Generalized Parton Distributions with CLAS and CLAS12

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for the CLAS Collaboration

From Quarks and Gluons to Hadrons and Nuclei

Erice (Italia) – September 22nd 2011
Generalized Parton Distributions with CLAS and CLAS12

- Interest of GPDs
- GPDs and Deeply Virtual Compton Scattering
  - The CLAS detector
  - DVCS results with CLAS
- GPDs and Deeply Virtual Meson Production
  - DVMP results with CLAS
- The JLab 12 GeV upgrade and CLAS12
- Future experiments on GPDs with CLAS12

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Generalized Parton Distributions

GPDs: $H$, $E$, $\tilde{H}$, $\tilde{E}$
Fully correlated quark
distributions in both coordinate
and momentum space

Form factors:
transverse quark
distribution in
coordinate space

Parton distributions:
longitudinal
quark distribution
in momentum space

Accessible in
hard exclusive processes

$\int H(x,\xi,t)dx = F_1(t)$ ($\forall \xi$)
$\int E(x,\xi,t)dx = F_2(t)$ ($\forall \xi$)

$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$
Deeply Virtual Compton Scattering and GPDs

\[ \gamma \rightarrow e + e' + \gamma \]

\[ \gamma_L^* (Q^2) \]

\[ x + \xi, x - \xi \] longitudinal momentum fractions

\[ t = (p - p')^2 \]

\[ \xi \approx x_B / (2 - x_B) \]

«Handbag» factorization valid in the Bjorken regime:

- high \( Q^2 \), \( \nu \) (fixed \( x_B \)), \( t \ll Q^2 \)

4 GPDs for each quark flavor

- Vector: \( H(x, \xi, t) \)
- Axial-Vector: \( \tilde{H}(x, \xi, t) \)
- Tensor: \( E(x, \xi, t) \)
- Pseudoscalar: \( \tilde{E}(x, \xi, t) \)

conserves nucleon helicity

flip nucleon helicity

Quark angular momentum (Ji’s sum rule)

\[ J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} dx \left[ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right] \]


«3D» quark/gluon image of the nucleon
Accessing GPDs through DVCS

\[ \sigma(eN \rightarrow eN\gamma) = T_{DVCS} + T_{BH} \]

\[ \sigma \sim |T_{DVCS} + T_{BH}|^2 \]

\[ \Delta \sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH) \]

\[ A = \frac{\Delta \sigma}{2\sigma} \propto \frac{I(DVCS \cdot BH)}{|BH|^2 + |DVCS|^2 + I} \]

Only \( \xi \) and \( t \) are accessible experimentally
Sensitivity to GPDs of DVCS spin observables

\[ \text{Re} \mathcal{H}_q = e_q^2 P \int_0^1 \left( H^q(x, \xi, t) - H^q(-x, \xi, t) \right) \left[ \frac{1}{\xi - x} + \frac{1}{\xi + x} \right] dx \]

\[ \text{Im} \mathcal{H}_q = \pi e_q^2 \left[ H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right] \]

\( \xi = x_B/(2-x_B) \quad k = -t/4M^2 \)

Polarized beam, unpolarized target:

\( \Delta \sigma_{LU} \sim \sin \phi \ \text{Im} \left\{ F_1 \text{H} + \xi (F_1 + F_2) \tilde{\text{H}} - kF_2 \tilde{E} \right\} d\phi \)

Unpolarized beam, longitudinal target:

\( \Delta \sigma_{UL} \sim \sin \phi \ \text{Im} \left\{ F_1 \tilde{\text{H}} + \xi (F_1 + F_2) (\text{H} + x_B/2E) - \xi kF_2 \tilde{E} + \ldots \right\} d\phi \)

Polarized beam, longitudinal target:

\( \Delta \sigma_{LL} \sim (A + B \cos \phi) \text{Re} \left\{ F_1 \tilde{\text{H}} + \xi (F_1 + F_2) (\text{H} + x_B/2E) + \ldots \right\} d\phi \)

Unpolarized beam, transverse target:

\( \Delta \sigma_{UT} \sim \sin \phi \ \text{Im} \left\{ k (F_2 \text{H} - F_1 \tilde{E}) + \ldots \right\} d\phi \)
The CLAS detector (Jefferson Lab, Hall B)

- Toroidal magnetic field (6 supercond. coils)
- Drift chambers (argon/CO$_2$ gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov Counters (e/π separation)

Performances:
- large acceptance for charged particles
  $8^\circ < \theta < 142^\circ$, $p_p > 0.3$ GeV/c, $p_\pi > 0.1$ GeV/c
- good momentum and angular resolution
  $\Delta p/p \leq 0.5\%-1.5\%$, $\Delta \theta$, $\Delta \phi \leq 1$ mrad

Optimal for measurements of exclusive reactions with multi-particle final states
Part 1 of the e1-DVCS experiment:
- Data taken from March 11 until May 27, 2005
- Beam energy ~ 5.766 GeV
- Beam current = 20-25 nA
- Beam polarization ~ 80%
- Integrated luminosity ~ 3.33 x 10^7 nb^{-1}
- Target LH_2

**CLAS + Solenoid (Moeller shield) + IC**

More data taken in fall 2008, under analysis
DVCS Beam Spin Asymmetries

\[ \Delta \sigma_{LU} \sim \sin\phi \, \text{Im}\{F_1 H + \xi(F_1 + F_2)\tilde{H} - kF_2 E\}\,d\phi \]

**Fit** = \( a \sin\phi/(1+b \cos\phi) \)


\* Guidal, Polyakov, Radyushkin, Vanderhaegen, PRD 72 (2005)
DVCS Beam Spin Asymmetries

\( \Delta \sigma_{LU} \sim \sin \phi \) Im \{ F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} - k F_2 \mathcal{E} \} d\phi

**DVCS polarized and unpolarized cross sections:** analyses in the final stages

Fit = \( a \sin \phi / (1 + b \cos \phi) \)


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(*) Guidal, Polyakov, Radyushkin, Vanderhaegen, PRD 72 (2005)

What we learn from the published CLAS asymmetries

Model-independent fit at fixed $x_B$, $t$, $Q^2$ of DVCS observables

ImH has steeper $t$-slope than ImH: is axial charge more concentrated than the electromagnetic charge?

S. Chen et al., PRL 97, 072002 (2006)

• Data taken from February 4 to September 21 2009
• Beam energy = 4.735, 5.764, 5.892, 5.967 GeV
• Target: longitudinally polarized NH₃ (~80%) and ND₃ (~30%)
• IC to detect forward photons
The eg1-DVCS experiment: TSA

- Data taken from February 4 to September 21 2009
- Beam energy = 4.735, 5.764, 5.892, 5.967 GeV
- Target: longitudinally polarized NH$_3$ (~80%) and ND$_3$ (~30%)
- IC to detect forward photons

Double-spin (beam-target) asymmetry analysis also underway

\[ \Delta \sigma_{LL} \sim (A + B \cos \phi) \text{Re}\{F_1 \hat{H} + \xi (F_1 + F_2) (\hat{H} + x_B/2 E) \ldots \} d\phi \]

\[ \Delta \sigma_{UL} \sim \sin \phi \text{Im}\{F_1 \hat{H} + \xi (F_1 + F_2) (\hat{H} + x_B/2 E) - \xi k F_2 E + \ldots \} d\phi \]
Deeply virtual meson production and GPDs

Different mesons $\rightarrow$ different sensitivity to GPDs

Vector mesons $(\rho, \omega, \phi)$

Pseudoscalar mesons $(\pi, \eta)$

<table>
<thead>
<tr>
<th>Meson</th>
<th>Flavor Decomposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$2\Delta u+\Delta d$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$2\Delta u-\Delta d$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$2u+d$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$2u-d$</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>$u-d$</td>
</tr>
</tbody>
</table>

Factorization proven only for **longitudinally polarized** virtual photons and valid at **high** $Q^2$ and **small** $t$

Quark flavor decomposition accessible via meson production

Complications: effective scale in the hard scattering process, meson distribution amplitude
Deeply virtual meson production at CLAS

Vector mesons: exclusive $\rho^0$, $\omega$, $\phi$ and $\rho^+$ electroproduction on the proton with CLAS:

- K. Lukashin et al., Phys. Rev. C 63, 065205, 2001 ($\phi@4.2$ GeV)
- C. Hadjidakis et al., Phys. Lett. B 605, 256-264, 2005 ($\rho^0@4.2$ GeV)
- L. Morand et al., Eur. Phys. J. A 24, 445-458, 2005 ($\omega@5.75$ GeV)
- J. Santoro et al., Phys. Rev. C 78, 025210, 2008 ($\phi@5.75$ GeV)
- S. Morrow et al., Eur. Phys. J. A 39, 5-31, 2009 ($\rho^0@5.75$ GeV)
- A. Fradi, Orsay Univ. PhD thesis ($\rho^+@5.75$ GeV)

There are also results on exclusive pseudoscalar meson electroproduction on the proton with CLAS:

- R. De Masi et al., Phys. Rev. C 77, 042201(R), 2008 ($\pi^0@5.75$ GeV)
- K. Park et al., Phys. Rev. C 77, 015208, 2008 ($\pi^+@5.75$ GeV)
- I. Bedlinskiy et al., paper in preparation ($\pi^0@5.75$ GeV)
Comparison between vector mesons ($\sigma$)
Comparison between vector mesons

\( b \) increases with \( W (\sim 1/x) \): valence (fast) quarks in the center and sea (slow) quarks at the periphery of the nucleon

\[ \frac{d\sigma}{dt} \sim e^{bt} \]

\( b \) decreases with \( Q^2 \): by increasing the resolution of the probe, smaller objects in the nucleon can be seen
The GPD models fail to reproduce the behavior at low $W$ ($W < 5$ GeV).


VGG GPD model
GK GPD model

VGG: Vanderhaeghen, Guichon, Guidal
GK: Goloskokov, Kroll
GPDs: where we stand, where we are going

- Pioneering dedicated experiments on **DVCS** (Hall A, CLAS), show evidence for **handbag (twist-2) dominance** (asymmetry $\sim \sin \phi$) and **unexpected scaling at $Q^2 \sim 2 \text{ GeV}^2$** (Hall A)
- **DVMP** experiments at CLAS ($\rho, \omega, \pi^0$) and Hall A ($\pi^0$) hint that either **scaling cannot be reached** for $Q^2$ as low as for DVCS or **something is missing** in GPDs parameterizations
- Model-independent fits need to combine **several observables** to constrain GPDs
- Hall A’s first attempt to measure **nDVCS** showed the importance of this channel for Ji’s **sum rule** and the extraction of $J_q$

More data needed on DVCS and DVMP:
- **High $Q^2$** to verify scaling for DVCS on a wider $Q^2$ range, and to approach GPD validity regime for DVMP
- **Wide $x_B$ coverage**
- **High accuracy** on measured observables to test models (**high luminosity required**)  
- **Measurements of spin-asymmetries and cross sections on proton and neutron**

CLAS12 will be the optimal facility for these goals
JLab upgrade to 12 GeV

E = 2.2, 4.4, 6.6, 8.8, 11 GeV
Beam polarization \( P_e > 80\% \)

Upgrade of the instrumentation of the existing Halls

Beam Power: **1MW**
Beam Current: **90 \( \mu \)A**
Max Energy/pass: **2.2 GeV**
Max Energy Hall A-C: **11 GeV**
Max Energy Hall D: **12 GeV**

Continuous Electron Beam Accelerator Facility
Hall B @12 GeV: CLAS12

Design luminosity
$L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Acceptance for charged particles:
- Central (CD), $40^\circ < \theta < 135^\circ$
- Forward (FD), $5^\circ < \theta < 40^\circ$

Acceptance for photons:
- IC $2^\circ < \theta < 5^\circ$
- EC, $5^\circ < \theta < 40^\circ$

High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes
Hall B@12 GeV: CLAS12

**Forward Detector:**
- TORUS magnet
- Forward tracker
- HT Cherenkov Counter
- Drift chambers (3 regions)
- LT Cherenkov Counter
- Forward ToF System
- Preshower calorimeter
- E.M. calorimeter (EC)
- Inner Calorimeter (IC, not shown)

**Central Detector:**
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

**Proposed upgrades:**
- Micromegas (CD)
- Neutron detector (CD)
- RICH detector (FD)
- Forward Tagger (FD)
Large phase space ($\xi,t,Q^2$) and high luminosity
DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
$P_{\text{beam}} = 85\%$
$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
$1 < Q^2 < 10 \text{ GeV}^2$
$0.1 < x_B < 0.65$
$-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$
Statistical error: 1% to 10% on $\sin \phi$ moments
Systematic uncertainties: ~6-8%

120 days of beam time
$P_{\text{beam}} = 85\%$, $P_{\text{target}} = 80\%$
$L = 2.10^{35} \text{ cm}^{-2}\text{s}^{-1}$
$1 < Q^2 < 10 \text{ GeV}^2$
$0.1 < x_B < 0.65$
$-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$
Statistical error: 2% to 15% on $\sin \phi$ moments
Systematic uncertainties: ~6-8%
DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
P_{beam} = 85%
L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}
1 < Q^2 < 10 \text{ GeV}^2
0.1 < x_B < 0.65
-t_{\text{min}} < -t < 2.5 \text{ GeV}^2
Statistical error: 1% to 10% on sin\phi moments
Systematic uncertainties: ~6-8%

Impact of CLAS12 DVCS-BSA data on model-independent fit to extract Im(H)
BSA for DVCS on the neutron with CLAS12

\[
(H, E)_n(\xi, \xi, t) = \frac{9}{15}[4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)]
\]

\[
(H, E)_d(\xi, \xi, t) = \frac{9}{15}[4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]
\]

\(\Delta \sigma_{LU} \sim \sin \phi \text{ Im}\{F_1H + \xi(F_1+F_2)\hat{\mathcal{H}} - kF_2\mathcal{E}\}d\phi\)

The most sensitive observable to the GPD E

ed → e(p)nγ
CLAS12 + Forward Calorimeter + Neutron Detector

80 days of data taking
\(L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}\)

First-time measurement

Under construction at IPN Orsay
BSA for DVCS on the neutron with CLAS12

\[ (H, E)_u(\xi, \xi, t) = \frac{9}{15} [4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)] \]

\[ (H, E)_d(\xi, \xi, t) = \frac{9}{15} [4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)] \]

\[ \Delta \sigma_{LU} \sim \sin \phi \, \text{Im}[F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} - k F_2 E] \, d\phi \]

The most sensitive observable to the GPD E

\[ ed \rightarrow e(p)n\gamma \]

CLAS12 + Forward Calorimeter + Neutron Detector

80 days of data taking

L = 10^{35} \text{ cm}^{-2} \text{s}^{-1}/\text{nucleon}

Model predictions (VGG) for different values of quarks’ angular momentum

First-time measurement
Transverse-target spin asymmetry is highly sensitive to the $u$-quark contributions to proton spin.

$\Delta \sigma \sim \sin \phi \text{Im}\{k_1(F_2H - F_1E) + \ldots\}d\phi$

$A_{UTx}$ Target polarization in scattering plane

$A_{UTy}$ Target polarization perpendicular to scattering plane

Projected results

$Q^2=2.2 \text{ GeV}^2, x_B = 0.25, -t = 0.5 \text{GeV}^2$

Transversely polarized target not part of CLAS12 base equipment. R&D underway

LOI approved by PAC38
Transverse-target spin asymmetry is highly sensitive to the $u$-quark contributions to proton spin.

Transversely polarized target not part of CLAS12 base equipment. **R&D underway**

*LOI approved by PAC38*

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**Transversely polarized target**

$e \uparrow p \rightarrow ep\gamma$

$\Delta \sigma \sim \sin \phi \text{Im}\{k_1(F_2H - F_1E) + \ldots\}\,d\phi$

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**CLAS12: DVCS transverse target-spin asymmetry**

$E = 11$ GeV

Projected results

$Q^2=2.2 \text{ GeV}^2, x_B = 0.25, -t = 0.5\text{GeV}^2$

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**…and CLAS12 will allow us to measure also**

**DVCS polarized and unpolarized cross sections, vector and pseudo-scalar meson electroproduction…**

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$A_{UTx}$ Target polarization in scattering plane

$A_{UTy}$ Target polarization perpendicular to scattering plane

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With $Q^2=2.2 \text{ GeV}^2$, $x_B = 0.25$, and $-t = 0.5\text{GeV}^2$, the projected results show significant asymmetries in $A_{UTx}$ and $A_{UTy}$, indicating the potential for measuring DVCS cross sections in polarized and unpolarized configurations.

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**CLAS12: DVCS transverse target-spin asymmetry**

$e \uparrow p \rightarrow ep\gamma$

$\Delta \sigma \sim \sin \phi \text{Im}\{k_1(F_2H - F_1E) + \ldots\}\,d\phi$

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Transversely polarized target not part of CLAS12 base equipment. **R&D underway**

*LOI approved by PAC38*
Summary

- GPDs are a unique tool to explore the internal landscape of the nucleon:
  - 3D quark/gluon imaging of the nucleon
  - orbital angular momentum carried by quarks

- Their extraction from experimental data is very difficult:
  - they depend on 3 variables, only two (ξ, t) experimentally accessible
  - they appear as integrals in cross sections

- We need to measure several exclusive channels and observables over a wide phase space to constrain the parametrizations of GPDs

- Very promising experimental results on DVCS and DVMP are coming from CLAS:
  - first constraints on GPD models
  - first model-independent GPD fits

- The JLab 12 GeV upgrade is essential for the study of 3-D nucleon structure in the valence region with high precision, allowing the measurement of deeply virtual exclusive processes (to access GPDs) with polarized beam and polarized targets

- CLAS12 will be world wide the only full acceptance, general purpose detector for high luminosity electron scattering experiments, and it will be perfectly suited for the GPD program

- The first 11 GeV electron beam will hit the CLAS12 target at the end of 2014