Multiparton interactions of hadrons and photons with nuclei - revealing transverse structure of nuclei and strong gluon field dynamics

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Abstract

We argue that multiparton interactions in proton - nucleus collisions at the LHC should be strongly enhanced as compared to naive expectation of cross section been proportional to atomic number - the antishadowing phenomenon. Study of the such processes will allow to measure in a model independent way double parton distributions in nuclei and, in combination with the pp measurements - transverse correlations of partons in nucleons. It is also emphasized that ultraperipheral collisions (UPC) of nuclei will allow to study multiparton interactions of photons with nuclei well before the pA collisions will be available at the LHC. UPC will also provide a quick and effective way to test onset of a novel perturbative QCD regime of strong absorption for the interaction of small dipoles at the collider energies in the process $\gamma + A \to J/\psi + \text{" gap"} + X$ at large momentum transfer t.

1 Multiparton collisions and generalized parton distributions

It was recognized already more than two decades ago [1] 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-vice independent hard interactions. As a result at the LHC the multiparton interactions will be a generic feature of the pp and pA collisions. Although the production of multijets through the double parton scattering mechanism was investigated in several experiments [2–7] at $pp, p\bar{p}$ colliders, the interpretation of the data is somewhat 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 correlations of partons in the nucleon as well as to check the validity of the underlying picture of multiple collisions.

It is worth mentioning also that understanding of multiparton interactions is important for proper modeling of central pp collisions which dominate in the production of new particles and where such multijet interactions are enhanced. Such modeling should be done in a way consistent with the information about the structure of nucleons/nuclei available from hard processes which were studied at HERA. So far this is not the case (see below).

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 $\leq (1/x_1 + 1/x_2)/p_{c.m.}$. Thus two hard collisions occur practically simultaneously as soon as x_1, x_2 are not too small and hence a cross talk between two hard collisions is not possible. 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 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 $\Gamma(x, x', \rho, \rho')$. It depends also on the virtualities of the partons, 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 α and β in an inelastic interaction between hadrons a and b can be written as:

$$\begin{aligned}\sigma_D(\alpha,\beta) &= \frac{m}{2}\int \Gamma_a(x_1,x_2;\rho_1,\rho_2)\hat{\sigma}_\alpha(x_1,x_1')\cdot\hat{\sigma}_\beta(x_2,x_2')\Gamma_b(x_1',x_2';\rho_1,\rho_2)\\ &\qquad dx_1dx_1'dx_2dx_2'd^2\rho_1d^2\rho_2, \end{aligned} \quad (1)$$

where $m = 1$ for indistinguishable parton processes and $m = 2$ for distinguishable parton processes. We also took into account that transverse distances in the binary collisions are small as compared to the hadron size scale. Note that though the factorization approximation of Eq.(1) 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.

The QCD factorization theorems for exclusive hard processes: $\gamma^*_L + p \rightarrow$ "$vector\ meson + p$, $\gamma^*_L + p \rightarrow \gamma + p$ give a unique tool for determining transverse distributions of partons in nucleons as a function of x and resolution scale - the generalized parton distribution (GPD). The discussed processes are proportional to the GPDs in non-diagonal kinematics at finite longitudinal momentum transfer. However corrections for this effect are small and one can extract diagonal GPDs from the analysis of the data.They could be written as $f_j(x, Q^2, \rho) = f_j(x, Q^2)F_j(x, Q^2, \rho)$, where $f_j(x, Q^2)$ is the parton density and the probability to find a parton with given x at transverse distance ρ from the nucleon center $\int d^2\rho F_j(x, Q^2, \rho) = 1$.

Currently, the best information about the gluon transverse distributions is provided by the data on J/ψ exclusive production: in the scaling limit $d\sigma/dt \propto F_g^2(x, t)$. The analysis of the experimental data indicates that dipole with $F_g = 1/(1 - t/m_g(x)^2)$ with the x-dependent $m_g(x)$ gives a reasonable description of the data: $m_g^2(x = 0.05) \sim 1GeV^2, m_g^2(x = 0.001) \sim 0.6GeV^2$.

The transverse distribution of partons is expressed through $F_g(x, t)$ as

$$F_g(x,\rho;Q^2) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{i(\mathbf{\Delta}_\perp\rho)}\, F_g(x,t=-\mathbf{\Delta}_\perp^2;\mathbf{Q}^2). \quad (2)$$

In the case of the dipole parametrization one find

$$F_g(x,\rho) = \frac{m_g^2}{2\pi}\,\left(\frac{m_g\rho}{2}\right)\,K_1(m_g\rho), \tag{3}$$

where K_1 is the modified Bessel function.

Our analysis of the data the transverse distribution of gluons indicates that it is significantly more narrow than the one which would follow from the naive assumption that it should be the same as given by the e.m. nucleon form factors. A likely reason for the difference of sizes is that pion field which contributes significantly to the e.m. nucleon radius gives non-negligible contribution to the gluon GPD only for $x \leq 0.1$.

The distribution over ρ also somewhat broadens with decrease of x with a initial broadening at $x \sim 0.05$ due to the pion field effects. Also, there are indications that transverse distribution of quarks is somewhat broader than that for gluons, for the recent analysis and references see [9].

Distribution over the impact parameters in pp collisions with production of jets is given by the convolution of $F_j's$ (for simplicity we assume in the following that only gluons contribute to the jet production:

$$P_2(b) = \int d^2\rho_1 \int d^2\rho_2 \delta^{(2)}(\rho_1+\rho_2-b)F_g(x_1,Q^2,\rho_1)\cdot F_g(x_2,Q^2,\rho_2). \tag{4}$$

Using parametrization of Eq.3 one finds

$$P_2(b) \;\; = \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b) \tag{5}$$

If partons "i" and "j" are not correlated in the transverse plane

$$\Gamma_{ij}(x_1,x_2;\rho,\rho') = F_i(x_1,\rho)\cdot F_j(x_2,\rho'), \tag{6}$$

one can use $P_2(b)$ to calculate the rate of the production of four jets in two binary collisions. This cross section is usually written as (we give here expression for the process studied by CDF [6] and D0 [7] of production three jets and a photon where combinatoric effect of identical collisions is absent)

$$\frac{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}}}{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2)}{d\Omega_{1,2}}\cdot\frac{d\sigma(p+\bar{p}\to jet_3+\gamma)}{d\Omega_{3,4}}} = \frac{f(x_1,x_3)f(x_2,x_4)}{\sigma_{eff}f(x_1)f(x_2)f(x_3)f(x_4)}, \tag{7}$$

where $f(x_1,x_3), f(x_2,x_4)$ are longitudinal light-cone double parton densities and σ_{eff} which may depend on x_i, p_t is the "transverse correlation area". The CDF reported $\sigma_{eff} = 14.5 \pm 1.7^{+\,1.7}_{-\,2.3}$ mb [6]. The recent D0 analysis [7] reports $\sigma_{eff} = 15.1 \pm 1.9$ mb which is very close to the CDF result. However there is a difference in the analyses - the D0 treatment is completely inclusive, while CDF was removing the events with extra jets. The correction for this extra selection may reduce the CDF result by about 35% [10]. Hence, a more detailed comparison of two data analyses is necessary. In the following we will use the value of $\sigma_{eff} = 14$ mb for numerical estimates.

One can express σ_{eff} through $P_2(b)$ as

$$\sigma_{\rm eff} \;=\; \left[\int d^2b\; P_2^2(b)\right]^{-1} = \frac{28\pi}{m_g^2} \;\approx\; 34 \text{ mb}. \qquad (8)$$

This number is substantially larger than experimental result though it is smaller than a naive estimate based on the e.m. form factor of the nucleon (~ 60 mb) [1]. A more than a factor two discrepancy between the data and Eq.8 implies *presence of a strong transverse correlation between partons in the nucleon.* Global fluctuations of the transverse size of nucleons may reduce σ_{eff} by about $\sim 20\%$ [11] as compared to Eq.8. Larger effects may arise from concentration of gluons near quarks (constituent quarks) - possible reduction of σ_{eff} by a factor of about two [9]. Together these two effects may explain magnitude of σ_{eff} observed by CDF and D0. Additional effect results from the process of the QCD evolution since the emitted partons are localized in a small transverse area near the parton involved in the dijet process. However this effect is relevant mostly for small enough x which were practically not covered by the CDF and D0 measurements.

Though the data are consistent with the double parton distribution been a product of two single parton distributions it would be preferable to avoid need for making this assumption. Studies of proton (deuteron) - nucleus collisions would be very valuable for this purpose.

2 Multijet production in proton - nucleus collisions

In the case of scattering of a hadron off a nucleus the parton density of the nucleus does not change noticeably on the scale of transverse size of the projectile hadron. Non-additive effects in the parton densities are known to be less than few % for $0.02 \leq x \leq 0.5$. Hence they could be neglected for production of jets in this x interval (correction for these effects could be easily introduced). Therefore in this kinematics we have to take into account only transverse correlations of partons in individual nucleons of the nucleus.

Thus there are two different contributions to the double parton scattering cross section: $\sigma_D = \sigma_D^1 + \sigma_D^2$. The first one, σ_1^D, 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 [8]

$$\sigma_D^1 = \sigma_D \int d^2B T(B) = A\sigma_D, \qquad (9)$$

where

$$T(B) = \int_{-\infty}^{\infty} dz \rho_A(r), \int T(B) d^2B = A, \qquad (10)$$

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

The contribution to the term in $\Gamma_A(x_1', x_2', \rho,)$ due to the partons originated from different nucleons of the target, σ_D^2, can be calculated *solely* from the geometry of the process by observing

[1] The PYTHIA Monte Carlo reproduces the observed rate of multijet production assuming much more narrow distribution of partons in ρ than the one allowed by the measurements of the GPDs.

that the nuclear density does not change within a transverse scale $\langle b \rangle \ll R_A$. It rapidly increases with A $\propto \int T^2(B) d^2 B$. Taking σ_{eff} reported by the CDF double scattering experiment [6] we finds that the contribution of the second term should dominate in the case of proton - heavy nucleus collisions [8]:

$$R \equiv \frac{\sigma_2}{\sigma_1 \cdot A} \approx \frac{(A-1)}{A^2} \cdot \sigma_{eff} \int T^2(b)\, d^2 b \approx 0.68 \cdot \left(\frac{A}{12}\right)^{0.39}_{|A \geq 12, \sigma_{eff} \sim 14 mb} . \quad (11)$$

Hence we predict the Antishadowing effect: for A=200, and σ_{eff}=14 mb: $\sigma_{pA}/\sigma_{pp} \approx 4$. The effect is linear in σ_{eff}. Measurements with a set of nuclei would allow 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.

Recently an event generator for the configurations in nuclei including short-range correlations was developed [12]. It allows to check the accuracy of Eq.11 for the number of collisions where partons from two different nucleons of the nucleus are involved. It was found that for $A \sim 200$ the ratio R is reduced by $\sim 5\%$.

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 of the nucleus in the shadowing region, $x_A \leq x_{sh} \sim 10^{-2}$. [2] Since the shadowing effect is larger at small B and since four jet events select smaller B than two jet events the antishadowing effect should be somewhat smaller in this case (for the same σ_{eff}).

It is possible to extend this analysis to the case of production of six jets. We find [8]:

$$\begin{aligned}
\sigma_1^T &= \sigma_T \int d^2 B T(B) = A\sigma_T, \\
\sigma_2^T &= \frac{1}{3!} \int G(x_1, x_2, x_3) \hat{\sigma}(x_1, x_1') \hat{\sigma}(x_2, x_2') \hat{\sigma}(x_3, x_3') dx_1 dx_1' dx_2 dx_2' dx_3 dx_3' \\
&\times \Big[G(x_1', x_2') G(x_3') + G(x_2', x_3') G(x_1') + G(x_1', x_3') G(x_2') \Big] \\
&\times \int d^2 B T^2(B) \frac{1}{\sigma_{eff}'}, \\
\sigma_3^T &= \frac{1}{3!} \int G(x_1, x_2, x_3) \hat{\sigma}(x_1, x_1') G(x_1') G(x_2') G(x_3') \\
&\times \hat{\sigma}(x_2, x_2') \hat{\sigma}(x_3, x_3') dx_1 dx_1' dx_2 dx_2' dx_3 dx_3'. \int d^2 B T^3(B).
\end{aligned} \quad (12)$$

The estimate using assumption that $\sigma_1 \propto 1/\sigma_{eff}^2$ leads to prediction of a factor $\sim$ 12 large antishadowing for the scattering off heavy nuclei:

$$\sigma_1 : \sigma_2 : \sigma_3 = 1 : 1.45 \cdot (A/10)^{0.5} : 0.25(A/10) \to 1 : 6.5 : 5. \quad (13)$$

It is worth noting that studying associated hadron production in central region, nuclear fragmentation in the multijet events would provide additional interesting information. Indeed,

[2] The A-dependence of the ratio of σ_2/σ_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 $x \geq x_{sh}$.

four (six) jet events are due to much more central collisions than minimal bias pA collisions. As a result one expects for moderate $x_{1p}, x_{2p} \leq 0.3$ an increase of the central multiplicity, larger rate of forward neutron production, etc. At the same time a new physics is possible for $x_{1p} + x_{2p} \geq 0.7$ since such a trigger may start to select configurations in the proton with fewer gluons and also of probably of a smaller transverse size? Another interesting limit is when one x's is moderate, while a leading hadron with moderate p_t few GeV/c is detected. In this case one pair of jets serves as a trigger for centrality, while the presence / suppression of the leading hadron measures effect of fractional energy losses in the black disk limit [15].

3 Multijet production in photon - nucleus collisions

The pA collisions at the LHC are probably rather far in the future. At the same time there appears to be another opportunity to study multiple collisions with nuclei which will be available as soon as the heavy ion program will start. It comes from the possibility to study ultraperipheral collisions of nuclei where two nuclei pass each other at large impact parameters. In this case direct strong interactions are not possible though interaction via emission of the photon by one of the nucleus (which is left practically intact) is possible, has a large cross section and can be experimentally separated from the ordinary heavy ion collisions, see review in [13]. This will allow to measure multiparton photon wave function without need to model nucleon wave function via study of the A-dependence of the multijet production. Using information about similar collisions in γp collisions available at HERA it will be possible to measure reliably σ_{eff} for different configurations of partons in the photon wave function. For example, for the photon component containing heavy quarks the transverse size is $\propto 1/m_Q$ is much smaller than the nucleon size, leading to σ_{eff} determined solely by the nucleon structure. Though σ_{eff} in this case is significantly smaller than for pp collisions, the antishadowing effect is likely to be large enough to perform the analysis of the correlations of partons in the photon and allow a more reliable determination of σ_{eff} for $\gamma - p$ collisions..

It would be interesting also to study the gap survival probability for γA scattering with production of one or two pairs of jets with one of the jets of each pair in the photon fragmentation region and another one (two) across the gap. This would probe both the multiparton structure of the photon and the probability of the dipole to pass through the nucleus without inelastic interactions. An important advantage of the photon is that there are several handles to regulate the transverse size of the components in the photon wave function involved in the process. For example, one can select events with different x_γ, with leading D-mesons, etc.

The simplest process which allows to track propagation of a small dipole through the strong gluon fields in the nuclei is the process $\gamma + A \rightarrow$ vector meson + rapidity gap + X in the kinematics where $t = (p_\gamma - p_{VM})^2$ is large [14]. In the rest frame of the nucleus the process corresponds to a transformation of γ to a a $q\bar{q}$ pair of a small transverse size $\propto 1/\sqrt{-t}$ which interacts with a target through a two gluon ladder. If the gluon fields are strong enough the interaction would approach the black disk regime of complete absorption. In this limit it is impossible for a dipole to pass though the nucleus at small impact parameters without additional inelastic interactions. This would reduce the A-dependence of the process from $\propto A$ to $\propto A^{1/3}$. Since the gluon fields increase with increase of energy one expects a significant deviation of the A-dependence from $\propto A$ in the LHC kinematics. The rate of the process is sufficiently high to observe it during the first heavy ion run [14]. Note also that this process has several practical advantages as compared to he case of coherent J/ψ production. Production of hadrons in wide range of rapidities make it easier to trigger on these events. Also, location of the gap allows to determine on the event by event basis which of the nuclei emitted a photon. As a result it will be feasible to study the dipole - nucleus interactions up to $\sqrt{s_{\gamma p}} \sim 1$ TeV as compared to $\sqrt{s_{\gamma p}} \sim 0.2$ TeV for the coherent case.

4 Conclusions

Theoretical analysis of the exclusive hard phenomena studied at HERA produced a unique information about the transverse structure of nucleon. When combined with the information from the experimental studies of multiparton interactions at Tevatron, it leads to the unambigous conclusion that large transverse correlations between partons are present in the nucleon. Study of multiparton interactions with nuclei will allow to separate longitudinal and transverse correlations of partons in nucleons and photons. In the near future such studies will be possible in the ultraperipheral photon - lead collisions at the LHC. Similar studies can be done at RHIC in the deuteron - gold collisions if acceptance of detectors is increased. It appears that the fastest way to establish how black are interactions of small dipoles at ultra high energies will be a study of the rapidity gap events with large t in UPC heavy ion collisions. Studies of the leading jet production in the UPC will also allow to investigate the regime of fractional energy losses in the proximity of the black disk regime.

Acknowledgments

This work was supported by the DOE grant DE-FGO2 93ER40771. Many thanks to my collaborators in the research reported in this contribution: L.Frankfurt, D.Treleani, C.Weiss, M.Zhalov. I also thank L. Sonnenschein for the information concerning D0 multiparton interaction measurements.

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