Unpolarized Twist-Two GPDs and the Role of Different IR Regulators

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Outline

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- **Study of the Vector Current: Dimensional Regularization (DR) as IR Regulator**
- **Conclusions**

Motivation: Anomaly Poles in Feynman Diagrams?

Doubts in the ***theoretical framework*** to extract PDFs and GPDs from experimental data?

Tarasov-Venugopalan (TV) (2020, 2021, 2024) in ***DIS***:

We find that in both asymptotics, the matrix element for the $g_1(x_B, Q^2)$ structure function is identically controlled by the triangle anomaly, which has an infrared pole in the forward scattering limit. As we discussed at length in the introduction, the cancellation of this pole involves a subtle interplay of perturbative and nonperturbative physics that is deeply related to the $U_A(1)$ problem in QCD. As a further consequence, our results bring up important questions regarding the applicability of QCD factorization to observables that are sensitive to the anomaly.

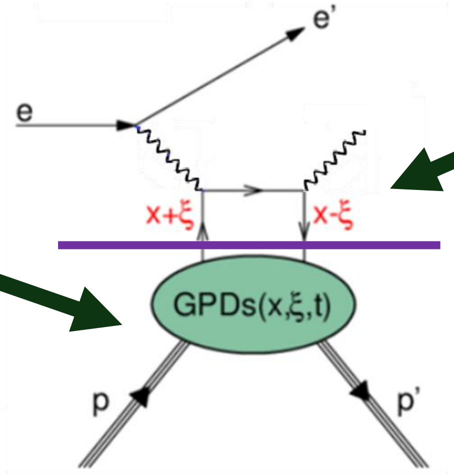
Bhattacharya, Hatta and Vogelsang (BHV) (2022, 2023) in ***DVCS***:
Bhattacharya, Hatta and Schoenleber (BHS) (2025)

Remarkably, we also find poles in the unpolarized case which are remnants of the trace anomaly. We argue that these poles are canceled by the would-be massless glueball poles in the GPDs H and E as well as in their moments, the nucleon gravitational form factors A, B and D. This mechanism sheds light on the connection between the gravitational form factors and the gluon condensate operator $F^{\mu\nu}F_{\mu\nu}$.

Recent Claims: Explanation for DVCS

Factorization theorems rely on the ***cancellation of IR divergences*** in the ‘hard part’ with the ones in the ‘soft part’ of the process .

Non-perturbative (internal hadron dynamics).



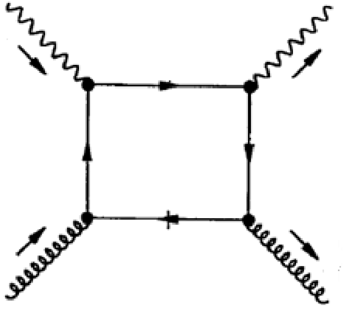
Perturbative probe (high energy photon).

Recent claim: original proof of factorization theorems did not consider the ‘anomaly pole’ effects, that can be captured only when using *off-forward kinematics*.

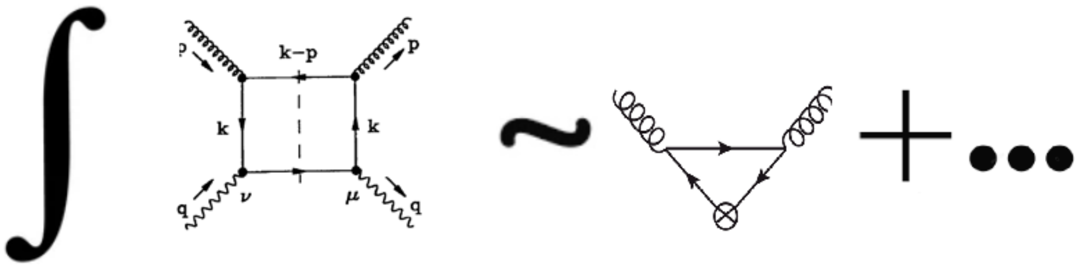
In DIS (defined in forward kinematics) the off-forward momentum *serves as a possible IR regulator*.

In DVCS (defined in off-forward kinematics) the off-forward momentum *is also a possible IR regulator.*

Motivation: Explanation



The non-local box diagram in DIS/DVCS is connected to the local singlet axial current through x integration.

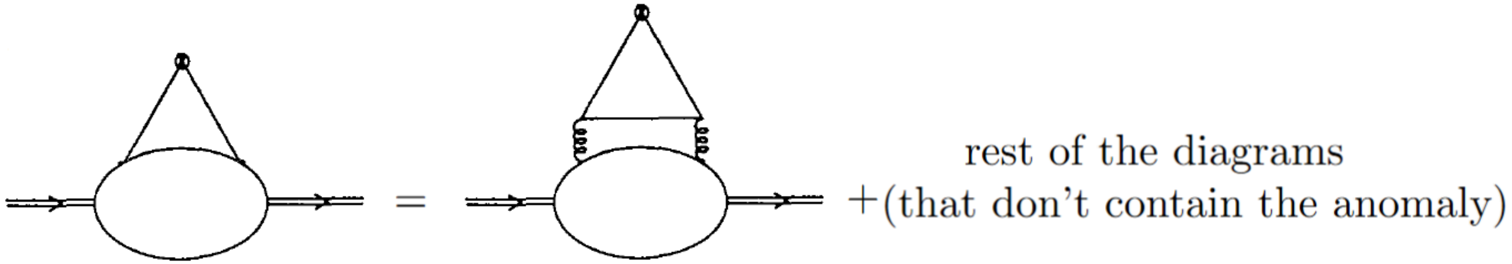


Claim: when using ***off-forward kinematics as IR regulator*** of the ‘hard’ box diagram (perturbative part) one finds (new) apparent collinear poles.

In the chiral limit, these poles can be uniquely related to the matrix element of the ***anomaly*** operator $F\tilde{F}$.

$$j_5^\mu = \sum_{i=1}^{N_f} \bar{q}_i \, \gamma^\mu \gamma_5 \, q_i \qquad \partial_\mu j_5^\mu = \frac{\alpha_s N_f}{8\pi} \sum_{a=1}^{8} \epsilon_{\mu\nu\rho\sigma} \, F_a^{\mu\nu} F_a^{\rho\sigma}$$

In the full process, and after x integration of the PDF:



Has poles in the collinear limit?

Motivation: Previous Work- Local Case

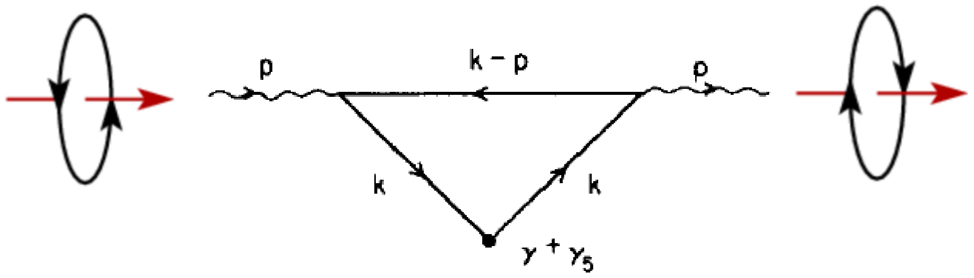
$$\Gamma_5^\mu = G_1(\Delta^2)\left(A_1^\mu + \frac{\Delta^2}{\Delta^2 - 4p^2} A_3^\mu\right) + \underline{G_2(\Delta^2)\, A_2^\mu}$$

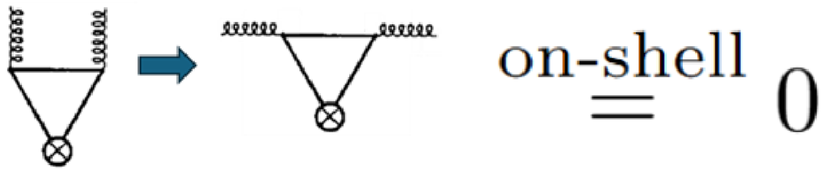
$$A_2^\mu = \frac{2i}{\Delta^2}\, \Delta^\mu\, \varepsilon^{\epsilon\, \epsilon'^*\, P\, \Delta}$$

2) We performed a first order calculation by including the quark mass (m) as IR regulator, and the form factor $G_2\left(\frac{\Delta^2}{m^2} \to 0\right) \to 0.$

The logic for introducing an extra IR regulator (m) is to keep an IR regulator even in the limit $\Delta^2 \to 0$.

3) The form factor G_2 describes a helicity-flip, so it should vanish in the collinear limit $\Delta^2 \to 0$ due to conservation of angular momentum.





Based on: 2408.00554

Motivation: Summary

We also studied the non-local axial current for on-shell gluons, and found that the ***PDF limit is safe*** when considering a quark mass.

$$F^{[\gamma^+\gamma_5]}_{\lambda\lambda'}(x,\Delta) = \int \frac{dz^-}{4\pi}\, e^{ik\cdot z}\, \langle g(p',\lambda')\,|\,\bar q(-\tfrac{z}{2})\,\gamma^+\gamma_5\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\,q(\tfrac{z}{2})\,|\,g(p,\lambda)\rangle\big|_{z^+=0,\,\vec z_\perp=\vec 0_\perp}$$
$$= \tilde S_1\,\tilde H^q_1(x,\xi,\Delta^2) + \tilde S_2\,\tilde H^q_2(x,\xi,\Delta^2)\,,$$

$$\tilde S_1 = -\,i\,\frac{\varepsilon^{+\epsilon\epsilon'^*P}}{(1-\xi^2)P^+} + \frac{2\,i\,\xi}{\Delta^2}\left(\frac{\varepsilon^{\epsilon\epsilon'^*P\Delta}}{1-\xi^2} - \frac{(\epsilon\cdot P)\,\varepsilon^{+\epsilon'^*P\Delta} - (\epsilon'^*\cdot P)\,\varepsilon^{+\epsilon P\Delta}}{(1-\xi^2)P^+}\right)$$
$$-\,\frac{i}{2}\,\frac{\epsilon^+\,\varepsilon^{+\epsilon'^*P\Delta} + (\epsilon'^*)^+\,\varepsilon^{+\epsilon P\Delta}}{(1-\xi^2)(P^+)^2}$$
$$\tilde S_2 = -\,\frac{2\,i\,\xi}{\Delta^2}\,\varepsilon^{\epsilon\epsilon'^*P\Delta}\,.$$

Structures $\widetilde{S_1}$ and $\widetilde{S_2}$ are apparently problematic ($1/\Delta^2$) in the forward limit.

After contraction with physical polarization vectors the apparent divergence disappears:

$$(\tilde S_1)_{++} = -\,(\tilde S_1)_{--} = 1\,, \qquad (\tilde S_2)_{+-} = -\,(\tilde S_2)_{+-} = \xi$$

$$\lim_{\Delta^2\to 0}\,\xi\,\tilde H^q_2(x,\xi,\Delta^2) = 0$$

1) Will the conclusions hold (safe collinear (PDF) limit?) in the same way for other IR regulators? Standard perturbative calculations are made in DR.

2) Will the conclusions hold for the vector current? (Related to the trace anomaly).

Consistency Conditions for the PDF Limit: Vector Current

PDF decomposition for external on-shell gluons:

$$\Phi^{[\gamma^+]}_{\lambda\lambda'}(x) = \int \frac{dz^-}{4\pi}\, e^{ik\cdot z} \langle g(p,\lambda')\,|\,\bar{q}(-\tfrac{z}{2})\,\gamma^+\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\,q(\tfrac{z}{2})\,|\,g(p,\lambda)\rangle\Big|_{z^+=0,\,\vec{z}_\perp=\vec{0}_\perp} = -(\epsilon\cdot\epsilon'^*)\, f_1^q(x)$$

GPD decomposition for external on-shell gluons:

$$F^{[\gamma^+]}_{\lambda\lambda'}(x,\Delta) = \int \frac{dz^-}{4\pi}\, e^{ik\cdot z} \langle g(p',\lambda')\,|\,\bar{q}(-\tfrac{z}{2})\,\gamma^+\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\,q(\tfrac{z}{2})\,|\,g(p,\lambda)\rangle\Big|_{z^+=0,\,\vec{z}_\perp=\vec{0}_\perp}$$
$$= S_1\, H_1^q(x,\xi,\Delta^2) + S_2\, H_2^q(x,\xi,\Delta^2)\,,$$

$$S_1 = -(\epsilon\cdot\epsilon'^*) + \frac{\Delta^2}{2\,(P^+)^2}\,\frac{\epsilon^+\,(\epsilon'^*)^+}{1-\xi^2} - \frac{1}{1+\xi}\,\frac{\epsilon^+\,(\epsilon'^*\cdot\Delta)}{P^+} + \frac{1}{1-\xi}\,\frac{(\epsilon\cdot\Delta)\,(\epsilon'^*)^+}{P^+}\,,$$
$$S_2 = 2\,\frac{(\epsilon\cdot\Delta)\,(\epsilon'^*\cdot\Delta)}{\Delta^2} - (\epsilon\cdot\epsilon'^*)\,,$$

$$(S_1)_{++} = (S_1)_{--} = 1\,, \qquad (S_2)_{+-} = (S_2)_{+-} = 1$$

Conditions on the GPDs for a well-defined collinear limit.

$$\lim_{\Delta\to 0} H_1^q(x,\xi,\Delta^2) = f_1^q(x)\,, \qquad \lim_{\Delta^2\to 0} H_2^q(x,\xi,\Delta^2) = 0\,.$$

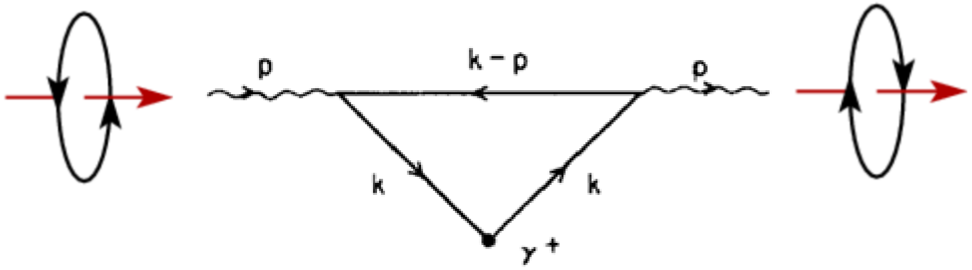
Consistency Conditions for the PDF Limit: Vector Current (Some Remarks)

1) A similar analysis can be made for the axial current.

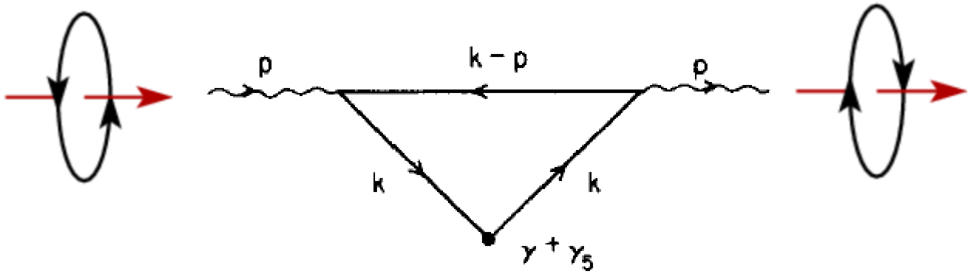
2) In both cases, the ***consistency condition*** for the helicity-flip GPDs H_2 and $\widetilde{H}_2$ is ***also imposed by conservation of angular momentum***:

$$\lim_{\Delta^2 \to 0} H_2^q(x, \xi, \Delta^2) = 0 \,.$$

$$\lim_{\Delta^2 \to 0} \xi \, \tilde{H}_2^q(x, \xi, \Delta^2) = 0$$



Non-local ***vector*** current.



Non-local ***axial*** current.

GPD Results at One-Loop Massive Quarks

$$H_1^q(x,\xi,\Delta^2;m) = \frac{\alpha_s}{4\pi}\begin{cases} \dfrac{(1-x)^2+x^2-\xi^2}{1-\xi^2}\left(\dfrac{1}{\varepsilon_{\mathrm{UV}}}-\log\dfrac{m^2}{\bar\mu^2}\right)-\dfrac{2x(1-x)}{1-\xi^2} \\ -\dfrac{((1-x)^2+x^2-\xi^2)\kappa-4x(1-x)}{(1-\xi^2)\sqrt{\kappa(4+\kappa)}}\log\dfrac{\sqrt{4+\kappa}+\sqrt{\kappa}}{\sqrt{4+\kappa}-\sqrt{\kappa}} & \xi\le x\le 1, \\ \dfrac{(x+\xi)(\xi-2x+1)}{2\xi(1+\xi)}\left(\dfrac{1}{\varepsilon_{\mathrm{UV}}}-\log\dfrac{m^2}{\bar\mu^2}\right)-\dfrac{x}{\xi}\dfrac{x+\xi}{1+\xi} \\ -\dfrac{x}{\xi}\dfrac{1+\xi^2-2x}{2(1-\xi^2)}\log\left(1+\dfrac{(\xi^2-x^2)(1-\xi^2)}{4\xi^2(1-x)^2}\kappa\right) \\ -\dfrac{((1-x)^2+x^2-\xi^2)\kappa-4x(1-x)}{2(1-\xi^2)\sqrt{\kappa(4+\kappa)}}\log\dfrac{h_+}{h_-}-(x\to -x) & -\xi<x<\xi, \end{cases}$$

$$H_2^q(x,\xi,\Delta^2;m) = -\frac{\alpha_s}{4\pi}\begin{cases} \dfrac{2x(1-x)}{1-\xi^2}\left(1-\dfrac{2}{\sqrt{\kappa(4+\kappa)}}\log\dfrac{\sqrt{4+\kappa}+\sqrt{\kappa}}{\sqrt{4+\kappa}-\sqrt{\kappa}}\right) & \xi\le x\le 1, \\ \dfrac{x}{\xi}\dfrac{x+\xi}{1+\xi}-\dfrac{2x(1-x)}{1-\xi^2}\dfrac{1}{\sqrt{\kappa(4+\kappa)}}\log\dfrac{h_+}{h_-}-(x\to -x) & -\xi<x<\xi, \end{cases}$$

$$h_\pm = 4\xi(1-x)\pm(1-\xi)(x+\xi)\sqrt{\kappa}\left(\sqrt{4+\kappa}\pm\sqrt{\kappa}\right).$$

Full results for ***massive quark and off-forward kinematics*** (nonzero m and Δ^2).

$$\kappa = \tau(1-x)^2/(1-\xi^2)$$

$$\tau = -\Delta^2/m^2$$

GPD Collinear Limit Results at One-Loop Massive Quarks

$$f_1^q(x;m) = \frac{\alpha_s}{4\pi}\left(\frac{1}{\varepsilon_{\mathrm{UV}}} - \log\frac{m^2}{\bar{\mu}^2}\right)\begin{cases}(1-x)^2 + x^2 & 0 < x \leq 1\,, \\ -\left((1+x)^2 + x^2\right) & -1 \leq x < 0\,,\end{cases}$$

PDF result, direct calculation.

$$H_1^q(x,\xi,\Delta^2;m) = \frac{\alpha_s}{4\pi}\begin{cases}\frac{(1-x)^2 + x^2 - \xi^2}{1-\xi^2}\left(\frac{1}{\varepsilon_{\mathrm{UV}}} - \log\frac{m^2}{\bar{\mu}^2}\right) + \mathcal{O}(\tau) & \xi \leq x \leq 1\,, \\ \frac{x}{\xi}\,\frac{1-\xi}{1+\xi}\left(\frac{1}{\varepsilon_{\mathrm{UV}}} - \log\frac{m^2}{\bar{\mu}^2}\right) + \mathcal{O}(\tau) & -\xi < x < \xi\,,\end{cases}$$

PDF result, GPD ***collinear limit*** calculation $\Delta^2 \to 0$.

$$H_2^q(x,\xi,\Delta^2;m) = -\frac{\alpha_s}{4\pi}\begin{cases}-\frac{x\,(1-x)^3}{3\,(1-\xi^2)^2}\,\tau + \mathcal{O}(\tau^2) \overset{\tau\to 0}{\to} 0 & \xi \leq x \leq 1\,, \\ \frac{x}{\xi}\,\frac{3x^2 - \xi\,(2+\xi)}{6\,(1+\xi)^2}\,\tau + \mathcal{O}(\tau^2) \overset{\tau\to 0}{\to} 0 & -\xi < x < \xi\,.\end{cases}$$

The helicity-flip GPD vanishes in the collinear limit.

We argue that to take the limit $\Delta^2 \to 0$ another mass scale (IR regulator) should be kept. Here we use ***a nonzero mass of the quark*** m.

GPD Results at One-Loop Dimensional Regularization for IR Divergences

Dimensionless integral of this kind appear in the ***PDF calculations***:

$$\mu^{2\varepsilon}\int\frac{d^{2-2\varepsilon}\vec{k}_\perp}{(2\pi)^{2-2\varepsilon}}\frac{1}{\vec{k}_\perp^2}=\frac{1}{4\pi}\left(\frac{1}{\varepsilon_{\rm UV}}-\frac{1}{\varepsilon_{\rm IR}}\right).$$

That separates UV and IR divergences.

Integral of the following kind appear in the ***GPD calculations***:

$$\mu^{2\varepsilon}\int\frac{d^{2-2\varepsilon}\vec{k}_\perp}{(2\pi)^{2-2\varepsilon}}\frac{1}{\vec{k}_\perp^2+M^2}=\mu^{2\varepsilon}\int\frac{d^{2-2\varepsilon}\vec{k}_\perp}{(2\pi)^{2-2\varepsilon}}\left(\frac{1}{\vec{k}_\perp^2+M^2}-\frac{1}{\vec{k}_\perp^2}\right)+\mu^{2\varepsilon}\int\frac{d^{2-2\varepsilon}\vec{k}_\perp}{(2\pi)^{2-2\varepsilon}}\frac{1}{\vec{k}_\perp^2}$$
$$=\frac{1}{4\pi}\left[\left(\frac{M^2}{4\pi\mu^2}\right)^{-\varepsilon_{\rm IR}}\Gamma(\varepsilon_{\rm IR})+\left(\frac{1}{\varepsilon_{\rm UV}}-\frac{1}{\varepsilon_{\rm IR}}\right)\right],$$

Here M is a physical mass scale (in this case, Δ^2) that ***can be taken to zero safely*** in the first term of the second line (heuristically, the sign of ϵ_{IR} is negative).

In this way, we recover the PDF results from the GPD results in dimensional regularization.

GPD Results at One-Loop Dimensional Regularization for IR Divergences

$$H_1^q(x,\xi,\Delta^2;\varepsilon_{\rm IR}) = \frac{\alpha_s}{4\pi}\begin{cases} \dfrac{(1-x)^2+x^2-\xi^2}{1-\xi^2}\,\dfrac{1}{1-2\,\varepsilon}\left(\dfrac{1}{\varepsilon_{\rm UV}}-\dfrac{1}{\varepsilon_{\rm IR}}\right) \\ -\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{(1-x)^2}{1-\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(1+\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}\,\tilde{B}(\varepsilon_{\rm IR},1;\infty)\left(\dfrac{x^2-x+1-\xi^2}{1-\xi^2}(1-\varepsilon_{\rm IR})-\dfrac{1}{2}\right) & \xi\le x\le 1\,, \\ \dfrac{(1+\xi-2x)(x+\xi)}{2\,\xi\,(1+\xi)}\,\dfrac{1}{1-2\,\varepsilon}\left(\dfrac{1}{\varepsilon_{\rm UV}}-\dfrac{1}{\varepsilon_{\rm IR}}\right) \\ -\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{(1-x)^2}{1-\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(1+\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}\,\tilde{B}(\varepsilon_{\rm IR},\zeta;\infty)\left(\dfrac{x^2-x+1-\xi^2}{1-\xi^2}(1-\varepsilon_{\rm IR})-\dfrac{1}{2}\right) \\ +\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{\xi^2-x^2}{4\,\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}\,\dfrac{x}{\xi}\left(\dfrac{1-x}{1-\xi^2}(1-\varepsilon_{\rm IR})-\dfrac{1}{2}\right)-(x\to -x) & -\xi<x<\xi\,, \end{cases}$$

$$H_2^q(x,\xi,\Delta^2;\varepsilon_{\rm IR}) = \frac{\alpha_s}{4\pi}\begin{cases} \dfrac{x\,(1-x)}{1-\xi^2}\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{(1-x)^2}{1-\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(1+\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}\,\varepsilon_{\rm IR}\,\tilde{B}(\varepsilon_{\rm IR},1;\infty) & \xi\le x\le 1\,, \\ \dfrac{x\,(1-x)}{1-\xi^2}\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{(1-x)^2}{1-\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(1+\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}\,\varepsilon_{\rm IR}\,\tilde{B}(\varepsilon_{\rm IR},\zeta;\infty) \\ -\dfrac{x}{\xi}\,\dfrac{x-\xi^2}{1-\xi^2}\left(-\dfrac{\Delta^2}{4\pi\mu^2}\,\dfrac{\xi^2-x^2}{4\,\xi^2}\right)^{-\varepsilon_{\rm IR}}\dfrac{\Gamma(1+\varepsilon_{\rm IR})}{1-2\,\varepsilon_{\rm IR}}-(x\to -x) & -\xi<x<\xi\,, \end{cases}$$

$$\tilde{B}(\varepsilon,\zeta;\kappa) = \int_0^\zeta d\alpha\,\left(\kappa^{-1}+\alpha\,(1-\alpha)\right)^{-1-\varepsilon}\,.$$

$$\kappa = \tau\,(1-x)^2/(1-\xi^2)$$

$$\tau = -\Delta^2/m^2$$

GPD Collinear Limit Results at One-Loop Dimensional Regularization for IR Divergences

$$f_1^q(x;\varepsilon_{\rm IR}) = \frac{\alpha_s}{4\pi}\frac{1}{1-2\varepsilon}\left(\frac{1}{\varepsilon_{\rm UV}}-\frac{1}{\varepsilon_{\rm IR}}\right)\begin{cases}(1-x)^2+x^2 & 0<x\leq 1\,,\\ -\left((1+x)^2+x^2\right) & -1\leq x<0\,.\end{cases}$$

PDF result, direct calculation.

$$H_1^q(x,\xi,\Delta^2;\varepsilon_{IR}) = \frac{\alpha_s}{4\pi}\begin{cases}\frac{(1-x)^2+x^2-\xi^2}{1-\xi^2}\frac{1}{1-2\varepsilon}\left(\frac{1}{\varepsilon_{\rm UV}}-\frac{1}{\varepsilon_{\rm IR}}\right)+O\left((-\Delta^2/\mu^2)^{-\varepsilon_{\rm IR}}\right) & \xi\leq x\leq 1\,,\\ \frac{x}{\xi}\frac{1-\xi}{1+\xi}\frac{1}{1-2\varepsilon}\left(\frac{1}{\varepsilon_{\rm UV}}-\frac{1}{\varepsilon_{\rm IR}}\right)+O\left((-\Delta^2/\mu^2)^{-\varepsilon_{\rm IR}}\right) & -\xi<x<\xi\,,\end{cases}$$

PDF result, GPD ***collinear limit*** calculation $\Delta^2 \to 0$.

$$H_2^q(x,\xi,\Delta^2;\varepsilon_{IR}) = O\left((-\Delta^2/\mu^2)^{-\varepsilon_{\rm IR}}\right)\,.$$

The helicity-flip GPD vanishes in the collinear limit.

We argue that to take the limit $\Delta^2 \to 0$ another mass scale (IR regulator) should be kept.
Here we use ***a nonzero mass scale*** $\boldsymbol{\mu^2}$.

Side Remark: We Have Results not Expanded in the quark mass m or in ϵ

For the DGLAP region results look:

$$H_1^q(x,\xi,\Delta^2) = \frac{\alpha_s}{4\pi}\left[\left(1 - \frac{2x(1-x)}{1-\xi^2}\frac{1-\varepsilon}{1-2\varepsilon}\right)D_1 - \frac{4}{\tau}\frac{x}{1-x}\frac{D_2}{1-2\varepsilon}\right],$$
$$H_2^q(x,\xi,\Delta^2) = -\frac{\alpha_s}{4\pi}\left[\frac{2x(1-x)}{1-\xi^2}\frac{\varepsilon D_1}{1-2\varepsilon} + \frac{4}{\tau}\frac{x}{1-x}\frac{D_2}{1-2\varepsilon}\right],$$

with:

$$D_1 = \left(\frac{m^2}{4\pi\mu^2}\right)^{-\varepsilon}\Gamma(1+\varepsilon)\left(\frac{-\kappa^{-\varepsilon}}{2}\tilde{B}(\varepsilon_{\rm IR},1;\kappa) + \frac{1}{\varepsilon_{\rm UV}}\right),$$
$$D_2 = -\frac{1}{2}\left(\frac{m^2}{4\pi\mu^2}\right)^{-\varepsilon}\Gamma(1+\varepsilon)\,\kappa^{-\varepsilon}\,\tilde{B}(\varepsilon_{\rm IR},1;\kappa),$$

These results are for general: Δ^2, m and not expanded in ϵ.

For the ERBL region results look:

$$H_1^q(x,\xi,\Delta^2) = \frac{\alpha_s}{4\pi}\left[\left(1 - \frac{2x(1-x)}{1-\xi^2}\frac{1-\varepsilon}{1-2\varepsilon}\right)E_1 - \frac{4}{\tau}\frac{x}{1-x}\frac{E_2}{1-2\varepsilon} - 2\frac{\xi^2-x^2}{1-\xi^2}\frac{1-\varepsilon}{1-2\varepsilon}E_3\right] - (x\to -x),$$
$$H_2^q(x,\xi,\Delta^2) = -\frac{\alpha_s}{4\pi}\left[\frac{2x(1-x)}{1-\xi^2}\frac{\varepsilon E_1}{1-2\varepsilon} + \frac{4}{\tau}\frac{x}{1-x}\frac{E_2}{1-2\varepsilon} + 2\frac{\xi^2-x^2}{1-\xi^2}\frac{\varepsilon E_3}{1-2\varepsilon}\right] - (x\to -x),$$

with:

$$E_1 = \left(\frac{m^2}{4\pi\mu^2}\right)^{-\varepsilon}\Gamma(1+\varepsilon)\left[\frac{-\kappa^{-\varepsilon}}{2}\tilde{B}(\varepsilon_{\rm IR},\zeta;\kappa) + \frac{1}{2}\left(1+\frac{x}{\xi}(1+\zeta(1-\zeta)\kappa)^{-\varepsilon}\right)\frac{1}{\varepsilon_{\rm UV}}\right],$$
$$E_2 = -\frac{1}{2}\left(\frac{m^2}{4\pi\mu^2}\right)^{-\varepsilon}\Gamma(1+\varepsilon)\,\kappa^{-\varepsilon}\,\tilde{B}(\varepsilon_{\rm IR},\zeta;\kappa),$$
$$E_3 = -\frac{1}{2}\frac{x}{\xi}\left(\frac{m^2}{4\pi\mu^2}\right)^{-\varepsilon}\Gamma(1+\varepsilon)(1+\zeta(1-\zeta)\kappa)^{-\varepsilon}\frac{1}{\varepsilon_{\rm UV}}.$$

We can get the results from the previous slides by expanding these integrals.

Conclusions

- We extended our previous work to the study of the nonlocal vector current.
- We identified conditions under which the GPDs have a well-defined PDF limit.
- Using dimensional regularization and a quark mass as an extra IR regulator in perturbation theory, these conditions are satisfied.
- We find ***no poles in the collinear limit***, indicating that the existing factorization framework of DVCS/DIS does not need to be modified.