Possible studies of gluon transversity in the spin-1 deuteron at hadron-accelerator facilities

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28th International workshop on
Deep-Inelastic Scattering and Related Subjects (DIS-2021)
Online, Stony Brook, New York, USA, April 12-16, 2021
https://indico.bnl.gov/event/9726/timetable/#all.detailed

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

April 14, 2021

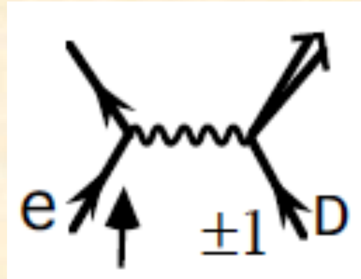
Contents

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

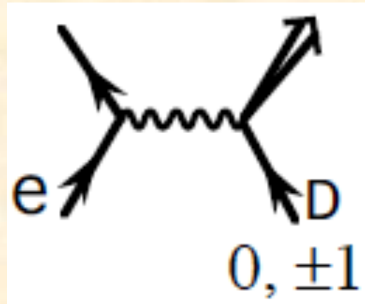
Structure Functions

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

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



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



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

Parton Model

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

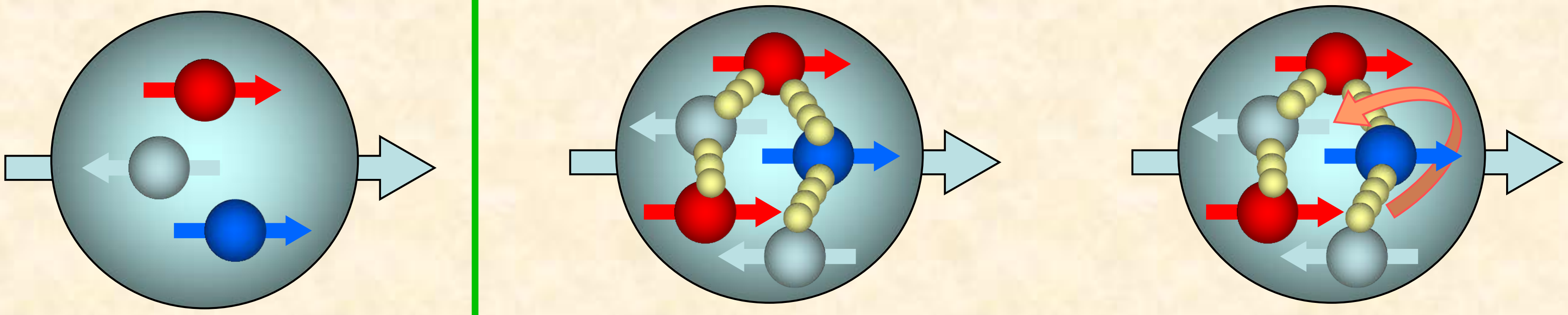
$$g_1 = \frac{1}{2}\sum_i e_i^2 \left(\Delta q_i + \Delta \bar{q}_i\right) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

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

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

Nucleon spin

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

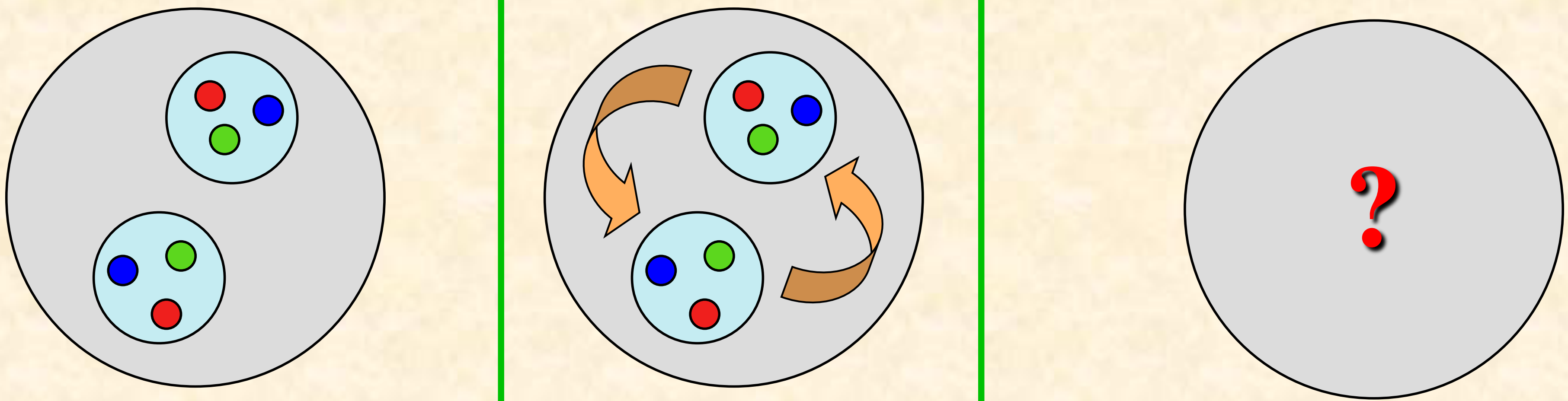


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure crisis!?



only S wave | S + D waves

$b_1 = 0$ | standard model $b_1 \neq 0$ | $b_1^{\text{experiment}} \neq b_1^{\text{“standard model”}}$

Standard model prediction for b_1 of deuteron

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

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

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

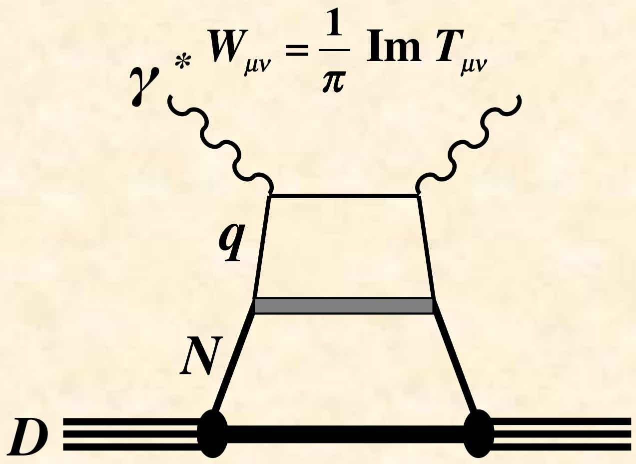
D-state admixture: $\phi^H(\vec{p}) = \phi_{\ell=0}^H(\vec{p}) + \phi_{\ell=2}^H(\vec{p})$

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

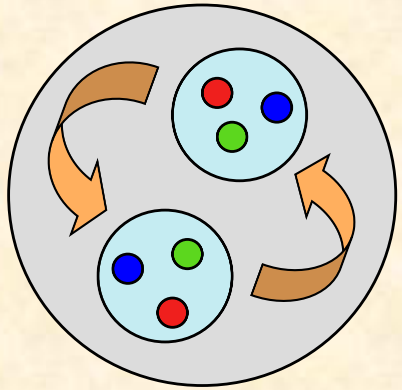
$$\delta_T f(y) = f^0(y) - \frac{f^+(y) + f^-(y)}{2}$$

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

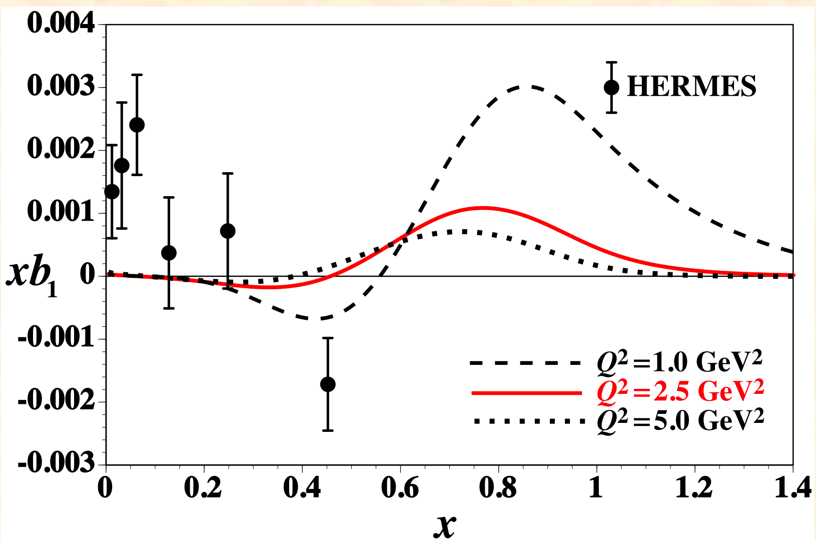
S-D term D-D term

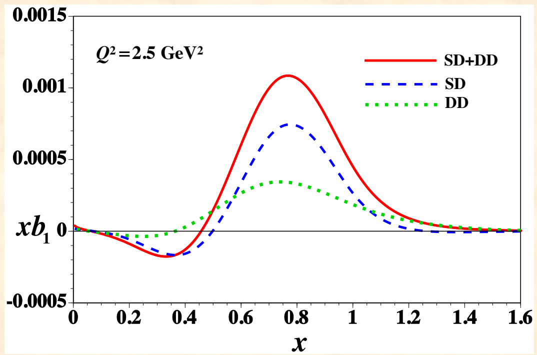


Standard model of the deuteron



S + D waves





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

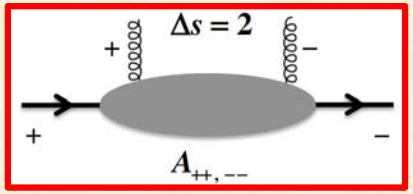
W. Cosyn, Yu-Bing Dong, S. Kumano, M. Sargsian, PRD 95 (2017) 074036.

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

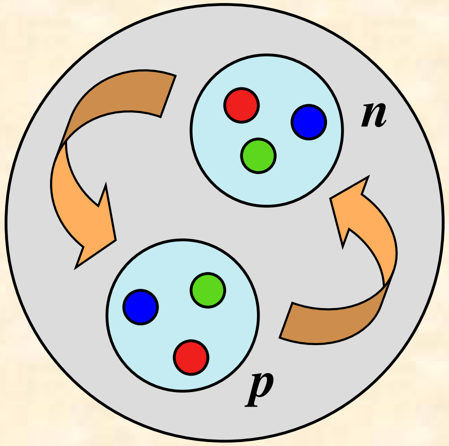
Gluon transversity $\Delta_T g$

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

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

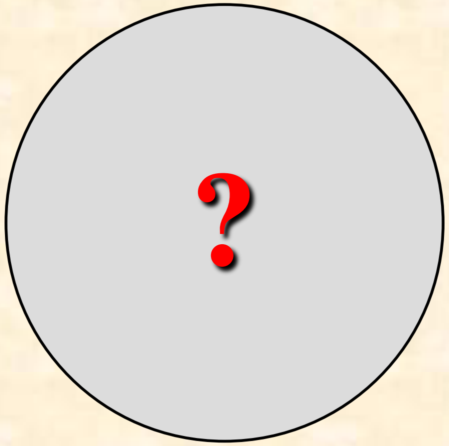


Note: Gluon transversity does not exist for spin-1/2 nucleons.



S + D waves

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



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

Possible studies on gluon transversity

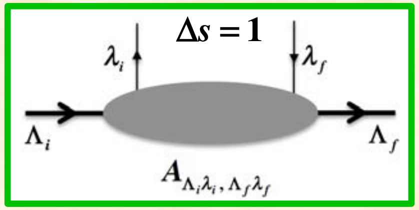
S. Kumano and Qin-Tao Song, Phys. Rev. D 101 (2020) 054011 & 094013;
A. Arbuzov *et al*., arXiv:2011.15005, Progress in Nuclear and Particle Physics in press.

Gluon transversity $\Delta_T g$

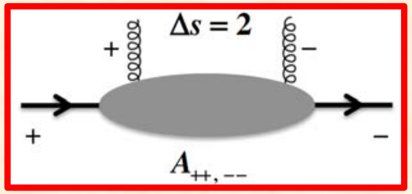
Helicity amplitude $A(\Lambda_i, \lambda_i, \Lambda_f, \lambda_f)$, **conservation** $\Lambda_i - \lambda_i = \Lambda_f - \lambda_f$

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

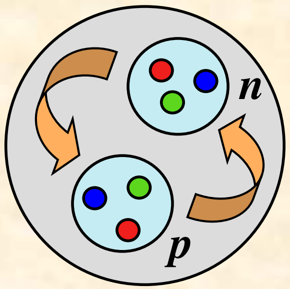
Quark transversity in nucleon: $\Delta_T q(x) \sim A\left(+\frac{1}{2}+\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}\right)$, $\lambda_i = +\frac{1}{2} \rightarrow \lambda_f = -\frac{1}{2}$ **quark spin flip** ($\Delta s = 1$)



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.



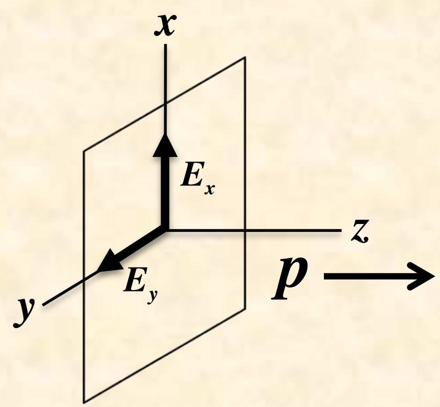
S + D waves

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

$\downarrow$

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

Gluon transversity distribution in deuteron



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

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

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

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

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

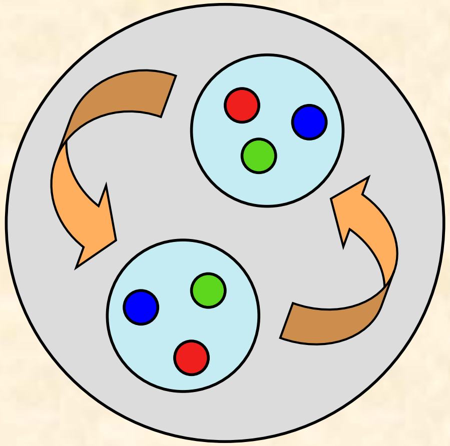
Confusing situation of gluon transversity

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

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

→ One can imagine how premature this field is!

Exotic components in nuclei beyond simple bound states of nucleons



S + D waves

Deuteron = proton + neutron

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

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

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

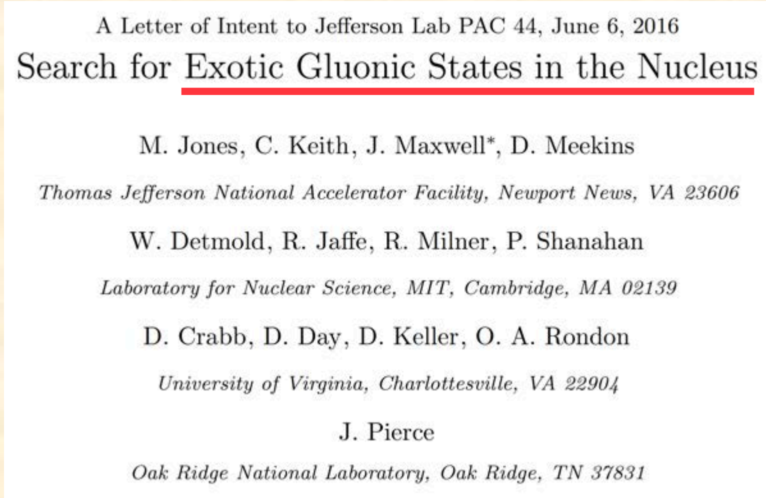
So far, the paper of Nzar-Hoodbhoy is the only one on a physics mechanism of gluon transversity, so that further theoretical works are needed.

(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

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

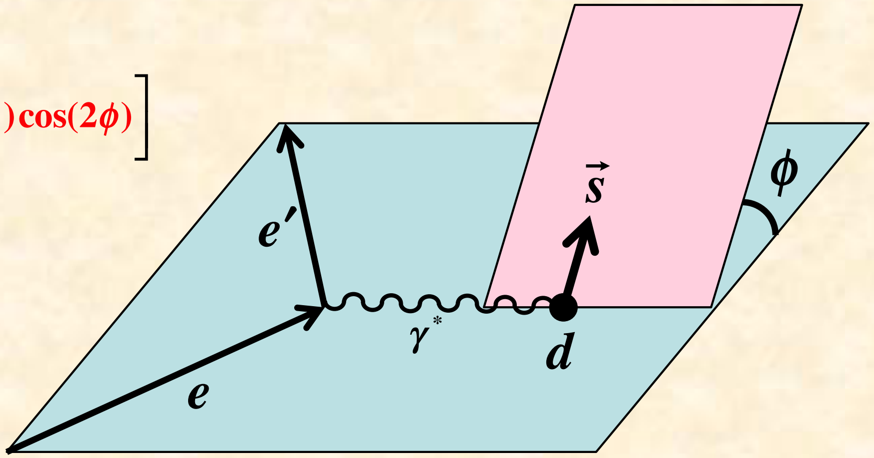
For development of polarized deuteron target, see D. Keller, D. Crabb, D. Day Nucl. Inst. Meth. Phys. Res. A981 (2020) 164504.

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.



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.

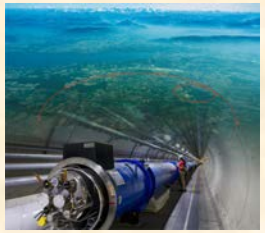
Fermilab-MI

NICA

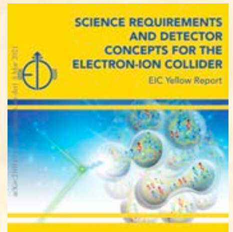
RHIC (fixed target)

GSI-FAIR

J-PARC

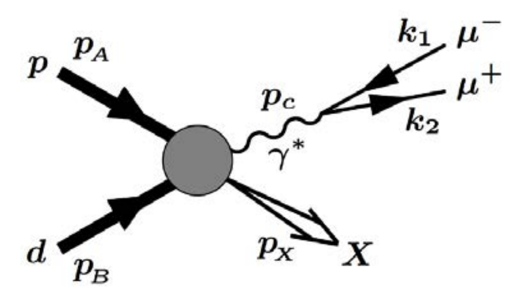


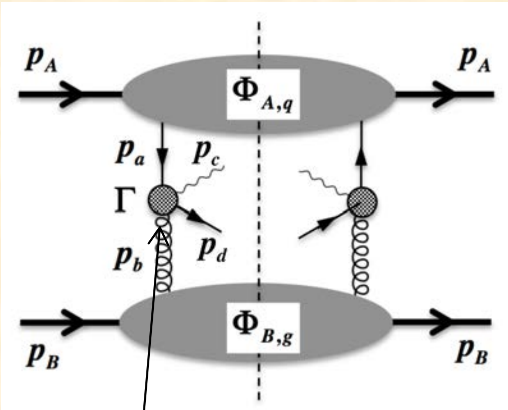
LHC (fixed target)
COMPASS

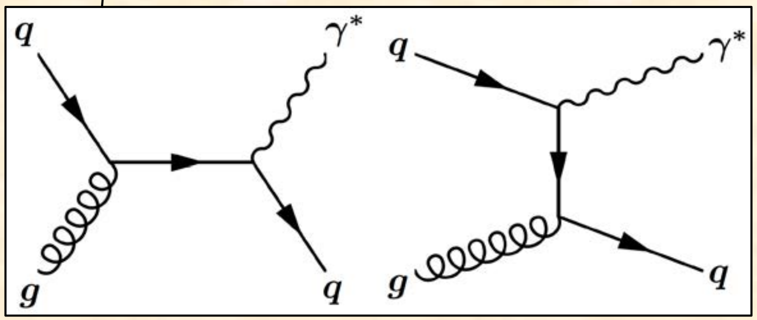


EIC,
EicC

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

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

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

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)

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

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

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

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

Proton-deuteron Drell-Yan cross section

Drell-Yan cross section

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

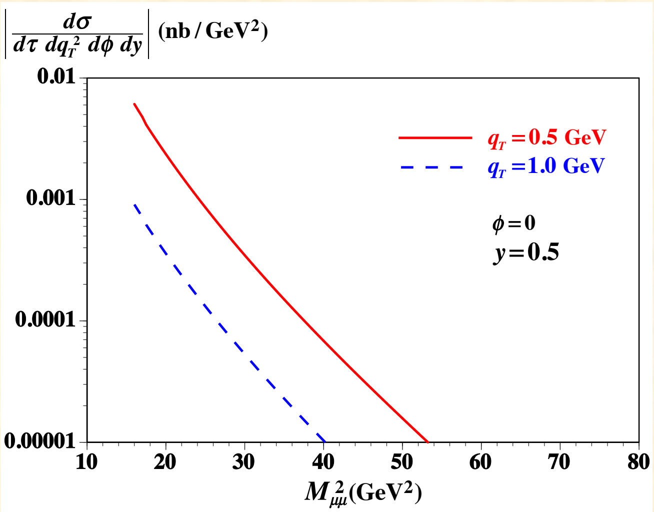
$$C_F = \frac{N_c^2 - 1}{2N_c}, \quad \min(x_a) = \frac{x_1 - \tau}{1 - x_2}, \quad x_b = \frac{x_a x_2 - \tau}{x_a - \tau}$$

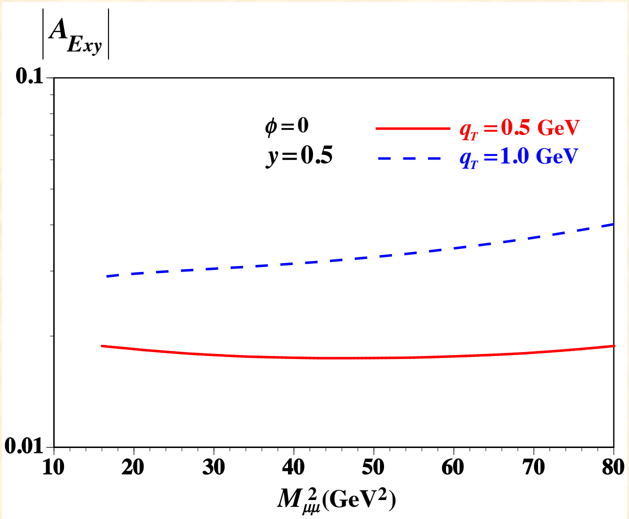
= (unpolarized PDFs of proton) * (gluon transversity distribution in the deuteron)

- Consider the Fermilab-E1039 experiment with the proton beam of $p = 120$ GeV
- No available $\Delta_T g$, so we may tentatively assume $\Delta_T g = \Delta g_p + \Delta g_n$ $\left(\text{or } \dfrac{\Delta g_p + \Delta g_n}{2}, \dfrac{\Delta g_p + \Delta g_n}{4}\right)$
- 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: $$A_{E_{xy}} = \frac{\dfrac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_x) - \dfrac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_y)}{\dfrac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_x) + \dfrac{d\sigma_{pd\to\mu^+\mu^-X}}{d\tau\, dq_T^2\, d\phi\, dy}(E_y)}$$





New proposal at Fermilab-PAC in 2021 (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.

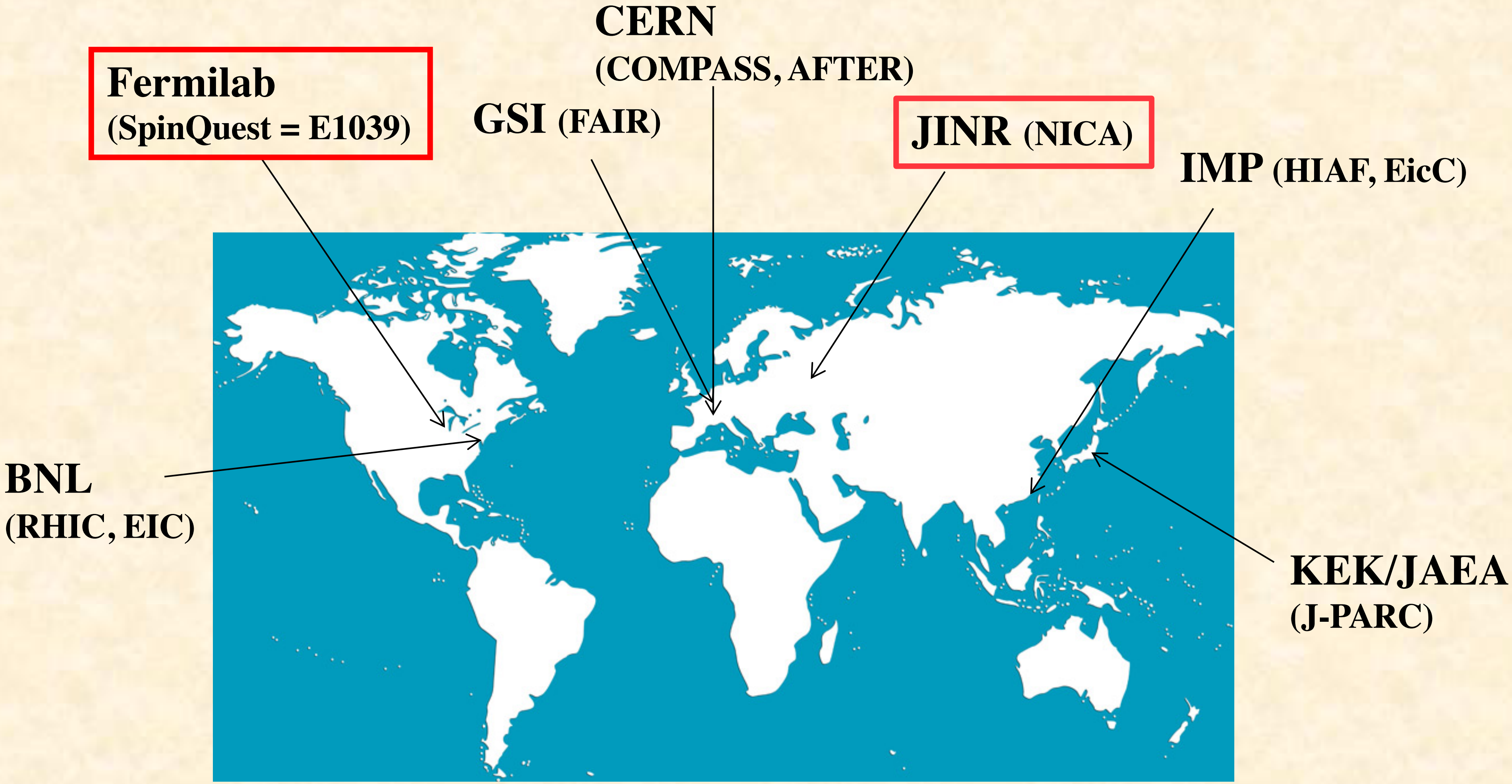
$$\boldsymbol{S} = (S_T^x, S_T^y, S_L),$$

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

	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

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

Possible hadron facilities for gluon transversity



Experimental possibility at Fermilab in 2020's

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

J-PARC?

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.

The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

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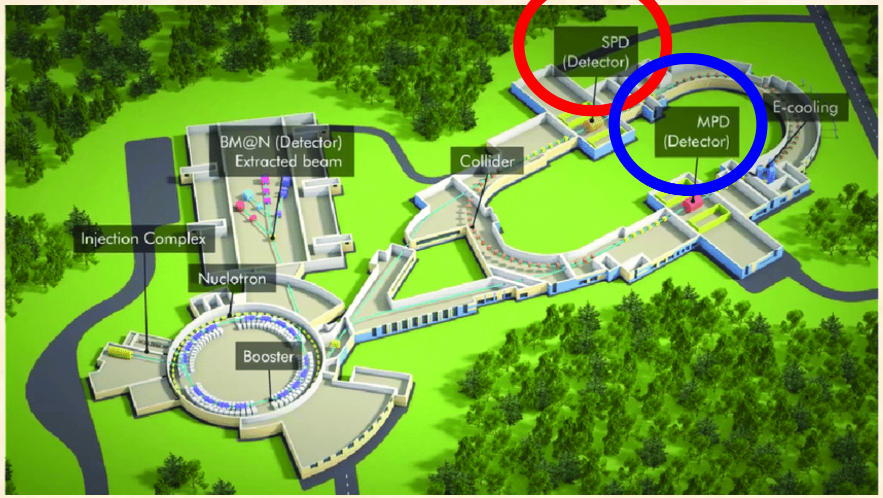
New proposal is being written for a Fermilab-PAC in 2021.

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), arXiv:2011.15005, Progress in Nuclear and Particle Physics in press.

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).

skip

TMDs for spin-1 hadrons

Qin-Tao Song's
flash talk (poster)
at this DIS workshop

S. Kumano and Qin-Tao Song,
Phys. Rev. D 103 (2021) 014025.

Typos in abstract and summary: $h_{LT} \to g_{LT}$

$$\int d^2k_T \cancel{h}_{LT} = \int d^2k_T h_{LL} = \int d^2k_T h_{3LL} = 0$$

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

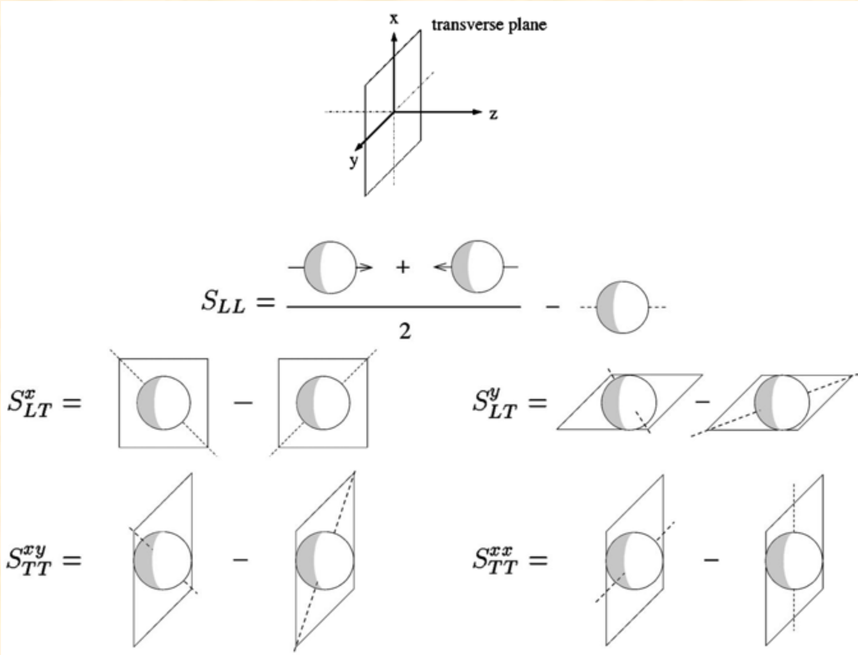
Spin-1 hadrons

Bacchetta-Mulders, PRD 62 (2000) 114004.

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						



Twist-3,4 TMDs for spin-1 hadrons

Kumano-Song (2021)

New TMDs and PDFs!

Twist-3 TMDs

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	$f^\perp$ $[e]$			$g^\perp$		$[h]$
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

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

Twist-3 collinear PDFs

$[\cdots]$= chiral odd

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

Twist-4 collinear PDFs

$[\cdots]$= chiral odd

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						
TT						

Sum rules for TMDs of spin-1 hadrons

Twist-2 TMDs

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					$[h_1^\perp]$
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}		$[h_{1TT}], [h_{1TT}^\perp]$

Time-reversal invariance in colliear corrlation functions (PDFs)

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

New sum rules for the TMDs of spin-1 hadrons

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

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

For example, in the twist-4

$$\int d^2k_T\, h_{3LT}(x,k_T^2) \equiv \int d^2k_T \left[h'_{3LT}(x,k_T^2) - \frac{k_T^2}{2M^2} h_{3LT}^\perp(x,k_T^2) \right] = 0$$

$$\Phi^{[\sigma^{i-}]} = \frac{M^2}{P^{+2}} \Big[h_{3LL}^\perp(x,k_T^2) S_{LL} \frac{k_T^i}{M} + h'_{3LT}(x,k_T^2) S_{LT}^i - h_{3LT}^\perp(x,k_T^2) \frac{k_T^i S_{LT}\cdot k_T}{M^2} - h'_{3TT}(x,k_T^2) \frac{S_{TT}^{ij} k_{Tj}}{M} + h_{3TT}^\perp(x,k_T^2) \frac{k_T\cdot S_{TT}\cdot k_T}{M^2} \frac{k_T^i}{M} \Big]$$

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

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, EicC.
- $\Delta_T g$ → "exotic" components in nuclei beyond bound states of nucleons.

The End

The End