Deeply virtual Compton Scattering cross section measured with CLAS

Baptiste GUEGAN

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Deeply Virtual Compton Scattering

Generalized Parton Distributions (GPD):

→ correlation between $x$ and $t$
Deeply Virtual Compton Scattering

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Accessible via Deeply Virtual Compton Scattering:

\[
(x + \xi) \quad \xi \quad (x - \xi)
\]

longitudinal momentum fractions of quark

\[
t = \Delta^2 = (p' - p)^2: \text{ squared momentum transfer}
\]
Deeply Virtual Compton Scattering

Generalized Parton Distributions (GPD):

→ correlation between $x$ and $t$

Accessible via Deeply Virtual Compton Scattering:

$B(x, \xi, t) = \frac{Q^2}{2p \cdot q}$

$\xi \approx \frac{x_B}{2 - x_B}$

At large $Q^2$, small $t$ and fixed $x_B$, the process can be factorized and described by 4 Generalized Parton Distributions
Exclusive electroproduction of a photon

Contribution from both DVCS and Bethe-Heitler (undistinguishable experimentally):

\[ \sigma_{(ep \rightarrow ep\gamma)} \propto |T^{DVCS} + T^{BH}|^2 \]

- \( T^{BH} \): At low t, the nucleon FFs (Dirac, Pauli) are well known so that \( T^{BH} \) is precisely calculable.

- \( T^{DVCS} \propto \int_{-1}^{1} dx \frac{GPD(x, \xi, t)}{x \pm \xi \mp i \epsilon} = \mathcal{P} \int_{-1}^{1} dx \frac{\boxed{GPD(x, \xi, t)}}{x \pm \xi} \pm i \pi GPD(x = \mp \xi, \xi, t) \)

  \[ \rightarrow \] GPDs appear in the real part through an integral over \( x \)

  \[ \rightarrow \] GPDs appear in the imaginary part at the lines \( x = \pm \xi \)
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With a polarized beam and an unpolarized target, one can measure 2 observables:

\[ \frac{d^4\sigma}{dt dQ^2 dx_B d\phi} \propto |T^{BH}|^2 + 2T^{BH} \text{Re}(T^{DVCS}) + |T^{DVCS}|^2 \]

\[ \frac{d^4\sigma - d^4\tilde{\sigma}}{dt dQ^2 dx_B d\phi} \propto 2T^{BH} \text{Im}(T^{DVCS}) + \left[ |T^{DVCS}|^2 - |T^{DVCS}|^2 \right] \]
DVCS experiment

- CLAS + dedicated equipment (IC electromagnetic calorimeter + solenoid)

Beam energy: 5.88 GeV
Beam polarization: 82-87%
Beam current: 20nA

DVCS photons are mostly emitted at forward angles
Identification of the final-state particles: $e, p, \gamma$

$$\Delta \beta = \beta^{SC}_{measured} - \beta^{DC}_{calculated}(M_p) = \frac{d}{ct} - \frac{p}{\sqrt{p^2 + M_p^2}}$$
DVCS analysis steps

- Identification of the final-state particles: $e$, $p$, $\gamma$
- Exclusivity selection of the DVCS channel

![Graph showing $\Delta\phi$ distribution with peaks at -2 and 2 (deg)]
DVCS analysis steps

- Identification of the final-state particles: $e, p, \gamma$
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- Evaluation of the contamination of the DVCS channel by the $\pi^0$ when one of the two photons is undetected: $ep \rightarrow ep\pi^0 \rightarrow ep\gamma(\gamma)$
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- Acceptance computation: $\frac{N_{ep\gamma}^{REC}}{N_{ep\gamma}^{GEN}} \frac{MC}{MC}$
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- The integrated luminosity for the whole DVCS2 data set
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- Hyper-volume computation of the bins
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- The integrated luminosity for the whole DVCS2 data set

- Hyper-volume computation of the bins

- The radiative corrections calculated in each bin in order to compute the cross section at the Born term: $\sim 20\%$ in the BH approximation
The kinematics of the DVCS reaction is defined by 4 independent variables:

\[ Q^2, x_B, -t, \Phi \]

→ 4-dimensional binning
Kinematic coverage of the e1-DVCS data and binning

$Q^2 > 1 \text{GeV}^2$, $W > 2 \text{GeV}$, $21^\circ < \theta_e < 45^\circ$, $p_e > 0.8 \text{GeV}$

The kinematics of the DVCS reaction is defined by 4 independent variables:

- $Q^2$, $x_B$, $-t$, $\Phi$

→ 4-dimensional binning
DVCS differential cross section

\[ Q^2 \in [1, 4.75] \text{GeV}^2 \]
\[ x_B \in [0.1, 0.58] \]
\[ -t \in [0.1, 2] \text{GeV}^2 \]

189 \( \Phi \) distributions
DVCS differential cross section

$Q^2 \in [1, 4.75] GeV^2$

$x_B \in [0.1, 0.58]$

$-t \in [0.1, 2] GeV^2$

189 $\Phi$ distributions
Unpolarized cross section

\[ \frac{d^4 \sigma_{ep \rightarrow ep\gamma}}{dQ^2 \ dx_B \ dt \ d\phi} \ (nb/GeV^4) \]

- VGG
  M. Vanderhaeghen
  P.A.M. Guichon,
  M. Guidal

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Difference of polarized cross sections

\[ \frac{1}{2} \left( \frac{d^4 \sigma^{\rightarrow}_{ep\rightarrow ep\gamma}}{dQ^2 \ dx_B \ dt \ d\Phi} - \frac{d^4 \sigma^{\leftarrow}_{ep\rightarrow ep\gamma}}{dQ^2 \ dx_B \ dt \ d\Phi} \right) \ (nb/GeV^4) \]

\[ = \sin(\Phi) \Gamma_{\Phi} \Im \left[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right] \]

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Extraction of Compton Form Factors (CFFs)


→ One does not extract the GPDs, but associated quantities called Compton Form Factors

\[ \mathcal{T}^{DVCS} \propto \int_{-1}^{1} dx \frac{GPD(x, \xi, t)}{x \pm \xi \mp i\epsilon} = \mathcal{P} \int_{-1}^{1} dx \frac{GPD(x, \xi, t)}{x \pm \xi} \pm i\pi GPD(x = \mp \xi, \xi, t) \]

Real part \hspace{2cm} Imaginary part

→ One has two CFFs for each GPD \( H, \tilde{H}, E, \tilde{E} \) → 8 CFFs
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Real part \hspace{2cm} Imaginary part

→ One has two CFFs for each GPD \( H, \tilde{H}, E, \tilde{E} \) \( \rightarrow 8 \) CFFs

→ 2 independent observables, 8 unknowns (the CFFs):

→ Non-linear problem, strong correlations

→ Bounding the domain of variation of the CFFs (5xVGG)

→ At fixed \((Q^2, x_B, -t)\), extraction of the CFFs from the unpolarized and polarized cross sections \((x189 \text{ bins})\) with MINUIT + MINOS.
Extraction of Compton Form Factors (CFFs)


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Real part \hspace{1cm} \text{Imaginary part}

→ One has two CFFs for each GPD \( H, \tilde{H}, E, \tilde{E} \rightarrow 8 \text{ CFFs} \)
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→ Bounding the domain of variation of the CFFs (5xVGG)

→ At fixed \( (Q^2, x_B, -t) \), extraction of the CFFs from the unpolarized and polarized cross sections (x189 bins) with MINUIT + MINOS.

→ Extraction of the real part and the imaginary part of the GPD \( H \rightarrow \mathcal{H}_{Im} \mathcal{H}_{Re} \)
Extraction of Compton Form Factors (CFFs)

Imaginary part of the CFF $H$ for four values of $x$:

- $x_B = 0.125$
- $x_B = 0.185$
- $x_B = 0.245$
- $x_B = 0.4$

Results of model-independent fit

VGG model prediction
From CFFs to spatial densities

- $\mathcal{H}_{Im}$ is a combination of GPDs at the line: $x = \pm \xi$

Neglecting the antiquark contribution $\rightarrow H_{Im}(\xi, t) = H(\xi, \xi, t)$

Density distribution: $\rho(x = \xi, b) = \int_0^\infty \frac{dt}{4\pi} J_0(b\sqrt(t))H(x = \xi, 0, t)$

M. Burkardt

**BUT:** $H(\xi, 0, t) \neq H(\xi, \xi, t)$

Model dependent correction factors (VGG):

$$\frac{H(\xi, 0, t)}{H(\xi, \xi, t)}$$

Effect is < 20%

$x_B = 0.125$
$x_B = 0.185$
$x_B = 0.245$
$x_B = 0.4$
From CFFs to spatial densities

Fit of the t-dependence of $H_{Im}$ with: $e^{a+bt}$ (uncorrected)
From CFFs to spatial densities

Fit of the t-dependence of $H_{Im}$ with: $e^{a+bt}$ (uncorrected)

Fit of the t-dependence of $H_{Im}$ with: $e^{a+bt}$ (corrected)
From CFFs to spatial densities

\[ \rho(x = x_B, b) = \int_0^\infty dt \frac{1}{4\pi} J_0(b\sqrt{t}) H(x = x_B, 0, t) \]
From CFFs to spatial densities

$\mathcal{H}_{Im}$: Correlation between transverse position and longitudinal momentum

- The sea quarks (low $x$) spread to the periphery of the nucleon
- The valence quarks (large $x$) remain in the center
Summary and outlook

- GPDs are a unique tool to explore the internal landscape of the nucleon:
  → 3D quark/gluon imaging of the nucleon

- Extraction of DVCS unpolarized and polarized cross sections in the largest
  kinematic domain ever explored in the valence region

- Extraction of the spatial densities as a function of $x$

- Analyses in the final stage to extract $A_{UL}$ and $A_{LL} (H, \tilde{H})$
  from CLAS data at 6 GeV with longitudinally-polarized target

- Dedicated GPD program at Jlab 12GeV:
  Target spin asymmetry: $A_{UT}, A_{LT}$
  Beam/Target spin asymmetries: $A_{UL}, A_{LU}$
  DVMP: pseudoscalar/vector mesons
\[ \mathcal{T}^{DVCS} \propto \int_{-1}^{1} dx \frac{f(x, \xi, t)}{x \pm \xi \mp i\epsilon} = \mathcal{P} \int_{-1}^{1} dx \frac{f(x, \xi, t)}{x \pm \xi} \pm i\pi f(x = \mp \xi, \xi, t) \]

<table>
<thead>
<tr>
<th>Real part</th>
<th>Imaginary part</th>
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<tbody>
<tr>
<td>( \mathcal{H}<em>{Re}(\xi, t) = \mathcal{P} \int</em>{0}^{1} dx [H(x, \xi, t) - H(-x, \xi, t)] C^{+}(x, \xi) )</td>
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With: \( C^{\pm}(x, \xi) = \frac{1}{x - \xi} \pm \frac{1}{x + \xi} \)
<table>
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<th>Sensitivity</th>
<th>Experiment</th>
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| $\sigma_{unp} = \sigma^+ + \sigma^-$ | $\propto \mathcal{H}_{Re}$ | H1 (2001), (2005), (2008)  
ZEUS (2003), (2009)  
Hall-A (2006)  
Hall-B (E1-DVCS experiment: data under analysis) |
| $\sigma_{pol} = \sigma^+ - \sigma^-$ | $\propto \mathcal{H}_{Im}$ | Hall-A (2006)  
Hall-B (E1-DVCS experiment: data under analysis) |
| $A_C$         | $\propto \mathcal{H}_{Re}$ | HERMES (2007), (2008), (2009) |
| $A_{LU}$      | $\propto \mathcal{H}_{Im}$ | HERMES (2001), (2009)  
| $A_{UL}$      | $\propto \mathcal{H}_{Im}, \tilde{\mathcal{H}}_{Im}$ | Hall-B (2006)  
HERMES (2010)  
Hall-B (Eg1-DVCS experiment: data under analysis) |
| $A_{LL}$      | $\propto \mathcal{H}_{Re}, \tilde{\mathcal{H}}_{Re}$ | HERMES (2010)  
Hall-B (Eg1-DVCS experiment: data under analysis) |
| $A_{UT}$      | $\propto \mathcal{E}_{Im}$ | HERMES (2008)  
Hall-B proposal |
| $A_{LT}$      | $\propto \mathcal{H}_{Re}, \mathcal{E}_{Re}$ | HERMES (2011)  
Hall-B proposal |
- The second moment of \((E+H)\) when \(t \to 0\) : total angular momentum

\[
\int_{-1}^{1} dx \, x [H^q(x, \xi, 0) + E^q(x, \xi, 0)] = 2J_{\text{quarks}} \quad \text{(Ji sum rule)}
\]

Nucleon spin decomposition:

\[
\frac{1}{2} = J_{\text{quarks}} + J_{\text{gluons}} = S_{\text{quarks}} + L_{\text{quarks}} + S_{\text{gluons}} + L_{\text{gluons}}
\]

- At \(\xi = 0\), a GPD is a \(x\)-decomposition of the form factor:
  - \(u\)-quark distribution in a unpolarized proton
  - \(u\)-quark distribution in a polarized proton

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

\[
q_{+X}(x, 0, b_\perp) = q(x, 0, b_\perp) - \frac{1}{2M} \frac{\partial}{\partial y} \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{ib_\perp \Delta_\perp} E^q(x, 0, -\Delta_\perp^2)
\]
Figure 54. “Deskewing” factor $H(\xi, 0, t)/H(\xi, \xi, t)$ as a function of $-t$ for the VGG model (red curves), the GK model (blue curves) and the dual model (black curves). The solid curves correspond to $x_B=0.1$ (HERMES kinematics) and the dashed ones to $x_B=0.25$ (CLAS kinematics).