Quark-gluon tomography of helium-4 via coherent DVCS

Víctor Martínez-Fernández

Postdoc at IRFU/CEA (Paris-Saclay, France) and CFNS (USA)

Based on: **arXiv:2604.25677 [hep-ph]** & **arXiv:2605.18519 [hep-ph]**

in collab. with B. Pire, P. Sznajder, & J. Wagner.

Outline

- Introduction: GPDs and CFFs.
- Twist corrections.
- Kleiss-Stirling techniques.
- Helium-4 model: **first model beyond leading twist.**
- Results: beam-spin asymmetry and tomography.
- Take aways.

Introduction

Generalized Parton Distributions

GPD

Generalized Parton Distribution ≈ "3D version of a PDF (Parton Distribution Function)." With x the average fraction of the hadron's longitudinal momentum carried by a quark:

$$H_f(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{p}^+z^-} \langle p'|\bar{q}_f(-z/2)\gamma^+\mathcal{W}[-z/2,z/2]q_f(z/2)|p\rangle\Big|_{z_\perp=z^+=0}$$

$$t = \Delta^2 = (p'-p)^2\,, \quad \xi = -\frac{\Delta n}{2\bar{p}n}\,, \quad \bar{p} = \frac{p+p'}{2}$$

Importance

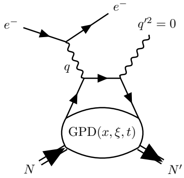
- Connected to **QCD energy-momentum tensor.** GPDs are a way to study **"mechanical" properties** and to address the hadron's spin puzzle (*X. Ji's sum rule*[*]).
- **Tomography:**[$] imaging of longitudinal momentum by transverse sections:

$$f(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{4\pi^2}\; e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H_f(x,0,-\vec{\Delta}_\perp^2)$$

[*] PRL 78 (1997) 610-613; [$] Burkardt, Int. J. Mod. Phys. A 21 (2006) 926-929.

Accessing GPDs: DVCS

- In the 1990s, Müller et al.,[†] Ji[*] and Radyushkin[#] introduced GPDs and deeply virtual Compton scattering (DVCS):



- At LO ($O(\alpha_s^0)$) and LT ($\Lambda/Q^2 \to 0$, $\Lambda \in \{|t|,\, M^2\}$):

$$\mathcal{H}_{\mathrm{DVCS}}(\xi,t) = -\mathrm{PV}\left(\int_{-1}^{1} dx\, \frac{1}{x-\xi} H^{(+)}(x,\xi,t)\right) + \int_{-1}^{1} dx\;\, i\pi\delta(x-\xi) H^{(+)}(x,\xi,t)\,,$$

$$H^{(+)}(x,\xi,t) = H(x,\xi,t) - H(-x,\xi,t)\,.$$

- $\xi = \frac{-n\Delta}{2\bar{p}n}\,, \quad \bar{p} = \frac{p+p'}{2}\,, \quad \Delta = p' - p\,, \quad t = \Delta^2\,.$

[†] Fortsch. Phys. 42 (1994) 101-141. [*] PRD 55 (1997) 7114-7125. [#] PLB 449 (1999) 81-88.

Higher-twist corrections to DVCS off proton: Braun et al., PRD 111 (2025) 7, 076011... and earlier works.

Compton tensor (DVCS, vector comp.):

$$T^{\mu\nu} = i\int d^4z\, e^{iq'z}\langle p'|\mathcal{T}\{j^\mu(z)j^\nu(0)\}|p\rangle = -g_\perp^{\mu\nu} \underbrace{\mathcal{A}^{++}}_{\mathrm{LT}(1+O(\alpha_s))\,\oplus\,|t|/Q^2\,\oplus\,\xi^2M^2/Q^2}$$

$$+\frac{1}{|\bar{p}_\perp|^2}\left[p_\perp^\mu p_\perp^\nu - \widetilde{p}_\perp^\mu \widetilde{p}_\perp^\nu\right] \underbrace{\mathcal{A}^{+-}}_{O(\alpha_s\cdot\,\mathrm{LT})\,\oplus\,|t|/Q^2\,\oplus\,\xi^2M^2/Q^2}$$

$$+\frac{\sqrt{2}}{|\bar{p}_\perp|}p_\perp^\mu\left[\frac{1}{Q}q^\nu - \frac{2Q}{\mathbb{Q}^2}q'^\nu\right] \underbrace{\mathcal{A}^{0+}}_{\sqrt{|t|}/Q}\,,$$

$$\boxed{\mathcal{A}^{\Lambda\Lambda'} \sim \int dx\, C^{\Lambda\Lambda'}(x/\xi)\, H(x,\xi,t)}$$

Braun, Ji & Manashov, JHEP 03 (2021) 051; and JHEP 01 (2023) 078.

VMF, Pire, Sznajder & Wagner, PRD 111 (2025) 7, 074034.

Kinematic-twist corrections

Compton tensor (DVCS, vector comp.):

$$T^{\mu\nu} = i \int d^4z\, e^{iq'z} \langle p' | \mathcal{T}\{ j^\mu(z) j^\nu(0) \} | p \rangle = -g_\perp^{\mu\nu} \underbrace{\mathcal{A}^{++}}_{\mathrm{LT}(1+O(\alpha_s)) \oplus |t|/Q^2 \oplus \xi^2 M^2/Q^2}$$

$$+ \frac{1}{|\bar{p}_\perp|^2} \left[p_\perp^\mu p_\perp^\nu - \widetilde{p}_\perp^\mu \widetilde{p}_\perp^\nu \right] \underbrace{\mathcal{A}^{+-}}_{O(\alpha_s \cdot \mathrm{LT}) \oplus |t|/Q^2 \oplus \xi^2 M^2/Q^2}$$

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Why to go beyond leading twist?

1. **Nucleon and nuclei tomography.**
2. Reduce cuts in experimental data.
3. Universality tests $\rightarrow \mathcal{A}^{++}_{\mathrm{DVCS}} \overset{\mathrm{LO,\,HT}}{\neq} \left(\mathcal{A}^{++}_{\mathrm{TCS}}\right)^*$.
4. Access to gravitational form factors BEYOND pressure.

Helicity amplitudes: NLO-LT, LO-HT

3 components: squared-charge-weighted quark sum H^{Σ}, & gluons H^{g}, H_T^{g}

$$\mathcal{A}^{++}(\xi,t) = \int_{-1}^{1} \frac{dx}{\xi} \Bigg\{ \Bigg[C_0(x/\xi) + \frac{\alpha_s C_F}{4\pi} C^{q}_{\mathrm{NLO}}(x/\xi) + \frac{t}{\mathbb{Q}^2}\left(C^{++}_{0,\,\mathrm{HT}}(x/\xi) - \xi\partial_\xi C^{++}_{1,\,\mathrm{HT}}(x/\xi)\right) + \frac{2\xi^2 \bar{p}_\perp^2}{\mathbb{Q}^2}\xi^2\partial_\xi^2 C^{++}_{1,\,\mathrm{HT}}(x/\xi)\Bigg] H^{\Sigma} + \frac{\alpha_s T_F}{4\pi}\frac{1}{\xi} C^{g}_{\mathrm{NLO}}(x/\xi) H^{g} \Bigg\},$$

$$\mathcal{A}^{+-}(\xi,t) = \int_{-1}^{1} \frac{dx}{\xi} \left\{ \frac{2\xi^2 \bar{p}_\perp^2}{\mathbb{Q}^2}\xi^2\partial_\xi^2 C^{+-}_{0,\,\mathrm{HT}}(x/\xi) H^{\Sigma} + \frac{\alpha_s T_F}{4\pi}\frac{2\xi^2 \bar{p}_\perp^2}{M^2}\frac{1}{\xi} C^{+-}_{\mathrm{NLO}}(x/\xi) H_T^{g} \right\},$$

$$\mathcal{A}^{0+}(\xi,t) = -\frac{Q\sqrt{2}\xi|\bar{p}_\perp|}{\mathbb{Q}^2}\int_{-1}^{1}\frac{dx}{\xi}\left(1-\xi\partial_\xi\right) C^{0+}_{0,\,\mathrm{HT}}(x/\xi) H^{\Sigma}.$$

Kleiss-Stirling techniques

Formulation *à la* KS

- **Amplitudes as complex-valued numbers** $\rightarrow$ get rid of spinors and gamma matrices.

- **2 scalars as building blocks,** a^μ and b^μ as lightlike vectors:

$$s(a,b) = \bar{u}(a,+)u(b,-) = -s(b,a)\,,$$

$$t(a,b) = \bar{u}(a,-)u(b,+) = [s(b,a)]^*\,,$$

$$s(a,b) = (a^2 + ia^3)\sqrt{\frac{b^0 - b^1}{a^0 - a^1}} - (a \leftrightarrow b)\,.$$

Kleiss & Stirling, Nuclear Physics B262 (1985) 235-262

- **g = contraction of massless current with lightlike vector:**

$$\begin{aligned} g(s,\ell,a,k) &= \bar{u}(\ell,s)\not{a}u(k,s) \\ &= \delta_{s+}s(\ell,a)t(a,k) + \delta_{s-}t(\ell,a)s(a,k)\,, \end{aligned}$$

- **j_μ = massless vector current:**

$$\begin{aligned} j_\mu(s,k',k) &= \bar{u}(k',s)\gamma_\mu u(k,s) \\ &= \frac{1}{N_{k'k}}\left\{k'_\mu(k\kappa_0) + k_\mu(k'\kappa_0) - \kappa_{0,\,\mu}(k'k) + is\epsilon_{\mu\alpha\beta\gamma}k'^\alpha k^\beta \kappa_0^\gamma\right\}\,, \end{aligned}$$

$$\kappa_0^\mu = (1,1,0,0)\,, \qquad N_{k'k} = \sqrt{(k'\kappa_0)(k\kappa_0)}\,.$$

DVCS amplitude *à la* KS

$$
\begin{aligned}
i\mathcal{M}^{s\lambda}_{\chi,\,\mathrm{DVCS}} = \frac{-ie^3\chi}{Q^2}\Bigg[&\boldsymbol{\mathcal{A}}^{++}\left(\frac{\sqrt{2}}{2|\bar{p}_\perp|}\right)\left(\sum_{j=1}^{3} B_j\,\mathbf{g}(s,k',L_j,k) - i\lambda p_\mu \epsilon_\perp^{\mu\nu}\boldsymbol{j}_{\boldsymbol{\nu}}(s,k',k)\right)\\
&+\boldsymbol{\mathcal{A}}^{+-}\left(\frac{\sqrt{2}}{2|\bar{p}_\perp|}\right)\left(\sum_{j=1}^{3} B_j\,\mathbf{g}(s,k',L_j,k) + i\lambda p_\mu \epsilon_\perp^{\mu\nu}\boldsymbol{j}_{\boldsymbol{\nu}}(s,k',k)\right)\\
&-\boldsymbol{\mathcal{A}}^{\mathbf{0+}}\frac{2Q}{\mathbb{Q}^2}\,\mathbf{g}(s,k',q',k)\Bigg]\,,
\end{aligned}
$$

$\chi =$ sign charge of beam , $\quad s =$ polariz. beam , $\quad \lambda =$ polariz. out photon

Same methods can be applied to the Bethe-Heitler contribution.

Helium-4 model

^{4}He model for GPDs: quarks and gluons

- GPD as Radon transform of a Radyushkin **Double Distribution** $\rightarrow$ **polynomiality** ✓ and **PDF reduction** (nNNPDF30 – EPJC 82, 507 (2022)) as $(\xi, t) \rightarrow (0,0)$ ✓

$$H^i(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \; \delta(\beta + \xi\alpha - x) F^i(\beta,\alpha,t)\,,$$

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- Not fully factorized t-dependence.

$$F^i(\beta, \alpha, t) = f_i^A(\beta, t) \underbrace{h_i(\beta, \alpha)}_{\xi\text{-dep. typical Radyushkin}} , \qquad f_i^A(\beta, t) = \underbrace{f_i^A(\beta)}_{\text{PDF}} \frac{k_i(|\beta|, t)}{k_i(|\beta|, 0)} \,,$$

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- $i \in \{u_{\mathrm{val}},\, d_{\mathrm{val}}\}$ fit to $F_1(t)$ [$n = 4$ minima]:

$$k_i(|\beta|,t) = \left(\frac{1}{1 - p_0(1-|\beta|)^2 t}\right)^{p_1} \prod_{j=1}^{n} \left(\frac{|p_{2,j} + t|}{|p_{2,j} + t| - p_{3,j}(1-|\beta|)^2 t}\right)^{p_{4,j}}\,,$$

- $i \in \{u_{\mathrm{sea}}, d_{\mathrm{sea}}, s, g\}$ fit to BSA from CLAS6:

$$k_i(|\beta|,t) = \exp\Big(p(1-|\beta|^2)t\Big)\,.$$

^{4}He model for GPDs: gluon transversity

- Positivity constrain$^+$ ($|t| \geq |t_0|$):

$$|H_T^g(x,\xi,t)| < \frac{1}{\xi}\sqrt{\frac{x^2-\xi^2}{1-\xi^2}}\sqrt{\frac{t}{t-t_0}}\sqrt{\frac{t_0}{t-t_0}}\sqrt{g\left(\frac{x+\xi}{1+\xi}\right)g\left(\frac{x-\xi}{1-\xi}\right)},$$

For $\xi \to 0$,

$$|H_T^g(x,\xi\to 0,t)| < x\,g(x)\sqrt{\frac{1}{-t/(4M^2)}},$$

suggesting the Ansatz:

$$\boxed{H_T^g(x,\xi,t) = H^g(x,\xi,0)\sqrt{\frac{1}{1-t/(4M^2)}}\,.}$$

$^+$Kirch, Pobylitsa, & Goeke, PRD 72, 054019 (2005).

Results

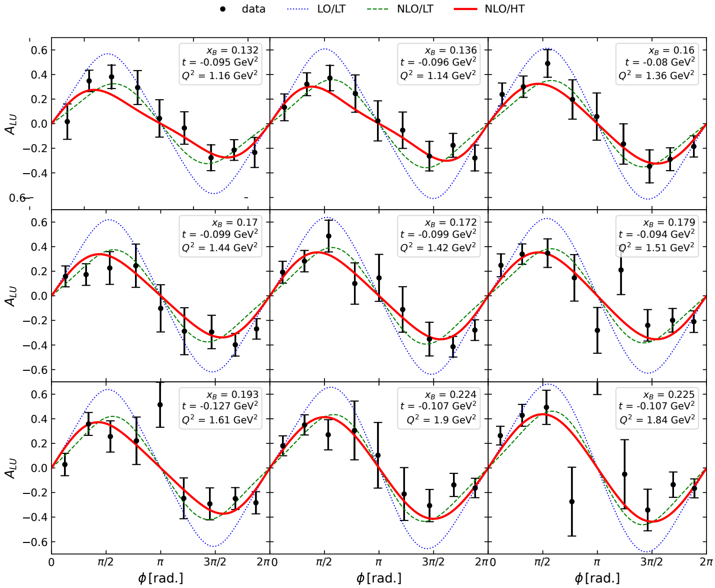
Beam-spin asymmetry

Unpolarized target + longitudinally polarized electron beam:

$$A_{LU}(\phi) = \frac{\sigma_-^{++} + \sigma_-^{+-} - \sigma_-^{-+} - \sigma_-^{--}}{\sigma_-^{++} + \sigma_-^{+-} + \sigma_-^{-+} + \sigma_-^{--}}\,, \qquad \sigma_\chi^{s\lambda}$$

DVCS off ^{4}He – BSA: JLab6 data vs our model

1st helium-4 fitting and model beyond LT. *(preliminary plots)*



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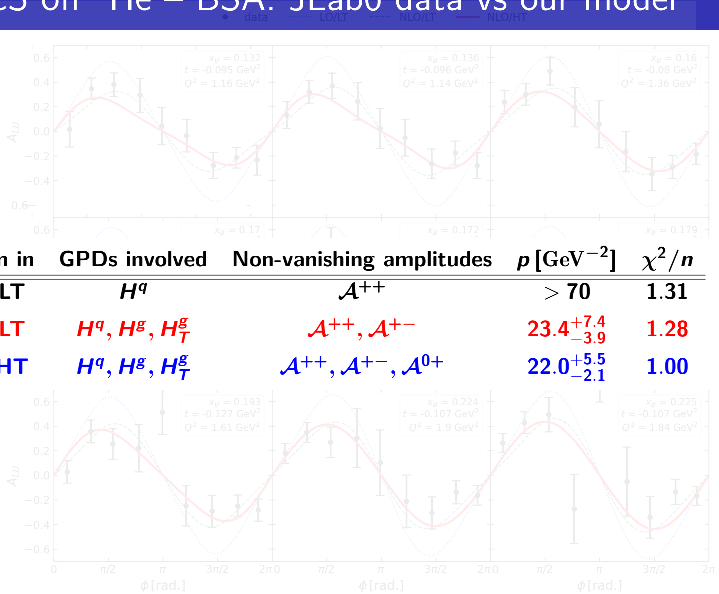


Precision in		GPDs involved	Non-vanishing amplitudes	$p\,[\mathrm{GeV}^{-2}]$	χ^2/n
LO	LT	H^q	$\mathcal{A}^{++}$	>70	1.31
NLO	LT	H^q, H^g, H^g_T	$\mathcal{A}^{++}, \mathcal{A}^{+-}$	$23.4^{+7.4}_{-3.9}$	1.28
NLO	HT	H^q, H^g, H^g_T	$\mathcal{A}^{++}, \mathcal{A}^{+-}, \mathcal{A}^{0+}$	$22.0^{+5.5}_{-2.1}$	1.00

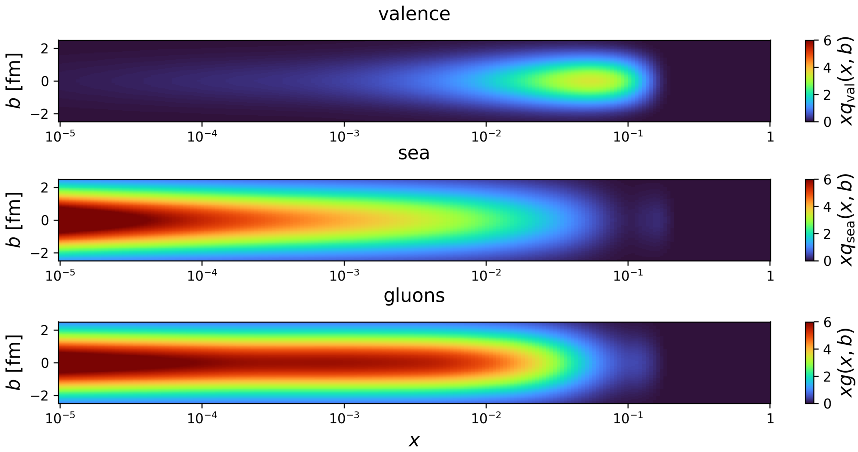
Tomography of partons in the nucleus

$$f_i^A(x, \boldsymbol{b_T}) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta_T}}{(2\pi)^2} e^{-i\boldsymbol{b_T}\cdot\boldsymbol{\Delta_T}} H^i(x, 0, -\boldsymbol{\Delta_T}^2)$$

The impact parameter, $\boldsymbol{b_T} = (b_x, b_y)$, is defined in a coordinate system whose origin is set at the center of momentum of all proton constituents.

Tomography of ^{4}He

- **1st helium tomography.**



(preliminary plots)

Thank you!