Partonic structure of tensor-polarized deuteron

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (SOKENDAI)
http://research.kek.jp/people/kumanos/

Workshop on Exploring QCD with light nuclei at EIC
Stony Brook University, Stony Brook, New York, USA
https://indico.bnl.gov/event/6799/

Recent papers: (1) SK and Qin-Tao Song, Phys. Rev. D 94 (2016) 054022.
(2) W. Cosyn, Yu-Bing Dong, SK, M. Sargsian,
Phys. Rev. D 95 (2017) 074036.
(3) SK and Qin-Tao Song, arXiv:1910.12523.

January 23, 2020

Personal studies on tensor structure of the deuteron

- Sum rule for b_1
  F. E. Close and SK, Phys. Rev. D42 (1990) 2377.
- Polarized proton-deuteron Drell-Yan: General formalism
  M. Hino and SK, Phys. Rev. D59 (1999) 094026.
- Polarized proton-deuteron Drell-Yan: Parton model
  M. Hino and SK, Phys. Rev. D60 (1999) 054018.
- Extraction of $\Delta\bar{u}/\Delta\bar{d}$ and $\Delta_T\bar{u}/\Delta_T\bar{d}$ from polarized pd Drell-Yan
  SK and M. Miyama, Phys. Lett. B497 (2000) 149.
- Projections to $b_1, \ldots, b_4$ from $W\ \mu\nu$
  T.-Y. Kimura and SK, Phys. Rev. D 78 (2008) 117505.
- Tensor-polarized distributions from HERMES data
  SK, Phys. Rev. D82 (2010) 017501.
- Tensor-polarization asymmetry in pd Drell-Yan
  SK and Qin-Tao Song, Phys. Rev. D94 (2016) 054022.
- Convolution calculation for b_1
  W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, Phys. Rev. D 95 (2017) 074036.
- Gluon transversity by proton-deuteron Drell-Yan
  SK and Qin-Tao Song, arXiv:1910.12523.

JLab experiment soon!, Fermilab pd Drell-Yan?, EIC

Motived by the following works.

Hoodbhoy-Jaffe-Manohar (1989)

↓

Polarized deuteron acceleration at RHIC:
E. D. Courant, Report BNL-65606 (1998)

↓

HERMES measurement on b_1 (2005)

↓

Future possibilities
at JLab, Fermilab, J-PARC,
RHIC, ILC, …

↓

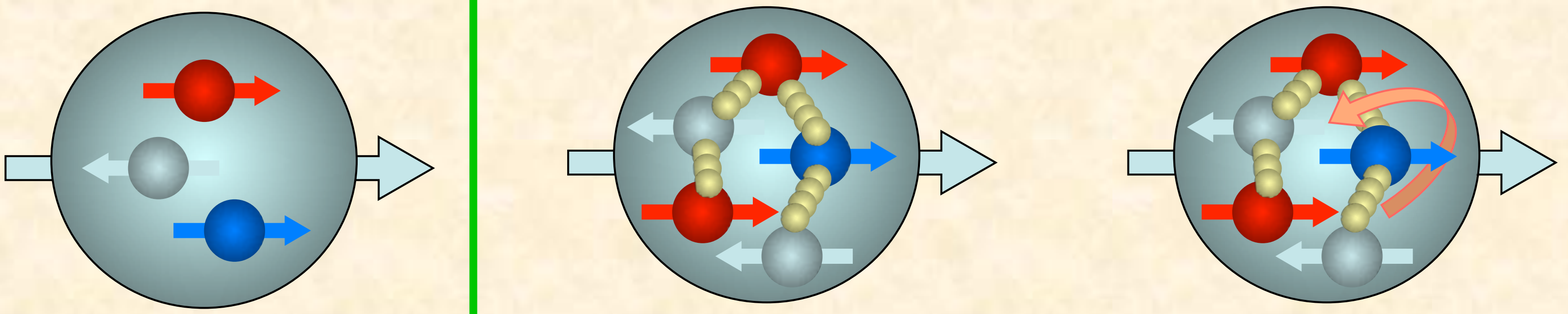
JLab PAC-38 proposal, PR12-11-110,
J.-P. Chen *et al.* (2011) → approved!
Fermilab-E1039, under consideration.

Contents

Because these topics were discussed at the last EIC workshop on light ions at Ghent in 2018, I explain briefly.

Nucleon spin

Almost none of nucleon spin is carried by quarks! → **Nucleon spin crisis!?**

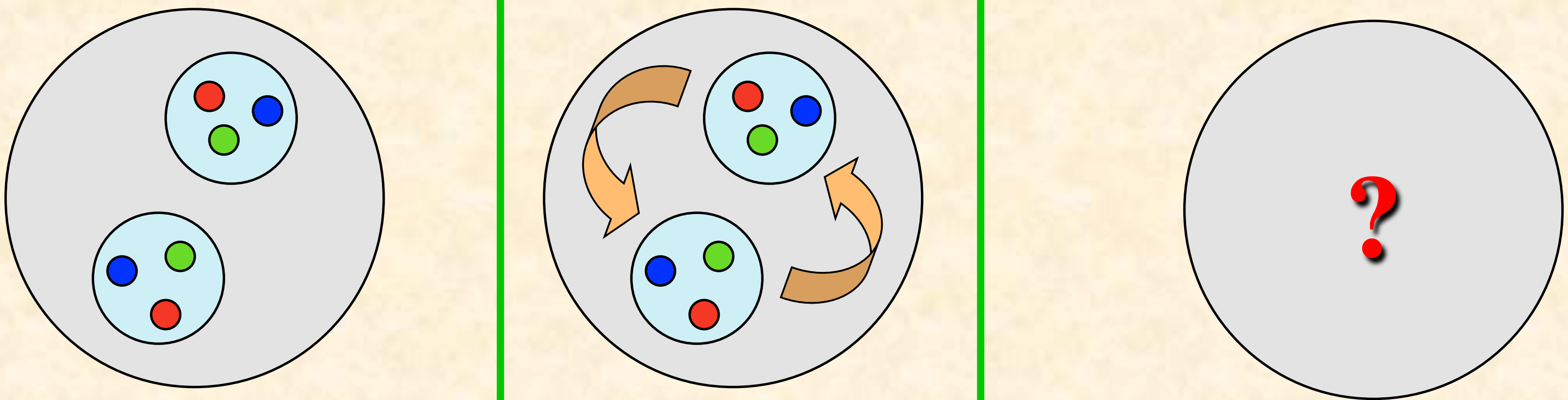


Naïve Quark Model — Sea-quarks and gluons? — Orbital angular momenta ?

"old" standard model

Tensor structure b_1 (*e.g.* deuteron)

Tensor-structure crisis!?



only S wave

$b_1 = 0$

S + D waves

standard model $b_1 \neq 0$

$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

Gluon transversity $\Delta_T g$

Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

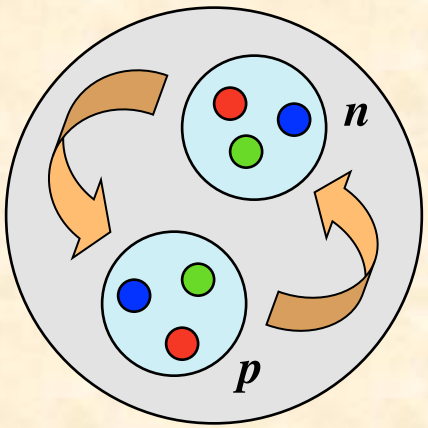
Unpolarized quark in nucleon: $q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ +\frac{1}{2}+\frac{1}{2}\right) + A\left(+\frac{1}{2}-\frac{1}{2},\ +\frac{1}{2}-\frac{1}{2}\right)$

Longitudinally-polarized quark in nucleon: $\Delta q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ +\frac{1}{2}+\frac{1}{2}\right) - A\left(+\frac{1}{2}-\frac{1}{2},\ +\frac{1}{2}-\frac{1}{2}\right)$

Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \to \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)

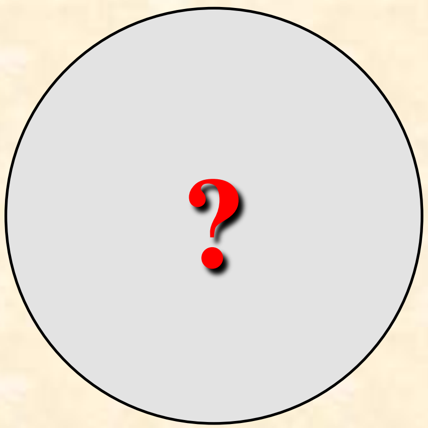
Gluon transversity in deuteron: $\Delta_T g(x) \sim A(+1+1,\ -1-1)$, $\cancel{A\left(+\frac{1}{2}+1,\ -\frac{1}{2}-1\right)}$ not possible for nucleon

Note: Gluon transversity does not exist for spin-1/2 nucleons.



S + D waves

$b_1\ (\delta_T q,\ \delta_T g) \neq 0 \ \Leftrightarrow\ $ still $\Delta_T g = 0$



What would be the mechanism(s) for creating $\Delta_T g \neq 0$?

Electron scattering from a spin-1 hadron

P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

[L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557.]

$$W_{\mu\nu} = \boxed{-F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} + g_1 \frac{i}{\nu} \varepsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + g_2 \frac{i}{\nu^2} \varepsilon_{\mu\nu\lambda\sigma} q^\lambda \left(p \cdot q s^\sigma - s \cdot q p^\sigma \right)}$$

spin-1/2, spin-1

$$\boxed{- b_1 r_{\mu\nu} + \frac{1}{6} b_2 \left(s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu} \right) + \frac{1}{2} b_3 \left(s_{\mu\nu} - u_{\mu\nu} \right) + \frac{1}{2} b_4 \left(s_{\mu\nu} - t_{\mu\nu} \right)}$$

spin-1 only

Note: Obvious factors from $q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0$ are not explicitly written.

$E^\mu =$ polarization vector

$$\nu = p \cdot q, \quad \kappa = 1 + M^2 Q^2 / \nu^2, \quad E^2 = -M^2, \quad s^\sigma = -\frac{i}{M^2} \varepsilon^{\sigma\alpha\beta\tau} E^*_\alpha E_\beta p_\tau$$

$b_1, \cdots, b_4$ tems are defined so that they vanish by spin average.

$$r_{\mu\nu} = \frac{1}{\nu^2} \left(q \cdot E^* q \cdot E - \frac{1}{3} \nu^2 \kappa \right) g_{\mu\nu}, \quad s_{\mu\nu} = \frac{2}{\nu^2} \left(q \cdot E^* q \cdot E - \frac{1}{3} \nu^2 \kappa \right) \frac{p_\mu p_\nu}{\nu}$$

$$t_{\mu\nu} = \frac{1}{2\nu^2} \left(q \cdot E^* p_\mu E_\nu + q \cdot E^* p_\nu E_\mu + q \cdot E p_\mu E^*_\nu + q \cdot E p_\nu E^*_\mu - \frac{4}{3} \nu p_\mu p_\nu \right)$$

$$u_{\mu\nu} = \frac{1}{\nu} \left(E^*_\mu E_\nu + E^*_\nu E_\mu + \frac{2}{3} M^2 g_{\mu\nu} - \frac{2}{3} p_\mu p_\nu \right)$$

b_1, b_2 tems are defined to satisfy $2xb_1 = b_2$ in the Bjorken scaling limit.

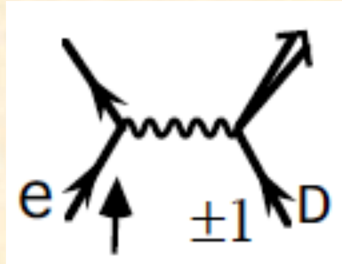
$2xb_1 = b_2$ in the scaling limit $\sim O(1)$

$b_3, b_4 =$ twist-4 $\sim \frac{M^2}{Q^2}$

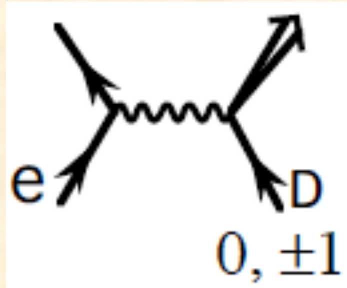
Structure Functions

$$F_1 \propto \langle d\sigma \rangle$$

$$g_1 \propto d\sigma\left(\uparrow,+1\right) - d\sigma\left(\uparrow,-1\right)$$



$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2}$$



note: $\sigma(0) - \frac{\sigma(+1)+\sigma(-1)}{2} = 3\langle\sigma\rangle - \frac{3}{2}\left[\sigma(+1)+\sigma(-1)\right]$

Parton Model

$$F_1 = \frac{1}{2}\sum_i e_i^{\,2}\left(q_i + \bar{q}_i\right) \qquad q_i = \frac{1}{3}\left(q_i^{+1} + q_i^{0} + q_i^{-1}\right)$$

$$g_1 = \frac{1}{2}\sum_i e_i^{\,2}\left(\Delta q_i + \Delta\bar{q}_i\right) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

$$\left[q_\uparrow^H\left(x,Q^2\right)\right] \qquad b_1 = \frac{1}{2}\sum_i e_i^2\left(\delta_T q_i + \delta_T \bar{q}_i\right) \qquad \delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

HERMES results on b_1

A. Airapetian *et al.* (HERMES), PRL 95 (2005) 242001.

27.6 GeV/c $\rightleftarrows$, 0

positron → ● deuteron

b_1 measurement in the kinematical region

$$0.01 < x < 0.45, \;\; 0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$$

b_1 sum rule

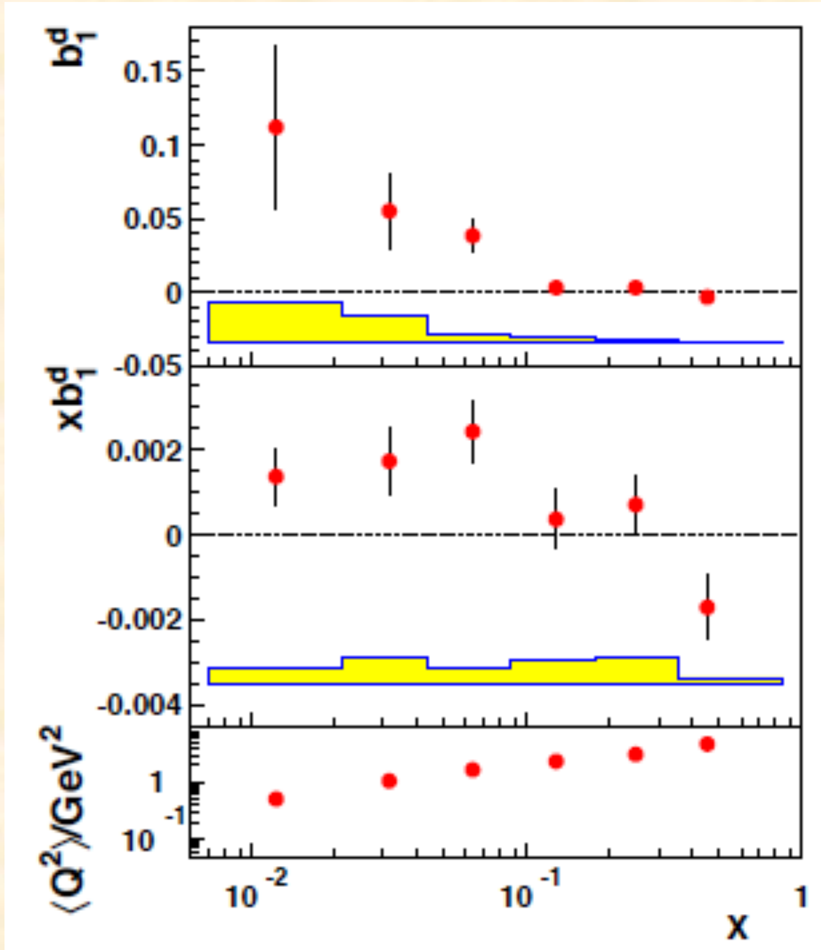
$$\int_{0.002}^{0.85} dx\, b_1(x) = \left[1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})\right] \times 10^{-2}$$

at $Q^2 = 5$ GeV^2

In the restricted Q^2 range $Q^2 > 1$ GeV^2

$$\int_{0.02}^{0.85} dx\, b_1(x) = \left[0.35 \pm 0.10(\text{stat}) \pm 0.18(\text{sys})\right] \times 10^{-2}$$

at $Q^2 = 5$ GeV^2



$$\int dx\, b_1^D(x) = \lim_{t\to 0} -\frac{5}{12}\frac{t}{M^2}F_Q(t) + \underline{\frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{\text{sea}}} = 0 \;?$$

b$_1$ sum rule: F. E. Close and SK, PRD 42 (1990) 2377.

$$\int \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3}\int dx\left[u_v - d_v\right] + \underline{\frac{2}{3}\int dx\left[\bar{u} - \bar{d}\right]} \neq 1/3$$

Drell-Yan experiments probe these antiquark distributions.

“Standard” deuteron model prediction for b_1

W. Cosyn, Yu-Bing Dong, S. Kumano, M. Sargsian,
Phys. Rev. D 95 (2017) 074036.

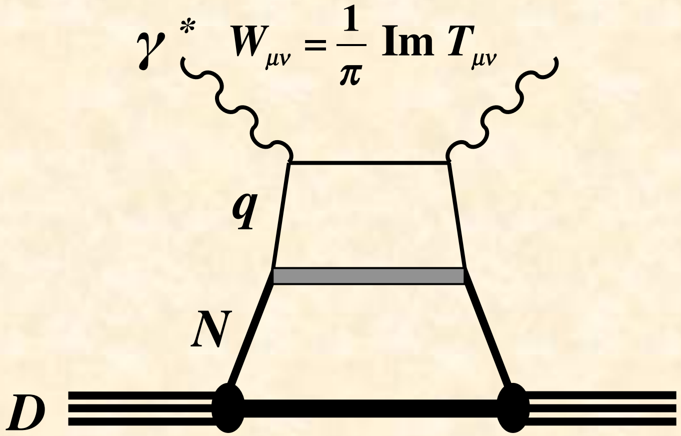
(1) Basic convolution model
(2) Virtual nucleon approximation and higher-twist effects

Theory 1: Basic convolution approach

Convolution model: $A_{hH,\,hH}(x,Q^2) = \int \frac{dy}{y} \sum_s f_s^H(y) \hat{A}_{hs,hs}(x/y,\, Q^2) \equiv \sum_s f_s^H(y) \otimes \hat{A}_{hs,hs}(y,Q^2)$

$$A_{hH,\,h'H'} = \varepsilon_{h'}^{*\mu} W_{\mu\nu}^{H'H} \varepsilon_h^{\nu}, \quad b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2}$$

$$\hat{A}_{+\uparrow,+\uparrow} = F_1 - g_1, \quad \hat{A}_{+\downarrow,+\downarrow} = F_1 + g_1$$



Momentum distribution: $f^H(y) = \int d^3p\; y\, |\phi^H(\vec{p})|^2 \delta\left(y - \frac{E - p_z}{M_N}\right)$

$$y = \frac{Mp\cdot q}{M_N P\cdot q} \simeq \frac{2p^-}{P^-}, \qquad f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$

D-state admixture: $\phi^H(\vec{p}) = \phi_{\ell=0}^H(\vec{p}) + \phi_{\ell=2}^H(\vec{p})$

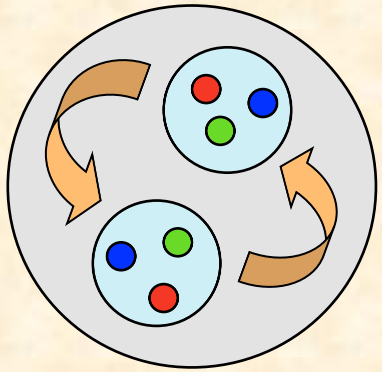
$\Downarrow$

$$b_1(x) = \int \frac{dy}{y} \delta_T f(y) F_1^N(x/y,\, Q^2)$$

$$\delta_T f(y) = f^0(y) - \frac{f^+(y) + f^-(y)}{2}$$

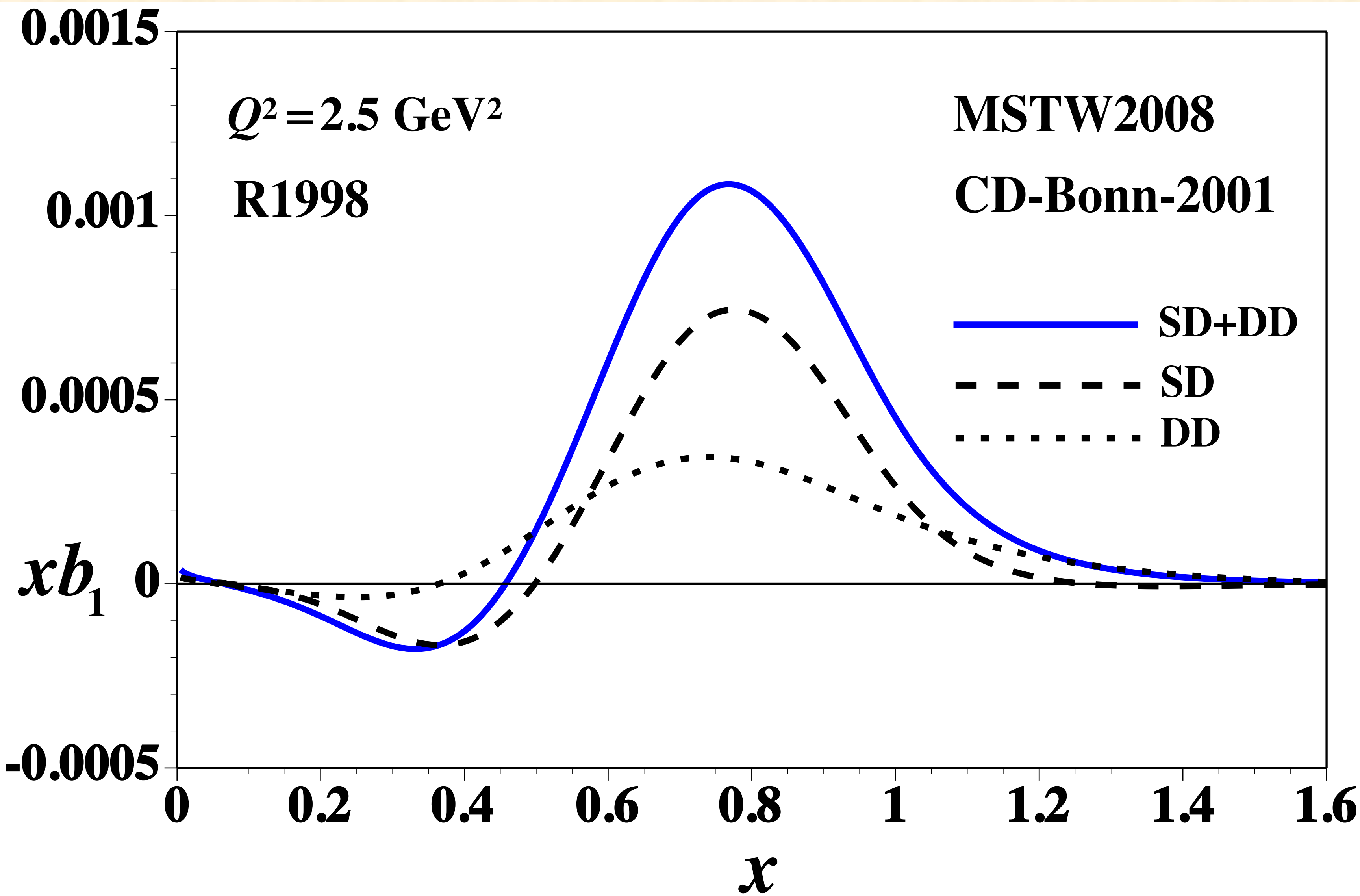
$$= \int d^3p\; y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p)\phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] (3\cos^2\theta - 1)\, \delta\left(y - \frac{p\cdot q}{M_N \nu}\right)$$

Standard model of the deuteron



S + D waves

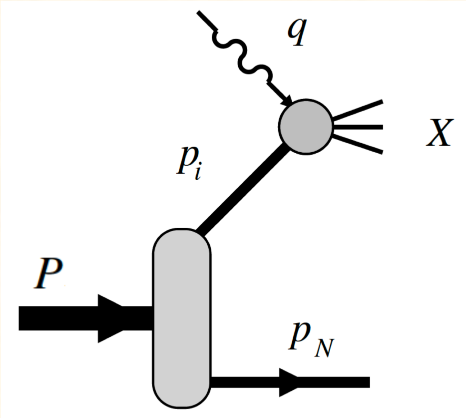
Results on b_1 in the convolution description



Theory 2: Virtual nucleon approximation with higher-twist effects

W. Cosyn' talk

L. L. Frankfurt and M. I. Strikman, Phys. Rep. 76, 215 (1981);
B. D. Keister and W. Polyzou, Adv. Nucl. Phys. 20, 225 (1991);
W. Cosyn and M. Sargsian, Phys. Rev. C 84, 014601 (2011);
W. Cosyn, W. Melnitchouk, and M. Sargsian, Phys. Rev. C 89, 014612 (2014).
For b_1, see W. Cosyn, M. Sargsian, and C. Weiss, Proc. Sci., DIS2016 (2016) 210.



Virtual nulceon approximation (VNA)

$$W_{\mu\nu}^{\lambda'\lambda}(P,q) = 4(2\pi)^3 \int d\Gamma_N \frac{\alpha_N}{\alpha_i} W_{\mu\nu}^{N}(p_i,q)\rho_D(\lambda',\lambda)$$

momentum-fractions for interacting (i) and spectator nucleons (N):

$$\alpha_i = \frac{2p_i^-}{P^-}, \quad \alpha_N = \frac{2p_N^-}{P^-} = 2-\alpha_i, \quad P = p_i + p_N$$

phase space: $d\Gamma_N = \dfrac{d^3 p_N}{2E_{p_N}(2\pi)^3}$

deuteron density: $\rho_D(\lambda',\lambda) = \displaystyle\sum_{\lambda_N,\lambda'_N} \frac{[\psi^D_{\lambda'}(\vec{k},\lambda'_N,\lambda_N)]^\dagger \psi^D_{\lambda'}(\vec{k},\lambda'_N,\lambda_N)}{\alpha_N \alpha_i}$

Results on b_1 in the convolution description

Very different from

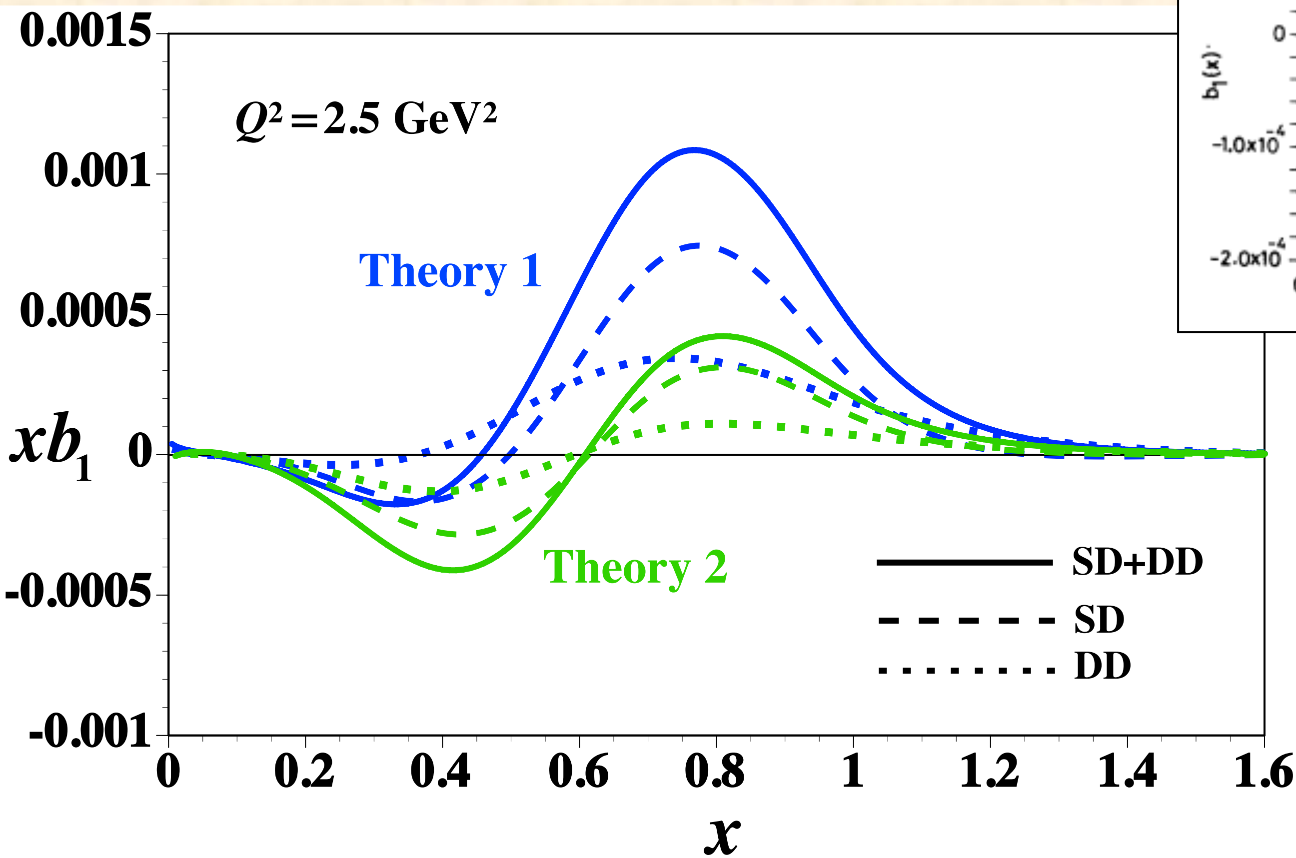
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

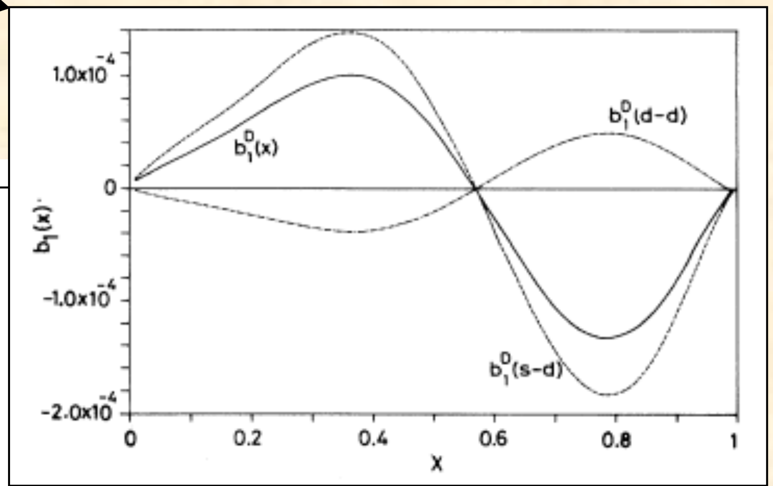
H. Khan and P. Hoodbhoy, PRC44 (1991) 1219;

(1) SD term is opposite,

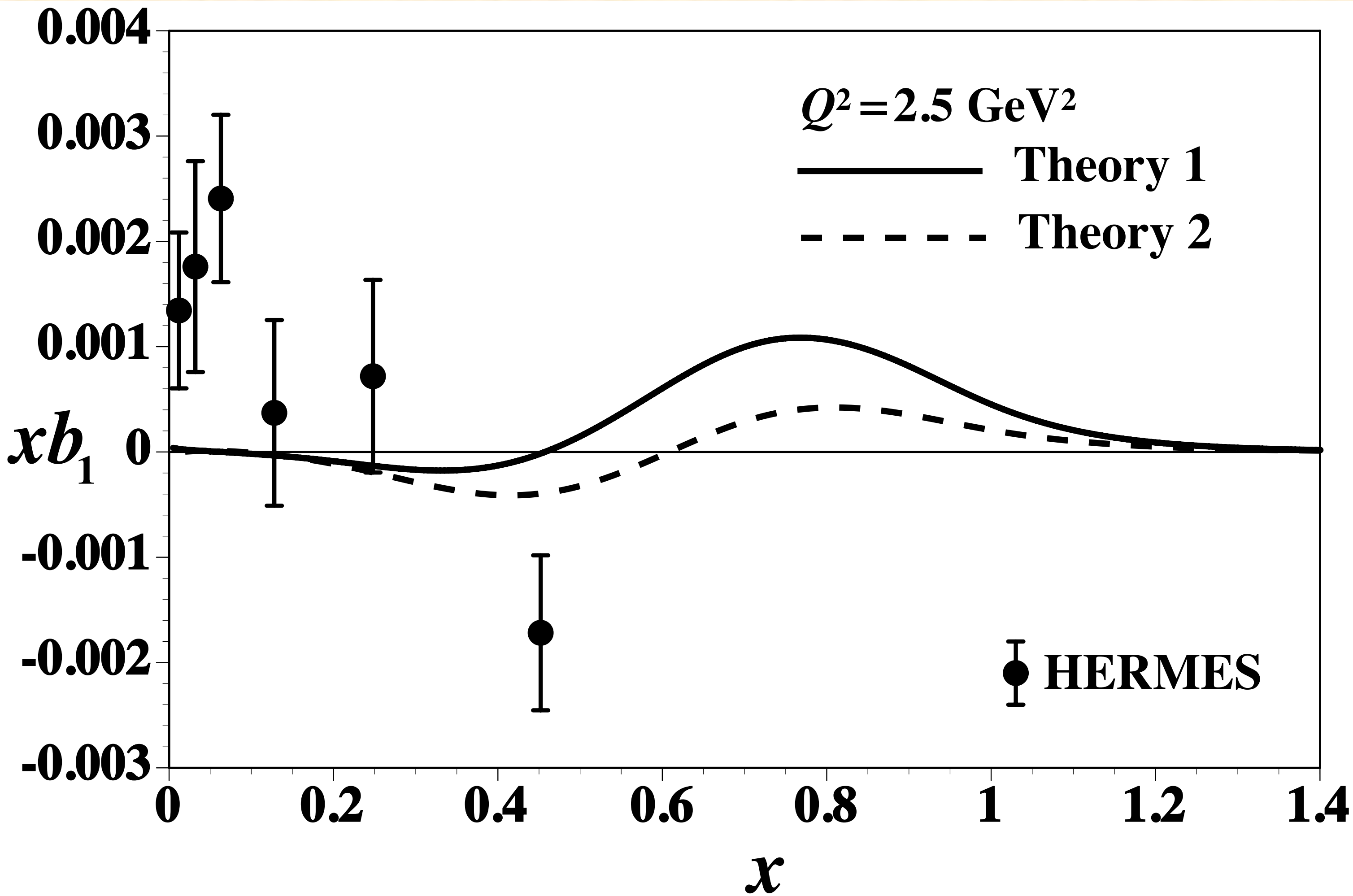
(2) $b_1(x)$ exists even at $x > 1$,

(3) $|b_1(\text{CDKS})| = 10^{-3} \gg |b_1(\text{KH})| = 10^{-4}$.





Comparison with HERMES measurements



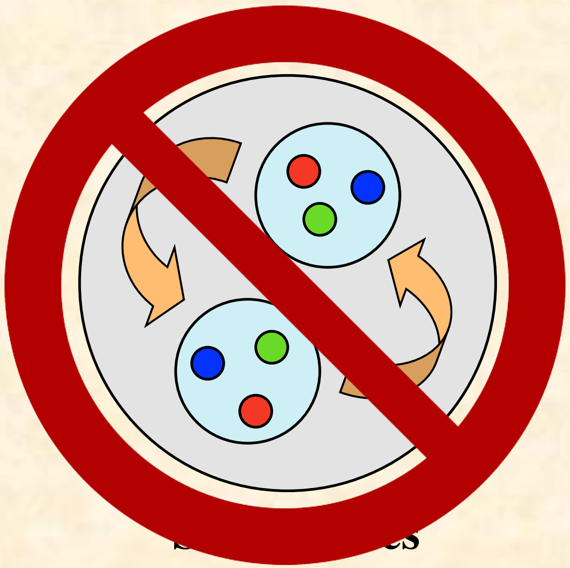
$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$
at $x < 0.5$

Standard convolution model does not work for the deuteron tensor structure!?

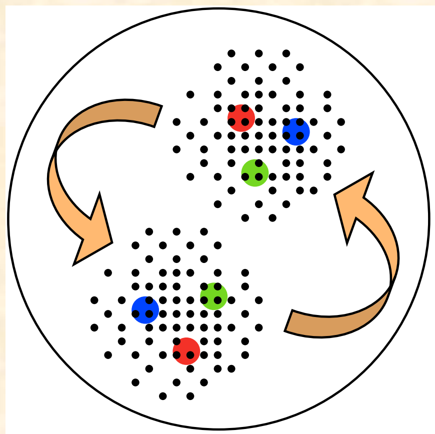
Summary on b_1 prediction

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: JLab (approved), Fermilab, ... , EIC, ILC, ...
- EIC → appropriate to study tensor-polarized antiquark distributions at small-x, Q^2 evolution of b_1



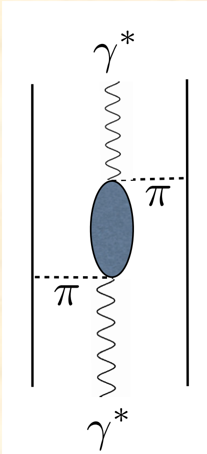
standard model

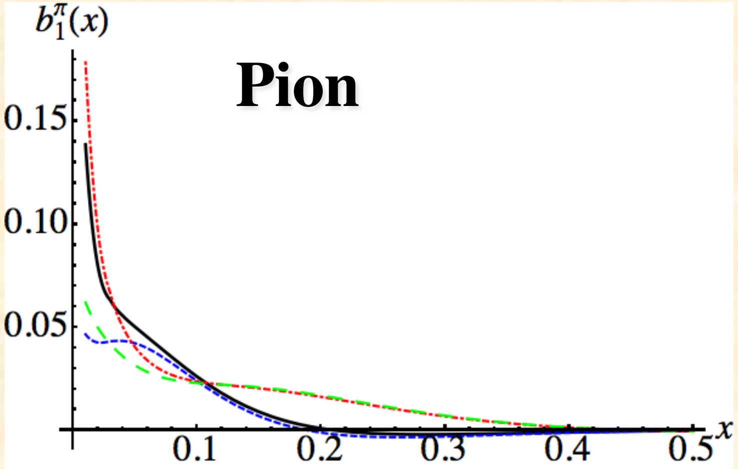


? new exotic mechanism?

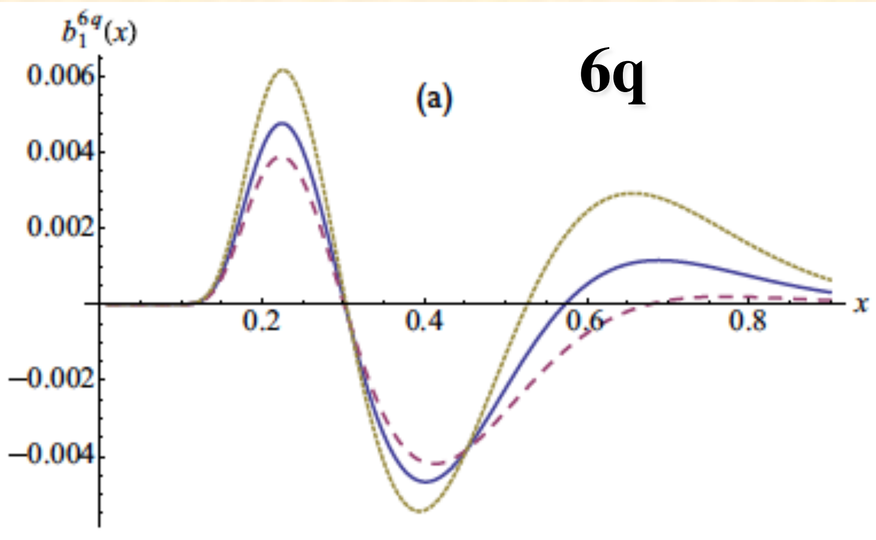
Recent work: Pion, Hidden-color, Six-quark

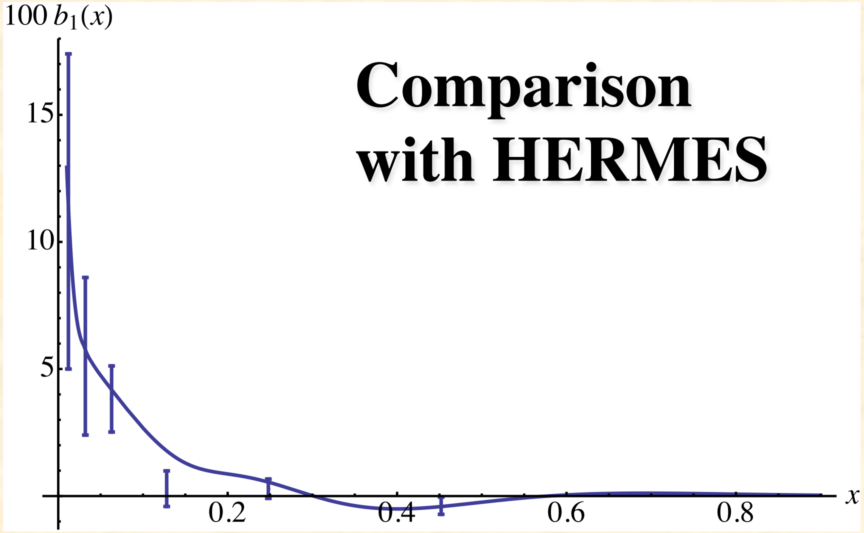
G. A. Miller,
PRC 89 (2014) 045203.





$$|6q\rangle = |NN\rangle + |\Delta\Delta\rangle + |CC\rangle + \cdots$$





JLab PAC-38 (Aug. 22-26, 2011) proposal, PR12-11-110

The Deuteron Tensor Structure Function b_1

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

J.-P. Chen (co-spokesperson), P. Solvignon (co-spokesperson),
K. Allada, A. Camsonne, A. Deur, D. Gaskell,
C. Keith, S. Wood, J. Zhang
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

N. Kalantarians (co-spokesperson), O. Rondon (co-spokesperson)
Donal B. Day, Hovhannes Baghdasaryan, Charles Hanretty
Richard Lindgren, Blaine Norum, Zhihong Ye
University of Virginia, Charlottesville, VA 22903

K. Slifer[†](co-spokesperson), A. Atkins, T. Badman,
J. Calarco, J. Maxwell, S. Phillips, R. Zielinski
University of New Hampshire, Durham, NH 03861

J. Dunne, D. Dutta
Mississippi State University, Mississippi State, MS 39762

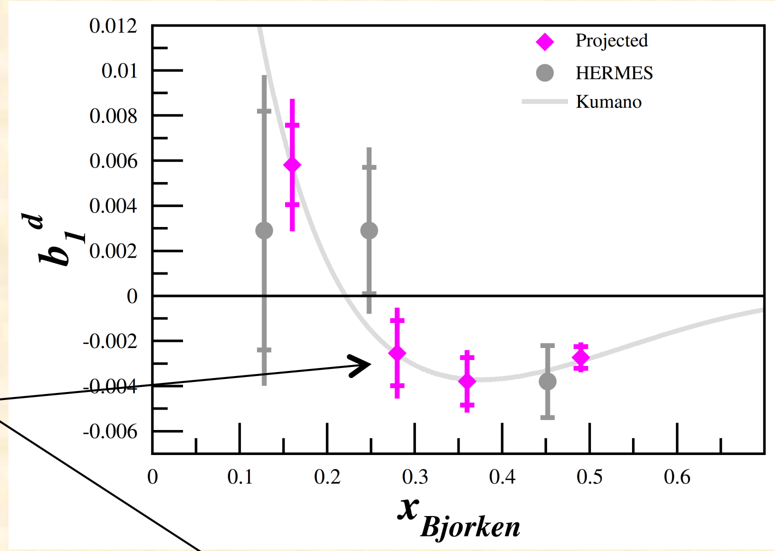
G. Ron
Hebrew University of Jerusalem, Jerusalem

W. Bertozzi, S. Gilad,
A. Kelleher, V. Sulkosky
Massachusetts Institute of Technology, Cambridge, MA 02139

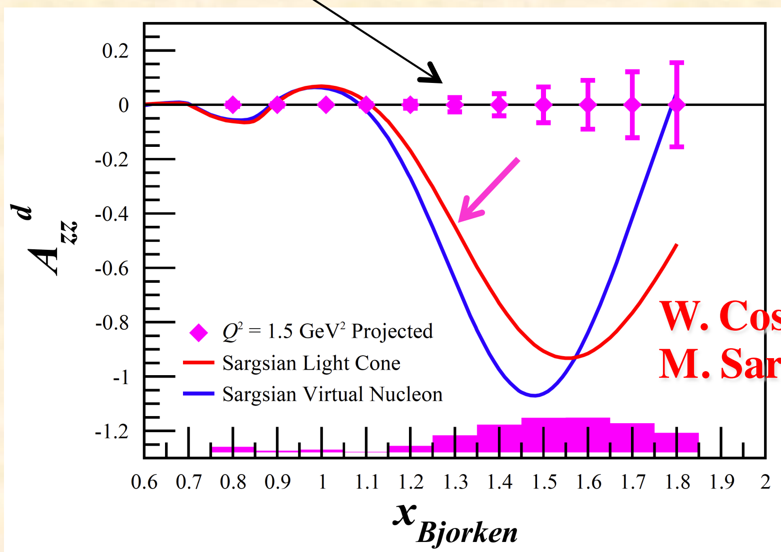
K. Adhikari
Old Dominion University, Norfolk, VA 23529

R. Gilman
Rutgers, The State University of New Jersey, Piscataway, NJ 08854

Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
Seoul National University, Seoul 151-747 Korea



Expected errors by JLab

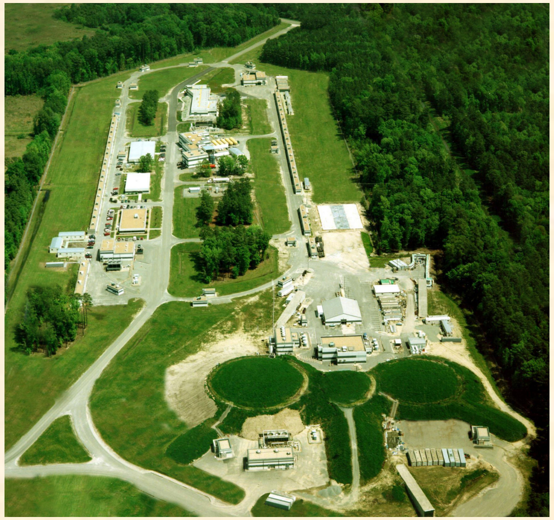


W. Cosyn, M. Sargsian

Approved!

$$-\frac{3}{2}A_{zz} \sim \frac{b_1}{F_1}$$

Experimental possibilities



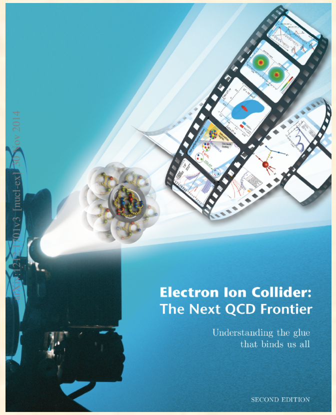
Approved experiment! (soon)

© JLab

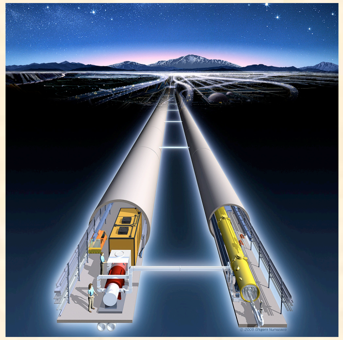
E1039 experiment

© Fermilab

EIC (arXiv:1212.1701)



Linear Collider (with fixed target)



Possibilities: Spin-1 projects are possible in principle at other hadron facilities.

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Theoretical estimation on tensor-polarization asymmetry in Drell-Yan at Fermilab

S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

Basic polarized proton-deuteron Drell-Yan formalisms:
M. Hino and SK, Phys. Rev. D59 (1999) 094026; D60 (1999) 054018.

Parametrization of tensor-polarized PDFs:
SK, Phys. Rev. D82 (2010) 017501.

Spin asymmetries in the parton model

unpolarized: q_a, longitudinally polarized: Δq_a,
transversely polarized: $\Delta_T q_a$, tensor polarized: δq_a

Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A dx_B d\Omega} \right\rangle = \frac{\alpha^2}{4Q^2}\left(1+\cos^2\theta\right)\frac{1}{3}\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]$$

Spin asymmetries

$$A_{LL} = \frac{\sum_a e_a^2\left[\Delta q_a(x_A)\Delta\bar{q}_a(x_B)+\Delta\bar{q}_a(x_A)\Delta q_a(x_B)\right]}{\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{TT} = \frac{\sin^2\theta\cos(2\phi)}{1+\cos^2\theta}\frac{\sum_a e_a^2\left[\Delta_T q_a(x_A)\Delta_T\bar{q}_a(x_B)+\Delta_T\bar{q}_a(x_A)\Delta_T q_a(x_B)\right]}{\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{UQ_0} = \frac{\sum_a e_a^2\left[q_a(x_A)\delta_T\bar{q}_a(x_B)+\bar{q}_a(x_A)\delta_T q_a(x_B)\right]}{2\sum_a e_a^2\left[q_a(x_A)\bar{q}_a(x_B)+\bar{q}_a(x_A)q_a(x_B)\right]}$$

$$A_{LT} = A_{TL} = A_{UT} = A_{TU} = A_{TQ_0} = A_{UQ_1}$$
$$= A_{LQ_1} = A_{TQ_1} = A_{UQ_2} = A_{LQ_2} = A_{TQ_2} = 0$$

Advantage of the hadron reaction ($\delta\bar{q}$ measurement)

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A)\delta_T\bar{q}_a(x_B)}{2\sum_a e_a^2 q_a(x_A)\bar{q}_a(x_B)}$$

Note: $\delta \neq$ transversity in my notation

Functional form of parametrization

SK, Phys. Rev. D82 (2010) 017501

Assume flavor-symmetric antiqurk distributions: $\delta_T \bar{q}^D \equiv \delta_T \bar{u}^D = \delta_T \bar{d}^D = \delta_T s^D = \delta_T \bar{s}^D$

$$b_1^D(x)_{LO} = \frac{1}{18}\left[4\delta_T u_v^D(x) + \delta_T d_v^D(x) + 12\ \delta_T \bar{q}^D(x)\right]$$

At $Q_0^2 = 2.5\ \text{GeV}^2$, $\delta_T q_v^D(x,Q_0^2) = \delta_T w(x) q_v^D(x,Q_0^2)$, $\delta_T \bar{q}^D(x,Q_0^2) = \alpha_{\bar{q}} \delta_T w(x) \bar{q}^D(x,Q_0^2)$

Certain fractions of quark and antiquark distributions are tensor polarized and such probabilities are given by the function $\delta_T w(x)$ and an additional constant $\alpha_{\bar{q}}$ for antiquarks in comparison with the quark polarization.

$$b_1^D(x,Q_0^2)_{LO} = \frac{1}{18}\left[4\delta_T u_v^D(x,Q_0^2) + \delta_T d_v^D(x,Q_0^2) + 12\delta_T \bar{q}^D(x,Q_0^2)\right]$$
$$= \frac{1}{36}\delta_T w(x)\left[5\left\{u_v(x,Q_0^2) + d_v(x,Q_0^2)\right\} + 4a_{\bar{q}}\left\{2\bar{u}(x,Q_0^2) + 2\bar{d}(x,Q_0^2) + s(x,Q_0^2) + \bar{s}(x,Q_0^2)\right\}\right]$$

$$\delta_T w(x) = a x^b (1-x)^c (x_0 - x)$$

Two types of analyses

Set 1: $\delta_T \bar{q}^D(x) = 0$ Tensor-polarized antiquark distributions are terminated $(\alpha_{\bar{q}} = 0)$,

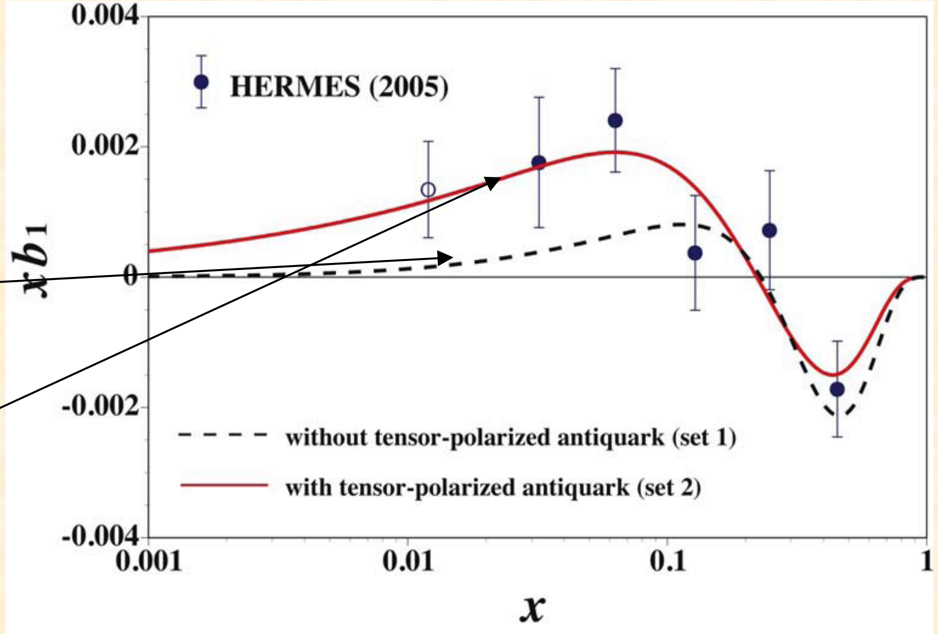
Set 2: $\delta_T \bar{q}^D(x) \neq 0$ Finite tensor-polarized antiquark distributions are allowed $(\alpha_{\bar{q}} \neq 0)$.

Results

SK, PRD 82 (2010) 017501

Two-types of fit results:

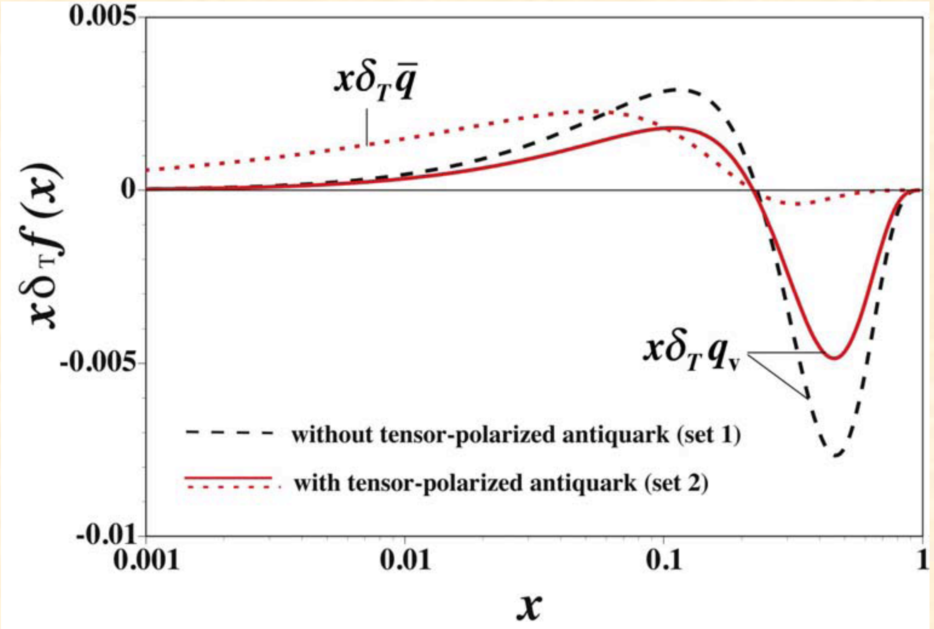
- set-1: $\chi^2 / \text{d.o.f.} = 2.83$
  Without $\delta_T q$, the fit is not good enough.
- set-2: $\chi^2 / \text{d.o.f.} = 1.57$
  With finite $\delta_T q$, the fit is reasonably good.



Obtained tensor-polarized distributions
$\delta_T q(x)$, $\delta_T \bar{q}(x)$ from the HERMES data.

→ They could be used for

- experimental proposals,
- comparison with theoretical models.



Finite tensor polarization for antiquarks:

$$\int_0^1 dx b_1(x) = 0.058$$
$$= \frac{1}{9}\int_0^1 dx \left[4\delta_T \bar{u}(x) + \delta_T \bar{d}(x) + \delta_T \bar{s}(x) \right]$$

Experimental possibility at Fermilab

E1039

Polarized fixed-target experiments at the Main Injector

Drell-Yan experiment with a polarized proton target

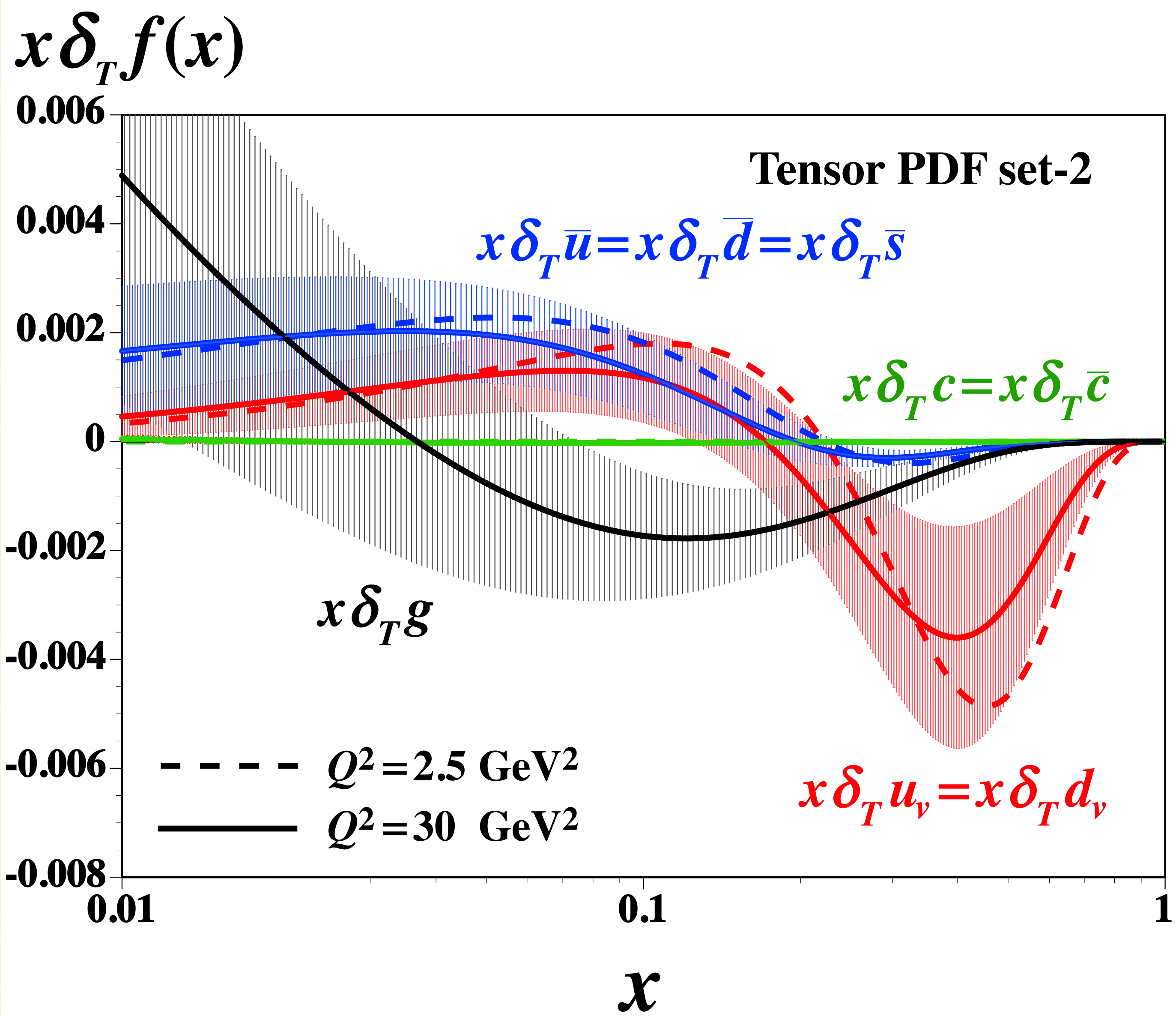
Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

List of Collaborators:

D. Geesaman, P. Reimer
Argonne National Laboratory, Argonne, IL 60439
C. Brown , D. Christian
Fermi National Accelerator Laboratory, Batavia IL 60510
M. Diefenthaler, J.-C. Peng
University of Illinois, Urbana, IL 61081
W.-C. Chang, Y.-C. Chen
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
T.-H. Chang
Ling-Tung University, Taiwan
J. Huang, X. Jiang, M. Leitch, A. Klein, K. Liu, M. Liu, P. McGaughey
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, K. Nakahara
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond
University of Michigan, Ann Arbor, MI 48109-1040
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
R.-S. Guo
National Kaohsiung Normal University, Taiwan
Y. Goto
RIKEN, Wako, Saitama 351-01, Japan
L. El Fassi, K. Myers, R. Ransome, A. Tadepalli, B. Tice
Rutgers University, Rutgers NJ 08544
J.-P. Chen
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904

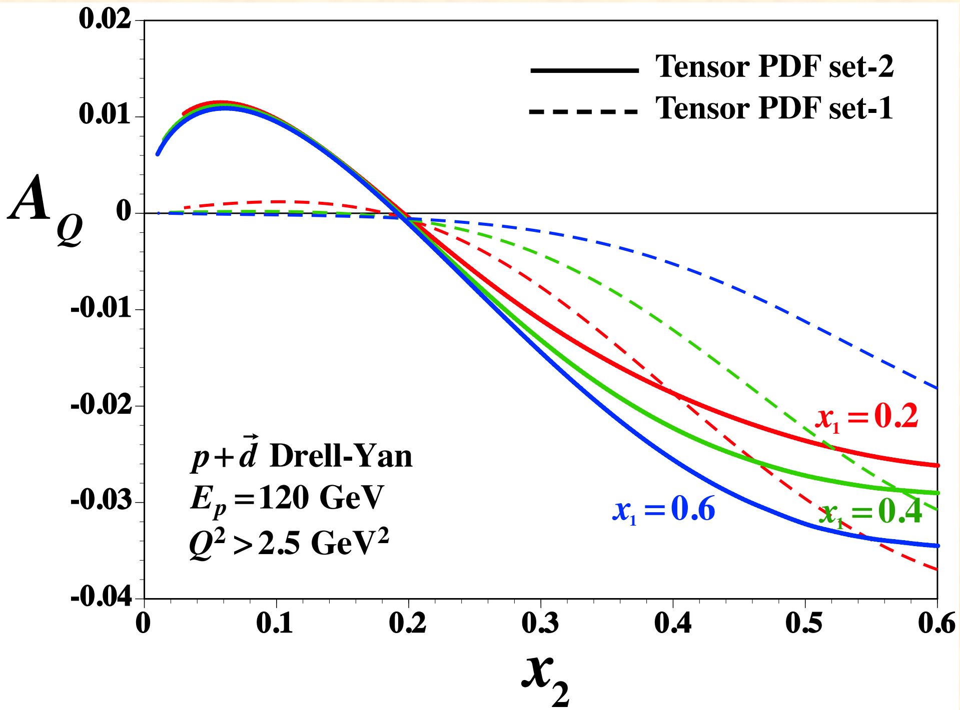
Q^2 evolution

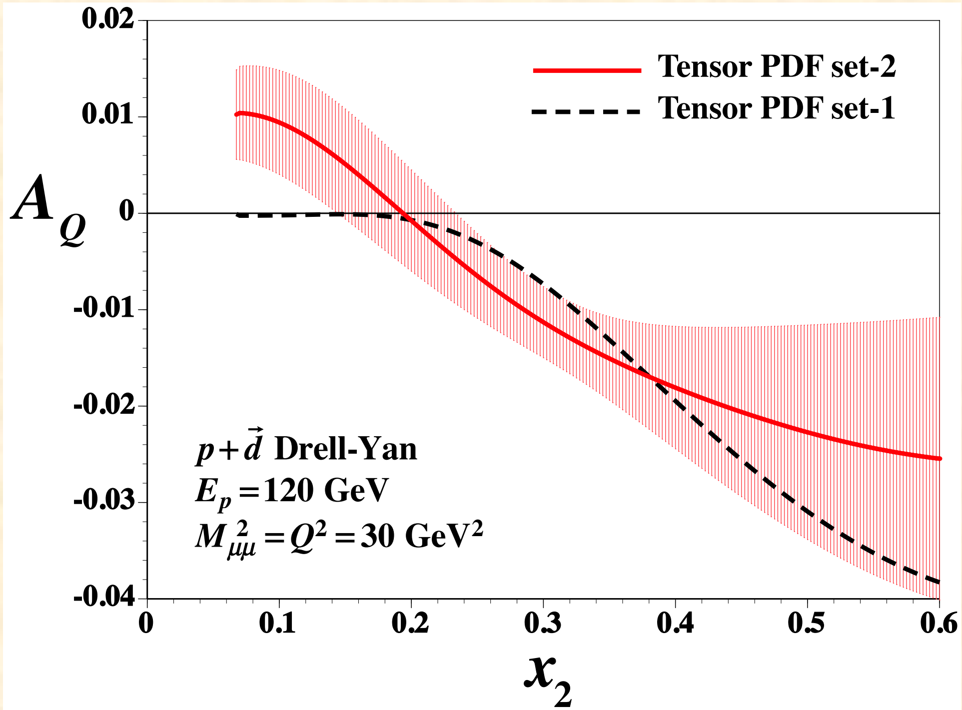
$$Q^2 = 2.5\ \text{GeV}^2 \rightarrow 30\ \text{GeV}^2$$



Tensor-polarized spin asymmetry

$$A_Q = \frac{\sum_a e_a^2 \left[q_a(x_A)\,\delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A)\,\delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A)\,\bar{q}_a(x_B) + \bar{q}_a(x_A)\,q_a(x_B) \right]}$$





S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

Summary tensor-polarization asymmetry in Drell-Yan

JLab PR12-11-110 (soon) : $b_1 = \frac{1}{2}\sum_i e_i^{\,2}\left(\delta_T q_i + \delta_T \bar{q}_i\right)$

No separation between $\delta_T q$ and $\delta_T \bar{q}$

Fermiab E1039 (20xx) : $A_Q\left(\text{large } x_F\right) \approx \dfrac{\sum_a e_a^2 q_a\left(x_1\right)\delta_T \bar{q}_a\left(x_2\right)}{2\sum_a e_a^2 q_a\left(x_1\right)\bar{q}_a\left(x_2\right)}$

Separation of $\delta_T \bar{q}$

$\rightarrow$ possible new exotic hadron physics mechanism

Gluon transversity in proton-deuteron Drell-Yan process

S. Kumano and Qin-Tao Song,
arXiv:1910.12523.

Our works on transversity distributions

- **Two-loop anomalous dimension for $\Delta_T q$,**
  S. Kumano and M. Miyama, Phys. Rev. D56 (1997) R2504-R2508; arXiv:hep-ph/9709298.

- **Numerical solution for Q^2 evolution of $\Delta_T q$,**
  M. Hirai, S. Kumano, and M. Miyama, Comput. Phys. Commun. 111 (1998) 150-166.

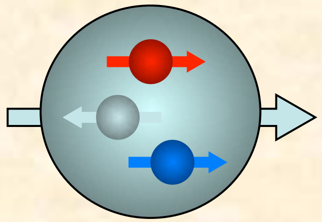
- **Proton-deuteron Drell-Yan processes for $\Delta_T \bar{u}$ / $\Delta_T \bar{d}$**
  S. Kumano and M. Miyama, Phys. Lett. B479 (2000) 149-155.

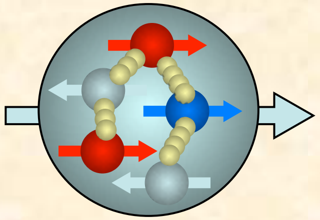
- **Proton-deuteron Drell-Yan for $\Delta_T g$,**
  S. Kumano and Qin-Tao Song, arXiv:1910.12523, submitted for publication.

Please look at arXiv:1910.12523 reference section for a complete reference list.

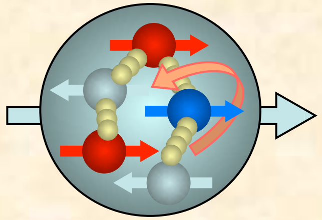
Recent progress on origin of nucleon spin

“old” standard model





gluon spin



angular momentum

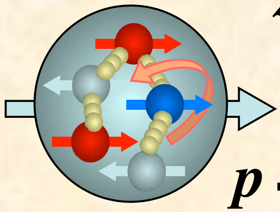
$$p_{\uparrow} = \frac{1}{3\sqrt{2}}\left(uud\left[2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow \right] + \text{permutations} \right)$$

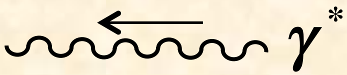
$$\boxed{\begin{array}{l} \Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x) \\ \Delta\Sigma = \sum_i \int dx \left[\Delta q_i(x) + \Delta \bar{q}_i(x) \right] \to 1 \ (100\%) \end{array}}$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_{q,g}$$

So far, mainly the longitudinal spin has been mainly investigated.

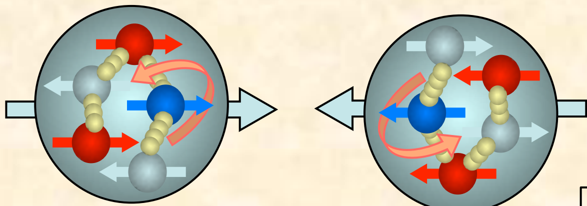
$z \longrightarrow$





$p \longrightarrow$

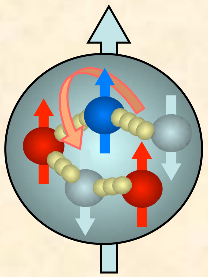
COMPASS
JLab



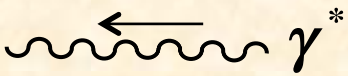
$p \longrightarrow$ $\longleftarrow$

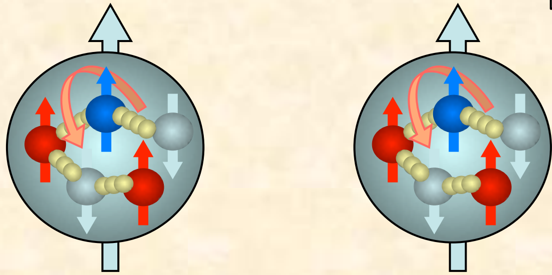
RHIC
Fermilab

For quark transversity



$z \longrightarrow$





Parton distribution functions (PDFs)

Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

Unpolarized quark in nucleon: $q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ +\frac{1}{2}+\frac{1}{2}\right) + A\left(+\frac{1}{2}-\frac{1}{2},\ +\frac{1}{2}-\frac{1}{2}\right)$

Longitudinally-polarized quark in nucleon: $\Delta q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ +\frac{1}{2}+\frac{1}{2}\right) - A\left(+\frac{1}{2}-\frac{1}{2},\ +\frac{1}{2}-\frac{1}{2}\right)$

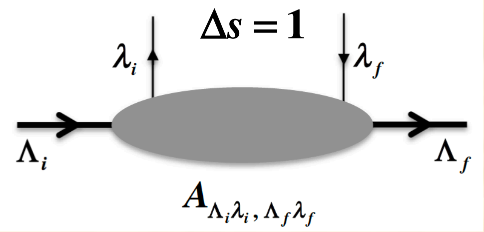
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \to \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)

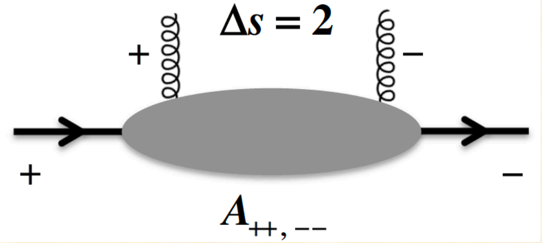
Gluon transversity in deuteron: $\Delta_T g(x) \sim A(+1+1,\ -1-1)$, $\cancel{A\left(+\frac{1}{2}+1,\ -\frac{1}{2}-1\right)}$ not possible for nucleon

Quark transversity distribution exists in the proton
because the quark-spin flip ($\Delta s = 1$) is possible in the spin-1/2 proton;
however, the gluon transversity does not exist because $\Delta s = 2$ is not possible.

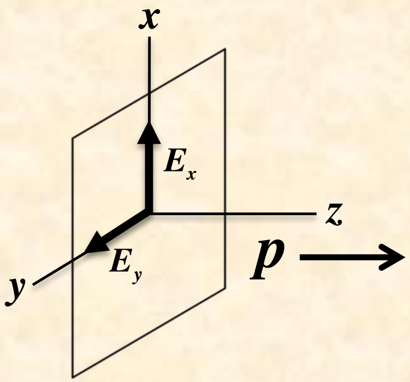
$\to$ It is possible in the spin-1 deuteron.

$\boxed{\text{Transversity distributions = Spin-flip distributions } (\Delta s = 1 \text{ for quarks}, \Delta s = 2 \text{ for gluon}) \quad \text{So, they are often called as chiral-odd distributions.}}$





Gluon transversity distribution in deuteron



Linear-polarization difference: $d\sigma(E_x - E_y) \propto \Delta_T g$

$$\Delta_T g(x) = \int \frac{d\xi^-}{2\pi} xp^+ \, e^{ixp^+\xi^-} \left\langle pE_x \middle| A^x(0)A^x(\xi) - A^y(0)A^y(\xi) \middle| pE_x \right\rangle_{\xi^+ = \vec{\xi}_T = 0}$$
$$= g_{\hat{x}/\hat{x}} - g_{\hat{y}/\hat{x}}$$

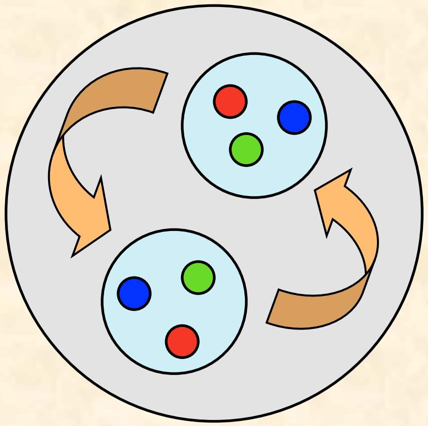
Confusing situation of gluon transversity

(no consensus even on its notation: publication # ≈ different notation #)

$$\begin{aligned}
\Delta_2 G(x) &= g_{\hat{x}/\hat{x}}(x) - g_{\hat{y}/\hat{x}}(x) && [13,\ 44], \\
a(x) &= g_{\hat{x}/\hat{x}}(x) - g_{\hat{y}/\hat{x}}(x) && [23,\ 25], \\
\Delta_L g(x) &= g_{\hat{x}/\hat{x}}(x) - g_{\hat{y}/\hat{x}}(x) && [19], \\
\delta G(x) &= -g_{\hat{x}/\hat{x}}(x) + g_{\hat{y}/\hat{x}}(x) && [26,\ 45], \\
h_{1TT,g}(x) &= -g_{\hat{x}/\hat{x}}(x) + g_{\hat{y}/\hat{x}}(x) && [36,\ 38,\ 46], \\
\Delta_T g(x) &= g_{\hat{x}/\hat{x}}(x) - g_{\hat{y}/\hat{x}}(x) && [47],\ \text{this work},
\end{aligned}$$

→ One can imagine how premature this field is!

Exotic components in nuclei beyond simple bound states of nucleons



S + D waves

Deuteron = proton + neutron

Because the gluon transversity does not exist in the spin-1/2 nucleons, a finite gluon transversity distribution could indicate an exotic aspect of the deuteron (or in general nuclei) beyond the simple bound system of nucleons.

M. Nzar and P. Hoodbhoy, PRD 45 (1992) 2264.

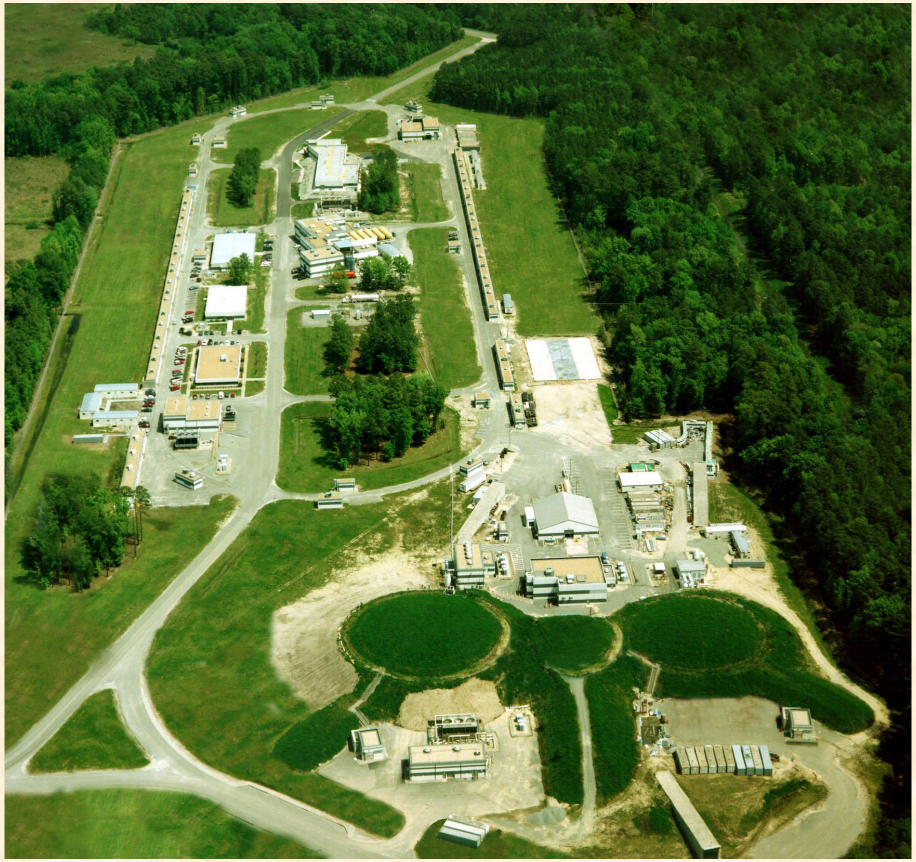
$$\left| d \right\rangle = \left| pn \right\rangle + \varepsilon \left| \Delta\Delta \right\rangle$$

So far, the paper of Nzar-Hoodbhoy is the only one on a physics mechanism of gluon transversity, so that further theoretical works are needed.

(There was no experimental possibility for 2019 – 1992 = 27 years, so that theorists were not interested in studying this topic.)

Letter of Intent at Jefferson Lab (exp. early 2020's)

Jefferson Lab,
Electron accelerator ~12 GeV



© JLab

LoI, arXiv:1803.11206

A Letter of Intent to Jefferson Lab PAC 44, June 6, 2016

Search for Exotic Gluonic States in the Nucleus

M. Jones, C. Keith, J. Maxwell*, D. Meekins

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

W. Detmold, R. Jaffe, R. Milner, P. Shanahan

Laboratory for Nuclear Science, MIT, Cambridge, MA 02139

D. Crabb, D. Day, D. Keller, O. A. Rondon

University of Virginia, Charlottesville, VA 22904

J. Pierce

Oak Ridge National Laboratory, Oak Ridge, TN 37831

Experiment is expected to start in the near future.

Experimental possibility at Fermilab (middle 2020's)

Polarized fixed-target experiments at the Main Injector, Proton beam = 120 GeV

© Fermilab

Fermilab-E1039

Drell-Yan experiment with a polarized proton target

Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

List of Collaborators:

D. Geesaman, P. Reimer
Argonne National Laboratory, Argonne, IL 60439
C. Brown , D. Christian
Fermi National Accelerator Laboratory, Batavia IL 60510
M. Diefenthaler, J.-C. Peng
University of Illinois, Urbana, IL 61081
W.-C. Chang, Y.-C. Chen
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
T.-H. Chang
Ling-Tung University, Taiwan
J. Huang, X. Jiang, M. Leitch, A. Klein, K. Liu, M. Liu, P. McGaughey
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, K. Nakahara
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond
University of Michigan, Ann Arbor, MI 48109-1040
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
R.-S. Guo
National Kaohsiung Normal University, Taiwan
Y. Goto
RIKEN, Wako, Saitama 351-01, Japan
L. El Fassi, K. Myers, R. Ransome, A. Tadepalli, B. Tice
Rutgers University, Rutgers NJ 08544
J.-P. Chen
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904

J-PARC?

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Fermilab experimentalists are interested in the gluon transversity by replacing the E1039 proton target for the deuteron one. (Spokesperson of E1039: D. Keller)

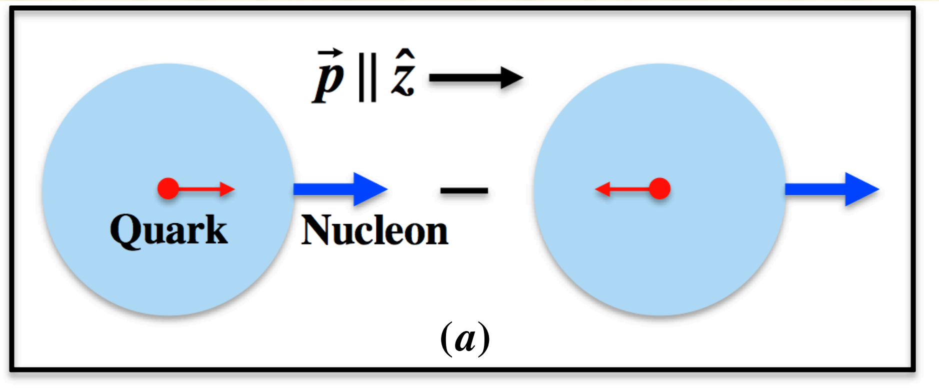
However, there was no theoretical formalism until our work.

Quark transversity distributions

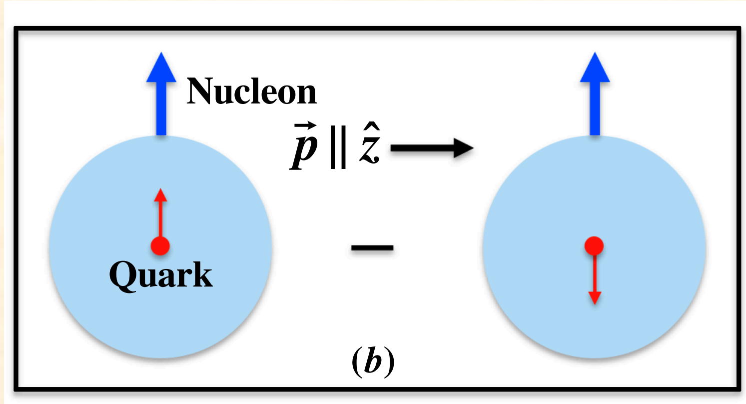
Motivations:

- **Understanding the origin of nucleon spin by transverse observables**
- **Different scaling violation from the longiduinal-spin case**
- **As the conversion coefficient from quark EDMs to nucleon EDMs for actual comparison with experimental data**

Quark transversity distributions



Longitudinally-polarized quark distribution



Quark transversity distribution

$$\Delta_T q(x) = \int \frac{d\xi^-}{4\pi} e^{ixp^+\xi^-} \left\langle p s_{T_j} \middle| \bar{\psi}(0) i\gamma^5 \sigma^{j+} \psi(\xi) \middle| p s_{T_j} \right\rangle_{\xi^+ = \vec{\xi}_T = 0}$$

Notations on quark transversity: h_T, h_1, δq, $\Delta_1 q$, $\Delta_T q$

The situation is confusing in the same with the gloun-transversity notation.

Electric dipole moment of neutron

For the details, see slides of
Workshop on Nucleon EDMs and spin structure
KEK Tokai, Japan, January 11, 2020
https://kds.kek.jp/indico/event/33396/

e.g. T. Liu, Z. Zhao, H. Gao, PRD 97 (2018) 074018.

$$L = -\frac{1}{2}\sum_q d_q \bar{\psi}_q i\gamma_5 \sigma^{\mu\nu}\psi_q F_{\mu\nu}, \qquad d_n = \sum_q d_q g_T^q$$

g_T^q = tensor charge (often δq) = $\Delta_T q$ (in our notation) = $\int_0^1 dx\left[\Delta_T q(x) - \Delta_T \bar{q}(x)\right]$

$$d_p = g_T^u d_u + g_T^d d_d + g_T^s d_s, \quad d_n = g_T^d d_u + g_T^u d_d + g_T^s d_s, \quad \left\langle p' \,\middle|\, \bar{q}\gamma_5\sigma^{\mu\nu}q \,\middle|\, p \right\rangle = g_T^q \bar{u}(p')\gamma_5\sigma^{\mu\nu}u(p)$$

Naive quark model: $\psi_p = \frac{1}{\sqrt{18}}\left(2u_\uparrow u_\uparrow d_\downarrow - u_\uparrow u_\downarrow d_\uparrow - u_\downarrow u_\uparrow d_\uparrow + \text{permutations}\right)$

$$\to g_T^u = \frac{4}{3},\ g_T^d = -\frac{1}{3}, \qquad 3\left(\frac{4}{18}+\frac{4}{18}+\frac{1}{18}-\frac{1}{18}-\frac{1}{18}+\frac{1}{18}\right) = \frac{4}{3}, \quad 3\left(-\frac{4}{18}+\frac{1}{18}+\frac{1}{18}\right) = -\frac{1}{3}$$

According to our current quark transversity: $g_T^u = 0.405,\ g_T^d = -0.225 \ \Leftrightarrow\ g_T^u = \frac{4}{3},\ g_T^d = -\frac{1}{3}$

For an order of magntude estimate, simple quark models would be enough.
However, for an accurate comparison with experimental data in future,
we need to have precise information on the tensor charge (transversity distributions).

$$\left\langle n(p') \,\middle|\, J_\mu^{\text{em}} \,\middle|\, n(p) \right\rangle = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{\kappa}{2M_N} i\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{d_n}{2M_N}\gamma_5\sigma_{\mu\nu}q^\nu F_3(q^2)\right]u(p)$$

Electric dipole moment: $d_n = \sum_q d_q \Delta_T q$, $\Delta_T q = \int_0^1 dx\left[\Delta_T q(x) - \Delta_T \bar{q}(x)\right]$ = called "tensor charge" (often denoted as δq)

$\Delta_T q(x)$ = quark transversity distribution

Namely, Hadron/Nuclear electric dipole moment
= (electric dipole moment in the quark level) * (quark transversity in hadron/nucleus)

Scaling violation

DGLAP (Dokshitzer, Gribov, Lipatov, Altarelli, Parisi) evolution equations
for the longitudinally-polarized parton distributions

$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix} \Delta q_s(x,Q^2) \\ \Delta g(x,Q^2) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\begin{pmatrix} \Delta P_{qq}(x/y) & \Delta P_{qg}(x/y) \\ \Delta P_{gq}(x/y) & \Delta P_{gg}(x/y) \end{pmatrix}\begin{pmatrix} \Delta q_s(y,Q^2) \\ \Delta g(y,Q^2) \end{pmatrix}$$

However, the gluon transversiy does not exist for the proton,
so that the quark transversity distributions evolve by themselves:

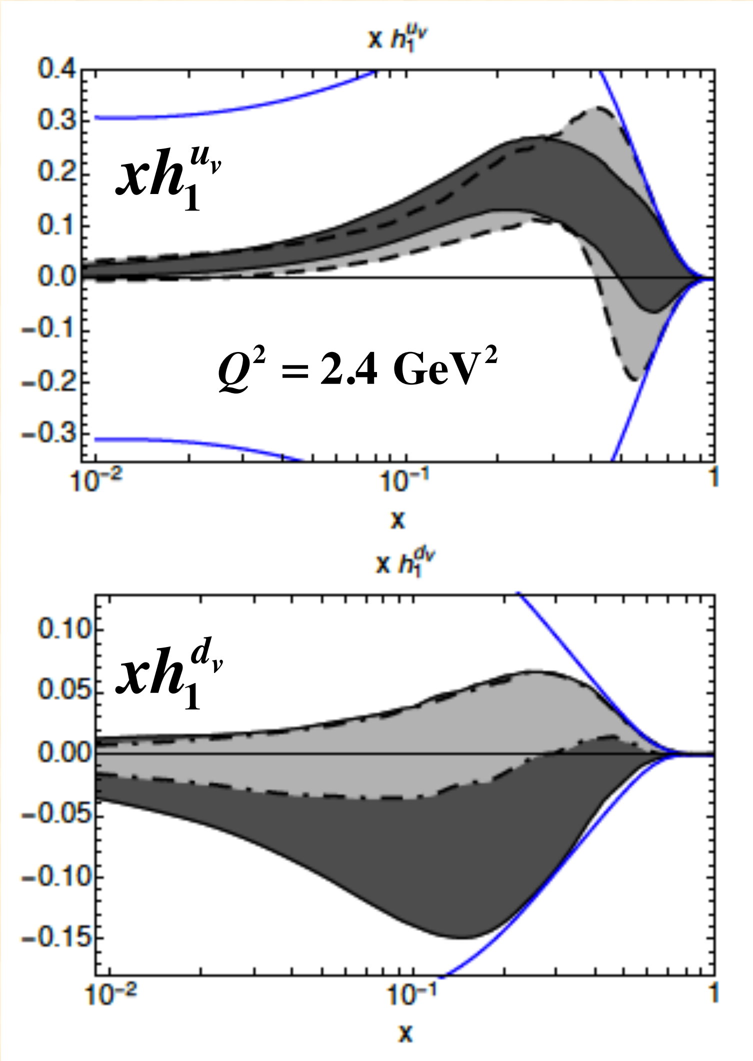
$$\frac{\partial}{\partial \log Q^2}\Delta_T q(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\Delta_T P_{qq}\left(\frac{x}{y}\right)\Delta_T q(y,Q^2)$$

significant difference
in scaling violation

The Q^2 evolution difference between the longitudinally-polarized PDFs and
the transversity distributions is an interesting test of perturbative QCD
in high-energy spin physics.

Numerical solution for Q^2 evolution of $\Delta_T q$,
M. Hirai, SK, and M. Miyama,
Comput. Phys. Commun. 111 (1998) 150.

Quark transversity distriubutions



M. Radici and A. Bacchetta (2018)

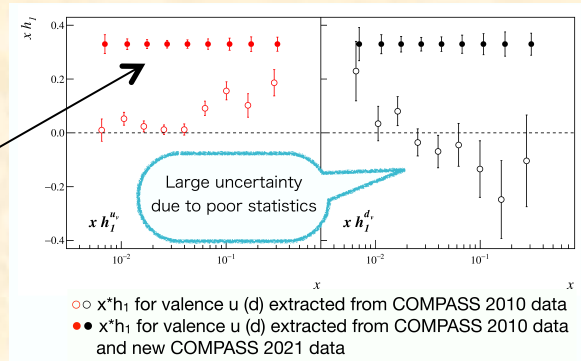
2015 : Previous analysis of $\ell + N^{\uparrow} \to \ell' + H_1 H_2 + X$

2018 : New analysis of $\ell + N^{\uparrow} \to \ell' + H_1 H_2 + X$ and $p + p^{\uparrow} \to H_1 H_2 + X$

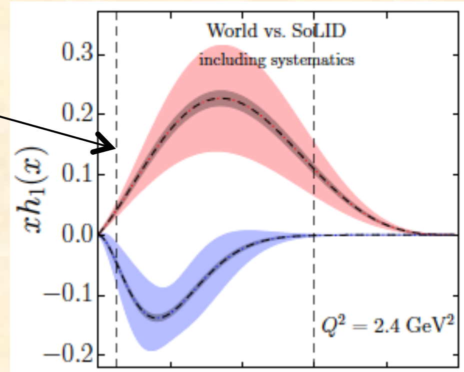
Future developments are expected:

- Accurate distributions with further data
- Q^2 evolution difference from longitudinal one
- Relation to longitudinally-polarized PDFs
- Gluon transversity

Future expectation I by COMPASS 2021



Future expectation II by JLab SoLID experiment (then continued at EIC)



Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, Phys. Rev. D 93 (2016) 014009.
M. Radici and A. Bacchetta, Phys. Rev. Lett. 120 (2018) 192001.

Gluon transversity distribution in proton-deuteron Drell-Yan process

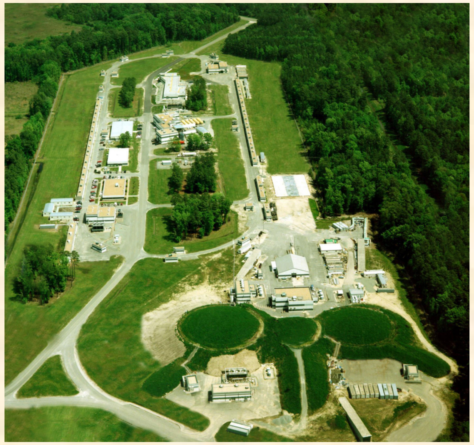
Gluon transversity in polarized proton-deuteron Drell-Yan process,
S. Kumano and Qin-Tao Song,
arXiv:1910.12523, submitted for publication.

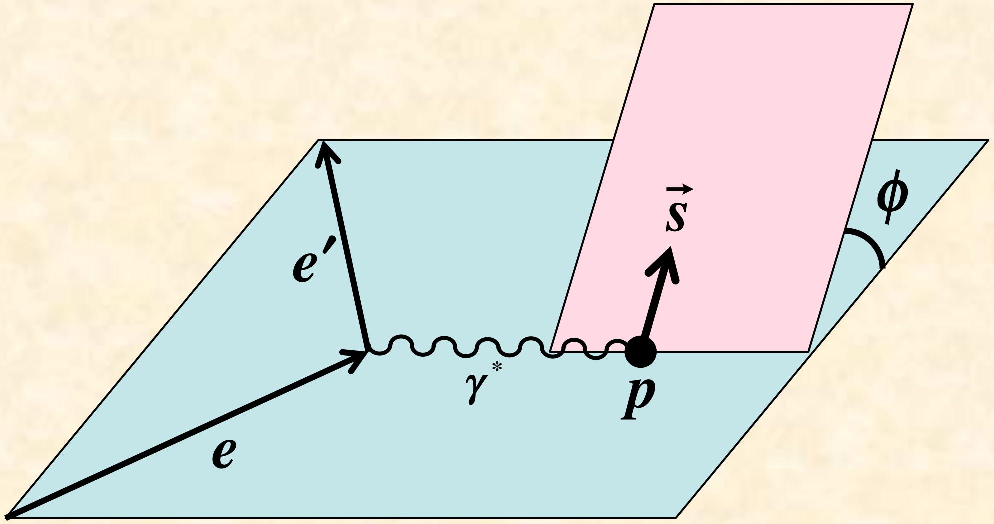
Motivations:

- **Understanding the origin of hadron spin by transverse observables**
- **For finding exotic components in nuclei**
  beyond the simple binding system of nucleons
- **It does not exist in the spin-1/2 nucleon.**

Proposed JLab experiment

LoI, arXiv:1803.11206





Electron scattering with polarized-proton target

$$\left.\frac{d\sigma}{dx\,dy\,d\phi}\right|_{Q^2 \gg M^2} = \frac{e^4 ME}{4\pi^2 Q^4}\left[xy^2 F_1(x,Q^2) + (1-y)F_2(x,Q^2) - \frac{1}{2}x(1-y)\Delta(x,Q^2)\cos(2\phi)\right]$$

$$\Delta(x,Q^2) = \frac{\alpha_s}{2\pi}\sum_q e_q^2 x^2 \int_x^1 \frac{dy}{y^3}\Delta_T g(y,Q^2)$$

By looking at the proton polarization angle ϕ, the quark transversty $\Delta_T g$ can be measured.

Our motivation by considering the JLab experiment

We propose to use hadron accelerator facilities for studying the gluon transversity.

Advantages:

- Independent experiment from JLab
- Different kinematical regions: larger Q^2, smaller x
- Hadron facilities are often useful for probing gluon distributions
- Hadron cross sections are generally larger (not for Drell-Yan).
- The gluon transversity could be measured in a different form
  from the integral $\int_x^1 \frac{dy}{y^3} \Delta_T q(y, Q^2)$ in the JLab experiment.

→ In the report arXiv:1910.12523, we propose proton-deuteron Drell-Yan process by considering the Fermilab-E1039.

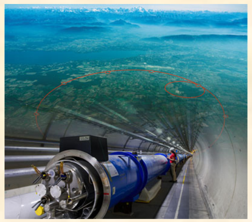
However, our formalism is valided for Drell-Yan experiments at any other facilities.

Fermilab-MI

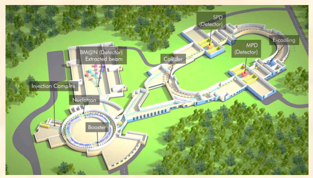
RHIC (fixed target)

GSI-FAIR

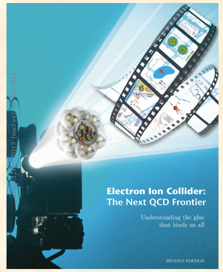
J-PARC



LHC (fixed target)
COMPASS

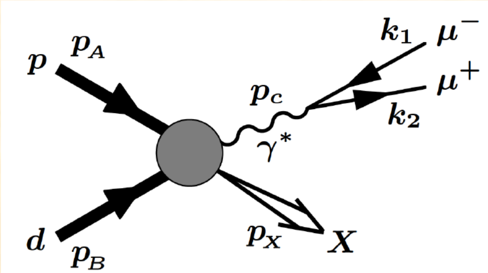


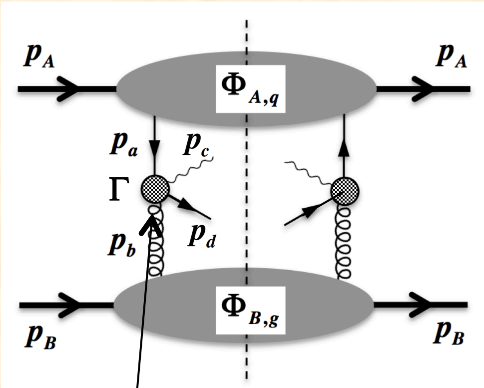
NICA



EIC (fixed target)

Proton-deuteron Drell-Yan cross section





Drell-Yan cross section

$$d\sigma_{pd\to\mu^+\mu^-X} = \int_0^1 dx_a \int_0^1 dx_b f_a(x_a) f_b(x_b) d\hat{\sigma}_{ab\to\mu^+\mu^-d}, \quad M_{ab\to\mu^+\mu^-d} = eM^{\mu}_{\gamma^*\to\mu^+\mu^-}\frac{-1}{Q^2}eM_{ab\to\gamma^* d}$$

In terms of lepton tensor $L^{\mu\nu}$ and hadron tensor $W_{\mu\nu}$

$$\frac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy} = \frac{\alpha^2}{12\pi^2 Q^4}\left[\int d\Phi_2(q;\, k_1,\, k_2)\; 2L^{\mu\nu}\right] W_{\mu\nu}$$

dilepton phase space: $d\Phi_2(q;\, k_1,\, k_2) = \delta^4(q-k_1-k_2)\dfrac{d^3k_1}{2E_1(2\pi)^3}\dfrac{d^3k_2}{2E_2(2\pi)^3}$

$$L^{\mu\nu} = 2(k_1^{\mu}k_2^{\nu} + k_1^{\nu}k_2^{\mu} - k_1\cdot k_2 g^{\mu\nu})$$

$$W_{\mu\nu} = \overline{\sum_{\text{spin, color}}}\sum_q e_q^2 \int_{\min(x_a)}^1 dx_a \frac{\pi}{p_g^-(x_a - x_1)} \mathrm{Tr}\left[\Gamma_{\nu\beta}\left\{\Phi_{q/A}(x_a) + \Phi_{\bar{q}/A}(x_a)\right\}\hat{\Gamma}_{\mu\alpha}\Phi^{\alpha\beta}_{g/B}(x_b)\right], \quad \hat{\Gamma}_{\nu\beta} = \gamma^0\Gamma_{\nu\beta}\gamma^0$$

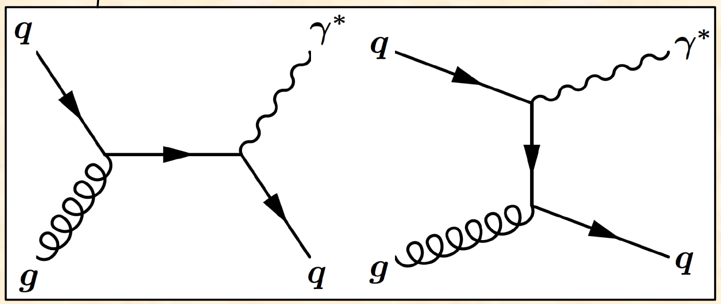
Collinear correlation functions

Refs. A. Bacchetta and P. J. Mulders, Phys. Rev. D 62 (2000) 114004.
D. Boer et al., JHEP 10 (2016) 013.
T. van Daal, arXiv:1812.07336 (Ph.D. Thesis)

$$\Phi_{q/A}(x_a)_{\text{our}} = \frac{1}{2}\left[\bar{\not{n}} f_{1,q/A}(x_a) + \gamma_5 \bar{\not{n}} S_{A,L} g_{1,q/A}(x_a) + \bar{\not{n}}\gamma_5 \not{S}_{A\perp} h_{1,q/A}(x_a)\right]$$

$$\Phi_{q/B}(x_b)_{\text{our}} = \frac{1}{2}\left[\not{n} f_{1,q/B}(x_b) + \gamma^5 \not{n}\, S_{B,L}\, g_{1,q/B}(x_b) + i\sigma_{\mu\nu}\gamma^5 n^{\mu} S^{\nu}_{B,T} h_{1,q/B}(x_b) + \not{n}\, S_{LL}\, f_{1LL,q/B}(x_b) + \sigma_{\mu\nu} n^{\nu} S^{\mu}_{B,LT} h_{1LT,q/B}(x_b)\right]$$

$$\Phi^{ij}_{g/B}(x_b)_{\text{our}} = \frac{1}{2}\left[-g_T^{ij} f_{1,g/B}(x_b) + i\varepsilon_T^{ij} S_{B,L} g_{1L,g/B}(x_b) - g_T^{ij} S_{B,LL} f_{1LL,g/B}(x_b) + S^{ij}_{B,TT} h_{1TT,g/B}(x_b)\right]$$



Tr $[8\gamma$ matrices$]$ calculated by

(1) analytical method with symmtries for $\mu\nu$, $\alpha\beta$

(2) FeynCal with Mathematica

(3) Tracer with Mathematica

Proton-deuteron Drell-Yan cross section

Drell-Yan cross section

$$\frac{d\sigma_{pd\to\mu^+\mu^-X}(E_x - E_y)}{d\tau\, dq_T^2\, d\phi\, dy} = \frac{\alpha^2 \alpha_s C_F q_T^2}{6\pi s^3}\cos(2\phi)\int_{\min(x_a)}^{1} dx_a \frac{1}{(x_a x_b)^2 (x_a - x_1)(\tau - x_a x_2)^2}\sum_q e_q^2 x_a \left[q_A(x_a) + \bar{q}_A(x_a)\right] x_b \Delta_T g_B(x_b)$$

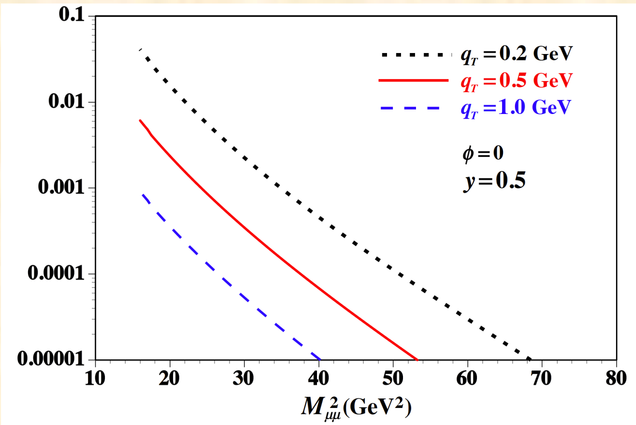
$$C_F = \frac{N_c^2 - 1}{2N_c}, \quad \min(x_a) = \frac{x_1 - \tau}{1 - x_2}, \quad x_b = \frac{x_a x_2 - \tau}{x_a - \tau}$$

= (unpolarized PDFs of proton) * (gluon transversity distribution in the deuteron)

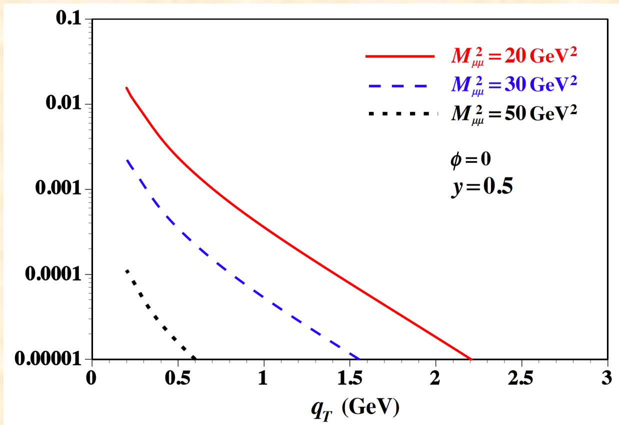
- Consider the Fermilab-E1039 experiment with the proton beam of $p = 120$ GeV
- No available $\Delta_T g$, so we may tentatively assume $\Delta_T g = \Delta g_p + \Delta g_n$, or $\dfrac{\Delta g_p + \Delta g_n}{2}$, $\dfrac{\Delta g_p + \Delta g_n}{4}$
- CTEQ14 for $q(x) + \bar{q}(x)$, NNPDFpol1.1 for $\Delta g(x)$

Dimuon mass squred ($M_{\mu\mu}^2 = Q^2$) dependence

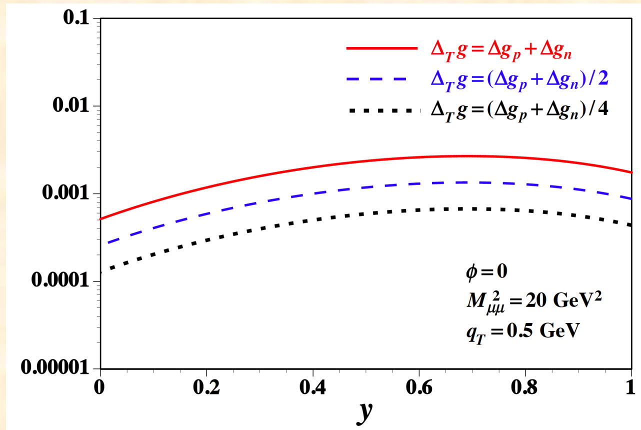
$\dfrac{d\sigma}{d\tau\, dq_T^2\, d\phi\, dy}$ (nb / GeV²)



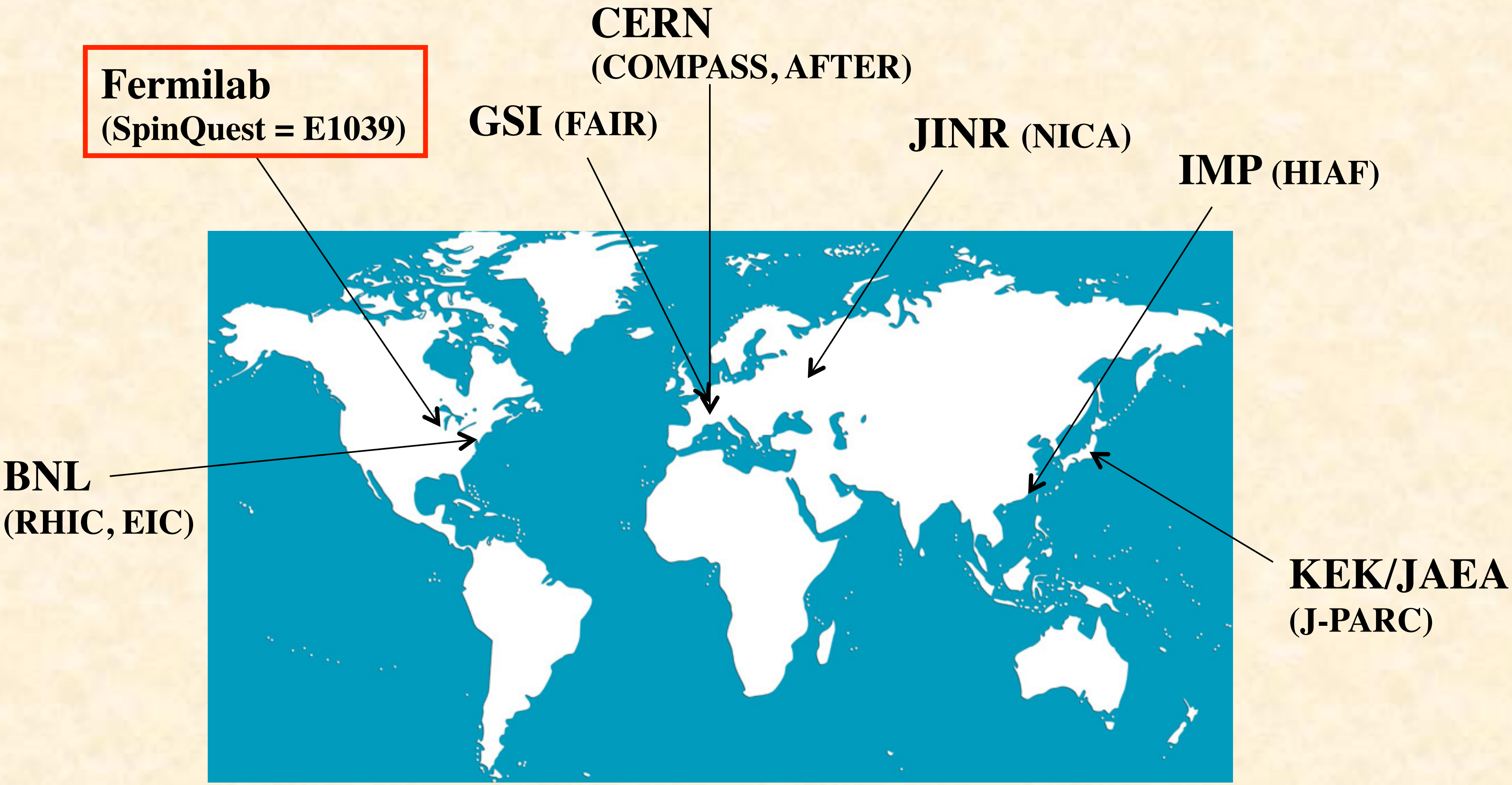
Dimuon transverse momentum (q_T) dependence



Dimuon c.m. rapididy (y) and assumed Δ_Tg dependencies



Possible hadron facilities for gluon transversity



Summary on transversity situation

- The quark-transversity distributions will be measured accurately in next 5-10 years by COMPASS, JLab-SoLID, and EIC projects.
- Accurate quark-transversity distributions can be used for EDM studies.
- There is no experiment and only a few theoretical papers on the gluon transversity $\Delta_T g$, which does not exist for spin-1/2 nucleons.
- Hadrons with spin $\geqq 1$ are needed, for example, the deuteron for $\Delta_T g$.
- There is a plan to measure $\Delta_T g$ at JLab in the early 2020's.

- We proposed to use hadron facilities for measuring $\Delta_T g$.
  In particular, we showed the theoretical formalism and cross sections for the proton-deuteron Drell-Yan process with $\Delta_T g$.
- It could be proposed within the Fermilab-E1039 experiment (D. Keller).
- Our formalism can be used at any other hadron facilities, COMPASS, RHIC (fixed), GSI-FAIR, J-PARC, NICA, LHC (fixed), EIC (fixed).
- $\Delta_T g \rightarrow$ "exotic" components in nuclei beyond bound states of nucleons.

EIC and future prospects

Electron-ion collider projects in the world

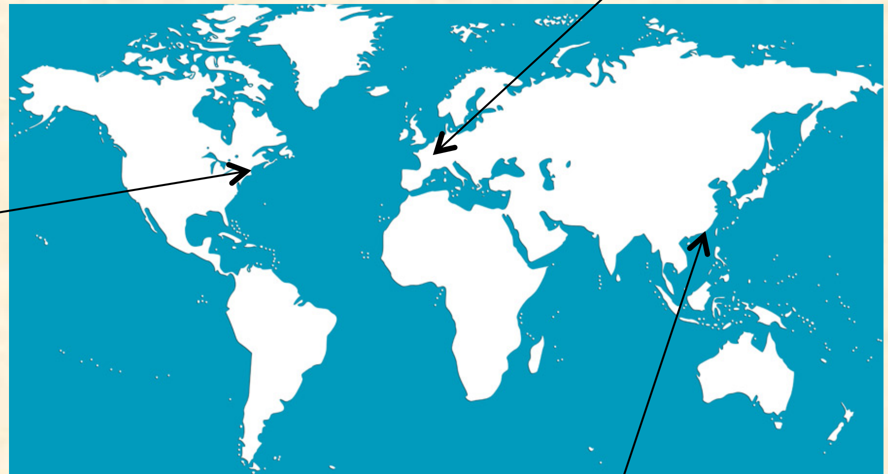
The EIC Science case: a report on the joint BNL/INT/JLab program

Gluons and the quark sea at high energies:
distributions, polarization, tomography

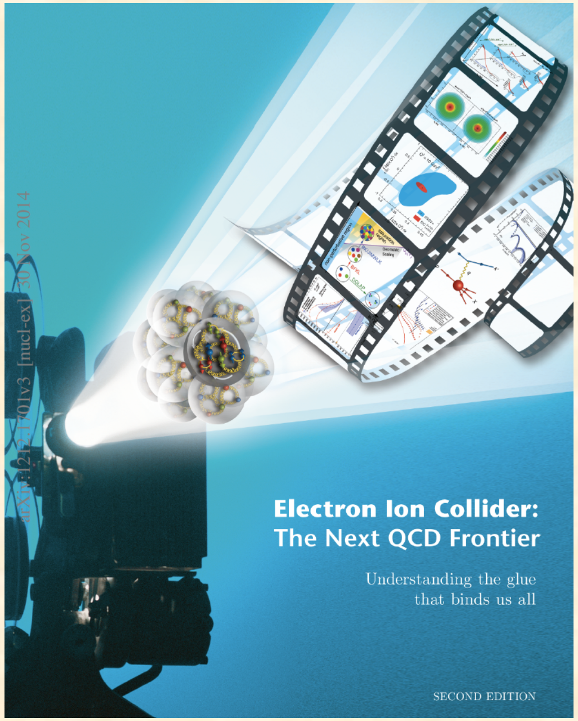
arXiv:1108.1713 (551 pages)

CERN

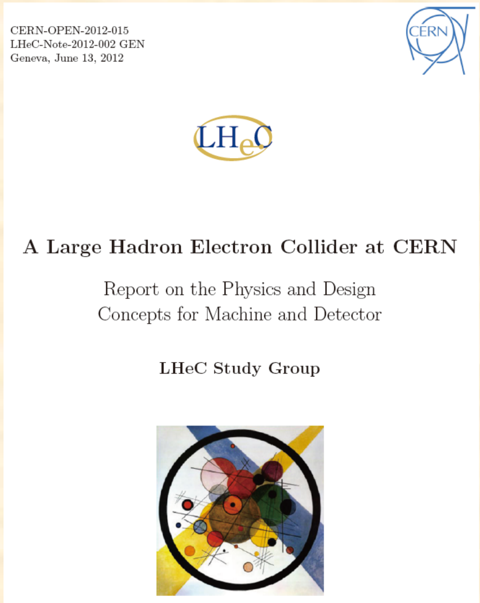
BNL



arXiv:1212.1701 (180 pages)



J. Phys. G: Nucl. Part. Phys.
39 (2012) 075001(632 pages)



CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

LHeC

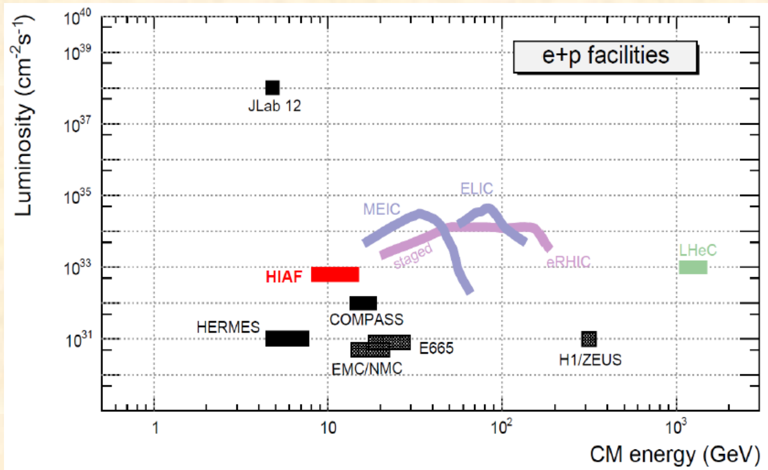
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

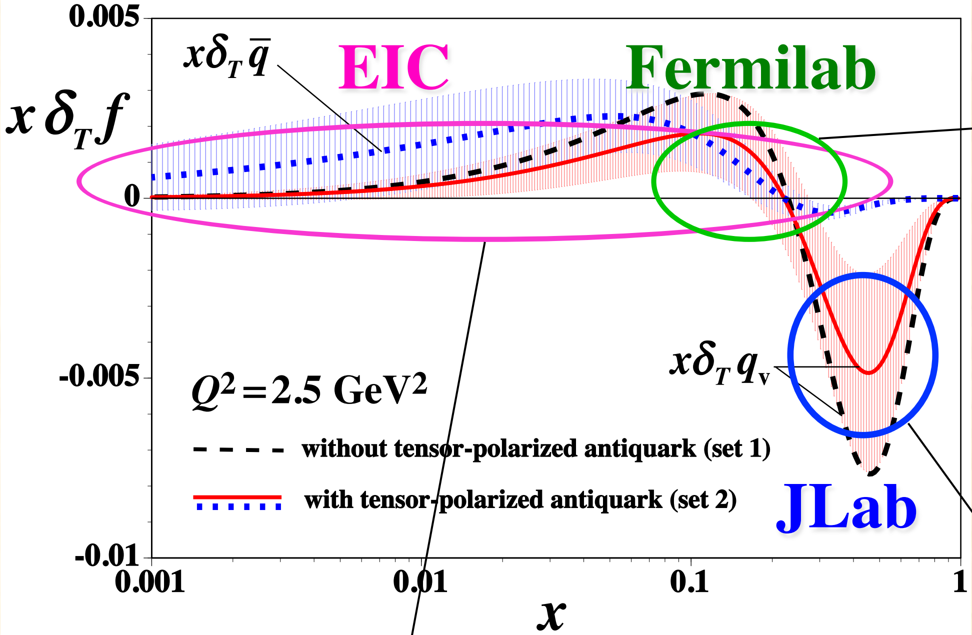
LHeC Study Group

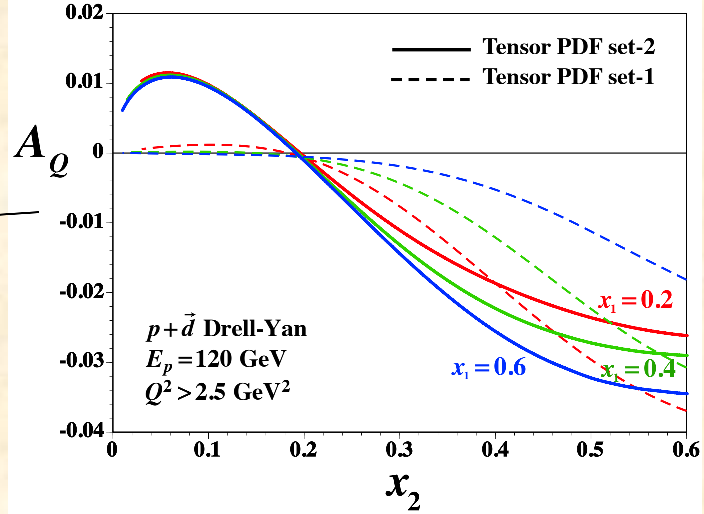
High Intensity Heavy Ion Accelerator Facility (HIAF)

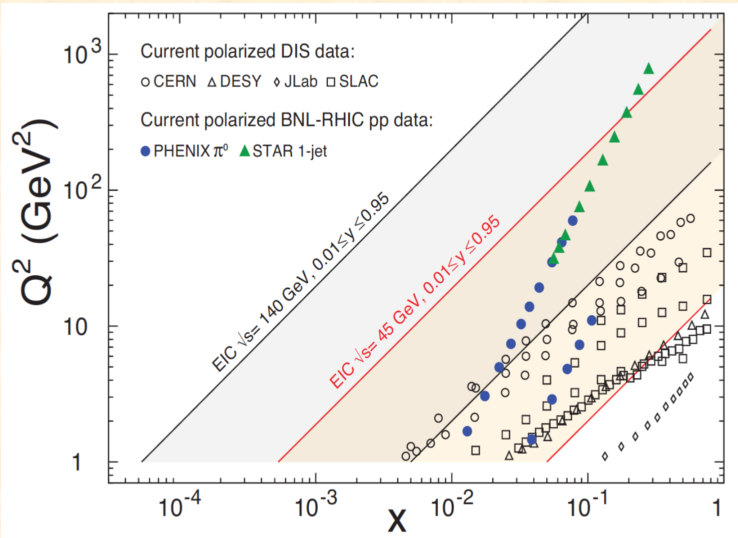
(Plan by Institute of Modern Physics, Chinese Academy of Sciences)

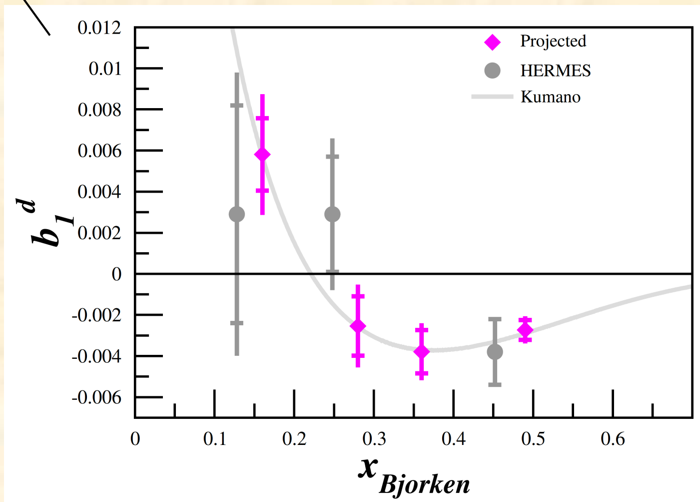


Small-x physics of b_1 at EIC



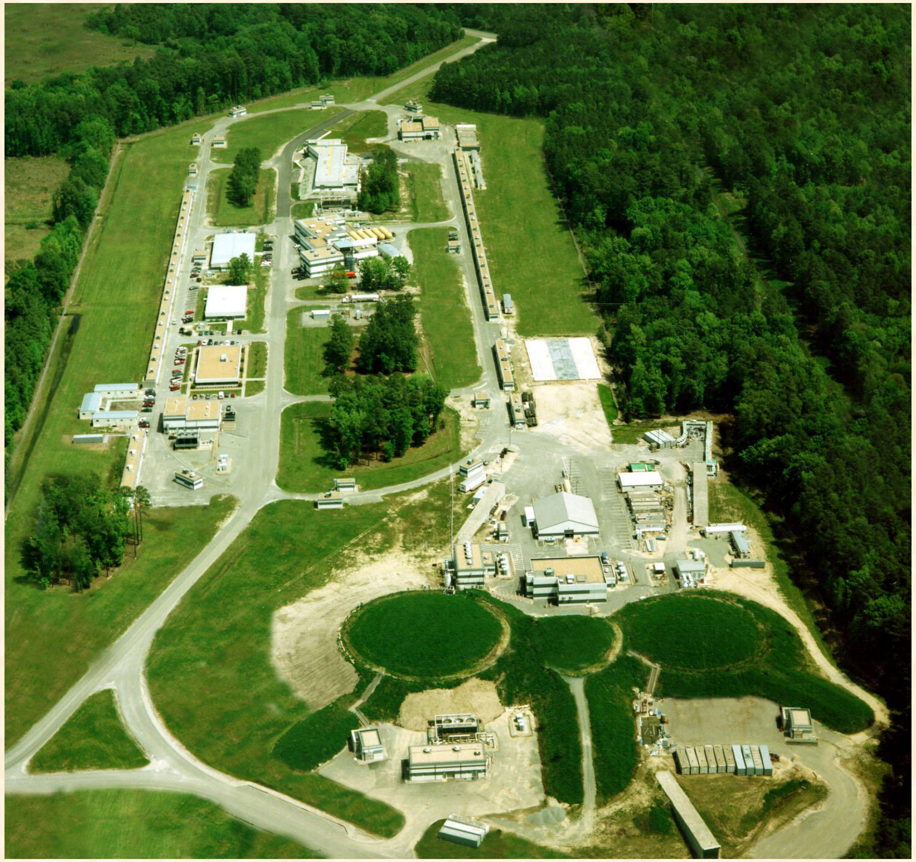






Letter of Intent at Jefferson Lab (exp. early 2020's)

Jefferson Lab,
Electron accelerator ~12 GeV



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LoI, arXiv:1803.11206

A Letter of Intent to Jefferson Lab PAC 44, June 6, 2016

Search for Exotic Gluonic States in the Nucleus

M. Jones, C. Keith, J. Maxwell*, D. Meekins

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

W. Detmold, R. Jaffe, R. Milner, P. Shanahan

Laboratory for Nuclear Science, MIT, Cambridge, MA 02139

D. Crabb, D. Day, D. Keller, O. A. Rondon

University of Virginia, Charlottesville, VA 22904

J. Pierce

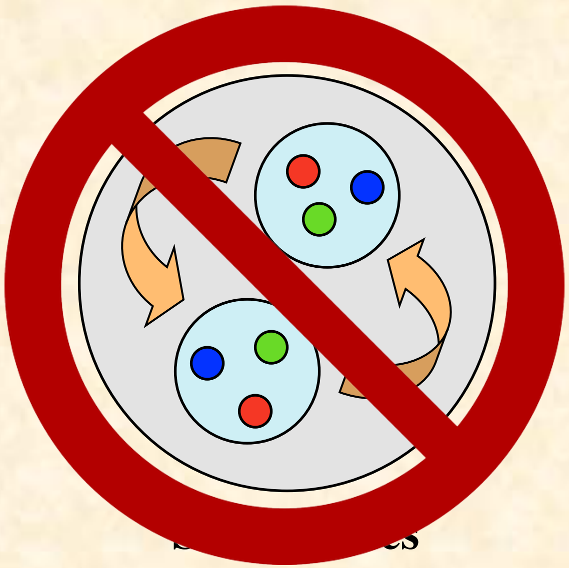
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Experiment is expected to start in the near future.

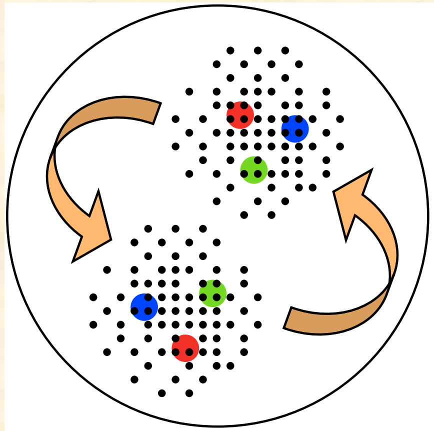
Summary

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: JLab (approved), Fermilab, ... , EIC, ILC, ...
- EIC → appropriate to study tensor-polarized antiquark distributions at small-x, Q^2 evolution of b_1 gluon transversity



standard model



? New exotic mechanisms in b_1 ($\delta_T q$, $\delta_T g$) and $\Delta_T g$

The End

The End