Backward DVCS on the pion in Sullivan processes

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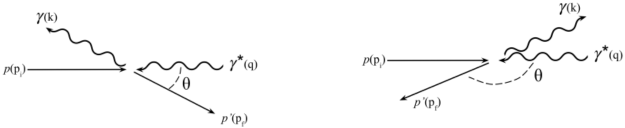
IRFU/CEA/PARIS-SACLAY

Summary

Can we measure in the backward region DVCS on pion?



(a) Forward Compton Scattering

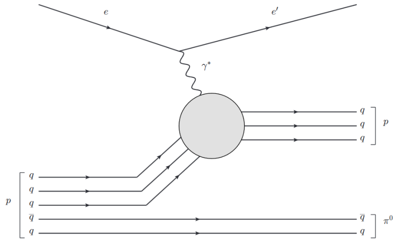
(b) Backward Compton Scattering

In forward region → FEASIBLE! (Chávez, Bertone, et al., 2022).
In backward region → Object of our work!

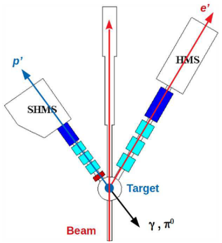
Accessing DEMP and DVCS at Backward Angles above the Resonance Region

Li, Stevens, and Huber, 2022a

- Determine if exclusive π^0 electroproduction has a significant backward-angle peak;
- Phenomenology study of extracting the u-dependence for the separated cross sections;
- Lay down a path to continue studying u-channel physics in the future EIC.



(c) Backward-angle meson production reaction above the resonance region ($\sqrt{s} = W > 2GeV$).



(d) Experimental configuration for $1H(e', ep)\pi^0$with the standard Hall C equipment

DVCS

DVCS is a window to access the structure of hadronic matter, allowing us to investigate the partonic content and dynamics inside of hadrons.

- **Object of theoretical and experimental effort (H1, ZEUS, HERMES, Jlab CLAS + Hall A, COMPASS...),**
  (Stepanyan, Burkert, et al., 2001; Belitsky and Müller, 2001; Ventura, 2021, and others);
- **Colinear factorization theorem →the scattering amplitude: the coefficient function x GPD**
  (Collins and Freund, 1999; Collins, Soper, and Sterman, 2004);
- **GPD: Access to spin, pressure, quarks and gluons densities information inside of the hadrons**
  (Müller, Robaschik, et al., 1994; Radyushkin, 1996; Ji, 1997);
- **Feasibility of measuring it on forward and backward region**
  (Airapetian, Akopov, et al., 2001, d'Hose, Burtin, et al., 2002;Gayoso, Bibrzycki, et al., 2021;Li, Stevens, and Huber, 2022b;...).

Pion

- **Goldstone boson** → insight on the mass generation phenomena quest.
- **Sullivan Process**: photon interaction with pion from the meson cloud inside of protons → Indirect measurement of the meson structure.
- We have theoretical and experimental data on DVCS on nucleons! What for DVCS on pion?

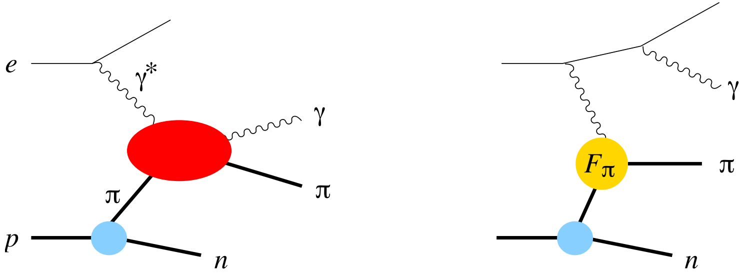


Figure: The Sullivan Process (Amrath, Diehl, and Lansberg, 2008).

Different regions → different kinematics → different structure functions!

- Forward region → small t-channel: GPDs;
- Backward region → large t-channel but small u-channel: Transition Distribution Amplitudes;

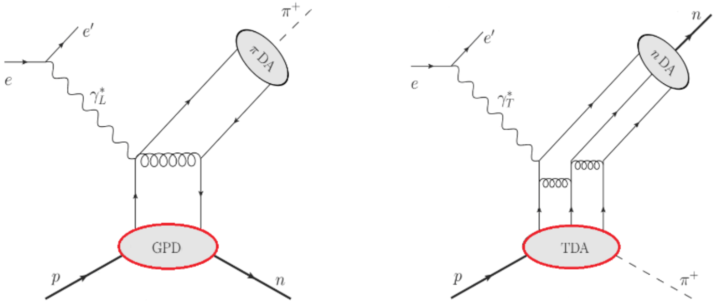


Figure: Exclusive $ep \to en\pi^+$ process description (S. Diehl and Joo, 2020).

Transition Distribution Amplitudes

- Physical picture similar to GPDs, but on backward region (Pire and Szymanowski, 2005; Tiburzi, 2005);
- Generalization of parton distributions to the case where the initial and final states correspond to different particles (Courtoy and Noguera, 2007).

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \gamma(p',\varepsilon)|O_V^\mu|\pi^+(p)\rangle|_{z^+=0,z_T=0} = \frac{1}{P^+}\frac{ie}{f_\pi}\epsilon^{\mu\nu\rho\sigma}\varepsilon_{\perp\nu}P_\rho\Delta_{\perp\sigma}V(x,\xi,t), \qquad O_V^\mu = \bar{d}(-z/2)\gamma^\mu u(z/2),$$

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \gamma(p',\varepsilon)|O_A^\mu|\pi^+(p)\rangle|_{z^+=0,z_T=0} = \frac{1}{P^+}\frac{e}{f_\pi}(\vec{\varepsilon}\cdot\vec{\Delta})P^\mu A(x,\xi,t), \qquad O_A^\mu = \bar{d}(-z/2)\gamma^\mu\gamma_5 u(z/2),$$

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \gamma(p',\varepsilon)|O_T^{\mu\nu}|\pi^+(p)\rangle|_{z^+=0,z_T=0} = \frac{e}{P^+}\epsilon^{\mu\nu\rho\sigma}P_\sigma\left[\varepsilon_{\perp\rho}T_1(x,\xi,t) - \frac{1}{f_\pi}(\vec{\varepsilon}\cdot\vec{\Delta})\Delta_{\perp\rho}T_2(x,\xi,t)\right],$$
$$O_T^{\mu\nu} = \bar{d}(-z/2)\sigma^{\mu\nu}u(z/2),$$

Figure: Leading twist TDAs for mesonic case (Pire and Szymanowski, 2005).

Pion-Photon Transition Distribution Amplitudes (TDAs)

The theoretical estimation of the TDAs is model dependent. Previous studies exist in the literature!

- ”Estimates for Pion-Photon Transition Distributions”, B.C. Tiburzi, 2005;
- ”Backward DVCS and Proton to Photon Transition Distribution Amplitudes”, Lansberg, J. P., Pire, B. and L. Szymanowski, 2006.
- ”Pion-photon Transition Distribution Amplitudes in the Spectral Quark Model”, W. Broniowski and E. R. Arriola, 2007.
- ”Pion-photon transition distribution amplitudes in the Nambu–Jona-Lasinio model”, A. Courtoy and S. Noguera, 2007;
- ”Pion-photon and kaon-photon transition distribution amplitudes in the Nambu–Jona-Lasinio model”, J. Zhang, J. Wu, 2024.

Our model

We present a model of these TDAs based on the overlap of light front wave functions primarily developed for GPDs, using a previously developed pion light front wave function (Chouika, Mezrag, et al., 2018) and deriving a consistent model for the light front wave functions of the photon.

Our model

The vector and axial pion to photon chiral-even TDAs are defined as presented in Lansberg, Pire, et al., 2012

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p_{\pi^-})|\bar{d}(-\frac{z}{2})\gamma^\mu u(\frac{z}{2})|\gamma(p_\gamma,\varepsilon)\rangle\Big|_{z^+=0,\, z_T=0} = \frac{1}{P^+}\frac{i\ e}{f_\pi}\epsilon^{\mu\varepsilon P\Delta_\perp} V^{\pi^-}(x,\xi,t), \tag{1}$$

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p_{\pi^-})|\bar{d}(-\frac{z}{2})\gamma^\mu \gamma^5 u(\frac{z}{2})|\gamma(p_\gamma,\varepsilon)\rangle\Big|_{z^+=0,\, z_T=0} = \frac{1}{P^+}\frac{e}{f_\pi}(\varepsilon\cdot\Delta)P^\mu A^{\pi^-}(x,\xi,t)\,. \tag{2}$$

In our model we are calculating the TDAs using the overlap representation (M. Diehl, Feldmann, et al., 2001) where one can write the matrix elements in terms of light front wave functions (LFWF)

$$\langle \gamma_{out}|\Psi^+(-\frac{z}{2})\gamma^+\Psi^+(\frac{z}{2})|\pi_{in}\rangle \tag{3}$$

Overlap Representation

In the DGLAP region ($\xi < x < 1$), the momenta kinematics is given by

$$\begin{aligned} \hat{x}_1 &= \frac{\bar{x}_1 - \xi}{1-\xi}, \quad \hat{x}_2 = \frac{\bar{x}_2}{1-\xi}, \\ \tilde{x}_1 &= \frac{\bar{x}_1 + \xi}{1+\xi}, \quad \tilde{x}_2 = \frac{\bar{x}_2}{1+\xi}, \\ \hat{k}_{1\perp} &= \bar{k}_{1\perp} + \frac{1-\bar{x}_1}{1-\xi}\frac{\Delta_\perp}{2} \quad \hat{k}_{2\perp} = \bar{k}_{2,\perp} - \frac{\bar{x}_2}{1-\xi}\frac{\Delta_\perp}{2} \\ \tilde{k}_{1\perp} &= \bar{k}_{1\perp} - \frac{1-\bar{x}_1}{1+\xi}\frac{\Delta_\perp}{2}, \quad \tilde{k}_{2\perp} = \bar{k}_{2,\perp} + \frac{\bar{x}_2}{1+\xi}\frac{\Delta_\perp}{2}, \end{aligned} \tag{4}$$

where $\bar{k}_i = (k'_i + k_i)/2$ and $\bar{x}_i = \bar{k}_i^+ / P^+$. The variable $\bar{x}$ represents the momentum fraction carried by the partons, ξ is the skewedness parameter, and t is the squared momenta transfer.

$$x_1 = \bar{x}_1 + \xi, \quad x'_1 = \bar{x}_1 - \xi \quad ; \quad k_{1\perp} = \bar{k}_{1\perp} - \frac{\Delta}{2}, \quad k'_{1\perp} = \bar{k}_{1\perp} + \frac{\Delta}{2} \quad ; \quad k_2 = k'_2 = \bar{k}_2, \tag{5}$$

Overlap Representation

The hadronic states are characterised by momenta p and helicity λ

$$|H;p,\lambda\rangle = \sum_{N,\beta}\int [dx]_N[d^2\mathbf{k}_\perp]_N \Psi^{\lambda}_{N,\beta}|N,\beta,;k_1,...,k_N\rangle \tag{6}$$

where β labels the parton composition, helicity and colour of each parton. The $\Psi^{\lambda}_{N,\beta}$ is the momentum LFWF of the N-parton Fock state.
The transition amplitude in our case will be written in terms of the in incoming pion states and outgoing photon states

$$\left\langle\gamma, P+\frac{\Delta}{2}\right| = \left\langle\gamma, P+\frac{\Delta}{2}\right|_{\gamma\cdot n} + \left\langle\gamma, P+\frac{\Delta}{2}\right|_{\gamma\cdot n\gamma_5} + \left\langle\gamma, P+\frac{\Delta}{2}\right|_{\sigma^{n\perp}} \tag{7}$$

$$\left|\pi, P-\frac{\Delta}{2}\right\rangle = \left|\pi, P-\frac{\Delta}{2}\right\rangle_{\gamma\cdot n\gamma_5} + \left|\pi, P-\frac{\Delta}{2}\right\rangle_{\sigma^{n\perp}} \tag{8}$$

Out of the six possible combinations, only two are non vanishing and are given as:

$$\int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \left(\left\langle \gamma, P + \frac{\Delta}{2} \right|_{\gamma\cdot n} \right) \bar{\psi}(-\frac{z}{2})\gamma \cdot n\gamma_5 \psi(\frac{z}{2}) \left| \pi, P - \frac{\Delta}{2} \right\rangle_{\gamma\cdot n\gamma_5} = \frac{e}{f_\pi} \epsilon \cdot \Delta A^\pi_{\gamma\cdot n} \quad (9)$$

$$\int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \left(\left\langle \gamma, P + \frac{\Delta}{2} \right|_{\sigma^{n\perp}} \right) \bar{\psi}(-\frac{z}{2})\gamma \cdot n\gamma_5 \psi(\frac{z}{2}) \left| \pi, P - \frac{\Delta}{2} \right\rangle_{\sigma^{n\perp}} = \frac{e}{f_\pi} \epsilon \cdot \Delta A^\pi_{\sigma^{n\perp}} \quad (10)$$

with $A^\pi = A^\pi_{\gamma\cdot n} + A^\pi_{\sigma^{n\perp}}$. Expanding the incoming and outgoing states in terms of LFWFs, one can derive the expressions of $A^\pi_{\gamma\cdot n}$ and $A^\pi_{\sigma^{n\perp}}$.

The pion LFWF used are the ones presented at Chouika, Mezrag, et al., 2018

$$\psi^{\pi}_{\uparrow,\downarrow}(x,k_\perp) = 8\sqrt{15}\pi\frac{M^3}{(k_\perp^2+M^2)^2}x(1-x), \tag{11}$$

$$ik_\perp\psi^{\pi}_{\uparrow,\uparrow}(x,k_\perp) = 8\sqrt{15}\pi\frac{k_\perp M^2}{(k_\perp^2+M^2)^2}x(1-x), \tag{12}$$

For the photon we developed a LFWF model where the photon to photon GPD were consistent with Friot, Pire, and Szymanowski, 2007:

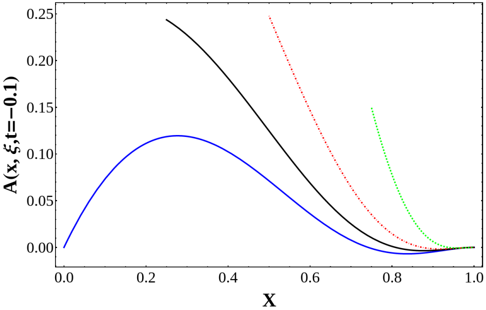
$$\psi_{\gamma\cdot n}(x,k_\perp) = -2\frac{(1-2x)}{(k_\perp^2+M^2)}, \tag{13}$$

$$\psi_{\gamma\cdot n\gamma_5}(x,k_\perp) = 2\frac{1}{(k_\perp^2+M^2)}, \tag{14}$$

$$\psi_{\sigma^{n\perp}}(x,k_\perp) = 2\frac{M}{(k_\perp^2+M^2)}. \tag{15}$$

Axial Pion-Photon TDA on DGLAP region

At this moment, we were able to calculate the active parton contribution of the axial transition amplitude:



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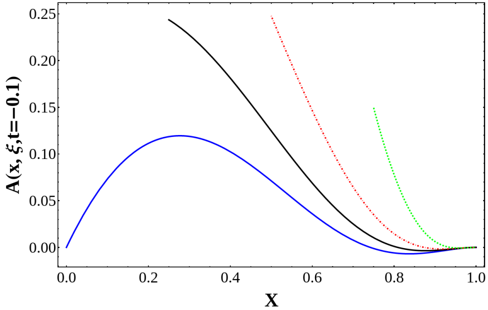

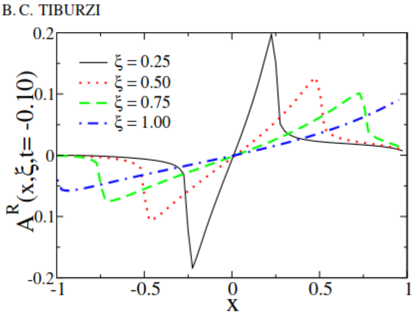

Conclusions & Future Work

- The main purpose of this work is to see if is feasible to measure Sullivan process in backward region.
- Our motivation is that it is already shown that is feasible to measure the DVCS on nucleons in both regions, and on pion in the forward region (Chávez, Bertone, et al., 2022).
- Based on the overlap LFWF for pion and photon, we are developing a phenomenological study on the backward pion-photon TDA.
- We obtained partial results that resembles results from literature.
- Next we are going to calculate the complete axial TDA in DGLAP region and ERBL region;
- Obtain the backward DVCS cross-sections, thus be able to analyse the feasibility of measuring such processes;

Thank you!

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References I

Chávez, J. M. M., Bertone, V., De Soto Borrero, F., Defurne, M., Mezrag, C., Moutarde, H., Rodríguez-Quintero, J., & Segovia, J. (2022).Pion generalized parton distributions: A path toward phenomenology. *Phys. Rev. D*, *105*, 094012. https://doi.org/10.1103/PhysRevD.105.094012

Li, W. B., Stevens, J. R., & Huber, G. M. (2022a).Accessing DEMP and DVCS at Backward Angles above the Resonance Region.

Stepanyan, S., Burkert, V. D., Elouadrhiri, L., Adams, G. S., Anciant, E., Anghinolfi, M., Asavapibhop, B., Audit, G., Auger, T., Avakian, H., Ball, J., Barrow, S., Battaglieri, M., Beard, K., Bektasoglu, M., Bertin, P., Bianchi, N., Biselli, A., Boiarinov, S., … Zhou, Z. (2001).Observation of exclusive deeply virtual compton scattering in polarized electron beam asymmetry measurements. *Physical Review Letters*, *87*(18). https://doi.org/10.1103/physrevlett.87.182002

Belitsky, A. V., & Müller, D. (2001). Overview of deeply virtual compton scattering.

Ventura, B. (2021). *Study of Deeply Virtual Compton Scattering at COMPASS at CERN* [Doctoral dissertation, HAL CCSD, U. Paris-Saclay].

Collins, J. C., & Freund, A. (1999).Proof of factorization for deeply virtual Compton scattering in QCD. *Phys. Rev. D*, *59*, 074009. https://doi.org/10.1103/PhysRevD.59.074009

Collins, J. C., Soper, D. E., & Sterman, G. (2004). Factorization of hard processes in qcd.

Müller, D., Robaschik, D., Geyer, B., Dittes, F.-M., & Hořejši, J. (1994).Wave functions, evolution equations and evolution kernels from light-ray operators of qcd. *Fortschritte der Physik/Progress of Physics*, *42*(2), 101–141. https://doi.org/10.1002/prop.2190420202

Radyushkin, A. (1996).Scaling limit of deeply virtual compton scattering. *Physics Letters B*, *380*(3–4), 417–425. https://doi.org/10.1016/0370-2693(96)00528-x

Ji, X. (1997).Deeply virtual compton scattering. *Phys. Rev. D*, *55*, 7114–7125. https://doi.org/10.1103/PhysRevD.55.7114

Airapetian, A., Akopov, N., Akopov, Z., Amarian, M., Aschenauer, E. C., Avakian, H., Avakian, R., Avetissian, A., Avetissian, E., Bailey, P., Bains, B., Baturin, V., Baumgarten, C., Beckmann, M., Belostotski, S., Bernreuther, S., Bianchi, N., Böttcher, H., Borissov, A., … Zohrabian, H. (2001).Measurement of the beam-spin azimuthal asymmetry associated with deeply-virtual compton scattering. *Physical Review Letters*, *87*(18). https://doi.org/10.1103/physrevlett.87.182001

References II

d'Hose, N., Burtin, E., Guichon, P., Kerhoas-Cavata, S., Marroncle, J., & Mossé, L. (2002).Feasibility study of deeply virtual compton scattering using compass [European Workshop on the QCD Structure of the Nucleon]. *Nuclear Physics A*, *711*(1), 160–164. https://doi.org/https://doi.org/10.1016/S0375-9474(02)01208-3

Gayoso, C. A., Bibrzycki, Ł., Diehl, S., Heppelmann, S., Higinbotham, D. W., Huber, G. M., Kay, S. J. D., Klein, S. R., Laget, J. M., Li, W. B., Mathieu, V., Park, K., Perry, R. J., Pire, B., Semenov-Tian-Shansky, K., Stanek, A., Stevens, J. R., Szymanowski, L., Weiss, C., & Yu, B.-G. (2021).Progress and opportunities in backward angle (u-channel) physics. *The European Physical Journal A*, *57*(12). https://doi.org/10.1140/epja/s10050-021-00625-2

Li, W. B., Stevens, J. R., & Huber, G. M. (2022b).Accessing DEMP and DVCS at Backward Angles above the Resonance Region.

Amrath, D., Diehl, M., & Lansberg, J. P. (2008).Deeply virtual compton scattering on a virtual pion target. *The European Physical Journal C*, *58*(2). https://doi.org/10.1140/epjc/s10052-008-0769-1

Diehl, S., & Joo, K. (2020).GPD and TDA measurements based on hard exclusive pion electroproduction with CLAS at JLAB. *18th International Conference on Hadron Spectroscopy and Structure*, 597–601. https://doi.org/10.1142/9789811219313_0102

Pire, B., & Szymanowski, L. (2005).Hadron annihilation into two photons and backward virtual compton scattering in the scaling regime of qcd. *Phys. Rev. D*, *71*, 111501. https://doi.org/10.1103/PhysRevD.71.111501

Tiburzi, B. C. (2005).Estimates for pion-photon transition distributions. *Physical Review D*, *72*(9). https://doi.org/10.1103/physrevd.72.094001

Courtoy, A., & Noguera, S. (2007).Pion-photon transition distribution amplitudes in the nambu–jona-lasinio model. *Phys. Rev. D*, *76*, 094026. https://doi.org/10.1103/PhysRevD.76.094026

Chouika, N., Mezrag, C., Moutarde, H., & Rodríguez-Quintero, J. (2018).A nakanishi-based model illustrating the covariant extension of the pion gpd overlap representation and its ambiguities. *Physics Letters B*, *780*, 287–293. https://doi.org/10.1016/j.physletb.2018.02.070

Lansberg, J. P., Pire, B., Semenov-Tian-Shansky, K., & Szymanowski, L. (2012).Consistent model for¡mml:math xmlns:mml="http://www.w3.org/1998/math/mathml" display="inline"¿¡mml:mi¿¡/mml:mi¿¡mml:mi¿n¡/mml:mi¿¡/mml:math¿transition distribution amplitudes and backward pion electroproduction. *Physical Review D*, *85*(5). https://doi.org/10.1103/physrevd.85.054021

References III

Diehl, M., Feldmann, T., Jakob, R., & Kroll, P. (2001).Erratum to: "the overlap representation of skewed quark and gluon distributions". *Nuclear Physics B*, *605*(1–3), 647. https://doi.org/10.1016/s0550-3213(01)00183-3

Friot, S., Pire, B., & Szymanowski, L. (2007).Deeply virtual compton scattering on a photon and generalized parton distributions in the photon. *Phys. Lett. B*, *645*, 153–160. https://doi.org/10.1016/j.physletb.2006.12.038