Proton Structure in a Light-Front Hamiltonian Approach

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BLFQ Collaboration

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Overview

Introduction

Basis Light-Front Quantization (BLFQ) to

Proton : $(|qqq\rangle + |qqqg\rangle)$

Proton : $(|qqq\rangle + |qqqg\rangle + |qqqq\bar{q}\rangle)$

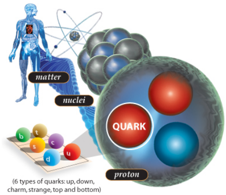
Conclusions

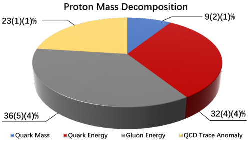
PRD 108 094002 (2023); PLB 847 138305 (2023); PLB 855 138829 (2024); PLB 855 138831 (2024); 2408.11298 [hep-ph]

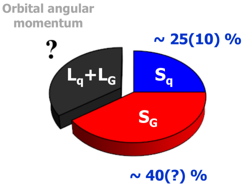
Fundamental Properties: Mass and Spin

- About 99% of the visible mass is contained within nuclei
- Nucleon: composite particles, built from nearly massless quarks ($\sim$ 1% of the nucleon mass) and gluons
- Quantitative decomposition of *nucleon spin* in terms of quark and gluon degrees of freedom is not yet fully understood.
- To address these fundamental issues $\rightarrow$ nature of the subatomic force between quarks and gluons, and the internal landscape of nucleons.
- Ideal facilities : EIC & EicC

talked by H. Gao and S. Peng





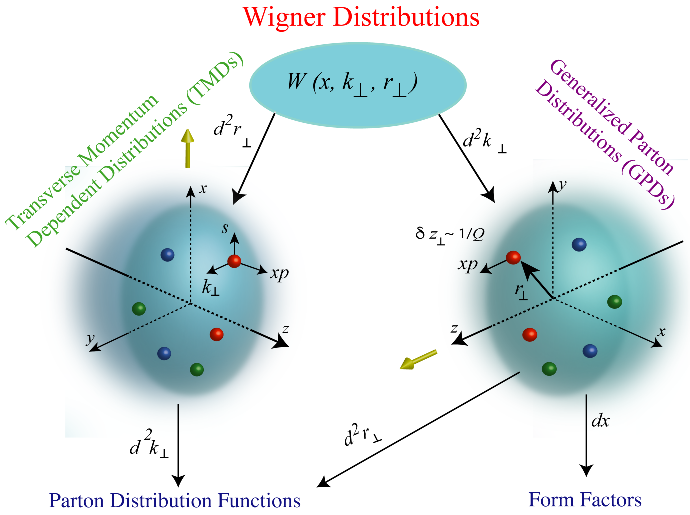


[1] Yang, *et al.*, PRL 121, 212001 (2018)

[2] Bhattacharya, *et al.*, PRL 128, 182002 (2022); PRL 133, 051901 (2024)

[3] Pictures (top to bottom) adopted from A. Signori, S. Peng, C. Lorce

Hadron Tomography

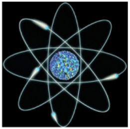
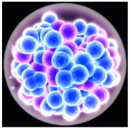


- $x \to$ longitudinal momentum fraction; $k_\perp \to$ parton transverse momentum; $r_\perp \to$ transverse distance from the center.

Nonperturbative Approaches

Lagrangian formalism	Hamiltonian formalism
Euclidean space-time	Minkowski space-time
correlators: $\langle \mathcal{O}(x_1, \cdots, x_n) \rangle$	wave functions: $\lvert\psi_h\rangle$
$\langle \mathcal{O} \rangle = \int \mathcal{D}_\psi \mathcal{O} \exp\Big(- S_E[\psi] \Big)$	$H\lvert\psi_h\rangle = E_h\lvert\psi_h\rangle$
—	$i\frac{\partial}{\partial t}\lvert\psi_h(t)\rangle = H\lvert\psi_h(t)\rangle$
Lattice QCD, Dyson-Schwinger, FRG	DLCQ, BLFQ, Tamm-Dancoff, RGPEP

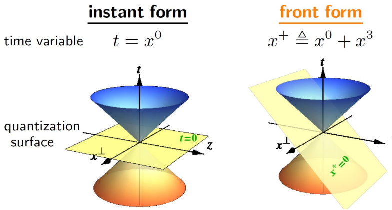
Schrödinger Equation $H|\psi\rangle = E|\psi\rangle$

		
nonrelativistic	nonrelativistic	relativistic
few-body	many-body	many-body
quant, AMO	nucl, quant chem	hadron, QFT

[1] Adopted from Yang Li

Basis Light-Front Quantization (BLFQ)

A computational framework for solving relativistic many-body bound state problems in quantum field theories



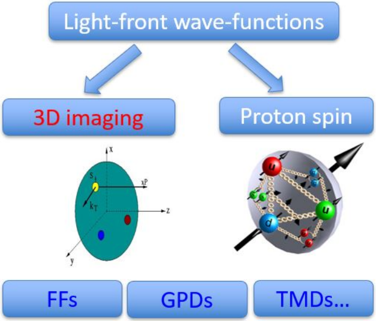
$$P^- P^+ |\Psi\rangle = M^2 |\Psi\rangle$$

- $P^\pm \equiv P^0 \pm P^3$: light-front momentum (Hamiltonian)
- First-principle / effective Hamiltonian as input
- Access to mass (M) and LFWFs

- Evaluate observables

$$O \sim \langle \Psi | \hat{O} | \Psi \rangle$$

GOAL



[1] Vary, Honkanen, Li, Maris, Brodsky, Harindranath, *et. al.*, Phys. Rev. C 81, 035205 (2010).

- Fock expansion of baryonic bound states:

$$|\text{Proton}\rangle = \psi_{(3q)}|qqq\rangle + \psi_{(3q+1g)}|qqqg\rangle + \psi_{(3q+q\bar{q})}|qqqq\bar{q}\rangle + \dots ,$$

Solution proposed by BLFQ

Discrete basis and their direct product	Truncation
2D HO $\phi_{nm}(p^{\perp})$ in the transverse plane	$\sum_i (2n_i + \lvert m_i\rvert + 1) \leq N_{\max}$
Plane-wave in the longitudinal direction	$\sum_i k_i = K, \quad x_i = \frac{k_i}{K}$
Light-front helicity state for spin d.o.f.	$\sum_i (m_i + \lambda_i) = M_J$
$\alpha_i = (k_i, n_i, m_i, \lambda_i)$ $\lvert\alpha\rangle = \otimes_i \lvert\alpha_i\rangle$	Fock sector truncation

Large $N_{\max}$ and $K \rightarrow$ High UV cutoff & low IR cutoff

- Exact factorization between center-of-mass motion and intrinsic motion

[1] Vary, Honkanen, Li, Maris, Brodsky, Harindranath, *et. al.*, Phys. Rev. C 81, 035205 (2010).

Nucleon within BLFQ

- The LF eigenvalue equation: $H_{\text{eff}}|\Psi\rangle = M^2|\Psi\rangle$

$$H_{\text{eff}} = \sum_a \frac{\vec{p}^{\,2}_{\perp a} + m_a^2}{x_a} + \frac{1}{2}\sum_{a\neq b}\kappa^4\left[x_a x_b(\vec{r}_{\perp a} - \vec{r}_{\perp b})^2 - \frac{\partial_{x_a}(x_a x_b \partial_{x_b})}{(m_a + m_b)^2}\right]$$
$$+ \frac{1}{2}\sum_{a\neq b}\frac{C_F 4\pi\alpha_s}{Q^2_{ab}}\bar{u}_{s'_a}(k'_a)\gamma^\mu u_{s_a}(k_a)\bar{u}_{s'_b}(k'_b)\gamma^\nu u_{s_b}(k_b)g_{\mu\nu}$$

Publications:

- Mondal et al., Phys. Rev. D 102, 016008 (2020) : Form Factors, PDFs,...
- Xu et al., Phys. Rev. D 104, 094036 (2021) : Nucleon structure, ...
- Liu et al., Phys. Rev. D 105, 094018 (2022) : Angular Momentum, ...
- Hu et al., Phys. Lett. B 833, 137360 (2022) : TMDs, ...
- Kaur et al., Phys. Rev. D 109, 014015 (2024) : Chiral-odd GPDs, ...
- Zhang et al., Phys. Rev. D 109, 034031 (2024) : Twist-3 GPDs, ...
- Liu et al., Phys. Lett. B 855, 138809 (2024) : Skewed GPDs, ...
- Nair et al., Phys. Rev. D 110, 056027 (2024) : GFFs, ...
- Peng et al., coming soon : Double parton correlations, ...

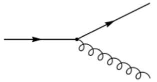
Proton with One Dynamical Gluon

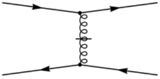
$$P^+P^-|\Psi\rangle = M^2|\Psi\rangle \qquad |\text{proton}\rangle = \psi_{uud}|uud\rangle + \psi_{uudg}|uudg\rangle$$

$$P^- = P^-_{\rm QCD} + P^-_C$$

QCD Interaction:

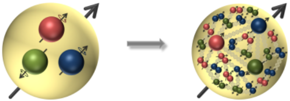
$$P^-_{\rm QCD} = \int dx^- d^2x^\perp \Big\{ \frac{1}{2}\bar{\psi}\gamma^+ \frac{m_0^2 + (i\partial^\perp)^2}{i\partial^+}\psi - \frac{1}{2}A^i_a\left[m_g^2 + (i\partial^\perp)^2\right]A^i_a + g_s\bar{\psi}\gamma_\mu T^a A^\mu_a \psi + \frac{1}{2}g_s^2\bar{\psi}\gamma^+T^a\psi\frac{1}{(i\partial^+)^2}\bar{\psi}\gamma^+T^a\psi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





Confinement only in leading Fock:

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



Parameters:

Truncation: Nmax=9, K=16.5
HO parameters: b=0.7GeV, $b_{\rm inst}$=3GeV

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

[1] S. Xu, CM, X. Zhao, Y. Li, J. P. Vary, Phys.Rev.D 108 (2023) 094002.
[2] Brodsky, Teramond, Dosch and Erlich, Phys. Rep. 584, 1 (2015).
[3] Li, Maris, Zhao and Vary, Phys. Lett. B (2016); M. Burkardt, Phys. Rev. D 58, 096015 (1998).

Proton with One Dynamical Gluon

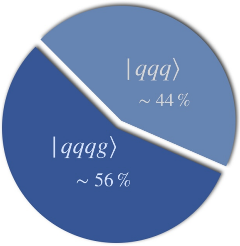
Fock expansion:

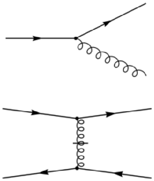
$$|\text{Proton}\rangle = a\,|uud\rangle + b\,|uudg\rangle + \ldots$$

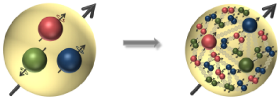
Light-front effective Hamiltonian :

$$H_{\text{eff}} = \sum_a \frac{\vec{p}^{\,2}_{\perp a} + m_a^2}{x_a} + H_{\text{confinement}} + H_{\text{vertex}} + H_{\text{inst}}$$

Fock Sector Decomposition



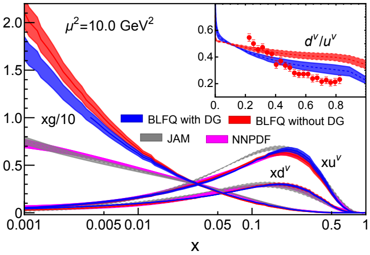


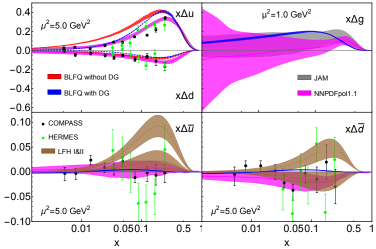


[1] S. Xu, CM, X. Zhao, Y. Li, J. P. Vary, Phys.Rev.D 108 (2023) 094002.

Unpolarized and Helicity PDFs

BLFQ: PRD 108 (2023) 094002





Diagonalizing H_{eff} $\Rightarrow$ LF wavefunction $\Rightarrow$ Initial PDFs $\Rightarrow$ Scale evolution

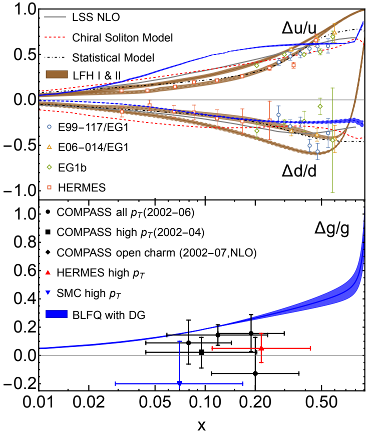
$$\text{Model scale } \mu_0^2 = 0.24 \pm 0.01 \text{ GeV}^2$$

- Quark momentum : $\langle x \rangle_u = 0.261 \pm 0.005$, $\langle x \rangle_d = 0.109 \pm 0.005$ at 10 GeV^2.
- Quark spin: $\frac{1}{2}\Sigma_u = 0.438 \pm 0.004$, $\frac{1}{2}\Delta\Sigma_d = -0.080 \pm 0.002$.
- Gluon spin: $\Delta G = 0.131 \pm 0.003$, PHENIX: $\Delta G^{[0.02,0.3]} = 0.2 \pm 0.1$.
- Sea quarks: solely generated from the QCD evolution.

[1] LFH: PRL 124 (2020), 082003; PHENIX: PRL 103 (2009) 012003.

Helicity Asymmetries

BLFQ: PRD 108 (2023) 094002



- Experimentally, the expected increase of $\Delta u/u$ is observed.
- For d quark: remains negative in the experimentally covered region.
- Global analyses favor negative values of $\Delta d/d$ at large-x.

BLFQ Predictions for Spin Decomposition

Fock expansion:

$$|\,\text{Proton}\rangle = a\,|\,uud\rangle + b\,|\,uudg\rangle + \ldots$$

Quark and gluon helicities :

$$\Delta\Sigma_q = \int \mathrm{d}x\,\Delta q(x)$$

$$\Delta\Sigma_g = \int \mathrm{d}x\,\Delta G(x)$$

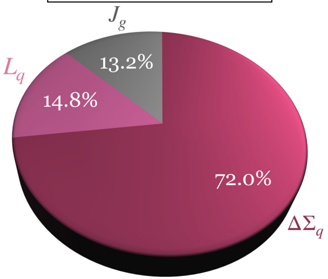
Total AM[2] :

$$J_i = \frac{1}{2}\int \mathrm{d}x\,x\,[H_i(x,0,0) + E_i(x,0,0)]$$

Kinetic OAM[2] :

$$L_q = \frac{1}{2}\int \mathrm{d}x\,[x\,\{H_q(x,0,0)+E_q(x,0,0)\}-\widetilde{H}_q(x,0,0)]$$

$$\boxed{\frac{1}{2}\Sigma_q + L_q + J_g = \frac{1}{2}}$$

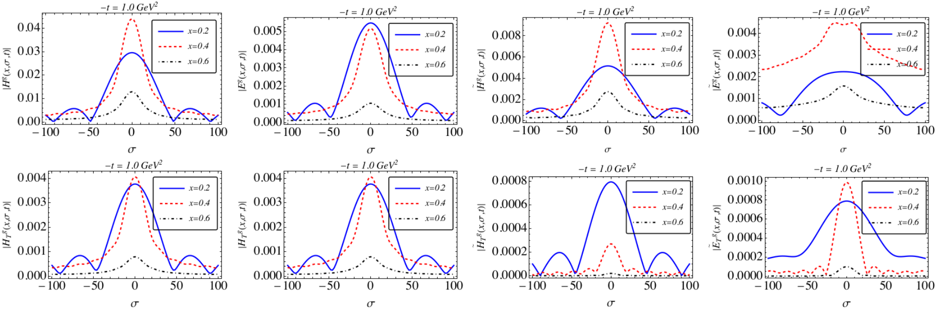


Kinetic[1]

[1] S. Xu, CM, X. Zhao, Y. Li, J. P. Vary, Phys.Rev.D 108, 094002 (2023).
[2] X. Ji, Phys.Rev.Lett. 78, 610 (1997).

Gluon GPDs in Longitudinal Position Space

$$f(x,\sigma,t) = \int_0^{\xi_f} \frac{d\xi}{2\pi} e^{i\xi P^+ b^-/2} G(x,\xi,t) = \int_0^{\xi_f} \frac{d\xi}{2\pi} e^{i\xi\sigma} G(x,\xi,t),$$



- Boost-invariant longitudinal position space, $\sigma = \frac{1}{2} b^- P^+$.
- Pattern similar to that observed in single-slit optical experiments.
- Influenced by the functional behavior of the GPDs; differ from quark GPDs.
- Similar pattern in DVCS amplitude, Parton density, Wigner distributions. . .

[1] Zhang, Liu, Xu, CM, *et. al.*, coming soon.

[2] Liu, Xu, CM, *et. al.*, PLB 855 (2024); Brodsky, *et. al.*, PLB 641 (2006); CM, EPJC 77 (2017);

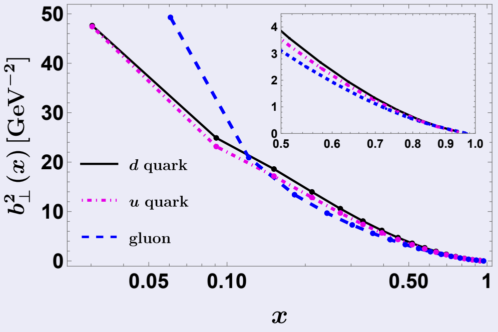
x-Dependent Squared Radius

$$\langle b_\perp^2 \rangle^i(x) = \frac{\int d^2\vec{b}_\perp b_\perp^2 \mathcal{H}^i(x, b_\perp)}{\int d^2\vec{b}_\perp \mathcal{H}^i(x, b_\perp)},$$

- Transverse squared radius:

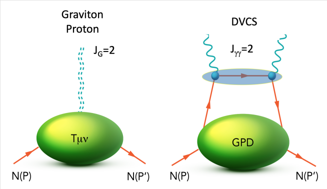
$$\langle b_\perp^2 \rangle = \sum_i e_q \int_0^1 \mathrm{d}x f^i(x) \langle b_\perp^2 \rangle^i(x)$$

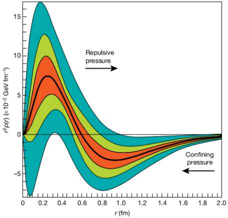
- BLFQ[1]: $\langle b_\perp^2 \rangle = 0.47 \pm 0.04\ \mathrm{fm}^2$
- Experimental data [2]: $\langle b_\perp^2 \rangle_{\exp} = 0.43 \pm 0.01\ \mathrm{fm}^2$



[1] B. Lin, S. Nair, S.Xu, CM, X. Zhao, J. P. Vary, PLB 847, 138305 (2023).
[2] R. Dupre, M. Guidal and M. Vanderhaeghen, PRD 95, 011501 (2017).

Proton Gravitational Form Factors





- Parametrization of matrix element in terms of GFFs

$$\langle P'|T_i^{\mu\nu}(0)|P\rangle = \bar{U}'\Big[- B_i(q^2)\frac{\bar{P}^\mu \bar{P}^\nu}{M} + (A_i(q^2) + B_i(q^2))\frac{1}{2}(\gamma^\mu \bar{P}^\nu + \gamma^\nu \bar{P}^\mu)$$

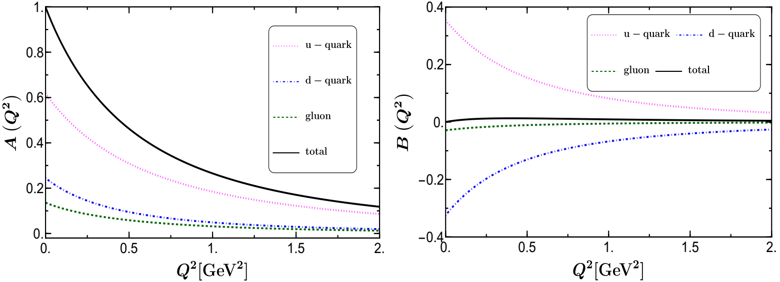
$$+ C_i(q^2)\frac{q^\mu q^\nu - q^2 g^{\mu\nu}}{M} + \bar{C}_i(q^2) M g^{\mu\nu}\Big] U$$

- Momentum sum rule : $\sum_i A^i(0) = 1$
- Gravitomagnetic moment sum rule : $\sum_i B^i(0) = 0$
- Spin sum rule: $J^i = \frac{1}{2}\left[A^i(0) + B^i(0)\right]$
- $4C(q^2) = D(q^2)$ provides shear forces and the pressure distributions

[1] Burkert *et. al.*: Rev. Mod. Phys. 95, 041002 (2023); Ji, Phys. Rev. Lett. 78, 610 (1997)

$A(Q^2)$ and $B(Q^2)$

$$|\text{Nucleon}\rangle = \psi_{(3q)}|qqq\rangle + \psi_{(3q+1g)}|qqqg\rangle$$



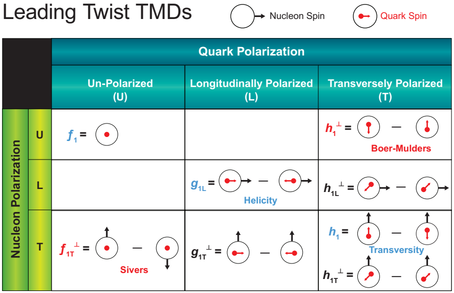
- $A(Q^2)$ and $B(Q^2)$: T^{++} component
- Spin sum rule: $J^i = \frac{1}{2}\left(A^i(0) + B^i(0)\right)$

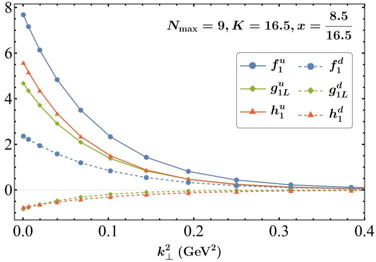
$$\boxed{\sum_i A^i(0) = 1 \text{ and } \sum_i B^i(0) = 0}$$

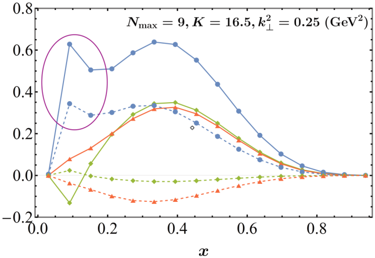
- $D(Q^2) = 4C(Q^2)$: T^{ij} components

[1] S. Nair, CM, *et. al.* coming soon...

Quark TMDs







- Positivity bounds

$$f_1^g(x, \boldsymbol{k}_\perp^2) > 0, \quad f_1^g(x, \boldsymbol{k}_\perp^2) \geq |g_{1L}^g(x, \boldsymbol{k}_\perp^2)|,$$

$$f_1^g(x, \boldsymbol{k}_\perp^2) \geq \frac{|\boldsymbol{k}_\perp|}{M} |g_{1T}^g(x, \boldsymbol{k}_\perp^2)|,$$

$$f_1^g(x, \boldsymbol{k}_\perp^2) \geq \frac{|\boldsymbol{k}_\perp|^2}{2M^2} |h_1^{\perp g}(x, \boldsymbol{k}_\perp^2)|$$

[1] Hongyao Yu, *et. al.* coming soon...

[2] A. Accardi *et al.*, Eur.Phys.J.A 52 (2016) 9, 268.

Gaussian Ansatz Compatibility?

- To check compatibility of BLFQ results with the Gaussian ansatz :

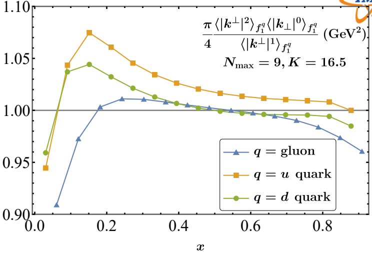
$$f_1^i(x, k_\perp^2) \approx a \frac{\exp\left(-\frac{|k_\perp|^2}{r}\right)}{\pi r}$$

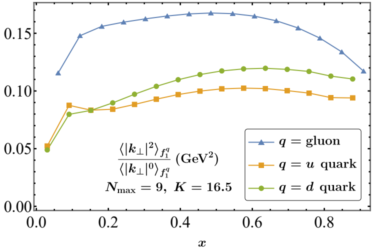
where $a = \langle |k_\perp|^0 \rangle_{f_1^i}$ and $r = \langle |k_\perp|^2 \rangle_{f_1^i}$

- If the Gaussian ansatz holds :

$$\frac{\langle |k_\perp|^2 \rangle_{f_1^i} \times \langle |k_\perp|^0 \rangle_{f_1^i}}{(\langle |k_\perp|^1 \rangle_{f_1^i})^2} \times \frac{\pi}{4} = 1$$

BLFQ results do not support Gaussian ansatz





[1] Hongyao Yu, *et. al.* in preparation
[2] Hongyao Yu, *et. al.* Phys.Lett.B 855, 138831 (2024)

Effective Hamiltonian with Dynamical Gluon and Sea Quarks

Fock expansion:

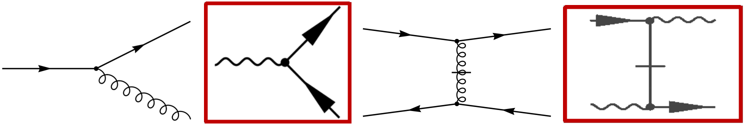
$$|\,\text{Proton}\rangle = a\,|\,uud\rangle + b\,|\,uudg\rangle + c_1\,|\,uudu\bar{u}\rangle + c_2\,|\,uudd\bar{d}\rangle + c_3\,|\,uuds\bar{s}\rangle + \ldots$$

Light-front QCD Hamiltonian :

$$H_{\text{LF}} = \sum_a \frac{\vec{p}_{\perp a}^{\,2} + m_a^2}{x_a} + \sout{H_{\text{confinement}}} + H_{\text{vertex}} + H_{\text{inst}}$$

$$H_{\text{vertex}} + H_{\text{inst}} = g_s \bar{\psi}\gamma_\mu T^a A_a^\mu \psi + \frac{1}{2} g_s^2 \bar{\psi}\gamma^+ T^a \psi \frac{1}{(i\partial^+)^2} \bar{\psi}\gamma^+ T^a \psi$$

$$+ \frac{1}{2} g_s^2 \bar{\psi}\gamma^\mu A_\mu \frac{\gamma^+}{(i\partial^+)} A_\nu \gamma^\nu \psi$$



[1] Brodsky, Pauli, and Pinsky, Phys. Rep. 301, 299 (1998).
[2] Siqi Xu, Yiping Liu, CM, *et. al.*, 2408.11298 [hep-ph]

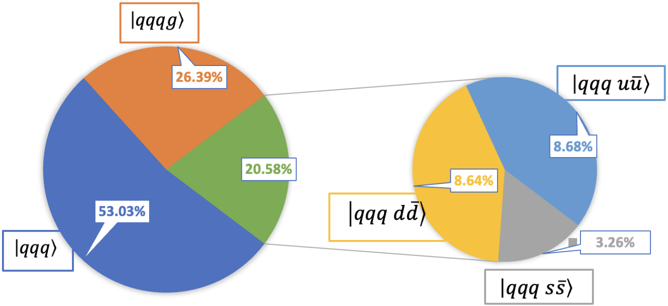
Fock Sector Decomposition

$$|P_{proton}\rangle \to |qqq\rangle + |qqqg\rangle + |qqqu\bar{u}\rangle + |qqqd\bar{d}\rangle + |qqqs\bar{s}\rangle$$

Truncation parameter: $N_{\max} = 7$ and $K_{\max} = 16$

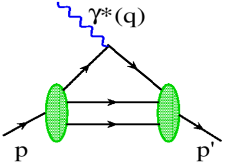
m_u	m_d	m_f	g	b	b_{inst}
0.99 GeV	0.94 GeV	5.9 GeV	3.0	0.6 GeV	2.7 GeV

In five quark Fock sector, we use current quark mass



[1] Siqi Xu, Yiping Liu, CM, *et. al.*, 2408.11298 [hep-ph]

Proton EM Form Factors



Sach's form factors

$$G_E(q^2) = F_1(q^2) - \frac{q^2}{4M^2} F_2(q^2),$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2).$$

- EM current: $J^\mu = \bar{\psi}\gamma^\mu\psi$
- $\langle p'; \uparrow | J^+(0) | p; \uparrow (\downarrow)\rangle \sim F_{1(2)}(q^2)$
- Two FFs: $F_{1(2)}(q^2 = -Q^2)$

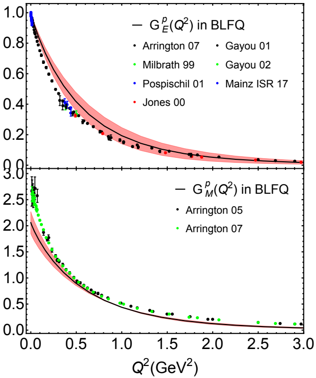
Proton Radii

$$\langle r_{\rm E}^2 \rangle = -6 \frac{{\rm d}G_{\rm E}(Q^2)}{{\rm d}Q^2}\bigg|_{Q^2=0},$$

$$\langle r_{\rm M}^2 \rangle = -\frac{6}{G_{\rm M}(0)} \frac{{\rm d}G_{\rm M}(Q^2)}{{\rm d}Q^2}\bigg|_{Q^2=0}.$$

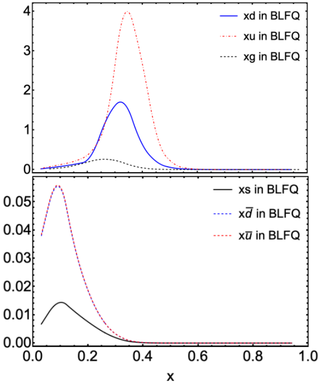
$$\sqrt{\langle r_E^2\rangle} = 0.72 \pm 0.05\,(0.840^{+0.003}_{-0.002})\ \text{fm}$$

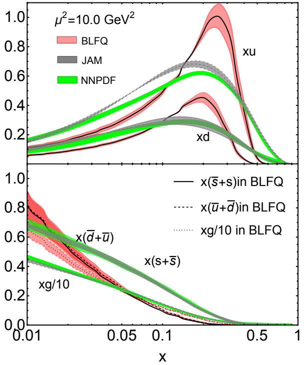
$$\sqrt{\langle r_M^2\rangle} = 0.73 \pm 0.02\,(0.849^{+0.003}_{-0.003})\ \text{fm}$$



[1] Siqi Xu, Yiping Liu, CM, *et. al.*, 2408.11298 [hep-ph]

Unpolarized PDFs



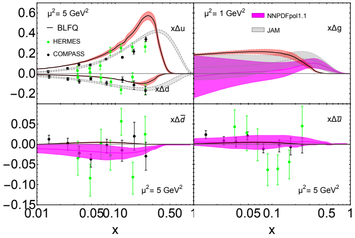


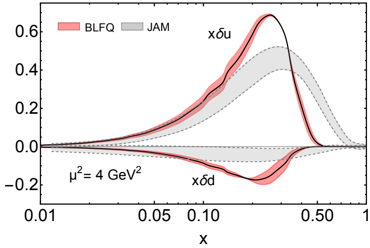
Diagonalizing H_{LFQCD} $\Rightarrow$ LFWFs $\Rightarrow$ Initial PDFs $\Rightarrow$ Scale evolution

- Model scale $\mu_0^2 = 0.22 \pm 0.02$ GeV^2, $\langle x \rangle_{u+d} = 0.37 \pm 0.01$ 10 GeV^2.
- Longitudinal excitations challenging, in absence of confining potential.

[1] Siqi Xu, Yiping Liu, CM, *et. al.*, 2408.11298 [hep-ph]

Helicity and Transversity PDFs

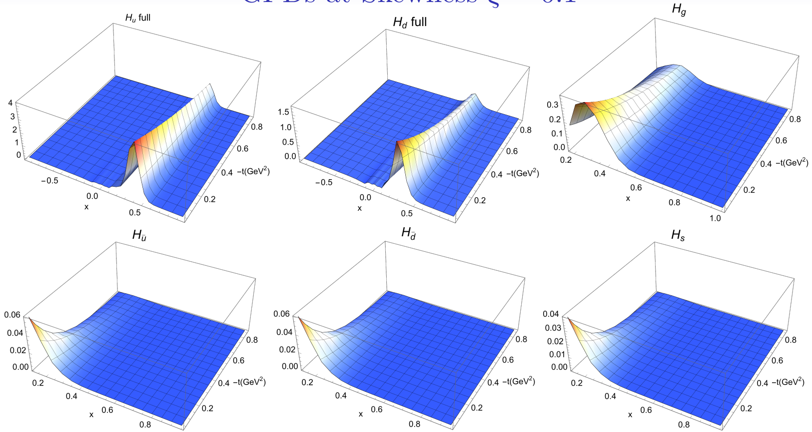




- Gluon spin $\Delta G = 0.29 \pm 0.03$[1] for $x_g \in [0.05, 0.2]$ at 10 GeV^2
- NNPDF[2] analysis: $\Delta G = 0.23(6)$; lattice QCD[3]: $\Delta G = 0.251(47)(16)$
- Tensor Charges: $\delta u = 0.81 \pm 0.08$, $\delta d = -0.22 \pm 0.01$[1]
- JAM[4] analysis: $\delta u = 0.71(2)$, $\delta d = -0.200(6)$; lattice QCD[5]: $\delta u = 0.784(28)$, $\delta d = -0.204(11)$.

[1] Siqi Xu, Yiping Liu, CM, *et. al.*, 2408.11298 [hep-ph]
[2] E. R. Nocera, *et. al.* (NNPDF), Nuclear Physics B 887, 276 (2014)
[3] Y.-B. Yang, *et. al.* (Lattice) Phys. Rev. Lett. 118, 102001 (2017)
[4] C. Cocuzza, *et. al.* (JAM), Phys. Rev. Lett. 132, 091901 (2024)
[5] R. Gupta, *et. al.* (Lattice), Phys. Rev. D 98, 091501 (2018)

GPDs at Skewness $\xi = 0.1$



- u and d GPDs from $-1 < x < 1$; exhibit similar distributions
- At $\xi = 0.1$, DGLAP region dominates
- Discontinuity at $x = \pm\xi$
- Gluon and sea quarks GPDs in DGLAP region

[1] Y. Liu, S. Xu, CM, *et. al.*, coming soon. . .

Conclusions

- Basis Light-front Quantization : A non-perturbative approach based on light-front QCD Hamiltonian
- LF Hamiltonian ⇒ Wavefunctions ⇒ Observables.
- $|qqq\rangle + |qqqg\rangle$ $(P^- = P^-_{\rm QCD} + P^-_{\rm C})$ ⇒ Provides good description of data/global fits for various observables.
- $|qqq\rangle + |qqqg\rangle + |qqqq\bar{q}\rangle$, $(P^- = P^-_{\rm QCD})$ ⇒ Provides qualitative description of data/global fits for mass, spin, EMFFs, PDFs, axial and tensor charges . . . .

Outlook

- Expand Fock sectors
- Include three-gluon and four-gluon interactions in the Hamiltonian.

Enormous amount of possibilities with future EICs . . . . . . Thank You

LIGHT CONE 2024

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- Spin physics
- Relativistic many-body physics
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- Light-front field theory
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- Nonperturbative QFT methods
- Effective field theories
- Lattice field theories
- Quantum computing
- Present and future facilities

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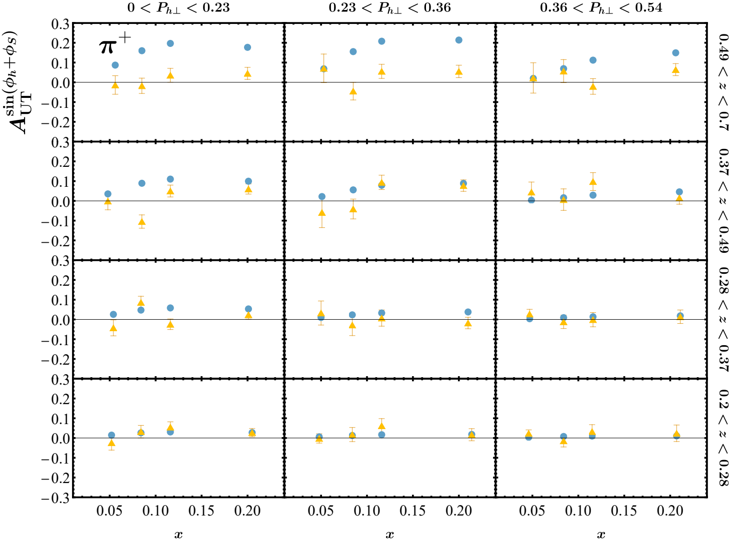
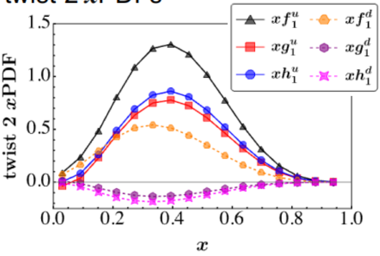
Spin Asymmetry in SIDIS



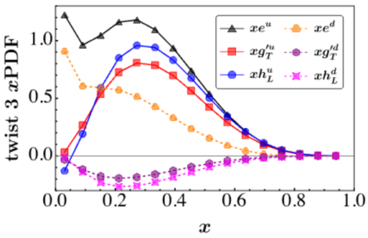
[1] Honhyao, *et. al.* in preparation

xPDFs: Twist-2 vs Twist-3

twist-2 xPDFs

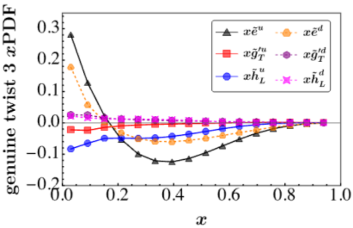


twist-3 xPDFs



$$\int \frac{d^2 k_\perp}{(2\pi)^2} f(x, k_\perp) = f(x)$$

genuine twist-3 xPDFs

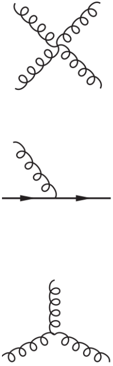


Twist-3 PDFs:

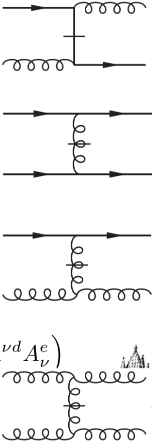
- more concentrating in small x
- similar magnitude to twist-2 PDFs

[1] Zhimin Zhu, *et. al.* in preparation

Light-Front QCD with Light-Cone Gauge ($A^+ = 0$)



$$
\begin{aligned}
\hat{P}^-_{\text{LFQCD}} = & \frac{1}{2}\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; \overline{\psi}\gamma^+\frac{(i\partial^\perp)^2+m^2}{i\partial^+}\psi + A^{ia}(i\partial^\perp)^2A^{ia} \\
& + g_s\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; \overline{\psi}\gamma_\mu A^{\mu a}T^a\psi \\
& + \frac{g_s^2}{2}\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; \overline{\psi}\gamma_\mu A^{\mu a}T^a\frac{\gamma^+}{i\partial^+}\left(\gamma_\nu A^{\nu b}T^b\psi\right) \\
& + \frac{g_s^2}{2}\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; \overline{\psi}\gamma^+T^a\psi\frac{1}{(i\partial^+)^2}\left(\overline{\psi}\gamma^+T^a\psi\right) \\
& - g_s^2\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; if^{abc}\,\overline{\psi}\gamma^+T^c\psi\frac{1}{(i\partial^+)^2}\left(i\partial^+A^{\mu a}A^b_\mu\right) \\
& + g_s\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; if^{abc}\,i\partial^\mu A^{\nu a}A^b_\mu A^c_\nu \\
& + \frac{g_s^2}{2}\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; if^{abc}\,if^{ade}\,i\partial^+A^{\mu b}A^c_\mu\frac{1}{(i\partial^+)^2}\left(i\partial^+A^{\nu d}A^e_\nu\right) \\
& - \frac{g_s^2}{4}\int \mathrm{d}x^-\mathrm{d}^2x^\perp \; if^{abc}\,if^{ade}A^{\mu b}A^{\nu c}A^d_\mu A^e_\nu.
\end{aligned}
$$



[1] S.J. Brodsky, H.C. Pauli, S.S. Pinsky, Phys. Rep. 301, 299-486 (1998).