Phenomenology of timelike Compton scattering

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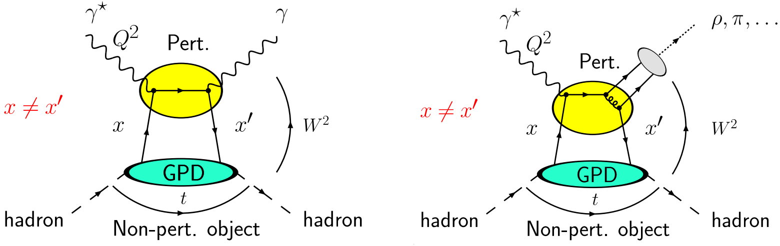
International Workshop on DVCS: From Observables to GPDs,
Ruhr-Universitä Bochum, February 10-12, 2014

B. Pire, L. Szymanowski and JW - Phys. Rev. D83 (2011),
D. Mueller, B. Pire, L. Szymanowski and JW - Phys. Rev. D86 (2012),
H. Moutarde, B. Pire, F. Sabatié, L. Szymanowski and JW - Phys. Rev. D87 (2013),

Processes



- Universality of GPDs,
- Meson production - additional difficulties,

So, in addition to spacelike DVCS ...

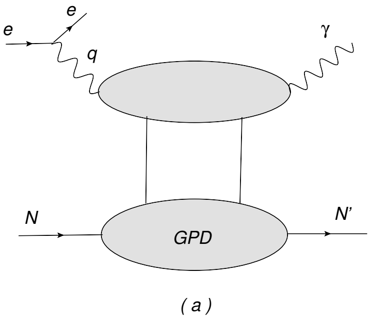


Figure: Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS

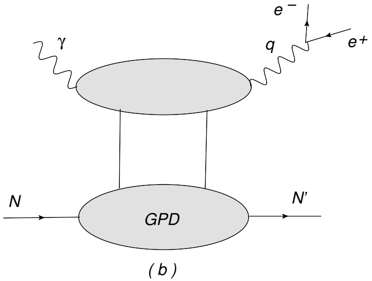


Figure: Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs
- another source for GPDs (special sensitivity on real part of GPD H),
- spacelike-timelike crossing,

Coefficient functions and Compton Form Factors

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

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

,where:

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

Coefficient functions

Renormalized coefficient functions for DVCS are given by

$$
\begin{aligned}
T^q(x) &= \left[C_0^q(x) + C_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^q(x)\right] - (x \to -x)\,, \\
T^g(x) &= \left[C_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^g(x)\right] + (x \to -x)\,, \\
\widetilde{T}^q(x) &= \left[\widetilde{C}_0^q(x) + \widetilde{C}_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \widetilde{C}_{coll}^q(x)\right] + (x \to -x)\,, \\
\widetilde{T}^g(x) &= \left[\widetilde{C}_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \widetilde{C}_{coll}^g(x)\right] - (x \to -x)\,.
\end{aligned}
$$

The results for DVCS and TCS cases are simply related:

$$
{}^{TCS}T(x,\eta) = \pm\left({}^{DVCS}T(x,\xi=\eta) + i\pi \cdot C_{coll}(x,\xi=\eta)\right)^* \,,
$$

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

where $+$ $(-)$ sign corresponds to vector (axial) case.

Models

In our analysis we use two GPD models based on double distibution:

$$F_i(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-x)\, f_i(\beta,\alpha,t) + D_i^F\left(\frac{x}{\xi},t\right)\Theta(\xi^2-x^2)\,,$$

The DD f_i reads

$$f_i(\beta,\alpha,t) = g_i(\beta,t)\, h_i(\beta)\, \frac{\Gamma(2n_i+2)}{2^{2n_i+1}\Gamma^2(n_i+1)} \frac{[(1-|\beta|)^2-\alpha^2]^{n_i}}{(1-|\beta|)^{2n_i+1}}\,,$$

where:

$$\begin{aligned}
h_g(\beta) &= |\beta|\, g(|\beta|)\,, & \tilde{h}_g(\beta) &= \beta\, \Delta g(|\beta|)\,,\\
h^q_{\rm sea}(\beta) &= q_{\rm sea}(|\beta|)\, {\rm sign}(\beta)\,, & \tilde{h}^q_{\rm sea}(\beta) &= \Delta q_{\rm sea}(|\beta|)\,,\\
h^q_{\rm val}(\beta) &= q_{\rm val}(\beta)\, \Theta(\beta)\,, & \tilde{h}^q_{\rm val}(\beta) &= \Delta q_{\rm val}(\beta)\, \Theta(\beta)\,.
\end{aligned}$$

D_i^F denotes the Polyakov-Weiss D-term. In our estimates we will use parametrizations obtained by a fit to the chiral soliton model.

- Factorized:
  based on MSTW08 PDFs with simple factorizing ansatz for t - dependence

$$
\begin{aligned}
g_u(\beta,t) &= \frac{1}{2}F_1^u(t)\,, & F_1^u(t) &= 2F_1^p(t) + F_1^n(t)\,,\\
g_d(\beta,t) &= F_1^d(t)\,, & F_1^d(t) &= F_1^p(t) + 2F_1^n(t)\,,\\
g_s(\beta,t) = g_g(\beta,t) &= F_D(t)\,, & F_D(t) &= (1 - t/M_V^2)^{-2}\,,
\end{aligned}
$$

  with $M_V = 0.84\,\mathrm{GeV}$, F_1^p and F_1^n are electromagnetic Dirac form factors of the proton and neutron. We use that model to construct only $\mathcal{H}$.
- Goloskokov-Kroll:
  based on CTEQ6m PDFs, and

$$
g_i(\beta,t) = \mathrm{e}^{b_i t}\,|\beta|^{-\alpha_i' t}
$$

  and simple parametrization of the sea quarks:

$$
\begin{aligned}
H^u_{\rm sea} &= H^d_{\rm sea} = \kappa_s H^s_{\rm sea}\,,\\
\text{with} \quad \kappa_s &= 1 + 0.68/(1 + 0.52\ln Q^2/Q_0^2)\,,
\end{aligned}
$$

  with the initial scale of the CTEQ6m PDFs $Q_0^2 = 4$ GeV^2. $\widetilde{H}$ is constructed using the Blümlein - Böttcher (BB) polarized PDF parametrization to fix the forward limit. Meson electroproduction data from HERA and HERMES have been considered to fix parameters for this GPD in the GK model.

Compton Form Factors - DVCS - $Re(\mathcal{H})$

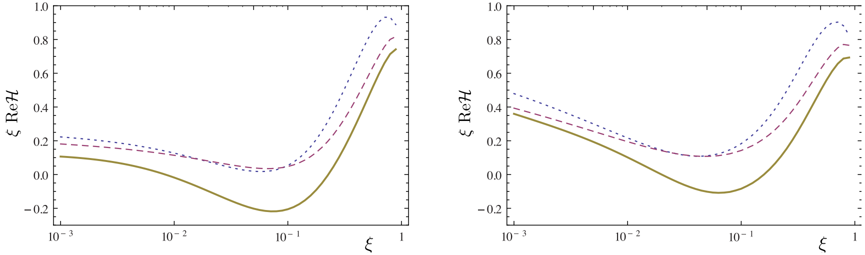


Figure: The real part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Compton Form Factors - DVCS - $Im(\mathcal{H})$

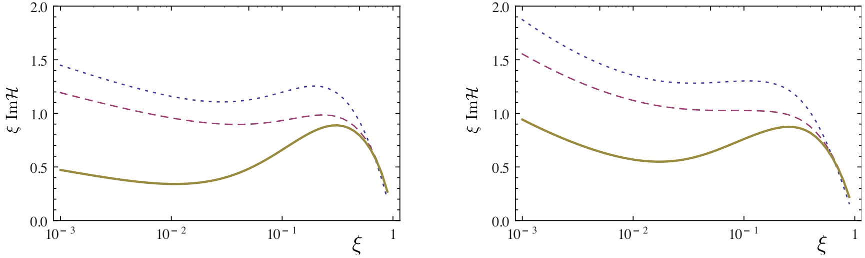


Figure: The imaginary part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Few words about factorization scale (PRELIMINARY).

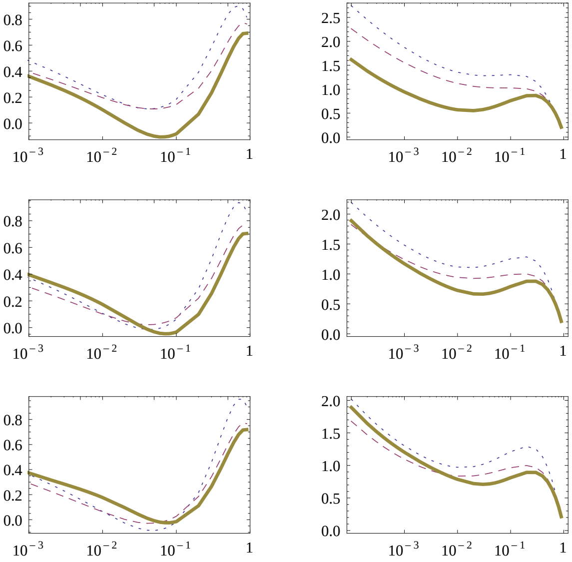


Figure: Left column - $Re(\mathcal{H}(\xi))$, right column - $Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

Few words about factorization scale (PRELIMINARY).

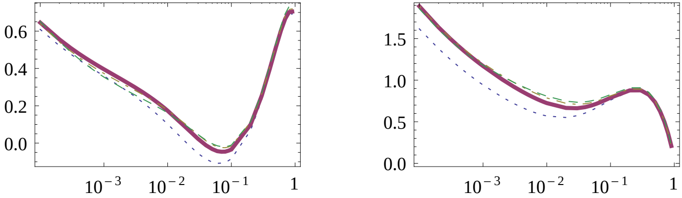


Figure: Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

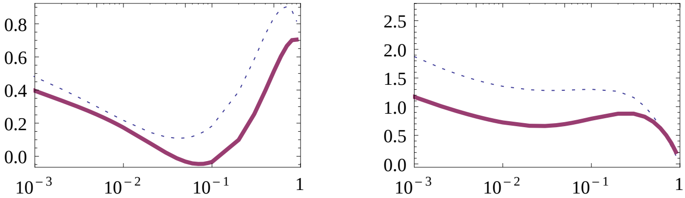


Figure: Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$. Dotted - LO with $Q^2 = mu_F^2$, Solid NLO with $Q^2 = \mu_F^2/2$.

Compton Form Factors - TCS - $Re(\mathcal{H})$

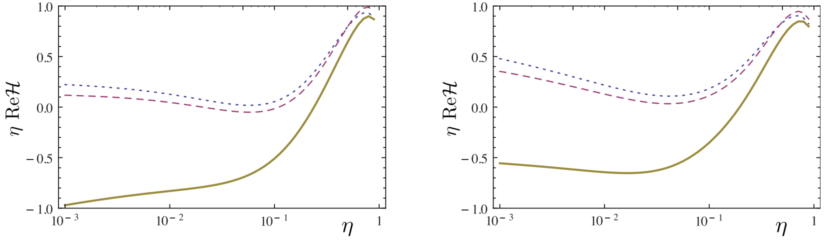


Figure: The real part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

Compton Form Factors - TCS - $Im(\mathcal{H})$

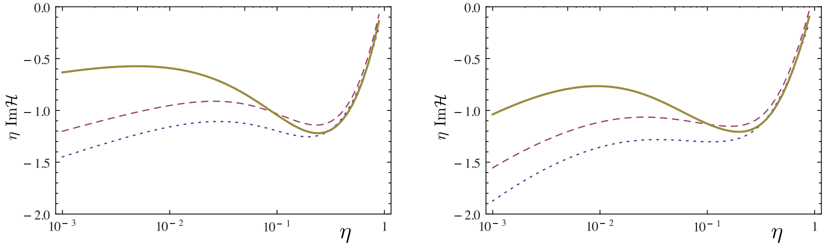
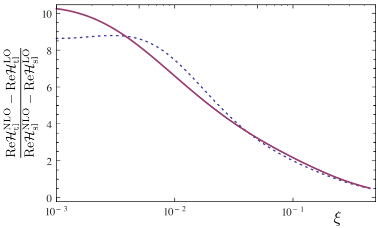


Figure: The imaginary part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

DVCS vs TCS



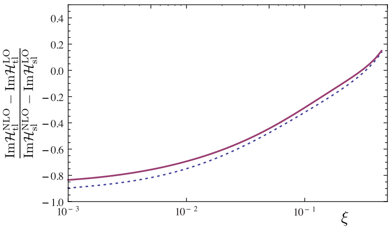


Figure: The **ratio** of the timelike to spacelike NLO corrections in the real (left) and imaginary (right) part of the CFF $\mathcal{H}$, in the GK (dashed) and factorized MSTW08 (solid)

"Model (in)dependence"

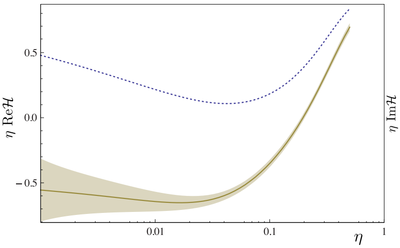


Figure: The dotted line shows the LO result and shaded bands around solid lines show the effect of a one sigma uncertainty of the input MSTW08 fit to the full NLO result.

Few words about factorization scale (PRELIMINARY).

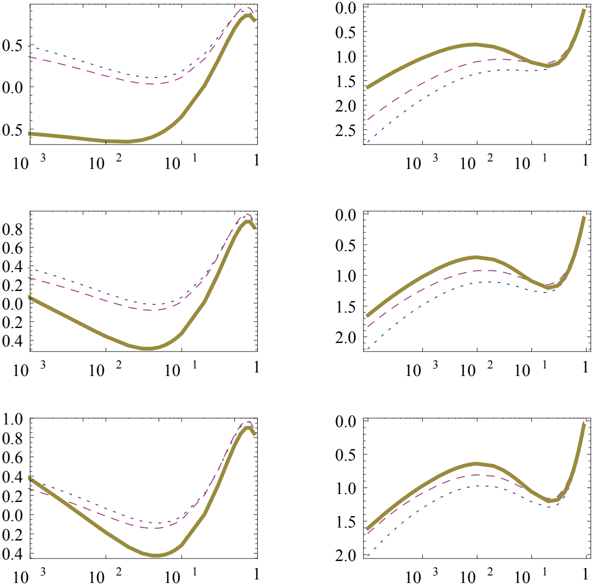


Figure: Left column - $Re(\mathcal{H}(\xi))$, right column - $Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

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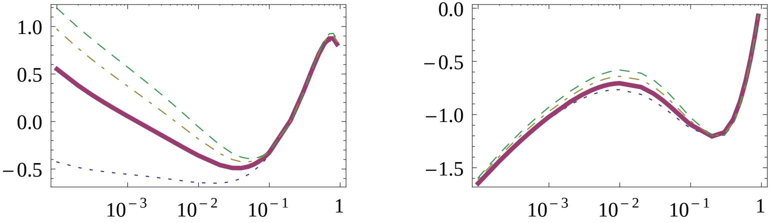


Figure: Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

TCS and Bethe-Heitler contribution to exlusive lepton pair photoproduction.

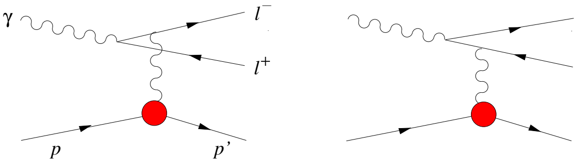


Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

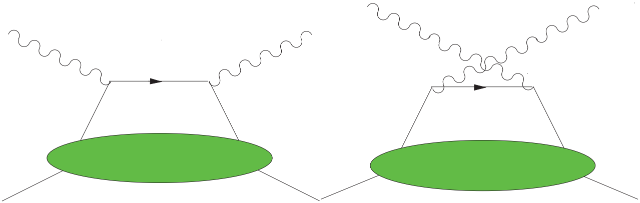


Figure: Handbag diagrams for the Compton process in the scaling limit.

TCS

Berger, Diehl, Pire, 2002

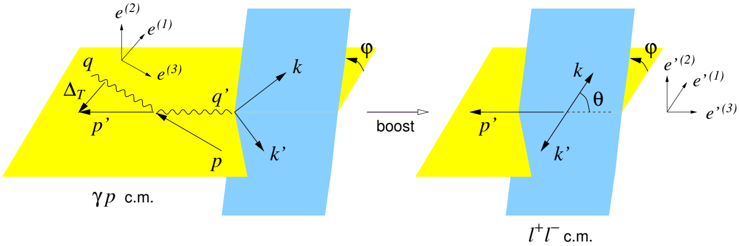
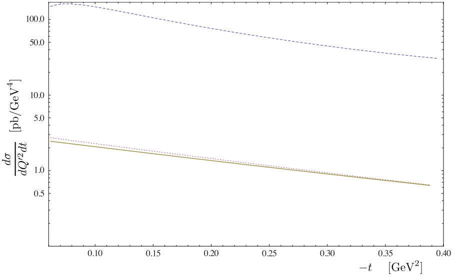


Figure: Kinematical variables and coordinate axes in the γp and $\ell^+\ell^-$ c.m. frames.

Interference

B-H dominant for not very high energies:



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

$$\frac{d\sigma_{INT}}{dQ'^2 \, dt \, d\cos\theta \, d\varphi} \sim \cos\varphi \cdot \ \mathrm{Re}\,\mathcal{H}(\eta, t)$$

Linear in GPD's, odd under exchange of the l^+ and l^- momenta $\Rightarrow$ angular distribution of lepton pairs is a good tool to study interference term.

JLAB 6 GeV data

Rafayel Paremuzyan PhD thesis

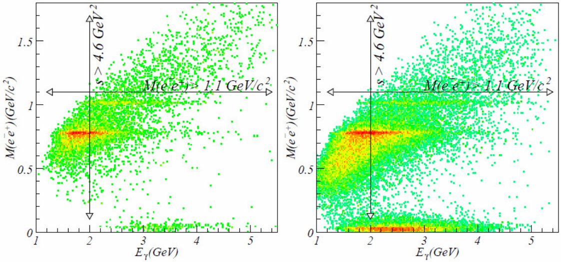


Figure: e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1\,\mathrm{GeV}$ and $s_{\gamma p} > 4.6\,\mathrm{GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

Theory vs experiment

R.Paremuzyan and V.Guzey:

$$R = \frac{\int d\phi \;\; \cos\phi \; d\sigma}{\int \;\; d\phi \; d\sigma}$$

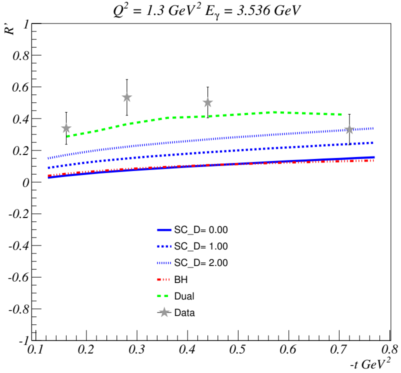


Figure: Thoeretical prediction of the ratio R for various GPDs models. Data points after combining both e1-6 and e1f data sets.

Jefferson Lab PAC 39 Proposal
Timelike Compton Scattering and J/ψ photoproduction on the proton in e^+e^- pair production with CLAS12 at 11 GeV

I. Albayrak,[1] V. Burkert,[2] E. Chudakov,[2] N. Dashyan,[3] C. Desnault,[4] N. Gevorgyan,[3]
Y. Ghandilyan,[3] B. Guegan,[4] M. Guidal*,[4] V. Guzey,[2,5] K. Hicks,[6] T. Horn*,[1] C. Hyde,[7]
Y. Ilieva,[8] H. Jo,[4] P. Khetarpal,[9] F.J. Klein,[1] V. Kubarovsky,[2] A. Marti,[4] C. Munoz Camacho,[4]
P. Nadel-Turonski*†,[2] S. Niccolai,[4] R. Paremuzyan*,[4,3] B. Pire,[10] F. Sabatié,[11] C. Salgado,[12]
P. Schweitzer,[13] A. Simonyan,[3] D. Sokhan,[4] S. Stepanyan*,[2] L. Szymanowski,[14]
H. Voskanyan,[3] J. Wagner,[14] C. Weiss,[2] N. Zachariou,[8] and the CLAS Collaboration.

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[2] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*
[3] *Yerevan Physics Institute, 375036 Yerevan, Armenia*
[4] *Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France*
[5] *Hampton University, Hampton, Virginia 23668*
[6] *Ohio University, Athens, Ohio 45701*

Approved experiment at Hall B, and LOI for Hall A.

TCS

$$R(\eta) = \frac{2\int_0^{2\pi} d\varphi\ \cos\varphi\ \frac{dS}{dQ'^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2 dt d\varphi}}\ ,$$

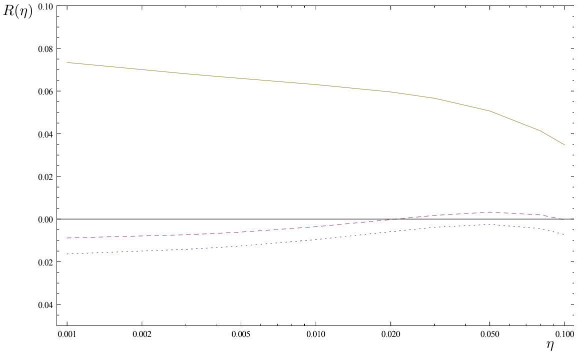


Figure: Ratio R as a function of η, for $Q^2 = \mu_F^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. The dotted line represents LO contribution and the solid line represents NLO result.

TCS

The photon beam circular polarization asymmetry:

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \,,$$

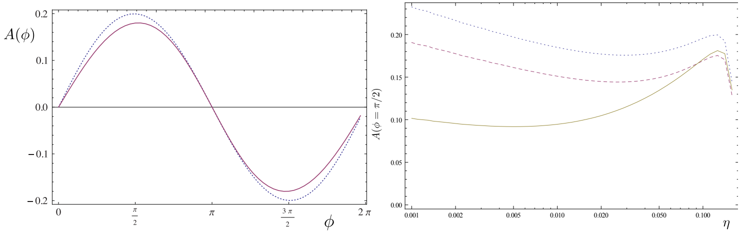


Figure: (Left) Photon beam circular polarization asymmetry as a function of ϕ, for $t = -0.1$ GeV^2, $Q^2 = \mu^2 = 4$ GeV^2, integrated over $\theta \in (\pi/4, 3\pi/4)$ and for $E_\gamma = 10$ GeV ($\eta \approx 0.11$). (Right) The η dependence of the photon beam circular polarization asymmetry for $Q^2 = \mu^2 = 4$ GeV^2, and $t = -0.2$ GeV^2 integrated over $\theta \in (\pi/4, 3\pi/4)$. The LO result is shown as the dotted line, the full NLO result by the solid line.

Linear polarization

Work in progress with Alexander Goritchnig, Bernard Pire.

$$\epsilon(q)^\mu = \delta^{1\mu} \tag{1}$$

Momenta of other particles in $\gamma - p$ c.m. frame are given by:

$$\begin{aligned} q^\mu &= (q^0, 0, 0, q^0) \\ p^\mu &= (p^0, 0, 0, -q^0) \\ q'^\mu &= (q'^0, \Delta_T \cos\Phi_h, \Delta_T \sin\Phi_h, q'^3) \\ p'^\mu &= (p'^0, -\Delta_T \cos\Phi_h, -\Delta_T \sin\Phi_h, -q'^3) \end{aligned} \tag{2}$$

where Φ_h is the angle between polarization vector and hadronic plane:

$$\sin\Phi_h = \vec{\epsilon}(q) \cdot \vec{n} = \vec{\epsilon}(q) \cdot \frac{\vec{p'} \times \vec{p}}{|\vec{p'} \times \vec{p}|} \tag{3}$$

where $\vec{n}$ is the vector normal to the hadronic plane.

$$
\begin{aligned}
\sigma_x^{(INT)} &= \frac{\alpha^3}{16\pi^2 s^2}\frac{1}{Q^2}\left(\frac{4s \mid \Delta_\perp \mid}{Qt}\right)\Bigg\{ \\
& \left[\frac{1+\cos^2\theta}{\sin\theta}\cos\phi - \sin\theta\cos(2\Phi_h+3\phi)\right]\left(\mathsf{Re}(\mathcal{H}F_1) - \frac{t}{4M^2}\mathsf{Re}(\mathcal{E}F_2)\right) \\
- & \left[\frac{1+\cos^2\theta}{\sin\theta}\cos\phi + \sin\theta\cos(2\Phi_h+3\phi)\right]\mathsf{Re}(\eta\tilde{\mathcal{H}}(F_1+F_2))\Bigg\}
\end{aligned}
$$

We propose the following observable which is sensitive only to the interference term, and which provides us with an information about $\tilde{\mathcal{H}}$:

$$
C = \frac{a_1}{a_3}, \tag{4}
$$

where:

$$
\begin{aligned}
a_1 &= \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{1}{\pi}\int_0^{2\pi} d\phi\cos(\phi)\frac{d\sigma}{dtdQ^2 d\Omega d\Phi_h}, \\
a_3 &= \int_{\pi/4}^{3\pi/4} \sin\theta d\theta \frac{1}{\pi}\int_0^{2\pi} d\phi\cos(3\phi)\frac{d\sigma}{dtdQ^2 d\Omega d\Phi_h}.
\end{aligned} \tag{5}
$$

,so:

$$
C = \frac{2-3\pi}{2+\pi}\frac{1}{\cos(2\Phi_h)}\frac{\left(\mathsf{Re}(\mathcal{H}F_1) - \frac{t}{4M^2}\mathsf{Re}(\mathcal{E}F_2)\right) - \left(\mathsf{Re}(\eta\tilde{\mathcal{H}}(F_1+F_2)\right)}{\left(\mathsf{Re}(\mathcal{H}F_1) - \frac{t}{4M^2}\mathsf{Re}(\mathcal{E}F_2)\right) + \left(\mathsf{Re}(\eta\tilde{\mathcal{H}}(F_1+F_2)\right)} \tag{6}
$$

Experimental possibilities

Hall D - rates probably too small.
Approved CLAS12 experiment - "Meson Spectroscopy with low Q^2 electron scattering in CLAS12".

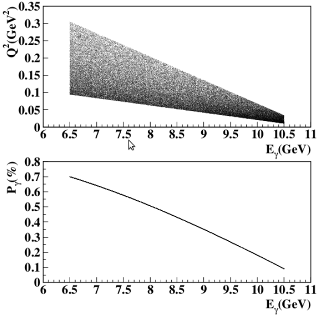
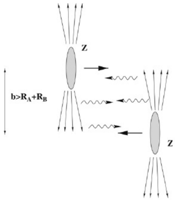


Figure 8: Q^2 and linear polarization of inelastic events within the geometrical and momentum acceptance of the FT.

Ultraperipheral collisions



$$\sigma = \int \frac{dn(k)}{dk} \sigma_{\gamma p}(k) dk$$

$\sigma_{\gamma p}(k)$ is the cross section for the $\gamma p \to p l^+ l^-$ process and k is the γ's energy, and $\frac{dn(k)}{dk}$ is an equivalent photon flux.

$$\frac{dn}{dk} = \frac{2Z^2 \alpha_{EM}}{\pi k} \left[\omega^{pA} K_0(\omega^{pA}) K_1(\omega^{pA}) - \frac{{\omega^{pA}}^2}{2} \left(K_1^2(\omega^{pA}) - K_0^2(\omega^{pA}) \right) \right] \quad (7)$$

First predictions made for LHC (in p-p), work in progress for fixed target at AFTER (with LS and J.-P. Landsberg).

Summary

- inclusion of NLO corrections to the coefficient function is an important issue,
- difference of these corrections between the spacelike and timelike regimes is sizeable,
- This effect is particularly big when one considers the real part of CFFs in the timelike case.
- TCS already measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV, is it possible at COMPASS?
- Linear polarization in TCS may give some information on $\tilde{H}$.
- TCS accesible in Ultraperipheral collisions (LHC, RHIC, AFTER)
- DIS 2014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DVCS - JLab : beam spin asymmetry

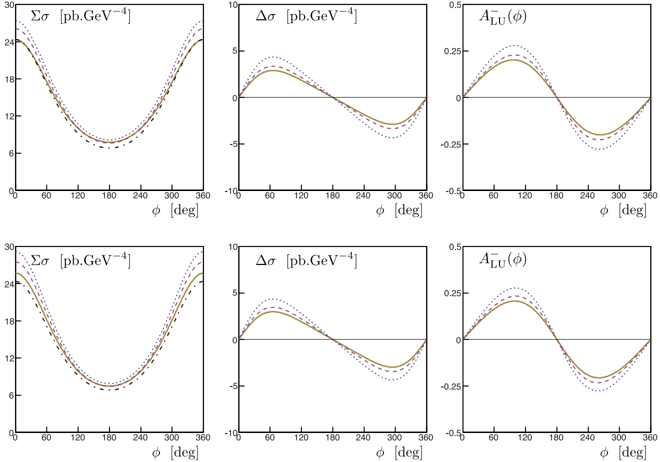


Figure: $E_e = 11\,\mathrm{GeV}, \mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.2$ GeV^2. On the first line, the GPD $H(x, \xi, t)$ is parametrized by the GK model, on the second line by factorized model based on the MSTW08 parametrization. The contributions from other GPDs are not included. In all plots, the LO - dotted line, the full NLO - solid line, NLO result without the gluonic contribution - dashed line, the BH- dashdotted line.

DVCS - COMPASS: mixed charge-spin asymmetry

$$\mathcal{S}_{\mathrm{CS,U}}(\phi) \equiv d\sigma^{\overset{+}{\rightarrow}} + d\sigma^{\overset{-}{\leftarrow}}, \mathcal{D}_{\mathrm{CS,U}}(\phi) \equiv d\sigma^{\overset{+}{\rightarrow}} - d\sigma^{\overset{-}{\leftarrow}}, \mathcal{A}_{\mathrm{CS,U}}(\phi) \equiv \frac{\mathcal{D}_{\mathrm{CS,U}}}{\mathcal{S}_{\mathrm{CS,U}}}$$

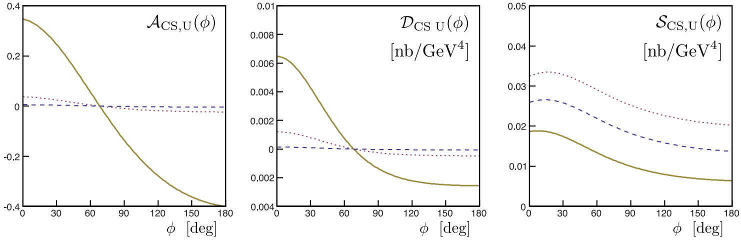
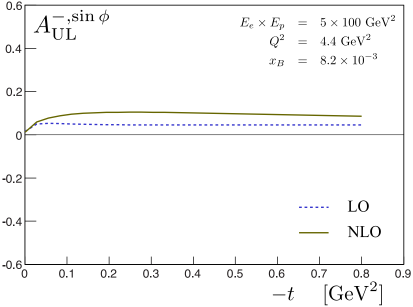


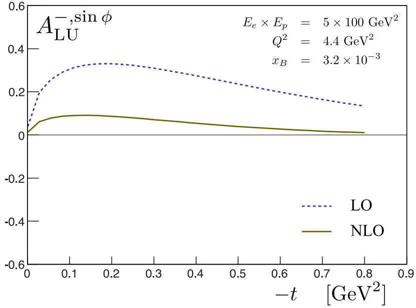
Figure: $\xi = 0.05, Q^2 = 4$ GeV^2, $t = -0.2$ GeV^2, GK model. In all plots, the LO result - dotted line, the full NLO result - solid line and the NLO result without the gluonic contribution as the dashed line.

DVCS - EIC: target longitudinal spin asymmetry A_{UL}



$$A_{UL}^{\sin\phi} \propto \mathrm{Im}\left[\xi(F_1+F_2)(\mathcal{H}+\frac{\xi}{1+\xi}\mathcal{E}) + F_1\widetilde{\mathcal{H}} - \xi(\frac{\xi}{1+\xi}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}\right]$$

DVCS - EIC: beam spin asymmetry A_{LU}



$$A_{LU}^{\sin\phi} \propto \mathrm{Im}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right]$$

Few words about factorization scale (PRELIMINARY).

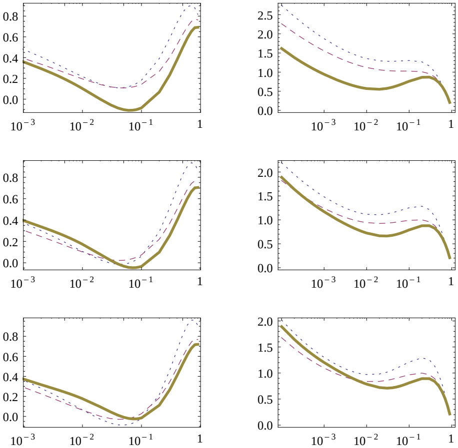


Figure: Left column - $Re(\mathcal{H}(\xi))$, right column - $Im(\mathcal{H}(\xi))$, $Q^2 = 4\,\mathrm{GeV}^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$