Timelike Compton Scattering off the nucleon: polarization observables and experimental perspectives for JLab @ 12 GeV

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In collaboration with M. Guidal and M. Vanderhaeghen
**Exclusive process:** measurement of $t$ and $\xi$

**Soft part:** Generalized Partons Distributions $\rightarrow$ GPD($x, \xi, t; Q'^2$)

$x$: average longitudinal momentum fraction of the struck quark

$\xi$: longitudinal momentum transfer

$Q'^2 >> 1 \text{ GeV}^2$

$\text{hard scale}$

$t << Q'^2$

$\text{momentum transfer}$
Generalized Parton Distributions (GPDs)

Correlation between longitudinal momentum fraction $x$ and transverse charge densities

Nucleon tomography: $H(x, b_\perp) = \text{FT of } H(x, \xi = 0, |t| = \Delta^2)$

Different GPDs: quark and nucleon helicities

$\rightarrow$

unpolarized nucleon $(H, E)$,
polarized nucleon $(\tilde{H}, \tilde{E})$,
nucleon helicity flip $(E, \tilde{E})$

Parton Distribution
$q(x) = H(x, \xi = 0, t = 0)$

$Q^2 = 10 \text{ GeV}^2$

$\int \text{dx}$ Transverse charge density
Form Factors $\Rightarrow \text{FT}[ F_1(t)]$

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Carlson, Vanderhaeghen, PRL 100 (2008) 032004
Part I

Theoretical predictions:
- cross sections
- spin asymmetries
- GPD dependencies of observables
Timelike Compton Scattering (TCS) sensitive to the nucleon GPDs

\[ \gamma N \rightarrow e^+ e^- N \]

Bethe-Heitler (BH) sensitive to the nucleon Form Factors

\[ \frac{d^4 \sigma}{d Q'^2 dt d\Omega} (\gamma p \rightarrow p' e^+ e^-) = \frac{1}{(2\pi)^4} \frac{1}{64} \frac{1}{(2 M E_\gamma)^2} \left| T^{BH} + T^{TCS} \right|^2 \]
\[ \gamma N \rightarrow e^+ e^- N \]

Fixed beam energy or \( \xi \)

\[ \frac{d\sigma}{dQ'^2 \, dt \, d\phi \, d(cos\theta)} \]

\[ \Psi: \text{(reaction plane, } \gamma \text{ spin)} \]
\[ \phi: \text{(hadronic plane, } e^+ e^- \text{ pair)} \]
\[ \Theta: (\gamma^*, e^-) \]

**Notations**

\( A_{ij} \): asymmetry

1st index: photon polarisation, \( \bigcirc = \text{circular} \), \( L = \text{linear} \), \( U = \text{unpolarized} \)

2nd index: nucleon polarisation, \( x \) (transverse, in plane), \( y \) (transverse), \( z \) (longitudinal)
Kinematical dependencies and comparisons

cross sections vs $Q'^2$ and vs $t$

integrated over decay angles

- $\theta \in [45^\circ, 135^\circ]$  
- $\Phi \in [0^\circ, 360^\circ]$  

BH $>>$ TCS  
order of pb

$R = \frac{\text{this work}}{\text{Berger, Diehl, Pire}^1 \ (\text{pioneer theoretical work})}$

Bethe-Heitler: $\approx$ equal

TCS: few % at low $Q'^2$  
$\sim$ we waived some $t/Q'^2$ approximations (some higher twist corrections)

$^1$Berger, Diehl, Pire, E.P.J. C23 (2002) 675
Asymmetries: circularly polarized beam

\( \xi = 0.2, Q^2 = 7 \text{ GeV}^2, -t = 0.4 \text{ GeV}^2, \theta \in [45^\circ, 135^\circ] \)

Angular dependence in \( \Phi \)

Kinematical dependence in \( -t \)

\( A_{\circ U} \propto \text{imaginary part of amplitudes} \Rightarrow A_{\circ U} = 0 \) for Bethe-Heitler

Asymmetry \( \approx 20\% \)

This observable: mostly sensitive to \( H \) and \( \bar{H} \)

\( \approx 20\% \) asymmetry coming from interference \( BH \times \text{TCS} \) and sensitive to GPDs
Polarized target: single spin asymmetries

Transversally polarized target asymmetries vs |t|

“in hadronic plane”

|t| ((GeV^2))

|t| ((GeV^2))

φ=90°

φ=0°

Longitudinally polarized target asymmetry vs |t|

GPD \( \tilde{H} \)

• Im part of amplitudes
  \( \Rightarrow A_{ui} [BH] = 0 \)

• Sensitive to \( H, \tilde{H}, E \)

10% to 20% asymmetries

\( \xi = 0.2, Q'^2 = 7 \text{ GeV}^2, -t = 0.4 \text{ GeV}^2, \theta \in [45^\circ, 135^\circ] \)
Polarized beam and target: double spin asymmetries

Circularly polarized beam and transversally pol. target vs $|t|$

“in hadronic plane”

- Very sensitive to the GPDs parameterization
- Sensitive to the real part of amplitudes
- But
  - $A[BH] \neq 0$, few % deviation from TCS signal
  - Bins in $\varphi$ and $\theta$ preferable for signal
  - Experimental difficulties (stat...)

Other observables: with linearly polarized photon beam (not shown)
unpolarized cross sections TCS and BH

\[ |\xi| = 0.2, Q'^2 = 7 \text{ GeV}^2 \]

- BH/proton (only BH)
- BH/neutron (only BH)
- TCS/proton (only TCS)
- TCS/neutron (only TCS)

\[ \Rightarrow \text{TCS off neutron is measurable but is more difficult experimentaly} \]
\[ \Rightarrow \text{Asymmetries } \approx \text{ same } \Phi \text{ and } t \text{ dependancies and same magnitudes} \]

- flavor separation: u and d quarks
- GPD E (next slide) \(\Rightarrow\) Ji sum rule
Beam spin asymmetry off the proton and off the neutron

Sensitivity to GPD E in BSA:
BSA as a function of $u$ and $d$ quark angular momenta $J_u$ and $J_d$

$\text{BSA}(t=0.4 \text{ GeV}^2)$ vs $J_u$ and $J_d$ for \textbf{proton:} 

$\text{for neutron:}$

5 % variations

Stronger sensitivity to $J_u$ and $J_d$ + change of sign for BSA off the neutron

$\rightarrow$ Ji sum rule... studies of angular momenta of quarks
Part II

- Extraction of GPDs with TCS
- Experimental perspectives
Interest of TCS and DVCS in parallel:
• Universality of GPDs
• Complementary observables
• Higher twist and higher order effects
GPDs and Compton Form Factors

\[ T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x, \xi, t)}{x + \xi + i \varepsilon} \, dx + \ldots \sim \int_{-1}^{+1} \frac{H(x, \xi, t)}{x + \xi} \, dx - i \pi H(\pm \xi, \xi, t) + \ldots \]

**CFFs are measurable:**

- \( \xi, t \): mesurables
- \( x \): loop variable
- \( x \pm \xi \): propagator

ReT: cross section and double spin asymmetries integrals over \( x \) of GPDs

ImT: beam or target single spin asymmetries

GPDs (real) \( \rightarrow \) CFFs (complex)

Goeke, Polyakov, Vanderhaeghen PPNP 47 (2001) 401
Could we extract CFFs from TCS fits?

- Pseudo-data based on our TCS calculation
- DVCS\(^1\) method is expanded for TCS and TCS+DVCS
- Local fits: MINUIT + MINOS
  - several sets of observables, \((\xi, t)\) points fitted independently
  - 7 free parameters: CFFs (\(\text{Im and Re} [ H, \tilde{H}, E], \text{Re}[\tilde{E}]\)) , the variation of parameters is limited in parameter space

\(^1\)M. Guidal, EPJA 37 (2008) 319
Set of results (uncertainties)

**Compton Form Factors (CFFs)**

Simulations; without smearing
\( \delta \sigma = 5\% \), \( \delta \Delta \sigma = 2\% \)

Generated "CFF" = 1

\( \xi = 0.2 \), \( Q^2 = 7 \text{ GeV}^2 \),
\( -t = 0.4 \text{ GeV}^2 \), \( \theta = 90^\circ \)

Observables:
With polarized beam and/or target

- underconstrained system: some CFFs are extracted: \( \text{Im}(H) \)
- 8 independent observables, 7 CFFs: all CFFs are extracted
- single spin asymmetries \( \propto \text{Im} T \implies \text{Im}(\text{CFFs}) \) are extracted with smaller error bars
- compared to DVCS: more difficult with TCS, but complementary

**CFFs can be extracted from TCS fits assuming 5% uncertainties on observables**
Hall A SoLID (large acceptance spectrometer, $L=10^{37}\text{cm}^{-2}\text{s}^{-1}$)
- (LOI in 2013 and proposal in progress) unpolarized target, polarized "quasi-real" photon beam
- near future: polarized target and polarized beam

Hall B CLAS12 (large acceptance spectrometer, Luminosity=$10^{35}\text{cm}^{-2}\text{s}^{-1}$)
- accepted proposal (2012): unpolarized cross sections with "quasi-real" photon beam
- experimental feasibility was shown with analysis @ 6 GeV (R. Paremuzyan PhD thesis)
- (proposal in progress) linearly polarized beam asymmetries (not shown, sensitive to the real part of amplitudes)

Hall C
- (LOI in progress) dedicated measurement with transversally polarized target and "quasi real" photon beam

Hall D
- studies of faisability, only Hall with a real linearly polarized photon beam
Some predictions for JLab @ 12 GeV with CLAS12

CLAS12 accepted configuration

Unpolarized cross section

Bin 1: 0.17 < ξ < 0.20
Bin 2: 0.20 < ξ < 0.23
θ ∈ [45°, 135°]
Q'^2 ∈ [4, 7] GeV^2
-t ∈ [0.2, 0.4] GeV^2

Circular beam spin asymmetry

Bin 1: 0.17 < ξ < 0.20
Bin 2: 0.20 < ξ < 0.23
θ ∈ [45°, 135°]
Q'^2 ∈ [4, 7] GeV^2
-t ∈ [0.2, 0.4] GeV^2

~5% statistical error: justification of the 5% error for the fits,
- Observables are measurable
- Extraction of GPD H is possible

100 days, A ≈ 0.2, L = 10^{35} cm^{-2}s^{-1}, E(e^-) = 11 GeV, "quasi-real" photons
Calculations of unpolarized + beam and/or target polarized cross sections\textsuperscript{1}

- Single spin asymmetries (circularly polarized beam or target) most favorable for GPDs, sensitive to the imaginary part of amplitudes
- TCS off the neutron: flavor separation, GPD E, angular momenta of quarks
- Some higher twist corrections taken into account here (not shown)

Fits on pseudo-data and GPD extraction

- CFFs and GPDs can be extracted with TCS
- Comparisons to DVCS in the kinematical range: universality of GPDs, evaluation of higher twist effects...

Experimental perspectives for JLab

- Accepted experiment for CLAS12, LOI for SOLID
- New proposals for CLAS12 and SOLID (in progress)
- New LOI for Hall C with transversally polarized target (in progress)

\textsuperscript{1}MB, M. Guidal, M. Vanderhaeghen, arXiv:1501.00270 [hep-ph]
<table>
<thead>
<tr>
<th>Asymmetries</th>
<th>sensitivity of Im or Re part in amplitudes</th>
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<tr>
<td>BSA (circ)</td>
<td>Im</td>
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<td>BSA (lin)</td>
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<td>TSA (long)</td>
<td>Im</td>
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<td>TSA (trans)</td>
<td>Im</td>
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<tr>
<td>BTSA (beam circ)</td>
<td>Re</td>
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<tr>
<td>BTSA (beam lin)</td>
<td>Im</td>
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Comparison:
(DVCS+BH)$^1$

proton

neutron

$^1$JLab PAC37
Photon beam polarization rate

11 GeV electron beam
- **circular polarization** (red line)
- **linear polarization** (blue dotted line)

$P_\gamma$ vs $E_\gamma$ [GeV]