

Timelike vs spacelike deeply virtual Compton scattering at next to leading order: role of gluons

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Outline

- 1 Timelike Compton Scattering - Introduction
- 2 Basic properties of TCS, first experimental results
- 3 TCS at NLO
- 4 Ultraperipheral collisions

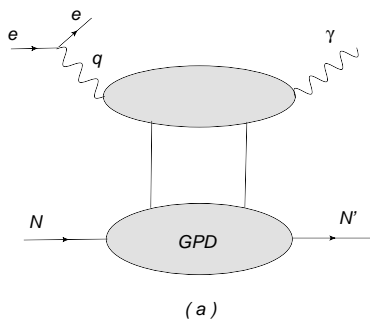


Figure: Deeply Virtual Compton Scattering : $lN \rightarrow l'N'\gamma$

Skewness ξ :

$$\xi = -\frac{(P' - P)n}{(P + P')n}$$

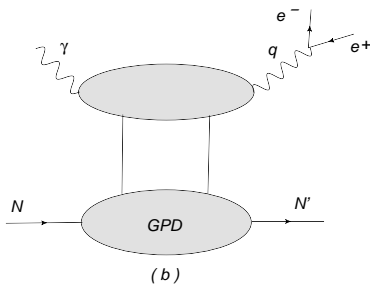


Figure: Timelike Compton Scattering: $\gamma N \rightarrow l^+ l^- N'$

Skewness η :

$$\eta = -\frac{(P' - P)n}{(P + P')n}$$

Why TCS?

- GPDs enter factorization theorems for hard exclusive reactions (DVCS, deeply virtual meson production, TCS etc.), in a similar manner as PDFs enter factorization theorem for DIS
- First moment of GPDs enters the Ji's sum rule for the angular momentum carried by partons in the nucleon,
- Deeply Virtual Compton Scattering (DVCS) is a golden channel for GPDs extraction,
- Why TCS: universality of the GPDs, spacelike-timelike crossing and understanding the structure of the NLO corrections,
- Experiments *at low energy*: CLAS 6 GeV \rightarrow CLAS 12 GeV, *at high energy*: COMPASS, RHIC, LHC and AFTER@LHC ?

Coordinates

Berger, Diehl, Pire, 2002

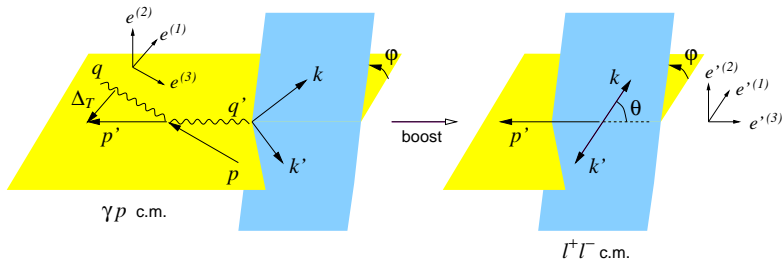


Figure: Kinematical variables and coordinate axes in the γp and $\ell^+ \ell^-$ c.m. frames.

The Bethe-Heitler contribution

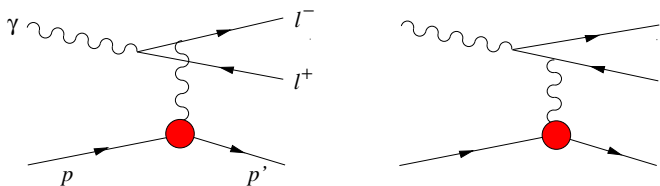


Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

$$\frac{d\sigma_{BH}}{dQ'^2 dt d\cos\theta} \approx 2\alpha^3 \frac{1}{-tQ'^4} \frac{1 + \cos^2\theta}{1 - \cos^2\theta} \left(F_1(t)^2 - \frac{t}{4M_p^2} F_2(t)^2 \right),$$

For small θ BH contribution becomes very large

The Compton contribution

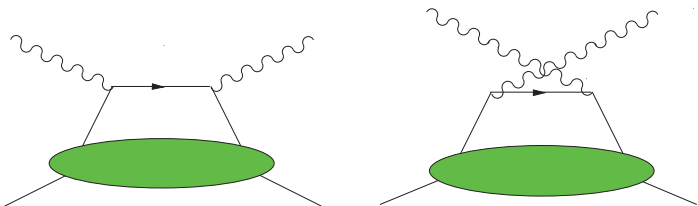


Figure: Handbag diagrams for the Compton process in the scaling limit.

$$\frac{d\sigma_{TCS}}{dQ'^2 d\Omega dt} \approx \frac{\alpha^3}{8\pi} \frac{1}{s^2} \frac{1}{Q'^2} \left(\frac{1 + \cos^2 \theta}{4} \right) 2(1 - \xi^2) |\mathcal{H}(\xi, t)|^2,$$

$$\mathcal{H}(\xi, t) = \sum_q e_q^2 \int_{-1}^1 dx T(x, \xi, Q') H^q(x, \xi, t),$$

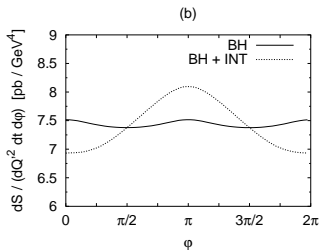
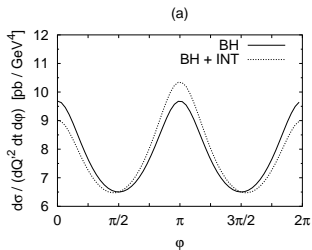
Interference

The interference part of the cross-section for $\gamma p \rightarrow l^+ l^- p$ with unpolarized protons and photons is given at leading order by

$$\frac{d\sigma_{INT}}{dQ^2 dt d\cos\theta d\varphi} \sim \cos\varphi \operatorname{Re}\mathcal{H}(\xi, t)$$

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.

Berger, Diehl, Pire, 2002



B-H dominant for small energies;

JLAB 6 GeV data

Rafael Paredes PhD thesis

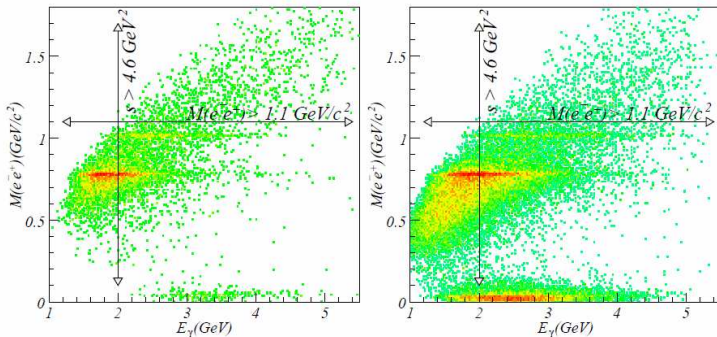


Figure: e^+e^- invariant mass distribution vs quasi-real photon energy. For TCS analysis $M(e^+e^-) > 1.1 \text{ GeV}/c^2$ and $s_{\gamma p} > 4.6 \text{ GeV}^2$ regions are chosen. Left graph represents e1-6 data set, right one is from e1f data set.

There is more data from g12 data set, soon to be analyzed. 12 GeV upgrade enables exploration of invariant masses up to $Q^2 = 9 \text{ GeV}^2$ mass.

Theory vs experiment

R.Paremuzyan and V.Guzey:

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

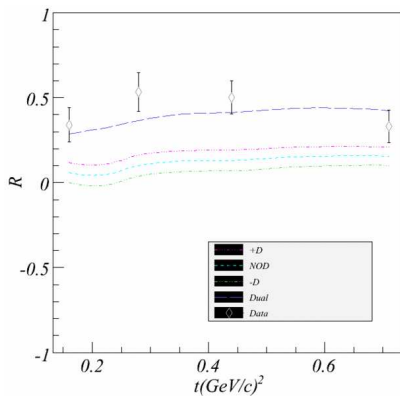


Figure: Theoretical prediction of the ratio R for various GPDs models.

Motivation for NLO

Why do we need NLO corrections to TCS:

- gluons enter at NLO,
- DIS versus Drell-Yan: big K-factors
- reliability of the results, factorization scale dependence,

$$\log \frac{-Q^2}{\mu_F^2} \rightarrow \log \frac{Q^2}{\mu_F^2} \pm i\pi,$$

Belitsky, Mueller, Niedermeier, Schafer, Phys.Lett.B474 ,2000.

Pire, L.Sz., Wagner, Phys.Rev.D83, 2011.

General Compton Scattering:

$$\gamma^*(q_{in})N \rightarrow \gamma^*(q_{out})N'$$

- DVCS: $q_{in}^2 < 0$, $q_{out}^2 = 0$
- TCS: $q_{in}^2 = 0$, $q_{out}^2 > 0$
- DDVCS: $q_{in}^2 < 0$, $q_{out}^2 > 0$

Amplitude:

$$\mathcal{A}^{\mu\nu} = -g_T^{\mu\nu} \int_{-1}^1 dx \left[\sum_q^{n_F} T^q(x) F^q(x) + T^g(x) F^g(x) \right] \\ + i\epsilon_T^{\mu\nu} \int_{-1}^1 dx \left[\sum_q^{n_F} \tilde{T}^q(x) \tilde{F}^q(x) + \tilde{T}^g(x) \tilde{F}^g(x) \right],$$

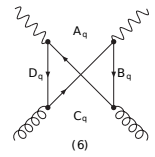
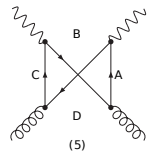
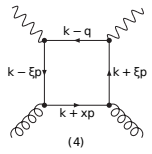
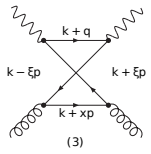
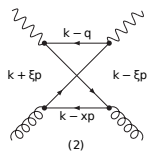
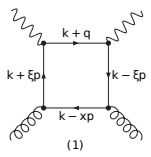
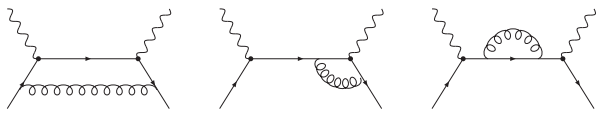
$$T^q(x) = \left[C_0^q(x) + C_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^q(x) \right] - (x \rightarrow -x),$$

$$T^g(x) = \left[C_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^g(x) \right] + (x \rightarrow -x),$$

$$\tilde{T}^q(x) = \left[\tilde{C}_0^q(x) + \tilde{C}_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \tilde{C}_{coll}^q(x) \right] + (x \rightarrow -x),$$

$$\tilde{T}^g(x) = \left[\tilde{C}_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \tilde{C}_{coll}^g(x) \right] - (x \rightarrow -x).$$

Diagrams



Results: TCS + DVCS + DDVCS

DVCS:

Quark coefficient functions:

$$C_0^q(x, \xi) = -e_q^2 \frac{1}{x + \xi - i\varepsilon},$$

$$C_1^q(x, \xi) = \frac{e_q^2 \alpha_S C_F}{4\pi} \frac{1}{x + \xi - i\varepsilon} \left[9 - 3 \frac{x + \xi}{x - \xi} \log\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) - \log^2\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) \right],$$

$$C_{coll}^q(x, \xi) = \frac{e_q^2 \alpha_S C_F}{4\pi} \frac{1}{x + \xi - i\varepsilon} \left[-3 - 2 \log\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) \right],$$

$$\tilde{C}_0^q(x, \xi) = -e_q^2 \frac{1}{x + \xi - i\varepsilon},$$

$$\tilde{C}_1^q(x, \xi) = \frac{e_q^2 \alpha_S C_F}{4\pi} \frac{1}{x + \xi - i\varepsilon} \left[9 - \frac{x + \xi}{x - \xi} \log\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) - \log^2\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) \right],$$

$$\tilde{C}_{coll}^q(x, \xi) = \frac{e_q^2 \alpha_S C_F}{4\pi} \frac{1}{x + \xi - i\varepsilon} \left[-3 - 2 \log\left(\frac{x + \xi}{2\xi} - i\varepsilon\right) \right],$$

where $C_F = (N_c^2 - 1)/(2N_c)$

DVCS

Gluon coefficient functions:

$$C_1^g(x, \xi) = \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{1}{(x + \xi - i\varepsilon)(x - \xi + i\varepsilon)} \times \left[2 \frac{x + 3\xi}{x - \xi} \log \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) - \frac{x + \xi}{x - \xi} \log^2 \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) \right],$$

$$C_{coll}^g(x, \xi) = \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{2}{(x + \xi - i\varepsilon)(x - \xi + i\varepsilon)} \left[-\frac{x + \xi}{x - \xi} \log \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) \right],$$

$$\tilde{C}_1^g(x, \xi) = \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{1}{(x + \xi - i\varepsilon)(x - \xi + i\varepsilon)} \times \left[-2 \frac{3x + \xi}{x - \xi} \log \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) + \frac{x + \xi}{x - \xi} \log^2 \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) \right],$$

$$\tilde{C}_{coll}^g(x, \xi) = \frac{\Sigma e_q^2 \alpha_S T_F}{4\pi} \frac{2}{(x + \xi - i\varepsilon)(x - \xi + i\varepsilon)} \left[\frac{x + \xi}{x - \xi} \log \left(\frac{x + \xi}{2\xi} - i\varepsilon \right) \right],$$

where $T_F = \frac{1}{2}$

Discussion

D. Mueller, B. Pire, L. Sz. and J. Wagner, Phys. Rev. D 86 (2012)

The relation between the coefficient functions for NLO DVCS and NLO TCS:

$$\begin{aligned} TCS_{T^q} &= DVCS_{T^q}^* - i\pi^{DVCS} C_{coll}^{q*} \\ TCS_{T^g} &= DVCS_{T^g}^* - i\pi^{DVCS} C_{coll}^{g*} . \end{aligned}$$

Models for GPDs

Double distribution + D-term

Müller 94, Ji 97, Radyushkin 97,
Polyakov, Weiss 99

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

- the polynomiality (Lorentz inv.) of the Mellin moments satisfied automatically

Models for GPDs

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- the polynomiality (Lorentz inv.) of the Mellin moments satisfied automatically
- models for DD $f_i(\beta, \alpha, t)$:

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

the profile function $h_i(\beta)$ related to forward PDF e.g. $h_{\text{val}}^q(\beta) = q_{\text{val}}(\beta) \Theta(\beta)$

$g_i(\beta, t)$ controls t -dependence of GPDs

Models for GPDs

Our predictions are based on two models of GPDs:

- Goloskokov-Kroll (GK) model

CTEQ6m PDFs and Regge type t -dependence $g_i(\beta, t) = e^{b_i t} |\beta|^{-\alpha'_i t}$

- model based on MSTW08 PDFs and on nucleon e-m. FFs

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

where

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

H. Moutarde, B. Pire, F. Sabatie, L.Sz. and J. Wagner, "On timelike and spacelike deeply virtual Compton scattering at next to leading order," Phys. Rev. D 87 (2013)

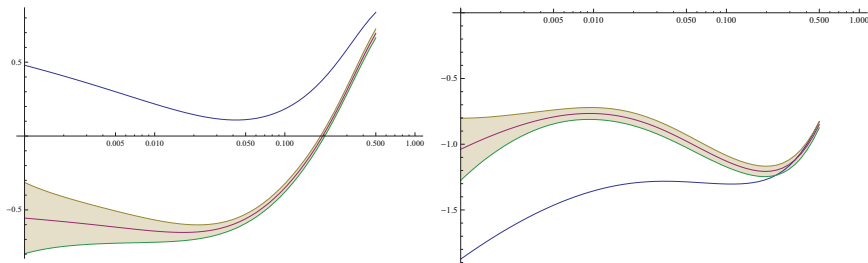


Figure: The real (left) and imaginary(right) parts of the TCS Compton Form Factor \mathcal{H} multiplied by ξ , as a function of ξ in the double distribution model based on MSTW08 parametrization, for $\mu_F^2 = Q^2 = 4 \text{ GeV}^2$ and $t = -0.1 \text{ GeV}^2$.

LO : solid line

Full NLO : shaded band

(one sigma uncertainty of the input MSTW08 fit to the parton distributions)

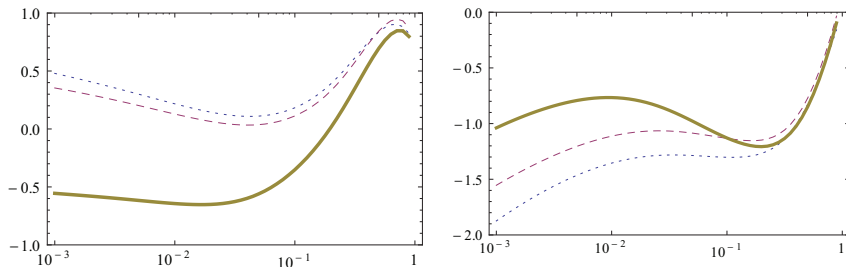


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LO : dotted line

LO + NLO-quark : dashed line

LO + NLO-quark + NLO-gluon: solid line

TCS:

GK

vs

MSTW

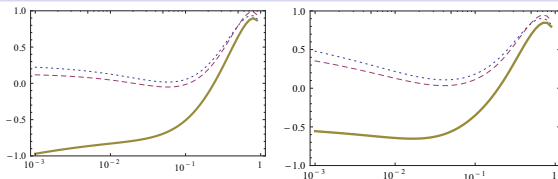


Figure: The real parts of the TCS Compton Form Factor \mathcal{H} multiplied by ξ , as a function of ξ in the double distribution model, for $\mu_F^2 = Q^2 = 4 \text{ GeV}^2$ and $t = -0.1 \text{ GeV}^2$.

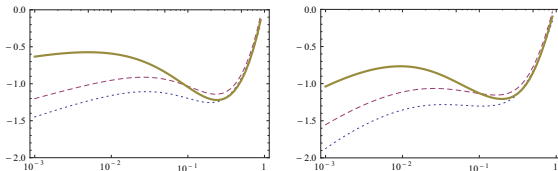


Figure: The imaginary parts of the TCS Compton Form Factor \mathcal{H} multiplied by ξ , as a function of ξ in the double distribution model, for $\mu_F^2 = Q^2 = 4 \text{ GeV}^2$ and $t = -0.1 \text{ GeV}^2$.

LO: dotted line

LO + NLO-quark: dashed line

LO + NLO-quark + NLO-gluon: solid line

Observables

These CFFs are the GPD dependent quantities which enter the scattering amplitudes

For DVCS they are defined as

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

Similar relation holds for TCS with ξ replaced by η .

$$d\sigma(l_+) + d\sigma(l_-)$$

$$d\sigma(l_-) - d\sigma(l_+)$$

Asymmetry

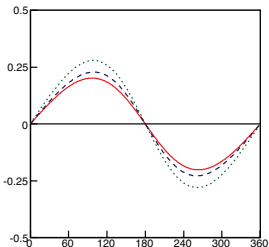
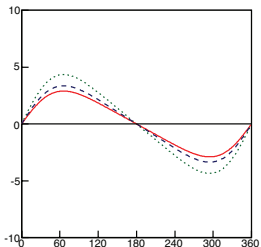
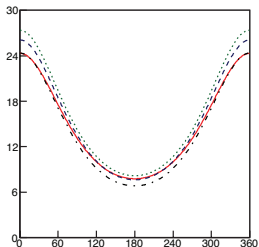


Figure: From left to right, the total DVCS cross section in pb/GeV^4 , the difference of cross sections for opposite lepton helicities in pb/GeV^4 , the corresponding asymmetry, all as a function of the usual ϕ angle (in Trento conventions) for $E_e = 11 \text{ GeV}$; $\mu_F^2 = Q^2 = 4 \text{ GeV}^2$ and $t = -0.2 \text{ GeV}^2$.

BH (left plot): dash-dotted line

LO: dotted line

LO + NLO-quark: dashed line

LO + NLO-quark + NLO-gluon: solid line

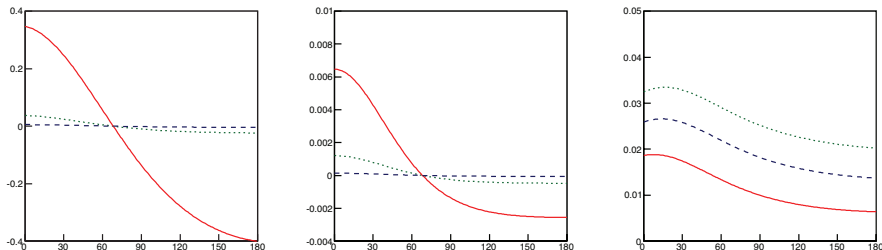


Figure: From left to right: mixed charge-spin asymmetry, mixed charge-spin difference and mixed charge-spin sum. The kinematical point is chosen as $\xi = 0.05$, $Q^2 = 4 \text{ GeV}^2$, $-t = 0.2 \text{ GeV}^2$.

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

LO: dotted line

LO + NLO-quark: dashed line

LO + NLO-quark + NLO-gluon: solid line

TCS: Observables for JLab@12GeV

Cross-section:

fixed $t = -0.2\text{GeV}^2$

fixed $\eta = 0.11$

LO: dotted line

LO + full NLO : solid line

BH (right plot): dashed line

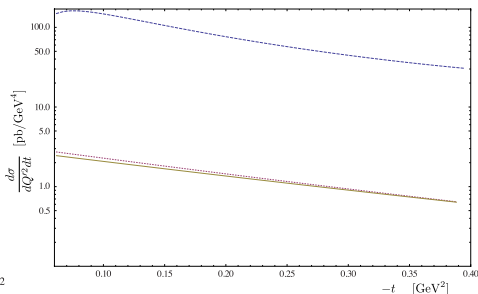
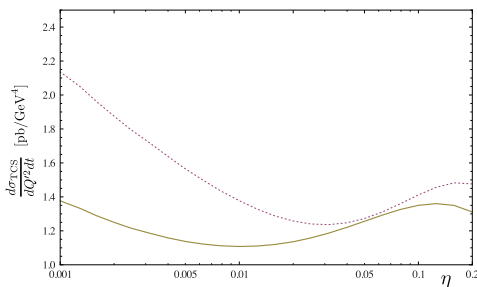


Figure: left : TCS contribution to the cross-section as a function of η for $Q^2 = \mu^2 = 4 \text{ GeV}^2$, and $t = -0.2 \text{ GeV}^2$ integrated over $\theta \in (\pi/4, 3\pi/4)$ and over $\phi \in (0, 2\pi)$. Right : TCS and Bethe-Heitler contributions to the cross-section as a function of t for $Q^2 = \mu^2 = 4 \text{ GeV}^2$ integrated over $\theta \in (\pi/4, 3\pi/4)$ and over $\phi \in (0, 2\pi)$ for $E_\gamma = 10 \text{ GeV}$ ($\eta \approx 0.11$).

large BH \Rightarrow need for more differential observables

TCS: Observables for JLab@12GeV

Azimuthal-dependent cross-section:

pure BH: dashed line

BH + Int LO: dotted line

BH + Int NLO : solid line

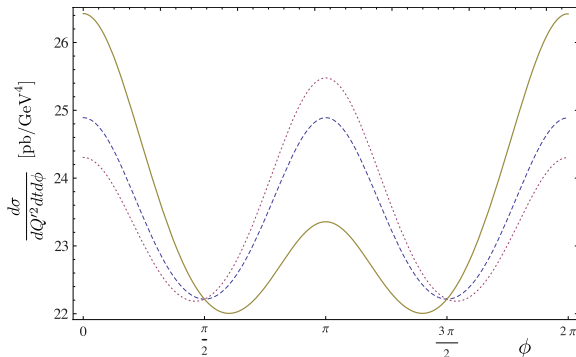


Figure: The ϕ dependence of the cross-section at $E_\gamma = 10$ GeV, $Q^2 = \mu^2 = 4$ GeV², and $t = -0.1$ GeV² integrated over $\theta \in (\pi/4, 3\pi/4)$.

TCS: Observables for JLab@12GeV

Observable linear in $Re\mathcal{H}$:

$$R(\eta) = \frac{2 \int_0^{2\pi} d\phi \cos\phi \frac{d\sigma}{dQ^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{d\sigma}{dQ^2 dt d\phi}}$$

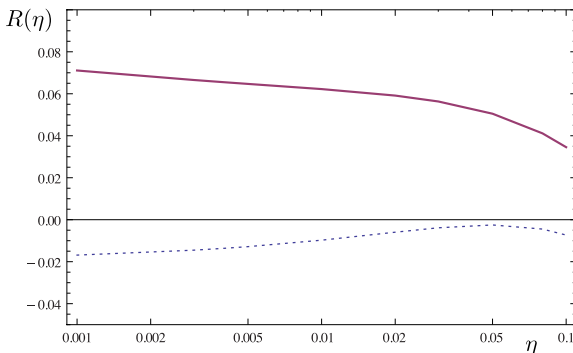


Figure: Ratio R as a function of η , for $Q^2 = \mu_F^2 = 4 \text{ GeV}^2$ and $t = -0.1 \text{ GeV}^2$.
 LO: dotted line NLO: solid line.

TCS: Observables for JLab@12GeV

The measure of $Im\mathcal{H}$:

the photon beam circular polarization asymmetry

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

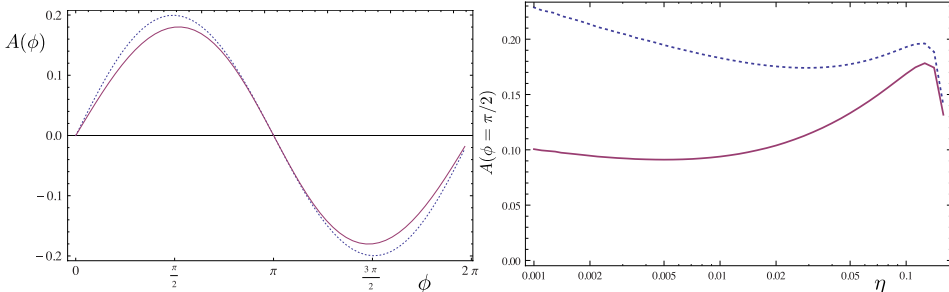


Figure: (left) Photon beam circular polarization asymmetry as a function of ϕ , for $t = -0.1 \text{ GeV}^2$, $Q^2 = \mu^2 = 4 \text{ GeV}^2$, integrated over $\theta \in (\pi/4, 3\pi/4)$ and for $E_\gamma = 10 \text{ GeV}^2$ ($\eta \approx 0.11$). (right) The η dependence of the photon beam circular polarization asymmetry for $Q^2 = \mu^2 = 4 \text{ GeV}^2$, and $t = -0.2 \text{ GeV}^2$ integrated over $\theta \in (\pi/4, 3\pi/4)$.

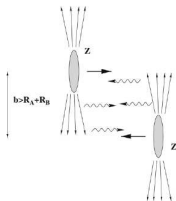
LO: dotted line

full NLO: solid line.

Summary

- TCS already measured in JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV.
- Big NLO corrections from gluon sector,
- Better understanding of large terms is needed - factorization scheme? resummation ?
- Compton scattering in ultraperipheral collisions at hadron colliders opens a new way to measure generalized parton distributions
- TCS is an experimentally challenging study at JLab, COMPASS, RHIC and LHC, in many cases due to limitations of original detectors

Ultraperipheral collisions



$$\sigma_{pp} = 2 \int \frac{dn(k)}{dk} \sigma_{\gamma p}(k) dk$$

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

For $\theta = [\pi/4, 3\pi/4]$, $\phi = [0, 2\pi]$, $t = [-0.05 \text{ GeV}^2, -0.25 \text{ GeV}^2]$, $Q'^2 = [4.5 \text{ GeV}^2, 5.5 \text{ GeV}^2]$, and photon energies $k = [20, 900] \text{ GeV}$ we get:

$$\sigma_{pp}^{BH} = 2.9 \text{ pb} .$$

The Compton contribution gives:

$$\sigma_{pp}^{TCS} = 1.9 \text{ pb} .$$

The interference cross section

B. Pire, L. Sz, J. Wagner, Phys. Rev. D (2009)

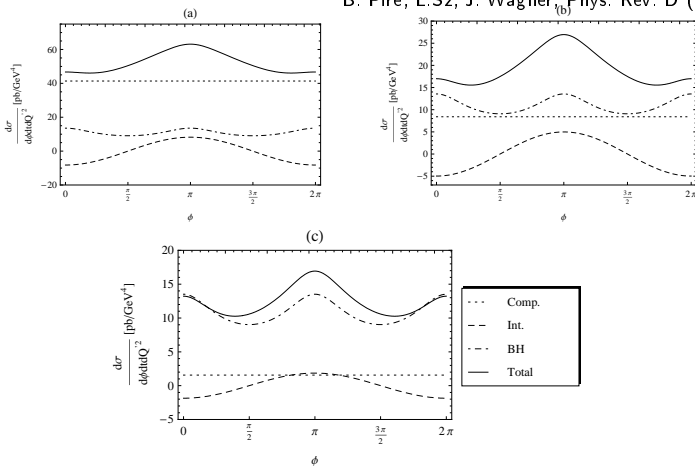


Figure: The differential cross sections (solid lines) for $t = -0.2 \text{ GeV}^2$, $Q'^2 = 5 \text{ GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of ϕ , for $s = 10^7 \text{ GeV}^2$ (a), $s = 10^5 \text{ GeV}^2$ (b), $s = 10^3 \text{ GeV}^2$ (c) with $\mu_F^2 = 5 \text{ GeV}^2$.

Ultraperipheral collisions at RHIC

$$L \cdot k \frac{dn}{dk} (\text{mb}^{-1} \text{sec}^{-1})$$

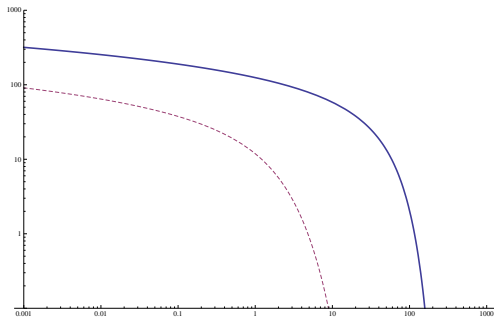


Figure: Effective luminosity of the photon flux as a function of photon energy k (GeV) in Au-Au (dashed line) and proton-proton (solid line) collisions.

$$\frac{d\sigma^{AuAu}}{dQ^2 dt d\phi} (\mu\text{b GeV}^{-4})$$

J. Wagner

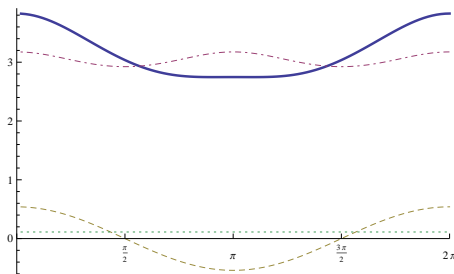


Figure: The differential cross sections (solid lines) for $t = -0.1 \text{ GeV}^2$, $Q'^2 = 5 \text{ GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of ϕ .

Compton: dotted line, B-H: dash-dotted line and Interfer.: dashed line

Total BH cross section (for $Q \in (2, 2.9) \text{ GeV}$, $t \in (-0.2, -0.05) \text{ GeV}^2$, $\theta = [\pi/4, 3\pi/4]$ and $\phi \in (0, 2\pi)$)

$$\sigma_{BH} = 41 \mu\text{b}$$

$$\text{Rate} = 0.04 \text{ Hz}$$

$$\frac{d\sigma^{PP}}{dQ^2 dt d\phi} \text{ (pb GeV}^{-4}\text{)}$$

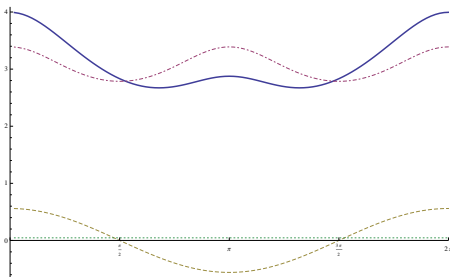


Figure: The differential cross sections (solid lines) for $t = -0.1 \text{ GeV}^2$, $Q'^2 = 5 \text{ GeV}^2$ and integrated over $\theta = [\pi/4, 3\pi/4]$, as a function of ϕ .

Compton: dotted line, B-H: dash-dotted line and Interf.: dashed line

Total BH cross section (for $Q \in (2, 2.9) \text{ GeV}$, $t \in (-0.2, -0.05) \text{ GeV}^2$, $\theta = [\pi/4, 3\pi/4]$ and $\phi \in (0, 2\pi)$)

$$\sigma_{BH} = 9\text{pb} \quad \text{Rate} = 5/\text{day}$$

THANK YOU FOR ATTENTION !