

GPDs in UPC with lepton pair production

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In collaboration with:

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In addition to spacelike DVCS ...

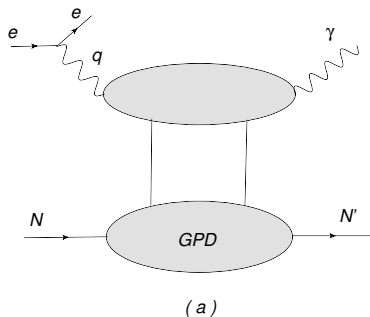
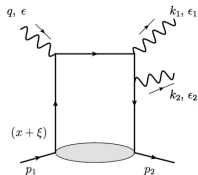
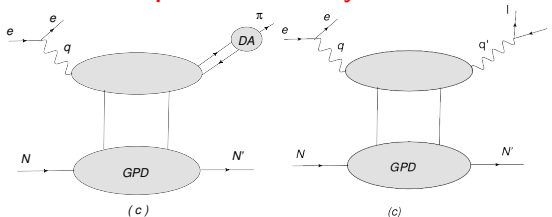


Figure: Deeply Virtual Compton Scattering (DVCS) : $lN \rightarrow l'N'\gamma$

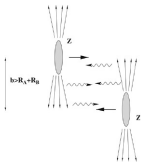
Other channels - what else is needed

- ▶ flavour separation:
 - ▶ DVCS on neutron
 - ▶ Deeply Virtual Meson Production (also with CC)
- ▶ $x = \xi$ line, deconvolution problem:
 - ▶ Double Deeply Virtual Compton Scattering (DDVCS) - Solid, HL-CLAS, EIC, JLAB20+
 - ▶ Hard photo- and electroproduction of a diphoton with a large invariant mass
- ▶ Universality checks, sensitivity to NLO effects:
 - ▶ **Timelike Compton Scattering (TCS)**
- ▶ Sensivity to gluons:
 - ▶ **Photoproduction of heavy mesons**

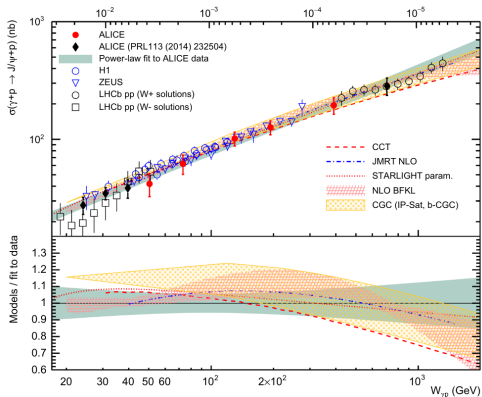


Photoproduction processes in Ultraperipheral Collisions:

LHCb, CMS, ALICE, RHIC, AFTER



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



Gluon GPDs in the UPC production of heavy mesons

Ivanov, Schafer, Szymanowski, Krasnikov - EPJ C34 (2004)

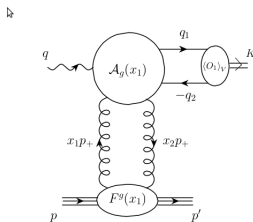


Figure 1: Kinematics of heavy vector meson photoproduction.

► Amplitude:

$$\mathcal{M} \sim \left(\frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \int_{-1}^1 dx \left[T_g(x, \xi) F^g(x, \xi, t) + T_q(x, \xi) F^{q,S}(x, \xi, t) \right],$$

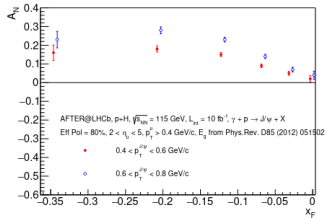
At LO $T^q = 0$, only gluons contribute!

► Single Transverse Spin Asymmetry:

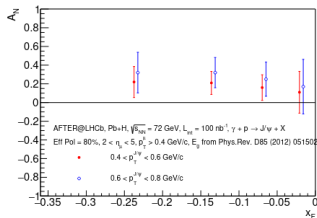
$$\mathcal{A}_N^\gamma \sim \text{Im}(\mathcal{H}^g \mathcal{E}^{g*})$$

sensitive to poorly known GPD E^g , important for the spin rule.

Single Transverse Spin Asymmetry



(a) pH †



(b) PbH †

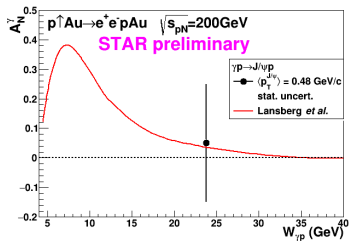
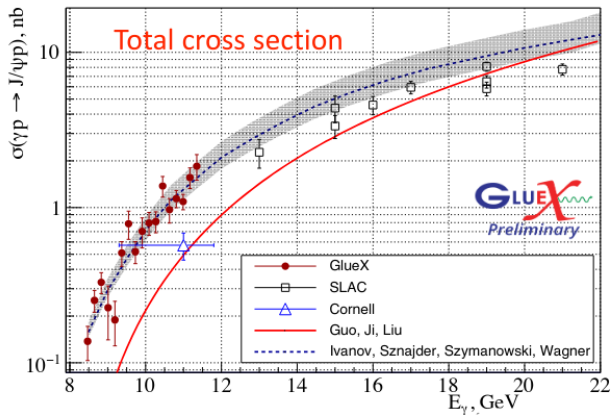
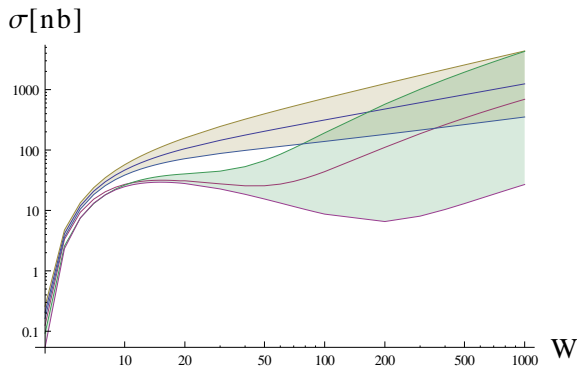


Figure 7: STSAs in the exclusive J/ψ photo-production in UPCs with a proton beam (a) and a lead beam (b) on an transversely polarised hydrogen target.



Photoproduction amplitude and cross section - LO and NLO.

$$\sim \frac{\alpha_S(\mu_R) N_c}{\pi} \ln\left(\frac{1}{\xi}\right) \ln\left(\frac{\frac{1}{4} M_V^2}{\mu_F^2}\right)$$



Various approaches: scale fixing, resummation, ?

we MUST also study **timelike** DVCS

Berger, Diehl, Pire, 2002

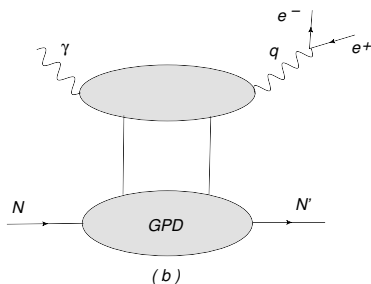


Figure: Timelike Compton Scattering (**TCS**): $\gamma N \rightarrow l^+ l^- N'$

Why **TCS**:

- ▶ same proven factorization properties as DVCS
- ▶ universality of the GPDs
- ▶ another source for GPDs (special sensitivity on real part of GPD H),
- ▶ the same final state as in J/ψ , but cleaner theoretical description!

First Measurement of Timelike Compton Scattering

P. Chatagnon^{20,*} S. Niccolai,²⁰ S. Stepanyan,³⁶ M. J. Amarian,²⁹ G. Angelini,¹² W. R. Armstrong,¹ H. Atac,³⁵ C. Ayerbe Gayoso,^{44,†} N. A. Baltzell,³⁶ L. Barion,¹³ M. Bashkanov,⁴² M. Battaglieri,^{36,15} I. Bedlinskiy,²⁵ F. Benmokhtar,⁷ A. Bianconi,^{39,19} L. Biondo,^{15,18,40} A. S. Biselli,⁸ M. Bondi,¹⁵ F. Bossù,³ S. Boiarinov,³⁶ W. J. Briscoe,¹² W. K. Brooks,^{37,36} D. Bulumulla,²⁹ V. D. Burkert,³⁶ D. S. Carman,³⁶ J. C. Carvajal,¹⁰ M. Caudron,²⁰ A. Celentano,¹⁵ T. Chetry,^{24,28} G. Ciullo,^{13,9} L. Clark,⁴¹ P. L. Cole,²² M. Contalbrigo,¹³ G. Costantini,^{39,19} V. Crede,¹¹ A. D'Angelo,^{16,32} N. Dashyan,⁴⁵ M. Defurne,³ R. De Vita,¹⁵ A. Deur,³⁶ S. Diehl,^{30,5} C. Djalali,²⁸ R. Dupré,²⁰ H. Egiyan,³⁶ M. Ehrhart,^{20,‡} A. El Alaoui,³⁷ L. El Fassi,²⁴ L. Elouadrhiri,³⁶ S. Fegan,⁴² R. Fersch,⁴ A. Filippi,¹⁷ G. Gavalian,³⁶ Y. Ghandilyan,⁴⁵ G. P. Gilfoyle,³¹ F. X. Girod,³⁶ D. I. Glazier,⁴¹ A. A. Golubenko,³³ R. W. Gothe,³⁴ Y. Gotra,³⁶ K. A. Griffioen,⁴⁴ M. Guidal,²⁰ L. Guo,¹⁰ H. Hakobyan,^{37,45} M. Hattawy,²⁹ T. B. Hayward,^{5,44} D. Heddle,^{4,36} A. Hobart,²⁰ M. Holtrop,²⁶ C. E. Hyde,²⁹ Y. Ilieva,³⁴ D. G. Ireland,⁴¹ E. L. Isupov,⁵³ H. S. Jo,²¹ K. Joo,⁵ M. L. Kabir,²⁴ D. Keller,⁴³ G. Khachatryan,⁴⁵ A. Khanal,¹⁰ A. Kim,⁵ W. Kim,²¹ A. Kripko,³⁰ V. Kubarovskiy,³⁶ S. E. Kuhn,²⁹ L. Lanza,¹⁶ M. Leali,^{39,19} S. Lee,²³ P. Lenisa,^{13,9} K. Livingston,⁴¹ I. J. D. MacGregor,⁴¹ D. Marchand,²⁰ L. Marsicano,¹⁵ V. Mascagna,^{38,19,8} B. McKinnon,⁴¹ C. McLaughlin,³⁴ S. Migliorati,^{39,19} M. Mirazita,¹⁴ V. Mokeev,³⁶ R. A. Montgomery,⁴¹ C. Munoz Camacho,²⁰ P. Nadel-Turonski,³⁶ P. Naidoo,⁴¹ K. Neupane,³⁴ T. R. O'Connell,⁵ M. Osipenko,¹⁵ M. Ouillon,²⁰ P. Pandey,²⁹ M. Paolone,^{27,35} L. L. Pappalardo,^{13,9} R. Paremuzyan,^{36,26} E. Pasyuk,³⁶ W. Phelps,^{4,12} O. Pogorelko,²⁵ J. Poudel,²⁹ J. W. Price,² Y. Prok,²⁹ B. A. Raue,¹⁰ T. Reed,¹⁰ M. Ripani,¹⁵ A. Rizzo,^{16,32} P. Rossi,³⁶ J. Rowley,²⁸ F. Sabatié,³ A. Schmidt,¹² E. P. Segarra,²³ Y. G. Sharabian,³⁶ E. V. Shirokov,³³ U. Shrestha,^{5,28} D. Sokhan,^{3,41} O. Soto,^{14,37} N. Sparveris,³⁵ I. I. Strakovsky,¹² S. Strauch,³⁴ N. Tyler,³⁴ R. Tyson,⁴¹ M. Ungaro,³⁶ S. Vallarino,¹³ L. Venturelli,^{39,19} H. Voskanyan,⁴⁵ A. Vossen,^{6,36} E. Voutier,²⁰ D. P. Watts,⁴² K. Wei,⁵ X. Wei,³⁶ R. Wishart,⁴¹ B. Yale,⁴⁴ N. Zachariou,⁴² J. Zhang,⁴³ and Z. W. Zhao⁶

(CLAS Collaboration)

→ P. Chatagnon et al. (CLAS), PRL 127, 262501 (2021)

Future of TCS

- ▶ Experiments at JLab
- ▶ Prospects for EIC
 - ▶ Yellow Report: *Confronting DVCS and TCS results together is a mandatory goal of the EIC to prove the consistency of the collinear QCD factorization framework and to test the universality of GPDs.*
 - ▶ Preliminary predictions see Daria Sokhan talk
 - ▶ TCS included in EPIC, event generator for exclusive processes, interfaced to PARTONS (e-Print: 2205.01762 [hep-ph]), see also Kemal Tezgin talk
- ▶ Ultrapерipheral Collisions at the LHC

Coefficient functions and Compton Form Factors

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

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

where:

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

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:

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

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

DVCS CFFs from Artificial Neural Network fit - PARTONS

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

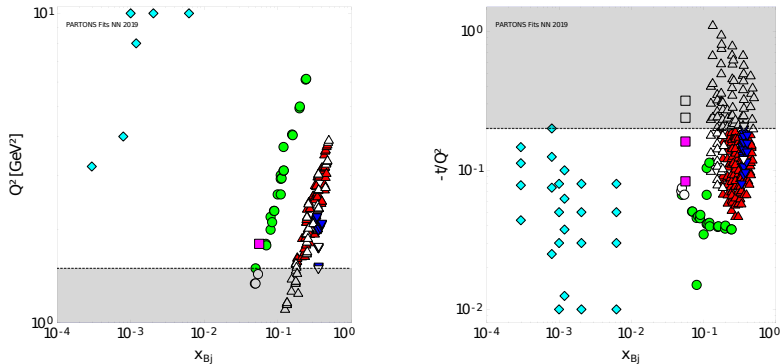


Figure: Coverage of the (x_{Bj}, Q^2) (left) and $(x_{Bj}, -t/Q^2)$ (right) phase-spaces by the experimental data used in DVCS CFFs fit. The data come from the Hall A (∇ , ∇), CLAS (\blacktriangle , \triangle), HERMES (\bullet , \circ), COMPASS (\blacksquare , \square) and HERA H1 and ZEUS (\blacklozenge , \blacklozenge) 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)

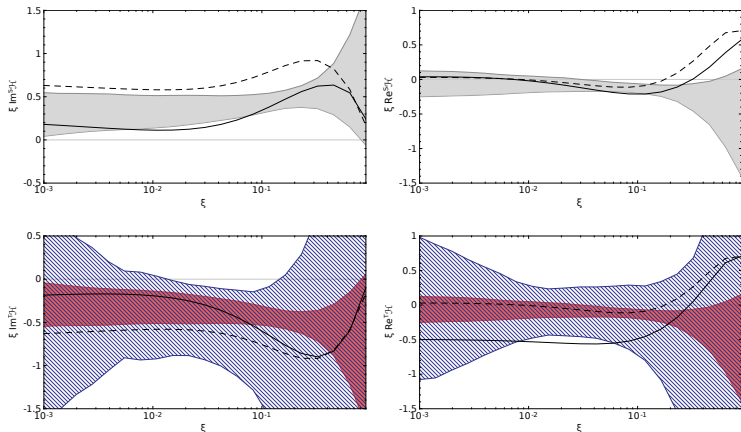


Figure: Imaginary (left) and real (right) part of DVCS (up) and TCS (down) CFF for $Q^2 = 2 \text{ GeV}^2$ and $t = -0.3 \text{ GeV}^2$ as a function of ξ . The shaded red (dashed blue) bands correspond to the data-driven predictions coming from the ANN global fit of DVCS data and they are evaluated 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.

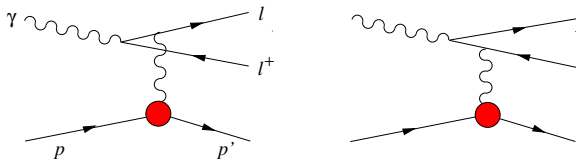


Figure: The Feynman diagrams for the **Bethe-Heitler** amplitude.

The cross-section for photoproduction of a lepton pair:

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

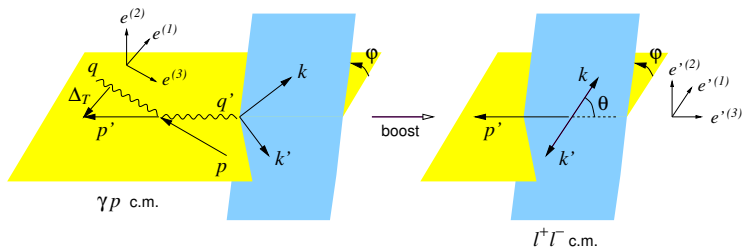


Figure: Kinematical variables and coordinate axes in the γp and $l^+ l^-$ c.m. frames.

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

- ▶ Important to measure ϕ !
- ▶ BH dominates at θ close to 0 and π !

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

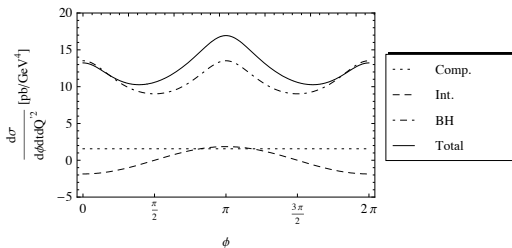


Figure: The differential cross section for $t = -0.2 \text{ GeV}^2$, $Q'^2 = 5 \text{ GeV}^2$, and integrated over $\theta \in (\pi/4, 3\pi/4)$ as a function of ϕ , for $s = 10^3 \text{ GeV}^2$.

Interference

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

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

R ratio:

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

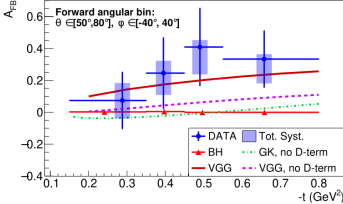
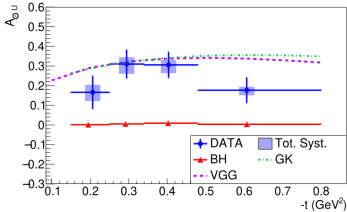
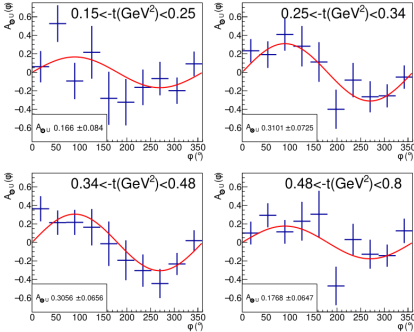
Forward Backward Asymmetry (from Pierre Chatagnon PhD thesis):

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

- ▶ The **interference** part depending on photons circular polarization ν :

$$\frac{d\sigma_{INT}}{dQ'^2 dt d\cos\theta d\varphi} \sim \nu \sin\varphi \cdot \text{Im } \mathcal{H}(\xi, t)$$

Results from CLAS12



Unpolarized cross section

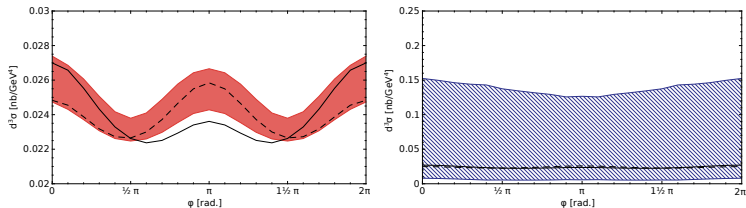


Figure: Differential TCS cross section integrated over $\theta \in (\pi/4, 3\pi/4)$ for $Q'^2 = 4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$ and the photon beam energy $E_\gamma = 10 \text{ GeV}$ as a function of the angle ϕ . In the left (right) panel the data-driven predictions evaluated using LO (NLO) 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

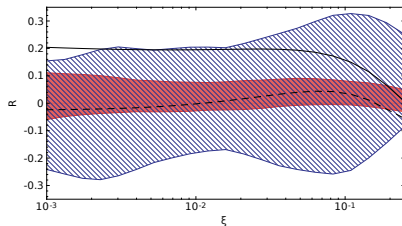


Figure: Ratio R evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4 \text{ GeV}^2$, $t = -0.35 \text{ GeV}^2$ as a function of ξ .

Circular asymmetry

The photon beam **circular polarization** asymmetry:

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

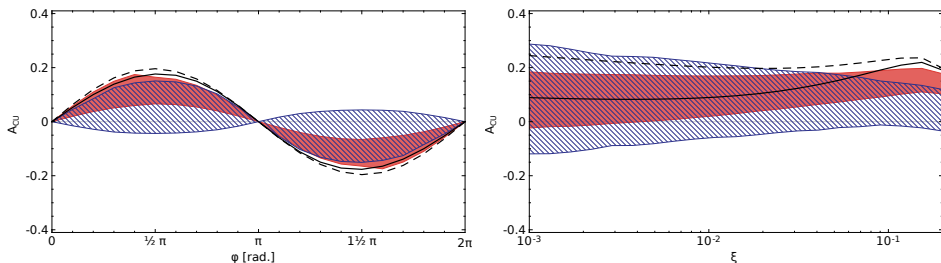


Figure: Circular asymmetry A_{CU} evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$ and (left) $E_\gamma = 10 \text{ GeV}$ as a function of ϕ (right) and $\phi = \pi/2$ as a function of ξ . The cross sections used to evaluate the asymmetry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

Transverse target asymmetry

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

The transverse spin asymmetry:

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

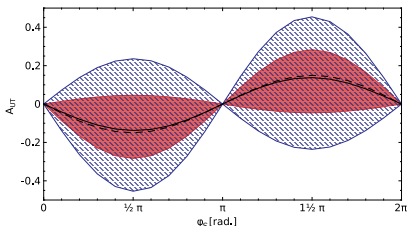


Figure: Transverse target spin asymmetry A_{UT} evaluated with LO and NLO spacelike-to-timelike relations for $Q'^2 = 4 \text{ GeV}^2$, $t = t_0$ and $E_\gamma = 10 \text{ GeV}$ as a function of φ_S . The cross sections used to evaluate the asymmetry are integrated over $\theta \in (\pi/4, 3\pi/4)$.

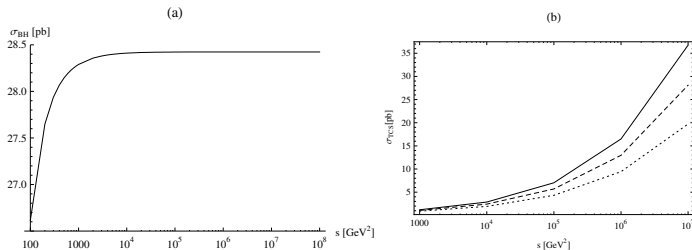


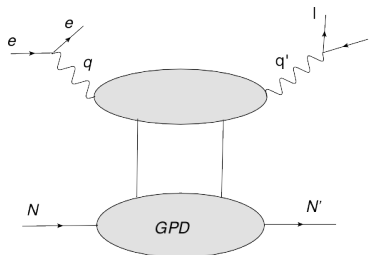
Figure: (a) The BH cross section (b) σ_{TCS} as a function of γp c.m. energy squared s

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

$$\sigma_{pp}^{BH} = 2.9 \text{ pb} \quad \sigma_{pp}^{TCS} = 1.9 \text{ pb} .$$

Even better with pA collisions. [Lansberg, Szymanowski, Wagner JHEP 09 \(2015\) 087](#)

Double DVCS



(c)

$$\xi = -\frac{q_{out}^2 + q_{in}^2}{q_{out}^2 - q_{in}^2} \eta, \quad \eta = \frac{q_{out}^2 - q_{in}^2}{(p + p') \cdot (q_{in} + q_{out})}.$$

$${}^{DDVCS} \text{Re}(\mathcal{H}) \sim P \int \frac{1}{x \pm \xi} H^q(x, \eta, t), \quad {}^{DVCS} \text{Im}(\mathcal{H}) \sim i\pi H^q(\pm \xi, \eta, t)$$

DDVCS can provide unique information, but is very challenging experimentally. But recent measurement of TCS should also make us more optimistic about DDVCS!

Summary

- ▶ UPCs is a promising tool to study exclusive photoproduction processes
- ▶ Heavy vector meson already measured in UPC - question of stability of theoretical prediction
- ▶ 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
- ▶ Results from CLAS12 !!!
- ▶ EIC - TCS study in Yellow Report
- ▶ TCS included in EPIc event generator.
- ▶ Measurement of TCS should also make us more optimistic about the DDVCS , but we need muon detection. → see [Victor Martinez-Fernandez talk on Friday](#)
- ▶ Natural extension : replace in final state high mass dilepton by high mass diphoton! → see [Lech Szymanowski talk](#)