

Hidden-color Dynamics of Deuteron on the Light Front



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Chueng-Ryong Ji, James P. Vary**



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Outline



Motivation

LF holographic QCD approach: Properties of Deuteron

Basis Light-Front Quantization: Ongoing

Summary

Everything in the visible universe is made of atoms, and atoms themselves are built from nuclei.

Deuteron

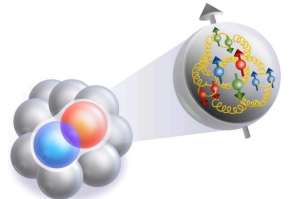
What do we know?

- Simplest nuclear bound state (p+n)
- Weakly bound, B.E. ~ 2.2 MeV
- At large distances: Meson exchange b/w nucleons



What happens at short distances?

- Overlapping of nucleons
- Strong interactions among quarks and gluons in shaping the deuteron.



Deuteron serves as a bridge between QCD and nuclear physics

Deuteron properties

- Charge Radius: 2.12799(74)fm
- Mass: 1875.61294257(57)MeV
- Binding Energy: 2.22452(20)MeV
- Quantum Number:

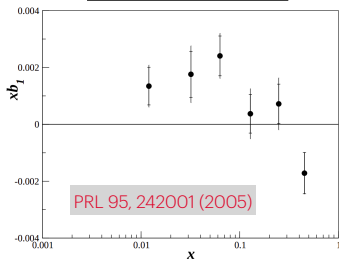
$$I = 0$$

$$J = 1$$

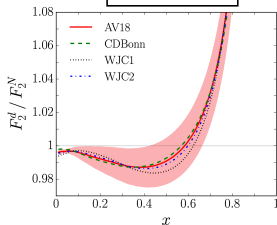
$$L = 0/2, S = 1$$

$$P = +$$

Tensor-polarized
Structure function



EMC effects

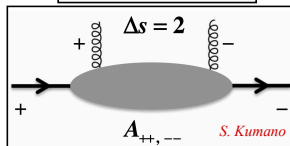


Accardi, Brady, WM, Owens, Sato (2016)

Exotic effects
in nuclei?

$$\frac{F_2^D(x)}{F_2^P(x) + F_2^N(x)} \neq 1$$

Gluon transversity:
double spin flip



Nucleonic description of deuteron is not sufficient!

A Proposal to Jefferson Lab PAC-38
(Update to LOI-11-003)

LOI-11-003

J.-P. Chen (co-spokesperson), P. Solvignon (co-spokesperson),

K. Allada, A. Camsonne, A. Deur, D. Gaskell,
M. Jones, C. Keith, S. Wood, J. Zhang

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

FERMILAB-PUB-22-381-V

The Transverse Structure of the Deuteron with Drell-Yan

The SpinQuest Collaboration^a

FERMILAB-PUB-22-381-V

Eur. Phys. J. A (2016) 52: 208
DOI 10.1140/epja/i2016-16208-0

Review

THE EUROPEAN
PHYSICAL JOURNAL A

Electron-Ion Collider: The next QCD frontier

Understanding the glue that binds us all

A. Accardi^{1,2,8}, J.L. Albacete¹⁶, M. Anselmino²⁰, N. Armesto²⁷, E.C. Aschenauer^{2,8}, A. Bacchetta¹⁰, D. Boer³³, W.K. Brooks^{36,4}, T. Burton³, N.-B. Chang²⁵, W.-T. Deng^{15,22}, A. Deshpande^{26,3,3,3}, M. Diehl^{11,3}, A. Dumitriu², R. Dupré⁷, B. Ezer^{36,4}, S. Fazio¹, H. Gao^{3,8}, V. Gayo²³, H. Hokenjyan²⁸, Y. Hao², D. Haseh¹⁹, R. Heh^{1,3}, T. Heron^{3,4}, M. Huang²¹, A. Hutton^{28,4}, C. Hyde²⁰, J. Jauchian-Maria²⁵, S. Klein¹⁷, B. Kopeliovich²⁶, Y. Kovalov^{29,38}, K. Kumar^{25,4}, K. Kumericki³⁰, M.A.C. Lamont³, T. Lappi³⁴, J.-H. Lee³, Y. Lee³, E.M. Levin^{26,38}, F.-L. Lin³, V. Litvinenko², T.W. Ludlam^{3,1}, C. Marquet³, Z.-E. Meziani^{27,3,3,3}, R. McKeown^{36,4}, A. Metz²⁷, R. Milner¹⁸, V.S. Morozov²⁶, A.H. Mueller^{3,4}, B. Müller^{12,4}, D. Müller³, P. Nadez-Turonaki²⁸, H. Panikvar²⁶, A. Prokudin²⁸, V. Pitsyn¹, X. Qian⁴, J.-W. Qin^{1,3,3,3}, M. Ramsey-Musul^{29,4}, T. Rose^{3,4}, F. Sabatia^{7,8}, R. Sassot³¹, G. Schaef²⁰, P. Schweitzer³², E. Sichterman^{17,4}, M. Stratmann³⁹, M. Strikman²¹, M. Sullivan²¹, S. Taneja^{10,25}, T. Toll², D. Trbojević², T. Ulbrich³, R. Venugopalan¹, S.V. W. Wobisch^{39,4}, C. Weiss²³, B.-W. Xiao³, F. Yuan^{17,3}, Y.-H. Zhang³, and L. Zhang³

the spatial distribution of gluons in the nucleus. Exclusive vector meson production in diffractive $e + A$ collisions is the cleanest such process, due to the low number of particles in the final state. This would not only provide us with further insight into saturation physics but also constitute a highly important contribution to heavy-ion physics by providing a quantitative understanding of the initial conditions of a heavy-ion collision as described in sect. 3.4.2.

It might even shed some light on the role of glue and thus QCD in the nuclear structure of light nuclei (see sect. 3.3).

M. Brooks, A. Klein (CoSpokesperson), D. Kleinjan, K. Liu, M. Liu
M. McCumber, P. McGaughy, C. Da Silva
Los Alamos National Laboratory, Los Alamos, NM 87545



Progress in Particle and Nuclear Physics

Volume 119, July 2021, 103858



Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

A. Arbutov^a, A. Bacchetta^{b,c}, M. Butenschoen^d, F.G. Celiberto^{b,c,e,f}, U. D'Alesio^{g,h}, M. Deka^g, I. Denisenko^g, M.G. Echevarria^g, A. Efremov^g, N.Yu. Ivanov^g, A. Guskov^{g,h}, 张, A. Karpishkov^g, Y. Klöppt^{g,m}, B.A. Kniehl^g, A. Kotzinian^g, S. Kumano^g, J.P. Lansberg^g, Keh-Fei Liu^g, F. Murgia^g, M. Nefedov^g, O. Teryaev^g



Frontiers of Physics

<https://doi.org/10.1007/s11467-021-1062-0>

Front. Phys.

16(6), 64701 (2021)

REVIEW ARTICLE

Electron-ion collider in China


Danièle P. Anderle¹, Valerio Bertone², Xu Cao^{3,4}, Lei Chang⁵, Ningbo Chang⁶, Gu Chen⁷, Xurong Chen^{3,4}, Zhuojun Chen³, Zhufang Cui⁹, Lingyun Dai³, Weitian Deng¹⁰, Minghui Ding¹¹, Xu Feng¹², Chang Gong¹², Longcheng Gui¹³, Feng-Kun Guo¹⁴, Chengdong Han^{3,4}, Jun He¹⁵, Tie-Jun Hou¹⁶, Hongxia Huang¹⁷, Yin Huang¹⁸, Kresimir Kumericki¹⁹, L. P. Kaptari^{20,21}, Dennis Li²², Hengze Li²³, Mingxiang Li²⁴, Xiaojian Li²⁵, Yutian Liang²⁶, Zuotang Liang²⁷, Chen Liu²², Chuan Liu²⁸, Guoming Liu¹, Jie Liu⁴, Liuming Liu^{3,4}, Xiang Liu^{3,4}, Tianbo Liu²⁷, Xiaofeng Luo²⁸, Zhun Lyu²¹, Boqiang Ma¹², Fu Ma^{3,4}, Jianping Ma^{11,4}, Yugang Ma^{2,26,26}, Lijun Mao^{1,4}, Cédric Mezrag²⁹, Hervé Moutarde³⁰, Jianjun Ping³¹, Sibux Qin³², Hang Ren³³, Craig D. Roberts³⁴, Juan Rojas^{35,36}, Guodong Shen³¹, Chao Shi³⁷, Qintao Song³², Hao Sun³¹, Pavel Suvorov³⁸, Enke Wang³, Fan Wang³, Qiao Wang³, Rong Wang³, Huirui Wang³, Tsoufeng Wang³, Wei Wang^{3,4}, Xiaoyu Wang²², Xiaoyun Wang²², Jiahui Wu³, Xianzeng Wu³², Lei Xia²², Bowen Xiao^{23,27}.

Home > The European Physical Journal A > Article

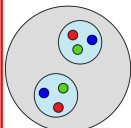
Experimental study of tensor structure function of deuteron

Review | Published: 18 April 2025

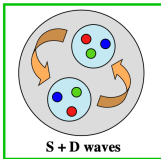
Volume 61, article number 81, (2025) [Cite this article](#)

Jiwan Poudel , Alessandro Bacchetta, Jian-Ping Chen & Nathaly Santiesteban

Spin-1 deuteron



only S wave
 $b_1=0$



S + D waves
standard model $b_1 \neq 0$

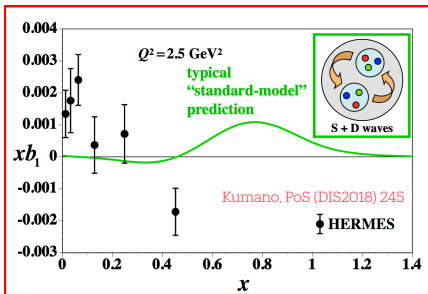
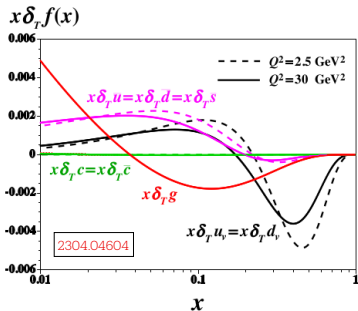
New hadronic mechanism!?



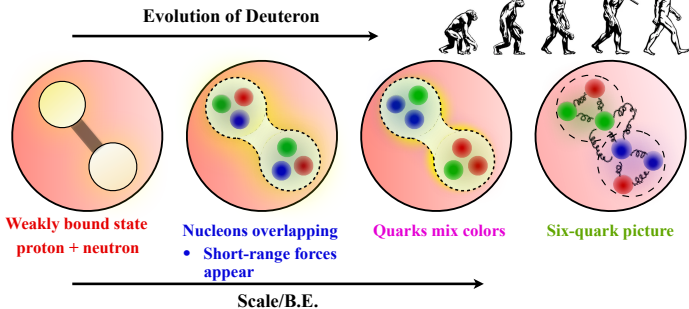
b_1 experiment
 $\neq b_1$ "standard model"

S. Kumano

Cosyn et al. PRD 95, 074036 (2017)



What are we missing?



New color configurations emerge: **Hidden Color**
Possibility of deuteron formation from Octet-Octet configurations

Extreme 1 (2 nucleons)
Singlet-singlet dominates

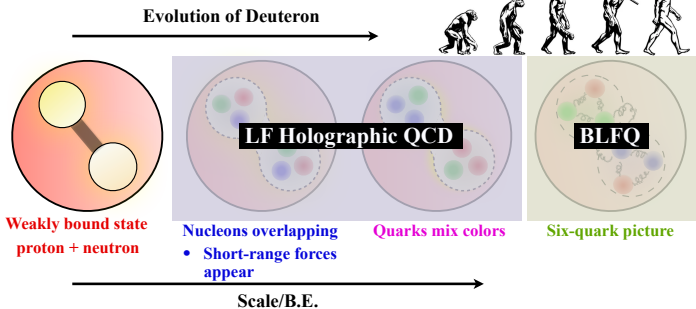
↔

Extreme 2
short distance (6 quarks)
Octet-Octet dominates
80% (octet-octet)

-Brodsky, Ji et al. *PRL* 51, 83 (1983)

- ▶ Deuteron can be formed from:
 - ▶ **1 Singlet-Singlet** → conventional 2-nucleon (colorless state)
 - ▶ **4 Octet-Octet** → hidden color components (mixed states)

¹ J.Phys.Conf.Ser.543, 012004 (2014); Prog.Part.Nucl.Phys. 74, 1 (2014); PRC 89, 045203 (2014)



New color configurations emerge: **Hidden Color**
Possibility of deuteron formation from Octet-Octet configurations

Extreme 1 (2 nucleons)
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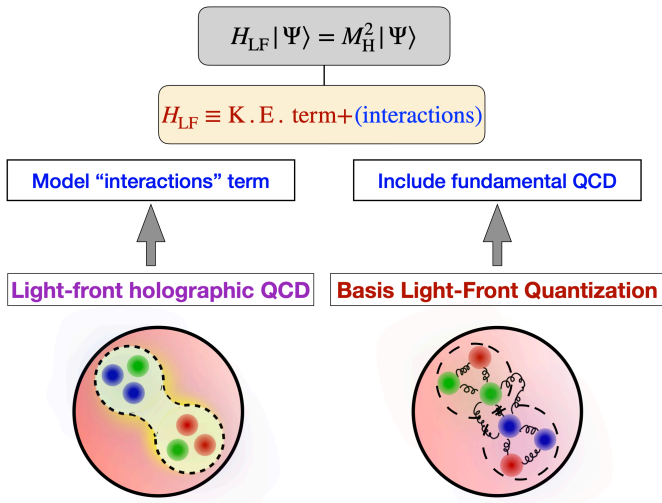
↔

Extreme 2
short distance (6 quarks)
Octet-Octet dominates
80% (octet-octet)

-Brodsky, Ji et al. PRL 51, 83 (1983)

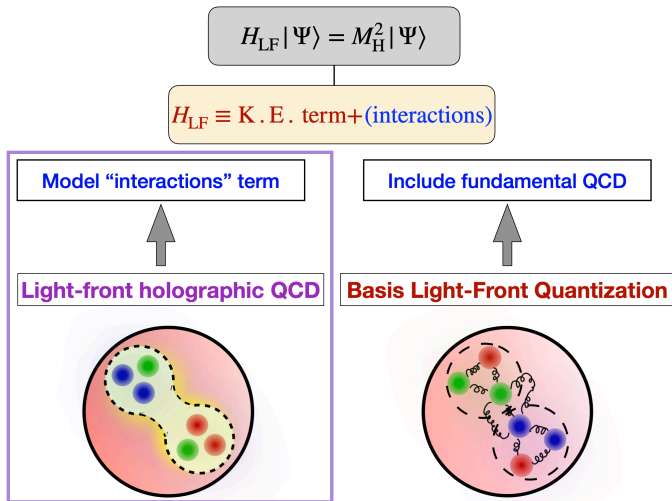
- ▶ Deuteron can be formed from:
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¹J.Phys.Conf.Ser.543, 012004 (2014); Prog.Part.Nucl.Phys. 74, 1 (2014); PRC 89, 045203 (2014)



¹ J.P. Vary, et al., Phys. Rev. C 81, 035205 (2010)

² S.J. Brodsky et al., Physics Reports 584 (2015) 1–105



¹ J.P. Vary, et al., Phys. Rev. C 81, 035205 (2010)

² S.J. Brodsky et al., Physics Reports 584 (2015) 1–105

LF Holographic QCD + 't Hooft Equation



Assumption: The internal cluster dynamics of the deuteron are governed by light-front Schrödinger equation

Light-Front Schrödinger Equation

$$\left(\frac{m_c^2}{z(1-z)} - \frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_{\text{eff}} \right) \chi(z) \phi(\zeta) = M^2 \chi(z) \phi(\zeta) \quad U_{\text{eff}} = U_{\text{Transverse}} + U_{\text{Longitudinal}}$$

Separately solve the transverse ($\phi(\zeta)$) and longitudinal parts ($\chi(z)$) of the wave functions

$\phi(\zeta)$: Using LF holographic QCD approach,
(3+1)-dim.;
 ζ : transverse separation b/w 2 clusters

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_{\text{Trans.}}(\zeta) \right) \phi(\zeta) = M_{\text{Trans.}}^2 \phi(\zeta)$$

$$U_{\text{Trans.}}(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(J-1)$$

$\chi(z)$: Using 't Hooft Equation, (1+1)-dim.;
 z : longitudinal momentum fraction carried by
the active cluster

$$\left(\frac{m_c^2}{z(1-z)} + U_{\text{Longi.}}(z) \right) \chi(z) = M_{\text{Longi.}}^2 \chi(z)$$

$$U_{\text{Longi.}}(z) \chi(z) = \frac{g^2}{\pi} \mathcal{P} \int dZ \frac{\chi(Z) - \chi(z)}{(z-Z)^2}$$

¹ Phys. Rept. 584, 1 (2015); Nucl. Phys. B 75, 461 (1974)

² PLB 823, 136754 (2021); PRD 104, 074013 (2021); PLB 836, 137628 (2023); PRD 109, 094017 (2024); PRD 111, 094002 (2025); 2507.01506 [hep-ph]; 2507.09886 [hep-ph]



- ▶ LFWF¹:

$$\Psi(z, \zeta, \theta) = \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}} e^{iL\theta} X(z) \quad ; \quad X(z) = \sqrt{z(1-z)}\chi(z)$$

- ▶ Spin-orbit part of the wavefunction: through Melosh rotations

Parameters (in GeV):

$$m_c = 0.838 \pm 0.083; \kappa = 0.13 \pm 0.013; g = 0.50 \pm 0.05$$

- ▶ Parameters are fixed by fitting $M_D = 1.875 \pm 0.185$ GeV and behavior of EM form factors G_C and G_M for $Q^2 \leq 0.5$ GeV² with $\chi^2/d.o.f. = 0.98$.

¹Phys. Rept. 584, 1 (2015)

Our Previous Study (only S-wave)

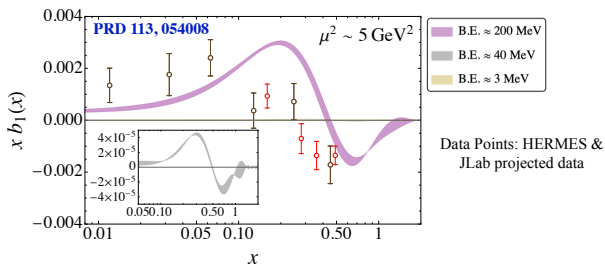
Kaur et al. PRD 113, 054008 (2026)



Included only S-wave!

Very initial study: to see the effects of hidden color components

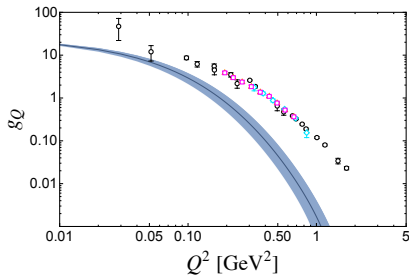
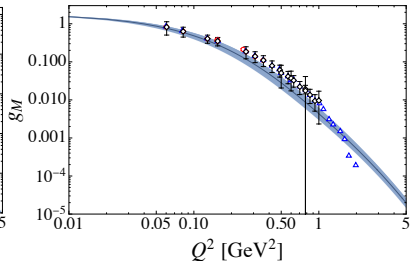
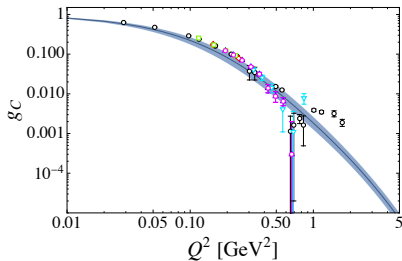
- ✓ **Good agreement with data:** Charge FF, Magnetic FF
Unpolarized, helicity and tensor structure functions



✗ **Disagreement with the data:** Quadrupole moment, $Q_D = 0.079 \text{ GeV}^{-2}$ (7.34 GeV^{-2})

Motivation to include D-wave

Electromagnetic Form Factors (S+D waves)



	S-wave	S & D waves	Exp. Data
μ_D	0.84	0.82	0.85
\hat{Q}_D [GeV ⁻²]	0.079	7.40	7.34
$\sqrt{\langle r_C^2 \rangle}$ [fm]	2.17 ± 0.20	2.21 ± 0.20	2.13 ± 0.003
$\sqrt{\langle r_M^2 \rangle}$ [fm]	1.98 ± 0.19	1.97 ± 0.19	1.90 ± 0.14

Probability of D-wave: 0.85%

Richness of Deuteron's Spin Structure



Quark \ Hadron	U (γ^+)		L ($\gamma^+ \gamma_s$)		T ($i\sigma^{it} \gamma_s / \sigma^{it}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		f_{1T}^\perp	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$

- Spin-0: 2 TMDs
- Spin-1/2: 8 TMDs
- Spin-1: 18 TMDs

Twist-2 TMDs.

Kumano et al. 2406.01180

Quark \ Hadron	U (γ^+)		L ($\gamma^+ \gamma_s$)		T ($i\sigma^{it} \gamma_s / \sigma^{it}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1 $[h_{1LT}]$
TT						

Twist-2 PDFs.

Longitudinal Momentum-dependent Distribution Functions

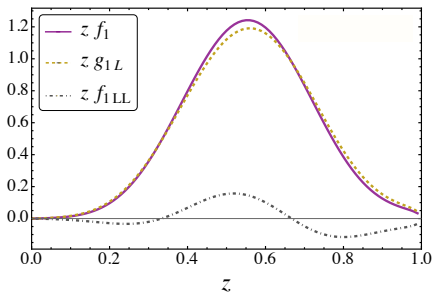


$$\begin{aligned} f_1(z) &= \frac{2}{3} \left(P_{\uparrow}^1(z) + P_{\uparrow}^{-1}(z) + P_{\uparrow}^0(z) \right), && \text{unpolarized cluster \& deuteron} \\ g_{1L}(z) &= P_{\uparrow}^1(z) - P_{\downarrow}^1(z), && \text{longitudinally-polarized cluster \& deuteron} \\ f_{1LL}(z) &= 2P_{\uparrow}^0(z) - \left(P_{\uparrow}^1(z) + P_{\uparrow}^{-1}(z) \right). && \text{unpolarized cluster \& tensor-polarized deuteron} \end{aligned}$$

$$P_{\uparrow}^{\Lambda}(z) = \int d^2\mathbf{k}_{\perp} \sum_{\hbar} |\Psi_{\uparrow\hbar}^{\Lambda}(z, \mathbf{k}_{\perp}^2)|^2 \quad P_{\downarrow}^{\Lambda}(z) = \int d^2\mathbf{k}_{\perp} \sum_{\hbar} |\Psi_{\downarrow\hbar}^{\Lambda}(z, \mathbf{k}_{\perp}^2)|^2$$

Our distribution functions satisfy the sum rules:

$$\int_0^1 dz f_1(z) = 1 \text{ and } \int_0^1 dz f_{1LL}(z) = 0 \quad \text{JHEP 01, 136 (2021)}$$



Structure Functions

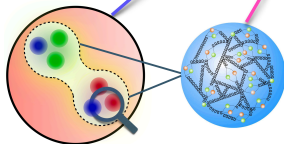


$$SF^D(x, Q^2) = x \sum_q e_q^2 \mathcal{F}_q^D(x, Q^2),$$

$\mathcal{F}_q^D(x, Q^2)$: Quark distribution inside the deuteron at scale Q^2

factorizes: (i) LMDF of 2 clusters within the deuteron
(ii) quark PDF within each cluster

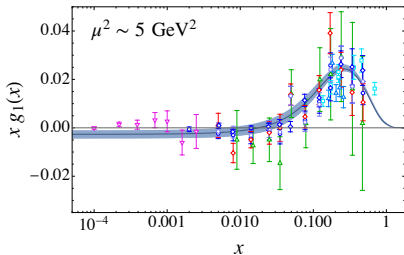
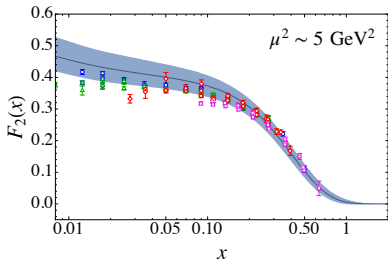
$$\mathcal{F}_q^D(x, Q^2) = \frac{1}{2} \sum_N \int_x^1 \frac{dz}{z} \text{LMDF}(z) \mathcal{F}_q^N\left(\frac{x}{z}, Q^2\right)$$



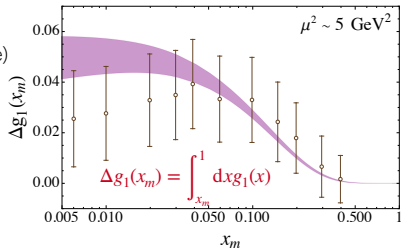
F_2	\rightarrow	f_1	\otimes	unpolarized NNPDF
g_1	\rightarrow	g_{1L}	\otimes	helicity NNPDF
b_1	\rightarrow	f_{1LL}	\otimes	unpolarized NNPDF

PRC 44, 1219 (1991)

Structure Functions: Unpolarized and Helicity (S+D waves)

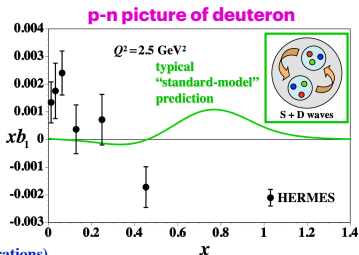
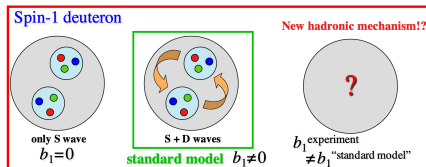


- Matches with previous results (only S-wave)
- Insensitive to D-wave component
- Consistent with exp. Data



Tensor-polarized Structure Function (S+D waves)

S. Kumano, EPJ A 60, 205 (2024)



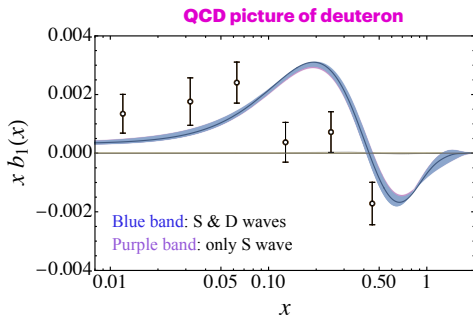
PRD 113, 054008 (2026) (only S-wave + hidden color configurations)

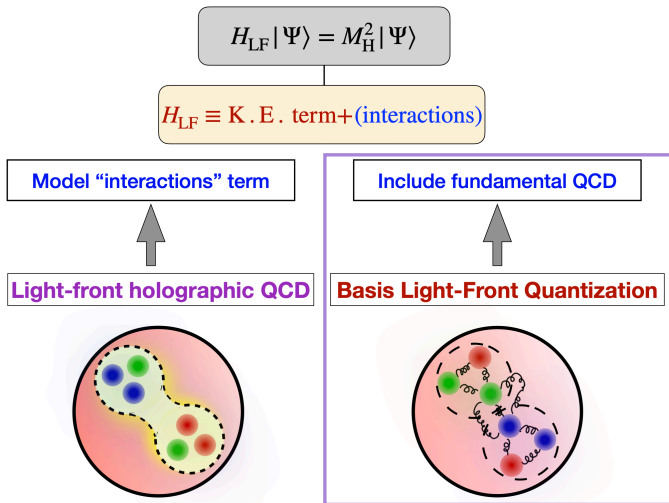
- Loosely bound state,
 $b_1(x) \approx 0$
- With hidden color d.o.f.,
 $b_1(x) \neq 0$, describes exp. data

Possible explanation for HERMES
and JLab projected data

PRL 95, 242001 (2005)

EPJ A 61, 81 (2025)





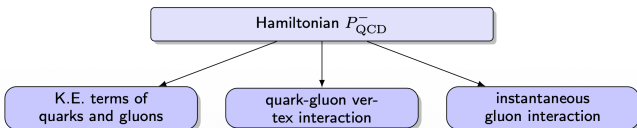
¹ J.P. Vary, et al., Phys. Rev. C 81, 035205 (2010)

² S.J. Brodsky et al., Physics Reports 584 (2015) 1–105

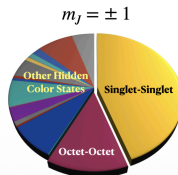
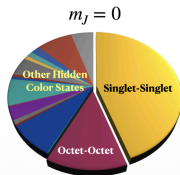


Fock state expansion of the deuteron state

$$|\Psi\rangle_D = \left\{ \psi_{6q} |qqq qqq\rangle + \psi_{6q+1g} |qqq qqq g\rangle \right\} + \psi_{6q+q\bar{q}} |qqq qqq q\bar{q}\rangle + \dots$$



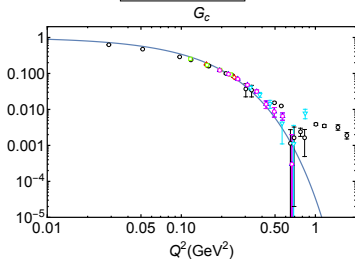
	Color Configurations	Total Color Singlet States	Probability (%) (Preliminary)	
			$m_J = 0$	$m_J = 1$
$ qqq qqq\rangle$	Singlet-Singlet	1	44.56	44.52
	Octet-Octet	4	12.98	13.02
$ qqq qqq g\rangle$	Decuplet-Octet-Octet	2	42.46	42.46
	Octet-Decuplet-Octet	2		
	Octet-Octet-Octet	8		
	Octet-Singlet-Octet	2		
	Singlet-Octet-Octet	2		



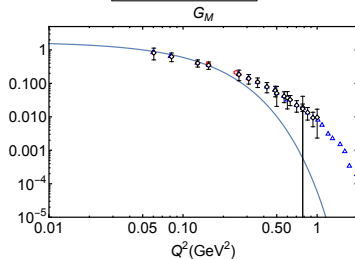
EM Form Factors : Preliminary results from BLFQ



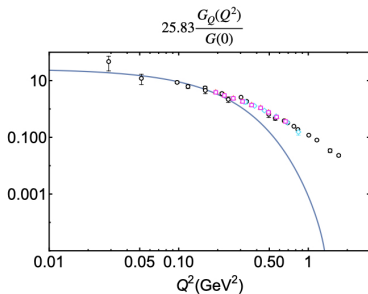
Charge FF



Magnetic FF



Quadrupole FF



m_J	M_D
0	1.927 GeV
± 1	1.874 GeV

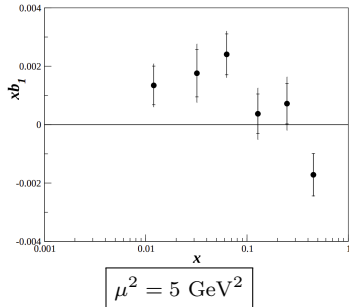
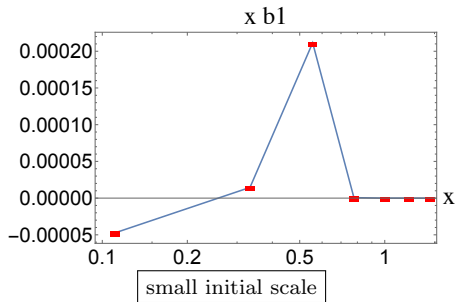
$$\Delta M_D = 0.053 \text{ GeV}$$

**Rotational symmetry
is not severely broken**

$$\mu_D = 0.86 \text{ (Exp. } 0.857)$$

$$\mathcal{Q}_D = 0.20 \text{ GeV}^{-2} \text{ (7.34 GeV}^{-2})$$

Tensor-polarized structure function b_1 : Preliminary results from BLFQ



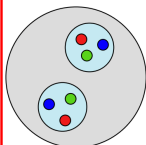
- ▶ Qualitatively consistent with HERMES results
- ▶ Small magnitude at small scale: **small basis size**
- ▶ Absence of D-wave can still generate b_1
- ▶ Another evidence of producing b_1 only with color dynamics
- ▶ **Capability to achieve the gluon transversity**

D-wave is important in describing the quadrupole moment, but the structure functions remain insensitive to it, including the tensor SF.

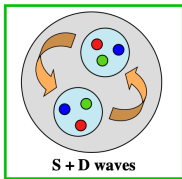


D-wave is important in describing the quadrupole moment, but the structure functions remain insensitive to it, including the tensor SF.

Spin-1 deuteron

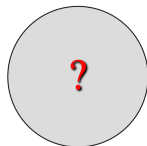


only S wave
 $b_1=0$



S + D waves
standard model $b_1 \neq 0$

New hadronic mechanism!?

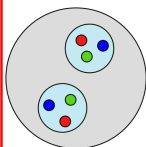


b_1 experiment
 $\neq b_1$ "standard model"

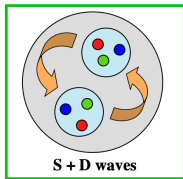


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Spin-1 deuteron



only S wave
 $b_1=0$



S + D waves
standard model $b_1 \neq 0$

New hadronic mechanism!?



b_1 experiment
 $\neq b_1$ "standard model"

The tensor-polarized structure function b_1 emerges naturally from color dynamics.

Thank you!

Complementation of LF holography and 't Hooft Equation



- | | |
|---|---|
| <ul style="list-style-type: none">◦ Defined in (3+1)-dimensional QCD◦ Governs transverse dynamics◦ Connection with AdS₅/CFT correspondence◦ Preserves the chiral symmetry, $M_{\pi}=0$ | <ul style="list-style-type: none">◦ Defined in (1+1)-dimensional QCD◦ Governs longitudinal dynamics◦ Connection with AdS₃/CFT correspondence◦ Breaks the chiral symmetry (satisfies GMOR) |
|---|---|

Makes sense of the world!

Together, they describe full hadron spectra

— *Phys. Lett. B* **823** (2021) 136754

— *Phys. Rev. D* **104** (2021) 7, 074013

Deuteron as an effective mixture of singlet-singlet and octet-octet



$$|\Psi\rangle_D = c_1 |\psi\rangle_{\text{singlet-singlet}} + c_2 |\psi\rangle_{\text{octet-octet}}$$

Kaur et al. PRD 113, 054008 (2026)

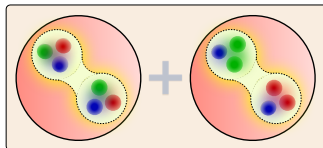
Included only S-wave!

Very initial study: to see the effects of hidden color components

c_1 & c_2 are unknown

Can be determined through QCD Evolution (Future plans)

— Brodsky, Ji, Lepage, PRL 51, 83 (1983)



Goal is to see the QCD effects on the physical observables

Extreme 1

(2 nucleons)

Singlet-singlet dominates

Extreme 2

very short distance (6 quarks)

Octet-Octet dominates

80% (octet-octet)

— Brodsky et al. PRL 51, 83 (1983)

Effective B.E. of deuteron: $M_D - 2m_c$

- **Weakly interacting state: B.E. ~3 MeV**
- **Strongly interacting state: B.E. ~200 MeV**

Switching b/w the two channels
(singlet-singlet & octet-octet dominant states)



$$\begin{aligned} \langle V(P', \Lambda') | J^\mu | V(P, \Lambda) \rangle = & -\epsilon_{\Lambda'}^* \cdot \epsilon_\Lambda (P + P')^\mu F_1(Q^2) + (\epsilon_\Lambda^\mu q \cdot \epsilon_{\Lambda'}^* - \epsilon_{\Lambda'}^{*\mu} q \cdot \epsilon_\Lambda) F_2(Q^2) \\ & + \frac{(\epsilon_{\Lambda'}^* \cdot q)(\epsilon_\Lambda \cdot q)}{2M_N^2} (P + P')^\mu F_3(Q^2) \end{aligned}$$

Overlap form of LFWFs

PRD 70, 053015 (2004)

$$\begin{aligned} G_C = F_1 + \frac{2}{3}\eta G_Q = \frac{1}{2P^+} & \left[\frac{3-2\eta}{3} I_{++}^+ + \frac{4\eta}{3} \frac{I_{+0}^+}{\sqrt{2\eta}} + \frac{I_{+-}^+}{3} \right], \\ G_M = -F_2 = \frac{2}{2P^+} & \left[I_{++}^+ - \frac{I_{+0}^+}{\sqrt{2\eta}} \right], \\ G_Q = F_1 + F_2 + (1 + \eta)F_3 = \frac{1}{2P^+} & \left[-I_{++}^+ + 2 \frac{I_{+0}^+}{\sqrt{2\eta}} - \frac{I_{+-}^+}{\eta} \right], \end{aligned}$$

$$I_{\Lambda', \Lambda}^{\pm}(Q^2) \triangleq \langle V(P', \Lambda') | \frac{J^{\pm}(0)}{2P^+} | V(P, \Lambda) \rangle = \sum_{h, \bar{h}} \int_0^1 \int_0^\infty \frac{dx d^2\mathbf{k}_\perp}{16\pi^3} \Psi_{h\bar{h}}^{\Lambda'*}(x, \mathbf{k}_\perp + (1-x)\mathbf{q}_\perp) \Psi_{h\bar{h}}^\Lambda(x, \mathbf{k}_\perp),$$

Reduced FFs

$$g_{C,M,Q}(Q^2) \equiv \frac{G_{C,M,Q}(Q^2)}{F_N^2(Q^2/4)}$$

 to isolate the genuine nuclear
 structure effects

PRL 51, 83 (1983)

$$F_N(Q^2) = \left(1 + \frac{Q^2}{0.71 \text{ GeV}^2} \right)^{-2}$$

PDFs : Preliminary results from BLFQ

