Timelike Compton Scattering with CLAS12 at Jefferson Lab

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Abstract. Generalized Parton Distributions (GPDs) describe the correlations between the longitudinal momentum and the transverse position of the partons inside the nucleon. They are nowadays the subject of an intense effort of research, in the perspective of understanding nucleon structure. GPDs have been studied mainly using Deeply Virtual Compton Scattering (DVCS, $ep \rightarrow e'p'\gamma$). Here we highlight the measurement of the time-reversal conjugate process of DVCS, Timelike Compton Scattering (TCS) using data taken by CLAS12. The experimental measurement of the TCS angular asymmetry will provide new information on the real part of GPDs. This proceeding assesses the current status of the TCS analysis and presents preliminary results based on CLAS12 data.

1. Introduction

The partonic structure of the nucleon has been a very active field of research for more than 50 years. Generalized Parton Distributions (GPDs) have been introduced in the 1990s [1, 2, 3, 4]. They describe nucleon structure in terms of longitudinal momentum and transverse position of quarks and gluons. GPDs allow for a tomographic imaging of the nucleon combining momentum and position informations [5, 6]. They are also closely related to the angular momentum contribution of partons to the spin of the nucleon [7]. Thus GPDs have been at the center of many experimental programs. In this proceeding we focus on the measurement of the time-reversal conjugate process of Deeply Virtual Compton Scattering (DVCS), Timelike Compton Scattering (TCS). Data collected by the CLAS12 detector at Jefferson Lab are shown.

2. Physics motivations

2.1. Deeply Virtual Compton Scattering and Compton Form Factors

At leading order, four quark helicity conserving GPDs (H, H, E and E) per quark flavour describe nucleon structure, each of them depends on three variables: x, ξ and t (see [2] for extensive review). The simplest process to access GPDs experimentally is DVCS $(ep \rightarrow e'p'\gamma)$. For large enough photon virtuality Q^2 and small $-t \ll Q^2$, DVCS can be factorized (see diagram in Figure 1) and interpreted as a electron interacting via a virtual photon with a single quark, which then re-emits a photon. The soft part of the diagram is parametrized by GPDs. GPDs enter the DVCS amplitude as complex quantities called Compton Form Factors (CFFs) defined for the GPD H as:

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

and similarly for other GPDs.

DVCS observables are mostly sensitive to the imaginary part of CFFs. Many DVCS observables have been measured so far [8]. These measurements provide good constraints to the imaginary part of CFFs. On the contrary the real part is much less known.



Figure 1. DVCS diagram at leading twist and leading order. At high photon virtuality Q^2 and small transferred momentum $-t = (p' - p)^2$ the interaction happens at the single quark level. The hit quark carries a momentum fraction $x + \xi$ before the interaction, $x - \xi$ after.



Figure 2. TCS diagram at leading twist and leading order. At high photon virtuality Q'^2 and small $-t = (p' - p)^2$ the interaction happens at the single quark level.

2.2. Timelike Compton Scattering

Timelike Compton Scattering (TCS) is the time reversal conjugate process of DVCS ($\gamma p \rightarrow \gamma^* p' \rightarrow e^+ e^- p'$). As for DVCS, TCS can be factorized in term of GPDs (see diagram in Figure 2) and its amplitude depends on CFFs. The cross-section of the photo-production of lepton pairs $\gamma p \rightarrow e^+ e^- p'$ has contributions from TCS, from the Bethe-Heitler process and from their interference. Beithe-Heitler (BH) is the decay of the incoming real photon in a lepton pair, one of the leptons then interacting with the proton. The contribution of BH to the $\gamma p \rightarrow e^+ e^- p'$ cross section is at least ten times bigger than the TCS contribution, according to model calculations [9, 10]. Thus direct measurement of the TCS contribution is difficult. However, the interference between BH and TCS gives direct access to the real part of the CFF \mathcal{H} . It is accessible via the ratio R (see [10] for detailed calculations):

$$R(\sqrt{s}, Q'^{2}, t) = \frac{\int_{0}^{2\pi} d\phi \, \cos(\phi) \, \frac{dS}{dQ'^{2}dtd\phi}}{\int_{0}^{2\pi} d\phi \frac{dS}{dQ'^{2}dtd\phi}}$$
(2)



Figure 3. Definition of the kinematic variables for the $\gamma p \rightarrow \gamma^* p' \rightarrow e^+ e^- p'$ reaction (Figure extracted from [10]). The hadronic plane in yellow is defined by the momenta of the incoming and outgoing proton in the γp center-of-mass frame. The leptonic plane in blue is defined by the lepton-pair momenta.

where

$$\frac{dS}{dQ'^2 dt d\phi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L}{L_0} \frac{d\sigma}{dQ'^2 dt d\phi d\theta}$$
(3)

where $L = \frac{(Q'^2-t)^2-b^2}{4}$, $L_0 = \frac{Q'^4 \sin^2 \theta}{4}$, b = 2(k-k')(p-p'), and $k, k', p, p', \theta, \phi$ are defined in Figure 3. As of today, only exploratory TCS measurements have been performed [11].

3. Data analysis

3.1. The CLAS12 detector

The angular modulation of the TCS cross section will be extracted from data taken by the CLAS12 detector. CLAS12 is a newly built detector located in the Hall B of Jefferson Lab. It collected data on proton target in spring and fall 2018, with a 10.6 GeV electron beam inpinging on a liquid hydrogen target. CLAS12 is equipped with tracking and Time-of-Flight (TOF) detectors in both the Central Detector surrounding the target and in the Forward Detector where most particles are emitted. It also comprises Cherenkov detectors and electromagnetic Calorimeters for lepton identification in the forward detector. A toroidal magnetic field allow for charge and momentum reconstruction in the FD. During data taking two field polarities were used: negative charge inbending and outbending.

3.2. Events selection

The selection of TCS events is done in three steps. First, events with one electron, one positron and one proton were selected from the complete data set. We allow for other particles to be detected in order to keep events where fake tracks or noise in the TOF and calorimeter were recorded. Protons are identified by matching the time-of-flight measured by the TOF detectors and the one calculated from the reconstructed momentum. The identification of leptons relies on tracking for the determination of the charge and on Cherenkov and Calorimeters for lepton/pion separation. The High Threshold Cherenkov Counter of CLAS12 allows for good pion/lepton separation below 4.9 GeV. For leptons with momenta above this value, the energy deposited in the PreShower Calorimeter and the sampling fraction ($\frac{E_{deposited}}{p}$, where $E_{deposited}$ is the total energy deposited in the CLAS12 Calorimeter and p is the momentum of the particle) are used.

TCS is accessible in the photo-production of a lepton pair off a proton, while in our experiment we have an electron beam inpinging on a proton target. For our measurement, we select events



Figure 4. Exclusivity cuts (mass and transverse momentum fraction of the undetected scattered electron) applied on simulation events (top two plots) and data in the inbending electron magnetic field configuration (bottom two plots). Exclusive events have null transverse momentum fraction and missing mass equal to the electron mass.

where the beam electron radiated a real photon, that will then interact with a proton in the target. The electron is then scattered at very low angle and thus stays undetected. From the calculated momenta of the three final-state particles, one can deduce the four-momentum of the scattered electron that radiated the real photon:

$$p_{scat.\ e^{-}}^{\mu} = p_{beam}^{\mu} + p_{target}^{\mu} - p_{proton}^{\mu} - p_{e^{+}}^{\mu} - p_{e^{-}}^{\mu}.$$
(4)

The missing mass of the scattered electron $(M_{scat.\ e^-}^2 = p_{scat.\ e^-}^2)$ is required to be close to zero. The transverse momentum fraction of the missing particle is cut around zero to ensure that a real photon is emitted. The effect of the channel-selection cuts on simulation and data can be seen in Figure 4.

The above mentioned cuts ensure the photo-production of a lepton pair. One has to make sure that this lepton pair is produced by the decay of a virtual photon. The invariant mass of the lepton pair $M_{pair}^2 = (p_{e^+}^{\mu} + p_{e^-})^2$ in both torus magnetic field configuration is shown in Figure 5. The low mass region is dominated by vector-meson resonances ($\rho(770)$, $\omega(782)$, and $\phi(1020)$). Events included in the analysis are selected in the 2-3 GeV region to avoid resonances. The data set shown here corresponds to approximately 6% of the total amount of collected data. The rest of the data is currently being processed.

4. Projected results

From the data shown in Figure 5, we expect to accumulate around 4000 events in the selected mass range out of the whole data set. To estimate the achievable statistical precision with the



Figure 5. Lepton-pair invariant mass for the two torus magnetic field polarities. The events in the 2-3 GeV region are selected for the measurement.

current available data set, we simulated $\gamma p \rightarrow e^+ e^- p'$ weighted by BH and TCS/BH interference term. The GPDs double distribution parametrization [12] is used to calculate the interference weight. The strength of the D-term can be adjusted with a multiplying factor κ as:

$$H(x,\xi,t) = H_{DD}(x,\xi,t) + \kappa \frac{1}{N_f} \Theta(\xi - |x|) D(\frac{x}{\xi},t)$$
(5)

where $H_{DD}(x,\xi,t)$ is the double distribution parametrization of the GPD, N_f is the number of active flavours and κ is the D-term strength (see [10]). We calculated the R ratio (equation 2) in the CLAS12 acceptance as a function of -t for three different values of κ and for BHonly weighted events. The results are shown in Figure 6, including projected error bars. Our measurement is expected to provide a good insight on the strength of the D-term.

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Figure 6. R ratio calculated as a function of transferred momentum t in the CLAS12 acceptance for different strengths of the D-term and for BH-only weighted events. The values of R for the green dots are arbitrary, and the error bars correspond to the expected statistical errors achievable for the current data set taken by CLAS12.