Timelike Compton Scattering

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Generalized Parton Distributions (GPDs) [exclusive reactions]

Transverse spatial distribution of quarks with longitudinal momentum fraction x

GPDs “unify” form factors and parton distributions
Compton Scattering

- Real Compton Scattering
- Deeply Virtual Compton Scattering (DVCS)
  - Outgoing photon is real
  - Simplest probe of GPDs
- Timelike Compton Scattering (TCS)
  - Incoming photon is real
  - Complementary to DVCS
- Double DVCS
  - Both photons are virtual
  - Can provide most information
  - Experimentally challenging

GPDs can be extracted from Helicity Amplitudes or Compton Form Factors
Probing GPDs through Compton Scattering

\((\text{Im, } x=\xi)\)
DVCS: spin asymmetries
HERMES, CLAS, Hall A

\(|\text{Re}|\)
TCS: azimuthal asymmetry
CLAS
DVCS: charge asymmetry
HERMES

\(H(x, \xi, 0)\)

\((\text{Im, } x \neq \xi, x < |\xi| )\)
DDVCS

\(|\text{Re}|^2\)
DVCS: cross sections
H1, Hall A
TCS vs. DVCS

Pros

- Excellent tool for measuring the real part

- TCS and DVCS amplitudes are equivalent only to leading order
  - at finite $Q^2$, data on both reduces model dependence of GPD extraction

- TCS asymmetries are easy to compare directly with GPD models
  - Polyakov-Weiss D-term

Cons

- Cross section smaller than for DVCS
  - enhancement through interference with Bethe-Heitler always needed

- Resonances in timelike final state limit $Q^2$ coverage
GPD models sensitive to real part at large $x$

$Q'^2 = 5 \text{ GeV}^2$ and $t = 0$

\[ \tau = \frac{Q'^2}{s-M_P^2} \]

is the equivalent of Bjorken $x$, hard scale is given by $Q'^2 = M_{e+e^-}^2$.

- Model predictions similar for $\text{Im} \, H$, but large differences for $\text{Re} \, H$
- Reliable measurements of real part are needed!
D-term in DD-parameterization of GPDs

D-term – allows to satisfy polynomiality of Mellin moments of GPD

GPD with D-term

GPD without D-term

Real part of the Compton amplitude is very sensitive to the D-term
Photoproduction of Lepton Pairs

\[ s = (q + p)^2 \]

\[ t = (p - p')^2 \]

- TCS cross section is small compared with Bethe-Heitler for all kinematics
  - cannot be accessed directly

- The interference term is, however, larger and easy to isolate

\[ E_\gamma = 13 \text{ GeV}, Q'^2 = 5 \text{ GeV}^2 \]

• Under reversal of the lepton charge:
  – Compton and BH amplitudes are even
  – Interference term is odd
  – Observables that change sign project out only the interference term

• Example of observable: azimuthal angular distribution of the lepton pair
To leading order, in terms of helicity amplitudes:

\[
\frac{d\sigma_{INT}}{dQ'^2 \, dt \, d(cos \theta) \, d\varphi} = -\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \cos \varphi \, \frac{1 + \cos^2 \theta}{\sin \theta} \Re \tilde{M}^{--} \right.
\]

\[
- \cos 2\varphi \sqrt{2} \cos \theta \Re \tilde{M}^{0-} + \cos 3\varphi \sin \theta \Re \tilde{M}^{+-} + O\left(\frac{1}{Q'}\right),
\]

\[
- \sqrt{\nu} \frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{-t} \frac{M}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \left[ \sin \varphi \, \frac{1 + \cos^2 \theta}{\sin \theta} \Im \tilde{M}^{--} \right.
\]

\[
- \sin 2\varphi \sqrt{2} \cos \theta \Im \tilde{M}^{0-} - \sin 3\varphi \sin \theta \Im \tilde{M}^{+-} + O\left(\frac{1}{Q'}\right) \Bigg] \]

\[\nu: \text{circular polarization of incoming photon also gives access to imaginary part}\]

\[
\frac{1}{2} \sum_{\lambda, \lambda'} |M^{\lambda-\lambda'}|^2 = (1 - \eta^2) \left( |\mathcal{H}_1|^2 + |\tilde{\mathcal{H}}_1|^2 \right) - 2\eta^2 \Re(\mathcal{H}_1^* \mathcal{E}_1 + \tilde{\mathcal{H}}_1^* \tilde{\mathcal{E}}_1)
\]

\[- \left( \eta^2 + \frac{t}{4M^2} \right) |\mathcal{E}_1|^2 - \eta^2 \frac{t}{4M^2} |\tilde{\mathcal{E}}_1|^2 \]
Azimuthal $e^+e^-$ asymmetries in TCS

- Example: ratio of weighted cross sections

$$R = \frac{2\pi \int_0^{2\pi} d\phi \cos \phi \frac{dS}{dQ^2 dt \phi}}{2\pi \int_0^{2\pi} d\phi \frac{dS}{dQ^2 dt \phi}}$$

- Numerator is proportional to Re $M^-$
  - $\cos \phi$ part of interference term

- $R$ can be compared directly with GPD models even in experiments with limited statistics

- Sensitive to Polyakov-Weiss D-term

$E_\gamma = 13$ GeV

$E_\gamma = 6$ GeV

$|t| = 11.76$ (GeV/c)$^2$

$Q^2 = 15$ (GeV/c)$^2$

[V. Guzey, 2010]

Tanja Horn, Timelike Compton Scattering - a first look,
MENU 2010
6 GeV

- New CLAS data collected with tagged real photons (g12)
  - Data ready for analysis (will start in the fall)

- Several CLAS data sets with quasi-real photons (e1-6, e1f)
  - Analysis in final stages (1 PhD completed)

12 GeV

- Experiments with quasireal photons planned at CLAS12
  - Very good electron identification and momentum resolution

- Experiments with real photons in Hall D natural next step
  - Linear polarization at 9 GeV, circular at 12 GeV
  - Good forward and backward acceptance
The g12 experiment carried out between March 29 and June 8, 2008.
Tagged real photons with energies of 3.6 – 5.4 GeV on LH2 target.
CLAS Cerenkovs and calorimeter allow good pion rejection
  • $10^{-7}$ with two leptons detected, $10^{-4}$ with one lepton detected
• 25 billion two- and three-track events collected (mostly hadron triggers)
Missing momentum analysis of final state

\[ ep \rightarrow e^+e^- \]

X – is identified as an electron scattered at 0 degrees, \( Q^2 < 0.01 \) (GeV/c)^2 and \( |M_X|^2 < 0.1 \) (GeV)^2
CLAS e1-6 and e1f experiments

CLAS/e1-6

- Several CLAS data sets with 6 GeV electron beams available
- CLAS has good particle identification and resolution, but complicated acceptance
- Comparison with hermetic detector (GLUEX) would be interesting
TCS at 12 GeV

CLAS12 in Hall B

- TCS with quasi-real photons
- Circular photon polarization

GlueX in Hall D

- TCS with tagged real photons
- Linear photon polarization

- Can be run in parallel with other experiments
- Several years of beam time potentially available
Timelike window at 12 GeV

• JLab 12 GeV kinematics are ideally suited for TCS
• Data can be taken in the resonance-free region between $\rho'$ and $J/\Psi$
Summary

- TCS can be an important part of the JLab DVCS program, providing
  - Real part of amplitude
  - Corrections at finite $Q^2$
  - Direct comparison with GPD models
- First experiments completed in Hall B at Jefferson Lab
  - $g_{12}$ with tagged real photons – analysis to begin soon
  - several data sets using electron beams – analysis in progress
- Natural extension to 12 GeV (in two Halls?)
  - Can share several years of beam time with approved experiments
• \( p, p' \) = momentum of the incoming and scattered proton
• \( q, q' \) = momentum of the incoming and scattered photon
• \( k, k' \) = momentum of \( e^- \), \( e^+ \)
• \( \theta \) = angle between the scattered proton and the electron
• \( \phi \) = angle between lepton scattering and reaction plane
Factorization Scale in Compton Scattering

Space-like: DVCS

\[ \gamma^* p \rightarrow \gamma p \]
- \( \gamma^* \) has a large spacelike virtuality
- \(-t\) is small

Time-like: TCS

\[ \gamma p \rightarrow \gamma^* p \]
- \( \gamma^* \) has a large timelike virtuality
- \(-t\) is small

- Accessing physics contained in GPDs requires hard-soft factorization to apply
- In TCS, the hard scale is given by the mass of the final state photon \((Q')\)
  - experimentally accessed as the invariant mass of the produced lepton pair