Proton structure from deeply virtual Compton scattering with the CLAS detector at Jefferson Lab

Gary Smith
garys@jlab.org
Proton Structure

**Form Factors**
- **Elastic Scattering**

**Parton Distribution Functions**
- **Deep Inelastic Scattering**

**Generalised Parton Distributions**
- **Deep Exclusive Reactions**
  (e.g. DVCS)

**spatial** distributions of currents and charges in the transverse plane

**longitudinal momentum** distributions of quarks and gluons

**correlated transverse spatial and longitudinal momentum** distributions of quarks and gluons
Deeply Virtual Compton Scattering (DVCS)

Kinematic Variables

- $Q^2$: negative four momentum of virtual photon squared
- $\xi$: 1/2 longitudinal momentum fraction of struck quark
- $x$: average total momentum fraction of struck quark
- $t$: four momentum transfer to proton squared

Bjorken scaling regime

- momentum transfer $Q^2$ large

Handbag approximation

- electron interacts with a single quark

Factorisation

- hard scattering + parameterisation
  - (calculable)
  - (measured)
EG1DVCS experiment

CEBAF Large Acceptance Spectrometer (CLAS) in experimental Hall B

Continuous Electron Beam Accelerator Facility (CEBAF)

Hall B
EG1DVCS experiment

- over 80 days of data taken with polarised proton target
- > 70 fb^{-1} (>20 billion triggers) on proton target
- ~10 x statistics of previous CLAS target spin asymmetry result
- polarised (~85%) electron beam up to 6 GeV
- undergoing analyses include DIS, SIDIS, DVCS, DVMP
EG1DVCS experiment

- **Dynamically polarised target**
  - Accommodates measurement of target spin asymmetry

- **Ammonia NH3/ND3**
  - Proton polarisation ~75%

- **Carbon**
  - Additional targets for background studies

- **Empty**
EG1DVCS experiment

- Inner Calorimeter (IC)

- Enhanced photon acceptance at small angles (4-16 degrees)

Monte Carlo simulation of DVCS photon angle
Particle data cuts

Negatively charged particles

electron ID

\[ \frac{e}{p} = \beta \approx 1 \]

Positively charged particles

proton ID

\[ \beta = \frac{d}{ct} = \frac{p}{\sqrt{p^2 + M_p^2}} \approx 0 \]

Negatively charged particles
Particle data cuts

Negatively charged particles

electron ID

\[ e/p = \beta \approx 1 \]

Positively charged particles

proton ID

\[ \beta = \frac{d}{ct} = \frac{p}{\sqrt{p^2 + M_p^2}} \approx 0 \]
Exclusivity data cuts

\( ep \rightarrow epg \)

- Missing energy (GeV)
- Missing photon angle (deg)
- Missing mass \( ep \) (GeV/c^2)
- Missing mass \( epg \) (GeV/c^2)

NH3 (polarised protons)

Scaled Carbon (background studies)
Asymmetries

$$\frac{d\sigma}{dx_B dy dt d\phi d\varphi} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + I$$

Bethe-Heitler Process (BH)
Asymmetries

\[
\frac{d\sigma}{dx_B dy dt d\phi d\varphi} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + \mathcal{I}
\]

\[
\mathcal{I} \propto \sum_{n=0}^{3} \left[ c_n^T \cos(n\phi) + s_n^T \sin(n\phi) \right]
\]

\[A_{UL} = \frac{d\sigma_{\rightarrow} - d\sigma_{\leftarrow}}{d\sigma_{\rightarrow} + d\sigma_{\leftarrow}} \sim \frac{x_B}{y} \frac{s_{1,LP}}{c_{0, unp} + \ldots} \sin(\phi)\]

Fourier deconvolution
(Belitsky, Mueller, Kirchner 2002
Nuclear Physics B)

Target Spin Asymmetry
(longitudinal polarisation)

Asymmetries → Fourier coefficients → Compton Form Factors → GPDs
Asymmetries

Fit function \( p_0 \sin \phi / (1 + p_1 \cos \phi) \)

\[ \chi^2 / \text{ndf} = 3.823 / 9 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_0 )</td>
<td>0.1585 ± 0.0074</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>-0.3262 ± 0.0704</td>
</tr>
</tbody>
</table>

Beam Spin Asymmetry (Integrated)

\[ A_{LU} = \frac{d\sigma^\rightarrow - d\sigma^\leftarrow}{d\sigma^\rightarrow + d\sigma^\leftarrow} = \frac{1}{P_B} \frac{N^\rightarrow - N^\leftarrow}{N^\rightarrow + N^\leftarrow} \]
Asymmetries

Target Spin Asymmetry (binned in $x_B$)

$$A_{UL} = \frac{d\sigma \Rightarrow - d\sigma \Leftarrow}{d\sigma \Rightarrow + d\sigma \Leftarrow} = \frac{1}{P_T D} \frac{N \Rightarrow - N \Leftarrow}{N \Rightarrow + N \Leftarrow}$$

Fit function $p_0 \sin \phi + p_1 \sin 2\phi$

- Black squares: previous result (Chen PRL 2006)
- Blue circles: Chi-squared fit
- Red circles: Maximum Likelihood fit

Dashed lines are VGG model predictions (Vanderhagen et al)

$$x_B^{lab} = \frac{Q^2}{2M_p(E - E')}$$
Conclusions

- GPDs are accessible through DVCS spin asymmetries and give access to new information about proton structure.

- Beam, Target and Double Spin Asymmetry amplitudes are used to constrain Compton Form Factors which are used to measure GPDs.

- EG1DVCS data accommodates precise measurements of asymmetry amplitudes as a function of DVCS kinematics.

- From 2015 experiments will begin with CLAS12.

- Higher $Q^2$ available and forward focused design will suit DVCS and other exclusive channels (e.g. DVMP).
Backup Slides
Kinematic coverage

![Kinematic coverage diagram]

- **Motivation**
- **Experiment**
- **Analysis**
- **Results**
- **Conclusions**
**CLAS detector**

**Electron Beam**
longitudinally polarised (~80%)
with energies up to 6 GeV

**Drift Chambers**
track reconstruction
and particle ID

**Electromagnetic Calorimeters (EC)**
primary electron triggering, pion rejection
and neutral particle detection

**Cherenkov Counters**
electron ID

**Scintillation Counters**
time of flight
Asymmetries and Compton Form factors

\[ A_{UL}(\phi) \sim \frac{x_B}{y} \frac{s_{1,LP}^{T}}{c_{BH}} \sin(\phi) \]
\[ \propto \Im \left\{ F_1 \tilde{\mathcal{H}} + \frac{x_B}{2-x_B} (F_1 + F_2) \left( \mathcal{H} + \frac{x_B}{2} \mathcal{E} \right) + \ldots \right\} \sin(\phi) \]
\[ A_{LU} \propto \Im \left\{ F_1 \mathcal{H} + \frac{x_B}{2-x_B} (F_1 + F_2) \left( \mathcal{H} - \frac{\Delta^2}{4M^2} F_2 \mathcal{E} \right) + \ldots \right\} \sin(\phi) \]
\[ A_{LL}(\phi) \sim \frac{x_B}{y} \frac{c_{0,LP}^{BH}}{c_{BH,unp}^{T}} + \frac{c_{0,LP}^{T}}{c_{BH}^{T}} + (c_{1,LP}^{BH} + c_{1,LP}^{T}) \cos(\phi) \]
\[ \propto \Re \left\{ F_1 \tilde{\mathcal{H}} + \frac{x_B}{2-x_B} (F_1 + F_2) \left( \mathcal{H} + \frac{x_B}{2} \mathcal{E} \right) + \ldots \right\} \]

<table>
<thead>
<tr>
<th>Asymmetry Amplitude</th>
<th>Contributing Fourier-Coefficient</th>
<th>Twist Level</th>
<th>CFF Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{UL}^\sin(\phi) )</td>
<td>( s_{1,LP}^{T} )</td>
<td>2</td>
<td>( \Im m C_{LP}^{T} )</td>
</tr>
<tr>
<td>( A_{UL}^{\sin(2\phi)} )</td>
<td>( s_{2,LP}^{T} )</td>
<td>3</td>
<td>( \Im m C_{LP}^{DVCS} )</td>
</tr>
<tr>
<td>( A_{UL}^{\sin(3\phi)} )</td>
<td>( s_{3,LP}^{T} )</td>
<td>2</td>
<td>( \Re C_{LP}^{T} )</td>
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<td>( A_{LL}^{\cos(0\phi)} )</td>
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Dominant terms at twist level 2 for CLAS kinematics.
Target

- four cells on insert controlled by stepper motor
- Dynamic Nuclear Polarisation
  - target cooled to 1K using Helium
  - uniform 5T field $\Delta B/B \sim 10^{-4}$
- polarisation monitored with NMR system
- precise value: compare elastic and measured elastic asymmetries
Inner Calorimeter (IC)

- 424 lead tungstate tapered crystals
- light measurement with Avalanche Photodiodes (APDs)
- laser system to monitor gain changes with temperature
- low noise (7-8 MeV) fast pre-amps
- placed in the centre of CLAS ~65cm from target
- angular coverage of 4-16 degrees