

# Timelike Compton Scattering off the nucleon: observables and experimental perspectives for JLab at 12 GeV

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## Abstract.

Hard exclusive processes such as photoproduction or electroproduction of photon or meson off the nucleon provide access to the Generalized Parton Distributions (GPDs), in the regime where the scattering amplitude is factorized into a hard and a soft part. GPDs contain the correlation between the longitudinal momentum fraction and the transverse spatial densities of quarks and gluons in the nucleon. Timelike Compton Scattering (TCS) correspond to the reaction  $\gamma N \rightarrow \gamma^* N \rightarrow e^+ e^- N$ , where the photon is scattered off a quark. It is measured through its interference with the associated Bethe-Heitler process, which has the same final state. TCS allows to access the GPDs and test their universality by comparison to the results obtained with the DVCS process ( $eN \rightarrow e\gamma N$ ). Also, results obtained with TCS provide additional independent constraints to the GPDs parameterization.

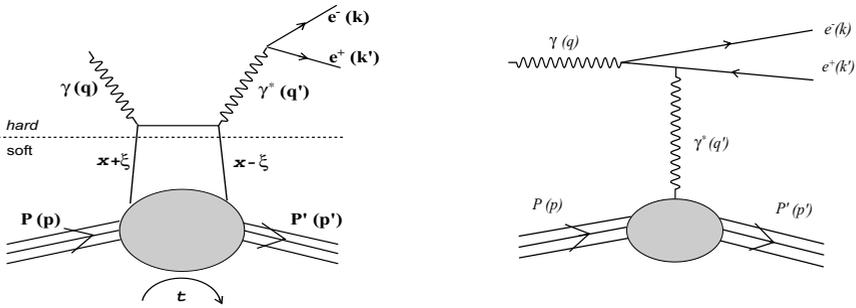
We will present the physical motivations for TCS, with our theoretical predictions for TCS observables and their dependencies. We calculated for JLab 12 GeV energies all the single and double beam and/or target polarization observables off the proton and off the neutron. We will also present the experimental perspectives for the next years at JLab. Two proposals were already accepted at JLab: in Hall B, with the CLAS12 spectrometer, in order to measure the unpolarized cross section and in Hall A, with the SoLID spectrometer, in order to measure the unpolarized cross section and the beam spin asymmetry at high intensity. A Letter Of Intent was also submitted in order to measure the transverse target spin asymmetries in Hall C. We will discuss the merits of this different experiments and present some of the expected results.

## 1 Introduction

Timelike Compton Scattering (TCS) correspond to the scattering of a high energy photon off a quark. A timelike virtual photon is emitted and decays into a lepton pair (Fig. 1, left panel). We will focus on TCS off the nucleon and on the case where the virtual photon decays into an electron-positron pair of invariant mass between 2 and 3 GeV. This condition ensures to avoid the region of vector mesons resonances. It also ensures a high enough virtuality (typically  $Q'^2 > 2 \text{ GeV}^2$ ) to allow for factorization of TCS amplitude between a hard perturbative part, which is calculable, and a non perturbative

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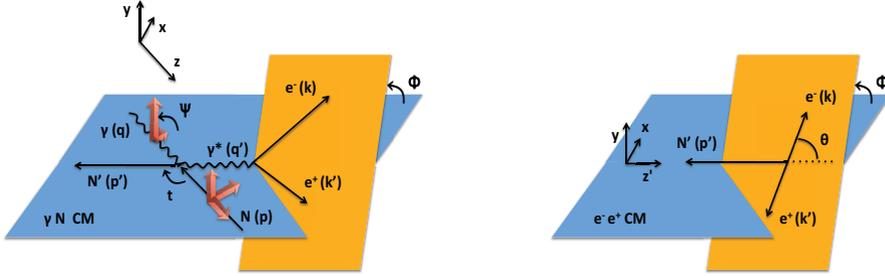


**Figure 1.** Left panel: diagram for TCS off the nucleon, right panel: Bethe-Heitler process. Crossed diagrams are not represented.

part corresponding to low energy interactions in the nucleon. The later could be parameterized by Generalized Parton Distributions (GPDs) [1–5]. The GPDs are Fourier transform into momentum space of the QCD bilocal operators involved in the soft part of the amplitude. Without taking account evolution effects (running in  $Q^2$ ), the GPDs depend on 3 independent variables,  $x$ ,  $\xi$  and  $t$ , which represent respectively the longitudinal momentum fraction carried by the struck quark, the longitudinal momentum transfer to the quark (with  $\xi \simeq \frac{Q^2}{2s-Q^2}$  for TCS on a fixed nucleon target) and the 4-momentum transfer squared  $t = (p' - p)^2$ . GPDs contain the correlation between the longitudinal momentum fraction  $x$  of the struck quark and its transverse spatial distribution, implicitly contained in the  $t$  (momentum transfer squared) dependence. For instance, it can be shown in a model independent way [6] that the Fourier transform of  $\text{GPD}(x, \xi = 0, t)$  gives the probability to find a quark with momentum fraction  $x$  of the nucleon at a transverse distance  $b_\perp$  of the center of the nucleon, where  $b_\perp$  is the conjugate variable of  $t$ . At leading twist, the amplitude for massless quarks involves 4 chiral-even GPDs (without quark helicity flip) that are associated to 4  $\gamma$  matrix structures: vector (GPD  $H$ ), tensor (GPD  $E$ ), axial (GPD  $\tilde{H}$ ) and pseudo-scalar (GPD  $\tilde{E}$ ).

TCS interferes with Bethe-Heitler (BH) process (Fig. 1, right panel), where the lepton pair comes from splitting of the initial photon and one lepton of the pair interacts with the nucleon. BH non perturbative part is parameterized by Form Factors.

TCS off the proton was originally theoretically investigated in [7, 8]. The TCS and BH unpolarized, circularly and linearly beam polarized cross sections were derived. In our study, we calculated the BH and TCS amplitudes, where we waived some of the  $t/Q^2$  and  $M^2/Q^2$  (where  $M$  is the proton mass) approximations, compared to the previous theoretical works. We also included correction terms to restaure gauge invariance to the twist 2 amplitudes, which are not gauge invariant. We studied the impact of these corrections on our results and found few percent deviations for the TCS cross sections and  $< 1\%$  deviations for the spin asymmetries, in the phase space of concern. We then calculated all the unpolarized and beam and/or target polarized cross sections, with circularly or linearly polarized beam and with longitudinally or transversally polarized proton or neutron [9, 10]. In this proceeding, we briefly summarize the formalism that we used and we present some of these results. We will discuss the interest of the measurement of some of these observables, for TCS off the proton and off the neutron, and we will present the experimental project at for JLab at 12 GeV.



**Figure 2.** Left panel: scheme of the TCS reaction in the  $\gamma P$  C.M.. The red arrows represent the 3 polarization states for the proton (along the  $x, y$  or  $z$  axis, where the  $xz$  plane is the reaction plane) and 2 polarization states for a linearly polarized photon (along the  $x$ - and  $y$ -axis). The angle between the beam polarization vector and the reaction plane is noted  $\Psi$ . Right panel: we boost the system and we define the 2 decay angles of the electron in the  $e^+e^-$  C.M., where  $\theta$  and  $\phi$  are respectively the polar and azimuthal angles with respect to the  $\gamma P$  plane and the direction of the  $\gamma^*$  axis.

## 2 Observables

### 2.1 Unpolarized cross section and formalism

The unpolarized  $\gamma P \rightarrow e^+ e^- P'$  (where  $P$  stands for a proton or a neutron) cross section depends on 5 independent kinematic observables. We decided to derive it at fixed beam energy or at fixed  $\xi$ , where it can be expressed as a function of the kinematic variables  $Q'^2$  and  $t$  and as a function of the solid angle of the electron in the  $\gamma^*$  rest frame,  $\Omega = (\theta, \phi)$  (Fig. 2). At fixed beam energy the unpolarized cross section reads

$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} = \frac{1}{64 (2\pi)^4 (2ME_\gamma)^2} |T^{BH} + T^{TCS}|^2, \quad (1)$$

where  $T^{BH}$  and  $T^{TCS}$  are respectively the BH and the TCS amplitudes. The  $|T^{BH} + T^{TCS}|^2$  term is averaged over the proton and photon polarization and summed over the outgoing proton helicities.

We use a frame where the average photon momenta  $\bar{q} = \frac{1}{2}(q + q')$  and nucleon momenta  $P = \frac{1}{2}(P + P')$  are collinear along the  $z$ -axis and in opposite directions. We define the lightlike vectors along the positive and negative  $z$  directions as:

$$\begin{aligned} \tilde{p}^\mu &= P^+ / \sqrt{2} (1, 0, 0, 1), \\ n^\mu &= 1/P^+ \cdot 1/\sqrt{2} (1, 0, 0, -1), \end{aligned} \quad (2)$$

and we define the light-cone components  $a^\pm$  by  $a^\pm \equiv (a^0 \pm a^3)/\sqrt{2}$ . The light cone momentum fractions  $x$  and  $\xi$  are defined respectively by  $k^+ = xP^+$  and by  $\Delta^+ = -2\xi P^+$  where  $\Delta = (p' - p) = (q - q')$ . In the asymptotic limit (neglecting terms in  $t/Q'^2$ ), the variable  $\xi$  can be expressed as a function of  $Q'^2$  and  $s$ , the squared center of mass energy, as  $\xi = \frac{Q'^2}{2s - Q'^2}$ . The results that we present in this proceeding are calculated for the asymptotic limit. Within this formalism, the BH amplitude reads

$$T^{BH} = -\frac{e^3}{\Delta^2} \bar{u}(p') \Gamma^\nu u(p) \epsilon^\mu(q) \bar{u}(k) \left( \gamma_\mu \frac{\not{k} - \not{q}}{(k - q)^2} \gamma_\nu + \gamma_\nu \frac{\not{q} - \not{k}}{(q - k')^2} \gamma_\mu \right) u(k'), \quad (3)$$

with the virtual photon-proton electromagnetic vertex matrix

$$\Gamma^\nu = \gamma^\nu F_1(t) + \frac{i\sigma^{\nu\rho}\Delta_\rho}{2M} F_2(t). \quad (4)$$

In this work, we used the Dirac and Pauli form factors  $F_1(t)$  and  $F_2(t)$  parameterization of [11, 12]. The TCS amplitude reads (using Ji convention for the GPDs [5]):

$$T^{TCS} = -\frac{e^3}{q^2} \bar{u}(k)\gamma^\nu v(k') \epsilon^\mu(q) \left[ \right. \quad (5)$$

$$\frac{1}{2}(-g_{\mu\nu})_\perp \int_{-1}^1 dx \left( \frac{1}{x-\xi-i\epsilon} + \frac{1}{x+\xi+i\epsilon} \right) \left( H^P(x, \xi, t) \bar{u}(p') \not{h} u(p) + E^P(x, \xi, t) \bar{u}(p') i\sigma^{\alpha\beta} n_\alpha \frac{\Delta_\beta}{2M} u(p) \right)$$

$$\left. -i(\epsilon_{\nu\mu})_\perp \int_{-1}^1 dx \left( \frac{1}{x-\xi-i\epsilon} - \frac{1}{x+\xi+i\epsilon} \right) \left( \tilde{H}^P(x, \xi, t) \bar{u}(p') \not{h} \gamma_5 u(p) + \tilde{E}^P(x, \xi, t) \bar{u}(p') \gamma_5 \frac{\Delta \cdot n}{2M} u(p) \right) \right].$$

We have used the metrics

$$\begin{aligned} (-g_{\mu\nu})_\perp &= -g_{\mu\nu} + \tilde{p}_\mu n_\nu + \tilde{p}_\nu n_\mu, \\ (\epsilon_{\nu\mu})_\perp &= \epsilon_{\nu\mu\alpha\beta} n^\alpha \tilde{p}^\beta, \end{aligned} \quad (6)$$

and we used the VGG model for the GPDs parameterization [13, 14]. More details about the formalism may be found in [9].

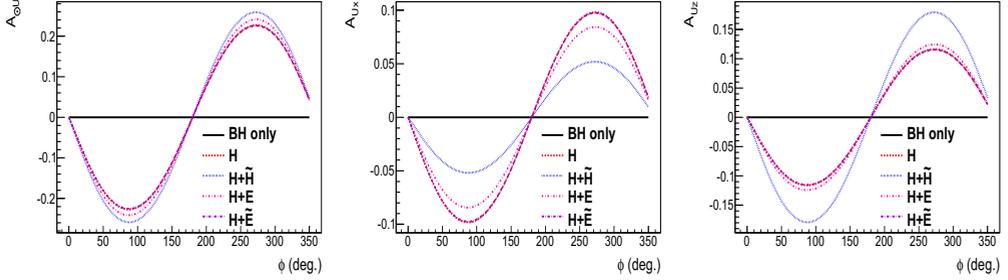
## 2.2 Single spin asymmetries

Single spin asymmetries with a polarized target or a polarized photons beam are defined as

$$A_{\odot U} (A_{LU}, A_{Ui}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}, \quad (7)$$

where the notations  $A_{\odot U}$ ,  $A_{LU}$  and  $A_{Ui}$  correspond respectively to the circularly polarized beam spin asymmetry, the longitudinally polarized beam spin asymmetry and the target spin asymmetries with a nucleon polarized along the  $i$ -axis, where  $i = x, y$  or  $z$ . The  $\sigma^\pm$  terms stand for the 4-differential polarized cross sections, with a polarization vector in the direction of the corresponding axis (+ sign) or in the opposite direction (- sign). The  $A_{\odot U}$  and  $A_{Ui}$  asymmetries are proportionnal to the imaginary part of the amplitudes and are sensitive to the interference between BH and TCS. They would cancel if they were only BH in the reaction. This fact simplify the extraction of physics information about the imaginary part of TCS amplitude by fitting the asymmetries with a phenomenological model. We display on Fig. 3 the  $A_{\odot U}$ ,  $A_{Ux}$  and  $A_{Uz}$  asymmetries as a function of  $\phi$ . The different curves correspond to different scenarii of GPD parametrization. These results show that these observables are mostly sensitive to the GPD  $H$ , and present non negligible sensitivities to the GPDs  $\tilde{H}$  and  $E$ .

Remark: whereas GPD are purely real, they appear in TCS amplitude through integral over  $x$  (Eq. 5). We access them indirectly through complex functions called Compton Form Factors (CFF). Indeed, previous asymmetries access  $\Im(\mathcal{H})$  (CFF associated to GPD  $H$ ), which is proportionnal to  $H(\pm\xi, \xi, t)$  (it is the same for the other GPDs).



**Figure 3.** Single spin asymmetries as a function of  $\phi$  for BH and for BH+TCS, with different scenarios of GPD parametrization. Left panel:  $A_{\odot U^*}$ , central panel:  $A_{U^*}$ , right panel:  $A_{Uz}$ . Calculations have been done for  $\xi = 0.2$  ( $E_\gamma \simeq 11.2$  GeV),  $t = -0.4$  GeV<sup>2</sup>,  $Q^2 = 7$  GeV<sup>2</sup> and  $\theta$  integrated over  $[45^\circ, 135^\circ]$ .

### 2.3 Proton and neutron comparison: circularly polarized beam spin asymmetry

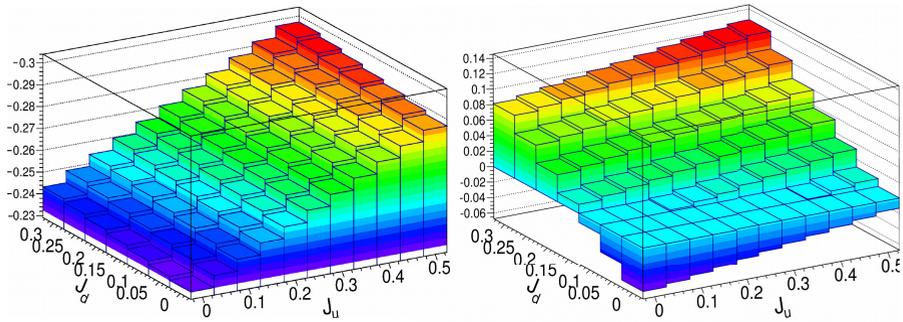
Nucleon GPDs decompose into quark GPDs as

$$H^p = \frac{4}{9}H^u + \frac{1}{9}H^d; \quad H^n = \frac{4}{9}H^d + \frac{1}{9}H^u, \quad (8)$$

where  $H^{p,n}$  are proton or neutron GPDs and  $H^{u,d}$  are GPDs for quarks  $u$  or  $d$ . The knowledge of both proton and neutron GPDs leads to quark flavor decomposition. An other interest of studying both proton and neutron TCS comes from that some factors in the amplitudes may enhance some GPD dependencies for one of the nucleon more than for the other one. Indeed proton and neutron TCS observables may present different sensitivities to GPDs and different kinematic distributions. Fig. 4 presents the circularly polarized beam spin asymmetries and its quark angular momenta  $J_u$  and  $J_d$  dependencies, entering GPD E parametrization. We notice a  $\sim 3$  times stronger sensitivity (for this kinematic) to quarks angular momenta for the neutron, accompanied by a sign change of the asymmetry. More details about comparison of TCS off the proton and off the neutron may be found in [10].

## 3 Experimental perspectives for TCS at JLab at 12 GeV

Several programs aiming at measuring TCS off the proton at JLab at 12 GeV have been developed or are still in development. Two proposals [15, 16] have been already approved. Both of them aim at measuring the unpolarized BH+TCS cross section and the circularly polarized beam spin asymmetry. The proposal [15] plans to run for 100+20 days at a luminosity of  $10^{35}$  cm<sup>-2</sup>s<sup>-1</sup> with the JLab Hall B large acceptance CLAS12 spectrometer. An analysis using the CLAS spectrometer and the 6 GeV electron beam has been performed [17]. It shows the experimental feasibility of such measurement in JLab Hall B. The proposal [16] plans to measure the same observables with the SoLID large acceptance spectrometer in Hall A, with a luminosity of  $10^{37}$  cm<sup>-2</sup>s<sup>-1</sup> for 50 days. The luminosity improvement of Hall A will provide a better precision for the study of the  $Q^2$  and  $t$  evolution of the TCS cross section. These two experiments plan to measure TCS using quasi-real photons coming from the electron beam radiations, providing a photon beam energy in a range from 4 GeV to 10



**Figure 4.** Evolution of the circularly polarized beam spin asymmetries for TCS+BH off the proton (left) or off the neutron (right) as a function of the quark angular momenta  $J_u$  and  $J_d$ . Calculation have been done for  $\xi = 0.2$  ( $E_\gamma \simeq 11.2$  GeV),  $t = -0.4$  GeV<sup>2</sup>,  $Q^2 = 7$  GeV<sup>2</sup>,  $\phi = 90^\circ$  and  $\theta$  integrated over  $[45^\circ, 135^\circ]$ . Four nucleon GPD enter TCS parametrization.

GeV. They are complementary. Another program is in development for the JLab Hall C with the NPS spectrometer. It aims at measuring the single target spin asymmetries using a transversally polarized  $NH_3$  target [18]. The main interests of these measurement are the sensitivity of the transverse target spin asymmetries to the GPDs  $\tilde{H}$  and E and the fact that these observables have never been measured and will provide new independent constrains to CFF fits.

The measurement of observables related to TCS off the neutron would be complementary to TCS off the proton and present lot of interests (see previous section). However, it is experimentally more challenging to measure TCS off the neutron due to a lower cross section compared to proton and due to experimental issues such as neutron detection... No experimental programs have been developed yet for such measurement, but some studies may be done in a next future.

## 4 Conclusion

We presented a sample of our results for TCS and BH off the proton and off the neutron. We shown some of the single and double beam and/or target polarized spin asymmetries. We then discussed the interest of their experimental measurement in a purpose of extracting Compton Form Factors in order to parametrize the GPDs. We also presented some of the experimental perspectives for studying TCS at JLab at 12 GeV.

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