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Hadron Structure: the Fundamental Physics to Access via GPDs

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An introductory review of generalized parton distributions (GPDs) is given.

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Hadron structure: the fundamental physics to access via GPDs

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1. INTRODUCTION

The fundamental physics to be accessed via the recently introduced generalized parton distributions [1–3] is the structure of hadrons. This is a rather general statement, and we may want to have a more specific one. A classic example of such a specific case is the search for the Higgs boson (HB). The motivation for the search is that HB is supposed to be responsible for generation of masses, in particular, quark masses. However, far the largest part of visible mass is due to nucleons: from 940 MeV of the nucleon mass, less than 30 MeV (current quark masses) may be related to HB. The remaining 97% of the nucleon mass is due to gluons – which are massless! This is a characteristic illustration of the situation in hadron physics: *i*) All the relevant particles are already established, – no “higgses” to find. *ii*) QCD Lagrangian is known. *iii*) But we still need to understand how QCD works, - i.e., to understand hadronic structure in terms of quark and gluon fields.

Projecting quark and gluon fields $q(z_1)$, $q(z_2)$, ... onto hadronic states $|p, s\rangle$ gives matrix elements: $\langle 0 | \bar{q}_\alpha(z_1) q_\beta(z_2) | M(p), s \rangle$, $\langle 0 | q_\alpha(z_1) \bar{q}_\beta(z_2) q_\gamma(z_3) | B(p), s \rangle$ that can be interpreted as hadronic wave functions. In particular, in the light-cone formalism [4] a hadron is described by its Fock components in the infinite-momentum frame. For the nucleon, one can schematically write: $|P\rangle = |q(x_1 P, k_{1\perp}) q(x_2 P, k_{2\perp}) q(x_3 P, k_{3\perp})\rangle + |qqqG\rangle + |qqq\bar{q}q\rangle + \dots$, where x_i are momentum fractions satisfying $\sum_i x_i = 1$ and $k_{i\perp}$ are transverse momenta, $\sum_i k_{i\perp} = 0$. In principle, solving the bound-state equation $H|P\rangle = E|P\rangle$ one should get the wave function $|P\rangle$ that contains complete information about the hadron structure. In practice, however, the equation (involving infinite number of Fock components) has not been solved yet. Moreover, the LC wave functions are not directly accessible experimentally. The way out in this situation is the description of hadron structure in terms of phenomenological functions. Among the “old” functions used for a long time we can list Form Factors, Usual Parton Densities, and Distribution Amplitudes. The new functions, Generalized Parton Distributions (for a recent review see [5]), are hybrids of form factors, parton densities and distribution amplitudes. Furthermore, the “old” functions are limiting cases of the “new” ones.

2. FORM FACTORS

The form factors are defined through matrix elements of electromagnetic and weak currents between hadronic states. In particular, the nucleon electromagnetic form factors are given by

$$\langle p', s' | J^\mu(0) | p, s \rangle = \bar{u}(p', s') \left[\gamma^\mu F_1(t) + \frac{r^\nu \sigma^{\mu\nu}}{2m_N} F_2(t) \right] u(p, s) , \quad (1)$$

where $r = p - p'$ is the momentum transfer and $t = r^2$. The electromagnetic current is given by the sum of its flavor components $J^\mu(z) = \sum_f e_f \bar{\psi}_f(z) \gamma^\mu \psi_f(z)$. The helicity non-flip form factor $F_1(t)$ can also be written as a sum $\sum_f e_f F_{1f}(t)$. Similar decomposition holds for the helicity flip form factor $F_2(t) = \sum_f e_f F_{2f}(t)$. At $t = 0$, these functions have well known limiting values. In particular, $F_1(t = 0) = e_N = \sum_f N_f e_f$ gives the total electric charge of the nucleon (N_f is the number of valence quarks of flavor f) and $F_2(t = 0) = \kappa_N$ gives its anomalous magnetic moment. The form factors are measurable through elastic eN scattering.

Figure 1. Elastic eN scattering in the one-photon exchange approximation.

3. USUAL PARTON DENSITIES

The parton densities are defined through forward matrix elements of quark/gluon fields separated by lightlike distances. In particular, in the unpolarized case we have

$$\langle p | \bar{\psi}_a(-z/2) \gamma^\mu \psi_a(z/2) | p \rangle \Big|_{z^2=0} = 2p^\mu \int_0^1 \left[e^{-ix(pz)} f_a(x) - e^{ix(pz)} f_{\bar{a}}(x) \right] dx . \quad (2)$$

In the local limit $z = 0$, the operators in this definition coincide with the operators contributing into the non-flip form factor F_1 . Since $t = 0$ for the forward matrix element, we obtain the sum rule for the numbers of valence quarks

$$\int_0^1 [f_a(x) - f_{\bar{a}}(x)] dx = N_a . \quad (3)$$

The definition of parton densities has the form of the plane wave decomposition. This observation allows to give the momentum space interpretation: $f_{a(\bar{a})}(x)$ is the probability to find $a(\bar{a})$ -quark with momentum xp inside a nucleon with momentum p . The classic process to access the usual parton densities is deep inelastic scattering (DIS) $\gamma^* N \rightarrow X$.

Figure 3. Form factor and wide-angle Compton scattering amplitude in terms of nonforward parton densities.

The handbag term is approximately given by the product of a new form factor $R_V^a(t)$ and the cross section of the Compton scattering off an elementary fermion

$$\frac{d\sigma}{dt} = \left[\sum_a e_a^2 R_V^a(t) \right]^2 \frac{d\sigma}{dt} \Big|_{KN} \quad \text{with} \quad R_V^a(t) = \int_0^1 \frac{\mathcal{F}^a(x, t)}{x} dx. \quad (5)$$

The predictions based on handbag dominance and NPDs [6,7] are in much better agreement with the existing Cornell data than the predictions based on two-gluon hard exchange mechanism of asymptotic perturbative QCD: the predicted cross section is too small in the latter case. The absolute normalization for predictions is settled by the form of the nonperturbative functions (NPDs in the handbag approach and nucleon distribution amplitudes in the pQCD approach) which were fixed by fitting the F_1 form factor data. Still, when there is an uncertain overall factor, it is risky to make strong statements. Remarkably, the perturbative QCD hard scattering mechanism and soft handbag mechanism give drastically different predictions for the polarization asymmetry A_{LL} [7]. Experiment E-99-114 recently performed at Jefferson Lab strongly favors handbag mechanism that predicts the value close to the asymmetry for the scattering on a single quark.

5. DISTRIBUTION AMPLITUDES

Another example of nonperturbative functions describing the hadron structure are the distribution amplitudes (DAs). They can be interpreted as light cone wave functions integrated over transverse momentum, or as $\langle 0 | \dots | p \rangle$ matrix elements of light cone operators. In the case of the pion we have

$$\langle 0 | \bar{\psi}_d(-z/2) \gamma_5 \gamma^\mu \psi_u(z/2) | \pi^+(p) \rangle \Big|_{z^2=0} = i p^\mu f_\pi \int_{-1}^1 e^{-i\alpha(pz)/2} \varphi_\pi(\alpha) d\alpha, \quad (6)$$

with $x_1 = (1 + \alpha)/2$, $x_2 = (1 - \alpha)/2$ being the fractions of the pion momentum carried by the quarks. The distribution amplitudes describe the hadrons in situations when

pQCD hard scattering approach is applicable to exclusive processes. The classic example is the process of $\gamma^*\gamma \rightarrow \pi^0$ transition. Its amplitude is proportional to the $1/(1 - \alpha^2)$ moment of $\varphi_\pi(\alpha)$. The predictions for the $\gamma^*\gamma \rightarrow \pi^0$ form factor based on two competing models for the pion DA, the asymptotic $\varphi_\pi^{as}(\alpha) = \frac{3}{4}(1 - \alpha^2)$ and Chernyak-Zhitnitsky DA $\varphi_\pi^{CZ}(\alpha) = \frac{15}{4}\alpha^2(1 - \alpha^2)$ differ by factor of 5/3, which allows for an experimental discrimination between them.

Figure 4. Lowest-order pQCD factorization for $\gamma^*\gamma \rightarrow \pi^0$ transition amplitude and for the pion EM form factor.

Comparison with CLEO and CELLO data for $Q^2 F_{\gamma^*\gamma\pi^0}(Q^2)$ favors $\varphi_\pi^{as}(\alpha)$. It is also worth noting that perturbative QCD works here from rather small values of momentum transfer $Q^2 \sim 2 \text{ GeV}^2$. Another classic application of pQCD to exclusive processes is the pion electromagnetic form factor. With the asymptotic pion DA $\varphi_\pi^{as}(\alpha)$, the hard pQCD contribution to $F_\pi(Q^2)$ is $(2\alpha_s/\pi)(0.7 \text{ GeV}^2)/Q^2$, which is less than 1/3 of experimental value. So, in this case we deal with the dominance of the competing soft mechanism that is described by nonforward parton densities, exactly in the same way as the proton $F_1^p(t)$ form factor discussed in the previous section.

6. HARD ELECTROPRODUCTION PROCESSES

A more recent attempt to use perturbative QCD to extract new information about hadronic structure is the study of deep exclusive photon [2] or meson [3,8] electroproduction reactions. In the hard kinematics when both Q^2 and $s \equiv (p + q)^2$ are large while the momentum transfer $t \equiv (p - p')^2$ is small, one can use pQCD factorization which represents the amplitudes as a convolution of a perturbatively calculable short-distance amplitude and nonperturbative parton functions describing the hadron structure. The hard pQCD subprocesses in these two cases have different structure. Since the photon is a pointlike particle, the deeply virtual Compton scattering amplitude has the structure similar to that of the $\gamma^*\gamma\pi^0$ form factor: the pQCD hard term is of zero order in α_s , and there is no competing soft contribution. Thus, we can expect that pQCD works from $Q^2 \sim 2 \text{ GeV}^2$. On the other hand, the deeply virtual meson production process is similar

to the pion EM form factor: the hard term has $O(\alpha_s/\pi) \sim 0.1$ suppression factor. As a result, the dominance of the hard pQCD term may be postponed to $Q^2 \sim 5 - 10 \text{ GeV}^2$.

Figure 5. Lowest-order factorization for deeply virtual photon and meson production.

One should also have in mind that the competing soft mechanism can mimic the same power-law Q^2 -behavior (just like in case of pion and nucleon EM form factors). Hence, a mere observation of a “right” power-law behavior of the cross section may be insufficient to claim that pQCD is already working. One should look at other characteristics of the reaction, especially its spin properties, to make strong statements about the reaction mechanism.

7. DEEPLY VIRTUAL COMPTON SCATTERING AND GENERALIZED PARTON DISTRIBUTIONS

It is convenient to visualize DVCS in the γ^*N center-of-mass frame, with the initial hadron and the virtual photon moving in opposite directions along the z -axis. Since the momentum transfer t is small, the hadron and the real photon in the final state also move close to the z -axis. This means that the virtual photon momentum $q = q' - x_{Bj}p$ has the component $-x_{Bj}p$ canceled by the momentum transfer r . In other words, the momentum transfer r has the longitudinal component $r^+ = x_{Bj}p^+$, where $x_{Bj} = Q^2/2(pq)$ is the DIS Bjorken variable. One can say that DVCS has a skewed kinematics in which the final hadron has the “plus” momentum $(1 - \zeta)p^+$ that is smaller than that of the initial hadron. In the particular case of DVCS, we have $\zeta = x_{Bj}$.

The parton picture for DVCS has some similarity to that of DIS, with the main difference that the plus-momenta of the incoming and outgoing quarks in DVCS are not equal. They are Xp^+ and $(X - \zeta)p^+$. Another difference is that the invariant momentum transfer t in DVCS is nonzero: the matrix element of partonic fields is essentially nonforward.

Thus, the nonforward parton distributions (NFPDs) $\mathcal{F}_\zeta(X; t)$ describing the hadronic structure in DVCS depend on X , the fraction of p^+ carried by the outgoing quark, on ζ , the skewedness parameter characterizing the difference between initial and final hadron momenta, and on t , the invariant momentum transfer. In the forward $r = 0$ limit, we have a reduction formula $\mathcal{F}_{\zeta=0}^a(X, t = 0) = f_a(X)$ relating NFPDs with the usual parton densities. The nontriviality of this relation is that $\mathcal{F}_\zeta(X; t)$ appear in the amplitude of the exclusive DVCS process, while the usual parton densities are measured from the cross section of the inclusive DIS reaction.

Another limit for NFPDs is zero skewedness $\zeta = 0$, where they correspond to nonforward

parton densities $\mathcal{F}_{\zeta=0}^a(X, t) = \mathcal{F}^a(X, t)$. The local limit relates NFPDs to form factors

$$\int_0^1 \mathcal{F}_{\zeta}^a(X, t) dX = F_1^a(t) . \quad (7)$$

The description in terms of NFPDs has the advantage of using the variables most close to those of the usual parton densities. However, the initial and final hadron momenta are not treated symmetrically in this scheme. Ji [2] proposed to use symmetric variables in which the plus-momenta of the hadrons are $(1 + \xi)P^+$ and $(1 - \xi)P^+$, and those of the active partons are $(x + \xi)P^+$ and $(x - \xi)P^+$, P being the average momentum $P = (p + p')/2$.

Figure 6. Comparison of NFPDs and OFPDs.

To take into account the spin properties of the hadrons and of the quarks, one needs 4 off-forward parton distributions $H, E, \tilde{H}, \tilde{E}$, each of which is a function of x, ξ, t . The skewedness parameter $\xi \equiv r^+/2P^+$ can be expressed in terms of the Bjorken variable $\xi = x_{Bj}/(2 - x_{Bj})$, but does not coincide with it. Depending on the value of x , each OFPD has 3 distinct regions. When $\xi < x < 1$, they are analogous to usual quark distributions; when $-1 < x < -\xi$ they are similar to antiquark distributions. In the region $-\xi < x < \xi$, the “returning” quark has a negative momentum, and should be treated as an outgoing antiquark with momentum $(\xi - x)P$. The total $q\bar{q}$ pair momentum $r = 2\xi P$ is shared by the quarks in fractions $r(1 + x/\xi)/2$ and $r(1 - x/\xi)/2$. Hence OFPD in this region $-\xi < x < \xi$ is similar to a distribution amplitude $\Phi(\alpha)$ with $\alpha = x/\xi$.

In the local limit, OFPDs reduce to form factors

$$\sum_a e_a \int_{-1}^1 H^a(x, \xi; t) dx = F_1(t) \quad , \quad \sum_a e_a \int_{-1}^1 E^a(x, \xi; t) dx = F_2(t) . \quad (8)$$

The E function, like F_2 , comes with the r_μ factor, hence, it is invisible in DIS described by exactly forward $r = 0$ Compton amplitude. However, the $t = 0, \xi = 0$ limit of E exists: $E^{a,\bar{a}}(x, \xi = 0; t = 0) \equiv \kappa^{a,\bar{a}}(x)$. In particular, its integral gives the proton anomalous magnetic moment κ_p , and its first moment enters into Ji’s sum rule for the total quark contribution J_q into the proton spin

$$\sum_a e_a \int_{-1}^1 (\kappa^a(x) - \kappa^{\bar{a}}(x)) dx = \kappa_p \quad , \quad J_q = \frac{1}{2} \sum_a \int_{-1}^1 x [f^a(x) + f^{\bar{a}}(x) + \kappa^a(x) + \kappa^{\bar{a}}(x)] dx . \quad (9)$$

Note that only valence quarks contribute to κ_p , while J_q involves also sea quarks. Furthermore, the values of $\kappa_{p,n}$ (unlike $e_{p,n} \equiv F_1^{p,n}(0)$) strongly depend on dynamics, e.g., $\kappa_N \sim 1/m_q$ in constituent quark models.

8. DOUBLE DISTRIBUTIONS

To model GPDs, two approaches are used: a direct calculation in specific dynamical models: bag model, chiral soliton model, light-cone formalism, etc., and a phenomenological construction based on the relation of SPDs to usual parton densities $f_a(x)$, $\Delta f_a(x)$ and form factors $F_1(t)$, $F_2(t)$, $G_A(t)$, $G_P(t)$. The key question in the second approach is the interplay between x , ξ and t dependencies of GPDs. There are not so many cases in which the pattern of the interplay is evident. One example is the function $\tilde{E}(x, \xi; t)$ that is related to $G_P(t)$ form factor and is dominated for small t by the pion pole term $1/(t - m_\pi^2)$. It is also proportional to the pion distribution amplitude $\varphi(\alpha) \approx \frac{3}{4}f_\pi(1 - \alpha^2)$ taken at $\alpha = x/\xi$. The construction of self-consistent models for other GPDs is performed using the formalism of double distributions [9].

The main idea behind the double distributions is a “superposition” of P^+ and r^+ momentum fluxes, i.e., the representation of the parton momentum $k^+ = \beta P^+ + (1 + \alpha)r^+/2$ as the sum of a component βP^+ due to the average hadron momentum P (flowing in the s -channel) and a component $(1 + \alpha)r^+/2$ due to the t -channel momentum r . Thus, the double distribution $f(\beta, \alpha)$ (we consider here for simplicity the $t = 0$ limit) looks like a usual parton density with respect to β and like a distribution amplitude with respect to α . The connection between the DD variables β, α and the OFPD variables x, ξ is obtained from $r^+ = 2\xi P^+$, which results in the basic relation $x = \beta + \xi\alpha$.

Figure 7. Comparison of GPD and DD descriptions.

The forward limit $\xi = 0, t = 0$ corresponds to $x = \beta$, and gives the relation between DDs and the usual parton densities

$$\int_{-1+|\beta|}^{1-|\beta|} f_a(\beta, \alpha; t = 0) d\alpha = f_a(\beta) . \quad (10)$$

The DDs live on the rhombus $|\alpha| + |\beta| \leq 1$ and they are symmetric functions of the “DA” variable α : $f_a(\beta, \alpha; t) = f_a(\beta, -\alpha; t)$ (“Munich” symmetry [10]). These restrictions suggest a factorized representation for a DD in the form of a product of a usual parton density in the β -direction and a distribution amplitude in the α -direction. In particular, a toy model for a double distribution $f(\beta, \alpha) = 3[(1 - |\beta|)^2 - \alpha^2] \theta(|\alpha| + |\beta| \leq 1)$ corresponds to the toy “forward” distribution $f(\beta) = 4(1 - |\beta|)^3$, and the α -profile like that of the asymptotic pion distribution amplitude.

To get usual parton densities from DDs, one should integrate (scan) them over vertical lines $\beta = x = \text{const.}$ To get OFPDs $H(x, \xi)$ with nonzero ξ from DDs $f(\beta, \alpha)$, one should integrate (scan) DDs along the parallel lines $\alpha = (x - \beta)/\xi$ with a ξ -dependent slope. One can call this process the DD-tomography. The basic feature of OFPDs $H(x, \xi)$ resulting from DDs is that for $\xi = 0$ they reduce to usual parton densities, and for $\xi = 1$ they have a shape like a meson distribution amplitude. A more complete truth is that such a DD modeling misses terms invisible in the forward limit: meson exchange contributions and so-called D-term, which can be interpreted as σ -exchange. The inclusion of the D-term induces nontrivial behavior in the central $|x| < \xi$ region (for details, see [5]).

9. SOME LESSONS

Hadronic structure is a complicated subject, it requires a study from many sides, in many different types of experiments. The description of specific aspects of hadronic structure is provided by several different functions: form factors, usual parton densities, distribution amplitudes. Generalized parton distributions provide a unified description: all these functions can be treated as particular or limiting cases of GPDs $H(x, \xi, t)$.

Usual Parton Densities $f(x)$ correspond to the case $\xi = 0, t = 0$. They describe a hadron in terms of probabilities $\sim |\Psi|^2$. But QCD is a quantum theory: GPDs with $\xi \neq 0$ describe correlations $\sim \Psi_1^* \Psi_2$. Taking only one point $t = 0$ corresponds to integration over impact parameters $b_\perp$ - information about the transverse structure is lost.

Form Factors $F(t)$ contain information about the distribution of partons in the transverse plane, but $F(t)$ involve integration over momentum fraction x - information about longitudinal structure is lost

A simple “hybridization” of usual densities and form factors in terms of NPDs $\mathcal{F}(x, t)$ (GPDs with $\xi = 0$) shows that behavior of $F(t)$ is governed both by transverse and longitudinal distributions. GPDs provide adequate description of nonperturbative soft mechanism, they also allow to study transition from soft to hard mechanism.

Distribution Amplitudes $\varphi(x)$ provide quantum level information about longitudinal structure of hadrons. In principle, they are accessible in exclusive processes at large momentum transfer, when hard scattering mechanism dominates. GPDs have DA-type structure in the central region $|x| < \xi$.

Generalized Parton Distributions $H(x, \xi; t)$ provide a 3-dimensional picture of hadrons. GPDs also provide some novel possibilities, such as “magnetic distributions” related to the spin-flip GPD $E(x, \xi, t)$. In particular, the structure of the nonforward density $E(x, \xi = 0, t)$ determines the t -dependence of $F_2(t)$. Recent JLab data give $F_2(t)/F_1(t) \sim 1/\sqrt{-t}$ rather than $1/t$ expected in hard pQCD and many models – a puzzle waiting to be resolved. The forward reductions $\kappa^a(x)$ of $E(x, \xi, t)$ look as fundamental as $f^a(x)$ and $\Delta f^a(x)$: Ji’s sum rule involves $\kappa^a(x)$ on equal footing with $f(x)$. Magnetic properties of hadrons are strongly sensitive to dynamics, thus providing a testing ground for models. Another novel possibility is the study of flavor-nondiagonal distributions, e.g., proton-to-neutron GPDs accessible through processes like exclusive charged pion electroproduction, proton-to- Λ GPDs (they appear in kaon electroproduction); proton-to-Delta – this one can be related to form factors of proton-to-Delta transition (another puzzle for hard pQCD). The GPDs for $N \rightarrow N + \text{soft } \pi$ processes can be used for testing the soft pion theorems and physics

of chiral symmetry breaking.

An interesting problem is the separation and flavor decomposition of GPDs. The DVCS amplitude involves all 4 types: $H, E, \widetilde{H}, \widetilde{E}$ of GPDs, so we need to study other processes involving different combinations of GPDs. An important observation is that, in hard electroproduction of mesons, the spin nature of the produced meson dictates the type of GPDs involved, e.g., for pion electroproduction, only $\widetilde{H}, \widetilde{E}$ appear, with $\widetilde{E}$ dominated by the pion pole at small t . This gives access to (generalization of) polarized parton densities without polarizing the target.

10. SUMMARY AND CONCLUSIONS

The structure of hadrons is the fundamental physics to be accessed via GPDs. GPDs describe hadronic structure on the quark-gluon level and provide a 3-dimensional picture (“tomography”) of hadronic structure. GPDs adequately reflect the quantum-field nature of QCD (correlations, interference). They also provide new insights into spin structure of hadrons (spin-flip distributions, orbital angular momentum). GPDs are sensitive to chiral symmetry breaking effects, a fundamental property of QCD. Furthermore, GPDs unify existing ways of describing hadronic structure. The GPD formalism provides nontrivial relations between different exclusive reactions and also between exclusive and inclusive processes.

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