A new hard QCD phenomenon - proton diffraction into three jets

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Abstract
We argue that the process of the proton diffraction into three jets in proton-nucleus scattering at LHC will allow to investigate the light-cone wave function of protons, generalized gluon densities in nuclei at small x, as well as the interplay of the color transparency and opacity phenomena.

1. Introduction
During the last ten years a number of new hard small x phenomena have been observed and calculated in QCD based on the QCD factorization theorems for inclusive DIS and hard exclusive processes. This includes (i) the observation at HERA of a fast increase of parton distributions with energy which is reasonably described within the QCD evolution equation approximation[(i)] ; (ii) the discovery of the color transparency phenomenon in the pion coherent dissociation into two high \( p_T \) jets[2] which is consistent with the predictions of[3, 4]; (iii) the observation of various regularities in the exclusive electroproduction of vector meson at HERA induced by longitudinally polarized photons and photoproduction of mesons with hidden heavy flavor which is consistent with the predictions of[5]. These processes in a wide kinematic range of small x have provided effective ways of studying the interaction of small colorless dipoles with hadrons at high energies and of studying the hadron wave functions in the minimal Fock space configurations. Here we outline new QCD phenomena[6] which may become important at LHC because their cross sections are rapidly increasing with energy.

Fast increase with energy of cross sections of hard diffractive processes predicted within the leading twist (LT) approximation would be in variance with the unitarity of \( S \)-matrix for the interaction with a hadron target of spatially small wave package of quarks and gluons at given impact parameter. This new phenomenon may reveal itself at sufficiently small x and/or sufficiently heavy nuclei. In the structure functions off a proton this physics is masked by the significant contribution for the hard collisions off nucleon periphery. Thus the unitarity of the \( S \) matrix does not preclude fast increase of structure functions of a nucleon as fast as \( \propto \ln(1/x)^3 \)[7]. Hence no dramatic signals for the breakup of DGLAP regime are expected in this case. On the contrary, a breakdown of the LT approximation in the hard diffractive processes off nuclei leads to the drastic changes of the dependence of cross sections on atomic number, the incident energy and the transverse momenta of the jets.

2. Diffraction into three jets
A nucleon (meson) has a significant amplitude to be in a configuration where valence partons are localized in a small transverse area together with the rest of the partons. These configurations are usually referred to as minimal Fock space configurations - \( |3q\rangle \). The significant amplitude of the decay \( \pi \to leptons \) as well as the observed significant cross section of the process: \( \pi + A \to 2 jet + A \)[2] is the experimental evidence for the significant contribution for the hard collisions off nucleon periphery. Thus the unitarity of the \( S \) matrix does not preclude fast increase of structure functions of a nucleon as fast as \( \propto \ln(1/x)^3 \)[7]. Hence no dramatic signals for the breakup of DGLAP regime are expected in this case. On the contrary, a breakdown of the LT approximation in the hard diffractive processes off nuclei leads to the drastic changes of the dependence of cross sections on atomic number, the incident energy and the transverse momenta of the jets.

Hadrons, in small size configurations of the transverse size \( d \), interact with a small cross section \( \propto d^2 x G_N(x, Q^2) \), where \( Q^2 \sim 10/d^2 \). The factor \( x G_N(x, Q^2) \) leads to a fast increase of the small

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¹A comprehensive review of the HERA data on inclusive and exclusive processes and the relevant theory is given in[1].
cross section with energy. In the case of the “elastic scattering” of such a proton configuration off another proton, this three-quark system with large relative momenta should preferentially dissociate diffractively into a system of three jets with large transverse momenta \( p_{ti} \sim \pi b^{-1} \), where \( b \) is the transverse size of the minimal configuration. The kinematics of this process is presented at the lego plot of Fig. 1 for the case of the coherent scattering off nuclei (proton).

The production cross-section for the three jets can be evaluated based on the kind of QCD factorization theorem deduced in [4]. The cross-section is proportional to the square of the gluon density in the nucleon at \( x \approx M^2_{3 \text{jets}}/s \), and virtuality \( \sim (1 - 2) p_t^2 \) [8]. The distribution over the fractions of the longitudinal momentum carried by the jets is proportional to the square of the light cone wave function of the \( |3q\rangle \) configuration, \( \psi(z_1, z_2, z_3, p_{t1}, p_{t2}, p_{t3}) \) and large transverse momenta where

\[
\psi(z_1, z_2, z_3, p_{t1}, p_{t2}, p_{t3}) \propto z_1 z_2 z_3 \sum_{j \neq i} \frac{1}{p_{t1}^2 p_{tj}^2} \psi(z_1, z_2, z_3, p_{t1}, p_{t2}, p_{t3}) \propto z_1 z_2 z_3 \sum_{j \neq i} \frac{1}{p_{t1}^2 p_{tj}^2}. \tag{1}
\]

It is implied that proper renormalization procedure is performed which accounts for cancellation of infrared divergences. Or the light cone gauge \( p_{N,\mu} A_\mu = 0 \) should be used to describe diffractive fragmentation region: where there are no infrared divergences. Here \( p_N \) is the momentum of diffracting proton. Besides summation over collinear radiation is included in the definition of the jets.

Application of the QCD factorization theorem resolves puzzle with the fact that a hadron contains infinite number of partons - other partons are hidden into structure functions of a target. Hence the diffraction of a proton into three jets provides important information about the short-distance quark structure of the proton, and also provides unique information about the longitudinal momentum distribution in the \( |3q\rangle \) configuration at high \( p_t \). The amplitude of the process can be written as

\[
A = \left[ -\Delta \psi(z_1, z_2, z_3, p_{t1}, p_{t2}, p_{t3}) \right] \left[ \frac{2\pi^2}{3} \alpha_s(x G(x, Q^2, t)_{skewed}) \right]. \tag{2}
\]

Here \( \Delta = \sum_{i=1}^3 \frac{\partial^2}{\partial p_{ti}^2} \). An additional factor of 2 in the numerator as compared to the pion case is due to the...
The coefficient occurs for the discussed estimate of the cross section of production of three jets with factor of a nucleon is known to some extent from the hard diffractive processes \[10\]. The numerical fraction, virtuality of the exchanged photon, and integrated over all other variables gives for time in the case of the nucleus break up the e.m. process has nosingularity at where
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enhancement of absolute value of cross section but will not influence strongly A-dependence. The amplitude of the process is
\[F_{2g}(t)\]

\[\phi_N(z_1, z_2, z_3) = z_1 z_2 z_3.\] The two-gluon form factor of a nucleon is known to some extent from the hard diffractive processes \[10\]. The numerical estimate of the cross section of production of three jets with \(p_t\) of one of the jets larger than a given one and integrated over all other variables gives for \(p_t \geq 10\) GeV/c:
\[\sigma(pp \rightarrow 3\text{jets} + p) \propto \frac{|\alpha_s x G(x, Q^2)|^2}{p_t^2} \times 10^{-6} - 7 \left(\frac{10\text{GeV}}{p_t}\right)^8 mb\]
(4)
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 \(x \sim 10^{-5}\). The probability of the \(|3q|\) configuration is estimated using a phenomenological fit to the probability of configurations of different interaction strengths in a nucleon (cf. \[5, 9\]).

A study of the same process in the proton nucleus collisions would provide an unambiguous test of the dominance of hard physics in this process. The cross section of this process should grow with \(A = \frac{A^2 G_2^2(x, Q^2)}{A^2 G_2^2(x, Q^2)}\). Account of skewedness of gluon distribution will lead to some enhancement of absolute value of cross section but will not influence strongly A-dependence.

Our estimates indicate for the relevant LHC kinematics - \(x \sim 10^{-5}, Q_{eff}^2 \sim p_t^2\) nuclear shadowing in the gluon channel is a rather small correction reducing the A-dependence of cross section by a factor \(A^{0.1}\). The A-dependence of total inelastic cross section is \(\propto A^{0.7}\). Hence we expect that counting rate per one inelastic interaction will be enhanced in \(pA\) collisions for heavy nuclear target by a factor \(\propto A^{0.55}\). At the same time the background from the soft diffraction should be strongly reduced. Indeed, if we estimate the A-dependence of the soft diffraction based on the picture of color fluctuations which provides a good description of the total cross section of the inelastic diffraction off nuclei at fixed target energies \[3\] we find \(\sigma_{pA}^{\text{inel. diff.}} \propto A^{0.25}\). Note also that scattering off nuclei has an obvious advantage in terms of selecting coherent processes since practically all inelastic interactions with nuclei would lead to the emission of neutrons at the zero angle.

A competing process is the proton diffraction into 3 jets off the nuclear Coulomb field. It follows from the theorem proved in \[3\] that in the LO over \(\alpha_s\) the dominant contribution is given in the Weizecker-Williams representation by the transverse photon interaction with the external quark lines. The amplitude of the process is
\[-e^2 \psi_N(z_i, p_{ti}) Z F_A(t) \frac{A s}{M^2(3\text{jet})} \sum \frac{e_i(\vec{p}_{ti} \cdot \vec{q}_i)}{z_i},\]
where \(e_i\) is the electric charge of the quark in the units of the electric charge of the electron, \(q^2\) is the virtuality of the exchanged photon.

In the kinematics where the LT dominates in the QCD mechanism for production of three jets the e.m. process is a small correction. However if the screening effects (approach to the black body limit) occurs for the discussed \(p_t\) range the e.m. process may compete with the QCD contribution. At the same time in the case of the nucleus break up the e.m. process has no singularity at \(q^2 = 0\) besides the QCD process is \(\propto A\) and much larger than the e.m. process. Note also that in the case of QCD interactions one can consider the processes with large rapidity gap. They have the same \(z_i, p_{ti}\) dependence as the coherent process but have significantly larger cross section.
Another interesting group of hard processes is proton diffraction into two high $p_T$ jets and one collinear jet. These processes are in general dominated at high energies by collisions of two nucleons at large impact parameters (otherwise multiple soft interactions would destroy the coherence). Hence the $A$-dependence of the dominant term should be similar to that for $\sigma_{pA}^{inel.\ diff.}$. However already fluctuations with cross section of $\sim 40mb$ would have much stronger $A$-dependence $\sim A^{0.7}$. Thus the study of the $A$-dependence of coherent diffraction will allow to filter out the smaller than average components in the nucleons at the LHC energies.

3. Violation of LT approximation and new QCD strong interactions

Energy dependence of cross section in the LT approximation follows from the properties of gluon distribution within the target. Hence for the virtualities probed in the three jet production the energy dependence is $\propto x^2 G^2(x, Q^2_{eff}) \propto s^{0.8}$ for $Q^2_{eff} \sim 100-1000 GeV^2$ and $10^{-5} \leq x \leq 10^{-2}$. In the black body limit the inelastic diffractive processes are strongly suppressed and hence the energy dependence of cross section the three jet production integrated over $p_T \geq p_T,0$ should slow down as only scattering off the grey edge of nucleus (nucleon) will effectively survive. For the $Q^2$ relevant for this process the black body limit maybe an interesting hypothesis for the scattering off heavy nuclei only. It would manifest itself in a strong decrease of the $A$-dependence of the three jet production at $p_T$ corresponding to the black body limit. At sufficiently small $x$ for a heavy nuclear target: $\frac{d\sigma(pA \rightarrow 3jet+X)}{dp_T^2} \propto A^{1/3}$. This is in a striking contrast with the expectations for the $A$ dependence parton distributions $\propto A^{2/3}$.

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