High-energy hadron physics at future facilities

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Abstract

We outline several directions for future investigations of the three-dimensional structure of nucleon, including multiparton correlations, color transparency, and branching processes at hadron colliders and at hadron factories. We also find evidence that pQCD regime for non-vacuum Regge trajectories sets in for $-t \geq 1\,\mathrm{GeV}^2$ leading to nearly t-independent trajectories.

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1. Introduction

So far major successes of QCD in describing high energy hadron hadron collisions were for hard inclusive processes - collision of two partons. To describe these processes it is sufficient to know only longitudinal single parton densities.

At the same time the knowledge of the transverse spread of partons, longitudinal and transverse correlations of partons, their dependence on flavor, x polarization of the parton, are necessary for building a realistic description of the global structure of the final states in pp collisions, understanding microscopic structure of nucleon bound state.

Hard exclusive processes in *ep* scattering allow to probe not only the distribution of partons with respect to longitudinal momentum, but also their spatial distribution in the transverse plane. Examples include the hard electroproduction of light mesons and real photons (deeply virtual Compton scattering), as well as the photoproduction of heavy quarkonia ($J/\psi, \psi', \Upsilon$). Thanks to QCD factorization theorems the amplitudes for these processes can be separated into a “hard” part, calculable in perturbative QCD, and “soft” parts characterizing the non-perturbative structure of the involved hadrons. The information about the nucleon is contained in so-called generalized parton distributions (GPD’s). These are functions of the parton momentum fractions, x and x', as well as of the invariant momentum transfer to the nucleon, t, and thus combine aspects of the usual parton distributions, measured in inclusive deep–inelastic scattering, with those of

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the elastic nucleon form factors. For $x = x'$, their Fourier transform with respect to t describes the spatial distribution of partons in the transverse plane. The GPD's thus, in a sense, provide us with a "3D parton image" of the nucleon.

Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including transverse size of the wave function of vector meson explain key elements of high Q^2 data. In particular, they confirm prediction of [1] that t-slope of convergence of the slopes of the ρ-meson diffractive electroproduction at large Q^2 to the slope of the J/ψ meson photo(electro) production and describe the Q^2 dependence of the difference of the slopes [2]. Hence the t-dependence of J/ψ photo/electro production is given (up to small corrections) by the square of two - gluon form factor of the nucleon, which is related to the transverse distribution of the gluons at given x as:

$$F_g(x,t) \;\; = \;\; \int d^2\rho \; e^{i(\vec{\Delta}_\perp \vec{\rho})} \; F_g(x,\rho), \qquad\qquad (t = -\vec{\Delta}_\perp^2). \tag{1}$$

The function $F_g(x,\rho)$ is normalized as $\int d^2\rho \, F_g(x,\rho) = 1$. Concerning the shape of the two-gluon form factor, it has been argued that at $x \geq 10^{-1}$ (where pion cloud contributions are absent) the two–gluon form factor should follow the axial form factor of the nucleon, and thus be described by the dipole parameterization

$$F_g(x,t) \;\; = \;\; (1 - t/m_g^2)^{-2}, \qquad\qquad m_g^2 \;\; = \;\; 1.1\,\mathrm{GeV}^2 \qquad\qquad (x \geq 10^{-1}). \tag{2}$$

This form indeed describes well the t–dependence of the fixed–target J/ψ photoproduction experiments. Increase of the slope between $x \sim 0.1$ and $x \sim 0.01$ appears to be mostly due to the scattering off the pion field [3] Based on Eq. (2), we have suggested in Ref. [5] a generalized dipole parametrization valid also at small x, which incorporates the observed increase in the gluonic transverse size (as well as the effects of DGLAP evolution) by way of an x– and Q^2–dependent of the dipole mass parameter, $m_g^2(x, Q^2)$. For details, see Refs. [5,7].

2. Collider options

Exclusive processes in *ep* scattering, however, are not the only reactions which probe the "3D" parton distributions. In fact, a lot more information about the longitudinal momentum and transverse spatial distribution of partons, as well as about multiparton correlations, can be obtained from the study of selected hard processes in (not necessarily exclusive) *pp* and *pA* scattering. Comparative studies of *ep* and *pp*/*pA* induced hard processes will help to improve the quantitative description of both classes of processes and offer many new, fascinating insights into the partonic structure of the nucleon.

Turning now to *pp* collisions, an immediate application of the transverse spatial distribution of partons is in the description of the impact parameter dependence of the cross section for hard dijet production [5]. In a *pp* collision with c.m. energy $\sqrt{s}$, a hard dijet with transverse momentum $q_\perp$ at zero rapidity is produced in the collision of two partons carrying momentum fractions x_1, x_2. The probability for such a parton–parton collision, as function of the impact parameter of the *pp* system, b, is given by the convolution of the spatial distributions of the partons; for gluons

$$P_2(b) \;\; \equiv \;\; \int d^2\rho_1 \int d^2\rho_2 \; \delta^{(2)}(\vec{b} - \vec{\rho}_1 + \vec{\rho}_2) \; F_g(x_1, \rho_1) \; F_g(x_2, \rho_2). \tag{3}$$

The scale of the parton distributions here is $q_\perp^2$.

While exclusive processes in *ep* scattering provide in principle the cleanest way to access the transverse spatial distribution of partons, there are several instances in which *pp* scattering is more effective. One is the study of large x, where the cross sections for exclusive processes in *ep* are small. In this case the global transverse distribution of matter can be measured more directly using various reactions combining a soft and hard trigger, in particular in connection with *pA* collisions [8]. New opportunities for such studies will emerge at LHC, where the high luminosity will allow, for example, to compare the characteristics of W^+ and W^- production at the same forward rapidities, corresponding to sufficiently high x. By studying the accompanying production of hadrons one can learn which configurations in the nucleon have larger transverse size — those with a leading u–quark or with a leading d-quark. One suitable observable is, for example, the distribution of the number of events over the number of the produced soft particles. A larger transverse size corresponds to a larger probability of soft interactions, and hence to a larger probability of events with large multiplicity. It is interesting to note that the studies of the associated soft hadron multiplicity in the production of $W^\pm$ and Z bosons in $\bar{p}p$ collisions at $\sqrt{s} = 2\,TeV$ find an increase of this multiplicity by a factor of two as compared to generic inelastic events [9]. This appears natural if one takes into account that the hard quarks producing the weak bosons have a narrower transverse spatial distribution than the soft partons. As a result, the average impact parameters in events with weak boson production are much smaller than in generic inelastic collisions, leading to an enhancement of multiple soft and semi-hard interactions [5].

Single parton densities and GPDs do not carry information about longitudinal and transverse correlations of partons in the hadron wave function. Such information can be extracted from high energy *pp* and *pA* collisions where two (or more) pairs of partons can collide to produce multiple dijets, with a kinematics distinguishable from those produced in 2 → 4 parton processes. Since the momentum scale of the hard interaction, p_t, corresponds to much smaller transverse distances in coordinate space than the hadronic radius, in a double parton collision the two interaction regions are well separated in transverse space. Experimentally, one measures the ratio

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

where $f(x_1,x_3), f(x_2,x_4)$ are the longitudinal light-cone double parton densities at the hard scale μ^2 (we assume for simplicity that the virtuality in both hard processes is comparable; in the following equations we suppress dependence on μ^2), and the quantity σ_{eff} can be interpreted as the "transverse correlation area". The variables Ω_i characterize phase volume of the observed jets (or photons).

Parton correlations can emerge due to nonperturbative effects at a low resolution scale, or due to the effects of QCD evolution. One possible nonperturbative mechanism is the existence of "constituent quarks" within the nucleon, which appear due to the interaction of current quarks with localized non-perturbative gluon fields, resulting in local short–range correlations in the transverse spatial distribution of gluons. The instanton model of the QCD vacuum suggests a constituent quark radius of about 1/3 the nucleon radius, $r_q \approx r_N/3$. Another nonperturbative mechanism, relevant at small x, are fluctuations of the color field in the nucleon due to the fluctuations of the transverse size of the quark distribution. Perturbative correlations emerge due to small transverse distances in the emission process in the perturbative partonic ladder in DGLAP evolution. Of all the mentioned mechanisms, only the first one is effective at $x \geq 0.05$, where the data on production of two balanced jets, and jet plus photon [6] were collected. They found $\sigma_{\rm eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb which is significantly smaller than the naive estimate obtained by taking a uniform distribution of partons of a transverse size determined by the e.m. form factor of the nucleon, which gives $\sigma_{\rm eff} \approx 53$ mb, indicating strong correlations between the transverse positions of partons in the transverse plane. The longitudinal correlation between partons in the measured kinematics due to energy conservation is likely to be small, as $x_1 + x_2$ and $x_3 + x_4$ are much smaller than 1. If this effect were important it would likely lead to a suppression of the double parton collision cross section, and hence to an increase of $\sigma_{\rm eff}$. However, no dependence of $\sigma_{\rm eff}$ on x_i was observed in the experiment.

We can calculate σ_{eff} using the information about the transverse spatial distribution of gluons gained from J/ψ photoproduction, as summarized above. Since the x values of the partons probed were reasonably small compared to 1, the simple "geometric" picture of the $\bar{p}p$ collision in transverse position in the spirit of Eq. (3) is justified, and one has

$$\sigma_{\rm eff} \;\; = \;\; \left[\int d^2 b \; P_2^2(b) \right]^{-1} . \tag{5}$$

Evaluating this with the dipole parametrization of the two–gluon form factor (2), this comes to $\sigma_{\rm eff} \;=\; 28\pi/m_g^2 \;\approx\; 34$ mb. Thus, about 50% of the enhancement compared to the naive estimate of the previous paragraph is due to smaller actual transverse radius of the gluon distribution. Still, our value indicates significant correlations in the transverse positions of the partons. In the kinematics discussed here the relevant partons are both quarks and gluons. We can estimate the effect of correlations assuming that most of the partons are concentrated in a small transverse area associated with the "constituent quarks", as implied by the instanton liquid model [10]. Assuming a constituent quark radius of $r_q \sim r_N/3$, we obtain an enhancement factor due to transverse spatial correlations of partons of $\frac{8}{9} + \frac{1}{9}\,\frac{r_N^2}{r_q^2} \;\sim\; 1.6 \div 2$. This is roughly the value needed to explain the remaining discrepancy with the CDF data. Thus, the combination of the relatively small transverse size of the distribution of large–x gluons and the quark–gluon correlations implied by "constituent quarks" with $r_q \approx r_N/3$ is sufficient to explain the trend of the CDF data. Further studies of multijet events at hadron–hadron colliders, with a broader range of final states, would in principle allow to measure separately quark–quark, quark–gluon, and gluon–gluon correlations for different x.

However, studies based on $\bar{p}p$ or pp collisions alone do not allow for a model–independent separation of transverse and longitudinal correlations. This is possible only in pA collisions at RHIC and LHC. The reason is that the nucleus, having a thickness which practically does not change on the nucleon transverse scale, provides an important contribution which is sensitive only to the longitudinal correlations of hadrons [11]. This is the contribution when two partons of the incident nucleon interact with partons belonging to two different nucleons in the nucleus, σ_2,

$$\sigma_2 \;\; = \;\; \sigma^{NN}_{\rm double} \frac{A-1}{A} \int d^2 b \, T^2(b) \; \frac{f(x_1) f(x_2)}{f(x_1, x_2)} . \tag{6}$$

The other term is the impulse approximation — two partons of the incoming nucleon interact with two partons of the same nucleon in the nucleus, σ_1, which is simply equal to A times the cross section of double scattering in pp collisions. Thus, by measuring the ratio of pA and pp double scattering cross sections we can determine $1/\sigma_{\rm eff}$. Taking the CDF value of $\sigma_{\rm eff} \sim 14$ mb, we obtain $\sigma_2/\sigma_1 \sim 3$ for $A \sim 200$. Thus, the separation of the two terms will be quite straightforward. Even in the case of deuteron–nucleus scattering, which was studied at RHIC recently, the contributions from two partons of one nucleon of the deuteron interacting with two different nucleons in the nucleus remains significant.It constitutes about 50% of the cross section for $A \sim 200$. Hence it will be possible to measure $\sigma_{\rm eff}$ in pA and dA collisions if it is ≥ 5 mb, with pA being a better option. Finally, if $\sigma_{\rm eff}$ will have been measured in pA collisions, it will be possible to extract the longitudinal two–parton distributions in a model independent way.

To summarize, we have demonstrated that future experiments will be able to measure independently the longitudinal and transverse two–parton distributions in the nucleon. With a detector of sufficiently large acceptance it would be possible to extend these studies even to the case of three parton correlations.

3. Fixed target opportunities

Experiments at fixed target facilities: BNL, CERN, FNAL, Serpukhov were performed for many years. However most of the these experiments were planned in the pre QCD/ early QCD period. From the angle of current studies in QCD the most interesting topic is large momentum transfer semi/exclusive processes with small cross sections which were beyond capabilities of previous machines - beam intensity, detector electronics. Here I discuss briefly several possible directions: study of quark exchanges in pQCD via two body processes, large angle two body processes, color transparency phenomena, branching 2 → 3 processes. I will not have time/space to cover very promising direction of the study of the properties on cold dense nuclear matter - structure of the short-range correlations using large momentum exclusive processes with high-energy hadron beams.

3.1. *Quark exchanges in pQCD via two body processes*

In the Regge theory two body processes in the limit of fixed t and $s \to \infty$ is given by the exchange of the corresponding Regge trajectory, $\alpha_R(t)$ with the amplitude given by $A(s,t) = f(t)s^{\alpha_R(t)}$. This amplitude is usually assumed to be linear function of t. Two simplest types of processes with largest cross sections (except the ones where vacuum Pomeron exchange is allowed) are $\pi^- p \to \pi^0 n$ where exchange by a $q\bar{q}$ is allowed and $\pi^- p \to p\pi^-$ where exchange by three quarks is allowed. In pQCD we may expect that for large t instead of exchange by a meson/ baryon trajectory an exchange by (anti) quarks should dominate which are reggeized in pQCD [12]. Since at large t the QCD coupling is a weak function of t, $\alpha_q(t)$ should weakly depend on t. Hence using Azimov displacement relation [13] we find

$$A_{q\bar{q}} \propto s^{2\alpha_q(t)-1},\ A_{qqq} \propto s^{3\alpha_q(t)-2}, \tag{7}$$

leading to a an expectation of nearly t-independent meson and baryon trajectories at at large negative t with

$$\alpha_N(t) = 3\alpha_M(t)/2 - 0.5 \approx const. \tag{8}$$

We inspected the current data which are very fragmentary and found they are consistent with $\alpha_M(-t\,1\,GeV^2) = -(0.2 \div 0.4), \alpha_B(-t\,1\,GeV^2) = -(0.8 \div 1.1)$ which is consistent with $\alpha_q(-t\,1\,GeV^2) \sim 0.3 \div 0.4$ as compared to the case of nonreggeized quark exchange of $\alpha_q = 0.5$ indicating that pQCD sets up already at $-t \sim 1GeV^2$ and that reggeization effect is rather small. One may expect that at large t the coupling of $q\bar{q}$ to the meson and baryon vertices is given by the corresponding GPDs. Note also that in the case of baryon exchange the pQCD diagrams involve $q\bar{q}g$ configurations in mesons, cf [14].

3.2. *Large angle two body processes*

So far we do not understand the origin of one of the most fundamental hadronic processes in pQCD -large angle two body reactions ($-t/s = const, s \to \infty$): $\pi + p \to \pi + p, p + p \to p + p$. The most extensive set of processes was studied in the BNL experiment at 5.9 and 9.9 GeV/c [15]. The data indicate dominance of the quark exchanges and appear to be consistent with quark counting rules[16] based dominance of the minimal Fock components in the wave functions of the colliding hadrons.

We find that several features of the data are consistent with dominance of small size configurations. In particular

$$\frac{d\sigma^{K^+p\to K^+p}}{d\theta_{c.m.}}(\theta = 90^o)/\frac{d\sigma^{\pi^+p\to\pi^+p}}{d\theta_{c.m.}}(\theta = 90^o) \sim (f_K/f_\pi)^2 \sim 1.7, \tag{9}$$

while the data gives 1.69 ± 0.25. Also

$$\frac{d\sigma^{\pi^+p\to\pi^+p}}{d\theta_{c.m.}}(\theta = 90^o)/\frac{d\sigma^{\pi^-p\to\pi^-p}}{d\theta_{c.m.}}(\theta = 90^o) \sim u(x)/d(x) \sim 2, \tag{10}$$

agrees with the data with accuracy $10 \div 15\%$ both for elastic and for ρ-meson production channel. Overall it appears likely that these processes are dominated by short distances for -t > 5GeV^2. Clearly new experiments are necessary to determine details of the dynamics. J-PARC is in the optimal energy range.

3.3. *Color transparency phenomena*

At high energies weakness of interaction of point-like configurations with nucleons - is routinely used for explanation of DIS phenomena at HERA.

First experimental observation of high energy weakness of interaction with nuclei - color transparency (CT) - for pion interaction was reported for the process: $\pi + A \to jet + jet + A$ in [17]. It confirmed our predictions of pQCD for A-dependence, distribution over energy fraction, u carried by one jet, dependence on $p_t(jet)$, etc. There is also experimental evidence for CT phenomenon in exclusive produciton of ρ and π- mesons by virtual photons - see [18] and references therein.

Main issues are (a) at what $Q^2(t)$ particular processes start to be dominated by point-like configurations - for example interplay of end point and LT contributions in the e.m. form factors, (b) If the point-like configuration is formed, how long it will remain smaller than average configuration? This involves both expansion after interaction to an average configurations and contraction before interaction from an average configurations. The recent data[18] see to be in agreement with an early estimate of this phenomenon within the color diffusion model [19]. In particular, the data are consistent with the estimate of [19] of the coherence length $l_{coh} = (0.3 \div 0.4) fm \cdot p_h/GeV$. (It is worth noting that this coherence length is much smaller than the one usually assumed in the heavy ion collisions).

In spite of progress with studies of CT with virtual photons, investigation of CT for the hadronic projectiles remains a challenge - no definitive conclusions were reached in the BNL experiments. It is critical to perform new studies of CT phenomenon in hadronic reactions at energies above 10 GeV where expansion effects are moderate. Such measurements would complement the program of CT in eA scattering at Jlab at 12 GeV. Natural places to perform such experiments would be J-PARC and FAIR at GSI. Obvious advantages as compared to the previous round of experiments are progress in electronics leading to a possibility to work at higher luminosity, wider range of hadron beams including antiprotons at GSI, possibility of using polarized beams. It would be desirable to perform (p,2p) experiments at the range of 10-20 GeV for all angles including those close to $\theta_{c.m.} \sim 90^0$ and extend measurements to $E_p > 20GeV$. In the latter case the rates at $\theta_{c.m.} \sim 90^0$ are too small, and one should probably adopt another strategy - measure transparency for large but fixed t. In this case l_{coh} for initial and the fastest of two final nucleons is very large. Only the slow nucleon has time to expand leading to a large CT effect –transparency similar to the one in $A(e, ep)$ reaction.

3.4. *Branching processes and GPDs*

Detectors which can study CT are well suited also to study generalized parton distributions using hadronic projectiles complementing the studies with lepton projectiles. Such studies will be especially beneficial if they will be performed in parallel with 12 GeV program at Jlab (GPD studies is the main trust of Jlab 12 GeV program).

The idea is to consider new type of hard hadronic processes - branching exclusive processes of large c.m.angle scattering on a cluster in a target/projectile [20]. Examples of such reactions include $h + p \to h' + M + B$ where M is a meson carrying most of the transfered momentum, while B is recoil system which mass and momentum are kept fixed in the target rest frame, and reverse processes in which a fast baryon is ejected from the target: $h + p \to h' + B + M$ (Fig.1). Among interesting channels are production of exotic meson states in the recoil kinematics, study of hidden/intrinsic strangeness and charm in hadrons in the processes like $pp \to \Lambda(spectator) + K^+ + p, \Lambda + K^+(spectator) + p, \phi(spectator) + p + p$. It would be also advantageous to use polarized beams and/or targets.

In the limit when CT is valid for the elementary $2 \to 2$ reaction one can try to connect cross sections of processes where $q\bar{q}$ pair scatters at large angles to the nucleon GPDs in the kinematics where x's of both removed partons are positive (ERBL region). Similarly in the process $pp \to N + \pi + \Delta(spectator)$ one would probe non-diagonal $N \to \Delta$ GPDs. Theoretical calculations along these lines are under way [21].

To summarize, in order to understand the complexity of the structure of nucleons (as well as other hadrons) a diverse program studies of parton correlations, fluctuations of the size of the hadrons, structure of minimal and higher order Fock components of

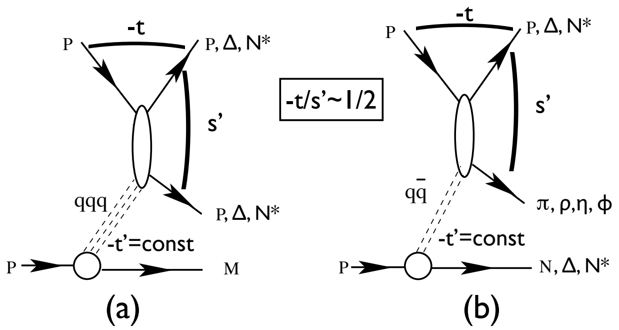

Fig. 1. *(a) Production of fast baryon and recoiling mesonic system, (b) Production of fast meson and recoiling baryonic system.*

the hadron wave function are necessary. This would require use of both colliders and fixed target facilities, combining leptonic and hadronic probes. The currently opertating facilities and facilities which are now under construction provide excellent opportunities for such studies.

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