DESY 01-080

GENERALIZED PARTON DISTRIBUTIONS

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I give an brief introduction to generalized parton distributions, and highlight recent progress made in studying their properties and the processes where they appear.

1 Introduction

The study of generalized parton distributions (GPDs) has made important progress since their introduction some years ago [1,2,3,4]. Unifying the concepts of parton distributions and of hadronic form factors, these quantities contain a wealth of information about how quarks and gluons interact within hadrons. Advances in experimental technology raise hope to measure the exclusive processes where GPDs appear, and the first results from HERA and JLAB are encouraging.

A good way to highlight the similarities and differences between usual parton densities and their generalization is to look at the Compton amplitude. The inclusive DIS cross section can be obtained from the imaginary part of the *forward* amplitude $\gamma^* p \to \gamma^* p$. In the Bjorken region of large photon virtuality Q^2 and collision energy, this amplitude factorizes into a parton distribution and a perturbatively calculable scattering process at the level of quarks and gluons. The amplitude for deeply virtual Compton scattering $\gamma^* p \to \gamma p$, a completely exclusive process, factorizes in an analogous way if in addition to the Bjorken limit we require a small invariant momentum transfer t to the proton. Since the two proton momenta in the diagram of Fig. 1a are now different, the non-perturbative dynamics is not described by ordinary parton distributions, but by quantities which generalize them.

Other processes where GPDs occur are exclusive meson electroproduction, Fig. 1b and c, and timelike Compton scattering [5], $\gamma p \to \gamma^* p$, where the final state photon has a large timelike virtuality and decays into a lepton pair. At high energy, one can also consider hard diffractive processes in kinematical regions where the diffractive final state can be described by a quark-antiquark pair [6]. In a different dynamical context, generalized parton distributions appear in Compton scattering and exclusive meson production at large momentum transfer t, where they describe the physics of the Feynman mechanism for large-angle scattering [7].

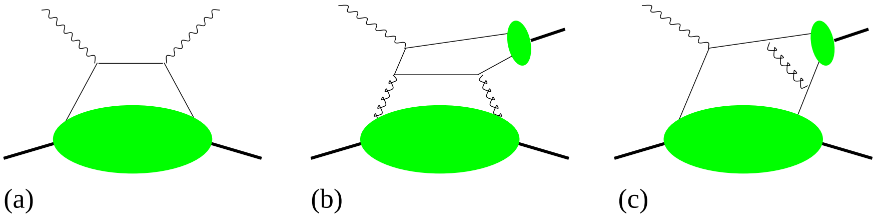

Figure 1. Feynman diagrams for (a) the Compton amplitude, (b) and (c) meson production in the regime where they factorize into a hard partonic scattering and a generalized parton distribution.

2 Some physics aspects

2.1 Parton distributions and wave functions

The key difference between the usual parton distributions and their generalizations is seen by representing them in terms of the quark and gluon light-cone wave functions of the hadron [8,9]. The usual parton distributions are obtained from the squared wave functions for all partonic configurations containing a parton with specified polarization and longitudinal momentum fraction x in the fast moving hadron (Fig. 2a). This represents the *probability* for finding such a parton. In contrast, GPDs represent the *interference* of different wave functions, one where a parton has momentum fraction $x+\xi$ and one where this fraction is $x-\xi$ (Fig. 2b). GPDs thus correlate different parton configurations in the hadron at the quantum mechanical level. There is also a kinematical regime where the initial hadron emits a quark-antiquark or gluon pair (Fig. 2c). This has no counterpart in the usual parton distributions and carries information about $q\bar{q}$ and gg-components in the hadron wave function.

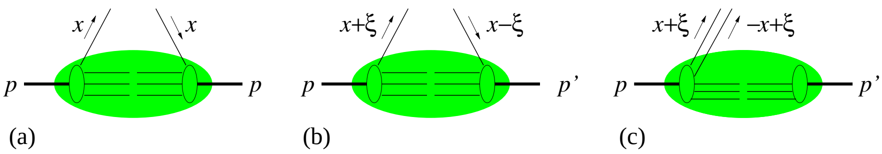

Figure 2. (a) Usual parton distribution, representing the probability to find a parton with momentum fraction x in the nucleon. All configurations of the spectator partons are summed over. (b) GPD in the region where it represents the emission of a parton with momentum fraction $x+\xi$ and its reabsorption with momentum fraction $x-\xi$. (c) GPD in the region where it represents the emission of a parton pair. Here $x+\xi>0$ and $x-\xi<0$.

Apart from the momentum fraction variables x and ξ GPDs depend on the invariant momentum transfer t. This is an independent variable because the momenta p and p' may differ not only in their longitudinal components but also in their transverse ones, p_T and p'_T. GPDs thus contain information on how the transverse distribution of partons in a fast moving hadron is correlated with their longitudinal momentum fraction. The former is connected with t and the latter with ξ, which is related to the energy of the overall process, so that at small ξ this can also be viewed as a particular instance of the shrinkage phenomenon in diffractive processes. A perhaps more intuitive picture of the transverse structure can be obtained by Fourier transforming from $p_T - p'_T$ to impact parameter space [10].

2.2 Spin and orbital angular momentum

GPDs have a rich structure in the polarization of both the hadrons and the partons. For quarks and for gluons, four different combinations contribute to the processes mentioned above. The distributions H and E are summed over the parton helicity, and $\tilde{H}$ and $\tilde{E}$ involve the difference between right and left handed partons. H and $\tilde{H}$ conserve the helicity of the proton, whereas E and $\tilde{E}$ allow for the possibility that the proton helicity is flipped. In that case the overall helicity is not conserved: the proton changes helicity but the partons do not, so that angular momentum conservation has to be ensured by a transfer of *orbital* angular momentum. This is only possible for nonzero transverse momentum transfer, and therefore cannot be observed with ordinary parton distributions, where the momenta p and p' are equal. That GPDs deeply involve the orbital angular momentum of the partons is reflected in Ji's sum rule [2], which states that the second moment $\int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)]$ of quark distributions is a form factor whose value at $t = 0$ gives the *total* angular momentum carried by quarks, both its spin and orbital part.

2.3 Small x

The momentum fraction variables x and ξ of the generalized distributions play different roles in the amplitude of physical processes: x parameterizes a loop momentum and is always integrated over, whereas ξ is fixed to $x_B/(2 - x_B)$ by external kinematics, where x_B is the usual Bjorken variable as defined for deep inelastic scattering. Broadly speaking, the loop integrals will however probe smaller values of x when ξ becomes small.

As ξ becomes very small, the relative difference of momentum fractions in the GPD is small over an increasingly large region of x. There is a hope that the measurement of GPDs in this regime can help constrain the usual parton distributions, in particular the gluon density H_g, which is expected to dominate the amplitudes for Vector meson production and the Compton process. Vector meson data from the HERA collider have already been used in an attempt to get information on the gluon density $g(x)$ at small x [11]. It is not a trivial task to relate the function $H_g(x, \xi, t)$ of three variables with $g(x)$, but theoretical arguments [12] building on the QCD evolution equations for GPDs suggest that at small enough ξ this can be done within reasonable uncertainties. Careful analysis will be necessary here: recent numerical studies [13] suggest for example that the *real* part of the amplitude for deeply virtual Compton scattering can receive significant contributions from the region $-\xi < x < \xi$, even at small ξ. This is the $q\bar{q}$ or gg region depicted in Fig. 2c, whose physics is not easily related with the ordinary parton densities.

3 Progress and tasks

3.1 Modeling GPDs

The wealth of information contained in GPDs comes with the challenge to handle functions of three kinematical variables x, ξ, and t. A good understanding of what this functional dependence may look like is important to formulate realistic models of these functions. It is also needed in order to devise physically motivated parameterizations for them, which will probably be the starting point in trying to extract information from data, just as is the case for the ordinary parton densities.

Efforts to model GPDs are proceeding along different lines. Many current parameterizations are based on the concept of double distributions [1,3], which may be seen as "generating functions" for the GPDs. They incorporate the nontrivial requirements on the x and ξ dependence imposed by Lorentz invariance, and present a convenient way to use the known parton densities as an input to the model. Since one cannot expect to obtain the physics of the $q\bar{q}$ or gg region by "extrapolating" information from the usual parton densities, such approaches are typically supplemented with terms that only have support in the interval $-\xi < x < \xi$, such as the Polyakov-Weiss D-term and contributions describing pion exchange in the t-channel [14].

Other approaches include models based on the representation of generalized distributions in terms of light-cone wave functions [15]. The possible structure of GPDs can also be explored in field theories such as QED [8] or two-dimensional QCD [16], which are simpler than full QCD. Finally, there have been attempts to calculate GPDs in approximations of QCD such as the MIT bag [17] and the chiral quark soliton model [18]. Let us remark that several of these approaches do *not* support a simple factorizing ansatz of the type $f(x,\xi,t) = g(x,\xi)F(t)$ for the GPDs. In the light of our discussion above, this reflects that the correlation between transverse and longitudinal structure in the proton in indeed nontrivial.

3.2 Corrections in α_s and in $1/Q$

For a reliable extraction of GPDs from exclusive processes, a quantitative understanding of the reaction mechanisms is necessary. This includes a sufficient control over radiative corrections to the hard sub-processes, and of the corrections to the Bjorken limit, which are suppressed by inverse powers of the large scale Q. The evolution equations for GPDs are known to NLO accuracy, as are the hard scattering coefficients for Compton scattering [13], and also the NLO corrections to meson production via quark exchange (Fig. 1c) [19]. We will need to gain experience and understanding of when and why such corrections can be numerically important; a recent study for the Compton process has been presented at this meeting [13].

A large amount of work has recently been devoted to the first power corrections to the Bjorken limit in the Compton process, i.e., the terms going like $1/Q$ in the amplitude [20,21]. Their analysis can be done in close analogy to the spin dependent structure function g_2 of inclusive DIS. Notably, the $1/Q$ contributions can be grouped into two classes. The first involves the handbag diagram of Fig. 1a, taking into account the finite transverse momentum k_T of the quark in the hard scattering, and is related to the twist-two distributions H_q, E_q, $\tilde{H}_q$, $\tilde{E}_q$ through Wandzura-Wilczek type relations. The second kind of terms goes with twist-three non-forward proton matrix elements, diagrammatically represented by blobs with three parton legs instead of two. The relative size of these contributions is unknown, so that it remains to be seen whether the $1/Q$ power corrections can be used as additional handles on the twist-two distributions, or will provide a glimpse beyond g_2 on the size of higher parton correlations in the proton.

In this context it is important that, up to corrections, the $1/Q$ terms in the Compton amplitude contribute only to transitions where the initial virtual photon is longitudinal, whereas the leading terms only involve transverse initial photons. Using angular distributions in the final state of the electroproduction process $ep \to ep\gamma$, one can separate the two types of contributions [21,22]. This means on one hand that in suitable observables the leading terms do not suffer potentially large $1/Q$ corrections, and on the other hand, that the $1/Q$ terms can be studied for themselves, without a large background from leading scaling terms.

4 Conclusions

The basic properties and the basic physics potential of GPDs are rather well understood, and their appearance in the description of exclusive processes rests on solid ground. Progress has been made in understanding the possible shapes of GPDs, and the corrections to the simple dynamical pictures of Fig. 1, but more experience will be necessary in order for theory to keep up with the encouraging experimental developments in the field [23].

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