

Proton structure from holographic QCD

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Phys.Rev.D 112 (2025) 3, 036011; Phys.Rev.D 114 (2026) 2, 026013;
Eur.Phys.J.C 86 (2026) 8, 947

Significance of nucleon structure studies

1. Understanding the Origin of Mass

To answer the ultimate question: **"Where does most of our mass come from?"**

The answer lies not in the Higgs mechanism, but primarily in the **dynamical energy of QCD** and the non-perturbative structure of the nucleon.

2. Understanding the Origin of Spin

Similar to the mass puzzle: How does the proton's spin of **$1/2$ emerge** from the spins and orbital angular momenta of its constituent quarks and gluons?

This remains the central question of the **"spin crisis"** in particle physics.

3. Testing Fundamental Theory (QCD)

The nucleon serves as the most important **laboratory** for studying strong interactions in the non-perturbative regime.

It provides a crucial testing ground for validating and developing our understanding of QCD.

- Nucleon structure in holographic VQCD model
- Nucleon structure in holographic soft wall model

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Holographic VQCD model

Large- N_c Limits Comparison

Matti Jarvinen and Elias Kiritsis, JHEP 03 (2012) 002
U. Gürsoy, E. Kiritsis and F. Nitti, JHEP 02 (2008) 019

- **Standard 't Hooft limit:** $N_c \rightarrow \infty$, $\lambda = g_{\text{YM}}^2 N_c$ and N_f finite,
- **Veneziano limit:** $N_c \rightarrow \infty$, $N_f \rightarrow \infty$, $\frac{N_f}{N_c} = x$ fixed
- Preserves important quark effects while maintaining large- N_c simplifications

Holographic Construction

- **Gluon sector:** 5D Einstein-dilaton gravity

$$S_g = M^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

- **Flavor sector:** Tachyonic Dirac-Born-Infeld action

$$S_{DBI} = -M^3 N_c^2 \int d^5x \sqrt{g} V_f(\lambda, \tau) \sqrt{-\det(g_{ab} + \kappa(\lambda) \partial_a \tau \partial_b \tau + w(\lambda) F_{ab})}$$

- **Metric ansatz:**

$$ds^2 = e^{2A(z)} (dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu)$$

Mass Spectrum

substituting this metric into the equation of motion leads to a Schrödinger-like equation:

$$-\varphi_{R/L}''(z) + (m_5^2 e^{2A_5(z)} \pm m_5 e^{A_5(z)A_5'(z)})\varphi_{R/L}(z) = M_n^2 \varphi_{R/L}(z)$$

	proton	$M_{\text{exp}}/\text{Gev}$	other/Gev	Our/Gev	%M
n=1	N(939)	0.938	0.987	0.939	0.107
n=2	N(1440)	1.360 to 1.380	1.264	1.333	2.701
n=3	N(1710)	1.680 to 1.720	1.531	1.653	2.764
n=4	N(1880)	1.820 to 1.900	1.791	1.893	1.774
n=5	N(2100)	2.050 to 2.150	2.046	2.097	0.143
n=6	N(2300)	2.300	2.296	2.273	1.174

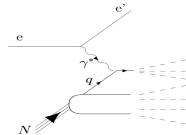
图: Mass spectrum results from numerical solution of the Schrödinger equation

Jiali Deng Defu Hou, Phys.Rev.D 112 (2025) 3, 036011
Eduardo Folco Capossoli, Miguel Angel Martín Contreras, Danning Li, etc, Phys.Rev.D 102 (2020) 8, 086004

Structure Function

The hadronic tensor is defined as:

$$W^{\mu\nu} = 4\pi \int d^4x e^{iq \cdot x} \langle P | J^\mu(x) J^\nu(0) | P \rangle$$



which is written in terms of two structure functions:

$$W^{\mu\nu} = F_1 \left(\eta^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) + \frac{2x}{q^2} F_2 \left(P^\mu + \frac{q^\mu}{2x} \right) \left(P^\nu + \frac{q^\nu}{2x} \right)$$

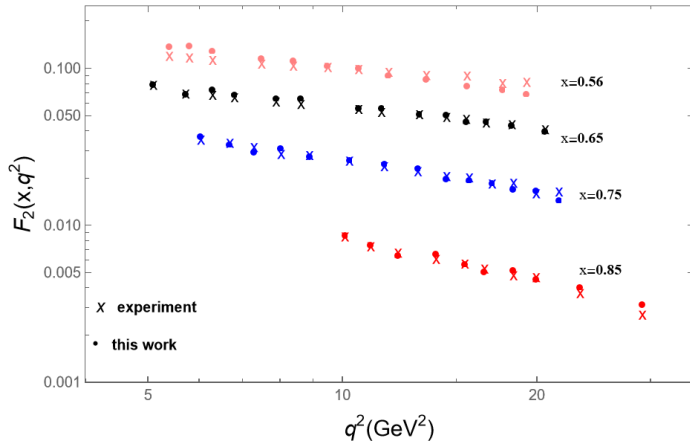
where $x = \frac{Q^2}{2P \cdot q}$ is the Bjorken scaling variable.

The interaction term in the holographic description:

$$\eta_\mu \langle P + q, s_X | J^\mu(0) | P, s \rangle = S_{\text{int}} = g_V \int dz d^4y \sqrt{-g} \phi^\mu \bar{\Psi}_X \Gamma_\mu \Psi_i,$$

Jian-Hua Gao and Zong-Gang Mou, Phys.Rev.D 90 (2014) 075018

Structure Function

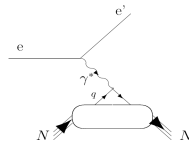


Jiali Deng and Defu Hou, Phys.Rev.D 112 (2025) 3, 036011
L. Whitlow, E. Riordan, S. Dasu, S. Rock, and A. Bodek, Phys. Lett. B 282, 475 (1992).

Electromagnetic form factors

Hadron matrix element

$$\langle p', s' | J^\mu(0) | p, s \rangle = e \bar{u}(p', s') \Gamma^\mu(p, p') u(p, s)$$



Vertex function:

$$\Gamma^\mu(p, p') = \underbrace{\gamma^\mu}_{\text{Dirac}} \underbrace{F_1(Q^2)}_{\text{Dirac}} + \frac{i\sigma^{\mu\nu} \Delta_\nu}{2M} \underbrace{F_2(Q^2)}_{\text{Pauli}}, \quad \Delta = p' - p, P = (p' + p)/2$$

$$= \frac{MP^\mu}{P^2} \underbrace{G_E(Q^2)}_{\text{Electric}} + \frac{i\epsilon^{\mu\alpha\beta\lambda} \Delta_\alpha P_\beta \gamma_\lambda \gamma^5}{2P^2} \underbrace{G_M(Q^2)}_{\text{Magnetic}}$$

Electric charge:

$$q_e = F_1(0) = G_E(0)$$

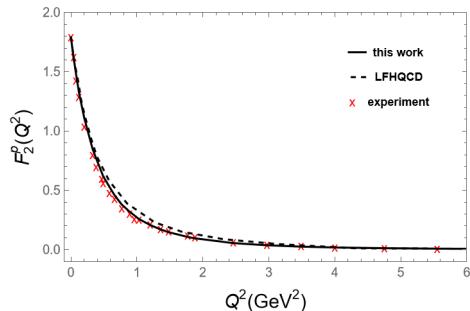
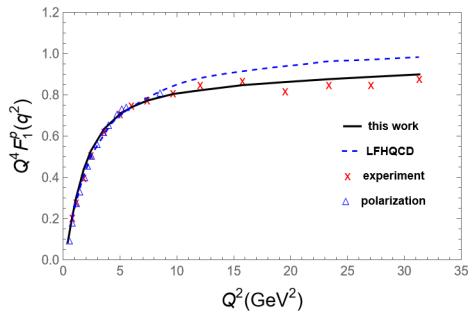
Magnetic moment:

$$\mu = q + F_2(0) = G_M(0)$$

Sachs EM FFs

$$\underbrace{G_E(Q^2)}_{\text{Electric}} = F_1(Q^2) - \frac{Q^2}{4M^2} F_2(Q^2), \quad \underbrace{G_M(Q^2)}_{\text{Magnetic}} = F_1(Q^2) + F_2(Q^2)$$

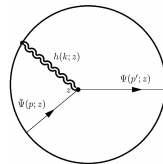
Electromagnetic form factors



Jiali Deng and Defu Hou, Phys.Rev.D 112 (2025) 3, 036011
Raza Sabbir Sufian, Guy F. de T´eramond, Stanley J. Brodsky, etc, Phys.Rev.D 95 (2017) 1, 014011
S. Riordan et al., Phys. Rev. Lett. 105, 262302 (2010)
I. A. Qattan and J. Arrington, Phys. Rev. C 86, 065210 (2012)

Hadron matrix element

$$\langle p', s' | T^{\mu\nu}(0) | p, s \rangle = e \bar{u}(p', s') \Gamma^{\mu\nu}(p, p') u(p, s)$$



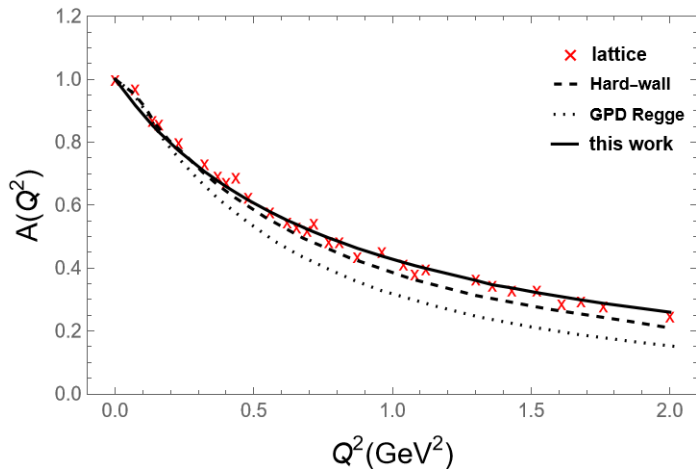
Vertex function:

$$\Gamma^{\mu\nu}(p, p') = \gamma^{(\mu} P^{\nu)} A(Q^2) + \frac{i P^{(\mu} \sigma^{\nu)\alpha} q_{\alpha}}{2M} B(Q^2) + \frac{q^{\mu} q^{\nu} - \eta^{\mu\nu} q^2}{2M} D(Q^2), \quad q = p' - p, P = (p' + p)/2$$

The interaction term in the holographic description:

$$\int d^5x \sqrt{g} h_{\mu\nu} T_F^{\mu\nu} \sim \langle p', s' | T^{\mu\nu}(0) | p, s \rangle$$

Gravitational Form Factors



Jiali Deng and Defu Hou, *Phys.Rev.D* 112 (2025) 3, 036011
Daniel C. Hackett, Dimitra A. Pefkou, Phiala E. Shanahan, *Phys.Rev.Lett.* 132 (2024) 25, 251904
Zainul Abidin and Carl E. Carlson, *Phys.Rev.D* 79 (2009) 115003

- Nucleon structure in holographic VQCD model
- Nucleon structure in holographic soft wall model

Mass Spectrum

We solve the equation of motion and get a Schrödinger-like equation:

$$-\varphi_{R/L}''(z) + [(m_5 + \Phi(z))^2 e^{2A(z)} \pm ((m_5 + \Phi(z))A'(z) + \Phi'(z))e^{A(z)}]\varphi_{R/L}(z) = M_n^2 \varphi_{R/L}(z),$$

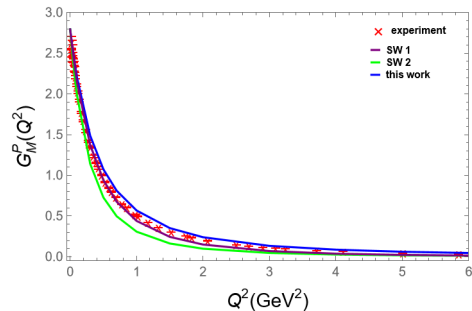
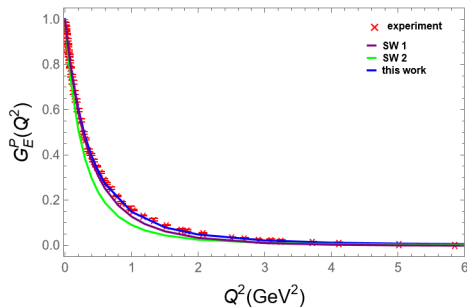
$$A(z) = -\ln(z), \quad \Phi(z) = k_1^2 z^2 \tanh(k_2^2 z^2).$$

	Proton	$M_{\text{exp}}/\text{Gev}$	MW/Gev	SW 1/Gev	SW 2/Gev	Our/Gev	%M
n=1	N(939)	0.938	0.987	1.137	0.990	0.936	0.21
n=2	N(1440)	1.36 to 1.38	1.264	1.392	1.213	1.363	0.50
n=3	N(1710)	1.68 to 1.72	1.531	1.608	1.400	1.669	1.84
n=4	N(1880)	1.82 to 1.9	1.791	1.799	1.566	1.912	2.80
n=5	N(2100)	2.05 to 2.15	2.046	1.970	1.716	2.122	1.07
n=6	N(2300)	2.30	2.296	2.129	1.857	2.312	0.52

图: Mass spectrum results from numerical solution of the Schrödinger equation

Jiali Deng and Defu Hou, EPJC (2026) arXiv:2512.17554
Eduardo Folco Capossoli, Miguel Angel Martin Contreras, Danning Li, etc, Chin.Phys.C 44 (2020) 6, 064104
Zainul Abidin and Carl E. Carlson, Phys.Rev.D 79 (2009) 115003

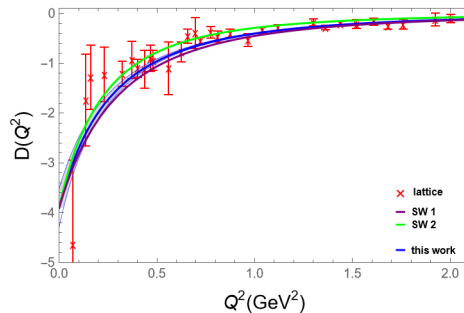
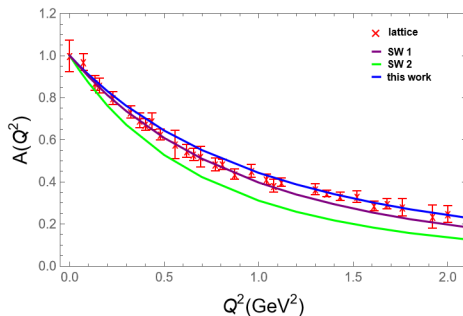
Electromagnetic form factors



$$r_E = 0.812 fm, \quad r_M = 0.762 fm.$$

Jiali Deng and Defu Hou, EPJC (2026), arXiv:2512.17554
Zainul Abidin and Carl E. Carlson, Phys.Rev.D 79 (2009) 115003
J. Arrington, W. Melnitchouk, and J. A. Tjon, Phys. Rev. C 76, 035205 (2007)

Gravitational form factors



$$r_{mass} = 0.713 fm, \quad r_{Mech} = 0.741 fm.$$

Jiali Deng and Defu Hou, EPJC (2026)
Daniel C. Hackett, Dimitra A. Pefkou, Phiala E. Shanahan, Phys.Rev.Lett. 132 (2024) 25, 251904
Zainul Abidin and Carl E. Carlson, Phys.Rev.D 79 (2009) 115003

model	mass spectrum	EFF	MFF	GFF A	GFF D
SW 1	21.2%	22.8%	13.9%	6.4%	34.1%
SW 2	19.3%	28.5%	28.6%	22.6%	25.2%
MW	9.9%	72.8%	73.8%	77.1%	97.8%
Our	2.8%	8.1%	12.0%	3.9%	25.9%

: Relative deviations from experimental and lattice data for different holographic models across all observables

Jiali Deng Defu Hou, EPJC(2026)

Summary and Outlook

- ① Using dynamical holographic VQCD models to calculate proton internal structure observables.
- ② Using the soft-wall model with a **single set of parameters**, we *simultaneously* describe proton observables, agreeing with data and lattice QCD.

Next, we will study flavor-decomposed quark and gluon distributions and the 3D structure of hadrons.