Studies of GPDs (and Time-like Compton Scattering) at Jefferson Lab

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The 3D Nucleon Structure

Generalised Parton and Transverse Momentum Distributions are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of Nuclear Physics.

- **TMDs**
  - Confined motion in a nucleon (semi-inclusive DIS)

- **GPDs**
  - Spatial imaging (exclusive DIS)

- **Requires**
  - High luminosity
  - Polarised beams and targets
  - Sophisticated detectors

**Major new capability with JLab12**
At sufficiently high $Q^2$, the process should be understandable in terms of the “handbag” diagram – can be verified experimentally.

- The non-perturbative (soft) physics is represented by the GPDs.

- DVMP: Shown to factorise from QCD perturbative processes for longitudinal photons [Collins, Frankfurt, Strikman, 1997]
  - Factorisation theorem predicts $\sigma_L$ scales in this regime as $Q^{-6}$
Experimental Access to GPDs: DVCS

Deep Virtual Compton Scattering (DVCS)

- DVCS interferes with BH, allowing access to DVCS amplitudes.
- DVCS is the cleanest way to probe GPDs.

As the DVCS process interferes with BH, one can access the DVCS amplitudes.

At leading twist: (L/T interference gives specific cos/sin $\phi$-dependence)

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

GPDs show up in integrals – definitions are related to helicity of quarks/gluons.

Access in helicity-independent cross section

Access in helicity-dependent cross-section
Spacelike DIS and timelike Drell-Yan processes both factorise into partonic cross section and a Parton Distribution Function (PDF)
  - Measurement of both demonstrated the universality of PDFs

For DVCS there is a similar factorisation at the amplitude level into a perturbative coefficient function and a Generalised Parton Distribution (GPD)
  - Amplitudes are related, but differ significantly at next to leading order

\[ Q^2 = M_{e^+e^-}^2 \]

is in TCS the virtuality of the outgoing photon, which gives the hard scale

Timelike and spacelike cases are complementary - their differences deserve special attention
Towards spin-flavor separation: DVMP

Deep Virtual Meson Production (DVMP)

• Nucleon structure described by 4 (helicity non-flip) GPDs:
  – $H, E$ (unpolarised), $\widehat{H}, \widehat{E}$ (polarised)

• Quantum numbers in DVMP probe individual GPD components selectively
  – Vector: $\rho^0/\rho^+/K^*$ select $H, E$
  – **Pseudoscalar: $\pi, \eta, K$ select the polarised GPDs, $\widehat{H}$ and $\widehat{E}$**

• Need good understanding of reaction mechanism
  – QCD factorisation for mesons is complex (additional interaction of the produced meson)
  – **L/T separated cross sections to test QCD Factorisation**

Exclusive Reactions: $\gamma^* N \rightarrow M + B$
Nucleon Imaging at JLab - Strategy

Nucleon Imaging Studies through deep exclusive processes with unique capabilities and complementarity of three experimental halls

- **Hall A:** small acceptance, high resolution spectrometer to define kinematic variables very precisely, extremely high luminosity allowing very accurate tests of the kinematic dependences of the observables
  - Precision tests of the absolute cross section and $Q^2$-dependence

- **Hall B:** large acceptance CLAS12, coverage and hermeticity
  - Experiments with all combinations of beam and target spin measurements

- **Hall C:** high luminosity, high resolution spectrometer also allowing momentum reach to 11 GeV/c, compact photon source
  - Precision cross sections to highest $Q^2$
  - Rigid connection to pivot allows for L/T separations – a unique feature

See talk by J. Roche…

See talk by K. Joo
**DVCS with CLAS12**

**E12-06-119:** Unpolarised liquid H₂ target
Beam-spin asymmetry $\rightarrow \text{Im}(H_p)$

**First experiment with CLAS12!** Autumn ‘17

**E12-16-010:** Unpolarised liquid H₂ target
Beam energy: 6.6 GeV, 8.8 GeV $\sim 2018/20$

**E12-11-003:** Unpolarised liquid D₂ target
$e + d \rightarrow e' + \gamma + n + (p_s)$
Beam-spin asymmetry $\rightarrow \text{Im}(E_n)$ $\sim 2019$

**E12-12-010:** Transversely polarised HD target.
Target-spin asymmetries
$\sim 2021/22$

**E12-06-109:** Longitudinally polarised NH₃ and ND₃ targets

- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a He evaporation cryostat.
- $P_{\text{proton}} = 80\%$, $P_{\text{deuteron}}$ up to 50\%

Target-spin asymmetry in proton- and neutron-DVCS $\rightarrow \text{Im}(\tilde{H}_p), \text{Im}(H_n)$ $\sim 2020$

- $P_{\text{beam}} = 85\%$
- $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- $1 < Q^2 < 10 \text{ GeV}^2$
- $0.1 < x_B < 0.65$
- $-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$
Projected Sensitivities: CLAS12

Projections for $Im(H)$ and $Im(E)$ up and down Compton Form Factors (CFFs) to be extracted from approved CLAS12 experiments

$Q^2 = 2.6 \text{ GeV}^2, x_B = 0.23$

$Im(H): u$

$Im(H): d$

$Q^2 = 5.9 \text{ GeV}^2, x_B = 0.35$

$Im(H): u$

$Im(H): d$

$Im(E): u$

$Im(E): d$

Using VGG fit (M. Guidal)
Cosine moment of weighted cross sections – $R$ can be compared directly with GPD models

$$R = \frac{\int_0^{2\pi} d\varphi \cos \varphi \frac{dS}{dq^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dq^2 dt d\varphi}} = \frac{\int L(\theta, \varphi) \frac{d\sigma}{dQ^2 dq a d\varphi d\theta}}{\int L_0(\theta) \frac{d\sigma}{dQ^2 dq a d\varphi d\theta}}$$

6 GeV data demonstrated feasibility of the procedure, but kinematics limited

TCS at 12 GeV (E12-12-001 and E12-12-006A)
- extend $s$ to 20 GeV$^2$
- $M_{e^+e^-}$ $\sim$ 3.5 GeV allowing access to resonance free region $> 2$ GeV
- higher luminosity for multi-dimensional binning

<table>
<thead>
<tr>
<th></th>
<th>CLAS12</th>
<th>SoLID</th>
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<tbody>
<tr>
<td>e$^+$, e$^-$ coverage</td>
<td>$\theta$: 5°-36°</td>
<td>$\theta$: 8°-17°, 18°-28°</td>
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<tr>
<td></td>
<td>$\phi$: $\sim$80%</td>
<td>$\phi$: 100%</td>
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<tr>
<td></td>
<td>asymmetric</td>
<td>symmetric</td>
</tr>
<tr>
<td>Proton coverage</td>
<td>$\theta$: 5°-36°, 38°-125°</td>
<td>$\theta$: 8°-17°, 18°-28°</td>
</tr>
<tr>
<td></td>
<td>$\phi$: $\sim$80%</td>
<td>$\phi$: 100%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{35}$/cm$^2$/s</td>
<td>$10^{37}$/cm$^2$/s</td>
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Acceptance important for cross section

Different angular acceptance
Projected Sensitivities with CLAS12 and SoLID

CLAS12

SoLID

E12-12-001 also measures J/Psi on proton near threshold – possibly verify existence of charmed pentaquark

SOLID projection with x10 more data allows for kinematic exploration
**Hall C: Cross Section L/T Separation Example**

- $\sigma_L$ is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed $W$, $Q^2$, $-t$
  - Simultaneous fit using the measured azimuthal angle ($\phi_\pi$) allows for extracting $L$, $T$, $LT$, and $TT$

- Careful evaluation of the systematic uncertainties is important due to the $1/\epsilon$ amplification in the $\sigma_L$ extraction
  - Spectrometer acceptance, kinematics, and efficiencies

- Magnetic spectrometers a must for such precision cross section measurements
  - This is only possible in Hall C at JLab

\[
2\pi \frac{d^2 \sigma}{dt d\phi} = \varepsilon \frac{d\sigma_R}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi
\]

$\sigma_L$ for testing QCD factorisation
Relative L/T contribution to the Pion cross section

Important for nucleon structure studies


- Data from JLab 6 GeV demonstrated the technique of measuring the $Q^2$ dependence of L/T separated cross sections at fixed $x/t$
  

- Separated cross sections over a large range in $Q^2$ are essential for:
  
  - testing factorisation required for studies of transverse spatial structure
  
  - understanding dynamical effects in both $Q^2$ and $-t$ kinematics
  
  - interpretation of non-perturbative contributions in experimentally accessible kinematics

$Q^2$ dependence of $\sigma_L$ relevant towards an interpretation in a GPD-based framework
Relative L/T contribution to the Kaon cross section

Much less known...

$$Fit = \frac{A}{Q^b}$$

6 GeV JLab cross section data appear to be consistent with expected scaling, but small $Q^2$ lever arm and relatively large uncertainties
**E12-07-105 (P12):** Measure the $Q^2$ dependence of the $\pi$ electro production cross section at fixed $x$ and $-t$

- Factorisation theorem predicts $\sigma_L$ scales to leading order as $Q^{-6}$

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$</th>
<th>$W$</th>
<th>$-t$</th>
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<tbody>
<tr>
<td>0.3</td>
<td>1.5-2.7</td>
<td>2.0-2.6</td>
<td>0.1</td>
</tr>
<tr>
<td>0.4</td>
<td>2.1-6.0</td>
<td>2.0-3.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>3.9-8.5</td>
<td>2.0-2.8</td>
<td>0.5</td>
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</table>

Considered for running in 2019
**JLab12: confirming potential for nucleon structure studies with kaon production**

- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of $Q^2$ and $t$

  E12-09-011 spokespersons: T. Horn, G. Huber, P. Markowitz

**JLab 12 GeV Kaon Program features:**

- First cross section data for $Q^2$ scaling tests with kaons
- Highest $Q^2$ for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above $W=2.2$ GeV

approved for 40 PAC days and **scheduled to run in 2018/19**

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>-$t$ (GeV/c$^2$)</th>
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</thead>
<tbody>
<tr>
<td>0.1-0.2</td>
<td>0.4-3.0</td>
<td>2.5-3.1</td>
<td>0.06-0.2</td>
</tr>
<tr>
<td>0.25</td>
<td>1.7-3.5</td>
<td>2.5-3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.40</td>
<td>3.0-5.5</td>
<td>2.3-3.0</td>
<td>0.5</td>
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[blue points from M. Carmignotto, PhD thesis (2017)]
The NPS is envisioned as a PbWO$_4$-based facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles ($\gamma$ and $\pi^0$).

Scientific program: 5 experiments approved by PAC to date

- E12-13-007: Measurement of Semi-inclusive $\pi^0$ production as Validation of Factorisation
- E12-13-010 – Exclusive Deeply Virtual Compton and $\pi^0$ Cross Section Measurements in Hall C
- E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
- E12-14-005 – Wide Angle Exclusive Photoproduction of $\pi^0$ Mesons
- C12-17-008 – Polarisation Observables in Wide Angle Compton Scattering
E12-13-010: precision DVCS cross sections

Simplest process $e + p \rightarrow e' + p + \gamma$ (DVCS)

E12-13-010 DVCS measurements follow up on measurements in Hall A:

- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:
  \[ \sigma = |BH|^2 + \text{Re}[DVCS^\perp BH] + |DVCS|^2 \sim E_{\text{beam}}^2 \]
- L/T separation of $p^0$ production

Hall A data for Compton form factor (over limited $Q^2$ range) agree with hard-scattering

12 GeV projections: confirm formalism

Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS$^2$–Interference separation)
E12-13-010: exclusive $\pi^0$ cross section

- Relative L/T contribution to $\pi^0$ cross section important in probing transversity
  - If $\sigma_T$ large: access to transversity GPDs

- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in $\pi^0$ production is non-zero up to $Q^2=2$ GeV$^2$

- Need to understand $Q^2/t$ dependence for final conclusion on dominance of $\sigma_T$

M. Defurne et al, PRL 117 (2016) no.26, 262001

E12-13-010 projections

E12-13-010 will provide essential data on $\sigma_T$ and $\sigma_L$ at higher $Q^2$ for reliable interpretation of 12 GeV GPD data
New Opportunities with NPS and a Compact Photon Source (CPS)

Example: Impact of the photon source for polarised WACS:
- The experiment productivity is improved x30 times due to higher target polarisation averaged over the experiment, and reduced overhead time for the target annealing procedure.
Compact Photon Source (CPS) – Concept

- **Strong magnet** after radiator deflects exiting electrons
- **Long-bore collimator** lets photon beam through
- No need in tagging photons, so the design could be **compact** as opposed to a Tagger Magnet concept
- The **magnet itself is** the electron beam **dump**
- **Water-cooled W-Cu core** for better heat dissipation
- **Hermetic shielding** all around and close to the source to limit prompt radiation and activation
- **High Z and high density** material for bulk shielding
- **Boron outer layer** for slowing, thermalising, and absorbing fast neutrons still exiting the bulk shielding

CPS is a novel concept allowing for **high photon intensity** (equivalent photon flux: $\sim 10^{12}$ photons/s) and **low radiation** (low activation: <1mrem/h after one hour) in the hall.
Features of TCS measurements with transversely polarised target

- Theoretical calculations show that transverse asymmetries are very sensitive to GPDs [M. Boer, M. Guidal, arXiv:1501:00270]
- Asymmetries for the BH, the main background for TCS, is zero
- Predictions for asymmetries with different assumption of GPDs vary up to 20%

TCS event detection with NPS

- Lepton pair will be detected by pair of NPS
- Recoil detection by combination of tracking and TOF

TCS measurements with transversally polarised target open interesting opportunities for probing GPD E
A comprehensive GPD program is enabled by 12 GeV JLab – combines the unique strengths of three experimental halls (A, B, C).

Validation of QCD factorisation in exclusive processes is key for accessing GPDs – requires precision cross sections.

Comparison of spacelike (DVCS) and timelike (TCS) Compton Scattering allows for testing universality of GPDs.

Progress towards flavour separation made possible through measurements of meson production – L/T separations are crucial for pions and kaons.

A Neutral Particle Spectrometer and a Compact Photon Source enable precision cross section measurements with neutral particles - the design/construction of both is underway in Hall C.