First-time measurement of Timelike Compton Scattering with the CLAS12 detector at JLab

Based upon e-print arXiv:2108.11746

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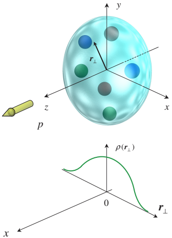
5th September 2021 - Online

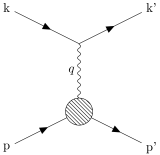
The Generalized Parton Distributions

Understanding the inner structure of nucleons is challenging
→ Perturbative formalism not applicable to QCD at low energies

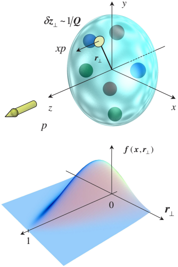
Form Factors
Position in the transverse plane



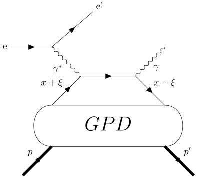
Accessed via elastic scattering



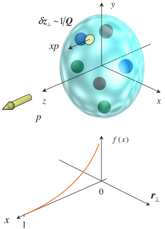
Generalized Parton Distributions



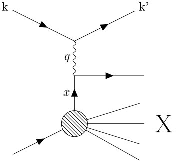
...and their **correlations**
Accessed in DVCS



Parton Distribution Functions
Momentum in the longitudinal direction



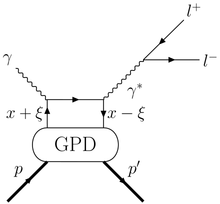
Accessed via **D**eep **I**nelastic **S**cattering



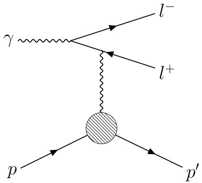
Figures in Belitsky, Radyushkin, *Physics Reports*, 2005

Timelike Compton Scattering

DVCS: $ep \to e'p'\gamma$ **TCS**: $\gamma p \to e^+e^-p'$

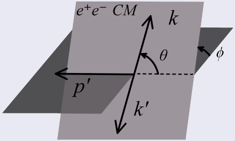


TCS (factorization regime)



Bethe-Heitler

Kinematic definitions



$$t = (p - p')^2$$
$$Q'^2 = (k + k')^2$$

- BH cross section only depends on electromagnetic FFs $\sigma_{BH} >> \sigma_{TCS}$ at JLab energies
- Unpolarized interference cross section Berger, Diehl, Pire, Eur.Phys.J.C23:675-689,2002

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L} \left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)} \mathrm{Re}\tilde{M}^{--} + \ldots \right]$$

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

- Polarized interference cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = \frac{d^4\sigma_{INT}|_{\mathrm{unpol.}}}{dQ'^2 dt d\Omega} - \nu \cdot A \frac{L_0}{L}\left[\sin(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\mathrm{Im}\tilde{M}^{--} + \ldots\right]$$

Both $\mathrm{Im}\mathcal{H}$ and $\mathrm{Re}\mathcal{H}$ can be accessed by TCS

Motivations to measure TCS

Test of universality of GPDs

- TCS is parametrized by GPDs
- **Comparison between DVCS and TCS** results allows to test the **universality** of GPDs
- TCS does not involve Distribution Amplitudes unlike Deeply Virtual Meson Production
  $\rightarrow$ direct comparison between DVCS and TCS

Real part of CFFs and nucleon D-term

- As for DVCS, TCS unpolarized cross section is sensitive to $\mathrm{Re}\mathcal{H}$, which is still not well constrained by existing data.
- The CFFs dispersion relation at leading order and leading twist :

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(\xi,t) + \Delta(t)$$

- $\Delta(t)$ can be related to the Energy-Momentum FF $D^Q(t)$, itself related to **mechanical properties** of the nucleon.

$$\Delta(t) \propto D^Q(t) \propto \int d^3\mathbf{r}\ p(r)\frac{j_0(r\sqrt{-t})}{t}$$

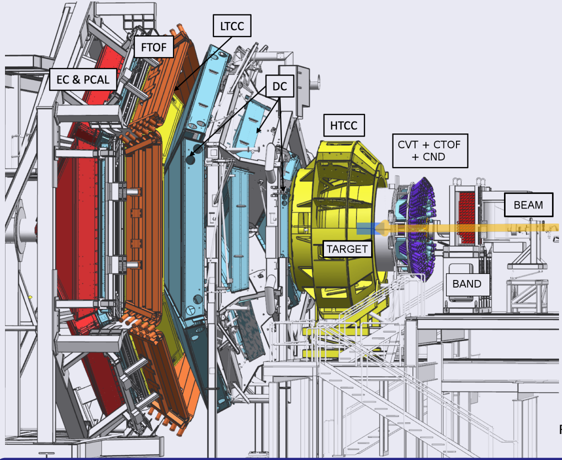
Review in Polyakov, Schweitzer, International Journal of Modern Physics A, 2018

M.V. Polyakov. Generalized parton distributions and strong forces inside nucleons and nuclei. PLB, 2003

V. D. Burkert, L. Elouadrhiri, and F. X. Girod. Nature 2018

Experimental setup

CLAS12



- **Forward Detector (6 sectors)**
  - Torus magnet
  - Drift Chambers
  - Forward Time-of-Flight
  - Calorimeters (EC and PCAL)
  - Cherenkov counters
- **Central Detector**
  - Solenoid magnet
  - Central Vertex Tracker (Silicon and micromegas)
  - Central Time-of-Flight
  - Central Neutron Detector

Figure in Burkert et al., *NIM A*, 2020

Data set used in this work

- **Fall 2018** run period
- ***LH_2*** target / **10.6 GeV** polarized e^- beam
- Inbending torus magnetic field
- Accumulated charge: $\sim$ 150 mC (200 fb^{-1})

Analysis strategy

CLAS12 PID + e^+ NN ID

$$e\ p \to (e')\gamma p \to (X)\ e^+ e^- p'$$

Exclusivity cuts

$$p_X = p_{beam} + p_{target} - p_{e^+} - p_{e^-} - p_{p'}$$

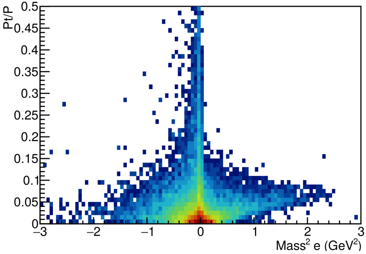
$$|M_X^2| < 0.4\ \mathrm{GeV}^2$$

Quasi-real photoproduction

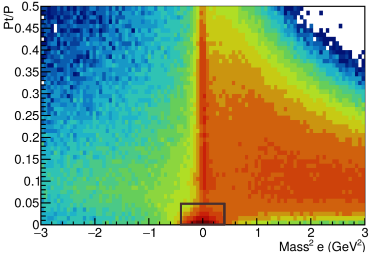
$$\frac{Pt_X}{P_X} < 0.05$$
$$\to Q^2 < 0.1\ \mathrm{GeV}^2$$

after momentum corrections and fiducial cuts

Simulation



Data



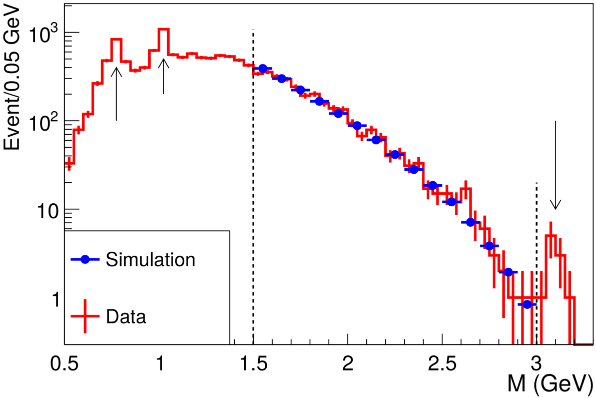
Data/Simulation comparison

Phase space of interest

- $0.15\ \mathrm{GeV}^2 < -t < 0.8\ \mathrm{GeV}^2$
- $4\ \mathrm{GeV} < E_\gamma < 10.6\ \mathrm{GeV}$
- $1.5\ \mathrm{GeV} < M_{e^+e^-} < 3\ \mathrm{GeV}$

Observations

- Vector mesons peaks are visible in data: ω (770 MeV), ρ (782 MeV), Φ (1020 MeV) and J/ψ (3096 MeV)
- Data/simulation are matching at 15 % level, up to normalization factor. No evident high mass vector meson production (ρ (1450 MeV, 1700 MeV)



Observable 1: Photon polarization asymmetry ($A_{\odot U}$)

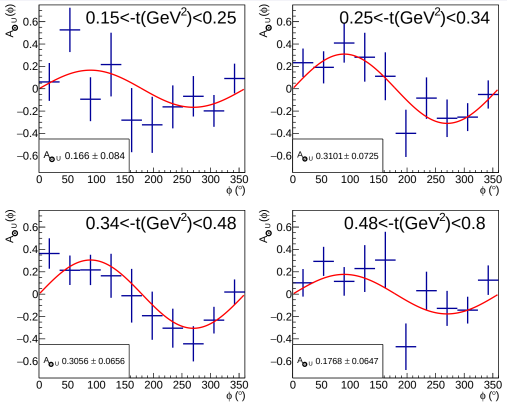
Definition

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\sin\phi\,\frac{(1+\cos^2\theta)}{\sin(\theta)}\,\mathrm{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

Experimental measurement

- $A_{\odot U}(-t, E\gamma, M; \phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$ where $N^{\pm} = \sum \frac{1}{Acc} P_{trans.}$
- $P_{trans.}$ is the **transferred polarization** from the **electron to the photon**, fully calculable in QED

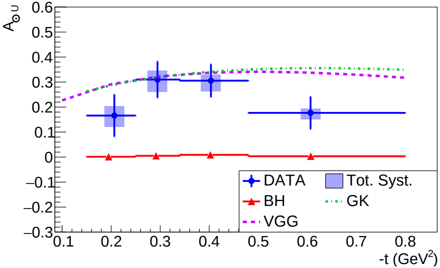
  Olsen, Maximon, Phys. Rev.114 (1959)
- P_b is the **polarization of the CEBAF** electron beam (85%)
- The ϕ-distribution is fitted with a sine function



$A_{\odot U}$ results

- First time measurement
- A **sizeable asymmetry** is measured (above the expected vanishing $A_{\odot U}$ of BH)
  $\rightarrow$ **signature of TCS**
- Theoretical predictions were provided by M.Vanderhaeghen, JGU Mainz (VGG model)
  and P.Sznajder, NCBJ Warsaw (GK model)
- Size of the asymmetry is **well reproduced** by VGG and GK models
  $\rightarrow$ **model dependent hints for universality of GPDs**

$< M >= 1.8$ GeV; $< E_\gamma >= 7.29$ GeV; $< \theta >= 92°$



Observable 2: Forward-Backward asymmetry

- Use the different parity of the TCS and BH amplitudes under the inversion of the leptons directions
  $k \leftrightarrow k' \Longleftrightarrow (\theta, \phi) \leftrightarrow (180^\circ - \theta, 180^\circ + \phi)$

BH cross section

$$\frac{d\sigma_{BH}}{dQ^2\, dt\, d\Omega} \propto \frac{1+\cos^2\theta}{\sin^2\theta} \xrightarrow{FB} \frac{d\sigma_{BH}}{dQ^2\, dt\, d\Omega}$$

Int. cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L}\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)} \xrightarrow{FB} -\frac{d\sigma_{INT}}{dQ^2\, dt\, d\Omega}$$

A_{FB} formula

$$A_{FB}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\cos\phi_0\frac{(1+\cos^2\theta_0)}{\sin(\theta_0)}\mathrm{Re}\tilde{M}^{--}}{d\sigma_{BH}(\theta_0, \phi_0) + d\sigma_{BH}(180^\circ - \theta_0, 180^\circ + \phi_0)}$$

Integration over forward angular bin: $\theta \in [50^\circ, 80^\circ] / \phi \in [-40^\circ, 40^\circ]$

- Concept initially explored for J/Ψ production
  Gryniuk, Vanderhaeghen, *Phys. Rev. D*, 2016.
- Exploratory studies for TCS performed alongside this work, during my thesis.
- Predictions for TCS have been published very recently + **LO radiative correction negligible**
  Heller, Keil, Vanderhaeghen, *Phys. Rev. D*, 2021.

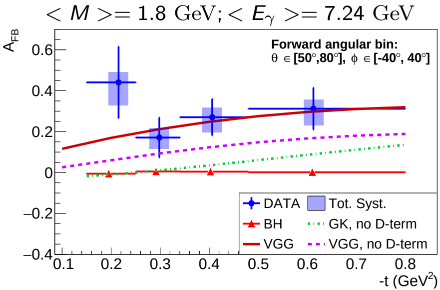
A_{FB} results

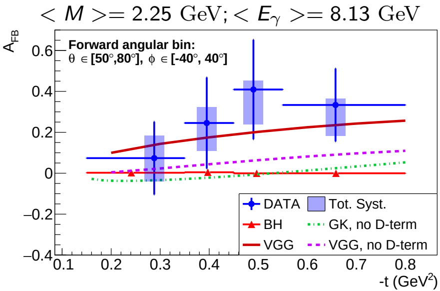
- A_{FB} measured in two mass regions: $M \in [1.5\text{ GeV}, 3\text{ GeV}]$ and $M \in [2\text{ GeV}, 3\text{ GeV}]$
- The measured A_{FB} is non-zero: **evidence for signal** beyond pure BH contribution
- Three model predictions
  1. VGG without D-term
  2. VGG with D-term

     D-term in Pasquini et al., *Physics Letters B*, 2014
  3. GK without D-term
- Measured asymmetry is better reproduced by the VGG model **including the D-term** in both mass bins

  → importance of the D-term in the parametrization of GPDs

  → TCS is a prime reaction to constrain the D-term





Conclusions

Takeaways

- TCS observables were measured for the **first time**
- Sizeable $A_{\odot U}$ (sensitive to Im$\mathcal{H}$) and A_{FB} (sensitive to Re$\mathcal{H}$) are **clear signatures of TCS**
- The results obtained allow to draw physical conclusions:
  - the $A_{\odot U}$ is well reproduced by models that reproduce existing DVCS data
    $\rightarrow$ hints for **universality of GPDs**
  - the Forward/Backward asymmetry appears to be better reproduced by model with a D-term
    $\rightarrow$ promising path to the measurement of the D-term
    $\rightarrow$ access to the **mechanical properties of the proton**

Opportunities ahead to measure TCS:

- EIC, Ultra-peripheral collisions (LHC) $\rightarrow$ test QCD NLO corrections
  Mueller,Pire,Szymanowski,Wagner, PRD, 2012
- CLAS12 high lumi/high energy upgrades $\rightarrow$ improve constraints on D-term

E-print: arXiv:2108.11746, submitted on 26th August 2021.
Article: submitted to PRL on the 31st August 2021

Back Up

Acceptance

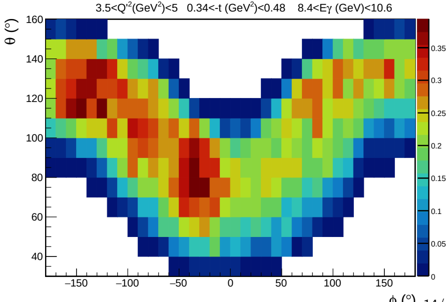
Acceptance calculation using BH-weighted events

$$Acc_{\mathcal{B}} = \frac{N_{\mathcal{B}}^{REC}}{N_{\mathcal{B}}^{GEN}} \qquad N_{\mathcal{B}}^{REC} = \sum_{REC \in \mathcal{B}} Eff_{corr} \; w \qquad N_{\mathcal{B}}^{GEN} = \sum_{GEN \in \mathcal{B}} w$$

Multidimensional binning of the acceptance

4 bins in $-t$, 3 bins in E_γ and Q'^2, 10° x 10° bins in the ϕ/θ plane. Bins with $\frac{\Delta Acc}{Acc} > 0.5$ and $Acc < 0.05$ are discarded (ΔAcc is statistical error).

Large region with no acceptance ($\phi \sim 0^\circ/\theta \sim 180^\circ$ and $\phi \sim 180^\circ/\theta \sim 0^\circ$)



Efficiency corrections

- **Data-driven correction** for the proton detection efficiency derived using $ep \rightarrow e'\pi^+\pi^-(p')$ reaction
- Efficiency correction from **background merging** using random trigger events

Positron identification

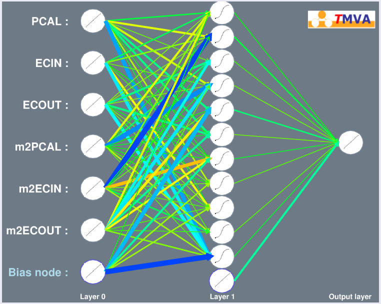
Above 4.5 GeV, the HTCC cannot distinguish positron from pions

Signal: e^+ identified as e^+ Background: π^+ identified as e^+

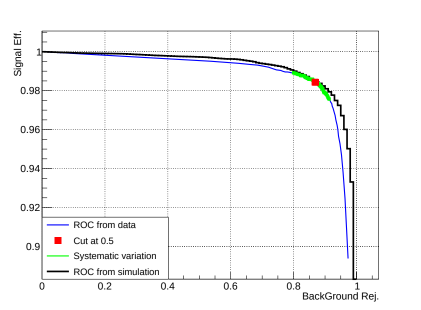
Strategy and discriminating variables: take advantage of the ECAL segmentation

Positron: electromagnetic shower Pion: Minimum Ionizing Particle (MIP)

$$SF_{\mathrm{EC\ Layer}} = \frac{E_{dep}(\mathrm{EC\ Layer})}{P} \qquad M_2 = \frac{1}{3}\sum_{U,V,W}\frac{\sum_{\mathrm{strip}}(x-D)^2 \cdot \ln(E)}{\sum_{\mathrm{strip}}\ln(E)} \rightarrow \textbf{6 variables}$$



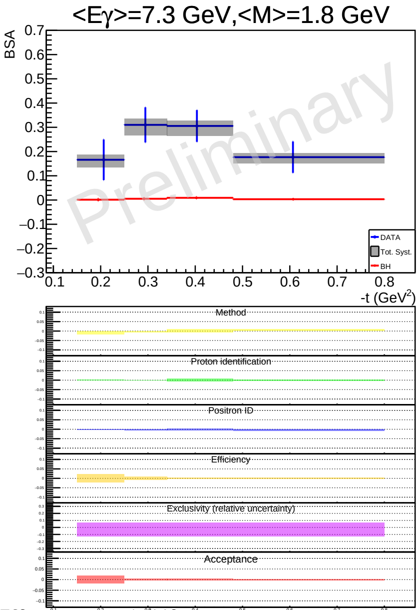
Output: Signal $\rightarrow$ 1 Background $\rightarrow$ 0



- Signal in data $\Rightarrow$ Outbending electrons
- Background in data $\Rightarrow$ $ep \rightarrow e\pi^+_{PID=e^+}(n)$

B/S from 50% to 5%

Systematics



Method

- Calculated from generated BH events, and full-chain simulated events.

Proton

- Apply χ^2 cut for the proton identification

Positron Identification

- Vary the positron ID cut (0.5 ± 0.3; max. significance region)

Efficiency

- Calculate observable with/without data-driven proton efficiency

Exclusivity cuts

- Vary the values of the exclusivity cuts: $|\ Pt/P\ | < 0.05 \pm 0.01$, $|\ M_X^2\ | < 0.4 \pm 0.1\ \mathrm{GeV}^2$

Fully integrated relative uncertainty

Acceptance

- Calculate observable with acceptance produced using BH-weighted events or unity weights

- Neighboring bins uncertainties are averaged
- Then added in quadrature