

Gravitational form factors and mechanical properties of proton

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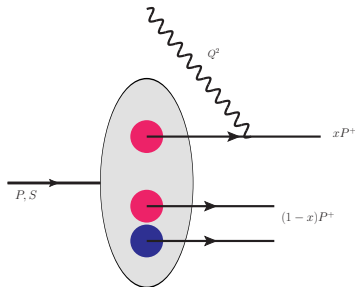
In collaboration with D. Chakrabarti (IITK, India),
A. Mukherjee (IITB, India), C. Mondal, X. Siqi, X. Zhao (IMP, China)



April 15, 2021

- 1 Quark-diquark model
 - Results : Gravitational Form Factor
 - Results : Mechanical Properties
- 2 Basis Light-Front Quantization (BLFQ)
 - Preliminary Results : BLFQ
- 3 Conclusion

Light-Front Quark-Diquark Model (LFQDM)



- $p = |u(\text{red})\rangle + |d(\text{blue})\rangle$
- a single quark and a scalar diquark state
- Light front wave functions are constructed from the *AdS/QCD soft wall model WFs*.
- The light-front wave functions:

$$\psi_{\lambda q}^{\pm}(x, \mathbf{p}_{\perp}) = N_q f(x, \mathbf{p}_{\perp}, \lambda, \Lambda_s = 0) \varphi_q^i(x, \mathbf{p}_{\perp}) \Big|_{i=1,2}$$

Light-front quark-diquark Model (LFQDM)

- The light-front wave functions:

$$\psi_{+q}^+(x, \mathbf{p}_\perp) = \varphi_q^{(1)}(x, \mathbf{p}_\perp),$$

$$\psi_{-q}^+(x, \mathbf{p}_\perp) = -\frac{p^1 + ip^2}{xM} \varphi_q^{(2)}(x, \mathbf{p}_\perp),$$

$$\psi_{+q}^-(x, \mathbf{p}_\perp) = \frac{p^1 - ip^2}{xM} \varphi_q^{(2)}(x, \mathbf{p}_\perp),$$

$$\psi_{-q}^-(x, \mathbf{p}_\perp) = \varphi_q^{(1)}(x, \mathbf{p}_\perp),$$

—Gutsche et. al. PRD 89 (2014)

- Modified soft-wall AdS/QCD wave function for two particle bound state:

$$\varphi_i^{(\nu)}(x, \mathbf{p}_\perp) = \frac{4\pi}{\kappa} \sqrt{\frac{\log(1/x)}{1-x}} x^{a_i^\nu} (1-x)^{b_i^\nu} \exp \left[-\frac{\mathbf{p}_\perp^2}{2\kappa^2} \frac{\log(1/x)}{(1-x)^2} \right].$$

with the AdS/QCD scale parameter $\kappa = 0.4 \text{ GeV}$

—G. F. de Teramond and S. J. Brodsky, arXiv:1203.4025 [hep-ph].

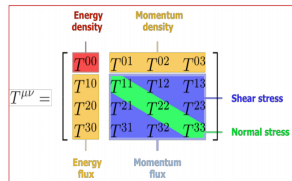
D. Chakrabarti and C. Mondal, Eur. Phys. J. C **73**, 2671 (2013).

Nucleon gravitational form factors

Nucleon scattering by the classical gravitational field is described by the gravitational (energy momentum tensor) form factors (GFFs).

$$\begin{aligned} \langle P' | T_i^{\mu\nu}(0) | P \rangle &= \bar{U}' \left[-B_i(q^2) \frac{\bar{P}^\mu \bar{P}^\nu}{M} + (A_i(q^2) + B_i(q^2)) \frac{1}{2} (\gamma^\mu \bar{P}^\nu + \gamma^\nu \bar{P}^\mu) \right. \\ &\quad \left. + C_i(q^2) \frac{q^\mu q^\nu - q^2 g^{\mu\nu}}{M} + \bar{C}_i(q^2) M g^{\mu\nu} \right] U \end{aligned}$$

- Matrix elements of the energy momentum tensor (EMT) contain fundamental information about various mechanical properties.



Nucleon gravitational form factors in LFQDM

$T^{\mu\nu}$ of a free quark inside the proton

$$T^{\mu\nu} = \frac{i}{2} [\bar{\psi} \gamma^\mu (\vec{\partial}^\nu \psi) - \bar{\psi} \gamma^\mu \overleftarrow{\partial}^\nu \psi]$$

$$\langle P', S' | T^{\mu\nu}(0) | P, S \rangle$$

μ	ν	S	S'	GFF
+	+	$\uparrow$	$\uparrow$	A
+	+	$\uparrow$	$\downarrow$	B
-	$\perp$	$\uparrow$	$\downarrow$	A, B, C
+	-	$\uparrow$	$\downarrow$	$A, B, C, \bar{C}$

- $A(Q^2)$ and $B(Q^2)$ are obtained from the $(++)$ component.
- $C(Q^2)$ and $\bar{C}(Q^2)$ are extracted from the $(- \perp)$ and $(+-)$ components.

Final analytic results

GFFs in terms of overlap integrals

- $A^q(Q^2) = \mathcal{I}_1^q(Q^2)$
- $B^q(Q^2) = \mathcal{I}_2^q(Q^2)$
- $C^q(Q^2) = -\frac{1}{4Q^2} [2M^2 \mathcal{I}_1^q(Q^2) - Q^2 \mathcal{I}_2^q(Q^2) - \mathcal{I}_3^q(Q^2)]$
- $\bar{C}^q(Q^2) = -\frac{1}{4M^2} [\mathcal{I}_3^q(Q^2) - \mathcal{I}_4^q(Q^2)]$

where

$$\mathcal{I}_1^q(Q^2) = \int dx x \left[N_1^2 x^{2a_1} (1-x)^{2b_1+1} + N_2^2 x^{2a_2-2} (1-x)^{2b_2+3} \frac{1}{M^2} \left(\frac{\kappa^2}{\log(1/x)} - \frac{Q^2}{4} \right) \right] g(x)$$

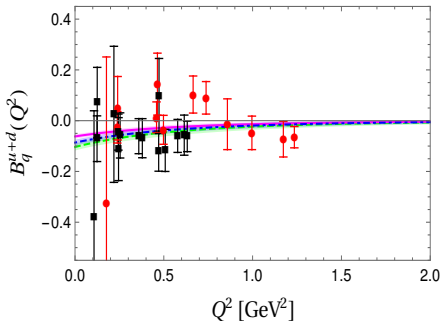
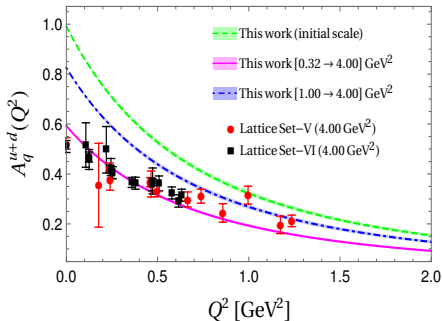
$$\mathcal{I}_2^q(Q^2) = 2 \int dx N_1 N_2 x^{a_1+a_2} (1-x)^{b_1+b_2+2} g(x)$$

$$\mathcal{I}_3^q(Q^2) = 2 \int dx N_2 N_1 x^{a_1+a_2-2} (1-x)^{b_1+b_2+2} \times \left[\frac{4(1-x)^2 \kappa^2}{\log(1/x)} + Q^2 (1-x)^2 - 4m^2 \right] g(x)$$

$$\mathcal{I}_4^q(Q^2) = -2 \int dx N_2 N_1 x^{a_1+a_2-2} (1-x)^{b_1+b_2+2} \left[\frac{\kappa^2 (1-x)^2}{\log(1/x)} + \frac{Q^2 (1-x)^2}{4} + m^2 \right] g(x)$$

$$g(x) = \exp \left[-\frac{\log(1/x)}{\kappa^2} \frac{Q^2}{4} \right]$$

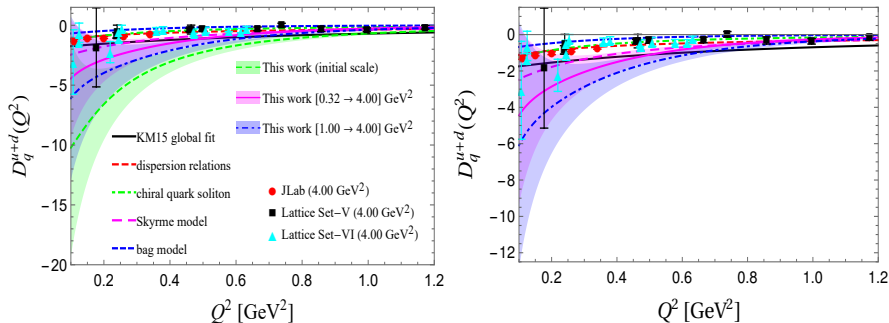
Results : $A(Q^2)$ and $B(Q^2)$



- $A(Q^2)$ and $B(Q^2)$ are consistent with the lattice QCD results for the lower initial scale.

—D. Chakrabarti, C. Mondal, A. Mukherjee, SN and X. Zhao, Phys. Rev. D **102**, 113011 (2020).

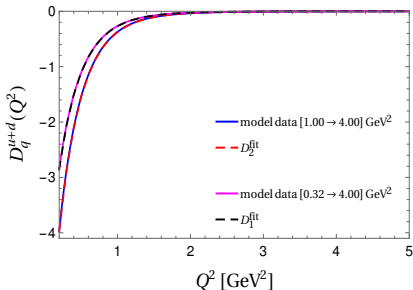
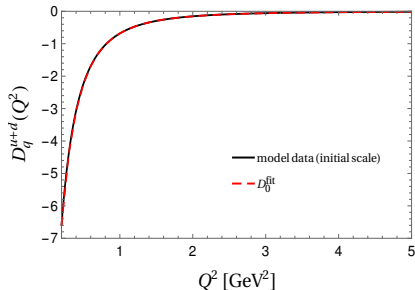
Results : $D(Q^2) = 4C(Q^2)$



- qualitative behavior of $D(Q^2)$ is compatible with lattice and the experimental data.
- large uncertainty as $Q^2 \rightarrow 0$ because of the pole at $D(Q^2 = 0)$. Here we show the region $Q^2 \geq 0.1 \text{GeV}^2$.

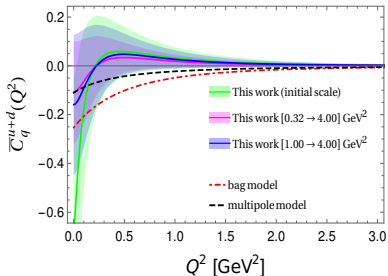
Fit Function for $D(Q^2)$

$$D_{\text{fit}}^q(Q^2) = 4C_{\text{fit}}^q(Q^2) = \frac{a_q}{(1+b_q Q^2)^{c_q}}$$



Parameters	$\mu^2(\text{GeV}^2)$	a_q	b_q	c_q
D_0^{fit}	initial scale	-18.8359	-2.2823	2.7951
D_1^{fit}	[0.32 → 4]	-5.5861	-0.29724	11.6641
D_2^{fit}	[1.00 → 4]	-7.77884	0.291081	11.884

Results : $\bar{C}(Q^2)$



Approaches/Models	$\bar{C}_q^{u+d}(0)$
This work ($\sqrt{0.32} \text{ GeV} \rightarrow 2 \text{ GeV}$)	-0.109
This work ($1.00 \text{ GeV} \rightarrow 2 \text{ GeV}$)	-0.159
IFF (2 GeV) [1]	-0.11
Asymptotic ($\infty \text{ GeV}$) [2]	-0.15
QCDSR-I (1 GeV) [3]	$\times 10^{-2}$
QCDSR-II (1 GeV) [3]	$\times 10^{-2}$
IP [4]	1.4×10^{-2}

- $\bar{C}(Q^2)$ is negative at low Q^2 ($< 0.22 \text{ GeV}^2$) like other models.
- distinctly different behavior in the region of $Q^2 > 0.22 \text{ GeV}^2$, where it exhibits positive distribution.
- The positive distribution decreases with QCD evolution.

— [1] C. Lorcé, H. Moutarde and A. P. Trawinski . Eur. Phys. J. C **79**, 89 (2019)

— [2] Y. Hatta, A. Rajan and K. Tanaka, JHEP **12**, 008 (2018)

— [3] K. Azizi and U. Ozdem, Eur. Phys. J. C **80**, 104 (2020)

— [4] M. V. Polyakov and H. D. Son, JHEP **09**, 156 (2018)

Mechanical Properties

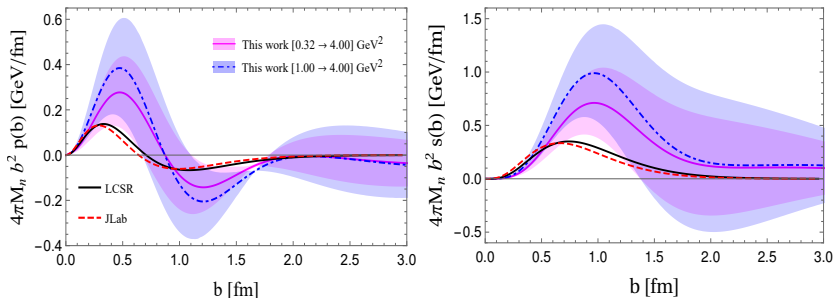
The distributions of pressure and shear forces inside the nucleon are given by

$$\begin{aligned}p(b) &= \frac{1}{6M_n} \frac{1}{b^2} \frac{d}{db} b^2 \frac{d}{db} \tilde{D}(b) \\s(b) &= -\frac{1}{4M_n} b \frac{d}{db} \frac{1}{b} \frac{d}{db} \tilde{D}(b)\end{aligned}$$

The nucleon also experiences normal and tangential forces: F_n and F_t , given by

$$\begin{aligned}F_n(b) &= 4\pi M_n b^2 \left(p(b) + \frac{2}{3} s(b) \right), \\F_t(b) &= 4\pi M_n b^2 \left(p(b) - \frac{1}{3} s(b) \right).\end{aligned}$$

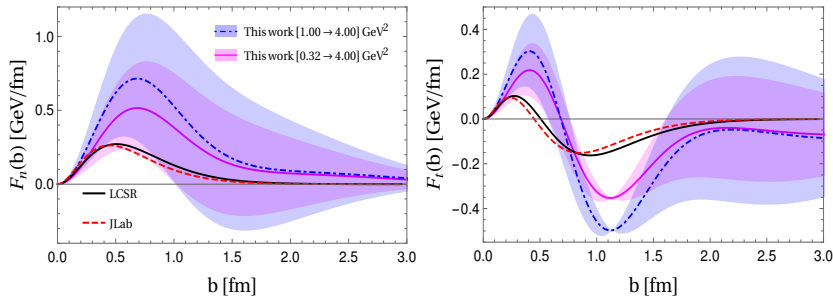
Results : Pressure and Shear in LFQDM



- overall qualitative behavior is in agreement with LCSR and Jlab.
- $p(b)$ has a positive core and a negative tail which ensures the mechanical stability of the system.
- $s(b)$ (central line) is positive in all region of b .

— D. Chakrabarti, C. Mondal, A. Mukherjee, SN and X. Zhao, Phys. Rev. D **102**, 113011 (2020).

Results : Normal and Tangential forces in LFQDM



- $F_n(b)$ (central line) is always positive.
- $F_t(b)$ has a positive core (repulsive force) surrounded by a negative tail (attractive force).
- the qualitative behavior is in agreement with LCSR and Jlab.

— D. Chakrabarti, C. Mondal, A. Mukherjee, SN and X. Zhao, Phys. Rev. D **102**, 113011 (2020).

Basis Light-Front Quantization (BLFQ)

- Nonperturbative approach
- Numerically solve the light-front eigenvalue equation $H_{LF} | \psi \rangle = M^2 | \psi \rangle$
- Fock space expansion $| N \rangle_{\text{phys}} = a | qqq \rangle + b | qqg \rangle + c | qq q \bar{q} \rangle + \dots$
- We consider the leading Fock sector (qqq) and the following effective Hamiltonian (H_{eff})

$$H_{eff} = \sum_a \frac{\mathbf{k}_{a\perp}^2 + m_a^2}{x_a} + \frac{1}{2} \sum_{a,b} V_{ab}^{(CON)} + \frac{1}{2} \sum_{a,b} V_{ab}^{(OGE)} + \text{other interactions}$$

Kinetic energy

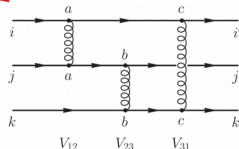
$$V_{ab}^{(SW)} = \kappa^4 x_a x_b (\mathbf{r}_{a\perp} - \mathbf{r}_{b\perp})^2$$

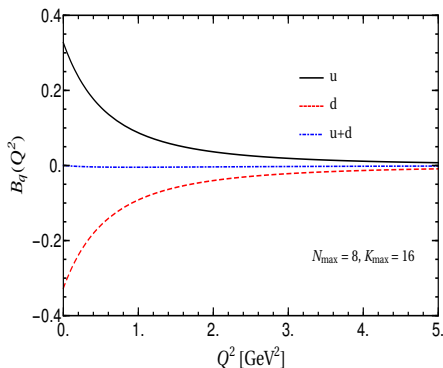
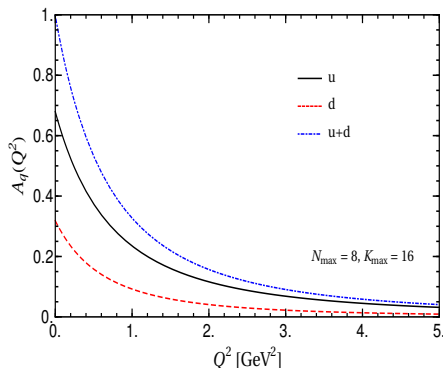
Transverse
confinement

$$V_{ab}^{(L)} = \frac{\kappa^4}{(m_a + m_b)^2} \partial_{x_a} (x_a x_b \partial_{x_b})$$

Longitudinal
confinement

One gluon exchange



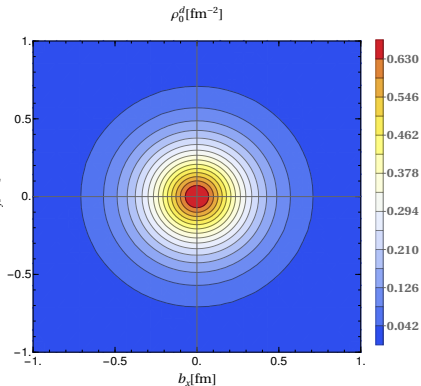
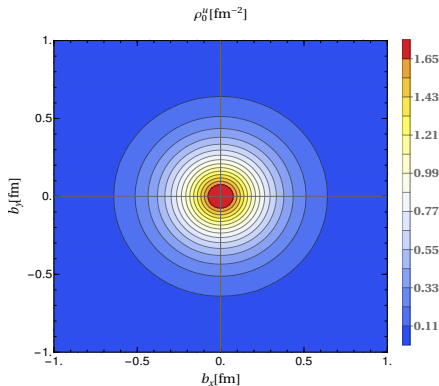


$$\sum_i k_i \leq K_{max}; \quad \sum_i [2n_i + |m_i| + 1] \leq N_{max}$$

K_{max} and N_{max} are the basis truncation parameter in the longitudinal and transverse direction respectively.

Unpolarized nucleon and unpolarized quark

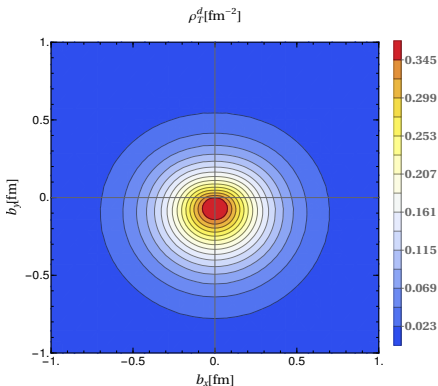
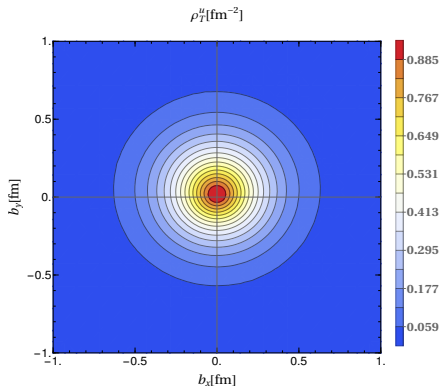
$$\rho_0(b_\perp) = \int \frac{d^2 q_\perp}{(2\pi)^2} A(q^2) e^{-iq_\perp b_\perp} = \int \frac{q_\perp dq_\perp}{2\pi} J_0(|q_\perp||b_\perp|) A(q^2)$$



$b = |b_\perp| \rightarrow$ impact parameter and $J_0 \rightarrow$ Bessel function of zeroth order

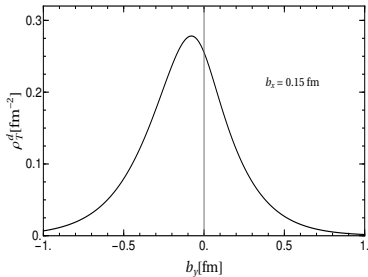
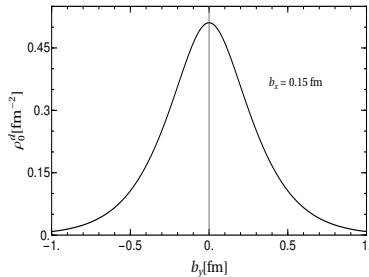
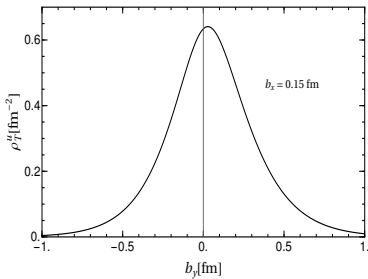
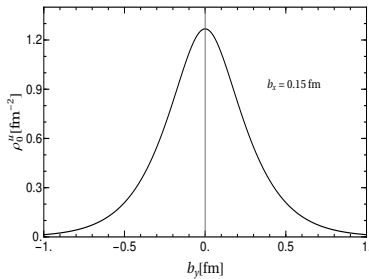
Transversely polarized nucleon and unpolarized quark

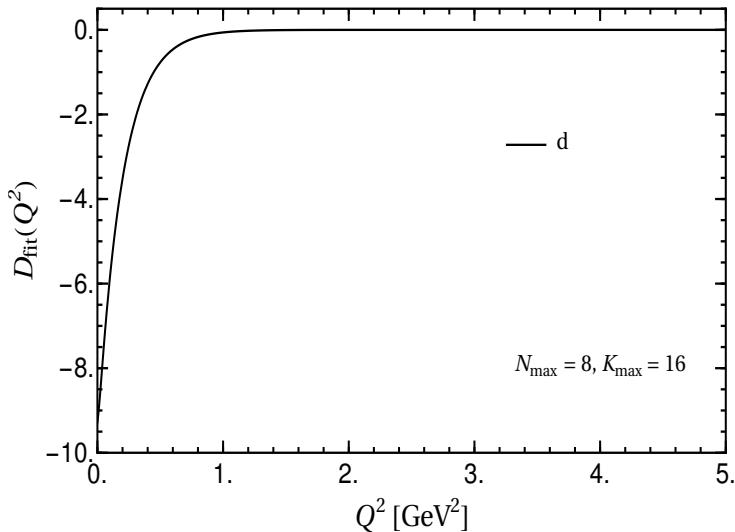
$$\rho_T(b_\perp) = \rho_0(b_\perp) - \frac{s_\perp^i \epsilon^{ij} b_\perp^j}{m_p} B'(b_\perp^2)$$



$$B' = \partial_{b_\perp^2} B, s_\perp^1 = 1 \text{ and } s_\perp^2 = 0$$

Profile plots at fixed b_x work in progress





Conclusion

- We calculated the GFFs of the proton in a light-front quark-diquark model.
- We observe that the qualitative nature of $D(Q^2)$ in this model agrees with the JLab data and lattice QCD results.
- The pressure $p(b)$, shear $s(b)$, normal force $F_n(b)$ and tangential force $F_t(b)$ distributions are consistent with the experimental observation and other theoretical predictions.
- Work is in progress on calculating the GFFs in the BLFQ approach.

Conclusion

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Thank You

Backup

Light Front Holography

Light-Front QCD

$\mathcal{L}_{QCD}$

H_{QCD}^{LF}

$$(H_{LF}^0 + H_{LF}^I) |\Psi\rangle = M^2 |\Psi\rangle$$

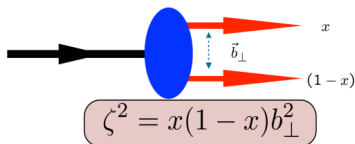
$$\left[\frac{\vec{k}_\perp^2 + m^2}{x(1-x)} + V_{\text{eff}}^{LF} \right] \psi_{LF}(x, \vec{k}_\perp) = M^2 \psi_{LF}(x, \vec{k}_\perp)$$

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta) \right] \psi(\zeta) = \mathcal{M}^2 \psi(\zeta)$$

AdS/QCD:

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Fixed $\tau = t + z/c$



Coupled Fock states

*Eliminate higher Fock states
and retarded interactions*

Effective two-particle equation

Azimuthal Basis

ζ, ϕ

$$m_q = 0$$

*Confining AdS/QCD
potential!*

$$\rho_T(b_\perp) = \rho_0(b_\perp) + \frac{b_y}{m_p} \int \frac{q_\perp^2 dq_\perp}{4\pi} J_1(|q_\perp||b_\perp|) B(q^2)$$

$b = |b_\perp| \rightarrow$ impact parameter

Light Front QCD

- LF Hamiltonian eigenvalue equation

$$H_{LF}|\psi(P)\rangle = \mathcal{M}^2|\psi(P)\rangle,$$

with $H_{LF} = P^\mu P_\mu = P^+ P^- - P_\perp^2$, where $P^\pm = P^0 \pm p^3$.

- Hadronic state $|\psi\rangle$ is an expansion in multiparticle Fock eigenstates $|n\rangle$: $|\psi\rangle = \sum_n \psi_n |n\rangle$.
- Using the frame $P = (P^+, \mathcal{M}^2/P^+, \vec{0}_\perp)$ where $P^2 = P^+ P^-$, we get

$$\begin{aligned} \mathcal{M}^2 &= \sum_n \int [dx_i] [d^2 k_{\perp i}] \sum_q \left(\frac{k_{\perp q}^2 + m_q^2}{x_q} \right) |\psi_n(x_i, k_{\perp i})|^2 \\ &+ \text{(interactions)}, \end{aligned}$$

- the momentum fraction $x_i = k_i^+/P^+$, Momentum conservation requires $\sum_{i=1}^n x_i = 1$ and $\sum_{i=1}^n k_{\perp i} = 0$.

- To simplify the discussion we will consider a two-parton hadronic bound state.
- In the limit of zero quark mass $m_q \rightarrow 0$ and in the co-ordinate or impact space

$$\mathcal{M}^2 = \int_0^1 \frac{dx}{x(1-x)} \int d^2 b_\perp \psi^*(x, b_\perp) (-\nabla_{b_\perp}^2) \psi(x, b_\perp) + (\text{interactions}).$$

- Write : $\zeta^2 = x(1-x)b_\perp^2$, $\psi(x, \zeta, \varphi) = e^{iL\varphi} X(x) \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}}$
- Laplacian : $\nabla_\zeta^2 = \frac{1}{\zeta} \frac{d}{d\zeta} \left(\zeta \frac{d}{d\zeta} \right) + \frac{1}{\zeta^2} \frac{\partial^2}{\partial \varphi^2}$,
- light-front wave equation for ϕ

$$\mathcal{M}^2 \phi(\zeta) = \left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta) \right) \phi(\zeta), \quad L = L_z.$$

- The longitudinal mode is normalized as $\int_0^1 \frac{X^2(x)}{x(1-x)} = 1$.

AdS/CFT $\rightleftharpoons$ Light Front QCD

- AdS/CFT : gravity theory in (d+1)-dim AdS space [$x^M = (x^d, z)$] is dual to a conformal theory in the d-dim boundary [$x^M = (x^d)$].
- QCD is not conformal theory!
- As QCD is not the scale invariant theory one needs to break the conformal invariance.
- A boundary condition in the extra dimension z in AdS_{d+1} breaks the conformal invariance and allows QCD mass scale and confinement.

AdS/CFT $\rightleftharpoons$ Light Front QCD

- **Confinement in AdS** : 1. **Hard-wall** 2. **Soft-wall**
- **In the hard-wall model**, an IR cutoff is set at $z_0 = 1/\Lambda_{QCD}$. The effective potential in a hard wall

$$U(z) = \begin{cases} 0 & \text{if } z \leq \frac{1}{\Lambda_{QCD}}, \\ \infty & \text{if } z > \frac{1}{\Lambda_{QCD}}. \end{cases}$$

- quarks propagate freely in the hadronic interior upto $z_0 = 1/\Lambda_{QCD}$.
- **In soft-wall model**, no cutoff in z but a confining potential in z like $U(z) \sim \kappa^4 z^2$ is introduced.
- The form of the effective confining potential is unique,

—Brodsky, Teramond, Dosch: Nuovo, Cim. C 036, 265 (2013)

Light Front Holographic mapping

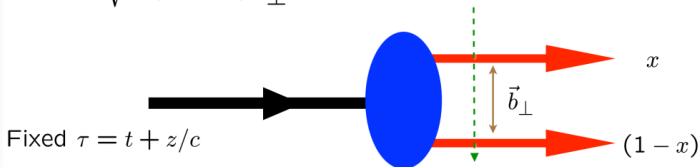
de Teramond,

$$LF(3+1) \longleftrightarrow AdS_5$$

Light-Front Holographic Dictionary

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)} \vec{b}_\perp^2 \longleftrightarrow z$$



$$\psi(x, \zeta) = \sqrt{x(1-x)} \zeta^{-1/2} \phi(\zeta)$$

$$(\mu R)^2 = L^2 - (J-2)^2$$

Mechanical properties

Two-dimensional Galilean energy density, radial pressure, tangential pressure, isotropic pressure, and pressure anisotropy, which in Drell-Yan-West frame are defined as follows:

$$\mu_a(b) = M_n \left\{ \frac{A_a(b)}{2} + \bar{C}_a(b) + \frac{1}{4M_n^2} \frac{1}{b} \frac{d}{db} \left(b \frac{d}{db} \left[\frac{B_a(b)}{2} - 4C_a(b) \right] \right) \right\}$$

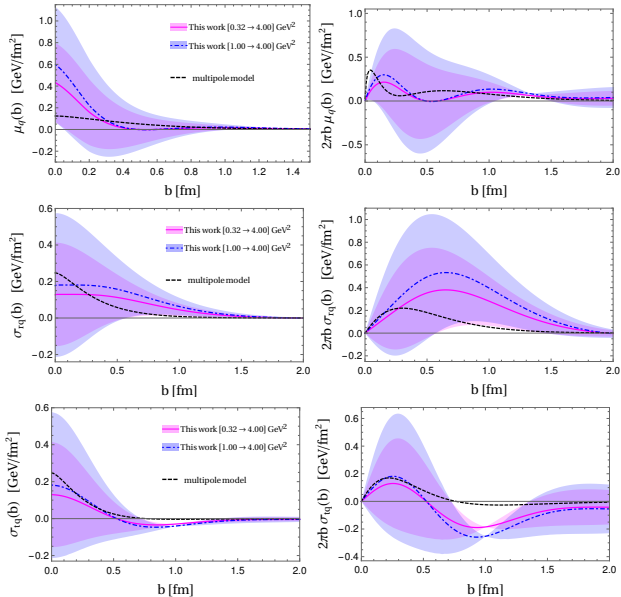
$$\sigma_{r,a}(b) = M_n \left\{ -\bar{C}_a(b) + \frac{1}{M_n^2} \frac{1}{b} \frac{dC_a(b)}{db} \right\}$$

$$\sigma_{t,a}(b) = M_n \left\{ -\bar{C}_a(b) + \frac{1}{M_n^2} \frac{d^2 C_a(b)}{db^2} \right\}$$

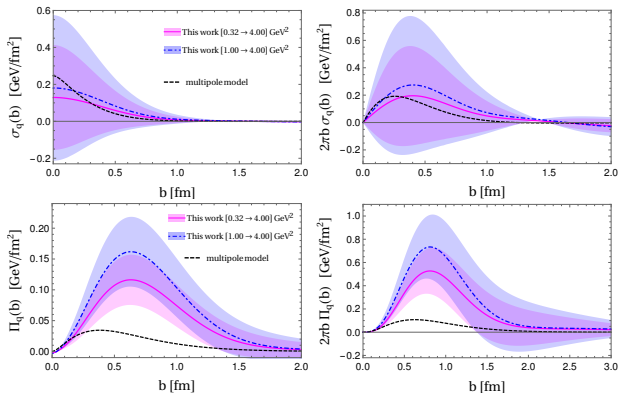
$$\sigma_a(b) = M_n \left\{ -\bar{C}_a(b) + \frac{1}{2} \frac{1}{M_n^2} \frac{1}{b} \frac{d}{db} \left(b \frac{dC_a(b)}{db} \right) \right\}$$

$$\Pi_a(b) = M_n \left\{ -\frac{1}{M_n^2} b \frac{d}{db} \left(b \frac{dC_a(b)}{db} \right) \right\}$$

Results: Mechanical properties



Results: Mechanical properties



Results: Mechanical properties

The pressure and the energy density in the center of nucleon are directly related to the GFFs

$$p_0 = -\frac{1}{24\pi^2 M_n} \int_0^\infty dQ^2 Q^3 D(Q^2),$$
$$\mathcal{E} = \frac{M_n}{4\pi^2} \int_0^\infty dQ^2 \left(A(Q^2) + \frac{Q^2}{4M_n^2} D(Q^2) \right),$$

respectively, while the mechanical radius can be obtained by

$$\langle r_{\text{mech}}^2 \rangle = 6D_{\text{fit}}(0) \left[\int_0^\infty dQ^2 D(Q^2) \right]^{-1}.$$

Results: Mechanical properties

The mechanical properties: pressure, energy density, and mechanical radius of nucleon.

Approaches/Models	p_0 [GeV/fm ³]	$\mathcal{E}$ [GeV/fm ³]	$\langle r_{\text{mech}}^2 \rangle$ [fm ²]
This work	0.29	3.21	0.74
QCDSR set-I (1 GeV)	0.67	1.76	0.54
QCDSR set-II (1 GeV)	0.62	1.74	0.52
Skyrme model	0.47	2.28	-
modified Skyrme model	0.26	1.445	-
χ QSM	0.23	1.70	-
Soliton model	0.58	3.56	-
LCSM-LO	0.84	0.92	0.54

Results

Approaches/Models	$A_q^{u+d}(0)$	$J_q(0) = \frac{1}{2}[A_q^{u+d}(0) + B_q^{u+d}(0)]$	$D_{\text{fit}}^{u+d}(0) = 4C_{\text{fit}}^{u+d}(0)$	$\bar{C}_q^{u+d}(0)$
This work ($\sqrt{0.32} \text{ GeV} \rightarrow 2 \text{ GeV}$)	0.593	0.269	-5.586	-0.109
This work ($1.00 \text{ GeV} \rightarrow 2 \text{ GeV}$)	0.825	0.369	-7.778	-0.159
LQCD (2 GeV) [?]	0.675	0.34	-	-
LQCD (2 GeV) [?]	0.547	0.33	-0.80	-
LQCD (2 GeV) [?]	0.553	0.238	-1.02	-
LQCD (2 GeV) [?]	0.520	0.213	-1.07	-
LQCD (2 GeV) [?]	0.572	0.226	-	-
LQCD (2 GeV) [?]	0.565	0.314	-	-
χ PT (2 GeV) [?]	0.538	0.24	-1.44	-
IFF (2 GeV) [?]	0.55	0.24	-1.28	-0.11
Asymptotic ($\infty \text{ GeV}$) [?]	-	0.18	-	-0.15
QCDSR-I (1 GeV) [?]	0.79	0.36	-1.832	-2.1×10^{-2}
QCDSR-II (1 GeV) [?]	0.74	0.30	-1.64	-2.5×10^{-2}
Skyrme [?]	1	0.5	-3.584	-
Skyrme [?]	1	0.5	-2.832	-
χ QSM [?]	1	0.5	-1.88	-
χ QSM [?]	1	0.5	-4.024	-
χ QSM [?]	-	-	-3.88	-
AdS/QCD Model I [?]	0.917	0.415	-	-
AdS/QCD Model II [?]	0.8742	0.392	-	-
LCSR-LO [?]	-	-	-2.104	-
KM15 fit [?]	-	-	-1.744	-
DR [?]	-	-	-1.36	-
JLab data [?]	-	-	-1.688	-
IP [?]	-	-	-	1.4×10^{-2}