# First-time observation of Timelike Compton Scattering, with the CLAS12 detector

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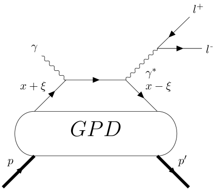
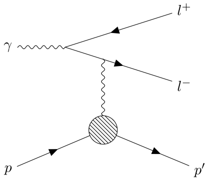
# Timelike Compton Scattering

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




**TCS** (factorization regime)




**Bethe-Heitler**

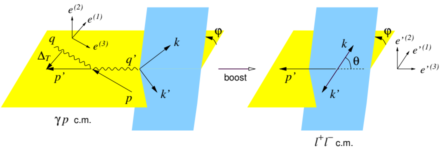



Figure in Berger et al., *EPJ C*, 2002

- BH cross section only depends on electromagnetic FFs $\sigma_{BH} >> \sigma_{TCS}$ at JLab energies
- Unpolarized interference cross section

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

- Polarized interference cross section

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

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

Both $\mathrm{Im}\mathcal{H}$ and $\mathrm{Re}\mathcal{H}$ can be accessed in 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 :

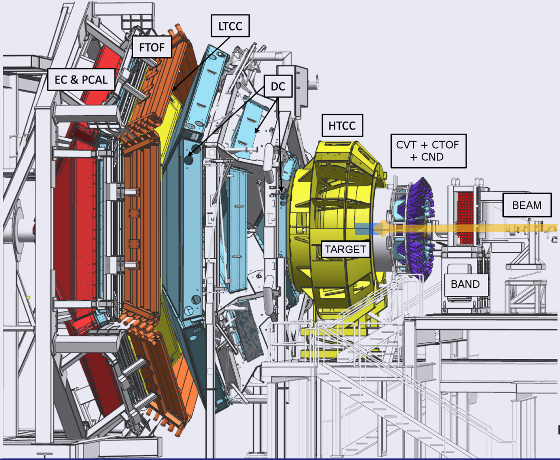
$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(\xi,t) + D(t)$$

- $D(t)$ can be related to the **mechanical properties** of the nucleon.

Review in Polyakov, Schweitzer, *International Journal of Modern Physics A*, 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** beam / RG-A
- Inbending torus magnetic field
- Accumulated charge: $\sim$ 150 mC ($\sim$ 200 fb$^{-1}$)

# Analysis strategy

From generic CLAS12 PID

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

## Exclusivity cuts

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

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

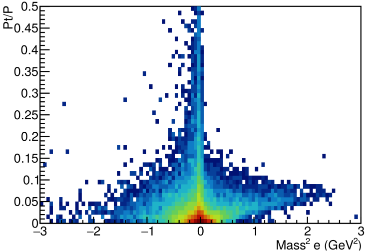
**Quasi-real photoproduction**

$\frac{Pt_X}{P_X} < 0.05$

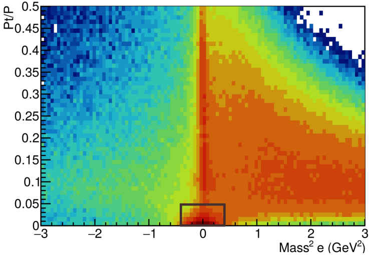
$\to Q^2 < 0.1\ \mathrm{GeV}^2$

after momentum corrections and fiducial cuts

Simulation




Data



# Positron identification

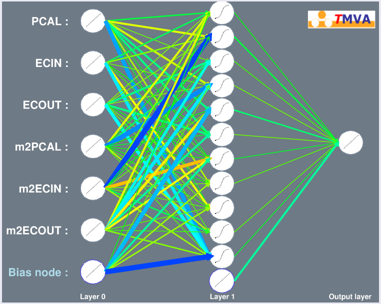
## Above 4.5 GeV, the HTCC cannot distinguish positron from pions

Signal: $e^+$ identified as $e^+$    Background: $\pi^+$ identified as $e^+$

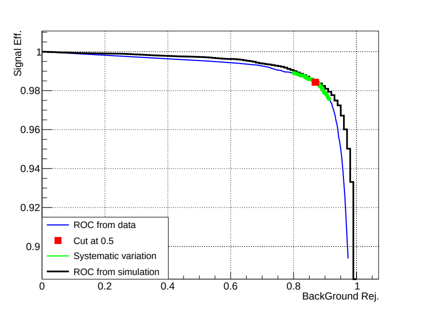
## Strategy and discriminating variables: take advantage of the ECAL segmentation

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

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




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

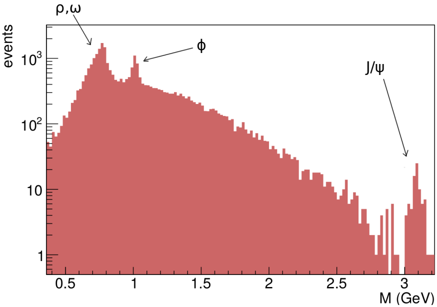



- Signal in data$\Rightarrow$ Outbending electrons
- Background in data$\Rightarrow$ $ep \rightarrow e\pi^+_{PID=e^+}(n)$

**B/S from 50% to 5%**

# Data/Simulation comparison

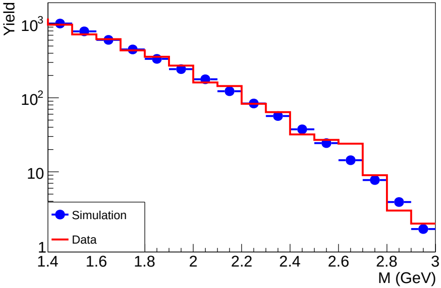
- Vector mesons peaks are visible in data: $\omega$ (770 MeV), $\rho$ (782 MeV), $\Phi$ (1020 MeV) and $J/\psi$ (3096 MeV)




- Data/BH comparison in the high mass region, no evident high mass vector meson production ($\rho$ (1450 MeV, 1700 MeV))

## Phase space of interest

- $1.5 \text{ GeV} < M_{e^+e^-} < 3 \text{ GeV}$
- $0.15 \text{ GeV}^2 < -t < 0.8 \text{ GeV}^2$
  $-t/M^2_{e^+e^-} < 1$ $\rightarrow$ Factorization regime
- $4 \text{ GeV} < E_\gamma < 10.6 \text{ GeV}.$




Data/simulation are matching at 15 % level, up to normalization factor

# Acceptance

## Acceptance calculation using BH-weighted events

$$Acc_{\mathcal{B}} = \frac{N^{REC}_{\mathcal{B}}}{N^{GEN}_{\mathcal{B}}} \qquad N^{REC}_{\mathcal{B}} = \sum_{REC\in\mathcal{B}} \boxed{Eff_{corr}}\ w \qquad N^{GEN}_{\mathcal{B}} = \sum_{GEN\in\mathcal{B}} w$$

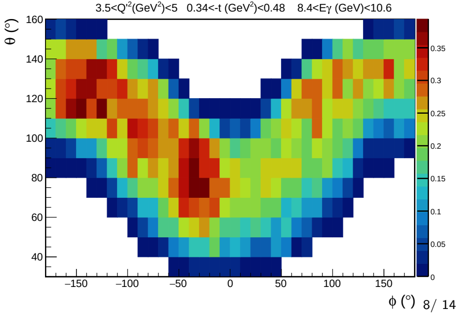
**Multidimensional binning of the acceptance**

4 bins in $-t$, 3 bins in $E_\gamma$ and $Q'^2$, $10^\circ$ x $10^\circ$ bins in the $\phi/\theta$ plane. Bins with $\frac{\Delta Acc}{Acc} > 0.5$ and $Acc < 0.05$ are discarded ($\Delta Acc$ is statistical error).

## Efficiency corrections

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

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



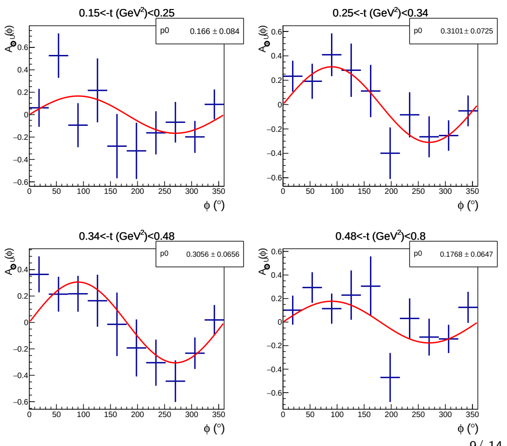
# Observable 1: Photon polarization asymmetry ($A_{\odot U}$)

## Access to the imaginary part of CFFs

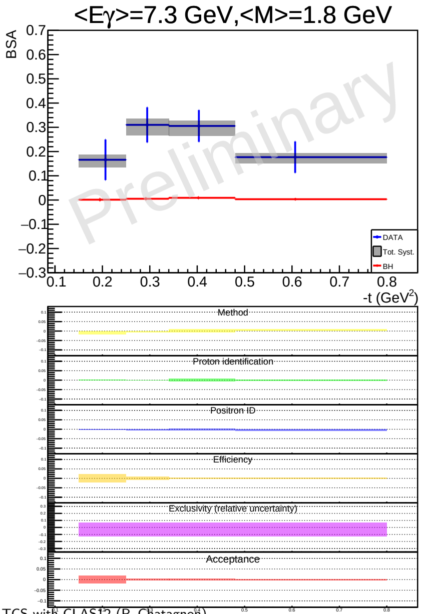
$$A_{\odot U} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} \sin\phi \frac{(1+\cos^2\theta)}{\sin(\theta)} \operatorname{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

## Experimental measurement

- $A_{\odot U}(-t, E\gamma, M; \phi) = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$ where $N^{\pm} = \sum \frac{1}{Acc} Pol_{transf.}$
- $Pol_{transf.}$ is the **transferred polarization** from the **electron to the photon**
- $P_B$ is the **polarization of the CEBAF** electron beam (85%)
- The $\phi$-distribution is fitted with a sine function



# Systematics




## Method

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

## Proton

- Apply $\chi^2$ cut for the proton identification

## Positron Identification

- Vary the positron ID cut ($0.5 \pm 0.3$; max. significance region)

## Efficiency

- Calculate observable with/without data-driven proton efficiency

## Exclusivity cuts

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

*Fully integrated relative uncertainty*

## Acceptance

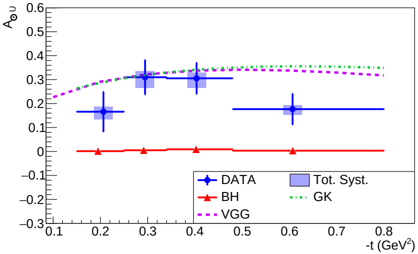
- Calculate observable with acceptance produced using BH-weighted events or unity weights

- Neighboring bins uncertainties are averaged
- Then added in quadrature

# $A_{\odot U}$ 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 (using the VGG model) and P.Sznajder (using the GK model)
- Size of the asymmetry is **well reproduced** by VGG and GK models
  $\rightarrow$ **model dependent hints for universality of GPDs**

$$< M >= 1.8 \text{ GeV}; < E_\gamma >= 7.29 \text{ GeV}; < \theta >= 92^\circ$$



# Observable 2: Forward-Backward asymmetry

- Concept explored for $J/\Psi$ production (Gryniuk, Vanderhaeghen, *Phys. Rev. D*, 2016).
- Exploratory studies for TCS performed during my thesis.
- Very first predictions for TCS have been published very recently (Heller, Keil, Vanderhaeghen, *Phys. Rev. D*, 2021).
- Use the different parity of the TCS and BH amplitudes under the inversion of the leptons directions $k \leftrightarrow k' \iff (\theta, \phi) \leftrightarrow (180^\circ - \theta, 180^\circ + \phi)$

**BH cross section**

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

**Int. cross section**

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

### $A_{FB}$ formula

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

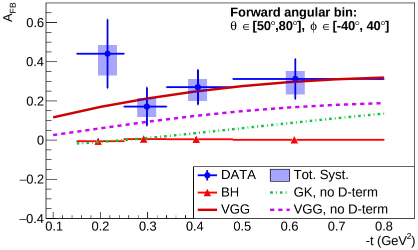
- Access to the real part of the CFFs with no integration over angles
- Removes large dependencies on angular acceptance → direct comparison with models
- But smaller phase space → lower statistics

# $A_{FB}$ selected results

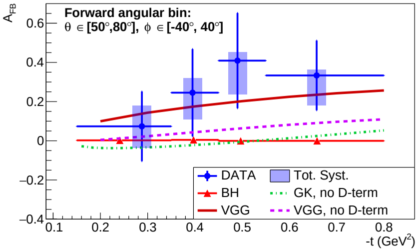
- $A_{FB}$ measured in two mass regions: $M \in [1.5\ \mathrm{GeV}, 3\ \mathrm{GeV}]$ and $M \in [2\ \mathrm{GeV}, 3\ \mathrm{GeV}]$
- The measured $A_{FB}$ is non-zero: **evidence for signal** beyond pure BH contribution
- Three model predictions
    1. VGG without D-term
    2. VGG with D-term

       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

$< M >= 1.8\ \mathrm{GeV}; < E_\gamma >= 7.24\ \mathrm{GeV}$

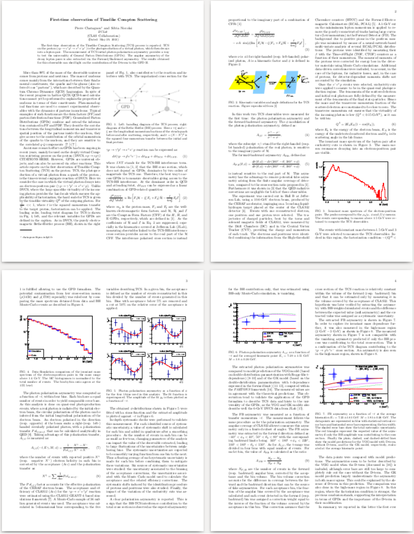



$< M >= 2.25\ \mathrm{GeV}; < E_\gamma >= 8.13\ \mathrm{GeV}$



# Conclusions

- 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 **mechanical properties of the proton**
- The analysis was reviewed by the CLAS collaboration and the article is currently under ad-hoc review (intended to submit to PRL).


First-time observation of Timelike Compton Scattering

Opportunities ahead to measure TCS: EIC, Ultra-peripheral collisions (LHC), CLAS12 high lumi. upgrade