Timelike Compton Scattering with CLAS12 at Jefferson Lab

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From **Deeply Virtual Compton Scattering** to **Timelike Compton Scattering**

DVCS ($\gamma^* p \rightarrow \gamma p$)  

\[ \text{DVCS (} \gamma^* p \rightarrow \gamma p \text{)} \]

TCS ($\gamma p \rightarrow \gamma^* p$)  

\[ \text{TCS (} \gamma p \rightarrow \gamma^* p \text{)} \]

**Compton Form Factors (CFF)**

\[ \mathcal{H} = \sum_q e_q^2 \left\{ \mathcal{P} \int_{-1}^{1} dx H^q(x, \xi, t) \left[ \frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + i\pi [H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)] \right\} \]

**Imaginary part**

- Measured in DVCS asymmetries
- Accessible in TCS photon polarization asymmetry

**Real part**

- Accessible in DVCS cross section
- Accessible in TCS in cross section angular modulation

Guidal, Moutarde and Vanderhaeghen (2013)
Physics Motivations

- The CFFs dispersion relation at leading-order and leading twist:

\[
\text{Re}\mathcal{H}(\xi, t) = \mathcal{P} \int_{-1}^{1} dx \left( \frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \text{Im}\mathcal{H}(\xi, t) + D(t)
\]

- D-term expansion

\[
D(t) = \frac{1}{2} \int_{-1}^{1} dz \frac{D(z, t)}{1 - z}
\]

\[
D(z, t) = (1 - z^2)[d_1(t) C_3^{3/2}(z) + ...]
\]

- \(d_1(t)\) is directly related to the pressure distribution in the nucleon.

- Measurement of photon polarization asymmetry will provide a test of universality of GPDs.
$\gamma p \rightarrow e^+ e^- p$

TCS (GPDs)

Bethe-Heitler (Form Factors)

TCS cross section

$$\frac{d^4\sigma}{dQ^2 dt d\Omega} = \sigma_{TCS} + \sigma_{BH} + \sigma_{INT}$$

TCS cross section not large enough to allow meaningful measurement

Use interference term to access GPDs

Berger, Diehl and Pire (2002)
\[ \gamma p \rightarrow e^+ e^- p \]  

**Kinematics**

\[ Q'^2 = (k + k')^2 \quad t = (p' - p)^2 \]

\[ L = \frac{(Q'^2 - t)^2 - b^2}{4} \quad L_0 = \frac{Q'^4 \sin^2 \theta}{4} \quad b = 2(k - k')(p - p') \]

\[ \tau = \frac{Q'^2}{2p \cdot q} = \frac{Q'^2}{s-M^2} \quad \xi = \frac{\tau}{2-\tau} \quad s = (p + q)^2 \quad t_0 = -\frac{4\xi^2 M^2}{(1-\xi^2)} \]
\( \gamma p \rightarrow e^+ e^- p \) Cross section and CFFs

**Interference cross section**

\[
\frac{d^4 \sigma_{\text{INT}}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{\text{em}}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau} \frac{L_0}{L} \frac{\cos(\phi)}{\sin(\theta)} \text{Re} \tilde{M}^{-+} + \ldots
\]

\[
\rightarrow \tilde{M}^{-+} = \frac{2\sqrt{t_0 - t}}{M} \frac{1 - \xi}{1 + \xi} \left[ F_1 \mathcal{H} - \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right]
\]

**BH cross section**

\[
\frac{d^4 \sigma_{\text{BH}}}{dQ'^2 dt d\Omega} \approx -\frac{\alpha_{\text{em}}^3}{2\pi s^2} \frac{1}{-t} \frac{1 + \cos^2(\theta)}{\sin^2(\theta)} \left[ (F_1^2 - \frac{t}{4M^2} F_2^2) \frac{2}{\tau^2} \frac{\Delta_T^2}{t} + (F_1 + F_2)^2 \right]
\]

BH cross section diverges at \( \theta \approx 0^\circ \) and \( 180^\circ \)

**Weighted cross section ratio**

\[
R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi \cos(\phi) \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \frac{dS}{dQ'^2 dt d\phi} = \frac{dS}{dQ'^2 dt d\phi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L_0}{L} \frac{d\sigma}{dQ'^2 dt d\phi d\theta}
\]
CLAS12 at Jlab

Central Detector
- Time-of-Flight (CTOF)
- Tracking (SVT and MM)
- Neutron detector (CND)

Forward Detector
- Drift Chambers (DC)
- Time-of-Flight (FTOF)
- Calorimeters (Pre-Shower Calorimeter/2 layer EC)
- Cherenkov Counters (HTCC and LTCC)
- RICH
- Forward tagger (FT)

Data Set
- First CLAS12 experiment, data were taken in the Spring and Fall 2018
- Beam energy 10.56 GeV / Liquid hydrogen target
- Two torus magnetic field configurations (Inbending/Outbending electrons)
- Total accumulated charge in the Faraday cup for data shown here : 18 mC ∼ 3% of the proposed total data (100 days at 75nA). Total taken data corresponds to 50% of total proposed data
Data analysis

\[ ep \rightarrow e' \gamma p \rightarrow (e') e^+ e^- p' \]

**Final state**
- Use the CLAS12 reconstruction software PID
- Events with exactly one \(e^+\), one \(e^-\) and one proton are selected

**Scattered electron**
- Cut on scattered electron missing mass
- Cut on missing transverse momentum of \(ep \rightarrow e^+ e^- pX\) system

**Incoming photon**
- The real photon is radiated by the beam electron
- Cuts on scattered electron constrain the virtuality of the photon
  \[ Q^2 \propto \cos(\Theta_{\text{scattered}}) \]
$e^+ e^- pX$ final state selection

**Protons**

- Matching $\beta$ calculated from Time-Of-Flight and momentum from tracking

**Leptons**

- Number of Cherenkov photons $> 2$
- Minimum energy deposited in the Pre-Shower Calorimeter (PCAL)
- Cuts on total calorimeters sampling fractions ($E_{deposited}/p$)
Exclusivity cuts

- Scattered electron: \( p_{\text{scattered}}^\mu e^- = p_{\text{beam}}^\mu + p_{\text{target}}^\mu - p_{\text{proton}}^\mu - p_{e^+}^\mu - p_{e^-}^\mu \)

Simulation (e^+e^-p events weighted with BH weight)

Data (inbending)
3% of total proposed data

Low $e^+e^-$ invariant mass spectrum is dominated by vector meson photoproduction $\rightarrow$ Mass cut between the $\rho$ region [$\rho(1450 \text{ MeV})$ and $\rho(1700 \text{ MeV})$] and $J/\psi(3 \text{ GeV})$ $\rightarrow$ The resonance-free mass region between 2 GeV and 3 GeV will be used for the analysis.
Projected results

Experimental cross section $\phi$ modulation ratio

$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi \cos(\phi) \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \rightarrow R' = \frac{\sum \cos(\phi) Y_\phi}{\sum \phi Y_\phi} \text{ where } Y_\phi = \sum_{\theta} \frac{L}{L_0} N^\phi_{\theta} \frac{1}{A^\phi_\theta}$$

Estimate of CLAS12 acceptance with BH simulation

Acceptance in the $\theta/\phi$ plane ($A^\phi_\theta = \frac{N_{REC}}{N_{GEN}}$)

$\rightarrow$ Yellow lines are CLAS12 acceptance limits

$\rightarrow$ Cut regions correspond to events where one lepton goes in the beam pipe (BH peaks are out of CLAS12 acceptance)
Projected results

Generator developed by R. Paremuzyan at Jefferson Lab.

→ Double distribution GPD parametrization

\[ H(x, \xi, t) = H_{DD}(x, \xi, t) + \kappa \frac{1}{N_f} \Theta(\xi - |x|) D\left(\frac{x}{\xi}, t\right) \]

- \( R' \) is sensitive to D-term strength within CLAS12 acceptance.
- Full data set (50% of total proposed data) will provide enough statistics to give insight on D-term strength (green points and associated error bars).
Projected results

- \( R' \) is sensitive to D-term strength **BUT** also depends on acceptance limits → difficulties to compare measurement with theoretical models
- Possibility to restore \( \theta \) dependence of the interference cross-section

We want to access the \( \phi \) moment of the cross section. We can measure:

\[
\frac{dS_{TOT}}{dQ'^2 dt d\phi} = \int_{b(\phi)}^{a(\phi)} d\theta \quad \frac{d^4 \sigma_{TOT}}{dQ'^2 dt d\Omega} \quad \frac{L}{L_0} = \frac{dS_{BH}}{dQ'^2 dt d\phi} + \frac{dS_{INT}}{dQ'^2 dt d\phi}
\]

- \( \frac{dS_{BH}}{dQ'^2 dt d\phi} \) is calculable from form factors.
- The \( \theta/\phi \) dependance of the interference term is fully known:

\[
\frac{dS_{INT}}{dQ'^2 dt d\phi} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \left[ \cos(\phi) \int_{b(\phi)}^{a(\phi)} (1 + \cos^2(\theta)) d\theta \cdot \text{Re} \tilde{M}^- + ... \right]
\]

This method will be implemented at a later stage of the analysis, as it requires good accumulated luminosity estimation.
Conclusion

- Timelike Compton Scattering allows to investigate the real part of CFFs which is difficult to constrain with DVCS.
- No published results on TCS yet.
- Main resonances in the $e^+e^-$ spectrum visible in CLAS12 data.
- Projected statistic will allow insight on the strength of the D-term.

Outlook

- The analysis procedure leading to $R'$ has been developed.
- More statistics is coming from the data processing of the 2018 run.
- Dependence on acceptance limits of $R'$ will be corrected to allow comparison with models and future TCS measurements.