Deeply Virtual Compton Scattering with CLAS12

Hyon-Suk Jo
for the CLAS collaboration

IPN Orsay

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Outline

• Introduction

• The CLAS12 detector

• DVCS on the proton: beam-spin asymmetries

• DVCS on the proton: longitudinally polarized target

• DVCS on the proton: transversely polarized target

• Extraction of Compton Form Factors from proton pseudo-data

• DVCS on the neutron: beam-spin asymmetries

• Summary
Deeply Virtual Compton Scattering (DVCS)

"handbag" diagram (high $Q^2$, small $t$, fixed $x_B$)

\[ \sigma(eN \rightarrow eN\gamma) = \]

DVCS and Bethe-Heitler (BH) experimentally undistinguishable interference between the 2 processes

\[ \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \approx \left| T^{DVCS} + T^{BH} \right|^2 = \left| T^{DVCS} \right|^2 + \left| T^{BH} \right|^2 + I \]

with \[ I = \frac{T^{DVCS} T^{*BH}}{\text{interference term}} + \frac{T^{*DVCS}}{} \]

DVCS is the key reaction allowing to access the GPDs → simplest interpretation in terms of GPDs

The kinematics of the DVCS reaction is defined by 4 independent variables: $Q^2$, $x_B$, $t$ and $\phi$

4-dimensional bins = ($Q^2$, $x_B$, $-t$, $\phi$)

The simplest interpretation in terms of GPDs

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Extracting GPDs from DVCS observables

Compton Form Factors (CFFs)

\[
\begin{align*}
Re \mathcal{H}_q &= e_q^2 P \int_0^1 \left( H^q(x, \xi, t) - H^q(-x, \xi, t) \right) \left[ \frac{1}{\xi - x} + \frac{1}{\xi + x} \right] dx \\
Im \mathcal{H}_q &= \pi e_q^2 \left[ H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right]
\end{align*}
\]

Beam Spin Asymmetry:

\[
A_{LU} = \frac{d\sigma - d\sigma}{d\sigma + d\sigma} = \frac{\Delta \sigma_{LU}}{d\sigma + d\sigma}
\]

\[\xi = x_B/(2-x_B) \quad k = t/4M^2\]

- Polarized beam, Unpolarized target

\[
\Delta \sigma_{LU} \sim \sin \phi \ \text{Im} \{ F_1 \mathcal{H} + \xi(F_1+F_2)\tilde{H} - kF_2E \} d\phi
\]

- Unpolarized beam, Longitudinally polarized target

\[
\Delta \sigma_{UL} \sim \sin \phi \ \text{Im} \{ F_1 \tilde{H} + \xi(F_1+F_2)(H + x_B/2E) - \xi kF_2\tilde{E} + \ldots \} d\phi
\]

- Unpolarized beam, Transversely polarized target

\[
\Delta \sigma_{UT} \sim \cos \phi \ \text{Im} \{ k(F_2\mathcal{H} - F_1E) + \ldots \} d\phi
\]

- Polarized beam, Longitudinally polarized target

\[
\Delta \sigma_{LL} \sim (A+B\cos \phi) \ \text{Re} \{ F_1 \tilde{H} + \xi(F_1+F_2)(H + x_B/2E) + \ldots \} d\phi
\]
JLab upgrade to 12 GeV

$E_{\text{max}}$ Halls A, B, C: 11 GeV
$E_{\text{max}}$ Hall D: 12 GeV
Beam polarization $P_e > 80\%$

CLAS12

Upgrade of the instrumentation of the existing Halls

Continuous Electron Beam Accelerator Facility

12 GeV
CLAS12

- $E_{\text{max}} = 11 \text{ GeV}$
- Design luminosity $L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- Large acceptance
- Large kinematic coverage
Kinematic coverage of CLAS12

JLab 12 GeV Upgrade is well matched for GPD studies in the valence quark regime.
DVCS $A_{LU}$ on the proton

80 days of beam time
- $P_{beam} = 85\%$
- $L = 10^{35}$ cm$^{-2}$s$^{-1}$
- $1 < Q^2 < 10$ GeV$^2$
- $0.1 < x_B < 0.65$
- $-t_{min} < -t < 2.5$ GeV$^2$

Systematic uncertainties: $\sim 6\%-8\%$

Large acceptance: measurements in large $Q^2$, $x_B$, $t$ ranges simultaneously

$A_{LU}(Q^2, x_B, t)$

$\sigma(Q^2, x_B, t)$

$\Delta \sigma(Q^2, x_B, t)$

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

DVCS $A_{LU}$ on proton is mostly sensitive to the GPD $H_p$
DVCS $A_{LU}$ on the proton

Projections 80 days - LH$_2$ target - 10$^{35}$ Luminosity - VGG model

$e^-p \rightarrow e^-p\gamma$

$A_{LU}$

80 days of beam time

$P_{beam} = 85\%$

$L = 10^{35}$ cm$^{-2}$s$^{-1}$

$1 < Q^2 < 10$ GeV$^2$

$0.1 < x_B < 0.65$

$-t_{min} < -t < 2.5$ GeV$^2$

Systematic uncertainties: $\sim 6-8\%$

Large acceptance: measurements in large $Q^2, x_B, t$ ranges simultaneously

$A_{LU}(Q^2, x_B, t)$

$\sigma(Q^2, x_B, t)$

$\Delta\sigma(Q^2, x_B, t)$

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

$DVCS\ A_{LU}$ on proton is mostly sensitive to the GPD $H_p$
**DVCS $A_{UL}$ on the proton**

Projections 120 days – polarized NH$_3$ target – 2.10$^{35}$ Luminosity – VGG model

$$ep \rightarrow ep\gamma$$

- **120 days of beam time**
  - $P_{beam} = 85\%$, $P_{target} = 80\%$
  - $L = 2.10^{35}$ cm$^{-2}$s$^{-1}$
  - $1 < Q^2 < 10$ GeV$^2$
  - $0.1 < x_B < 0.65$
  - $-t_{min} < t < 2.5$ GeV$^2$

- **Systematic uncertainties:**
  - $\sim 6$-$8\%$

**Large acceptance:**
- measurements in large $Q^2, x_B, t$ ranges simultaneously
- $A_{UL}(Q^2, x_B, t)$

**DVCS $A_{UL}$ and $A_{LL}$ on proton** is mostly sensitive to the GPDs $\tilde{H}_p$ and $H_p$
Transversely polarized target: DVCS $A_{UT}$ and $A_{LT}$ on the proton

Proposal submitted to PAC39
polarized HD target $e^- p \rightarrow e^- p\gamma$

100 days of beam time
$P_{beam} = 85\%$, $P_{target} = 60\%$, $L = 5.10^{33}$ cm$^{-2}$s$^{-1}$
$1 < Q^2 < 10$ GeV$^2$, $0.06 < x_B < 0.66$, $-t_{min} < t < 1.5$ GeV$^2$
Systematic uncertainties $\sim 8\%$

Projections for $Q^2 = 2.5$ GeV$^2$, $x_B = 0.2$

$e^- p \rightarrow e^- p\gamma$

$\Delta \sigma_{UT} \rightarrow \text{Im}\{H_p, E_p\}$

$\Delta \sigma_{LT} \rightarrow \text{Re}\{H_p, E_p\}$

Transverse-target spin asymmetries are highly sensitive to the GPD $E_p$

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Extraction of Compton Form Factors (CFFs)

\[
\begin{align*}
\text{Re}(\mathcal{H}) &= P \int_0^1 dx \left[ H(x, \xi, t) - H(-x, \xi, t) \right] C^+(x, \xi) \\
\text{Re}(\mathcal{E}) &= P \int_0^1 dx \left[ E(x, \xi, t) - E(-x, \xi, t) \right] C^+(x, \xi) \\
\text{Re}(\tilde{\mathcal{H}}) &= P \int_0^1 dx \left[ \tilde{H}(x, \xi, t) + H(-x, \xi, t) \right] C^-(x, \xi) \\
\text{Re}(\tilde{\mathcal{E}}) &= P \int_0^1 dx \left[ \tilde{E}(x, \xi, t) + E(-x, \xi, t) \right] C^-(x, \xi) \\
\text{Im}(\mathcal{H}) &= H(\xi, \xi, t) - H(-\xi, \xi, t) \\
\text{Im}(\mathcal{E}) &= E(\xi, \xi, t) - E(-\xi, \xi, t) \\
\text{Im}(\tilde{\mathcal{H}}) &= \tilde{H}(\xi, \xi, t) - \tilde{H}(-\xi, \xi, t) \\
\text{Im}(\tilde{\mathcal{E}}) &= \tilde{E}(\xi, \xi, t) - \tilde{E}(-\xi, \xi, t)
\end{align*}
\]

with \( C^\pm(x, \xi) = \frac{1}{x - \xi} \pm \frac{1}{x + \xi} \)

M. Guidal: model-independent fit, at fixed \( Q^2, x_B \) and \( t \) of DVCS observables with MINUIT + MINOS

8 unknowns (the CFFs), non-linear problem, strong correlations

Bounding the domain of variation of the CFFs (5xVGG)
Extraction of $\text{Im}(\mathcal{H})$ from proton pseudo-data
Extraction of $\text{Re}(\mathcal{H})$ from proton pseudo-data
Extraction of $\text{Im}(\tilde{H})$ from proton pseudo-data
Extraction of $\text{Re}(\tilde{E})$ from proton pseudo-data
Extraction of $\text{Im}(E)$ from proton pseudo-data

$\text{Im}(E)$  $\sigma, A_{LU}, A_{UL}, A_{LL}, A_{UT}, A_{LT}$

![Graph showing extraction of $\text{Im}(E)$ from proton pseudo-data.](image-url)
DVCS $A_{LU}$ on the neutron

This program requires adding a Central Neutron Detector (CND) to the CLAS12 base equipment.

Combined analysis of DVCS on proton and neutron allows flavor separation of GPDs.

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

DVCS $A_{LU}$ on neutron is mostly sensitive to the GPD $E_n$.

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

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

Needed to access $J^q$ (Ji's sum rule).
DVCS $A_{LU}$ on the neutron

80 days of beam time
$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

$Q^2 = 2.75 \text{ GeV}^2$, $\Delta Q^2 = 1.5 \text{ GeV}^2$
$x_B = 0.225$, $\Delta x_B = 0.15$
$t = -0.35 \text{ GeV}^2$, $\Delta t = 0.3 \text{ GeV}^2$

$J_u = 0.3$, $J_d = 0.3$
$J_u = 0.1$, $J_d = 0.1$

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

DVCS $A_{LU}$ on neutron is mostly sensitive to the GPD $E_n$

Needed to access $J^q$ (Ji's sum rule)
• JLab 12 GeV will provide high luminosity for high accuracy measurements to test models on a large $x_B$ scale and thus will be a great facility to study GPDs in the valence region and CLAS12 will be perfectly suited for a rich experimental GPD program.

• Four experiments proposed to study DVCS (DVCS on the proton/neutron, DVCS with polarized targets,...), among which three have been approved so far.

• Extraction of Compton Form Factors (M. Guidal) attempted using pseudo-data by fitting simultaneously the different DVCS observables gives a large set of results in a very large kinematic domain.

• Future DVCS results obtained with CLAS12 will provide strong constraints on a very large kinematic domain.

Thank you.
Backup slides
Extraction of $\text{Im}(\mathcal{E})$ without transversely polarized target data

$\text{Im}(\mathcal{E}), \sigma, \Delta\sigma, A_{LU}, A_{UL}, A_{LL}$