Tensor-polarized structure functions for spin-one hadron

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https://phys.cst.temple.edu/poetic-cteq-2016/

Collaborators: W. Cosyn, Yu-Bing Dong, M. Sargsian, Qin-Tao Song, ...

Recent papers: (1) SK and Qin-Tao Song, Phys. Rev. D 94 (2016) 054022.
(2) W. Cosyn *et al.*, to be submitted for publication.

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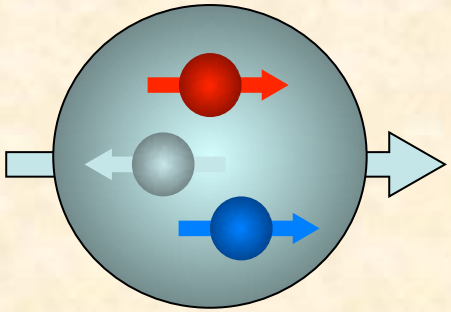
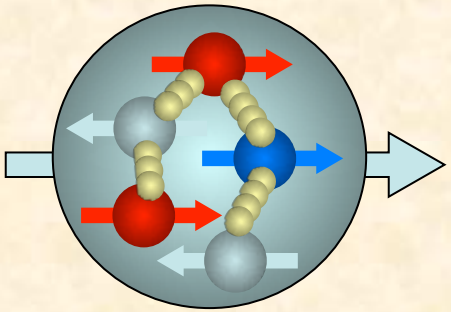
Nucleon spin

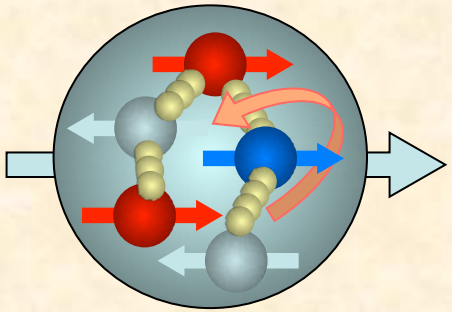
Almost none of nucleon spin is carried by quarks! → Nucleon spin crisis!?



Naïve Quark Model



Sea-quarks and gluons?

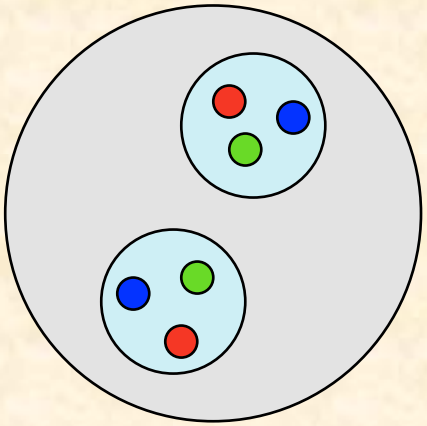


Orbital angular momenta ?

"old" standard model

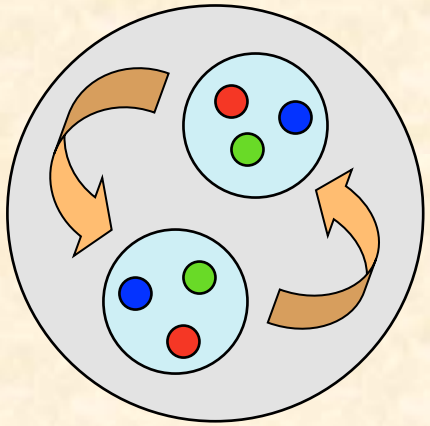
Tensor structure b_1 (*e.g.* deuteron)

Tensor-structure crisis!?



only S wave

$b_1 = 0$



S + D waves

standard model $b_1 \neq 0$

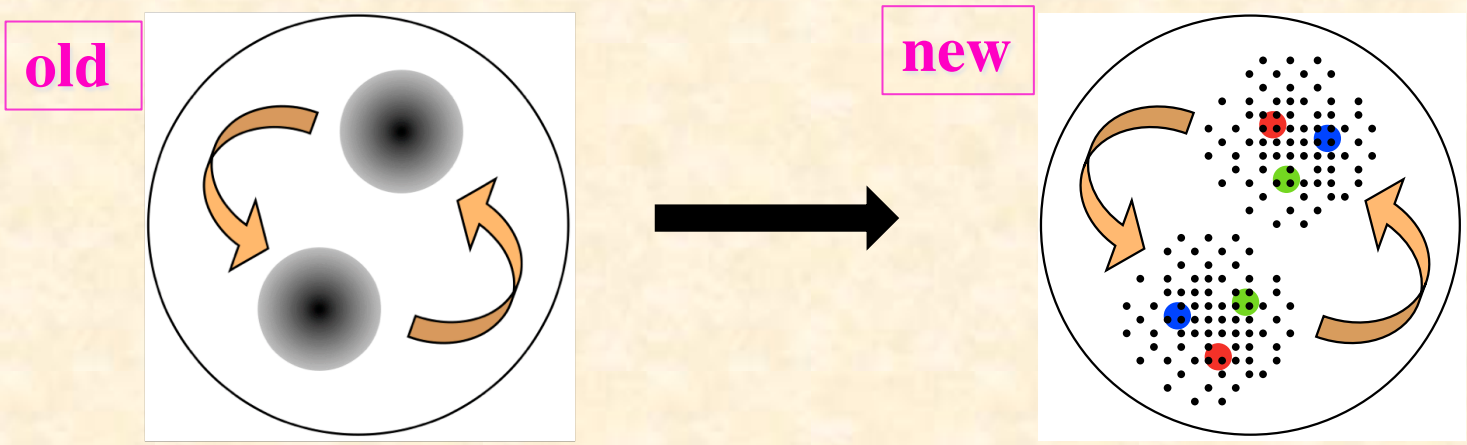
b_1 experiment $\neq b_1$ "standard model"

Roles of quark degrees of freedom in deuteron

The deuteron is a well-studied system by hadronic degrees of freedom

If we find that the deuteron is not simple bound system of a proton and a neutron (namely if we find an exotic quark signature), it is an important discovery and it could open a new field of spin physics (and possibly a new topic of nuclear physics), which is very different from current nucleon-spin physics.

Tensor structure of the deuteron = old topic (in terms of nucleon d.o.f.) but it is a good probe of new hadron phenomena in quark-gluon d.o.f.



Situation

- **Spin structure of the spin-1/2 nucleon**

  Nucleon spin puzzle: This issue is not solved yet,

  but it is rather well studied theoretically and experimentally.

- **Spin-1 hadrons (e.g. deuteron)**

  There are some theoretical studies especially on tensor structure in electron-deuteron deep inelastic scattering.

  → HERMES experimental results →JLab experiment

  No experimental measurement has been done for hadron (p, π, …) - polarized deuteron processes.

  → Hadron facility (Fermilab, J-PARC, RHIC, COMPASS, GSI, …) experiment ?

Personal studies on tensor structure of the deuteron

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

JLab experiment ~2019, Fermilab pd Drell-Yan?, EIC?

Motived by the following works.

Hoodbhoy-Jaffe-Manohar (1989)

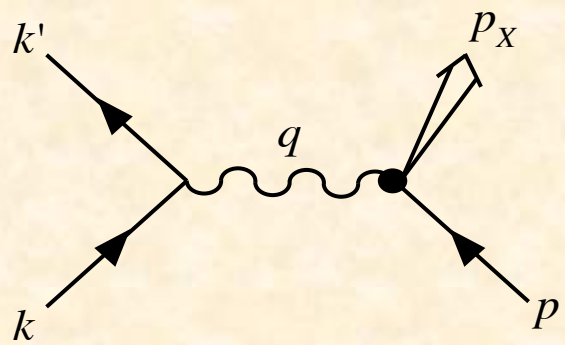
Polarized deuteron acceleration at RHIC:
E. D. Courant, Report BNL-65606 (1998)

HERMES measurement on b_1 (2005)

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

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

Cross section for $e + \vec{d} \to e' + X$



$$d\sigma = \frac{1}{4\sqrt{(k\cdot p)^2 - m^2 M_N^2}} \overline{\sum_{pol}} \sum_X (2\pi)^4 \delta^4(k+p-k'-p_X)\,|M|^2 \frac{d^3k'}{(2\pi)^3 2E'}$$

$$M = e\,\bar{u}(k',\lambda')\gamma_\mu\, u(k,\lambda)\,\frac{g^{\mu\nu}}{q^2}\,\langle X|\,e J_\nu^{em}(0)\,|p,\lambda_N\rangle$$

$$\overline{\sum_{pol}} \sum_X (2\pi)^4 \delta^4(k+p-k'-p_X)\,|M|^2 = \frac{e^4}{Q^2} \underline{\overline{\sum_{\lambda,\lambda'}}}\, \underline{\overline{\sum_{\lambda_N}} \sum_X (2\pi)^4 \delta^4(k+p-k'-p_X)}$$

$$\times \underline{\left[\bar{u}(k',\lambda')\gamma^\mu u(k,\lambda)\right]^* \left[\bar{u}(k',\lambda')\gamma^\nu u(k,\lambda)\right]}\ \underline{\langle p,\lambda_N|J_\mu^{em}(0)|X\rangle\langle X|J_\nu^{em}(0)|p,\lambda_N\rangle}$$

$$= \frac{(4\pi\alpha)^2}{Q^2}\, 4\pi M_N L^{\mu\nu} W_{\mu\nu}$$

Lepton tensor: $L^{\mu\nu} = \overline{\sum_{\lambda,\lambda'}} \left[\bar{u}(k',\lambda')\gamma^\mu u(k,\lambda)\right]^* \left[\bar{u}(k',\lambda')\gamma^\nu u(k,\lambda)\right] = 2\left[k^\mu k'^\nu + k'^\mu k^\nu - (k\cdot k' - m^2) g^{\mu\nu}\right]$

Hadron tensor: $W_{\mu\nu} = \frac{1}{4\pi M_N} \overline{\sum_{\lambda_N}} \sum_X (2\pi)^4 \delta^4(k+p-k'-p_X)\,\langle p,\lambda_N|J_\mu^{em}(0)|X\rangle\langle X|J_\nu^{em}(0)|p,\lambda_N\rangle$

$$d\sigma = \frac{2M_N}{s - M_N^2} \frac{\alpha^2}{Q^4} L^{\mu\nu} W_{\mu\nu} \frac{d^3k'}{E'}$$

Electron scattering from a spin-1 hadron

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

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

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

spin-1/2, spin-1

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

spin-1 only

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

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

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

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

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

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

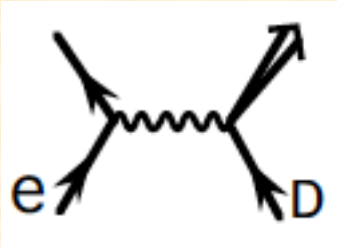
b_1, b_2 tems are defined to satisfy $2xb_1 = b_2$ in the Bjorken scaling limit.

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

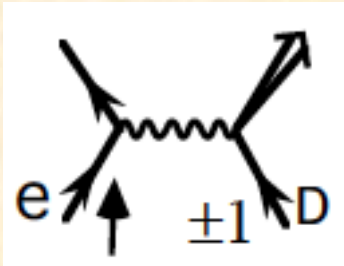
b_3, b_4 = twist-4 $\sim \dfrac{M^2}{Q^2}$

Structure Functions

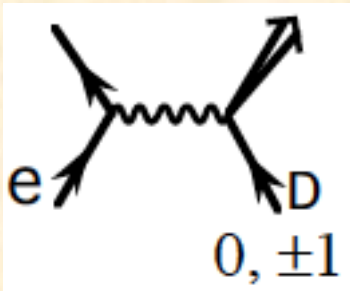
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

Parton Model

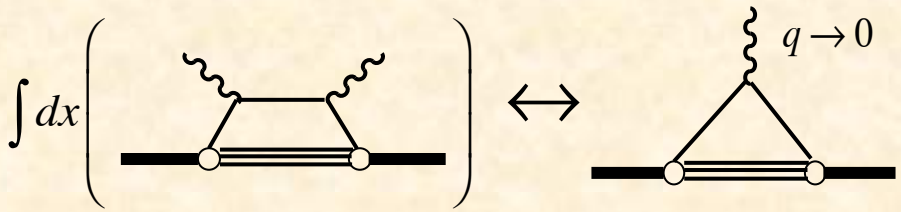
$$F_1 = \frac{1}{2}\sum_i e_i^2 \left(q_i + \bar{q}_i\right) \qquad q_i = \frac{1}{3}\left(q_i^{+1} + q_i^{0} + q_i^{-1}\right)$$

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

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

Constraint on valence-tensor polarization (sum rule)

F.E.Close and SK, PRD42, 2377 (1990).



Intuitive derivation without calculation:

$$\int dx\, b_1(x) = \text{ dimensionless quantity}$$
$$= \text{(mass)}^2 \cdot \text{(quadrupole moment)}$$

$$\int dx\, b_1^D(x) = \frac{5}{18}\int dx\left[\delta_T u_v + \delta_T d_v\right] + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

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

$$\delta_T q_i = q_i^0 - \frac{q_i^{+1} + q_i^{-1}}{2}$$

$$\delta_T q_v \equiv \delta_T q - \delta_T \bar{q}$$

Elastic amplitude in a parton model

$$\Gamma_{H,H} = \langle p,H|J_0(0)|p,H\rangle = \sum_i e_i \int dx\left[q_{i\uparrow}^H + q_{i\downarrow}^H - \bar{q}_{\Uparrow}^H - \bar{q}_{\Downarrow}^H\right]$$

$$\frac{1}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] = \frac{1}{3}\int dx\left[\delta_T u_v(x) + \delta_T d_v(x)\right]$$

Macroscopically $\Gamma_{0,0} = \lim_{t\to 0}\left[F_c(t) - \frac{t}{3}F_Q(t)\right]$, $\Gamma_{+1,+1} = \Gamma_{-1,-1} = \lim_{t\to 0}\left[F_c(t) + \frac{t}{6}F_Q(t)\right]$

$$\frac{1}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] = -\lim_{t\to 0}\frac{t}{2}F_Q(t)$$

$$\int dx\, b_1^D(x) = \frac{5}{9}\frac{3}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

$$= -\frac{5}{6}\lim_{t\to 0} tF_Q(t) + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

$$= 0 \text{ (valence)} + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

Constraint on tensor-polarized valence quarks: $\int dx\, \delta_T q_v(x) = 0$

Similarity to the Gottfried sum rule

SK, Phys. Rept. 303 (1998) 183.

$$S_G = \int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right]$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

$$= \frac{1}{3} \quad \text{if } \bar{u} = \bar{d}$$

(Gottfried sum rule)

$$F_2^{\mu p}(x)_{\rm LO} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$

$$F_2^{\mu n}(x)_{\rm LO} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]_n$$

$$= x\left[\frac{4}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$

$$\frac{1}{x}\left[F_2^{\mu p}(x)_{\rm LO} - F_2^{\mu n}(x)_{\rm LO}\right] = \frac{3}{9}\{u(x)+\bar{u}(x)\} - \frac{3}{9}\{d(x)+\bar{d}(x)\}$$

$$\int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x)_{\rm LO} - F_2^{\mu n}(x)_{\rm LO}\right] = \int_0^1 dx\left[\frac{1}{3}\{u_v(x)+2\bar{u}(x)\} - \frac{1}{3}\{d_v(x)+2\bar{d}(x)\}\right]$$

$$= \frac{2}{3} - \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

NMC measurement (PRL 66 (1991) 2712; PRD 50 (1994) R1)

$$\int_{0.004}^{0.8} \frac{dx}{x}\left[F_2^{\mu p}(x) - F_2^{\mu n}(x)\right] = 0.221 \pm 0.008 \pm 0.019$$

Extrapolating the NMC data, they obtained

$$S_G = 0.235 \pm 0.026$$

30% is missing! $\Rightarrow$ $\bar{u} < \bar{d}$?

$$\int_0^1 \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

$$\int dx\, b_1^D(x) = -\frac{5}{6}\lim_{t\to 0} tF_Q(t) + \frac{1}{18}\int dx\left[8\delta_T\bar{u}^D + 2\delta_T\bar{d}^D + \delta_T\bar{s}^D\right]$$

As the Gottfried-sum-rule violation indicated $\bar{u} < \bar{d}$, the b_1-sum-rule violation suggests a finite tensor polarization for antiquarks ($\delta_T\bar{u} \neq 0$).

HERMES results on b_1

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

27.6 GeV/c $\rightleftarrows$, 0

positron → deuteron

b_1 measurement in the kinematical region

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

b_1 sum rule

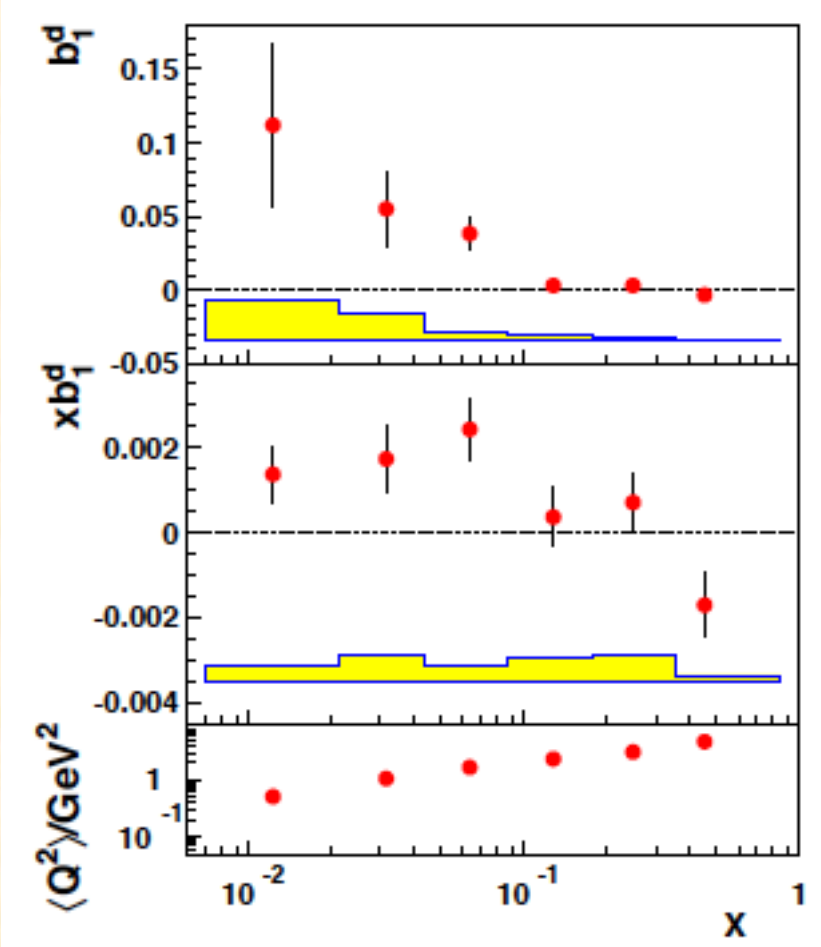
$$\int_{0.002}^{0.85} dx\, b_1(x) = \left[1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})\right] \times 10^{-2}$$

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

In the restricted Q^2 range $Q^2 > 1\ \text{GeV}^2$

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

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



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

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

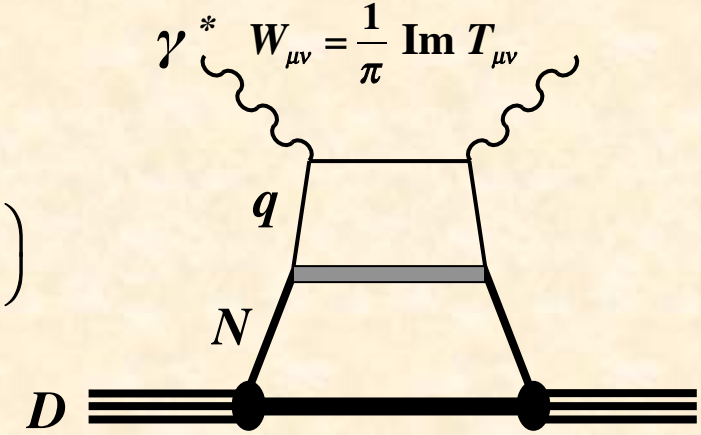
Drell-Yan experiments probe these antiquark distributions.

Standard convolution approach

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

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

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



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

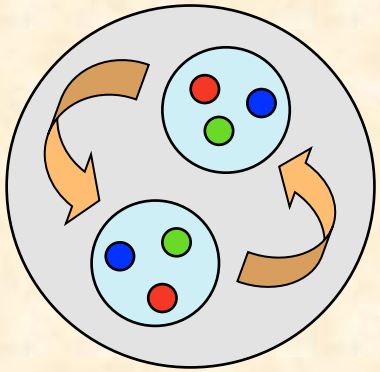
$$f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$

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

$$b_1(x) = \frac{1}{2} \int \frac{dy}{y} \sum_{i=p,n} \left[f^0(y) - \frac{f^+(y) + f^-(y)}{2} \right] F_1(x/y) = \int \frac{dy}{y} \delta f_T(y) F_1(x/y)$$

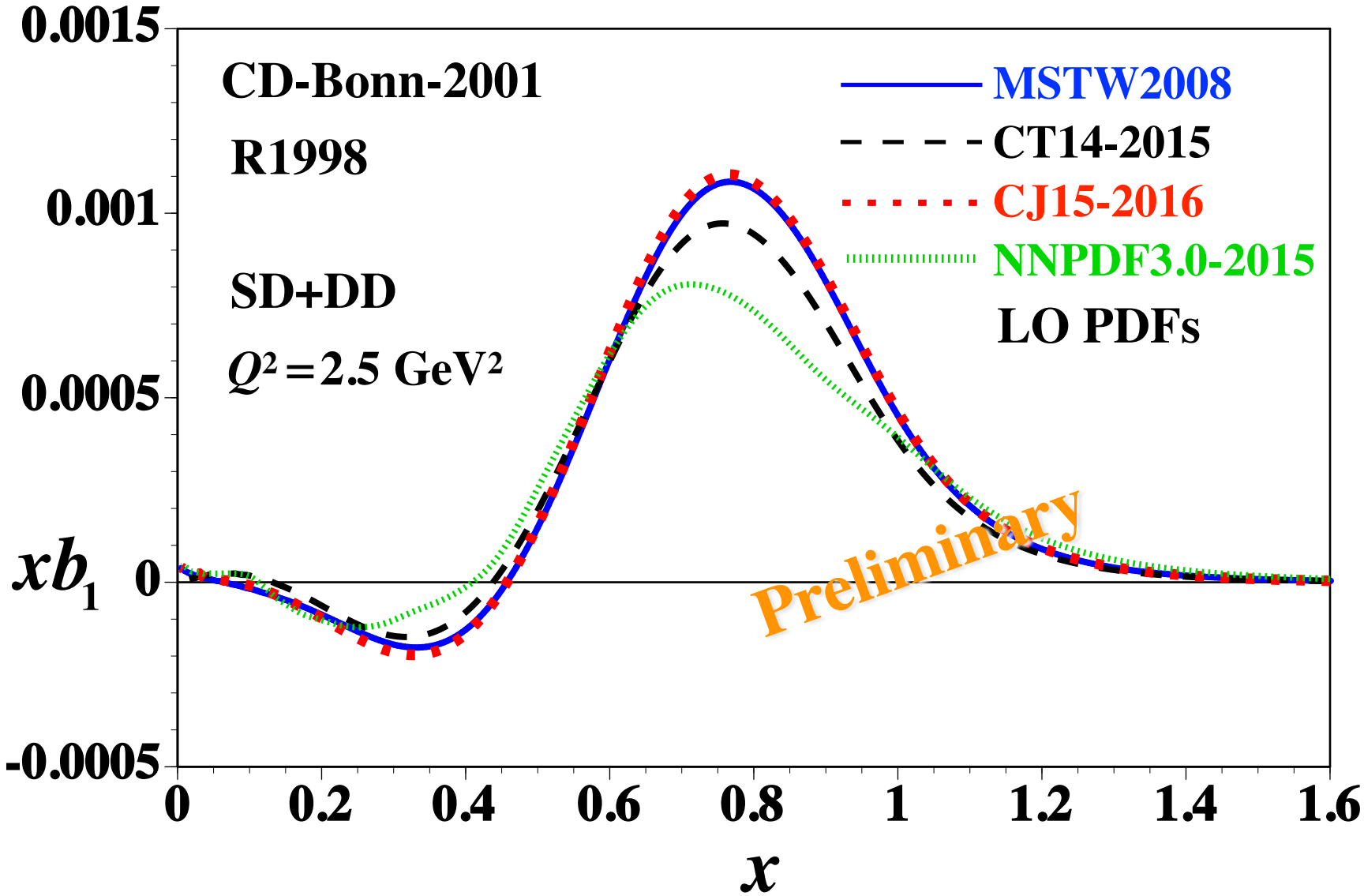
$$\delta_T f(y) = \int d^3p y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p)\phi_2(p) + \left|\phi_2(p)\right|^2 \frac{3}{16\pi} \right] (3\cos^2\theta - 1) \delta\left(y - \frac{p \cdot q}{M\nu}\right)$$

Standard model of the deuteron

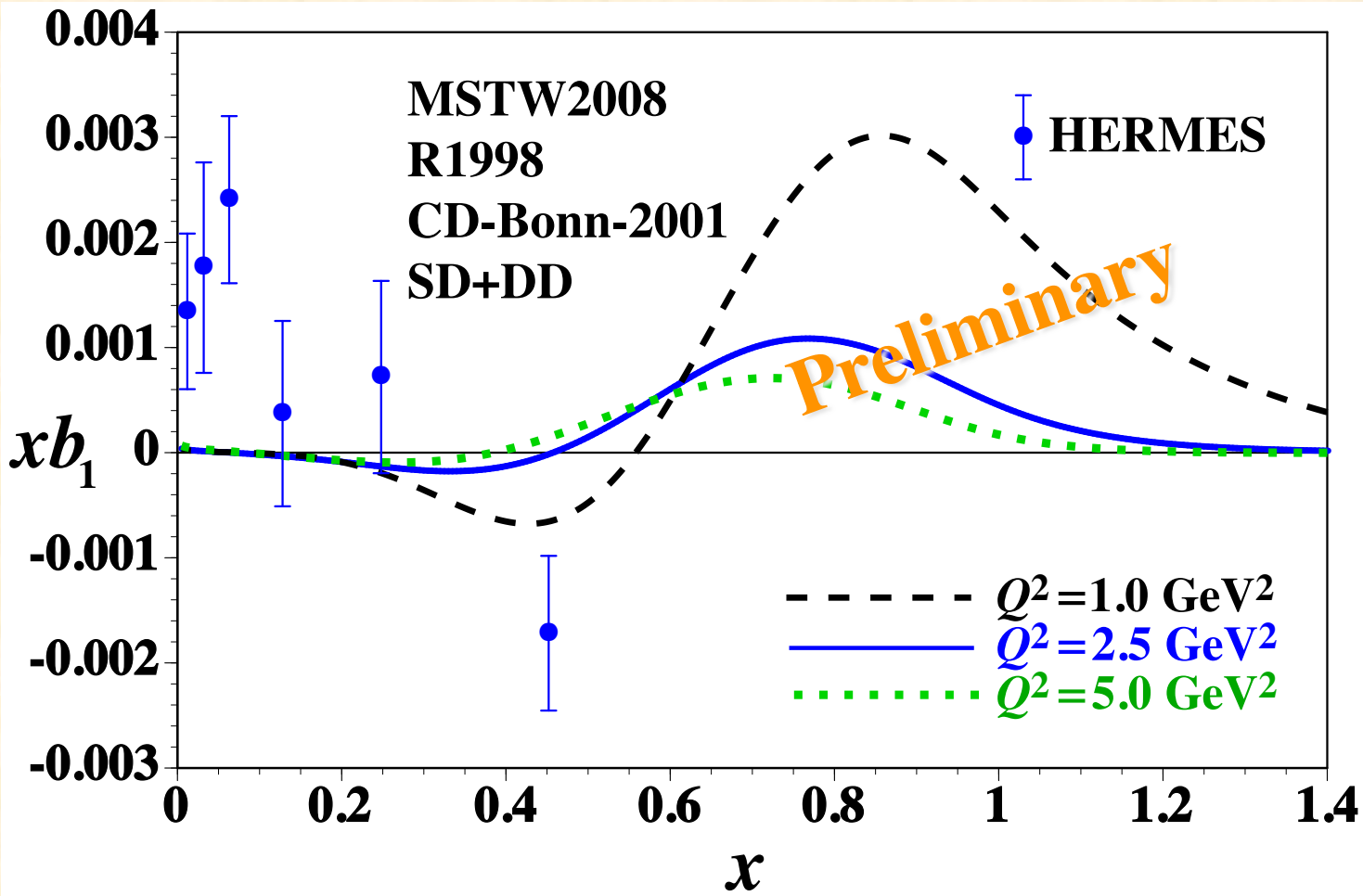


S + D waves

Results on b_1: used PDF dependence



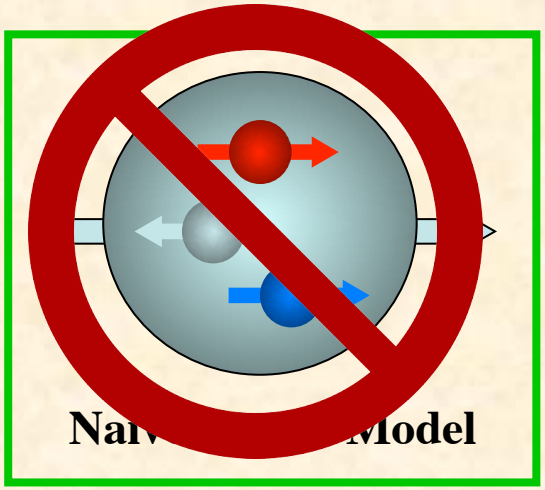
Comparison with HERMES measurements



$$|b_1(\text{theory})| \ll |b_1(\text{HERMES})|$$

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

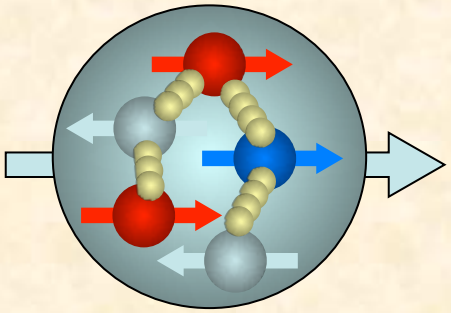
Summary I



Nai[illegible] Model

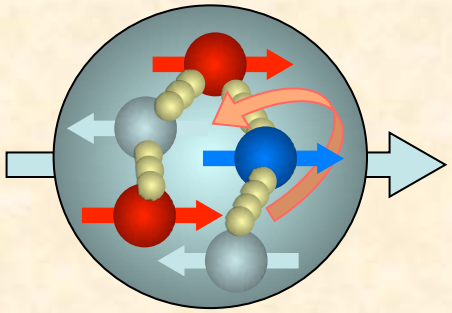
"old" standard model

Nucleon spin



Sea-quarks and gluons?

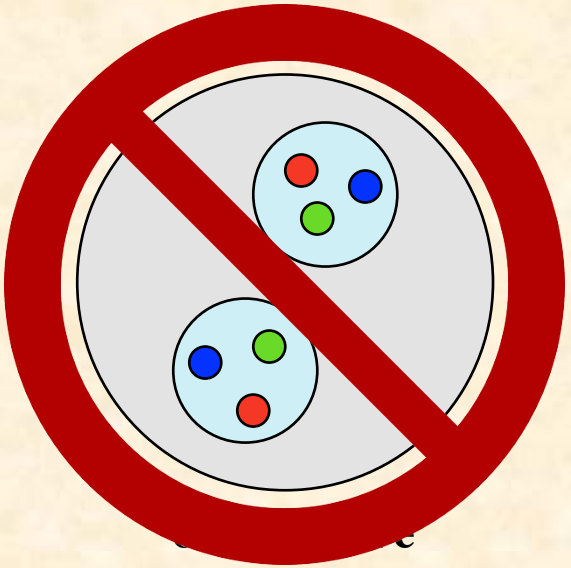
Nucleon spin crisis!?



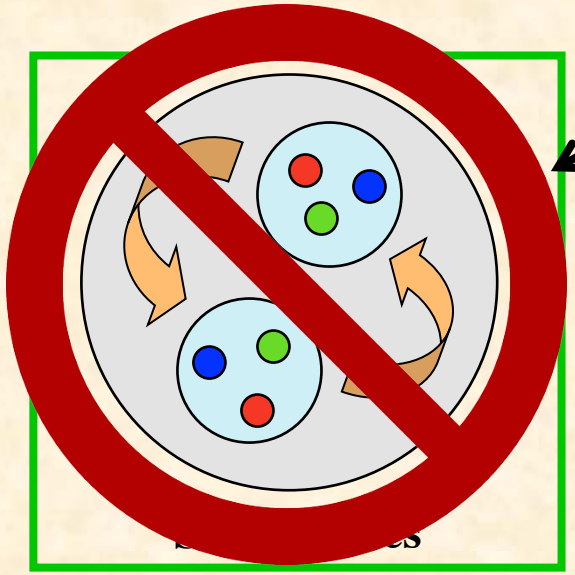
Orbital angular momenta ?

We have shown in this work
that the standard deuteron model
does not work!?
→ new hadron physics?!

Tensor structure

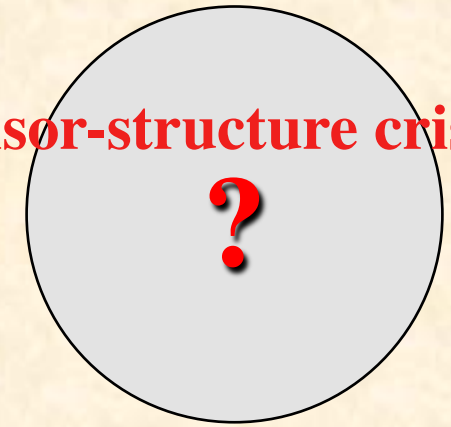


$b_1 = 0$



standard model $b_1 \neq 0$

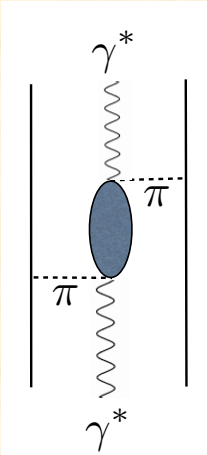
Tensor-structure crisis!?

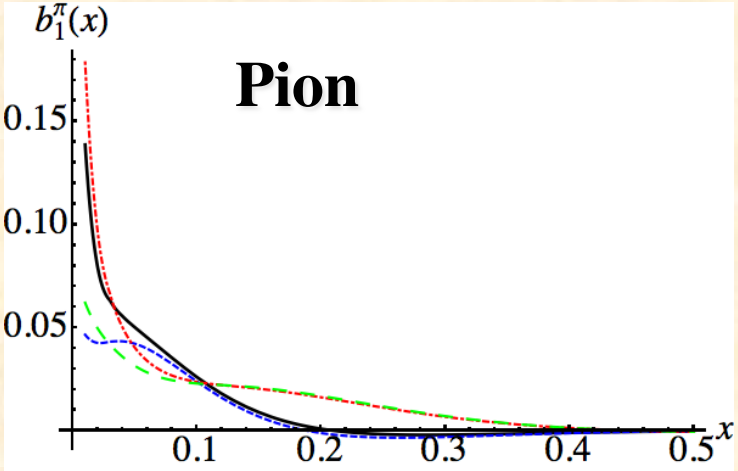


$b_1^{\text{experiment}} \neq b_1^{\text{"standard model"}}$

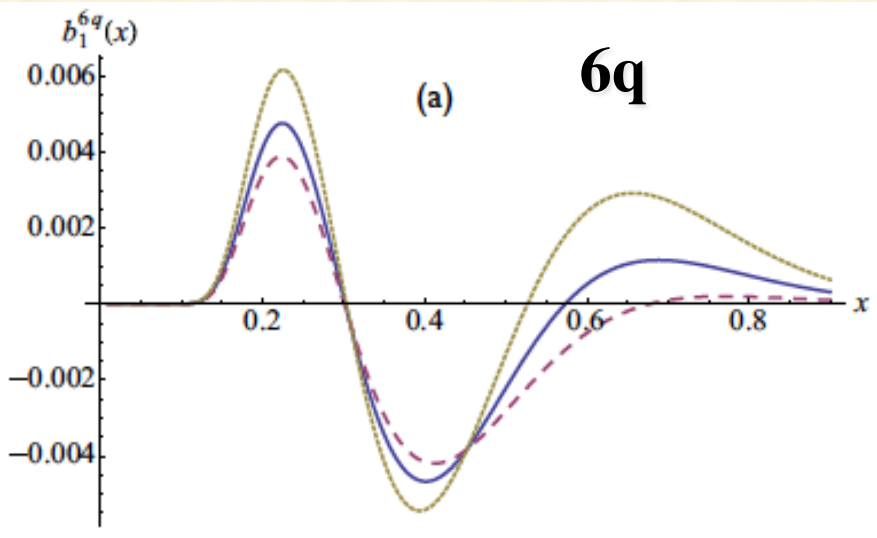
Recent work: Pion, Hidden-color, Six-quark

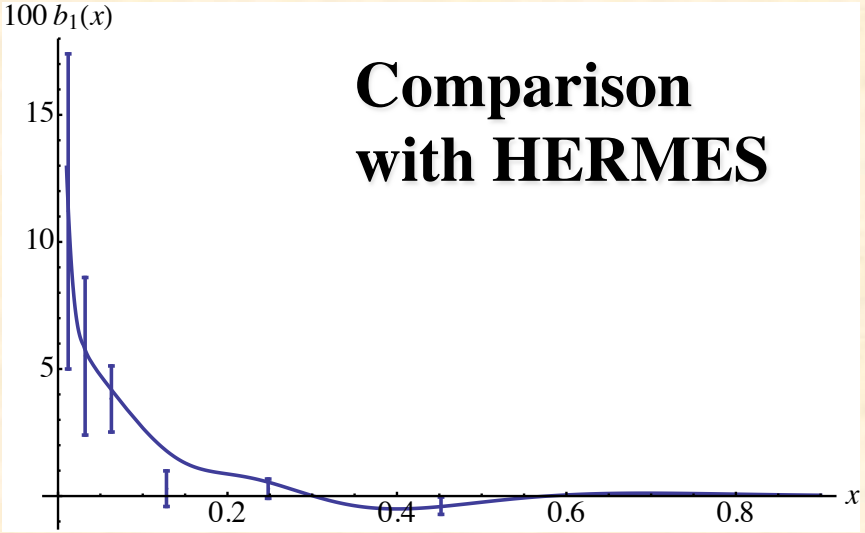
G. A. Miller,
PRC 89 (2014) 045203.





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





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

The Deuteron Tensor Structure Function b_1

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

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Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
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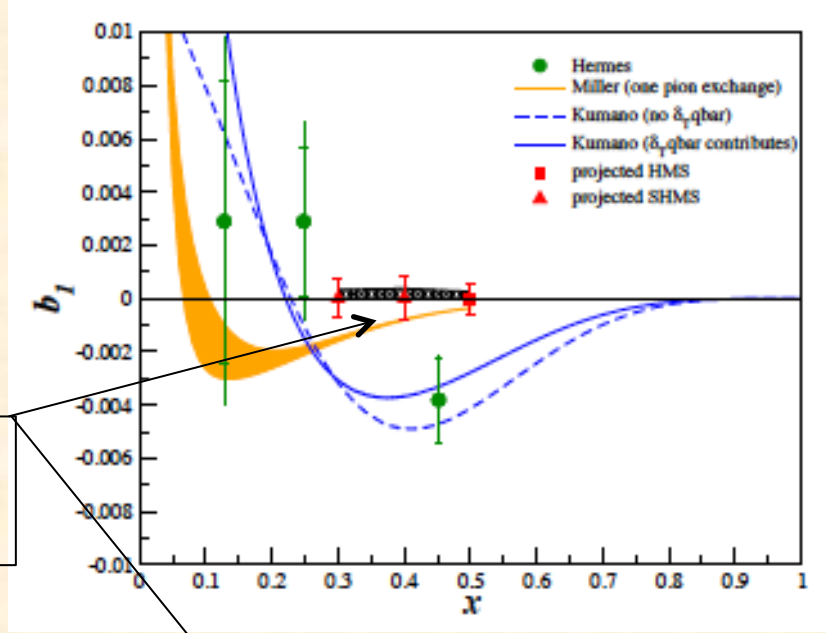
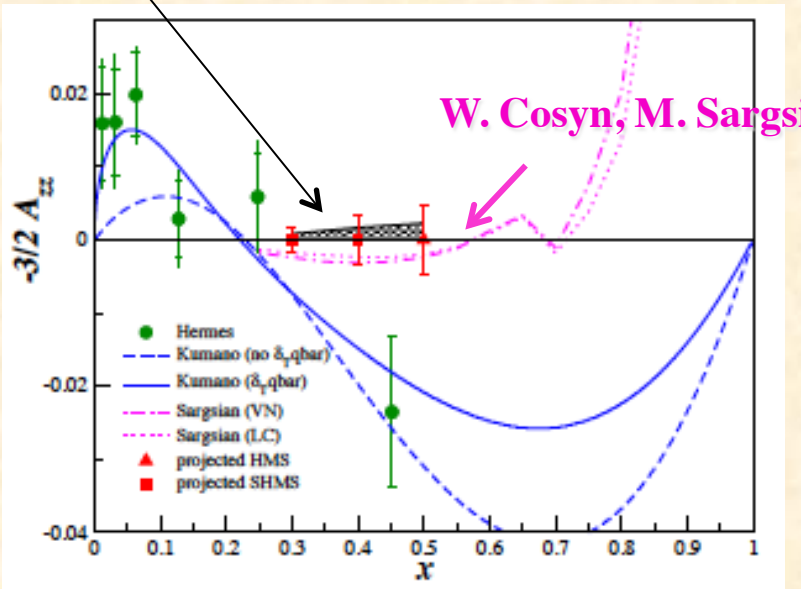
Expected errors by JLab

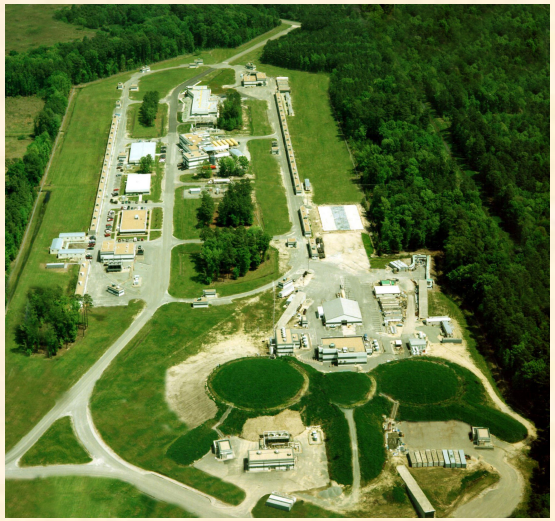




Approved!

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

Experimental possibilities



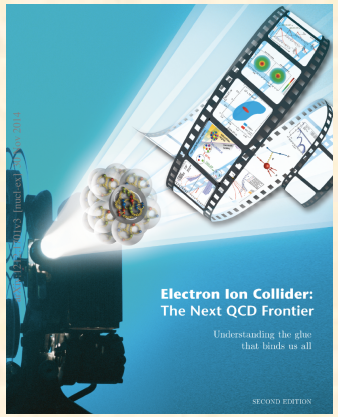
© JLab

Approved experiment! (2019~)

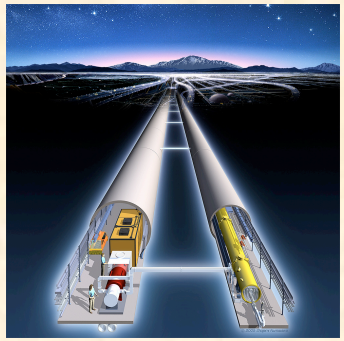
E1039 experiment

© Fermilab

EIC (arXiv:1212.1701)



Linear Collider (with fixed target)



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

© BNL

© J-PARC

© GSI

© CERN-COMPASS

© IHEP, Russia

Experimental possibility at Fermilab

E1039

Polarized fixed-target experiments at the Main Injector

© Fermilab

Drell-Yan experiment with a polarized proton target

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

List of Collaborators:

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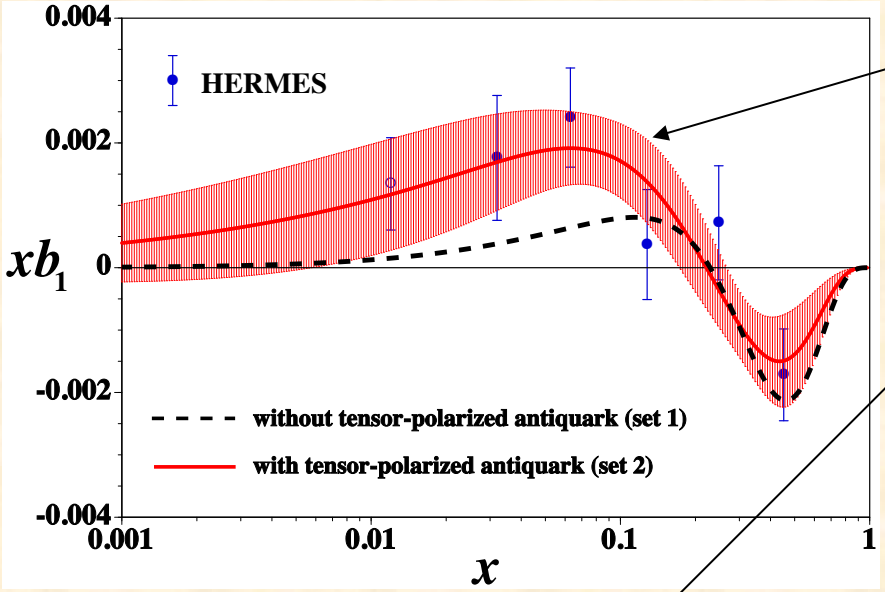
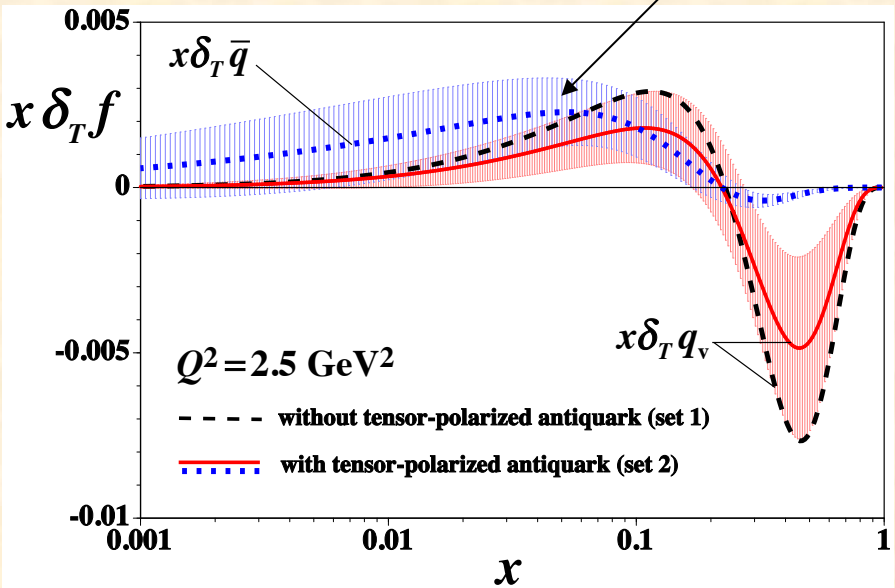
Tensor-polarized PDFs with errors



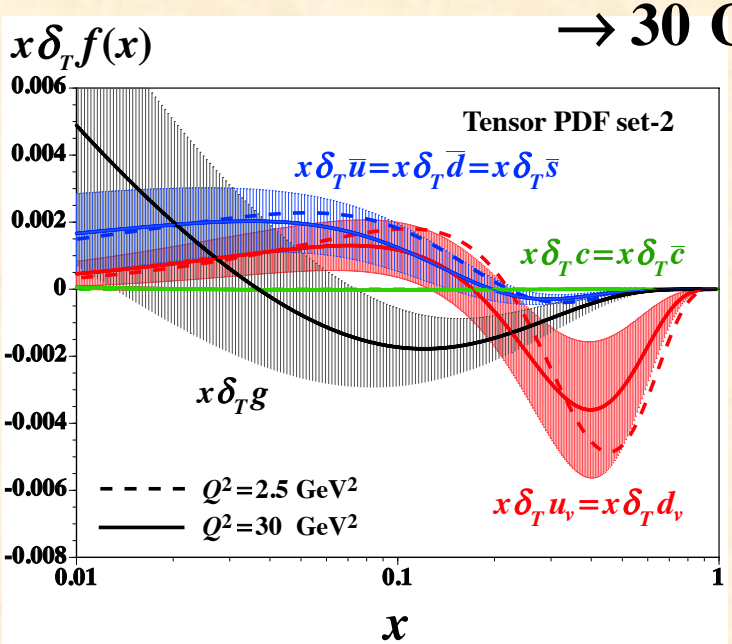


still large errors,
need experimental improvement
→ JLab, EIC, ...

experimental measurement
for antiquark distributions
→ Fermilab, ...

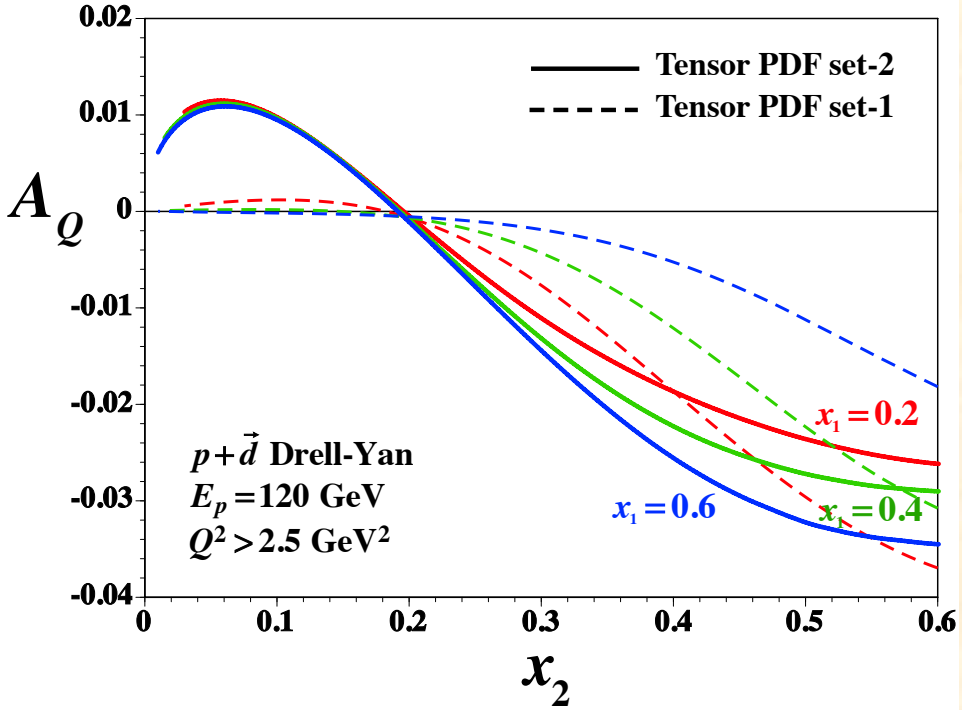
Q^2 evolution

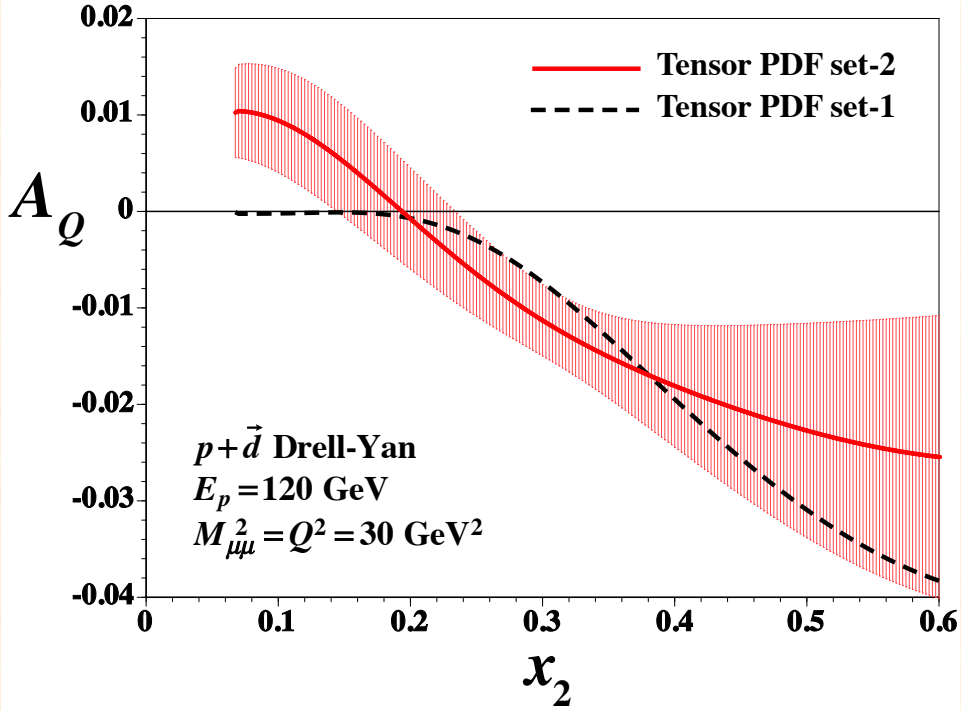
$Q^2 = 2.5$ GeV^2
→ 30 GeV^2



Tensor-polarized spin asymmetry

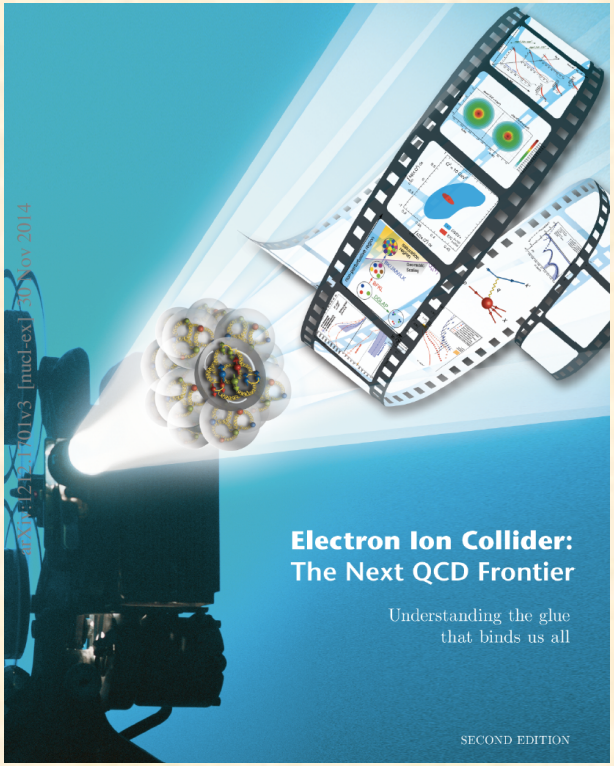
$$A_Q = \frac{\sum_a e_a^2 \left[q_a(x_A)\delta_T \bar{q}_a(x_B) + \bar{q}_a(x_A)\delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A)\bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$





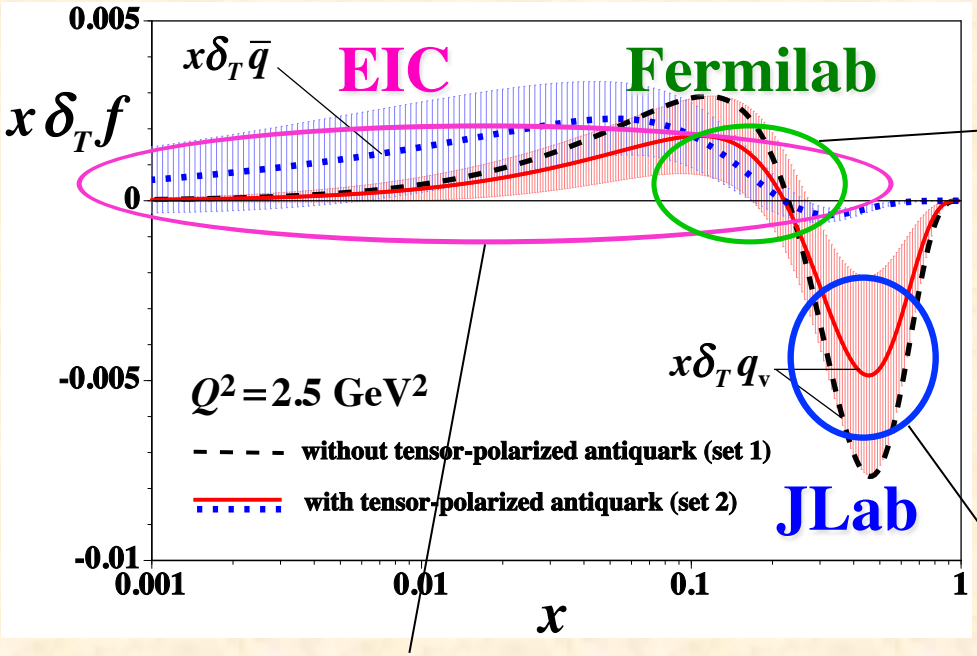
S. Kumano and Qin-Tao Song,
Phys. Rev. D94 (2016) 054022.

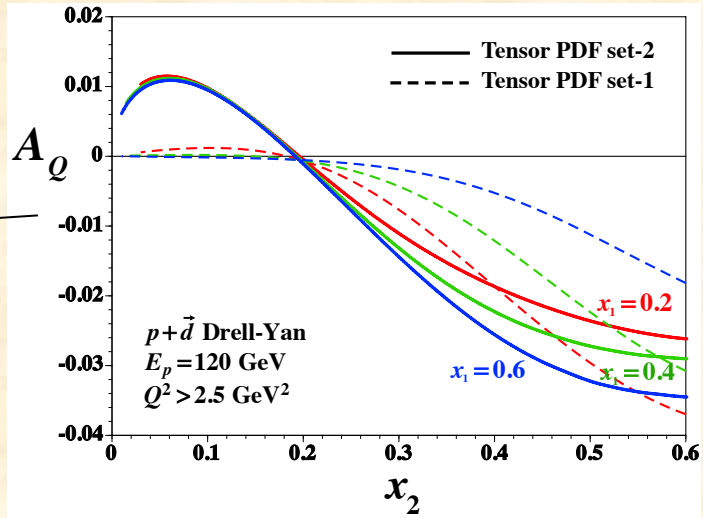
Electron-ion collider

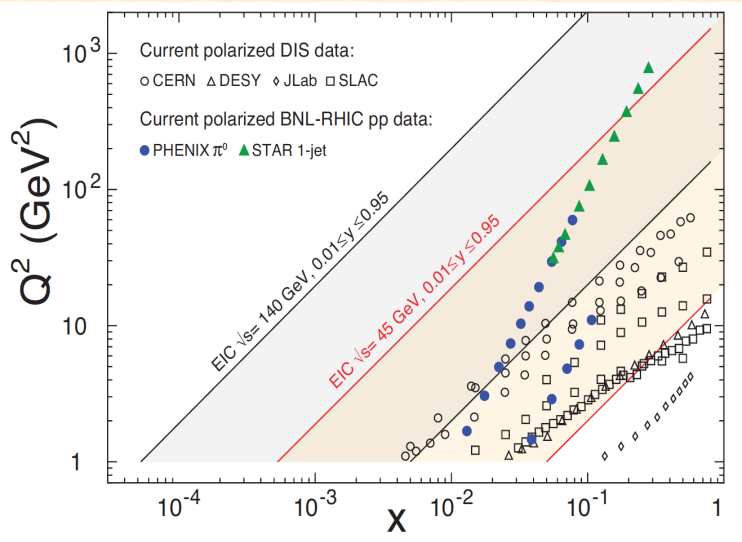


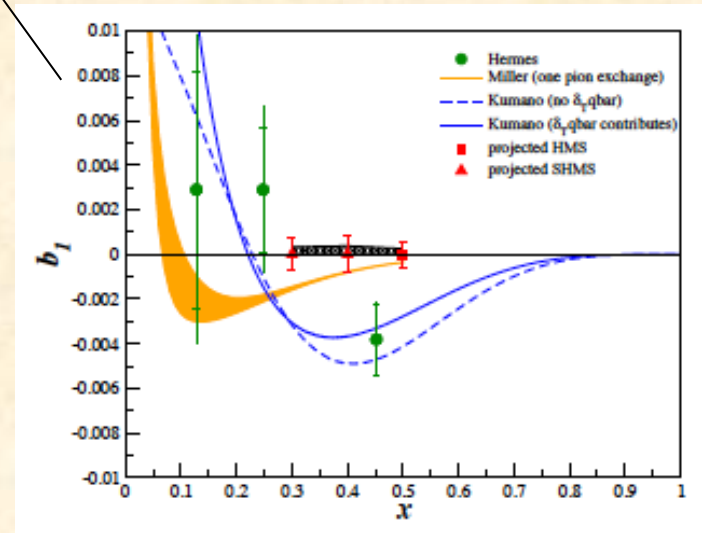
EIC (arXiv:1212.1701)

Small-x physics of b_1 at EIC





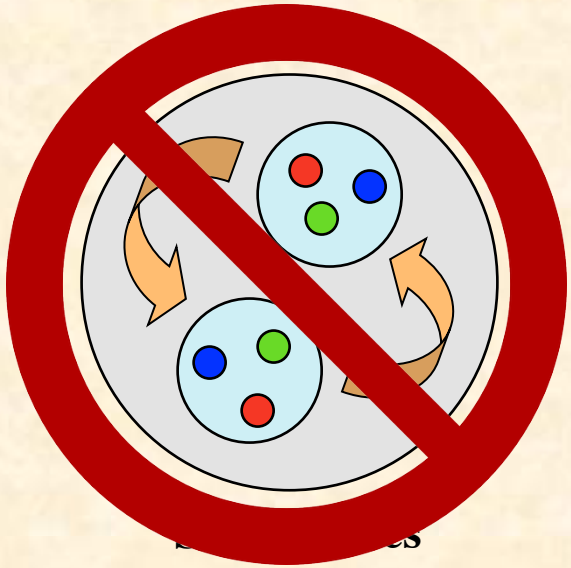




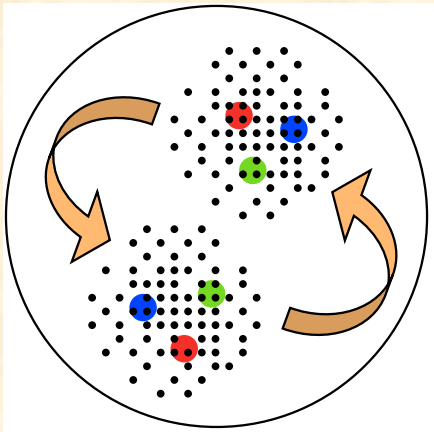
Summary

Spin-1 structure functions of the deuteron

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



standard model



? new exotic mechanism?

The End

The End