New Deeply Virtual Compton Scattering results from Jefferson Lab

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DIS 2015 (Dallas, TX)

April 27 – May 1, 2015
Outline

1. Very brief experimental introduction to GPDs (and how they can be accessed through DVCS)

2. Jefferson Lab overview:
   - Complementary DVCS programs in Hall A and Hall B
   - Very recent results (April 2015) released from both Hall A & B

3. Outlook
   - Jefferson Lab at 12 GeV
   - Hall A & B + new DVCS program in Hall C

4. Conclusion
Studying nucleon structure experimentally

- **Elastic scattering**
  - Form factors

- **Deep inelastic scattering**
  - Parton distributions

- **Hard exclusive processes**
  - Generalized Parton Distributions (GPDs)
Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \rightarrow \gamma p$

Motivation

Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \rightarrow \gamma p$

**Handbag diagram**

High $Q^2$

Perturbative QCD

Non-perturbative GPDs

Bjorken limit:

$$Q^2 = -q^2 \rightarrow \infty \quad \nu \rightarrow \infty \quad \left\{ \begin{array}{l} x_B = \frac{Q^2}{2M\nu} \quad \text{fixed} \end{array} \right.$$}

- GPDs accessible through DVCS only at $Q^2 \rightarrow \infty$
- Actual value of $Q^2$ must be tested and established by experiment
Generalized Parton Distributions

- Correlate between different partonic states
- Correlate momentum and position of partons
- Access to new fundamental properties of the nucleon

Contribution of the angular momentum of quarks to proton spin:

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

DVCS cleanest process to access GPDs
GPD experimentally: Compton Form Factors (CFFs)

Cross-section (\(\sigma\)) measurement and beam charge difference (\(\text{Re} T\)) integrate GPDs with \(1/(x \pm \xi)\) weight.

Beam or target spin \(\Delta \sigma\) contain only \(\text{Im} T\), therefore GPDs at \(x = \xi\) and \(-\xi\).

Lattice Moments

\[
= \int x^n H(x, \xi, t) dx
\]
DVCS experimentally: interference with Bethe-Heitler

At leading twist:

\[
\begin{align*}
\frac{d^5}{d\sigma} - \frac{d^5}{d\sigma} & = 2 \Im \left( T^{BH} \cdot T^{DVCS} \right) \\
\frac{d^5}{d\sigma} + \frac{d^5}{d\sigma} & = |BH|^2 + 2 \Re \left( T^{BH} \cdot T^{DVCS} \right) + |DVCS|^2
\end{align*}
\]

\[
T^{DVCS} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} + \cdots = \\
\mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi \ H(x = \xi, \xi, t) + \cdots
\]

Access in helicity-independent cross section

Access in helicity-dependent cross-section
Accessing different GDPs

Polarized beam, unpolarized target (BSA)

\[ d\sigma_{LU} = \sin \phi \cdot \Im \{ F_1 \mathcal{H} + x_B(F_1 + F_2)\tilde{\mathcal{H}} - kF_2 \mathcal{E} \} d\phi \]

Unpolarized beam, longitudinal target (ITSA)

\[ d\sigma_{UL} = \sin \phi \cdot \Im \{ F_1 \tilde{\mathcal{H}} + x_B(F_1 + F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_BkF_2 \tilde{\mathcal{E}} \ldots \} d\phi \]

Polarized beam, longitudinal target (BITSA)

\[ d\sigma_{LL} = (A + B \cos \phi) \cdot \Re \{ F_1 \tilde{\mathcal{H}} + x_B(F_1 + F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) \ldots \} d\phi \]

Unpolarized beam, transverse target (tTSA)

\[ d\sigma_{UT} = \cos \phi \cdot \Im \{ k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots \} d\phi \]
Kinematic complementarity between different facilities:

- H1, ZEUS
- H1, ZEUS
- JLab @ 12 GeV
- COMPASS
- HERMES
- E = 27 GeV
- E = 11 GeV
- E = 6 GeV
- W > 2 GeV
The DVCS program at Jefferson Lab

- **Hall A**: high accuracy, limited kinematic coverage
- **Hall B**: wide kinematic range, limited precision
- **Hall C**: high precision program at 11 GeV

Partially overlapping, partially complementary programs with different experimental setups

The roadmap:

- Early results (2001) from non-dedicated experiment (CLAS)
- 1st round of dedicated experiments in Halls A/B in 2004/5
- 2nd round on 2008–2010: precision tests + additional spin observables
- Compelling DVCS experiments in Halls A+B+C at 11 GeV (≥ 2017)
E00-110 experimental setup

- High Resolution Spectrometer
- 100-channel scintillator array
- 132-block PbF$_2$ electromagnetic calorimeter

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DVCS at JLab

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Kinematic settings: testing $Q^2$–dependance

<table>
<thead>
<tr>
<th>Kin</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$\theta_e$ (deg.)</th>
<th>$\theta_{\gamma^*}$ (deg.)</th>
<th>$P_e$ (GeV)</th>
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<tr>
<td>1</td>
<td>1.5</td>
<td>0.36</td>
<td>15.6</td>
<td>22.3</td>
<td>3.6</td>
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<td>2</td>
<td>1.9</td>
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<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>2.3</td>
<td>0.36</td>
<td>23.9</td>
<td>14.8</td>
<td>2.3</td>
</tr>
</tbody>
</table>

$\mathcal{P} = 75.3\%$

$\int \mathcal{L} \, dt = 13294 \, \text{fb}^{-1} \, (3.26 \, \text{Coulombs})$
**Data analysis: exclusivity and background subtraction**

\[ ep \to e\gamma X \text{ missing mass squared} \]

- **Symmetric Pion center-of-mass Laboratory frame**
  - \( M_X^2 \) cut window
  - \( \pi^0 \) cont.
  - After \( \pi^0 \) & accidental subt.

- **Asymmetric decay**
  - \( \theta \)

- **DVCS MC**

- Only \( e' \) & \( \gamma \) detected + \( M_X^2 \)-cut
- 2-3% uncertainty on exclusivity

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**DVCS cross sections: azimuthal analysis**

\[ Q^2 = 2.36 \text{ GeV}^2, \ x_B = 0.37, \ -t = 0.32 \text{ GeV}^2 \]

\[ d^4\sigma = T_{BH}^2 + T_{BH} \text{Re}(T_{DVCS}) + T_{DVCS}^2 \]

\[ \text{Re}(T_{DVCS}) \sim c_0^T + c_1^T \cos \phi + c_2^T \cos 2\phi \]

\[ T_{DVCS}^2 \sim c_0^{DVCS} + c_1^{DVCS} \cos \phi \]

\[ \Delta^4\sigma = \frac{d^4\sigma - d^4\sigma^*}{2} = \text{Im}(T_{DVCS}) \]

\[ \text{Im}(T_{DVCS}) \sim s_1^T \sin \phi + s_2^T \sin 2\phi \]
Recent results

DVCS cross sections: $Q^2$–dependance

No $Q^2$-dependance within limited range $\Rightarrow$ leading twist dominance
**Recent results**

**Hall A**

**DVCS cross sections: higher twist corrections**

**KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries**

Kumericki and Mueller (2010)

- **Target-mass corrections (TMC):** \( \sim \mathcal{O}(M^2/Q^2) \) and \( \sim \mathcal{O}(t/Q^2) \)

Braun, Manashov, Mueller and Pirnay (2014)

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Significant deviation from BH cross section

Twist-4 corrections may be necessary to fully explain experimental data
Hall A DVCS precision measurements

1. Initial indications of validity of GPD formalism at moderate $Q^2$

2. Significant deviation from BH

3. Higher twist corrections likely necessary to fully describe the data

4. Extremely accurate data to constrain model and global fits
E01-113: BSA in a large kinematic domain (Hall B)

CLAS+
dedicated calorimeter

\[ A = \frac{\vec{\sigma} - \sigma}{\vec{\sigma} + \sigma} \approx \frac{\alpha \sin \phi}{1 + \beta \cos \phi} \]

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

\[ 0.1 \ 0.2 \ 0.3 \ 0.4 \ 0.5 \]

\[ 0 \ 90 \ 180 \ 270 \ 360 \]

\[ -0.2 \ 0.0 \ 0.2 \]

\[ -t = 0.28 \text{ GeV}^2 \]

\[ -t = 0.49 \text{ GeV}^2 \]

F.X. Girod et al. PRL 97, 072002 (2006)
Hall B DVCS cross-section measurements

- Larger kinematic range covered: 110 ($Q^2$, $x_B$, $t$) bins
- Compatible with Hall A results in overlap region
- Leading twist models describe the data within uncertainties

Recent results

JLab 6 GeV program and beyond

1. Complementarity of Hall A and Hall B programs:
   - Precision measurements:
     - $Q^2$-dependences, higher-twist corrections...
   - Large kinematic coverage:
     - $x_B$ and $t$ dependences of observables

2. Upcoming at 6 & 12 GeV:
   - Beam energy dependence of the cross sections
   - Higher values and lever-arm in $Q^2$
Near-future experiments

E07-007 (Hall A)

\[ \sigma(ep \rightarrow ep\gamma) = |BH|^2 + I(BH \cdot DVCS) + |DVCS|^2 \]

Known to \( \sim 1\% \) Linear combination of GPDs Bilinear combination of GPDs

DVCS cross section has a very rich azimuthal structure:

- Azimuthal analysis allows the separation of the different contributions to \( I \) if DVCS\(^2\) is negligible.
- If DVCS\(^2\) is important, \( I \) and DVCS\(^2\) terms mix in an azimuthal analysis.
- The different energy dependence of \( I \) and DVCS\(^2\) allow a full separation.
E07-007: Rosenbluth-like DVCS$^2$–$\mathcal{I}$ separation

- Clean separation of BH-DVCS interference term from pure DVCS$^2$
- Scaling test on the real part of the DVCS amplitude
- Rosenbluth separation of $\sigma_L/\sigma_T$ for $ep \rightarrow ep\pi^0$

$d^4\sigma$ (nb/GeV$^4$)

- $E_b=6.0$ GeV
- $E_b=3.64$ GeV

- E07-007
- Systematic uncertainty

△ E00-110: assuming DVCS$^2=0$
Upgrade of Jefferson Lab to 12 GeV

- Add 5 cryomodules
- 20 cryomodules
- Add arc
- Enhanced capabilities in existing Halls
- New Hall

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DVCS at JLab
JLab 12 GeV DVCS experiments

- E12-06-114: Hall A unpolarized protons
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons
- E12-13-010: Hall C unpolarized protons
E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

\[ (6.6, 8.8, 11.0 \text{ GeV beam energy}) \]

DVCS measurements in Hall A/JLab

88 days
250k events/setting

1 year of operations in JLab/Hall A
E12-06-119: DVCS on the proton with CLAS12
E12-11-003: projections

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

\[ x_B \]

\[ 0 \quad -t \quad 1.2 \]

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E12-13-010: DVCS in Hall C

- HMS ($p < 7.3 GeV$): scattered electron
- PbWO$_4$ calorimeter: $\gamma/\pi^0$ detection
- Sweeping magnet
E12-13-010: beam energy separation in Hall C

Approved by the PAC, possible running in \( \gtrsim 2020 \)
Summary

- **DVCS golden channel to access GPDs experimentally**, but also accessible in:
  - Time-like Compton Scattering (WG1 M. Boër’s talk)
  - Deep meson production (WG6 M. Defurne’s next talk)

- **Large and accurate set of data** (cross-sections and asymmetries) is now available in the valence region
  - Dominance of leading twist, but . . .
  - Necessity of higher twist corrections to explain high precision data

- **Compelling GPD program in the future** at Jefferson Lab 12 GeV in all 3 electron Hall A, B & C