

# レプトン・原子核深非弾性散乱 と重陽子のテンソル構造関数

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**Recent papers:** (1) SK and Qin-Tao Song, Phys. Rev. D 94 (2016) 054022.  
(2) W. Cosyn, Yu-Bing Dong, SK, M. Sargsian,  
[arXiv:1702.05337](https://arxiv.org/abs/1702.05337), submitted for publication.

第11回高エネルギーQCD・構造関数勉強会  
山形大学、2017年3月24日(金)

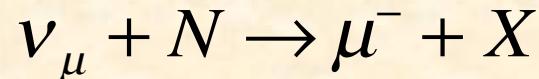
<https://indico2.riken.jp/indico/conferenceDisplay.py?confId=2463>

March 24, 2017

# **Introduction to Lepton-Nucleon (Nucleus) Deep Inelastic Scattering**

# Deep inelastic scattering

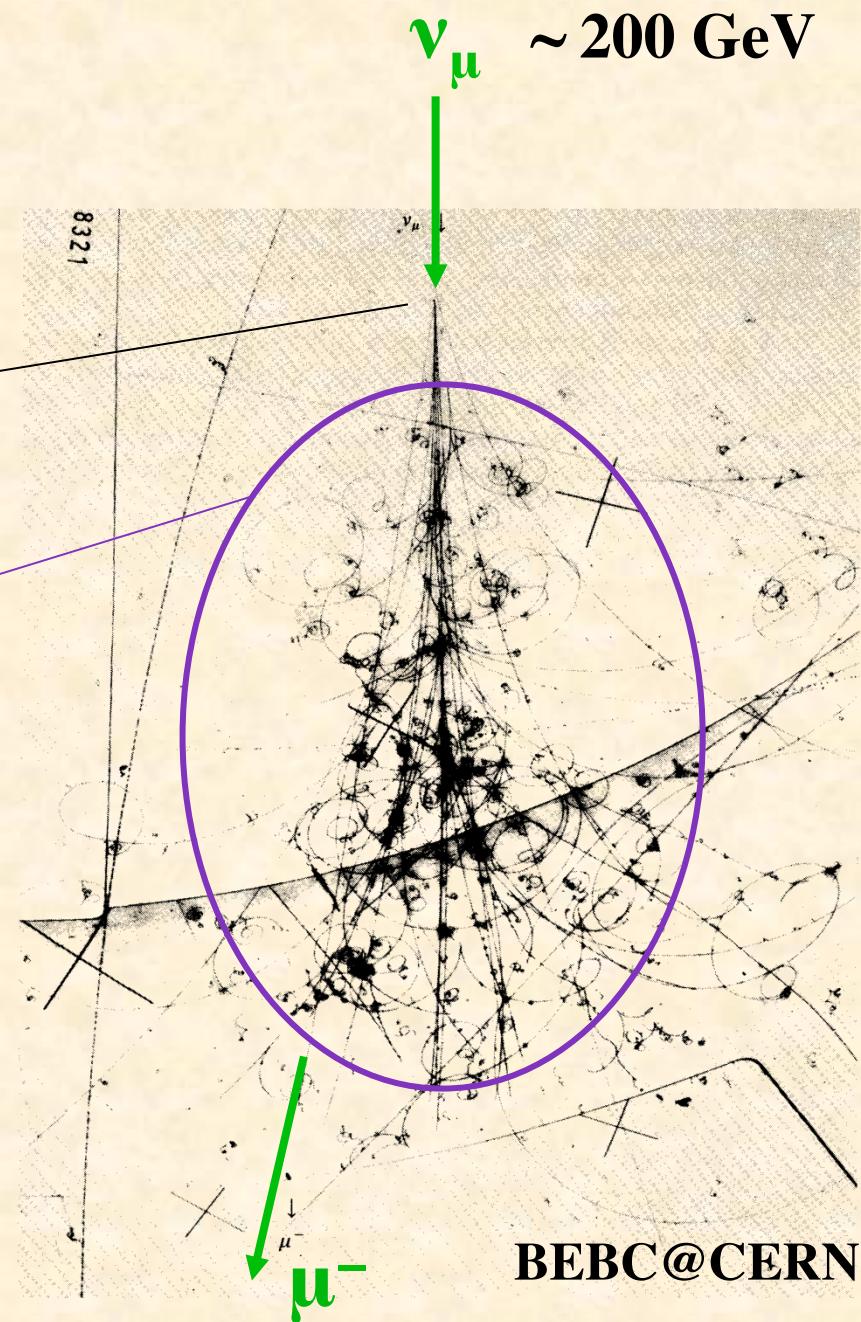
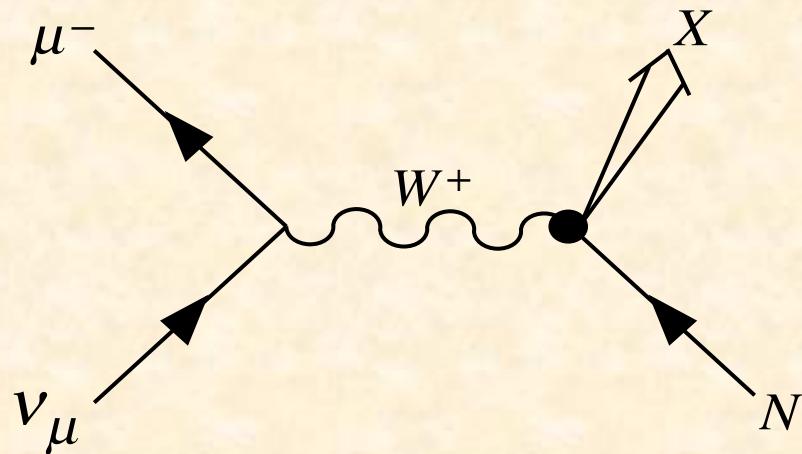
For example



A nucleon is broken up  
by a high-energy neutrino.

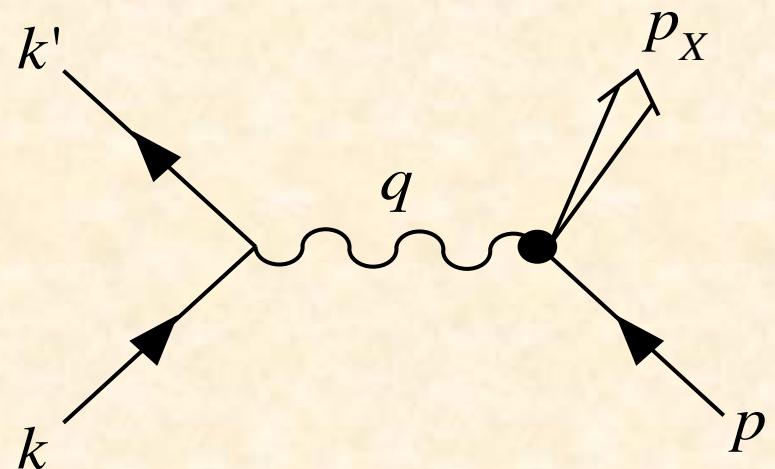
Hadrons are produced; however,  
these are not usually measured.  
(inclusive reaction)

exclusive, semi-inclusive



# Kinematics of $e+p \rightarrow e'+X$

note:  $q^2 = q_0^2 - \vec{q}^2$



$$q^2 = (k - k')^2 = -Q^2$$

Bjorken scaling variable:  $x = \frac{Q^2}{2p \cdot q}$

$$s = (p+k)^2 \quad \sqrt{s} = \text{c.m. energy}$$

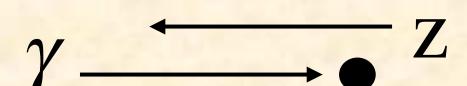
$$\text{invariant mass: } W^2 = p_X^2 = (p+q)^2$$

$v = \frac{p \cdot q}{M}$ : energy transfer  
in the rest frame of N

light-cone variables:  $a^\pm = \frac{a^0 \pm a^3}{\sqrt{2}}$ ,  $a \cdot b = a^+ b^- + a^- b^+ - \vec{a}_T \cdot \vec{b}_T$

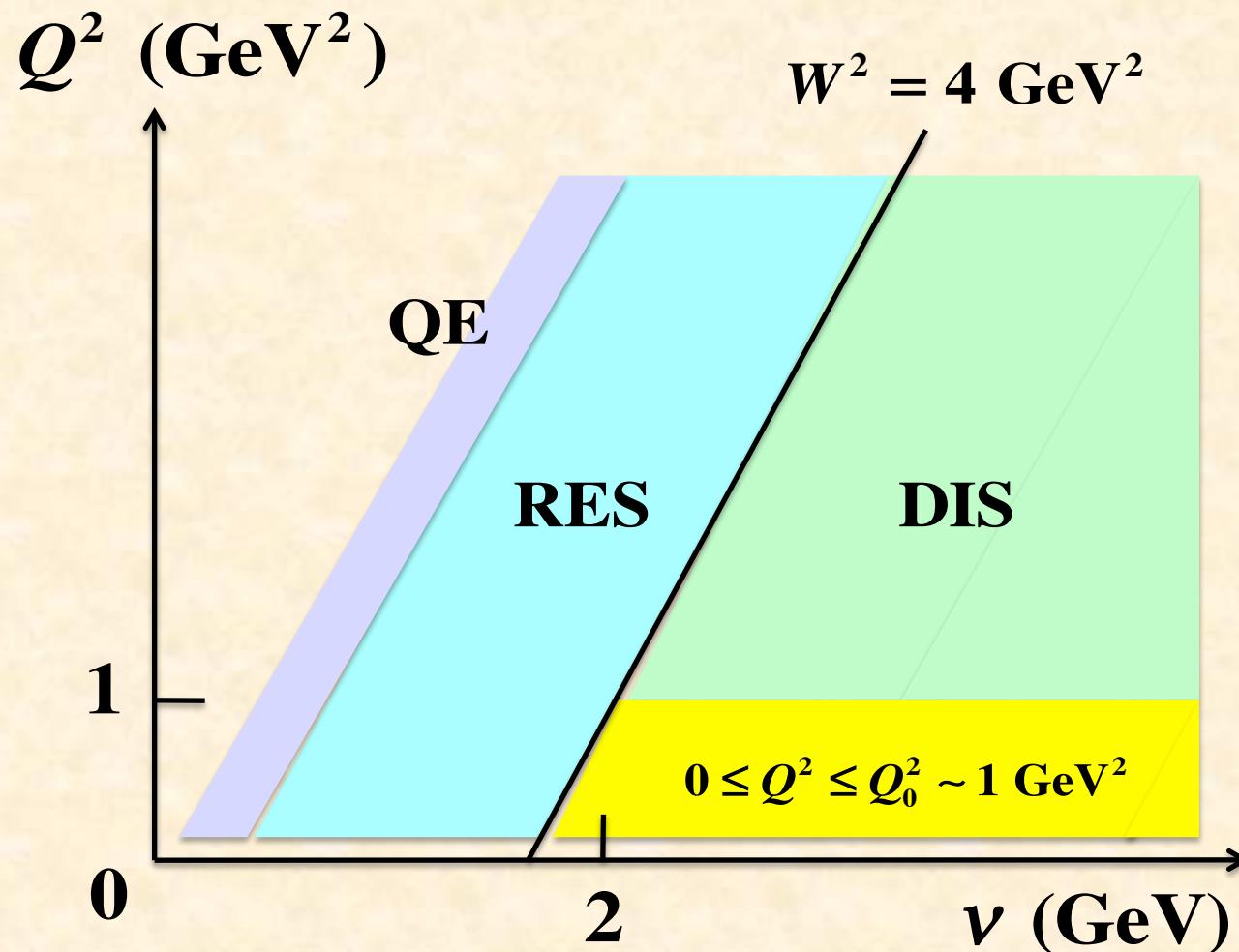
convenient choice:  $q = (v, 0, 0, -\sqrt{v^2 + Q^2})$

$$q^+ = -\frac{Mx}{\sqrt{2}}, \quad q^- = \frac{2v + Mx}{\sqrt{2}} = \sqrt{2}v \gg M$$



$$0 \leq Q^2 \leq Q_0^2 \sim 1 \text{ GeV}^2$$

# Kinematic of lepton-nucleus scattering

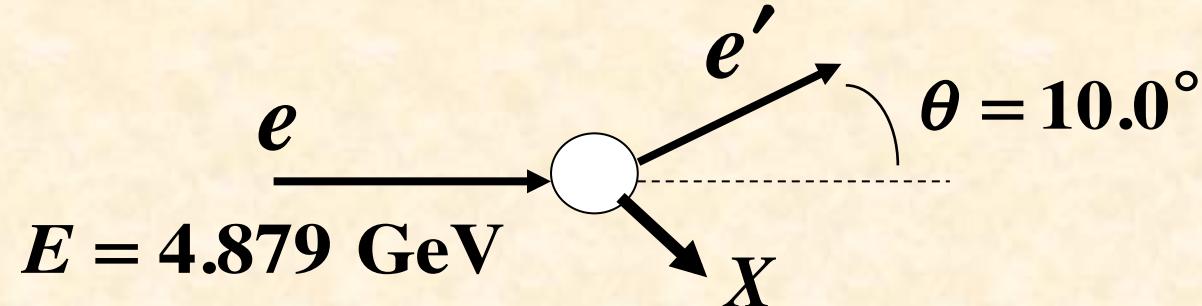


Depending on the neutrino beam energy, different physics mechanisms contribute to the cross section.

- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic)

Activities at the J-PARC branch, KEK theory center  
<http://j-parc-th.kek.jp/html/English/e-index.html>  
Towards construction of a unified model for the neutrino-nucleus reactions,  
S. X. Nakamura, H. Kamano, Y. Hayato, M. Hirai, W. Horiuchi,  
S. Kumano, T. Murata, K. Saito, M. Sakura, T. Sato, Y. Suzuki  
[arXiv:1610.01464](https://arxiv.org/abs/1610.01464), Rep. Prog. Phys. in press.

## Actual data

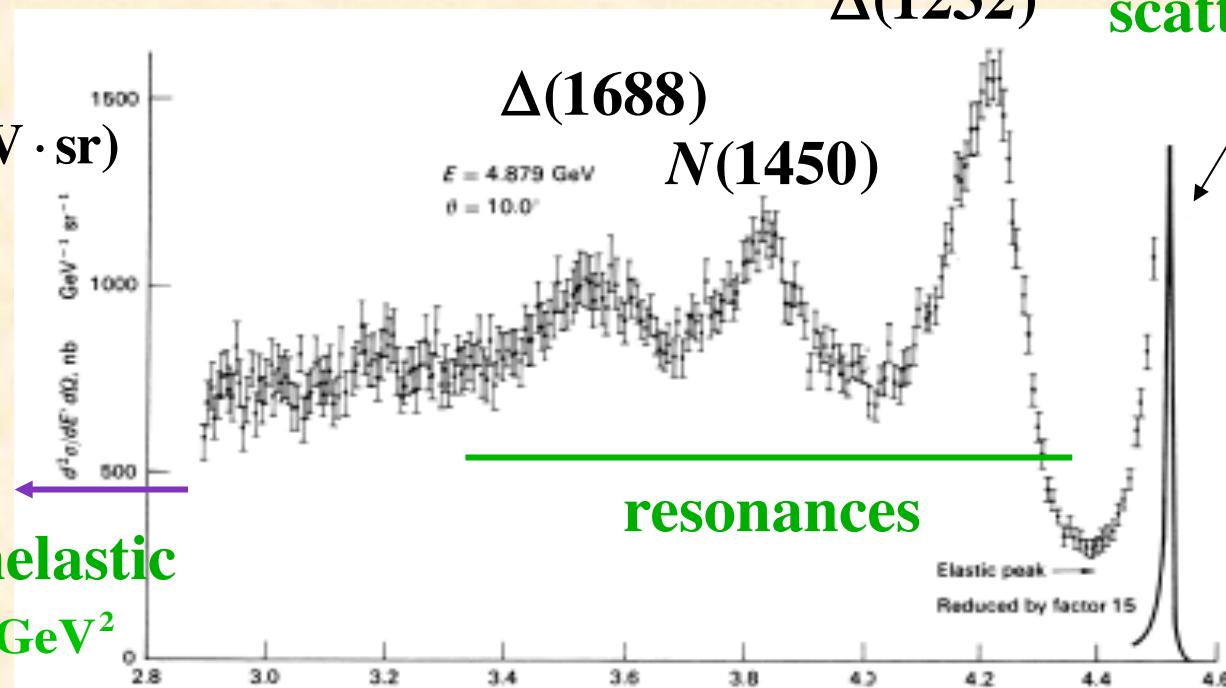


elastic scattering /15

$$\frac{d\sigma}{dE'd\Omega}$$

(nb/GeV · sr)

deep inelastic  
 $W^2 > 3 \sim 4 \text{ GeV}^2$



For example, for  $E' = 3.7 \text{ GeV}$

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$= 4 \cdot (4.879) \cdot (3.7) \cdot \sin^2(10^\circ/2)$$

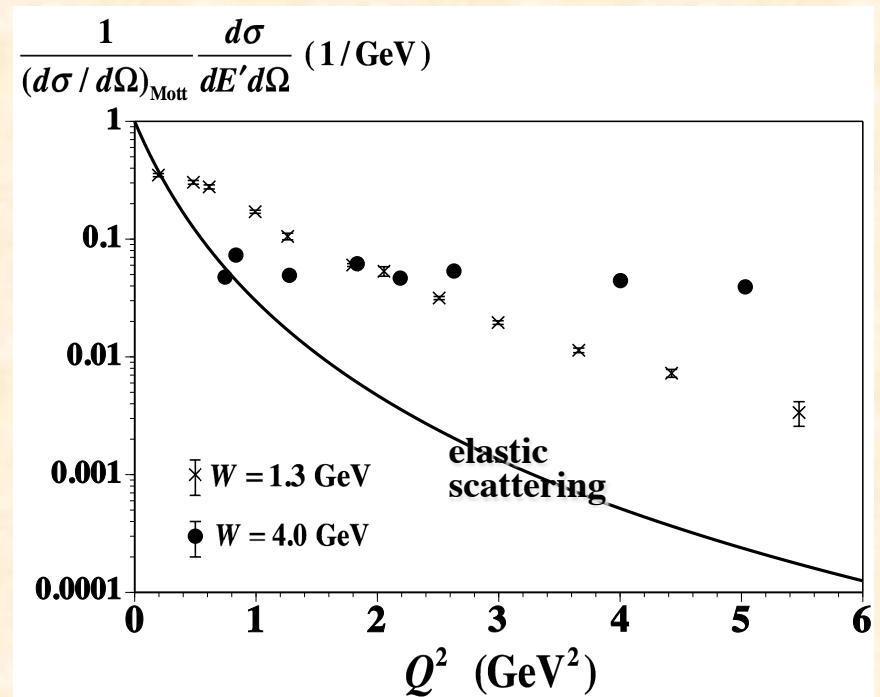
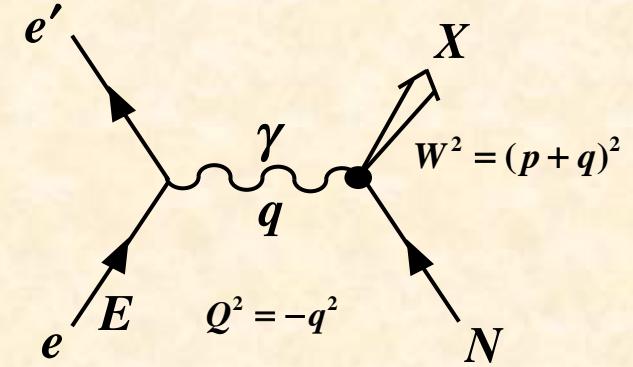
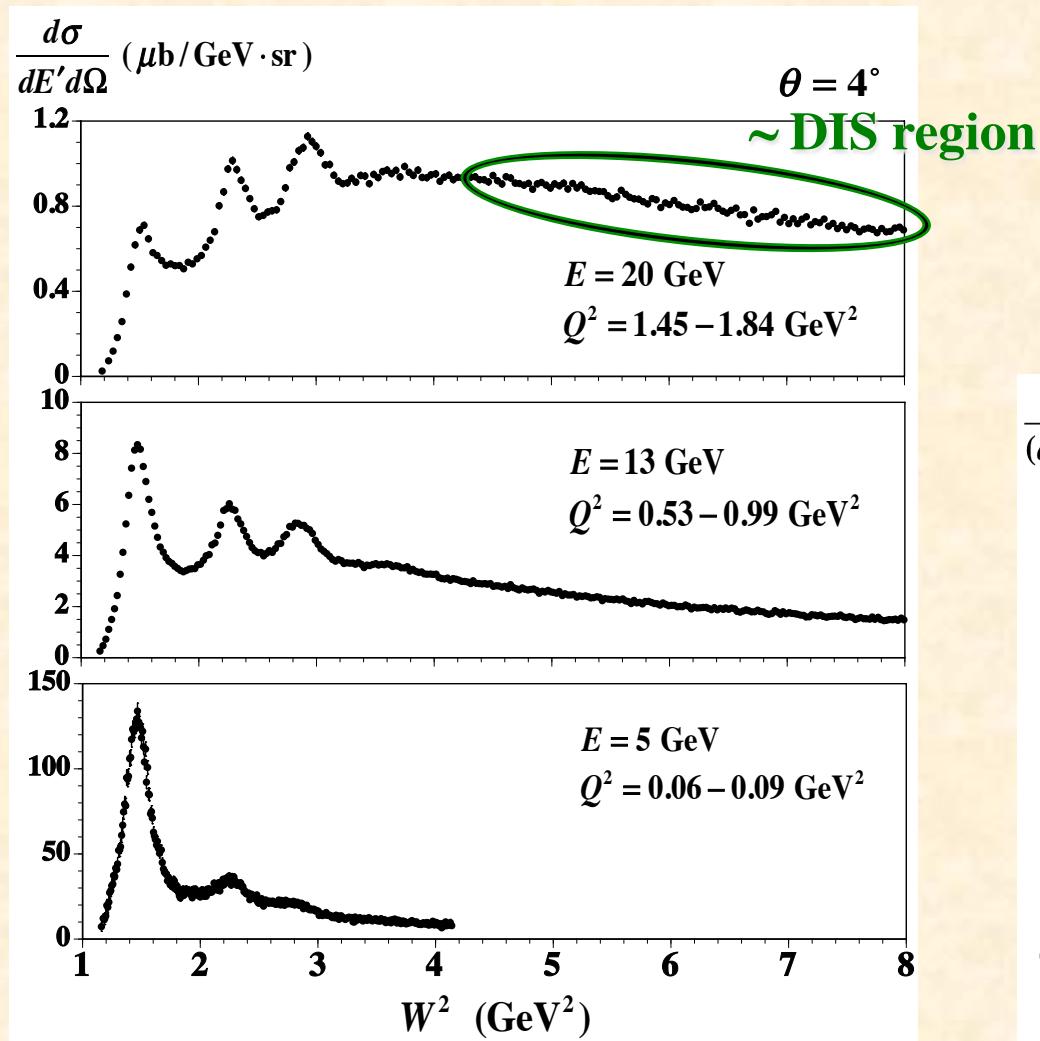
$$= 0.55 \text{ GeV}^2$$

$$x = \frac{Q^2}{2M_N(E - E')} = 0.24$$

$E'$  (GeV)

$W$  (GeV)

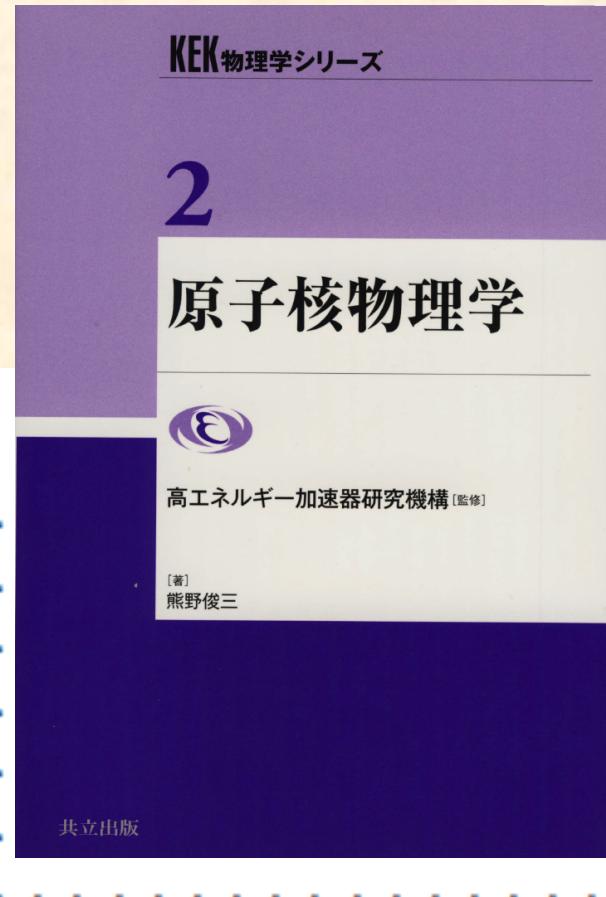




# References

## 4 核子の構造

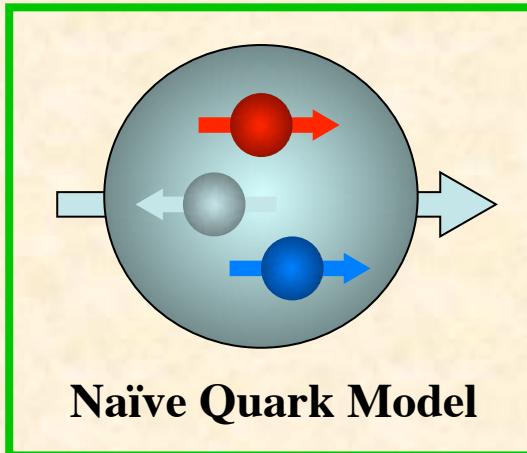
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# **Lepton-Polarized Deuteron**

# **Deep Inelastic Scattering**

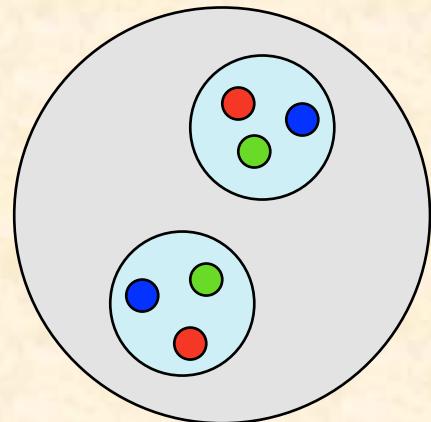
## Nucleon spin



Naïve Quark Model

“old” standard model

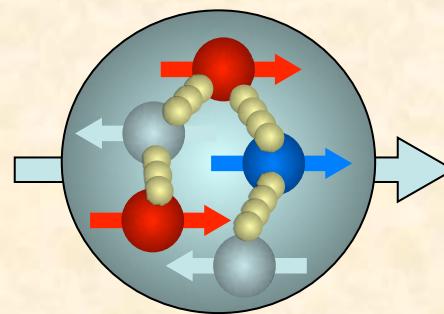
## Tensor structure



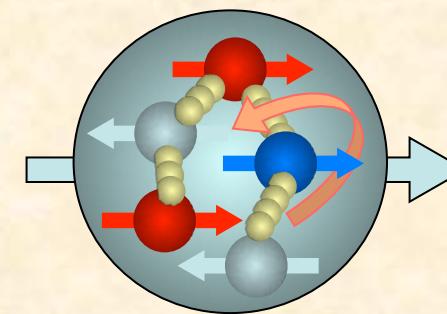
only S wave

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

Almost none of nucleon spin  
is carried by quarks!



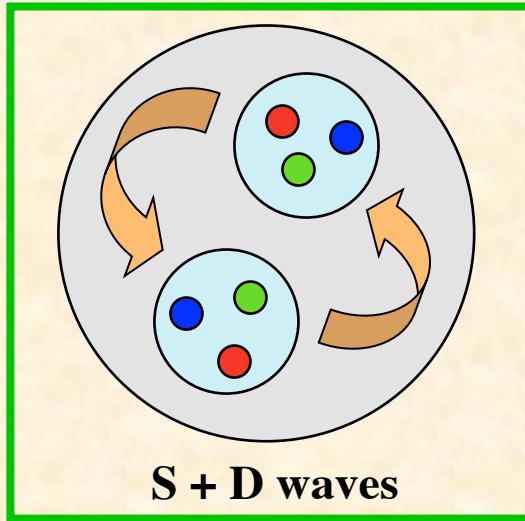
Sea-quarks and gluons?



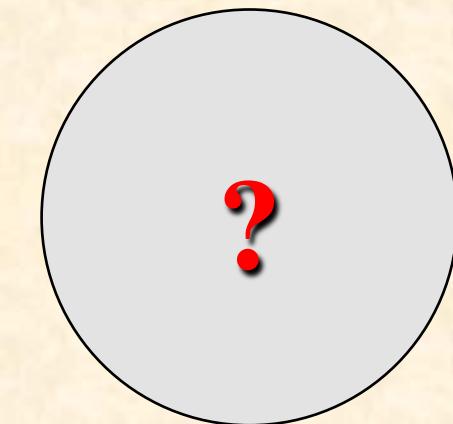
Orbital angular momenta ?

Tensor-structure crisis!?

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



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



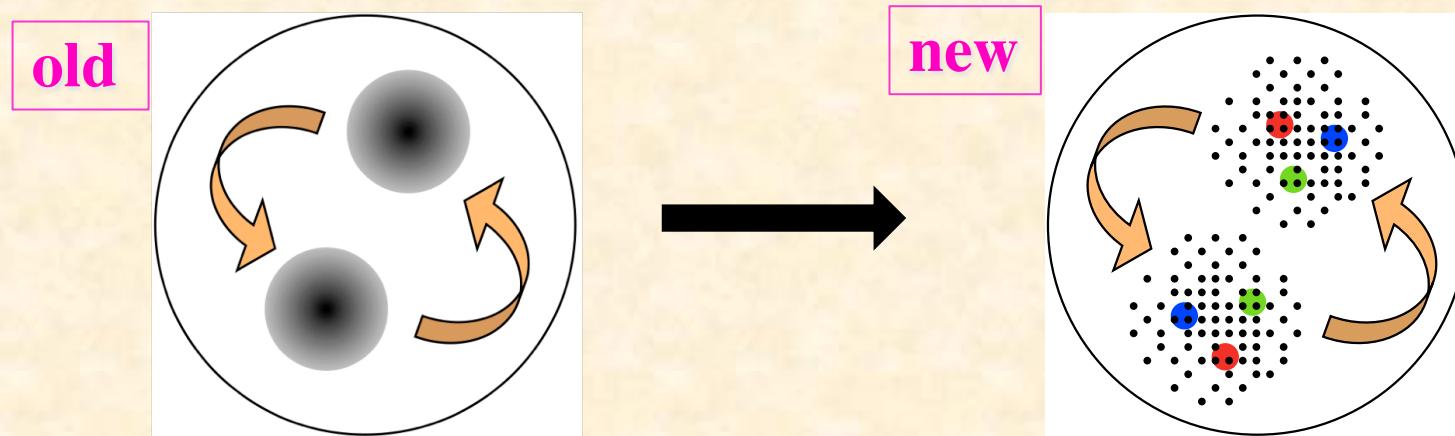
$\mathbf{b}_1^{\text{experiment}}$   
 $\neq \mathbf{b}_1^{\text{"standard model"}}$

# 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 ( $p$ ,  $\pi$ , ...) - 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  $b_1$**   
arXiv:1702.05337, submitted for publication.

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 $e + \vec{d} \rightarrow e' + X$

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

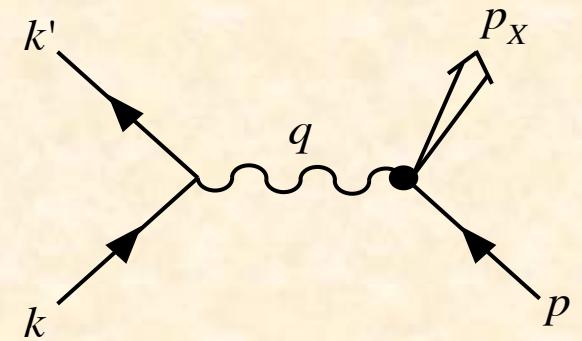
$$M = e \bar{u}(k', \lambda') \gamma_\mu u(k, \lambda) \frac{g^{\mu\nu}}{q^2} \langle X | e J_\nu^{em}(\mathbf{0}) | p, \lambda_N \rangle$$

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

**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. ]

$$W_{\mu\nu} = \boxed{-\mathbf{F}_1 g_{\mu\nu} + \mathbf{F}_2 \frac{p_\mu p_\nu}{v} + \mathbf{g}_1 \frac{i}{v} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + \mathbf{g}_2 \frac{i}{v^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)} \quad \text{spin-1/2, spin-1}$$

$$\boxed{-\mathbf{b}_1 r_{\mu\nu} + \frac{1}{6} \mathbf{b}_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} \mathbf{b}_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} \mathbf{b}_4 (s_{\mu\nu} - t_{\mu\nu})} \quad \text{spin-1 only}$$

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

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

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

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

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

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

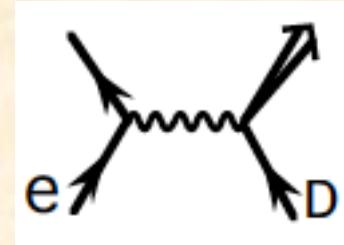
$b_1, b_2$  terms are defined to satisfy  
 $2x b_1 = b_2$  in the Bjorken scaling limit.

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

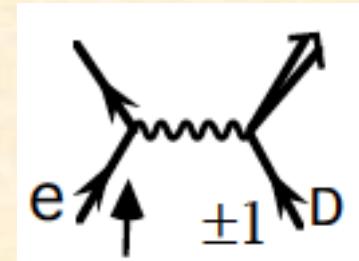
$b_3, b_4 = \text{twist-4} \sim \frac{M^2}{Q^2}$

# Structure Functions

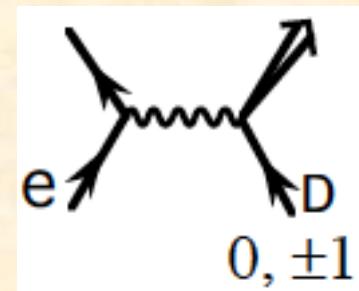
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

## Parton Model

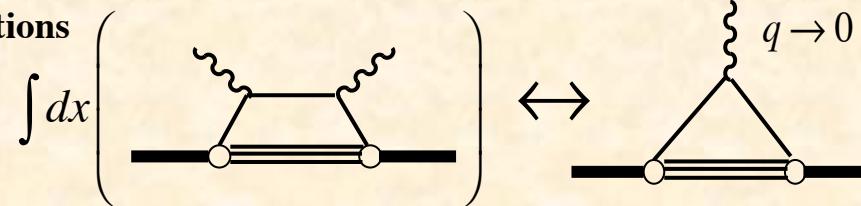
$$F_1 = \frac{1}{2} \sum_i e_i^2 (q_i + \bar{q}_i) \quad q_i = \frac{1}{3} (q_i^{+1} + q_i^0 + q_i^{-1})$$

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

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

# Constraint on valence-tensor polarization (sum rule)

Follow Feynman's book on  
Photon-Hadron Interactions



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

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

Elastic amplitude in a parton model

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

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

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

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

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

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

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

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

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

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

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)

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

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

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

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

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

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

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

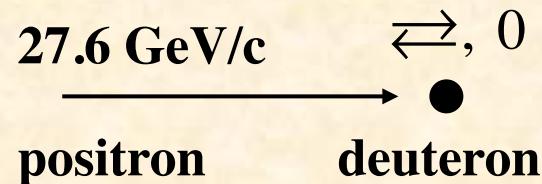
Extrapolating the NMC data, they obtained

$$S_G = 0.235 \pm 0.026$$

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  $Q^2 > 1 \text{ GeV}^2$

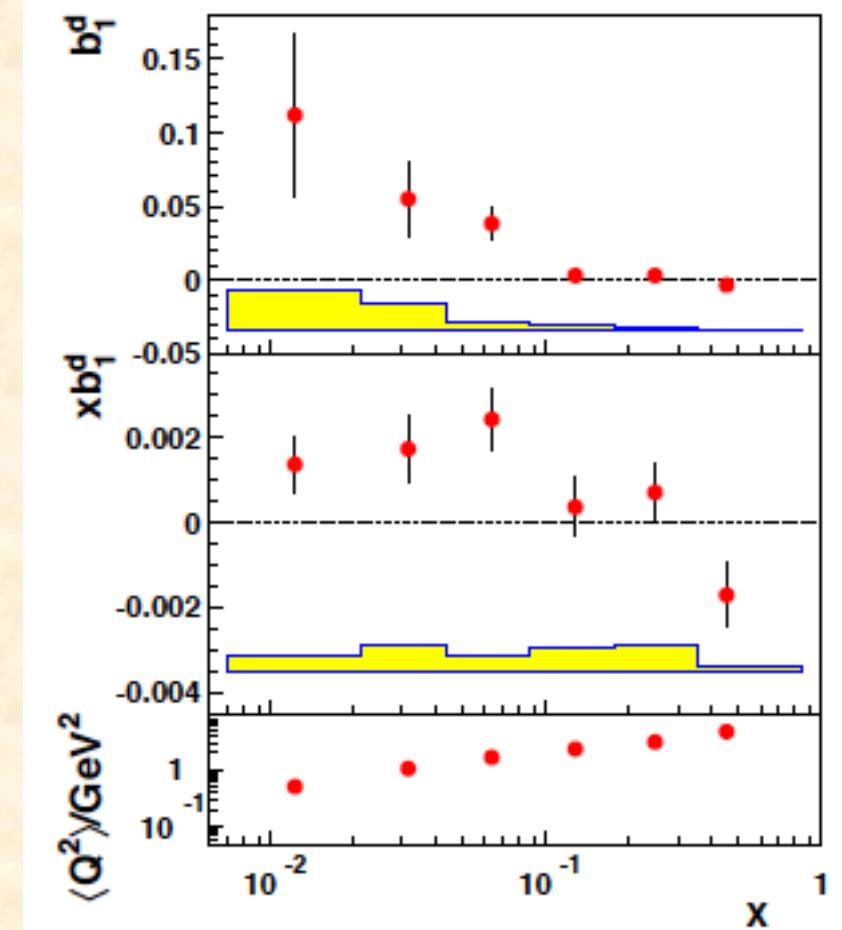
$$\int_{0.02}^{0.85} dx b_1(x) = [0.35 \pm 0.10(\text{stat}) \pm 0.18(\text{sys})] \times 10^{-2}$$

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 convolution approach

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

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

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

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

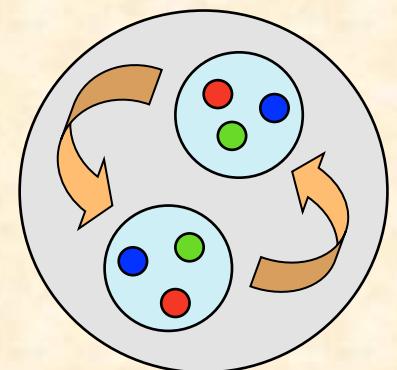
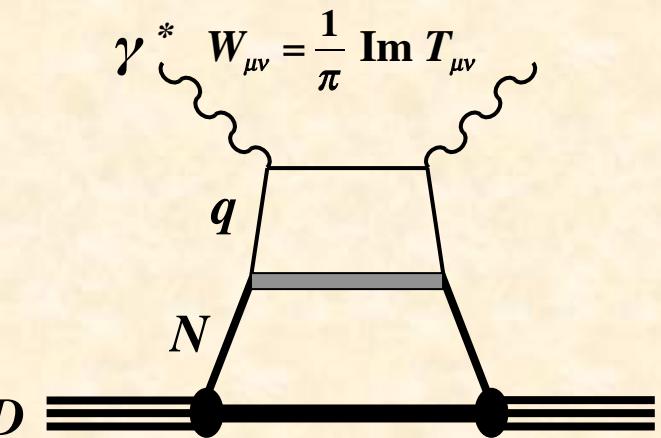
$$f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$

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

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

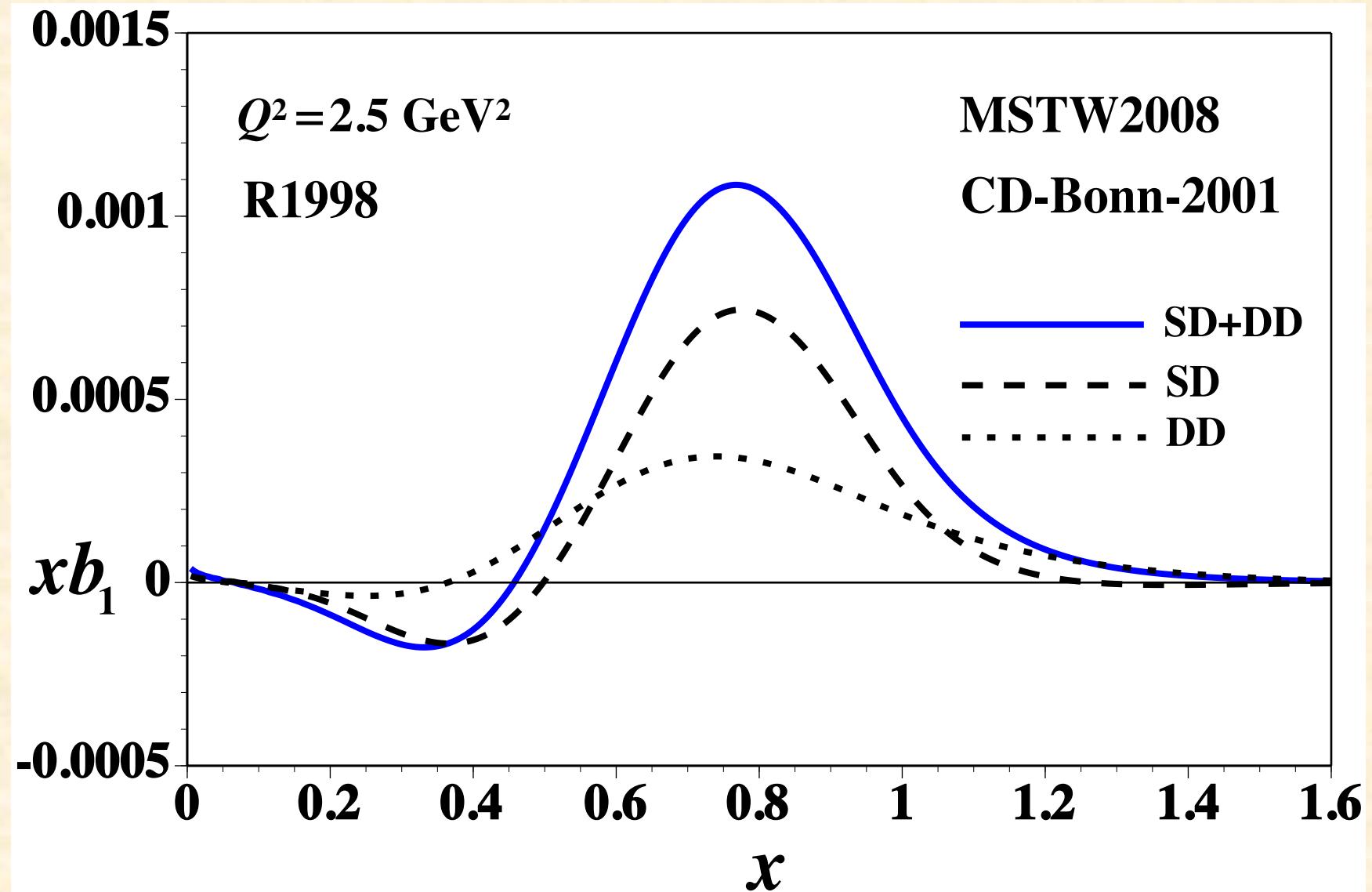
$$\delta_T f(y) = \int d^3 p y \left[ -\frac{3}{4\sqrt{2}\pi} \phi_0(p) \phi_2(p) + |\phi_2(p)|^2 \frac{3}{16\pi} \right] (3 \cos^2 \theta - 1) \delta\left(y - \frac{\vec{p} \cdot \vec{q}}{Mv}\right)$$

Standard model  
of the deuteron

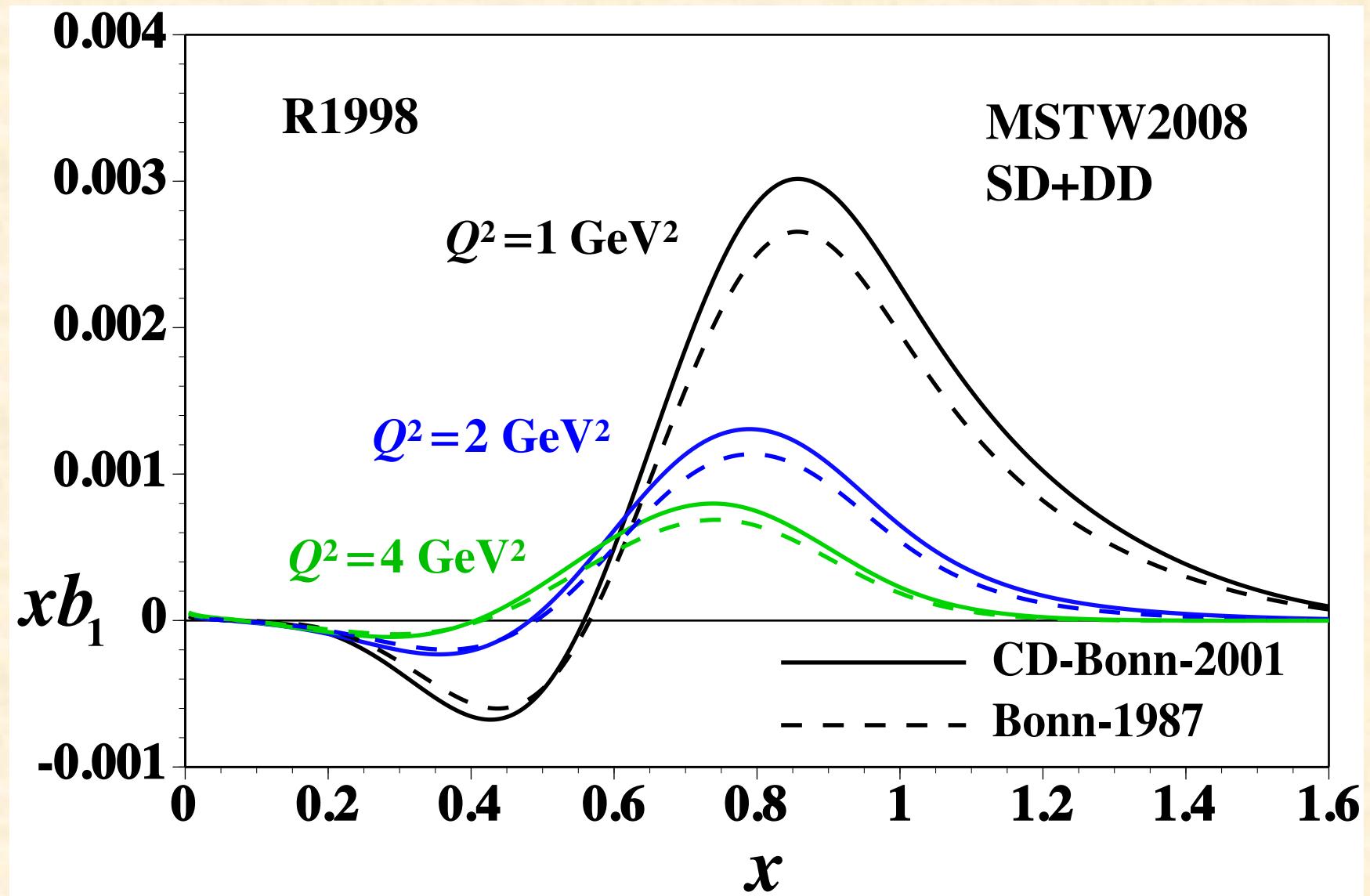


S + D waves

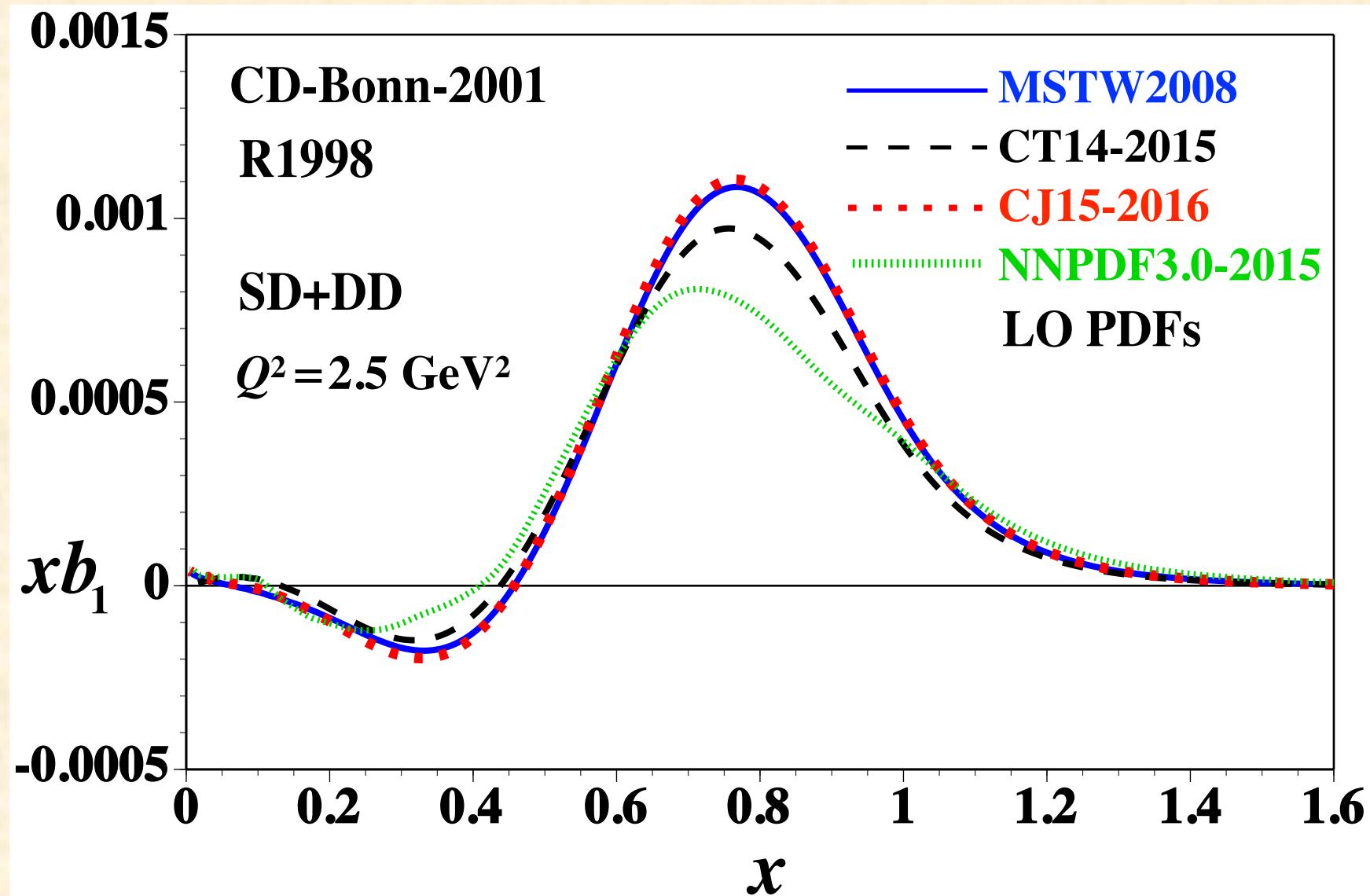
# Results on $b_1$ in the convolution description



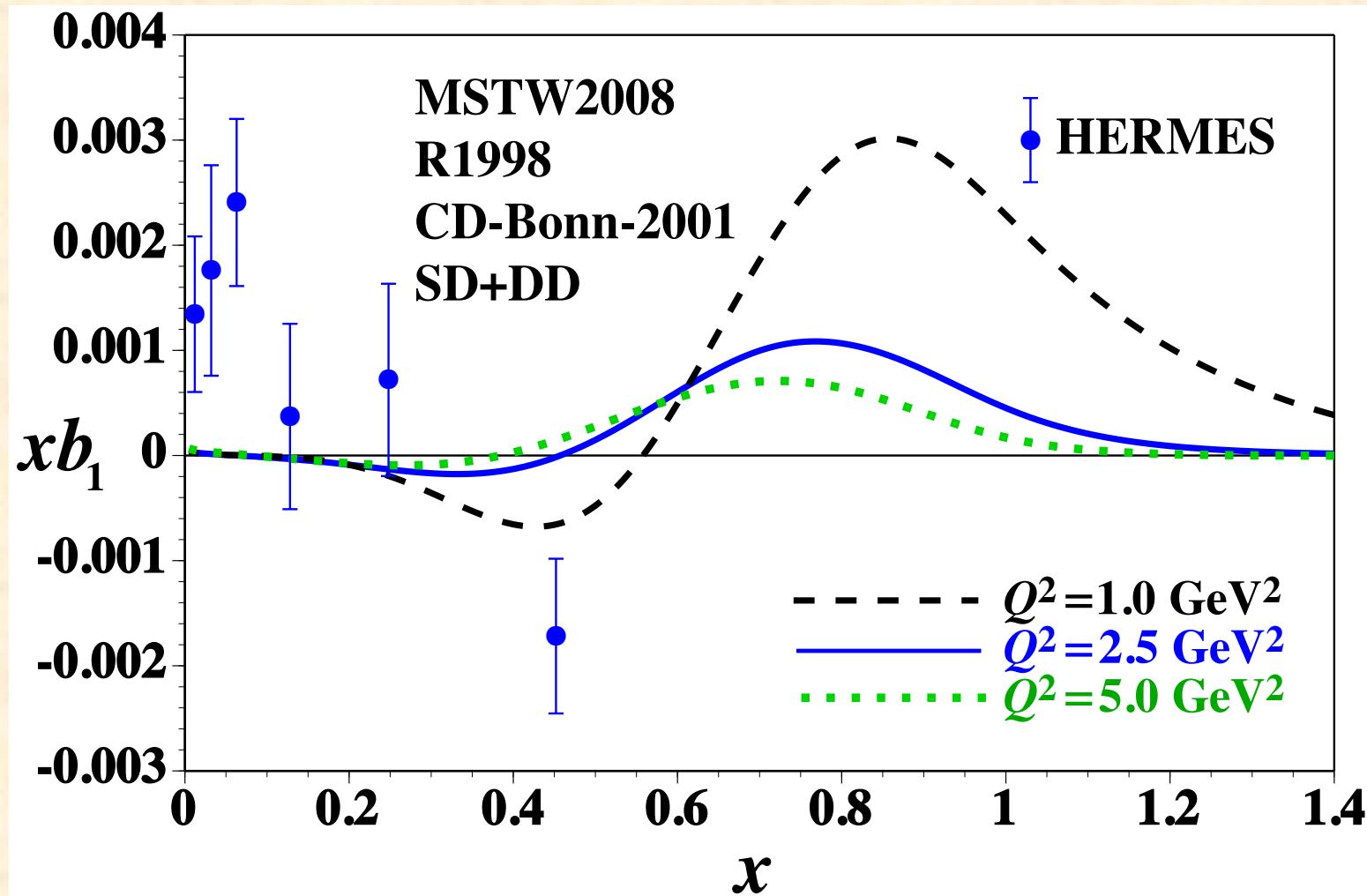
# Results on $b_1$ : deuteron-wave-function dependence



# Results on $b_1$ : used PDF dependence



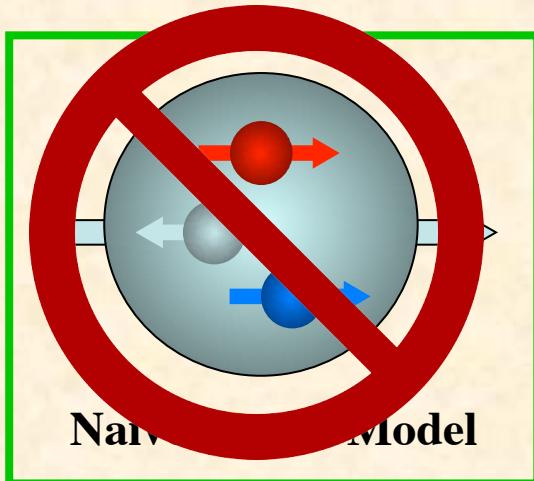
# Comparison with HERMES measurements



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

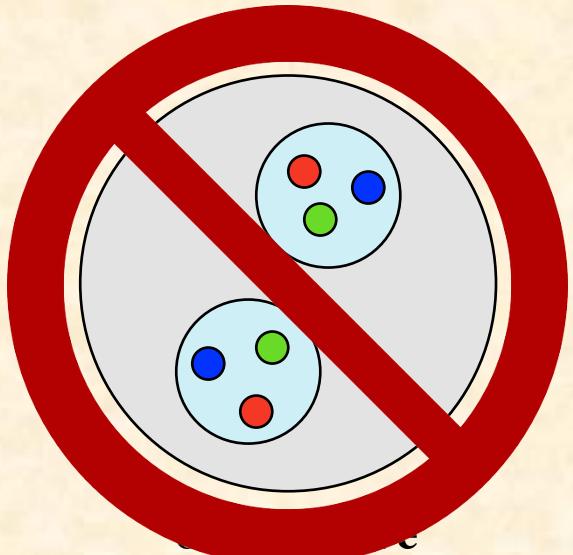
Standard convolution model does not  
work for the deuteron tensor structure!?

# Summary I



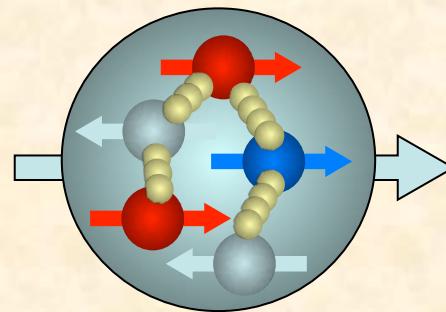
Naive quark Model

“old” standard model



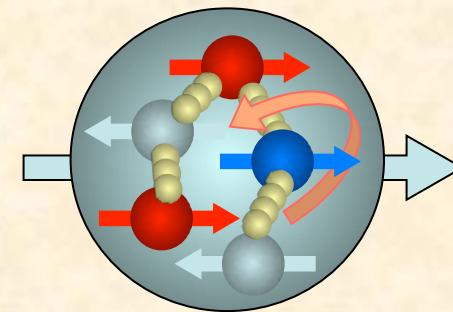
$$b_1 = 0$$

## Nucleon spin



Sea-quarks and gluons?

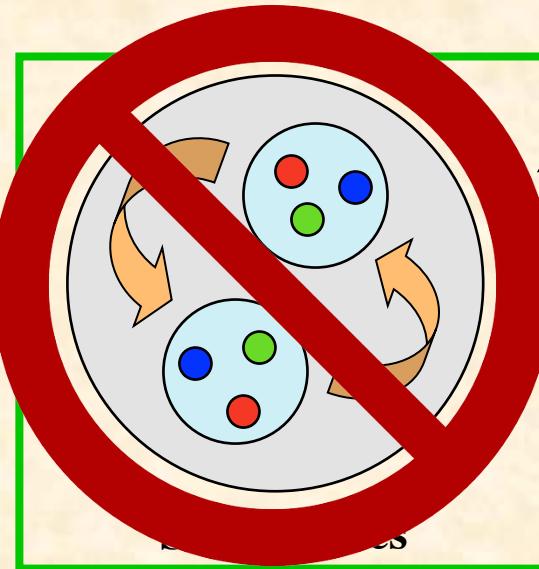
## Nucleon spin crisis!?



Orbital angular momenta ?

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

## Tensor structure



standard model  $b_1 \neq 0$

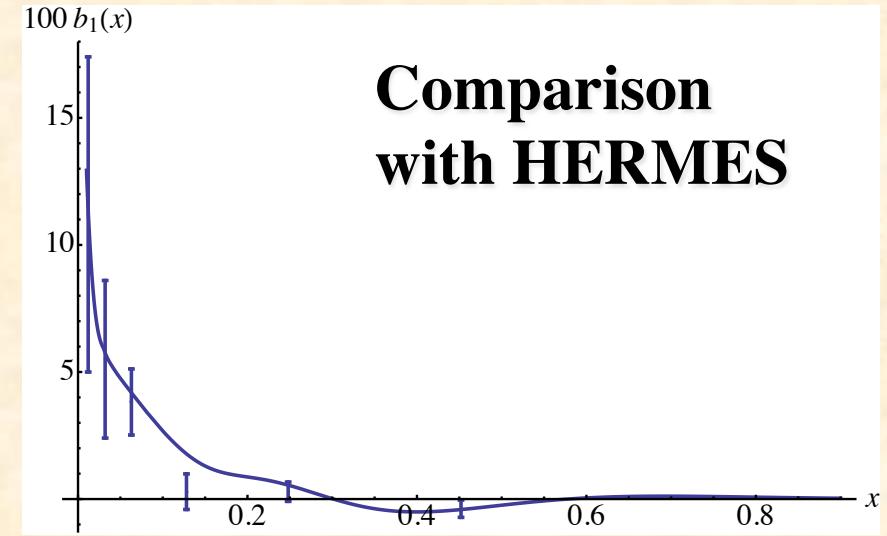
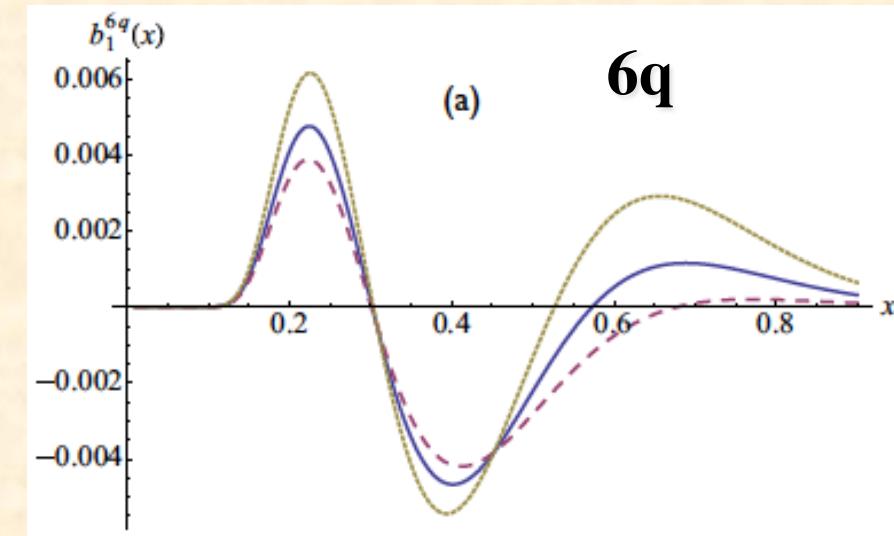
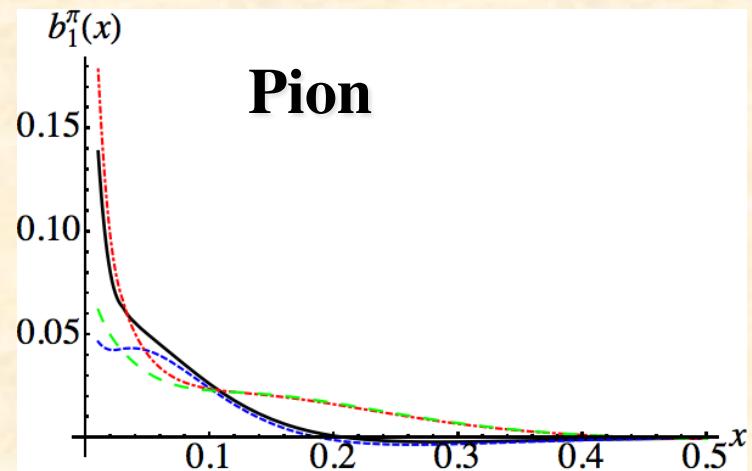
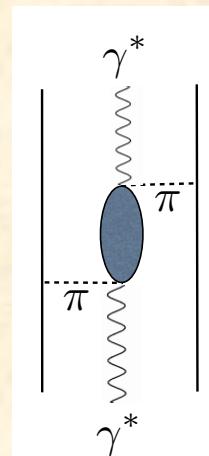
Tensor-structure crisis!?

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

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

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

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



# 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)

J.-P. Chen (co-spokesperson), P. Solvignon (co-spokesperson),  
K. Allada, A. Camsonne, A. Daur, D. Gaskell,  
C. Keith, S. Wood, J. Zhang  
*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*

N. Kalantarians (co-spokesperson), O. Rondon (co-spokesperson)  
Donal B. Day, Hovhannes Baghdasyan, Charles Hanretty  
Richard Lindgren, Blaine Norum, Zhihong Ye  
*University of Virginia, Charlottesville, VA 22903*

K. Slifer<sup>†</sup>(co-spokesperson), A. Atkins, T. Badman,  
J. Calarco, J. Maxwell, S. Phillips, R. Zielinski  
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J. Dunne, D. Dutta  
*Mississippi State University, Mississippi State, MS 39762*

G. Ron  
*Hebrew University of Jerusalem, Jerusalem*

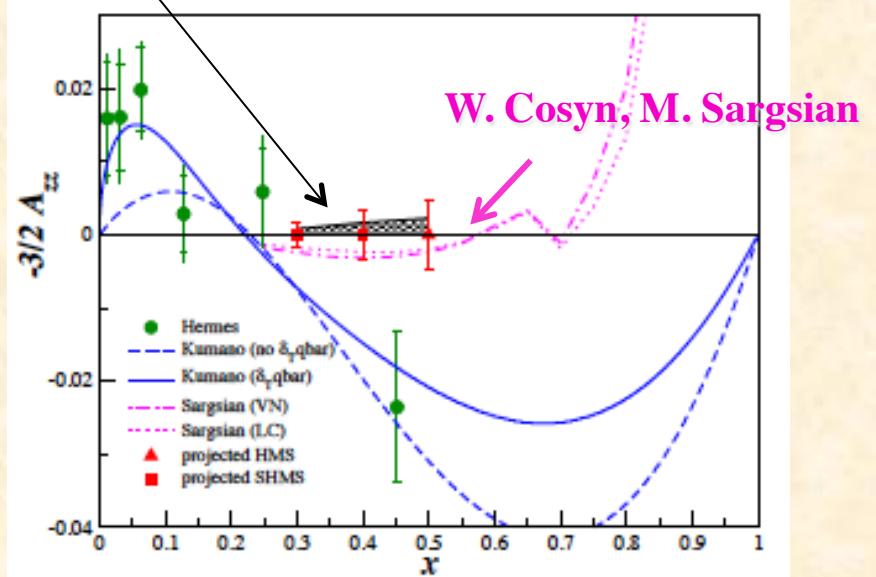
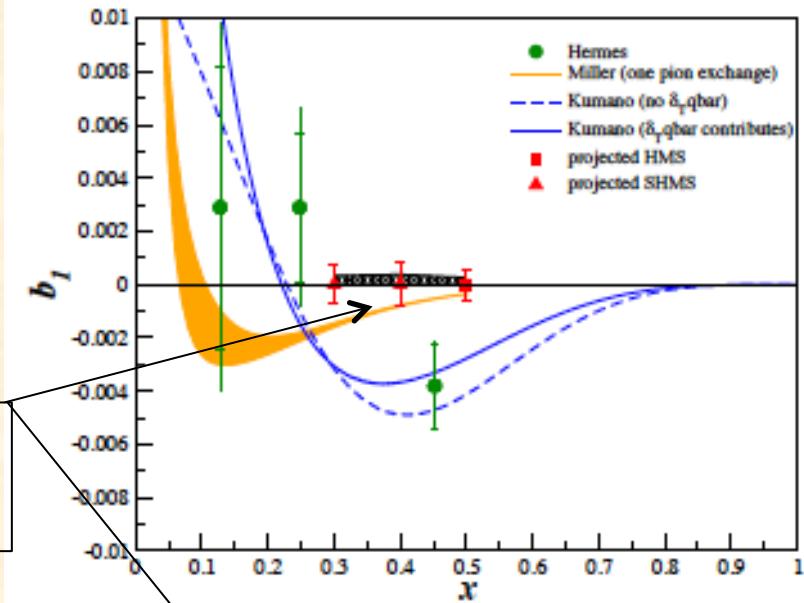
W. Bertozzi, S. Gilad,  
A. Kelleher, V. Sulcosky  
*Massachusetts Institute of Technology, Cambridge, MA 02139*

K. Adhikari  
*Old Dominion University, Norfolk, VA 23529*

R. Gilman  
*Rutgers, The State University of New Jersey, Piscataway, NJ 08854*

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

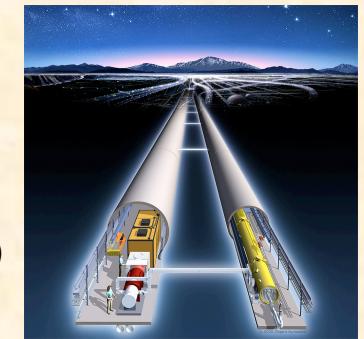
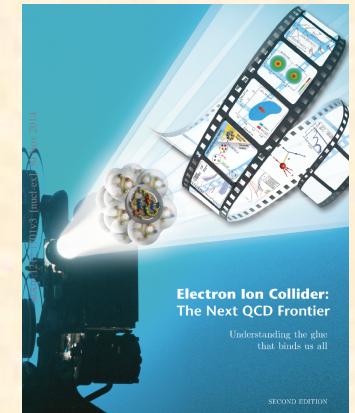
Approved  
experiment!  
(2019~)

## 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

# Experimental possibility at Fermilab

E1039

## Polarized fixed-target experiments at the Main Injector



© Fermilab

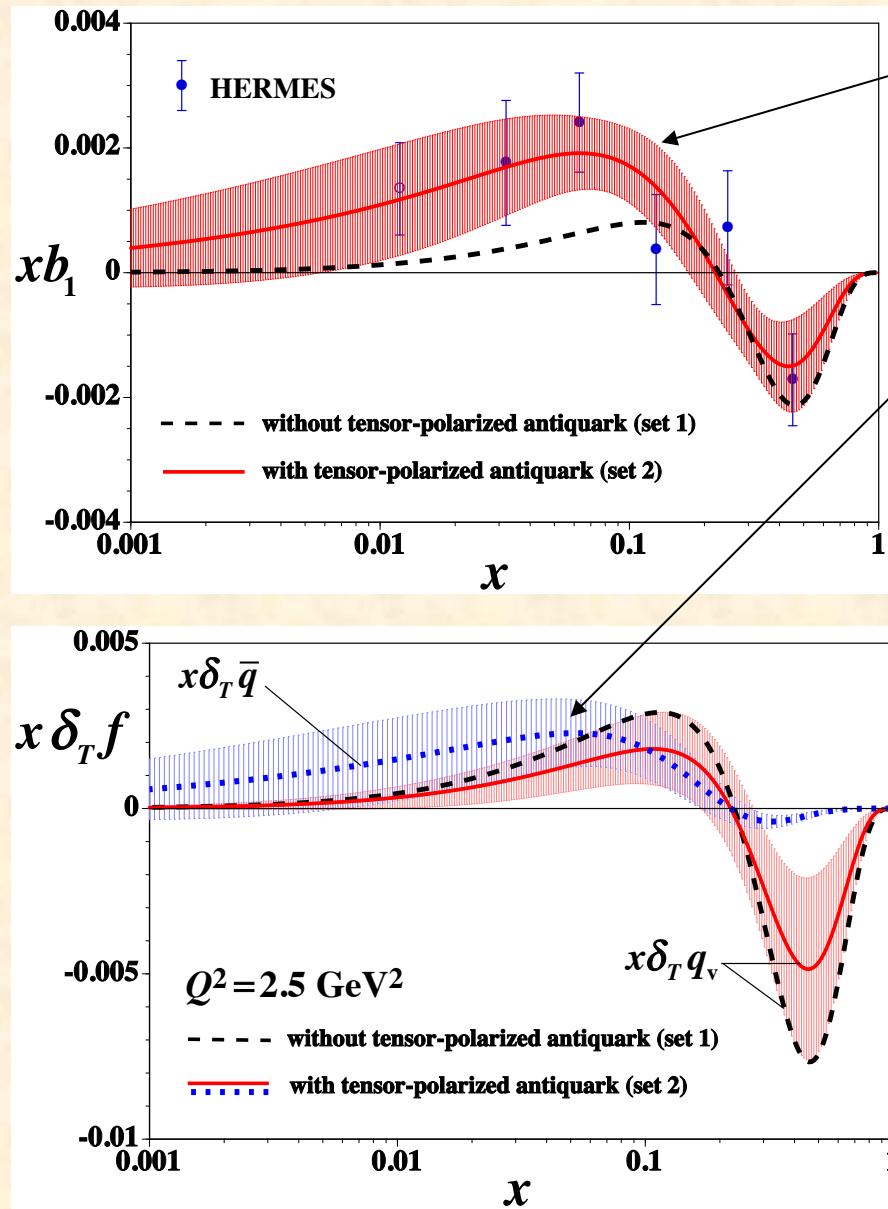
Drell-Yan experiment with a polarized proton target

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

### List of Collaborators:

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# Tensor-polarized PDFs with errors

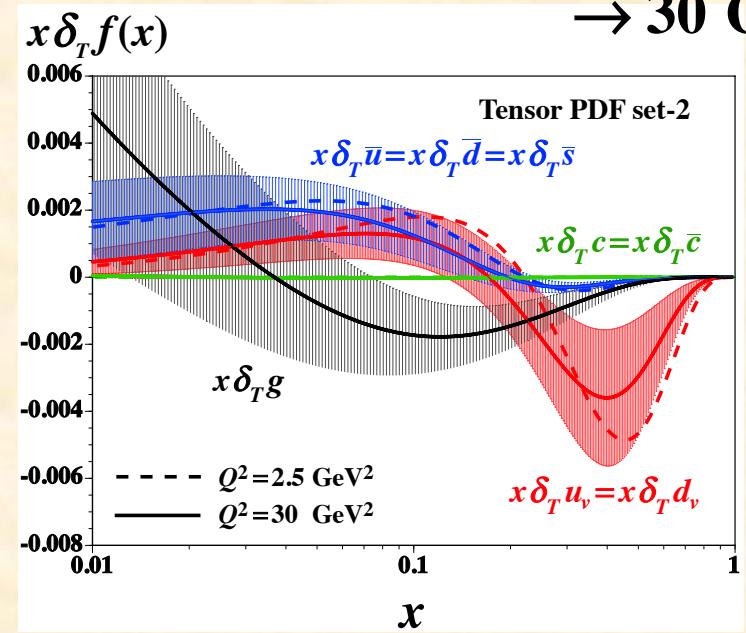


still large errors,  
need experimental improvement  
→ JLab, EIC, ...

experimental measurement  
for antiquark distributions  
→ Fermilab, ...

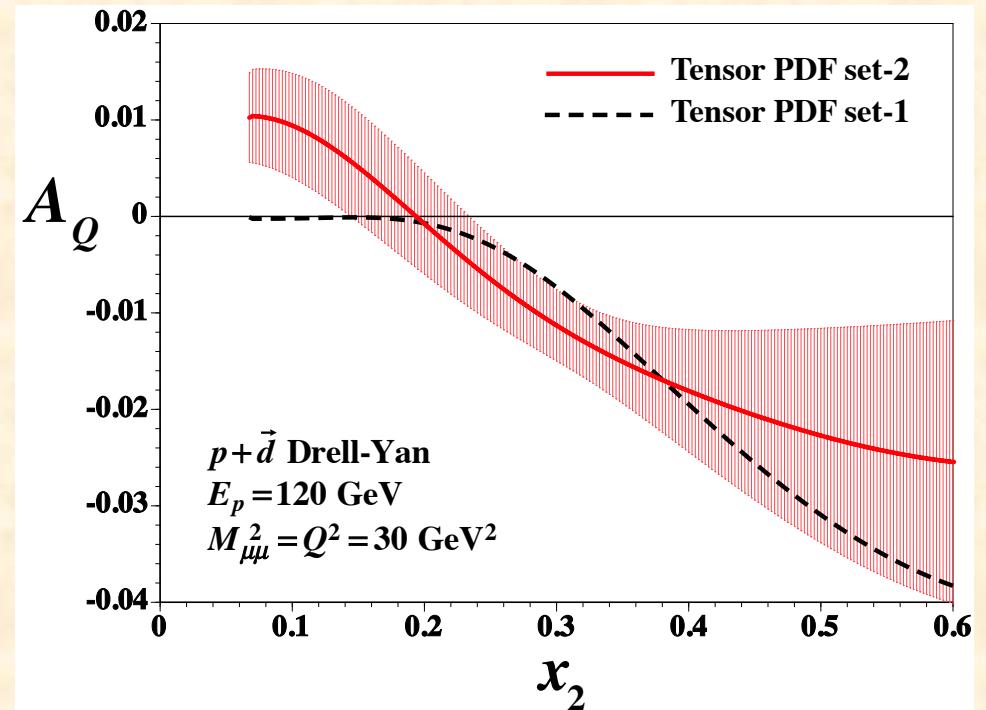
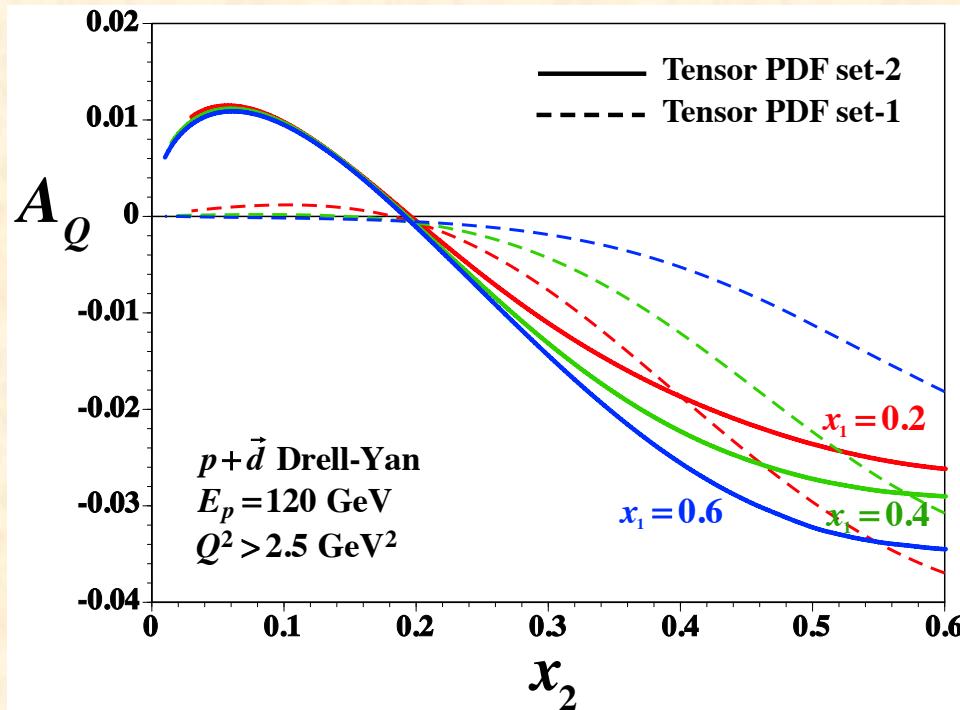
## $Q^2$ evolution

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



# 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.

# Electron-ion collider projects in the world

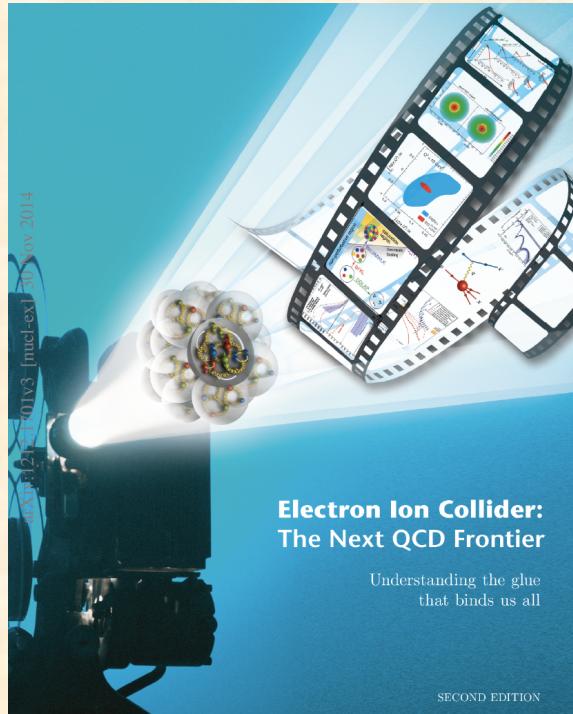
CERN

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

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

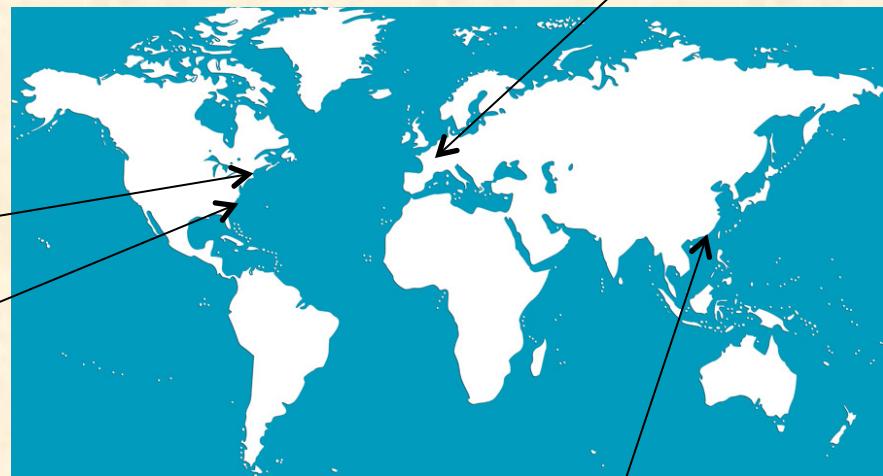
arXiv:1108.1713 (551 pages)

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



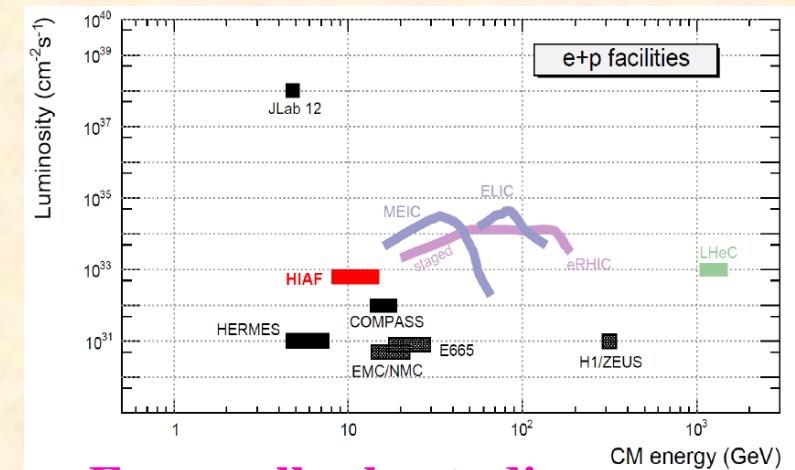
A Large Hadron Electron Collider at CERN

Report on the Physics and Design  
Concepts for Machine and Detector

LHeC Study Group

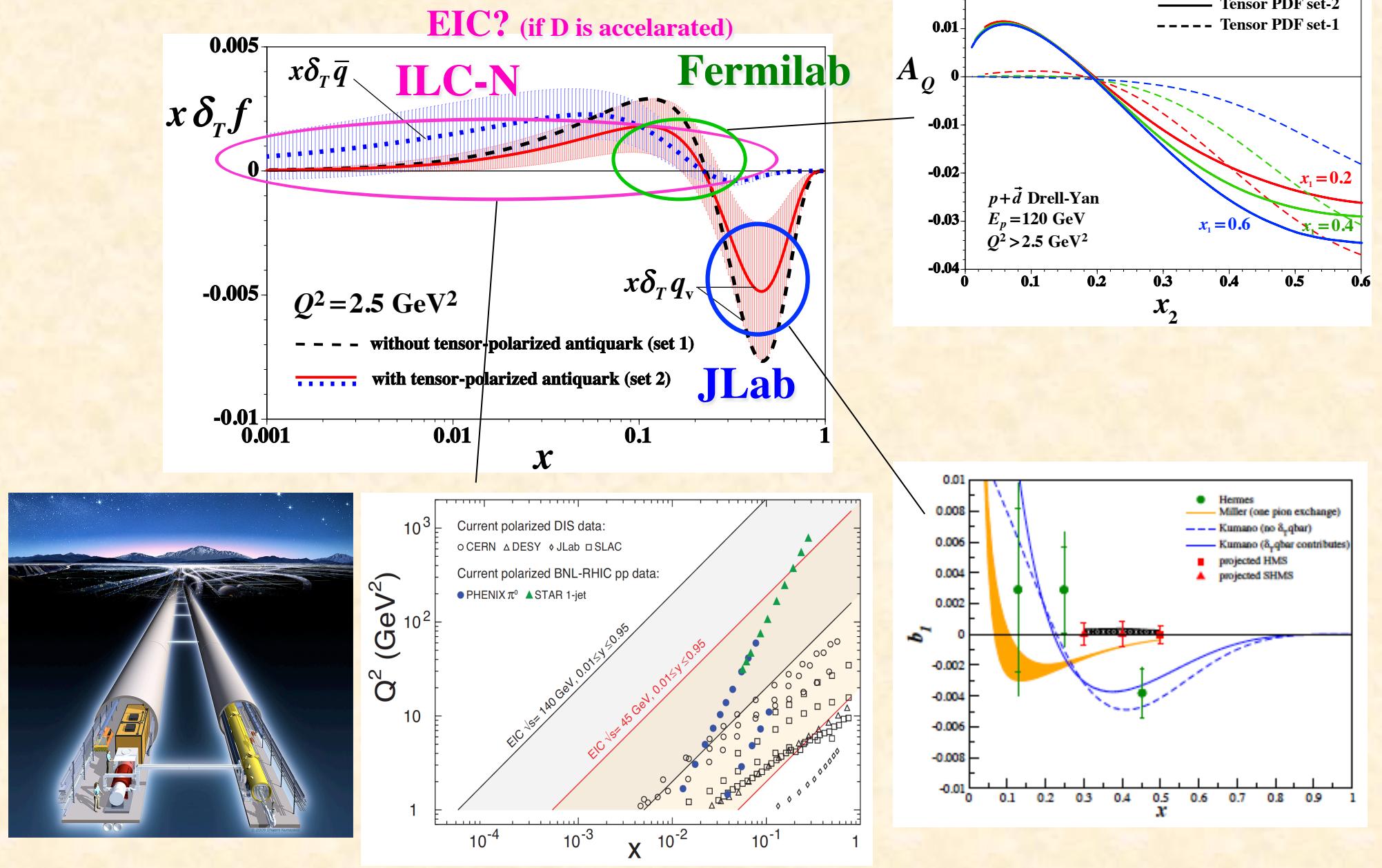


**High Intensity Heavy Ion  
Accelerator Facility (HIAF)**



**For small- $x$   $b_1$  studies,  
the deuteron needs  
to be accelerated (not easy).**

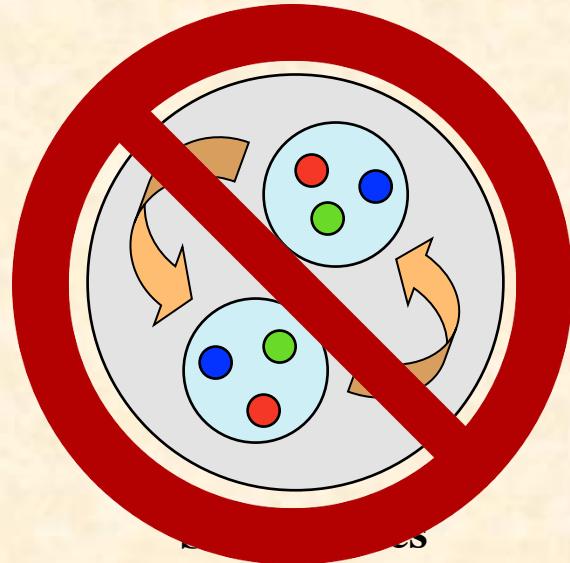
# Small- $x$ physics of $b_1$ at EIC



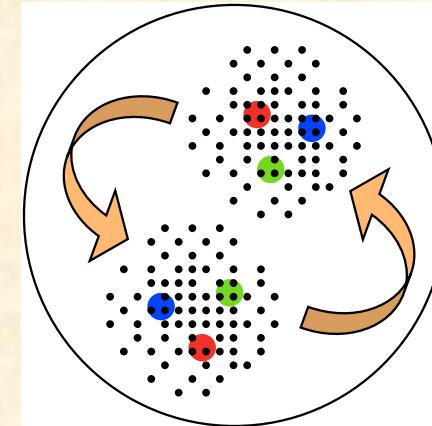
# Summary

## Spin-1 structure functions of the deuteron

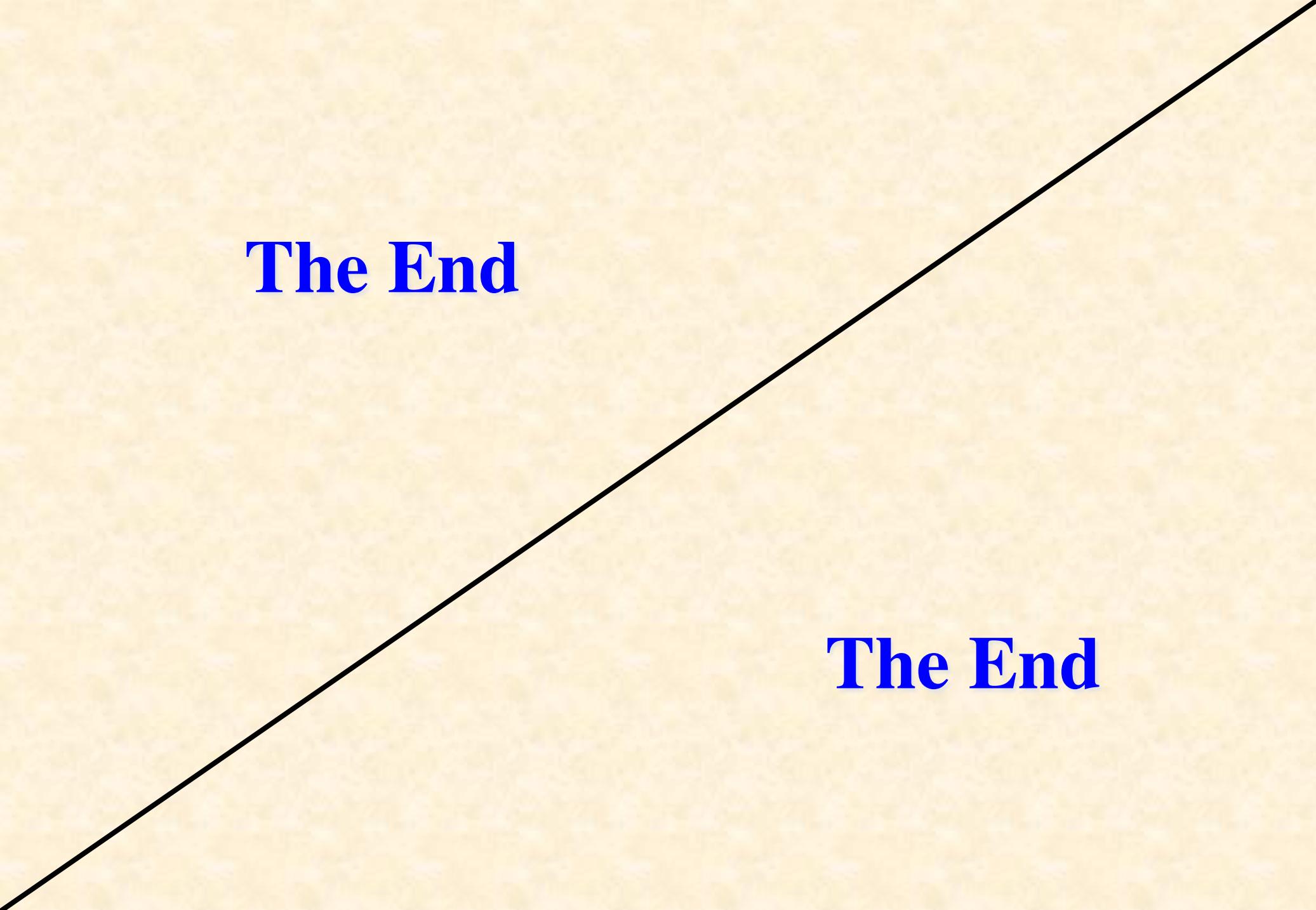
- new spin structure
- tensor structure in quark-gluon degrees of freedom
- new exotic signature in hadron-nuclear physics?
- experiments: Jlab (approved), Fermilab, ... , EIC, ILC, ...
- **ILC/EIC → appropriate to study tensor-polarized antiquark distributions at small- $x$ ,  $Q^2$  evolution of  $b_1$**



standard model



? new exotic  
mechanism?



**The End**

**The End**