Timelike Compton Scattering from E12-12-001 (RGA)

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

clas

NSF U.S. National Science Foundation

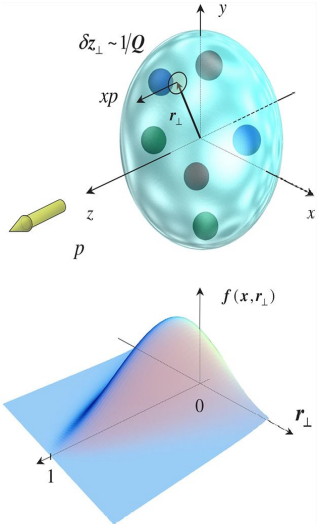
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Outline

- **Motivation: GPDs and Timelike Compton Scattering**
- **TCS observables:**
  - -Photon-polarization asymmetry (BSA)
  - -Forward-Backward Asymmetry (AFB)
  - -Weighted cross-section ratio (R′)
- **Analysis: Data set and particle identification**
- **Corrections and event selection**
- **Acceptance**
- **Results**
- **Summary and outlook**

Motivation

- Generalized Parton Distributions (GPDs) correlate the longitudinal momentum fraction and transverse spatial distribution of partons inside the nucleon.
- GPDs provide access to the 3D structure of the nucleon, including its spin and mechanical properties (pressure and shear forces through the D-term).
- Timelike Compton Scattering (TCS) is the timelike counterpart of DVCS and provides a complementary probe of GPDs.
- Beam-spin and forward-backward asymmetries provide complementary sensitivity to the imaginary and real parts of the CFFs, respectively.
- The first CLAS12 measurement with low statistics observed non-zero asymmetries. The full RG-A dataset offers an opportunity for more precise measurements and improved constraints on GPDs.

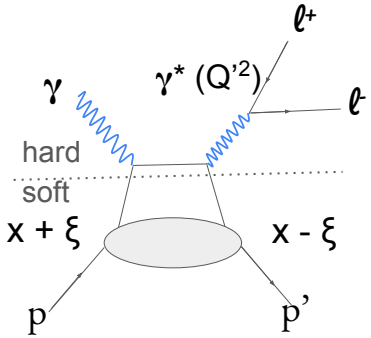


GPDs: 3-D imaging of the nucleon
Credit: A. Belitsky and A Radyushkin, Physics Report, 416 (2015)

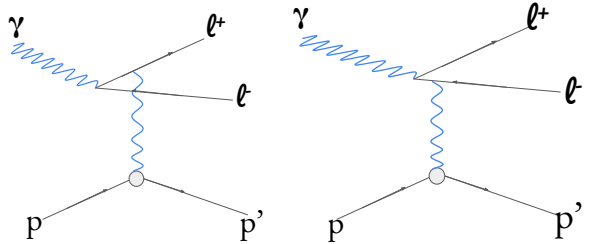
P. Chatagnon et al. (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)
M. Diehl, Phys. Rep. 388, 41–277 (2003)

Timelike Compton Scattering (TCS)

$\gamma p \rightarrow \gamma^* p' \rightarrow e^+ e^- p'$



TCS



Bethe-Heitler

TCS process interferes with Bethe-Heitler at the amplitude level

$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} = \sigma_{TCS} + \sigma_{BH} + \sigma_{INT}$$

- $Q^2 = -q^2 = 0$ virtuality of initial (real) photon
- $Q'^2 = q'^2 = (\ell^+ + \ell^-)^2$ invariant mass squared of lepton pair
- $t = (p' - p)^2$ squared momentum transfer to proton
- x = average longitudinal momentum fraction of struck quark
- ξ = half the longitudinal momentum fraction transferred between initial and final quark

TCS observables

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A \frac{1+\cos^2\theta}{\sin\theta}\left[\cos\phi\,\mathrm{Re}\tilde{M}^{--} - \nu\cdot\sin\phi\,\mathrm{Im}\tilde{M}^{--}\right], \text{ where } \tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

$$\frac{d^4\sigma_{BH}}{dQ'^2 dt d\Omega} \approx -\frac{\alpha_{em}^3}{2\pi s^2}\frac{1}{-t}\frac{1+\cos^2\theta}{\sin^2\theta}\left[\left(F_1^2 - \frac{t}{4M^2}F_2^2\right)\frac{2}{\tau^2}\frac{\Delta_T^2}{-t} + (F_1+F_2)^2\right]$$

BH cross section diverges at θ ≈ 0◦ and 180◦

Weighted Cross Section Ratio:

$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi \cos\phi \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}}, \quad \frac{dS}{dQ'^2 dt d\phi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L}{L_0}\frac{d\sigma}{dQ'^2 dt d\phi d\theta}$$

Photon-polarisation (beam-spin) asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

access to Im *H*

Forward - backward asymmetry:

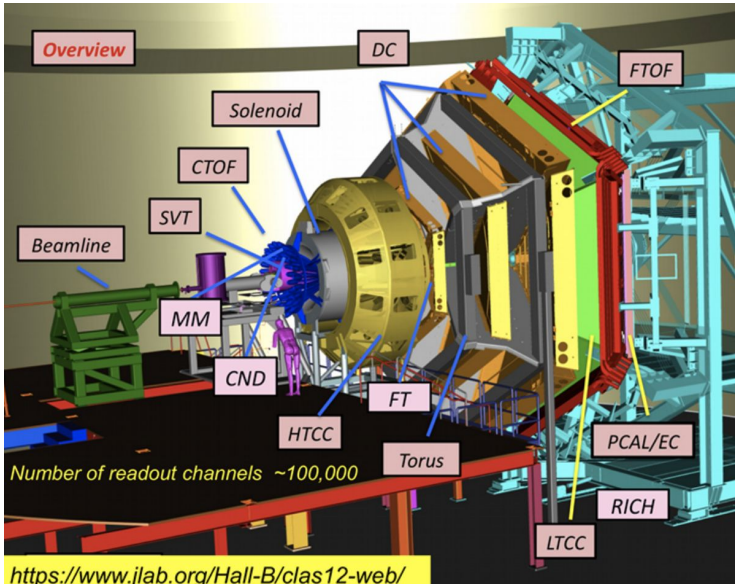
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

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Analysis details

Data Set

Run period	RG-A Fall 2018, inbending
Beam	10.6 GeV, polarized e^-
Target	Liquid hydrogen
Data	TCS/J/ψ (train), pass1/pass2
Runs	174 (5032–5419)/171 (5032–5419)



TCS: $ep \rightarrow (e')\gamma p' \rightarrow (e')\gamma^* p' \rightarrow (e')e^+e^-p'$

Goal: Identify TCS events by selecting the exclusive final-state particles:

1. One electron (e^-) 2. One positron (e^+) 3. One proton (p')

Leptons (e+/e-) Identification

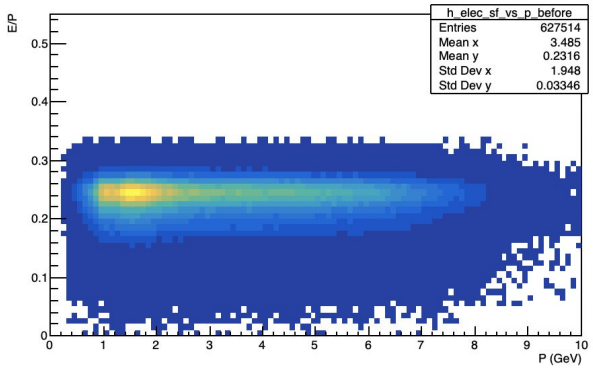
Electrons and positrons are identified with the standard CLAS12 Event Builder (EB).

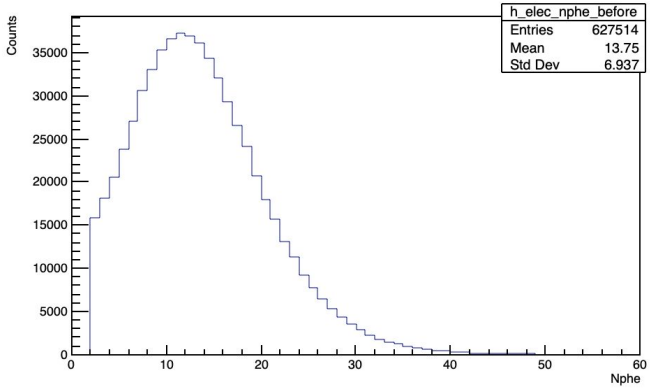
The EB assigns PID = 11 (e^-) or −11 (e^+) to particles with condition:

- ❑ A track in the DC matched to an ECAL shower.
- ❑ Number of HTCC photoelectrons, $N_{phe} > 2$
- ❑ Minimum energy deposit in the pre-shower calorimeter: $E_{PCAL} > 60$ MeV
- ❑ Total sampling fraction within 5σ of the parametrized Sampling Fraction (SF)

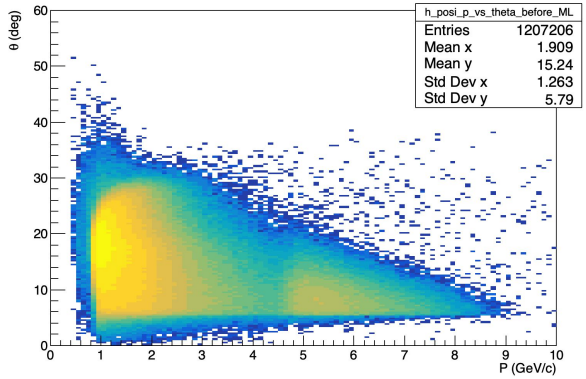
where **$SF = E_{dep} / p$** E_{dep}: total energy deposited in the Electromagnetic Calorimeter

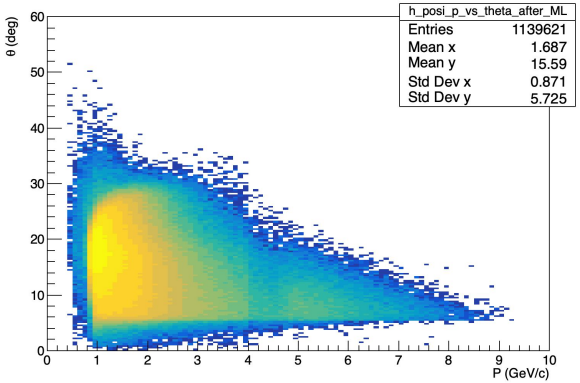
p: momentum of the particle reconstructed by the Drift Chambers (DC)





π^+ Contamination





- e+ sample is contaminated with π+ in the Cherenkov counter (HTCC) at momenta above 4.9 GeV/c
- Multivariate analysis (ROOT TMVA, 6D BDT): for positrons with p > 4.5 GeV, the BDT removes about 90% of misidentified pions

  Mariana's note
- e^+ and π^+ are separated by their shower shape in the calorimeter (PCAL, ECIN, ECOUT):

  SF: fraction of the track momentum deposited in each layer

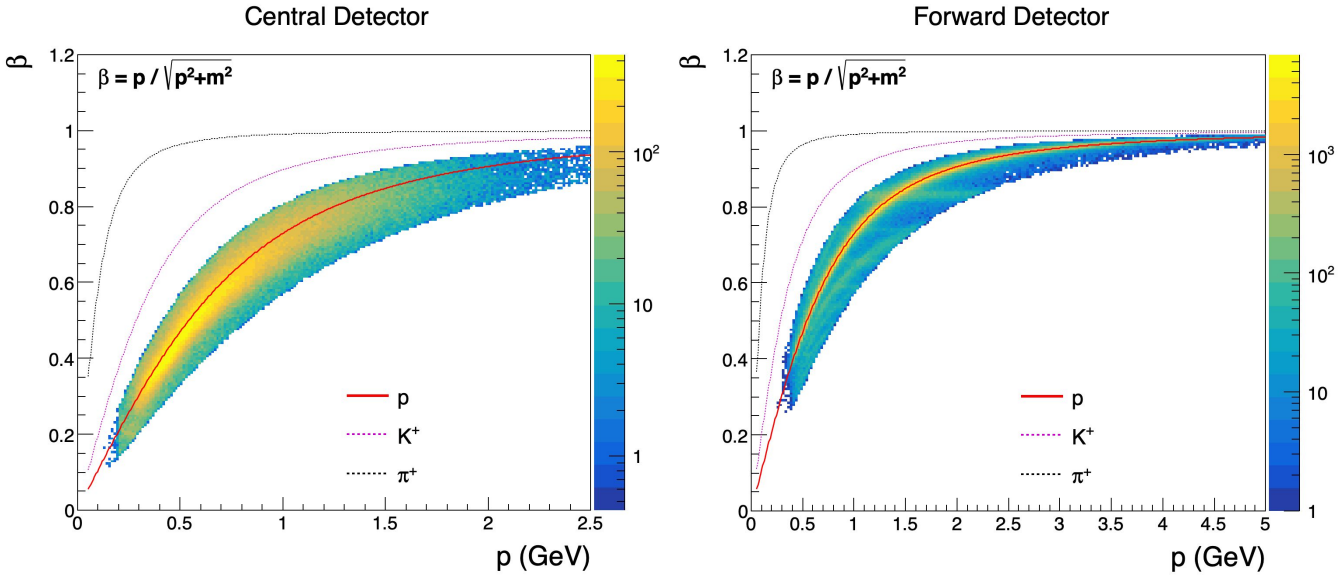
  M_2: transverse shower width squared in each layer

$$M_2 = \frac{\sum_{strip}(x-D)^2 \ln E}{\sum_{strip} \ln E}, \qquad D = \frac{\sum_{strip} x \ln E}{\sum_{strip} \ln E}$$

Where x is the strip position, E is the energy deposited in that strip, and D is the shower center. M_2 is averaged over the U, V and W views in each layer.

Proton Identification

Protons are also identified with the standard **CLAS12 Event Builder (EB)**.



$$\beta_{meas} = \frac{L}{c \cdot (t_{stop} - t_{start})}$$

$$\beta_{calc} = \frac{p}{E} = \frac{p}{\sqrt{p^2 + M_p^2}}$$

L: Path length of the track from vertex to scintillator

t_{stop}: Time recorded by the FTOF or CTOF

p: Magnitude of the momentum measured by the magnetic field curvature

M_p: Rest mass of the proton (0.938 GeV/c^2)

t_{start}: The Event Start Time (from the trigger electron)

Corrections

Radiative correction (leptons)

- Leptons can radiate photons, in the interaction itself (QED radiative corrections, arXiv:2012.09565) or as bremsstrahlung in detector material, which lowers the measured momentum
- Photons with $|\Delta\theta| < 1.5°$ (polar-angle difference) and a cone angle below 10° of the lepton are added to its reconstructed 4-momentum

Energy-loss correction (proton, MC-based)

- Protons lose energy in detector material before they are measured, especially at larger forward polar angles
- The momentum shift is estimated from Bethe–Heitler simulation in three detector regions. It is applied to both data and simulation

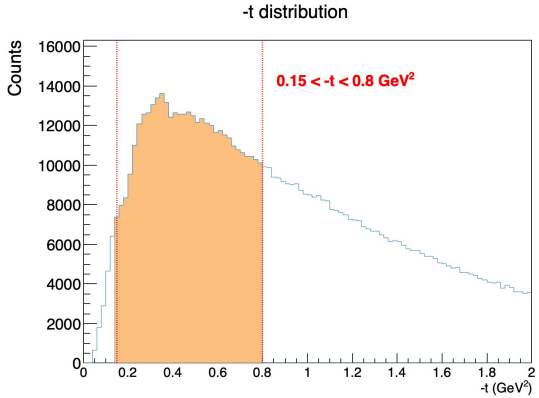
Central Detector correction (proton, data-driven)

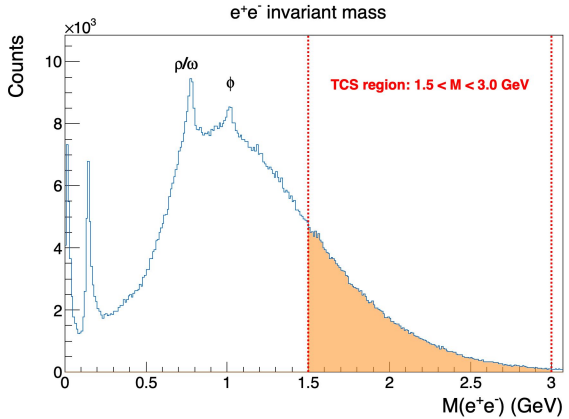
- Simulation does not reproduce misalignments and reconstruction effects in the CVT, which shift the momentum of central-detector protons
- The shift is measured from $ep \rightarrow e'p'\pi^+\pi^-$ as a function of the azimuthal angle in the CVT and is applied to data only

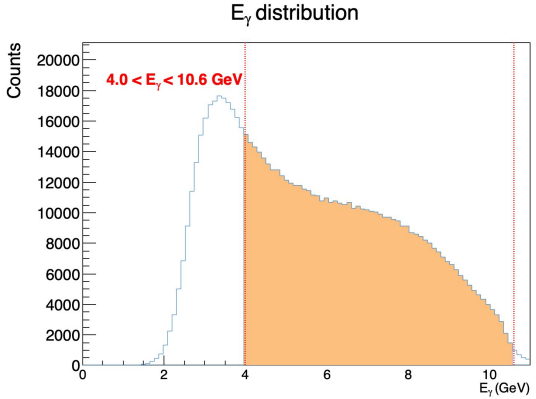
Fiducial cuts

- The PCAL fiducial cut removes showers reconstructed too close to the edge of the active region
- There the energy is incompletely measured and the simulation does not reproduce the efficiency

Event Selection



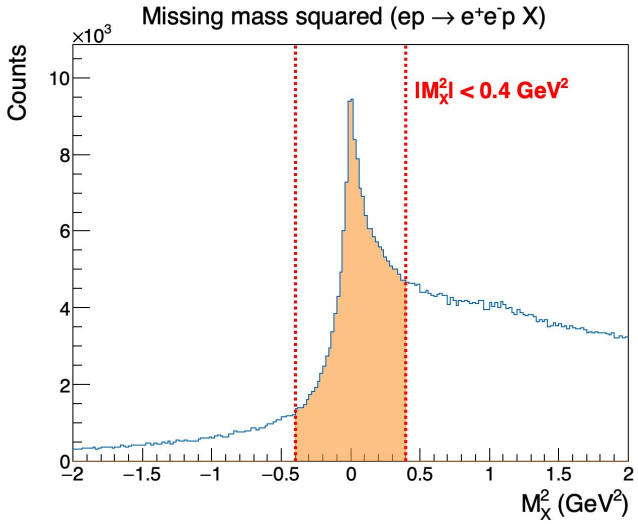


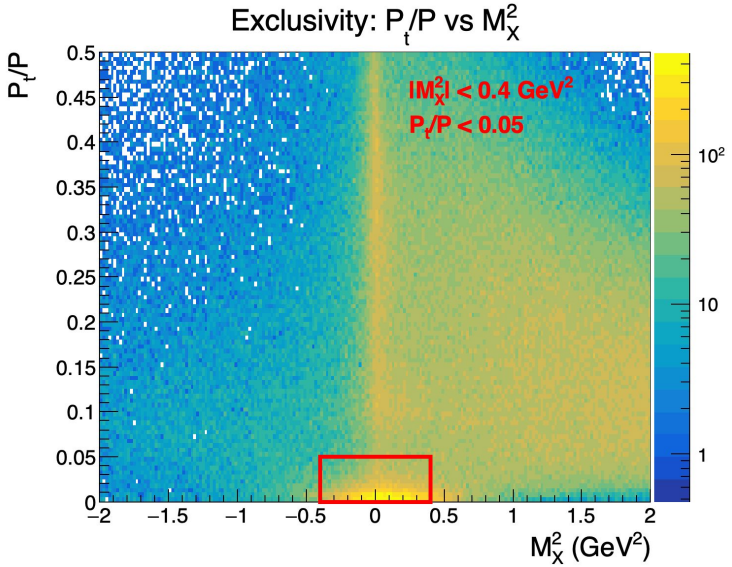


Phase space cuts:

- $1.5\ \text{GeV} < M(e^+e^-) < 3\ \text{GeV}$
- $0.15\ \text{GeV}^2 < -t < 0.8\ \text{GeV}^2$
- $4\ \text{GeV} < E\gamma < 10.6\ \text{GeV}$

Event Selection





TCS:

Conservation of Energy and Momentum:

$$M_X^2 = ((P_{beam} + P_{target}) - (P_{p'} + P_{e^-} + P_{e^+}))^2$$

Peak near zero~ TCS events

Acceptance

- CLAS12 detects most of the particles produced in the interaction
- Some particles escape detection due to:
  - Finite coverage
  - Gaps between subsystems
  - Detection inefficiencies

An acceptance correction is required

$$Acc_{\mathcal{B}} = \frac{N_{\mathcal{B}}^{REC}}{N_{\mathcal{B}}^{GEN}}$$

$$N_{\mathcal{B}}^{GEN} = \sum_{\{E_\gamma, -t, Q'^2, \theta, \phi\}_{GEN} \in \mathcal{B}} w,$$

$$N_{\mathcal{B}}^{REC} = \sum_{\{E_\gamma, -t, Q'^2, \theta, \phi\}_{REC} \in \mathcal{B}} w,$$

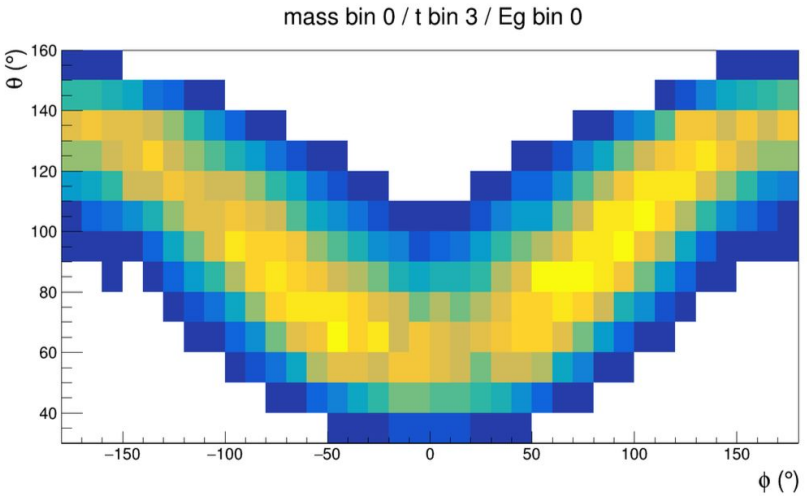


Fig. Acceptance of CLAS12 in the θ/φ plane

B is one bin of the 5D grid in (Eγ, −t, Q′², θ, φ), and **w** is the **TCSGen** weight of a generated event.

Photon Polarization Asymmetry

Quasi-real photon production: The longitudinally polarized electron beam produces quasi-real photons ($Q^2 \approx 0$). The photon helicity follows the electron helicity: positive (negative) electron helicity produces right- (left-) handed circular polarization.

Polarization transfer: The photon polarization is given by:

$$P = S\,L,$$

where $S = \pm 1$ is the beam helicity and L is the QED polarization-transfer factor

H. Olsen and L. C. Maximon. Phys. Rev., 114:887904, 195

Acceptance and polarization correction: Events are counted separately for positive and negative helicities in each $(-t, E\gamma, M; \varphi)$ bin. The corrected yields are:

$$N^{\pm} = \Sigma\,(P_{trans} / Acc)$$

where P_{trans} is the polarization-transfer factor and Acc is the detector acceptance.

Extraction of the asymmetry: The azimuthal distribution is fitted with:

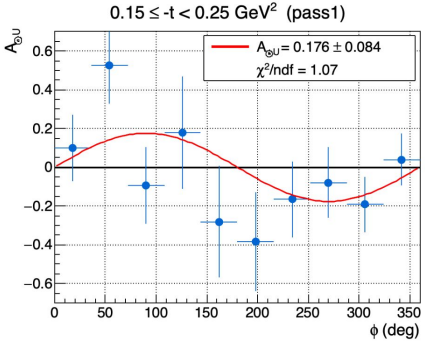
$$A_{\odot U} \sin\phi = \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-}$$

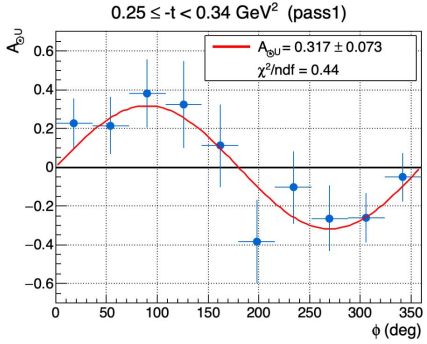
The fitted amplitude A⊙U gives the measured asymmetry, and its fit uncertainty gives the statistical uncertainty.

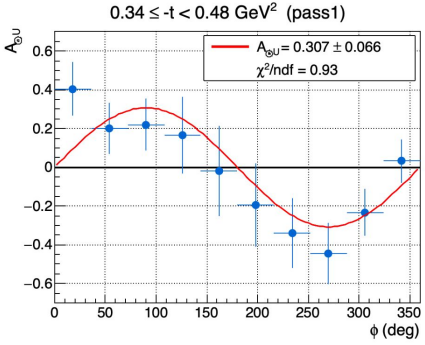
The photon polarization asymmetry is sensitive to the imaginary part of the Compton Form Factors (CFFs), providing access to the nucleon's GPDs.

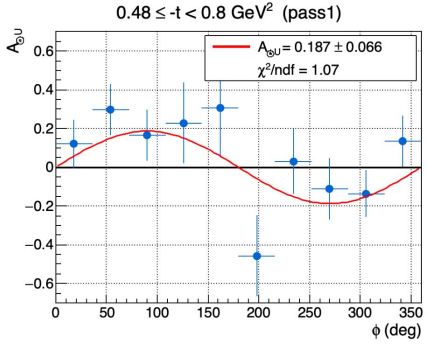
Photon Polarization Asymmetry: -t bins

F18 in pass1

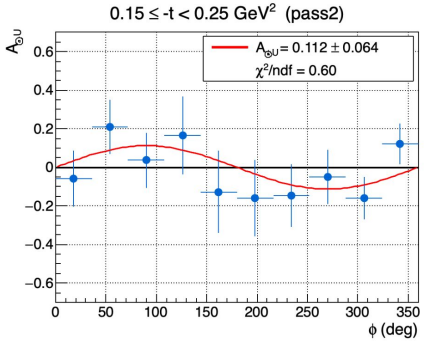


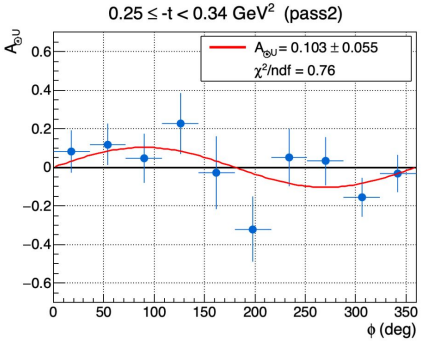


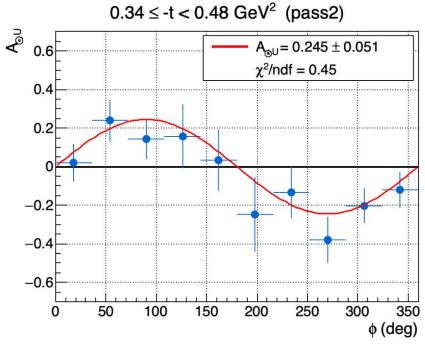


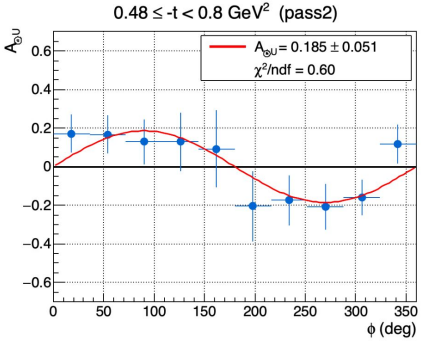


F18 in pass2

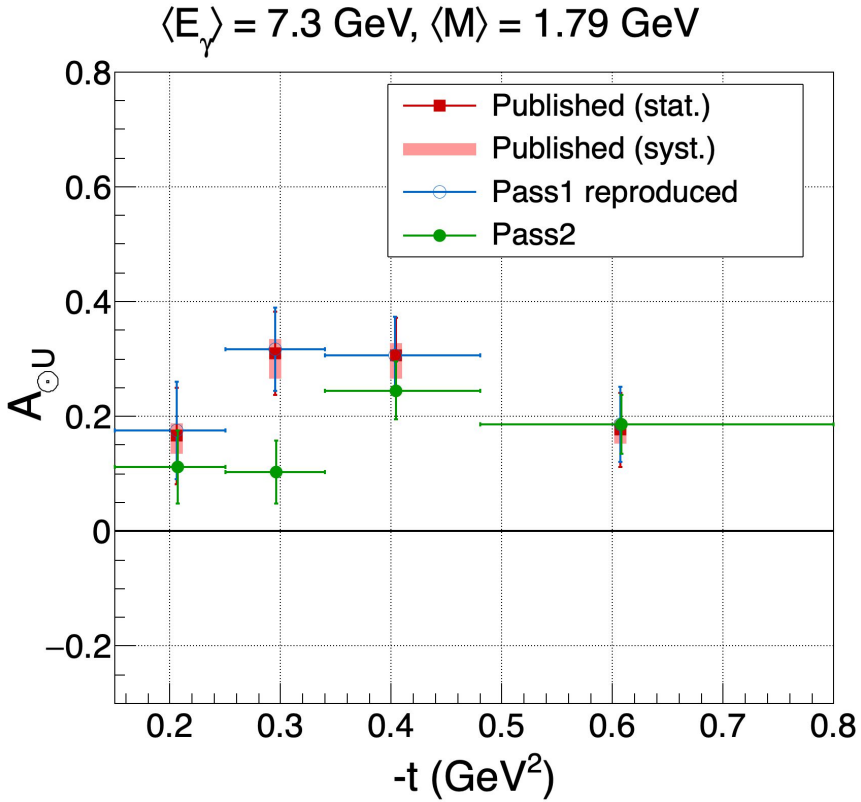






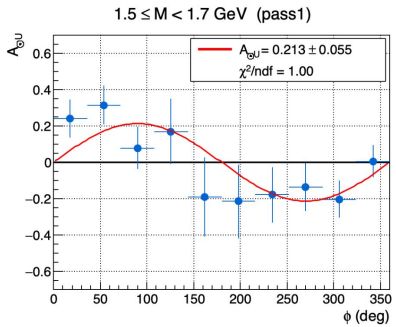


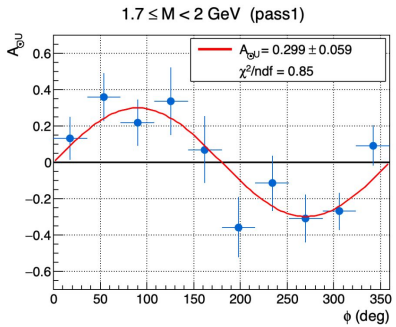
Photon Polarization Asymmetry: -t bins

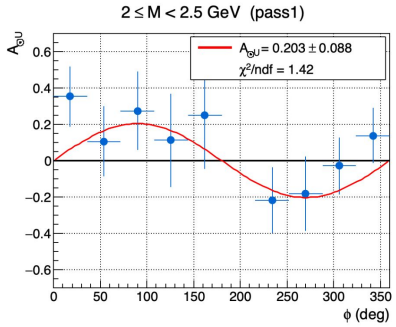


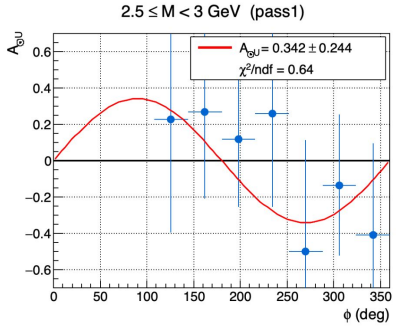
Photon Polarization Asymmetry: M bins

F18 in pass1

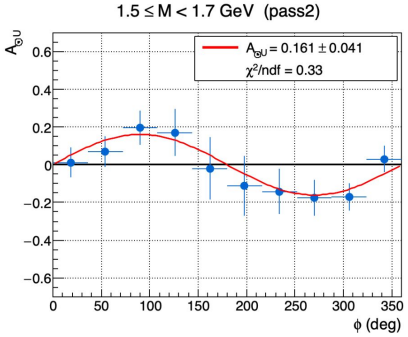


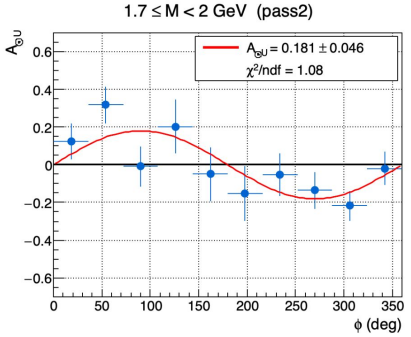


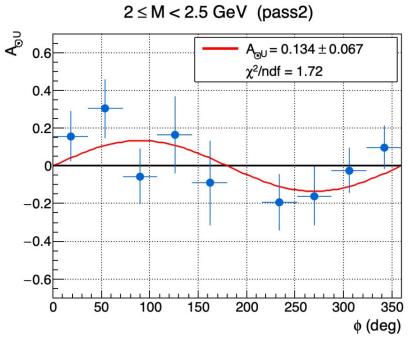


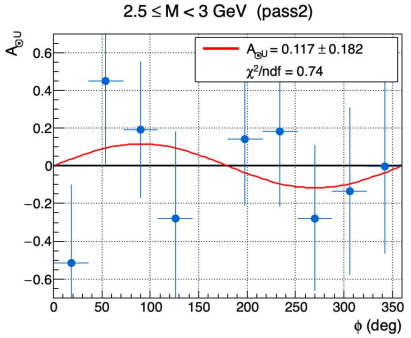


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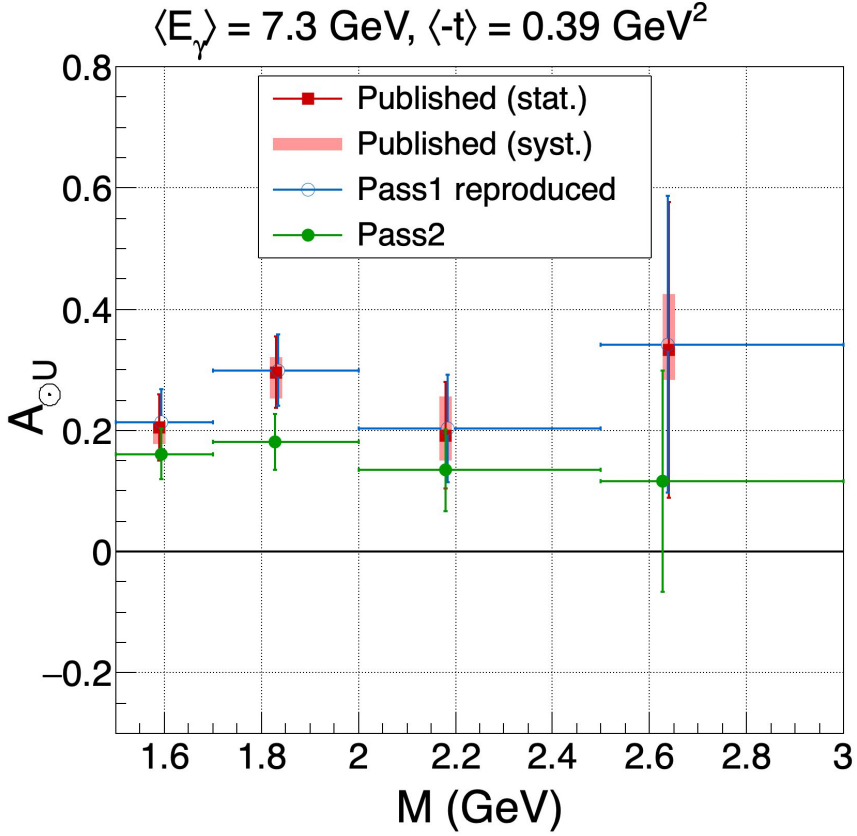






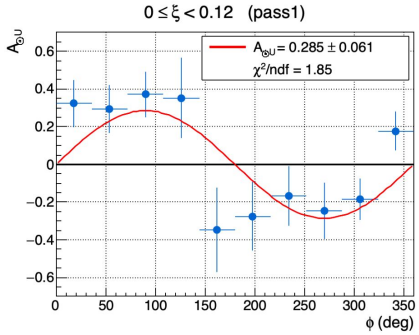


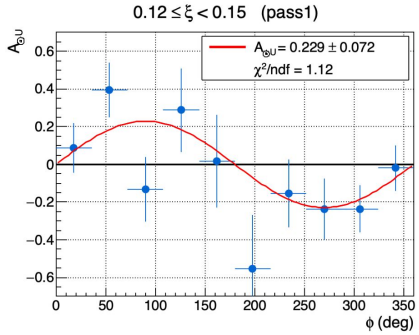
Photon Polarization Asymmetry: M bins

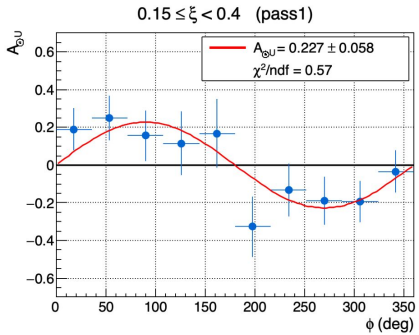


Photon Polarization Asymmetry: ξ bins

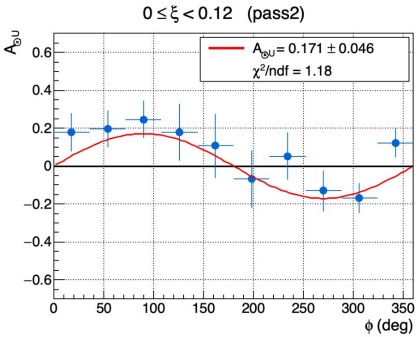
F18 in pass1

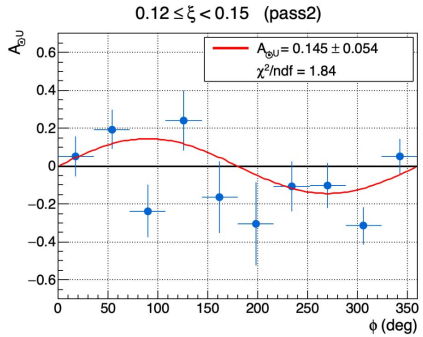


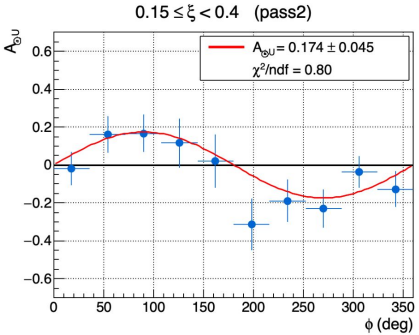




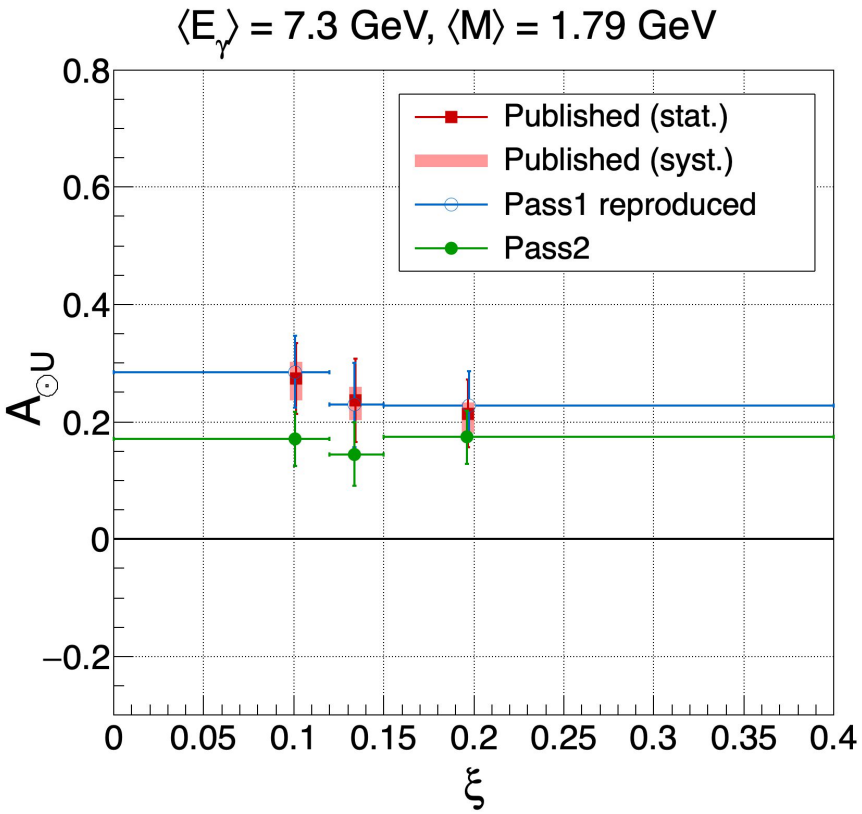
F18 in pass2







Photon Polarization Asymmetry: ξ bins



Forward-Backward Asymmetry

Forward bin: $-40° < \varphi < 40°$, $50° < \theta < 80°$
Backward bin: $140° < \varphi < 220°$, $100° < \theta < 130°$

In some ($E\gamma$, $-t$, Q'^2) bins, CLAS12 provides different angular coverage in the forward and backward regions. This difference can introduce a fake forward-backward asymmetry (A_{FB}).

Bin-volume correction:
For each ($E\gamma$, $-t$, Q'^2) bin, use the MC (θ, φ) acceptance map.

$BV_{F/B}$ = (Number of non-empty MC (θ, φ) bins) / (Total number of MC (θ, φ) bins in the region)

$BV_{F/B}$ represents the fraction of the angular region covered by the detector. The factor $1/BV_{F/B}$ accounts for the uncovered region.

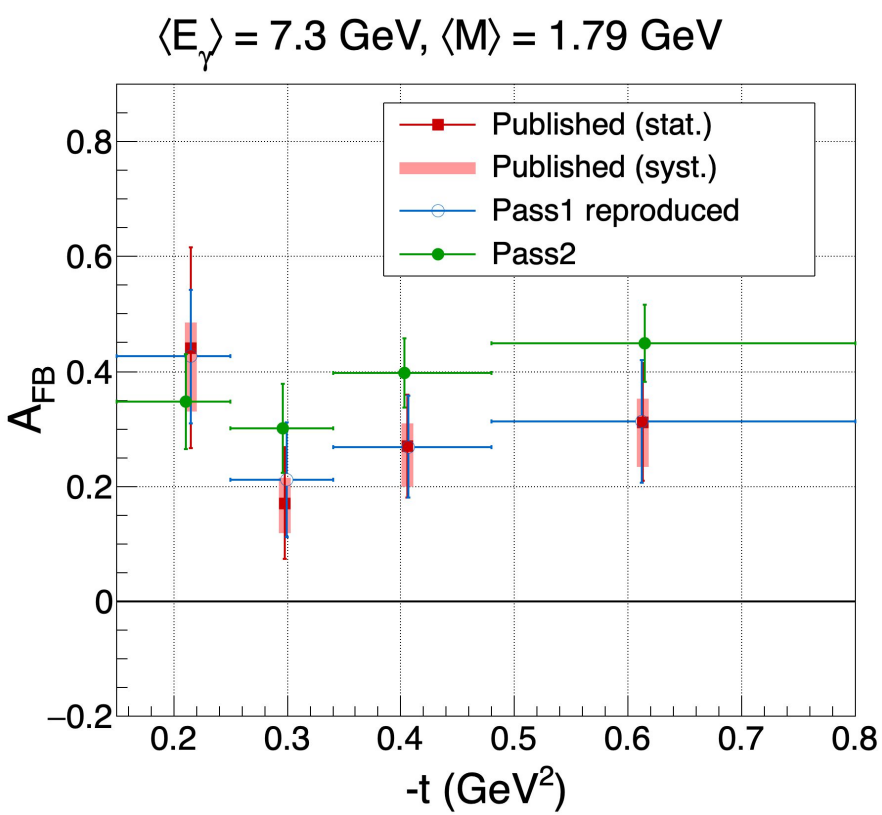
Each event is weighted by $1 / (Acc_i \times BV_{F/B})$, where Acc_i is the MC acceptance of event i in its ($E\gamma$, $-t$, Q'^2, θ, φ) bin.

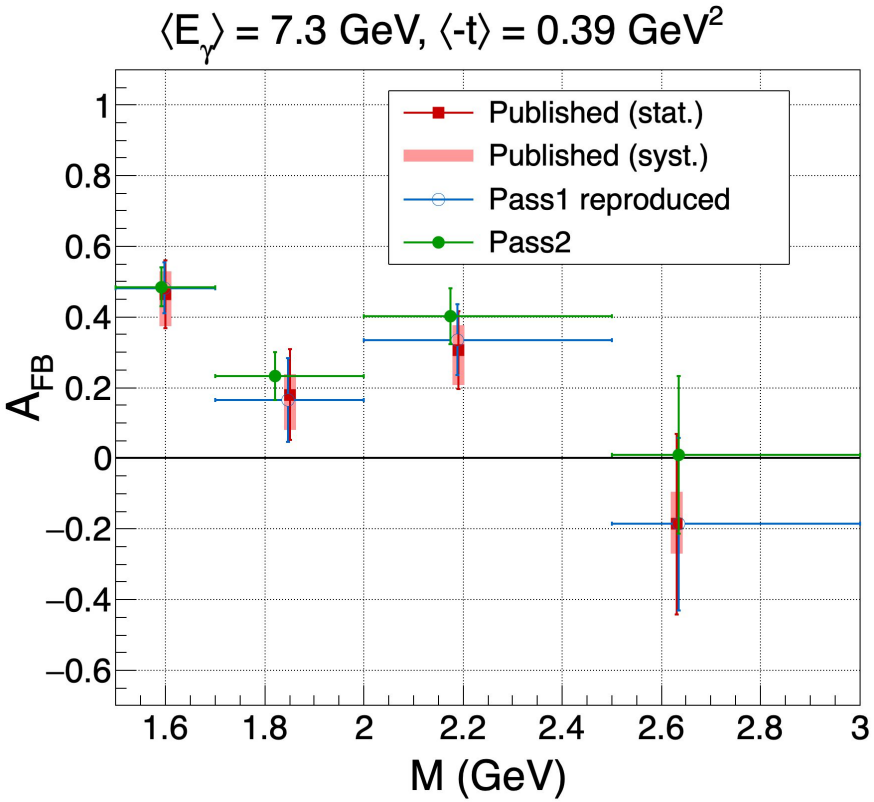
Corrected yields: $$N_{F/B} = \sum_{i \in F/B} \frac{1}{\mathrm{Acc}_i \times \mathrm{BV}_{F/B}}$$

Statistical uncertainty: $$\sigma^2(N_{F/B}) = \sum_{i \in F/B} \left[\frac{1}{\mathrm{Acc}_i \times \mathrm{BV}_{F/B}}\right]^2$$

Forward-Backward Asymmetry: $$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Forward-Backward Asymmetry





Summary and Outlook

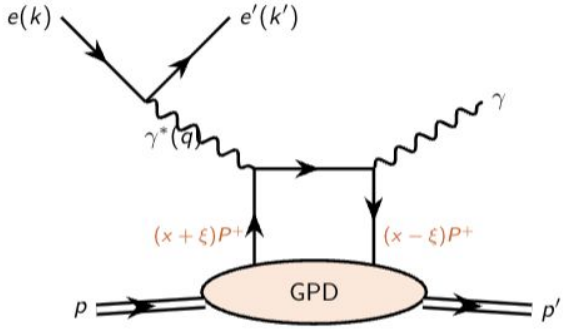
- Promising first look at Pass 2 data (RG-A Fall 2018, inbending): initial distributions of key kinematic and physics observables (Q'^2, $-t$, $E\gamma$, BSA, A_{FB}) show reasonable behavior.
- Next step: extend the analysis to the remaining RG-A data sets.
- Explore finer binning in Q'^2, $-t$, and $E\gamma$ (ξ), with larger statistics, to investigate the kinematic dependence beyond bin-averaged measurements.
- Aim to improve constraints on the imaginary part of the CFFs (through BSA) and the real part (through A_{FB}), providing greater sensitivity to the D-term and the nucleon's mechanical properties.

Thank you for your attention !

Outlook - Remaining RGA data

Data set	Torus	Pass	Status / Timeline
Fall 2018	Inbending	pass2	✔ Analyzed
Fall 2018	Outbending	pass2	Next: Winter 2027
Spring 2019	Inbending	pass2	Next: Spring 2027
Spring 2018	In/Outbending	pass1	Planned: Summer–Fall 2027

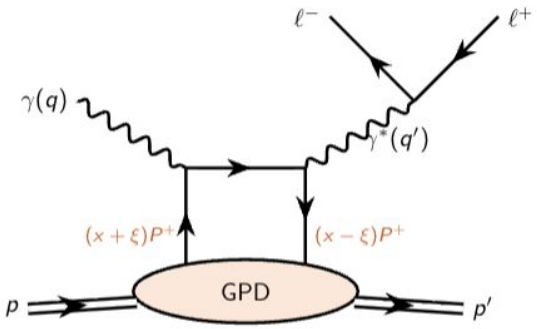
DVCS: $ep \to e'p'\gamma$



$Q^2 = -q^2$ large (spacelike)

variables: $x_B = \dfrac{Q^2}{2m\nu}$, Q^2, t, ϕ

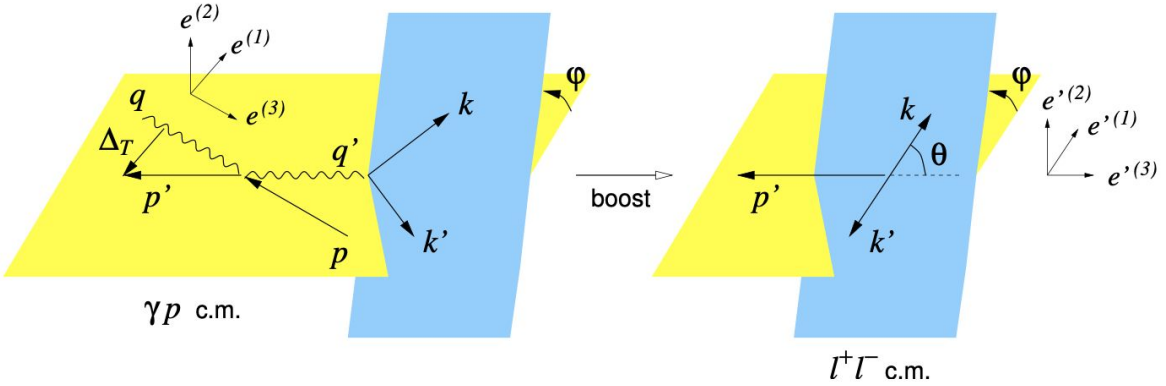
TCS: $\gamma p \to p'\,\ell^+\ell^-$



$Q'^2 = (k + k')^2$ large (timelike)

variables: s (or E_γ), Q'^2, t, ϕ, θ

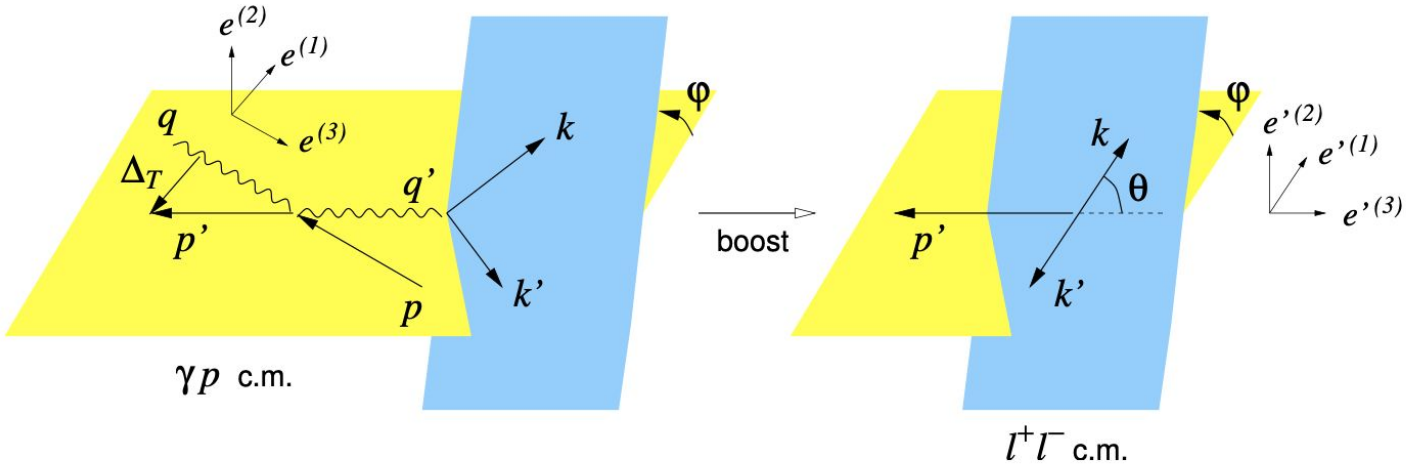
$$J_Q = \sum_q \frac{1}{2} \int_{-1}^{1} dx\; x(H^q(x,\xi,0) + E^q(x,\xi,0)).$$



Nucleon Polarization		Quark Pol: Unpolarized (U)	Quark Pol: Longitudinally Polariz (L)	
	U	H		
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

$$J_Q = \sum_q \frac{1}{2} \int_{-1}^{1} dx\ x(H^q(x,\xi,0) + E^q(x,\xi,0)).$$

$$A_{\odot U} \sin\phi = \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-} \text{ with } N^{\pm} = \sum_{events} Pol_{transf} * \text{ , and } \sigma_{A_{\odot U}} = \sqrt{\sum_{\pm} \left(\frac{\partial A_{\odot U}}{\partial N^{\pm}} \delta N^{\pm} \right)^2}$$


e(2)
e(1)
e(3)
q
Δ_T
q'
p'
p
k
k'
φ
γp c.m.
boost
k
θ
φ
p'
k'
e'(2)
e'(1)
e'(3)
l+l− c.m.