The Multi-Hall Deep Exclusive Scattering Program at 12 GeV

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The aim of the program in deep exclusive scattering is to extract information about the internal landscape of hadrons, encoded in Generalized Parton Distributions (GPDs) in a coordinated and systematic way. This note sets out this program.

I. INTRODUCTION

It is now more than forty years since the experimental discovery of the partonic structure of the nucleon. Over the past four decades, one dimensional information on the longitudinal momentum distribution of these partons, expressed in Parton Distribution Functions (PDFs), has become increasingly refined. However key properties of the nucleon are encoded in the correlation between their longitudinal momentum and their transverse position: most obviously the orbital motion of the partons. This correlation is expressed through Generalized Parton Distributions (GPDs), which can be understood as providing a tomographic image of the nucleon.

The key to extracting GPDs from experiment are QCD factorization theorems, which allow the amplitudes for deep exclusive processes to be expressed in terms of GPDs. This is the basis for the program described here. In perturbative QCD at leading-twist, there are eight GPDs (four helicity-conserving distributions H, E, $\tilde{H}$, $\tilde{E}$ and four helicity-non conserving ones H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$), which represent the various helicity-spin transitions between the initial and final states of the quark-nucleon system. GPDs depend on the three kinematic variables x, ξ, and t, at each resolution scale, defined below and illustrated in Fig. 1.

GPDs are accessed experimentally through the exclusive leptoproduction of a photon in *Deeply Virtual Compton Scattering* (DVCS) or of a meson in *Deeply Virtual Meson Production* (DVMP), at large probing photon virtuality, Q^2, and small momentum transfer between the initial and final nucleon, the square of which is t. For DVCS and DVMP, $\xi = x_B/(2 - x_B)$ and the resolution scale is Q^2, while the longitudinal momenta carried by the struck parton before and after the scattering are respectively $x+\xi$ and $x-\xi$, as fractions of the average proton momentum (Fig. 1). Though GPDs each depend on 3 variables, in general only two of these are accessible experimentally. One accesses either integrals of GPDs, or GPDs at the particular kinematic point $x = \xi$ (giving what are known as Compton Form Factors, CFFs).

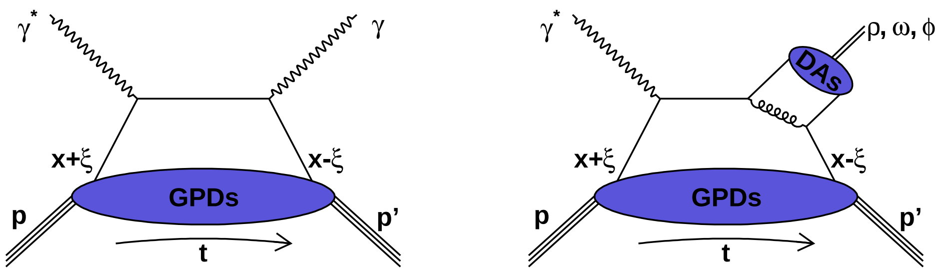

FIG. 1: "Handbag" diagrams representing Compton Scattering (DVCS) and Meson Production (DVMP) with a Deeply Virtual Photon γ^*.

Extracting GPDs requires a long-term experimental program with the measurement over a wide kinematic range of several observables (each spin observable being dominantly sensitive to a given CFF). A broad experimental program began already a few years ago at Jefferson Lab with a 6 GeV electron beam, at HERMES with a 27 GeV electron and positron energy, and at H1 and ZEUS with 920 GeV unpolarized protons colliding with 28 GeV electrons or positrons. A fit to some of these data led to the very first estimate (in a highly model-dependent way) of values for the orbital momentum contributions of the u and d quarks, J_u and J_d, to the nucleon's spin. However, most of these measurements are at rather small Q^2 values, or have sizeable statistical uncertainties. This seriously limits the determination of the extracted GPDs and does not permit their Q^2 evolution to be used as a helpful tool.

The development these past few years of codes and algorithms aimed at extracting the CFFs by fitting in more or less model-independent ways the available DVCS observables already provide valuable information. The current approach involves two complementary methods : *local* fits and *global* fits. *Local fits* use a set of observables at a single kinematic point and produce results for CFFs in a model independent way, while global fits use physically motivated parameterizations, and constrain them using observables at the measured kinematic points. One feature which emerges from such analyses is that the increase of the t-slope of $\mathrm{Im}H$ with decreasing x_B reflects the increasing transverse size of the nucleon, as one probes partons with smaller and smaller momentum fractions (in the so-called light-front frame). This yields an image of the nucleon with a core of valence quarks surrounded by a cloud of quark-antiquark pairs. Another feature, resulting from the observation that the CFF $\mathrm{Im}\tilde{H}$ has a flatter t-dependence than the $\mathrm{Im}H$ and barely varies with x_B is that the axial charge of the nucleon tends to stay concentrated within its core. With the upgrade in energy and luminosity of JLab, a set of data of unprecedented in precision and phase-space coverage is anticipated where it can be shown that essentially all leading-twist helicity-conserving CFFs can be extracted (some more precisely than others).

Moreover, there is a correspondence between spacelike and timelike processes implied by factorization, which closely relates DVCS to Timelike Compton Scattering (TCS), which is the exclusive photoproduction of a lepton pair with large invariant mass. A measurement of TCS will make it possible to test the implied universality of GPDs. The straightforward access in TCS to the real part of the CFFs through cosine moments of the weighted cross-section constrains models and parameterizations of GPDs over a wide range of kinematics.

Compton scattering can provide detailed and precise information about GPDs for different polarizations. However, its limitation is that it is only sensitive to sums of quark distributions. Exclusive meson production provides key additional information allowing the separation of different quark and anti-quark flavors. The theoretical description of these processes is more complicated requiring knowledge of the meson wave function. Moreover, theoretical work is still required to control corrections to the large Q^2 limit. In particular, at lower Q^2 accessible at JLab the measured t dependence receives contributions from the finite meson size and the structure of the proton target. Measurements that provide information about the reaction mechanism, *e.g.*, tests of hard-soft factorization, are thus essential on this front.

Specific features of the different meson production channels are presented below:

- The production of neutral mesons, ρ^0, ω, ϕ, includes quarks in particular $\overline{q}q$-flavor combinations, while ρ^+ provides direct information about *up* and *down* quark distributions and the K^* is naturally sensitive to *strange* quarks in the proton. The factorization theorem provides the means to calculate the longitudinal cross section and transverse spin asymmetry. At leading-twist only the longitudinal part of the cross section is interpretable in terms of the (helicity conserving) GPDs. An experimental separation of σ_L and σ_T can be achieved using vector meson decay, and so a Rosenbluth separation with different beam energies is not required. These reaction channels can be studied with a large acceptance device over a wide kinematic range. Vector meson data will also help resolve puzzles observed in ρ^0, ω, ρ^+ data. The current experimental results are underestimated by more than an order of magnitude with decreasing W by models with GPDs, which roughly account for DVCS cross-sections. A similar puzzle is why the high W ρ^0 and ω cross-sections (from H1 and ZEUS) are relatively well understood in terms of (gluonic) GPDs, while not in the valence region.

- The production of pseudoscalar mesons gives information about different flavor combinations for longitudinally polarized quarks, which are encoded in the GPDs $\tilde{H}$ and $\tilde{E}$. As for vector mesons, σ_L can be calculated from the factorization theorem and at leading-twist only the longitudinal part of the cross-section is interpretable in terms of the (helicity conserving) GPDs. To separate σ_L and σ_T one has to apply the Rosenbluth method requiring very good control over systematic uncertainties. Calculations of twist-3 terms have found the contribution of σ_T can be substantial. In a (model-dependent) extension of the formalism, the σ_T part is interpretable in terms of (transversity/helicity non-conserving) GPDs. Measurements with these reaction channels requiring precision cross-sections are best carried out with focusing spectrometers.

The program at JLab plans to cover all these issues.

II. HALL COMPLEMENTARITIES

Jefferson Lab is the only currently available facility in the world capable of performing nucleon imaging studies through deep exclusive processes. As such, the availability of several Halls to carry out this program independently is a must. Some of the program will be overlapping in several Halls, allowing cross-checks of systematic effects in different experimental setups. Most of it, however, will be complementary as each experimental setup has different advantages and drawbacks. Only by combining the measurements of all three Halls A, B and C, will a clear picture of the underlying physics emerge.

Hall A with its small acceptance and extremely high resolution spectrometer is able to define the kinematic variables of the reaction very precisely. Extremely high luminosities (up to $\sim 10^{38}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) can be achieved and thus very accurate tests of the kinematic dependences of observables can be made. This is important in order to study model-independent features of the reaction mechanism and the applicability of GPD framework at moderate Q^2 in the quark valence region. Accurate cross-section measurements performed in Hall A will serve as "calibration" points for beam and target spin asymmetries measured in a much larger kinematic range in Hall B, and a check for absolute normalization uncertainties for both, in the region of overlap.

Hall B has the greater number of experiments approved with all combinations of beam and target spin measurements. The large acceptance of CLAS12 will allow every observable to be measured in a much wider kinematic domain than is accessible in any of the other two experimental Halls. Extensively mapping three-dimensional distributions, such as GPDs, requires a vast kinematic survey that can only be performed with a large acceptance detector such as CLAS12. Multi-particle final state channels also benefit from the increased coverage and hermeticity of Hall B.

Hall C will play an increased role in the deep exclusive program at 12 GeV, compared to the 6 GeV era. Indeed, while the resolution of Hall C's magnetic spectrometers are almost as good as those in Hall A, Hall C's HMS and SHMS have the crucial advantage of allowing a much larger momentum reach. With a 12 GeV beam, Hall C will extend the precision measurements started in Hall A to additional kinematic points at higher Q^2 and small x_B. Furthermore, the rigid connection to the pivot allows for longitudinal-transverse separations, unique amongst the Hall experimental setups. Precision L/T cross-section measurements performed in Hall C will serve as "calibration" points for cross-sections measured in a much larger kinematic range in Hall B.

We describe below the currently approved program illustrating the complementarity mentioned above. New proposals are being submitted to PAC40 and additional extensions are in the works, with the inclusion of polarized targets as well as dedicated exclusive meson production studies.

III. HALL A

The GPD program with deep exclusive reactions in Hall A is devoted to high precision tests of the Q^2 dependence of cross-sections. Indeed, GPD measurements at Jefferson Lab rely on the assumption that deep exclusive reactions are well described by their leading twist mechanism. Theoretically this is true at high Q^2. The value of Q^2 at which this approximation is valid experimentally needs to be determined and the contributions of higher twist components to observables need to be quantified. The Q^2 dependence of cross-sections is the only unambiguous way to separate higher twist contributions to DVCS and other exclusive channels.

The **E12-06-114** experiment was approved by PAC30 and its beamtime allocated by PAC38. Its primary goal is to measure the Q^2 dependence of the DVCS and exclusive π^0 electroproduction cross-sections, for different fixed values of the Bjorken variable x_B and momentum transfer to the nucleon t. By independently measuring the unpolarized DVCS cross-section and the beam-helicity dependent cross-section, E12-06-114 will be able to separate the real and the imaginary parts of the DVCS amplitude. This will be performed at three values of $x_B = 0.36$, 0.5 and 0.6 with at least a factor of 2 lever arm in Q^2 at each value of x_B and t.

With a luminosity of up to $10^{38}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and by adjusting beamtime to each particular setting, cross-sections will be measured with 3–5% statistical accuracy, even at high values of Q^2. High statistics allow fine binning, which is particularly useful because of the very rapid variations of the Bethe-Heitler cross-section. Thanks to the well-understood acceptance of the Hall A High Resolution Spectrometer (HRS) and the simple and compact geometry of the DVCS calorimeter, the systematic uncertainties in the cross-section measurements will be around $\sim 4\%$. The high resolution of the HRS means that the kinematic variables will be very precisely determined, allowing an accurate study of the azimuthal dependences of the cross-sections.

A new proposal is being submitted to PAC40 to extend this program by exploiting the ε-dependence of the cross-section in order to separate the pure DVCS^2 cross-section from the DVCS interference with the Bethe-Heitler amplitude. This experiment is proposed in Hall C because of the requirement to detect scattered electron momenta higher than the Hall A HRS limitation of $\sim$4 GeV. With its higher momentum reach of up to 7.4 GeV, the Hall C High Momemtum Spectrometer (HMS) will allow an L/T separation of the DVCS and π^0 exclusive cross-sections to be performed. In addition, the kinematic coverage will be expanded to higher Q^2 and smaller values of x_B compared with those currently approved in Hall A.

IV. HALL B

The CLAS12 experiments assume a luminosity of 10^{35} cm^{2}s^{-1}. The GPD program is very well developed, with all combinations of beam and target spin proposals already approved for the DVCS on the proton, allowing for the extraction of all helicity amplitudes. With such a large acceptance spectrometer with a versatile trigger, some experiments can run in parallel and be completed without additional beam time. In this case, the collaboration may coordinate internally such new proposals to ensure the compability at run-time. Neutron target, vector and scalar meson deep exclusive electroproduction will also be measured, with some proposals already approved listed below. They will play an important role in disentangling the flavor- and spin-dependence of GPDs. In addition, Timelike Compton Scattering has also already been approved, providing a universality test of GPDs in a different regime.

The most extensive experiment **E12-06-119** will measure DVCS with a polarized electron beam on both unpolarized liquid hydrogen, and longitudinally dynamically polarized solid-state target, during separate, independent beam times of respectively 80 and 120 days of data taking. It will provide differential cross-sections, as well as beam spin, target spin, and double spin asymmetries, which are mostly sensitive to both the imaginary and the real parts of the CFF $\mathcal{H}$ and $\widetilde{\mathcal{H}}$. Spanning the ranges $0.1 < x_B < 0.7$ and $1 < Q^2 < 9$ GeV^2 with a precision of a few percent (asymmetries) and systematic errors below 10% for the cross-sections, the variations of the t-dependences across the x_B range encode information on nucleon imaging of quark position in the transverse plane, which will be extracted *via* first *local*, and then *global* analyses.

Completing the full measurement of the DVCS amplitudes on the proton, the experiment **E12-12-010** will use a transversely polarized HD-Ice target. It was conditionally approved for a 110 days with 1 nA polarized beam, upon the succesful completion of an electron beam test showing that the necessary cooling power can be achieved to sustain the frozen polarization for appropriate decay times of the order of several months. Such a target requires a relatively weak transverse magnetic field to hold the frozen-spin, with minimal impact on the detector backgrounds with electron beam operation. The low-Z material also mitigates the generation of bremsstrahlung backgrounds. Finally, low dilution constitutes an essential advantage of the HD-Ice target, which can achieve polarizations of 60% for H and 35% for D. Azimuthal moments in the cross-section provide access to the elusive GPD E, which encodes the *polarized* quark position distributions in the transverse plane, and enters into the well-known Ji sum rule for the total angular momentum carried by quarks in the nucleon. The experiment will provide target single spin asymetries to contrain *global* fits.

With a run of 90 days on liquid deuterium, experiment **E12-11-003** will detect the large angle recoil to select exclusive DVCS events on the neutron. With 3 layers of 48 scintillator paddles (per layer), a design detection efficiency of about 10% for momenta between 0.2 and 1.2 GeV/c will provide measurements of the beam spin asymmetries with errors and coverage comparable to that of the unpolarized hydrogen experiment. With enhanced sensitivity to the GPD E, it is crucial for the flavor separation of u and d quarks in the angular momentum sum rule.

The experiment **E12-12-001** will measure Timelike Compton Scattering and J/ψ photoproduction near threshold by detecting electron-positron pairs in coincidence with a proton in CLAS12. This will run for 100 days polarized beam with unpolarized liquid hydrogen, as well as an additional 30 days with reverse torus polarity for statistics and acceptance systematics. The angular analysis of TCS directly reveals the real part of the Compton amplitude, including the least known so called D-term. It appears as the subtraction constant in the relevant dispersion relation, providing an energy-independent contribution to the real part of the amplitude. It encodes the form-factors of the energy-momentum tensor, otherwise describing elastic scattering of the nucleon by a graviton, giving access to the distribution of forces inside the nucleon. These can also be computed in lattice QCD. By comparing the real part of the Compton amplitude extracted from TCS to the one extracted with DVCS in the timelike region, the experiment will also provide an important test of the universality of GPDs.

Experiment **E12-12-007** will measure exclusive ϕ deep electroproduction in both the charged and neutral kaon decay channels. Its first objective is to test the approach to the regime of small-size configurations by testing model independent features of the reaction mechanism. Secondly, it will extract the variations of the t-dependencies across the valence region, which will give access to the nucleon's "gluonic form-factor" with sensitivity to the radius of the gluon transverse position distribution. Thirdly, it will explore the speculative contribution of a possible intrinsic $s\bar{s}$ component of the nucleon in ϕ production near threshold.

Experiment **E12-06-108** was approved to measure π^0 and η deep exclusive electropoduction at 11 GeV. The aims are to test model-independent features of the reaction mechanism (t-slopes, Q^2-scaling) over a large kinematic range and obtain information on the flavor structure of the valence quark GPDs. The large acceptance of the CLAS is very well suited to measurement of the ϕ-dependent interference cross-sections (LT, TT') over a wide angular range. The theoretical interpretation originally focused on the longitudinal part of the cross-section and its connection to the axial vector GPDs. Recent theoretical work has shown that the transverse cross-sections are also amenable to a QCD-based description and sensitive to the quark transversity (helicity-flip) GPDs. This has opened the prospect of exploring quark transversity and its flavor structure through exclusive pseudoscalar meson production, complementing the information obtained from semi-inclusive measurements.

V. HALL C

The 12 GeV deep exclusive program in Hall C aims at precision cross-section measurements. The heavily-shielded detector setup in a highly-focusing magnetic spectrometer with large momentum reach, rigid connection to a sturdy pivot, well-reproducible magnetic properties, and access to the highest-luminosity data, are essential factors for meaningful longitudinal-transverse cross-section (L/T) separations. The anticipated excellent resolution and systematic understanding (less than 2% point-to-point) of the HMS-SHMS spectrometer pair best address the experimental requirements for a program of precision L/T separations and ratios of exclusive cross-sections with charged final states. The addition of a neutral particle detection facility would significantly augment these scientific capabilities. Precision measurements with a focusing spectrometer will often need to go hand-in-hand with survey experiments using large-acceptance setups.

The **E12-07-105** experiment was approved by PAC32, and will test the dominance of the longitudinal cross-section, σ_L, in charged π electroproduction by making systematic measurements of the Q^2-dependence of the longitudinal and transverse cross-sections above the resonance region and fixed values of x_B and t. The Q^2-dependence of σ_L and σ_T will show how the data for Q^2 < 10 GeV^2 evolve towards the Q^{-6} scaling predicted for hard exclusive processes. A significant longitudinal response may also be indicative of the expectations of the GPD formalism. The primary goal of this measurement is thus to provide a high quality, systematic data set of π^+ separated σ_L and σ_T, which may place a constraint on the value of Q^2 for which one can reliably apply perturbative QCD concepts and extract GPDs. The results from this measurement may also help to identify missing elements in existing calculations of the π production cross-section, which will help to constrain longitudinal backgrounds in the extraction of the pion form-factor from pion electroproduction data.

The **E12-09-011** experiment was approved by PAC34, and will for the first time make precision measurements of the L/T separated kaon electroproduction cross-sections as a function of Q^2 above the resonance region. These data will provide information about the onset of the Q^{-6} evolution in kaon production. A direct comparison of the scaling properties of the π^+ and K^+ separated cross-sections will be an important tool for the study of the onset of factorization in the transition from the hadronic to the partonic regime, and provide a possibility to study effects related to $SU(3)_F$-breaking. The flavor degree of freedom introduced with the addition of the strange quark will also help to determine basic coupling constants needed in nucleon-meson and quark models. If σ_L is large at lower Q^2, the data may be used to extract the kaon form-factor and revisit the meson form-factor puzzle. By comparing the observed Q^2 dependence and magnitude of the pion and kaon form-factors, one could test if the analogy between the pion cross-section and form-factor will also manifest itself for kaons.

The next natural step is the inclusion of neutral exclusive channels in the scientific program. In our quest to test the probe used to access and constrain GPDs reactions, a capability of including neutral final states will allow one to probe universal features of GPDs and to verify the GPD formalism in regions so far unexplored. Neutral meson data would also allow for a more reliable interpretation of the charged data. Since 2011 a collaboration has been working on the possibility to augment the science capabilities of Hall C with a neutral particle detection facility. The program with such a facility could initially include measurements of the energy dependence of DVCS allowing twist-2 and twist-3 effects to be isolated, DVCS with polarized targets allowing GPDs on the x=ξ line to be separated, Wide Angle Compton Scattering to validate the GPD formalism at large t, and systematic measurements of the neutral π and perhaps η production cross-sections.

Of course, a key objective of all these studies is to quantify the orbital momentum contribution of all the partons, namely quarks, in each flavor, as well as gluons, to the spin of the nucleon. This is expressed through the Ji sum rule as an integral over the relevant GPDs.

Proposal	Title	Spokespersons	Hall	Rating
E12-06-114	Measurement of Electron-Helicity Dependent Cross-Sections of Deeply Virtual Compton Scattering with CEBAF at 12 GeV	C. Hyde B. Michel C. Munoz-Camacho J. Roche	A	A
E12-06-108	Hard Exclusive Electroproduction of π^0 and η with CLAS12	P. Stoler K. Joo V. Kubarovsky M. Ungaro C. Weiss	B	B
E12-06-119	Deeply Virtual Compton Scattering with CLAS at 11 GeV	F. Sabatié A. Biselli H. Egiyan L. Elouadrhiri M. Holtrop D. Ireland W. Kim	B	A
E12-11-003	Deeply Virtual Compton Scattering on the Neutron with CLAS12 at 11 GeV	S. Niccolai V. Kubarovsky A. El Alaoui M. Mirazita	B	A
E12-12-001	Timelike Compton Scattering and J/ψ photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV	P. Nadel-Turonski M. Guidal T. Horn R. Paremuzyan S. Stepanyan	B	A-
E12-12-007	Exclusive ϕ Meson Electroproduction with CLAS12	P. Stoler C. Weiss F.-X. Girod M. Guidal V. Kubarovsky	B	B+
E12-12-010	Deeply Virtual Compton Scattering at 11 GeV with a transversely polarized target using the CLAS12 detector	L. Elouadrhiri V. D. Burkert M. Lowry M. Guidal S. Procureur	B	A
E12-07-105	Scaling Study of the L-T Separated π Electroproduction Cross-Section at 11 GeV	T. Horn G. Huber	C	A-
E12-07-105	Studies of the L-T Separated Kaon Electroproduction Cross-Section from 5 to 11 GeV	T. Horn G. Huber P. Markowitz	C	B+