Deeply Virtual Compton Scattering on the neutron with CLAS12 at 11 GeV

GPDs

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INPC 2019, Glasgow (UK) - August 1st, 2019
Deeply Virtual Compton Scattering and quark GPDs

\[ Q^2 = - (k-k')^2 \]
\[ x_B = Q^2/2M_v \quad n = E_e - E_e' \]
\[ x + \xi, x - \xi \text{ long. mom. fract.} \]
\[ t = \Delta^2 = (p-p')^2 \]
\[ x \cong x_B/(2-x_B) \]

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector
\[ \rightarrow 4 \text{ GPDs for each quark flavor} \]

**Quark angular momentum (Ji’s sum rule)**

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


**Nucleon tomography**

\[
q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} H(x,0,-\Delta_{\perp}^2)
\]

\[
\Delta q(x, b_{\perp}) = \int_0^{\infty} \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\Delta_{\perp} b_{\perp}} \tilde{H}(x,0,-\Delta_{\perp}^2)
\]

M. Burkardt, PRD 62, 71503 (2000)
Accessing GPDs through DVCS

DVCS allows access to 4 complex GPDs-related quantities: Compton Form Factors $\text{CFF}(\xi,t)$

\[
T_{\text{DVCS}}^{+} \sim P \int_{-1}^{+1} \frac{1}{x \pm \xi} GPDs(x, \xi, t) \, dx \pm i \pi GPDs(\pm \xi, \xi, t) + \ldots
\]

\[
\Re \mathcal{H}_q = e_q^2 P \int_{0}^{+1} \left( H_q^+(x, \xi, t) - H_q^-(x, \xi, t) \right) \left[ \frac{1}{\xi - x} + \frac{1}{\xi + x} \right] \, dx
\]

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

Polarized beam, unpolarized target:
\[
\Delta \sigma_{\text{LU}} \sim \sin \phi \Im \{ F_1 \mathcal{H} + \xi (F_1 + F_2) \mathcal{H} - kF_2 \mathcal{E} + \ldots \}
\]

Unpolarized beam, longitudinal target:
\[
\Delta \sigma_{\text{UL}} \sim \sin \phi \Im \{ F_1 \mathcal{H} + \xi (F_1 + F_2)(\mathcal{H} + x_b/2 \mathcal{E}) - \xi kF_2 \mathcal{E} \}
\]

Polarized beam, longitudinal target:
\[
\Delta \sigma_{\text{LL}} \sim (A + B \cos \phi) \Re \{ F_1 \mathcal{H} + \xi (F_1 + F_2)(\mathcal{H} + x_b/2 \mathcal{E}) + \ldots \}
\]

Unpolarized beam, transverse target:
\[
\Delta \sigma_{\text{UT}} \sim \cos \phi \sin(\phi - \phi) \Im \{ k(\mathcal{H} - F_1 \mathcal{E}) + \ldots \}
\]
Summary of proton-DVCS spin observables and tomography

R. Dupré, M. Guidal, M. Vanderhaeghen, PRD95, 011501 (2017)

Proton DVCS at JLab@12 GeV

<table>
<thead>
<tr>
<th>Observable (target)</th>
<th>12-GeV experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_{\text{beam}}(p)$</td>
<td>Hall A, CLAS12, Hall C</td>
</tr>
<tr>
<td>BSA(p)</td>
<td>CLAS12</td>
</tr>
<tr>
<td>TSA(p)</td>
<td>CLAS12</td>
</tr>
<tr>
<td>DSA(p)</td>
<td>CLAS12</td>
</tr>
<tr>
<td>tTSA(p)</td>
<td>CLAS12</td>
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</tbody>
</table>
Interest of DVCS on the neutron

A combined analysis of DVCS observables for proton and neutron targets is necessary for flavor separation of GPDs

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

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

Moreover, the beam-spin asymmetry for nDVCS is the most sensitive observable to the GPD E → Ji’s sum rule for Quarks Angular Momentum

Polarized beam, unpolarized target:

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

Unpolarized beam, transversely polarized target:

\[ \Delta \sigma_{UT} \sim \cos \phi \text{Im}\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots\}d\phi \] \[ \text{Im}\{\mathcal{H}_p, \mathcal{E}_p\} \]

The BSA for nDVCS:
- is complementary to the TSA for pDVCS on transverse target, aiming at E
- depends strongly on the kinematics → wide coverage needed
- is smaller than for pDVCS → more beam time needed to achieve reasonable statistics
DVCS on the neutron in Hall A at 6 GeV

\[ D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots \]

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

M. Mazouz et al., PRL 99 (2007) 242501

Q^2=1.9 GeV^2 and x_B=0.36

• E03-106: First-time measurement of \( \Delta \sigma_{LU} \) for nDVCS, model-dependent extraction of \( J_u, J_d \)

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

NEW! Hall-A experiment E08-025 (2010)

• Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target and two different beam energies
• First observation of non-zero nDVCS CS
• Results recently submitted for publication
**E12-11-003: nDVCS on the neutron with CLAS12 at 11 GeV**

**JLab PAC: high-impact experiment**

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

The most sensitive observable to the GPD \( E \)

**Fully exclusive final state:**

CLAS12 + Forward Tagger + Central Neutron Detector

\( \bar{e}d \rightarrow e(p)n\gamma \)

**Liquid deuterium target**

Beam polarization =85%  
\( L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon} \)

**Model predictions (VGG)**

for different values of quarks’ angular momentum

\( J_u = 0.3, J_d = 0.1 \)  
\( J_u = 0.1, J_d = 0.1 \)

\( J_u = 0.3, J_d = 0.3 \)  
\( J_u = 0.3, J_d = -0.1 \)

**Projections for 90 PAC days**

Hall-A@6 GeV kinematics
CLAS12 Run Group B
Electroproduction on deuterium with CLAS12

2019 schedule: first part of RG B in February 6th - March 25th 2019, second part in November 1st – December 19th → ~44.5 PAC days (~1/2 of approved run time)

Statistics for the spring run:
• 237 « good » production runs + various ancillary runs
• « Production » beam current: 50 nA
• ~9.7 B triggers at 10.6 GeV, 11.7 B triggers at 10.2 GeV
• Average beam polarization ~86% (22 Moeller runs)
• ~25% of the approved beam time

✓ First round of preliminary calibrations done
✓ Reconstruction ongoing
CLAS12 Run group B: experimental setup

Central Detector
Forward Detector

RICH
Forward Tagger

Central Neutron Detector

BAND
**CND: characteristics and performances with RGB data**

**Purpose:** detect the **recoiling neutron in nDVCS**

**Requirements/performances:**
- good neutron/photon separation for $0.2 < p_n < 1$ GeV/c $\rightarrow \sim 150$ ps time resolution ✓
- momentum resolution $\delta p/p < 10\%$ ✓
- neutron detection efficiency $\sim 10\%$ ✓

**CND design:** scintillator barrel - 3 radial layers, 48 bars per layer **coupled two-by-two** downstream by a “u-turn” lightguide, 144 long light guides with **PMTs** upstream

S.N. et al., NIM A 904, 81 (2018)

CND hits matched to charged tracks

CND hits **not** matched to charged tracks

Photons

Neutrons ($<p> \sim 0.5$ GeV)

Background
Very preliminary calibrations and reconstruction
- 11 full runs, at both beam energies (10.6 and 10.2 GeV)
- ~5% of the spring run statistics (1.25% of the approved beam time)

Final state: $e n\gamma$ reconstructed using basic CLAS12 PID
- no refined PID, no fiducial cuts, no corrections

Photons are reconstructed in FT and FEC
- Minimum energy 1 GeV
- The highest-energy photon of the event is chosen

Neutrons are reconstructed in CND and FEC
- The neutron having momentum closest to the average expected momentum for nDVCS (~0.6 GeV) is taken

nDVCS simulation on deuteron (GPD based generator)
- Same event selection as for the data
- Helps determine optimal detection topology and exclusivity cuts
Kinematics ($\theta$ vs $p$): electron, neutrons, photons

**Base cuts:**
- $Q^2 > 1$ GeV$^2$
- $\theta(e) > 5^\circ$
- $p(e) > 1$ GeV
- $v_z(e)$ cut
- $p_n > 0.3$ GeV
- No other charged particles detected

A lot of EC neutrons, at high $p$

A lot of low-energy photons, mainly in FEC

nDVCS neutrons mainly in CND

nDVCS photons mainly in FT, and with high energy
Kinematics ($\theta$ vs $p$): electron, neutrons, photons

**Base cuts:**
- $Q^2 > 1$ GeV$^2$
- $\theta(e) > 5^\circ$
- $p(e) > 1$ GeV
- $vz(e)$ cut
- $p_n > 0.3$ GeV
- No other charged particles detected

- **Neutrons in CND**

$E_\gamma > 2$ GeV cut to remove background

nDVCS photons mainly in ET, and with high energy
Exclusivity variables

\[ M(X)^2 (ed\rightarrow e'n\gamma X) \ (GeV^2) \]

\[ E(x) (ed\rightarrow e'n\gamma X) \ (GeV) \]

\[ M(X)^2 (en\rightarrow e'n\gamma X) \ (GeV^2) \]

\[ p(x) (ed\rightarrow e'n\gamma X) \ (GeV) \]

\[ \text{Cone angle } \theta_{\gamma X} \ (^\circ) \]

\[ \Delta\phi \ (^\circ) \]

Base cuts + \( E_\gamma > 2 \text{ GeV} \)

\text{en\gamma events with CND neutron}
\text{en\gamma events with CND neutron, FT photon}
enγ yield vs \( \phi \), after exclusivity cuts

Very preliminary

Data, all photons
Data, photons in FT

Very preliminary exclusivity cuts:
- \( 0 < M(X)^2 < 2 \text{ GeV}^2 \)
- \( 0 < E(X) < 2 \text{ GeV} \)
- \( 0 < p(X) < 1 \text{ GeV} \)
- \(-2^\circ < \Delta \phi < 2^\circ \)
- \(-1 < \Delta t < 1 \text{ GeV}^2 \)

To-do list:
- Refine calibrations
- Reconstruct all data
- Refine exclusivity cuts
- Study other topologies (FD…)
- Beam-helicity asymmetry
- \( \pi^0 \) background subtraction
- …. 
Future experiment: nDVCS, target-spin asymmetry

First time measurement of longitudinal target-spin asymmetry and double (beam-target) spin asymmetry

\[ \Delta \sigma_{UL} \sim \sin \phi \text{Im}\{F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2) (\mathcal{H} + x_B/2 \mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \ldots\} \]

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

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

eND_3 \rightarrow e(p)n\gamma

CLAS12 + Longitudinally polarized target + CND

\[ L = 3/20 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1} \]

Run time = 40 days

\[ P_t = 0.4; \ P_b = 0.85 \]

Will run in 2021
CLAS12: projections for flavor separation

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

\[
\frac{1}{2} \int_{-1}^{1} xdx (H^q (x, \xi, t = 0) + E^q (x, \xi, t = 0)) = J^q
\]

Fits done to all the projected observables for pDVCS (BSA, lTSA, lDSA, tTSA, CS, DCS) and nDVCS (BSA, lTSA, lDSA) of the CLAS12 program

Nucleon CFFs

Quark CFFs
Summary and outlook

• Now that a first tomographic image of the proton was delivered extracting CFFs from pDVCS, it is time to think about flavor separation and Ji’s sum rule
• The beam-spin asymmetry for nDVCS is a precious tool for this task
• The pioneering Hall-A experiment at 6 GeV showed the importance of this channel but the kinematics were unfavorable (~zero asymmetry signal)
• The CLAS12 experiment E12-11-003 is perfectly suited to measure BSA for nDVCS over a vast phase space
• The first ~25% of the experiment ran in the spring of 2019 at JLab
• The Central Neutron Detector, built for this experiment, is performing according to specifications
• A first exploratory analysis of a small fraction of the data shows that the nDVCS channel can be extracted
• The first half of E12-11-003 will be completed in the fall/winter of 2019
• Another nDVCS experiment on polarized deuterium target will be carried out in 2021 with CLAS12
• The two experiments will be combined to extract neutron CFFs (in particular Im$H$ and Im$E$)
• The combination of neutron and proton CFFs will allow flavor separation
• The Ji’s sum rule is the ultimate, ambitious goal of this program