Hadron structure from holographic QCD

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In collaborate with: Jiali Deng, Xiaolong Wang and Yang Zhou

Phys.Rev.D 112 (2025) 3, 036011; Phys.Rev.D 114 (2026) 2, 026013;
arXiv:2512.17554 EPJC(2026) in press ; arXiv:2606.05583; arXiv:2607.07305

The 1st Conference on Strong-Interaction Spin Physics

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.

Xiong-Hui Cao, Feng-Kun Guo, Qu-Zhi Li, Bo-Wen Wu and De-Liang Yao, Eur.Phys.J.ST 235 (2026) 9, 2121-2154
Minghui Ding, Craig D. Roberts and Sebastian M. SchmidtParticles
YuKun Song, Jian Zhou and Zuotang Liang, Chin. Sci. Bull.

How to "See" the internal structure?

Probe Type	Process	Revealed Physical Information	Key Observables
Electroweak Probe	DIS	Parton momentum distribution	Structure Functions $\rightarrow$ PDFs
Electroweak Probe	Elastic scattering	Electromagnetic distribution	EM FFs
Gravitational Probe	(Theoretical concept)	Mechanical distribution	GFFs
Hadron Spectrum	–	Global properties: Mass of nucleon as QCD bound state	Mass spectrum

Table: Experimental probes for studying nucleon internal structure

S. Kumano, Qin-Tao Song and O. V. Teryaev, Phys.Rev.D 97 (2018) 1, 014020

Outline

- Nucleon structure in holographic VQCD model
- Nucleon structure in holographic soft wall model
- Nucleon structure and the proton mass problem
- Pion structure in holographic model with a deformed background
- GFFs of the pion in light-front holographic QCD

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Holographic VQCD model

Large-N_c Limits Comparison

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

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

Holographic Construction

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

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

- **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

By solving the equations of motion, we obtain a Schrödinger-like equation:

$$-\varphi''_{R/L}(z) + (m_5^2 e^{2A_S(z)} \pm m_5 e^{A_S(z)} A'_S(z))\varphi_{R/L}(z) = M_n^2 \varphi_{R/L}(z)$$

	proton	M_{exp}/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

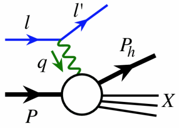
Figure: Mass spectrum results from numerical solution of the Schrödinger equation

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:

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



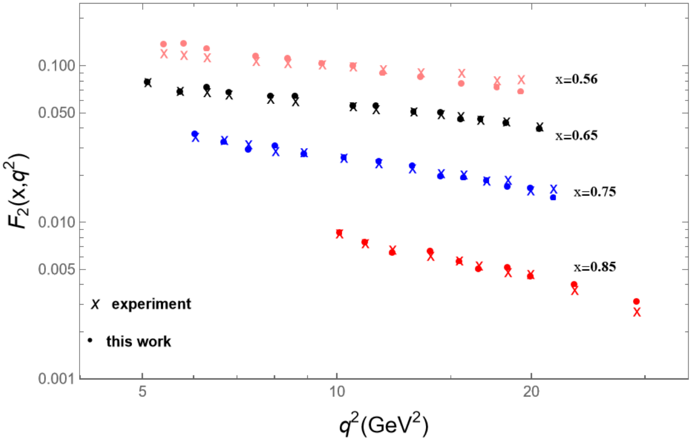
which can be decomposed into structure functions:

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

where $x = \frac{Q^2}{2P\cdot q}$ is the Bjorken scaling variable.
The interaction term in the holographic description:

$$\eta_\mu \langle P + q, s_X | J^\mu(0) | P, s \rangle = S_{\text{int}} = g_V \int dz\, d^4y \sqrt{-g}\, \Phi(z,y) A_\mu(z,y) J^\mu(y)$$

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



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

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

Electric charge:
$q_e = F_1(0) = G_E(0)$
Magnetic moment:
$\mu = q + F_2(0) = G_M(0)$

Vertex function:

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

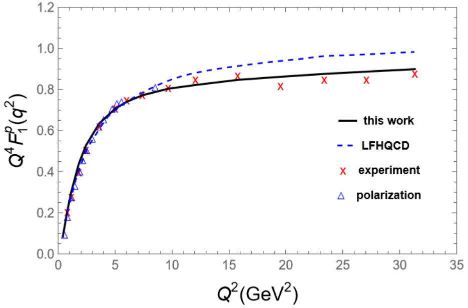
$$= \frac{MP^\mu}{P^2}\underbrace{G_E(Q^2)}_{\text{Electric}} + \frac{i\epsilon^{\mu\alpha\beta\lambda}\Delta_\alpha P_\beta \gamma_\lambda \gamma^5}{2P^2}\underbrace{G_M(Q^2)}_{\text{Magnetic}}$$

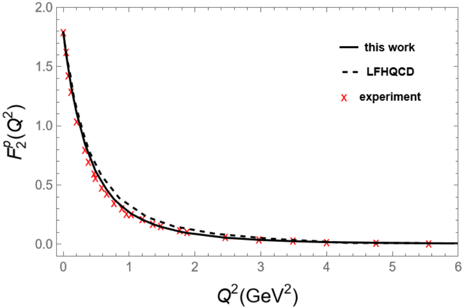
Sachs EM FFs

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

Tianbo Liu and Bo-Qiang Ma, Phys.Rev.D 92 (2015) 9, 096003

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. ArringtonPhys. Rev. C 86, 065210 (2012)

Gravitational Form Factors

Hadron matrix element

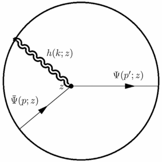
Xuan-Bo Tong, Jian-Ping Ma and Feng Yuan, JHEP 10 (2022) 046

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

Vertex function:

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

The interaction term in the holographic description:

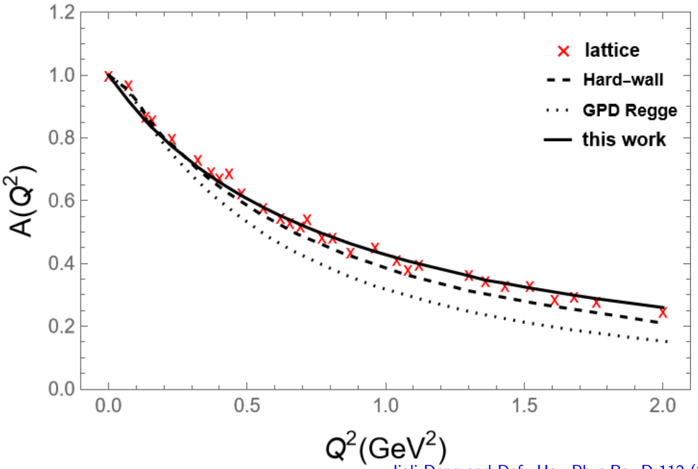


$$\int d^5x\sqrt{g}h_{\mu\nu}T_F^{\mu\nu} \sim \langle p', s' | T^{\mu\nu}(0) | p, s \rangle$$

The equation of motion for graviton

$$\frac{1}{\sqrt{-g}}\partial_M(\sqrt{-g}g^{mn}\partial_N h_{\mu\nu}) + m^2 h_{\mu\nu} = 0$$

Gravitational Form Factors



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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
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Mass Spectrum

By solving the equations of motion, we obtain a Schrödinger-like equation:

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

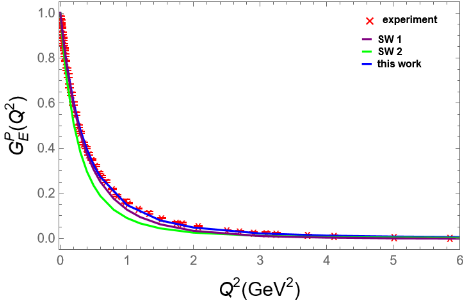
$$A(z) = -ln(z), \quad \Phi(z) = k_1^2 z^2 tanh(k_2^2 z^2).$$

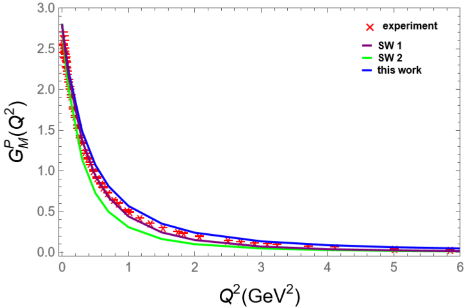
	Proton	$M_{\rm exp}$/Gev	MW/Gev	SW 1/Gev	SW 2/Gev	Our/Gev	%M
n=1	N(939)	0.938	0.987	1.137	0.990	0.936	0.21
n=2	N(1440)	1.36 to 1.38	1.264	1.392	1.213	1.363	0.50
n=3	N(1710)	1.68 to 1.72	1.531	1.608	1.400	1.669	1.84
n=4	N(1880)	1.82 to 1.9	1.791	1.799	1.566	1.912	2.80
n=5	N(2100)	2.05 to 2.15	2.046	1.970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

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

Jiali Deng and Defu Hou EPJC2026 arXiv:2512.17554
Eduardo Folco Capossoli, Miguel Angel Martín 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





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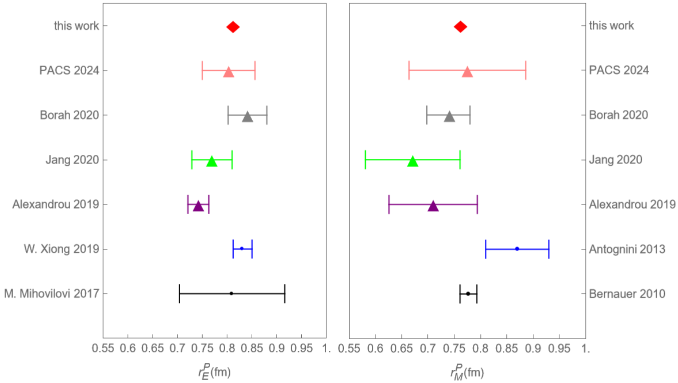
J. Arrington, W. Melnitchouk, and J. A. Tjon, , Phys. Rev. C 76, 035205 (2007)

Electromagnetic radius



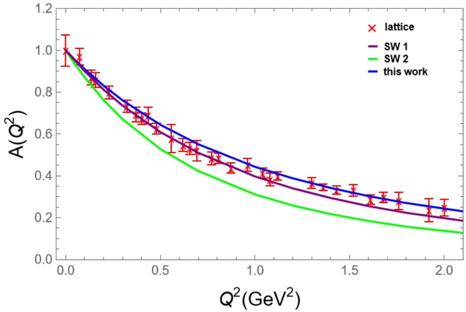
Our results:

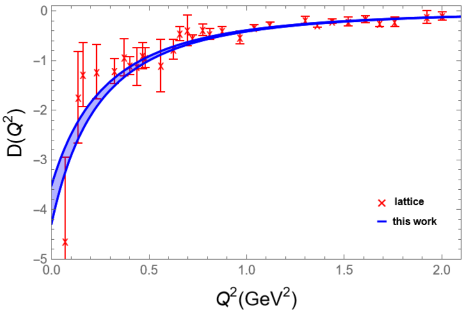
$r_E = 0.812 fm$,

$r_M = 0.762 fm$

Jiali Deng and Defu Hou, EPJC2026 arXiv:2512.17554

Gravitational form factors





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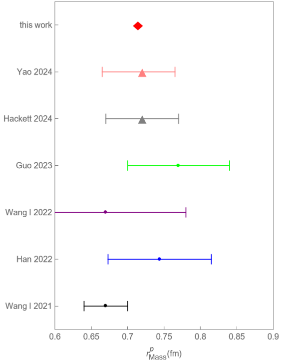
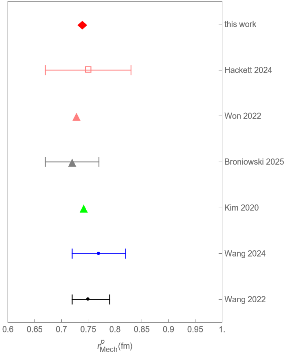
Daniel C. Hackett, Dimitra A. Pefkou, Phiala E. Shanahan, Phys.Rev.Lett. 132 (2024) 25, 251904
Zainul Abidin and Carl E. Carlson, Phys.Rev.D 79 (2009) 115003





Our results:
$r_{mass} = 0.713 fm$,
$r_{mech} = 0.741 fm$

Jiali Deng and Defu Hou, EPJC2026 arXiv:2512.17554

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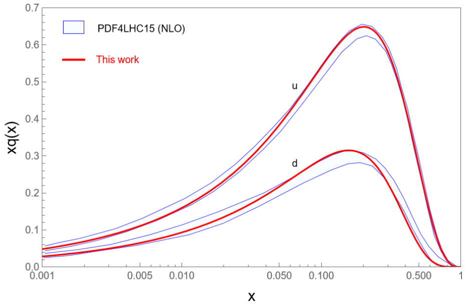
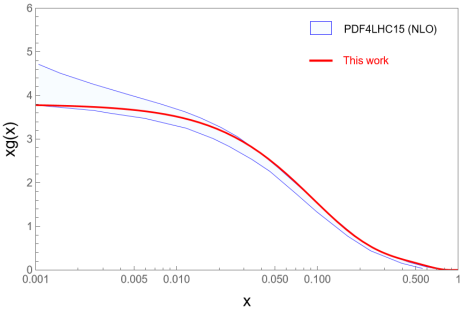
PDF





Jiali Deng and Defu Hou, Phys.Rev.D 114 (2026) 2, 026013
H.-W. Lin et al., Prog. Part. Nucl. Phys. 100, 107 (2018)

Nucleon mass decomposition

Yoshitaka Hatta and Di-Lun Yang, Phys.Rev.D 98 (2018) 7, 074003

Following Lorentz symmetry, one can parameterize their matrix elements as

$$\langle P|T^{\mu\nu}_{q,kin}|P\rangle = 2a(P^\mu P^\nu - \frac{\eta^{\mu\nu}}{4}M^2),$$

$$\langle P|T^{\mu\nu}_{g,kin}|P\rangle = 2(1-a)(P^\mu P^\nu - \frac{\eta^{\mu\nu}}{4}M^2),$$

$$\langle P|T^{\mu\nu}_{m}|P\rangle = \frac{1}{2}b\eta^{\mu\nu}M^2, \langle P|T^{\mu\nu}_{a}|P\rangle = \frac{1}{2}(1-b)\eta^{\mu\nu}M^2.$$

Then the proton mass can be expressed as

$$M = M_q + M_g + M_m + M_a,$$

$$M_q = \frac{3a}{4}M, \quad M_g = \frac{3(1-a)}{4}M, \quad M_m = \frac{b}{4}M, \quad M_a = \frac{1-b}{4}M.$$

Xiangdong Ji, Phys.Rev.Lett. 74 (1995) 1071-1074

Cross section computation via holography

The cross section of the photoproduction process takes the form

$$\sigma(\gamma p \to pJ/\psi) = \frac{e^2}{64\pi MKW|P_{cm}|} \int dt \langle P|\epsilon \cdot J(q)|P'k\rangle\langle P'k|\epsilon^* \cdot J(q)|P\rangle,$$

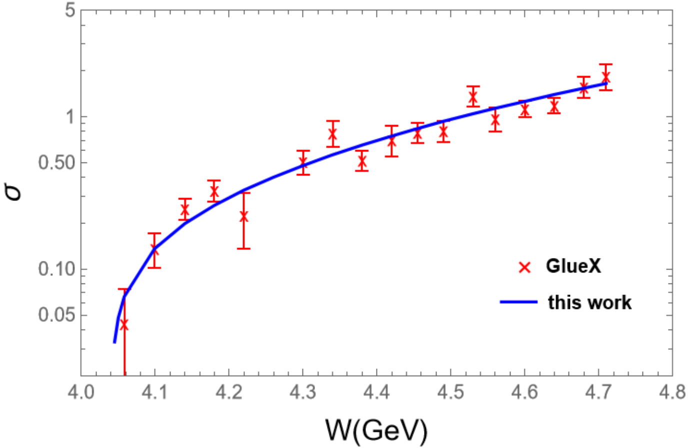
This matrix element can be represented by boundary operators $T^{\mu\nu}$ and $F^{\mu\nu}F_{\mu\nu}$

$$\begin{aligned} P|\epsilon \cdot J(q)|P'k\rangle \approx & -\frac{2k^2}{f_\psi R^3}\int_0^{z_m} dz\, \frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}} \frac{z^2}{R^2}\langle P|T^{gTT}_{\mu\nu}|P'\rangle \\ & + \frac{6k^2}{8 f_\psi R^3}\int_0^{z_m} dz\, \frac{\delta S_{D7}(q,k,z)}{\delta \phi}\frac{z^4}{4}\langle P|\frac{1}{4}F^{\mu\nu}_a F^a_{\mu\nu}|P'\rangle \end{aligned}$$

We incorporate charm quarks into the theory through the addition of a D7-brane with the action

$$S_{D7} = -T_{D7}\int d^8\xi e^{-\phi}\sqrt{-det(G_{ab} + 2\pi\alpha' F_{ab})}$$

Cross section



D. Winney et al. (Joint Physics Analysis Center) , Phys.Rev. D 108, 054018 (2023)

We choose the most suitable set of parameters for the experiment: $b = 0.04$. we can obtain that the contribution of trace anomaly to proton mass is approximately 24%

Jiali Deng, Defu Hou. Phys.Rev.D 114 (2026) 2, 026013

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Mass Spectrum

The form of the metric is:

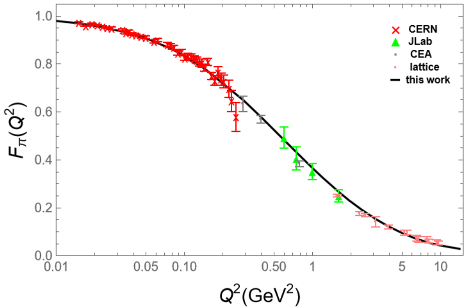
$$ds^2 = \frac{e^{2k_1^2 z^2(1-k_2 tanh(k_1^2 z^2))}}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2) = e^{2A(z)}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2).$$

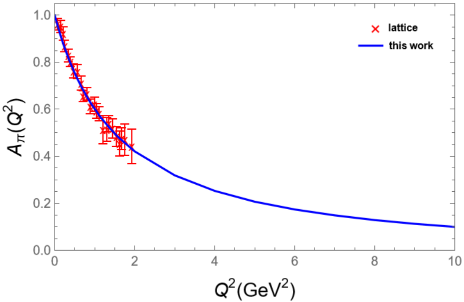
m_π	n=1	n=2	n=3	n=4	n=5
PDG(MeV)	139.6	1300±100	1812±12	2070±35	
Our(MeV)	139.6	1406	1892	2066	2278
Model 1(MeV)	140	1019	1793		
Model 2(MeV)	140	1520	2120		

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

Jiali Deng, Defu Hou and Xiaolong Wang and Yang Zhou, arXiv:2606.05583
Matteo Rinaldi, Federico Alberto Ceccopieri and Vicente Vento, Eur. Phys. J. C 82 (7) (2022) 626
Yang Li and James P. Vary, Phys. Lett. B 825 (2022) 136860

Form factors





r=0.694 fm

Jiali Deng, Defu Hou, Xiaolong Wang and Yang Zhou, arXiv:2606.05583
S. R. Amendolia, et al., Nucl. Phys. B 277 (1986) 168
C. L. Arnold, B. P. Roe, D. Sinclair, Phys. Rev. D 9 (1974) 1221–1229
J. Volmer, et al., Phys. Rev. Lett. 86 (2001) 1713–1716
H.-T. Ding, X. Gao, A. D. Hanlon, S. Mukher jee, Phys. Rev. Lett. 133 (18) (2024) 181902
D. C. Hackett, P. R. Oare, D. A. Pefkou, P. E. Shanahan, Phys. Rev. D 108 (11) (2023) 114504

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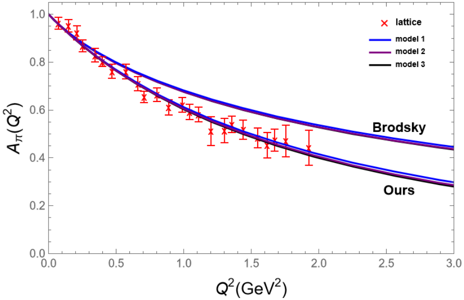
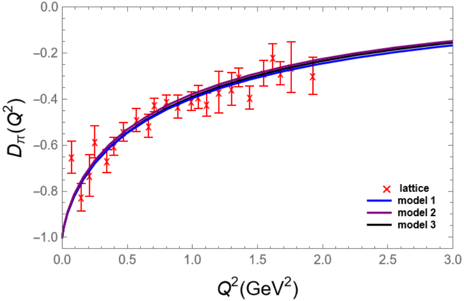
Gravitational form factors

The light-front wave function takes the form:

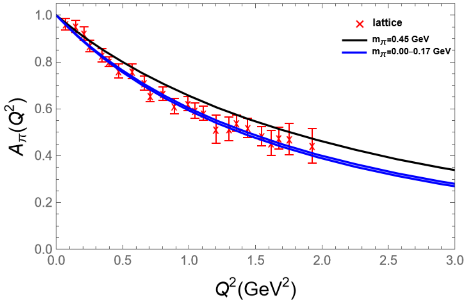
$$\psi(x,\zeta)=\frac{1}{\sqrt{2\pi}}\sqrt{x(1-x)}\frac{\varphi(\zeta)}{\sqrt{\zeta}},\qquad \psi(x,z)=\frac{1}{\sqrt{2\pi}}\sqrt{x(1-x)}\frac{\overline{\varphi}(z)}{\sqrt{z}}f(x),f(x)=\beta x(1-x)$$

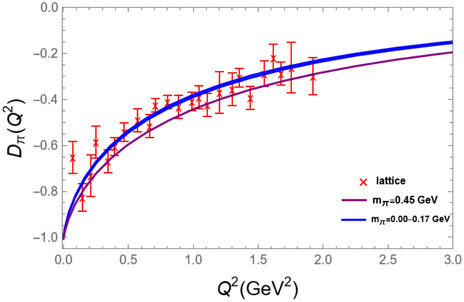




Jiali Deng, Xiaolong Wang, Defu Hou and Yang Zhou, arXiv:2607.07305
Stanley J. Brodsky and Guy F. de T´eramond, Phys.Rev.D 78 (2008) 025032
D. C. Hackett, P. R. Oare, D. A. Pefkou, P. E. Shanahan, Phys. Rev. D 108 (11) (2023) 114504

Gravitational form factors for different mass





rA=0.37 fm, rD=0.94 fm

Jiali Deng, Xiaolong Wang, Defu Hou and Yang Zhou, arXiv:2607.07305
D. C. Hackett, P. R. Oare, D. A. Pefkou, P. E. Shanahan, Phys. Rev. D 108 (11) (2023) 114504

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.
3. Using gravitational form factors as inputs, we compute $\gamma p \to J/\psi\, p$ cross section and extract trace anomaly $\sim 24\%$, consistent with theory.
4. Using the deformed holographic model with a **single set of parameters**, we describe the pion mass spectrum and form factors, consistent with experiment.
5. By introducing a light-front wave function, we compute pion gravitational form factors $A(t)$ and $D(t)$, agreeing with lattice QCD.

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