IL NUOVO CIMENTO Vol. 35 C, N. 2 Marzo-Aprile 2012
DOI 10.1393/ncc/i2012-11177-9

Colloquia: Transversity 2011

Transverse spin in exclusive experiments

S. Liuti(1), G. R. Goldstein(2) and J. O. Gonzalez Hernandez(1)

(1) *Department of Physics, University of Virginia - Charlottesville, VA 22901 USA*
(2) *Department of Physics and Astronomy, Tufts University - Medford, MA 02155 USA*

ricevuto il 7 Novembre 2011; approvato il 25 Novembre 2011
pubblicato online l'1 Marzo 2012

Summary. — We analyze a number of open questions in the application of the concept of generalized parton distribution to various high-energy exclusive processes. In particular we discuss the feasibility of global fits of the exclusive data, and provide a recursive procedure based on a physically motivated parametrization. By fixing the parameters to the Deeply Virtual Compton Scattering data we make predictions for chiral odd quantities, including transversity. All of our predictions include theoretical error.

PACS 13.60.Hb – Elastic and Compton scattering.
PACS 13.40.Gp – Electromagnetic form factors.
PACS 24.85.+p – Quarks, gluons, and QCD in nuclear reactions.

1. – Introduction

Generalized Parton Distributions (GPDs) were first introduced to describe the soft matrix elements for deeply virtual exclusive experiments, both Deeply Virtual Meson Production (DVMP) and Deeply Virtual Compton Scattering (DVCS). They have since then developed into one of the new tools, besides Transverse Momentum Distributions (TMDs), and Fracture Functions (FFs), for attacking the issue of whether hadron structure *including spin* can be described within our view of the strong interactions as described by QCD. What makes the GPDs concept unique is that, thanks to the working of QCD factorization, it allows us to describe deeply virtual exclusive processes by a loop diagram which is present directly at the tree amplitude level. One of the consequences is that, differently from both inclusive and semi-inclusive processes, GPDs can in principle provide access to the partons' transverse spatial distributions giving a holographic description of the proton. This also provides essential information for determining the Orbital Angular Momentum (OAM) contribution to the spin sum rule.

The development of a phenomenology of DVCS, DVMP and related processes using GPDs entails relating, and extracting information from a large number of observables (cross sections, and several beam and target spin asymmetries for different relative spin orientations). This program is particularly challenging because of the joint *deeply virtual* and *exclusive* nature of the processes. Their description requires both additional kinematical variables, and the combined measurement of the real and imaginary parts of the generalized form factors. The latter are interpreted, in the deep inelastic limit, as specific convolutions from which the GPDs, in principle, can be extracted.

This talk addresses the issues of how reliably can GPDs be measured/extracted from lepton scattering experiments in the multi-GeV kinematical regime, and of the feasibility of a global fit, given the specific way GPDs appear in the observables. In this phase model calculations play an important role, and particular care should be given to their construction. An important aspect of a global analysis is also the connection between the GPD and TMD sectors.

Finally, GPDs provide a framework in which to study the soft underlying mechanism for spin and color correlations in hadron-hadron collisions. Several aspects related to the extension of the GPD formalism to a broader class of processes are also discussed.

2. – Towards a global analysis?

The type of information we wish to obtain from high energy exclusive experiments is a sufficiently large range of values in (ζ, t, Q^2) that would enable us to reconstruct the partonic spatial distributions of the nucleon from a Fourier transformation in $\mathbf{\Delta}_\perp$. The question of whether the various GPDs can be extracted reliably from current experiments has been raised, given the complications inherent both in their convolution form, and in their complex multi-variable analysis (see, *e.g.*, [1]). A pragmatic response was given in [2,3] where an assessment was made of which GPDs can be extracted using the present body of data from Jefferson Lab and Hermes. In particular, it was concluded that the only Compton Form Factors (CFFs) that are presently constrained by experiments are Re$\mathcal{H}$ and Im$\mathcal{H}$, with rather large errors, up to 30%. Global fits using different models were also conducted in [1]. However, these approaches raise many concerns, among them whether the models used in the fits of [1] can accommodate all of the data with the given number of parameters, and whether a theoretical error can be evaluated.

As a first exploratory step, within the broader perspective of devising new ways of approaching the extraction of information from increasingly complex sets of data, we suggest the idea that a *progressive/recursive fit* should be used rather than a global fit. In our fitting procedure constraints are applied sequentially, the final result being updated upon including each new constraint. In a nutshell, in a first step we provide a flexible form that includes all constraints from inclusive data – DIS structure functions and elastic electroweak form factors. We subsequently evaluate the impact of presently available DVCS data from both Jefferson Lab [4, 5] and Hermes [6].

An important part of our formalism, that will allow us to extend our GPD based interpretation to *e.g. pp* scattering, is the connection between the Dirac basis formulation of the correlation function and the helicity amplitudes formalism (see also [7, 8]). We introduce the helicity amplitudes for DVCS,

$$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'} = \epsilon_\mu^{\Lambda_\gamma} \mathcal{M}^{\mu\nu}_{\Lambda\Lambda'} \epsilon_\nu^{*\Lambda'_\gamma}\,, \tag{1}$$

where ϵ_μ^Λ, are the photon polarization vectors, $(\Lambda_\gamma, \Lambda)$ refer to the initial (virtual) photon and proton helicities, and $(\Lambda'_\gamma, \Lambda')$ to the final ones. The following decomposition of

$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'}$ [8,9] into hard scattering (g), and soft/quark-proton (A) components can be made,

(2) $$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'} = \sum_{\lambda,\lambda'} g_{\lambda,\lambda'}^{\Lambda_\gamma,\Lambda'_\gamma}(X,\zeta,t;Q^2) \otimes A_{\Lambda',\lambda';\Lambda,\lambda}(X,\zeta,t)\,,$$

where, because of parity conservation, $A_{--,--} = A_{++,++}$, $A_{-+,-+} = A_{+-,+-}$, $A_{--,+-} = -A^*_{++,-+}$, and $A_{+-,--} = -A^*_{-+,++}$. The convolution in eq. (2) yields the following decomposition of the transverse photon helicity amplitudes:

(3) $$A_{++,++} + A_{+-,+-} = \frac{\sqrt{1-\zeta}}{1-\zeta/2} H + \frac{-\zeta^2/4}{(1-\zeta/2)\sqrt{1-\zeta}} E\,,$$

(4) $$A_{++,-+} + A_{-+,++} = \frac{1}{\sqrt{1-\zeta}(1-\zeta/2)} \frac{\Delta_1 + i\Delta_2}{2M} E\,,$$

(5) $$A_{++,++} - A_{+-,+-} = \frac{\sqrt{1-\zeta}}{1-\zeta/2} \widetilde{H} + \frac{-\zeta^2/4}{(1-\zeta/2)\sqrt{1-\zeta}} \widetilde{E}\,,$$

(6) $$A_{++,-+} - A_{-+,++} = \frac{\zeta/2}{\sqrt{1-\zeta}(1-\zeta/2)} \frac{\Delta_1 + i\Delta_2}{2M} \widetilde{E}\,.$$

Within the spectator model adopted in ref. [9] the equations above provide functional forms for each GPD, $F_q \equiv (H_q, E_q, \widetilde{H}_q, \widetilde{E}_q)$, $q = u, d$, depending on three mass parameters per quark flavor, plus a normalization factor (see ref. [9] for a detailed description),

(7) $$F_q = G_q(\mathcal{N}_q, m_q, M_X, M_\Lambda)\; X^{-[\alpha + \alpha'(1-X)^p\, t + \beta(\zeta) t]}\,,$$

The additional factor carries four more parameters, a Regge-type contribution, $X^{-\alpha}$, which ensures the correct behavior at low X, and t-dependent terms constructed so as to guarantee that upon Fourier transformation in $\mathbf{\Delta}_\perp$, one obtains finite values in coordinate space as $X \to 1$ [10, 11] at $\zeta = 0$, and accounting for the shift between the initial and final proton's coordinates at $\zeta \neq 0$ [12]. The fit was performed in three steps including: 1) DIS data (forward limit) thus determining all mass parameters in eq. (7) plus α; 2) the nucleon form factors data, determining the normalization, $\mathcal{N}_q$, and the parameters α' and p; 3) DVCS data, determining $\beta(\zeta)$. Results in fig. 1 show the GPD H, and the CFFs [9]. Our fit used the two currently available sets of data, from both Hall A and Hall B collaborations at Jefferson Lab [4, 5]. We then compared our results to data from the Hermes collaboration [6], in a different kinematical regime. In fig. 2 we show as an example our prediction for the Beam Charge Asymmetry A_C *vs.* Hermes data.

Turning to a slightly different problem, by using parity relations among the various quark-parton amplitudes we were recently able to extend our approach to evaluate the chiral odd amplitudes, and from there the chiral odd GPDs. The relations among the amplitudes differ depending on whether the spectator system has spin 0 or 1. The basic

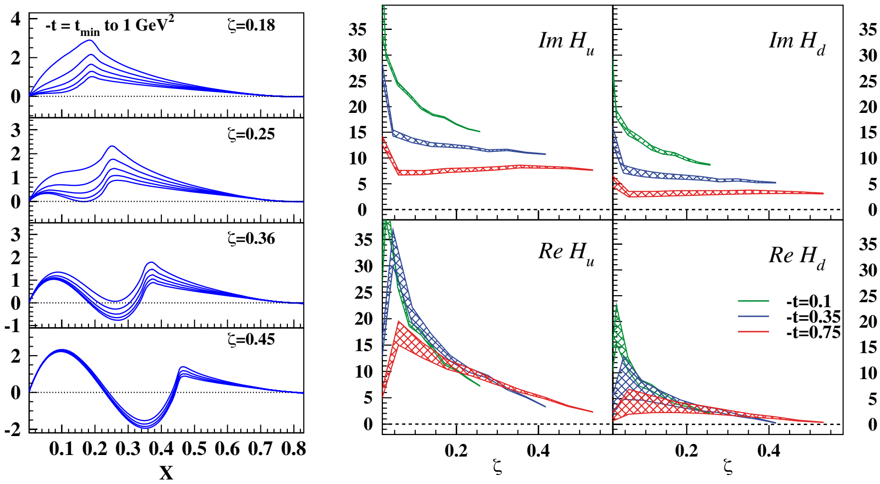

Fig. 1. – Left: $H_u(X,\zeta,t;Q^2)$ evaluated at $Q^2 = 2\,\mathrm{GeV}^2$. Each panel shows H_u plotted *vs.* X at different values of $\zeta = 0.18, 0.25, 0.36, 0.45$ in a range of values of $-t$. Right: Real and imaginary parts of the CFFs, $\mathcal{H}_q(\zeta,t)$ plotted *vs.* $x_{Bj} \equiv \zeta$, for different values of t, at $Q^2 = 2\,\mathrm{GeV}^2$ including theoretical uncertainties from the parameters Similar results are obtained for E, $\widetilde{H}$, $\widetilde{E}$. Adapted from ref. [9].

relations are given below. A more detailed description can be found in [13]:

$$A^{(0)}_{++,--} = A^{(0)}_{++,++}; \qquad A^{(1)}_{++,--} = -\frac{X+X'}{1+XX'}\, A^{(1)}_{++,++}\,, \tag{8}$$

$$A^{(0)}_{++,+-} = -A^{(0)}_{++,-+}; \qquad A^{(1)}_{++,+-} = -\sqrt{\frac{\langle \tilde{k}_\perp^2\rangle}{X'^2 + \langle \tilde{k}_\perp^2\rangle / P^{+2}}}\, A^{(1)}_{++,-+}\,, \tag{9}$$

$$A^{(0)}_{+-,++} = -A^{(0)}_{-+,++}; \qquad A^{(1)}_{+-,++} = -\sqrt{\frac{\langle k_\perp^2\rangle}{X^2 + \langle k_\perp^2\rangle / P^{+2}}}\, A^{(1)}_{-+,++}\,, \tag{10}$$

$$A^{(0)}_{+-,-+} \approx 0; \qquad A^{(1)}_{+-,-+} = 0\,. \tag{11}$$

Our method, applied to deeply virtual π^o electroproduction, improved by the connection displayed above provides the much needed normalizations for exploring the mostly unknown chiral odd GPDs [8, 14]. It also opens up a whole new way of determining transversity from a previously considered unrelated set of data. Our initial predictions for the preliminary π^o electroproduction data in one of the kinematics sets, using chiral odd GPDs are shown in fig. 3. In the figure we also show the values of transversity as extracted from these data.

3. – Future developments and conclusions

We conclude by pointing out a few aspects of the QCD-based description put forth for deeply virtual exclusive processes that require more careful future theoretical study.

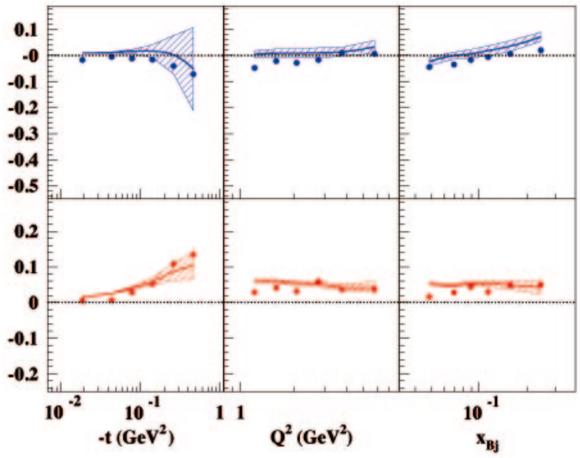

Fig. 2. – Prediction of GGL model including the model's theoretical errors, for the Beam Charge Asymmetry A_C, compared to Hermes data in different kinematical bins explained in [6].

First of all, it can be immediately deduced that, Im$\mathcal{H}_q$, given by the GPD value at the border between the DGLAP and ERBL regions, $H(\zeta, \zeta, t)$, measures the unusual partonic configuration involving an entirely transverse final quark. As one transitions from the DGLAP to ERBL regions, the returning quark acquires a negative longitudinal momentum. Performing the annihilation and creation operators expansion corresponding to this situation, one describes an intermediate state where now the struck quark is on mass shell, and the remnant X state is off mass shell. This corresponds to a semi-disconnected diagram [15, 16]. Care should be given to defining GPDs in this region as

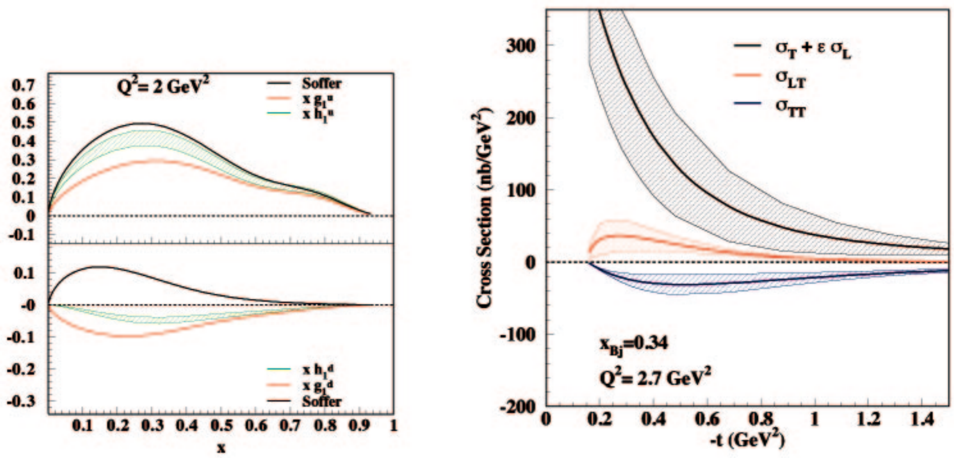

Fig. 3. – Left: Transversity prediction from ref. [13] along with theoretical errors (hashed area) for the up (top panel) and down (bottom panel) quarks. The other curves in the figure represent the Soffer bound, and the values of $g_1^{u,d}$, respectively. Right: exclusive π^o electroproduction cross section components plotted for one of the Hall B kinematics, $Q^2 = 2/7\,\text{GeV}^2$, and $x_{Bj} = 0.34$.

mere extensions of DAs since the quark-antiquark pair cannot be described as emerging directly from the proton target.

Another issue concerns the working of Dispersion Relations (DRs) for deeply virtual exclusive processes. In [17] it was shown that there are important limitations to the use of DRs for processes described by GPDs: DRs do not apply straightforwardly because of the appearance of t-dependent physical thresholds removed from the continuum ones. This mismatch in thresholds is not a higher twist, and/or it does not disappear at large Q^2. A possible characterization of this dilemma is that the derivation of DVCS from OPE might formally not be affected by physical thresholds because it involves the integration variable X which is not a physical observable. However, DRs involve observables. Obtaining the real part of the CFF from the measured "ridge" at $X = \zeta$ through DRs is therefore affected by physical thresholds. As a result, we reiterate that both the real and imaginary parts need to be extracted separately from experiment, at variance with what was recently suggested (see [17] for more details and references).

Barring the problems described above, we proceeded with a "bottom-up" perspective in the interpretation of high energy exclusive data. We introduced a flexible parametrization based on a spectator model that also incorporates Regge behavior at low X. While being consistent with theoretical constraints, we let the experimental data guide the shape of the parametrization as closely as possible. In the ERBL region, because of a potential problem with semi-disconnected diagrams, we adopted a minimal procedure that is consistent with the properties of continuity at $X = \zeta$, polynomiality, and crossing symmetry over the whole range of X.

* * *

This work is supported by the U.S. Department of Energy grants DE-FG02-01ER4120 (J.O.G.H., S.L.), and DE-FG02-92ER40702 (G.R.G.).

REFERENCES

[1] Kumericki K., Mueller D. and Passek-Kumericki K., *Nucl. Phys. B*, **794** (2008) 244.
[2] Guidal M. and Moutarde H., *Eur. Phys. J. A*, **42** (2009) 71.
[3] Moutarde H., *Phys. Rev. D*, **79** (2009) 094021; Moutarde H., [arXiv:1010.4521 [hep-ph]].
[4] Munoz Camacho C. *et al.* (Jefferson Lab Hall A and Hall A DVCS Collaborations), *Phys. Rev. Lett.*, **97** (2006) 262002.
[5] Girod F. X. *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, **100** (2008) 162002.
[6] Airapetian A. *et al.* (HERMES Collaboration), *JHEP*, **0806** (2008) 066; Murray M., *JHEP*, **0911** (2009) 083.
[7] Diehl M., *Phys. Rep.*, **388** (2003) 41.
[8] Ahmad S., Goldstein G. R. and Liuti S., *Phys. Rev. D*, **79** (2009) 054014.
[9] Goldstein G. R., Hernandez J. O. and Liuti S., *Phys. Rev. D*, **84** (2011) 034007.
[10] Burkardt M., *Int. J. Mod. Phys. A*, **18** (2003) 173 and references therein.
[11] Liuti S. and Taneja S. K., *Phys. Rev. D*, **70** (2004) 074019.
[12] Diehl M., *Eur. Phys. J. C*, **25** (2002) 223.
[13] Goldstein G. R., Hernandez J. O. and Liuti S., arXiv:1201.6088 [hep-ph].
[14] Goloskokov S. V. and Kroll P., *Eur. Phys. J. A*, **47** (2011) 112.
[15] Jaffe R. L., *Nucl. Phys. B*, **229** (1983) 205; *Phys. Lett. B*, **116** (1982) 437.
[16] Goldstein G. R. and Liuti S., [arXiv:1006.0213 [hep-ph]].
[17] Goldstein G. R. and Liuti S., *Phys. Rev. D*, **80** (2009) 071501.