中国科学院大学
University of Chinese Academy of Sciences
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Dynamical gluon effects in twist-3 generalized parton distributions of the proton

Ziqi Zhang
Supervisor: Xingbo Zhao

with

Chandan Mondal, Siqi Xu, Xingbo Zhao,
and James P. Vary
(BLFQ collaboration)

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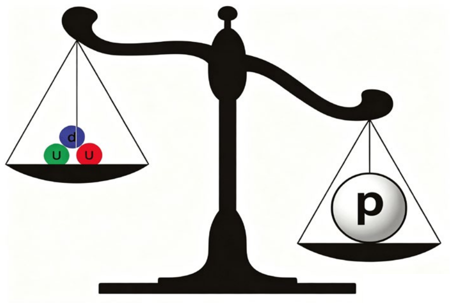
Outline

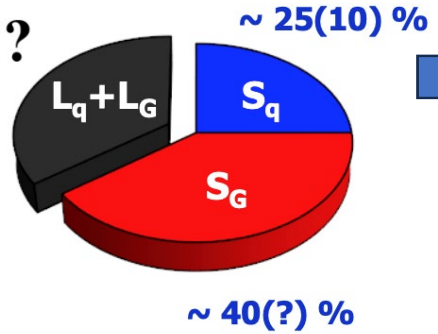
- **Proton structure:**
  history and challenges
- **Basis Light-front Quantization:**
  basis construction
  QCD Hamiltonian interactions
- **Twist-3 generalized parton distributions:**
  numerical results
  conclusion and outlook

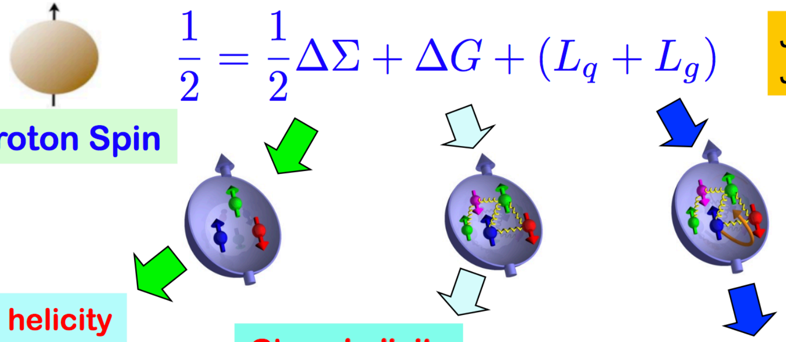
Proton structure

Origin of mass



Spin puzzle





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …

Proton Spin

Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Sea quarks?

Gluon helicity
Start to know

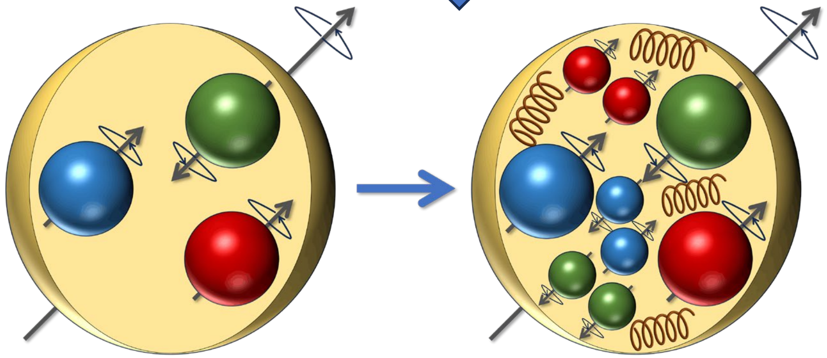
$$\Delta G = \int dx \Delta g(x)$$

$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

Need 3D structure of nucleon from QCD



valence quarks → gluons → sea quarks

- Quantum Chromodynamics (QCD): fundamental theory for strong interaction

Nobel Prize, 2004

$$\mathcal{L} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\Psi}(iD - m)\Psi$$

Basis Light-front Quantization

- **Hamiltonian eigenvalue equation:** [Vary, 2009]

$$P^-|\beta\rangle = P^-_\beta|\beta\rangle$$

- P^-: Light-Front Hamiltonian
- $|\beta\rangle$: Eigenstates (wave function)
- P^-_β: Eigenvalues (mass)

- **Basis setup:**
  - **Fock sector expansion**

    This work: $|qqq\rangle + |qqqg\rangle$

    $$|P,\Lambda\rangle = |qqq\rangle + |qqqg\rangle + |qqqq\bar{q}\rangle + |qqqgg\rangle + \cdots$$
  - **Longitudinal direction**

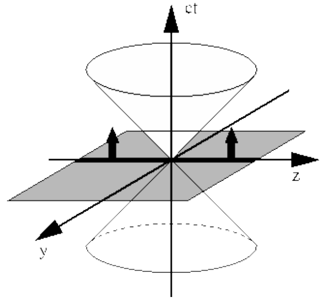
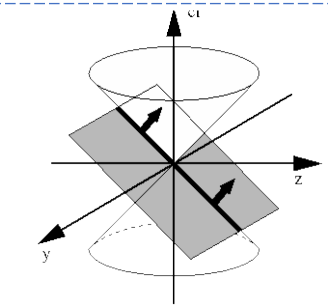
    — discrete longitudinal momentum (labeled by **k**)
  - **Transverse direction**

    — 2D harmonic oscillator (labeled by **n** , **m**)
  - **Truncation:**

$$\Lambda = \sum_i (\lambda_i + m_i) \qquad \sum_i k_i^+ = K_{\max} \qquad \sum_i (2n_i + |m_i| + 1) \le N_{\max}$$

- **Advantages:**
  1. Rotational symmetry in transverse plane
  2. Exact factorization between center-of-mass motion and intrinsic motion
  3. Harmonic oscillator basis supplies adequate infrared behavior for hadrons

[Dirac, 1949]

Equal time quantization	Light-front quantization
$t \equiv x^0$	$t \equiv x^+ = x^0 + x^3$
	
x^1, x^2, x^3	$x^- = x^0 - x^3$, $x^\perp = x^{1,2}$
$P^0, \vec{P}$	$P^- = P^0 - P^3$, $P^+ = P^0 + P^3$, $P^\perp = P^{1,2}$
$i\frac{\partial}{\partial t}\|\varphi(t)\rangle = H\|\varphi(t)\rangle$	$i\frac{\partial}{\partial x^+}\|\varphi(x^+)\rangle = \frac{1}{2}P^-\|\varphi(x^+)\rangle$
$P^0 = \sqrt{m^2 + \vec{P}^2}$	$P^- = \frac{m^2 + P_\perp^2}{P^+}$

Light-front QCD Hamiltonian

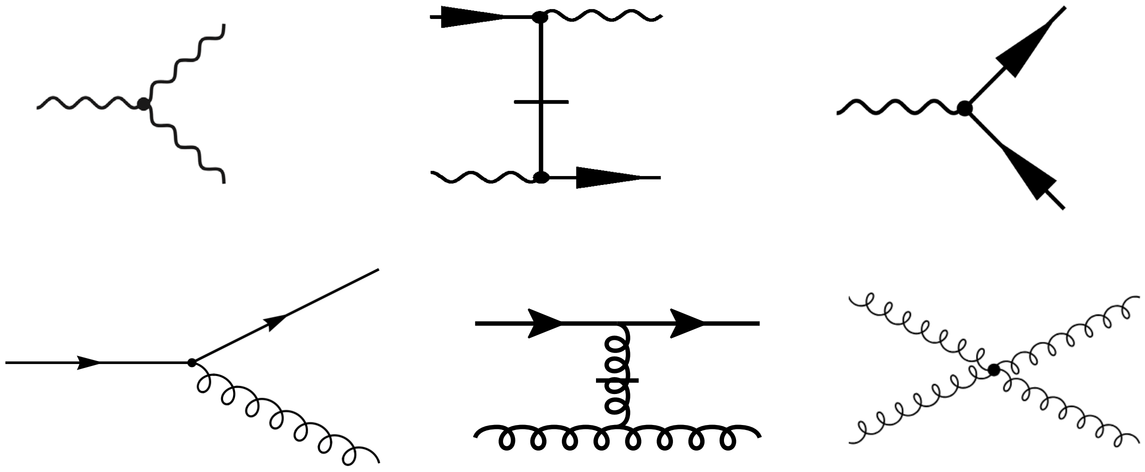
[S. Brodsky, H-C Pauli, S. Pinsky, '97]

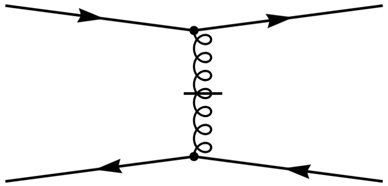
➢ **Light-front QCD Hamiltonian can be derived from QCD Lagrangian:**

$$\mathcal{L}_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha}$$

$\xrightarrow{\quad}$ $A^+ = 0$

$$\begin{aligned}
P^-_{QCD} &= \tfrac{1}{2}\int \mathrm{d}^3x\, \bar{\psi}\gamma^+ \frac{(\mathrm{i}\partial^\perp)^2 + m^2}{\mathrm{i}\partial^+}\psi - \tfrac{1}{2}\int \mathrm{d}^3x\, A^i_a (\mathrm{i}\partial^\perp)^2 A \\
&+ g\int \mathrm{d}^3x\, \bar{\psi}\gamma_\mu A^\mu \psi \\
&+ \tfrac{1}{2}g^2 \int \mathrm{d}^3x\, \bar{\psi}\gamma_\mu A^\mu \frac{\gamma^+}{\mathrm{i}\partial^+}\gamma_\nu A^\nu \psi \\
&- \mathrm{i}g^2 \int \mathrm{d}^3x\, f^{abc}\bar{\psi}\gamma^+ T^c \psi \frac{1}{(\mathrm{i}\partial^+)^2}\left(\mathrm{i}\partial^+ A^\mu_a A_{\mu b}\right) \\
&+ \tfrac{1}{2}g^2 \int \mathrm{d}^3x\, \bar{\psi}\gamma^+ T^a \psi \frac{1}{(\mathrm{i}\partial^+)^2}\bar{\psi}\gamma^+ T^a \psi \\
&+ \mathrm{i}g \int \mathrm{d}^3x\, f^{abc}\mathrm{i}\partial^\mu A^{\nu a} A^b_\mu A^c_\nu \\
&- \tfrac{1}{2}g^2 \int \mathrm{d}^3x\, f^{abc} f^{ade}\mathrm{i}\partial^+ A^\mu_b A_{\mu c}\frac{1}{(\mathrm{i}\partial^+)^2}\left(\mathrm{i}\partial^+ A^\nu_d A_{\nu e}\right) \\
&+ \tfrac{1}{4}g^2 \int \mathrm{d}^3x\, f^{abc} f^{ade} A^\mu_b A^\nu_c A_{\mu d} A_{\nu e}.
\end{aligned}$$



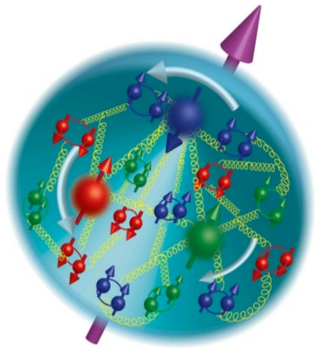


ψ: quark field operator
A^a_μ: gluon field operator

Truncated Light-front Hamiltonian

$$|\text{proton}\rangle = \psi_{uud}|uud\rangle + \psi_{uudg}|uudg\rangle \qquad P^+P^-|\Psi\rangle = M^2|\Psi\rangle$$

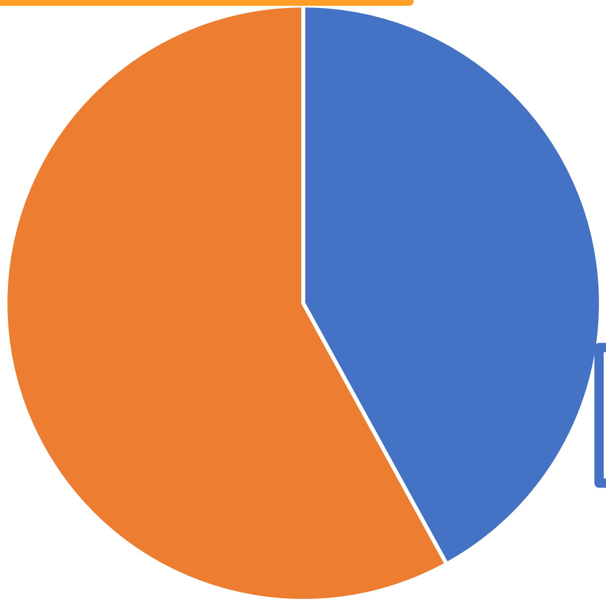
[Siqi Xu, et al., PRD 108 (2023) 9, 094002]



➢ QCD Interaction:

$$P^-_{\text{QCD}} = \int \mathrm{d}x^-\mathrm{d}^2x^\perp \Big\{ \frac{1}{2}\bar{\psi}\gamma^+ \frac{m_0^2 + (i\partial^\perp)^2}{i\partial^+}\psi + \frac{1}{2}A_a^i\left[m_g^2 + (i\partial^\perp)^2\right]A_a^i + g_s\bar{\psi}\gamma_\mu T^a A_a^\mu \psi + \frac{1}{2}g_s^2\bar{\psi}\gamma^+T^a\psi\frac{1}{(i\partial^+)^2}\bar{\psi}\gamma^+T^a\psi \Big\},$$

Dynamic gluon Fock sectors
$|qqqg\rangle$ ~ 58%



Valence Fock sector
$|qqq\rangle$ ~ 42%

➢ Confinement:

[Y. Li et al., PLB 758 (2016)]

$$P^-_{\text{C}}P^+ = \frac{\kappa^4}{2}\sum_{i\neq j}\left\{ \{\vec{r}^{\,2}_{ij\perp} - \frac{\partial_{x_i}(x_i x_j \partial_{x_j})}{(m_i+m_j)^2} \right\}$$

➢ Truncation parameters:

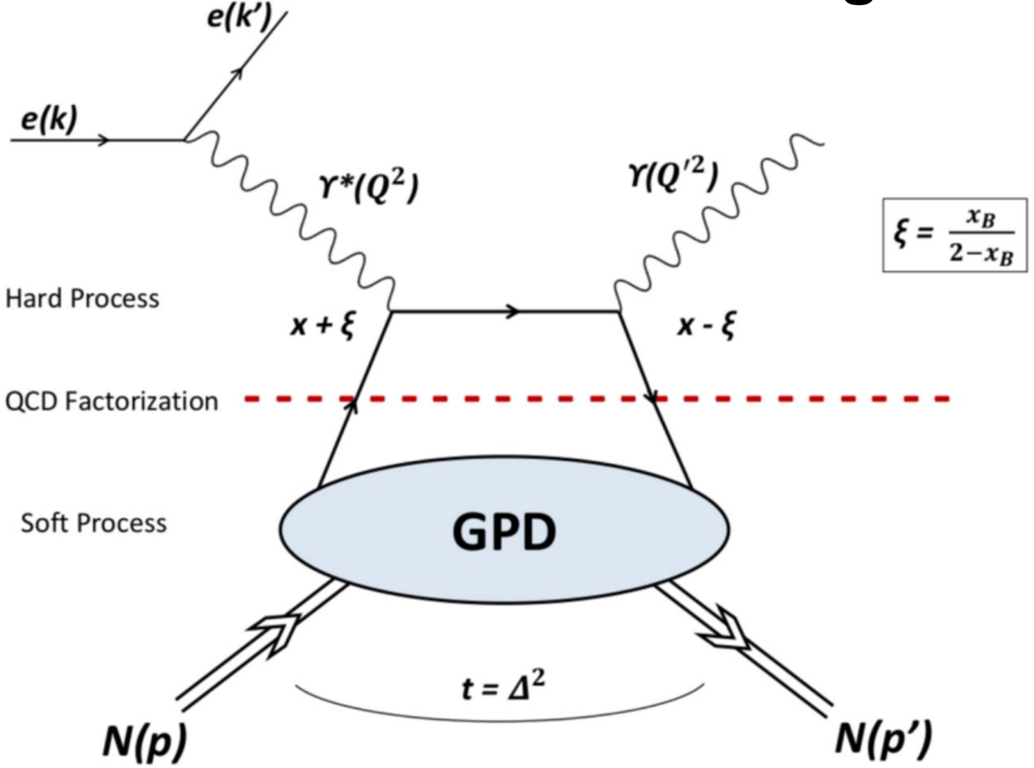
basis truncation: N_{max}=9, K=16.5

HO parameters: b=0.7 GeV, b_{inst}=3 GeV

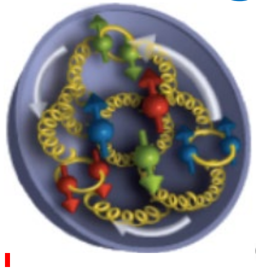
m_u	m_d	m_g	κ	m_f	g
0.31GeV	0.25GeV	0.50GeV	0.54GeV	1.80GeV	2.40

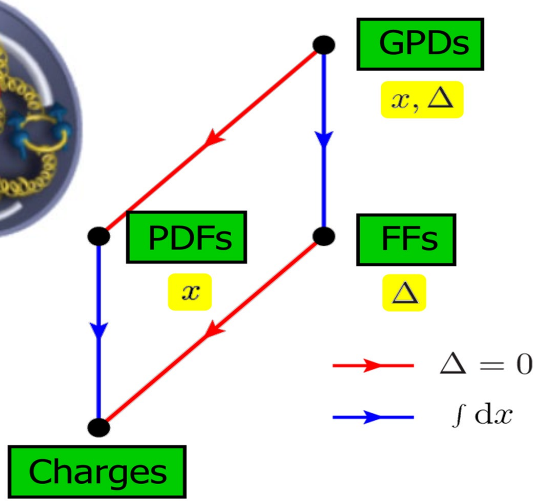
Generalized parton distribution functions

➤ GPDs can be assessed through deeply virtual Compton scattering (DVCS):



- Encode 3D spatial information
- Contain information about spin and orbital angular momentum
- Appear also in DVMP / TCS / DDVCS …





➤ Twist decomposition:

$$\Psi = \Psi^+ + \Psi^-$$

$$\Psi^- = \frac{\gamma^+}{2i\partial^+}(m_q - i\gamma^\perp\partial_\perp + g\gamma^\perp A_\perp)\Psi^+$$

➤ GPDs are functions of three variables:

- Longitudinal momentum fraction → $x = \frac{k^+}{P^+}$
- Longitudinal momentum transfer → skewness $\xi = \frac{\Delta^+}{P^+}$
- Square of total momentum transfer → $t = \Delta^2 = (P' - P)^2$

twist-2: $\langle P', \Lambda' | \bar{\Psi}^+ \Gamma \Psi^+ | P, \Lambda \rangle$ — qqq: $\langle uud | \ldots | uud \rangle$

twist-3: $(\bar{\Psi}^+ \Gamma \Psi^- + \bar{\Psi}^- \Gamma \Psi^+) =$ — qqqg: $\langle uudg | \ldots | uudg \rangle$

twist-4: $\bar{\Psi}^- \Gamma \Psi^-$ — genuine: $\langle uudg | \ldots | uud \rangle + h.c.$

Generalized parton distribution functions

- **GPDs are defined through the following bilocal operator:**

$$F^{[\Gamma]}_{\Lambda'\Lambda}(x,\xi,\Delta^2)=\int\frac{dz^-}{4\pi}e^{ip\cdot x}\left\langle P',\Lambda'\middle|\bar{\psi}\left(-\frac{z}{2}\right)\mathcal{W}\left(-\frac{z}{2},\frac{z}{2}\right)\Gamma\psi\left(\frac{z}{2}\right)\middle|P,\Lambda\right\rangle\Bigg|_{z^+=z^\perp=0}$$

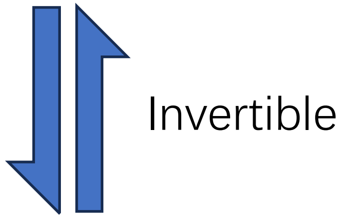
- **GPDs are parameterized by taking different Γ matrices:** [Stephan. M, 2009]

$$F^{[\gamma^j]}_{\Lambda'\Lambda}=\frac{M}{2(P^+)^2}\bar{u}\left[i\sigma^{+j}H_{2T}+\frac{\gamma^+\Delta^j_T-\Delta^+\gamma^j}{2M}E_{2T}+\frac{P^+\Delta^j_T-\Delta^+P^j_T}{M^2}\widetilde{H}_{2T}+\frac{\gamma^+P^j_T-P^+\gamma^j}{M}\widetilde{E}_{2T}\right]u,$$

$$F^{[\gamma^j\gamma_5]}_{\Lambda'\Lambda}=\frac{-i\varepsilon^{ij}_T M}{2(P^+)^2}\bar{u}\left[i\sigma^{+i}H'_{2T}+\frac{\gamma^+\Delta^i_T-\Delta^+\gamma^i}{2M}E'_{2T}+\frac{P^+\Delta^j_T-\Delta^+P^j_T}{M^2}\widetilde{H}'_{2T}+\frac{\gamma^+P^j_T-P^+\gamma^j}{M}\widetilde{E}'_{2T}\right]u,$$

Twist	Γ	GPDs	Num
Twist-2	$\gamma^+,\gamma^+\gamma_5,i\sigma^{j+}\gamma_5$	$H,E,\widetilde{H},\widetilde{E},H_T,E_T,\widetilde{H}_T,\widetilde{E}_T$	8
Twist-3	$1,\gamma_5,\gamma^\perp,\gamma^\perp\gamma_5,$ $i\sigma^{ij}\gamma_5,i\sigma^{+-}\gamma_5$	$H_2,E_2,\widetilde{H}_2,\widetilde{E}_2,H_{2T},E_{2T},\widetilde{H}_{2T},\widetilde{E}_{2T},$ $H'_2,E'_2,\widetilde{H}'_2,\widetilde{E}'_2,H'_{2T},E'_{2T},\widetilde{H}'_{2T},\widetilde{E}'_{2T}$	16
Twist-4	$\gamma^-,\gamma^-\gamma_5,i\sigma^{j-}\gamma_5$	$H_3,E_3,\widetilde{H}_3,\widetilde{E}_3,H_{3T},E_{3T},\widetilde{H}_{3T},\widetilde{E}_{3T}$	8

G_1,G_2,G_3,G_4
$\tilde{G}_1,\tilde{G}_2,\tilde{G}_3,\tilde{G}_4$

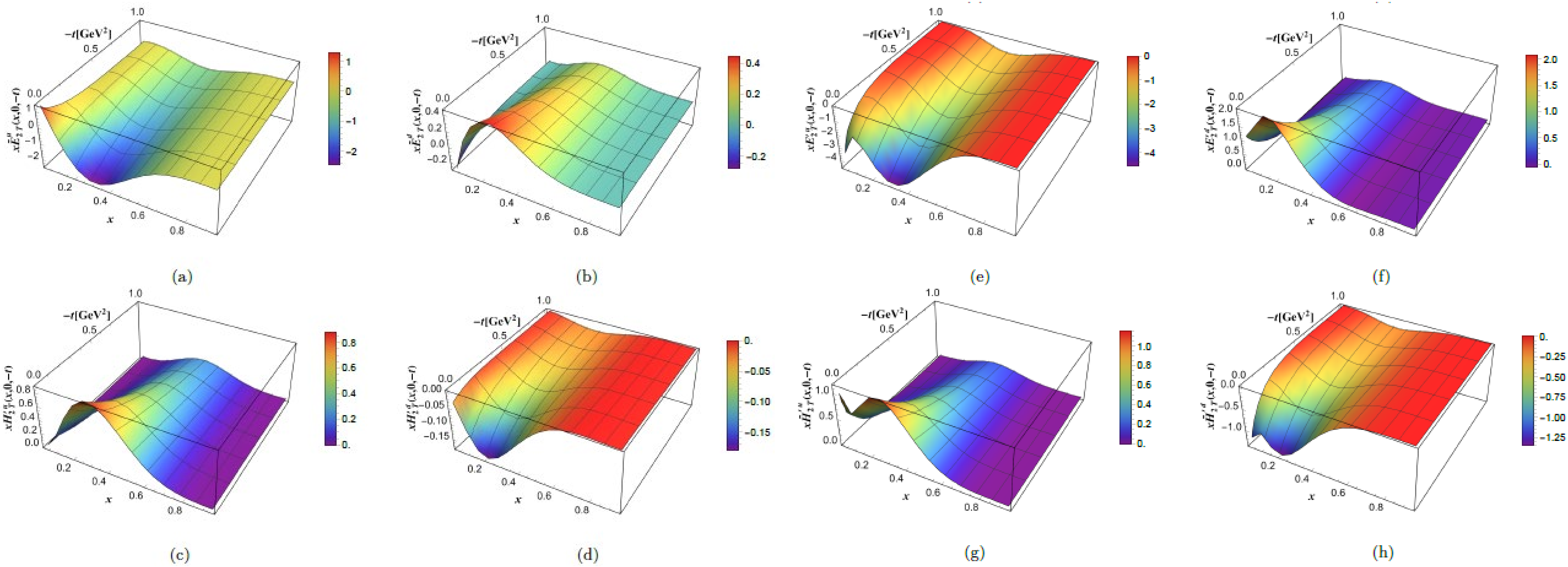


$H_{2T},E_{2T},\widetilde{H}_{2T},\widetilde{E}_{2T}$
$H'_{2T},E'_{2T},\widetilde{H}'_{2T},\widetilde{E}'_{2T}$

Numerical results of twist-3 GPDs

➢ **3D images of $\Gamma = \gamma^{\perp}$ and $\Gamma = \gamma^{\perp}\gamma_5$ related twist-3 GPDs from BLFQ:**

[Ziqi Zhang, et.al., PRD (2026)]

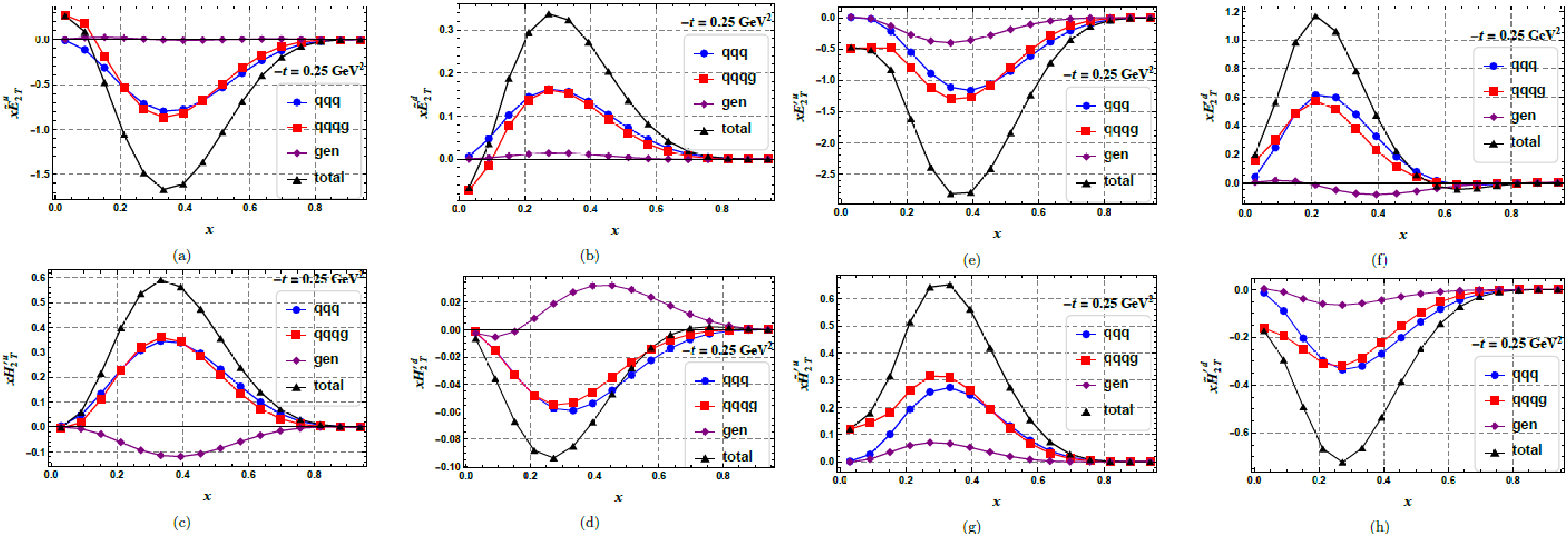


At zero-skewness, GPDs $\boldsymbol{H_{2T}}, \boldsymbol{E_{2T}}, \boldsymbol{\widetilde{H}_{2T}}$ and $\boldsymbol{\widetilde{E}'_{2T}}$ are consistent with 0.

Numerical results of twist-3 GPDs

➢ **2D images with fixed $-t$ of $\Gamma = \gamma^{\perp}$ and $\Gamma = \gamma^{\perp}\gamma_5$ related twist-3 GPDs from BLFQ:**

[Ziqi Zhang, et.al., PRD (2026)]

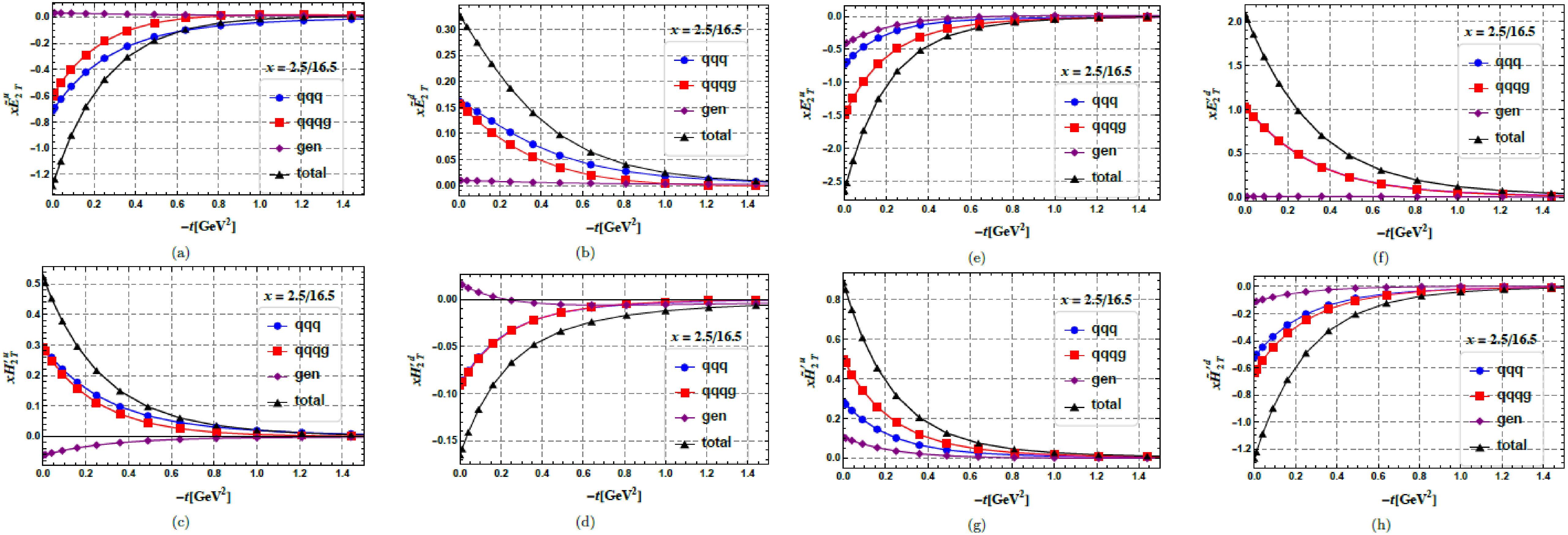


At zero-skewness, GPDs $H_{2T}, E_{2T}, \tilde{H}_{2T}$ and $\tilde{E}'_{2T}$ are consistent with 0.

Numerical results of twist-3 GPDs

➢ **2D images with fixed x of $\Gamma = \gamma^{\perp}$ and $\Gamma = \gamma^{\perp}\gamma_5$ related twist-3 GPDs from BLFQ:**

[Ziqi Zhang, et.al., PRD (2026)]



At zero-skewness, GPDs $H_{2T}, E_{2T}, \widetilde{H}_{2T}$ and $\widetilde{E}'_{2T}$ are consistent with 0.

Numerical results of twist-3 GPDs

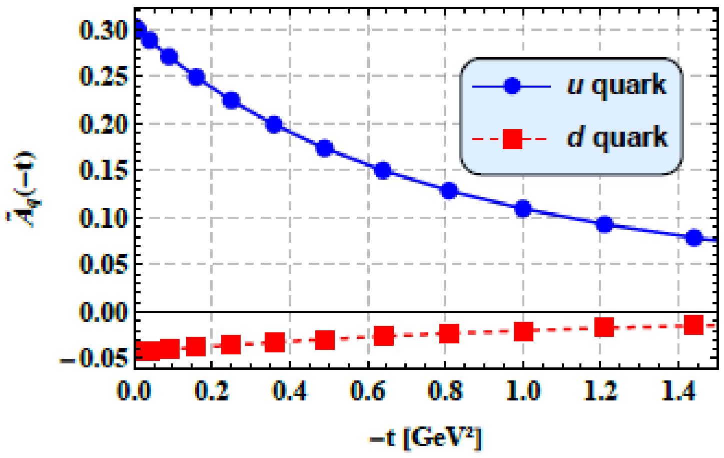
➢ Spin-orbit correlations:

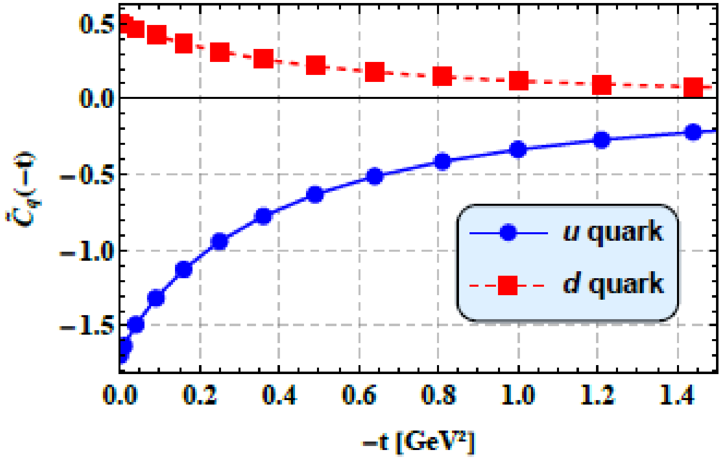
$$\hat{T}^{\mu\nu}_{q5} = \frac{1}{2}\bar{\psi}\gamma^{\mu}\gamma_5 i\overleftrightarrow{D}^{\nu}\psi$$

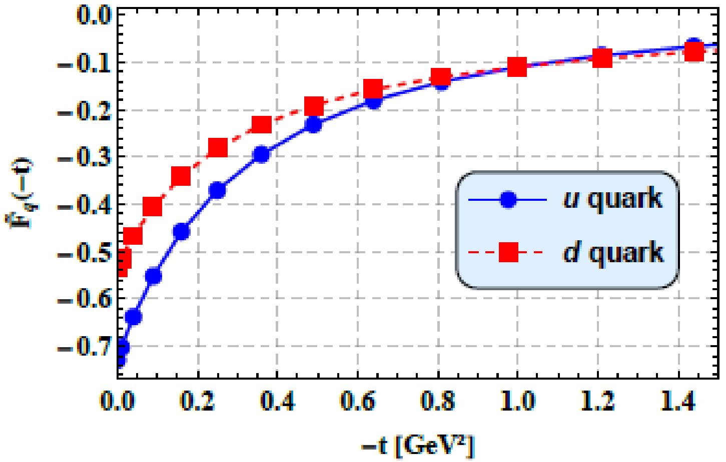
$$\langle p', s'|\hat{T}^{\mu\nu}_{q5}|p, s\rangle = \bar{u}(p', s')\Gamma^{\mu\nu}_{q5}u(p, s)$$

$$\Gamma^{\mu\nu}_{q5} = \frac{\bar{P}^{\{\mu}\gamma^{\nu\}}\gamma_5}{2}\tilde{A}_q(-t) + \frac{\bar{P}^{\{\mu}\Delta^{\nu\}}\gamma_5}{4M}\tilde{B}_q(-t) + \frac{\bar{P}^{[\mu}\gamma^{\nu]}\gamma_5}{2}\tilde{C}_q(-t) + \frac{\bar{P}^{[\mu}\Delta^{\nu]}\gamma_5}{4M}\tilde{D}_q(-t) + Mi\sigma^{\mu\nu}\gamma_5\tilde{F}_q(-t).$$

[C Lorce´, PLB, 735:344–348, 2014]







$$C_z^q = -\int dx x\left(\tilde{G}_2^q(x,0,0) + 2\tilde{G}_4^q(x,0,0)\right)$$

Theoretical Approach	C_z^u	C_z^d
BLFQ (model scale, this work)	−0.761	−0.515
NQM, LFCQM, LFχQSM [92]	≈ −0.8	≈ −0.55
LSS ($\mu^2 = 1$ GeV^2) [93]	≈ −0.9	≈ −0.53
Spectator Diquark Model [58]	−0.775	−0.586

➢ Total quark contribution:

[Y. Guo et.al., NPB, 969:115440, 2021]

$$J_q = \frac{1}{2}\int dx\,[xH(x,0,0) + xE(x,0,0)]$$
$$= -\int dx\left[x\tilde{E}_{2T}(x,0,0) + \frac{1}{2}\tilde{H}(x,0,0)\right]$$

J_q	Twist-3
J_u	0.443827
J_d	-0.0796096

Conclusion and outlook

➢ Conclusion:

- We include the $|qqqg\rangle$ Fock sector with one dynamical gluon to investigate quark-gluon interactions.
- Owing to the Fock-space truncation, we cannot incorporate all QCD interactions at this stage and therefore employ a confinement potential.
- We have calculated twist-3 GPDs within the BLFQ framework and further evaluated the spin-orbit correlations. Our results are consistent with other theoretical calculations.

➢ Outlook:

- Expand to higher Fock sectors to include full QCD Hamiltonian.
- Gluon GPDs / twist-3 CFFs / DVCS cross sections.
- Investigate proton mass decomposition / spin structure.

Thank you for your time!