Generalized parton distributions in the context of HERA measurements

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Abstract

We present the recent experimental results from deeply virtual Compton scattering (DVCS) from H1 and ZEUS experiments at HERA. Their interpretation encoded in the generalized parton distributions is discussed.

1 Introduction

Measurements of the deep-inelastic scattering (DIS) of leptons and nucleons, $e + p \rightarrow e + X$, allow the extraction of Parton Distribution Functions (PDFs) which describe the longitudinal momentum carried by the quarks, anti-quarks and gluons that make up the fast-moving nucleons. While PDFs provide crucial input to perturbative Quantum Chromodynamic (QCD) calculations of processes involving hadrons, they do not provide a complete picture of the partonic structure of nucleons. In particular, PDFs contain neither information on the correlations between partons nor on their transverse motion. Hard exclusive processes, in which the nucleon remains intact, have emerged in recent years as prime candidates to complement this essentially one dimensional picture. The simplest exclusive process is the deeply virtual Compton scattering (DVCS) or exclusive production of real photon, $e + p \rightarrow e + \gamma + p$. This process is of particular interest as it has both a clear
experimental signature and is calculable in perturbative QCD. The DVCS reaction can be regarded as the elastic scattering of the virtual photon off the proton via a colourless exchange, producing a real photon in the final state [1, 2, 3, 4]. In the Bjorken scaling regime, QCD calculations assume that the exchange involves two partons, having different longitudinal and transverse momenta, in a colourless configuration. These unequal momenta or skewing are a consequence of the mass difference between the incoming virtual photon and the outgoing real photon. This skewedness effect can be interpreted in the context of generalised parton distributions (GPDs) [5].

With \( t = (p - p')^2 \), the momentum transfer (squared) at the proton vertex, the measurement of the VM and DVCS cross section, differential in \( t \) is one of the key measurement in exclusive processes. A parameterization in \( d\sigma/dt \sim e^{-b|t|} \), as shown in Fig. 1, gives a very good description of measurements. In addition, in Fig. 1 we show that fits of the form \( d\sigma/dt \sim e^{-b|t|} \) can describe DVCS measurements to a very good accuracy for different \( Q^2 \) and \( W \) values.

![Figure 1: The DVCS cross section, differential in \( t \), for three values of \( Q^2 \) expressed atand for three values of \( W \). The solid lines represent the results of fits of the form \( e^{-b|t|} \).](image)

Then, we can define a generalised gluon distribution \( F_g \) which depends both on \( x \) and \( t \) (at given \( Q^2 \)). From this function, we can compute a gluon density which also depends on a spatial degree of freedom, a transverse size
(or impact parameter), labeled $R_\perp$, in the proton. Both functions are related by a Fourier transform

$$g(x, R_\perp; Q^2) \equiv \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i(\Delta_\perp R_\perp)} F_g(x, t = -\Delta_\perp^2; Q^2).$$

From the Fourier transform relation above, the average impact parameter (squared), $\langle r_T^2 \rangle$, of the distribution of gluons $g(x, R_\perp)$ is given by

$$\langle r_T^2 \rangle \equiv \frac{\int d^2 R_\perp g(x, R_\perp) R_\perp^2}{\int d^2 R_\perp g(x, R_\perp)} = 4 \frac{\partial}{\partial t} \left[ \frac{F_g(x, t)}{F_g(x, 0)} \right]_{t=0} = 2b,$$

(1)

where $b$ is the exponential $t$-slope. In this expression, $\sqrt{\langle r_T^2 \rangle}$ is the transverse distance between the struck parton and the center of momentum of the proton. The latter is the average transverse position of the partons in the proton with weights given by the parton momentum fractions. At low $x_{Bj}$, the transverse distance defined as $\sqrt{\langle r_T^2 \rangle}$ corresponds also to the relative transverse distance between the interacting parton (gluon in the equation above) and the system defined by spectator partons. Therefore provides a natural estimate of the transverse extension of the gluons probed during the hard process. In other words, a Fourier transform of momentum to impact parameter space readily shows that the $t$-slope $b$ is related to the typical transverse distance in the proton. This $t$-slope, $b$, corresponds exactly to the slope measured once the component of the probe itself contributing to $b$ can be neglected, which means at high scale: $Q^2$ or $M_{VM}^2$. Indeed, at high scale, the $q\bar{q}$ dipole is almost point-like, and the $t$ dependence of the cross section is given by the transverse extension of the gluons in the proton for a given $x_{Bj}$ range.

DVCS results lead to $\sqrt{\langle r_T^2 \rangle} = 0.65 \pm 0.02$ fm at large scale $Q^2 > 8$ GeV$^2$ for $x_{Bj} \simeq 10^{-3}$. This is not useless to recall that this observation is extremely challenging on the experimental analysis side. We are dealing with nano-barn cross sections, that we measure as a function of $t$, and finally, we measure the energy dependence of this behavior in $t$. Of course, the gain is important. In particular, the great interest of the DVCS is that the $t$ dependence measured is free of effects that could come from VM wave functions (in case of VMs) and then spoil (to a certain limit) the interpretation of $b$ described above. Thus, with DVCS, we have the advantage to work in a controlled environment (photon wave functions) where the generic Eq. (1) can be applied to the measurement (almost directly) and must not be corrected with effects arising from VMs wave function.
2 Generalised parton distributions

In the previous section, we have shown that data on DVCS can give access to the spatial distribution of quarks and gluons in the proton at femto-meter scale. Then, we have defined functions, which model this property (for gluons) through the relation

$$g(x, R_\perp; Q^2) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i(\Delta_\perp R_\perp)} F_g(x, t = -\Delta_\perp^2; Q^2).$$

Of course, a similar relation holds for quarks, linking the two functions $q(x, R_\perp; Q^2)$ and $F_q(x, t = -\Delta_\perp^2; Q^2)$. The general framework for this physics is encoded in the so-called generalized parton distributions (GPDs) (see Ref. [5, 6]).

We already know that the reconstruction of spatial images from scattering experiments by way of Fourier transform of the observed scattering pattern is a technique widely used in physics, for example, in X-rays scattering from crystals. In simple words, what we have done experimentally is that we have extended this technique to the spatial distribution of quarks and gluons within the proton, using processes that probe the proton at a tiny resolution scale. Of course, as already mentioned, working at a femto-meter scale with nano-barn cross sections is very challenging from the experimental front. We have achieved this and it immediately opens a way in the ambitious program of mapping out the GPDs. We come back below in a more systematic way on different aspects of that program that requires a large amount of experimental informations, for which future programs at JLab and CERN are appealing.

Let us give a short overview of GPDs, in simple terms. It is interesting, even for an experimentalist, as it clarifies the Fourier transform relation discussed above and makes more transparent the goals for the future. For complete reviews, see Ref. [5, 6]. GPDs are defined through matrix elements $\langle p'|\mathcal{O}|p \rangle$ between hadron states $|p\rangle$ and $|p'\rangle$, with non-local operators $\mathcal{O}$ constructed from quark and gluon fields. From this expression, we understand why GPDs are directly related to the amplitude for VM or real gamma exclusive production. For unpolarized quarks there are two distributions $H^q(x, \xi, t)$ and $E^q(x, \xi, t)$, where $x$ and $\xi$ are defined in Fig. 2. The former is diagonal in the proton helicity, whereas the latter describes proton helicity flip. For $p = p'$ and equal proton helicities, we recover the diagonal matrix element parameterized by usual quark and antiquark densities, so that $H^q(x, 0, 0) = q(x)$ and $H^q(-x, 0, 0) = -\bar{q}(x)$ for $x > 0$. Note that the
functions of type $E$ are not accessible in standard DIS, as it corresponds to matrix elements $\langle p', s'|O| p, s \rangle$ with $s \neq s'$. Even in DVCS-like analysis, it is very difficult to get a sensitivity to these functions, as in most observables, their contributions are damped by kinematic factors of orders $|t|/M_p^2$, with an average $|t|$ value in general much smaller that 1 GeV$^2$. Then, till stated otherwise, our next experimental discussions are concentrated on the determination of GPDs of type $H_q$ or $H_g$. We come back later on this point and show specific cases where $E$-type functions can be accessed and why this is an important perspective.

An interesting property of GPDs, which lightens their physics content, is that their lowest moments give the well-known Dirac and Pauli form factors

$$\sum_q e_q \int dx \, H^q(x, \xi, t) = F_1(t) \quad \sum_q e_q \int dx \, E^q(x, \xi, t) = F_2(t), \quad (2)$$

where $e_q$ denotes the fractional quark charge. It means that GPDs measure the contribution of quarks/gluons, with longitudinal momentum fraction $x$, to the corresponding form factor. In other words, GPDs are like mini-form factors that filter out quark with a longitudinal momentum fraction $x$ in the proton. Therefore, in the same way as Fourier transform of a form factor gives the charge distribution in position space, Fourier transform of GPDs (with respect to variable $t$) contains information about the spatial distribution of partons in the proton.

The strong interest in determining GPDs of type $E$ is that these functions appear in a fundamental relation between GPDs and angular momenta of
partons. Indeed, GPDs have been shown to be related directly to the total angular momenta carried by partons in the nucleon, via the Ji relation \[5\]

\[
\frac{1}{2} \int_{-1}^{1} dx \left( H_q(x, \xi, t) + E_q(x, \xi, t) \right) = J_q.
\] (3)

As GPDs of type \(E\) are essentially unknown apart from basic sum rules, any improvement of their knowledge is essential. From Eq. (3), it is clear that we could access directly to the orbital momentum of quarks if we had a good knowledge of GPDs \(H\) and \(E\). Indeed, \(J_q\) is the sum of the longitudinal angular momenta of quarks and their orbital angular momenta. The first one is relatively well known through global fits of polarized structure functions. It follows that a determination of \(J_q\) can provide an estimate of the orbital part of its expression. In Ji relation (Eq. (3)), the function \(H\) is not a problem as we can take its limit at \(\xi = 0\), where \(H\) merges with the PDFs, which are well known. But we need definitely to get a better understanding of \(E\).

In order to give more intuitive content to the Ji relation (3), we can comment further its dependence in the function \(E\). From our short presentation of GPDs, we know that functions of type \(E\) are related to matrix elements of the form \(\langle p', s'| O | p, s \rangle\) for \(s \neq s'\), which means helicity flip at the proton vertex \((s \neq s')\). That’s why their contribution vanish in standard DIS or in processes where \(t\) tends to zero. More generally, their contribution would vanish if the proton had only configurations where helicities of the partons add up to the helicity of the proton. In practice, this is not the case due to angular momentum of partons. This is what is reflected in a very condensed way in the Ji relation (Eq. (3)).

Then, we get the intuitive interpretation of this formula: it connects \(E\) with the angular momentum of quarks in the proton. A similar relation holds for gluons [4], linking \(J_g\) to \(H_g\) and \(E_g\) and both formulae, for quarks and gluons, add up to build the proton spin

\[ J_q + J_g = 1/2. \]

This last equality must be put in perspective with the asymptotic limits for \(J_q\) and \(J_g\) at large scale \(Q^2\), which read \(J_q \to \frac{3n_f}{2 + 3n_f}\) and \(J_g \to \frac{16}{2 + 3n_f}\), where \(n_f\) is the number of active flavors of quarks at that scale (typically \(n_f = 5\) at large scale \(Q^2\)) [5].
In words, half of the angular momentum of the proton is carried by gluons (asymptotically). It is not trivial to make quantitative estimates at medium scales, but it is a clear indication that orbital angular momentum plays a major role in building the angular momentum of the proton. It implies that all experimental physics issues that intend to access directly or indirectly to GPDs of type $E$ are essential in the understanding of the proton structure, beyond what is relatively well known concerning its longitudinal momentum structure in $x_{Bj}$. And that’s also why first transverse target-spin asymmetries (which can provide the best sensitivity to $E$) are so important and the fact that such measurements have already been done is promising for the future [5, 6].

Clearly, we understand at this level the major interest of GPDs and we get a better intuition on their physics content. They simultaneously probe the transverse and the longitudinal distribution of quarks and gluons in a hadron state and the possibility to flip helicity in GPDs makes these functions sensitive to orbital angular momentum in an essential way. This is possible because they generalize the purely collinear kinematics describing the familiar twist-two quantities of the parton model. This is obviously illustrating a fundamental feature of non-forward exclusive processes [5, 6].

3 Outlook

We have reviewed the most recent experimental results from DVCS at HERA. Exclusive processes in DIS, like DVCS, have appeared as key reactions to trigger the generic mechanism of diffractive scattering. Decisive measurements have been performed recently, which provide first experimental features concerning proton tomography, on how partons are localized in the proton. A unified picture of this physics is encoded in the GPDs formalism.

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