

Tensor polarized DIS theory

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**Workshop on ‘Polarized light ion physics with EIC’
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<https://www.jlab.org/indico/event/246/>**

Recent papers: (1) **SK and Qin-Tao Song, Phys. Rev. D 94 (2016) 054022.**
(2) W. Cosyn, Yu-Bing Dong, SK, M. Sargsian,
Phys. Rev. D 95 (2017) 074036.

February 8, 2018

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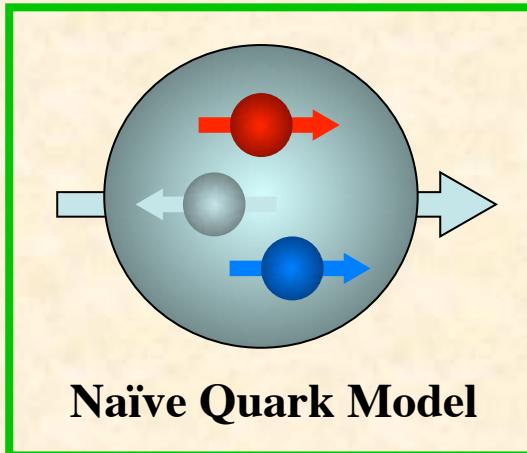
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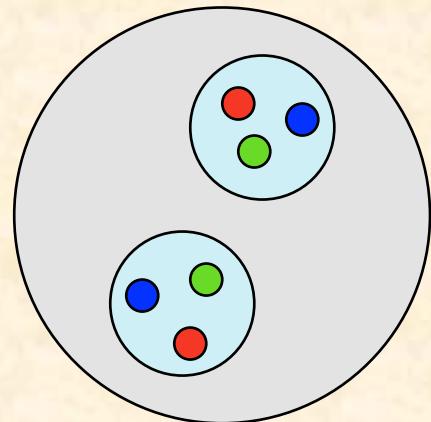
Nucleon spin



Naïve Quark Model

“old” standard model

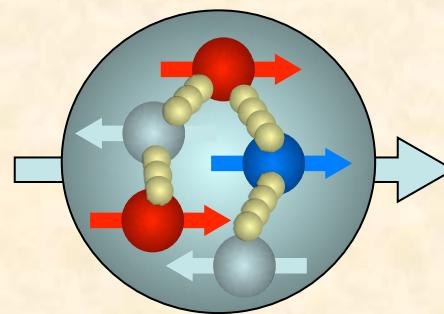
Tensor structure



only S wave

$$\mathbf{b}_1 = \mathbf{0}$$

Almost none of nucleon spin
is carried by quarks!

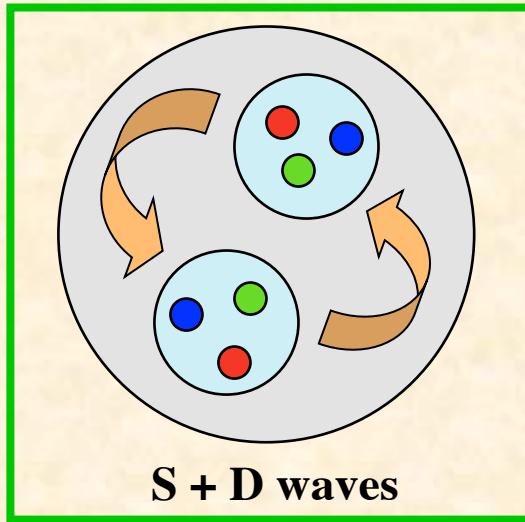


Sea-quarks and gluons?

Orbital angular momenta ?

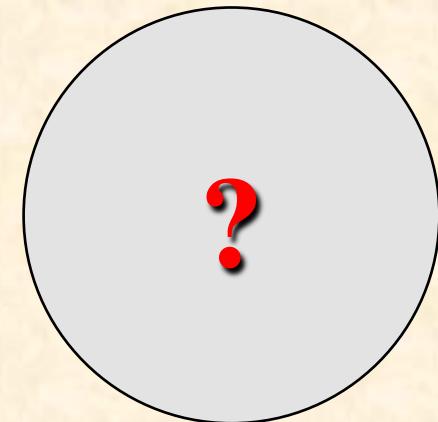
Nucleon spin crisis!?

\mathbf{b}_1 (e.g. deuteron)



standard model $\mathbf{b}_1 \neq \mathbf{0}$

Tensor-structure crisis!?



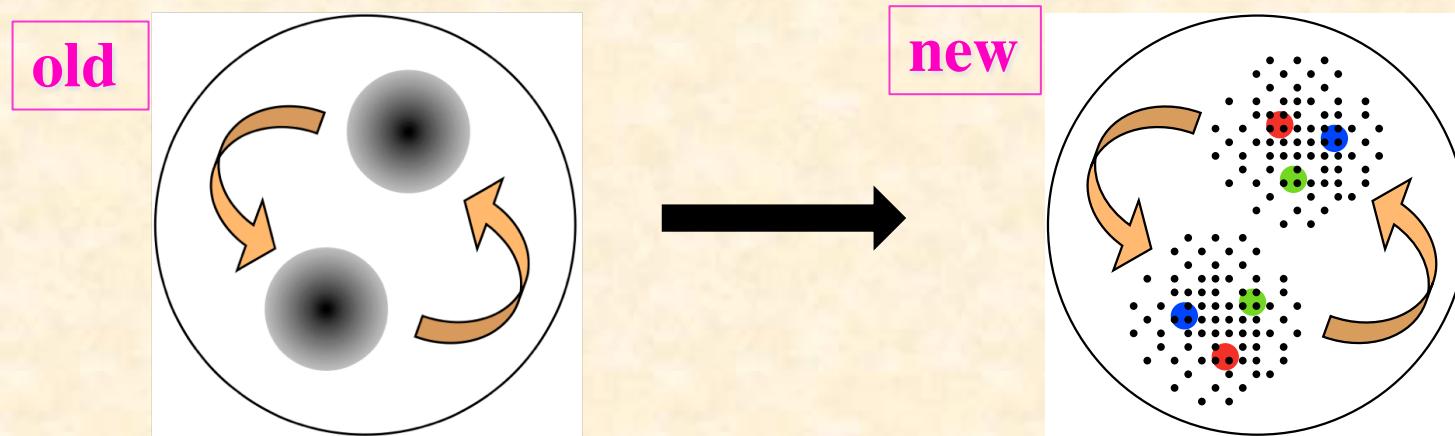
$\mathbf{b}_1^{\text{experiment}}$
 $\neq \mathbf{b}_1^{\text{"standard model"}}$

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

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.

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

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

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

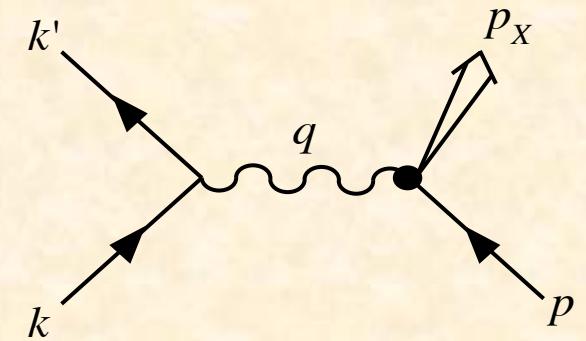
$$M = e \bar{u}(k', \lambda') \gamma_\mu u(k, \lambda) \frac{g^{\mu\nu}}{q^2} \langle X | e J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle$$

$$\begin{aligned} \sum_{pol} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) |M|^2 &= \frac{e^4}{Q^2} \sum_{\lambda, \lambda'} \sum_{\lambda_N} \sum_X (2\pi)^4 \delta^4(k + p - k' - p_X) \\ &\times \left[\bar{u}(k', \lambda') \gamma^\mu u(k, \lambda) \right]^* \left[\bar{u}(k', \lambda') \gamma^\nu u(k, \lambda) \right] \langle p, \lambda_N | J_\mu^{em}(\mathbf{0}) | X \rangle \langle X | J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle \\ &= \frac{(4\pi\alpha)^2}{Q^2} 4\pi M_N L^{\mu\nu} W_{\mu\nu} \end{aligned}$$

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

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

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



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.]

$$W_{\mu\nu} = \boxed{-F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{v} + g_1 \frac{i}{v} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + g_2 \frac{i}{v^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)} \quad \text{spin-1/2, spin-1}$$

$$\boxed{-b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})} \quad \text{spin-1 only}$$

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

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

b_1, \dots, b_4 terms are defined so that they vanish by spin average.

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

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

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

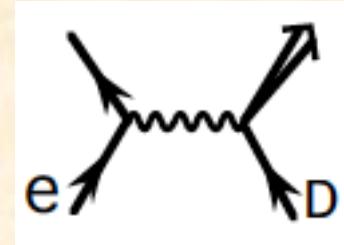
$2x b_1 = b_2$ in the scaling limit $\sim O(1)$

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

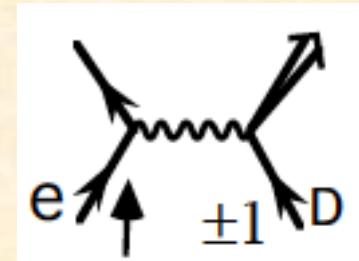
b_3, b_4 = twist-4 $\sim \frac{M^2}{Q^2}$

Structure Functions

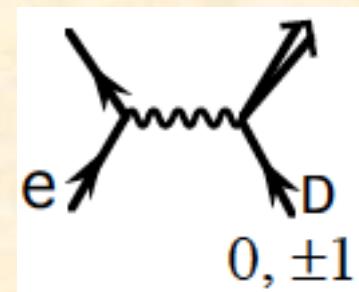
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

Parton Model

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

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

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

Constraint on valence-tensor polarization (sum rule)

Follow Feynman's book on
Photon-Hadron Interactions



$$\int dx \left(\text{Feynman diagram} \right) \leftrightarrow \text{Feynman diagram with } q \rightarrow 0$$

$$\int dx b_1^D(x) = \frac{5}{18} \int dx [\delta_T u_\nu + \delta_T d_\nu] + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D]$$

Elastic amplitude in a parton model

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

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

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

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

$$\begin{aligned} \int dx b_1^D(x) &= \frac{5}{9} \frac{3}{2} \left[\Gamma_{0,0} - \frac{1}{2} (\Gamma_{1,1} + \Gamma_{-1,-1}) \right] + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D] \\ &= -\frac{5}{6} \lim_{t \rightarrow 0} t F_Q(t) + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D] \\ &= 0 \text{ (valence)} + \frac{1}{18} \int dx [8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D] \end{aligned}$$

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

Intuitive derivation without calculation:
 $\int dx b_1(x) = \text{dimensionless quantity}$
 $= (\text{mass})^2 \cdot (\text{quadrupole moment})$

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

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

$$\delta_T q_\nu \equiv \delta_T q - \delta_T \bar{q}$$

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

Similarity to the Gottfried sum rule

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

$$\begin{aligned} S_G &= \int_0^1 \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] \\ &= \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x) - \bar{d}(x)] \\ &= \frac{1}{3} \quad \text{if } \bar{u} = \bar{d} \end{aligned}$$

(Gottfried sum rule)

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

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

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

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

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

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

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

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

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

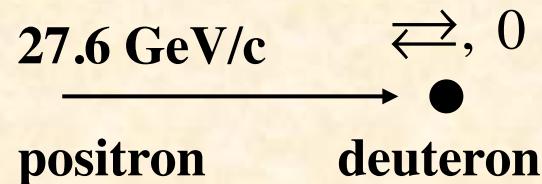
Extrapolating the NMC data, they obtained

$$S_G = 0.235 \pm 0.026$$

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

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



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

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

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

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

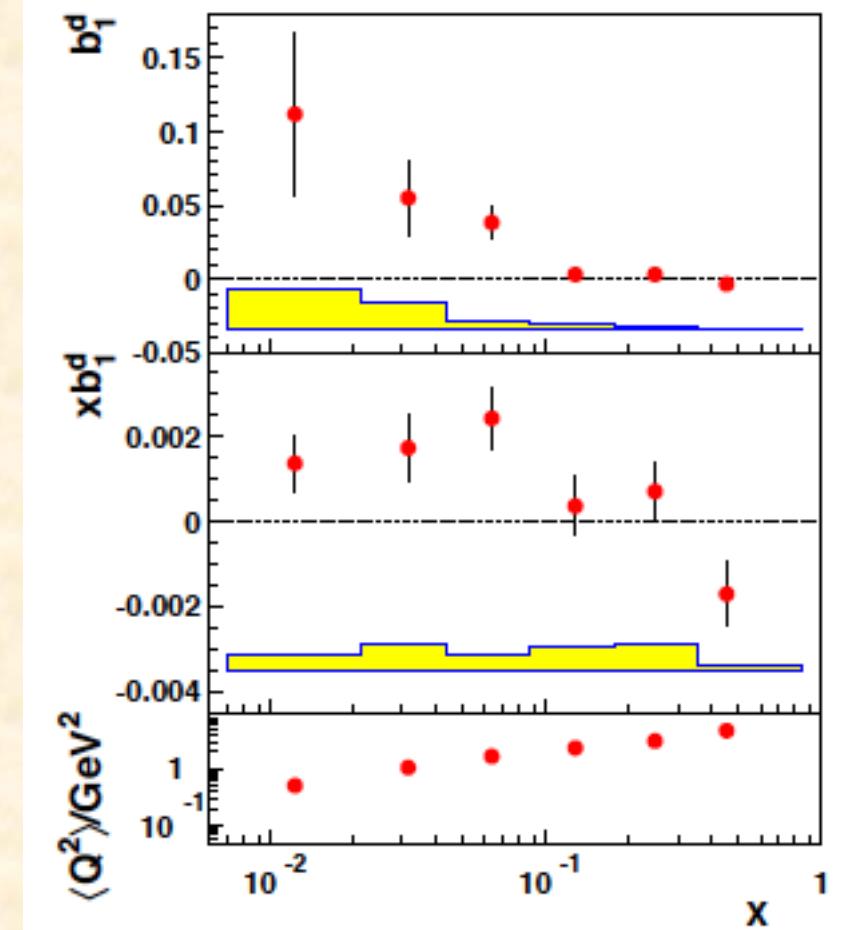
$$\int_{0.02}^{0.85} dx b_1(x) = [0.35 \pm 0.10(\text{stat}) \pm 0.18(\text{sys})] \times 10^{-2}$$

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

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

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

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

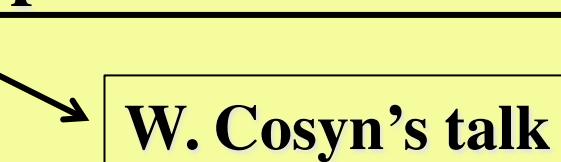


Drell-Yan experiments probe
these antiquark distributions.

“Standard” deuteron model prediction for b_1

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

- (1) Basic convolution model
- (2) Virtual nucleon approximation and higher-twist effects



Theory 1: Basic convolution approach

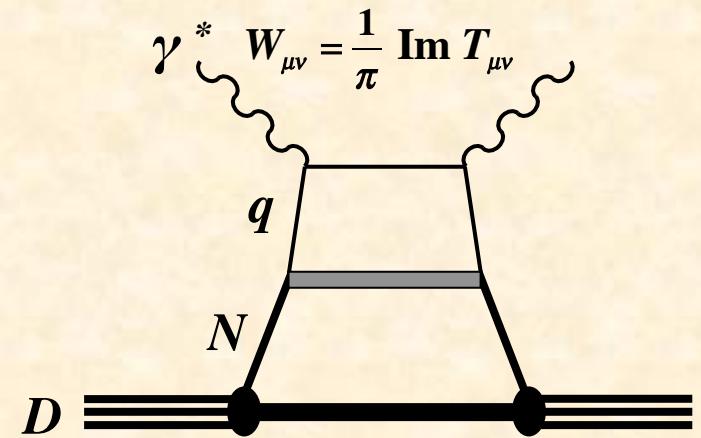
Convolution model: $A_{hH, hH}(x, Q^2) = \int \frac{dy}{y} \sum_s f_s^H(y) \hat{A}_{hs, hs}(x/y, Q^2) \equiv \sum_s f_s^H(y) \otimes \hat{A}_{hs, hs}(y, Q^2)$

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

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

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

$$y = \frac{Mp \cdot q}{M_N P \cdot q} \simeq \frac{2p^-}{P^-}, \quad f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$



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

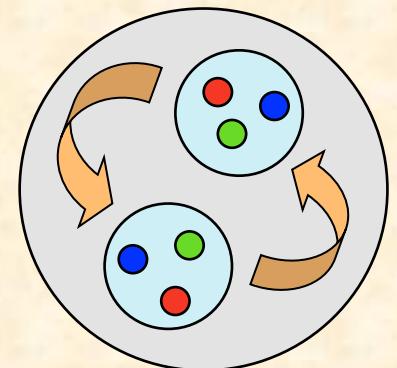
↓

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

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

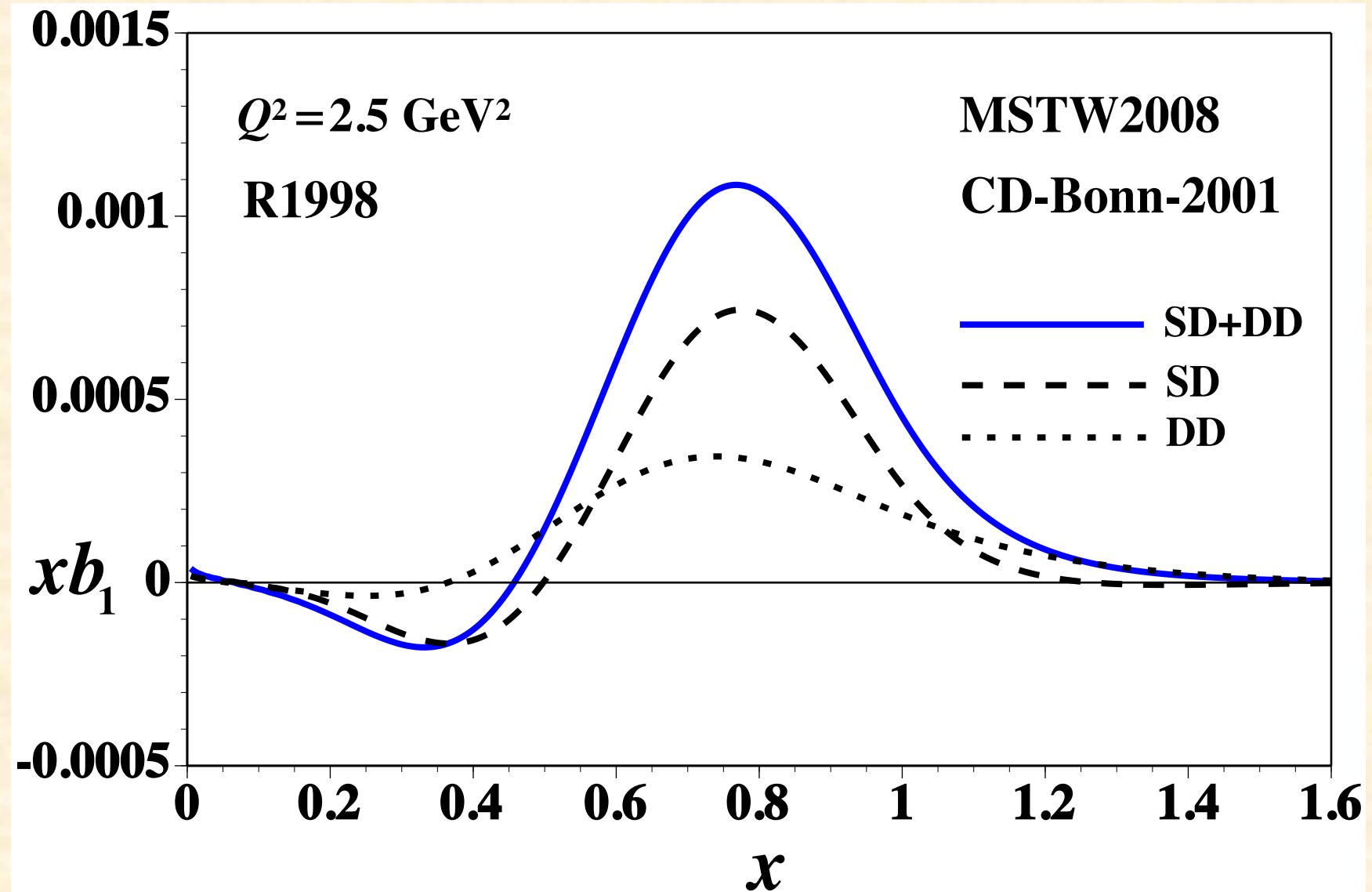
$$= \int d^3 p \, y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p) \phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] (3 \cos^2 \theta - 1) \delta\left(y - \frac{p \cdot q}{M_N v}\right)$$

**Standard model
of the deuteron**

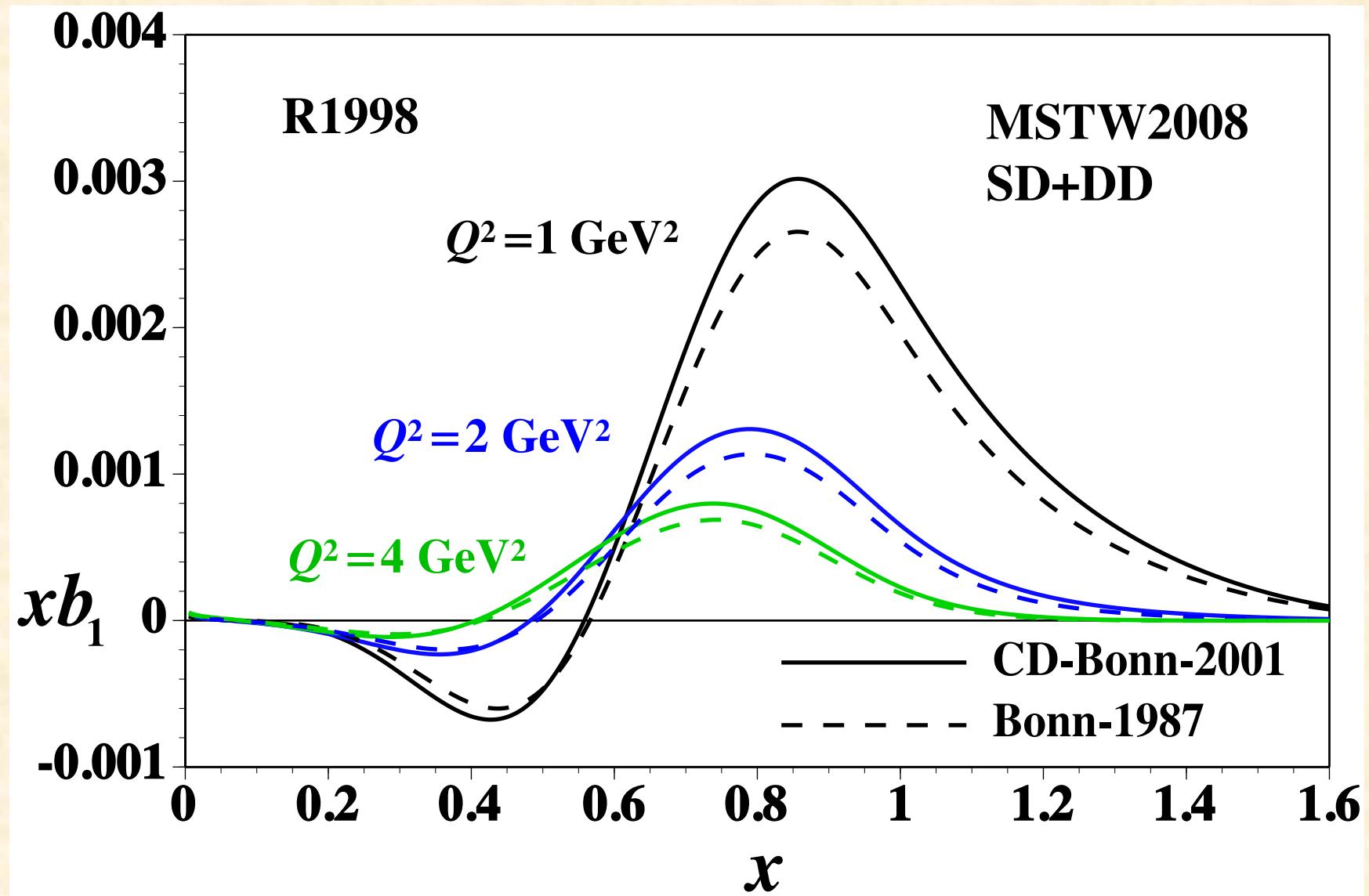


S + D waves

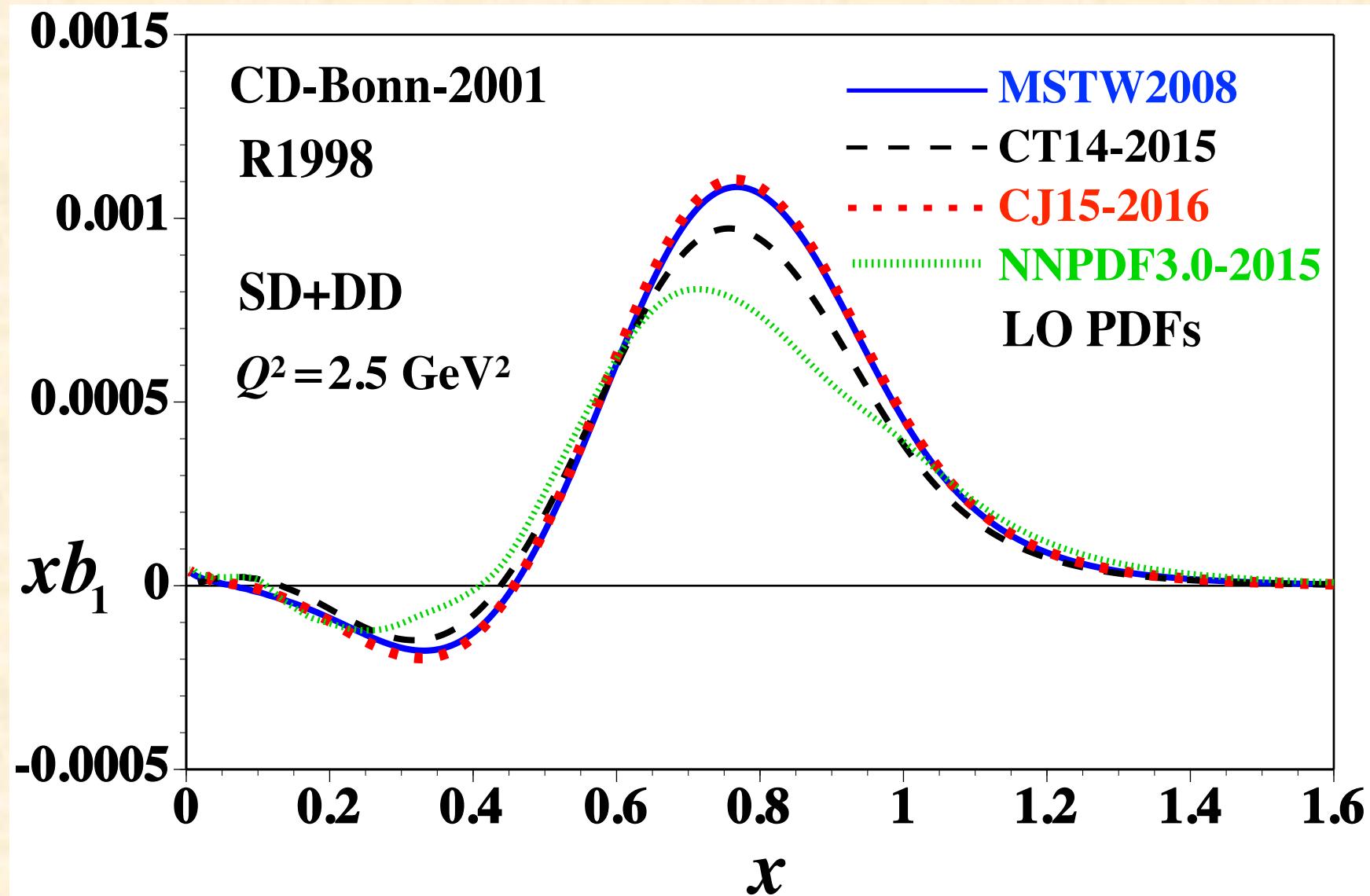
Results on b_1 in the convolution description



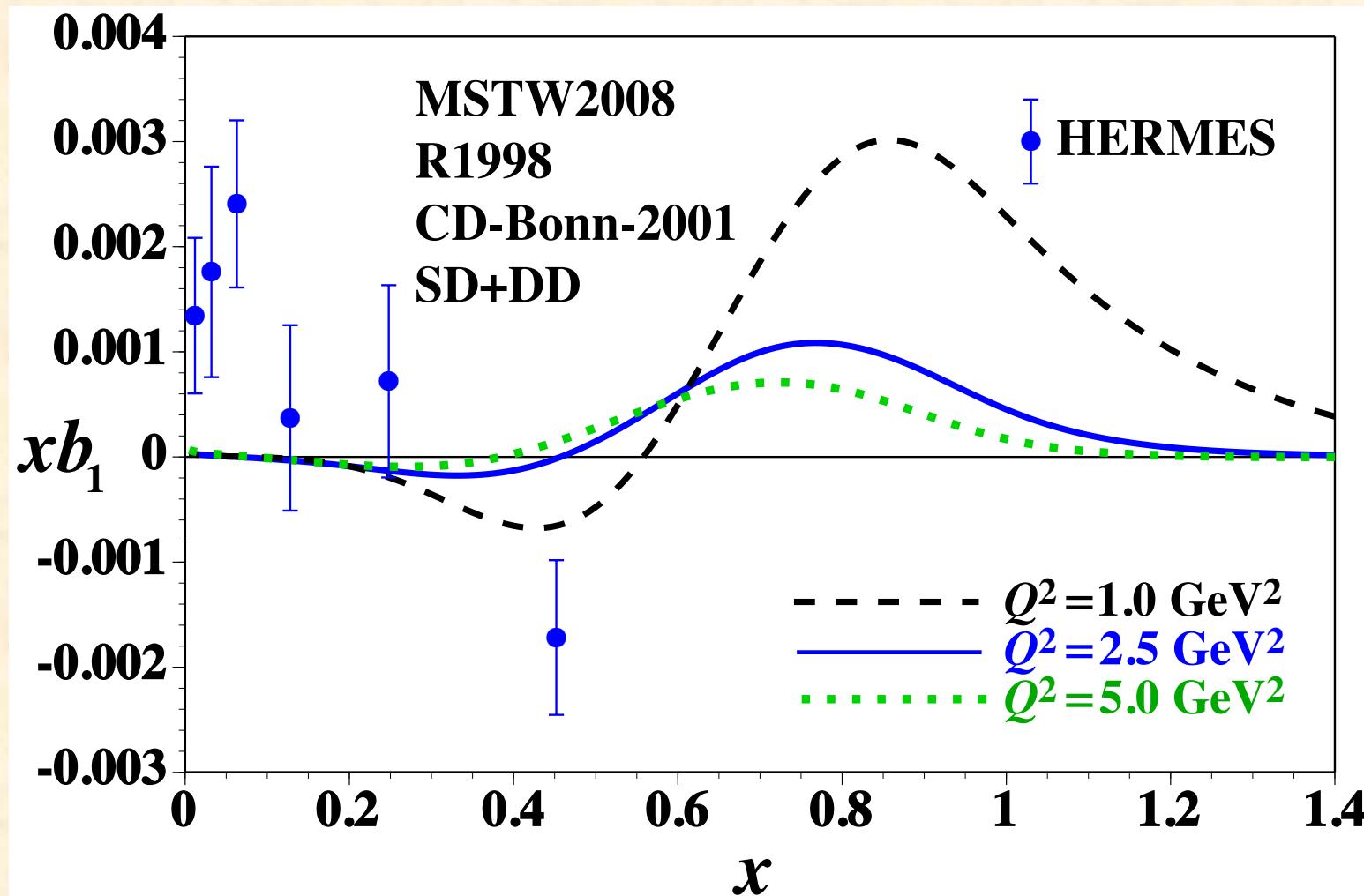
Results on b_1 : deuteron-wave-function dependence



Results on b_1 : used PDF dependence



Comparison with HERMES measurements



Theory 2: Virtual nucleon approximation with higher-twist effects

L. L. Frankfurt and M. I. Strikman, Phys. Rep. 76, 215 (1981);

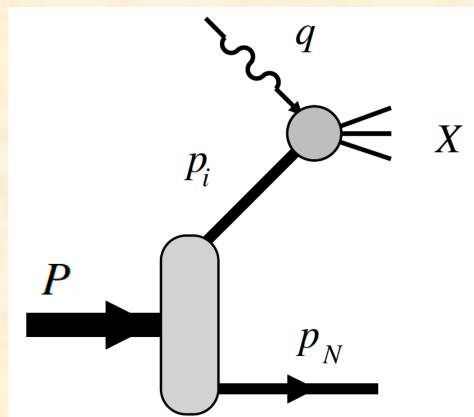
B. D. Keister and W. Polyzou, Adv. Nucl. Phys. 20, 225 (1991);

W. Cosyn and M. Sargsian, Phys. Rev. C 84, 014601 (2011);

W. Cosyn, W. Melnitchouk, and M. Sargsian, Phys. Rev. C 89, 014612 (2014).

For b_1 , see W. Cosyn, M. Sargsian, and C. Weiss, Proc. Sci., DIS2016 (2016) 210.

W. Cosyn's talk



Virtual nucleon approximation (VNA)

$$W_{\mu\nu}^{\lambda'\lambda}(P, q) = 4(2\pi)^3 \int d\Gamma_N \frac{\alpha_N}{\alpha_i} W_{\mu\nu}^N(p_i, q) \rho_D(\lambda', \lambda)$$

momentum-fractions for interacting (i) and spectator nucleons (N):

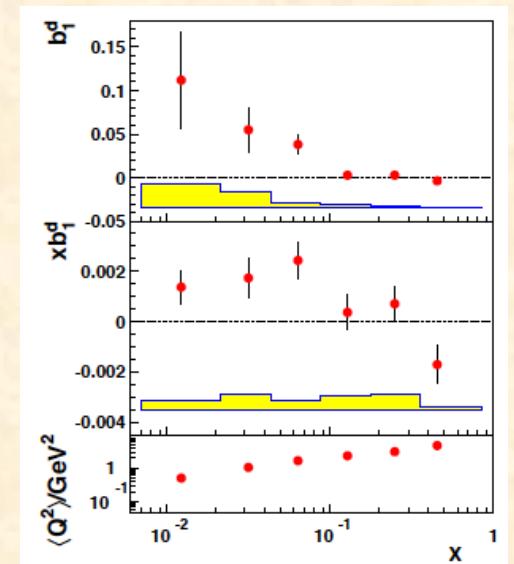
$$\alpha_i = \frac{2p_i^-}{P^-}, \quad \alpha_N = \frac{2p_N^-}{P^-} = 2 - \alpha_i, \quad P = p_i + p_N$$

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

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

Virtual nucleon approximation and high-twist effects

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



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

Tensor spin asymmetry A_{zz}

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

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

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

We need to be careful about higher-twist effects.

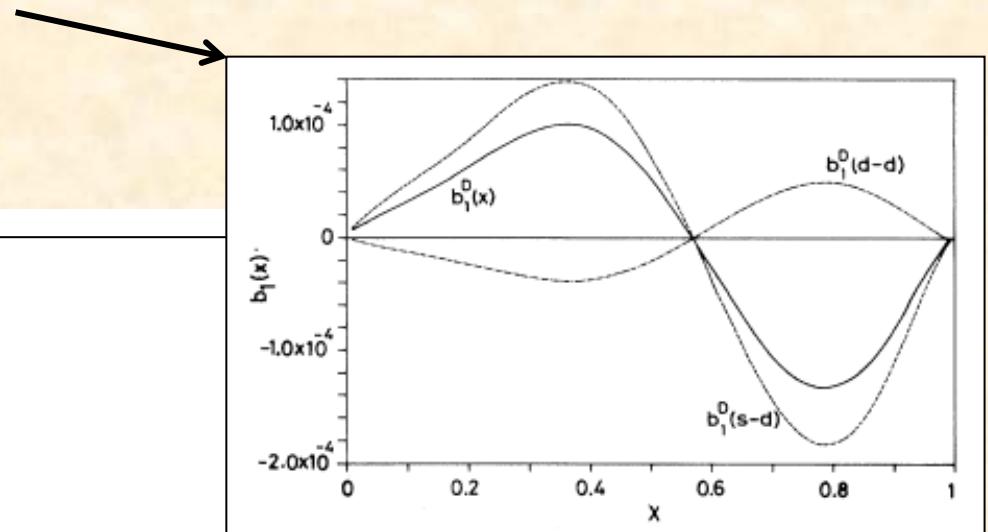
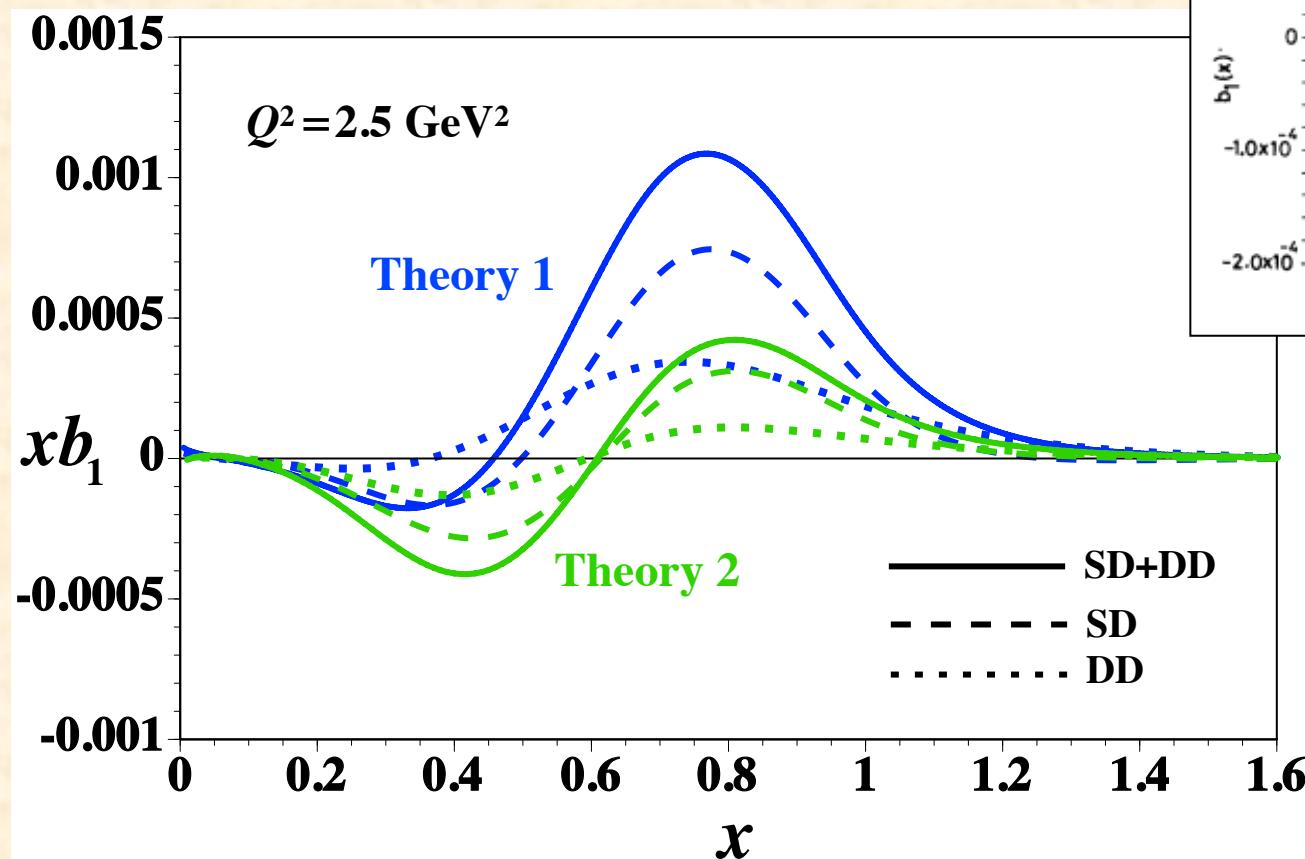
Results on b_1 in the convolution description

Very different from

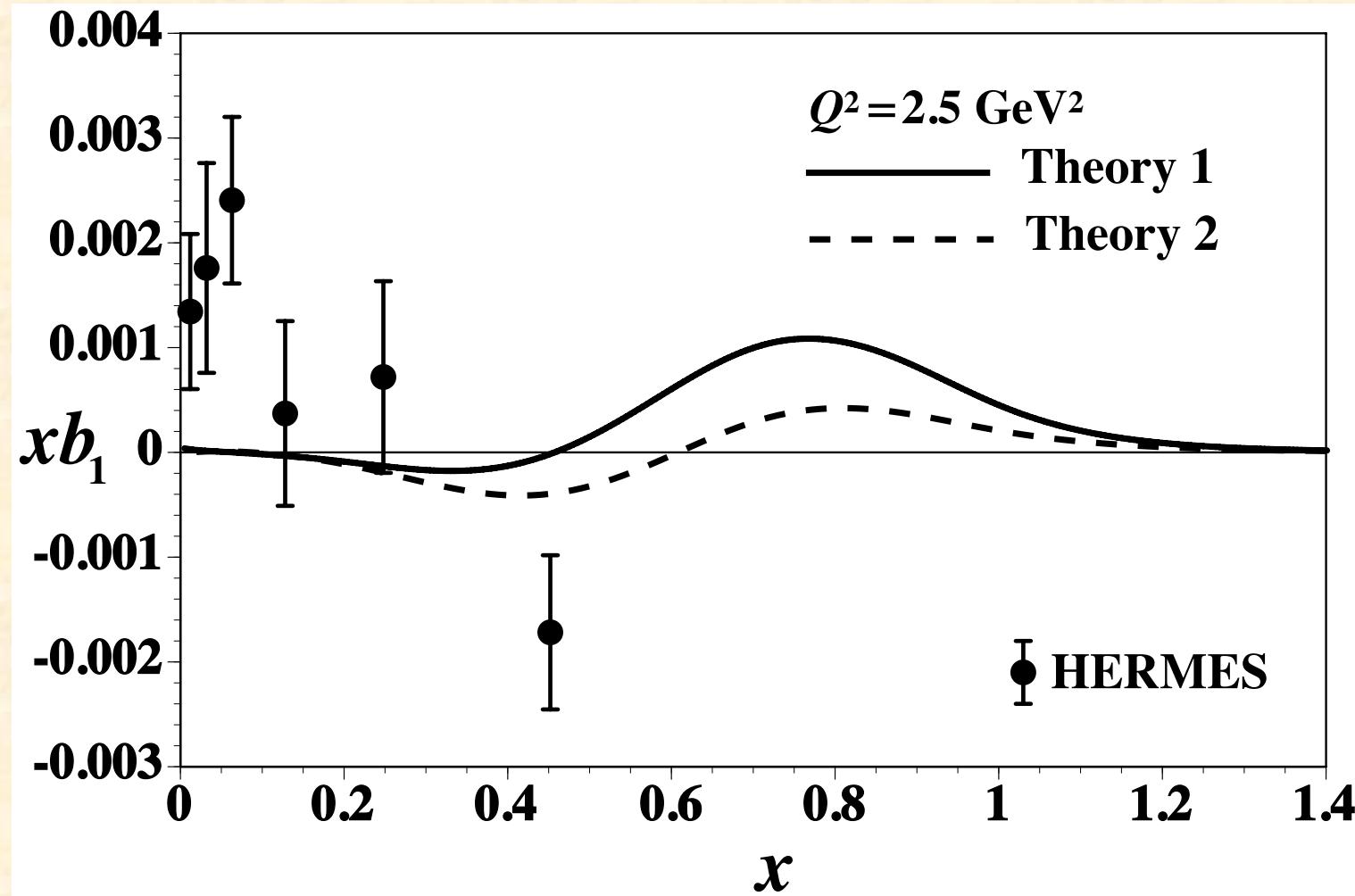
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

H. Khan and P. Hoodbhoy, PRC44 (1991) 1219;

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



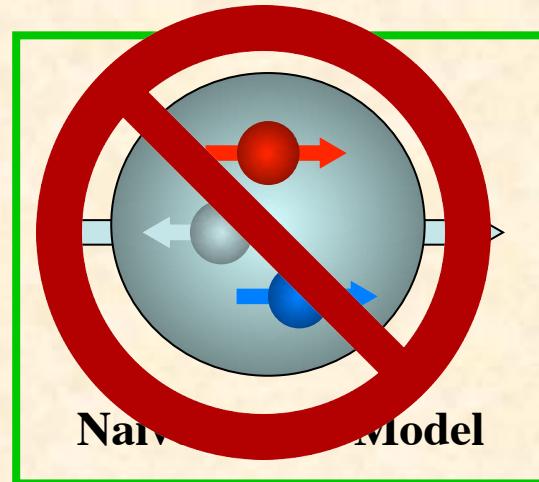
Comparison with HERMES measurements



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

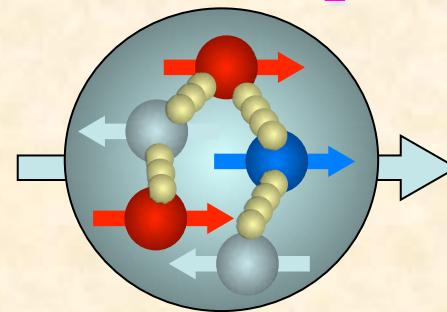
Standard convolution model does not
work for the deuteron tensor structure!?

Situation of tensor structure by b_1



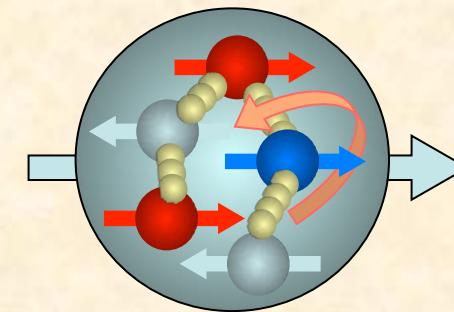
“old” standard model

Nucleon spin

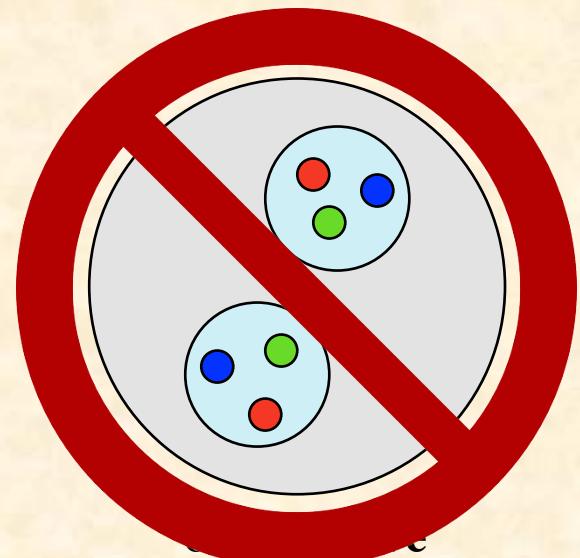


Sea-quarks and gluons?

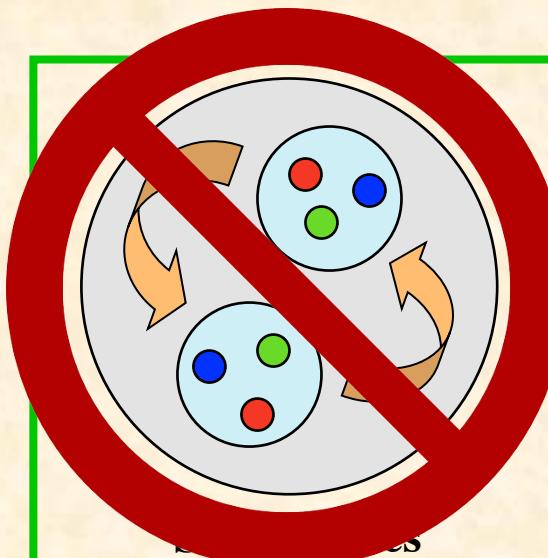
Nucleon spin crisis!?



Orbital angular momenta ?



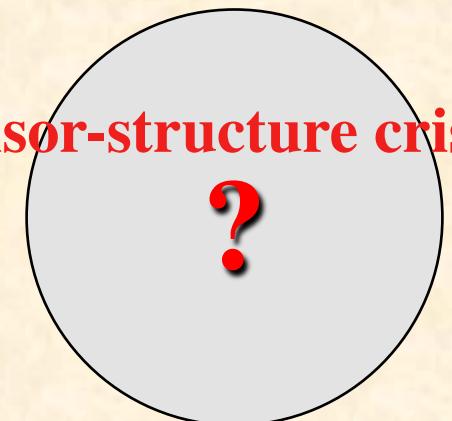
$b_1 = 0$



standard model $b_1 \neq 0$

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

Tensor-structure crisis!?

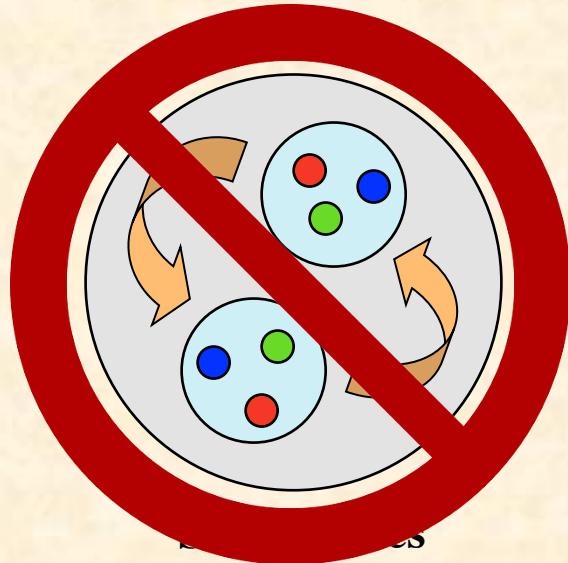


$b_1^{\text{experiment}}$
 $\neq b_1^{\text{“standard model”}}$

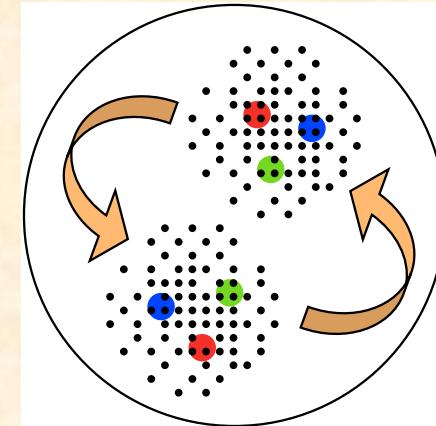
Summary I

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

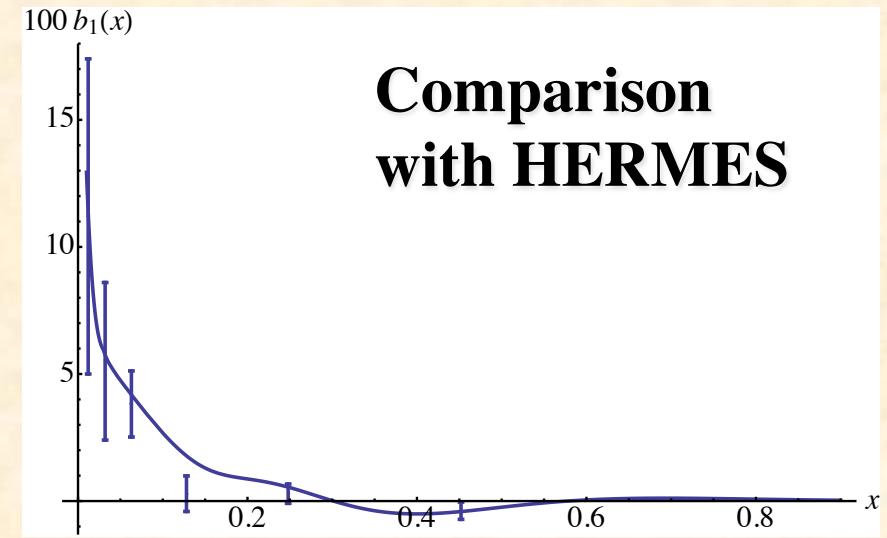
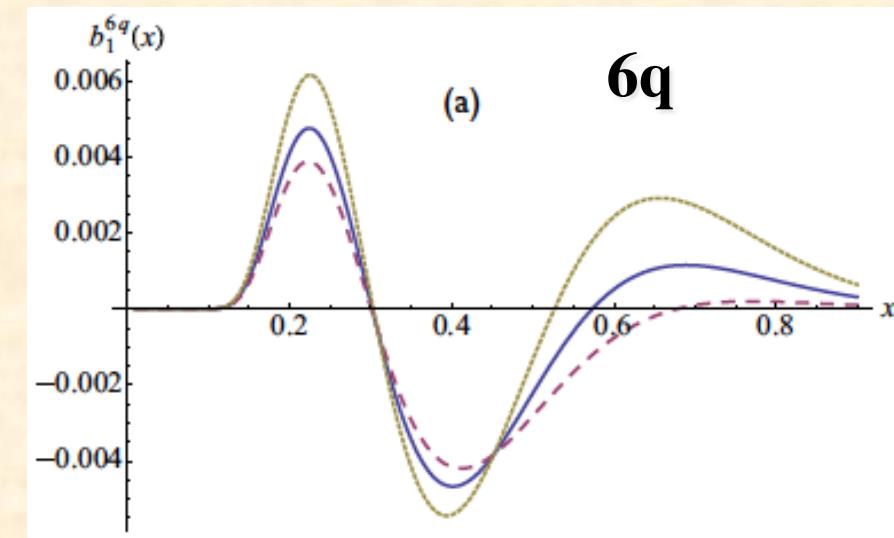
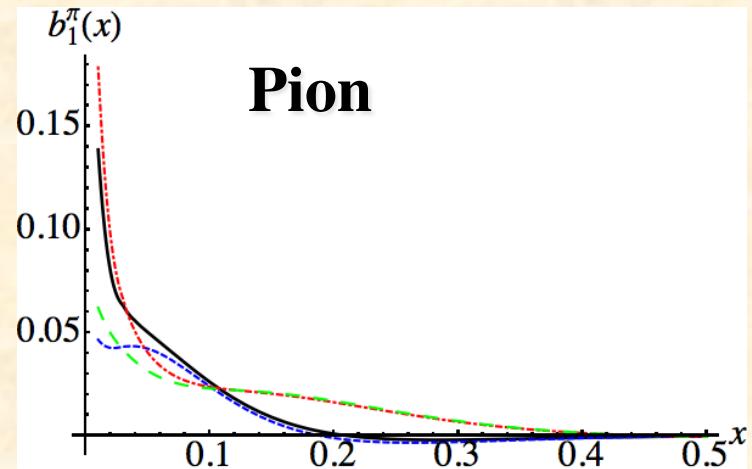
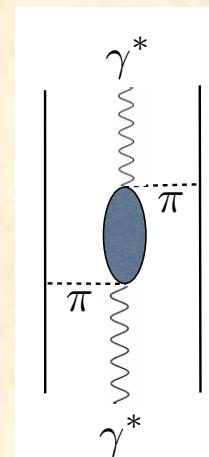


? new exotic
mechanism?

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

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

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



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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G. Ron
Hebrew University of Jerusalem, Jerusalem

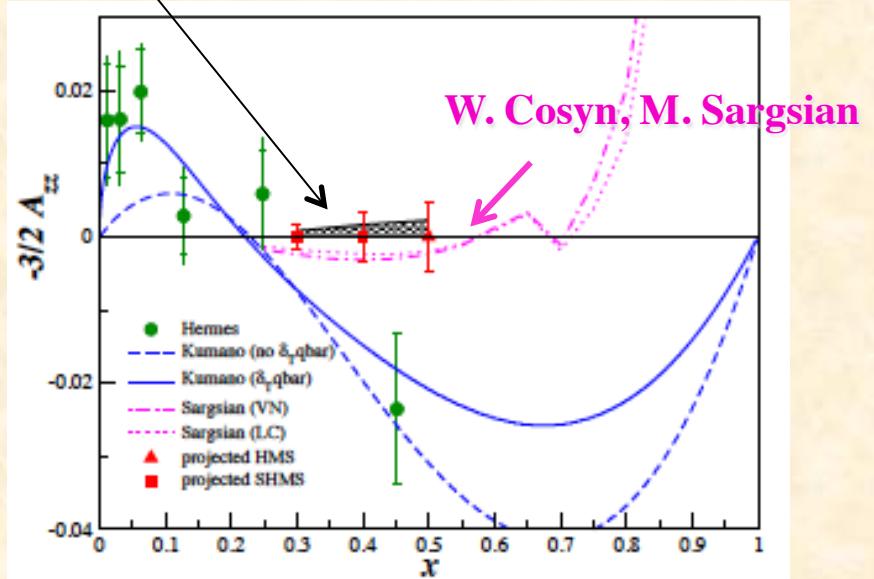
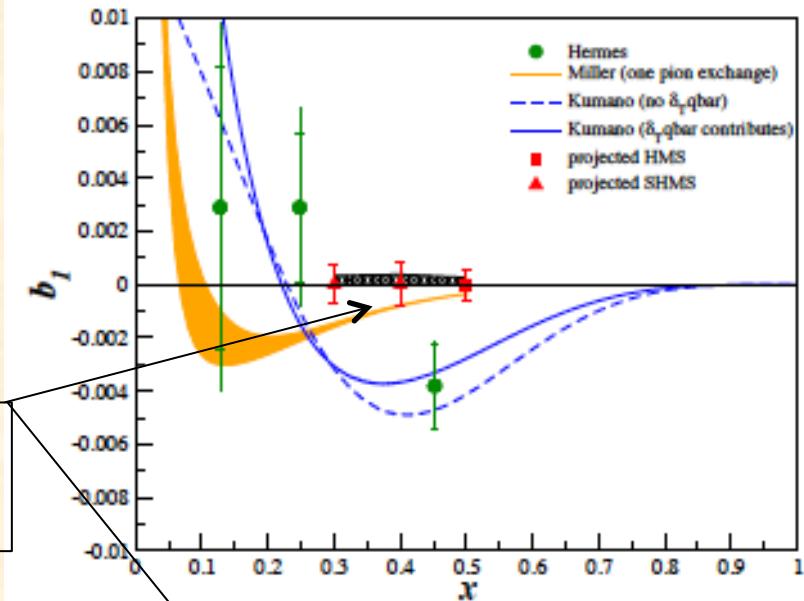
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Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
Seoul National University, Seoul 151-747 Korea

**Expected errors
by JLab**



Approved!

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

Experimental possibilities



© JLab

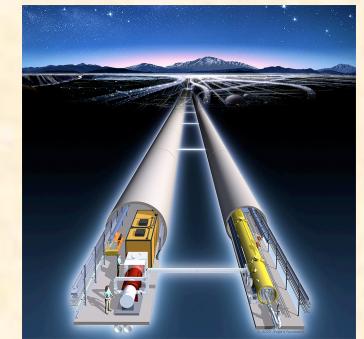
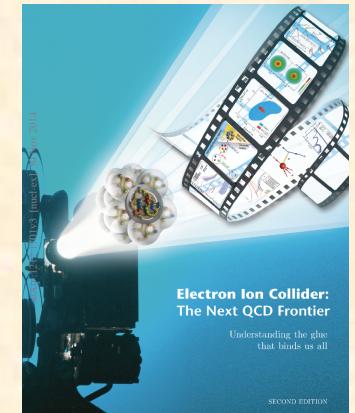
Approved
experiment!
(2019~)

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

Theoretical estimation on tensor-polarization asymmetry in Drell-Yan at Fermilab

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

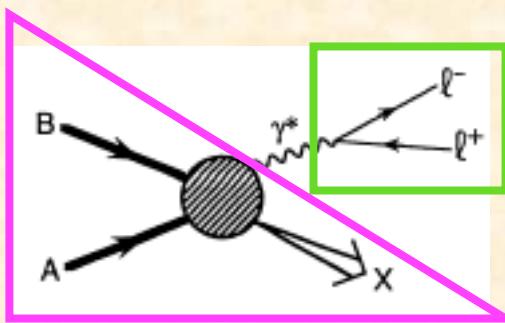
Drell-Yan cross section and hadron tensor

$$d\sigma = \frac{1}{4\sqrt{(P_A \cdot P_B)^2 - M_A^2 M_B^2}} \sum_{S_r} \sum_{S_{r^+}} (2\pi)^4 \delta^4(P_A + P_B - k_{r^+} - k_{r^-} - P_X) \left| \langle l^+ l^- X | T | AB \rangle \right|^2 \frac{d^3 k_{r^+}}{(2\pi)^3 2E_{r^+}} \frac{d^3 k_{r^-}}{(2\pi)^3 2E_{r^-}}$$

$$\langle l^+ l^- X | T | AB \rangle = \bar{u}(k_{r^-}, \lambda_{r^-}) e \gamma_\mu v(k_{r^+}, \lambda_{r^+}) \frac{g^{\mu\nu}}{(k_{r^+} + k_{r^-})^2} \langle X | e J_\nu(0) | AB \rangle$$

$$\frac{d\sigma}{d^4 Q d\Omega} = \frac{\alpha^2}{2sQ^4} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\mu\nu} \equiv \int \frac{d^4 \xi}{(2\pi)^4} e^{iQ \cdot \xi} \langle P_A S_A P_B S_B | J^\mu(0) J^\nu(\xi) | P_A S_A P_B S_B \rangle$$

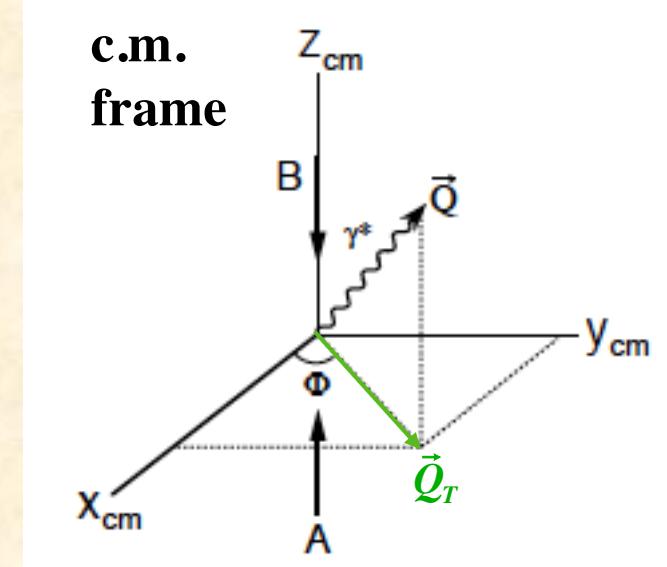


For the details, see

- M. Hino and SK, Phys. Rev. D59 (1999) 094026.
- M. Hino and SK, Phys. Rev. D60 (1999) 054018.

Formalism of pd Drell-Yan process

See Ref. PRD59
(1999) 094026.



proton-proton proton-deuteron

Number of
structure functions

48

108

After integration over \vec{Q}_T
(or $\vec{Q}_T \rightarrow 0$)

11

22

In parton model

3

Additional structure
functions due to
tensor structure

4

I explain
in the next page.

Spin asymmetries in the parton model

unpolarized: q_a ,

longitudinally polarized: Δq_a ,

transversely polarized: $\Delta_T q_a$,

tensor polarized: δq_a

Unpolarized cross section

$$\left\langle \frac{d\sigma}{dx_A dx_B d\Omega} \right\rangle = \frac{\alpha^2}{4Q^2} (1 + \cos^2 \theta) \frac{1}{3} \sum_a e_a^2 [q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B)]$$

Spin asymmetries

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

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

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

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

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

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

Note: $\delta \neq \text{transversity}$ in my notation

Functional form of parametrization

Assume flavor-symmetric antiquark distributions: $\delta_T \bar{q}^D \equiv \delta_T \bar{u}^D = \delta_T \bar{d}^D = \delta_T s^D = \delta_T \bar{s}^D$

$$b_1^D(x)_{LO} = \frac{1}{18} [4\delta_T u_v^D(x) + \delta_T d_v^D(x) + 12 \delta_T \bar{q}^D(x)]$$

At $Q_0^2 = 2.5 \text{ GeV}^2$, $\delta_T q_v^D(x, Q_0^2) = \delta_T w(x) q_v^D(x, Q_0^2)$, $\delta_T \bar{q}^D(x, Q_0^2) = \alpha_{\bar{q}} \delta_T w(x) \bar{q}^D(x, Q_0^2)$

Certain fractions of quark and antiquark distributions are tensor polarized and such probabilities are given by the function $\delta_T w(x)$ and an additional constant $\alpha_{\bar{q}}$ for antiquarks in comparison with the quark polarization.

$$\begin{aligned} b_1^D(x, Q_0^2)_{LO} &= \frac{1}{18} [4\delta_T u_v^D(x, Q_0^2) + \delta_T d_v^D(x, Q_0^2) + 12 \delta_T \bar{q}^D(x, Q_0^2)] \\ &= \frac{1}{36} \delta_T w(x) [5 \{ u_v(x, Q_0^2) + d_v(x, Q_0^2) \} + 4a_{\bar{q}} \{ 2\bar{u}(x, Q_0^2) + 2\bar{d}(x, Q_0^2) + s(x, Q_0^2) + \bar{s}(x, Q_0^2) \}] \end{aligned}$$

$$\delta_T w(x) = ax^b(1-x)^c(x_0 - x)$$

Two types of analyses

Set 1: $\delta_T \bar{q}^D(x) = 0$ Tensor-polarized antiquark distributions are terminated ($\alpha_{\bar{q}} = 0$),

Set 2: $\delta_T \bar{q}^D(x) \neq 0$ Finite tensor-polarized antiquark distributions are allowed ($\alpha_{\bar{q}} \neq 0$).

Results

SK, PRD 82 (2010) 017501

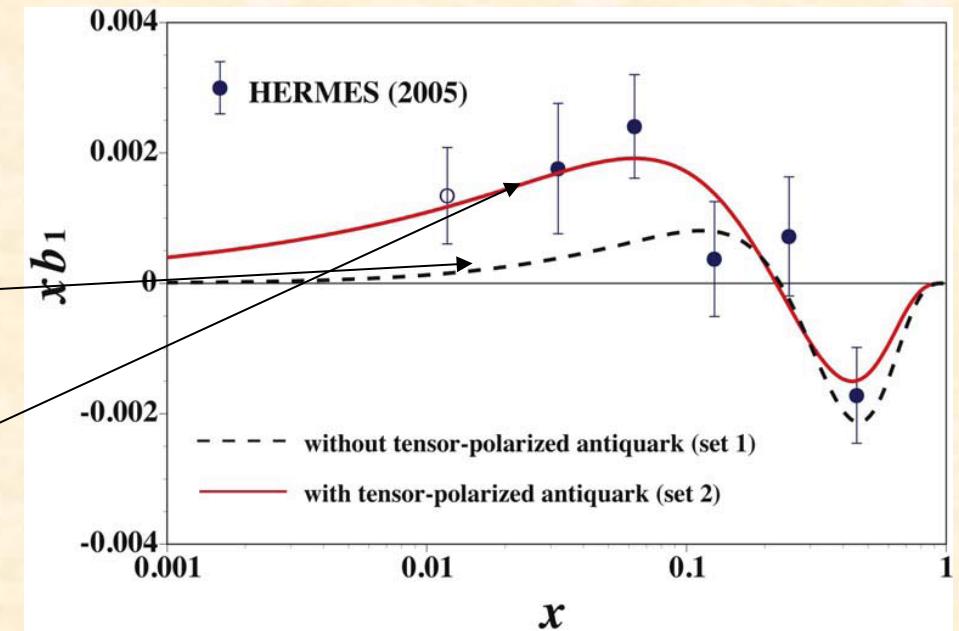
Two-types of fit results:

- set-1: $\chi^2 / \text{d.o.f.} = 2.83$

Without $\delta_T q$, the fit is not good enough.

- set-2: $\chi^2 / \text{d.o.f.} = 1.57$

With finite $\delta_T q$, the fit is reasonably good.



Obtained tensor-polarized distributions

$\delta_T q(x)$, $\delta_T \bar{q}(x)$ from the HERMES data.

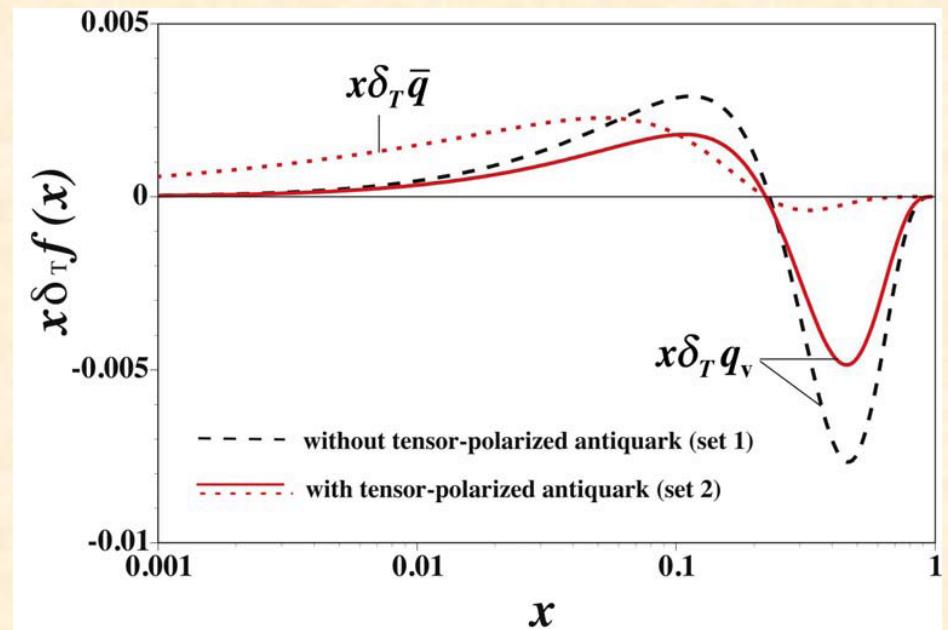
→ They could be used for

- experimental proposals,
- comparison with theoretical models.

Finite tensor polarization for antiquarks:

$$\int_0^1 dx b_1(x) = 0.058$$

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



Experimental possibility at Fermilab

E1039

Polarized fixed-target experiments at the Main Injector



© Fermilab

Drell-Yan experiment with a polarized proton target

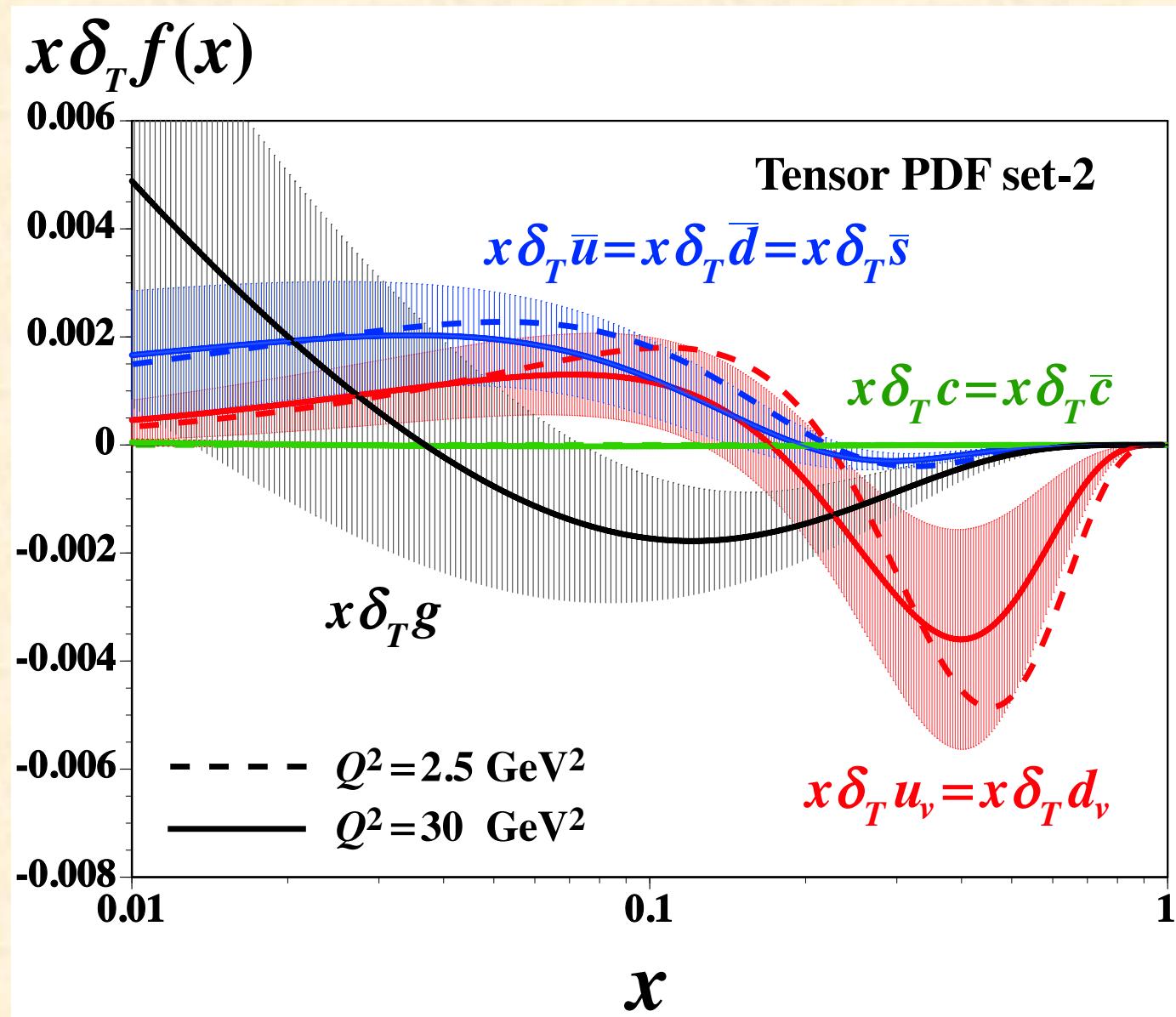
Co-Spokespersons: A. Klein, X. Jiang, Los Alamos National Laboratory

List of Collaborators:

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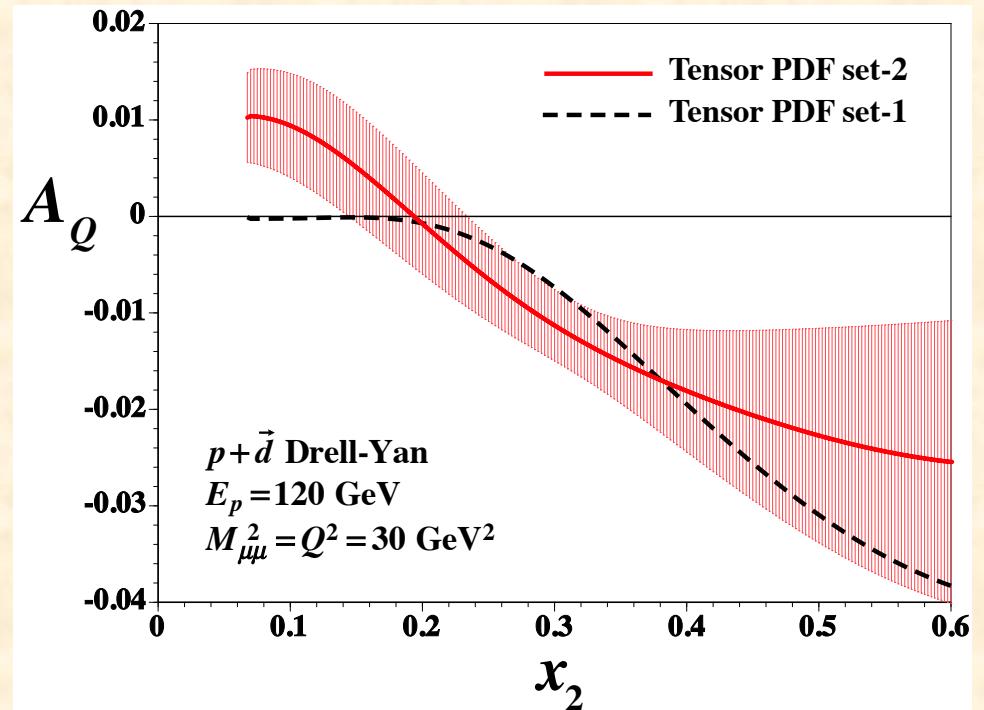
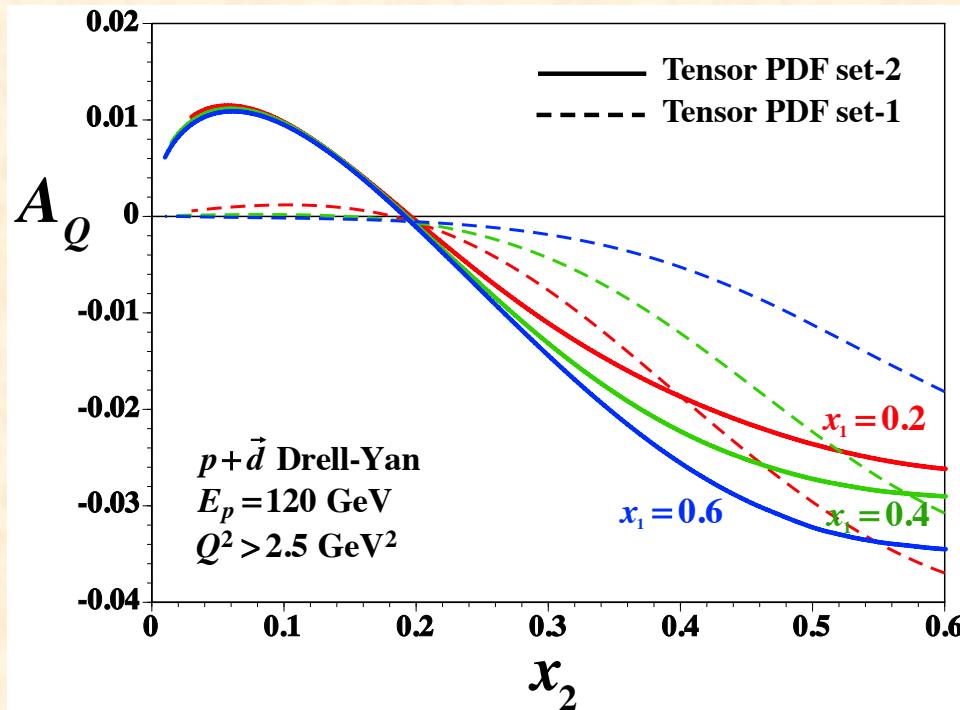
Q^2 evolution

$Q^2 = 2.5 \text{ GeV}^2 \rightarrow 30 \text{ GeV}^2$



Tensor-polarized spin asymmetry

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



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

Summary II

JLab PR12-11-110 (2019~) : $b_1 = \frac{1}{2} \sum_i e_i^2 (\delta_T q_i + \delta_T \bar{q}_i)$

No separation between $\delta_T q$ and $\delta_T \bar{q}$

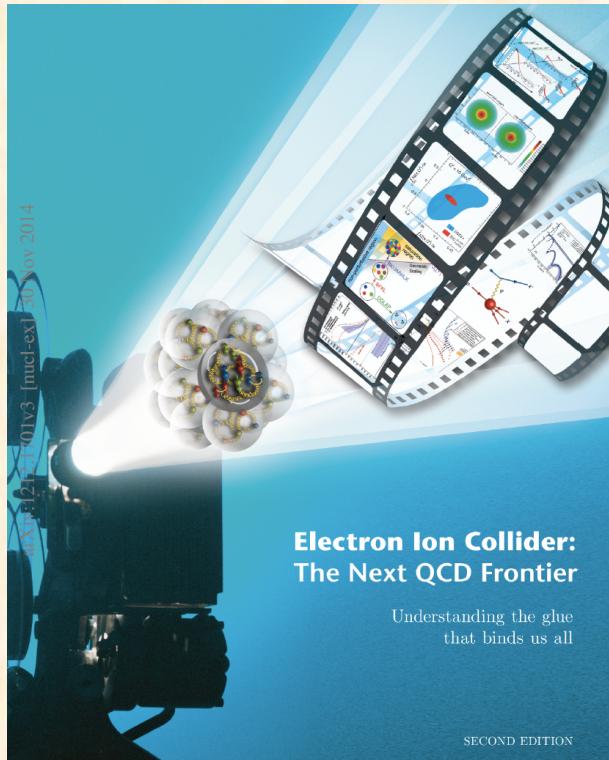
Fermilab E1039 (20xx) : A_Q (large x_F) $\approx \frac{\sum_a e_a^2 q_a(x_1) \delta_T \bar{q}_a(x_2)}{2 \sum_a e_a^2 q_a(x_1) \bar{q}_a(x_2)}$

Separation of $\delta_T \bar{q}$

→ possible new exotic hadron physics mechanism

EIC and future prospects

Electron-ion collider (US)



EIC (arXiv:1212.1701)

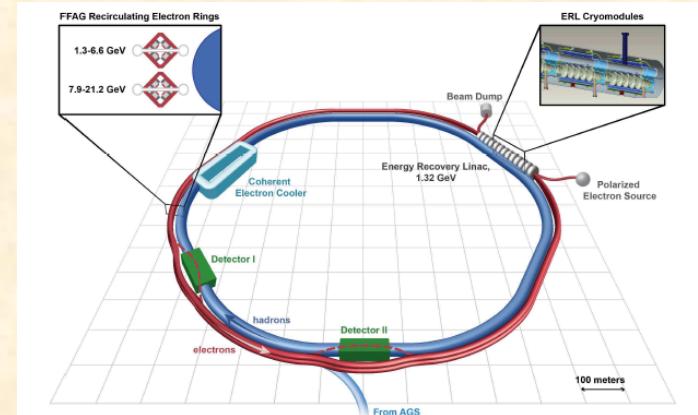
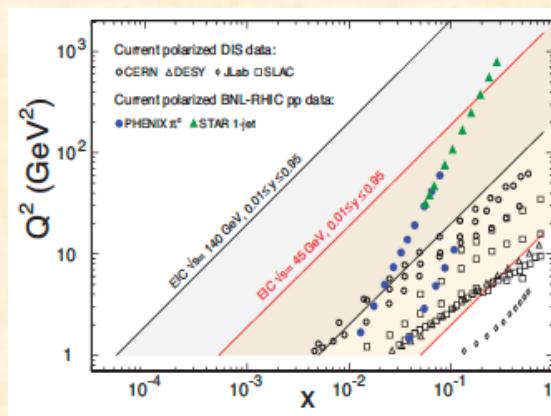


Figure 5.1: The layout of the ERL-based, 21 GeV \times 250 GeV high-energy high-luminosity eRHIC.

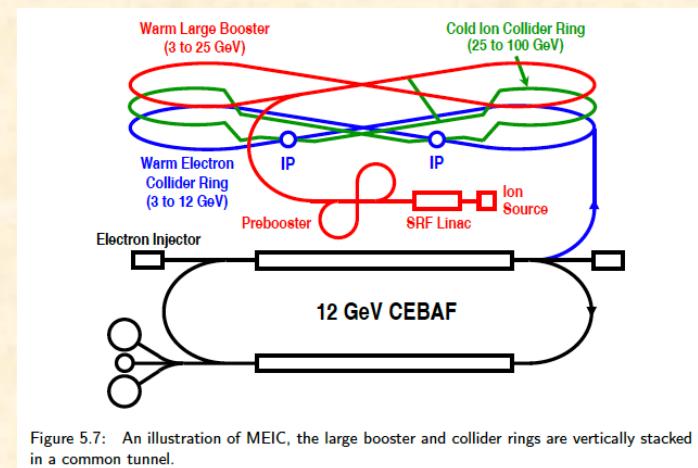


Figure 5.7: An illustration of MEIC, the large booster and collider rings are vertically stacked in a common tunnel.

Electron-ion collider projects in the world

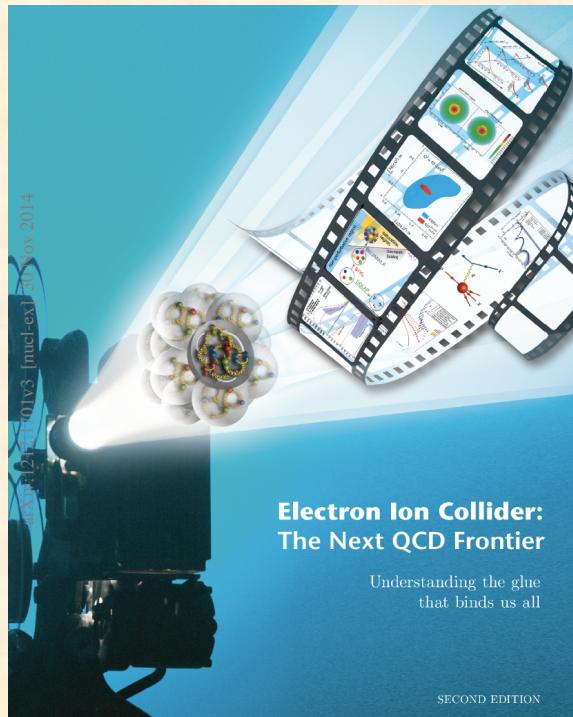
CERN

The EIC Science case: a report on the joint BNL/INT/JLab program

Gluons and the quark sea at high energies:
distributions, polarization, tomography

arXiv:1108.1713 (551 pages)

arXiv:1212.1701 (180 pages)



BNL
JLab



J. Phys. G: Nucl. Part. Phys.
39 (2012) 075001(632 pages)

CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012



A Large Hadron Electron Collider at CERN

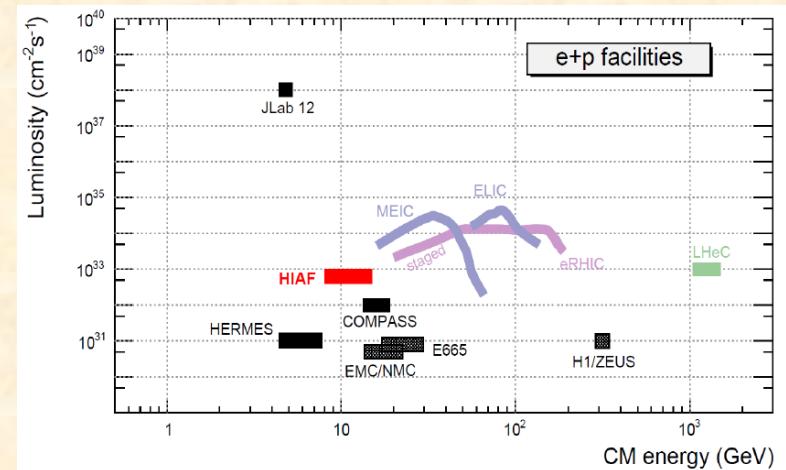
Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

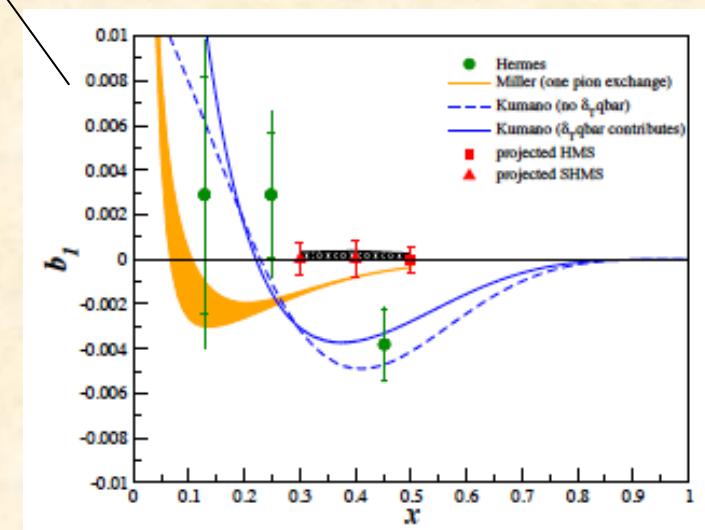
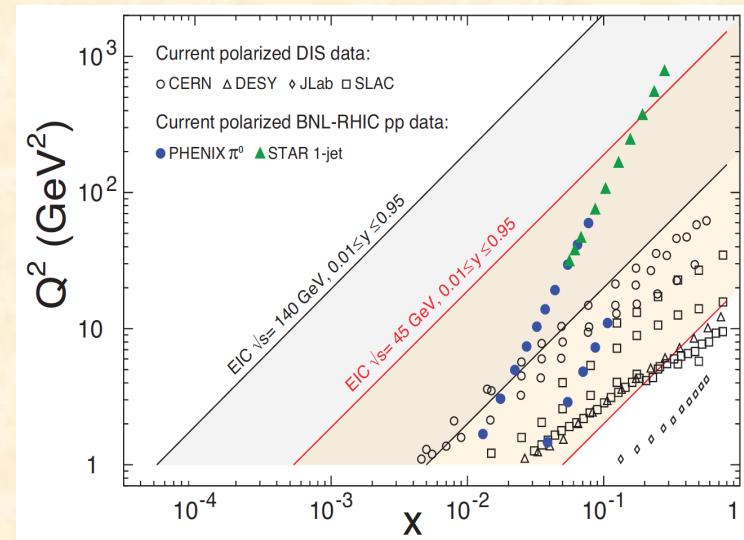
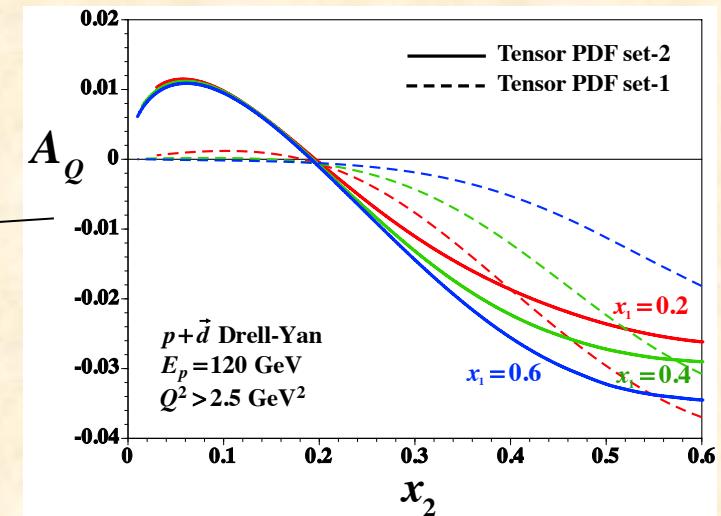
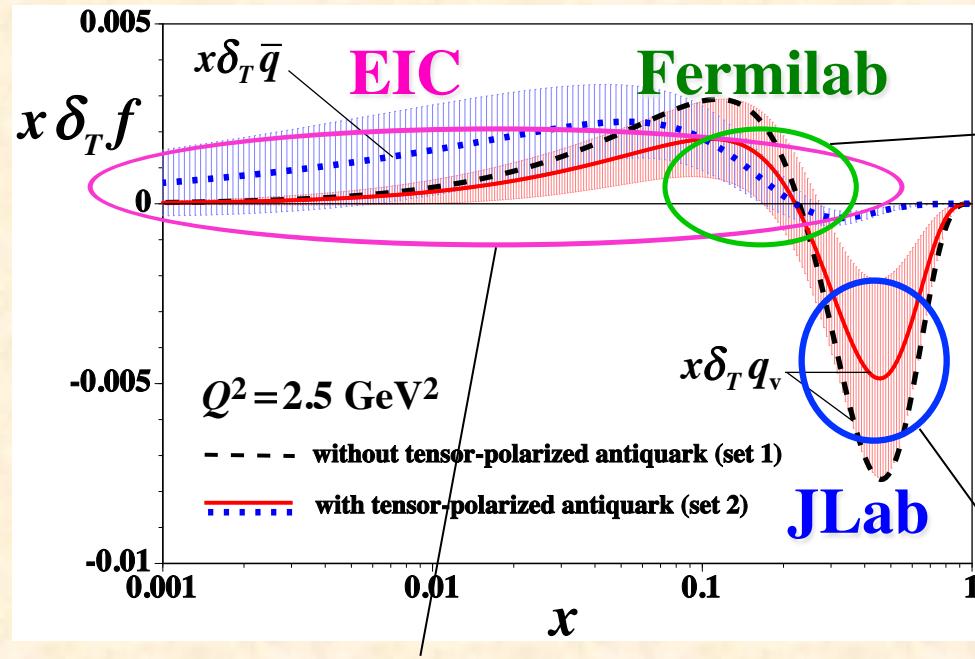


**High Intensity Heavy Ion
Accelerator Facility (HIAF)**

(Plan by Institute of Modern Physics,
Chinese Academy of Sciences)



Small- x physics of b_1 at EIC

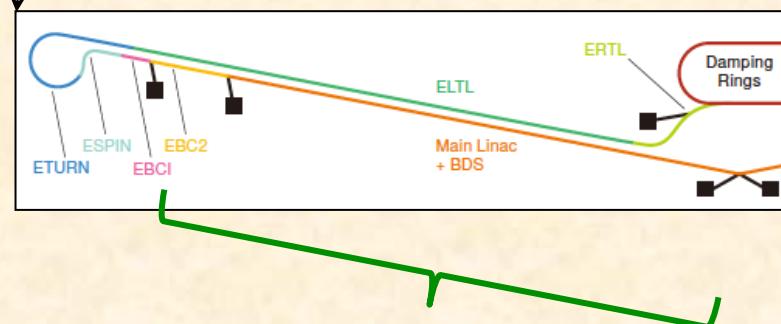
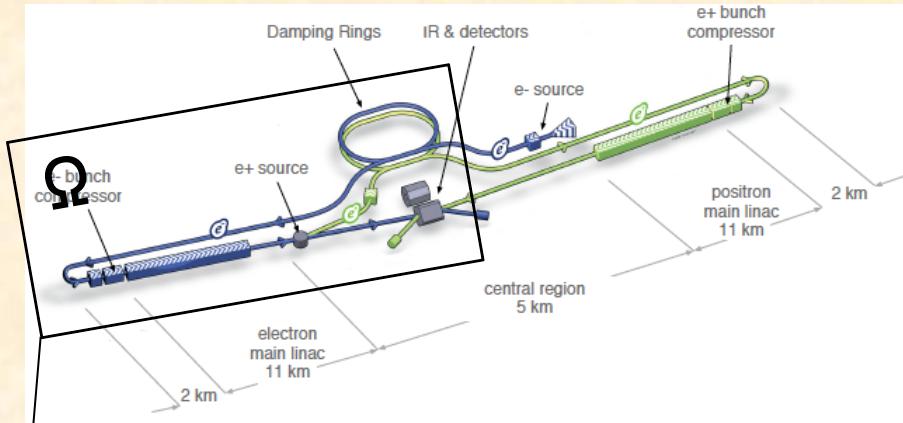
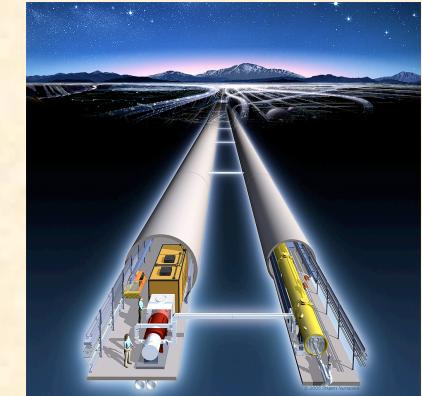


International Linear Collider

ILC-N (Fixed target option) for hadron physics?

ILC TDR (Technical Design Report)

<https://www.linearcollider.org/ILC/Publications/Technical-Design-Report>



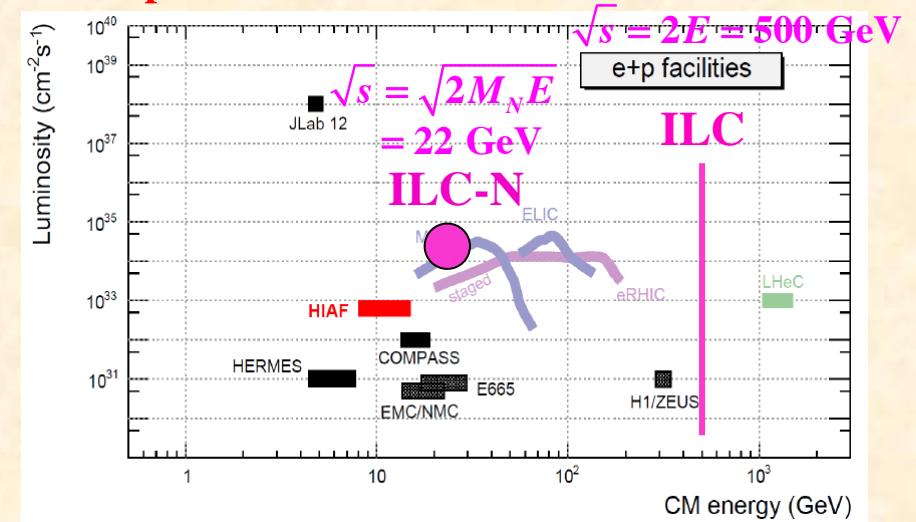
5 – 250 GeV electron beams
for fixed target experiments

Possibilities for hadron and nuclear physics

- e^+e^- annihilation processes
- fixed target experiments
- with 5 – 250 GeV electron beams (ILC-N)

→ No serious studies about these feasibilities.

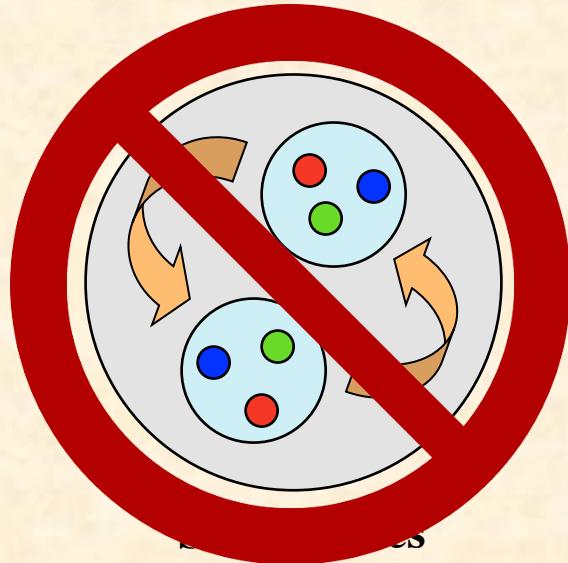
ILC-N is better than on-going COMPASS
but it is in competition with EIC in 2025 !



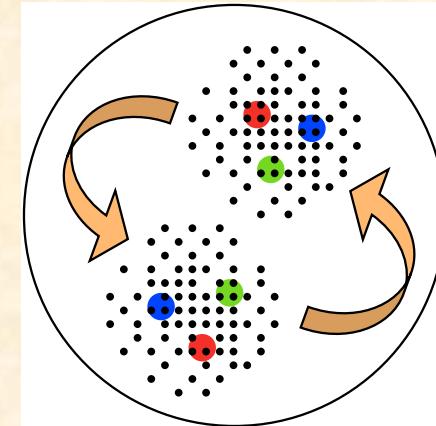
Summary III

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?

8th International Conference on Quarks and Nuclear Physics

November 13-17, 2018, Tsukuba, Japan

<http://www-conf.kek.jp/qnp2018/>

Quark and gluon structure of hadrons:

- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, ...

Hadron spectroscopy:

- heavy quark physics, exotics, N^* , ...

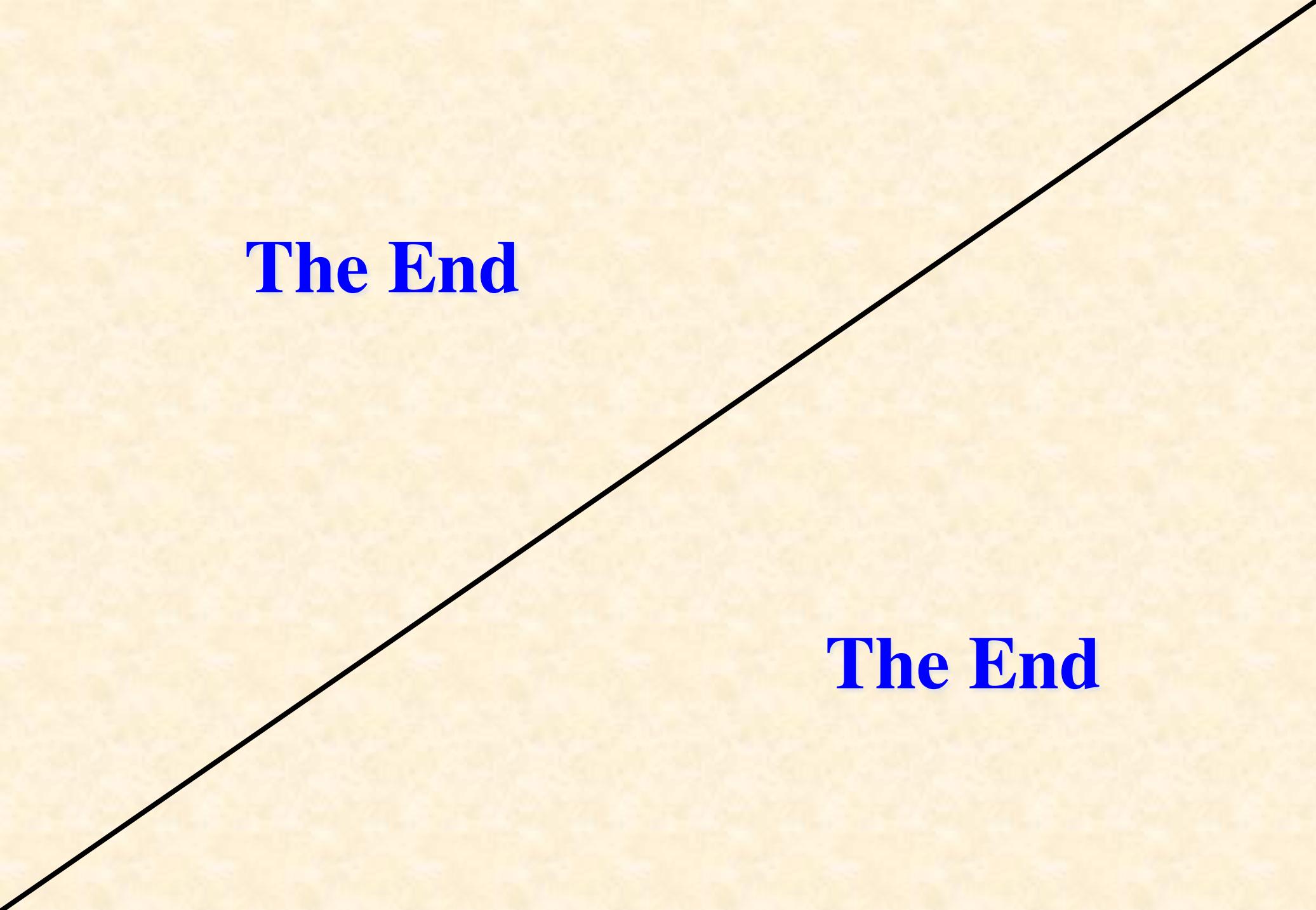
Hadron interactions and nuclear structure:

- hypernuclear physics, kaonic nuclei, baryon interactions, ...

Hot and cold dense matter:

- quark-gluon plasma, color glass condensate, dense stars,
- strong magnetic field, mesons in nuclear medium, hadronization, ...





The End

The End