Deeply Virtual Compton Scattering at Jefferson Lab

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Deeply Virtual Compton Scattering

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

\[ Q^2 = -q^2 \gg \Lambda_{QCD}^2, \]
\[ s = (q+p)^2 \gg M^2, \]
\[ -t = -(p - p')^2 \ll Q^2 \]

QCD Factorization (Ji, Radyushkin, Collins & Freund et al)
DVCS = Simplest hard exclusive process

\[ Q^2 = -q^2 = -(k - k')^2 \gg M^2 \]
\[ t = (p - p')^2 = \Delta^2 \ll Q^2 \]

\[ x_B = \frac{Q^2}{2pq} = \frac{Q^2}{2M\nu} \]
\[ \xi = \frac{x_B}{2 - x_B} \]
\[ \xi \pm x = \text{fraction of lightcone momentum} \]

Generalized Parton Distributions

\[ H, E \leftarrow \langle p' | \bar{\psi}(-y/2)\gamma^+\psi(y/2) | p \rangle \]
\[ \bar{H}, \bar{E} \leftarrow \langle p' | \bar{\psi}(-y/2)\gamma^+\gamma_5\psi(y/2) | p \rangle \]
Structure of GPDs

- $H_f(x, \xi, t, Q^2), E_f(x, \xi, t, Q^2) = \text{Matrix elements of vector current}$
- $\widetilde{H}_f(x, \xi, t, Q^2), \widetilde{E}_f(x, \xi, t, Q^2) = \text{Matrix elements of axial current}$
- $Q^2, t, \xi = \text{external kinematic variables}$
- $f = \text{quark flavor}$
- $Q^2 : \text{QCD evolution, DGLAP} \oplus \text{ERBL}$
- $t - t_{\text{min}} = -\Delta_\perp \text{fourier conjugate to transverse coordinate } b \text{ of quark in infinite momentum frame (M. Burkardt)}$
- $\xi = x_{Bj} / (2 - x_{Bj}) = \text{skewness}$,
  - Momentum fraction $= x_{\pm \xi}$,
  - Impact parameter $= b / (1 \pm \xi)$ (M. Diehl)
  - Quark—anti-quark content of proton for $|x| < \xi$.
- GPDs are complicated, but:
  - Each variable has physical meaning.
New Physics from GPDs

- Decomposition of elastic electro-weak form factors (\(G_E, G_M, G_A\)) into lightcone momentum fraction (3d-Tomography)
  - Proton size is a function of \(x\).

- Moments of GPDs are form factors of Stress Energy Tensor
  - X. Ji: Angular Momentum Sum Rule

\[
J_q = \frac{1}{2} \Delta \Sigma_q + L_q = \frac{1}{2} \sum_f \int_{-1}^{1} x dx [H(x, \xi, 0) + E(x, \xi, 0)] = \frac{1}{2} - J_{\text{gluons}}
\]

- Mass density of nucleons and nuclei
  - (Not the same as charge or baryon densities)

- M. Polyakov: Shear force density on quarks
GPD$(x, \xi, t)$: $t \leftrightarrow b_\perp$ Fourier Transform of density of quarks of momentum-fraction $x \pm \xi$  
($\xi=0$: M. Burkardt,  $\xi \neq 0$: M. Diehl)

Unpolarized, Transversely polarized proton.

up-quarks

down-quarks

$u(x, b_\perp)$  
$u_\chi(x, b_\perp)$  
$d(x, b_\perp)$  
$d_\chi(x, b_\perp)$

by

$b_y$

b_x

x

$0.3$  
$0.1$  
$0.5$  
$0.3$  
$0.1$  
$0.5$  
$0.3$  
$0.1$  
$0.5$
Wigner Distributions of Quarks inside the Proton: Short, Medium, and Long wavelength quarks.

Scale is 1 fm ≈ r.m.s. charge radius of proton. Wavelength ≈ $\frac{h}{(Mx)}$

Surfaces of constant density

Courtesy, X. Ji, UMd
DVCS at JLAB

\[
\frac{d^4\sigma}{dQ^2 d\phi_{dB} dt d\phi} \sim |T_{\text{DVCS}} + T_{\text{BH}}|^2
\]

\[T^2 = |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + I\]

\[I = T_{\text{DVCS}} T^*_{\text{BH}} + T^*_{\text{DVCS}} T_{\text{BH}}\]

\[I = \pm \frac{e^6}{x_B^2 y^3 \Delta^2 P_1(\phi) P_2(\phi)} \left\{ c'_0 \sum_{n=1}^2 \left[ c'_n \cos(n\phi) + s'_n \sin(n\phi) \right] \right\}\]

Finite fourier series in azimuth of \(q'\) around \(q\)

Finite fourier series in azimuth of \(q'\) around \(q\)

Cross section of ep→e'p' at \(Q^2=2\ GeV^2\) and \(x_B=0.35\)

\[Q^2 = 2 \text{ GeV}^2\]

\[|\text{DVCS}|^2 \text{ is small for most (but not all) JLab kinematics at 6 GeV}\]
Helicity dependent cross-section

\[ \frac{d\tilde{\sigma}}{dx_B \, dy \, d^2\phi} - \frac{d\tilde{\sigma}}{dx_B \, dy \, d^2\phi} = \Gamma(x_B, y, \Delta^2, \phi) \cdot (A \sin \phi + B \sin 2\phi) \]

with \( x_B = Q^2 / 2 \cdot p \cdot q \), \( y = q \cdot p / k \cdot p \), \( \Delta = p' - p \),

and \( \phi \) the angle between the leptonic and photonic planes.

Γ contains BH propagators and some kinematics

B contains higher twist terms

A is a linear combination of three GPDs evaluated at \( x = \xi \), interfering with elastic form factors (+ higher twist)

\[ A = F_1(t) \cdot H + \frac{x_B}{2 - x_B} \cdot \left( F_1(t) + F_2(t) \right) \cdot \tilde{H} - \frac{t}{4M^2} F_2(t) \cdot E \]
First JLab measurements (CLAS)

CLAS 4.2 GeV H(e,ep)X
(S.Stepanyan et al, Phys Rev Lett 87 (2001))

Beam Spin Asymmetry at 5.7 GeV
2001-2003:
A typical \( H(e,e'p)\gamma \) event in CLAS

2005:
Added a calorimeter at \( 3^\circ < \theta_\gamma < 16^\circ \)
For \( H(e,e'p\gamma) \).

A superconducting Solenoidal Möller shield added at the target
The new Calorimeter consists of 424 PbWO₄ crystals 13x13x100mm³
Light read out via avalanche photo-diodes
Temperature stabilization for high precision energy measurements.

\[ \pi^0(\eta) \rightarrow \gamma\gamma \]

First run completed Spring 2005
Second run 2006?
Proton Target

\[ A = F_1(t) \cdot H + \frac{x_B}{2 - x_B} \cdot (F_1(t) + F_2(t)) \cdot \tilde{H} - \frac{t}{4M^2} F_2(t) \cdot E \]

<table>
<thead>
<tr>
<th>(-t)</th>
<th>(F_2^p(t))</th>
<th>(F_1^p(t))</th>
<th>((F_1^p(t) + F_2^p(t)) \cdot x_B/(2 - x_B))</th>
<th>((-t/4M^2) \cdot F_2^p(t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.34</td>
<td>0.81</td>
<td>0.38</td>
<td>0.04</td>
</tr>
<tr>
<td>0.3</td>
<td>0.82</td>
<td>0.56</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td>0.5</td>
<td>0.54</td>
<td>0.42</td>
<td>0.17</td>
<td>0.07</td>
</tr>
<tr>
<td>0.7</td>
<td>0.38</td>
<td>0.33</td>
<td>0.13</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Proton

Model:

- \(Q^2 = 2 \text{ GeV}^2\)
- \(x_B = 0.3\)
- \(-t = 0.3\)

Target | H | \(\tilde{H}\) | E  |
-------|---|-------------|----|
Proton | 1.13 | 0.70 | 0.98 |

Goeke, Polyakov and Vanderhaeghen
Neutron Target

\[ A = F_1(t) \cdot H + \frac{x_B}{2 - x_B} \cdot (F_1(t) + F_2(t)) \cdot \tilde{H} - \frac{t}{4M^2} F_2(t) \cdot E \]

<table>
<thead>
<tr>
<th>(-t)</th>
<th>(F_2^p(t))</th>
<th>(F_1^p(t))</th>
<th>((F_1^p(t) + F_2^p(t)) \cdot x_B / (2 - x_B))</th>
<th>((-t / 4M^2) \cdot F_2^p(t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-1.46</td>
<td>-0.01</td>
<td>-0.26</td>
<td>-0.04</td>
</tr>
<tr>
<td>0.3</td>
<td>-0.91</td>
<td>-0.04</td>
<td>-0.17</td>
<td>-0.06</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.6</td>
<td>-0.05</td>
<td>-0.12</td>
<td>-0.08</td>
</tr>
<tr>
<td>0.7</td>
<td>-0.43</td>
<td>-0.06</td>
<td>-0.09</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

\(F_1^n(t) \ll F_2^n(t) \) !!!

**Model:**

\[ Q^2 = 2 \text{ GeV}^2 \]
\[ x_B = 0.3 \]
\[ -t = 0.3 \]

**Target**

<table>
<thead>
<tr>
<th>Target</th>
<th>(H)</th>
<th>(\tilde{H})</th>
<th>(E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutron</td>
<td>0.81</td>
<td>-0.07</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Goeke, Polyakov and Vanderhaeghen

\[ t = -0.3 \]

\[ A = -0.03 + 0.01 - 0.12 \]
JLab Hall A Experimental method

Proton: (E00-110)  \( e \, p \rightarrow e \, \gamma \, p \)

Neutron: (E03-106)  \( e \, D \rightarrow e \, \gamma \, n \, (p) \)

Left High Resolution Spectrometer

Polarized beam

Scintillator Array (Proton Array)

LH2 or (LD2) target

Electromagnetic Calorimeter (photon detection)

Scintillating paddles (proton veto)

Only for Neutron experiment

Recoil nucleon position

Reaction kinematics is fully defined

Check of the recoil nucleon position

\( e \, p \rightarrow e \, \gamma \, p \)

\( e \, D \rightarrow e \, \gamma \, n \, (p) \)
Calorimeter in the black box (132 PbF2 blocks)

Proton Array (100 blocks)

Proton Tagger (57 paddles)
Electronics

1 GHz Analog Ring Sampler (ARS)

* x 128 samples x 289 detector channels

CEA-Saclay & Clermont-Ferrand

Sample each PMT signal in 128 values (1 value/ns)

Extract signal properties (charge, time) with a waveform Analysis.

Allows to deal with pile-up events.
Not all the calorimeter channels are read for each event

Calorimeter trigger

Following HRS trigger, stop ARS.

30MHz trigger FADC digitizes all calorimeter signals in 85ns window.

- Compute all sums of 4 adjacent blocks.
- Look for at least 1 sum over threshold
- Validate or reject HRS trigger within 340 ns

Not all the Proton Array channels are read for each event
Analysis status – preliminary

Time difference between the electron arm and the detected photon

Selection of events in the coincidence peak

Determination of the missing particle (assuming DVCS kinematics)

Check the presence of the missing particle in the predicted block (or region) of the Proton Array

Sigma = 0.6ns

2 ns beam structure

Sigma = 0.9ns

Time spectrum in the predicted block (LH$_2$ target)
The analysis focuses on the reaction $ep \rightarrow e\pi^0 X$. The invariant mass distribution shows a peak near $0.160\text{ GeV}^2$ for the missing mass squared, with a threshold for $2\pi$ production. The invariant mass of 2 photons in the calorimeter is noted, with a cross-section of $9.5\text{MeV}$. The plot also highlights the production threshold for $\pi^0$.
Absolute cross sections necessary to extract helicity dependence of neutron

\[ p(e,e'\gamma)X \]

\[ d(e,e'\gamma)X - p(e,e'\gamma)X \]
After applying $H(e,e'\gamma)$ and $H(e,e'\gamma p)$ timing cuts we compare the detected scintillation signal to the predicted direction for an exclusive $H(e,e'\gamma p)$ event.

Missing mass$^2$ of $H(e,e'\gamma)X$, events with coplanar hit in the Proton Array.
JLab at 6 GeV

- First Helicity Dependent results 2006
- Complete set of single spin asymmetries (longitudinal beam, longitudinal target, transverse target) can separate $H, E, \bar{H}, \bar{E}$ at $x = \pm \xi$.
  - Longitudinal target proposal in Hall B (2005)
  - Feasibility studies:
    Transverse target polarization in Hall B, and Proton recoil polarization measurements in Hall A.

- Coherent Nuclear DVCS
  - $D(e,e'\gamma D)$ proposal in preparation
JLab at 12 GeV: CLAS12

High luminosity \((10^{35})\) polarized CW beam

Wide physics acceptance (exclusive, semi-inclusive current and target fragmentation)

Large acceptance for low momentum recoil particles: \(p, D\ldots\)
**CLAS12 - DVCS/BH Beam Asymmetry**

\[ e p \rightarrow ep\gamma \]

\[ E = 11 \text{ GeV} \]

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

Sensitive to GPD \( H \)

Selected Kinematics

\[ L = 1 \times 10^{35} \]
\[ T = 2000 \text{ hrs} \]
\[ \Delta Q^2 = 1 \text{ GeV}^2 \]
\[ \Delta x = 0.05 \]
**CLAS12 - DVCS/BH Target Asymmetry**

Longitudinally polarized target

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

CLAS preliminary

\[ A_{UL} \]

\[ E = 11 \text{ GeV} \]

\[ \langle Q^2 \rangle = 2.0 \text{GeV}^2 \]

\[ \langle x \rangle = 0.2 \]

\[ \langle -t \rangle = 0.25 \text{GeV}^2 \]

\[ L = 2 \times 10^{35} \text{cm}^{-2}s^{-1} \]

\[ T = 1000 \text{hrs} \]

\[ \Delta Q^2 = 1 \text{GeV}^2 \]

\[ \Delta x = 0.05 \]
Transversely polarized target

\[ E = 11 \text{ GeV} \]

\[ \Delta \sigma \sim \sin \phi \text{Im}\{ k_1 (F_2 H - F_1 E) + \ldots \} d\phi \]

- \( A_{UTx} \) Target polarization in scattering plane
- \( A_{UTy} \) Target polarization perpendicular to scattering plane

Asymmetry highly sensitive to the u-quark contributions to the proton spin.
JLab 12 GeV, Hall C (6.6, 8.8, 11 GeV)

- New Super HMS (or MAD) spectrometer.
  - High precision LT separations of H(e,e'π+)n
JLab 12 GeV: Hall A (4.4, 6.6, 8.8, 11 GeV)

- Opportunity for specialized equipment.
- Wide kinematic range accessible with $E = 8.8$ GeV and existing HRS in similar configuration to 6 GeV measurements.
  - Magnetic field at target: $L \rightarrow 10^{38}/cm^2/s$.
  - Double DVCS: $H(e,e'pl^+l^-)$
    - Single spin asymmetries measure GPDs at $|x| \neq \xi$. 
JLab Conclusions and Outlook

- New equipment allows precise exclusive DVCS measurements at 6 GeV in Halls A and B.
  - Kinematics are centered on $x_{Bj}=0.35$ $Q^2=2.5\text{GeV}^2$
  - $t$-dependence at fixed $\xi$ measures spatial distribution of correlation of quarks of momentum fraction 0, 2$\xi$.
  - A complete set of single spin asymmetries can separate all four GPDs at $x=\xi$.
  - Quasi-free D(e,e’n$\gamma$)p primarily sensitive to E.

- Comprehensive program of DVCS and exclusive Deep Virtual Meson Production at 12 GeV:
  - $Q^2$ evolution and higher twist studies for $2<Q^2<9\text{GeV}^2$
  - Flavor decomposition via meson production
  - Beam in 2010+?
Separating GPDs through polarization

$\xi = x_B/(2-x_B)$

$k = t/4M^2$

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

Polarized beam, unpolarized target:

$\Delta \sigma_{LU} \sim \sin \phi \{ F_1 H + \xi (F_1 + F_2) \tilde{H} + k F_2 E \} d\phi$

\[\text{Kinematically suppressed}\]

Unpolarized beam, longitudinal target:

$\Delta \sigma_{UL} \sim \sin \phi \{ F_1 \tilde{H} + \xi (F_1 + F_2) (H + \ldots) \} d\phi$

Unpolarized beam, transverse target:

$\Delta \sigma_{UT} \sim \sin \phi \{ k (F_2 H - F_1 E) + \ldots \} d\phi$

$\text{H, } \tilde{H}, \text{ and } E$
Helicity Dependent Cross Sections.

$$\sigma(eN \rightarrow eN\gamma) = \left| \begin{array}{c} \text{DVCS} \\ \text{Bethe-Heitler (BH)} \end{array} \right|^2 + 2 \Re(DVCS) \cdot BH$$

- High precision measurement can extract
  $$\Re(DVCS) = P \int dx \frac{GPD(x, \xi, t)}{[x \pm \xi]}$$

$$d^5\sigma \propto |BH|^2 + 2 \Re(DVCS) \cdot BH$$

$$d^5\tilde{\sigma} - d^5\tilde{\sigma} \propto BH \cdot \text{Im}(DVCS)$$

Spin Dependent Cross sections give direct handle on the imaginary part of the DVCS amplitude

$$GPD(x = \pm \xi, x, t)$$
p-DVCS and n-DVCS in Hall A

Goal: Measure the absolute cross section of DVCS on proton (3 $Q^2$ values: 1.4, 1.9, 2.3 GeV$^2$) and on neutron ($Q^2$=1.9 GeV$^2$)

DVCS on the proton: E00-110
- Check Handbag dominance & Test factorization
- Deduce $Q^2$ dependence and relative importance of leading twist: A and higher twists: B in helicity dependent cross-section
- Constrain GPD’s
  …including Re(DVCS)

DVCS on the neutron: E03-106 $D(e,e'\gamma n)p \oplus D(e,e'\gamma p)n$
- Simplest access to the least known of GPDs: E
- First constraint of nucleon orbital angular momentum through model of $E$
Background subtraction

Accidental $\pi^0$

Decorrelated photons
\( \pi^0 \) electroproduction – background subtraction

\[
\text{accidentals} = \left[ -3, 3 \right] \left[ 5, 11 \right] + \left[ 5, 11 \right] \left[ -3, 3 \right] + \left[ 5, 11 \right] \left[ 5, 11 \right] - 2 \left[ 5, 11 \right] \left[ -5, -11 \right]
\]
Exclusive π^0 electroproduction cross-section

t-dependence (very preliminary)

exclusive π^0 production

\[ \frac{d^4\sigma}{dk'd\Omega'dt} \text{ pbarn GeV}^{-3} \text{ sr}^{-1} \]

4.4 < s < 5.4 GeV^2

\( <Q^2> = 2.3 \text{ GeV}^2 \)

\( <x_{Bj}> = 0.37 \)

\( q_t, q_x > 1.2 \text{ GeV} \)

\( M_x^2 < 1.2 \text{ GeV}^2 \)

40 runs out of 255 !!
We have demonstrated that in Hall A with High Resolution spectrometer and a good calorimeter, we are able to measure:

- **Real** and **Imaginary** parts of DVCS•BH interference:

  Work at precisely defined kinematics: $Q^2$, $s$ and $x_{Bj}$

  Work at a luminosity up to $L_{nucleon} = 4.10^{37} cm^{-2} s^{-1}$

  **But**

  - Requires wave form electronics
  - 10% of detector components almost unusable as expected after 3 months of data taking

**Absolute cross sections** and **cross section difference** are determined with the precision of HRS (**better than 5%**)

Analysis is in progress
**First measurements** (also H1 and Zeus)

**HERMES Beam Spin Asymmetry**

\[ H(e,e\gamma)X. \]

- \(e\gamma\) missing mass cut
- \(-3 < M_X^2 < 3 \text{ GeV}^2\)


**CLAS 4.2 GeV H(e,ep)X**

(S.Stepanyan et al, Phys Rev Lett 87 (2001))

Fixing photon and pion missing mass
Properties $G_\gamma$ and $G_\pi$

\[ F = N_\gamma \cdot G_\gamma + N_\pi \cdot G_\pi + \text{Polynomial}(a_{1,2,3}) \]

Fit of missing mass
with double gaussian
function $H(ep,ep)X$

$H(e,e'p\gamma)$

$H(e,e'p\pi^0)$

$H(e,e'p)X$ Missing Mass$^2$
$e^+e^- \rightarrow e'\pi X$: kinematic coverage at 11 GeV

- Acceptance in $Q^2, M_x, P_T$ gained with high luminosity and energy upgrade (at 6GeV $M_x<2.5$GeV, $Q^2<4.5$GeV$^2$, $P_T<1$GeV)

- Test factorization in a wide kinematical range
- Study the transition between the non-perturbative and perturbative regimes of QCD
- Measure PDFs and study higher twists
GPDs $H$ from expected DVCS $A_{LU}$ data

- $Q^2 = 3.5$ GeV$^2$
- $b_{val} = b_{sea} = 1$
- MRST02 NNLO distribution

- Other kinematics measured concurrently
JLab 12 GeV: Hall A

  - Full acceptance for DVCS at $L=10^{37}$