Timelike Compton Scattering with CLAS12 at Jefferson Lab

CLAS Collaboration meeting - 2nd June 2021

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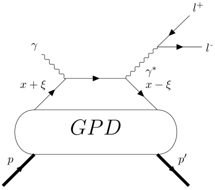
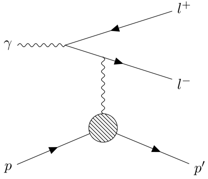
Timelike Compton Scattering

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



TCS



Bethe-Heitler

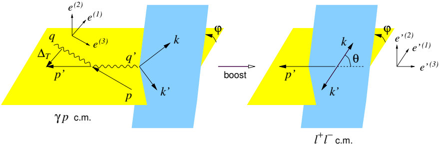


Figure in Berger et al., *EPJ C*, 2002

- BH cross section only depends on electromagnetic FFs
- Unpolarized interference cross section

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

- Polarized interference cross section

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

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

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 :

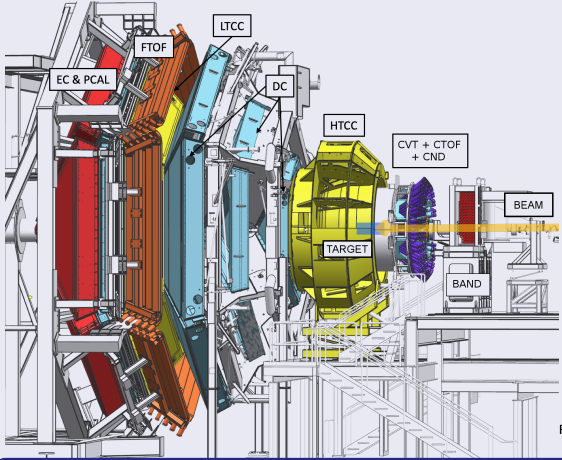
$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(\xi,t) + D(t)$$

- $D(t)$ 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

Final state selection from PID

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

Exclusivity cuts

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

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

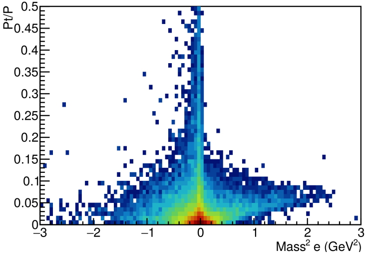
Quasi-real photoproduction

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

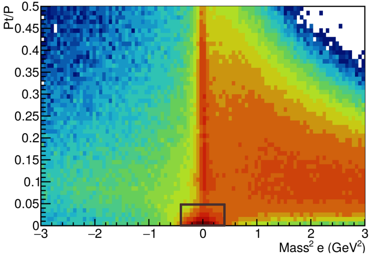
$\rightarrow Q^2 < 0.1\ \mathrm{GeV}^2$

after momentum corrections and fiducial cuts ▸ Here

Simulation



Data



Positron identification

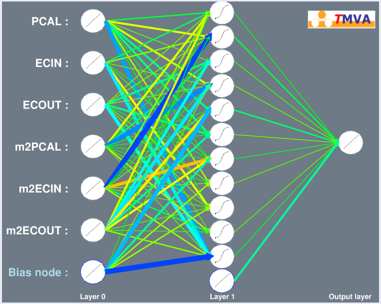
Definitions

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

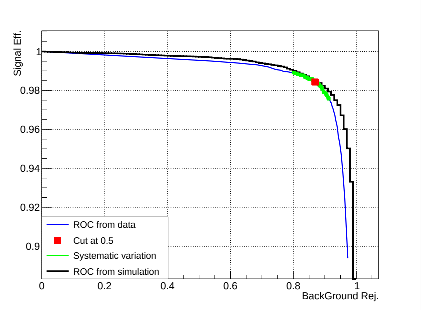
Strategy and discriminating variables

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

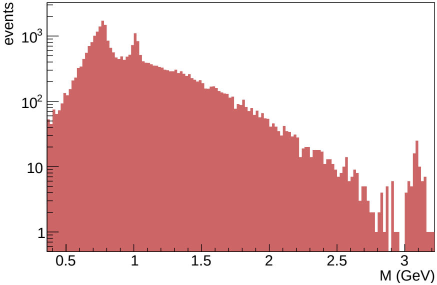


- Signal in data $\Rightarrow$ Outbending electrons
- Background in data $\Rightarrow$ $ep \rightarrow e\pi^+_{PID=e^+}(n)$

B/S from 50% to 5%

Data/Simulation comparison

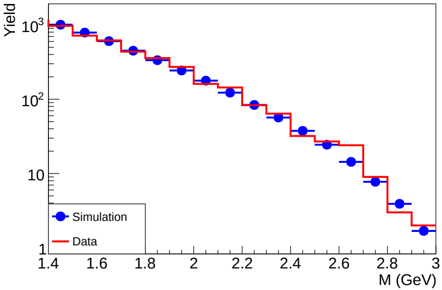
- Vector mesons peaks are visible in data: ω (770 MeV), ρ (782 MeV), Φ (1020 MeV) and J/ψ (3096 MeV)



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

Phase space of interest

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



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

Acceptance

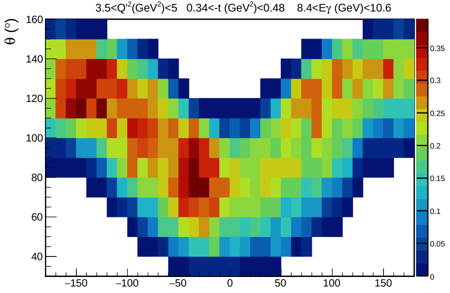
Acceptance calculation using BH-weighted events

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

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

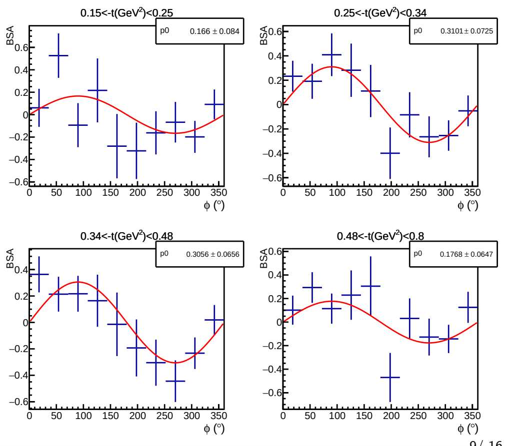
Observable 1: Photon polarization asymmetry (BSA)

Access to the imaginary part of CFFs

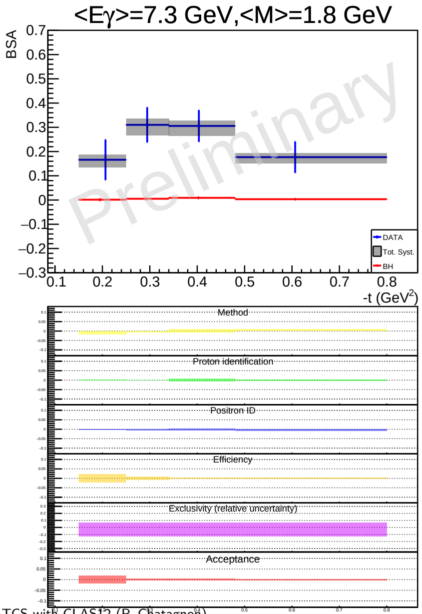
$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\sin\phi\frac{(1+\cos^2\theta)}{\sin(\theta)}\mathrm{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

Experimental measurement

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



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: $\mid Pt/P \mid < 0.05 \pm 0.01$, $\mid M_X^2 \mid < 0.4 \pm 0.1 \text{ GeV}^2$

Fully integrated relative uncertainty

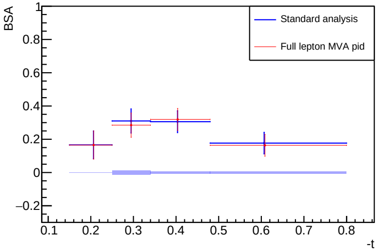
Acceptance

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

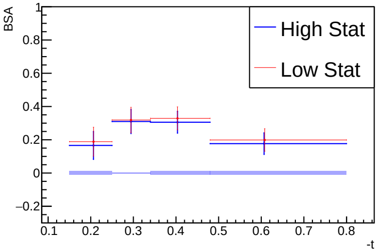
- Neighboring bins uncertainties are averaged
- Then added in quadrature

Additional systematics checks

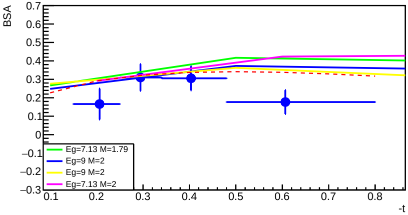
- Stability of the MVA at low momenta for all leptons



- MC statistic: acceptance calculated with 16M/36M generated events



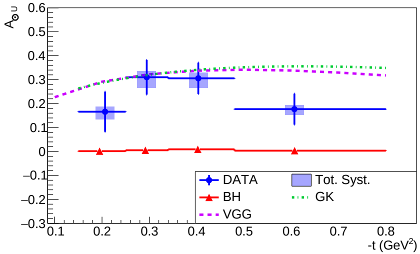
- Study the stability of the model prediction within the integrated kinematic range



BSA selected results

- First time measurement
- A **sizeable asymmetry** is measured (above the expected vanishing BSA 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**

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



Observable 2: Forward-Backward asymmetry

- Concept explored for J/Ψ production (Gryniuk, Vanderhaeghen, *Phys. Rev. D*, 2016).
- Exploratory studies for TCS performed in 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

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

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

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

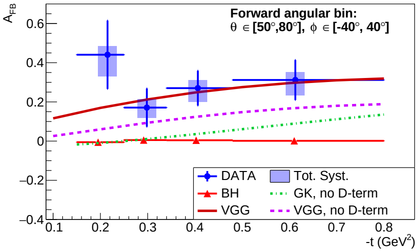
- Access to the real part of the CFFs with no integration over angles
- Removes large dependencies on angular acceptance → direct comparison with models
- But smaller phase space → lower statistics

A_{FB} selected results

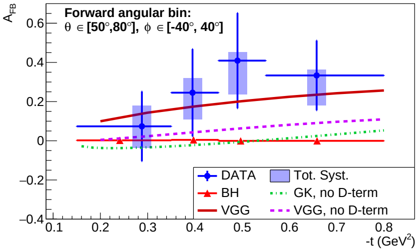
- A_{FB} measured in two mass regions: $M \in [1.5\ \text{GeV}, 3\ \text{GeV}]$ and $M \in [2\ \text{GeV}, 3\ \text{GeV}]$
- The measured A_{FB} is non-zero: **evidence for signal** beyond pure BH contribution
- Three model predictions
  1. VGG without D-term
  2. VGG with D-term

     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

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



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



Documentation and code

Analysis review

Review #1461061: "Timelike Compton scattering with CLAS12"
$\rightarrow$ ended Monday 31st of May
We are ready for ad-hoc review ! Request sent yesterday

Analysis note

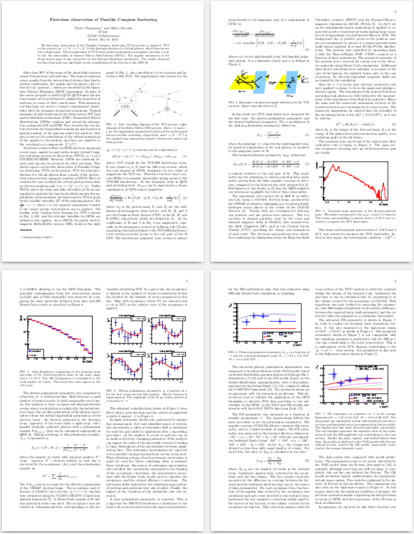
Final version of the analysis note available ▸ here

Analysis scripts

(Personal) Github repository containing all the scripts used for the analysis is being set up ▸ here

Conclusions

- TCS observables were measured for the **first time**
- Sizeable BSA (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 BSA 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 is reviewed (final approval this monday) and fully documented**
- **The article is (90%) ready for ad-hoc review**


First-time observation of Timelike Compton Scattering