# What DVCS data tell us about TCS observables?

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# In addition to spacelike DVCS ...

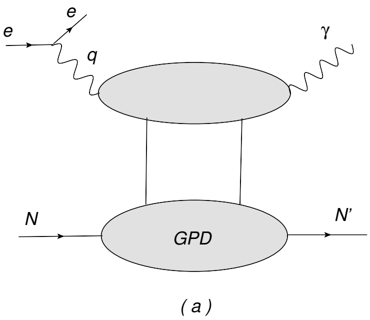



Figure: Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

# we MUST also study timelike DVCS

Berger, Diehl, Pire, 2002

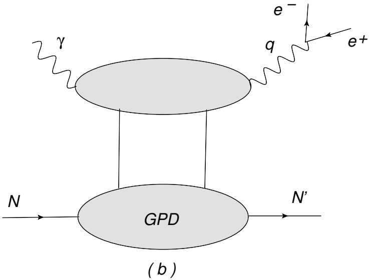



Figure: Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- same proven factorization properties as DVCS
- universality of the GPDs
- another source for GPDs (special sensitivity on real part of GPD $H$),
- spacelike-timelike crossing (different analytic structure - cut in $Q^2$)

# Exciting times - DATA is coming!!!

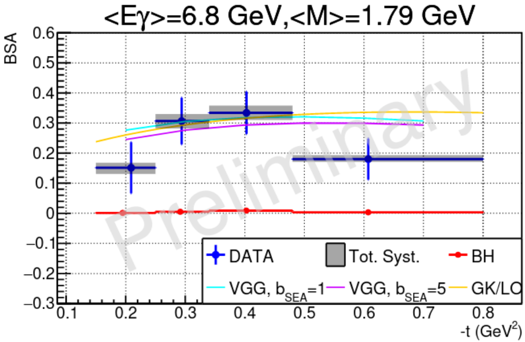



Figure 6.14: CLAS12 data points for the TCS BSA as a function of $-t$, evaluated at $\phi = 90°$, integrated over CLAS12 acceptance and over all the other variables. The vertical blue error bars are statistical uncertainties while the grey bands correspond to systematic uncertainties. Three model predictions, obtained using the VGG and GK models, are also displayed. The model predictions are calculated at the mean kinematic point given above the plot. The red points are the expected values of the BSA for BH-only events, obtained using BH-weighted simulations.

Data from CLAS12 at JLab - PhD thesis of Pierre Chatagnon (2020, Orsay)

# Coefficient functions and Compton Form Factors

CFFs are the GPD dependent quantities which enter the amplitudes. They are defined through relations:

$$\mathcal{A}^{\mu\nu}(\xi,t) = -e^2 \frac{1}{(P+P')^+}\,\bar{u}(P')\Bigg[ g_T^{\mu\nu}\left(\mathcal{H}(\xi,t)\,\gamma^+ + \mathcal{E}(\xi,t)\,\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right) + i\epsilon_T^{\mu\nu}\left(\widetilde{\mathcal{H}}(\xi,t)\,\gamma^+\gamma_5 + \widetilde{\mathcal{E}}(\xi,t)\,\frac{\Delta^+\gamma_5}{2M}\right)\Bigg] u(P)\,,$$

where:

$$\mathcal{H}(\xi,t) = +\int_{-1}^{1} dx \left(\sum_q T^q(x,\xi) H^q(x,\xi,t) + T^g(x,\xi) H^g(x,\xi,t)\right)$$

$$\widetilde{\mathcal{H}}(\xi,t) = -\int_{-1}^{1} dx \left(\sum_q \widetilde{T}^q(x,\xi) \widetilde{H}^q(x,\xi,t) + \widetilde{T}^g(x,\xi) \widetilde{H}^g(x,\xi,t)\right).$$

# Spacelike vs Timelike

D.Mueller, B.Pire, L.Szymanowski, J.Wagner, Phys.Rev.D86, 2012.

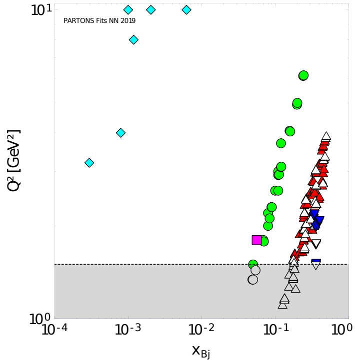
Thanks to simple spacelike-to-timelike relations, we can express the timelike CFFs by the spacelike ones in the following way:

$$
\begin{aligned}
{}^{T}\mathcal{H} &\overset{\text{LO}}{=} {}^{S}\mathcal{H}^{*}\,,\\
{}^{T}\widetilde{\mathcal{H}} &\overset{\text{LO}}{=} -{}^{S}\widetilde{\mathcal{H}}^{*}\,,\\
{}^{T}\mathcal{H} &\overset{\text{NLO}}{=} {}^{S}\mathcal{H}^{*} - i\pi\,\mathcal{Q}^2\frac{\partial}{\partial\mathcal{Q}^2}{}^{S}\mathcal{H}^{*}\,,\\
{}^{T}\widetilde{\mathcal{H}} &\overset{\text{NLO}}{=} -{}^{S}\widetilde{\mathcal{H}}^{*} + i\pi\,\mathcal{Q}^2\frac{\partial}{\partial\mathcal{Q}^2}{}^{S}\widetilde{\mathcal{H}}^{*}\,.
\end{aligned}
$$

The corresponding relations exist for (anti-)symmetric CFFs $\mathcal{E}$ ($\widetilde{\mathcal{E}}$).

# DVCS CFFs from Artificial Neural Network fit

H. Moutarde, P. Sznajder, J. Wagner, Eur.Phys.J. C79 (2019)



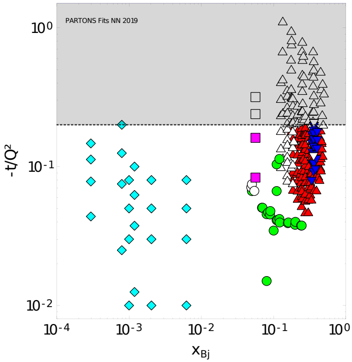




Figure: Coverage of the $(x_{\mathrm{Bj}}, Q^2)$ (left) and $(x_{\mathrm{Bj}}, -t/Q^2)$ (right) phase-spaces by the experimental data used in DVCS CFFs fit. The data come from the Hall A (▼, ▽), CLAS (▲, △), HERMES (●, ○), COMPASS (■, □) and HERA H1 and ZEUS (♦, ◊) experiments. The gray bands (open markers) indicate phase-space areas (experimental points) being excluded from this analysis due to the cuts.

# DVCS vs TCS CFFs

O. Grocholski, H. Moutarde, B. Pire, P. Sznajder, J. Wagner, Eur.Phys.J. C80 (2020)

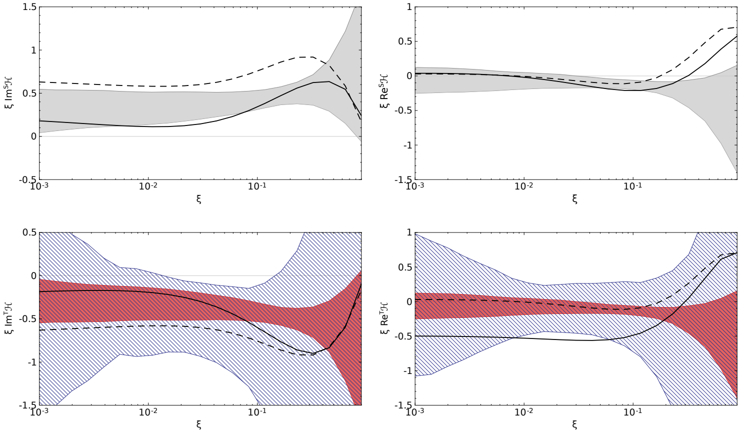



Figure: Imaginary (left) and real (right) part of DVCS (up) and TCS (down) CFF for $Q^2 = 2$ GeV$^2$ and $t = -0.3$ GeV$^2$ as a function of $\xi$. The shaded red (dashed blue) bands correspond to the data-driven predictions coming from the ANN global fit of DVCS data and they are evaluated using LO (NLO) spacelike-to-timelike relations. The dashed (solid) lines correspond to the GK GPD model evaluated with LO (NLO) coefficient functions.

# TCS and Bethe-Heitler contribution to exclusive lepton pair photoproduction.

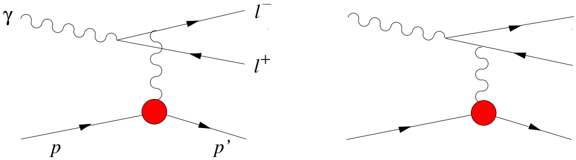



Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

The cross-section for photoproduction of a lepton pair:

$$\frac{d\sigma}{dQ'^2\ dt\ d\phi\ d\cos\theta} = \frac{d\left(\sigma_{\mathrm{BH}} + \sigma_{\mathrm{TCS}} + \sigma_{\mathrm{INT}}\right)}{dQ'^2\ dt\ d\phi\ d\cos\theta}$$

# TCS

Berger, Diehl, Pire, 2002

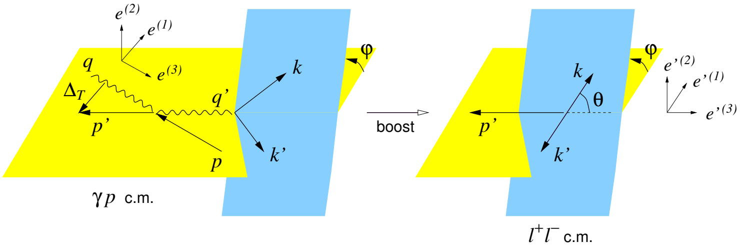



Figure: Kinematical variables and coordinate axes in the $\gamma p$ and $\ell^+\ell^-$ c.m. frames.

$$\frac{d\sigma}{dQ'^2\ dt\ d\phi\ d\cos\theta}$$

- Important to measure $\phi$ !
- BH dominates at $\theta$ close to $0$ and $\pi$ !

# Interference

- B-H dominant for not very high energies (JLAB), at higher energies the TCS/BH ratio is bigger due to growth of the gluon and sea densities.

Pire, Szymanowski, JW PRD 83

Moutarde, Pire, Sabatié, Szymanowski, JW PRD 87

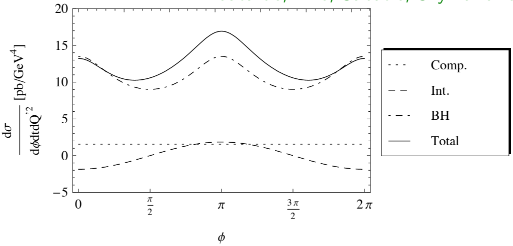



Figure: The differential cross section for $t = -0.2$ GeV$^2$ , $Q'^2 = 5$ GeV$^2$ , and integrated over $\theta \in (\pi/4, 3\pi/4)$ as a function of $\phi$, for $s = 10^3$ GeV$^2$.

- The interference part of the cross-section for $\gamma p \to \ell^+ \ell^- p$ with unpolarized protons and photons is given by:

$$\frac{d\sigma_{INT}}{dQ'^2\, dt\, d\cos\theta\, d\varphi} \sim \cos\varphi \cdot \ \mathrm{Re}\,\mathcal{H}(\xi, t) \leftarrow \text{Sensitivity to the D-term!}$$

Charge asymmetry selects interference - in DVCS one needs positron beam, here this is given by the angular dependence!

# Interference

R ratio:

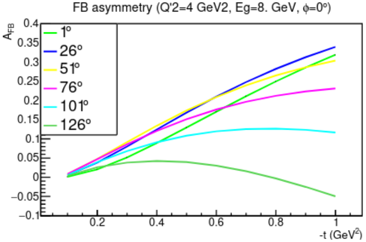
$$R = \frac{2\int_0^{2\pi} \cos\phi \; d\phi \int_{\pi/4}^{3\pi/4} d\theta \, \frac{dS}{dQ'^2 dt d\phi d\theta}}{\int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} d\theta \, \frac{dS}{dQ'^2 dt d\phi d\theta}},$$

where $S$ is the weighted cross section :

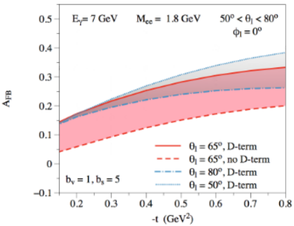
$$\frac{dS}{dQ'^2 dt d\phi d\theta} = \frac{L(\theta,\phi)}{L_0(\theta)} \frac{d\sigma}{dQ'^2 dt d\phi d\theta},$$

Asymmetry (Chatagnon & Vanderhaeghen):

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




(a)




(b)

# Unpolarized cross section

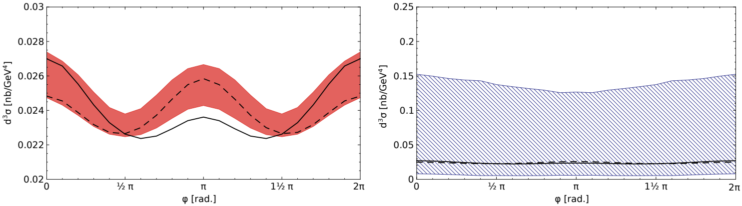



Figure: Differential TCS cross section integrated over $\theta \in (\pi/4, 3\pi/4)$ for $Q'^2 = 4$ GeV$^2$, $t = -0.1$ GeV$^2$ and the photon beam energy $E_\gamma = 10$ GeV as a function of the angle $\phi$. In the left (right) panel the data-driven predictions evaluated using LO (NLO) spacelike-to-timelike relations are shown. The dashed (solid) lines correspond to the GK GPD model evaluated with LO (NLO) TCS coefficient functions (the curves are the same in both panels). Note the different scales for the upper and lower panels.

# R ratio

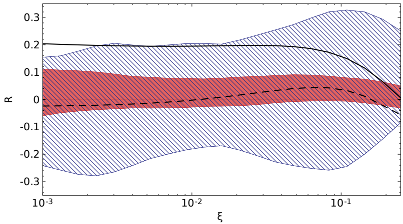



Figure: Ratio $R$ evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4$ GeV$^2$, $t = -0.35$ GeV$^2$ as a function of $\xi$.

The photon beam circular polarization asymmetry:

$$A_{CU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim Im(H)$$

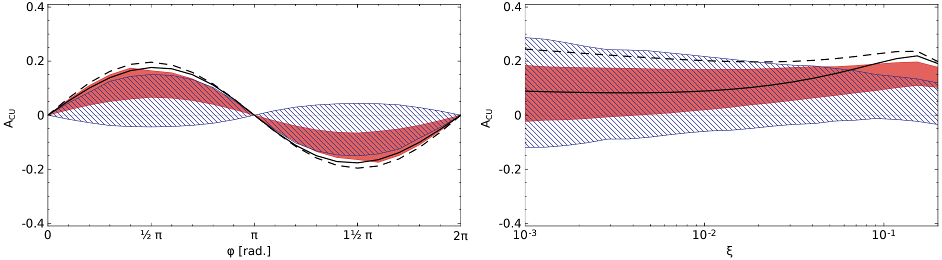



Figure: Circular asymmetry $A_{CU}$ evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4$ GeV$^2$, $t = -0.1$ GeV$^2$ and (left) $E_\gamma = 10$ GeV as a function of $\phi$ (right) and $\phi = \pi/2$ as a function of $\xi$. The cross sections used to evaluate the asymmetry are integrated over $\theta \in (\pi/4, 3\pi/4)$.

# Transverse target asymmetry

$$\frac{d\sigma_{\rm INT}^{\rm tpol}}{dQ'^2 d(\cos\theta) d\phi dt d\varphi_S} \sim \sin\varphi_S \Im\Big[\mathcal{H} - \frac{\xi^2}{1-\xi^2}\mathcal{E} + \widetilde{\mathcal{H}} + \frac{t}{4M^2}\widetilde{\mathcal{E}}\Big]. \quad (1)$$

The transverse spin asymmetry:

$$A_{UT}(\varphi_S) = \frac{\sigma(\varphi_S) - \sigma(\varphi_S - \pi)}{\sigma(\varphi_S) + \sigma(\varphi_S - \pi)}, \quad (2)$$

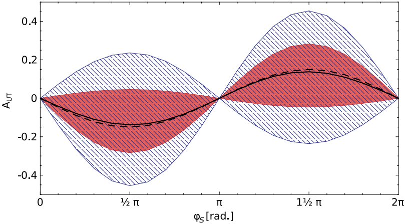



Figure: Transverse target spin asymmetry $A_{UT}$ evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4$ GeV$^2$, $t = t_0$ and $E_\gamma = 10$ GeV as a function of $\varphi_S$. The cross sections used to evaluate the asymmetry are integrated over $\theta \in (\pi/4, 3\pi/4)$.

# Experimental status

Rafayel Paremuzyan PhD thesis

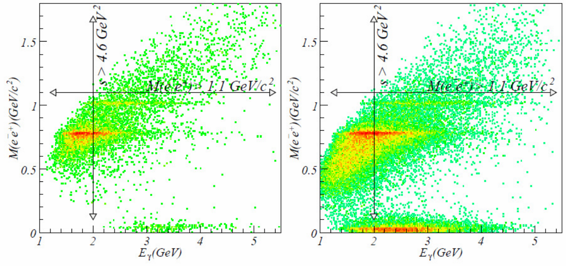



Figure: $e^+e^-$ invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

# Experimental status

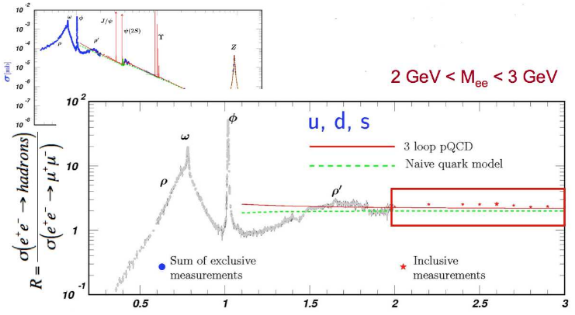
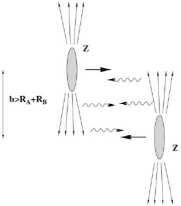



FIG. 4: Measurements of $e^+e^-$ annihilation into hadrons show a resonance-free window between the $\rho'$ and the $J/\psi$, which is ideal for TCS studies at 12 GeV.

- CLAS - E12-12-001 : Preliminary results in the Pierre Chatagnon PhD thesis !

# Experimental prospects - Ultraperipheral collisions

B.Pire, L.Szymanowski, J.Wagner, PRD86




$$\sigma^{AB} = \int dk_A \frac{dn^A}{dk_A} \sigma^{\gamma B}(W_A(k_A)) + \int dk_B \frac{dn^B}{dk_B} \sigma^{\gamma A}(W_B(k_B))$$

(a) (b)

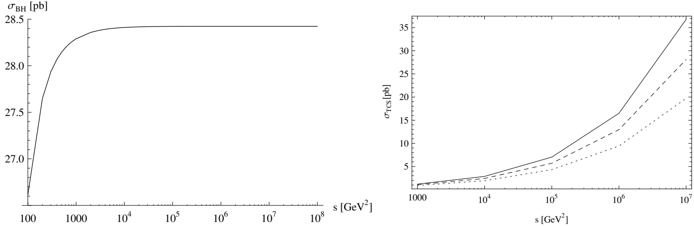



Figure: (a) The BH cross section (b) $\sigma_{TCS}$ as a function of $\gamma p$ c.m. energy squared $s$

# EIC

Yellow Report:

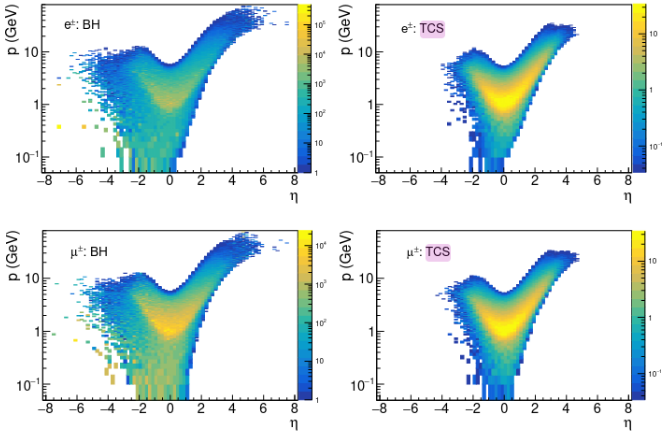



**Figure 8.69:** Momentum vs pseudorapidity for $e^+e^-$ (top) and $\mu^+\mu^-$ (bottom) at the $5 \times 41$ GeV collision energy, for an integrated luminosity of 10 $\text{fb}^{-1}$. Left: BH, right: TCS.

More detailed analysis under way: Kayleigh Gates, Daria Sokhan.

# Summary

- TCS is a mandatory complementary measurement to DVCS, cleanest way to test universality of GPDs,
- Timelike-spacelike relations at LO/NLO gives us tools to use TCS data in DVCS CFF fits, with special sensitivity to $Q^2$ dependence,
- First data-driven and model-free predictions for TCS using global DVCS data
- TCS measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV, results from CLAS12 expected soon!
- Possible also in UPCs in LHC.
- EIC - TCS study in Yellow Report
- Natural extension : replace in final state high mass dilepton by high mass diphoton: do not miss **Oskar Grocholski's** presentation in **20 minutes** !