Timelike Compton Scattering with CLAS12 at Jefferson Lab

Pierre Chatagnon

Institut de Physique Nucleaire d'Orsay
For the CLAS Collaboration
chatagnon@ipno.in2p3.fr

Glasgow, August 1st, 2019
From deeply virtual Compton scattering to timelike Compton scattering

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

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

**Compton Form Factors (CFF)**

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

**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)

\( H(x, \xi, 0) \)
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
  \[ D(t) = \frac{1}{2} \int_{-1}^{1} dz \frac{D(z, t)}{1 - z} \]

  \[ D(z, t) = (1 - z^2)[d_1(t) C_1^{3/2}(z) + \ldots] \]

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

- Measurement of photon polarization asymmetry will provide a test of universality of GPDs.
**TCS and Bethe-Heitler**

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

**TCS (GPDs)**

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

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

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

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

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

**Interference cross section**

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

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

**BH cross section**

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

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

**Weighted cross section ratio**

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

- Cuts on scattered electron
- Look at 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 deposit in the Pre-Shower Calorimeter (PCAL)
- Cuts on Calorimeters sampling fractions
**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)**

- Pt/P scattered electron
- Pt/P vs Mass^2 scattered electron

**Data (inbending)**

- Pt/P scattered electron
- Pt/P vs Mass^2 scattered electron
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 mass region between 2 GeV and 3 GeV will be used for the analysis
Projected results

**Experimental cross section $\phi$ modulation ratio**

\[
R(\sqrt{s}, Q'^2, t) = \int_0^{2\pi} d\phi \cos(\phi) \frac{dS}{dQ'^2 dt d\phi} \quad \Rightarrow \quad R' = \sum_{\phi} \frac{\cos(\phi) Y_{\phi}}{\sum_{\phi} Y_{\phi}} \quad \text{where} \quad Y_{\phi} = \sum_{\theta} \frac{L}{L_0} \frac{N_{\phi}}{A_{\phi}^0}
\]

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

\[
\frac{d^4 \sigma_{TOT}}{dQ'^2 dt d\Omega} = \frac{d^4 \sigma_{BH}}{dQ'^2 dt d\Omega} + \frac{d^4 \sigma_{INT}}{dQ'^2 dt d\Omega} \\
\frac{d^4 \sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau \sqrt{1 - \tau}} \frac{L_0}{L} \]

\[
[\cos(\phi) \frac{1 + \cos^2(\theta)}{\sin(\theta)} \text{Re} \tilde{M}^{--} + ...]
\]
**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.