Structure functions of the spin-1 deuteron

From April 1, 2022

Shunzo Kumano

Japan Women's University

High Energy Accelerator Research Organization (KEK)

http://research.kek.jp/people/kumanos/

View of the Ikebukuro downtown from my JWU office

ECT* workshop on Tensor Spin Observables

(In-person and online) ECT*, Trento, Italy, July 10-14, 2023

https://indico.ectstar.eu/event/173/

July 10, 2023

Contents

1. Introduction

- Tensor-polarized structure function b_1, gluon transversity

2. b_1, gluon transversity, TMDs, PDFs, fragmentation functions, multiparton distribution functions of spin-1 hadrons

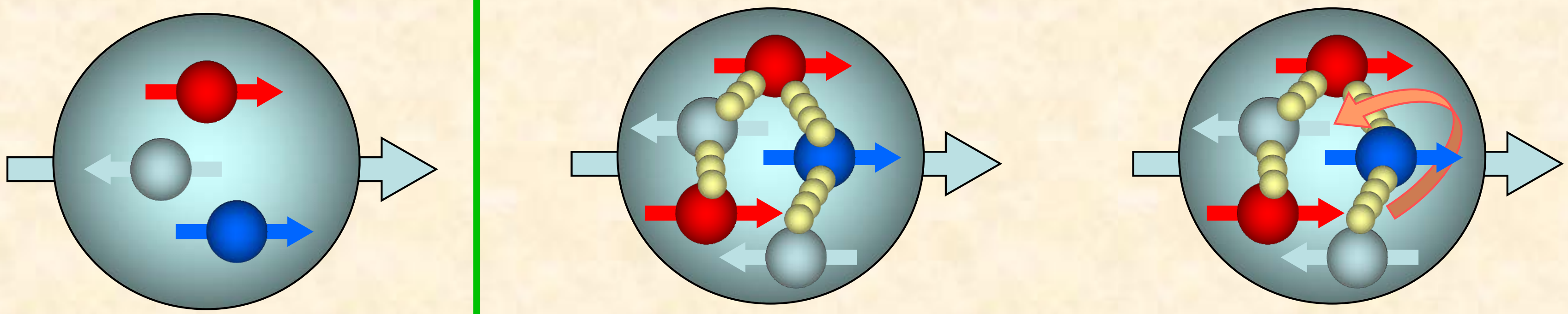
- b_1 by "standard" deuteron model [1]
- Tensor-polarized PDFs at hadron accelerator facilities (Drell-Yan) [2]
- Gluon transversity at hadron accelerator facilities (Drell-Yan) [3]
- TMDs and PDFs up to twist 4 [4]
- Twist-2 relation and sum rule for PDFs [5]
- Relations from equation of motion and a Lorentz-invariance relation [6]

3. Future prospects and summary

References [1] W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, PRD 95 (2017) 074036.
[2] SK and Qin-Tao Song, PRD 94 (2016) 054022.
[3] PRD 101 (2020) 054011 & 094013.
[4] PRD 103 (2021) 014025.
[5] JHEP 09 (2021) 141.
[6] PLB 826 (2022) 136908.

Nucleon spin

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

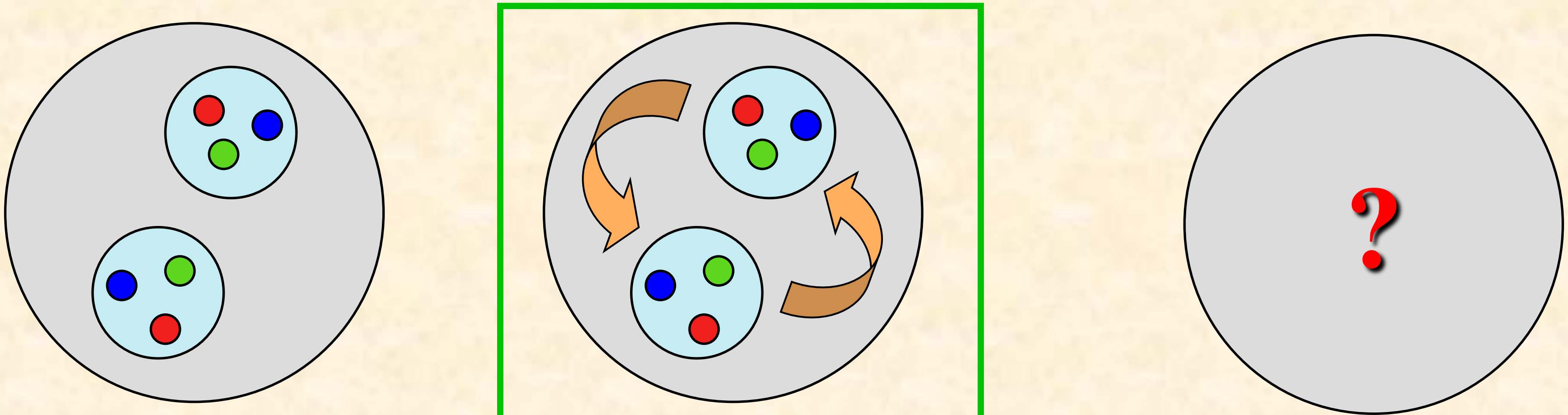


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure puzzle!?



only S wave
$b_1 = 0$

S + D waves

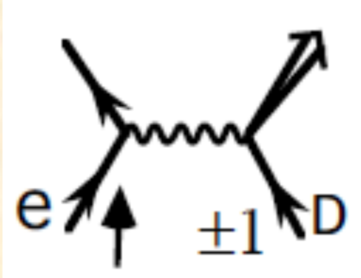
standard model $b_1 \neq 0$

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

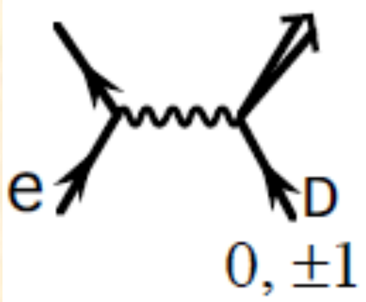
Structure Functions

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

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



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



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

Parton Model

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

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

$$\left[q_{\uparrow}^{H}\left(x,Q^2\right)\right]$$

$$b_1 = \frac{1}{2}\sum_i e_i^2 \left(\delta_T q_i + \delta_T \bar{q}_i\right) \qquad \delta_T q_i = q_i^{0} - \frac{q_i^{+1} + q_i^{-1}}{2}$$

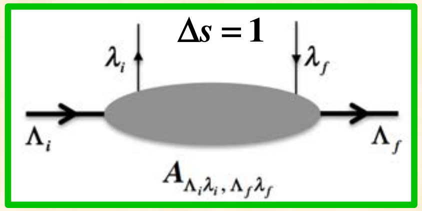
Gluon transversity $\Delta_T g$

Note on our notations:
Tensor-polarized gluon distribution: $\delta_T g$
Gluon transversity: $\Delta_T g$

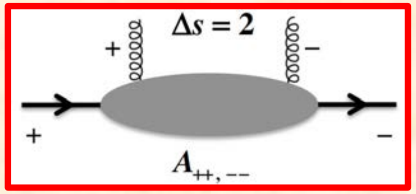
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

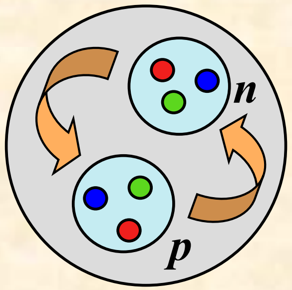
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2}, -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \to \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)



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



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



S + D waves

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

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

Physics beyond "the standard model" in nuclear physics?

(Physics beyond the standard model in particle physics???)

“Standard” deuteron model prediction for b_1

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.]

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

spin-1/2, spin-1

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

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.

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

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

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

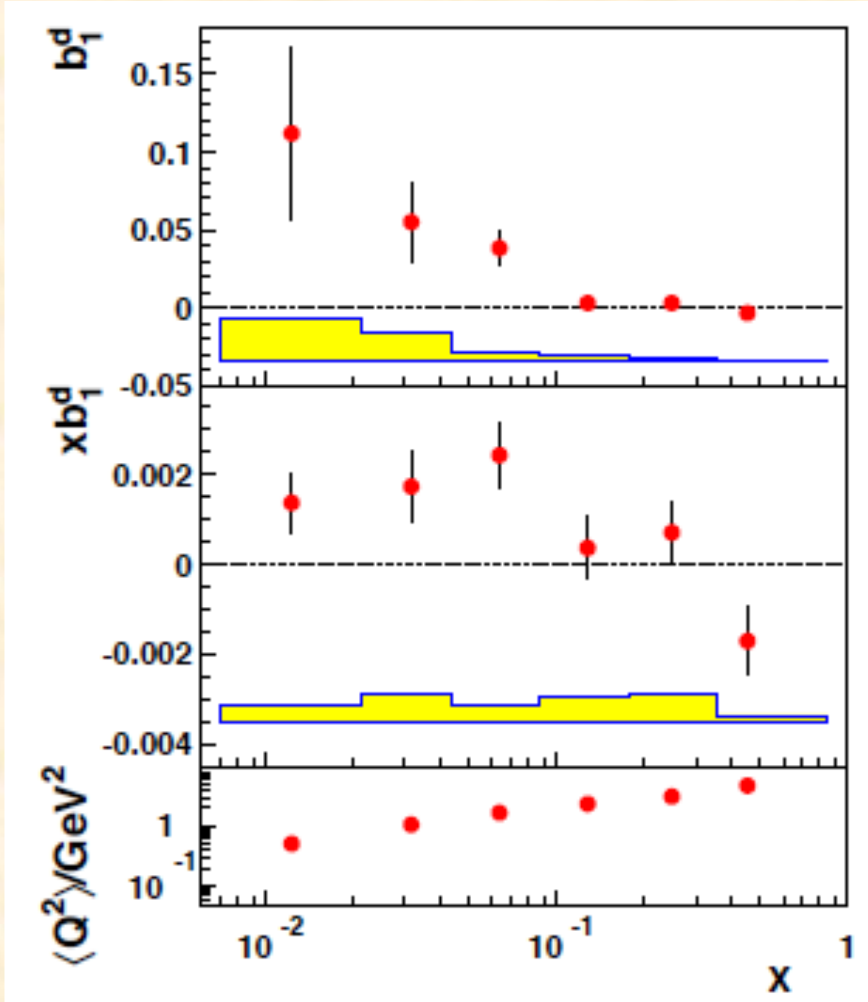
$$u_{\mu\nu} = \frac{1}{\nu}\left(E^*_\mu E_\nu + E^*_\nu E_\mu + \frac{2}{3} M^2 g_{\mu\nu} - \frac{2}{3} p_\mu p_\nu \right)$$

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

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

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**

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

b_1 **sum in the restricted** Q^2 **range** $Q^2 > 1$ **GeV**^{2}

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

at $Q^2 = 5$ **GeV**^{2}

$$\int dx\, b_1^D(x) = \lim_{t \to 0} -\frac{5}{24} \frac{t}{M^2} F_Q(t) + \sum_i e_i^2 \int dx\, \delta_T \bar{q}_i(x) = 0 \ ?$$

b_1 sum rule: F. E. Close and SK, PRD 42 (1990) 2377.

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

Drell-Yan experiments probe these antiquark distributions.

Theory 1: Basic convolution approach

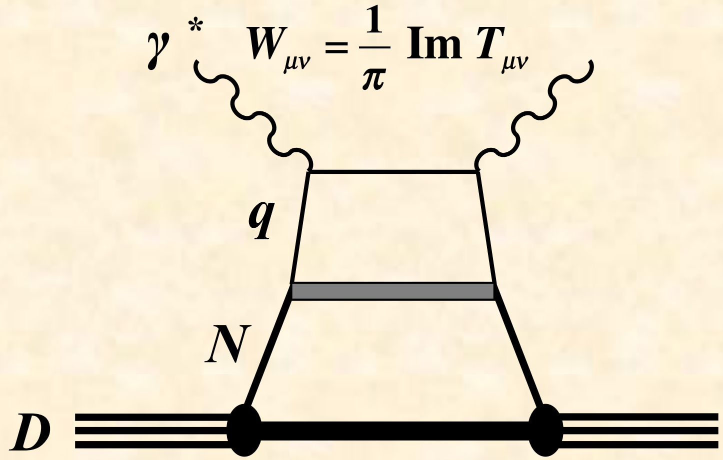
Convolution model: $A_{hH,\,hH}(x,Q^2)=\int \frac{dy}{y}\sum_s f_s^H(y)\hat{A}_{hs,hs}(x/y,\,Q^2)\equiv \sum_s f_s^H(y)\otimes \hat{A}_{hs,hs}(y,Q^2)$

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

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

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: $\phi^H(\vec{p})=\phi^H_{\ell=0}(\vec{p})+\phi^H_{\ell=2}(\vec{p})$

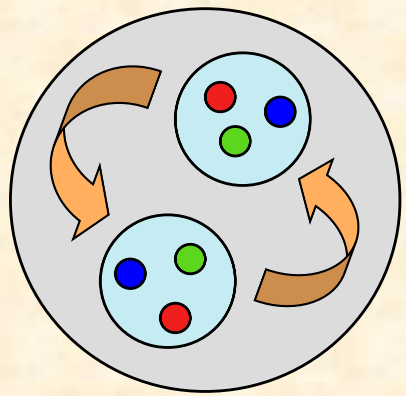
$\Downarrow$

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

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

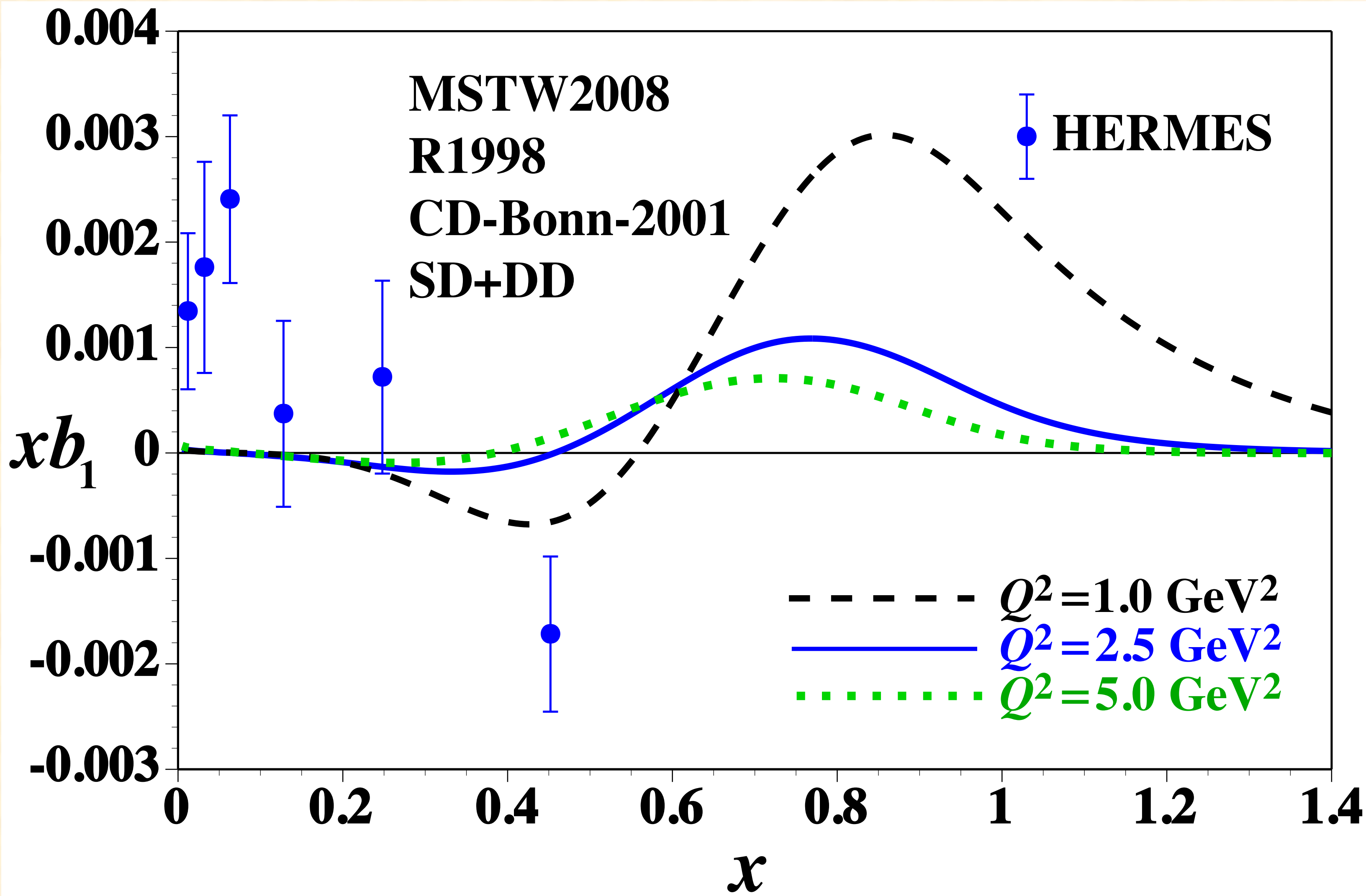
$$=\int d^3p\; y\left[-\frac{3}{4\sqrt{2}\pi}\phi_0(p)\phi_2(p)+\frac{3}{16\pi}|\phi_2(p)|^2\right](3\cos^2\theta-1)\delta\left(y-\frac{p\cdot q}{M_N\nu}\right)$$

Standard model of the deuteron



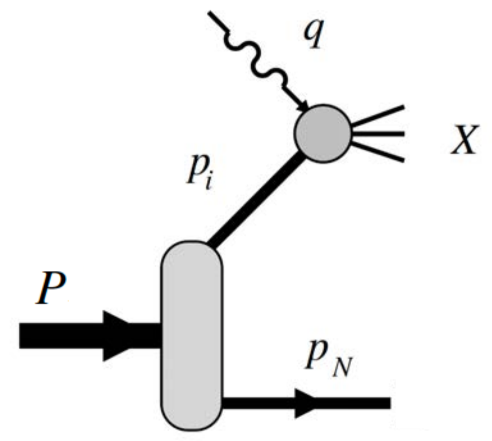
S + D waves

Comparison with HERMES measurements



Theory 2: Virtual nucleon approximation with higher-twist effects

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).
W. Cosyn and C. Weiss, Phys. Rev. C 102 (2020) 065204.



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):

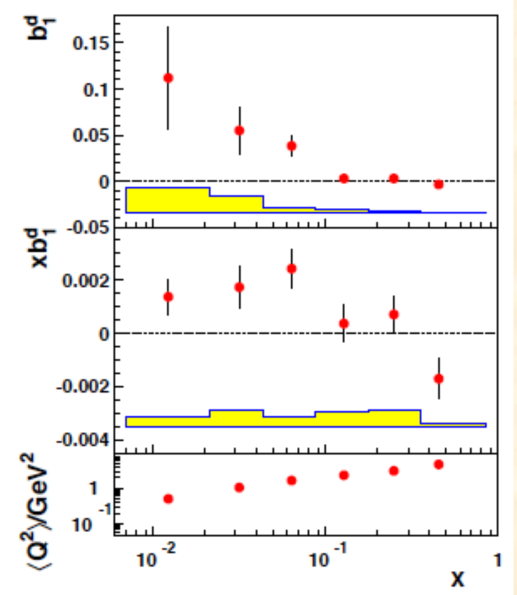
$$\alpha_i = \frac{2p_i^-}{P^-}, \quad \alpha_N = \frac{2p_N^-}{P^-} = 2-\alpha_i, \quad P = p_i + p_N$$

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

deuteron density: $\rho_D(\lambda',\lambda) = \sum_{\lambda_N,\lambda'_N} \dfrac{[\psi_{\lambda'}^{D}(\vec{k},\lambda'_N,\lambda_N)]^\dagger \psi_{\lambda'}^{D}(\vec{k},\lambda'_N,\lambda_N)}{\alpha_N \alpha_i}$

Virtual nucleon approximation and high-twist effects

x	Q^2 (GeV^2)	$b_1(10^{-4})$	$b_2(10^{-5})$	$b_3(10^{-3})$	$b_4(10^{-3})$
0.012	0.51	2.81	0.264	−1.34	5.06
0.032	1.06	6.92	1.97	−1.87	7.51
0.063	1.65	3.50	0.265	−2.02	7.96
0.128	2.33	−1.80	−7.38	−2.13	7.49
0.248	3.11	−8.39	−28.1	−2.09	4.58
0.452	4.69	−6.18	−21.7	−1.11	−0.58



Higher-twist effects are not so small in the HERMES kinematical region of Q^2.

Tensor spin asymmetry A_{zz}

$$A_{zz} = \frac{2(\sigma^+ - \sigma^0)}{2\sigma^+ + \sigma^0} = \frac{\sqrt{2}}{4\sqrt{3}(F_{UU,T} + \varepsilon F_{UU,L})} \{ [1 + 3\cos(2\theta_q)](F_{UT_{LL},T} + \varepsilon F_{UT_{LL},L})$$

$$+ 3\sin(2\theta_q)\sqrt{2\varepsilon(1+\varepsilon)}\, F_{UT_{LT}}^{\cos\phi_{T\parallel}} + 3\,[1 - \cos(2\theta_q)]\, \varepsilon F_{UT_{TT}}^{\cos 2\phi_{T\perp}} \}$$

HERMES analysis: Only leading-twist b_1 and b_2, Callen-Gross relation for $b_2 = 2x_D b_1$.

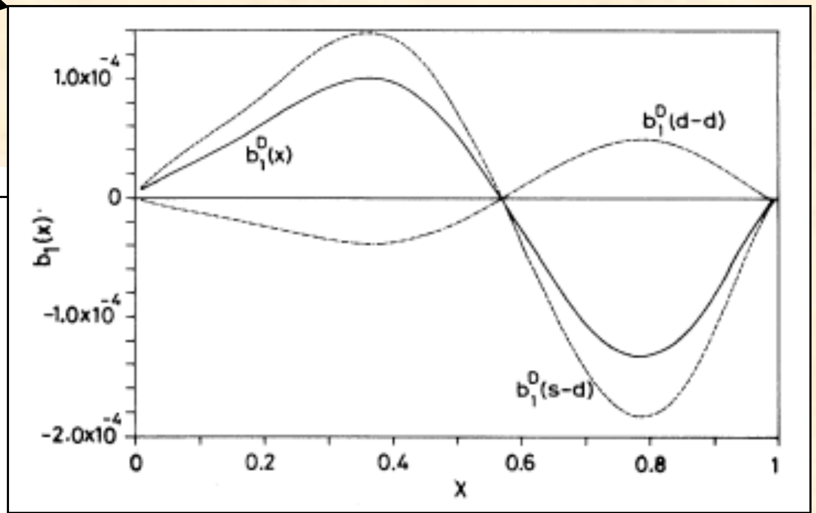
$$F_{UT_{LL},T} = -\frac{2\sqrt{2}}{\sqrt{3}} b_1, \quad F_{UU,T} = 2F_1, \quad F_{UU,L} = F_{UT_{LL},L}$$

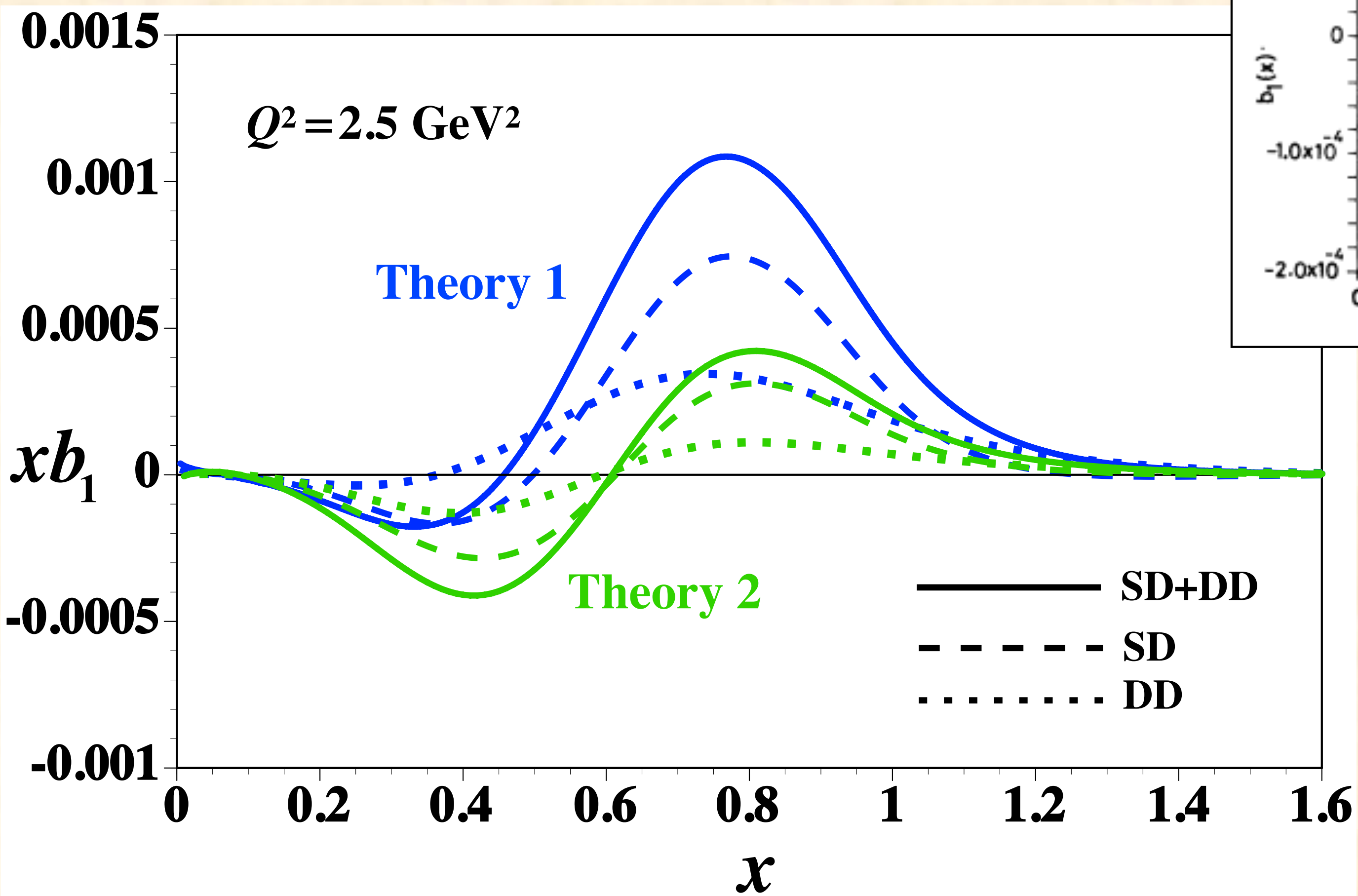
We need to be careful about higher-twist effects.

Results on b_1 in the convolution description

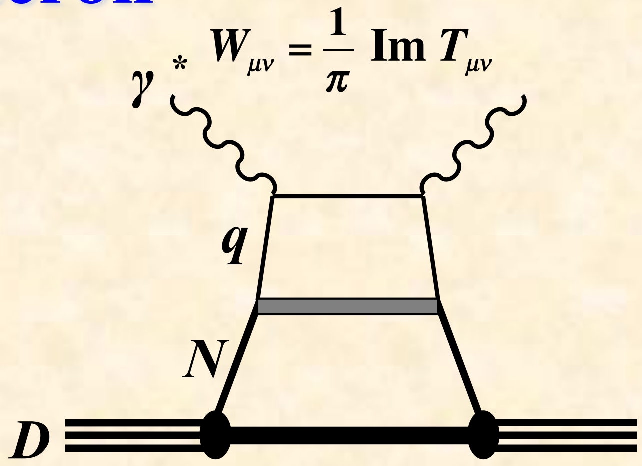
Very different from
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.
H. Khan and P. Hoodbhoy, PRC44 (1991) 1219;

(1) SD term is opposite,
(2) $b_1(x)$ exists even at $x > 1$,
(3) $|b_1(\text{CDKS})| = 10^{-3} \gg |b_1(\text{KH})| = 10^{-4}$.





"Standard-model" prediction for b_1 of deuteron



Standard model of the deuteron

$$b_1(x) = \int \frac{dy}{y} \delta_T f(y) F_1^N(x/y, Q^2), \quad y = \frac{M p \cdot q}{M_N P \cdot q} \simeq \frac{2p^-}{P^-}$$

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

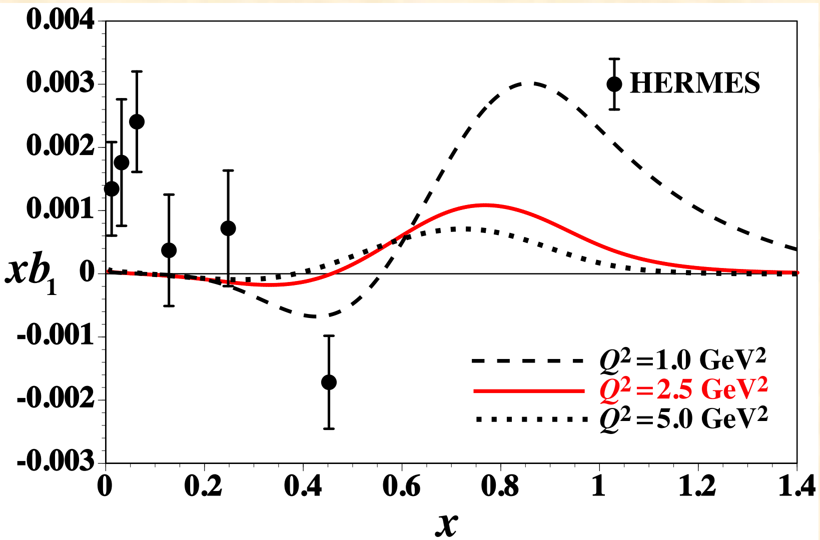
$$= \int d^3p \, y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p)\phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] (3\cos^2\theta - 1) \delta\left(y - \frac{p \cdot q}{M_N \nu} \right)$$

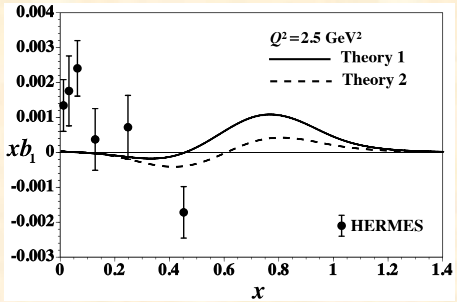
S-D term   D-D term

Nucleon momentum distribution:

$$f^H(y) \equiv f^H_\uparrow(y) + f^H_\downarrow(y) = \int d^3p \, y \, |\phi^H(\vec{p})|^2 \delta\left(y - \frac{E - p_z}{M_N} \right)$$

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

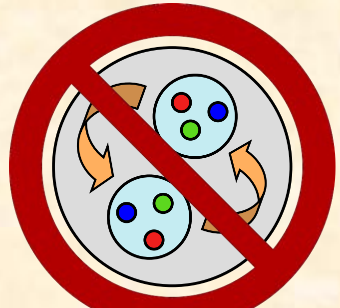


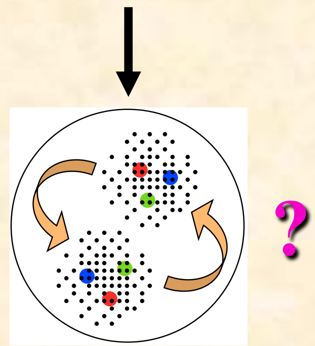


W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, Phys. Rev. D 95 (2017) 074036.

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

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





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

Interesting suggestions:
hidden-color, 6-quark, · · ·

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

Tensor-polarized PDFs at hadron accelerator facilities (*e.g.* Fermilab)

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

M. Hino and SK,
PRD 59 (1999) 094026;
60 (1999) 054018.

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

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

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

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

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

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

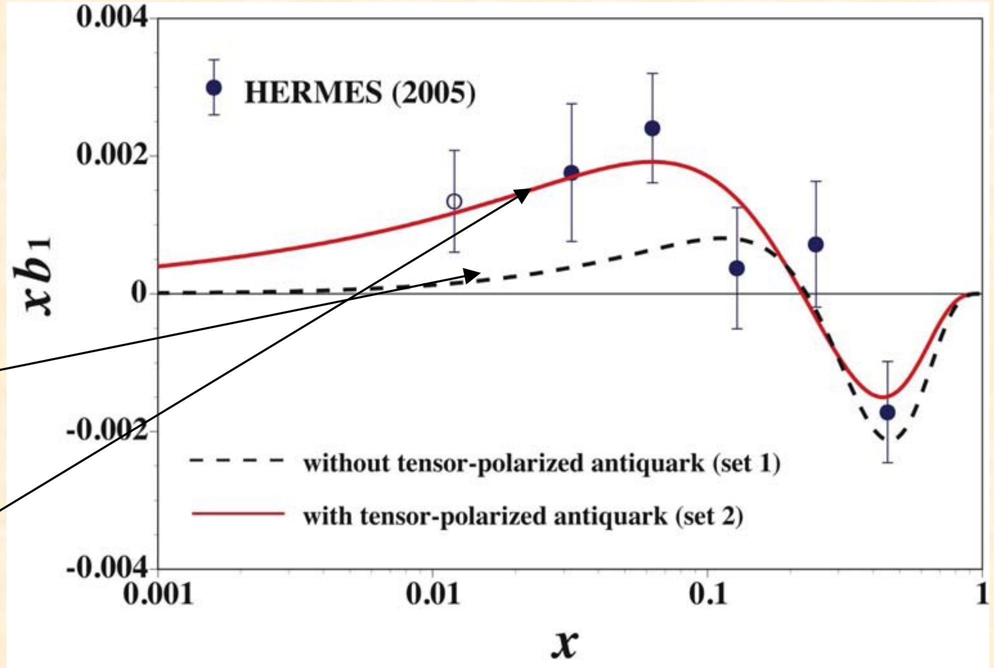
Note: $\delta \neq$ transversity in my notation

Tensor-polarized PDFs

SK, PRD 82 (2010) 017501.

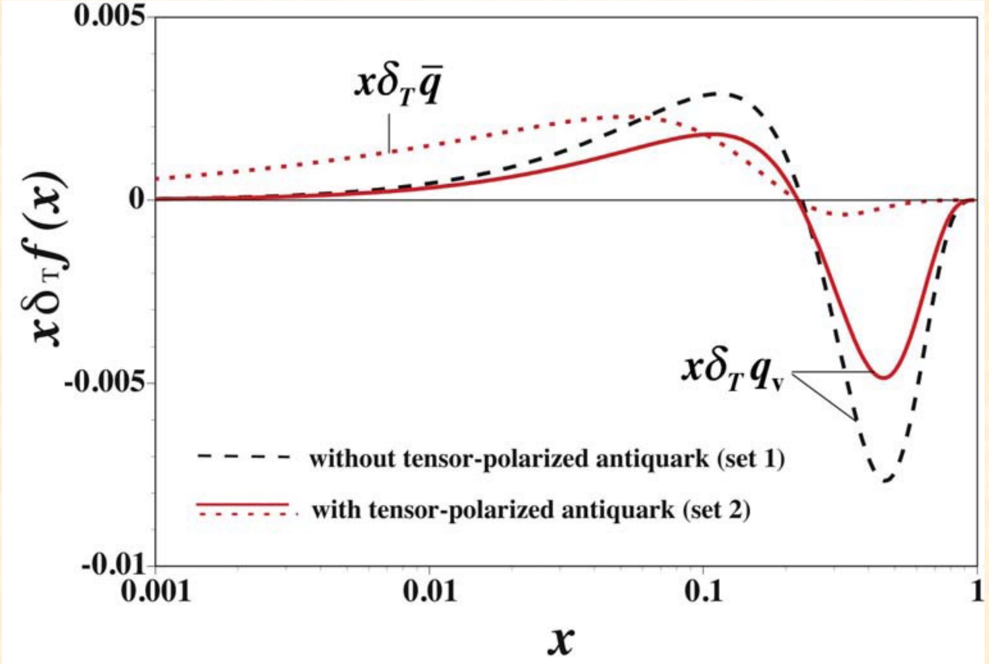
Two-types of fit results:

- set-1 ($\delta_T \bar{q} = 0$): χ^2 / d.o.f. = 2.83
  Without $\delta_T \bar{q}$, the fit is not good enough.
- set-2 ($\delta_T \bar{q} \neq 0$): χ^2 / d.o.f. = 1.57
  With finite $\delta_T \bar{q}$, the fit is reasonably good.



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

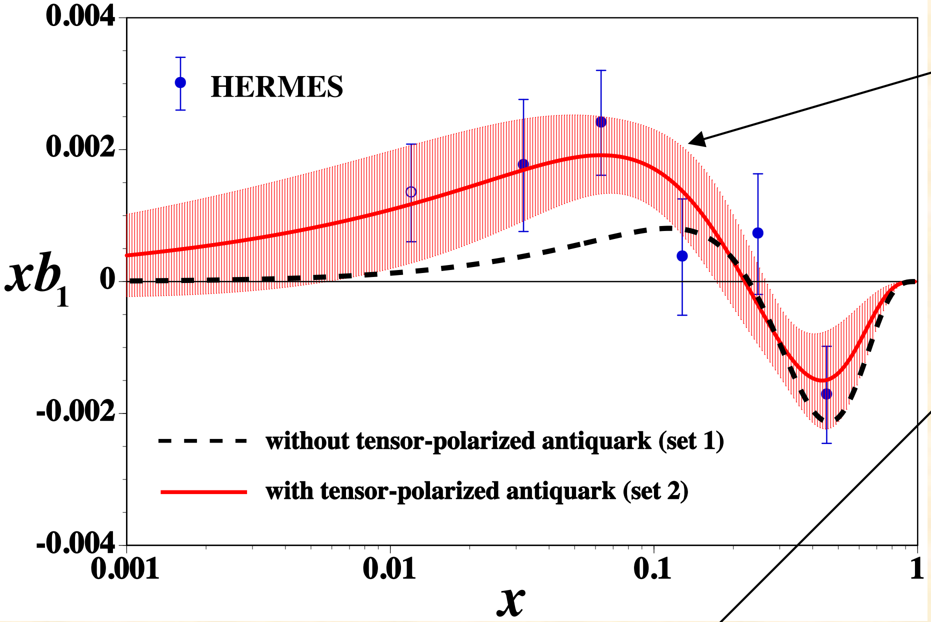
→ They could be used for
- experimental proposals,
- comparison with theoretical models.



Finite tensor polarization for antiquarks:

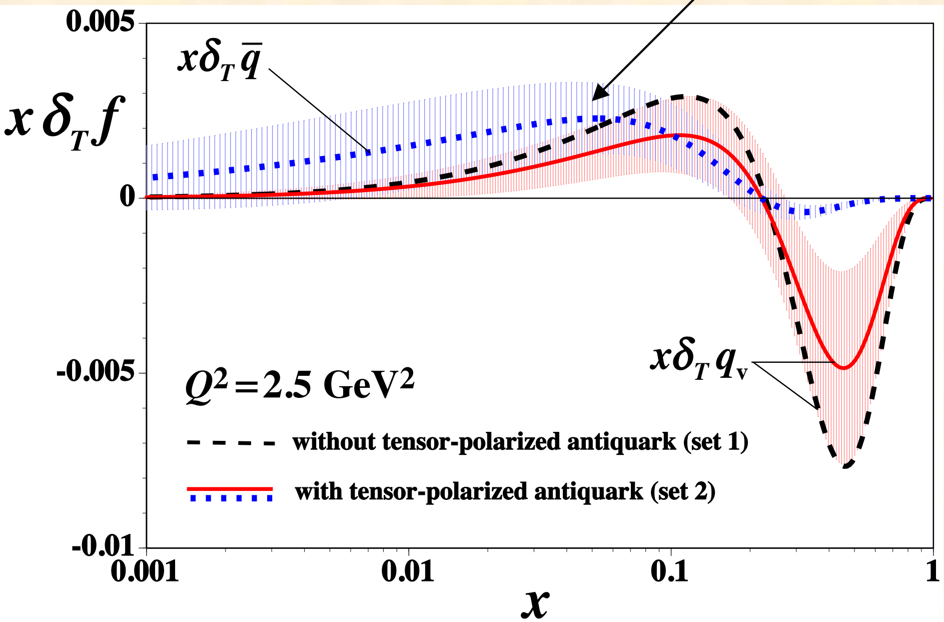
$$\int_0^1 dx b_1(x) = 0.058$$
$$= \frac{1}{9}\int_0^1 dx \left[4\delta_T \bar{u}(x) + \delta_T \bar{d}(x) + \delta_T \bar{s}(x) \right]$$

Tensor-polarized PDFs with errors



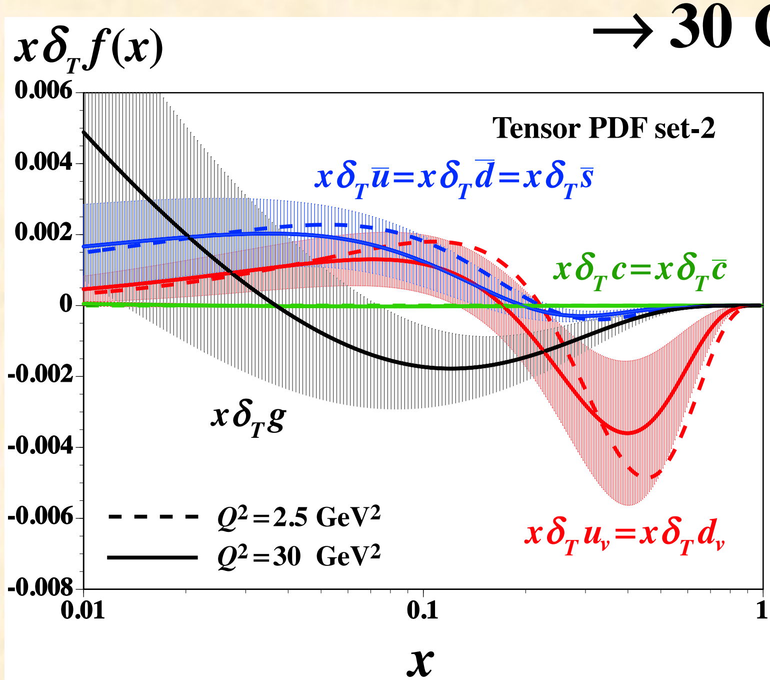
still large errors, need experimental improvement
→ JLab, EIC, ...

experimental measurement for antiquark distributions
→ Fermilab, ...



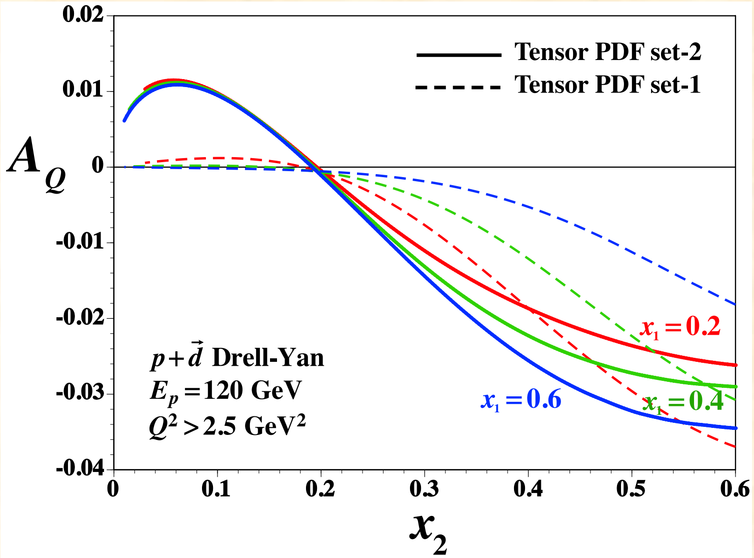
Q^2 evolution

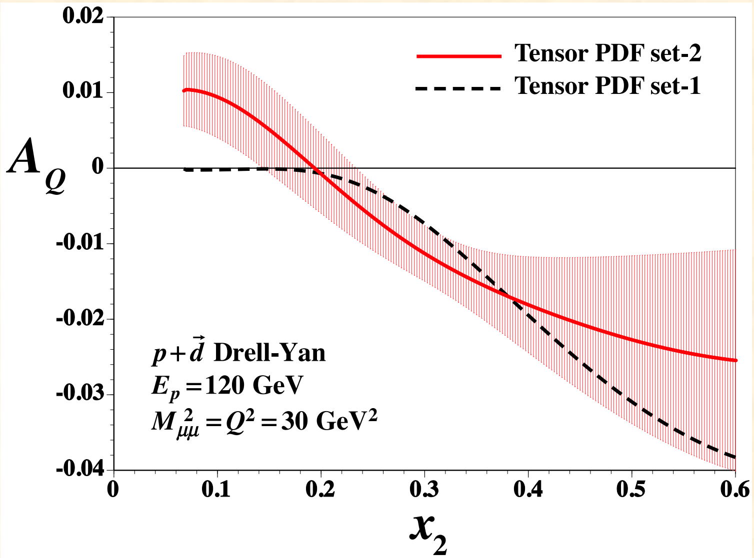
$Q^2 = 2.5$ GeV^2 → 30 GeV^2



Tensor-polarized spin asymmetry at Fermilab

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





Polarized fixed-target experiments at the Main Injector

E1039-SpinQuest

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

SK and Qin-Tao Song, PRD 94 (2016) 054022.

Gluon transversity at hadron accelerator facilities (*e.g.* Fermilab)

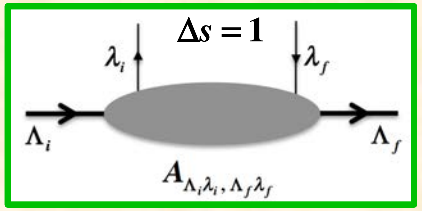
Gluon transversity $\Delta_T g$

Note on our notations:
Tensor-polarized gluon distribution: $\delta_T g$
Gluon transversity: $\Delta_T g$

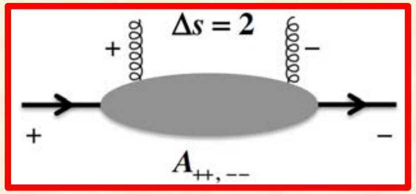
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

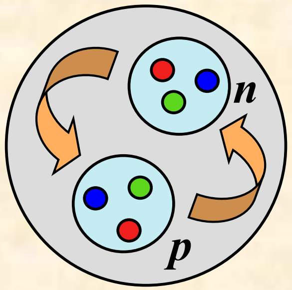
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \rightarrow \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)



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



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



S + D waves

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

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

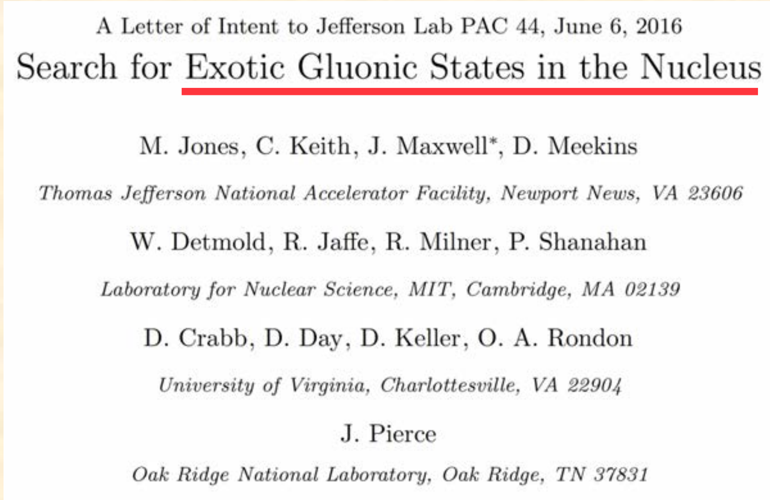
Physics beyond "the standard model" in nuclear physics?

(Physics beyond the standard model in particle physics???)

Letter of Intent at Jefferson Lab (middle 2020's)

Jefferson Lab,
Electron accelerator ~12 GeV

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

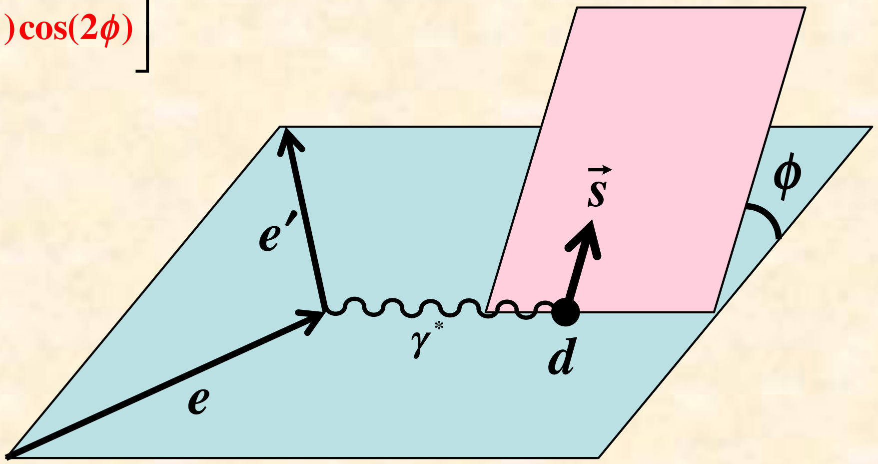
For development of polarized deuteron target,
see D. Keller, D. Crabb, D. Day
Nucl. Inst. Meth. Phys. Res. A981 (2020) 164504.

Electron scattering with polarized-deuteron 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 deuteron-polarization angle ϕ,
the quark transversty $\Delta_T g$ can be measured.



Lattice QCD estimates:
W. Detmold and P. E. Shanahan,
PRD 94 (2016) 014507; 95 (2017) 079902.

Our motivation by considering the JLab experiment

We proposed 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 (namely a leading effect).
- 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 our PRD 101 (2020) 054011 & 094013 , we proposed proton-deuteron Drell-Yan process by considering the Fermilab-E1039.

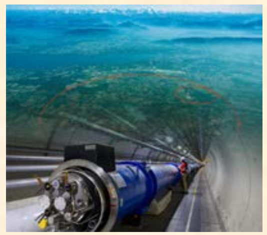
However, our formalism is valided for Drell-Yan experiments at any other facilities.

Fermilab-MI

NICA

GSI-FAIR

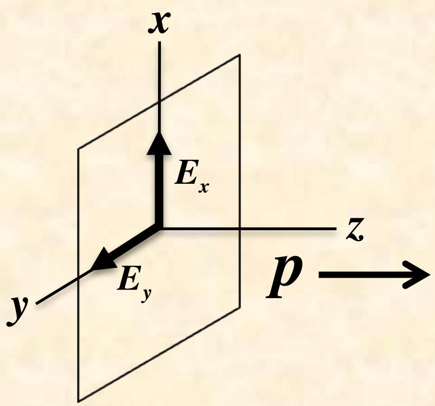
J-PARC



LHC (fixed target)
COMPASS/AMBER

EIC
/EicC

Gluon transversity distribution in deuteron



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

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

$$= g_{\hat{x}/\hat{x}} - g_{\hat{y}/\hat{x}}$$

$g_{\hat{y}/\hat{x}}$ = gluon distribution with the gluon linear polarization ε_y in the deuteron linear polarization E_x

Polarization vectors $\vec{E}_x = \vec{\varepsilon}_x = (1,\ 0,\ 0)$, $\vec{E}_y = \vec{\varepsilon}_y = (0,\ 1,\ 0)$

Spin and tensor of the deuteron

$$S^\mu = \frac{1}{M}\varepsilon^{\mu\nu\alpha\beta} p_\nu \,\mathrm{Im}(E^*_\alpha E_\beta), \quad T^{\mu\nu} = -\frac{1}{3}\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right) - \mathrm{Re}(E^{\mu *} E^\nu)$$

$$E^\mu = (0,\ \vec{E}), \quad \vec{E}_\pm = \frac{1}{\sqrt{2}}(\mp 1,\ -i,\ 0), \quad \vec{E}_0 = (0,\ 0,\ 1)$$

- $\vec{E}_+, \vec{E}_0, \vec{E}_-$: Spin states with z-components of spin $s_z = +1,\ 0,\ -1$
- $\vec{E}_x = (1,\ 0,\ 0)$, $\vec{E}_y = (0,\ 1,\ 0)$: Linear polarizations
  → to measure gluon transversity

(1) Prepare $s_x = 0$ [$\vec{E}_x = (1,\ 0,\ 0)$] by taking the quantization axis x and $s_y = 0$ [$\vec{E}_y = (0,\ 1,\ 0)$] by taking the quantization axis y.

(2) Combination of transverse polarizations.

$$\boldsymbol{S} = (S_T^x,\ S_T^y,\ S_L),$$

$$\boldsymbol{T} = \frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL} + S_{TT}^{xx} & S_{TT}^{xy} & S_{LT}^x \\ S_{TT}^{xy} & -\frac{2}{3}S_{LL} - S_{TT}^{xx} & S_{LT}^y \\ S_{LT}^x & S_{LT}^y & \frac{4}{3}S_{LL} \end{pmatrix}$$

$$S_{TT}^{xy} = S_{LT}^x = S_{LT}^y = 0$$

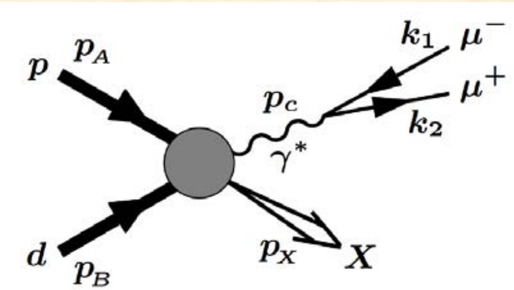
Polarizations	$\vec{E}$	S_T^x	S_T^y	S_L	S_{LL}	S_{TT}^{xx}
Longitudinal $+z$	$\frac{1}{\sqrt{2}}(-1,\ -i,\ 0)$	0	0	+1	$+\frac{1}{2}$	0
Longitudinal $-z$	$\frac{1}{\sqrt{2}}(+1,\ -i,\ 0)$	0	0	−1	$+\frac{1}{2}$	0
Transverse $+x$	$\frac{1}{\sqrt{2}}(0,\ -1,\ -i)$	+1	0	0	$-\frac{1}{4}$	$+\frac{1}{2}$
Transverse $-x$	$\frac{1}{\sqrt{2}}(0,\ +1,\ -i)$	−1	0	0	$-\frac{1}{4}$	$+\frac{1}{2}$
Transverse $+y$	$\frac{1}{\sqrt{2}}(-i,\ 0,\ -1)$	0	+1	0	$-\frac{1}{4}$	$-\frac{1}{2}$
Transverse $-y$	$\frac{1}{\sqrt{2}}(-i,\ 0,\ +1)$	0	−1	0	$-\frac{1}{4}$	$-\frac{1}{2}$
Linear x	(1, 0, 0)	0	0	0	$+\frac{1}{2}$	−1
Linear y	(0, 1, 0)	0	0	0	$+\frac{1}{2}$	+1

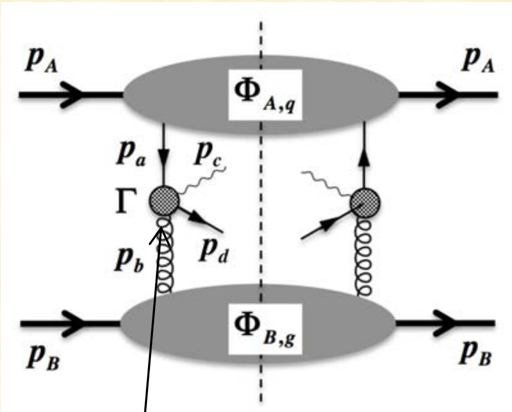
Transverse polarization

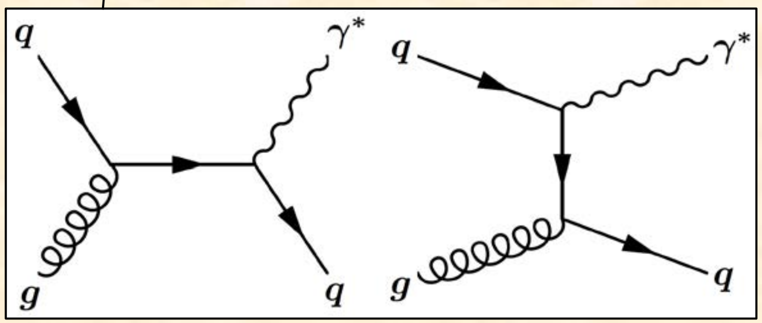
Linear polarization

SK and Qin-Tao Song,
PRD 101 (2020) 054011 & 094013.

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).

$$\Phi_{q/A}(x_a) = \frac{1}{2}\left[\bar{n}\!\!\!/ f_{1,q/A}(x_a) + \gamma_5 \bar{n}\!\!\!/ S_{A,L} g_{1,q/A}(x_a) + \bar{n}\!\!\!/ \gamma_5 S\!\!\!/_{A\perp} h_{1,q/A}(x_a)\right]$$

$$\Phi_{q/B}(x_b) = \frac{1}{2}\left[n\!\!\!/ f_{1,q/B}(x_b) + \gamma^5 n\!\!\!/\, S_{B,L}\, g_{1,q/B}(x_b) + i\sigma_{\mu\nu}\gamma^5 n^{\mu} S^{\nu}_{B,T} h_{1,q/B}(x_b) + n\!\!\!/\, S_{LL}\, f_{1LL,q/B}(x_b) + \sigma_{\mu\nu} n^{\nu} S^{\mu}_{B,LT} h_{1LT,q/B}(x_b)\right]$$

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

Gluon transversity: $\Delta_T g = h_{1TT,g}$
(Sorry to use two differenent notations in a talk.)

Proton-deuteron Drell-Yan cross section

SK and Qin-Tao Song,
PRD 101 (2020) 054011 & 094013.

Drell-Yan cross section

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

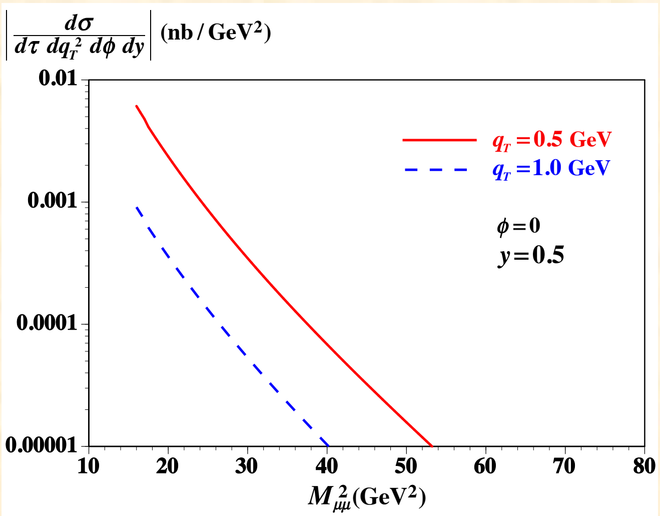
$$C_F=\frac{N_c^2-1}{2N_c},\quad \min(x_a)=\frac{x_1-\tau}{1-x_2},\quad x_b=\frac{x_a x_2-\tau}{x_a-\tau}$$

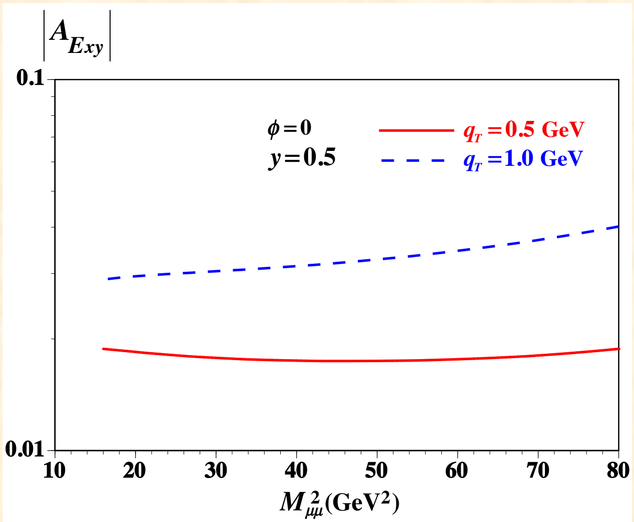
= (unpolarized PDFs of proton) * (gluon transversity distribution in the deuteron)

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

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

Spin asymmetry: $A_{E_{xy}}=\dfrac{\frac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_x)-\frac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_y)}{\frac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_x)+\frac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_y)}$





New proposal
at Fermilab-PAC (2023, D. Keller)

TMDs and PDFs for spin-1 hadrons up to twist 4

Note: Higher-twist effects are sizable at a few GeV^2 Q^2 in tensor-polarized structure functions,
W. Cosyn, Yu-Bing Dong, SK, M. Sargsian,
PRD 95 (2017) 074036.

TMD correlation functions for spin-1 hadrons

Correlation functions

$$\Phi_{ij}(k,P,T) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \left\langle P,T \left| \bar{\psi}_j(0) W(0,\xi) \psi_i(\xi) \right| P,T \right\rangle$$

$$W(0,\xi) = P \exp\left[-ig\int_0^\xi d\xi \cdot A(\xi)\right]$$

Spin vector: $S^\mu = S_L \frac{P^+}{M}\bar{n}^\mu - S_L \frac{M}{2P^+} n^\mu + S_T^\mu$

Tensor: $T^{\mu\nu} = \frac{1}{2}\left[\frac{4}{3} S_{LL} \frac{(P^+)^2}{M^2}\bar{n}^\mu \bar{n}^\nu + \frac{P^+}{M}\bar{n}^{\{\mu} S_{LT}^{\nu\}} - \frac{2}{3} S_{LL}\left(\bar{n}^{\{\mu} n^{\nu\}} - g_T^{\mu\nu}\right) + S_{TT}^{\mu\nu} - \frac{M}{2P^+} n^{\{\mu} S_{LT}^{\nu\}} + \frac{1}{3} S_{LL}\frac{M^2}{(P^+)^2} n^\mu n^\nu\right]$

Tensor part (twist-2): Bacchetta, Mulders, PRD 62 (2000) 114004

$$\Phi(k,P,T) = \left(\frac{A_{13}}{M} I + \frac{A_{14}}{M^2} \not{P} + \frac{A_{15}}{M^2}\not{k} + \frac{A_{16}}{M^3}\sigma_{\rho\sigma}P^\rho k^\sigma\right) k_\mu k_\nu T^{\mu\nu} + \left[A_{17}\gamma_\nu + \left(\frac{A_{18}}{M}P^\rho + \frac{A_{19}}{M}k^\rho\right)\sigma_{\nu\rho} + \frac{A_{20}}{M^2}\varepsilon_{\tau\nu\rho\sigma}P^\rho k^\sigma \gamma^\tau\gamma_5\right] k_\mu T^{\mu\nu}$$

Tensor part (twist-2, 3, 4): n^μ dependent terms are added for up to twist 4.

[For the spin-1/2 nucleon: Goeke, Metzand, Schlegel, PLB 618 (2005) ,90; Metz, Schweitzer, Teckentrup, PLB 680 (2009) 141.]

Kumano-Song-2021, for the details see PRD 103 (2021) 014025

Bacchetta -Mulders (2000):

$$\Phi(k,P,T\,|\,n) = \left(\frac{A_{13}}{M} I + \frac{A_{14}}{M^2} \not{P} + \frac{A_{15}}{M^2}\not{k} + \frac{A_{16}}{M^3}\sigma_{\rho\sigma}P^\rho k^\sigma\right) k_\mu k_\nu T^{\mu\nu} + \left[A_{17}\gamma_\nu + \left(\frac{A_{18}}{M}P^\rho + \frac{A_{19}}{M}k^\rho\right)\sigma_{\nu\rho} + \frac{A_{20}}{M^2}\varepsilon_{\tau\nu\rho\sigma}P^\rho k^\sigma \gamma^\tau\gamma_5\right] k_\mu T^{\mu\nu}$$

New terms in our paper (2021):

$$+\left(\frac{B_{21}M}{P\cdot n}k_\mu + \frac{B_{22}M^3}{(P\cdot n)^2}n_\mu\right) n_\nu T^{\mu\nu} + i\gamma_5 \varepsilon_{\mu\tau\rho\sigma}P^\rho\left(\frac{B_{23}}{(P\cdot n)M}k^\tau n^\sigma k_\nu + \frac{B_{24}M}{(P\cdot n)^2}k^\tau n^\sigma n_\nu\right) T^{\mu\nu}$$

$$+\left[\frac{B_{25}}{P\cdot n}\not{n} k_\mu k_\nu + \left(\frac{B_{26}M^2}{(P\cdot n)^2}\not{n} + \frac{B_{28}}{P\cdot n}\not{P} + \frac{B_{30}}{P\cdot n}\not{k}\right) k_\mu n_\nu + \left(\frac{B_{27}M^4}{(P\cdot n)^3}\not{n} + \frac{B_{29}M^2}{(P\cdot n)^2}\not{P} + \frac{B_{31}M^2}{(P\cdot n)^2}\not{k}\right) n_\mu n_\nu + \frac{B_{32}M^2}{P\cdot n}\gamma_\mu n_\nu\right] T^{\mu\nu}$$

$$-\left[\varepsilon_{\mu\tau\rho\sigma}\gamma^\tau P^\rho \left(\frac{B_{34}}{P\cdot n}n^\sigma k_\nu + \frac{B_{33}}{P\cdot n}k^\sigma n_\nu + \frac{B_{35}M^2}{(P\cdot n)^2}n^\sigma n_\nu\right) + \varepsilon_{\lambda\tau\rho\sigma}k^\lambda\gamma^\tau P^\rho n^\sigma\left(\frac{B_{36}}{P\cdot n M^2}k_\mu k_\nu + \frac{B_{37}}{(P\cdot n)^2}k_\mu n_\nu + \frac{B_{38}M^2}{(P\cdot n)^3}n_\mu n_\nu\right)\right]\gamma_5 T^{\mu\nu}$$

$$+\varepsilon_{\mu\tau\rho\sigma}k^\tau P^\rho n^\sigma\left(\frac{B_{39}}{(P\cdot n)^2}k_\nu + \frac{B_{40}M^2}{(P\cdot n)^3}n_\nu\right)\not{n}\gamma_5 T^{\mu\nu}$$

$$+\sigma_{\rho\sigma}\left[P^\rho k^\sigma\left(\frac{B_{41}}{(P\cdot n)M}k_\mu n_\nu + \frac{B_{42}M}{(P\cdot n)^2}n_\mu n_\nu\right) + P^\rho n^\sigma\left(\frac{B_{43}}{(P\cdot n)M}k_\mu k_\nu + \frac{B_{44}M}{(P\cdot n)^2}k_\mu n_\nu + \frac{B_{45}M^3}{(P\cdot n)^3}n_\mu n_\nu\right)\right] T^{\mu\nu}$$

$$+\sigma_{\rho\sigma}\left[k^\rho n^\sigma\left(\frac{B_{46}}{(P\cdot n)M}k_\mu k_\nu + \frac{B_{47}M}{(P\cdot n)^2}k_\mu n_\nu + \frac{B_{48}M^3}{(P\cdot n)^3}n_\mu n_\nu\right)\right] T^{\mu\nu} + \sigma_{\mu\sigma}\left[n^\sigma\left(\frac{B_{49}M}{P\cdot n}k_\nu + \frac{B_{50}M^3}{(P\cdot n)^2}n_\nu\right) + \left(\frac{B_{51}M}{P\cdot n}P^\sigma + \frac{B_{52}M}{P\cdot n}k^\sigma\right)n_\nu\right] T^{\mu\nu}$$

From this correlation function, new tensor-polarized TMDs are defined in twist-3 and 4 in addition to twist-2 ones.

Terms associated with $n = \frac{1}{\sqrt{2}}(1,\ 0,\ 0,\ -1)$

Twist-3 TMDs for spin-1 hadrons

$$\Phi^{[\Gamma]}(x, k_T, T) \equiv \frac{1}{2}\mathrm{Tr}\left[\Phi^{[\Gamma]}(x, k_T, T)\,\Gamma\right] = \frac{1}{2}\mathrm{Tr}\left[\int dk^- \Phi(k, P, T\,|\,n)\,\Gamma\right], \quad F(x, k_T^2) \equiv F'(x, k_T^2) - \frac{k_T^2}{2M^2}F^{\perp}(x, k_T^2)$$

$$\Phi^{[\gamma^i]}(x, k_T, T) = \frac{M}{P^+}\left[f_{LL}^{\perp}(x, k_T^2)\frac{S_{LL}k_T^i}{M} + f'_{LT}(x, k_T^2)S_{LT}^i - f_{LT}^{\perp}(x, k_T^2)\frac{k_T^i S_{LT}\cdot k_T}{M^2} - f'_{TT}(x, k_T^2)\frac{S_{TT}^{ij}k_{Tj}}{M} + f_{TT}^{\perp}(x, k_T^2)\frac{k_T^i k_T \cdot S_{TT}\cdot k_T}{M^3}\right]$$

$$\Phi^{[1]}(x, k_T, T) = \frac{M}{P^+}\left[e_{LL}(x, k_T^2)S_{LL} - e_{LT}^{\perp}(x, k_T^2)\frac{S_{LT}\cdot k_T}{M} + e_{TT}^{\perp}(x, k_T^2)\frac{k_T\cdot S_{TT}\cdot k_T}{M^2}\right]$$

$$\Phi^{[i\gamma_5]}(x, k_T, T) = \frac{M}{P^+}\left[e_{LT}(x, k_T^2)\frac{S_{LT\mu}\varepsilon_T^{\mu\nu}k_{T\nu}}{M} - e_{TT}(x, k_T^2)\frac{S_{TT\mu\rho}k_T^{\rho}\varepsilon_T^{\mu\nu}k_{T\nu}}{M^2}\right]$$

$$\Phi^{[\gamma^i\gamma_5]}(x, k_T, T) = \frac{M}{P^+}\left[-g_{LL}^{\perp}(x, k_T^2)\frac{S_{LL}\varepsilon_T^{ij}k_{Tj}}{M} - g'_{LT}(x, k_T^2)\varepsilon_T^{ij}S_{LTj} + g_{LT}^{\perp}(x, k_T^2)\frac{\varepsilon_T^{ij}k_{Tj}S_{LT}\cdot k_T}{M^2} + g'_{TT}(x, k_T^2)\frac{\varepsilon_T^{ij}S_{TTjl}k_T^l}{M} - g_{TT}^{\perp}(x, k_T^2)\frac{\varepsilon_T^{ij}k_{Tj}k_T\cdot S_{TT}\cdot k_T}{M^3}\right]$$

$$\Phi^{[\sigma^{-+}]}(x, k_T, T) = \frac{M}{P^+}\left[h_{LL}(x, k_T^2)S_{LL} - h_{LT}(x, k_T^2)\frac{S_{LT}\cdot k_T}{M} + h_{TT}(x, k_T^2)\frac{k_T\cdot S_{TT}\cdot k_T}{M^2}\right]$$

$$\Phi^{[\sigma^{ij}]}(x, k_T, T) = \frac{M}{P^+}\left[h_{LT}^{\perp}(x, k_T^2)\frac{S_{LT}^i k_T^j - S_{LT}^j k_T^i}{M} - h_{TT}^{\perp}(x, k_T^2)\frac{S_{TT}^{il}k_{Tl}k_T^j - S_{TT}^{jl}k_{Tl}k_T^i}{M^2}\right]$$

*2, *3 Because of the time-reversal invariance, the collinear PDFs $g_{LT}(x)$ and $h_{LL}(x)$ do not exist. However, the corresponding new collinear fragmentation functions $G_{LT}(z)$ and $H_{LL}(z)$ should exist. (see our PRD paper for the details)

Quark / Hadron	$\gamma^i, 1, i\gamma_5$		$\gamma^+\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$f^{\perp}$ $[e]$			$g^{\perp}$		$[h]$
L		$f_L^{\perp}$ $[e_L]$	$g_L^{\perp}$		$[h_L]$	
T		$f_T, f_T^{\perp}$ $[e_T, e_T^{\perp}]$	$g_T, g_T^{\perp}$		$[h_T], [h_T^{\perp}]$	
LL	$f_{LL}^{\perp}$ $[e_{LL}]$			$g_{LL}^{\perp}$		$[h_{LL}]$
LT	$f_{LT}, f_{LT}^{\perp}$ $[e_{LT}, e_{LT}^{\perp}]$			$g_{LT}, g_{LT}^{\perp}$		$[h_{LT}], [h_{LT}^{\perp}]$
TT	$f_{TT}, f_{TT}^{\perp}$ $[e_{TT}, e_{TT}^{\perp}]$			$g_{TT}, g_{TT}^{\perp}$		$[h_{TT}], [h_{TT}^{\perp}]$

Quark / Hadron	$\gamma^i, 1, i\gamma_5$		$\gamma^+\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$[e]$					
L					$[h_L]$	
T			g_T			
LL	$[e_{LL}]$					*3
LT	f_{LT}			*2		
TT						

New TMDs $[\cdot\cdot\cdot]$ = chiral odd **New collinear PDFs**

Twist-4 TMDs for spin-1 hadrons

may skip

$$\Phi^{[\Gamma]}(x,k_T,T) \equiv \frac{1}{2}\mathrm{Tr}\left[\Phi^{[\Gamma]}(x,k_T,T)\,\Gamma\right] = \frac{1}{2}\mathrm{Tr}\left[\int dk^- \Phi(k,P,T\,|\,n)\,\Gamma\right], \quad F(x,k_T^2) \equiv F'(x,k_T^2) - \frac{k_T^2}{2M^2}F^{\perp}(x,k_T^2)$$

$$\Phi^{[\gamma^-]}(x,k_T,T) = \frac{M^2}{P^{+2}}\left[f_{3LL}(x,k_T^2)S_{LL} - f_{3LT}(x,k_T^2)\frac{S_{LT}\cdot k_T}{M} + f_{3TT}(x,k_T^2)\frac{k_T\cdot S_{TT}\cdot k_T}{M^2}\right]$$

$$\Phi^{[\gamma^-\gamma_5]}(x,k_T,T) = \frac{M^2}{P^{+2}}\left[g_{3LT}(x,k_T^2)\frac{S_{LT\mu}\varepsilon_T^{\mu\nu}k_{T\nu}}{M} + g_{3TT}(x,k_T^2)\frac{S_{TT\mu\rho}k_T^{\rho}\varepsilon_T^{\mu\nu}k_{T\nu}}{M^2}\right]$$

$$\Phi^{[\sigma^{i-}]}(x,k_T,T) = \frac{M^2}{P^{+2}}\left[h_{3LL}^{\perp}(x,k_T^2)\frac{S_{LL}k_T^i}{M} + h'_{3LT}(x,k_T^2)S_{LT}^i - h_{3LT}^{\perp}(x,k_T^2)\frac{k_T^i S_{LT}\cdot k_T}{M^2} - h'_{3TT}(x,k_T^2)\frac{S_{TT}^{ij}k_{Tj}}{M} + h_{3TT}^{\perp}(x,k_T^2)\frac{k_T^i k_T\cdot S_{TT}\cdot k_T}{M^3}\right]$$

*4 Because of the time-reversal invariance, $h_{3LT}(x)$ does not exist; however, the corresponding new collinear fragmentation function $H_{3LT}(z)$ should exist because the time-reversal invariance does not have to be imposed.

Quark / Hadron	γ^-		$\gamma^-\gamma_5$		σ^{i-}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_3					$[h_3^{\perp}]$
L			g_{3L}		$[h_{3L}^{\perp}]$	
T		$f_{3T}^{\perp}$	g_{3T}		$[h_{3T}], [h_{3T}^{\perp}]$	
LL	f_{3LL}					$[h_{3LL}^{\perp}]$
LT	f_{3LT}			g_{3LT}		$[h_{3LT}], [h_{3LT}^{\perp}]$
TT	f_{3TT}			g_{3TT}		$[h_{3TT}], [h_{3TT}^{\perp}]$

New TMDs

$[\cdots]$ = chiral odd

Quark / Hadron	γ^-		$\gamma^-\gamma_5$		σ^{i-}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_3					
L			g_{3L}			
T					$[h_{3T}]$	
LL	f_{3LL}					
LT						*4
TT						

New collinear PDFs

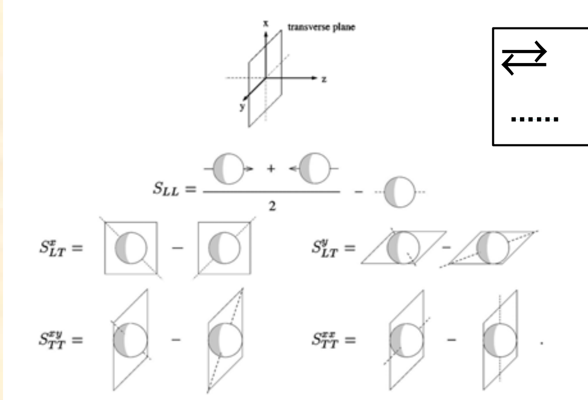
TMDs and their sum rules for spin-1 hadrons

see our PRD paper for the details

Twist-2 TMDs

Bacchetta-Mulders, PRD 62 (2000) 114004.

Quark / Hadron	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5$ / σ^{i+}) T-even	T ($i\sigma^{i+}\gamma_5$ / σ^{i+}) 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}		$[h_{1TT}], [h_{1TT}^\perp]$



$\rightleftarrows$ $m_s = \pm 1$

...... $m_s = 0$

Time-reversal invariance in colliear corrlation functions (PDFs)

$$\int d^2k_T \Phi_{\text{T-odd}}(x, k_T^2) = 0$$

Sum rules for the TMDs of spin-1 hadrons

$$\int d^2k_T\, h_{1LT}(x,k_T^2) = 0, \quad \int d^2k_T\, g_{LT}(x,k_T^2) = 0,$$

$$\int d^2k_T\, h_{LL}(x,k_T^2) = 0, \quad \int d^2k_T\, h_{3LT}(x,k_T^2) = 0$$

Twist-3 TMDs

SK and Qin-Tao Song, PRD 103 (2021) 014025.

Quark / Hadron	$\gamma^i, 1, i\gamma_5$ T-even	$\gamma^i, 1, i\gamma_5$ T-odd	$\gamma^+\gamma_5$ T-even	$\gamma^+\gamma_5$ T-odd	σ^{ij}, σ^{-+} T-even	σ^{ij}, σ^{-+} T-odd
U	$f^\perp$ $[e]$			$g^\perp$		$[h]$
L		$f_L^\perp$ $[e_L]$	$g_L^\perp$		$[h_L]$	
T		$f_T, f_T^\perp$ $[e_T, e_T^\perp]$	$g_T, g_T^\perp$		$[h_T], [h_T^\perp]$	
LL	$f_{LL}^\perp$ $[e_{LL}]$			$g_{LL}^\perp$		$[h_{LL}]$
LT	$f_{LT}, f_{LT}^\perp$ $[e_{LT}, e_{LT}^\perp]$			$g_{LT}, g_{LT}^\perp$		$[h_{LT}], [h_{LT}^\perp]$
TT	$f_{TT}, f_{TT}^\perp$ $[e_{TT}, e_{TT}^\perp]$			$g_{TT}, g_{TT}^\perp$		$[h_{TT}], [h_{TT}^\perp]$

Twist-4 TMDs

Quark / Hadron	γ^- T-even	γ^- T-odd	$\gamma^-\gamma_5$ T-even	$\gamma^-\gamma_5$ T-odd	σ^{i-} T-even	σ^{i-} T-odd
U	f_3					$[h_3^\perp]$
L			g_{3L}		$[h_{3L}^\perp]$	
T		$f_{3T}^\perp$	g_{3T}		$[h_{3T}], [h_{3T}^\perp]$	
LL	f_{3LL}					$[h_{3LL}^\perp]$
LT	f_{3LT}			g_{3LT}		$[h_{3LT}], [h_{3LT}^\perp]$
TT	f_{3TT}			g_{3TT}		$[h_{3TT}], [h_{3TT}^\perp]$

New fragmentation functions (FFs) for spin-1 hadrons

see arXiv:2201.05397

Corresponding fragmentation functions exist for the spin-1 haddrons
simply by changing function names and kinematical variables.

Collinear FFs:
X. Ji, PRD 49, 114 (1994).

TMD distribution functions: $f,\ g,\ h,\ e\ ;\quad x,\ k_T,\ S,\ T,\ M,\ n,\ \gamma^+,\ \sigma^{i+}$

$\Downarrow$

TMD fragmentation functions: $D,\ G,\ H,\ E\ ;\quad z,\ k_T,\ S_h,\ T_h,\ M_h,\ \bar{n},\ \gamma^-,\ \sigma^{i-}$

Collinear FFs, twist 2

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	D_1					
L			G_{1L}			
T					$[H_1]$	
LL	D_{1LL}					
LT						$[H_{1LT}]$
TT						

Collinear FFs, twist 3

Quark / Hadron	$\gamma^i, 1, i\gamma_5$		$\gamma^i\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$[E]$					
L					$[H_L]$	
T			G_T			
LL	$[E_{LL}]$					$[H_{LL}]$
LT	D_{LT}			G_{LT}		
TT						

Collinear FFs, twist 4

Quark / Hadron	γ^-		$\gamma^-\gamma_5$		σ^{i-}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	D_3					
L			G_{3L}			
T					$[H_{3T}]$	
LL	D_{3LL}					
LT						$[H_{3LT}]$
TT						

[ ] = chiral odd

TMD FFs, twist 2

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	D_1					$[H_1^\perp]$
L			G_{1L}		$[H_{1L}^\perp]$	
T		$D_{1T}^\perp$	G_{1T}		$[H_1], [H_{1T}^\perp]$	
LL	D_{1LL}					$[H_{1LL}^\perp]$
LT	D_{1LT}			G_{1LT}		$[H_{1LT}], [H_{1LT}^\perp]$
TT	D_{1TT}			G_{1TT}		$[H_{1TT}], [H_{1TT}^\perp]$

TMD FFs, twist 3

Quark / Hadron	$\gamma^i, 1, i\gamma_5$		$\gamma^i\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$D^\perp$ $[E]$			$G^\perp$		$[H]$
L		$D_L^\perp$ $[E_L]$	$G_L^\perp$		$[H_L]$	
T		$D_T, D_T^\perp$ $[E_T, E_T^\perp]$	$G_T, G_T^\perp$		$[H_T], [H_T^\perp]$	
LL	$D_{LL}^\perp$ $[E_{LL}]$			$G_{LL}^\perp$		$[H_{LL}]$
LT	$D_{LT}, D_{LT}^\perp$ $[E_{LT}, E_{LT}^\perp]$			$G_{LT}, G_{LT}^\perp$		$[H_{LT}], [H_{LT}^\perp]$
TT	$D_{TT}, D_{TT}^\perp$ $[E_{TT}, E_{TT}^\perp]$			$G_{TT}, G_{TT}^\perp$		$[H_{TT}], [H_{TT}^\perp]$

TMD FFs, twist 4

Quark / Hadron	γ^-		$\gamma^-\gamma_5$		σ^{i-}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	D_3					$[H_3^\perp]$
L			G_{3L}		$[H_{3L}^\perp]$	
T		$D_{3T}^\perp$	G_{3T}		$[H_{3T}], [H_{3T}^\perp]$	
LL	D_{3LL}					$[H_{3LL}^\perp]$
LT	D_{3LT}			G_{3LT}		$[H_{3LT}], [H_{3LT}^\perp]$
TT	D_{3TT}			G_{3TT}		$[H_{3TT}], [H_{3TT}^\perp]$

New TMD FFs

PDFs for spin-1 hadrons

Twist-2 PDFs

Hadron \ Quark	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	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
TT						

*1: $h_{1LT}(x)$, *2: $g_{LT}(x)$, *3: $h_{LL}(x)$, *4: $h_{3LT}(x)$

Because of the time-reversal invariance, the collinear PDF vanishes. However, since the time-reversal invariance cannot be imposed in the fragmentation functions, we should note that the corresponding fragmentation function should exist as a collinear fragmentation function.

[ ] = chiral odd

Twist-3 PDFs

Hadron \ Quark	$\gamma^i, 1, i\gamma_5$		$\gamma^+\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$[e]$					
L					$[h_L]$	
T			g_T			
LL	$[e_{LL}]$					*3
LT	f_{LT}			*2		
TT						

Twist-4 PDFs

Hadron \ Quark	γ^-		$\gamma^-\gamma_5$		σ^{i-}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_3					
L			g_{3L}			
T					$[h_{3T}]$	
LL	f_{3LL}					
LT						*4
TT						

New collinear PDFs

SK and Qin-Tao Song, PRD 103 (2021) 014025.

Summary on Spin-1 TMDs and PDFs

TMDs of spin-1 hadrons

- TMDs: interdisciplinary field of physics
- We proposed new 30 TMDs and 3 PDFs in twist 3 and 4.
- New sum rules for TMDs.
- New TMD fragmentation functions.

Twist-3 TMD: $f_{LL}^{\perp}, e_{LL}, f_{LT}, f_{LT}^{\perp}, e_{1T}, e_{1T}^{\perp}, f_{TT}, f_{TT}^{\perp}, e_{TT}, e_{TT}^{\perp},$
$g_{LL}^{\perp}, g_{LT}, g_{LT}^{\perp}, g_{TT}, g_{TT}^{\perp}, h_{1L}, h_{LT}, h_{LT}^{\perp}, h_{TT}, h_{TT}^{\perp}$

Twist-4 TMD: $f_{3LL}, f_{3LT}, f_{3TT}, g_{3LT}, f_{3TT}, h_{3LL}^{\perp}, h_{3LT}, h_{3LT}^{\perp}, h_{3TT}, h_{3TT}^{\perp}$

Twist-3 PDF: e_{LL}, f_{LT}

Twist-4 PDF: f_{3LL}

Sum rules: $$\int d^2k_T g_{LT}(x, k_T^2) = \int d^2k_T h_{LL}(x, k_T^2) = \int d^2k_T h_{3LL}(x, k_T^2) = 0$$

TMD distribution functions: $f,\ g,\ h,\ e;\quad x,\ k_T,\ S,\ T,\ M,\ n,\ \gamma^+,\ \sigma^{i+}$

$\Downarrow$

TMD fragmentation functions: $D,\ G,\ H,\ E;\quad z,\ k_T,\ S_h,\ T_h,\ M_h,\ \bar{n},\ \gamma^-,\ \sigma^{i-}$

Analogous relations to Wandzura-Wilczek relation and Burkhardt-Cottingham sum rule

Twist-2 PDFs

Quark \ Hadron	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

Twist-3 PDFs

Quark \ Hadron	$\gamma^i, 1, i\gamma_5$ T-even	$\gamma^i, 1, i\gamma_5$ T-odd	$\gamma^+\gamma_5$ T-even	$\gamma^+\gamma_5$ T-odd	σ^{ij}, σ^{-+} T-even	σ^{ij}, σ^{-+} T-odd
U	$[e]$					
L					$[h_L]$	
T			g_T			
LL	$[e_{LL}]$					*3
LT	f_{LT}			*2		
TT						

[ ] = chiral odd

We derived analogous relations to Wandzura-Wilczek relation and Burkhardt-Cottingham sum rule for f_{LT} and f_{1LL}.

SK and Qin-Tao Song, JHEP 09 (2021) 141.

For spin-1/2 nucleons,

$$g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) \text{ (Wandzura-Wilczek relation)}, \qquad \int_0^1 dx\, g_2(x) = 0 \text{ (Burkhardt-Cottingham sum rule)}$$

For tensor-polarized spin-1 hadrons, we obtained

$$f_{2LT}^+(x) = -f_{1LL}^+(x) + \int_x^1 \frac{dy}{y} f_{1LL}^+(y), \qquad \int_0^1 dx\, f_{2LT}^+(x) = 0, \qquad f_{2LT}(x) \equiv \frac{2}{3} f_{LT}(x) - f_{1LL}(x)$$

$$\int_0^1 dx\, f_{LT}^+(x) = 0 \text{ if } \int_0^1 dx\, f_{1LL}^+(x) = \frac{2}{3}\int_0^1 dx\, b_1^+(x) = 0$$

Existence of multiparton distribution functions: $F_{G,LT}(x_1,x_2)$, $G_{G,LT}(x_1,x_2)$, $H_{G,LL}^{\perp}(x_1,x_2)$, $H_{G,TT}(x_1,x_2)$

Relations from equation of motion and Lorentz-invariance relation for spin-1 hadrons

SK and Qin-Tao Song, PLB 826 (2022) 136908.

In the following, I explain derivations on relations from equation of motion for quarks

- $x f_{LT}(x) - \int_{-1}^{+1} dy \left[F_{D,LT}(x,y) + G_{D,LT}(x,y) \right] = 0, \quad x f_{LT}(x) - f_{1LT}^{(1)}(x) - \mathcal{P}\int_{-1}^{+1} dy \frac{F_{G,LT}(x,y) + G_{G,LT}(x,y)}{x-y} = 0$
- $x e_{LL}(x) - 2\int_{-1}^{+1} dy H_{D,LL}^{\perp}(x,y) - \frac{m}{M} f_{1LL}(x) = 0, \quad x e_{LL}(x) - 2\mathcal{P}\int_{-1}^{+1} dy \frac{H_{G,LL}^{\perp}(x,y)}{x-y} - \frac{m}{M} f_{1LL}(x) = 0$

and the Lorentz-invariance relation

- $\frac{d f_{1LT}^{(1)}(x)}{dx} - f_{LT}(x) + \frac{3}{2} f_{1LL}(x) - 2\mathcal{P}\int_{-1}^{+1} dy \frac{F_{G,LT}(x,y)}{(x-y)^2} = 0$

Lorentz invariance
= frame independence of twist-3 observables

transverse-momemtum moment of TMD: $f^{(1)}(x) = \int d^2 k_T \frac{\vec{k}_T^{\,2}}{2M^2} f(x, k_T^2)$

Twist-2 PDFs

Quark \ Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	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						
TT						

Twist-3 PDFs

Quark \ Hadron	$\gamma^i, 1, i\gamma_5$		$\gamma^+\gamma_5$		σ^{ij}, σ^{-+}	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	$[e]$					
L					$[h_L]$	
T			g_T			
LL	$[e_{LL}]$					
LT	f_{LT}					*1
TT						

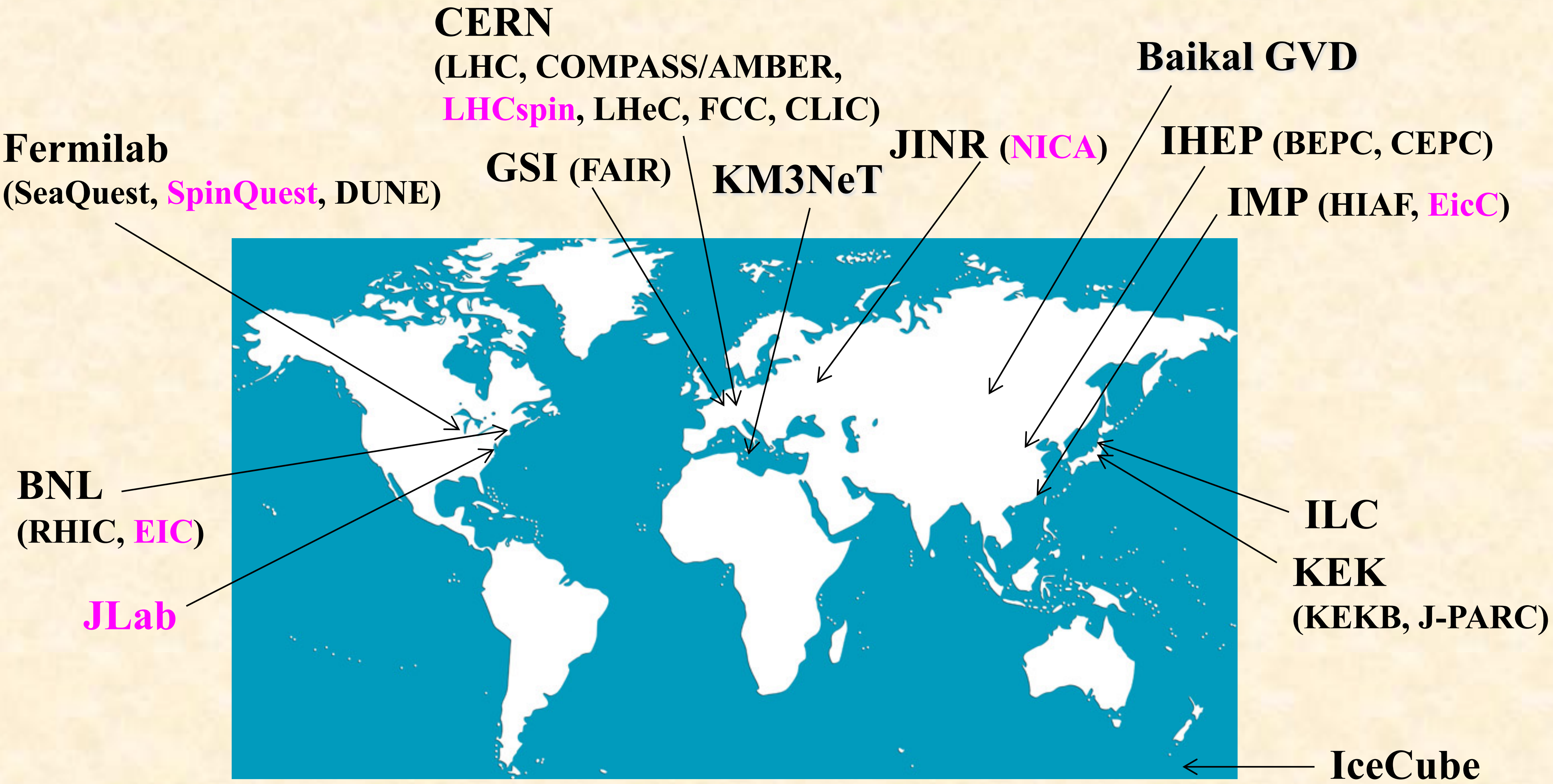
Twist-3 TMDs

Quark \ Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	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}		$[h_{1TT}], [h_{1TT}^{\perp}]$

[ ] = chiral odd

Future prospects and summary

High-energy hadron physics experiments



Facilities on spin-1 hadron structure functions including future possibilities.

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

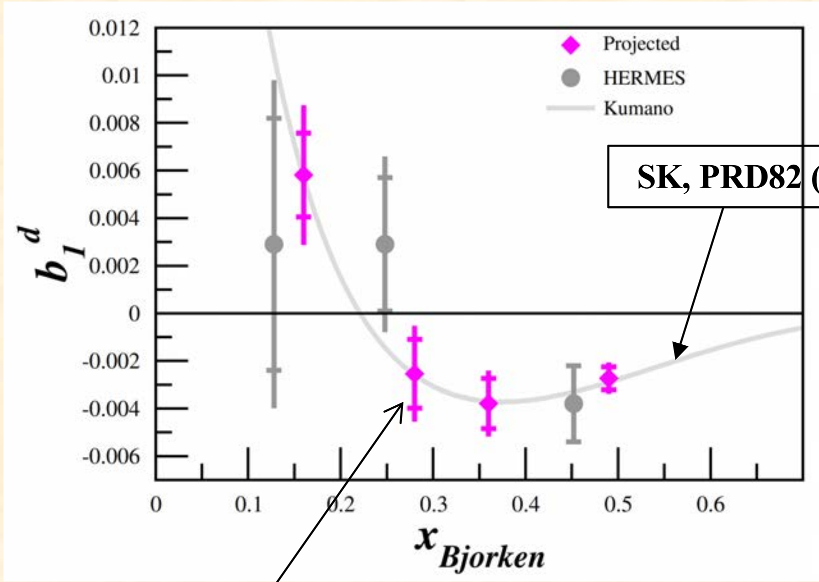
G. Ron
Hebrew University of Jerusalem, Jerusalem

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



SK, PRD82 (2010) 017501

Expected errors by JLab

Approved!

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

Experimental possibility at Fermilab in 2020's

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

© Fermilab

Fermilab-E1039 (SpinQuest)

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

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.

SK and Q.-T. Song, PRD 101 (2020) 054011 & 094013

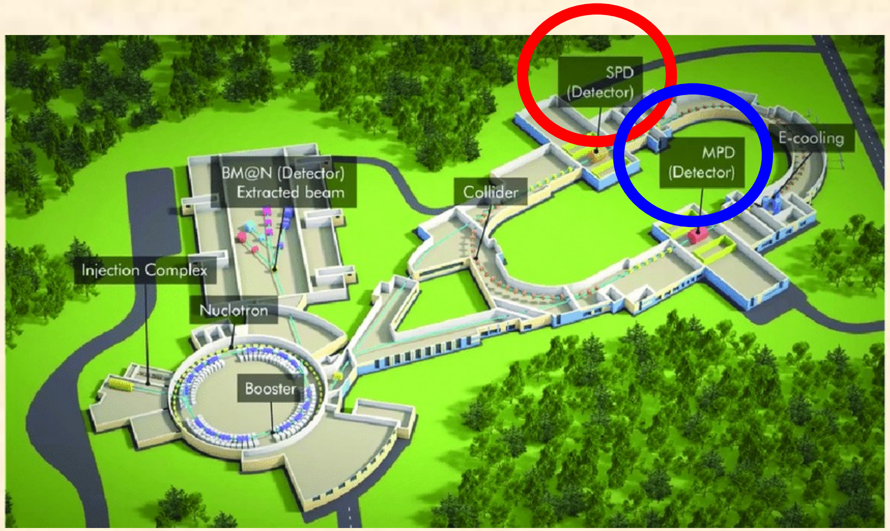
The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

[1] *University of Virginia, Charlottesville, VA 22904*

Proposal for a Fermilab-PAC in 2023.

Nuclotron-based Ion Collider fAcility (NICA)



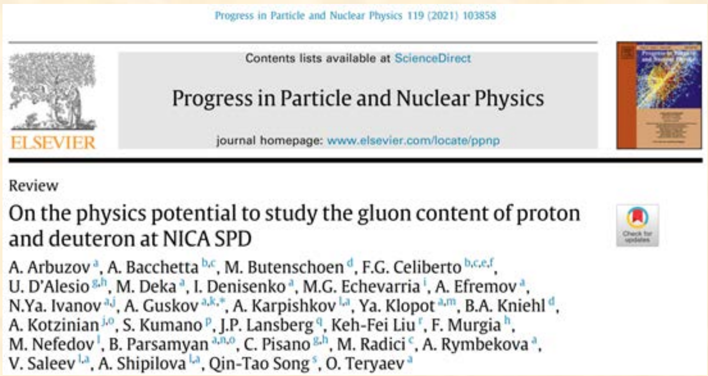
SPD (Spin Physics Detector for physics with polarized beams)
MPD (MultiPurpose Detector for heavy ion physics)

$$\vec{p}+\vec{p}: \quad \sqrt{s_{pp}} = 12 \sim 27 \text{ GeV}$$

$$\vec{d}+\vec{d}: \quad \sqrt{s_{NN}} = 4 \sim 14 \text{ GeV}$$

$\vec{p}+\vec{d}$ is also possilbe.

On the physics potential to study the gluon content of proton and deuteron at NICA SPD, A. Arbuzov *et al.* (NICA project), Nucl. Part. Phys. 119 (2021) 103858.


Progress in Particle and Nuclear Physics 119 (2021) 103858

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

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], B. Parsamyan[a,n,o], C. Pisano[g,h], M. Radici[c], A. Rymbekova[a], V. Saleev[l,a], A. Shipilova[l,a], Qin-Tao Song[s], O. Teryaev[a]

Unique opportunity in high-energy spin physics, especially on the deuteron spin physics.

→ Theoretical formalisms need to be developed.

Spin-1 deuteron experiments from the middle of 2020's

JLab

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

Proposal (approved),
Experiment: middle of 2020's

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

Fermilab

The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]
[1] *University of Virginia, Charlottesville, VA 22904*

Proposal,
Fermilab-PAC: 2022
Experiment: 2020's

NICA

Progress in Particle and Nuclear Physics 119 (2021) 103858
Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
ELSEVIER

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

A. Arbuzov, A. Bacchetta, M. Butenschoen, F.G. Celiberto, U. D'Alesio, M. Deka, I. Denisenko, M.G. Echevarria, A. Efremov, N.Ya. Ivanov, A. Guskov, A. Karpishkov, Ya. Klopot, B.A. Kniehl, A. Kotzinian, S. Kumano, J.P. Lansberg, Keh-Fei Liu, F. Murgia, M. Nefedov, B. Parsamyan, C. Pisano, M. Radici, A. Rymbekova, V. Saleev, A. Shipilova, Qin-Tao Song, O. Teryaev

Prog. Nucl. Part. Phys.
119 (2021) 103858,
Experiment: middle of 2020's

LHCspin

LHC spin

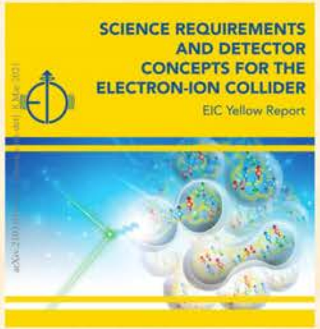
CERN-ESPP-Note-2018-111

The LHCSpin Project

C. A. Aidala[1], A. Bacchetta[2,3], M. Boglione[4,5], G. Bozzi[2,3], V. Carassiti[6,7], M. Chiosso[4,5], R. Cimino[8], G. Ciullo[6,7], M. Contalbrigo[6,7], U. D'Alesio[9,10], P. Di Nezza[8], R. Engels[11], K. Grigoryev[11], D. Keller[12], P. Lenisa[6,7], S. Liuti[12], A. Metz[13], P.J. Mulders[14,15], F. Murgia[10], A. Nass[11], D. Panzieri[5,16], L. L. Pappalardo[6,7], B. Pasquini[2,3], C. Pisano[9,10], M. Radici[3], F. Rathmann[11], D. Reggiani[17], M. Schlegel[18], S. Scopetta[19,20], E. Steffens[21], A. Vasilyev[22]

arXiv:1901.08002,
Experiment: ~2028

2030's EIC/EicC



R. Abdul Khalek *et al.*
Nucl. Phys. A 1026 (2022) 122447.

D. P. Anderle *et al.*,
Front. Phys. 16 (2021) 64701.

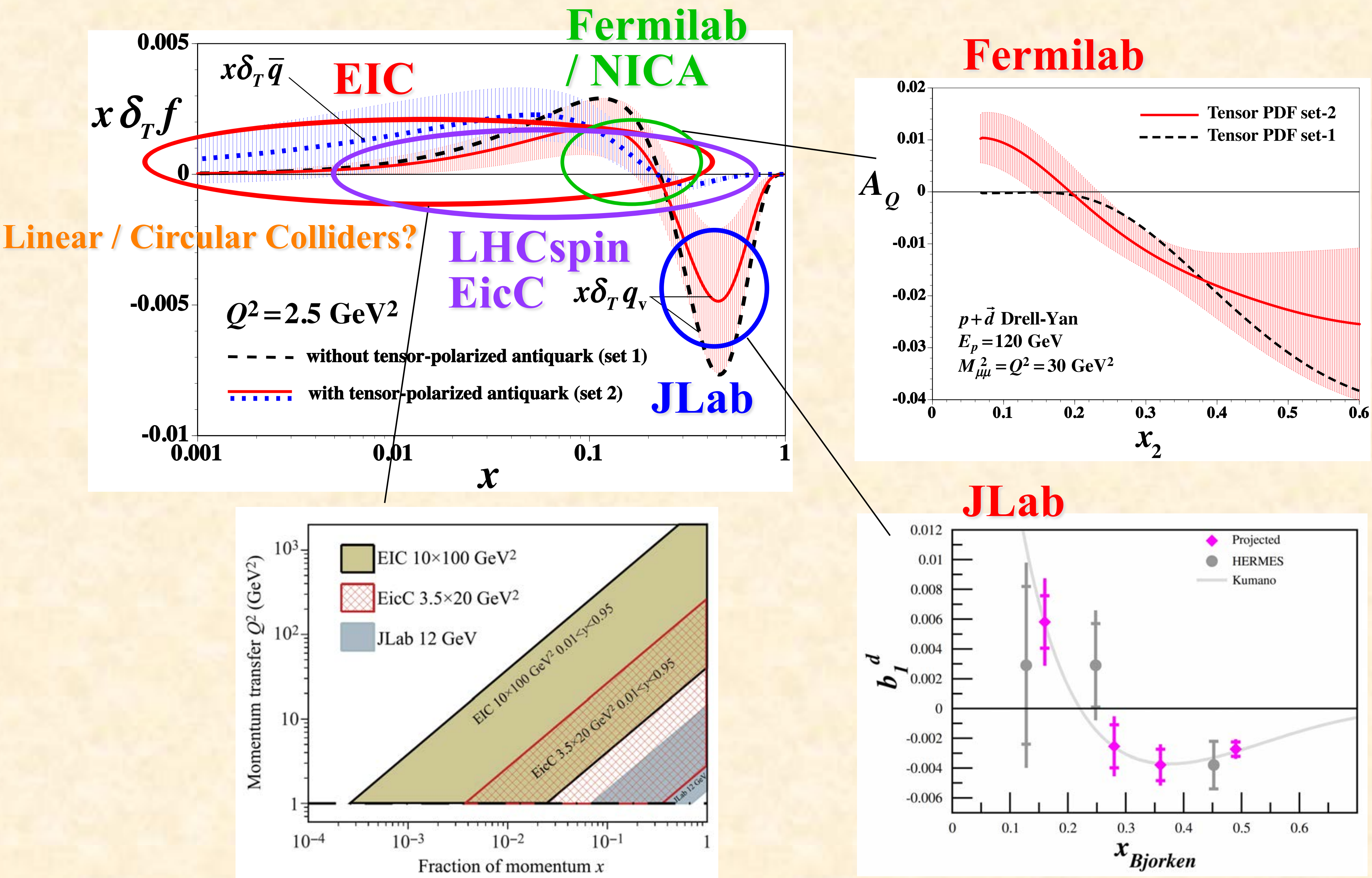
Frontiers of Physics
https://doi.org/10.1007/s11467-021-1062-0
Front. Phys. 16(6), 64701 (2021)

REVIEW ARTICLE

Electron-ion collider in China

Daniele P. Anderle, Valerio Bertone, Xu Cao, Lei Chang, Ningbo Chang, Gu Chen, Xurong Chen, Zhuojun Chen, Zhufang Cui, Lingyun Dai, Weitian Deng, Minghui Ding, Xu Feng, Chang Gong, Longcheng Gui, Feng-Kun Guo, Chengdong Han, Jun He, Tie-Jiun Hou, Hongxia Huang, Yin Huang, Krešimir Kumerički, L. P. Kaptari, Demin Li, Hengne Li, Minxiang Li, Xueqian Li, Yutie Liang, Zuotang Liang, Chen Liu, Chuan Liu, Guoming Liu, Jie Liu, Liuming Liu, Xiang Liu, Tianbo Liu, Xiaofeng Luo, Zhun Lyu, Boqiang Ma, Fu Ma, Jianping Ma, Yugang Ma, Lijun Mao, Cédric Mezrag, Hervé Moutarde, Jialun Ping, Sixue Qin, Hang Ren, Craig D. Roberts, Juan Rojo, Guodong Shen, Chao Shi, Qintao Song, Hao Sun, Paweł Sznajder, Enke Wang, Fan Wang, Qian Wang, Rong Wang, Ruiru Wang, Taofeng Wang, Wei Wang, Xiaoyu Wang, Xiaoyun Wang, Jiajun Wu, Xinggang Wu, Lei Xia, Bowen Xiao, Guoqing Xiao, Ju-Jun Xie, Yaping Xie, Hongxi Xing, Hushan Xu, Nu Xu, Shusheng Xu, Mengshi Yan, Wenbiao Yan, Wencheng Yan, Xinhu Yan, Jiancheng Yang, Yi-Bo Yang, Zhi Yang, Deliang Yao, Zhihong Ye, Peilin Yin, C.-P. Yuan, Wenlong Zhan, Jianhui Zhang, Jinlong Zhang, Pengming Zhang, Yifei Zhang, Chao-Hsi Chang, Zhenyu Zhang, Hongwei Zhao, Kuang-Ta Chao, Qiang Zhao, Yuxiang Zhao, Zhengguo Zhao, Liang Zheng, Jian Zhou, Xiang Zhou, Xiaorong Zhou, Bingsong Zou, Liping Zou

x regions of b_1 in 2020's and 2030's



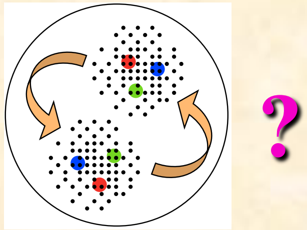
Summary

Spin-1 structure functions of the deuteron (additional spin structure to nucleon spin)

- Tensor structure in quark-gluon degrees of freedom
- Tensor-polarized structure function b_1 and PDFs, gluon transversity

  Experiments at JLab, Fermilab, NICA, LHCspin/AMBER, EIC/EicC, • • •
- New signature beyond "standard" hadron physics?

  (beyond the standard model in particle physics???)



- TMDs up to twist 4
- Higher-twist effects could be sizable at a few GeV^2 Q^2

  → Our relations (WW-like, BC-like, from eq. of motion, Lorentz invariance) could become valuable for future experimental analyses.

There are various experimental projects on the polarized spin-1 deuteron in 2020's and 2030', and "exotic" hadron structure could be found by focusing on the spin-1 nature.

- There is no nuclear effect in ρ and φ mesons, so that the gluon transversity, for example, could be sensitive to new physics?!

The End

The End