Timelike Compton Scattering with CLAS12 at Jefferson Lab

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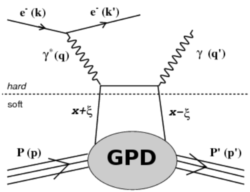
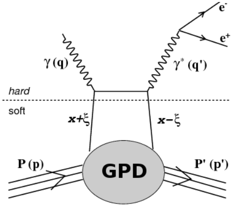
From Deeply Virtual Compton Scattering to Timelike Compton Scattering

DVCS $(\gamma^* p \to \gamma p)$



TCS $(\gamma p \to \gamma^* p)$



Compton Form Factors (CFF)

$$\mathcal{H} = \sum_q e_q^2 \left\{ \mathcal{P} \int_{-1}^{1} dx H^q(x,\xi,t) \left[\frac{1}{\xi - x} - \frac{1}{\xi + x} \right] + i\pi \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t) \right] \right\}$$

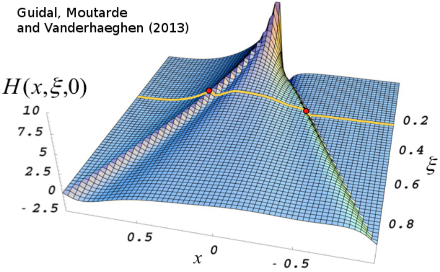
Imaginary part

- Measured in DVCS asymmetries
- Accessible in TCS photon polarization asymmetry

Real part

- Accessible in DVCS cross section
- Accessible in TCS in cross section angular modulation

Guidal, Moutarde and Vanderhaeghen (2013)



Physics Motivations

- The CFFs dispersion relation at leading-order and leading twist :

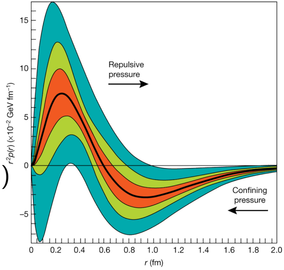
$$Re\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) Im\mathcal{H}(\xi,t) + D(t)$$

- D-term expansion

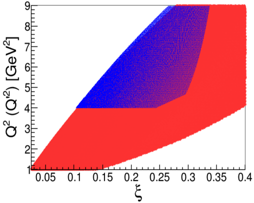
$$D(t) = \frac{1}{2}\int_{-1}^{1} dz \frac{D(z,t)}{1-z}$$

$$D(z,t) = (1-z^2)[d_1(t)C_1^{3/2}(z) + ...]$$

- $d_1(t)$ is directly related to the pressure distribution in the nucleon.
- Measurement of photon polarization asymmetry will provide a test of universality of GPDs.



Nature (2018) Burkert, Elouadrhiri, Girod

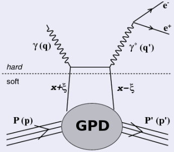


DVCS phase space
TCS phase space

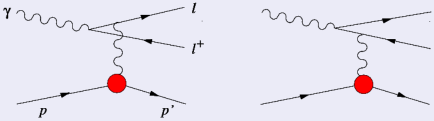
Boër, Guidal, Vanderhaeghen (2015)

TCS and Bethe-Heitler

$\gamma p \to e^+ e^- p$

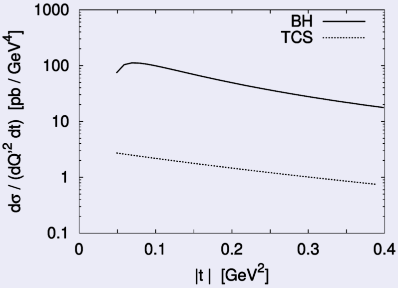


TCS (GPDs)



Bethe-Heitler (Form Factors)

TCS cross section



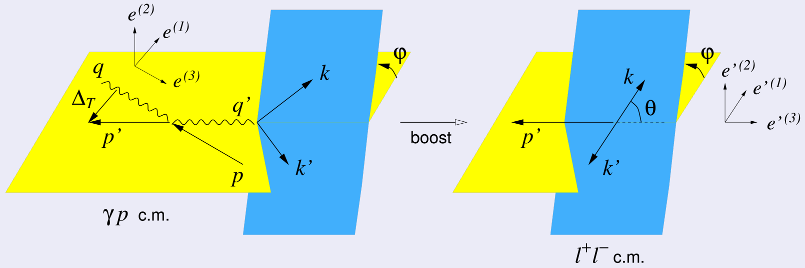
$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} = \sigma_{TCS} + \sigma_{BH} + \sigma_{INT}$$

TCS cross section not large enough to allow meaningful measurement

Use interference term to access GPDs

Berger, Diehl and Pire (2002)

$\gamma p \to e^+ e^- p$ kinematics



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

$$L = \frac{(Q'^2 - t)^2 - b^2}{4} \qquad L_0 = \frac{Q'^4 sin^2\theta}{4} \qquad b = 2(k - k')(p - p')$$

$$\tau = \frac{Q'^2}{2p \cdot q} = \frac{Q'^2}{s - M^2} \qquad \xi = \frac{\tau}{2 - \tau} \qquad s = (p + q)^2 \qquad t_0 = -\frac{4\xi^2 M^2}{(1 - \xi^2)}$$

$\gamma p \rightarrow e^+ e^- p$ Cross section and CFFs

Interference cross section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\boldsymbol{cos(\phi)}\frac{1+cos^2(\theta)}{sin(\theta)}\boldsymbol{Re\ \tilde{M}^{--}} + \ ...\right]$$

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

BH cross section

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

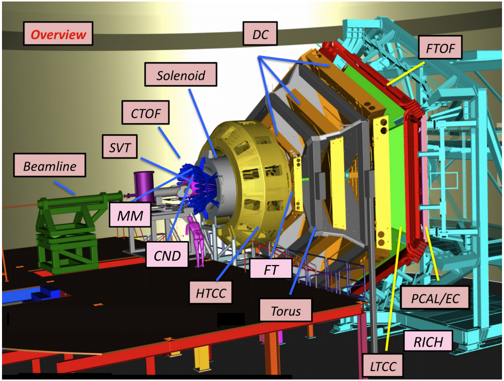
BH cross section diverges at $\theta \approx 0^\circ$ and 180°

Weighted cross section ratio

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

CLAS12 at Jlab

- Central Detector
  - Time-of-Flight (CTOF)
  - Tracking (SVT and MM)
  - Neutron detector (CND)
- Forward Detector
  - Drift Chambers (DC)
  - Time-of-Flight (FTOF)
  - Calorimeters (Pre-Shower Calorimeter/2 layer EC)
  - Cherenkov Counters (HTCC and LTCC)
  - RICH
  - Forward tagger (FT)



Data Set

- First CLAS12 experiment, data were taken in the Spring and Fall 2018
- Beam energy 10.56 GeV / Liquid hydrogen target
- Two torus magnetic field configurations (Inbending/Outbending electrons)
- Total accumulated charge in the Faraday cup for data shown here : 18 mC $\sim$ 3% of the proposed total data (100 days at 75nA). Total taken data corresponds to 50% of total proposed data

Data analysis

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

Final state

- Use the CLAS12 reconstruction software PID
- Events with exactly one e^+,one e^- and one proton are selected

Scattered electron

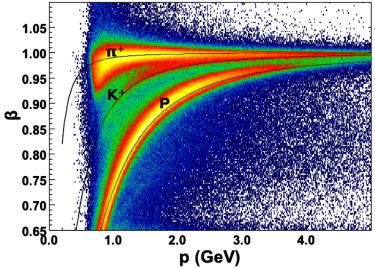
- Cut on scattered electron missing mass
- Cut on missing transverse momentum of $ep \to e^+e^-pX$ system

Incoming photon

- The real photon is radiated by the beam electron
- Cuts on scattered electron constrain the virtuality of the photon $Q^2 \propto cos(\Theta_{scattered})$

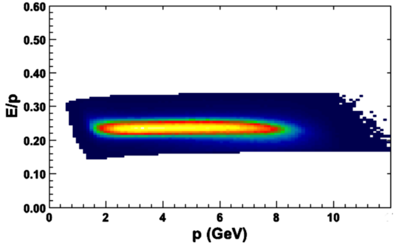
e^+e^-pX final state selection

Protons



- Matching β calculated from Time-Of-Flight and momentum from tracking

Leptons

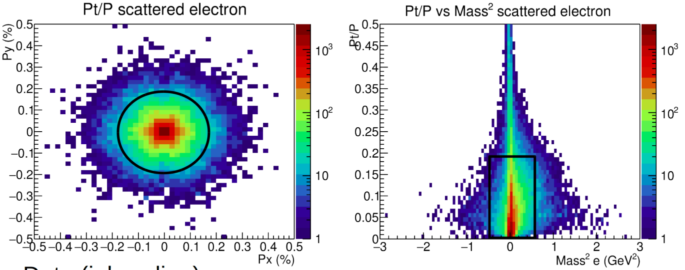


- Number of Cherenkov photons > 2
- Minimum energy deposited in the Pre-Shower Calorimeter (PCAL)
- Cuts on total calorimeters sampling fractions ($E_{deposited}/p$)

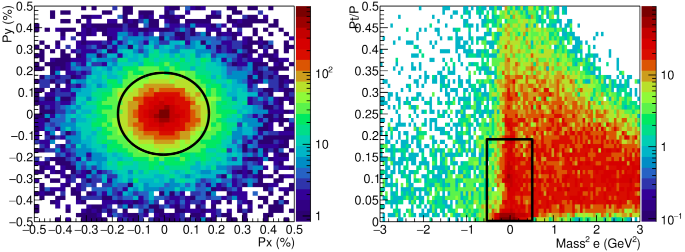
Exclusivity cuts

- Scattered electron: $p^{\mu}_{scattered\ e^-} = p^{\mu}_{beam} + p^{\mu}_{target} - p^{\mu}_{proton} - p^{\mu}_{e^+} - p^{\mu}_{e^-}$

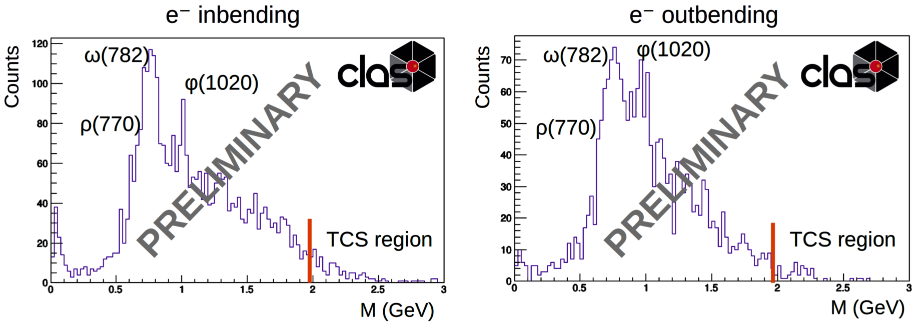
Simulation (e^+e^-p events weighted with BH weight)



Data (inbending)



Lepton-pair spectrum



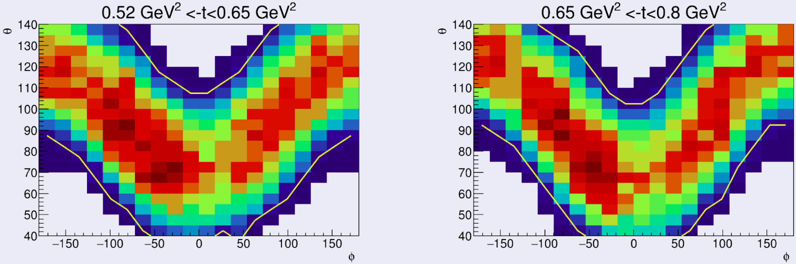
- 3% of total proposed data
- Low e^+e^- invariant mass spectrum is dominated by vector meson photoproduction → Mass cut between the ρ region [$\rho(1450\ MeV)$ and $\rho(1700\ MeV)$] and $J/\psi(3\ GeV)$ → The resonance-free mass region between 2 GeV and 3 GeV will be used for the analysis

Projected results

Experimental cross section ϕ modulation ratio

$$R(\sqrt{s}, Q'^2, t) = \frac{\int_0^{2\pi} d\phi \; \cos(\phi) \; \frac{dS}{dQ'^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ'^2 dt d\phi}} \quad \rightarrow \quad R' = \frac{\sum_\phi \cos(\phi) Y_\phi}{\sum_\phi Y_\phi} \text{ where } Y_\phi = \sum_\theta \frac{L}{L_0} N_\theta^\phi \frac{1}{A_\theta^\phi}$$

Estimate of CLAS12 acceptance with BH simulation



Acceptance in the θ/ϕ plane ($A_\theta^\phi = \frac{N_{REC}}{N_{GEN}}$)

$\rightarrow$ Yellow lines are CLAS12 acceptance limits

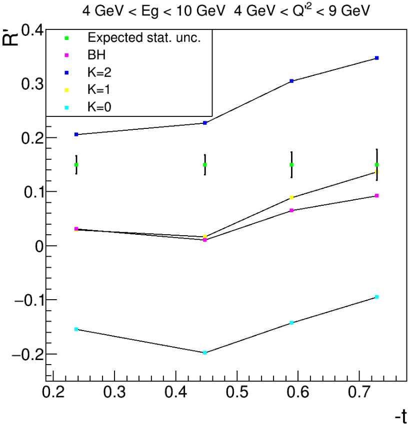
$\rightarrow$ Cut regions correspond to events where one lepton goes in the beam pipe (BH peaks are out of CLAS12 acceptance)

Projected results

Generator developed by R. Paremuzyan at Jefferson Lab.

$\rightarrow$ Double distribution GPD parametrization

$$H(x,\xi,t) = H_{DD}(x,\xi,t) + \kappa\frac{1}{N_f}\Theta(\xi - |x|)D(\frac{x}{\xi},t)$$



- R' is sensitive to D-term strength within CLAS12 acceptance.
- Full data set (50% of total proposed data) will provide enough statistics to give insight on D-term strengh (green points and associated error bars).

Projected results

- R' is sensitive to D-term strength BUT also depends on acceptance limits $\rightarrow$ difficulties to compare measurement with theoretical models
- Possibility to restore θ dependence of the interference cross-section

We want to access the ϕ moment of the cross section. We can measure :

$$\frac{dS_{TOT}}{dQ'^2 dtd\phi} = \int_{b(\phi)}^{a(\phi)} d\theta \frac{d^4\sigma_{TOT}}{dQ'^2 dtd\Omega} \frac{L}{L_0} = \frac{dS_{BH}}{dQ'^2 dtd\phi} + \frac{dS_{INT}}{dQ'^2 dtd\phi}$$

- $\frac{dS_{BH}}{dQ'^2 dtd\phi}$ is calculable from form factors.
- The θ/ϕ dependance of the interference term is fully known :

$$\frac{dS_{INT}}{dQ'^2 dtd\phi} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} [cos(\phi) \int_{b(\phi)}^{a(\phi)} (1 + cos^2(\theta)) d\theta \cdot Re\ \tilde{M}^{--} + ...]$$

This method will be implemented at a later stage of the analysis, as it requires good accumulated luminosity estimation.

Conclusion

- Timelike Compton Scattering allows to investigate the real part of CFFs which is difficult to constrain with DVCS.
- No published results on TCS yet.
- Main resonances in the e^+e^- spectrum visible in CLAS12 data.
- Projected statistic will allow insight on the strength of the D-term.

Outlook

- The analysis procedure leading to R' has been developed.
- More statistics is coming from the data processing of the 2018 run.
- Dependence on acceptance limits of R' will be corrected to allow comparison with models and future TCS measurements.