Studying GPDs at Jefferson Lab

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3-D picture of the nucleon and GPDs
Extracting GPDs from experimental observables
DVCS experiments with JLAB-6 GeV
Future plans with upgraded JLAB-12 GeV
Summary
3-D Picture of the Nucleon

**DIS Parton Distribution Functions**

No information on the spatial location of the constituents

**Elastic Form Factors**

No information about the underlying dynamics of the system

**Transverse Momentum Distributions & Generalized Parton Distributions**

3-D imaging of the nucleon, the correlation of quark/antiquark transverse spatial and longitudinal momentum distributions, and on the quark angular momentum distribution

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GPDs, PDFs, FFs

- **GPDs → PDFs** (in the limit $t \to 0$)
  \[ H^q(x,0,0) = q(x), -\bar{q}(-x) \]
  \[ \tilde{H}^q(x,0,0) = \Delta q(x), \Delta \bar{q}(-x) \]

- **GPDs → FFs** (first moments of GPDs)
  \[ \int_{-1}^{+1} dxF^q(x,\xi,t) = F^q_1(t) \]
  \[ \int_{-1}^{+1} dx\tilde{H}^q(x,\xi,t) = g^q_A(t) \]
  \[ \int_{-1}^{+1} dxE^q(x,\xi,t) = F^q_2(t) \]
  \[ \int_{-1}^{+1} dx\tilde{E}^q(x,\xi,t) = h^q_A(t) \]
Deep-exclusive reactions and GPD

A global analysis is needed to fully disentangle GPDs

<table>
<thead>
<tr>
<th>DVCS</th>
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<tbody>
<tr>
<td></td>
<td>$\mathcal{H}$</td>
<td>$A_{LU}$</td>
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<td></td>
<td>$\tilde{\mathcal{H}}$</td>
<td>$A_{UL}$</td>
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<td></td>
<td>$\mathcal{E}$</td>
<td>$A_{UT}$</td>
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<td></td>
<td>$\mathcal{R}e$</td>
<td>$\sigma$</td>
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<td>$\mathcal{R}e$</td>
<td>$A_{LL}, A_{LT}$</td>
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<th>DVMP</th>
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<tr>
<td>$\mathcal{H}, \mathcal{H}$</td>
<td>$\pi^+$</td>
<td>$\Delta u - \Delta d$</td>
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<td></td>
<td>$\pi^0$</td>
<td>$2\Delta u + \Delta d$</td>
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<td>$\eta$</td>
<td>$2\Delta u - \Delta d + 2\Delta s$</td>
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<tr>
<td>$\mathcal{H}, \mathcal{E}$</td>
<td>$\rho^+$</td>
<td>$u - d$</td>
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<td>$\rho^0$</td>
<td>$2u + d$</td>
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<td></td>
<td>$\omega$</td>
<td>$2u - d$</td>
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<td>$\phi$</td>
<td>$g$</td>
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Disentangling GPDs – model simulations


8 independent quantities to be fit -
\[ \text{Im}(H); \text{Im}(E); \text{Im}(\tilde{H}); \text{Im}(\tilde{E}) \]
\[ \text{Re}(H); \text{Re}(E); \text{Re}(\tilde{H}); \text{Re}(\tilde{E}) \]

Using 9 independent observables -
\[ \sigma; \Delta \sigma_{z0}; \Delta \sigma_{0x}; \Delta \sigma_{0y}; \Delta \sigma_{0z}; \]
\[ \Delta \sigma_{xz}; \Delta \sigma_{zy}; \Delta \sigma_{zz}; \Delta \sigma_c; \]

Assumption - \[ \text{Im}(\tilde{E}) = 0 \]
Angular momentum and Transverse Imaging

\[ J_q = \frac{1}{2} \Delta \Sigma + L_q = \lim_{t \to 0} \int_{-1}^{+1} dx \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right] \]

Target polarization

Flavor dipole


JLAB kinematic and experimental reach

<table>
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<tr>
<th>Reaction</th>
<th>$\gamma$</th>
<th>$\pi^+/\pi^-/\pi^0$</th>
<th>$\eta$</th>
<th>$\rho/\omega/\phi$</th>
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<tbody>
<tr>
<td>Deeply exclusive (GPDs)</td>
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Accessing GPDs experimentally - DVCS

\[ \text{ep} \rightarrow \text{ep} \gamma = \left( \begin{array}{c} \text{DVCS} \\ \text{Bethe-Heitler} \end{array} \right) \]

\[ \mathcal{T}^2 = \left| \mathcal{T}_{BH} \right|^2 + \left| \mathcal{T}_{DVCS} \right|^2 + \mathcal{T}_{DVCS}^* \mathcal{T}_{BH} + \mathcal{T}_{BH}^* \mathcal{T}_{DVCS} \]

\[ \mathcal{T}_{DVCS} \sim CFF \mathcal{H}(\xi, t) = i\pi \left[ H(\xi, \xi, t) - H(-\xi, \xi, t) \right] + P \int_{-1}^{+1} dx \left( \frac{1}{\xi - x} \pm \frac{1}{\xi + x} \right) \left[ H(x, \xi, t) \mp H(-x, \xi, t) \right] \]

Spin asymmetries \((\text{Im}, x=\xi)\)
HERMES, CLAS, Hall A, JLAB12, COMPASS

Charge asymmetry \((|\text{Re}|)\)
HERMES, COMPASS

Cross sections \((|\text{Re}|^2)\)
H1, Hall A, JLAB12, COMPASS

DDVCS \((x \neq \xi)\) – JLAB12

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GPDs and DVCS spin observables

Polarized beam, unpolarized proton target:
\[ \Delta \sigma_{LU} \propto \sin \phi \cdot \text{Im} \{ F_1^p H_p + \xi (F_1^p + F_2^p) \tilde{H}_p + k F_2^p E_p \} d\phi \]

Unpolarized beam, longitudinal proton target:
\[ \Delta \sigma_{UL} \propto \sin \phi \cdot \text{Im} \{ F_1^p \tilde{H}_p + \xi (F_1^p + F_2^p) (H_p + ...) \} d\phi \]

Unpolarized beam, transverse proton target:
\[ \Delta \sigma_{UT} \propto \sin \phi \cdot \text{Im} \{ k (F_1^p H_p - F_1^p E_p) + ... \} d\phi \]

Polarized beam, unpolarized neutron target:
\[ \Delta \sigma_{LU} \propto \sin \phi \cdot \text{Im} \{ F_1^n H_n + \xi (F_1^n + F_2^n) \tilde{H}_n + k F_2^n E_n \} d\phi \]

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma}{2\sigma} \]

\[ H_p(\xi, \xi, t) = \frac{4}{9} H_u(\xi, \xi, t) + \frac{1}{9} H_d(\xi, \xi, t) \]
\[ H_n(\xi, \xi, t) = \frac{1}{9} H_u(\xi, \xi, t) + \frac{4}{9} H_d(\xi, \xi, t) \]

Experiments for all combinations of polarized and unpolarized beam and target have been approved by JLAB PAC
First DVCS measurements

Analysis of existing CLAS data

Reaction: $e p \rightarrow e' p' X$

Missing momentum analysis $X \approx \gamma$

PRL 87, 182002 (2001)

PRL 97, 072002 (2006)
Hall-A DVCS measurements

- Helicity-dependent cross section ($\sigma^- - \sigma^+$) at $Q^2 = 1.5, 1.9$ and $2.3$ GeV$^2$
- Helicity-independent cross section ($\sigma^+ + \sigma^-$) at $Q^2 = 2.3$ GeV$^2$
- Twist-2 dominance is observed

With an additional charged particle veto in front of the proton detector DVCS on neutron has been measured, where the main contribution is from GPD $\mathcal{E}$

$$F_2^m(t) \gg F_1^m(t)$$

CLAS DVCS beam spin asymmetry

The first most extensive set of DVCS data with CLAS
Fully exclusive final state

\[ ep \rightarrow e'p'\gamma \]

\[ \alpha \sin \phi \]

\[ \frac{1}{1 + \cos \phi} \]

\[ Q^2 (\text{GeV}^2) \]

\[ \phi (\text{deg}) \]

\[ x_B, Q^2, t \]

Qualitative model agreement, quantitative constraints on parameters

F.-X. G. et al., PRL 100 (2008) 162002
CLAS target and double spin asymmetry

\[ A_{UL} \propto F_1 \text{Im} \hat{H} \]

\[ A_{LL} \propto F_1 \text{Re} \hat{H} \]


S. Pisano et al., Phys. Rev. D 91, 052014
CLAS DVCS cross sections

\[
\frac{d^4\sigma_{ep\rightarrow ep\gamma}}{dQ^2 dx_B df df_\Phi} \text{ (nb/GeV}^4)\]

- BH
- VGG (H only)
- KM10
- KM10a

VGG: Vanderhaeghen, Guichon, Guidal
KM: Kumericki, Mueller

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Extracting Compton form-factors

- The three sets of asymmetries (BSA, TSA and DSA) for all kinematic bins were processed using the local fitting procedure to extract the Compton FF.
- In the fit $\tilde{E}_{\text{Im}}$ is set to zero, as $\tilde{E}$ is assumed to be purely real.
- Thus seven out of the eight real and imaginary parts of the CFFs are left as free parameters in the fit.

$$F_{\text{Re}}(\xi, t) = \Re \mathcal{F}(\xi, t)$$

$$F_{\text{Im}}(\xi, t) = -\frac{1}{\pi} \Im \mathcal{F}(\xi, t) = [F(\xi, \xi, t) + F(-\xi, \xi, t)]$$

- Two out of seven have been reasonably constrained by the fit.

S. Pisano et al., Phys. Rev. D 91, 052014
Nuclear GPDs – $^4$He (CLAS)

SPIN ZERO target → ONE GPD IS NEEDED $H_A(x, \xi, t)$

$$A_{LU} = \frac{\alpha_0(\phi) \cdot \mathcal{H}_{Im}}{\alpha_1(\phi) + \alpha_2(\phi) \mathcal{H}_{Re} + \alpha_3(\phi) (\mathcal{H}_{Im}^2 + \mathcal{H}_{Re}^2)}$$

$A_{LU}$: Coherent

GEM based low energy recoil detector
Gaseous target at 6 atm, cell 6 mm ID, 27 µm wall thickness

---

$e^{-^4He} \rightarrow e^{-^4He}$

$e^{-^4He} \rightarrow e^{-^4He}$

$e^{-^4He} \rightarrow e^{-^4He}$

$e^{-^4He} \rightarrow e^{-^4He}$

$H_A$ vs. $-t$

$\chi^2 / ndf = 9.238 / 7$

$p_0 = 0.287 \pm 0.03053$

$p_1 = -0.2469 \pm 0.1795$

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The JLab 12 GeV Upgrade - Major Programs in Six Areas

- The Hadron spectra as probes of QCD (GluEx and CLAS12, heavy baryon and meson spectroscopy)
- The transverse structure of hadrons (Elastic and transition Form Factors)
- The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)
- The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)
- Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, few-body experiments)
- Low-energy tests of the Standard Model and Fundamental Symmetries (Møller, PVDIS, PRIMEX, Heavy Photons)
Hall-A DVCS

- $Q^2$ up to 9 GeV$^2$, only highest $Q^2$ shown, long lever arm
- Three Different beam energies for Rosenbluth separation of $I$ and DVCS$^2$
- High-precision scaling test on both Re and Im
- Combined with measurements in Hall-C at higher $Q^2$ and lower $x_B$ will cover significant parameter space

K=11 GeV, $Q^2=9$ GeV$^2$, $x_B=0.6$, $\theta_x=30.23^\circ$, $k'=3$ GeV, $\theta_{calo}=-11^\circ$
Calo 13x16 Blocks at 3 meters $L_u=2.97 \times 10^{38}$ cm$^{-2}$s$^{-1}$, 400 Hours

$0 < t_r < -0.7$, $t_z < -0.8$, $t_s < -0.93$, $t_t < -1.14$, $t_s < -1.6$ GeV$^2$

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\[ \vec{e} \ p \rightarrow \ ep\gamma \]

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma}{2\sigma} \]

\[ \Delta \sigma_{LU} \sim \sin \phi \{ F_1 H + \ldots \} d\phi \]

Extract \( H(\xi, t) \)

Large coverage in \( x_B, Q^2, \) and \( t \) with high statistical precision
CLAS12 DVCS with polarized targets

\[ A_{UL} = \frac{\sigma_{\Rightarrow} - \sigma_{\Leftarrow}}{\sigma_{\Rightarrow} + \sigma_{\Leftarrow}} \]

\[ \Delta \sigma_{UL} \sim \sin \phi \text{Im}\{F_1 \tilde{H} + \xi (F_1 + F_2)(H + \ldots)\} d\phi \]

\[ A_{UT} = \frac{\sigma_{\downarrow} - \sigma_{\uparrow}}{\sigma_{\downarrow} + \sigma_{\uparrow}} \]

\[ \Delta \sigma_{UT} \sim \sin \phi \text{Im}\{k(F_2 H - F_1 E) + \ldots\} d\phi \]
Time-like Compton Scattering (TCS)

\[
\frac{d^4\sigma}{dx dQ^2 dt d\phi} \propto |T^{BH}|^2 + T^{BH} \cdot \text{Re}(T^{VCS}) + \lambda T^{BH} \cdot \text{Im}(T^{VCS}) + |T^{VCS}|^2
\]

\[
\frac{d\sigma_{INT}}{dQ^2 dt d(\cos \theta) d\varphi} = -\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \cos \varphi \frac{1+\cos^2 \theta}{\sin \theta} \text{Re}\tilde{M}^{--} - \cos 2\varphi \sqrt{2} \cos \theta \text{Re}\tilde{M}^{0-} + \cos 3\varphi \sin \theta \text{Re}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right) \right]
\]

\[
- \lambda \frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \sin \varphi \frac{1+\cos^2 \theta}{\sin \theta} \text{Im}\tilde{M}^{--} - \sin 2\varphi \sqrt{2} \cos \theta \text{Im}\tilde{M}^{0-} + \sin 3\varphi \sin \theta \text{Im}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right) \right].
\]

Universality of GPDs

\[
\tilde{M}^{--} = \frac{2\sqrt{t_0-t}}{m} \frac{1-\eta}{1+\eta} \left[ F_1 \mathcal{H} - \eta (F_1 + F_2) \mathcal{H} - \frac{t}{4m^2} F_2 \mathcal{E} \right]
\]
TCS with 11 GeV electron beam

Lepton pair production will be studied in the range of outgoing photon virtualities $M_{ee}^2 = Q'^2$ from 4 GeV$^2$ to 9 GeV$^2$ (above the light-quark meson resonances and below charm threshold)

100 days of running at luminosity of $10^{35}$ cm$^{-2}$ sec$^{-1}$
Summary

- DVCS clearly is the best channel to study GPDs
- After the first proof-of-principal BSA and TSA results in DVCS from CLAS data mining efforts, JLAB made significant investment in dedicated experiments where BSA and TSA on proton and neutron targets were explored
- The new set of data initiated new theoretical approaches for extracting GPDs from experimental observables
- The 12 GeV Upgrade will greatly enhance the scientific “reach” of JLAB facility
- Detectors in experimental halls are well suited to carry out vigorous program for studying the nucleon structure in terms of GPDs
- Experimental program includes DVCS measurements with polarized beams and targets on the proton and the neutron, as well as Deeply Virtual Meson Production, and Time-like Compton Scattering – not all approved experiment have been covered in this talk
- Solid and CLAS12 collaborations exploring possibilities of Double DVCS measurements with improved detector in near future