Hidden-Color Effects in Deuteron Structure

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2507.09886 [hep-ph]

26th International Symposium on Spin Physics

A Century of Spin

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Outline

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

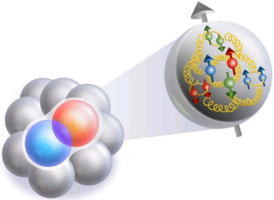
Deuteron

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.

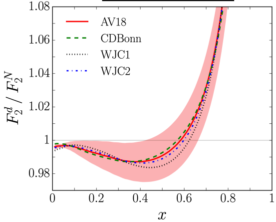


Deuteron serves as a bridge between QCD and nuclear physics

Deuteron properties

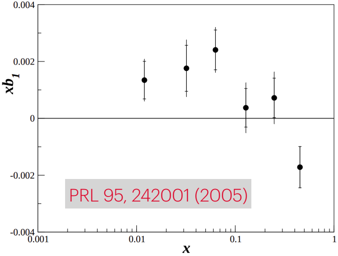
- Charge Radius: 2.12799(74)fm
- Mass: 1875.61294257(57)MeV
- Binding Energy: 2.22452(20)MeV
- Quantum Number:
  I = 0
  J = 1
  L = 0/2, S = 1
  P = +

EMC effects



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

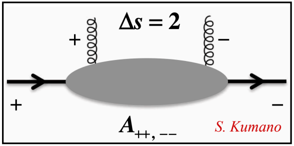
Tensor-polarized Structure function



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!

The Deuteron Tensor Structure Function b_1

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**: 268
DOI 10.1140/epja/i2016-16268-9

THE EUROPEAN PHYSICAL JOURNAL A

Review

Electron-Ion Collider: The next QCD frontier

Understanding the glue that binds us all

A. Accardi[14,28], J.L. Albacete[16], M. Anselmino[29], N. Armesto[37], E.C. Aschenauer[3,a], A. Bacchetta[36], D. Boer[33], W.K. Brooks[38,a], T. Burton[3], N.-B. Chang[23], W.-T. Deng[13,23], A. Deshpande[25,a,b,c], M. Diehl[11,a], A. Dumitru[2], R. Dupré[7], R. Ent[28,d], S. Fazio[3], H. Gao[12,a], V. Guzey[28], H. Hakobyan[38], Y. Hao[3], D. Hasch[15], R. Holt[1,a], T. Horn[5,a], M. Huang[23], A. Hutton[28,a], C. Hyde[20], J. Jalilian-Marian[2], S. Klein[17], B. Kopeliovich[38], Y. Kovchegov[19,a], K. Kumar[25,a], K. Kumerički[40], M.A.C. Lamont[3], T. Lappi[34], J.-H. Lee[3], Y. Lee[3], E.M. Levin[26,38], F.-L. Lin[28], V. Litvinenko[3], T.W. Ludlam[3,d], C. Marquet[8], Z.-E. Meziani[27,a,b,e], R. McKeown[28,d], A. Metz[27], R. Milner[18], V.S. Morozov[28], A.H. Mueller[9,a], B. Müller[3,12,d], D. Müller[22], P. Nadel-Turonski[28], H. Paukkunen[34], A. Prokudin[28], V. Ptitsyn[3], X. Qian[4], J.-W. Qiu[3,a,b,f], M. Ramsey-Musolf[35,a], T. Roser[3,a], F. Sabatié[7,a], R. Sassot[31], G. Schnell[30], P. Schweitzer[32], E. Sichtermann[17,a], M. Stratmann[39], M. Strikman[21], M. Sullivan[24], S. Taneja[10,25], T. Toll[3], D. Trbojevic[3], T. Ullrich[3,a], R. Venugopalan[3], S. V , W. Vogelsang[39,a], C. Weiss[28], B.-W. Xiao[6], F. Yuan[17,a], Y.-H. Zhang[28], and L. Zheng[3,6]

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).

SeaQuest with a Transversely Polarized Target (E1039)

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

ELSEVIER

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. Arbuzov [a], A. Bacchetta [b c], M. Butenschoen [d], F.G. Celiberto [b c e f], U. D'Alesio [g h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a j], A. Guskov [a k], A. Karpishkov [l a], Ya. Klopot [a m], B.A. Kniehl [d], A. Kotzinian [j o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r], F. Murgia [h], M. Nefedov [l]...O. Teryaev [a]

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

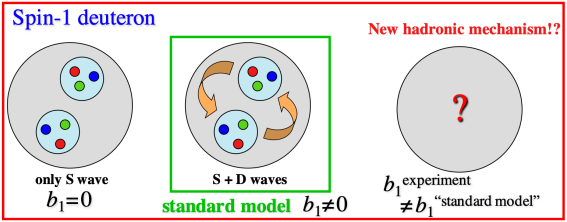
Daniele P. Anderle[1], Valerio Bertone[2], Xu Cao[3,4], Lei Chang[5], Ningbo Chang[6], Gu Chen[7], Xurong Chen[3,4], Zhuojun Chen[8], Zhufang Cui[9], Lingyun Dai[8], Weitian Deng[10], Minghui Ding[11], Xu Feng[12], Chang Gong[12], Longcheng Gui[13], Feng-Kun Guo[4,14], Chengdong Han[3,4], Jun He[15], Tie-Jiun Hou[16], Hongxia Huang[15], Yin Huang[17], KrešImir KumeričKi[18], L. P. Kaptari[3,19], Demin Li[20], Hengne Li[1], Minxiang Li[3,21], Xueqian Li[5], Yutie Liang[3,4], Zuotang Liang[22], Chen Liu[22], Chuan Liu[12], Guoming Liu[1], Jie Liu[3,4], Liuming Liu[3,4], Xiang Liu[21], Tianbo Liu[22], Xiaofeng Luo[23], Zhun Lyu[24], Boqiang Ma[12], Fu Ma[3,4], Jianping Ma[4,14], Yugang Ma[4,25,26], Lijun Mao[3,4], Cédric Mezrag[2], Hervé Moutarde[2], Jialun Ping[15], Sixue Qin[27], Hang Ren[3,4], Craig D. Roberts[9], Juan Rojo[28,29], Guodong Shen[3,4], Chao Shi[30], Qintao Song[20], Hao Sun[31], Paweł Sznajder[32], Enke Wang[1], Fan Wang[9], Qian Wang[1], Rong Wang[3,4], Ruiru Wang[3,4], Taofeng Wang[33], Wei Wang[34], Xiaoyu Wang[20], Xiaoyun Wang[35], Jiajun Wu[4], Xinggang Wu[27], Lei Xia[36], Bowen Xiao[23,37],

Experimental study of tensor structure function of deuteron

Review | Published: 18 April 2025
Volume 61, article number 81, (2025) Cite this article

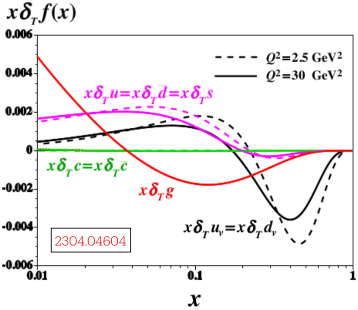
Jiwan Poudel, Alessandro Bacchetta, Jian-Ping Chen & Nathaly Santiesteban

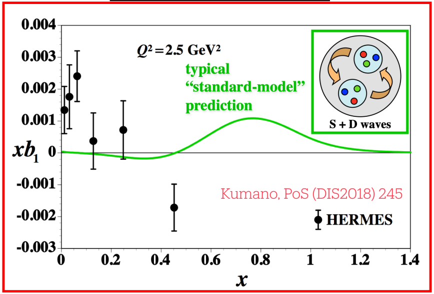
Talk by S. Kumano on b_1



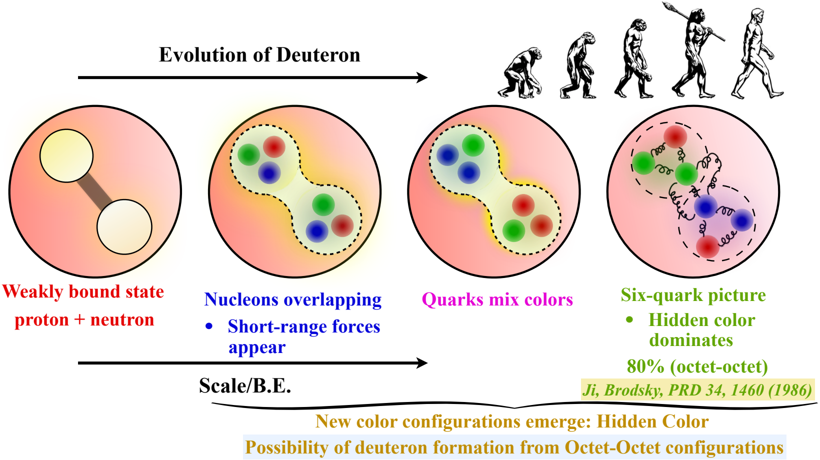
S. Kumano

Cosyn et al. PRD 95, 074036 (2017)





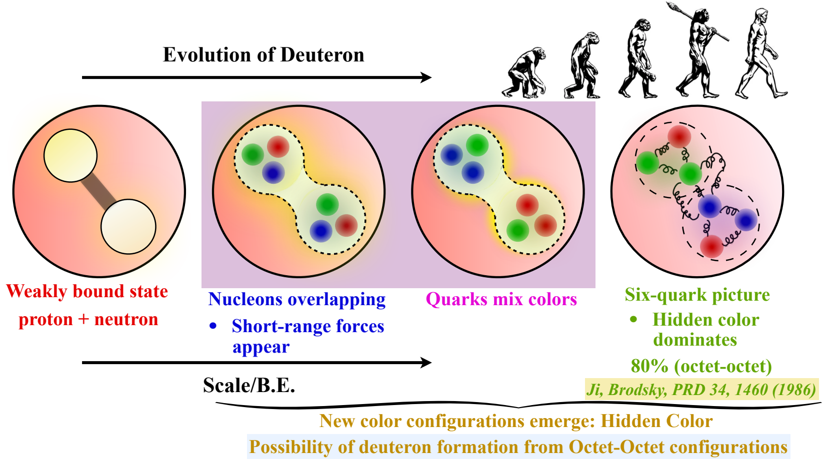
What are we missing?



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

We focus on the middle ground—where nucleons start to overlap but it's not yet the full quark-gluon picture.

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



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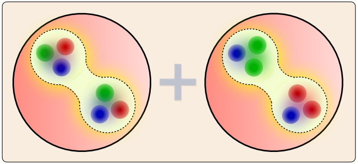
[1] J.Phys.Conf.Ser.543, 012004 (2014); Prog.Part.Nucl.Phys. 74, 1 (2014); PRC 89, 045203 (2014)

Deuteron as an Effective Mixture of Configurations

Aim: To understand the QCD effects (role of hidden color) in nuclear binding.

- **Deuteron** $\approx$ Effective mixture of (singlet-singlet) + (octet-octet)
- The proportion is not known
- Simple modelling: to understand the effects of hidden color d.o.f.
- Only S-wave spin structure ($L = 0$), no D-wave components ($L = 2$)
- Two effective clusters approach



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

Compute the corresponding B.E. $\rightarrow$ involvement of hidden color d.o.f.

Approach

Light-Front Schrödinger Equation

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

$$U_{\mathrm{eff}} = U_{\mathrm{Transverse}} + U_{\mathrm{Longitudinal}}$$

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

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

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

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

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

$$U_{\mathrm{Longi.}}(z)\chi(z) = \frac{g^2}{\pi}\mathscr{P}\int \mathrm{d}Z\,\frac{\chi(z)-\chi(Z)}{(z-Z)^2}$$

[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]

- Complete wavefunction[1]:

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

- Two-cluster spin wavefunction using Melosh transformation:

$$\Psi^{\Lambda}_{h,\bar{h}}(z,\mathbf{k}_\perp) = \frac{\bar{v}_{\bar{h}}(1-z,\mathbf{k}_\perp)}{\sqrt{1-z}} \gamma^\mu \epsilon^\Lambda_\mu \frac{u_h(z,\mathbf{k}_\perp)}{\sqrt{z}} \Psi(z,\mathbf{k}_\perp)$$

C.-R. Ji et al., PRD ***45****, 4214 (1992)*

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 $Q^2 \leq 0.5$ GeV^2 with $\chi^2/d.o.f. = 0.98$.

- B.E. of Deuteron: $M_D - 2m_c$

  Weakly bound p-n bound state: B.E. $\approx$ 2.2 MeV

  Our model B.E. $\approx$ 200 MeV $\rightarrow$ **indication of strong interactions among clusters (octet states): beyond the conventional p-n picture**

[1] Phys. Rept. 584, 1 (2015)

Electromagnetic Form Factors

SLAC-PUB-2318
May 1979
(T)

Phys.Rev.C 21, 1426 (1980)

ELASTIC ELECTRON-DEUTERON SCATTERING AT HIGH ENERGY*

SLAC-PUB-5763
March 1992
T/E

Phys.Rev.D 46, 2141 (1992)

Universal Properties of the Electromagnetic Interactions of Spin-One Systems*

$$\langle V(P',\Lambda')|J^\mu|V(P,\Lambda)\rangle = -\epsilon^*_{\Lambda'}\cdot\epsilon_\Lambda(P+P')^\mu F_1(Q^2) + (\epsilon^\mu_\Lambda q\cdot\epsilon^*_{\Lambda'} - \epsilon^{*\mu}_{\Lambda'} q\cdot\epsilon_{\Lambda'})F_2(Q^2) + \frac{(\epsilon^*_{\Lambda'}\cdot q)(\epsilon_\Lambda\cdot q)}{2M_V^2}(P+P')^\mu F_3(Q^2)$$

Overlap form of LFWFs

PRD 70, 053015 (2004)

$$G_C = F_1 + \frac{2}{3}\eta G_Q = \frac{1}{2P^+}\left[\frac{3-2\eta}{3}I^+_{++} + \frac{4\eta}{3}\frac{I^+_{+0}}{\sqrt{2\eta}} + \frac{I^+_{+-}}{3}\right],$$

$$G_M = -F_2 = \frac{2}{2P^+}\left[I^+_{++} - \frac{I^+_{+0}}{\sqrt{2\eta}}\right],$$

$$G_Q = F_1 + F_2 + (1+\eta)F_3 = \frac{1}{2P^+}\left[-I^+_{++} + 2\frac{I^+_{+0}}{\sqrt{2\eta}} - \frac{I^+_{+-}}{\eta}\right],$$

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

Reduced FFs

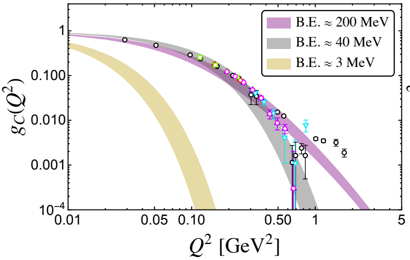
$$g_{C,M,Q}(Q^2) \equiv \frac{G_{C,M,Q}(Q^2)}{F_N^2(Q^2/4)}$$

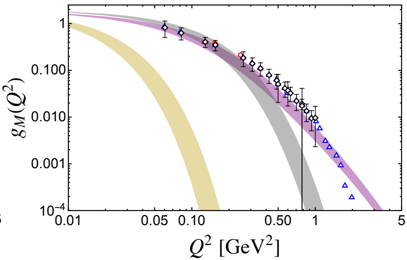
to isolates the genuine nuclear structure effects

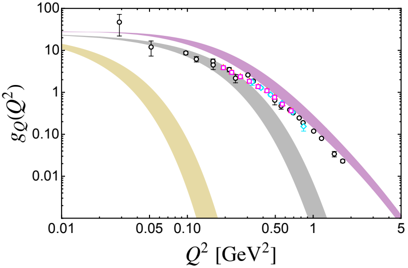
PRL 51, 83 (1983)

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

Electromagnetic Form Factors







$\mu_D = 0.84$ (Exp . value $= 0.85$)

$\mathcal{Q}_D = 0.079\ \text{GeV}^{-2}$ ($7.34\ \text{GeV}^{-2}$)

(No D-wave component)

$\sqrt{\langle r_C^2\rangle} = 2.17 \pm 0.20$ fm ($2.13 \pm 0.003 \pm 0.009$ fm)

$\sqrt{\langle r_M^2\rangle} = 1.98 \pm 0.19$ fm (1.90 ± 0.14 fm)

Longitudinal Momentum-dependent Distribution Functions

$$f_1(z) = \frac{2}{3}\left(P^1_\uparrow(z) + P^{-1}_\uparrow(z) + P^0_\uparrow(z)\right),$$
unpolarized cluster & deuteron

$$g_{1L}(z) = P^1_\uparrow(z) - P^1_\downarrow(z),$$
longitudinally-polarized cluster & deuteron

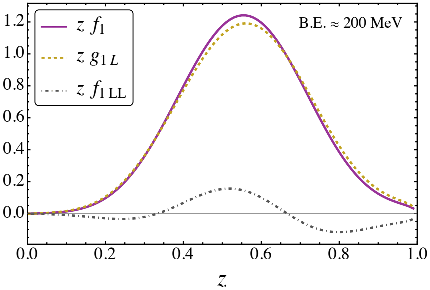
$$f_{1LL}(z) = 2P^0_\uparrow(z) - \left(P^1_\uparrow(z) + P^{-1}_\uparrow(z)\right).$$
unpolarized cluster & tensor-polarized deuteron

$$P^\Lambda_\uparrow(z) = \int \mathrm{d}^2\mathbf{k}_\perp \sum_{\bar h} |\Psi^\Lambda_{\uparrow\bar h}(z,\mathbf{k}^2_\perp)|^2 \qquad P^\Lambda_\downarrow(z) = \int \mathrm{d}^2\mathbf{k}_\perp \sum_{\bar h} |\Psi^\Lambda_{\downarrow\bar h}(z,\mathbf{k}^2_\perp)|^2$$

Our distribution functions satisfy the sum rules:

$$\int_0^1 \mathrm{d}z f_1(z) = 1 \text{ and } \int_0^1 \mathrm{d}z f_{1LL}(z) = 0$$

JHEP 01, 136 (2021)



Structure Functions

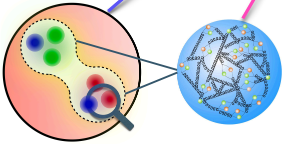
$$\mathrm{SF}^D(x,Q^2) = x\sum_q e_q^2 \mathcal{F}_q^D(x,Q^2),$$

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

factorizes: (i) LMDF of 2 clusters within the deuteron

(ii) quark PDF within each cluster

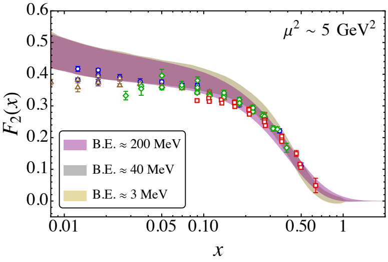
$$\mathcal{F}_q^D(x,Q^2) = \frac{1}{2}\sum_N \int_x^1 \frac{dz}{z} \boxed{\mathrm{LMDF}(z)} \boxed{\mathcal{F}_q^N\left(\frac{x}{z},Q^2\right)}$$

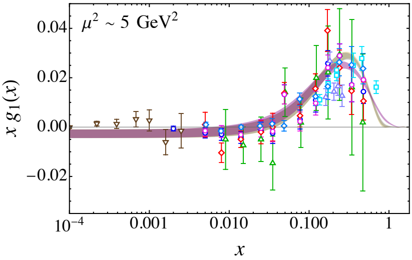


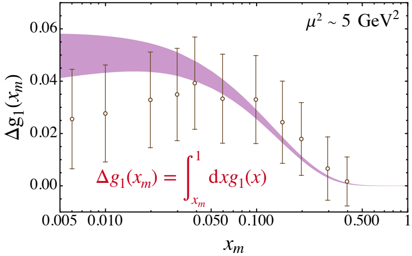
F_2	$\rightarrow$	f_1	$\otimes$	unpolarized NNPDF
g_1	$\rightarrow$	g_{1L}	$\otimes$	helicity NNPDF
b_1	$\rightarrow$	f_{1LL}	$\otimes$	unpolarized NNPDF

PRC 44, 1219 (1991)

Structure Functions: Unpolarized and Helicity



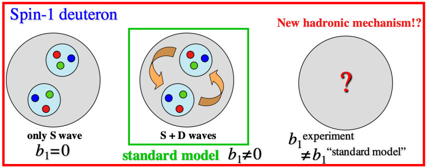


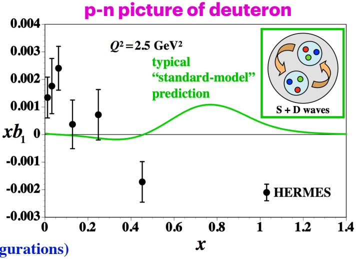


B.E. effects are insensitive to unpolarized and helicity SFs at small-x region

Tensor-polarized Structure Function

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



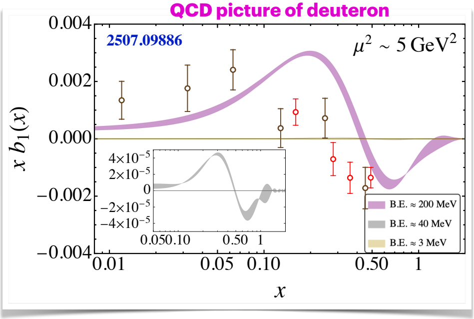


arXiv: 2507.09886 [hep-ph] (only S-wave + hidden color configurations)

- **At B.E. ~3 MeV (loosely bound),**
  $b_1(x) \approx 0$
- **At higher B.E., hidden-color d.o.f. become significant**

Possible explanation for HERMES and JLab projected data

PRL 95, 242001 (2005)
EPJ A 61, 81 (2025)



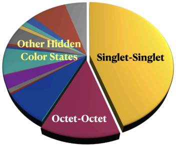
Outlook

- Quantify the relative weights of singlet-singlet and octet-octet components.
- Include D-wave component.
- Observe the effect of hidden-color in other physical observables of deuteron.
- Study deuteron directly from the partonic level with Basis Light-Front Quantization (BLFQ) approach

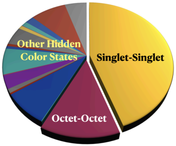
(in progress: $\psi_{6q}|6q\rangle + \psi_{6q1g}|6q1g\rangle$) *J.Subatomic Part.Cosmol.* 3 (2025) 100070 2503.21371

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

$m_J = 0$



$m_J = \pm 1$



Conclusions

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- Solved for the deuteron mass and wave functions with two Schrödinger-like equations with
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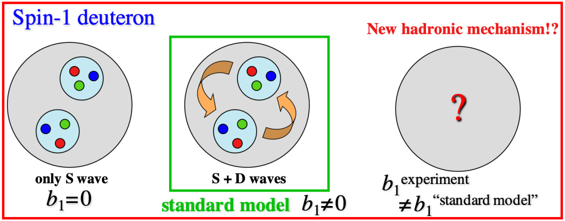
  - The 't Hooft potential at large N_c limit: longitudinal dynamics
- $b_1(x)$ showed the importance of hidden color in deuteron (*even with no D-wave*)



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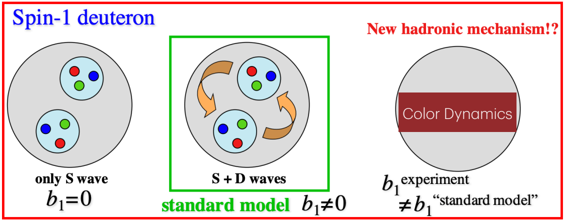

Effective mixture of singlet-singlet and octet-octet color states

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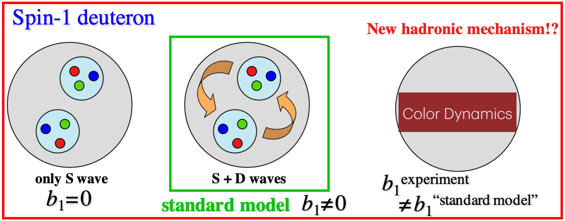

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Thank you!

Light-Front Holographic QCD : contains transverse dynamics

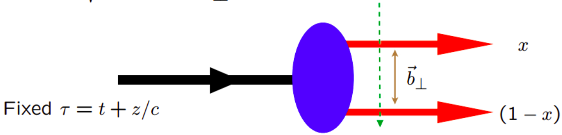
de Teramond, sjb

LF(3+1) ⟷ AdS_5

Light-Front Holographic Dictionary

$\psi(x, \vec{b}_\perp)$ ⟷ $\phi(z)$

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



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

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

Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

[1] S.J. Brodsky, arXiv-hep:1611.07194