

From Compton to gravitational form factors beyond pressure

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Based on: [PRD 113, 094004](#) & [PRD 113, 094003](#)

in collab. with C. Mezrag, D. Binosi, Z.-Q. Yao.

Outline

- Introduction: GPDs, Compton (CFFs) and gravitational form factors (GFFs).
- What is a twist correction?
- Dispersion relation beyond leading twist.
- CFFs $\leftrightarrow$ GFFs *beyond pressure*, and estimations.
- Take aways.

Introduction

Generalized Parton Distributions

GPD

Generalized Parton Distribution $\approx$ “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:

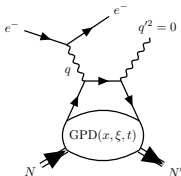
$$f(x, \vec{b}_\perp) = \int \frac{d^2 \vec{\Delta}_\perp}{4\pi^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H_f(x, 0, -\vec{\Delta}_\perp^2)$$

*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 ($\Lambda/Q^2 \rightarrow 0$, $\Lambda \in \{|t|, M^2\}$):

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

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

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

[†]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.

QCD energy-momentum tensor (EMT), $\Theta^{\mu\nu}$

$\Theta^{\mu\nu}$ parameterization $\rightarrow$ gravitational form factors (GFFs):

$$\begin{aligned} \langle p', s' | \Theta_a^{\mu\nu}(0) | p, s \rangle &\stackrel{\text{spin}=1/2}{=} \\ &= \bar{u}(p', s') \left\{ \frac{\bar{p}^\mu \bar{p}^\nu}{M} A_a(t) + \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu} \Delta^2}{M} C_a(t) + M \eta^{\mu\nu} \bar{C}_a(t) \right. \\ &\quad \left. + \frac{\bar{p}^{\{\mu} i \sigma^{\nu\} \rho} \Delta_\rho}{4M} [A_a(t) + B_a(t)] + \frac{\bar{p}^{[\mu} i \sigma^{\nu] \rho} \Delta_\rho}{4M} S_a(t) \right\} u(p, s). \end{aligned}$$

a = quarks and gluons.

Can we obtain GFFs from GPDs?

Yes, but GPDs are not directly accessible in experiments:

$$\begin{aligned} \int dx x^{1-\mathcal{P}_a} \begin{Bmatrix} H_a(x, \xi, t) \\ E_a(x, \xi, t) \end{Bmatrix} &= \begin{Bmatrix} A_a(t) + 4\xi^2 C_a(t) \\ B_a(t) - 4\xi^2 C_a(t) \end{Bmatrix}, \quad \mathcal{P}_a = \begin{cases} 0, & \text{if } a = \text{quark}, \\ 1, & \text{if } a = \text{gluon}. \end{cases} \\ J_a = \frac{A_a(0) + B_a(0)}{2} &= \frac{1}{2} \int dx x^{1-\mathcal{P}_a} [H_a(x, \xi, 0) + E_a(x, \xi, 0)], \quad \text{and other relations.} \end{aligned}$$

Can we obtain GFFs from CFFs?

Yes, by dispersion relations beyond LT.

Kinematic-twist corrections

Compton tensor (DVCS, vector comp.):

$$\begin{aligned}
 T^{\mu\nu} = & i \int d^4z \, e^{iq'z} \langle p' | \mathcal{T} \{ j^\mu(z) j^\nu(0) \} | p \rangle = -g_{\perp}^{\mu\nu} \underbrace{\mathcal{A}^{++}}_{\text{LT}(1+O(\alpha_s)) \oplus |t|/Q^2 \oplus \xi^2 M^2/Q^2} \\
 & + \frac{1}{|\vec{p}_{\perp}|^2} [p_{\perp}^{\mu} p_{\perp}^{\nu} - \tilde{p}_{\perp}^{\mu} \tilde{p}_{\perp}^{\nu}] \underbrace{\mathcal{A}^{+-}}_{O(\alpha_s \cdot \text{LT}) \oplus |t|/Q^2 \oplus \xi^2 M^2/Q^2} \\
 & + \frac{\sqrt{2}}{|\vec{p}_{\perp}|} p_{\perp}^{\mu} \left[\frac{1}{Q} q^{\nu} - \frac{2Q}{Q^2} q'^{\nu} \right] \underbrace{\mathcal{A}^{0+}}_{\sqrt{|t|}/Q},
 \end{aligned}$$

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

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

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

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 & + \frac{1}{|\vec{p}_\perp|^2} [p_\perp^\mu p_\perp^\nu - \tilde{p}_\perp^\mu \tilde{p}_\perp^\nu] \underbrace{\mathcal{A}^{+-}}_{O(\alpha_s \cdot \text{LT}) \oplus |t|/Q^2 \oplus \xi^2 M^2/Q^2} \\
 & + \frac{\sqrt{2}}{|\vec{p}_\perp|} p_\perp^\mu \left[\frac{1}{Q} q^\nu - \frac{2Q}{Q^2} q'^\nu \right] \underbrace{\mathcal{A}^{0+}}_{\sqrt{|t|}/Q},
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Why to go beyond leading twist?

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

Dispersion relation

Analyticity of the scattering amplitude

Extending the formalism developed in Dutriex, Meisgny, Mezrag & Moutarde, EPJC 85 (2025) 1, 105.

DVCS: fixed t + momentum conservation: amplitude $= \mathcal{F}(s)$.

Causality $\Rightarrow$ extension to the upper-half of the complex plane: $\mathcal{F}(s) \rightarrow \mathcal{F}(s + i0)$.

$$s + u = -\mathbb{Q}^2 \left[1 - \frac{2M^2}{\mathbb{Q}^2} \right], \quad \mathbb{Q}^2 = Q^2 + t.$$

① $s + u < 0$ if $M^2/\mathbb{Q}^2 < 1/2 \Rightarrow$

② $\exists$ region for both $s, u < 0 \Rightarrow$

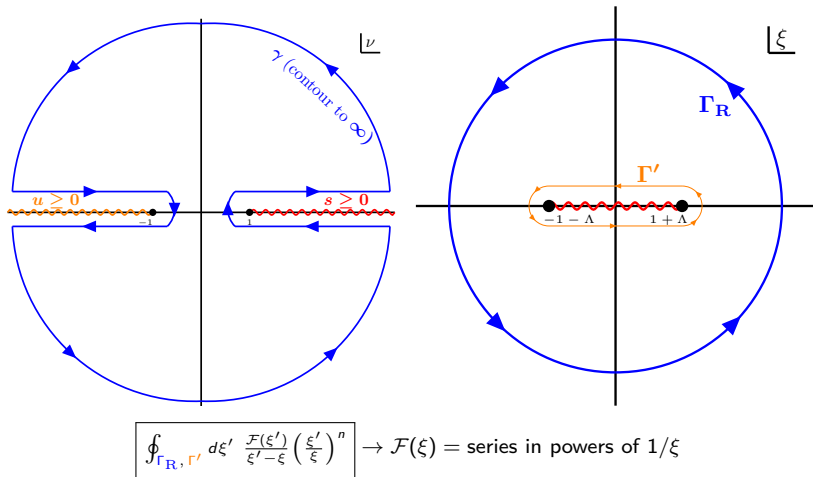
③ no particle production & $\text{Im}(\mathcal{F}) = 0$ (**optical theorem**) $\Rightarrow$

④ analytic continuation to the lower-half of the complex plane:

Schwartz's reflexion principle: $\mathcal{F}(s - i0) = \mathcal{F}^*(s + i0)$.

Domain of (guaranteed) analyticity in ν and ξ

$$s \rightarrow \nu \simeq 1/\xi + \Lambda, \quad \Lambda = 2M^2/\mathbb{Q}^2$$



Left: Path γ in ν 's complex plane $\rightarrow$ Diehl & Ivanov, EPJC 52 (2007) 919-932.

Dispersion relation

- $\mathcal{F} \rightarrow \mathcal{H}^{++}(\xi, t) \sim \text{LT} + \text{tw-4} + \dots$
- **n -times subtracted dispersion relation:** $\Lambda = 2M^2/\mathbb{Q}^2$,

$$\sum_{j=0}^n h_j^{++} \frac{1}{\xi^j} = \frac{1}{\pi} \text{PV} \int_{-(1+\Lambda)}^{1+\Lambda} d\xi' \frac{\text{Im}(\mathcal{H}^{++}(\xi'))}{\xi' - \xi} \left(\frac{\xi'}{\xi}\right)^n + \text{Re}(\mathcal{H}^{++}(\xi))$$

- $|\xi| > 1 \Rightarrow \text{GPDs on } x \in (-\xi, \xi) \Rightarrow \underbrace{\text{Im}(\mathcal{H}^{++}(\xi))}_{\text{NLO+tw-4} \in \text{DGLAP region } |x| > |\xi|} = 0:$

$$\sum_{j=0}^n h_j^{++} \frac{1}{\xi^j} = \frac{1}{\pi} \text{PV} \int_{-1}^1 d\xi' \frac{\text{Im}(\mathcal{H}^{++}(\xi'))}{\xi' - \xi} \left(\frac{\xi'}{\xi}\right)^n + \text{Re}(\mathcal{H}^{++}(\xi))$$

Subtraction constant and DDs

$$\sum_{j=0}^n h_j^{++} \frac{1}{\xi^j} \Rightarrow h_0^{++} = \text{subtraction constant of the DR.}$$

$$\text{Quarks} \rightarrow \left\{ \begin{matrix} H(x, \xi, t) \\ E(x, \xi, t) \end{matrix} \right\} = \iint_{\mathbb{D}} d\beta d\alpha \delta(x - \beta - \alpha\xi) \times \left\{ \begin{matrix} F(\beta, \alpha, t) + \xi D(\alpha, t)\delta(\beta) \\ K(\beta, \alpha, t) - \xi D(\alpha, t)\delta(\beta) \end{matrix} \right\}$$

Subtraction constant for spin-0

$$\begin{aligned} h_0^{++}(t) = & \int_{-1}^1 d\alpha \left[T_0^{++}(\alpha, t/Q^2) + \frac{t}{Q^2} T_1^{++}(\alpha) \right] \mathbf{D}(\alpha, t) \\ & - 4 \frac{M^2 - t/4}{Q^2} \iint_{\mathbb{D}} d\beta d\alpha \mathbf{F}(\beta, \alpha, t) \beta T_1^{++(1)}(\alpha) \end{aligned}$$

Subtraction constant for spin-1/2[‡]

$$\begin{aligned} h_0^{++}(t) = & \int_{-1}^1 d\alpha \left[T_0^{++}(\alpha, t/Q^2) + \frac{t}{Q^2} T_1^{++}(\alpha) \right] \mathbf{D}(\alpha, t) \\ & - 4 \frac{M^2}{Q^2} \iint_{\mathbb{D}} d\beta d\alpha \left[\mathbf{F}(\beta, \alpha, t) + \frac{t}{4M^2} \mathbf{K}(\beta, \alpha, t) \right] \beta T_1^{++(1)}(\alpha) \end{aligned}$$

$$T_1^{++(n)}(\alpha) = \partial_\alpha^n T_1^{++}(\alpha)$$

[‡]In agreement with previous work: Braun et al., PRD 89 (2014) 7, 074022 ↔ NO connection to GFFs.

Compton to gravitational FFs

$\int F(\beta, \alpha) \beta T_1^{++(1)} \sim$ GFFs, generalized FFs

Example spin-0 case:

$$h_0^{++}(t) = \left(\int D \right) - 4 \frac{M^2 - t/4}{Q^2} \underbrace{\int \int_{\mathbb{D}} d\beta d\alpha \mathbf{F}(\beta, \alpha, t) \beta T_1^{++(1)}(\alpha)}_{\mathcal{I}(t)} .$$

$$\mathcal{I}(t) = \int \int_{\mathbb{D}} d\beta d\alpha F(\beta, \alpha, t) \beta \underbrace{T_1^{++(1)}(\alpha)}_{\sum_{n=0}^{\infty} c_n \alpha^n, R < 1}$$

$$\stackrel{(\star)}{=} \sum_{\substack{n=0 \\ \text{even } n}}^{\infty} c_n \int \int_{\mathbb{D}} d\beta d\alpha F(\beta, \alpha, t) \beta \alpha^n$$

$$= c_0 \underbrace{\mathbf{A}(t)}_{\text{GFF}} + \sum_{\substack{n=2 \\ \text{even } n}}^{\infty} \frac{c_n 2^n}{n+1} \underbrace{\mathbf{A}_{n+2, n}(t)}_{\text{genFF}} .$$

Similarly, $(\int D) \propto C(t)$ upon Gegenbauer d_1 dominance.

($\star$) Lebesgue dominated, & monotone convergence thms.: Royden & Fitzpatrick, *Real analysis*, 4th ed., Prentice Hall, 2010.

$h_0 \sim \int \text{Compton} \sim \text{gravitational}$

85-90% of the correction is on the GFFs $\rightarrow$ neglect genFFs:

Spin 0, quarks of flavor q

$$h_{0,q}^{++}(t, Q^2) \approx 20C_q(t) \left(1 - \frac{t}{3Q^2}\right) - 4 \frac{M^2 - t/4}{Q^2} c_0 A_q(t)$$

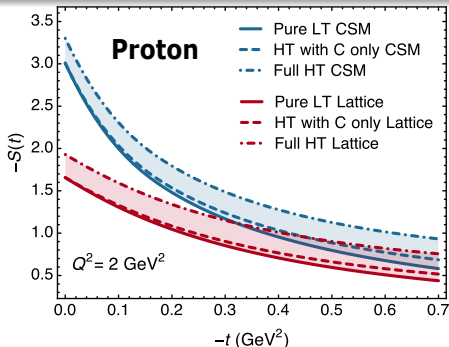
Spin 1/2, quarks of flavor q

$$h_{0,q}^{++}(t, Q^2) \approx 20C_q(t) \left(1 - \frac{t}{3Q^2}\right) - \frac{4M^2 c_0}{Q^2} \left[\frac{4M^2 - t}{4M^2} A_q(t) + \frac{t}{2M^2} J_q(t) \right]$$

$$S(t) = \sum_q e_q^2 h_{0,q}^{++}(t)$$

$c_0 \approx 0.864$

The **mass term dominates** the power corrections: up to **33% (lattice)** and **25% (CSM)** at $Q^2 = 2 \text{ GeV}^2$.



Take aways

- Analyticity of scattering amplitude $\leftrightarrow$ DR at all order $\leftrightarrow$ ab-initio calculation of scattering observables.
- **HT corrections carry unique info.** in the structure of the hadron:

$$\text{Re}\mathcal{H} + \int \frac{\text{Im}\mathcal{H}}{\xi' - \xi} \sim \text{pressure} + \frac{t, M^2}{Q^2} (\text{lin.} + \text{ang. momenta})$$

- **Large HT effects** on the DR with current data $\rightarrow$ further challenging previous extractions of proton's pressure.
- **DR provides new benchmarks** for GFFs obtained from continuum and lattice QCD.

Thank you!

Complementary slides

LT NLO coefficient functions

$$T_{\text{LT}}^{++}(x/\xi) = \left[C_0(x/\xi) + C_1(x/\xi) + \ln \left(\frac{Q^2}{\mu_F^2} \right) C_{\text{coll}}(x/\xi) \right] - (x/\xi \rightarrow -x/\xi),$$

$$C_0(x/\xi) = -\frac{\xi}{x + \xi - i0},$$

$$C_1(x/\xi) = \frac{\alpha_S C_F}{4\pi} \frac{\xi}{x + \xi - i0} \left[9 - 3 \frac{x + \xi}{x - \xi} \ln \left(\frac{x + \xi}{2\xi} - i0 \right) - \ln^2 \left(\frac{x + \xi}{2\xi} - i0 \right) \right],$$

$$C_{\text{coll}}(x/\xi) = \frac{\alpha_S C_F}{4\pi} \frac{\xi}{x + \xi - i0} \left[-3 - 2 \ln \left(\frac{x + \xi}{2\xi} - i0 \right) \right],$$

+ gluon terms.

NLO and higher-twist coefficient functions:

$C_i \rightarrow \text{Im}(C_i) \propto \theta(x - \xi), \delta(x - \xi)$, accessing therefore:

$$\begin{cases} \text{DGLAP:} & |x| > |\xi| \quad \checkmark \\ \text{ERBL:} & |x| < |\xi| \quad \times \end{cases}$$

Belitsky, Müller, PLB 417 (1998) 129; Ji, Osborne, PRD 58 (1998) 094018; Ji, Osborne, PRD 57 (1998) 1337;

Mankiewicz, Piller, Stein, Vanttinen, Weigl, PLB 425 (1998) 186; Pire, Szymanowski & Wagner, PRD 83 (2011)

034009.

Double DVCS' $\mathcal{A}^{++} = \text{LT} + \text{tw-4} + \text{O}(\text{tw-6})$, at LO

Spin-0 target:

$$\begin{aligned}
 \mathcal{H}^{++} = \mathcal{A}^{++} = & \int_{-1}^1 dx \left\{ - \left(\mathbf{1} - \frac{t}{2Q^2} + \frac{t(\xi - \rho)}{Q^2} \partial_\xi \right) \frac{H^{(+)}}{x - \rho + i0} \right. \\
 & + \frac{t}{\xi Q^2} \left[\mathbb{P}_{(i)} + \mathbb{P}_{(ii)} - \frac{\xi L}{2} + \frac{\tilde{\mathbb{P}}_{(iii)} - \tilde{\mathbb{P}}_{(i)}}{2} \right. \\
 & \quad \left. - \frac{\xi}{x + \xi} \left(\ln \left(\frac{x - \rho + i0}{\xi - \rho + i0} \right) - \frac{\xi + \rho}{2\xi} \ln \left(\frac{-\xi - \rho + i0}{\xi - \rho + i0} \right) - \tilde{\mathbb{P}}_{(i)} \right) \right] H^{(+)} \\
 & - \frac{t}{Q^2} \partial_\xi \left[\left(\mathbb{P}_{(i)} + \mathbb{P}_{(ii)} - \frac{\xi L}{2} \right. \right. \\
 & \quad \left. \left. - \frac{\xi}{x + \xi} \left(\ln \left(\frac{x - \rho + i0}{\xi - \rho + i0} \right) - \frac{\xi + \rho}{2\xi} \ln \left(\frac{-\xi - \rho + i0}{\xi - \rho + i0} \right) - \tilde{\mathbb{P}}_{(i)} \right) \right) \right] H^{(+)} \Bigg] \\
 & + \frac{\xi^2 \bar{p}_\perp^2}{Q^2} 2\xi \partial_\xi^2 \left[\left(\mathbb{P}_{(i)} + \mathbb{P}_{(ii)} - \frac{\xi L}{2} + \frac{\tilde{\mathbb{P}}_{(iii)} + \tilde{\mathbb{P}}_{(i)}}{2} \right) H^{(+)} \right] \Bigg\} \\
 & + \text{O}(\text{tw-6}) .
 \end{aligned}$$

- $\xi^2 \bar{p}_\perp^2 = \xi^2 M^2 - t (\xi^2 - 1) / 4$.

- **All amplitudes in VMF, Pire, Sznajder & Wagner, PRD 111 (2025) 7, 074034.**

- Coefficient functions of $\mathcal{A}^{++}$:

$$\mathbb{P}_{(i)}(x/\xi, \rho/\xi) = \frac{\xi - \rho}{x - \xi} \text{Li}_2 \left(-\frac{x - \xi}{\xi - \rho + i0} \right),$$

$$\widetilde{\mathbb{P}}_{(i)}(x/\xi, \rho/\xi) = -\frac{\xi - \rho}{x - \xi} \ln \left(\frac{x - \rho + i0}{\xi - \rho + i0} \right),$$

$$\mathbb{P}_{(ii)}(x/\xi, \rho/\xi) = \frac{\xi - \rho}{x + \xi} \left[\text{Li}_2 \left(-\frac{x - \xi}{\xi - \rho + i0} \right) - (x \rightarrow -\xi) \right],$$

$$\widetilde{\mathbb{P}}_{(iii)}(x/\xi, \rho/\xi) = -\frac{\xi + \rho}{x + \xi} \ln \left(\frac{x - \rho + i0}{-\xi - \rho + i0} \right),$$

$$L = \int_0^1 dw \frac{-4}{x - \xi - w(x + \xi)} \int_0^1 du \ln \left(1 + \frac{\bar{u}[x - \xi - w(x + \xi)]}{\xi - \rho + i0} \right) C_{\bar{u}, \bar{u}w},$$

$$C_{\bar{u}, v} = \ln \left(\frac{\bar{u} - v}{1 - v} \right) + \frac{1}{1 - v}.$$

- From the DDVCS result:

$$\begin{cases} \rho \rightarrow \xi \Rightarrow \text{DVCS}^\#, \\ \rho \rightarrow -\xi(1 - 2t/Q'^2) \Rightarrow \text{TCS to twist-4 accuracy.} \end{cases}$$

[#]DVCS for spin-0 target was already computed in: Braun, Ji & Manashov, JHEP 01 (2023) 078.

D-term at LO/NLO + LT precision

Parameterization of the D -term ($\rightarrow$ **connected to pressure**):

$$D_q(\alpha, t, \mu^2) = (1 - \alpha^2) \sum_{\text{odd } n} d_{n,q}(t, \mu^2) \underbrace{C_n^{(3/2)}(\alpha)}_{\text{Gegenbauer poly.}},$$

$$D_g(\alpha, t, \mu^2) = \frac{3}{2}(1 - \alpha^2)^2 \sum_{\text{odd } n} d_{n,g}(t, \mu^2) C_{n-1}^{(5/2)}(\alpha),$$

$$d_{n,a}(t, \mu^2) = d_{n,a}(0, \mu^2) \cdot (1 - t[\text{GeV}^2]/0.8^2)^{-3}, \quad a \in \{q, g\}.$$

LO h_0^{++} , $n = 1$, radiative gluons
 $d_{1,uds}(0, \mu_0^2)$ free (only)

NLO h_0^{++} , $n = 1$, free gluons
 $d_{1,uds}(0, \mu_0^2), d_{1,g}(0, \mu_0^2)$ free

$$\begin{aligned} d_{1,uds}(0, 2 \text{ GeV}^2) &= -0.6 \pm 1.1 \\ d_{1,g}(0, 2 \text{ GeV}^2) &= -0.8 \pm 1.5 \\ d_{1,c}(0, 2 \text{ GeV}^2) &= -0.003 \pm 0.005 \end{aligned}$$

$$\begin{aligned} d_{1,uds}(0, 2 \text{ GeV}^2) &= -1.1 \pm 7.7 \\ d_{1,g}(0, 2 \text{ GeV}^2) &= -6 \pm 78 \\ d_{1,c}(0, 2 \text{ GeV}^2) &= -0.02 \pm 0.27 \end{aligned}$$

Results from Dutrieux, Meisgny, Mezrag & Moutarde, EPJC 85 (2025) 1, 105.

Impact on the deconvolution problem of the D -term

LO + higher twist:

$$\left(\int D\right) = \int_{-1}^1 d\alpha \left[\left(1 - \frac{t}{2Q^2}\right) C_0^{(+)}(\alpha) + \frac{t}{2Q^2} \tilde{\mathbb{P}}_{(\text{iii})}^{(+)}(\alpha) \right] D(\alpha, t),$$

$$C_0^{(+)}(\alpha) = \frac{-1}{\alpha - 1 + i0} - (\alpha \rightarrow -\alpha), \quad \tilde{\mathbb{P}}_{(\text{iii})}^{(+)}(\alpha) = \frac{-2}{\alpha + 1} \ln \left(\frac{\alpha - 1 + i0}{-2 + i0} \right) - (\alpha \rightarrow -\alpha),$$

$$\left(\int D\right) = 4 \sum_{n=0}^{\infty} d_{2n+1}(t) \left[1 - \frac{t}{2Q^2} \left(1 - \frac{1}{(2n+3)(n+1)} \right) \right]$$

Shadow contributions— $\left(\int D^{\text{sh}}\right) = 0$ —assuming dominance by d_1, d_3 :

$$d_1^{\text{sh}}(t) = -d_3^{\text{sh}}(t) \frac{1 - \frac{9}{20} \frac{t}{Q^2}}{1 - \frac{1}{3} \frac{t}{Q^2}} \approx -d_3^{\text{sh}} \left(1 + \underbrace{0.12 |t/Q^2|}_{\text{need DRs of } \mathcal{H}^{0+,+-}} \right).$$