Polarized structure functions of spin-1 deuteron in proton-deuteron Drell-Yan processes

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17th International Workshops on Hadron Structure and Spectroscopy (IWHSS2020)
Trieste, Italy (remote), November 16-18, 2020
https://agenda.infn.it/event/20446/

Recent papers: (1) SK and Qin-Tao Song, PRD 94 (2016) 054022.
(2) W. Cosyn, Yu-Bing Dong, SK, M. Sargsian, PRD 95 (2017) 074036.
(3) SK and Qin-Tao Song, PRD 101 (2020) 054011 & 094013.
(4) SK and Qin-Tao Song, arXiv:2011.08583.

November 18, 2020

Contents

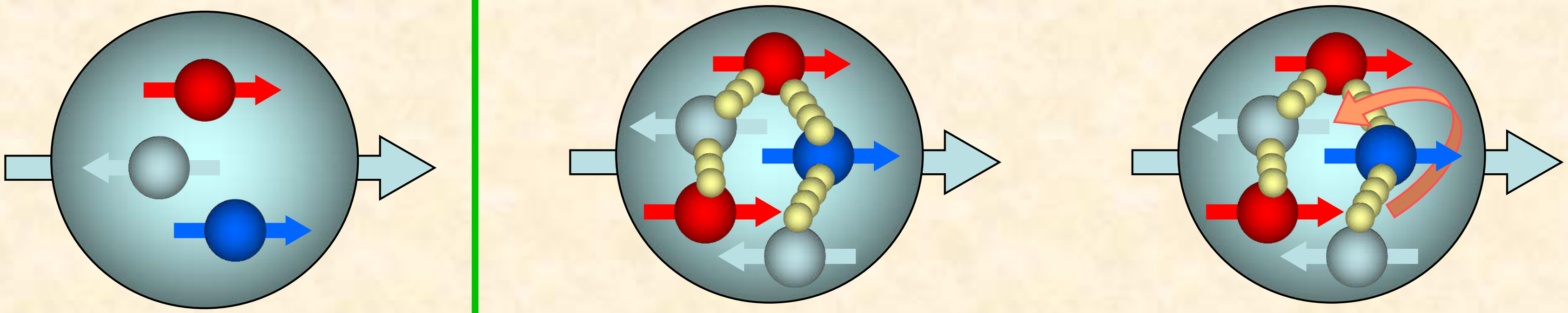
Note on my notations

Gluon transversity: $\Delta_T g$

Tensor-polarized gluon distribution: $\delta_T g$

Nucleon spin

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

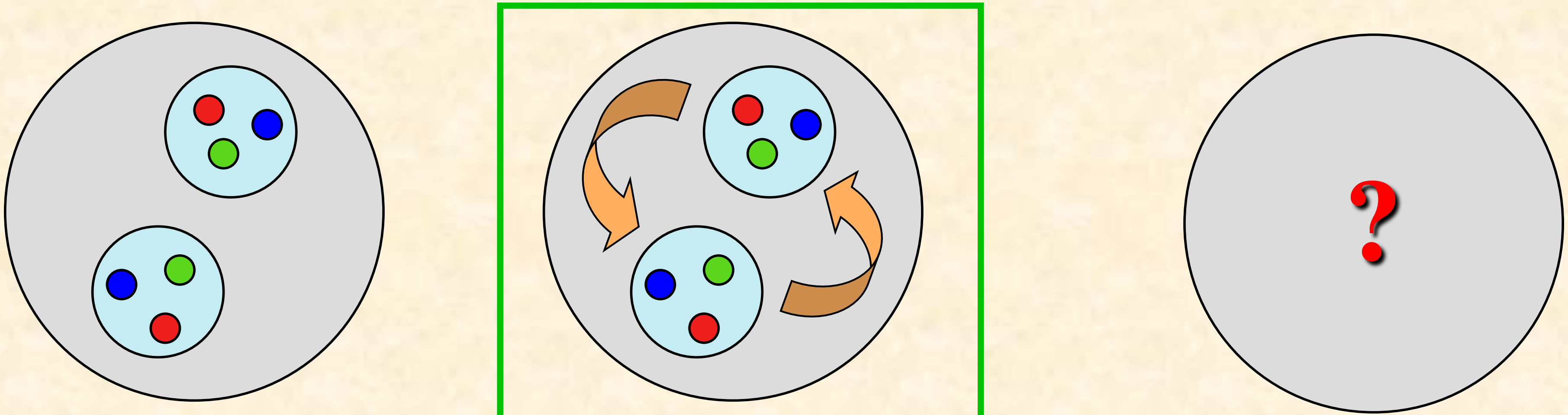


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure crisis!?



only S wave

$b_1 = 0$

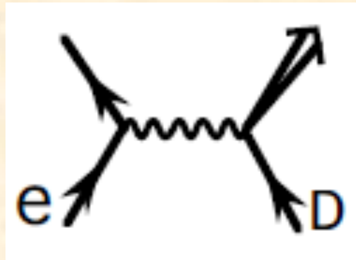
S + D waves

standard model $b_1 \neq 0$

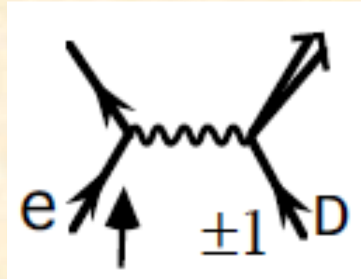
$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

Structure Functions

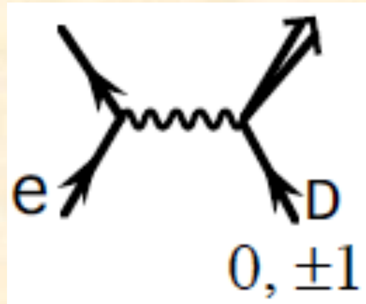
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

Parton Model

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

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

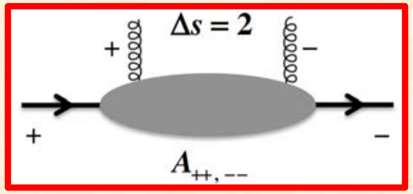
$\left[q_\uparrow^H\left(x,Q^2\right)\right]$

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

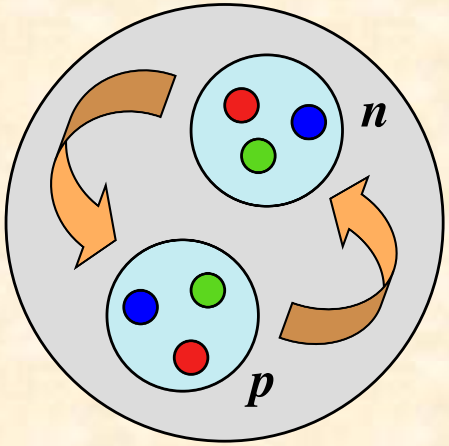
Gluon transversity $\Delta_T g$

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

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

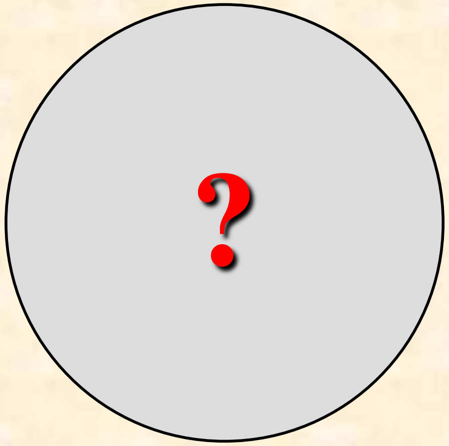


Note: Gluon transversity does not exist for spin-1/2 nucleons.



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 $\Delta_T g \neq 0$?

Tensor-polarized structure functions of spin-1 hadrons

S. Kumano, Phys. Rev. D82 (2010) 017501;

S. Kumano and Qin-Tao Song, PRD 94 (2016) 054022;

W. Cosyn, Yu-Bing Dong, S. Kumano, and M. Sargsian, PRD 95 (2017) 074036.

HERMES results on b_1

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

27.6 GeV/c $\rightleftarrows$, 0

positron → ● deuteron

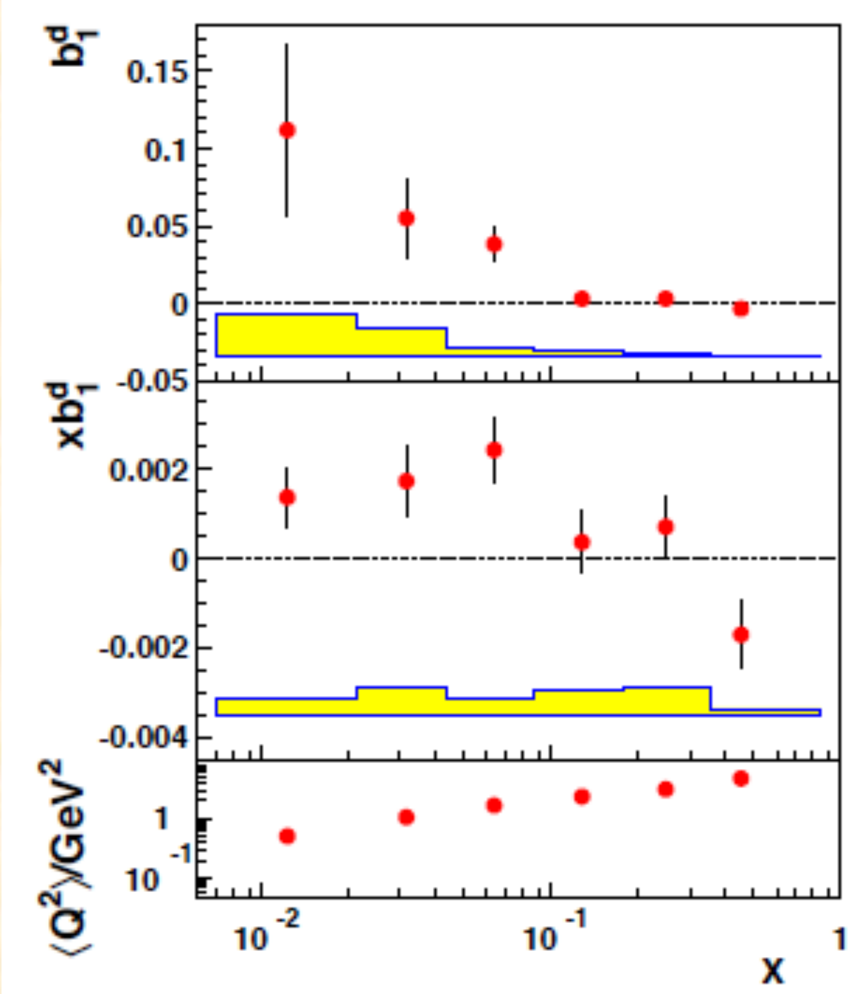
b_1 measurement in the kinematical region

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

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

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

at $Q^2 = 5\text{ GeV}^2$



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

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.

Standard model prediction for b_1 of deuteron

Convolution model: $A_{hH,hH}(x,Q^2) = \varepsilon_{h'}^{*\mu} W_{\mu\nu}^{H'H} \varepsilon_h^{\nu} = \int \frac{dy}{y} \sum_s f_s^H(y) \hat{A}_{hs,hs}(x/y, Q^2)$

$b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2}, \quad \hat{A}_{+\uparrow,+\uparrow} = F_1 - g_1, \quad \hat{A}_{+\downarrow,+\downarrow} = F_1 + g_1$

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

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

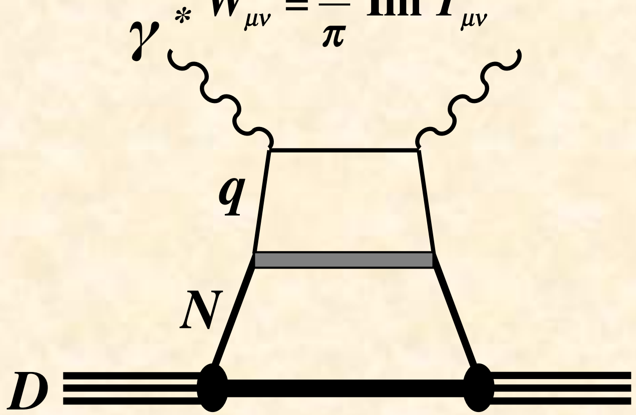
$b_1(x) = \int \frac{dy}{y} \delta_T f(y) F_1^N(x/y, Q^2), \quad y = \frac{Mp\cdot q}{M_N P\cdot q} \simeq \frac{2p^-}{P^-}$

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

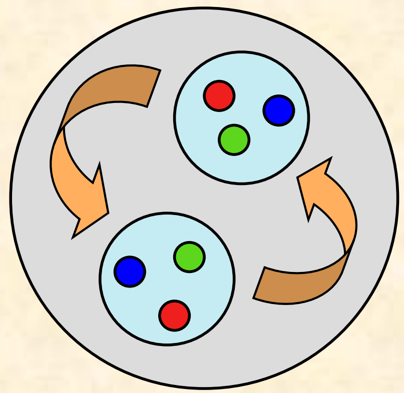
$= \int d^3p \, y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p)\phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] (3\cos^2\theta - 1) \delta\left(y - \frac{p\cdot q}{M_N \nu}\right)$

S-D term D-D term

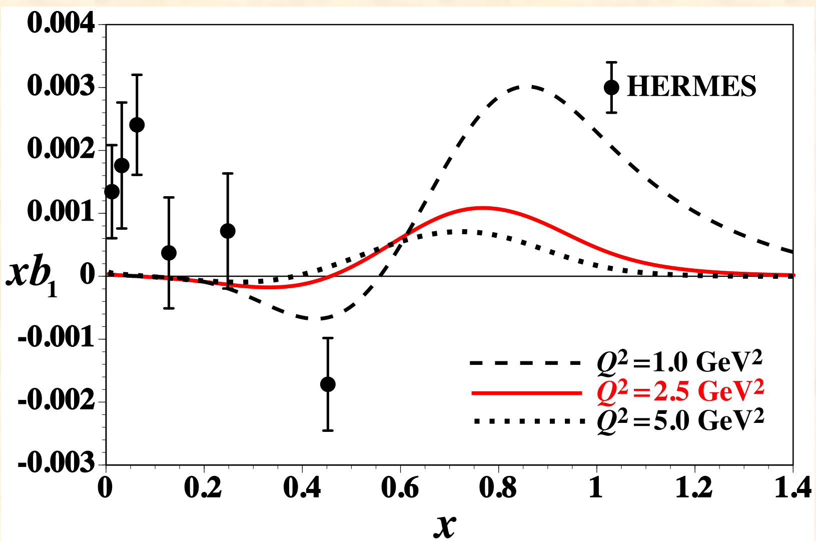
$W_{\mu\nu} = \frac{1}{\pi} \mathrm{Im}\, T_{\mu\nu}$



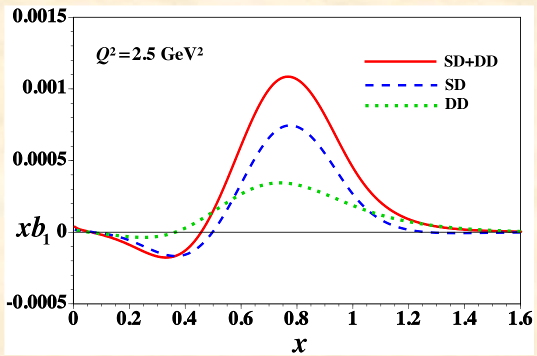
Standard model of the deuteron



S + D waves



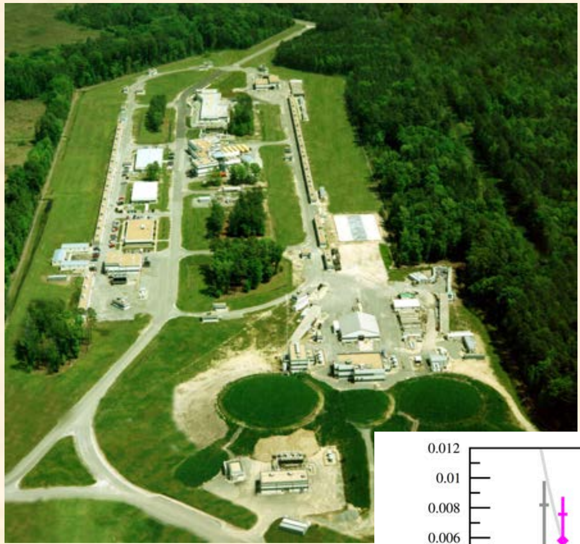
W. Cosyn, Yu-Bing Dong, S. Kumano, M. Sargsian, Phys. Rev. D 95 (2017) 074036.



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

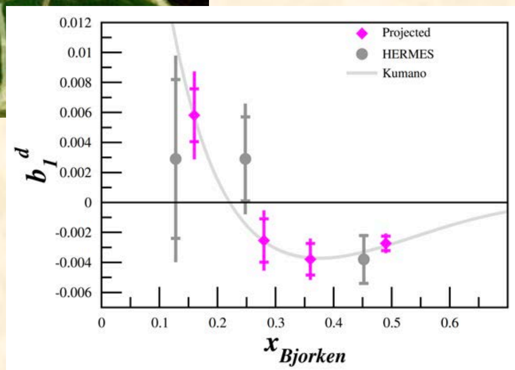
Standard convolution model does not work for the deuteron tensor structure!?

Experimental possibilities



© JLab

Approved experiment! (PR12-11-110)



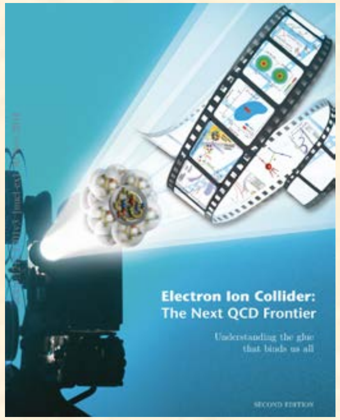
E1039 experiment

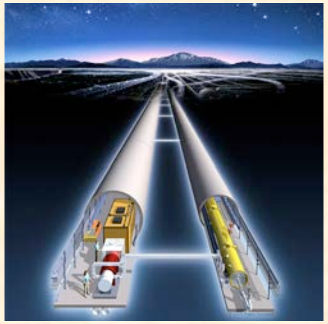
© Fermilab

NICA

© JINR

EIC/EicC





Linear Collider? (with fixed target)

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

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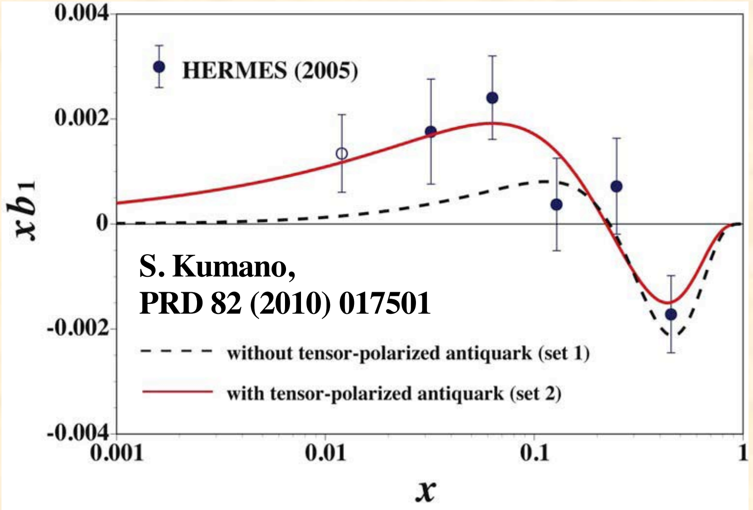
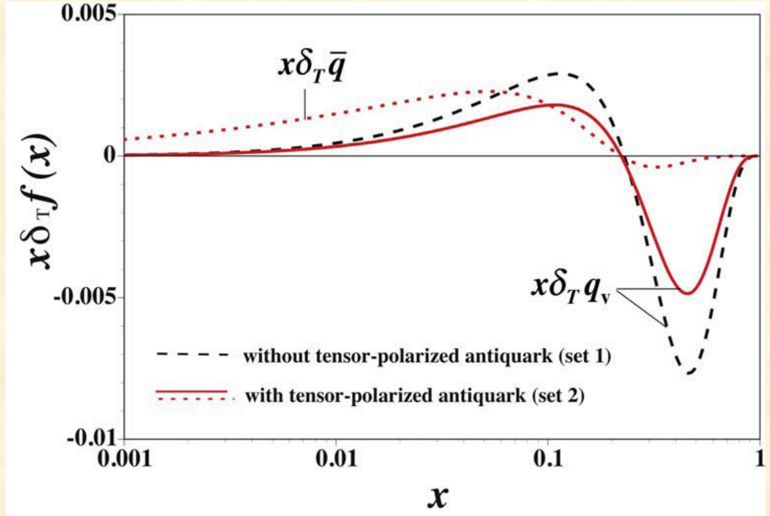
© CERN-COMPASS

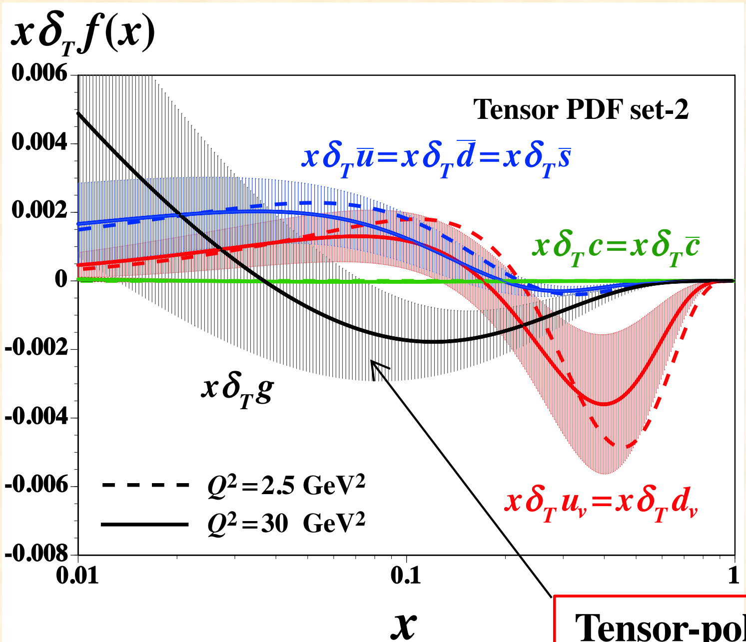
Private discussions with COMPASS experimentalist (Y. Miyachi) on tensor polarization

Tensor-polarized PDFs



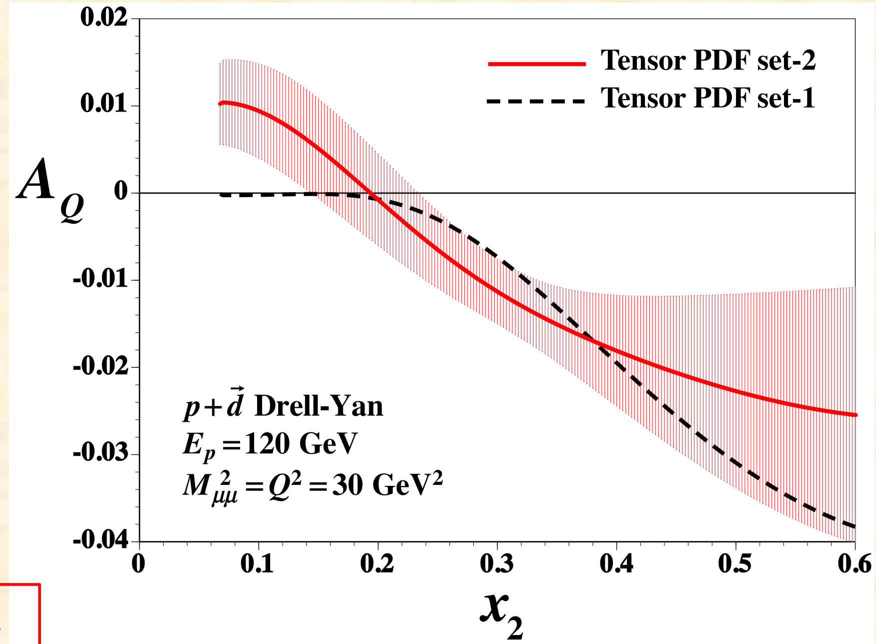


Q^2 evolution $\quad Q^2 = 2.5\ \mathrm{GeV}^2 \to 30\ \mathrm{GeV}^2$



Tensor-polarized gluon appears by Q^2 evolution.

Drell-Yan spin asymmetry@Fermilab



Experimental possibility at Fermilab

Polarized fixed-target experiments at the Main Injector

Drell-Yan experiment with a polarized proton target

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

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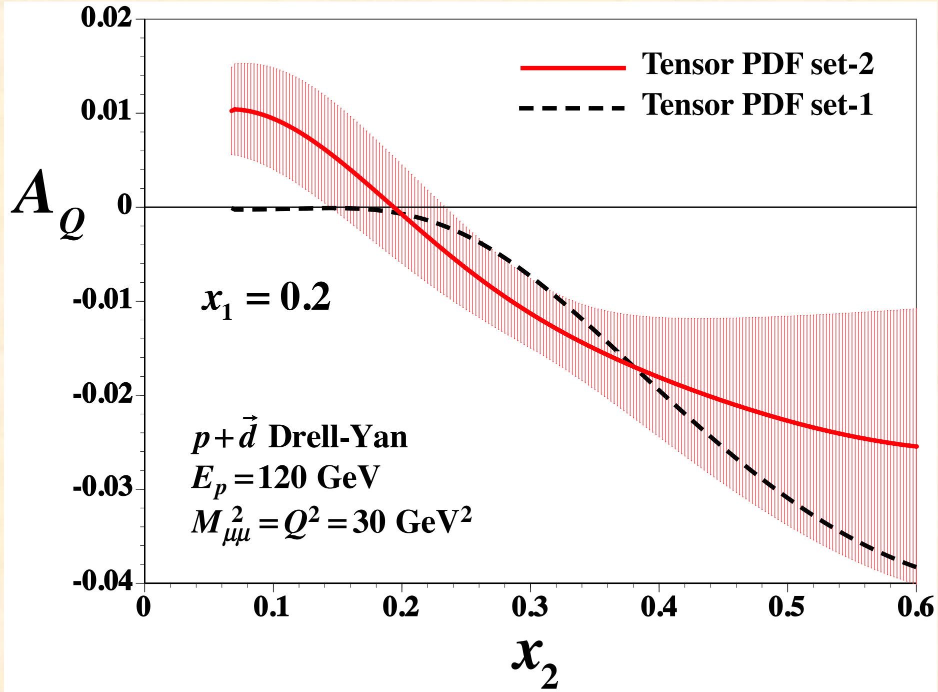
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904

Fermilab-E1039 (SpinQuest)

Tensor-polarized spin asymmetry

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

$$\simeq \frac{\sum_a e_a^2 q_a(x_1) \delta_T \bar{q}_a(x_2)}{2 \sum_a e_a^2 q_a(x_1) \bar{q}_a(x_2)} \quad \text{at large } x_F = x_1 - x_2$$

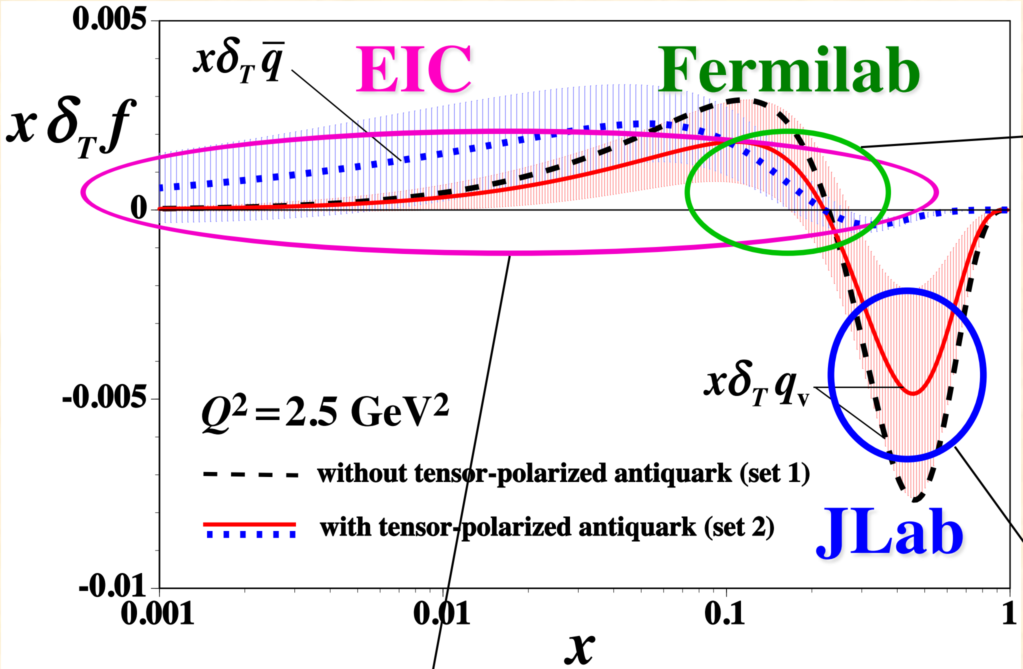


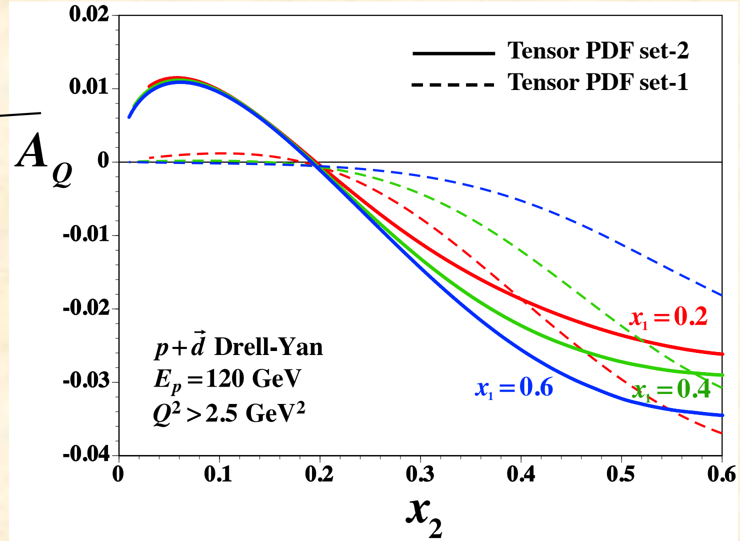
S. Kumano and Qin-Tao Song, Phys. Rev. D94 (2016) 054022.

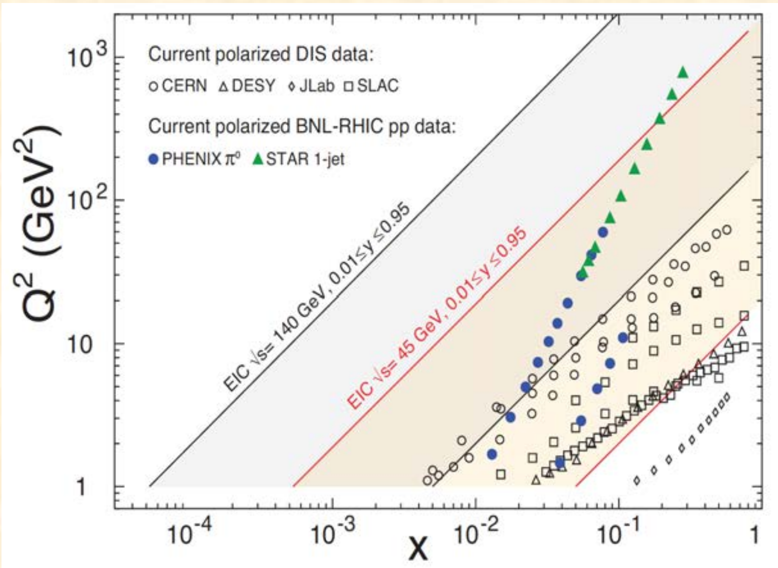
Future prospects on tensor-polarized PDFs

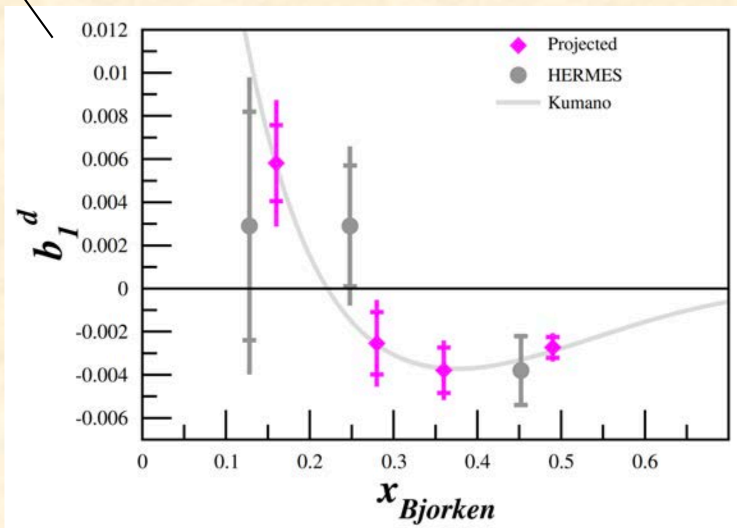
NICA

COMPASS?!





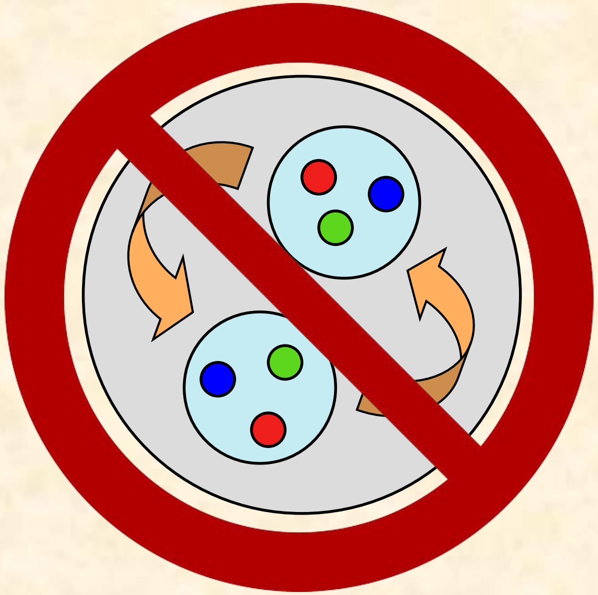




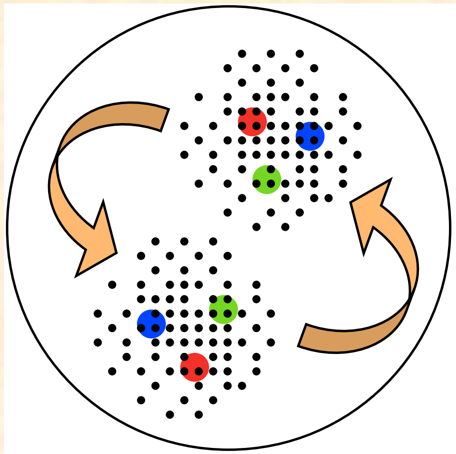
Summary on b_1 prediction

Spin-1 structure functions of the deuteron

- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: JLab (approved), Fermilab, NICA, ... , EIC, ILC, ...



standard model



? new exotic mechanism?

Hidden color in deuteron?

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

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

Possible studies on gluon transversity

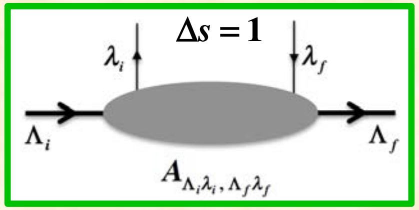
S. Kumano and Qin-Tao Song, Phys. Rev. D 101 (2020) 054011 & 094013;
A. Arbuzov *et al*., to be submitted to Progress in Nuclear and Particle Physics.

Gluon transversity $\Delta_T g$

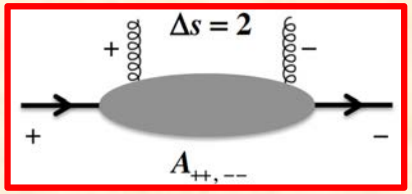
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, conservation $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

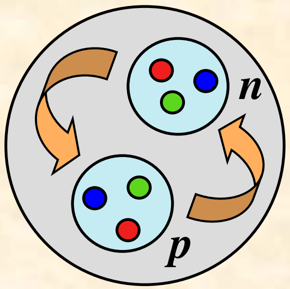
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \to \lambda_f = -\frac{1}{2}$ quark spin flip ($\Delta s = 1$)



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.

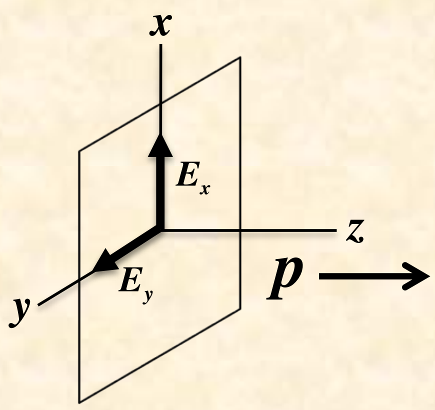


S + D waves

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

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

Gluon transversity distribution in deuteron



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

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

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

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

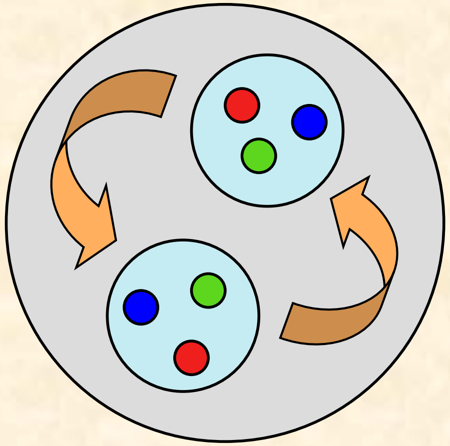
Confusing situation of gluon transversity

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

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

→ One can imagine how premature this field is!

Exotic components in nuclei beyond simple bound states of nucleons



S + D waves

Deuteron = proton + neutron

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

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

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

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

(There was no experimental possibility for 2020 – 1992 = 28 years, so that theorists were not interested in studying this topic.)

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

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University of Virginia, Charlottesville, VA 22904

J. Pierce

Oak Ridge National Laboratory, Oak Ridge, TN 37831

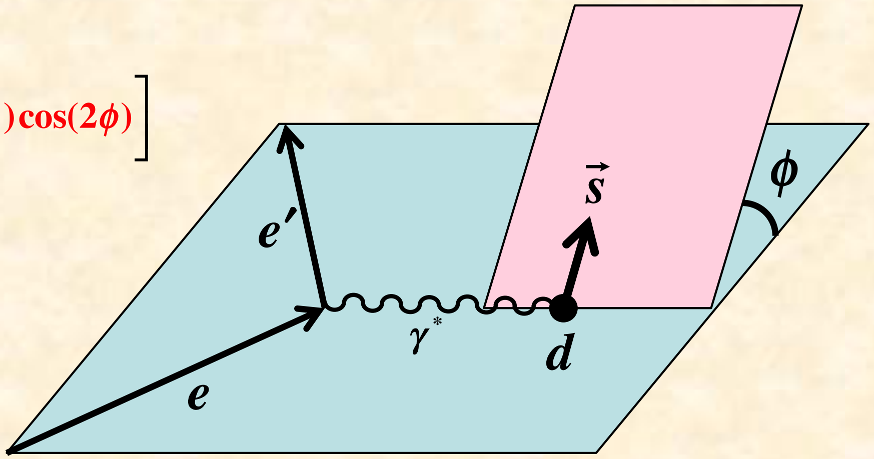
For development of polarized deuteron target, see D. Keller, D. Crabb, D. Day Nucl. Inst. Meth. Phys. Res. A981 (2020) 164504.

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.



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.

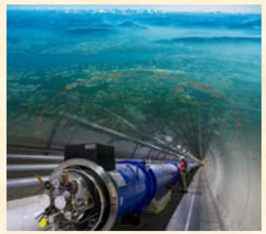
Fermilab-MI

NICA

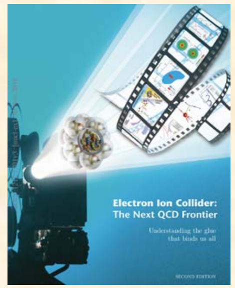
RHIC (fixed target)

GSI-FAIR

J-PARC

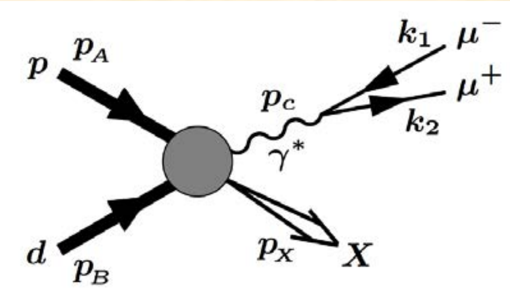


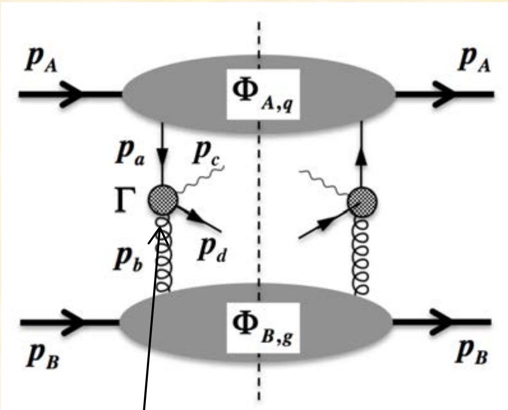
LHC (fixed target)
COMPASS

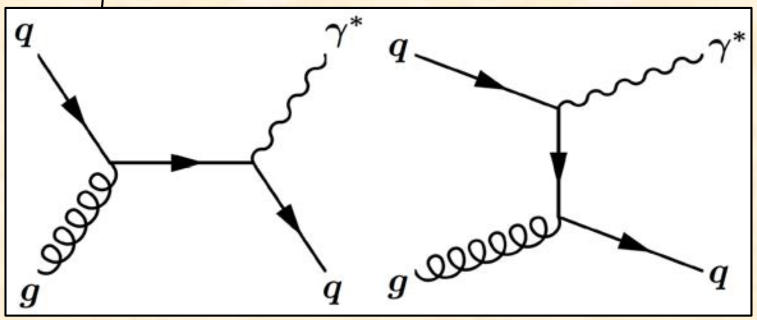


EIC

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)

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

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

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

We have not done on J/ψ production for NICA but similar formalism should be applied.

Proton-deuteron Drell-Yan cross section

Drell-Yan cross section

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

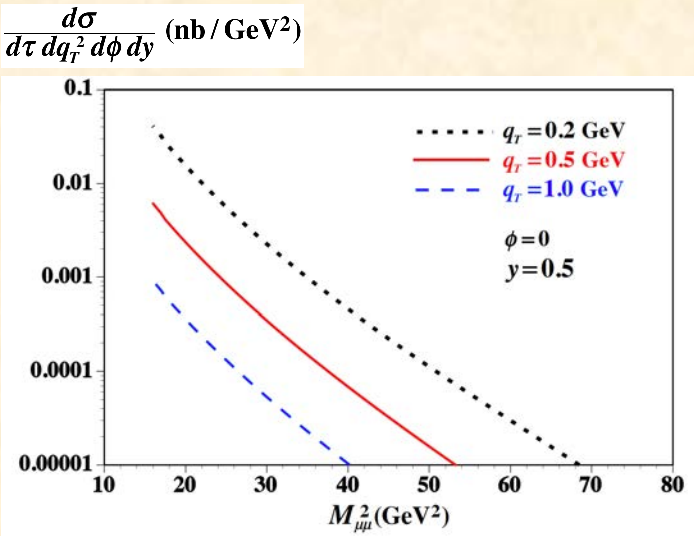
$$C_F = \frac{N_c^2 - 1}{2N_c}, \quad \min(x_a) = \frac{x_1 - \tau}{1 - x_2}, \quad x_b = \frac{x_a x_2 - \tau}{x_a - \tau}$$

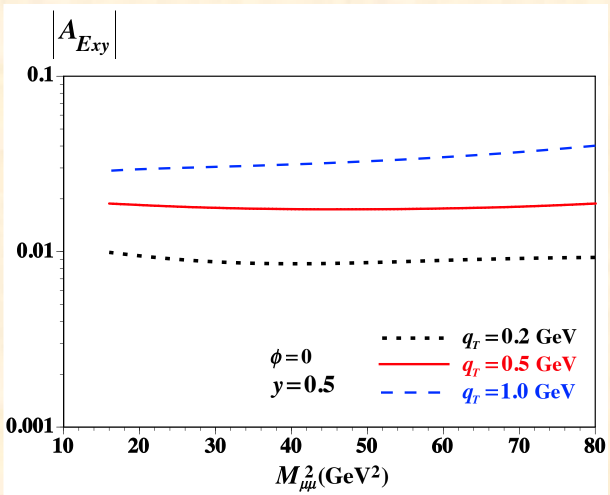
= (unpolarized PDFs of proton) * (gluon transversity distribution in the deuteron)

- Consider the Fermilab-E1039 experiment with the proton beam of $p = 120$ GeV
- No available $\Delta_T g$, so we may tentatively assume $\Delta_T g = \Delta g_p + \Delta g_n$ $\left(\text{or } \frac{\Delta g_p + \Delta g_n}{2}, \ \frac{\Delta g_p + \Delta g_n}{4}\right)$
- 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 in December, 2020 (D. Keller) !

Linear polarizations of the deuteron

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

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
  $\rightarrow$ to measure gluon transversity

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

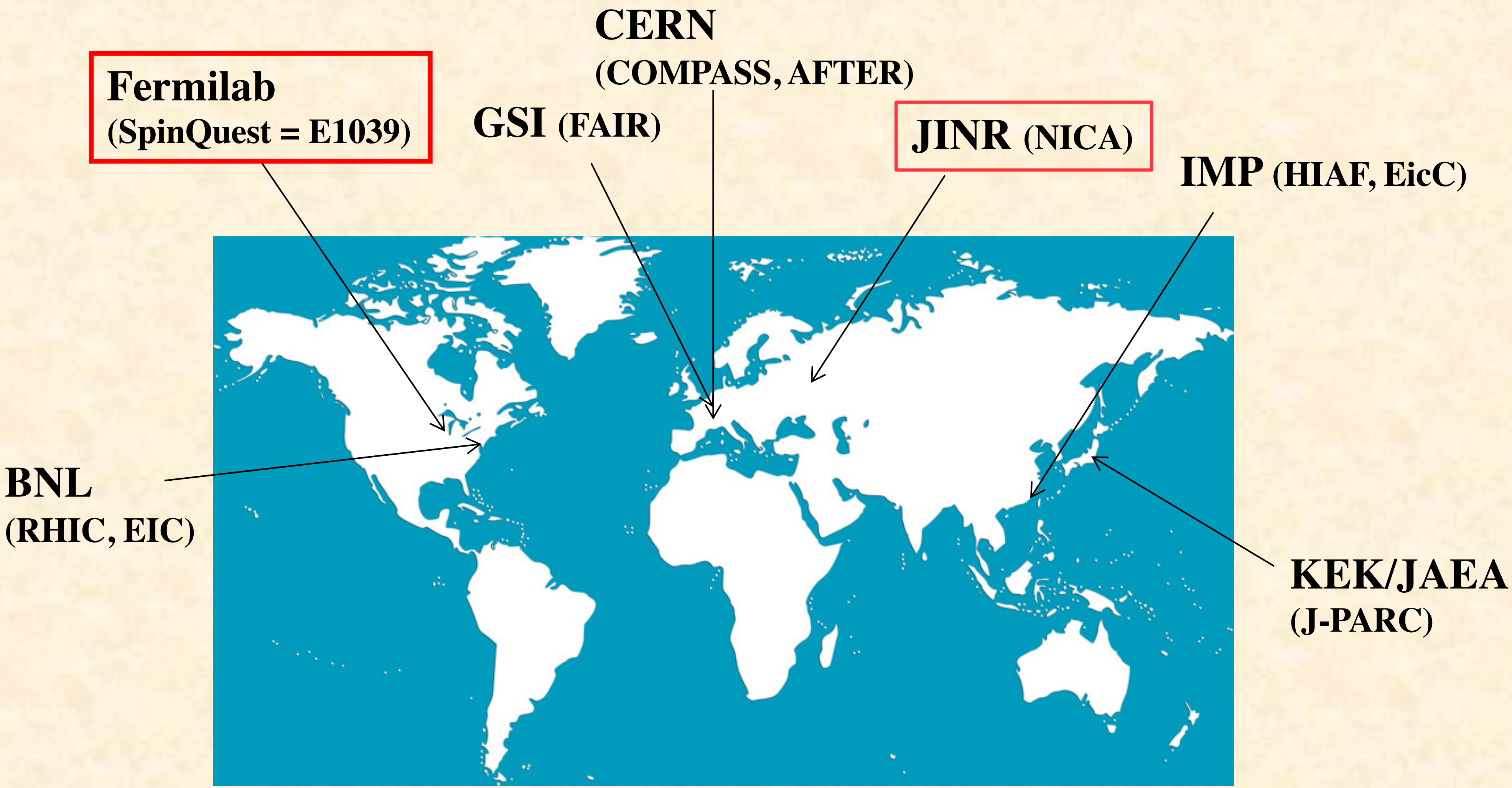
(2) Combination of transverse polarizations.

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

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

	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 polarization	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 polarization	Linear x	(1, 0, 0)	0	0	0	$+\frac{1}{2}$	−1
	Linear y	(0, 1, 0)	0	0	0	$+\frac{1}{2}$	+1

Possible hadron facilities for gluon transversity



Experimental possibility at Fermilab (middle 2020's)

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

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Fermilab-E1039

Drell-Yan experiment with a polarized proton target

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

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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.

J-PARC?

© J-PARC

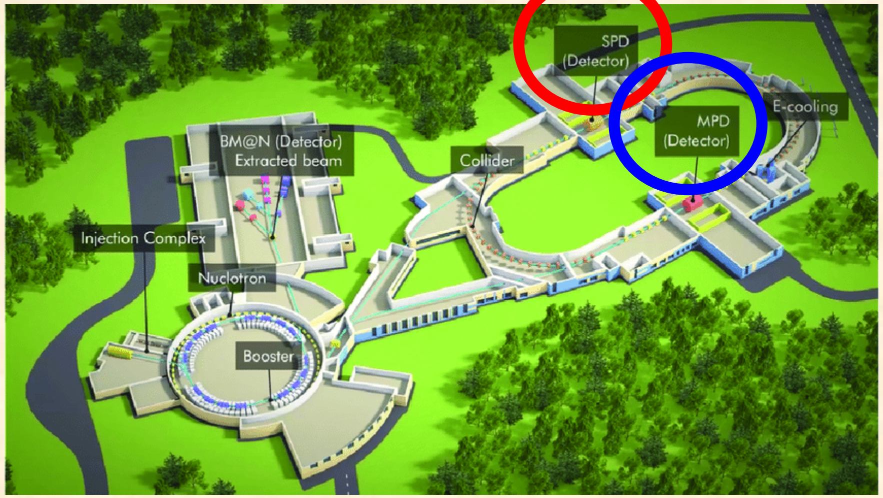
The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

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

New proposal is being written for a Fermilab-PAC in December, 2020.

Nuclotron-based Ion Collider fAcility (NICA)



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

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

$\vec{d}+\vec{d}: \quad \sqrt{s_{NN}} = 4 \sim 14$ 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.*, to be submitted to Progress in Nuclear and Particle Physics.

Unique opportunity in high-energy spin physics, especially on the deuteron spin physics.
→ Theoretical formalisms need to be developed.

It is a timely project in 2020's in competition with JLab, Fermilab, and EIC (possibly also J-PARC, GSI-FAIR, EicC).

Summary on transversity situation

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

- We proposed to use hadron facilities for measuring $\Delta_T g$.
  So far, we showed the theoretical formalism and cross sections for the proton-deuteron Drell-Yan process with $\Delta_T g$.
- It will be proposed within the Fermilab-E1039 experiment.
- $\Delta_T g$ should be measured also at NICA by J/ψ production
  → need theoretical formalism and numerical estimation.
- In principle, $\Delta_T g$ can be investigated at any other hadron facilities, COMPASS, RHIC, GSI-FAIR, J-PARC, LHC, EIC.
- $\Delta_T g$ → “exotic” components in nuclei beyond bound states of nucleons.

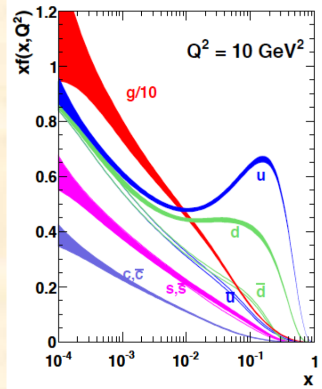
TMDs for spin-1 hadrons

S. Kumano and Qin-Tao Song,
arXiv:2011.08583 (appeared in arXiv today!)

GTMD and Wigner distribution for various structure functions

Form factor ← $\int dx\, d^2k_T$

PDF (Parton Distribution Function) ← $\int d^2k_T,\ \Delta \to 0$



e.g. HERA studies

GTMD $W(x, \vec{k}_T, \Delta) \xrightarrow{\Delta^+ \to 0}$ **Wigner** $W(x, \vec{k}_T, \vec{r}_T)$

$\Delta = p' - p$

3D world

$\int d^2k_T$ →

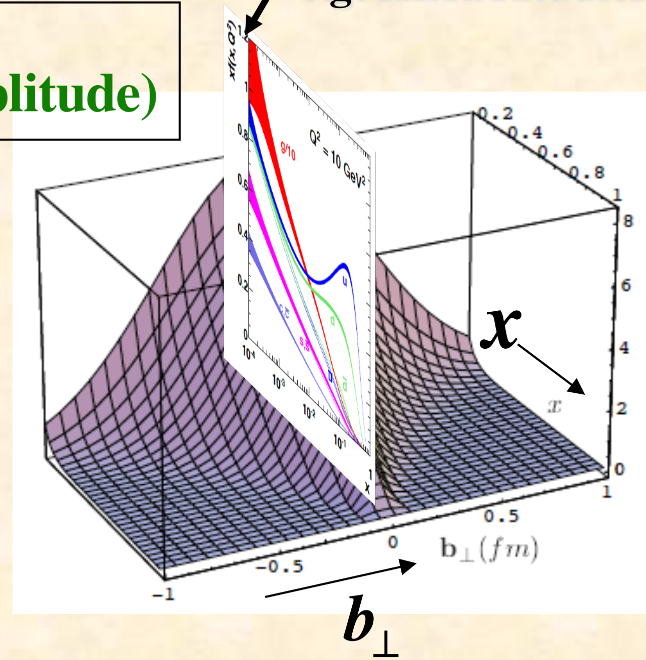
GPD (Generalized Parton Distribution)

$\xrightarrow{s \leftrightarrow t}$ **GDA (Generalized Distribution Amplitude)**

By the two-photon process $\gamma^* \gamma \to h\bar{h}$.

$\Delta \to 0$ →

TMD (Transverse Momentum Dependent) parton distribution

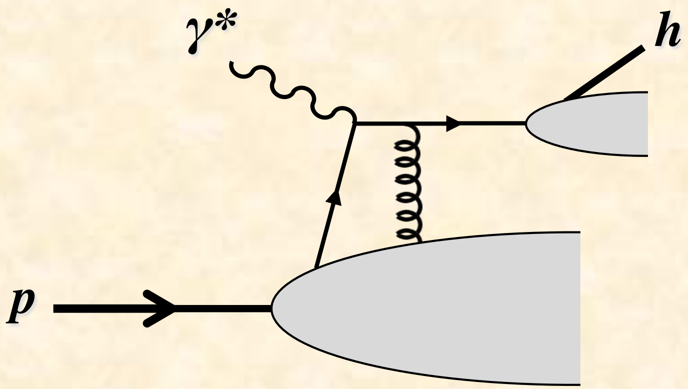


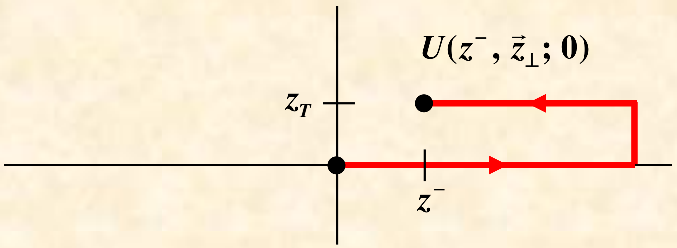
Importance of color flow (gauge link) in semi-inclusive DIS and Drell-Yan processes

$$q(x,k_\perp)=\int\frac{dz^- d^2z_\perp}{2(2\pi)^3}\,e^{-ixp^+z^-+i\vec{k}_\perp\cdot\vec{z}_\perp}\langle p|\bar{\psi}(z^-,\vec{z}_\perp)\gamma^+U(z^-,\vec{z}_\perp;0)\psi(0)|p\rangle\Big|_{z^+=0}$$

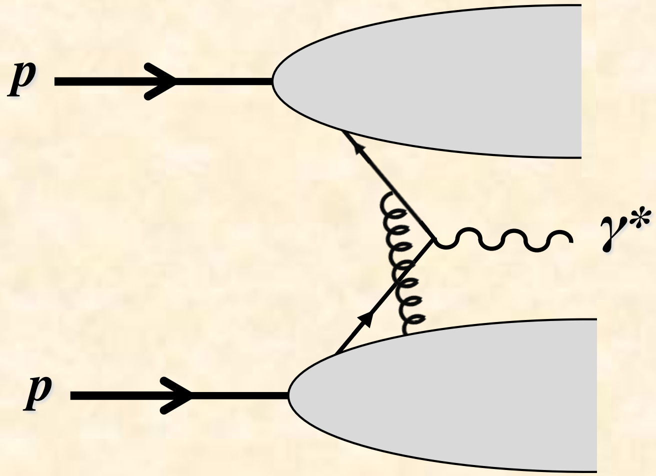
Semi-inclusive DIS (deep inelastic scattering):

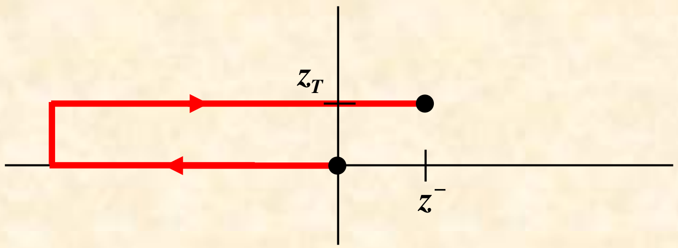
$e+p\to e'+h+X$





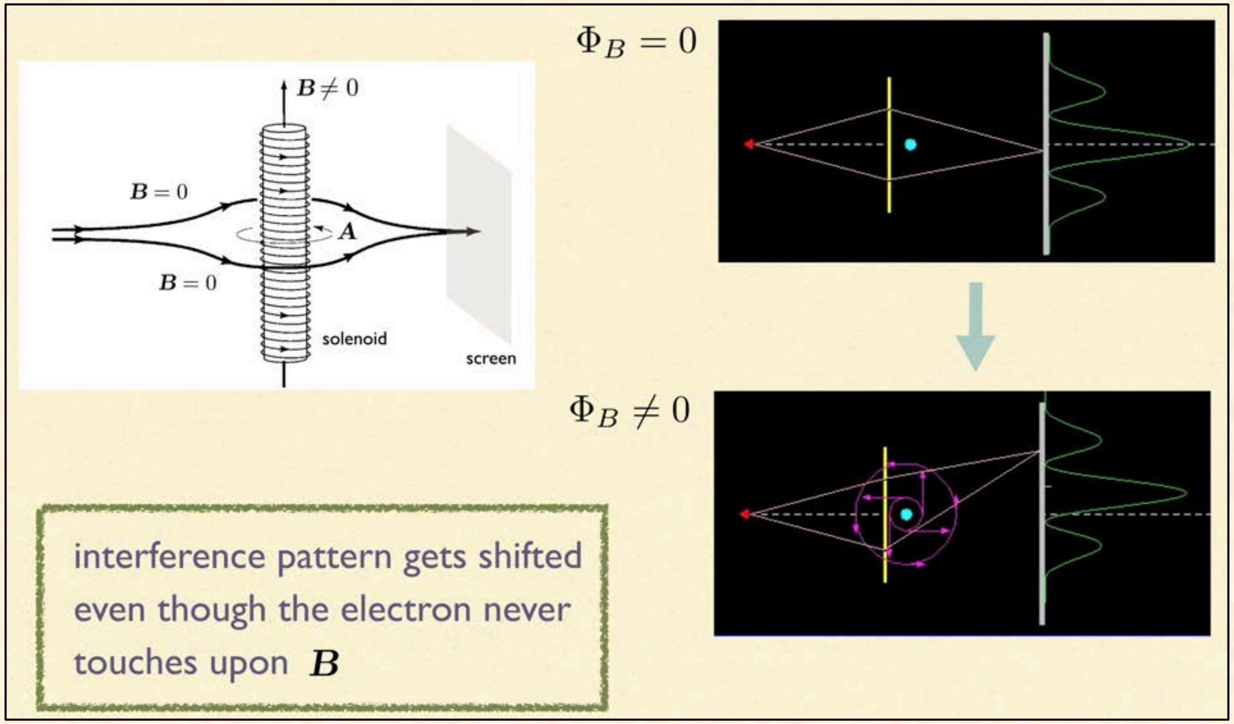
Drell-Yan process: $p+p\to\mu^+\mu^-+X$

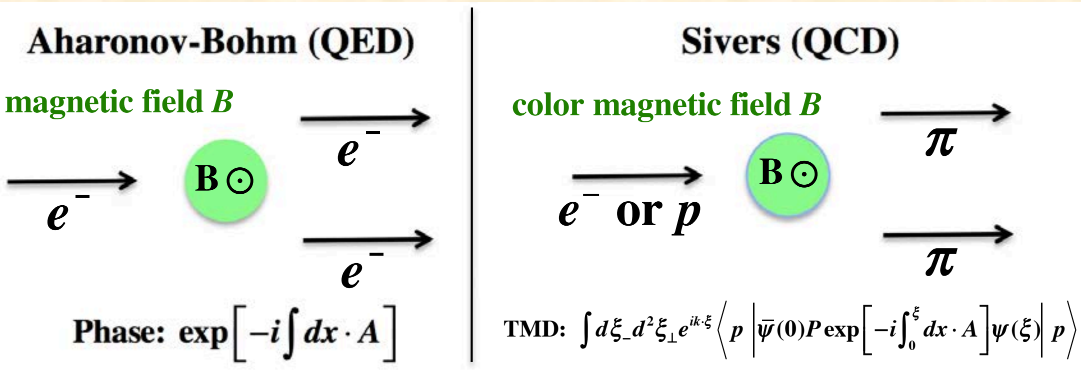




Aharonov-Bohm effect and TMDs

Tsutsui, Bacchetta@KEK Hadron physics workshop in March, 2015





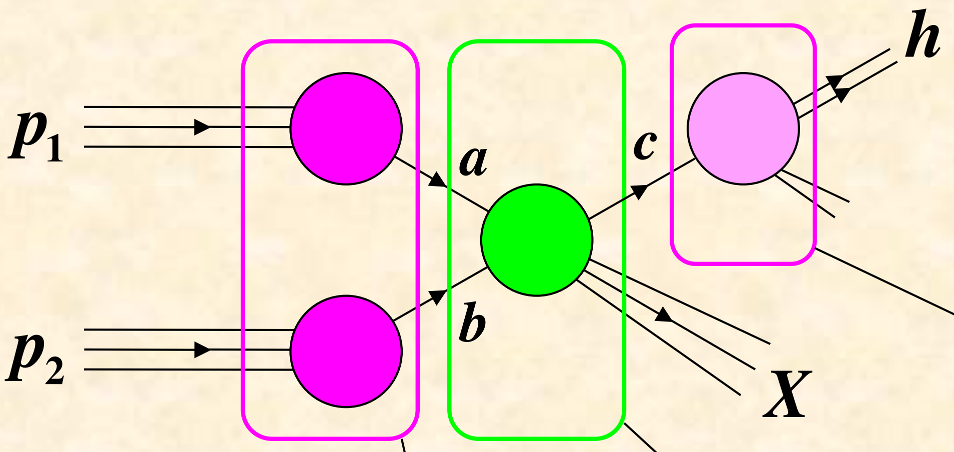
Aharonov-Bohm effects in QED and QCD

Let us consider, the pion production in electron-proton or proton-proton scattering with the polarized proton.

As the Aharanov-Bohm effect is the left-right asymmetry of the final electron, there is also a left-right asymmetry in the produced pion.

This is called a Sivers effect, which is an Aharanov-Bohm effect in QCD.

Factorization: Hadron production at LHC / RHIC



Soft part (nonperturbative)

Hard part (perturbative)

Cross section = soft part ⊗ hard part

$$\sigma = \sum_{a,b} f_a(x_a,Q^2) \otimes f_b(x_b,Q^2) \otimes \hat{\sigma}(ab \to HX) \otimes D_c^h(z,Q^2)$$

$f(x,Q^2)$ = parton distribution functions

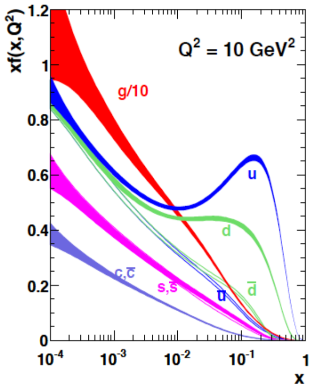
$\hat{\sigma}(ab \to HX)$ = parton-level cross sections

$D_c^h(z,Q^2)$ = fragmentation functions

fragmentation functions

+ ...

parton distribution functions



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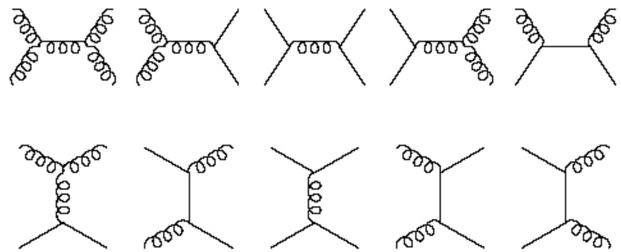
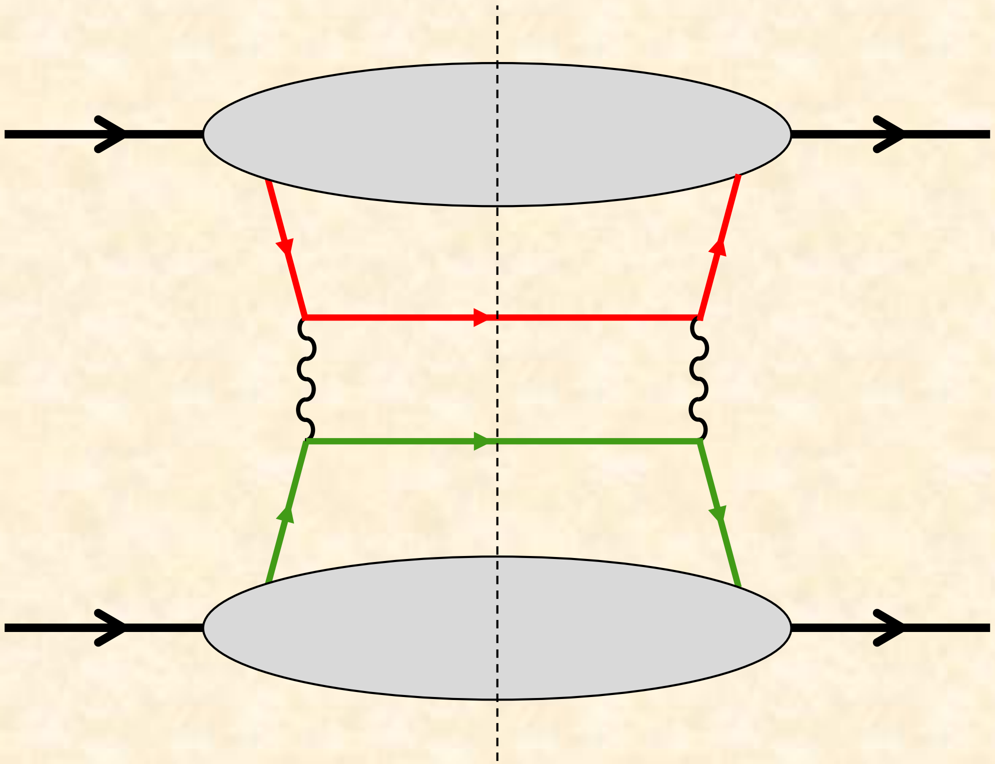
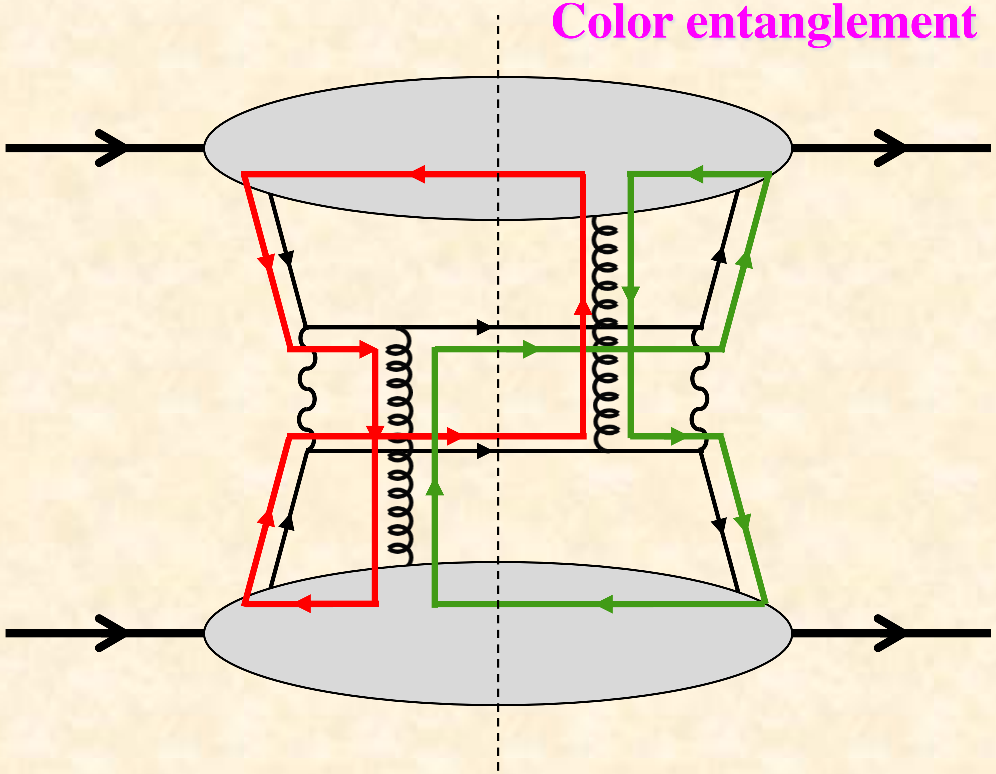


+ ...

Factorization breaking by color entanglement

Di-jet production: $p + p \to j_3 + j_4 + X$





Experimental effort:

A. Adare *et al*. (PHENIX), PRD 95 (2017) 072002.

(T. C. Rogers, P. J. Mulders, PRD 81 (2010) 094006.)

For finding the color-entanglement signature, we need good understanding on TMDs.
→ At this stage, it is inconclusive.

TMDs for spin-1 hadrons

Twist-2 TMDs

Hadron \ Quark	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					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^\perp]$

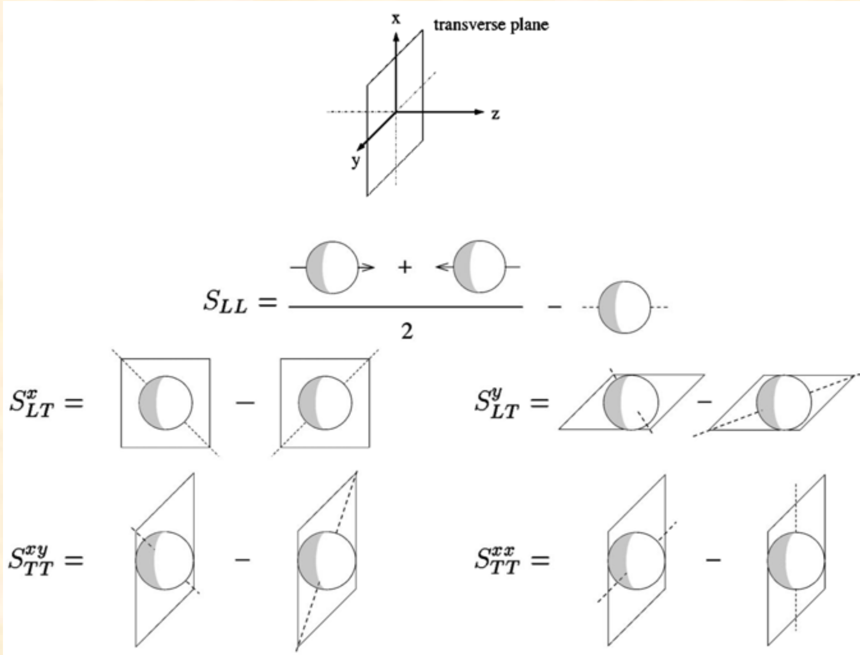
Spin-1/2 nucleon

Twist-2 collinear PDFs

$[\cdots]$= chiral odd

Hadron \ Quark	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			$g_{1L}\,(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}\,(b_1)$					
LT						
TT						

Bacchetta-Mulders, PRD 62 (2000) 114004.



TMD correlation functions for spin-1 hadrons

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-2020, for the details see KEK-TH-2258

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

New terms

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

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

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

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

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

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

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

Twist-3,4 TMDs for spin-1 hadrons

New TMDs and PDFs!

Kumano-Song-2020,
KEK-TH-2258

Twist-3 TMDs

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}		$[h_{3TT}], [h_{3TT}^\perp]$

Twist-3 collinear PDFs

$[\cdots]$ = chiral odd

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	$[e_{LL}]$					
LT	f_{LT}					
TT						

Twist-4 collinear PDFs

$[\cdots]$ = chiral odd

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					
L			g_{3L}			
T					$[h_{3T}]$	
LL	f_{3LL}					
LT						
TT						

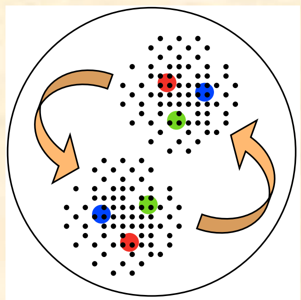
Summary

Spin-1 structure functions of the deuteron (new spin structure)

- **tensor structure in quark-gluon degrees of freedom**
- **gluon transversity**
- **new signature beyond "standard" hadron physics?**
- **experiments: JLab (approved), Fermilab (to be proposed), ... ,**
  NICA (in progress), COMPASS!?, EIC, EicC, ...
- **TMDs: interdisciplinary field of physics**
  ***e.g.* Color Aharonov-Bohm effect, Color entanglement**

We proposed new TMDs and PDFs in twist 3 and 4.

standard model



?

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

The End

The End