New Deeply Virtual Compton Scattering results from Jefferson Lab

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Introduction

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
   - Recent results (2015) published 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
- Generalized Parton Distributions (GPDs)

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

Handbag diagram

Bjorken limit:

$$Q^2 = -q^2 \rightarrow \infty \quad \nu \rightarrow \infty$$

$$x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

- GPDs accessible through DVCS only at $Q^2 \rightarrow \infty$
- Actual value of $Q^2$ must be tested and established by experiment
DVCS experimentally: interference with Bethe-Heitler

At leading twist:

\[
\begin{align*}
\frac{d^5}{d\sigma} & \rightarrow \frac{d^5}{d\sigma} = 2 \Im m (T_{BH} \cdot T_{DVCS}) \\
\frac{d^5}{d\sigma} & + \frac{d^5}{d\sigma} = |BH|^2 + 2 \Re e (T_{BH} \cdot T_{DVCS}) + |DVCS|^2
\end{align*}
\]

Access in helicity-independent cross section

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

Access in helicity-dependent cross-section
Accessing different GDPs

Polarized beam, unpolarized target (BSA)
\[ d\sigma_{LU} = \sin \phi \cdot \Im \{ F_1 \mathcal{H} + x_B (F_1 + F_2) \mathcal{H} - k F_2 \mathcal{E} \} d\phi \]

Unpolarized beam, longitudinal target (ITSA)
\[ d\sigma_{UL} = \sin \phi \cdot \Im \{ F_1 \mathcal{H} + x_B (F_1 + F_2) (\mathcal{H} + x_B/2\mathcal{E}) - x_B k F_2 \mathcal{E} \ldots \} d\phi \]

Polarized beam, longitudinal target (BITSA)
\[ d\sigma_{LL} = (A + B \cos \phi) \cdot \Re \{ F_1 \mathcal{H} + x_B (F_1 + F_2) (\mathcal{H} + x_B/2\mathcal{E}) \ldots \} d\phi \]

Unpolarized beam, transverse target (tTSA)
\[ d\sigma_{UT} = \cos \phi \cdot \Im \{ k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots \} d\phi \]
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)
### 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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>0.36</td>
<td>15.6</td>
<td>22.3</td>
<td>3.6</td>
</tr>
<tr>
<td>2</td>
<td>1.9</td>
<td>0.36</td>
<td>19.3</td>
<td>18.3</td>
<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>

\[ \int L \, dt = 13294 \text{ fb}^{-1} \text{ (3.26 Coulombs)} \]

\[ P = 75.3\% \]

\[ L = 10^{37} \text{ cm}^{-2} \text{ s}^{-1} \]

\[ 5.75 \text{ GeV} \]

\[ \theta = 23.3^\circ \]

\[ \theta_{\gamma^*} = 14.8^\circ \]

\[ 6.3^\circ \]

\[ 110 \text{ cm} \]
Recent results

Hall A

Data analysis: exclusivity and background subtraction

$e p \rightarrow e \gamma X$ missing mass squared

- $M^2_X$ cut window
- $\pi^0$ cont.
- After $\pi^0$ & accidental subt.
- Symmetric decay
- Pion center-of-mass Laboratory frame
- Direction of the boost

- DVCS MC

- Only $e'$ & $\gamma$ detected + $M^2_X$-cut
- 2-3% uncertainty on exclusivity

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DVCS at JLab

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**Recent results**

**Hall A**

### DVCS cross sections: azimuthal analysis

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

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

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

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

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

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

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DVCS cross sections: $Q^2$-dependance

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

DVCS cross sections: higher twist corrections

Significant deviation from BH cross section

Twist-4 corrections may be necessary to fully explain experimental data

Kin3

\[ x_B = 0.34 - 0.37 \]

\[ Q^2 = 2.2 - 2.4 \text{ GeV}^2 \]

- Bethe-Heitler
- KM10a
- KM10a + TMC*
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

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

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F.X. Girod et al. PRL 97, 072002 (2006)
Recent results

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

Long-polarized target

**DVCS target spin asymmetry from CLAS**

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH$_3$ target ($P \sim 80\%$)

![Graph showing DVCS asymmetries](image)

5 $Q^2$-$x_B$ bins, 4 $t$ bins, 10 $\phi$ bins

3 DVCS asymmetries

E. Seder et al., PRL 114 (2015) 032001

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Beam Spin Asymmetry from CLAS

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH$_3$ target ($\mathcal{P} \sim 80\%$)

3 DVCS asymmetries

S. Pisano et al., PRD 91, 052014 (2015)
Long-polarized target

Double Spin Asymmetry

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH$_3$ target ($\mathcal{P} \sim 80\%$)

\begin{align*}
\text{LL} & : \kappa = 0.2, 0.4, 0.6, 0.8 \\
\text{LL} & : Q^2 > 1.52 \text{ (GeV/c)}^2 \\
\text{LL} & : <Q^2> = 0.179 \\
\text{LL} & : x_b > 2.41 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.255 \\
\text{LL} & : -t (GeV/c) 0 0.5 1 1.5 2 \\
\text{LL} & : <Q^2> = 1.52 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.179 \\
\text{LL} & : x_b > 2.41 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.255 \\
\text{LL} & : -t (GeV/c) 0 0.5 1 1.5 2 \\
\text{LL} & : <Q^2> = 3.31 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.453 \\
\text{LL} & : -t (GeV/c) 0 0.5 1 1.5 2 \\
\text{LL} & : <Q^2> = 1.97 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.255 \\
\text{LL} & : x_b > 2.6 \text{ (GeV/c)}^2 \\
\text{LL} & : <x_b> = 0.345 \\
\text{LL} & : -t (GeV/c) 0 0.5 1 1.5 2 \\
\end{align*}

S. Pisano et al., PRD 91, 052014 (2015)
Upgrade of Jefferson Lab to 12 GeV

Add 5 cryomodules

20 cryomodules

Add arc

Enhanced capabilities in existing Halls

New Hall

20 cryomodules

Add 5 cryomodules
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 GeV beam energy)

DVCS measurements in Hall A/JLab

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

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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

Inaccessible with $E_b < 11$ GeV

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

- **DVCS golden channel to access GPDs experimentally**, but also accessible in:
  - Deep meson production
  - Time-like Compton Scattering, Double DVCS...

- **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