Deeply virtual Compton scattering with CLAS12
Professor Angela Biselli
Fairfield University

Baryons 2016
Florida State University, Tallahassee, FL, May 16-20 2016
Structure of the nucleon 50 years ago

1950
Elastic scattering
$ep \rightarrow e'p'$
Hofstadter

1967
Deep inelastic scattering
$ep \rightarrow e'X$
Friedman, Kendall, Taylor

Spatial distributions of electric charge and current

Momentum and spin distributions of quarks

Form Factors

PDF
$q(x), \Delta q(x)$

Baryons 2016, Florida State University, Tallahassee, FL, May 16-20 2016
Structure of the nucleon 50 years ago

1950
Elastic scattering
ep → e’p’
Hofstadter

Spatial distributions of electric charge and current

Form Factors

1967
Deep inelastic scattering
ep → e’X
Friedman, Kendall, Taylor

GPDs

Momentum and spin distributions of quarks

PDF
q(x), Δq(x)

multi-dimensional structure
Deeply Virtual Compton Scattering and GPDs

\[ ep \rightarrow ep\gamma \]

Large \(Q^2\), \(t\ll Q^2\) and fixed \(x_B\) :
- factorization
- soft part: 4 GPDs at LO

\[ \xi = x_B \frac{1 + \frac{t}{Q^2}}{2 - x_B + x_B \frac{t}{Q^2}} \]
\[ t = (p - p')^2 \]

\(2\xi\) longitudinal momentum transfer to the struck quark
\(t\) momentum transfer to the nucleon

\(GPDs\) “\(F\)”: \(H, \tilde{H}, E, \tilde{E}\)
\[ F(x, \xi, t) \]
4 GPDs for each quark flavor

Fourier transforms of QCD non-local and non-diagonal operator
\[ \langle p' | \bar{\psi}_q(0) \mathcal{O} \psi_q(y) | p \rangle \]
Deeply Virtual Compton Scattering and GPDs

Average over quark helicity unpolarized GPDs

Difference of quark helicity polarized GPDs

Hs conserve nucleon spin

Es flip nucleon spin

Quark helicity is conserved
Accessing GPDs via DVCS

Bethe Heitler experimentally indistinguishable from DVCS

\[
\frac{d^4 \sigma}{dQ^2 dx_B dtd\phi} \propto |T_{\text{DVCS}} + T_{\text{BH}}|^2 = |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + I
\]

Cross section measurement

Polarization measurements: asymmetries and cross-section differences \(\Rightarrow\)

\[
\sigma^+ - \sigma^- \propto I = T_{\text{DVCS}} T_{\text{BH}}^* + T_{\text{BH}}^* T_{\text{DVCS}}
\]

\[
A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \frac{|T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + I}{|T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + I}
\]

\[
T_{\text{DVCS}} \propto \mathcal{P} \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right] F(x, \xi, t) - i\pi [F(\xi, \xi, t) \pm F(-\xi, \xi, t)]
\]
Accessing GPDs experimentally

PDF $q(x), \bar{q}(x), \xi=0$

Cross section, $|Re|^2$
CLAS, Hall A, COMPASS, H1

BCA, Re
HERMES, COMPASS

TCS, Re

Spin Asymmetries, Im, $x=\xi$
HERMES, CLAS, Hall A, COMPASS

TCS, Im

DDVCS, Im, $x \neq \xi$
# GPDs sensitivity of DVCS spin observables

**Compton Form Factors:** 8 GPD-related quantities

\[
\Re F = \mathcal{P} \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right] F(x, \xi, t)
\]

\[
\Im F = \pi [F(\xi, \xi, t) \mp F(-\xi, \xi, t)]
\]

<table>
<thead>
<tr>
<th>Observable</th>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Spin Asymmetry</strong> $A_{LU}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{LU}(\phi) \propto \Im [F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}] \sin \phi$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Target Spin Asymmetry</strong> $A_{UL}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{UL}(\phi) \propto \Im [F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2) (\mathcal{H} + \frac{xB}{2} \mathcal{E}) - \xi (\frac{xB}{2} F_1 + \frac{t}{4M^2} F_2) \tilde{\mathcal{E}}] \sin \phi$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Double Spin Asymmetry</strong> $A_{LL}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{LL}(\phi) \propto \Re [F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2) (\mathcal{H} + \frac{xB}{2} \mathcal{E}) - \xi (\frac{xB}{2} F_1 + \frac{t}{4M^2} F_2) \tilde{\mathcal{E}}] (A + B \cos \phi)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transverse Target Spin Asymmetry</strong> $A_{UT}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{UT}(\phi) \propto \Im [k (F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots] \sin \phi$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## GPDs sensitivity of DVCS spin observables

Compton Form Factors: 8 GPD-related quantities

\[
\Re \mathcal{F} = \mathcal{P} \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} + \frac{1}{x + \xi} \right] F(x, \xi, t)
\]

\[
\Im \mathcal{F} = \pi [F(\xi, \xi, t) \mp F(-\xi, \xi, t)]
\]

<table>
<thead>
<tr>
<th>Observable</th>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Spin Asymmetry ( A_{LU} )</td>
<td></td>
<td>( \Im { \mathcal{H}_p, \mathcal{\bar{H}}_p, \mathcal{E}_p } )</td>
</tr>
<tr>
<td>( A_{LU}(\phi) \propto \Im [F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{\bar{H}} - \frac{t}{4M^2} F_2 \mathcal{E}] \sin \phi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target Spin Asymmetry ( A_{UL} )</td>
<td></td>
<td>( \Im { \mathcal{H}_p, \mathcal{\bar{H}}_p } )</td>
</tr>
<tr>
<td>( A_{UL}(\phi) \propto \Im [F_1 \mathcal{\bar{H}} + \xi (F_1 + F_2) (\mathcal{H} + \frac{x_B}{2} \mathcal{E}) - \xi (\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2) \mathcal{\bar{E}}] \sin \phi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Spin Asymmetry ( A_{LL} )</td>
<td></td>
<td>( \Re { \mathcal{H}_p, \mathcal{\bar{H}}_p } )</td>
</tr>
<tr>
<td>( A_{LL}(\phi) \propto \Re [F_1 \mathcal{\bar{H}} + \xi (F_1 + F_2) (\mathcal{H} + \frac{x_B}{2} \mathcal{E}) - \xi (\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2) \mathcal{\bar{E}}] (A + B \cos \phi) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse Target Spin Asymmetry ( A_{UT} )</td>
<td></td>
<td>( \Im { \mathcal{H}_p, \mathcal{E}_p } )</td>
</tr>
<tr>
<td>( A_{UT}(\phi) \propto \Im [k (F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots] \sin \phi )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### GPDs sensitivity of DVCS spin observables

**Compton Form Factors:** 8 GPD-related quantities

\[ \Re \mathcal{F} = \mathcal{P} \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right] F(x, \xi, t) \]

\[ \Im \mathcal{F} = \pi [F(\xi, \xi, t) \mp F(-\xi, \xi, t)] \]

<table>
<thead>
<tr>
<th>Observable</th>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Spin Asymmetry</strong> $A_{LU}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{LU}(\phi) \propto \Im [F_1 \mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}] \sin \phi$</td>
<td>$\Im {\mathcal{H}_p, \mathcal{H}_n, \mathcal{E}_p}$</td>
<td>$\Im {\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n}$</td>
</tr>
<tr>
<td><strong>Target Spin Asymmetry</strong> $A_{UL}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{UL}(\phi) \propto \Im [F_1 \mathcal{H} + \xi(F_1 + F_2)\mathcal{H} + \frac{x_B}{2} \mathcal{E}] - \xi(\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2)\mathcal{E}] \sin \phi$</td>
<td>$\Im {\mathcal{H}_p, \mathcal{H}_n}$</td>
<td>$\Im {\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n}$</td>
</tr>
<tr>
<td><strong>Double Spin Asymmetry</strong> $A_{LL}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{LL}(\phi) \propto \Re [F_1 \mathcal{H} + \xi(F_1 + F_2)\mathcal{H} + \frac{x_B}{2} \mathcal{E}] - \xi(\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2)\mathcal{E}] (A + B \cos \phi)$</td>
<td>$\Re {\mathcal{H}_p, \mathcal{H}_n}$</td>
<td>$\Re {\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n}$</td>
</tr>
<tr>
<td><strong>Transverse Target Spin Asymmetry</strong> $A_{UT}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{UT}(\phi) \propto \Im [k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots] \sin \phi$</td>
<td>$\Im {\mathcal{H}_p, \mathcal{E}_p}$</td>
<td>$\Im {\mathcal{H}_n}$</td>
</tr>
</tbody>
</table>
Upgrade of Jefferson Lab

Beam energies: 2.2, 4.4, 6.6, 8.8, 11
Polarization >80%

Upgrade of the accelerator completed in 2014

Upgrade of the instrumentation in the three Halls

Add 5 cryomodules

20 cryomodules

Add arc

CHL-2

12 GeV

New hall

New experimental hall, Hall D with beam energy up to 12 GeV

Beam Power: 1 MW
Beam Current: 90 µA
Max Energy/pass: 2.2 GeV
Max Energy Hall A-B-C: 11 GeV
Max Energy Hall D: 12 GeV

Baryons 2016, Florida State University, Tallahassee, FL, May 16-20 2016
CLAS12 DVCS experiments

CLAS12, FT, CND, NH3, HDIce
- Large kinematic coverage
- BSA, TSA, DSA, tTSA
- Cross-section
- CFF extraction

Central Detector

Forward Tagger 2.5-5 deg photons

Forward Detector

<table>
<thead>
<tr>
<th>CLAS exper.</th>
<th>physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>E12-06-112</td>
<td>pDVCS BSA TSA</td>
</tr>
<tr>
<td>E12-11-003</td>
<td>nDVCS BSA</td>
</tr>
<tr>
<td>E12-06-119</td>
<td>pol target nDVCS</td>
</tr>
<tr>
<td>E12-12-010</td>
<td>pDVCS transverse TSA</td>
</tr>
<tr>
<td>E12-12-001</td>
<td>Timelike DVCS</td>
</tr>
</tbody>
</table>

in preparation DDVCS
CLAS12 DVCS experiments

CLAS12, FT, CND, NH3, HDIce
- Large kinematic coverage
- BSA, TSA, DSA, tTSA
- Cross-section
- CFF extraction

CLAS12, FT, CND, NH3, HDIce

<table>
<thead>
<tr>
<th>CLAS exper.</th>
<th>physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>E12-06-112</td>
<td>pDVCS BSA TSA</td>
</tr>
<tr>
<td>E12-11-003</td>
<td>nDVCS BSA</td>
</tr>
<tr>
<td>E12-06-119</td>
<td>pol target nDVCS</td>
</tr>
<tr>
<td>E12-12-010</td>
<td>pDVCS transverse TSA</td>
</tr>
<tr>
<td>E12-12-001</td>
<td>Timelike DVCS</td>
</tr>
<tr>
<td>in preparation</td>
<td>DDVCS</td>
</tr>
</tbody>
</table>

Study of the high XB region to study the valence-quark regime

Baryons 2016, Florida State University, Tallahassee, FL, May 16-20 2016
Experiment E12-06-119 BSA pDVCS

BSA and x-sections were measured with CLAS @ 6GeV

A = a sinφ/(1+ cos φ)

σ and Δσ

Models
- VGG* twist 2
- VGG* twist 3 and 3
- Regge model (Laget)

F.X. Girod et al., PRL 100 (2008)

Sensitivity to Im, Re Hρ
Experiment E12-06-119 BSA pDVCS

- BSA
- cross section differences and cross section
- ~80 PAC days
- first experiment to run 2017
- CLAS12+FT

FT - Forward tagger PbW0₄ calorimeter

- liquid hydrogen target
- beam pol 85%
- L=10^{35} cm^{-2}s^{-1}
- 1<Q^{2}<10 \text{ GeV}^{2}
- 0.1<x_B<0.65
- -t_{\text{min}}<-t<2.5 \text{ GeV}^{2}
- 1-10\% stat errors on sin\phi
- 10\% syst. error
Experiment E12-06-119 TSA DSA pDVCS

TSA DSA were measured with CLAS @ 6GeV

\[ A_{UL} = \frac{\alpha_{UL} \sin \phi}{1 + \beta \cos \phi} \]

- Im\( H \) has a steeper slope than Im\( \tilde{H} \) - axial charge more concentrated?
- Slope of Im\( H \) decreasing as \( x_b \) increases - fast quarks (valence) more concentrated in the nucleon’s center, slow quarks (sea) more spread out
- Not enough A_{LL} statistical precision to extract real parts Re\( \tilde{H} \), Re\( \tilde{E} \)

Sensitivity to Im\( \tilde{H}_p \)

S. Pisano et al Phys. Rev. D.91 052014
Experiment E12-06-119 TSA DSA pDVCS

- TSA
- DSA
- ~120 PAC days
- scheduled to run 2018-2019
- CLAS12+pol target+FT(?)

Longitudinally polarized target

- NH3
- beam pol 85%
- target pol 80%
- \( L = 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)
- \( 1 < Q^2 < 10 \text{ GeV}^2 \)
- \( 0.1 < x_B < 0.65 \)
- \( -t_{\text{min}} < -t < 2.5 \text{ GeV}^2 \)
- 1-15% stat errors on sin\(\phi\)
- 10% syst. error
Experiment E12-06-119 pDVCS cont.

Expected sensitivity to $t$-dependence (Regge-type vs form factor, with or without D-term)

Increased precision in CFF extraction
Experiment E12-12-010 pDVCS tTSA tDSA

- transverse TSA and DSA
- ~100 PAC days
- conditionally approved
- CLAS12+HDLice target

HDIce
- beam pol 80%
- target pol 60%
- $L = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

1$<Q^2<10 \text{ GeV}^2$
- $0.06<x_B<0.656$
- $-t_{\text{min}}<-t<1.5 \text{ GeV}^2$

Need $H$ to constrain $J$

Sensitivity to:
- $\text{Im}E$, $\text{Re}E$
- $u$-quark contributions
DVCS on the neutron

- We can extract GPDs for proton or neutron but we want GPDs for quark flavors

\[(H, E)_{u}(\xi, \xi, t) = 9/15[4(H, E)_{p}(\xi, \xi, t) - (H, E)_{n}(\xi, \xi, t)] \]
\[(H, E)_{d}(\xi, \xi, t) = 9/15[4(H, E)_{n}(\xi, \xi, t) - (H, E)_{p}(\xi, \xi, t)] \]

- \(H, E\) for both proton and neutron are needed
  - \(E_n\) BSA on neutron
  - \(E_p\) TTSA on proton
  - \(H_n\) TSA on neutron
  - \(H_p\) BSA on proton

  nDVCS important for flavor separation

- with \(H_q, E_q\) can extract the quark angular momentum (Ji’s sum rule)

\[J_N = \frac{1}{2} = J^q + J^g = \frac{1}{2} \Sigma + L^q + \Delta g + L^g \]
\[J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{+1} x dx [H^q(x, \xi, 0) + E^q(x, \xi, 0)] \]

  information on quark orbital angular momentum
Experiment E12-11-003 nDVCS

- BSA
- ~80 PAC days
- CLAS12+CND+FT

Sensitivity to:
- ImE

BSA vs $\phi$

- deuteron
- beam pol 85%
- target pol 40%
- e d -> e(p) n g
- L=10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}
- 1<Q^2<10 \text{ GeV}^2
- 0.1<x_B<0.7
- $-t_{\min}<-t<1.2$ \text{ GeV}^2
Experiment E12-15-004 polarized nDVCS

- TSA and DSA
- ~65 PAC days (together with DIS)
- requesting other 65 at PAC44
- CLAS12+CND+pol target+FT?

- ND3
- beam pol 85%
- target pol 40%
- e d -> e(p) n g
- L=10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}
- 1<Q^2<10 \text{ GeV}^2 \quad 0.1<x_B<0.7
- -t_{\text{min}}<-t<1.2 \text{ GeV}^2
Experiment E12-15-004 polarized nDVCS

- Combining results of neutron experiments
- Fit of BSA, TSA, DSA to extract CFF for the neutron
- Assumption $\tilde{\epsilon}$ purely real: $\tilde{\epsilon}_{\text{im}}(n)=0$
- 7 CFF to be fitted
- Limit +/- 5VGG prediction

$E_{\text{im}}(n), \ H_{\text{im}}(n)$ best constrained
$\tilde{E}_{\text{Re}}(n)$, good sensitivity
$\tilde{H}_{\text{im}}(n), \ H_{\text{Re}}(n)$ constrained low $Q^2-x_B$
$\tilde{H}_{\text{Re}}(n)$ very limited
$E_{\text{Re}}(n)$ not constrained
Flavor separation with CLAS12

- Flavor separation by combining results pDVCS and nDVCS experiments

\[
(H, E)_u(\xi, \xi, t) = \frac{9}{15}[4(H, E)_p(\xi, \xi, t) - (H, E)_n(\xi, \xi, t)] \\
(H, E)_d(\xi, \xi, t) = \frac{9}{15}[4(H, E)_n(\xi, \xi, t) - (H, E)_p(\xi, \xi, t)]
\]
**Time-like Compton scattering**

Time-like Compton scattering is basically the inverse process of DVCS

\[ \gamma p \rightarrow p l^+ l^- \quad l = e, \mu \]

TCS depends on BOTH real and imaginary part of CFF

TCS can be done with unpolarized or circularly polarized photon beams

Higher twist TCS and DVCS ⇒ better constraints on GPDs

exploratory measurement work by Paremuzyan

Quasi-real photo-prod data

e p → e' e+ e- p'

Experimentally

e p → e+ e- p' X

Preliminary

Baryons 2016, Florida State University, Tallahassee, FL, May 16-20 2016
Timelike Compton Scattering with CLAS12

- \( R \propto M^{-2} \)
- \( \sim 100 \) PAC days (+20 inverse field)
- CLAS12

Sensitivity to:
- Im \( H \)
- Re \( H \)

Sensitivity to:
Dual parametrization vs Double distributions (D-term)

\[
R = \frac{2\int_0^{2\pi} d\phi \cos \phi \frac{dS}{dQ^2 dt d\phi}}{2\pi \int_0^{2\pi} d\phi \frac{dS}{dQ^2 dt d\phi}}
\]

\[
\tilde{M}_{\omega} = 2\sqrt{t_0^2 - t} \frac{1 - \eta}{1 + \eta} \left[ F_1 \mathcal{H}_1 - \eta (F_1 + F_2) \tilde{\mathcal{H}}_1 - t \frac{1}{4M^2 F_2 \mathcal{E}} \right]
\]

\[
\frac{d^2 \tau}{d\phi} = 2\int_0^{2\pi} d\phi \mathcal{S} \frac{d^2 \pi}{dQ^2 dt d\phi}
\]

\[
\frac{d^2 \tau}{d\phi} = \frac{2\pi}{2\pi} \int_0^{2\pi} d\phi \mathcal{S} \frac{d^2 \pi}{dQ^2 dt d\phi}
\]

\( \omega, d, s \)

2\( <M_{ee}<3 \) GeV resonance free region

Baryons 2016, Florida State University, Tallahassee, FL, May 16-20 2016
Double Deeply Virtual Compton Scattering (DDVCS)

**Diagram:**

\[ e^+p \rightarrow e^+p^+\mu^+\mu^- \]

**DVCS:**
\[ x = \pm \xi \]

**DDVCS:**
\[ x \neq \xi \]

The invariant mass of the two muons provides the extra degree of freedom to explore \( x \neq \xi \)

\[ e^+ + p \rightarrow e^+ + p + \gamma \]

\( E_e = 11 \text{ GeV}, x_B = 0.15, Q^2 = 2.75 \text{ GeV}^2, t = -0.3 \text{ GeV}^2 \)

Proposal in preparation:
- High luminosity
- New Moller cone (7 deg)
- Absorber/shield to filter muons
- PbWO4 calorimeter to detect electrons
Conclusions

• GPD are a powerful and unique tool explore the structure of the nucleon
• GPDs are fully-correlated quark distributions in both coordinate and momentum space -> 3D imaging
• Complex extraction from data
  • 4 GPD for each quark flavor
  • GPDs depend on 3 variables but only two are experimentally accessible. Need models to map the x dependence
  • Cross sections depend on integrals of GPDs
  • TCS and DDVC add new sensitivity
• 6 GeV program was very successful and gave us a first look at the structure of the nucleon
• Need extensive measurements of different observables for both proton and neutron over a large kinematic range for a reliable extraction of GPDs
• Rich experimental program planned CLAS12
Thank you
Thank you
Thank you