Generalized Parton Distributions : Experimental aspects

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1. INTRODUCTION

Much of the internal structure of the nucleon has been revealed during the last two decades through the inclusive scattering of high energy leptons on the nucleon in the Bjorken -or “Deep Inelastic Scattering” (DIS)- regime \( Q^2, \nu \gg 1 \) and \( x_B = \frac{Q^2}{2M\nu} \) finite). Simple theoretical interpretations of the experimental results and quantitative conclusions can be reached in the framework of QCD, when one sums over all the possible hadronic final states. For instance, unpolarized DIS brought us evidence of the quark and gluon substructure of the nucleon, quarks carrying about 45% of the nucleon momentum. Furthermore, polarized DIS revealed that no more than about 25% of the spin of the nucleon is carried by the quarks’ intrinsic spin.

Now, with the advent of the new generation of high-energy, high-luminosity lepton accelerators combined with large acceptance spectrometers, a wide variety of exclusive processes in the Bjorken regime can be envisaged to become accessible experimentally. Until recently, no sound theoretical formalism was available for a systematic interpretation, in particular for the electroproduction of photons and mesons. A unified description is now under way through the formalism of new “Generalized Parton Distributions” (GPDs) -also called “Skewed Parton Distributions”-. These distributions parametrize the complex structure of the nucleon and allow to describe various exclusive processes such as Virtual Compton Scattering ([1,2]) and (longitudinal) vector and pseudo-scalar meson electroproduction [3]. The GPDs contain information on the correlations between quarks (i.e. non-diagonal elements) and on their transverse momentum dependence in the nucleon. As a direct effect of these features, Ji also showed [1] that the second moment of these GPDs gives access to the sum of the quark spin and the quark orbital angular momentum to the nucleon spin, which may shed light on the so-called nucleon “spin-puzzle”. Most of these informations are not contained in the traditional inclusive parton distributions extracted from inclusive DIS which allows to access only partons densities, i.e. diagonal elements.

In this paper, after briefly outlining the formalism of the GPDs in section 2, we will discuss some general considerations for their experimental study in section 3 : in particular, the relation between GPDs and experimental observables and the need and requirements for a dedicated experimental facility. Finally, in section 4, we will review and comment the first experimental signatures of this physics recently observed by the HERMES and CLAS (at JLab) collaborations.
2. FORMALISM

A few years ago, Ji [1] and Radyushkin [2] have shown that the leading order pQCD amplitude for Deeply Virtual Compton Scattering (DVCS) in the forward direction can be factorized in a hard scattering part (exactly calculable in pQCD) and a nonperturbative nucleon structure part as is illustrated in Fig.(1-a). In these so-called “handbag” diagrams, the lower blob which represents the structure of the nucleon can be parametrized, at leading order pQCD, in terms of 4 generalized structure functions, the GPDs. These are traditionally called $H$, $\tilde{H}$, $E$, $\tilde{E}$, and depend upon three variables: $x$, $\xi$ and $t$. $x - \xi$ is the longitudinal momentum fraction carried by the initial quark struck by the virtual photon. Similarly, $x + \xi$ relates to the final quark going back in the nucleon after radiating a photon. $-2\xi$ is therefore the longitudinal momentum difference between the initial and final quarks. In comparison to $-2\xi$ which refers to longitudinal degrees of freedom, $t$, the standard squared 4-momentum transfer between the final nucleon and the initial one, contains transverse degrees of freedom (so-called “$k_\perp$”) as well.

$H$ and $E$ are spin independent, and are often called unpolarized GPDs, whereas $\tilde{H}$ and $\tilde{E}$ are spin dependent, and are often called polarized GPDs. The GPDs $H$ and $\tilde{H}$ are actually a generalization of the parton distributions measured in deep inelastic scattering. Indeed, in the forward direction, $H$ reduces to the quark distribution and $\tilde{H}$ to the quark helicity distribution measured in deep inelastic scattering. Furthermore, at finite momentum transfer, there are model independent sum rules which relate the first moments of these GPDs to the elastic form factors.

The GPDs reflect the structure of the nucleon independently of the reaction which probes the nucleon. They can also be accessed through the hard exclusive electroproduction of mesons $\pi^0$, $\rho^0$, $\omega$, $\phi$, etc.- (see Fig. (1-b)) for which a QCD factorization proof was given recently [3]. According to Ref.[3], the factorization applies when the virtual photon is longitudinally polarized because in this case, the end-point contributions in the meson wave function are power suppressed. It is shown in Ref.[3] that the cross section for a transversely polarized photon is suppressed by $1/Q^2$ compared to a longitudinally polarized photon. Because the transition at the upper vertices of Fig. (1-b) will be dominantly

![Figure 1. “Handbag” diagrams : a) for DVCS (left) and b) for meson production (right).](image-url)
helicity conserving at high energy and in the forward direction, this means that the vector meson should also be predominantly longitudinally polarized (notation $\rho^0_L, \omega_L, \phi_L$) for a longitudinal photon at QCD leading order and leading twist.

It was also shown in [3] that leading order pQCD predicts that the vector meson channels ($\rho^0_L, \omega_L, \phi_L$) are sensitive only to the unpolarized GPDs ($H$ and $E$) whereas the pseudo-scalar channels ($\pi^0, \eta, ...$) are sensitive only to the polarized GPDs ($\tilde{H}$ and $\tilde{E}$). In comparison to meson electroproduction, DVCS depends at the same time on both the polarized and unpolarized GPDs.

Another feature to mention, proper to these handbags diagrams, is the notion of scaling. It is predicted that, when asymptotia in $Q^2$ is reached, the differential cross section $d\sigma/dt$ of these “handbag” mechanisms should show a $Q^4$ behavior for DVCS and a $Q^6$ behavior for meson production. These $Q^2$ dependences are strong experimental signatures that the appropriate kinematical regime is reached and are necessary to observe before tempting to interpret data in terms of GPDs. It has been recently an intense effort from the theoretical community to control the corrections (Next to Leading Order, higher twists, ...) to this scaling behavior [4].

3. GENERAL CONSIDERATIONS FOR AN EXPERIMENTAL STUDY OF THE GPDs

3.1. Deconvolution issues

As mentioned in the previous section, the GPDs depend on three variables: $x$, $\xi$, and $t$. However, it has to be realized that only two of these three variables are accessible experimentally, i.e. $\xi (=-\frac{x_B}{2-x_B}$, fully defined by detecting the scattered lepton) and $t$ ($=-\Delta^2$, see Fig (1-a), fully defined by detecting either the recoil proton or the outgoing photon or meson). $x$ however is a variable which is integrated over, due to the loop in the “handbag” diagrams (see Fig. (1)). This means that in general a differential cross section will be proportional to: $|\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x-\xi+i\epsilon} + ...|^2$ (where “...” stands for similar terms for $E$, $\tilde{H}$, $\tilde{E}$ and $\frac{1}{x-\xi+i\epsilon}$ being the propagator of the quark between the incoming virtual photon and the outgoing photon -or meson-, see Fig. (1)). In general, one therefore will measure integrals (with a propagator as a weighting function) of GPDs.

To illustrate this point, Fig. (2) shows one particular model for the GPD $H$ as a function of $x$ and $\xi$ (at $t = 0$). One recognizes for $\xi = 0$ a standard quark density distribution with the rise around $x = 0$ corresponding to the diverging sea contribution. The negative $x$ part corresponds to antiquarks. One sees that the evolution with $\xi$ is not trivial and that measuring the integral over $x$ of a GPD at constant $\xi$ will not uniquely define it.

A particular exception is when one measures an observable proportional to the imaginary part of the amplitude (for instance, the beam asymmetry in DVCS which is non-zero in leading order due to the interference with the Bethe-Heitler process, see section 4). Then, because $\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x-\xi+i\epsilon} = PP(\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x-\xi}) - i\pi H(\xi, \xi, t)$, one actually measures directly the GPDs at some specific point, $x = \xi$ (i.e., $H(\xi, \xi, t)$).

For mesons, transverse target polarization observables are also sensitive to a different combination of the GPDs, i.e. combinations of the type: $\int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x-\xi} \times E(\xi, \xi, t)$ (the exact formula is more complicated, see for instance [5,6]). One sees that such transverse
spin asymmetries are sensitive to a product of the GPDs instead of a sum of their squares as is the case for a typical differential cross section.

It will therefore be a non-trivial (though a priori not impossible) task to actually extract the GPDs from the experimental observables as, to summarize, one actually only accesses in general (weighted) integrals of GPDs or GPDs at some very specific points or product of these two. In absence of any model-independent “deconvolution” procedure at this moment, one will therefore have to rely on some global model fitting procedure.

It should also be added that GPDs are defined for one quark flavor $q$ (i.e. $H^q, E^q,...$) similar to standard quark distributions. This “flavor” separation will require the measurement of several isospin channels; for instance, $\rho^0$ production is proportional to (in a succinct notation) $2/3H^u + 1/3H^d$ while $\omega$ production is proportional to $2/3H^u - 1/3H^d$. Similar arguments apply for the polarized GPDs with the $\pi^{0,\pm}, \eta,...$ channels. It can be viewed as an intrinsic richness for mesons channels to allow for such flavor separation.

In summary, it should be clear that a full experimental program aiming at the extraction of the individual GPDs is a broad program which requires the study of several isospin channels and several observables, each having its own characteristics. Only a global study and fit to all this information may allow an actual extraction of the GPDs.

3.2. A dedicated facility

An exploratory study of the GPDs can currently be envisaged at the JLab ($E_e=6$ GeV), HERMES ($E_e=27$ GeV) and COMPASS ($E_\mu=100-200$ GeV) facilities in a very complementary fashion, each having its own “advantages” and “disadvantages”. The considerations which are relevant for this “exclusive” physics are:

- Kinematical range: it is desirable to span a domain in $Q^2$ and $x_B$ as large as
possible, in particular to test scaling as mentionned in section 2,

- Luminosity: cross sections fall sharply with $Q^2$ and one has to measure small cross sections,

- Resolution: it is necessary to cleanly identify exclusive reactions. This can be achieved either by a good resolution with the missing mass technique or by detecting all the particles of the final states and thus overdetermining the kinematics of the reaction.

Also, a large acceptance detector is desirable as $t$ and $\Phi$ (for asymmetries, studies of decay angular distributions,...) coverages are needed and, more generally, the aim is, as emphasized previously, to measure several channels and kinematic variables simultaneously.

COMPASS, expected to start taking data in 2001, with a 100 to 200 GeV beam has the clear advantage that it is the only facility allowing to reach small $x_B$ (i.e. $\xi$) at sufficiently large $Q^2$. However, it suffers from a relatively low luminosity ($\approx 10^{32} cm^{-2}s^{-1}$) and relatively poor resolution to rely on the missing mass technique in order to identify an exclusive reaction (there is a project of overcoming this latter point by adding a recoil detector which would overconstrain the kinematics of the reaction [7]).

HERMES suffers basically from the same issues: relatively low luminosity ($\approx 10^{32-33} cm^{-2}s^{-1}$) and resolution not fine enough to fully select exclusive final states, where, for instance, a typical missing mass resolution of the order of 300 MeV allows the contamination of additional pions into a sample of exclusive events. Here, however, a recoil detector is already under construction which should be operational soon and will overcome this issue [8]. HERMES, which has been running since 1996, has the merit of being the first facility to have measured some experimental observables directly relevant to this physics ($\rho_L^0$ cross sections, DVCS beam asymmetry, exclusive $\pi^+$ target asymmetry) as will be discussed in the next section.

JLab (with 6 GeV maximum beam energy in its current running configuration) has the highest luminosity ($\approx 10^{34} cm^{-2}s^{-1}$ for the Hall B large acceptance spectrometer in order to compare fairly with the other two facilities) and very good resolution (a typical missing mass resolution is less than 100 MeV. This good resolution is of course highly correlated with the relatively low energy of the beam). The main drawback of JLab at 6 GeV is obviously the limited kinematical range (at $x_B=.3$, $W > 2$ GeV, one cannot exceed $Q^2=3.5$ GeV$^2$ for instance).

In spite of all the first “breakthrough” measurements related to the GPD physics that are currently being carried out at these facilities, all these considerations clearly call for a dedicated machine which would combine a high luminosity ($\approx 10^{35-36} cm^{-2}s^{-1}$ desirable) and a high energy ($\approx 30$ GeV) beam with a good resolution detector (a few tens of MeV for a typical missing mass resolution). The ELFE [9] and JLab upgrade [10] (with a 11 GeV beam energy) projects would be quite well suited for such a physics program devoted to the systematic study of exclusive reactions and the GPDs.
4. FIRST EXPERIMENTAL EVIDENCES

In this section, we review the first existing experimental data related to GPDs interpretation. Only these past 2 years, have been released by the CLAS and HERMES collaborations experimental data precise enough in the relevant kinematical regime. In this paper, we choose to focus on the valence quark region, i.e. $W < 10 \text{ GeV}$, where the quark exchange mechanism of Fig. (1) dominates. However, it is to be mentionned that DVCS [11] and vector mesons [12] cross sections at low $x_B$ have also been measured by the H1 and ZEUS collaborations which lend themselves to GPD interpretation through “gluon exchange”-type processes [13].

Clearly, the statistics of all these measurements are still not high enough to allow for a fine binning in the kinematical variables and therefore a precise test of GPD models. Nevertheless, they are very encouraging in the sense that the observed signals, although integrated over quite wide kinematical ranges, are generally compatible (in magnitude and in “shape”) with theoretical calculations. It is to be noted by the way that basically all of the calculations accompanying the figures in the following were indeed predictions as they were published before the experimental results.

The experimental observables to be discussed are the single spin beam asymmetry (SSA) in DVCS (measured by HERMES and CLAS) and the longitudinal cross section
of $\rho^0$ electroproduction (measured by HERMES). Fig. (3) shows the first measurement of the SSA for DVCS by HERMES with a 27 GeV positron beam. This asymmetry arises from the interference of the “pure” DVCS process (where the outgoing photon is emitted by the nucleon) and the Bethe-Heitler (BH) process (where the outgoing photon is radiated by the incoming or scattered lepton). The two processes are indistinguishable experimentally and interfere. The BH process being purely real and exactly calculable in QED, one has therefore access, through the difference of cross sections for different beam helicities which is sensitive to the imaginary part of the amplitude, to some linear combination of the GPDs at the kinematical point $(x = \xi, \xi, t)$ as mentioned in the previous subsection.

The beam asymmetry, which is this latter difference of cross sections divided by their sum, is more straightforward to access experimentally as normalization and systematics issues cancel, at first order, in the ratio. For this asymmetry, a shape close to $\sin\Phi$ (not an exact $\sin\Phi$ shape as higher twists and the Bethe-Heitler have some more complex $\Phi$ dependence) is expected, where $\Phi$ is the standard angle between the leptonic and the hadronic plane. At HERMES, the average kinematics is $<x> = .11$, $<Q^2> = 2.6$ GeV$^2$ and $<-t> = .27$ GeV$^2$ for which an amplitude of .23 for the $\sin\Phi$ moment is extracted from the fit [14]. The discrepancy between the theoretical prediction and the data on Fig. (3) can certainly be attributed on the one hand to the large kinematical range over which the experimental data have been integrated and where the model can vary significantly and, on the other hand, to higher twists corrections not calculated (so far, only twist-3 are under theoretical control for the handbag DVCS process -see Ref. [4]-, the leading twist being twist-2).

Also, the DVCS reaction at HERMES is identified by detecting the scattered lepton (positron) and the outgoing photon from which the missing mass of the non-detected proton is calculated. Due to the limited resolution of the HERMES detector, the selected peak around the proton mass is $-1.5 < M_x < 1.7$ GeV which means that contributions to this asymmetry from nucleon resonant states as well cannot be excluded. Let’s recall that a recoil detector aiming at the detection of the recoil proton is projected to be installed at HERMES by 2003 [8]; this will then allow to unambiguously sign the exclusivity of the reaction at HERMES.

This same observable has been measured at JLab with a 4.2 GeV electron beam with the 4$\pi$ CLAS detector [16]. Due to the lower beam energy compared to HERMES, the kinematical range accessed at JLab is different: $<x> = .19$, $<Q^2> = 1.25$ GeV$^2$ and $<-t> = .19$ GeV$^2$. In this case, the DVCS reaction was identified by detecting, besides the scattered lepton, the recoil proton and then calculating the missing mass of the photon (due to the geometry of the CLAS detector, the outgoing photon which is emitted at forward angles escapes detection). The contamination by $ep \rightarrow ep\pi^0$ events can be estimated and subtracted bin per bin, resulting in a rather clean signature of the exclusivity of the reaction.

Figure (4) shows the CLAS measured asymmetry along with theoretical calculations (predictions) which are in fair agreement (the different sign of the CLAS SSA relative to HERMES is due to the use of electron beams in the former case compared to positron beams in the latter). Again, discrepancies can be assigned to the fact that the theory is calculated at a single well-defined kinematical point whereas data has been integrated
over several variables and wide ranges. Furthermore, Next to Leading Order as well twist-4 corrections which may be important at these rather low $Q^2$ values, still need to be quantified.

![Graph showing the longitudinal $\rho^0$ electroproduction cross section in the intermediate $W$ range.](image)

Figure 5. The longitudinal $\rho^0$ electroproduction cross section in the intermediate $W$ range. The dashed curve represents the quark exchange process calculated in the GPD framework whereas the dotted line represents the 2-gluon exchange process. The solid line is the incoherent sum of the two mechanisms. Calculations are from Refs. [18]. Figure is taken from Ref. [19].

In the meson sector, the vector meson channel is the most accessible as it allows rather simply to separate the longitudinal from the transverse part of the cross section through its decay angular distribution (we recall, as mentioned in section 2, that only for the longitudinal part of the cross section is the factorization theorem valid at this stage and allows to make interpretations in terms of GPDs). So far, only the $\rho^0$ channel has yielded sufficient statistics, due to its relatively high cross section, to isolate $\sigma_L$. Figure (5) shows the two HERMES points [19] along with the GPD theoretical calculations (predictions). For vector mesons, two mechanisms contribute in two different kinematical regimes : at low $W$ (i.e. large $x_B$), 2-quark exchange ; at high $W$ (i.e. low $x_B$), 2-gluon exchange. The quark exchange process can be identified and calculated with the handbag diagrams of figure 1 [17,18]. For meson production, due to presence of the “extra” gluon exchange compared to DVCS, large corrections are expected to the leading order. These corrections can be modelled taking into account $k_\perp$ degrees of freedom [17,18]. At HERMES kinematics, this correction factor is found to be about 3 and allows to predict the magnitude of the cross section.

Figure 6. World data for the $\rho/\omega$ ratio as a function of $Q^2$. The figure has been taken and adapted from [21].
One way to get rid of such model dependency in the corrections is to look at ratios of cross sections. Indeed, as pointed out by Ref. [3, 20], these correction factors are expected to factorize and therefore cancel in ratio. One speaks of “precocious scaling”. The HERMES collaboration is about to release the measurement of the $\omega$ cross section in the same kinematical range as the $\rho^0$ cross section, it will be very interesting to compare the $\frac{\omega}{\rho^0}$ ratio to the theoretical prediction of the GPD formalism which yields $\approx 1/5$ [17, 18], this number, quite model independent, arising basically from the ratio of the u and d quark distributions weighted by known isospin factors. This has to be compared to the well-known SU(3) $1/9$ prediction in the low $x_B$ domain. A $W$ (or equivalently $x_B$) dependence is therefore expected for this ratio. This seems to be already observed with the current world data, see Fig. (6), where one can already distinguish a trend -in spite of quite large error bars- where the low $W$ data are close to $\approx 1/5$ whereas the large $W$ data are closer to $1/9$. The preliminary HERMES results tend to confirm this tendency [21].

Similarly, $\frac{\pi^+}{\pi^0}$, $\frac{\pi^0}{\eta}$, $\frac{\rho^+}{\rho^0}$, etc... ratios deserve to be measured as they can be directly compared to leading order and leading twist model independent theoretical predictions in the GPD framework.

5. Conclusion

In conclusion, we believe that the GPDs open a broad new area of physics, by providing a context for understanding exclusive reactions in the valence region (where the quark exchange mechanism dominates) at large $Q^2$. By “constraining” the final state of the DIS reaction, instead of summing over all final states, one accesses some more fundamental structure functions of the nucleon. These functions provide a unifying link between a whole class of various reactions (elastic and inelastic) and fundamental quantities as diverse as form factors and parton distributions. They allow to access new information on the structure of the nucleon, for instance quark’s orbital momentum and, more generally, correlations between quarks.

A full study aiming at the extraction of these GPDs from experimental data requires a new dedicated facility providing high energy and high luminosity lepton beams, equipped with large acceptance and high resolution detectors. First experimental exploratory results from the HERMES and CLAS collaboration provide some evidence that the manifestations of the handbag mechanisms are already observed. This is encouraging and paves the way for a future very rich harvest of hadronic physics and motivates the development of new dedicated projects and facilities.

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