Structure functions of the deuteron

especially, polarized structure functions specific to a spin-1 hadron

From April 1, 2022

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View of the Ikebukuro downtown from my JWU office

CFNS workshop on Electron-Nuclei Interaction at EIC
(In-person and online) CFNS, Stony Brook University,
Stony Brook, New York, USA, July 6-7, 2023
https://indico.bnl.gov/event/18415/timetable/?view=standard

July 7, 2023

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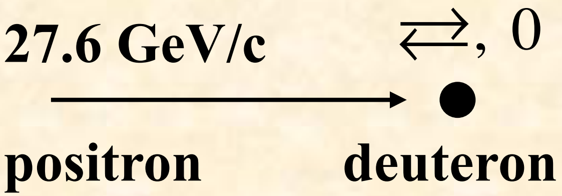
References [1] W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, PRD 95 (2017) 074036.
[2] SK and Qin-Tao Song, PRD 94 (2016) 054022.
[3] PRD 101 (2020) 054011 & 094013.
[4] PRD 103 (2021) 014025.
[5] JHEP 09 (2021) 141.
[6] PLB 826 (2022) 136908.

HERMES results on b_1

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



27.6 GeV/c

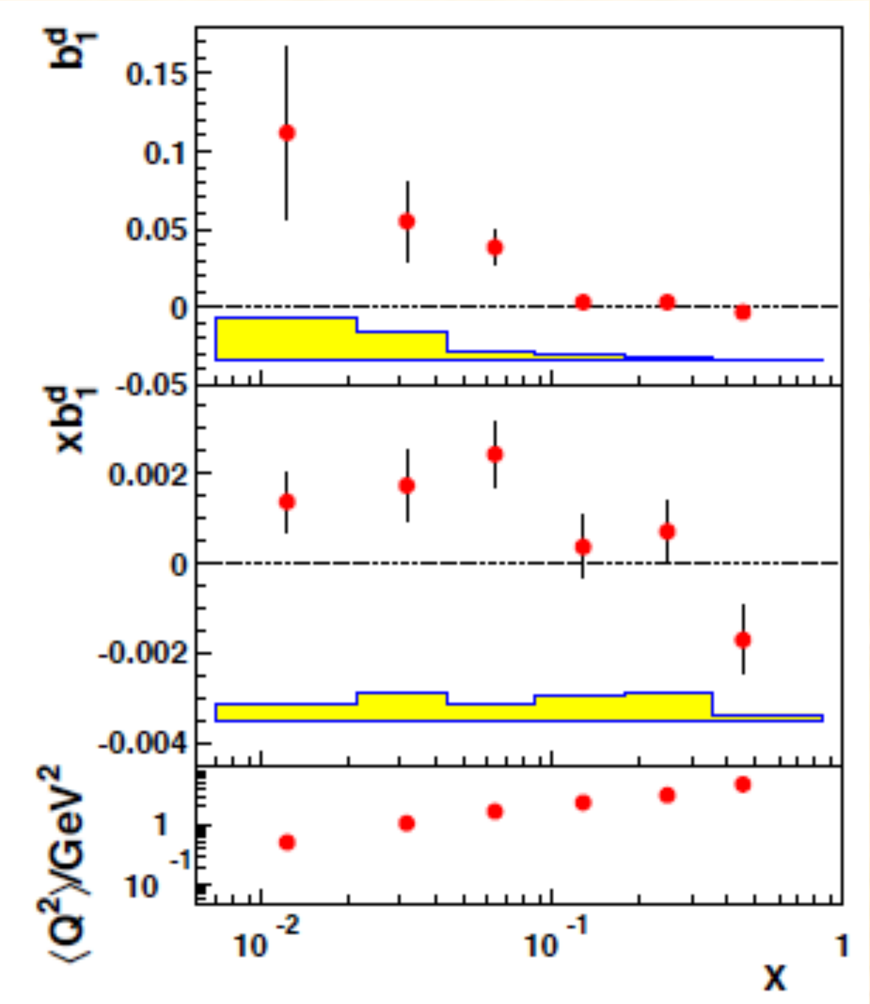
$\rightleftarrows, 0$

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 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

$$\int dx\, b_1^D(x) = \lim_{t \to 0} -\frac{5}{12}\frac{t}{M^2} F_Q(t) + \underline{\sum_i e_i^2 \int dx\, \delta_T \bar{q}_i(x)} = 0 \; ?$$

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

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

Drell-Yan experiments probe these antiquark distributions.

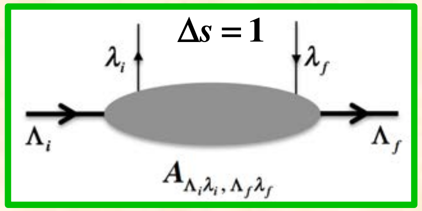
Gluon transversity $\Delta_T g$

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

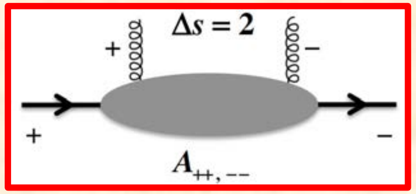
Helicity amplitude $A(\Lambda_i, \lambda_i,\ \Lambda_f, \lambda_f)$, **conservation** $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

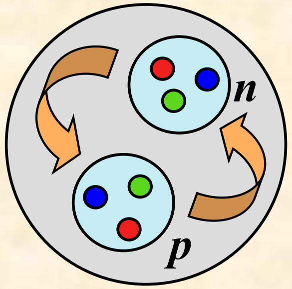
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \rightarrow \lambda_f = -\frac{1}{2}$ **quark spin flip** ($\Delta s = 1$)



Gluon transversity in deuteron: $\Delta_T g(x) \sim A(+1+1,\ -1-1)$, $\cancel{A\left(+\frac{1}{2}+1,\ -\frac{1}{2}-1\right)}$ **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 $\Delta_T g \neq 0$**?**

Physics beyond "the standard model" in nuclear physics?

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

Our recent works on spin-1 hadrons

- b_1 by standard deuteron model
- Tensor-polarized PDFs and gluon transversity at hadron accelerator facilities by Drell-Yan
- TMDs, PDFs, multiparton distributions, fragmentation functions up to twist-4
- Useful relations similar to Wandzura-Wilczek relation and Burkhardt-Cottingham sum rule
- Relations from equation-of-motion and Lorentz-invariance relations

Collaborator on recent works: Qin-Tao Song (Zhengzhou University)

“Standard-model” prediction for b_1 of deuteron

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

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

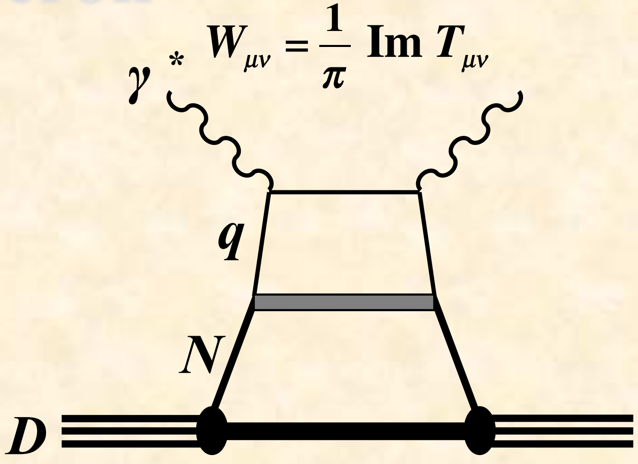
$$= \int d^3p\; y\left[-\frac{3}{4\sqrt{2}\pi}\phi_0(p)\phi_2(p) + \frac{3}{16\pi}|\phi_2(p)|^2\right](3\cos^2\theta - 1)\,\delta\!\left(y - \frac{p\cdot q}{M_N \nu}\right)$$

S-D term **D-D term**

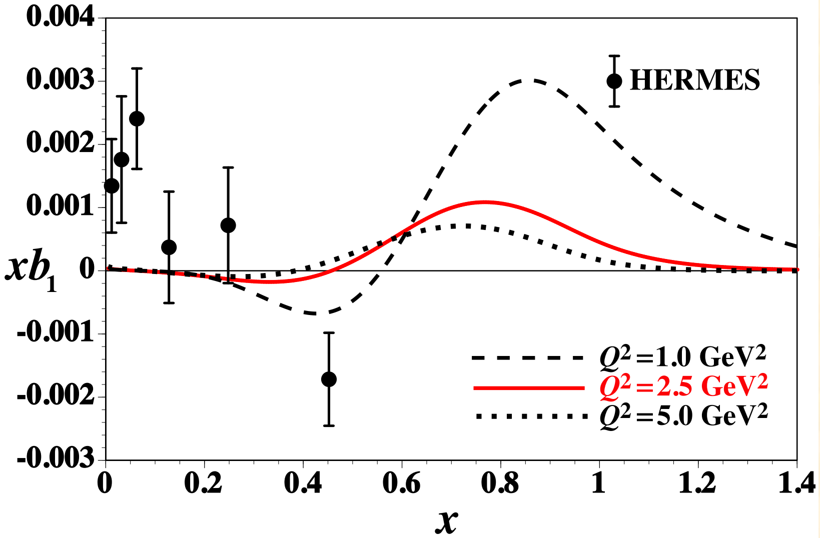
Nucleon momentum distribution:

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

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



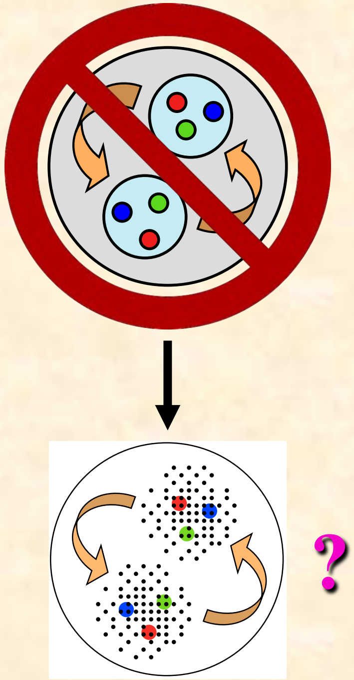
Standard model of the deuteron



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 spin asymmetry at Fermilab

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

Spin asymmetries

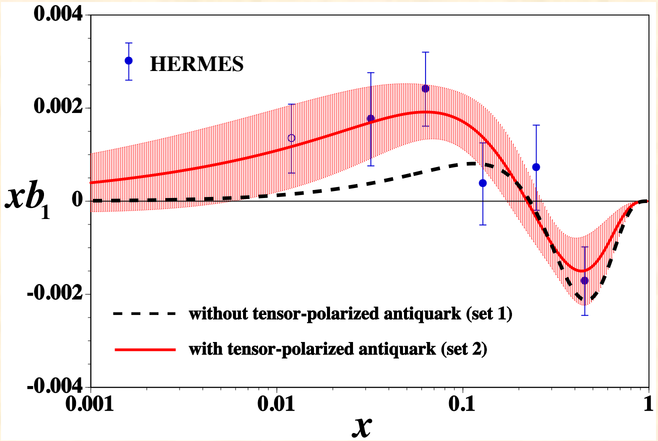
unpolarized: q_a, longitudinally polarized: Δq_a,
transversely polarized: $\Delta_T q_a$, tensor polarized: δq_a

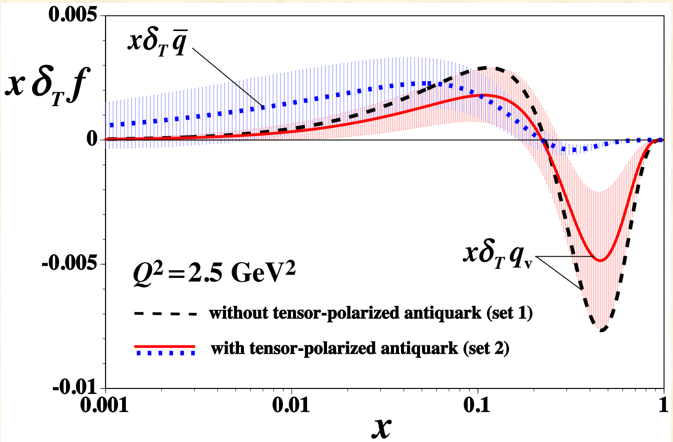
$$A_{LL} = \frac{\sum_a e_a^2 \left[\Delta q_a(x_A)\Delta \bar{q}_a(x_B) + \Delta \bar{q}_a(x_A)\Delta q_a(x_B)\right]}{\sum_a e_a^2 \left[q_a(x_A)\bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)\right]}, \quad A_{TT} = \frac{\sin^2\theta \cos(2\phi)}{1+\cos^2\theta} \frac{\sum_a e_a^2 \left[\Delta_T q_a(x_A)\Delta_T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

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

Tensor-polarized PDFs

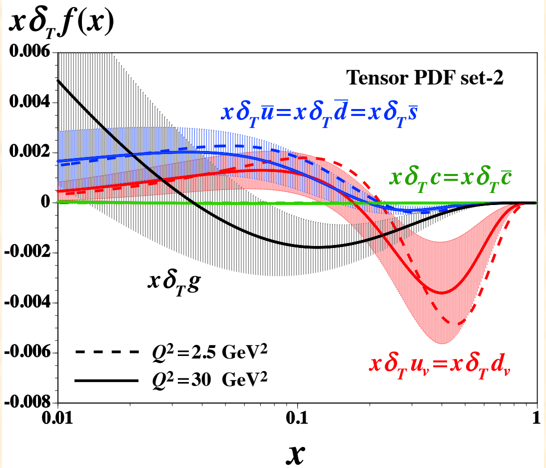
SK, PRD 82 (2010) 017501.





Q^2 evolution

$Q^2 = 2.5$ GeV^2 (HERMES)
→ 30 GeV^2 (Fermilab)



Fermilab-E1039-SpinQuest

Drell-Yan experiment with a polarized proton target

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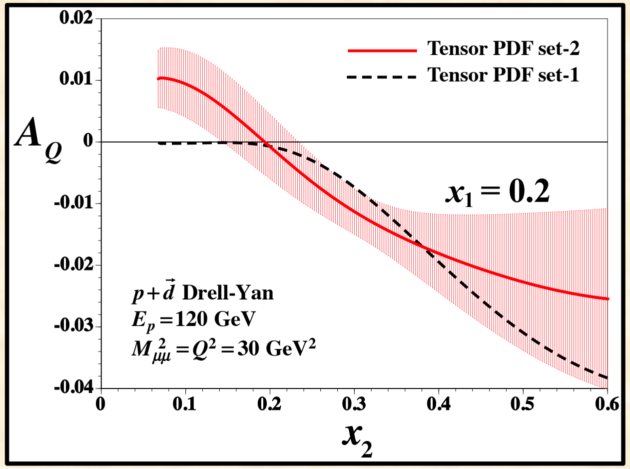
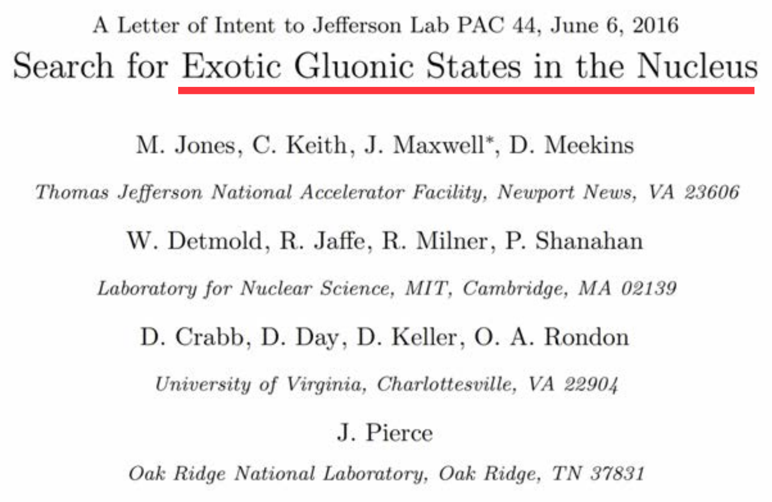


SK and Qin-Tao Song,
PRD 94 (2016) 054022.

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

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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

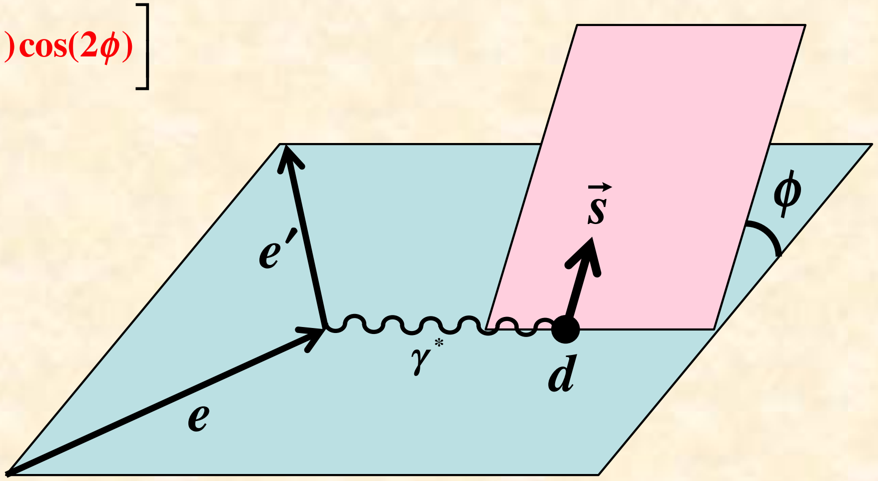
For development of polarized deuteron target,
see D. Keller, D. Crabb, D. Day
Nucl. Inst. Meth. Phys. Res. A981 (2020) 164504.

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.

Proton-deuteron Drell-Yan cross section

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

Drell-Yan cross section

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

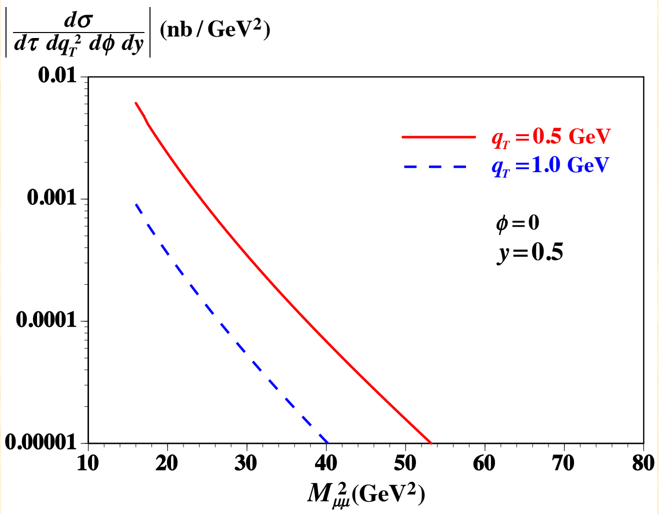
$$C_F=\frac{N_c^2-1}{2N_c},\quad \min(x_a)=\frac{x_1-\tau}{1-x_2},\quad x_b=\frac{x_a x_2-\tau}{x_a-\tau}$$

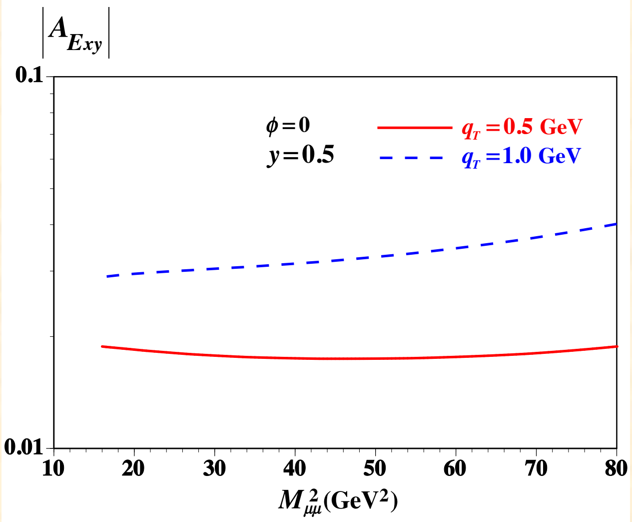
= (unpolarized PDFs of proton) * (gluon transversity distribution in the deuteron)

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





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

TMD correlation functions for spin-1 hadrons

Correlation functions

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

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

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

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

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

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

Bacchetta -Mulders (2000)

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

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

$$-\left[\varepsilon_{\mu\tau\rho\sigma}\gamma^{\tau}P^{\rho}\left(\frac{B_{34}}{P\cdot n}n^{\sigma}k_{\nu}+\frac{B_{33}}{P\cdot n}k^{\sigma}n_{\nu}+\frac{B_{35}M^2}{(P\cdot n)^2}n^{\sigma}n_{\nu}\right)+\varepsilon_{\lambda\tau\rho\sigma}k^{\lambda}\gamma^{\tau}P^{\rho}n^{\sigma}\left(\frac{B_{36}}{P\cdot nM^2}k_{\mu}k_{\nu}+\frac{B_{37}}{(P\cdot n)^2}k_{\mu}n_{\nu}+\frac{B_{38}M^2}{(P\cdot n)^3}n_{\mu}n_{\nu}\right)\right]\gamma_5T^{\mu\nu}$$

$$+\varepsilon_{\mu\tau\rho\sigma}k^{\tau}P^{\rho}n^{\sigma}\left(\frac{B_{39}}{(P\cdot n)^2}k_{\nu}+\frac{B_{40}M^2}{(P\cdot n)^3}n_{\nu}\right)\not{n}\gamma_5T^{\mu\nu}$$

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

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

New terms in our paper (2021)

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

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

Twist-3 TMDs for spin-1 hadrons

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

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

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

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

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

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

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

*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

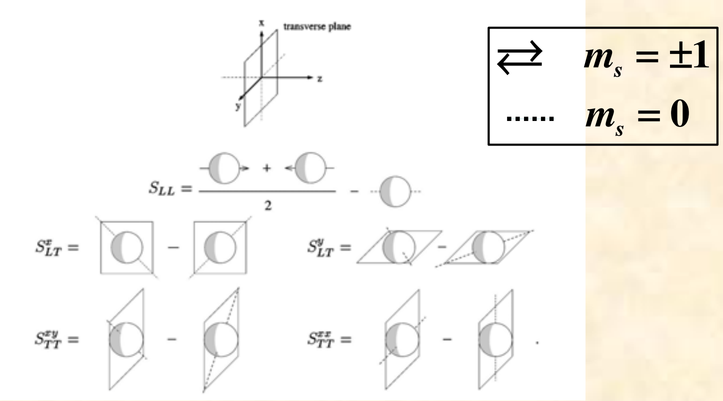
TMDs and their sum rules for spin-1 hadrons

see our PRD paper for the details

Twist-2 TMDs

Bacchetta-Mulders, PRD 62 (2000) 114004.

Quark / Hadron	U (γ^+)		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			$g_{1\mathrm{L}}$		$[h_{1\mathrm{L}}^\perp]$	
T		$f_{1\mathrm{T}}^\perp$	$g_{1\mathrm{T}}$		$[h_1], [h_{1\mathrm{T}}^\perp]$	
LL	$f_{1\mathrm{LL}}$					$[h_{1\mathrm{LL}}^\perp]$
LT	$f_{1\mathrm{LT}}$			$g_{1\mathrm{LT}}$		$[h_{1\mathrm{LT}}], [h_{1\mathrm{LT}}^\perp]$
TT	$f_{1\mathrm{TT}}$			$g_{1\mathrm{TT}}$		$[h_{1\mathrm{TT}}], [h_{1\mathrm{TT}}^\perp]$



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

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

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

Twist-3 TMDs

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

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

Twist-4 TMDs

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			$g_{3\mathrm{L}}$		$[h_{3\mathrm{L}}^\perp]$	
T		$f_{3\mathrm{T}}^\perp$	$g_{3\mathrm{T}}$		$[h_{3\mathrm{T}}], [h_{3\mathrm{T}}^\perp]$	
LL	$f_{3\mathrm{LL}}$					$[h_{3\mathrm{LL}}^\perp]$
LT	$f_{3\mathrm{LT}}$			$g_{3\mathrm{LT}}$		$[h_{3\mathrm{LT}}], [h_{3\mathrm{LT}}^\perp]$
TT	$f_{3\mathrm{TT}}$			$g_{3\mathrm{TT}}$		$[h_{3\mathrm{TT}}], [h_{3\mathrm{TT}}^\perp]$

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

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

Quark	$\gamma^i, 1, i\gamma_5$		$\gamma^+\gamma_5$		σ^{ij}, σ^{-+}	
Hadron	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

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

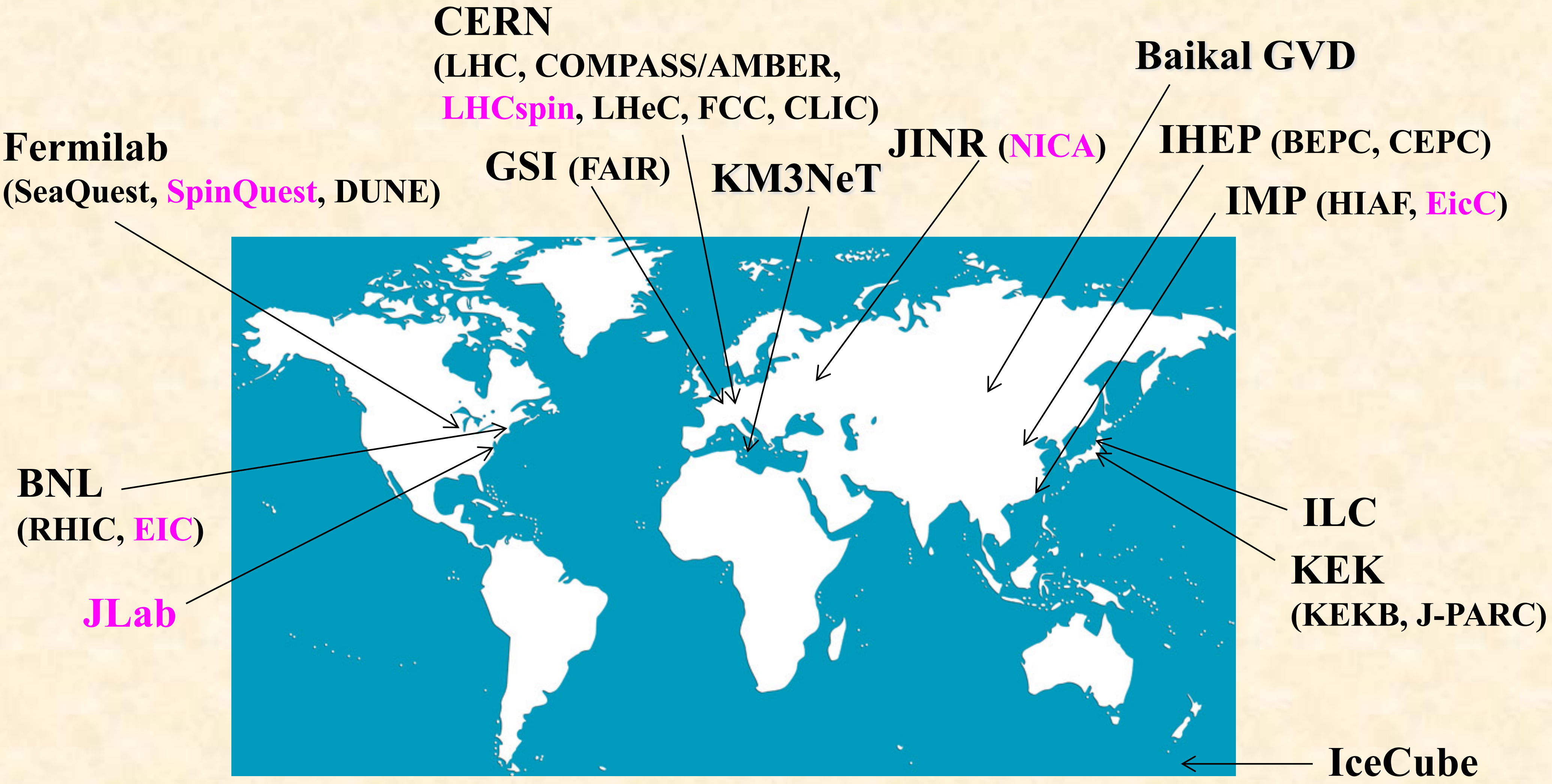
Twist-3 TMDs

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



CERN
(LHC, COMPASS/AMBER,
LHCspin, LHeC, FCC, CLIC)

Baikal GVD

Fermilab
(SeaQuest, SpinQuest, DUNE)

GSI (FAIR)

KM3NeT

JINR (NICA)

IHEP (BEPC, CEPC)

IMP (HIAF, EicC)

BNL
(RHIC, EIC)

JLab

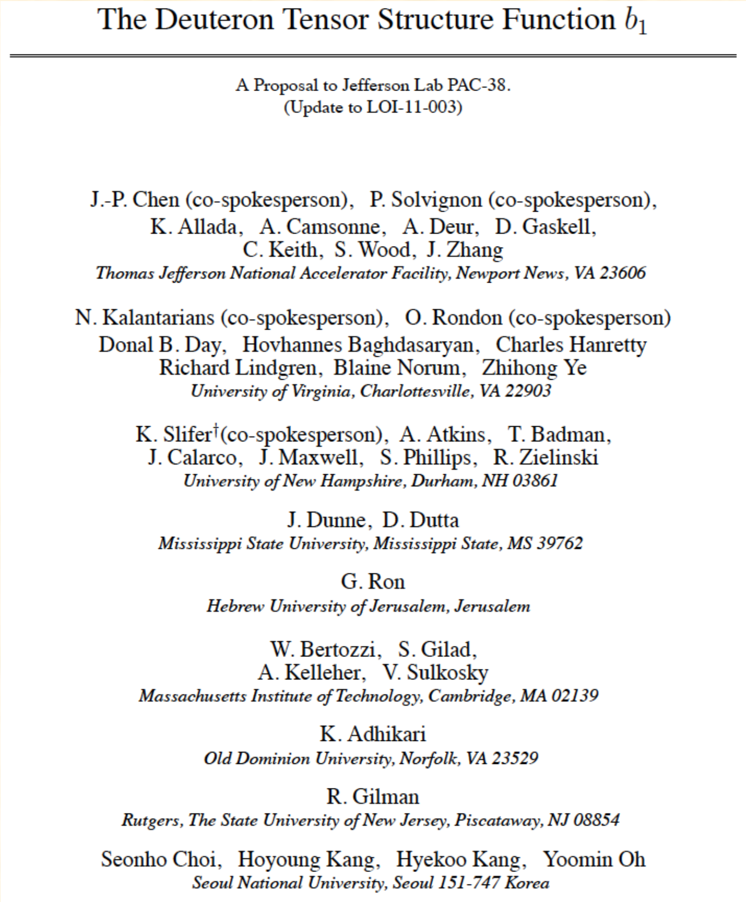
ILC

KEK
(KEKB, J-PARC)

IceCube

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)

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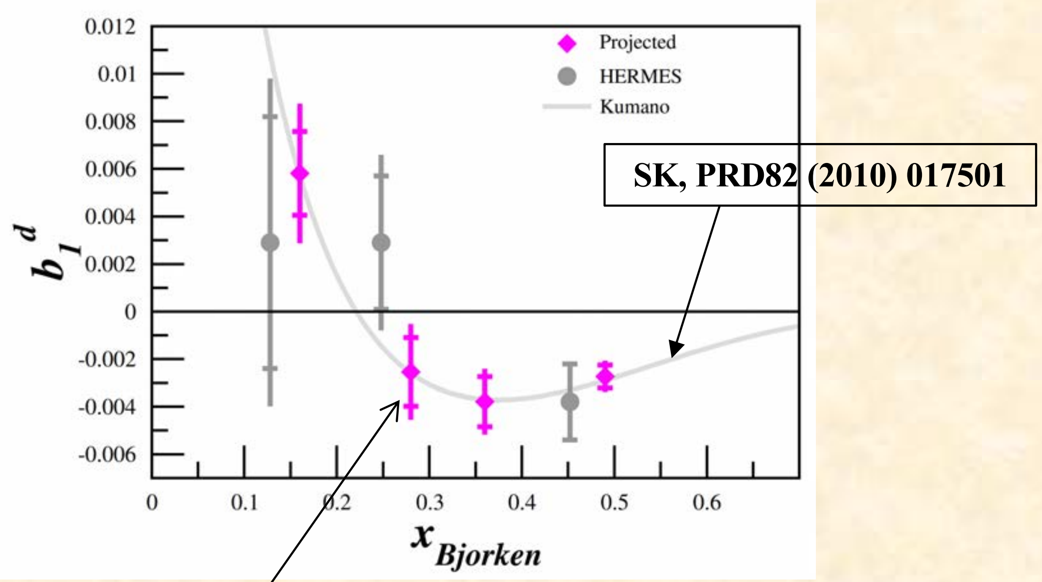
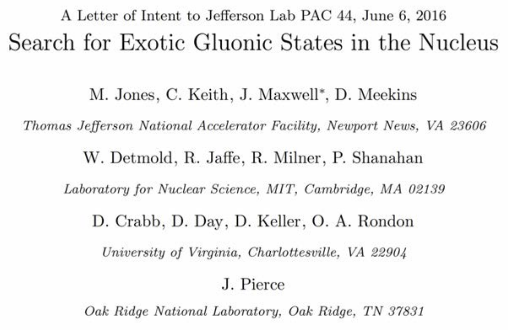


SK, PRD82 (2010) 017501

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

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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

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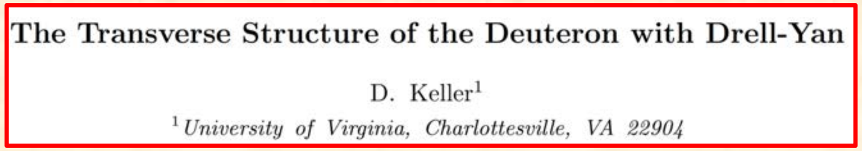
Fermilab experimentalists are interested in the gluon transversity by replacing the E1039 proton target for the deuteron one. (Spokesperson of E1039: D. Keller) However, there was no theoretical formalism until our work.

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



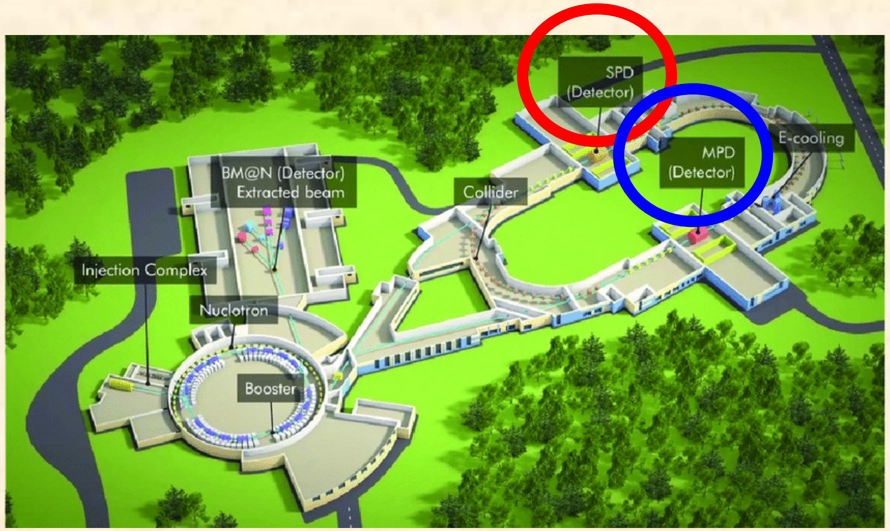
The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

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

Proposal for a Fermilab-PAC in 2023.

Nuclotron-based Ion Collider fAcility (NICA)



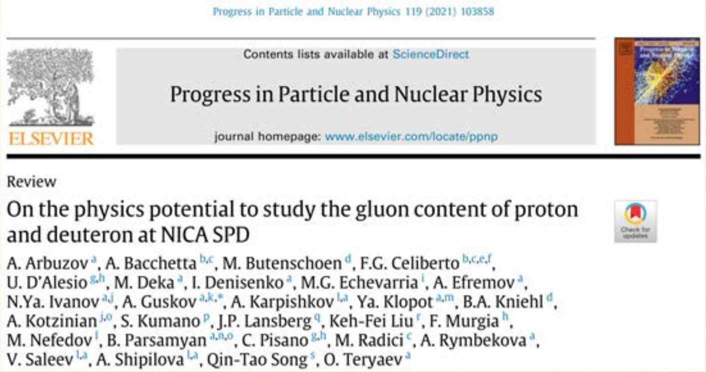
SPD (Spin Physics Detector for physics with polarized beams)
MPD (MultiPurpose Detector for heavy ion physics)

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

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

$\vec{p}+\vec{d}$ 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,
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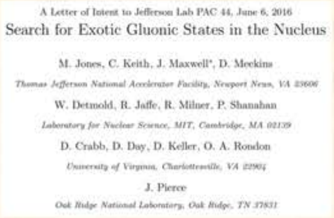
Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
Seoul National University, Seoul 151-747 Korea

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

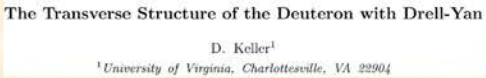
M. Jones, C. Keith, J. Maxwell*, D. Meekins
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

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

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

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

LHCspin

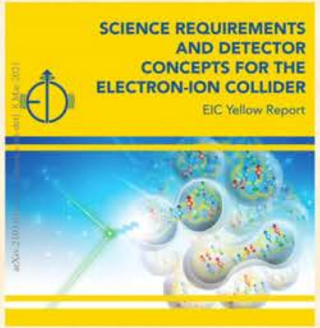
CERN-ESPP-Note-2018-111

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

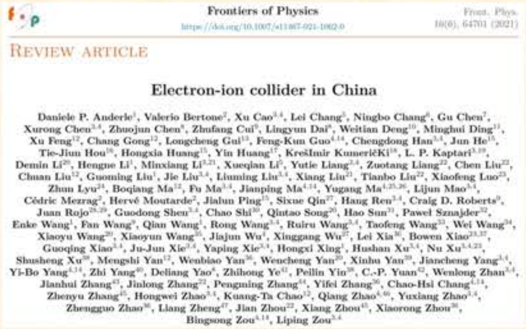


SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

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

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



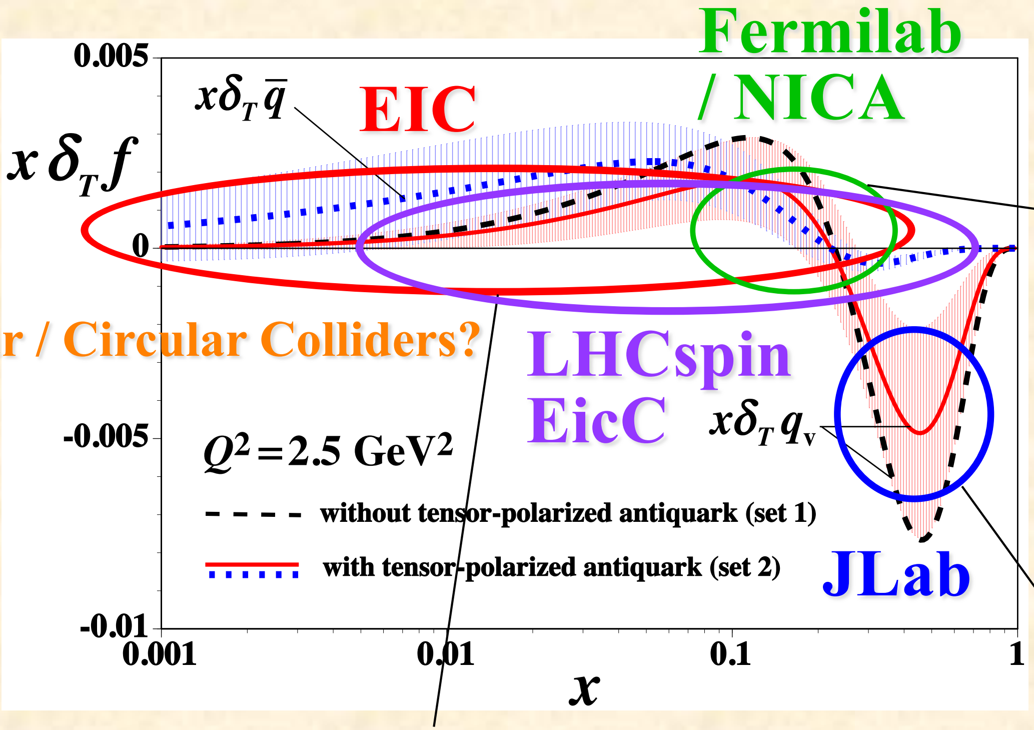
Frontiers of Physics
https://doi.org/10.1007/s11467-021-1062-0
Front. Phys. 16(6), 64701 (2021)

REVIEW ARTICLE

Electron-ion collider in China

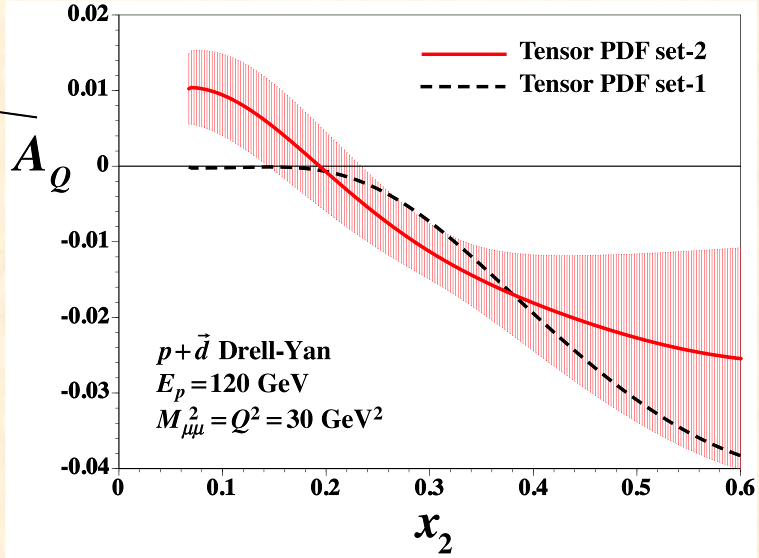
Daniele P. Anderle^{1}, Valerio Bertone^{2}, Xu Cao^{3,4}, Lei Chang^{5}, Ningbo Chang^{6}, Gu Chen^{7}, Xurong Chen^{3,4}, Zhuojun Chen^{8}, Zhufang Cui^{9}, Lingyun Dai^{8}, Weitian Deng^{10}, Minghui Ding^{11}, Xu Feng^{12}, Chang Gong^{12}, Longcheng Gui^{13}, Feng-Kun Guo^{4,14}, Chengdong Han^{3,4}, Jun He^{15}, Tie-Jiun Hou^{16}, Hongxia Huang^{15}, Yin Huang^{17}, Krešimir KumeričKi^{18}, L. P. Kaptari^{3,19}, Demin Li^{20}, Hengne Li^{1}, Minxiang Li^{3,21}, Xueqian Li^{5}, Yutie Liang^{3,4}, Zuotang Liang^{22}, Chen Liu^{22}, Chuan Liu^{12}, Guoming Liu^{1}, Jie Liu^{3,4}, Liuming Liu^{3,4}, Xiang Liu^{21}, Tianbo Liu^{22}, Xiaofeng Luo^{23}, Zhun Lyu^{24}, Boqiang Ma^{12}, Fu Ma^{3,4}, Jianping Ma^{4,14}, Yugang Ma^{4,25,26}, Lijun Mao^{3,4}, Cédric Mezrag^{2}, Hervé Moutarde^{2}, Jialun Ping^{15}, Sixue Qin^{27}, Hang Ren^{3,4}, Craig D. Roberts^{9}, Juan Rojo^{28,29}, Guodong Shen^{3,4}, Chao Shi^{30}, Qintao Song^{20}, Hao Sun^{31}, Paweł Sznajder^{32}, Enke Wang^{1}, Fan Wang^{9}, Qian Wang^{1}, Rong Wang^{3,4}, Ruiru Wang^{3,4}, Taofeng Wang^{33}, Wei Wang^{34}, Xiaoyu Wang^{20}, Xiaoyun Wang^{35}, Jiajun Wu^{4}, Xinggang Wu^{27}, Lei Xia^{36}, Bowen Xiao^{23,37}, Guoqing Xiao^{3,4}, Ju-Jun Xie^{3,4}, Yaping Xie^{3,4}, Hongxi Xing^{1}, Hushan Xu^{3,4}, Nu Xu^{3,4,23}, Shusheng Xu^{38}, Mengshi Yan^{12}, Wenbiao Yan^{36}, Wencheng Yan^{20}, Xinhu Yan^{39}, Jiancheng Yang^{3,4}, Yi-Bo Yang^{4,14}, Zhi Yang^{40}, Deliang Yao^{8}, Zhihong Ye^{41}, Peilin Yin^{38}, C.-P. Yuan^{42}, Wenlong Zhan^{3,4}, Jianhui Zhang^{43}, Jinlong Zhang^{22}, Pengming Zhang^{44}, Yifei Zhang^{36}, Chao-Hsi Chang^{4,14}, Zhenyu Zhang^{45}, Hongwei Zhao^{3,4}, Kuang-Ta Chao^{12}, Qiang Zhao^{4,46}, Yuxiang Zhao^{3,4}, Zhengguo Zhao^{36}, Liang Zheng^{47}, Jian Zhou^{22}, Xiang Zhou^{45}, Xiaorong Zhou^{36}, Bingsong Zou^{4,14}, Liping Zou^{3,4}

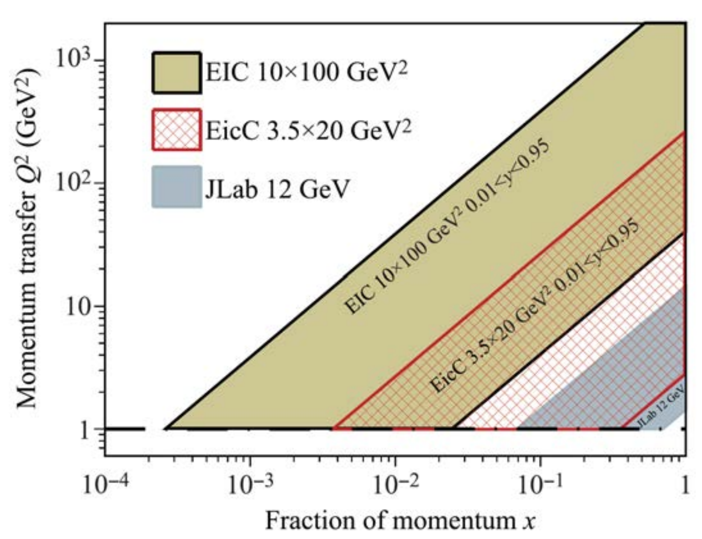
x regions of b_1 in 2020's and 2030's



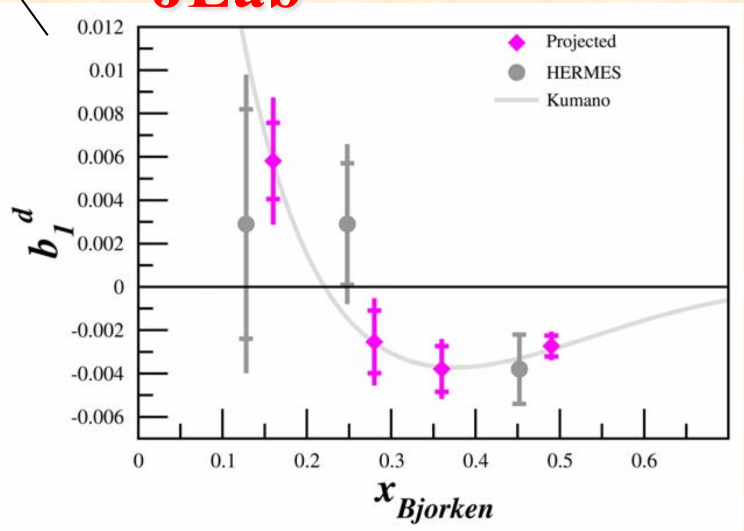
Linear / Circular Colliders?

Fermilab





JLab



Summary

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

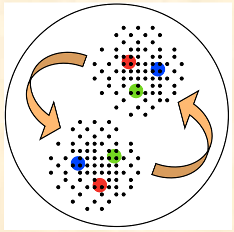
- Tensor structure in quark-gluon degrees of freedom
- Tensor-polarized structure function b_1 and PDFs, gluon transversity

  Experiments at JLab, Fermilab, NICA, LHCspin/AMBER, EIC/EicC, • • •

- New signature beyond "standard" hadron physics?

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

standard model



?

- 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