processes:

- The fast increase of cross sections of hard exclusive diffractive processes with energy follows from the QCD factorization theorem:

  \[ \sigma_{\text{hard diffraction}} \propto \left( \frac{\alpha_s x G_{\text{Target}}(x, Q^2)}{Q^n} \right)^2, \]  

  and \( n \geq 2 \). Such a behavior has been predicted in the leading ln \( x \) approximation. The fast increase with energy has been observed in the diffractive electroproduction of \( J/\psi, \phi \) and \( \rho \) mesons.

- An onset of approximate flavor independence of cross sections at large \( Q^2 \) (for the same transverse color separation) as a consequence of flavor blindness of QCD has been observed in the ratio of \( \phi \) and \( \rho \) mesons yields:

  \[ \sigma(\gamma^* + p \rightarrow \phi + p) : \sigma(\gamma^* + p \rightarrow \rho + p) = 2 : 9, \]  

  and in the increase of the relative yield of \( J/\psi \) and \( \rho \) mesons with \( Q^2 \).

- The prediction of an almost universal and practically energy independent slope of the \( t \) dependence of the differential cross section for any hard exclusive processes. This is because a hadron in such processes is predominantly produced in a configuration much smaller than the radius of the hadron. The smallness of the derivative over ln \( 1/x \) of the slope of \( t \) dependence:

  \[ \alpha'(\text{hard}) \ll \alpha'(\text{soft}) \]  

  is due to the hard physics occupying a considerable part of the rapidity interval within a parton ladder. Both predictions have been recently confirmed by ZEUS.

- The generalized Color Transparency Phenomenon has been predicted for the hard diffractive scattering of a \( q\bar{q} \) pair of small transverse size \( b \), off nuclei with a coherent nuclear recoil as

  \[ \frac{\sigma(q\bar{q} + A \rightarrow X + A)}{\sigma(q\bar{q} + N \rightarrow X + N)} = r_N^2 G_A(x, b^2_{\text{o} N}) \frac{R_A}{G_N(x, b^2_{\text{o} N})} \rightarrow A^{4/3} |_{A \gg 1}. \]  

This result should be valid at fixed \( x \) when \( b^2 \rightarrow 0 \).

Here \( r_N \), and \( R_A \) are radii of a nucleon (of a nucleus). The predicted \( A \) dependence is strikingly different from the \( A \) dependence of soft elastic (inelastic) coherent diffraction: \( A^{2/3} \ (A^{1/3}) \). The expected strong dependence on atomic number in QCD has been observed in \( \gamma + A \rightarrow J/\psi + A \) - \( \propto A^{1.45} \).

\(^b\)A larger value of \( |\Psi(0)| \) for mesons build of heavier quarks leads to a prediction of the high \( Q^2 \) enhancement of the \( \phi/\rho, J/\psi/\rho \) ratios as compared to the \( U(3)_f, U(4)_f \) expectations by the factor of 1.2, 3.4, respectively.
Very recently the \( A \)-dependence \( \propto A^{1.55\pm0.05} \) for the process \( \pi + A \rightarrow 2 \text{jet} + A \) was observed \(^3\) from the comparison of platinum and carbon targets. For this case \( \text{eq.4} \) leads to \( \sigma \propto A^{1.45} \). Note that the observed dijet production ratio for \( Pt \) and \( C \) is 8 times larger than the one measured in soft diffraction.

2.2 Fast increase of Parton Densities contradicts to Probability Conservation.

The key question for future research is whether the cross section of the interaction of spatially small quark-gluon wave package is always small or whether it will become comparable with the \( \pi N \) cross section of at sufficiently small \( x \) or even larger as the interpolation of conventional parton distributions suggests.

To see that the growth predicted by \( \text{eq.1} \) cannot continue forever, it is sufficient to consider the scattering of a trial hadron representing a small dipole off a hadron and to compare the total cross section of the inelastic scattering given by \( \text{eq.2} \) and the elastic cross section. The restriction follows from the inequality:

\[
\sigma_{\text{inel}}(q\bar{q}T) \gg \sigma_{\text{el}}(q\bar{q}T)
\]

Here \( B \) is the slope of the elastic cross section for the “small dipole”-nucleon scattering. Experimentally \( B \approx 4\text{GeV}^{-2} \) and practically energy independent as follows from the measurement of hard diffractive processes \(^4\). \( \eta \) is the ratio

\[
\eta = \frac{ReA}{ImA} \simeq \pi \frac{d}{2 d \ln 1/x} \ln (xG(x,Q^2))
\]

Another valuable restriction to the region of applicability of DGLAP comes from the requirement that cross sections of events with different multiplicities should be positive. Taking into account the screening due to the double interaction of the small dipole with the target, leads to

\[
\sigma_{\text{inel}}(q\bar{q}T) \geq 3[\sigma_{\text{el}}(q\bar{q}T) + \sigma_{\text{diff}}(q\bar{q}T)]
\]

Numerical calculations based on these inequalities and conventional structure functions show that DGLAP should be certainly violated within the kinematics of \( pp \) collision at LHC, and in \( eA \) collisions already at HERA.

2.3 Limiting behavior of parton densities at small \( x \).

With a decrease of \( x \) the restriction by the LO and NLO terms in \( \alpha_s \) in the kernels of the DGLAP evolution equation becomes suspicious because of the necessity to sum over all double logarithmic terms \( \ln(Q^2/Q_0^2)\ln x \). This is due to the contribution of PQCD diagrams with gluon exchange being enhanced
by powers of $\ln x$. This problem is not acute for the HERA kinematic range where the permitted interval for the PQCD evolution in rapidity is $\approx 7$ units for $x \sim 10^{-4}$ - therefore the PQCD ladder includes radiation of not more than 1-2 gluons. The distance in rapidity between the adjacent partons in the ladder in the multiRegge kinematics is at least 2-3 units and we exclude fragmentation regions of the projectile and the target $\approx \ln Q^2/Q_0^2 + 2 \approx 4$ units. For certainty we consider $Q^2 = 10 GeV^2$. At the same time, at the LHC, where $x$ down to $10^{-7}$ can be studied, the corresponding interval in rapidity can reach 14 units. Thus radiation of 3-4 gluons is possible in the kinematics of LHC. So PQCD predicts that structure functions should be polynomials over powers of $\ln x$. Maximal power of $\ln x$ should be 2-3 at HERA and 4-5 at LHC. But this PQCD gluon radiation leads to a large parton density which is in variance with probability conservation as has been explained above.

The expected physics and open questions can be visualized within the target rest frame description. A compact wave package is not an eigenstate of the QCD Lagrangian. Therefore it evolves to a larger size before hitting the target as a result of the Gribov diffusion in the impact parameter space. DGLAP and BFKL approximations include such a diffusion. If $\ln 1/x \gg \ln Q^2/\Lambda_{QCD}^2$ the number of steps in the parton ladder in the longitudinal direction is much larger than in the transverse one. Thus, as a result of Gribov diffusion in the transverse plane PQCD becomes inapplicable for the description of ultra-small $x$ behavior of the parton distributions since the system will expand to a soft scale long before hitting the target. (We want to draw attention that this reasoning does not imply violation of the QCD factorization theorem for DIS in $ep$ collisions). However small $x$ behavior can be hardly described by the Regge pole type formulae also because the formation length of the Pomeron $\approx q_0/\mu^2$ is much larger than the distances important in DIS $\approx q_0/Q^2$.

One option is that the growth slows down when the cross section reaches a value much smaller than the black limit $\sim \pi r_N^2$ (this value may decrease with the increase of $Q^2$) and the further increase will follow the pattern of meson-nucleon interactions. In this case, PQCD physics will occupy a fraction of the whole phase volume which is independent of $x$. The second option is that the fast growth will continue all the way to the unitarity limit. In this case PQCD physics may occupy almost the whole phase volume. In both cases Bjorken scaling will be strongly violated.

The structure function of a target within the black disc regime has been calculated by V.Gribov before QCD [7]:

$$
\sigma(\gamma + T \rightarrow X) = \frac{\alpha_{em}}{3\pi} r_T^2 \int \rho(m^2)m^2 \frac{dm^2}{(m^2 + Q^2)^2},
$$

(7)
Here \( \rho(m^2) = \frac{\sigma(e\bar{e}\rightarrow \text{hadrons})}{\sigma(e\bar{e}\rightarrow \mu\bar{\mu})} \). Eq. [7] leads to \( \sigma(\gamma * +T \rightarrow X) \propto \ln(s/Q^2) \). This is markedly different from the expectation of PQCD that the cross section should decrease as a power of \( Q^{-2} \).

3 Towards Superstrong Strong Interactions at the LHC

3.1 Coherence length and Interaction Strength Fluctuations

It is well known that due to the uncertainty principle and the Lorentz slowing of interaction between constituents within a fast projectile “a”, the formation length of a fast particle “a” for a transition into state \(|n>\) is given by the energy denominator:

\[
l_f \approx \frac{1}{E_n - E_a} \approx \frac{2E_a}{m_n^2 - m_a^2} \equiv \frac{1}{2m_N x},
\]

where \( E_a \) is the energy of particle \( a \) in the rest frame of the target, and \( m_n \) is the mass of state \(|n>\). For \( x = 10^{-3} \) (kinematics of HERA) \( l_f = 100 \text{Fm} \), for \( x = 10^{-6} \) (kinematics of LHC) \( l_f = 10^5 \text{Fm} \). Thus the wave function of fast projectile is build up at macroscopic (as compared to 1 Fm) distances. This should lead to a variety of Coherence Phenomena.

Perhaps the most straightforward application of eq.8 is the phenomenon of fluctuations in the strength of hadron interactions, which among other things is responsible for the process of inelastic diffractive dissociation. Indeed, it follows from the Lorentz slowing of interactions within a fast projectile, \( h \), that high energy processes should be described as the superposition of interactions of quark-gluon wave packages (instantaneous quark-gluon configurations of the projectile) with the weight given by the square of wave function of \( h \).

The crucial point is the possibility to use the closure over the intermediate states, \(|n>\). This is because the minimal momentum transferred to target in inelastic diffraction \(-t_{min} = (M_n^2 - m_h^2)^2/s\) tends to zero for all transitions with \( M_n^2 \ll s \). Thus it is necessary to generalize the notion of a cross section to the distribution over cross sections - \( P(\sigma) \), see [8] for review and references. Here the usual cross section is average over strengths: \( \sigma_{tot} \equiv < \sigma > = \int P(\sigma)\sigma d\sigma \). The contribution into \( P(\sigma) \) of small size configurations can be calculated by applying the QCD factorization theorem, while the contribution of large (soft) configurations has to be treated phenomenologically. The dispersion over fluctuations of strengths - the variance of the \( P(\sigma) \) distribution, \( \omega_\sigma \), - can be inferred from the data using the formulae of [8] for the ratio of inelastic and
elastic cross sections in forward scattering:

\[ \omega_\sigma = \frac{d\sigma(h+T \to X+T)}{d\sigma(h+T \to h+T)} \bigg|_{t=0, X \neq h} = \frac{<\sigma^2> - <\sigma>^2}{<\sigma>^2}. \]  

(9)

The analyses of diffractive processes of the proton and nuclei at fixed target energies show (i) the important role of components with small \( \sigma \)-color transparency phenomenon; (ii) the significant probability of “superstrong” - larger than \( \sigma_{tot} \) - interactions: \( \int P_N(\sigma \geq <\sigma>)d\sigma \approx 50\% \), \( \int P_N(\sigma \geq 60mb)d\sigma \approx 20\% \). By itself, the very existence of such superstrong strong interactions is not surprising since the large distance color forces are much more powerful than the usual internucleon forces. At the same time the practical question arises what is the origin of superstrong interactions: strong meson fields, confinement forces between quarks at distances larger than average, etc and how does one investigate and use them.

The generic property of QCD both in perturbative and nonperturbative regimes is that the smaller the cross sections, the faster is its increase with energy (V.Gribov). As a result of the fast increase with energy of small cross sections cf. eq. 1, the distribution \( P(\sigma) \) will become narrower at larger energies. Therefore \( \omega_\sigma \) should decrease with energy. Indeed such a decrease is consistent with the current data: \( \omega_\sigma(\sqrt{s} = 30GeV) = 0.3 - 0.35 \), \( \omega_\sigma(\sqrt{s} = 900GeV) \sim 0.20 \), and \( \omega_\sigma(\sqrt{s} = 1.8TeV) \sim 0.15 \). To reproduce this pattern and the observed increase of \( \sigma_{tot}(pp) \) starting from \( P_N(\sigma)(\sqrt{s} = 30GeV) \), one also needs to assume that cross sections of interactions of superstrong configurations grow with energy \( \propto \ln(s/s_0) \). (The impact parameter space framework provides a related interpretation of the decrease of \( \omega_\sigma \) as due to the blackening of the interaction at the central impact parameters, see e.g. A. Mueller’s talk.) Overall, one expects a transition of high-energy strong interactions from multi-scale semihard/soft dynamics (which was due to the presence of color screening and the existence of small size configurations in hadrons) to a new soft dynamics with essentially one scale at LHC energies. This is close to the underlying picture of the Gribov Reggeon calculus, though the Gribov picture assumed the validity of one scale dynamics at much smaller energies. However the difference from the situation discussed at lower energies is that these new strong interactions are likely to be close to a phase transition, section 3.2. Obviously, the one scale soft dynamics will be accompanied by multiple hard interactions - productions of 2, 4, 6 ... jets.

A related question is the rate of the energy variation of the slope of the \( t \) dependence of the elastic cross section given by \( a'(s) \). At high energies small configurations start to interact with large enough cross sections leading to the
onset of Gribov diffusion for the interaction of these configurations as well. This physics would lead to an increase of \( \alpha' \) with \( s \). This may be relevant for the difference of the value of \( \alpha' \sim 0.25 \text{GeV}^{-2} \) observed in pp collisions at the Tevatron collider and \( \alpha' \sim 0.15 \text{GeV}^{-2} \) observed at HERA for vector meson photoproduction and for \( \pi N \) scattering at fixed target energies. \( \alpha' \) should become universal at the energies where all parton fluctuations “forget” about the state of the hadron which emitted them.

For a photon projectile the QCD factorization theorem predicts that

\[
P_\gamma(\sigma) \propto 1/\sigma
\]

for small \( \sigma \). With increase of \( Q^2 \) this term should dominate in \( P_{\gamma^*}(\sigma) \). On the contrary, hard and soft physics give comparable contributions to \( \sigma_{\text{tot}}(\gamma N) \). Soft physics is further enhanced in the diffractive cross section. Thus in order to understand the physics relevant for the fluctuations of strength of the interaction, it is necessary to concentrate efforts on the separate investigation of phenomena where physics of small or large size quark-gluon configurations would dominate.

### 3.2 Soft QCD - on the way to a phase transitions?

Theoretical treatment of the physics relevant for large \( \sigma \) is still phenomenological although much of the gross features of soft QCD physics are well understood.

Elastic and inelastic soft diffractive QCD processes are shadow of inelastic processes. The starting assumption of theoretical efforts is that hadron radiation in inelastic processes is a random process -no long range correlations between partons in rapidity space. This assumption is in line with data at fixed target energies, leading to the hypothesis that high energy processes are dominated by the exchange of the Pomeranchuk trajectory \[39, 40\]. Pomeranchuk trajectory = parton ladder where correlations between partons in rapidity are short range only \[41\]. Further theoretical investigation for the intercept of the Pomeron: \( \alpha(0) \geq 1 \) found large long range correlations in rapidity between produced hadrons which are increasing with energy due to various multiPomeron type exchanges which could not be mimicked by an effective single Pomeron exchange \[42\].

Experimental support of these theoretical ideas comes among other things from (i) the observation at the SpS collider of significant long range correlations in rapidity. (ii) blackening of pp collisions at central impact parameters and (iii) the screening of inelastic diffraction in the triple Pomeron limit at collider energies.
The mathematical structure of the Gribov Reggeon calculus for $\alpha(0) \geq 1$ resembles the theory of second order phase transitions near a critical point. Indeed, applying the V.Abramovski, V.Gribov and O.Kancheli cutting rules, one finds that the analogous property would be very significant fluctuations of the density of the produced particles both for small and large rapidity intervals.

It is also important that due to the Gribov diffusion the transverse size of the Pomeron ladder reaches $\sim 1\text{fm}$ at LHC energies. Thus multiPomeron diagrams correspond to ladders with a strong spatial overlap. The overlap effects are further enhanced in $pA$ and in $AA$ collisions at the LHC since parton ladders from the interactions between different nucleons strongly overlap in the center of rapidity as a result of the Gribov diffusion in the impact parameter space making the formation of new forms of hadron matter in AA collisions plausible.

4 Experimental opportunities

Above we outlined a number of outstanding problems in high-energy QCD which need to be addressed experimentally: physics of small $x$, i.e., large parton densities, longitudinal and transverse multiparton correlations in hadrons, and fluctuations of the interaction strengths. In this section we will outline promising experimental avenues for further investigations.

4.1 Where to search for the limiting behavior of parton densities.

It would be possible to push the studies of small $x$ behavior of the parton densities beyond the HERA range at higher energy $ep$ colliders, for a summary see [25]. Another opportunity would be a very forward detector like FELIX at the LHC, which would be able to measure quark densities down to $x \sim 10^{-7}$ and gluon densities down to $x \sim 10^{-6}$ [26]. Also, by measuring in the same detector hard scattering of two partons with $x_1 \geq 0.2$ it would be possible to check whether QCD factorization for hard scattering is still valid at the LHC, or the higher twist effects due to high parton densities lead to effective screening of hard parton interactions.

Two types of studies can be made at HERA.

- **Diffractive photon production in DIS at HERA**

It is possible to measure the ratio of the real and imaginary parts of the scattering amplitude of the process $e + p \rightarrow e + \gamma + p$ via study of the azimuthal proton distribution of differential cross sections. The relevant term

\[ \text{For the extensive discussion of various experimental options in } pp \text{ and } pA \text{ collisions as well as relevant references see FELIX LOI [4].} \]
\[ \alpha \cos(\phi(p) - \phi(e)) \] arises due to the interference between diffractive photon production and the Bethe-Heitler process. Numerical studies indicate that this effect is large enough to be measured at HERA. Because of the relation between the \( \text{Re}/\text{Im} \) ratio and \( d\ln xG(x,Q^2)/d\ln x \), this study would allow one to directly measure the rate of increase of gluon densities with energy. This rate differs substantially for different models which fit \( F_2N(x,Q^2) \) and hence such measurements would allow one to discriminate between possible models.

- The study of \( eA \) scattering is feasible at HERA as well. The advantage of \( eA \) collisions is that nonlinear effects in the QCD evolution equation are enhanced by the factor \( A^{1/3} \) because \( A^{1/3} \) nucleons are at the same impact parameter. The enhancement would be even larger for central impact parameters.

If nonperturbative shadowing of the gluon distribution would be similar to that for \( F_{2A}(x,Q^2) \), regime of large nonlinear QCD effects will be achieved in \( eA \) collisions at HERA. The cross section for black interaction has been calculated by Gribov, see eq. 7. Caution: nonperturbative shadowing of gluon distributions in nuclei is unknown at present. If \( G_A/G_N = A^2/3 \), this may change the above conclusions. At the same time, it will change dramatically the theoretical expectations for hard processes in \( AA \) collisions at RHIC and LHC.

4.2 Exclusive Hard Diffraction Possibilities

We discussed above that the main question of small \( x \) dynamics can be formulated as a question of dynamics of the interaction of a small dipole with the target, hence the study of exclusive diffractive processes can provide the most direct information on this issue.

**ep and eA processes**

In \( ep \) scattering at HERA and beyond, this involves a more accurate study of exclusive vector meson production channels, exclusive production of two jets. The key question is the energy dependence of the cross sections at fixed \( Q^2 \) or \( p_t \) of the jet. Nonlinear effects would be manifested in a slowing down of the energy dependence at the highest energies. A crucial complementary measurement would be a high precision study of the slope of the \( t \) dependence. For large \( Q^2 \) the slope should be universal and independent of \( Q^2 \), and the process. Thus \( \alpha'_\text{eff} \ll \alpha'_\text{soft} \). The onset of soft dynamics would lead to the emergence of the Gribov diffusion and hence would increase the slope.

Since nonlinear effects are amplified in \( eA \) collisions, the study of the energy dependence of coherent diffraction off nuclei at HERA would be also very
promising. Overall, these measurements together with the measurements of nuclear structure functions, provide one of the realistic methods to observe the violation of the DGLAP approximation, and investigate the onset the regime of large parton densities.

**Hard diffractive processes at LHC.**

To select scattering of a hadron in a small size configuration, one needs a special trigger. It is provided by the selection of the final state where hadron is diffracting into a number of jets equal to the minimal number of constituents in the hadron. The simplest reaction is

\[ \pi^+ + T \rightarrow q(z, k_t) + \bar{q}(1 - z, -k_t) + T. \]

Here \( z \) is the fraction of pion momentum carried by a quark and \( k_t \) is its transverse momentum. The cross section of this process is calculable in terms of the light-cone wave function of pion - \( \phi(z) \): \( d\sigma/dt = c|\phi(z)|^2 \left( \frac{\alpha_s xG(x, k_t^2)}{k_t^8} \right)^2 F_{2g}^2(t). \) \( (10) \)

The coefficient \( c \) is calculable in QCD. \( F_{2g}^2(t) \approx \exp Bt, B \approx 4 \div 5 \text{GeV}^{-2} \) is the two gluon form factor of the nucleon. Experimentally for \( k_t^2 \geq 2 \text{GeV}^2 \) the pion wave function is close to the asymptotic one: \( \phi(z, k_t) \propto z(1 - z) \) thus this reaction is an effective method to measure the “small dipole”-nucleon interaction cross sections. At a collider, one can study this process using pion tagging: \( pp \rightarrow n(\Delta^{++}) + 2 \text{jets} + p \).

Another, theoretically, clean option is the process \( p + p(A) \rightarrow jet(z_1, k_{1i}) + jet(z_2, k_{1i}) + jet(z_3, k_{1i}) + p(A) \). Its cross section is calculable in terms of wave function of the minimal Fock \( |3q⟩ \) configuration within a proton if the relative \( k_{1i} \) of the jets are large, as:

\[
\frac{d\sigma(k_{1i}^2)}{dz_1dz_2dz_3dk_{1i}dk_{1j}dk_{1k}} = c_N|\alpha_s xG(x, Q^2)|^2 |\phi_N(z_1, z_2, z_3)|^2 \frac{1}{|k_{1i}|^4|k_{1j}|^4|k_{1k}|^4} F_{2g}^2(t) \delta(\sum k_{1i} - \sqrt{-t})\delta(\sum z_i). \quad (11)
\]

The coefficient \( c_N \) is also calculable in QCD. The numerical estimate of the cross section integrated over all variables except \( p_t \) of one jet gives:

\[
\sigma(3\text{jets}) \propto \frac{|\alpha_s xG(x, Q^2)|^2}{p_t^8} \propto 10^{-4} \div 5 \text{GeV} \frac{1}{(p_t)^8} \text{mb}
\]

12
for LHC energies. A pressing question is whether this cross section will grow up
to the LHC energies as it is assumed in this estimate based on extrapolations of
$G_N(x, Q^2)$ to $x \sim 10^{-6}$. Note that this process probes the minimal Fock three
quark component of the proton wave function, which is the same configuration
relevant for the calculations of the proton decay. A study of the same process
with a nuclear target would provide an unambiguous test of the dominance
of hard physics in this process. Indeed for soft diffraction at the LHC, one
expects the $A$ dependence $\propto A^{0.25}$, while this process will grow at least as $A^{0.7}$,
assuming a maximum possible gluon shadowing of $G_A / G_N \propto A^{2/3}$, which is
not likely.

4.3 Fluctuations and correlation phenomena

Long range rapidity correlations

We discussed in section 2 that $pp$ collisions may reach a situation close to a
phase transition at LHC energies. Hence it would be necessary to study long
range correlations in rapidity for the production of soft particles. Such correlations first emerge due to double Pomeron exchange. The simplest example
of such a correlation is the correlation of backward and forward multiplicities
observed at the S$p\bar{p}$S collider. the large rapidity interval available at the LHC
would allow one to study these and higher order correlations using a large
acceptance detector.

It is important to perform similar studies in deep inelastic scattering to
search for effects of the exchange of multiple soft ladders. Current HERA
detectors have rather limited acceptance in $y$ so the only practical approach
seems to be a study of the correlation between the yield of the leading baryons
at $x_F \sim 0.5 - 0.8$ and the central hadron multiplicity for multiplicities much
larger than average. If the forward coverage is improved many other options
would become feasible.

Geometry of Multijet production

At high energies the cross section of multiple parton collisions becomes large,
so it is feasible to measure double(triple) parton distributions in the pro-
cess of production of four(six) jets in the kinematics where $p^{jet, forward, 1}_1 \sim
-p^{jet, backward, 1}_1$, $p^{jet, forward, 2}_1 \sim -p^{jet, backward, 2}_1$. The probability of these pro-
cesses is sensitive to the longitudinal and transverse correlations between the
partons with a resolution $\sim p^{jet}_1$. Crucial for such studies is a sufficiently large
rapidity interval to separate these processes from the processes of two parton
collisions with a production of several jets. Recently CDF has reported
a cross section for double collisions which exceeds the expectations based on
the model where partons are distributed randomly in the impact area of the
nucleon by a factor of $\sim 2$. It appears that the study of such cross sections may
be one of the important steps in determining the three-dimensional structure
of the nucleon.

Also, the selection of events with multiple collisions strongly reduces the
average impact parameter for a collision. Hence, high density phenomena
should be manifested much more prominently in multiparton collision events
and can be used to experimentally distinguish peripheral and central $pp$
collisions.

**Breakdown of Pomeron type factorization in inclusive diffraction**

One of the distinctive features of diffractive physics is the interplay between
soft and hard QCD. Thus the investigation of diffractive processes in DIS may
help to elucidate physics relevant to the origin of the Pomeron. A key property
of the Pomeron exchange is the Regge pole factorization - lack of communica-
tion between projectile and target fragmentation regions. On the contrary,
QCD factorization is valid for the interaction of spatially small configurations
only. The mismatch between two factorizations is the source of many new
phenomena.

In the case of inclusive diffraction in DIS one can express the cross section
of diffractive scattering at fixed $x_p$ (Feynman $x$ of the proton) in the
leading twist through the $Q^2$ dependent parton densities, $f_{diff}^i(\beta, Q^2, x_p)$ which
are often referred to as Pomeron (anti)quark and gluon densities. However
in contrast with the usual parton densities which are process independent, a
“Pomeron parton density” is not a universal object since the soft screening
interactions depend both on the target and on the projectile. At HERA this
phenomenon can be studied in resolved photon hard diffraction where screen-
ing effects should reduce $f_{diff}^i$ as compared to the case of the DIS diffraction.
Striking nonuniversality should be present due to the filtering phenomenon
and presence of the $\gamma^*$ wave function with the masses $\sim Q^2$ in $eA$ diffraction
[31]. In particular, $f_{diff}^i(\beta, Q^2)$ should strongly depend on the atomic number
of the target increasing at $\beta \geq 0.4$ and decreasing at small $\beta \leq 0.1$.

In $pp$ collisions the strong suppression of $f_{diff}^i$ has been already observed
in experiments at the FNAL collider both in two jet, and $W$ - boson production
channels. Here the challenging problem is to try to observe the breakdown of
factorization as a function of the $x_1$ fraction carried by the hard parton of the
diffracting proton. Such a dependence seems natural due to fluctuations of the
strength of the interactions which we discussed in section [3]. Indeed if for large
$x_1$, configurations with smaller $\sigma$ are selected, screening effects are reduced and $f_{\text{eff}}$, extracted from the data, would be larger.

### 4.4 New phenomena in $pA$ collisions at the LHC

It is feasible to study collisions of protons and nuclei at the LHC. Such studies would be of utmost importance for the interpretation of the LHC heavy-ion collision data as well the cosmic rays of ultra-high energies. The transverse area of the proton at these energies is $\sim 4$ times larger than at fixed target energies, and thus, hard processes are dramatically enhanced. Therefore one expects a very different picture of $pA$ interactions at these energies from the one explored up to now at $\sqrt{\langle s \rangle} \leq 40$GeV. It would be possible to investigate many qualitatively new phenomena. We list here several of them.

- **Nonlinear phenomena** via the study of nuclear shadowing at $x$ down to $10^{-7}$.

- **Parton propagation in nuclear media** via the study of $p_t$ - broadening of leading Drell-Yan pairs, dijets in the proton fragmentation region, and parton energy losses. For the summary of QCD expectations see [2].

- **Multiparton distributions in a proton** via the study of double (triple) hard parton scattering. Comparison of the yields for $pp$ and $pA$ collisions would allow one to measure the transverse separation of hard partons in a model independent way.

- **Propagation of small color dipoles through nuclear media** would allow one to address the question whether interactions of small objects may become comparable to the interaction of ordinary hadrons at super-high energies. Tools to investigate this question include (i) hard exclusive diffraction of proton into three jets which we discussed above, and (ii) the production of a leading $J/\psi$. In the later case, one may expect a strong change of the $A$ dependence of the leading $J/\psi$ meson production in $pA$ collisions as compared to the fixed target energies where $\sigma(pA \rightarrow J/\psi + X) \propto A$ if $x_F(J/\psi) \ll 1$. Two effects are relevant: a large gluon shadowing for small $x \sim M^2_{J/\psi}/s$, and the large cross section for the interaction of a $c\bar{c}$ pair of the size $\sim 0.2 fm$ with the nuclear target. Overall this may lead to a reduction of the $A$-dependence to as low as $A^{1/3}$. A less dramatic but still significant effect may be expected for $\Upsilon$ production.

- **Color fluctuations in protons** via the study of correlation properties between soft hadron production and the presence of hard collision at large $x_p$. The expectation is that for $x_p \geq 0.5$, configurations in the colliding proton with a large interaction strength $\sigma \geq \sigma_{\text{tot}}$ are strongly suppressed, leading to a significant reduction of soft hadron multiplicity, etc [2].
Acknowledgments

We wish to express our sincere gratitude to J.Bartels, J.Bjorken, V.Gribov, A.Mueller, for the fruitful discussions of pressing problems of QCD, to V.Guzey for the calculation of the boundary of applicability of the QCD evolution equation to eA scattering. This work was supported by the U.S. Department of Energy under Contract No. DE-FG02-93ER40771, by the Israel Academy of Science under contract N 19-971.

References

1. J.Ellis, these proceedings.
2. A.De Rujula, S.L.Glashow, H.D.Politzer, S.B.Treiman, F.Wilczek and A.Zee, Phys.Rev. D10 (1974)1649;
   Yu.L. Dokshitzer, Sov.Phys.JETP 46 (1977)641;
   T.De Grand Nucl.Phys. B151 (1979)485;
   for a recent review see J.Blumlein, Surv.High Energy Phys. 7 (1994) 181.
3. D.Ashery, Proceedings of LISHEP98, in press.
4. M.D.Sokoloff, Phys.Rev.Lett. 57 (1986)3003.
5. L. Frankfurt, G. Miller, M. Strikman Annual Rev. Nucl. Part. Sci. 45 (1994)501
6. A.H.Mueller, these proceedings
7. L. Frankfurt, A. Radyushkin, M. Strikman Phys. Rev.D55 (1997)98;
   B. Blättel, et al. Phys. Rev. Lett. 71 (1993)896.
8. J.C.Collins,L.Frankfurt and M.Strikman, Phys.Rev. D56 (1997)2982.
9. L. L. Frankfurt and M. Strikman, Phys. Rev. Lett. 64 (1989) 1914
10. S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, Phys. Rev.D50 (1994) 3134.
11. L.Frankfurt, Proceedings of Grenoble workshop on Color Transparency, in press.
12. M. G. Ryskin, Z. Phys. C37 (1993) 89
13. L. Frankfurt, G. Miller, M. Strikman Phys. Lett. B304 (1993)1
14. S.Kananov, these proceedings.
15. H. Abramowicz, L. Frankfurt, M. Strikman DESY-95-047. 60pp. Published in SLAC Summer Inst. 1994:539-574.
16. A.Levy, Phys. Lett. B424 (1998)191
   T. Monteiro, these proceedings.
17. V.N.Gribov, Sov.Phys.JETP 30 (1970) 709.
18. H. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696; ; Phys. Rev. Lett. 42, 204 (1979).
19. V.N. Gribov, Nucl.Phys., 22 (1961)249.
20. G.F. Chew, S.C. Frautschi, Phys.Rev.Lett. 8 (1962)41.
21. V.N.Gribov, Yad.Fiz.,9 (1969)2.
22. V.N. Gribov, Sov.Phys.JETP 26 (1968) 414.
23. V. A. Abramovskii, V. N. Gribov, and O. V. Kancheli, Sov. J. Nucl.
   Phys. 18 (1974) 308.
24. FELIX Collaboration (E.Lippmaa et al.), CERN-LHCC-97-45, Aug 1997, 197pp.
25. A.Roeck, these proceedings.
26. J.Whitmore, these proceedings
27. L.Frankfurt, A.Freund, M.Strikman, these proceedings.
28. A.H. Mueller, Jian-wei Qiu, Nucl.Phys., B268 (1986)427.
29. L. Frankfurt, W.Koepf, M. Strikman,Phys.Lett. B405 (1997) 367.
30. F. Abe et al, Phys.Rev. D56 (1997)3811.
31. L. Frankfurt,M. Strikman, Phys.Lett. B382 (1996)6.
32. Y. L. Dokshitser, hep-ph/9803338
33. L. Frankfurt and M. Strikman Nucl. Phys. B250 (1985)147.