

Generalized Parton Distributions – theoretical review –

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Abstract

In this talk an introduction to generalized parton distributions is given. Recent developments are shortly reviewed, including non-perturbative calculations, phenomenological aspects and evaluation of higher order perturbative and power corrections.

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Generalized Parton Distributions – theoretical review –

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In this talk an introduction to generalized parton distributions is given. Recent developments are shortly reviewed, including non-perturbative calculations, phenomenological aspects and evaluation of higher order perturbative and power corrections.

1. Introduction

Generalized parton distributions (GPDs) [1, 2, 3, 4] and their crossed version, i.e., the generalized distribution amplitudes (GDAs) [1, 5] appear in the perturbative description of certain hard exclusive processes, e.g., in the lepton production of photon and mesons or in the production of hadron pairs in two photon annihilation. Although the first systematic study of GPDs and GDAs was done for more than one decade [1], their physical significance has been widely realized in connection with the proton spin puzzle. Namely, these distributions incorporate, besides other non-perturbative information that is not encoded in forward parton densities or form factors, also gravitational form factors from which the quark orbital angular momentum fraction contributing to the nucleon spin can be read off [2]. This perception induced then intensive theoretical and experimental studies, in which it has been fully realized that GPDs and GDAs are a new concept to study the structure of hadrons and nuclei, contain a link between exclusive and inclusive processes and open a new window for the exploration of non-perturbative QCD. In the following a mini review about these developments is given, for comprehensive ones see Refs. [6, 7, 8, 9].

In Sect. 2 the basic properties of GPDs and their partonic interpretation are presented. In Sect. 3 GPD ansätze are shortly discussed and is then devoted to the non-perturbative evaluation. The exclusive processes, which allow to gain access to these distributions, are listed in Sect. 4. In Sect. 5 results from the evaluation of radiative and power suppressed corrections beyond leading order (LO) are reported and finally, the conclusions are given.

2. Features of Generalized parton distributions

GPDs are defined as Fourier transform of light-ray operators, sandwiched between the initial and final hadronic states. There is a whole compendium of GPDs: corresponding to the species of hadrons, the initial and final states can have different quantum numbers (transition GPDs), and even we might replace the hadrons by nuclei (nucleus GPDs). Specified the initial and final states, GPDs are classified with respect to the twist of the

operators and the spin content of fields. At leading twist-two level three different types of quark and gluon GPDs can be defined (here the gauge link is omitted):

$$\left\{ \begin{array}{l} q_q^V \\ q_q^A \\ q_q^T \end{array} \right\} (x, \xi, \Delta^2, \mu^2) = \int \frac{d\kappa}{2\pi} e^{i\kappa x P_+} \langle P_2, S_2 | \bar{\psi}_q^r(-\kappa n) \left\{ \begin{array}{l} \gamma_+ \\ \gamma_+ \gamma_5 \\ i\sigma_{+\perp} \end{array} \right\} \psi_q^r(\kappa n) | P_1, S_1 \rangle, \quad (1)$$

$$\left\{ \begin{array}{l} G_q^V \\ G_q^A \\ G_q^T \end{array} \right\} (x, \xi, \Delta^2, \mu^2) = 2 \int \frac{d\kappa}{\pi P_+} e^{i\kappa x P_+} \langle P_2, S_2 | G_{+\mu}^a(-\kappa n) \left\{ \begin{array}{l} g_{\mu\nu} \\ i\epsilon_{\mu\nu-+} \\ \tau_{\mu\nu;\rho\sigma} \end{array} \right\} G_{\nu+}^a(\kappa n) | P_1, S_1 \rangle, \quad (2)$$

with $P_+ = n \cdot (P_1 + P_2)$, $V_- = n^* \cdot V$, $n^2 = (n^*)^2 = 0$, $n \cdot n^* = 1$. In the first (vector) and second (axial-vector) entry the in- and outgoing partons have the same helicities, where its sum or difference of left- and right-handed partons is taken, respectively. For the third entry, called transversity, a helicity flip appears. GPDs depend on the momentum fraction x , conjugated to the light-cone distance 2κ , the longitudinal momentum fraction $\xi = (P_1 - P_2)^+ / (P_1 + P_2)^+$ in the t -channel, the momentum transfer $\Delta^2 \equiv t = (P_2 - P_1)^2$, and the renormalization scale μ^2 . The latter is induced by the renormalization prescription of the operators, which is part of the GPD definition. To deal with the polarization of the hadronic states, one might introduces a form factor decomposition [6, 10]. For instance, for the nucleon GPD Dirac and Pauli-like form factors appear in the vector case [6]:

$$i_q^V = \bar{U}(P_2, S_2) \gamma_+ U(P_1, S_1) H_i(x, \xi, \Delta^2) + \bar{U}(P_2, S_2) \frac{i\sigma_{+\nu} \Delta^\nu}{2M} U(P_1, S_1) E_i(x, \xi, \Delta^2), \quad (3)$$

where $i = u, d, s, \dots, G$. Definitions (1)–(3) imply the basic properties:

- GPDs reduce in the forward limit $\Delta \rightarrow 0$ to parton densities [1, 3, 2, 4], e.g.,

$$q_i(x, \mu^2) = \lim_{\Delta \rightarrow 0} H_i(x, \xi, \Delta^2, \mu^2), \quad \text{and} \quad \lim_{\Delta \rightarrow 0} E_i(x, \xi, \Delta^2, \mu^2) \neq 0, \quad (4)$$

while the helicity flip contribution E_i decouples.

- The μ^2 -dependence is governed by linear evolution equations [1], which can be derived from the renormalization group equation of the light-ray operators [11, 12].
- Hermiticity together with time reversal invariance leads to a definite symmetry with respect to the skewness parameter ξ , e.g., $H_i(x, \xi) = H_i(x, -\xi)$.
- The Mellin moments of GPDs are expectation values of local twist-two operators:

$$\int dx x^n q_q^V(x, \xi, \Delta^2, Q^2) = n^{\mu_0} \dots n^{\mu_n} \langle P_2, S_2 | \mathbf{S} \bar{\psi}_q^r \gamma_{\mu_0} i \overleftrightarrow{D}_{\mu_1} \dots i \overleftrightarrow{D}_{\mu_n} \psi_q^r | P_1, S_1 \rangle. \quad (5)$$

Lorentz covariance induces that they are polynomials in ξ , which are even in (5).

Furthermore, GPDs are constrained in the region $x \geq |\xi|$ by the positivity of the norm in the Hilbert space of states. The most general form of such positivity bounds [13, 14], known so far, are given as an infinite set of constraints [15]. Since GPDs are implicitly

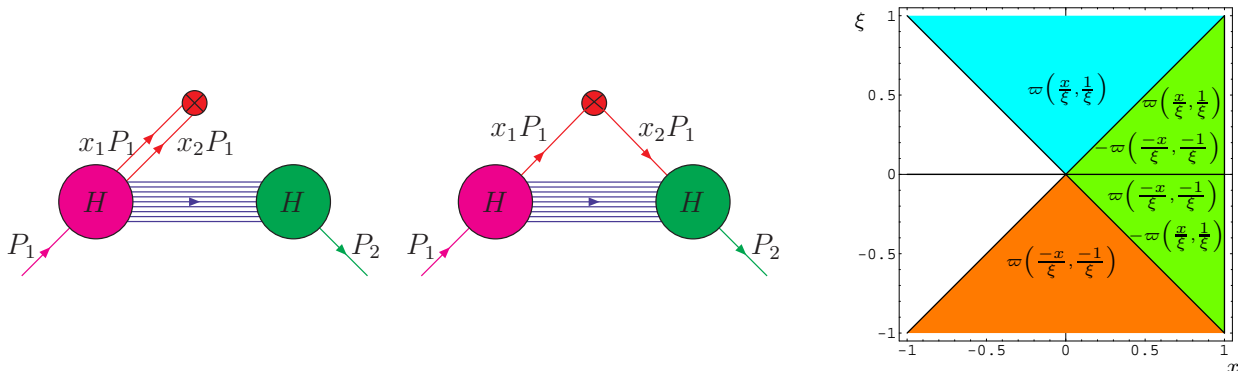


Figure 1. Partonic interpretation and support property (right) of GPDs.

scheme dependent, positivity bounds are a request on both the GPD model and scheme. Note also that GPDs can be represented as overlap of light-cone wave functions [16].

Let us give a partonic interpretation of GPDs. A generic quark GPD, e.g., in the vector case, $q(x, \xi, \Delta^2) = Q(x, \xi, \Delta^2) - \overline{Q}(-x, \xi, \Delta^2)$ is decomposed in its quark Q and anti-quark \overline{Q} part. In the central (exclusive or ER-BL) region $-\xi \leq x \leq \xi$, $Q(x, \xi, \Delta^2)$ might be interpreted as probability amplitude to have a meson like configuration inside the hadron, while the outer (inclusive or DGLAP) region $\xi \leq x \leq 1$ can be viewed as probability amplitude for emission and absorbing a quark with momentum fraction $x_1 P_1 = \frac{x+\xi}{1+\xi} P_1$ and $x_2 P_1 = \frac{x-\xi}{1+\xi} P_1$, respectively. Lorentz invariance ties this both regions, which can be read off from the representation¹ that ensures polynomiality (valid for $\xi \geq 0$):

$$Q(x, \xi, \Delta^2) = \theta(-\xi \leq x \leq 1) \frac{1}{\xi} \varpi \left(\frac{x}{\xi}, \frac{1}{\xi}, \Delta^2 \right) - \theta(\xi \leq x \leq 1) \frac{1}{\xi} \varpi \left(-\frac{x}{\xi}, -\frac{1}{\xi}, \Delta^2 \right). \quad (6)$$

Obviously, in the central region the GPD is given by $\varpi \left(\frac{x}{\xi}, \frac{1}{\xi} \right)$ from which the outer region, determined by the antisymmetric function $\varpi \left(\frac{x}{\xi}, \frac{1}{\xi} \right) - \varpi \left(-\frac{x}{\xi}, -\frac{1}{\xi} \right)$, can be restored, see Fig. 1. The uniqueness of this continuation procedure was shown in connection with the support extension of evolution kernels [1].

GPDs simultaneously possess a longitudinal and transversal momenta dependence and so they encode the three dimensional distribution of partons in the considered hadron or nucleus [17]. Indeed, a partonic density interpretation holds in the infinite momentum frame as long as $\xi = 0$ [18], see also Refs. [19, 20]. In this kinematics the central region, i.e., the parton number violating contributions, drops out. Thus, it could be shown that in the impact parameter space within the infinite momentum frame

$$h_i(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp \cdot \Delta_\perp} H_i(x, \xi = 0, -\Delta_\perp^2) \quad (7)$$

has the probabilistic interpretation to find a parton species i in dependence on the momentum fraction x and the relative distance \mathbf{b}_\perp from the proton center. It is noted that an interpretation of the three dimensional Fourier transform of GPDs in the rest frame has been suggested within the concept of phase space (Wigner) distributions [21, 22].

¹Eq. (6), where $\varpi(x, y, \Delta^2) = \int_0^{\frac{1+x}{1+y}} dw d(x, x - wy, \Delta^2)$ might be derived by means of a partonic Fock state decomposition and the so-called α -representation for Feynman diagrams.

3. Parametrization, model and lattice calculations of GPDs

GPDs are mostly unknown functions with a complex variable dependence, which must satisfy the basic properties. Because of the lack of further knowledge, GPD ansätze, needed for the estimation of cross sections and asymmetries, are constructed so far by simplicity and intuition [14]. Such an ansatz, given at the input scale \mathcal{Q}_0^2 , is based on the assumption of (x, ξ) and Δ^2 factorization and is now widely used in phenomenology:

$$H_i(x, \xi, \Delta^2, \mathcal{Q}_0^2) = F_i(\Delta^2)h_i(x, \xi), \quad h_i(x, \xi) = \int_{-1}^1 dy \int_{-1+|y|}^{1-|y|} \delta(x - y - \xi z) D_i(y, z). \quad (8)$$

Here $F_i(\Delta^2)$ are partonic form factors, partially fixed by sum rules. The reduced GPD $h_i(x, \xi)$ is given in terms of a factorized ansatz for the so-called double distribution $D_i(y, z) = q_i(y, \mathcal{Q}_0^2)\Pi(|z|/(1 - |y|))/(1 - |y|)$ with the parton density $q_i(y, \mathcal{Q}_0^2)$ and an unknown profile function Π [14, 8]. This ansatz might be refined by a regge-like ansatz for the parton densities at small x : $q_i(x) \sim x^{-\alpha_i} \rightarrow x^{-\alpha_i - \alpha'_i \Delta^2}$ [8]. To repair an artifact in the relation among GPD and DD [23] a so-called D -term is added in (8), intuitively understood as meson exchange contribution in the t -channel [24].

In the region $\xi < x$ for small x it also has been proposed to equate the reduced GPDs with the parton densities at the input scale and so skewness is purely generated by evolution [25]. We note that in this region, where gluon and sea quark contributions are dominating, the parameterization of the hard-scattering amplitude convoluted with a GPD drastically simplifies. Here, the skewness effect at the input scale effectively enters the normalization [26]. A further proposal for the GPD parametrization is based on their representation as an infinite sum of t -channel exchange contributions [27].

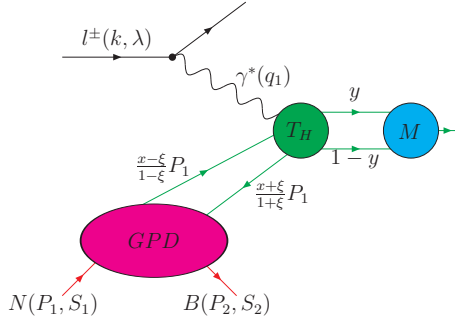
The GPD parameterizations, proposed so far, do not simultaneously satisfy the needs:

- Basic properties must be automatically fulfilled.
- Flexible parametrization of the degrees of freedom that are left.
- Simple numerical treatment of evolution and convolutions.

These requests can be mostly satisfied within a generalization of the Mellin representation for parton densities by adopting the concept of complex angular momentum to the conformal spin expansion of GPDs [28].

The poor knowledge about GPDs might be improved by non-perturbative model calculations, done at a low μ^2 scale. The resulting GPDs can then be evolved to the scale that is relevant for their phenomenological use. However, the scheme dependence of GPDs leads to uncertainties in this matching procedure, which should be considered as part of the model. Because of limited space, all the efforts cannot be reviewed here in detail, however, at least it should be mentioned a few of them, namely, calculations within the MIT bag model [29], chiral quark soliton model [30], constituent quark model [31], and Bethe-Salpeter and light-cone wave function approaches [32].

More recently, the first few Mellin moments (5) for proton GPDs have been measured on the lattice [33]. Especially, the quark orbital angular momentum fraction of the proton spin, the second moment of a certain GPD combination, could be extracted. Also the correlation of the Δ^2 dependence with the order n of moments leads to a valuable insight



Hadronic variables:

$$Q^2 = -q_1^2,$$

$$x_B = \frac{Q^2}{2P_1 \cdot q} \approx \frac{2\xi}{1+\xi}$$

Scaling limit:

$$Q \rightarrow \infty, \quad x_B = \text{fix}$$

$$\Delta^2 = (P_2 - P_1)^2 = \text{fix}$$

Figure 2. Factorization of the meson lepton production amplitude (left) and kinematics.

in the nucleon GPDs. The slope of the Δ^2 dependence decreases with increasing n and so the transversal size of the proton shrinks with increasing x , which has been argued in Ref. [18]. From this one concludes that the factorized ansatz (8) is oversimplified. It might be also possible to rich from lattice results a better understanding of the skewness dependence. So far the common GPD ansätze leads always to an enhancement of the (reduced) GPDs, compared to parton densities, at the crossing point $x = \xi$. For the phenomenology it is highly desired to have a more rigorous understanding of this issue.

4. Hard exclusive reactions to leading order

GPDs appear in the perturbative description of the hard photon or meson lepton production: $l^\pm N \rightarrow l^\pm BX$, where B is the final baryon state and X stands for the photon or the observed meson. The virtuality $-\mathcal{Q}^2$ of the intermediate photon must be sufficiently large. This implies that the hadronic scattering amplitude factorizes into a hard-scattering one convoluted with GPDs and eventually a meson distribution amplitude (DA), see Fig. 2 [4, 34, 35, 36]. Usually, one defines this factorization in such a way that the collinear divergencies are removed within a (modified) minimal subtraction scheme. Obviously, this procedure is ambiguous and induces, e.g., the factorization scale dependence. If the same factorization scheme is applied for all processes, GPDs and DAs are universal in the sense that they are process independent, however, they depend on the scheme and of the order at which the perturbation theory is truncated. Thus, GPDs serve at the first place as a tool that *connect* physical observables measured in different processes. Concerning their probabilistic interpretation, one must conclude that the number of measured partons depends on the scheme conventions (even in untruncated perturbation theory). This problem, appearing also for parton densities, might be resolved by choosing a reference process, e.g., the lepton production of photons, in which all radiative corrections (order by order) are absorbed in the GPD definitions.

Let us first consider the lepton production of a meson. So far the quantum numbers allow such a process and the virtual photon is longitudinally polarized, the process is for sufficient large \mathcal{Q}^2 perturbatively described as shown in Fig. 2. The initial and final hadron state might have different quantum numbers and so it is applicable for several processes, namely, the production of neutral and charged vector [38] and pseudo scalar [39] mesons and or even for exotic states like the pentaquark [40] or hybrid mesons [41]. Besides the cross section also the transversal target spin asymmetry is described within the perturbative framework, which might be justified at a lower scale \mathcal{Q}^2 as for the cross

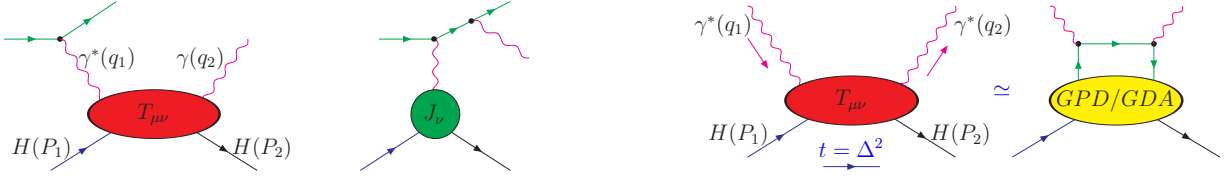


Figure 3. Deeply virtual Compton scattering and Bethe-Heitler bremsstrahlungs process (left) and factorization of the Compton amplitude to leading order (right).

section itself [42, 43]. To LO the convolution of GPDs and meson DA are separated

$$A_L(\xi, \Delta^2, Q^2, S_1, S_2) \propto \frac{\alpha_s}{Q} \sum_{f, \bar{f}=u, \dots, g} \int_{-1}^1 dx \int_0^1 dy q^{f\bar{f}}(x, \xi, \Delta^2, Q^2, S_1, S_2) \\ \times \left[\frac{Q_f}{(1-y)(x-\xi+i\epsilon)} + \frac{Q_{\bar{f}}}{y(x+\xi-i\epsilon)} \right] \phi_M^{f\bar{f}}(y, Q^2)$$

where $q^{f\bar{f}}$ and $\phi_M^{f\bar{f}}$ refers to the (transition) GPD and meson DA, respectively. $Q_f, Q_{\bar{f}}$ are the partonic charge factors, corresponding to the flavor content of the observed meson. Hence, the produced meson serves as a flavor filter and so a flavor decomposition for GPDs can be reached, e.g., by measuring the processes $e^-p \rightarrow e^-p\pi^0$ and $e^-p \rightarrow e^-p\eta$. The amplitude A_L scales with $1/Q$, which leads to a scaling law $d\sigma/d\Delta^2 \propto 1/Q^6$ for the cross section. However, this canonical scaling is logarithmically modified by evolution effects, mainly arising from GPDs.

Several of these processes have been measured or a planned in fixed target (HERMES, JLAB, COMPASS) and collider (H1, ZEUS) experiments, for a review see the contributions of F. Sabatie and L. Favart in this proceedings. I only like to give a short attention to the electroproduction of neutral (longitudinally polarized) vector mesons, measured in the small $x_{Bj} \sim 2\xi$ region up to rather large Q^2 by the H1 and ZEUS collaborations. Here the amplitude (9) drastically simplifies, since now it is dominated by gluon exchange, and thus such experiments are an ideal testing ground of the perturbative framework and the study of the gluonic GPD. Let me remind that under the assumption of SU(3) symmetric meson DAs the ratio of cross sections should be: $\sigma_{\rho^0} : \sigma_\omega : \sigma_\phi = 9 : 1 : 2$, which is in fair agreement with experimental data (plotted with respect to the scale $Q^2 + M_V^2$).

Another class of hard exclusive processes, in which GPDs are accessible, are those in which the struck parton is purely probed within the electromagnetic interaction via the absorption and emission of photons [1]: photo lepton production [47, 26], see Fig. 3, lepton pair photoproduction [48] and lepton pair lepton production [49]. In the first two processes the photon virtuality is space- and time-like respectively, while in the third one both photons are virtual. The latter one is experimentally most challenging, however, it is the only one in which a deconvolution of the GPDs is possible. In all these processes there are two interfering subprocesses, the hard virtual Compton scattering and the Bethe-Heitler (BH) bremsstrahlungs process, given in terms of the electromagnetic form factors. For the case that at least one photon has a large virtuality, the Compton scattering process factorizes, shown in Fig. 3 to LO.

Hence, the cross section has a rich azimuthal angular dependence and the interference term is linear in the GPDs. This offers the possibility to unveil the GPDs by measur-

ing asymmetries that are dominated by the interference term: charge, single beam and target spin asymmetries, while double spin asymmetries require the subtraction of the BH contribution. In collider experiments it is even possible to extract the deeply virtual Compton scattering (DVCS) cross section, since the BH amplitude is sufficiently small. A detailed compendium of asymmetries and their relations to GPDs is given in Ref. [26]. The first measurements of single beam spin and charge asymmetries and cross sections are compatible with the oversimplified GPD ansatz (8).

It was also argued that the amplitudes of the photon and meson photoproduction at large s and $-t$ factorize to LO in terms of the inverse GPD moments $\int_{-1}^1 dx q(x, \xi, t)/x$ [44, 45, 46]. For these processes also a perturbative treatment is used in which all valence partons are resolved via hard gluon exchanges [37]. In this conjecture here only the struck parton is resolved while all spectators are contained in the GPD. This is somehow analogous to the mechanism proposed by Feynman for the description of elastic form factors. Unfortunately, no factorization theorem could be established, since power corrections are uncontrolled. This problem has been attempted to resolve by the assumption that the virtuality of the partons in the initial and final state is always small [45].

Note that the perturbative framework is also applicable for the photon [50] and meson [51] leptonproduction off nuclei. This opens a new window for the study of nucleus binding effects, especially, for the deuteron [10, 52].

5. Beyond leading order predictions

To gain insight in the validity of the perturbative framework and to improve it, it is necessary to calculate higher order perturbative and power suppressed corrections or at least to estimate them. A large amount of work has been done in this direction during the last few years.

The factorization theorems, derived to leading power accuracy, state that the perturbative corrections are systematically calculable in this approximation. The next-to-leading order (NLO) corrections for the hard-scattering amplitude of both Compton scattering processes [53, 36] and for leptonproduction of mesons have been completed [43, 54]. While for the former process the perturbative corrections, which depends on the GPD ansatz, turn out to be moderate, the size of NLO corrections for the latter is rather large. However, these corrections partly cancel in the transversal proton spin asymmetry [43].

Employing conformal consistency predictions [55], the evolution kernels have been evaluated to NLO [56] and are implemented in numerical codes [57]. Note that conformal symmetry in the minimal subtraction scheme is broken in a subtle manner, which can be removed by a finite renormalization, providing the conformal subtraction (CS) scheme [58]. In such a scheme the next-to-next-to-leading order (NNLO) corrections to both the DVCS hard-scattering amplitude and evolution kernels can be borrowed from the known results in deep inelastic scattering, for a first discussion see Ref. [59].

Whether power suppressed contributions can be calculated within perturbative QCD depends on the process in question. For hard exclusive leptonproduction the exchange of a transversal polarized photon yields $1/Q$ suppressed contributions. However, they are affected by non-integrable singularities, which appear to LO in α_s and are induced by

large size quark-antiquark configurations of the produced meson [4]. In the case of photon leptonproduction $1/Q$ suppressed contributions are calculable to LO [60] and NLO [61] accuracy. In fact, they complete the azimuthal angular dependence of the cross section [26]. Interesting to remark, that within an appropriate definition of observables they do not interfere with the twist-two prediction, appearing at leading power.

Twist-two predictions will be affected by $1/Q^2$ power suppressed contributions appearing at twist-four level. Such contributions have been perturbatively calculated to LO by neglecting multi-particle operators [62]. Unfortunately, this approximation suffers from an ambiguity in the choice of the multi-particle operator basis, which shows up in the violation of current conservation. This problem is not resolved so far. Upper bounds of the power corrections to the hard electroproduction have been estimated within the renormalon approach and found to be large [21].

The fact that perturbative and non-perturbative corrections for leptonproduction of mesons are much larger as for photons indicates that the onset of the scaling region for the former process will be at a higher scale as for the latter one. For photon leptonproduction one would expect that, as in the case of deep inelastic scattering, a scale of few GeV^2 is sufficient to apply perturbative QCD.

6. Conclusions

In the last decade the concept of generalized parton distributions and distribution amplitudes has been enormously developed: a partonic interpretation has been given in depth, factorization theorems has been derived, predictions for numerous processes has been worked out, radiative corrections are calculated to NLO accuracy, including the evolution equations, first measurements on the lattice has been performed, and experimental accessibility has been demonstrated in pioneering experiments.

GPDs and also GDAs can be explored within measurements of hard exclusive, however, inelastic processes in fixed target and collider experiments, where a deconvolution with respect to the momentum fraction is practically impossible. Only the leptonproduction of a lepton pairs allows to scan the central region of GPDs. These functions are hybrids that incorporate parton densities, form factors, and distribution amplitudes. Thus, they form a link between exclusive and inclusive processes and encode information about non-perturbative QCD, which cannot be obtained from inclusive or elastic exclusive processes. GPDs/GDAs are a new tool that allows to study the structure of hadrons and nuclei from a new perspective. So for instance, their knowledge would provide the quark orbital angular momentum contributing to the hadron spin and the three dimensional distribution of partons inside hadrons and nuclei. Moreover, they can serve for the study of flavor and chiral symmetry breaking or nucleus binding effects, to name a few. As it has been stressed, GPDs are scheme dependent quantities and, thus, their probabilistic interpretation should be done within an appropriate scheme convention.

The solution of several open problems will require a large effort. The most challenging issue for the theory is whether factorization is applicable for the photon virtuality reached in present experiments. Here higher order calculations beyond the NLO accuracy might give some insight. Also the growing amount of experimental data will help to answer this question. A further issue concerns the appropriate and realistic parametrization of

GPDs. From the first photon leptonproduction measurements it becomes also clear that high precision data are needed to distinguish between GPD models. Certainly, in the last decade a huge, however, first step has been taken in reaching a deeper understanding of the hadron and nuclei structure within the concept of GPDs/GDAs.

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