Polarized structure functions of spin-one deuteron

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Workshop on Recent Developments in Quark-Hadron Sciences
Yukawa Institute for Theoretical Physics, Kyoto, Japan, June 11-15, 2018,
http://www2.yukawa.kyoto-u.ac.jp/~nfqcd2018/YKIS/

Recent works: (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.

June 11, 2018

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- Introduction to deep-inelastic lepton-deuteron scattering:
  Origin of nucleon spin,
  Tensor structure functions (b_1, …, b_4) for deuteron

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- Tensor-polarized asymmetry in Drell-Yan

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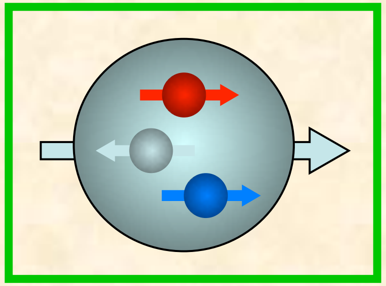
Polarized PDFs
for the nucleon

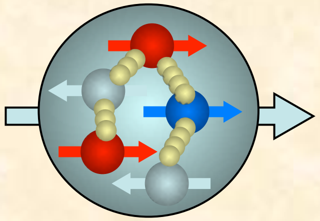
Recent progress on origin of nucleon spin

“old” standard model

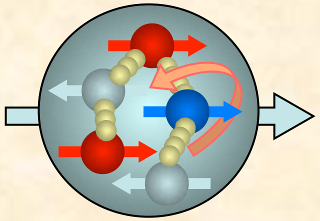


$$p_{\uparrow} = \frac{1}{3\sqrt{2}}\left(uud\left[2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\right] + \text{permutations}\right)$$

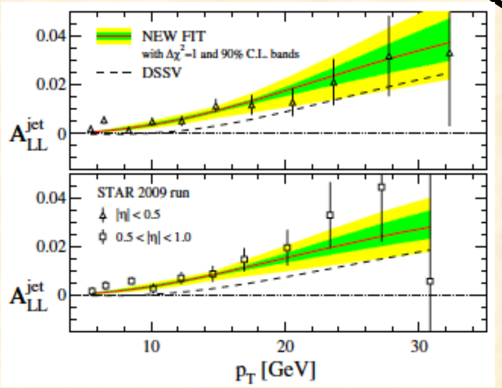
$$\boxed{\begin{aligned} &\Delta q(x) \equiv q_{\uparrow}(x) - q_{\downarrow}(x) \\ &\Delta\Sigma = \sum_i \int dx\left[\Delta q_i(x) + \Delta\bar{q}_i(x)\right] \to 1\ (100\%) \end{aligned}}$$

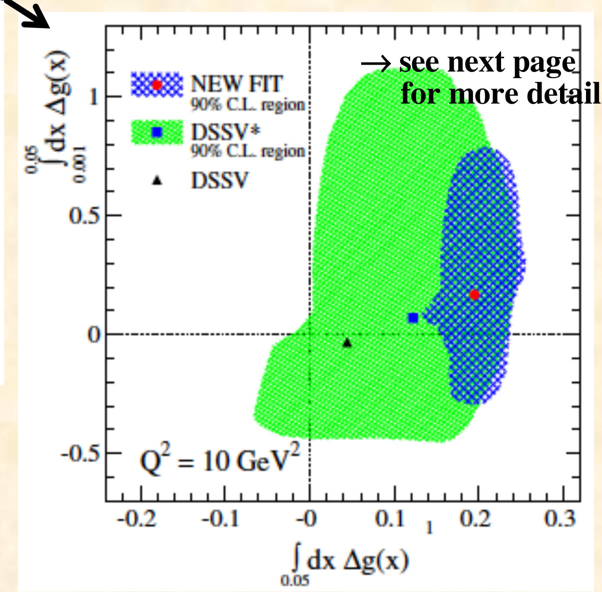


gluon spin



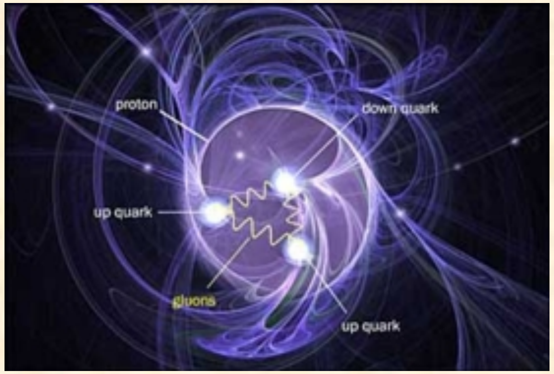
angular momentum





→ see next page for more details

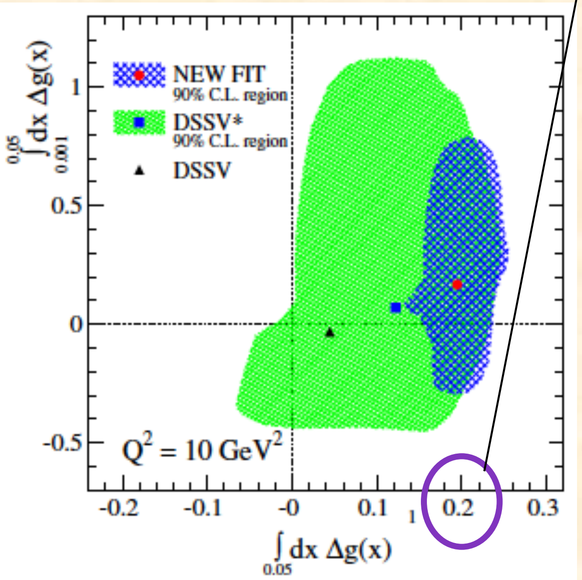
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_{q,g}$$



Scientific American (2014)

Gluon polarization and nucleon spin

small-x contribution: $\int_{0.001}^{0.05} dx\ \Delta g(x)$



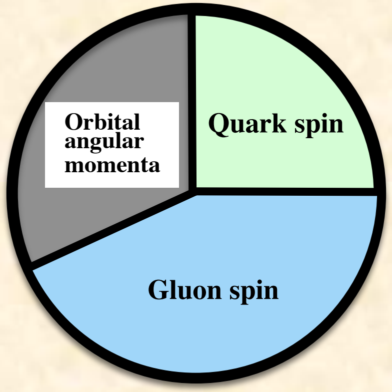
current experimental region: $\int_{0.05}^{1} dx\ \Delta g(x)$

In the current experimental region: $\int_{0.05}^{1} dx\ \Delta g(x) = 0.2$

$\dfrac{0.2}{1/2 \text{ spin}} = 40\%:$ 40% of the nucleon spin is carried by the gluon spin!?

The major carrier of the nucleon spin could be gluons instead of quarks. (CNN breaking news in 2014.)

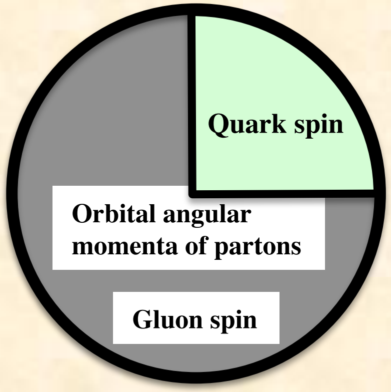
⇔ Completely different from the naive quark model.

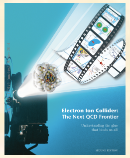


However, there are still large uncertainties from the small-x region.

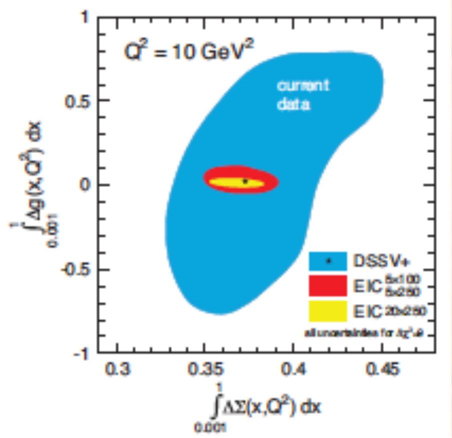
→ Importance of the EIC (electron-ion collider) project to measure small x.

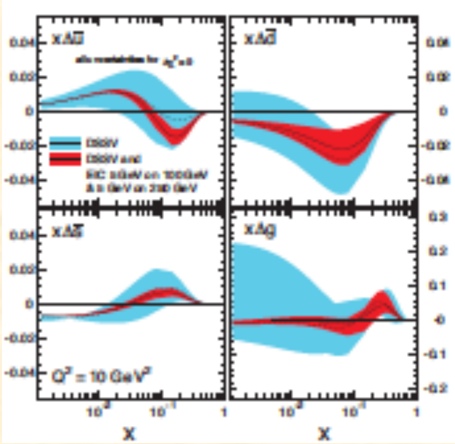
Real current experimental status →





Electron-Ion Collider (~2025) →

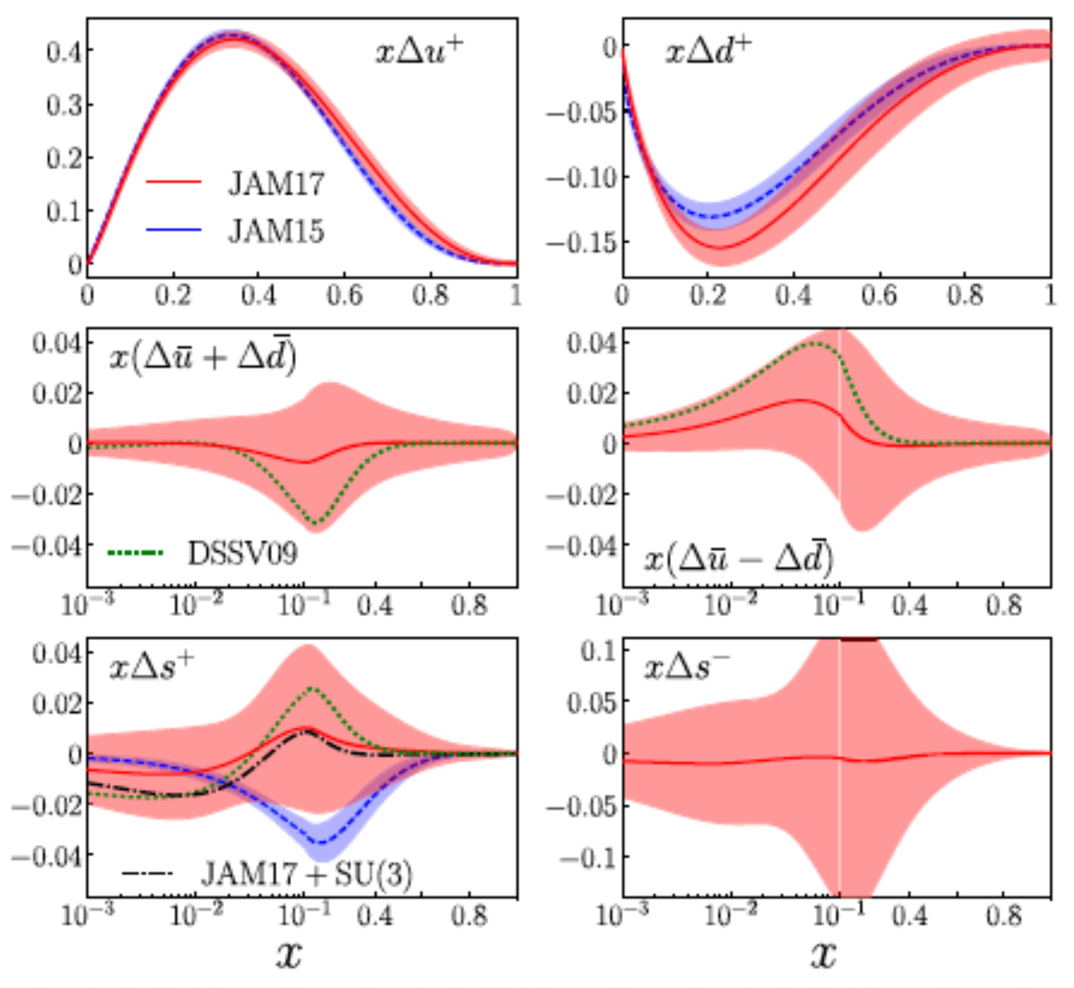




Toward "real" global analysis

J. J. Ethier, N. Sato, W. Melnitchouk, PRL 119 (2017) 132001

JAM: Analysis of Longitudinal-polarization data + Fragmentation data
CTEQ: Analysis of Unpolarized nucleon data + Nuclear data



"Real" global analysis
= unpolarized data
+ longitudinally-polarized
+ fragmentation
+ nuclear
+ transversity
+ spin-1 deuteron
+ • • •

Origin of nucleon spin: decomposition

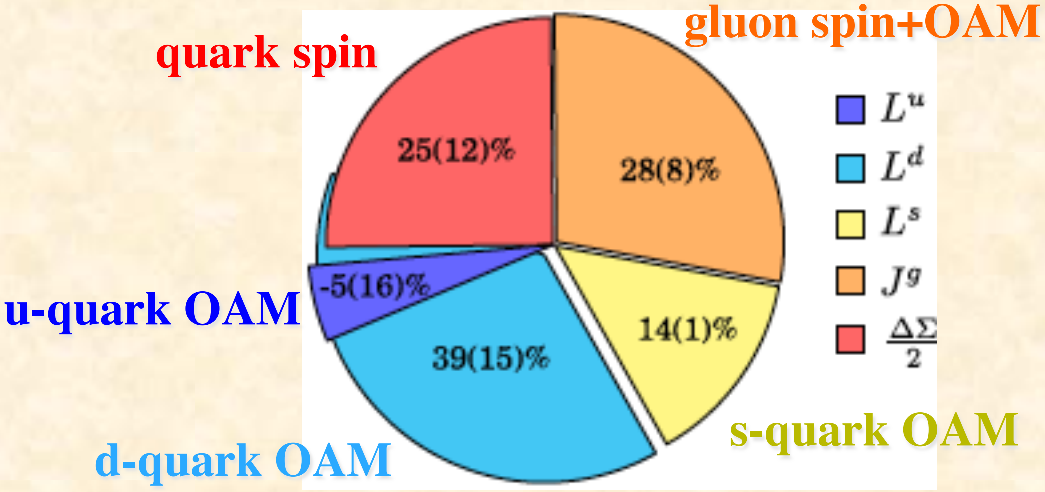
$$\frac{1}{2} = \left\langle p \middle| J^3 \middle| p \right\rangle, \quad J^3 = \frac{1}{2}\varepsilon^{3jk}\int d^3x\, M^{3jk}(x), \quad M^{\alpha\mu\nu}(x) = T^{\alpha\nu}(x)x^{\mu} - T^{\alpha\mu}(x)x^{\nu}$$

Gauge invariant decomposion: see review papers of M. Wakamatsu, Int. J. Mod. Phys. A29 (2014) 1430012;
E. Leader and C. Lorce, Phys. Rept. 541 (2014) 163;
and Y. Hatta (and S. Yoshida, K. Tanaka), Phys. Rev. D84 (2011) 041701;
Phys. Lett. B 708 (2012) 186; JHEP 1210 (2012) 080; 1302 (2013) 003.

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g,$$

$\Delta\Sigma$ = quark spin contribution, Δg = gluon spin contribution,
L_q = quark orbital-angular-momentum (OAM) contribution,
L_g = gluon orbital-angular-momentum (OAM) contribution

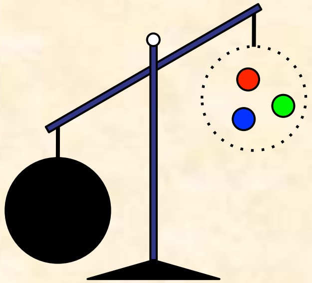
Lattice QCD estimate in M. Deke *et al*., Phys. Rev. D 91 (2015) 0145505



Spin decomposion

- **quark spin 25%**
- **quark OAM 45%**
- **gluon spin + OAM 30%**

Unsolved mysteries in physics

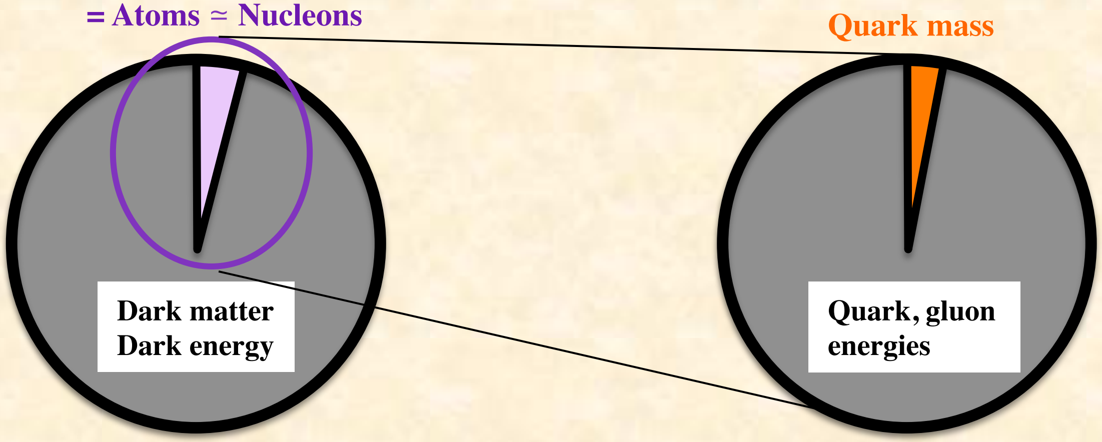


Mass and spin of the nucleon are two of fundamental quantities in physics.

Nucleon mass: $M = \left\langle p \middle| \int d^3x\, T^{00}(x) \middle| p \right\rangle$

Energy-momentum tensor:

$$T^{\mu\nu}(x) = \frac{1}{2}\bar{q}(x) i\overleftrightarrow{D}^{(\mu}\gamma^{\nu)}q(x) + \frac{1}{4}g^{\mu\nu}F^2(x) - F^{\mu\alpha}(x)F^{\nu}{}_{\alpha}(x)$$



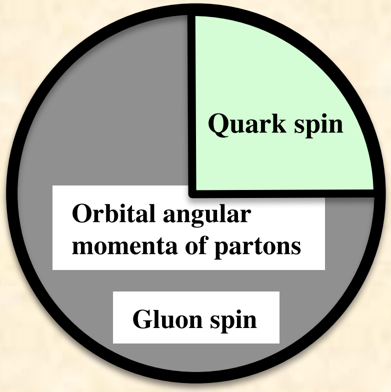
Dark matter

Origin of nucleon mass

Nucleon spin: $\frac{1}{2} = \left\langle p \middle| J^3 \middle| p \right\rangle$

3rd component of total angular momentum: $J^3 = \frac{1}{2}\varepsilon^{3jk}\int d^3x\, M^{3jk}(x)$

Angular-momentum density: $M^{\alpha\mu\nu}(x) = T^{\alpha\nu}(x)x^{\mu} - T^{\alpha\mu}(x)x^{\nu}$



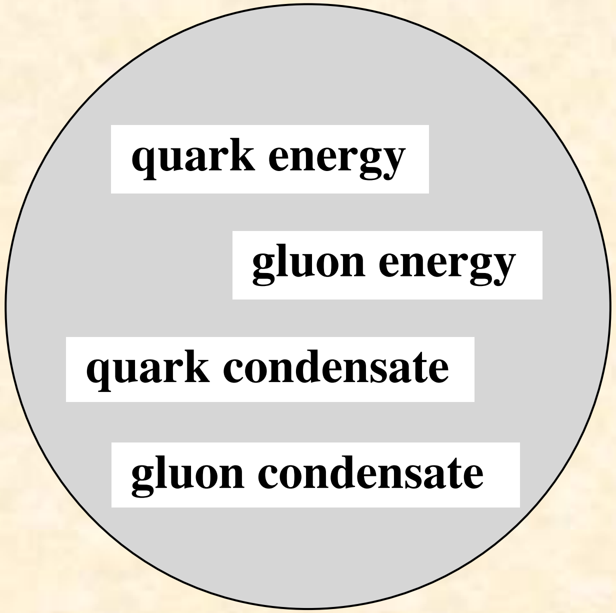
Origin of nucleon spin
("Dark spin")

Origin of nucleon mass: decomposition

Nucleon mass: $M = \langle p | H | p \rangle, \quad H = \int d^3x \, T^{00}(x)$

Energy-momentum tensor:

$$T^{\mu\nu}(x) = \frac{1}{2}\bar{q}(x) i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)} q(x) + \frac{1}{4} g^{\mu\nu} F^2(x) - F^{\mu\alpha}(x) F^{\nu}_{\ \alpha}(x)$$



We need theoretical and experimental efforts
to decompose nucleon mass for finding its origin.

Meeting in 2017 at KEK

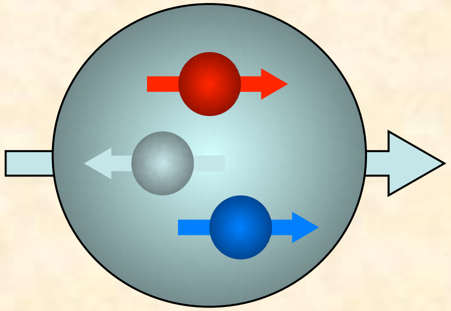
Mini-workshop on Origin of nucleon mass and its decomposition,
Conveners: S. Kumano, K. Tanaka,
September 1, 2017, KEK
http://j-parc-th.kek.jp/workshops/2017/09-01/

• Nucleon mass decomposion,	J. Qiu (JLab)
• Mass-modification experiment at J-PARC,	S. Yokkaichi (Riken)
• Hadron-mass radii from tomography,	Q.-T. Song (Sokendai / KEK)

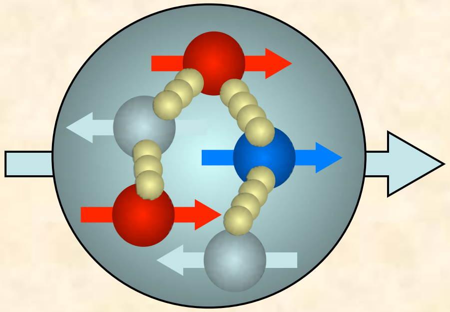
Polarized PDFs for spin-1 hadrons (deuteron)

Nucleon spin

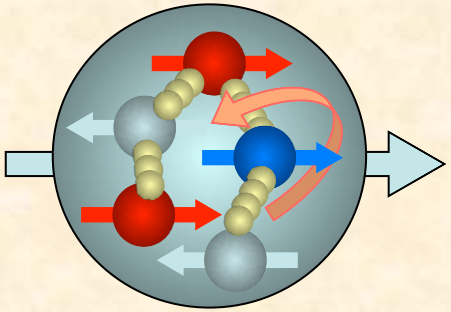
Almost none of nucleon spin is carried by quarks! → Nucleon spin crisis!?



Naïve Quark Model



Sea-quarks and gluons?

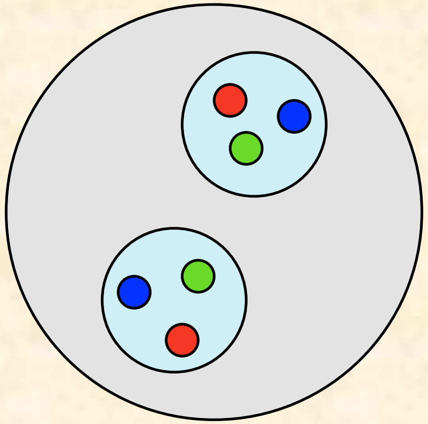


Orbital angular momenta ?

“old” standard model

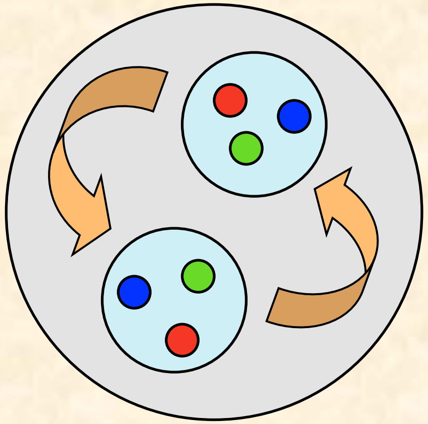
Tensor structure b_1 (*e.g.* deuteron)

Tensor-structure crisis!?



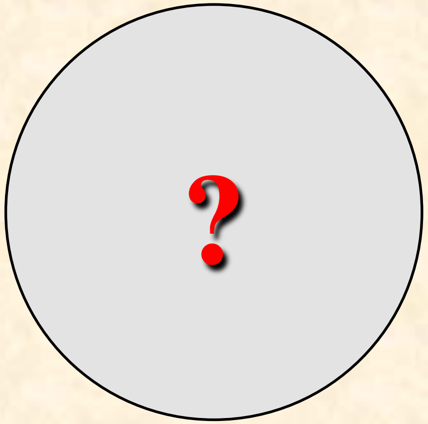
only S wave

$b_1 = 0$



S + D waves

standard model $b_1 \neq 0$



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

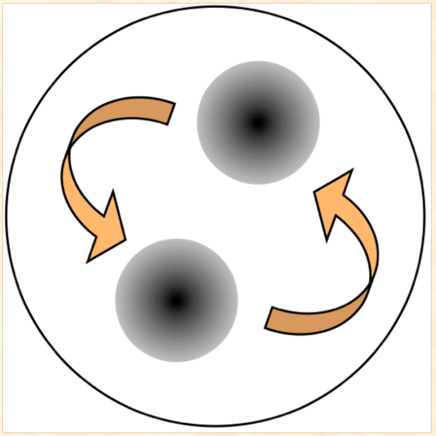
Roles of quark degrees of freedom in deuteron

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.

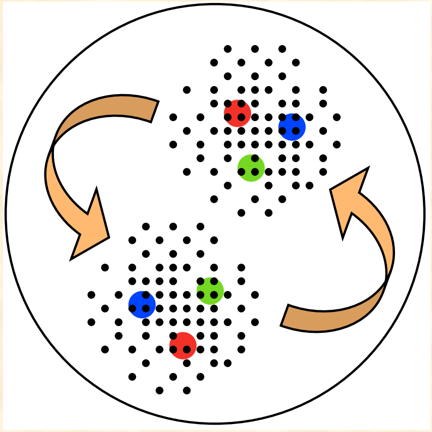
Tensor structure of the deuteron = old topic (in terms of nucleon d.o.f.) but it is a good probe of new hadron phenomena in quark-gluon d.o.f.

old



→

new



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.

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

Motived by the following works.

Hoodbhoy-Jaffe-Manohar (1989)

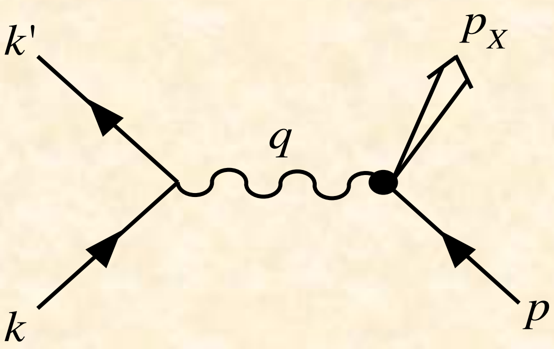
Polarized deuteron acceleration at RHIC:
E. D. Courant, Report BNL-65606 (1998)

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



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

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

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

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

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

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

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

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

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

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

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

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

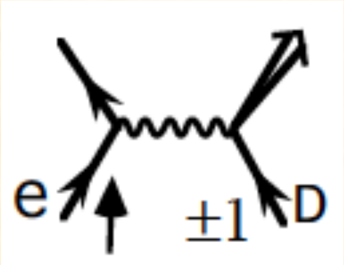
$2xb_1 = b_2$ in the scaling limit $\sim O(1)$

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

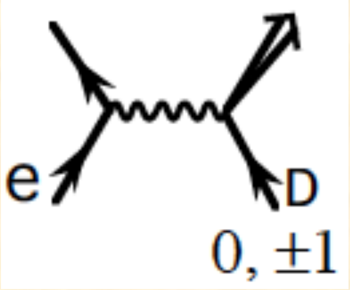
Structure Functions

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

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



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



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

Parton Model

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

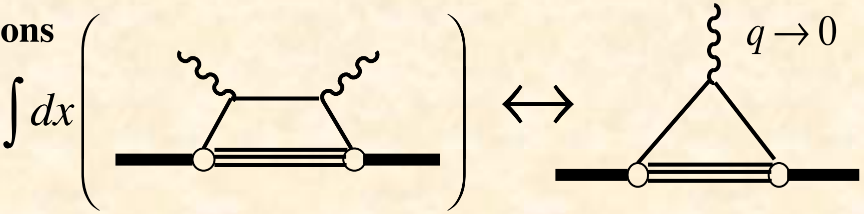
$$g_1 = \frac{1}{2}\sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

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

Constraint on valence-tensor polarization (sum rule)

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

Folow Feynman's book on Photon-Hadron Interactions



Intuitive derivation without calculation:

$\int dx\, b_1(x) =$ dimensionless quantity

$= (\text{mass})^2 \cdot$ (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

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

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

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.

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

(Gottfried sum rule)

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

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

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

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

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! ⇒ $\bar{u} < \bar{d}$?

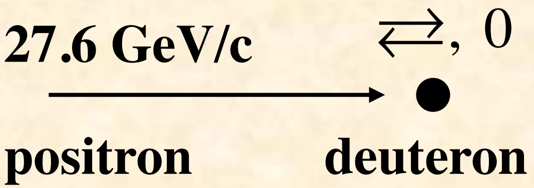
$$\int_0^1 \frac{dx}{x}\left[F_2^{p}(x) - F_2^{n}(x)\right] = \underline{\frac{1}{3}} + \underline{\frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]}$$

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

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

HERMES results on b_1

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

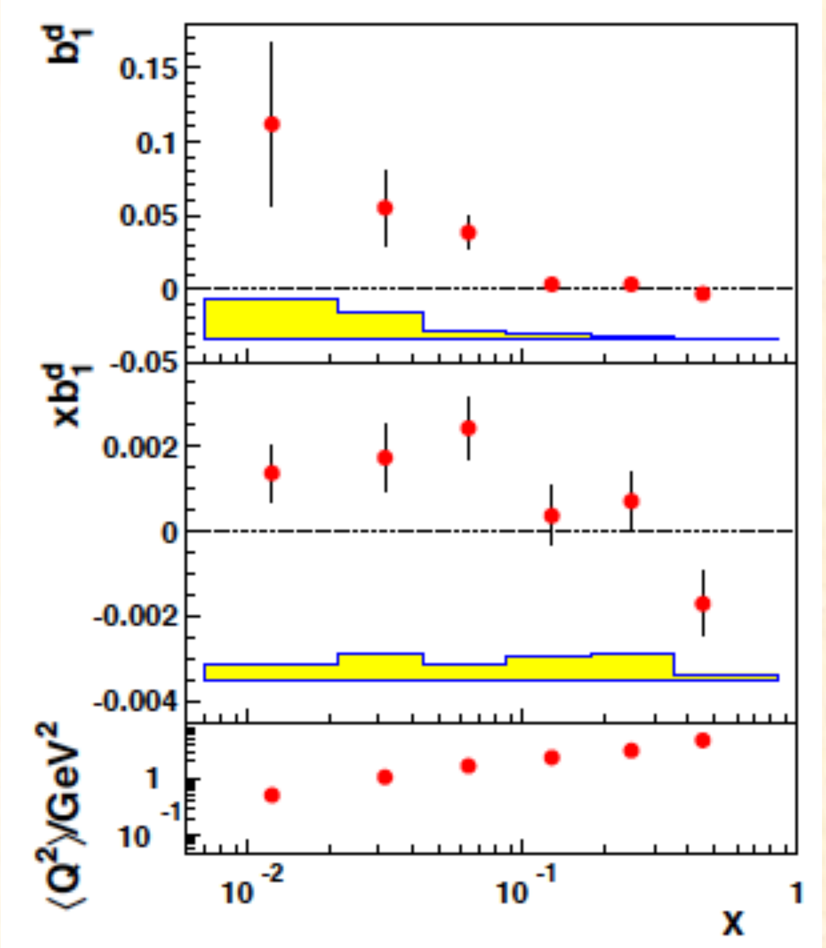


27.6 GeV/c

$\rightleftarrows$, 0

positron

deuteron



b_1 measurement in the kinematical region

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

b_1 sum rule

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

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

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

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

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

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

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

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.

Basic convolution model calculation for b_1 .

If future measurements deviate from our esitmate, there could be an interesting new mechanism.

Basic convolution approach

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

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

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

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

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

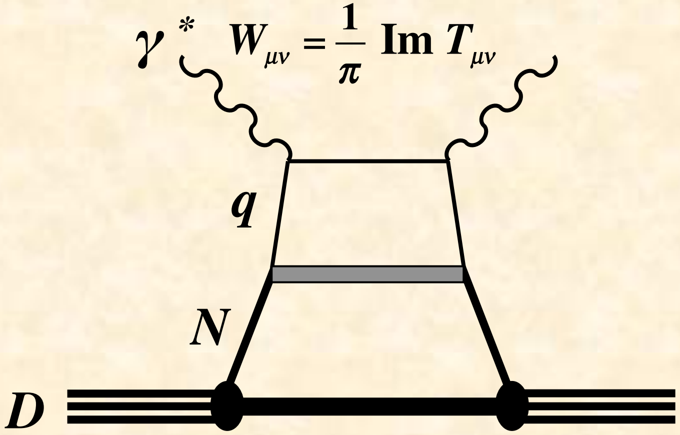
D-state admixture: $\phi^H(\vec{p})=\phi^H_{\ell=0}(\vec{p})+\phi^H_{\ell=2}(\vec{p})$

⇓

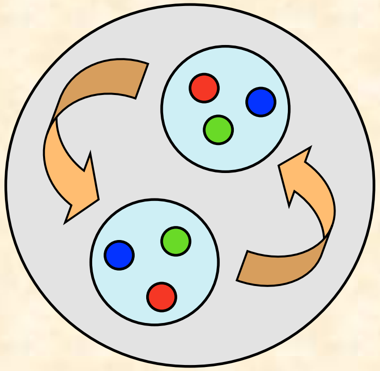
$$b_1(x)=\int\frac{dy}{y}\delta_T f(y)F_1^N(x/y,\,Q^2)$$

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

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

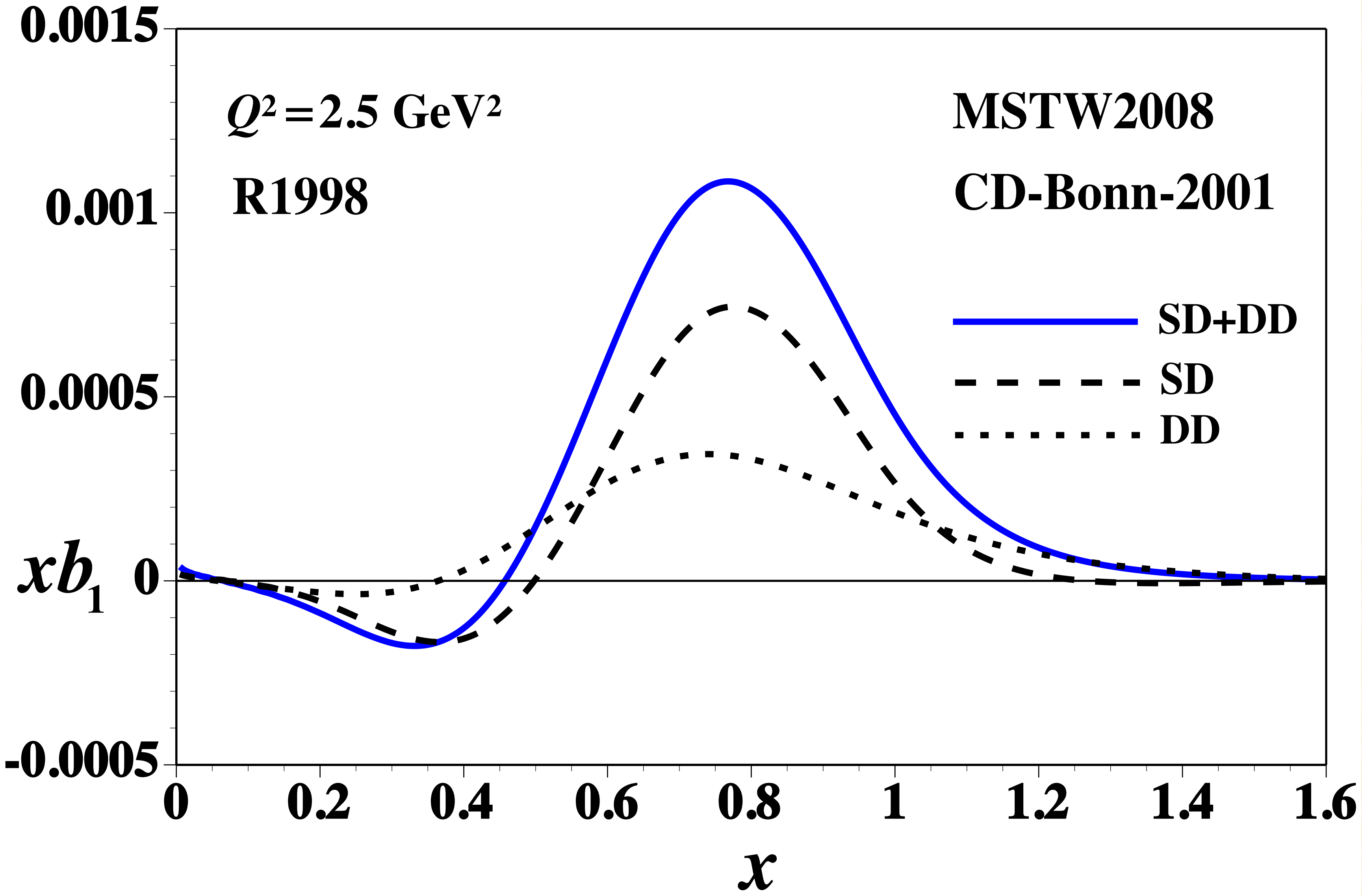


Standard model of the deuteron



S + D waves

Results on b_1 in the convolution description



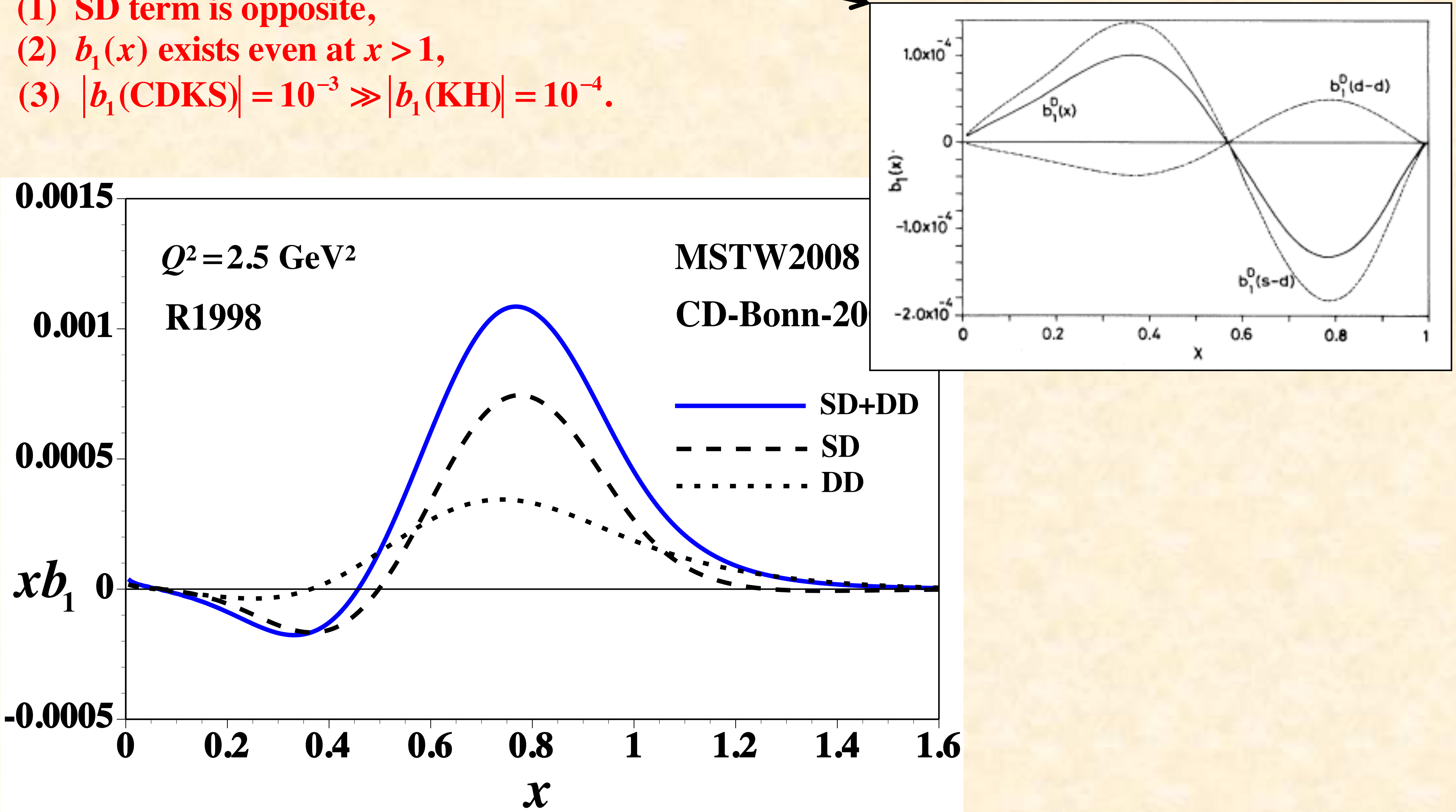
Results on b_1 in the convolution description

Very different from

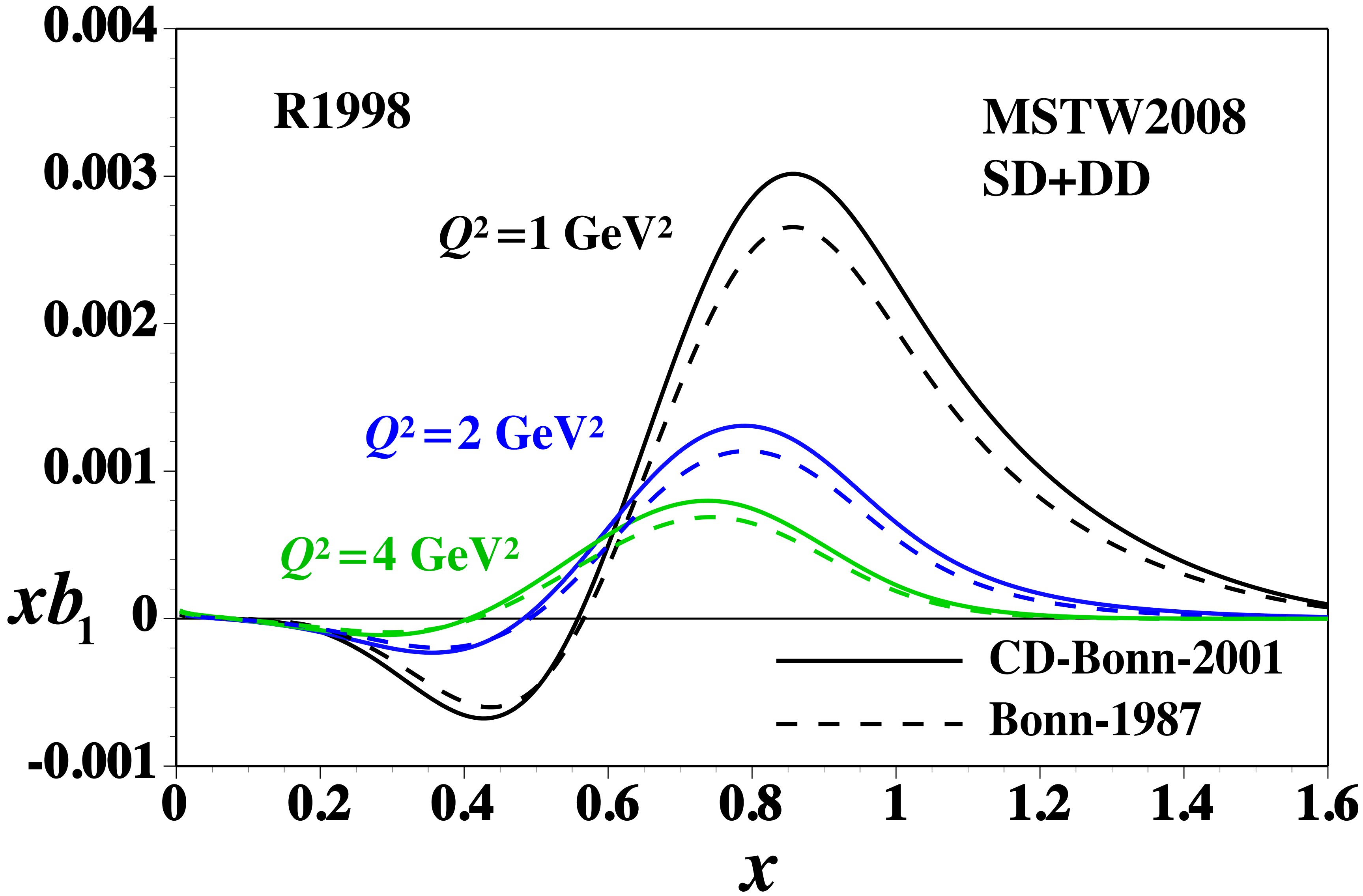
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571;

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

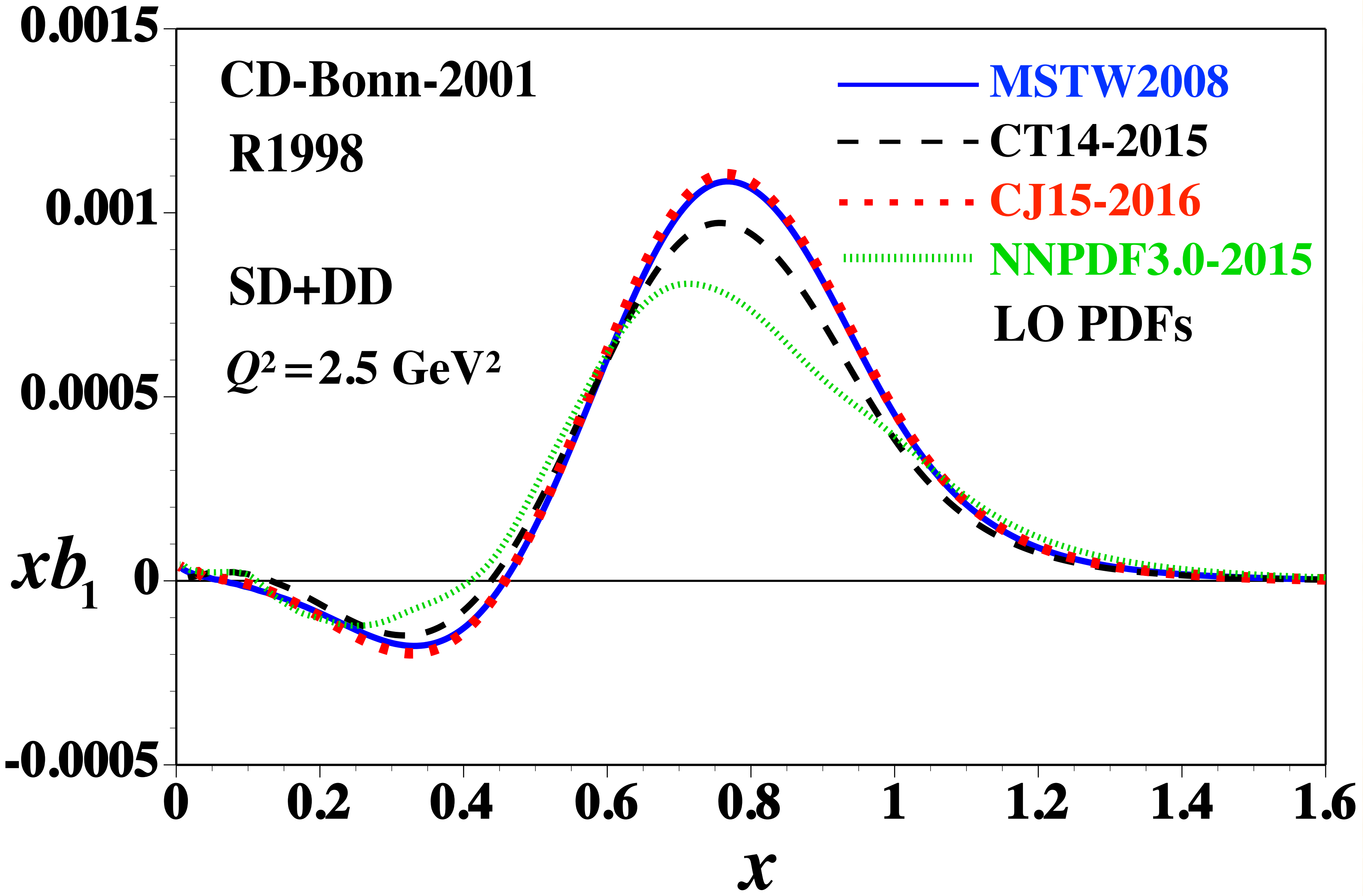
1. **SD term is opposite,**
2. **$b_1(x)$ exists even at $x > 1$,**
3. **$|b_1(\text{CDKS})| = 10^{-3} \gg |b_1(\text{KH})| = 10^{-4}$.**



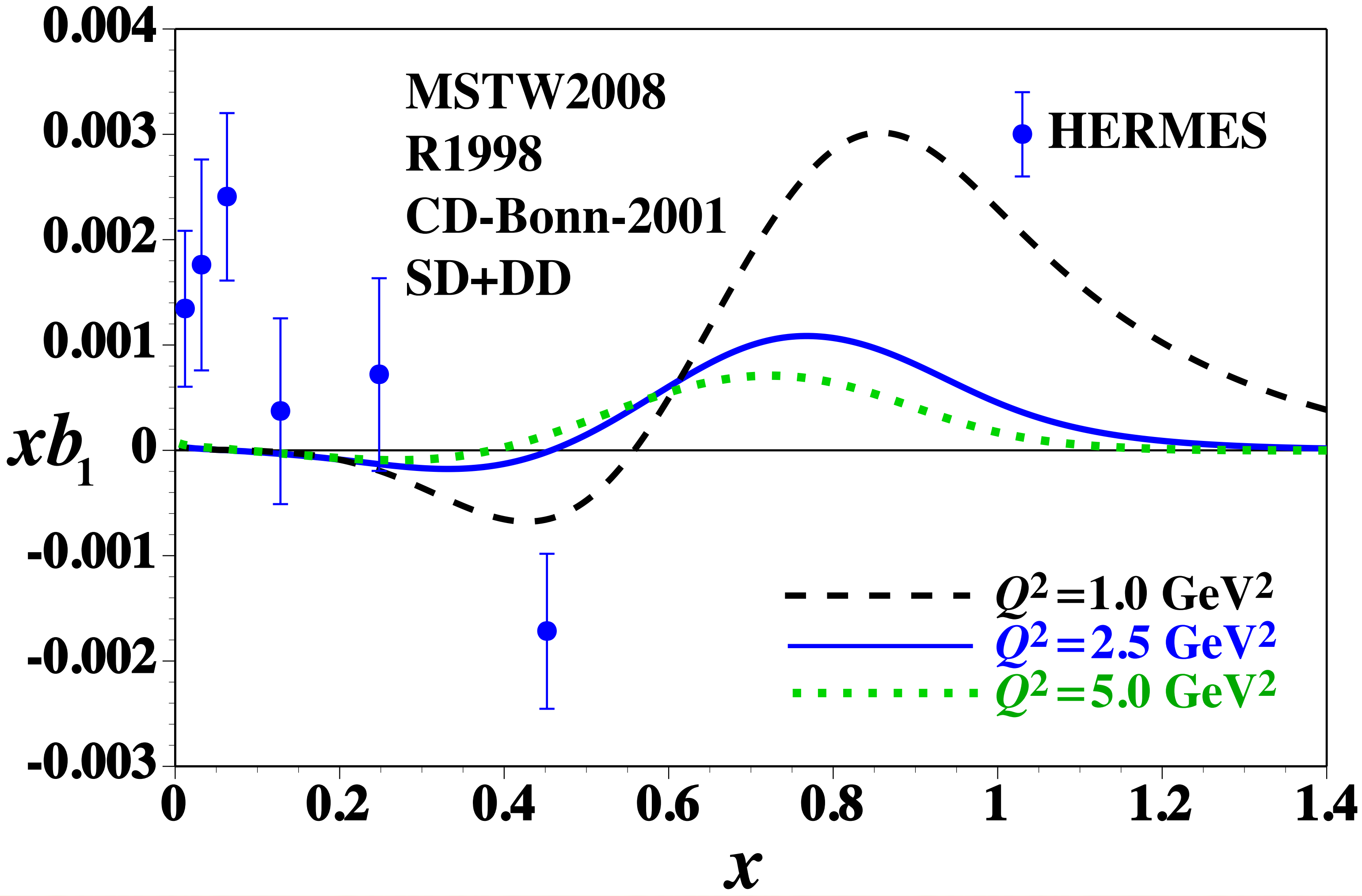
Results on b_1: deuteron-wave-function dependence



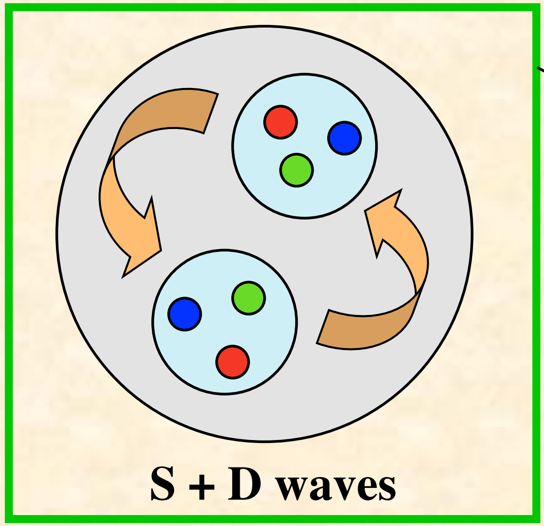
Results on b_1: used PDF dependence



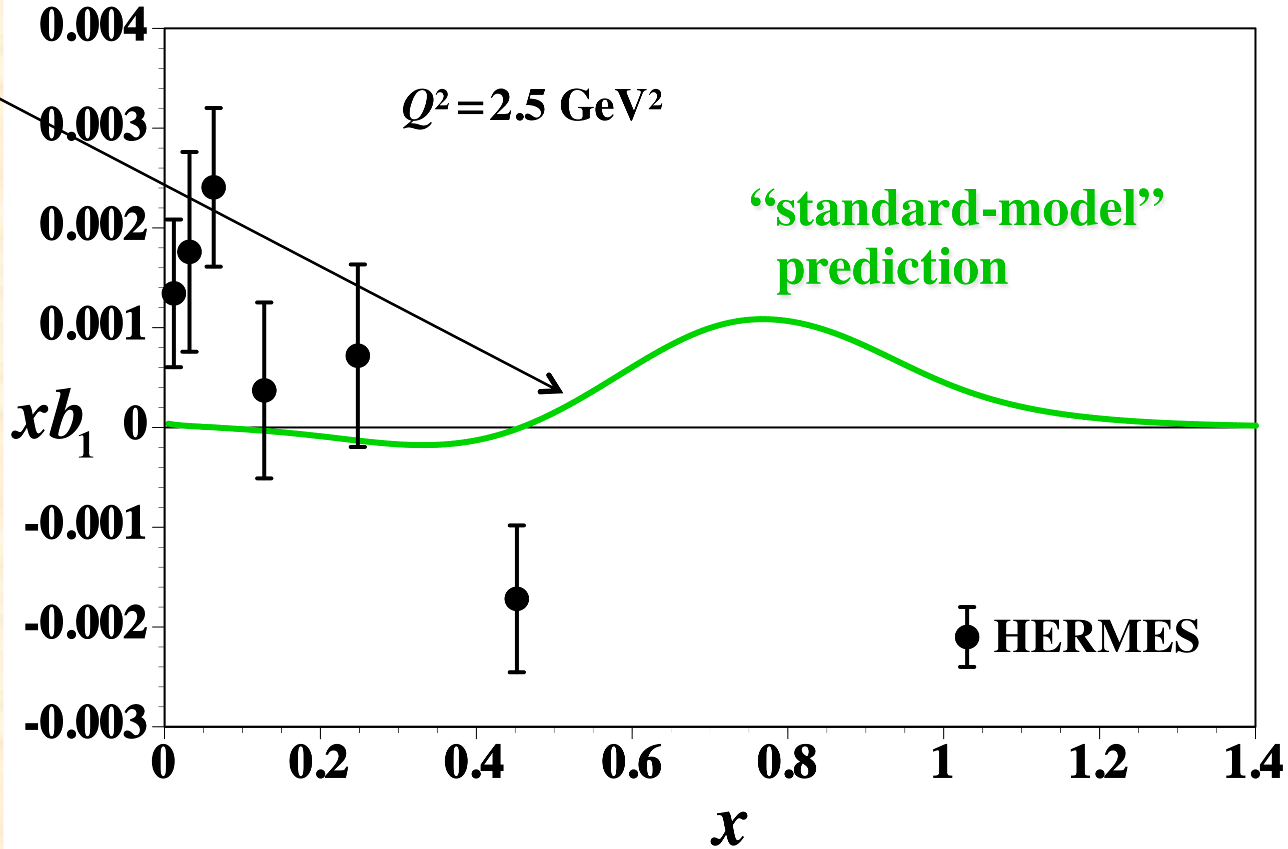
Comparison with HERMES measurements



Comparison with HERMES measurements



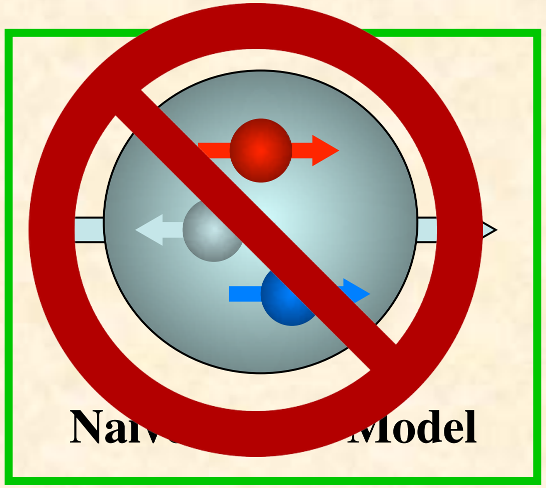
standard model



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

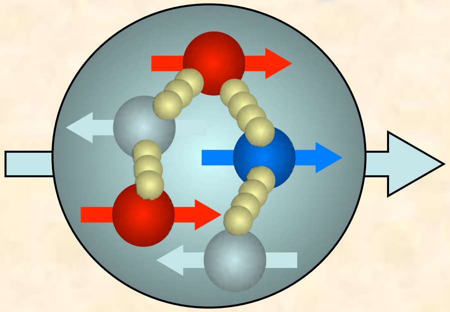
Standard convolution model does not work for the deuteron tensor structure?
→ New hadron physics !?

Situation of tensor structure by b_1

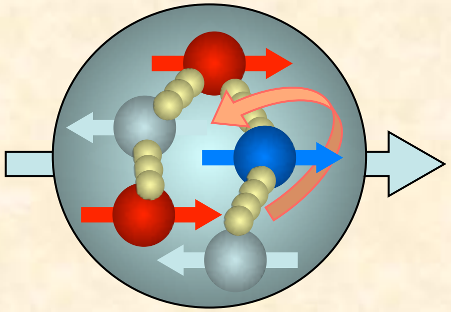

Naiv Model

"old" standard model

Nucleon spin

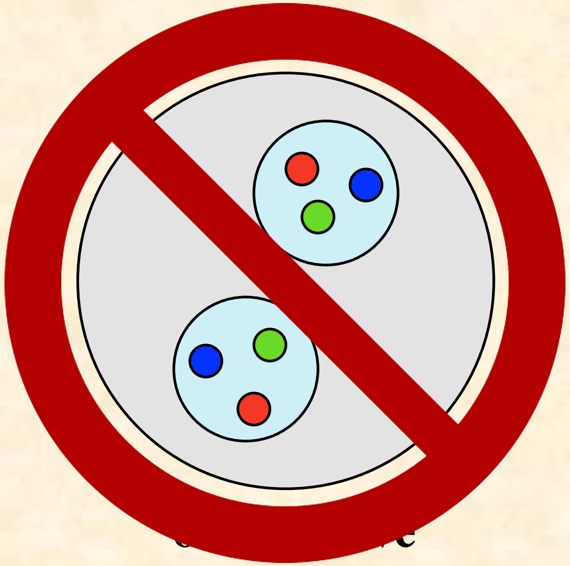

Sea-quarks and gluons?

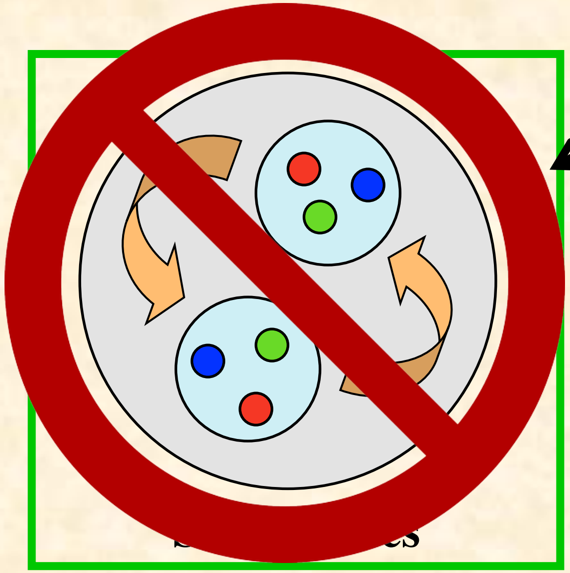
Nucleon spin crisis!?


Orbital angular momenta ?

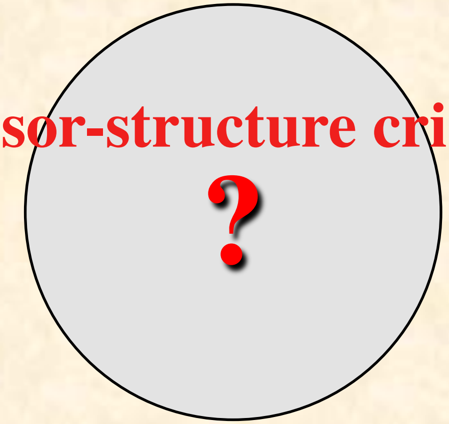
We have shown in this work
that the standard deuteron model
does not work!?
→ new hadron physics?!

Tensor structure


$b_1 = 0$


standard model $b_1 \neq 0$

Tensor-structure crisis!?

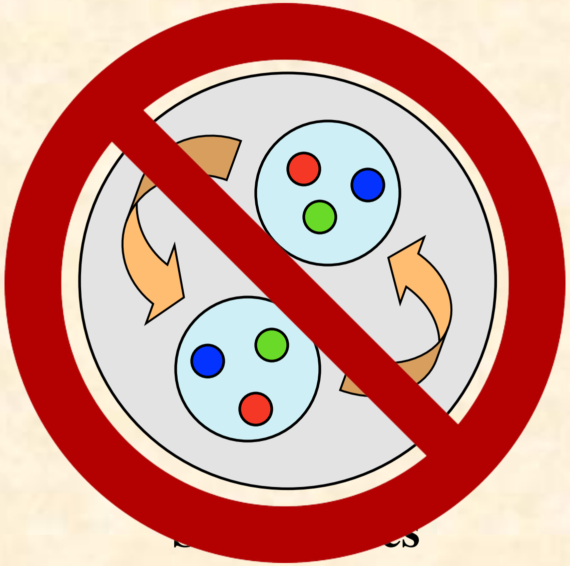


$b_1^{\text{experiment}} \neq b_1^{\text{“standard model”}}$

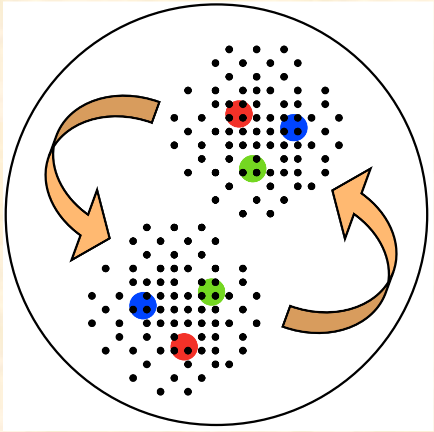
Summary I

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



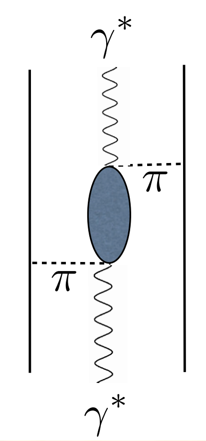
standard model

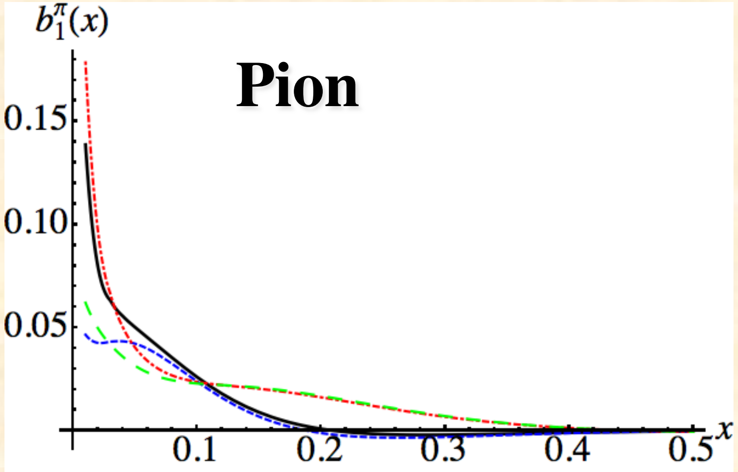


? new exotic mechanism?

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

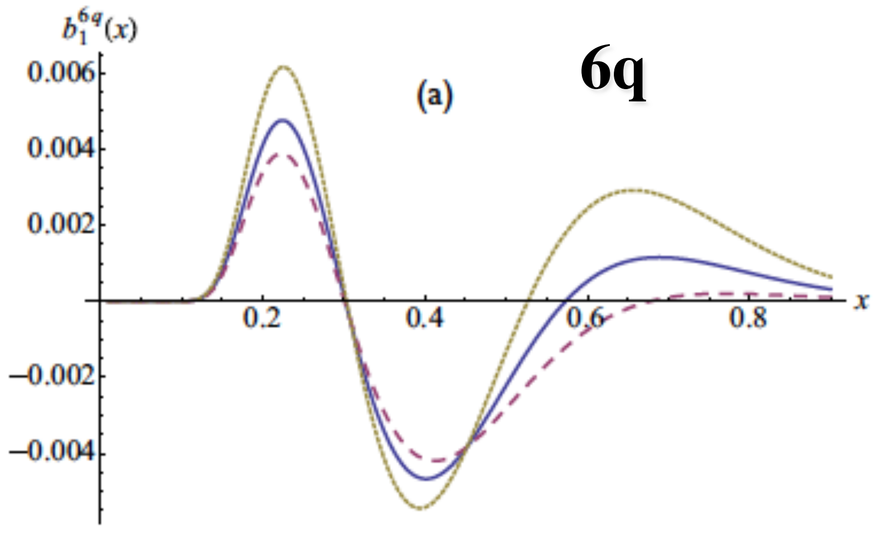
G. A. Miller,
PRC 89 (2014) 045203.



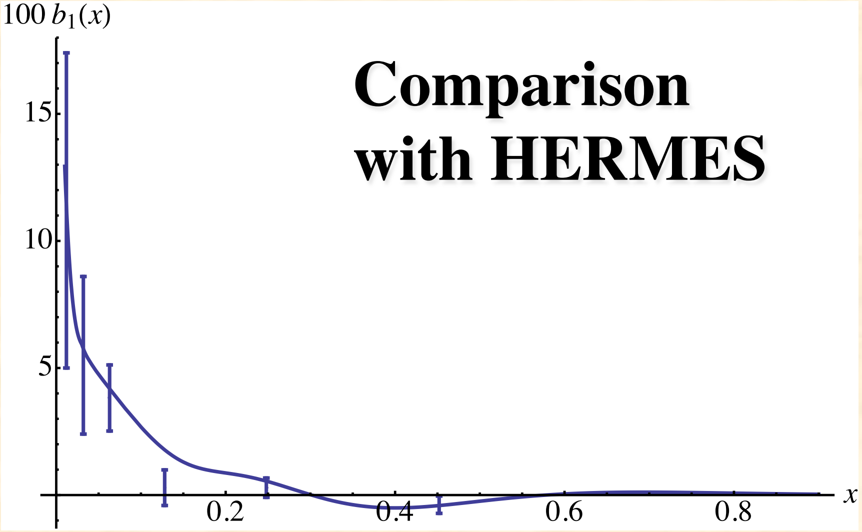


Pion

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

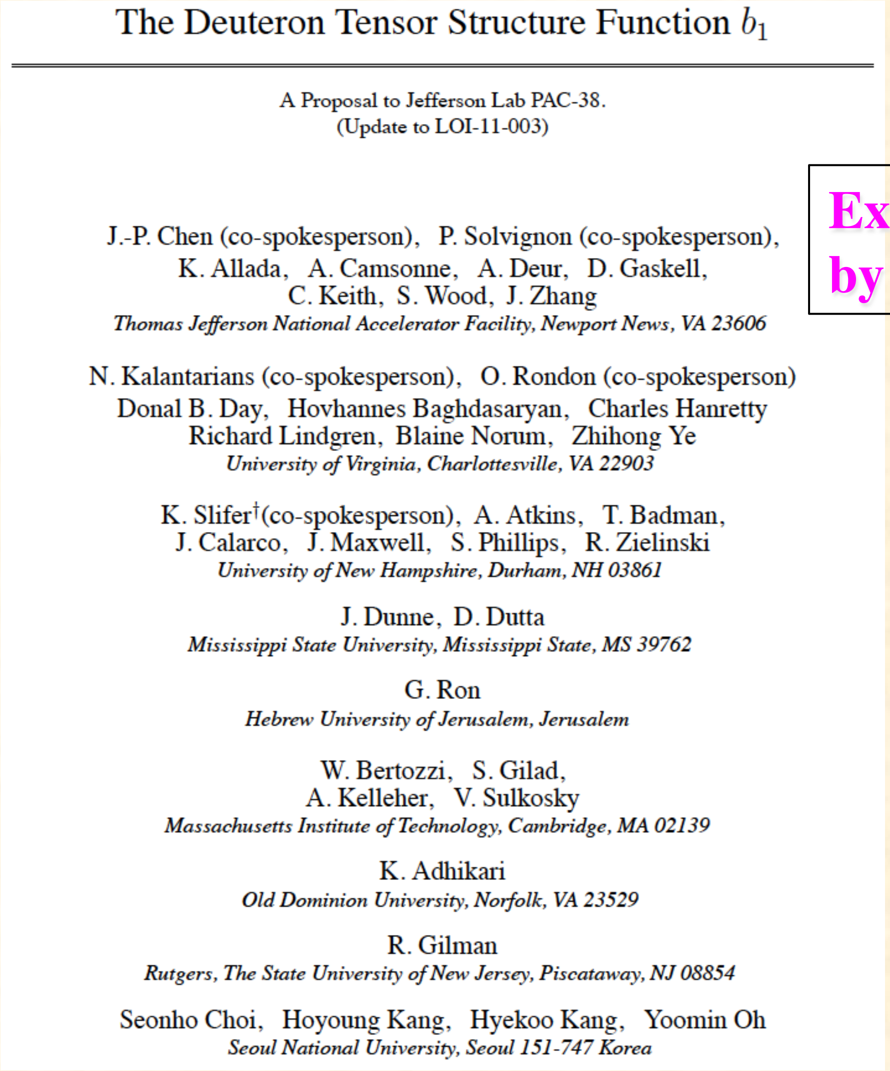


6q



Comparison with HERMES

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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K. Allada, A. Camsonne, A. Deur, D. Gaskell,
C. Keith, S. Wood, J. Zhang
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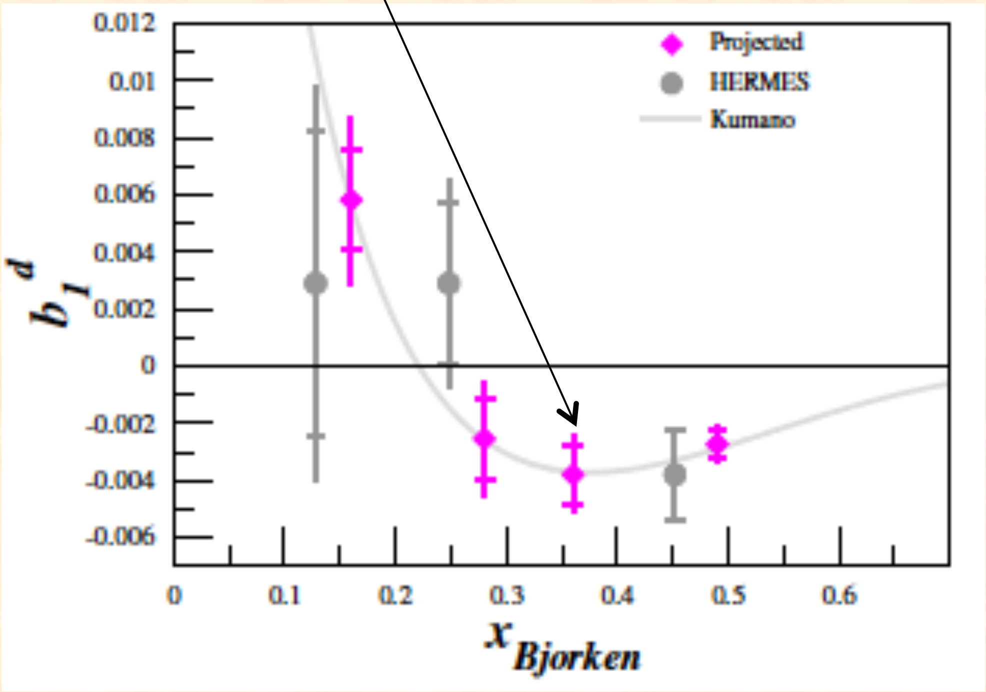
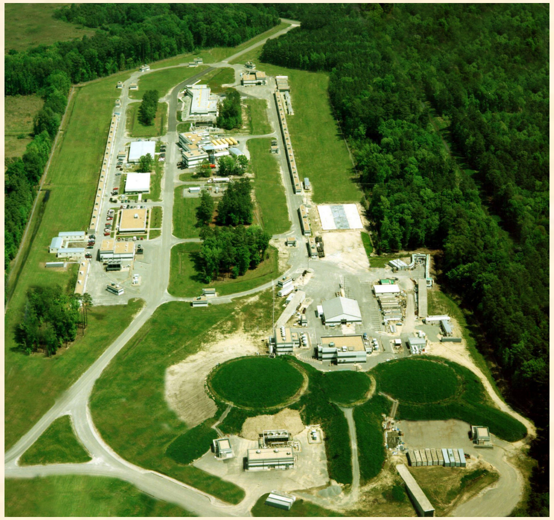
Seoul National University, Seoul 151-747 Korea

Approved!

Expected errors
by JLab



Experimental possibilities



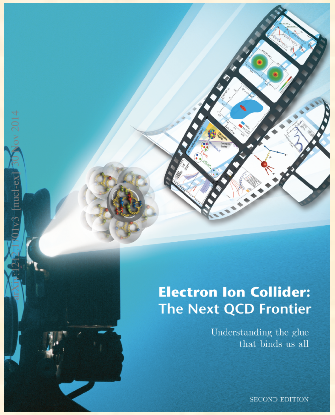
© JLab

Approved experiment! (2019~)

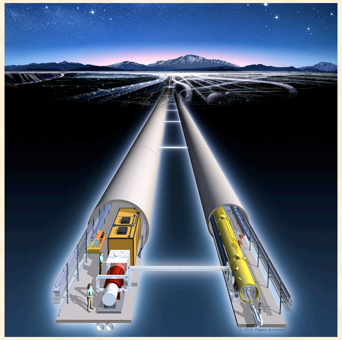
E1039 experiment

© Fermilab

EIC (arXiv:1212.1701)



Linear Collider (with fixed target)



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

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© 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.

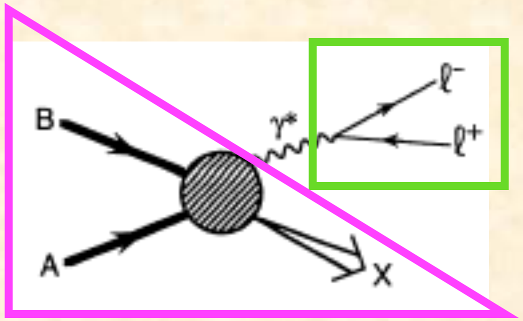
Drell-Yan cross section and hadron tensor

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

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

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

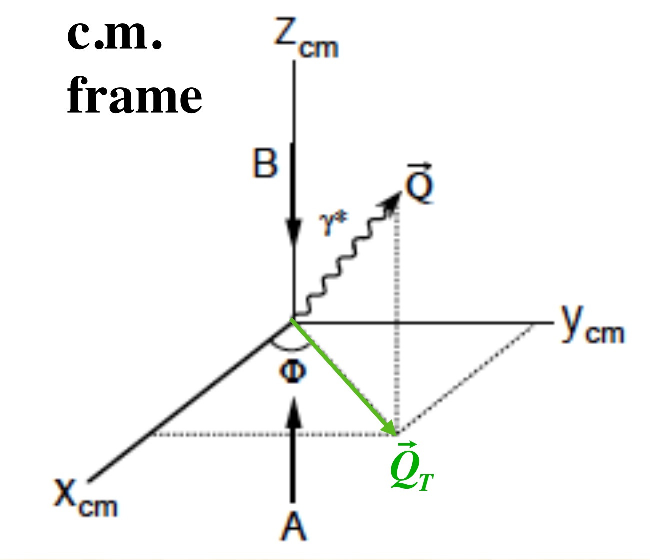
$$W^{\mu\nu} \equiv \int \frac{d^4\xi}{(2\pi)^4} e^{iQ\cdot\xi} \langle P_A S_A P_B S_B | J^\mu(0) J^\nu(\xi) | P_A S_A P_B S_B \rangle$$



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	Additional structure functions due to tensor structure
After integration over $\vec{Q}_T$ (or $\vec{Q}_T \to 0$)	11	22	
In parton model	3	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

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

Spin asymmetries

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

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

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

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

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: $\delta \neq$ **transversity in my notation**

Functional form of parametrization

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

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

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.

$$b_1^D(x,Q_0^2)_{LO} = \frac{1}{18}\left[4\delta_T u_v^D(x,Q_0^2) + \delta_T d_v^D(x,Q_0^2) + 12\delta_T\bar{q}^D(x,Q_0^2)\right]$$

$$= \frac{1}{36}\delta_T w(x)\left[5\left\{u_v(x,Q_0^2) + d_v(x,Q_0^2)\right\} + 4a_{\bar{q}}\left\{2\bar{u}(x,Q_0^2) + 2\bar{d}(x,Q_0^2) + s(x,Q_0^2) + \bar{s}(x,Q_0^2)\right\}\right]$$

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

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

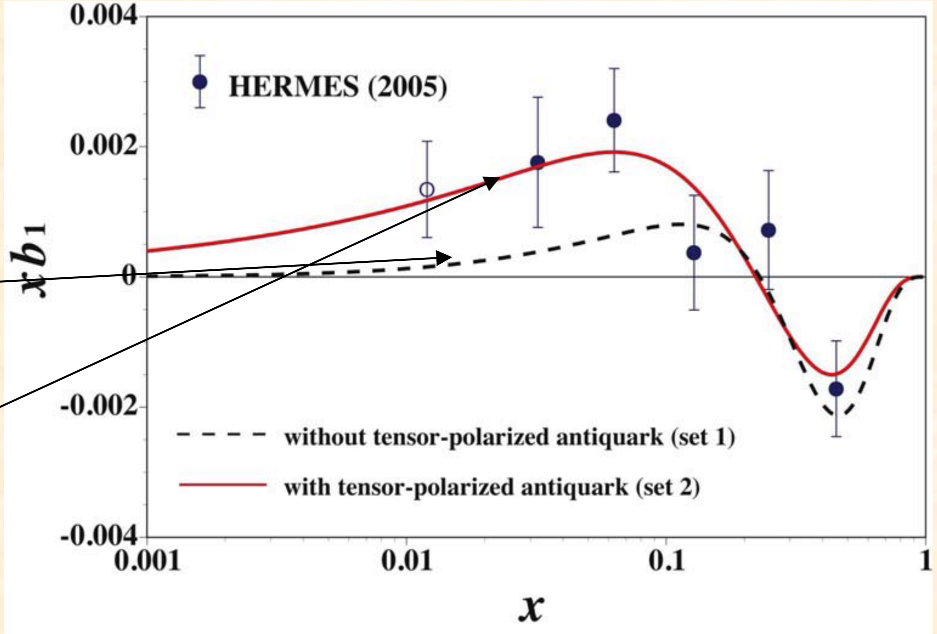
Two-types of fit results:

- 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.

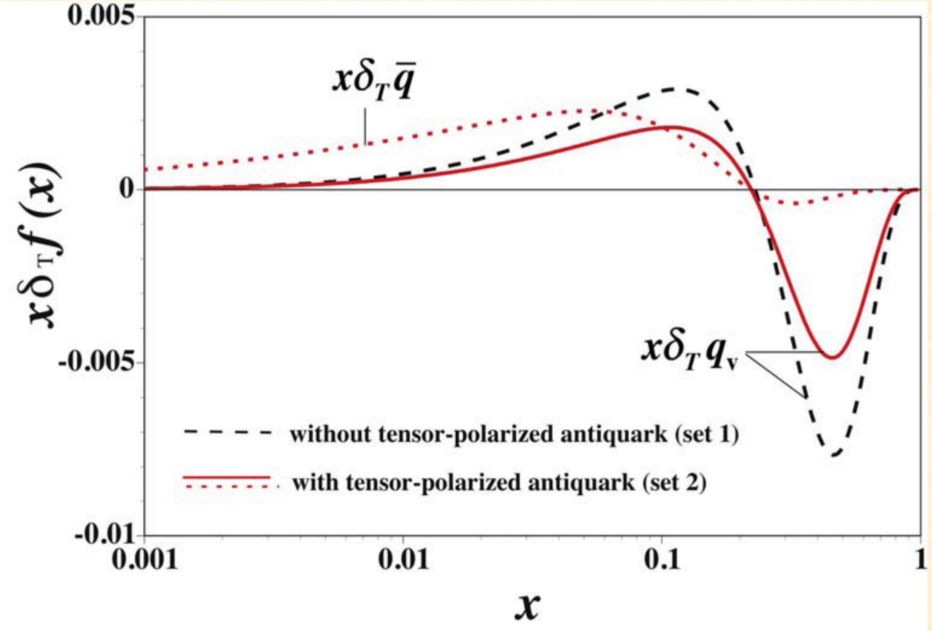


Obtained tensor-polarized distributions

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

→ They could be used for

- experimental proposals,
- comparison with theoretical models.



Finite tensor polarization for antiquarks:

$$\int_0^1 dx b_1(x) = 0.058$$
$$= \frac{1}{9}\int_0^1 dx \left[4\delta_T \bar{u}(x) + \delta_T \bar{d}(x) + \delta_T \bar{s}(x) \right]$$

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

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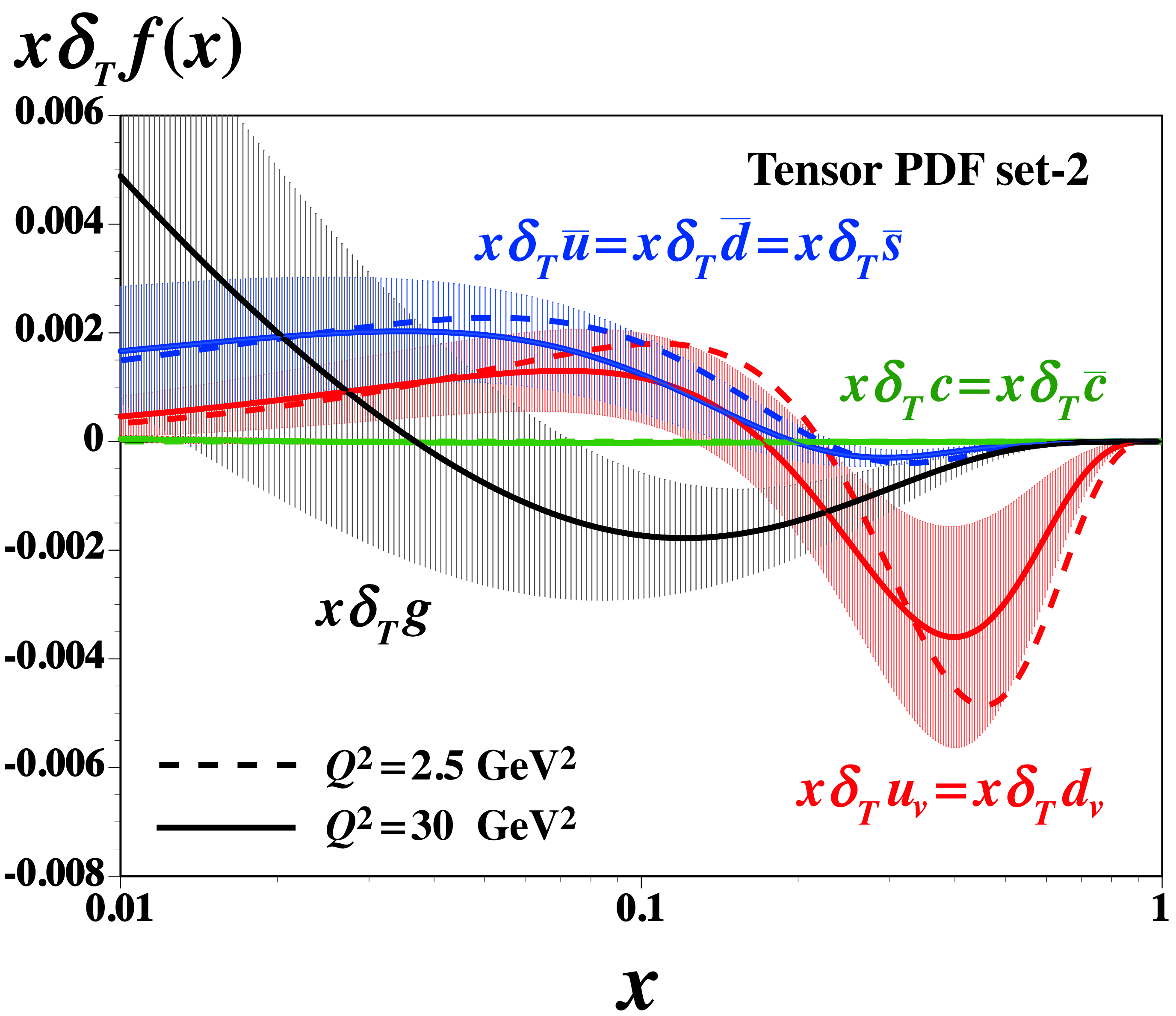
University of Virginia, Charlottesville, VA 22904

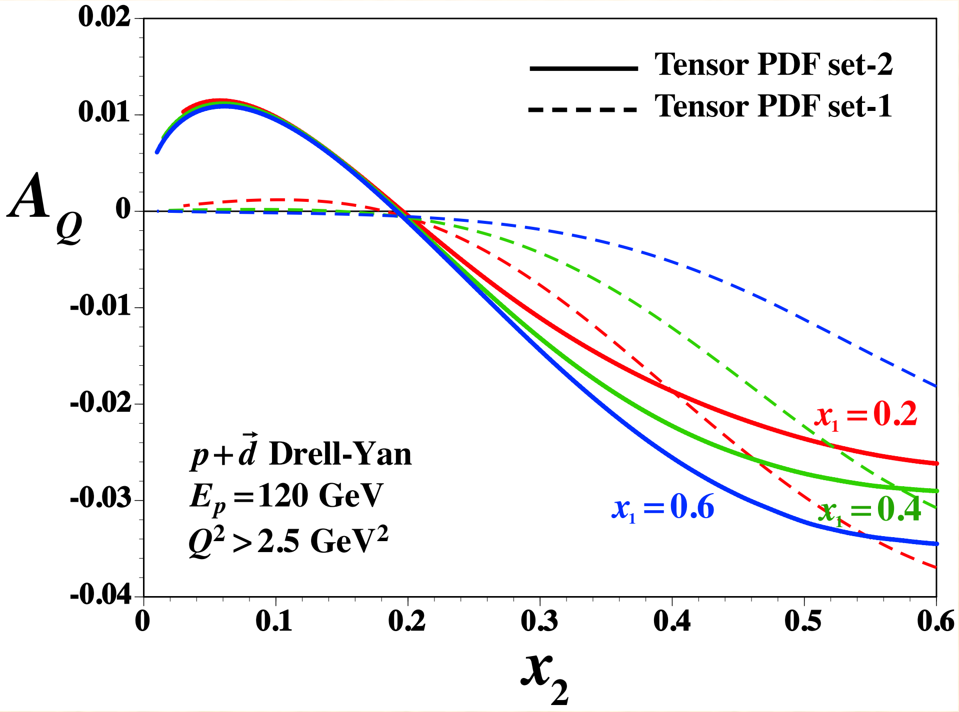
Q^2 evolution

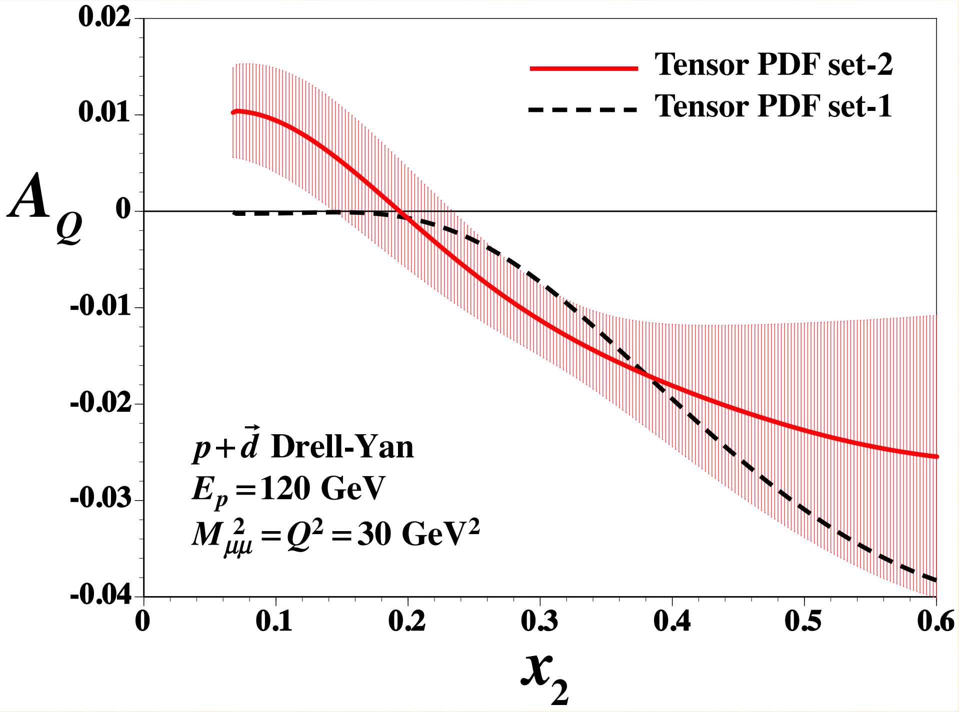
$Q^2 = 2.5\ \mathrm{GeV}^2 \to 30\ \mathrm{GeV}^2$



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.

Summary II

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

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

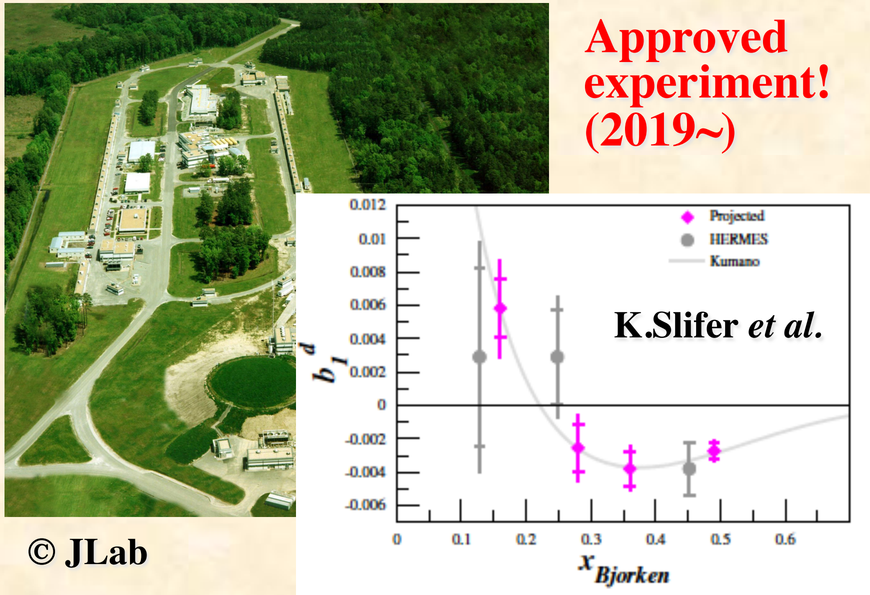
Fermiab E1039 (20xx) : $A_Q\left(\text{large } x_F\right) \approx \frac{\sum_a e_a^2 q_a\left(x_1\right)\delta_T\bar{q}_a\left(x_2\right)}{2\sum_a e_a^2 q_a\left(x_1\right)\bar{q}_a\left(x_2\right)}$

Separation of $\delta_T \bar{q}$

→ possible new exotic hadron physics mechanism

EIC and future prospects

Experimental possibilities

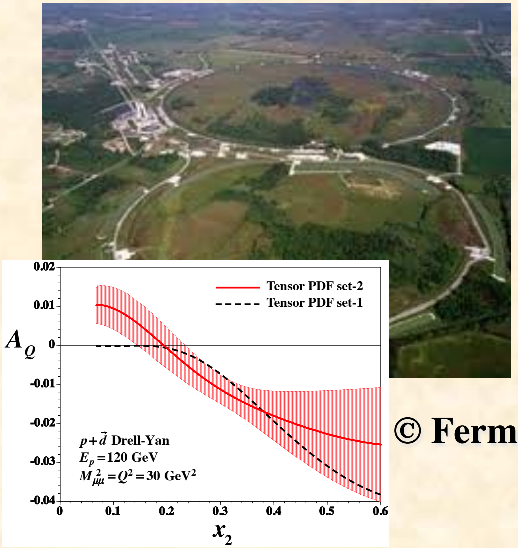


Approved experiment! (2019~)

© JLab

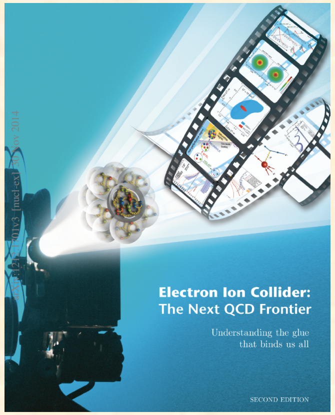
K.Slifer *et al.*

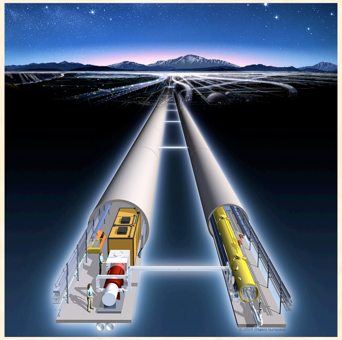
E1039 experiment



© Fermilab

EIC (arXiv:1212.1701)





Linear Collider (with fixed target)

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

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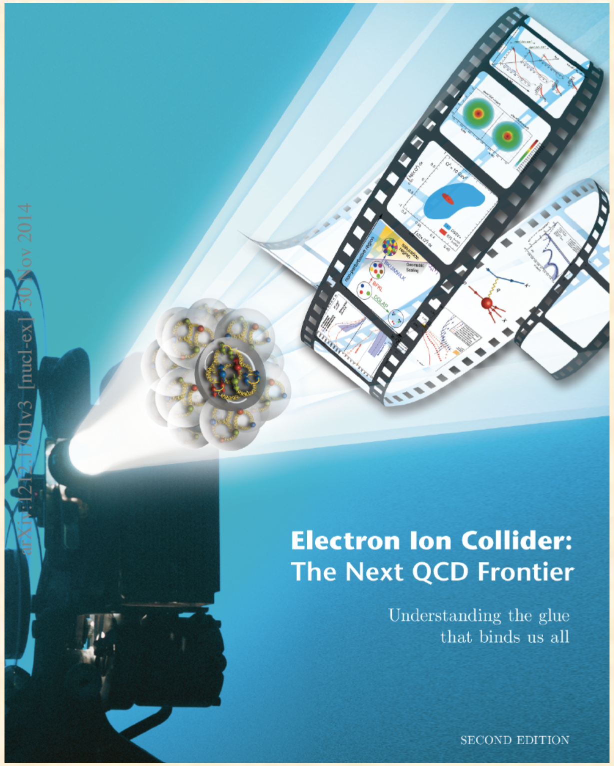
Electron-ion collider (US)

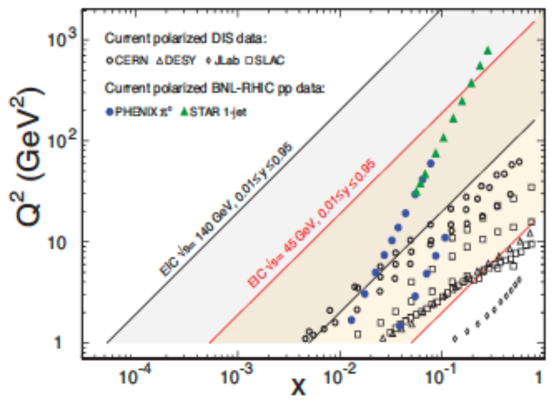


Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

EIC (arXiv:1212.1701)



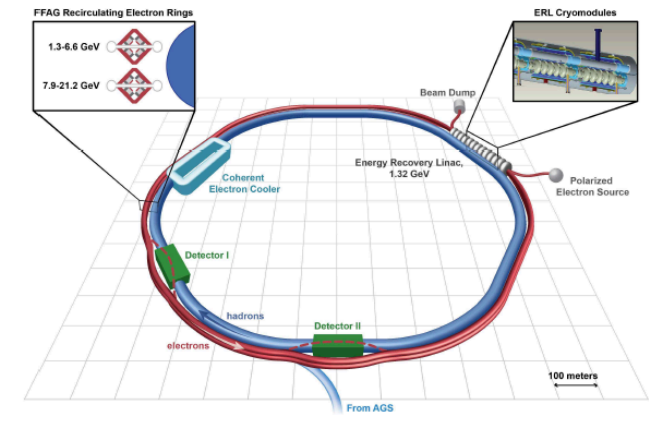


Figure 5.1: The layout of the ERL-based, 21 GeV x 250 GeV high-energy high-luminosity eRHIC.

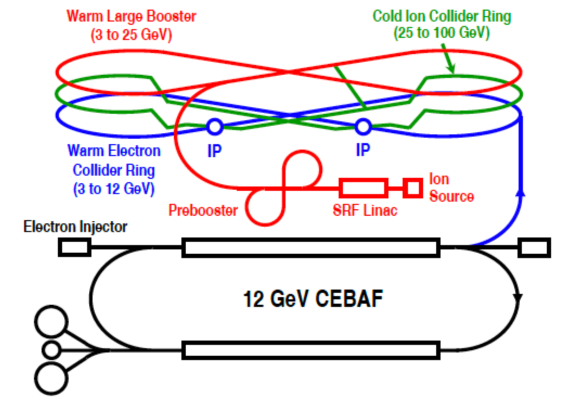
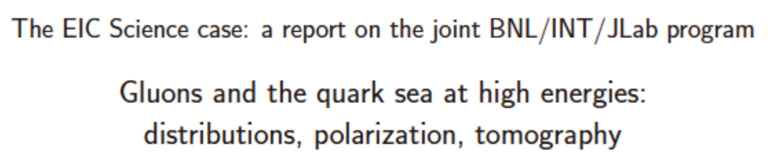


Figure 5.7: An illustration of MEIC, the large booster and collider rings are vertically stacked in a common tunnel.

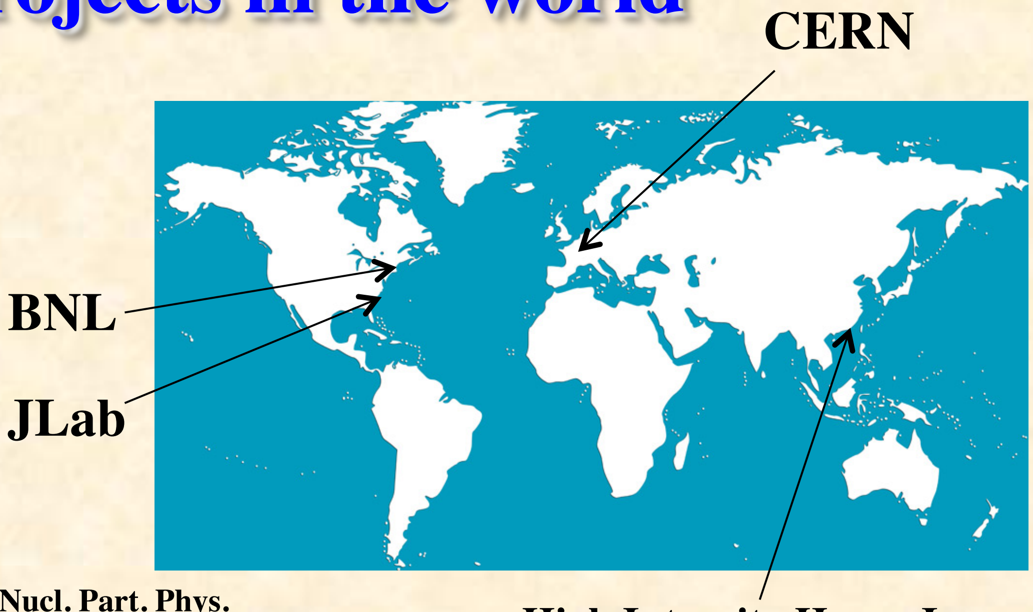
Electron-ion collider projects in the world



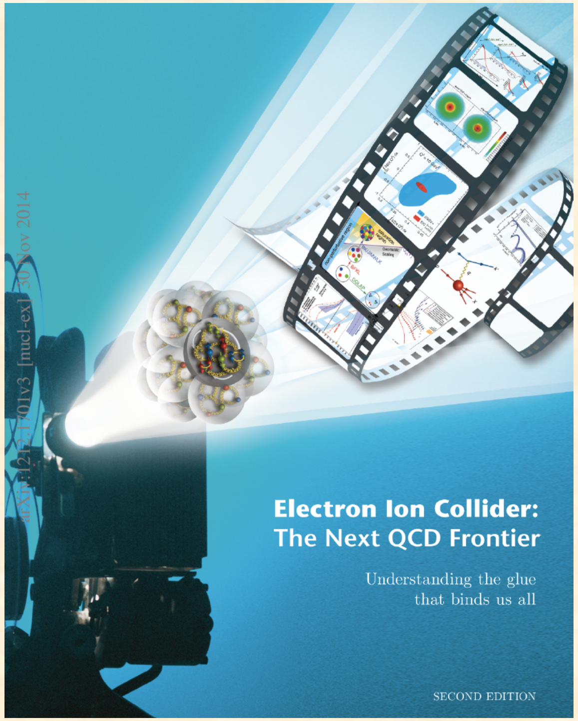
The EIC Science case: a report on the joint BNL/INT/JLab program

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

arXiv:1108.1713 (551 pages)



arXiv:1212.1701 (180 pages)

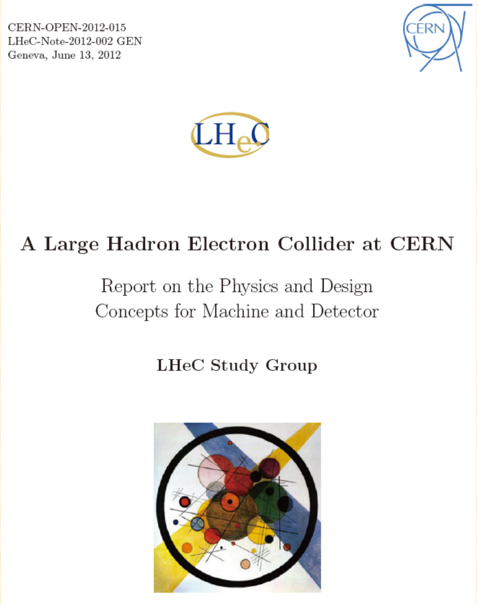


Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

SECOND EDITION

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



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

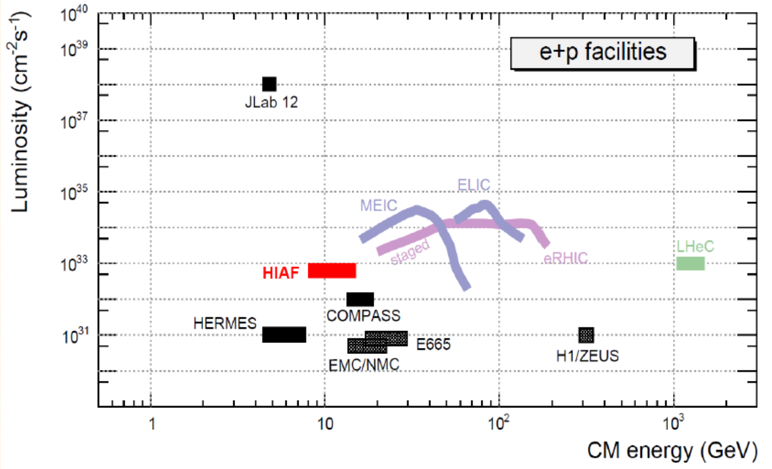
A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

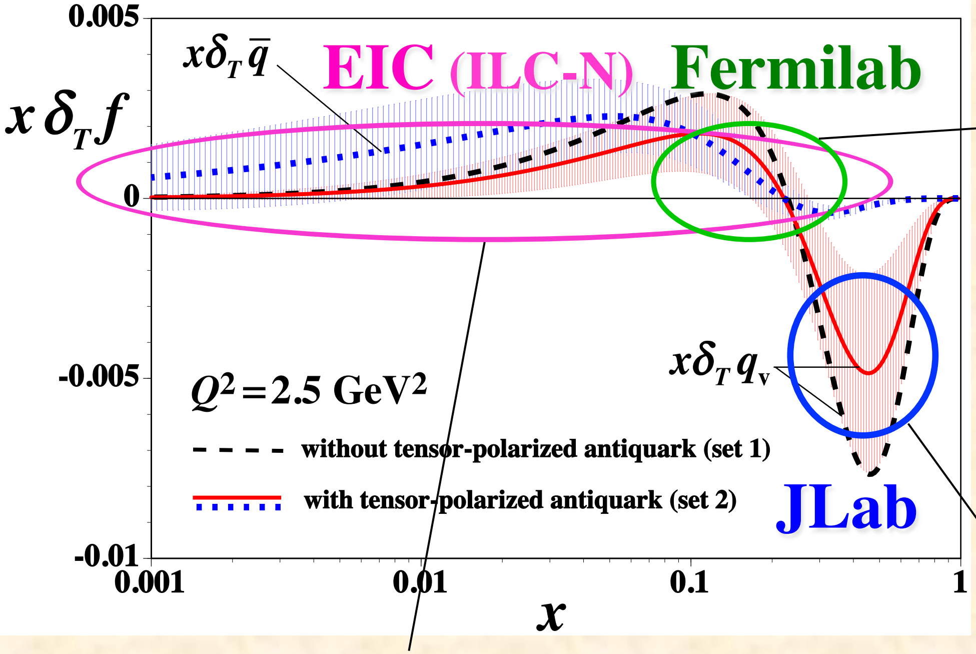
LHeC Study Group

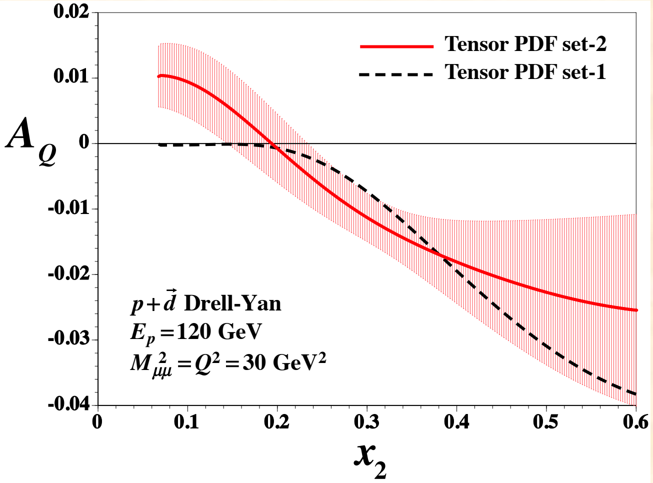
High Intensity Heavy Ion Accelerator Facility (HIAF)

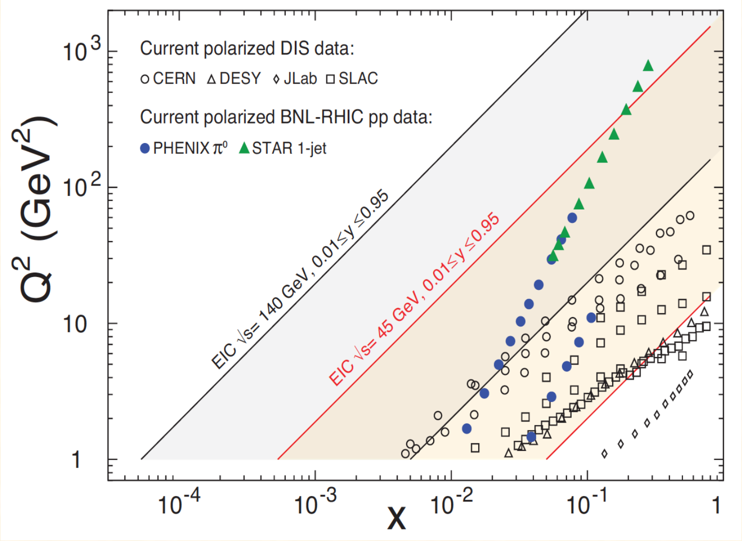
(Plan by Institute of Modern Physics,
Chinese Academy of Sciences)

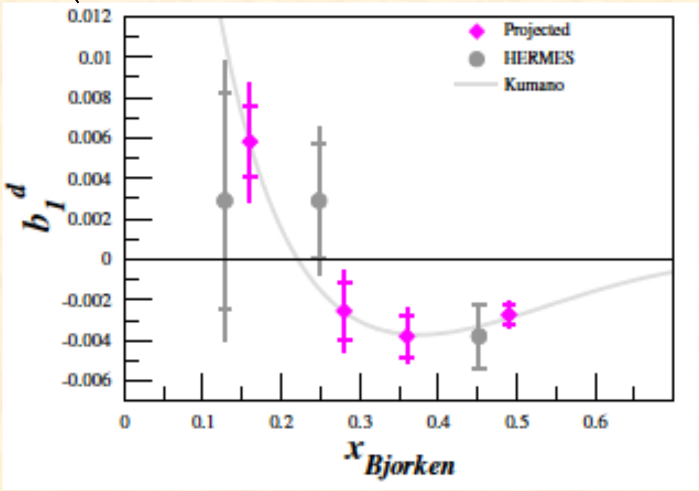


Future possibilities of b_1

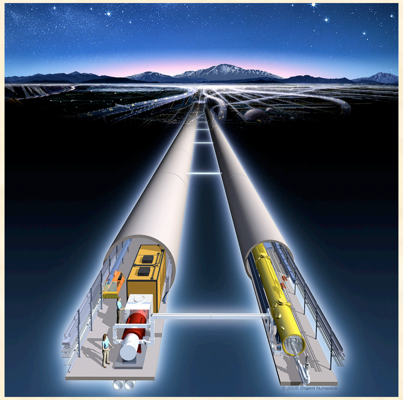








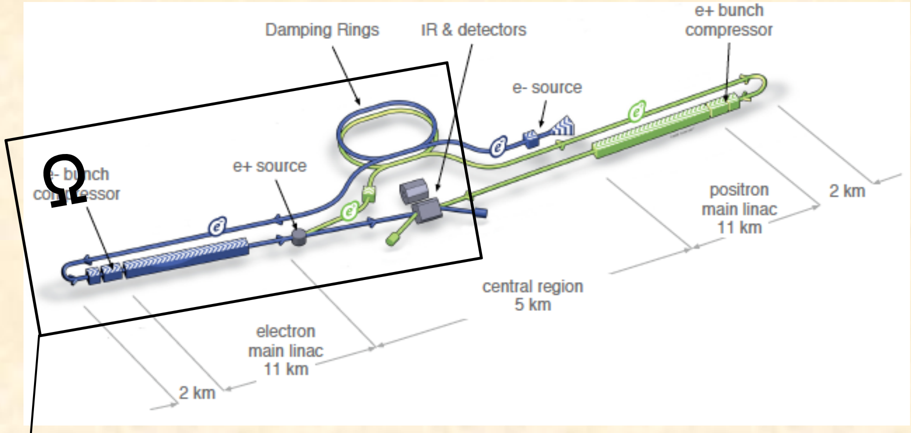
International Linear Collider

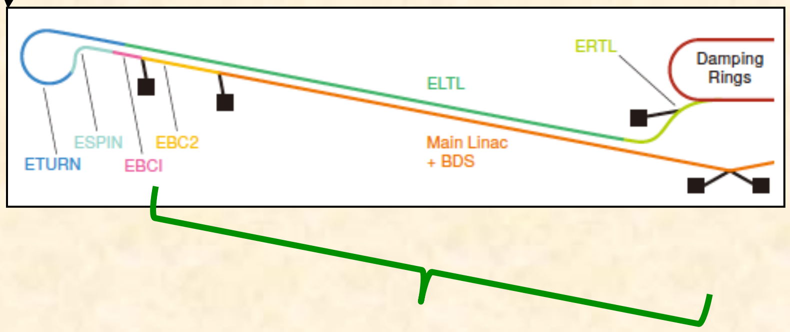


ILC-N (Fixed target option) for hadron physics?

ILC TDR (Technical Design Report)

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



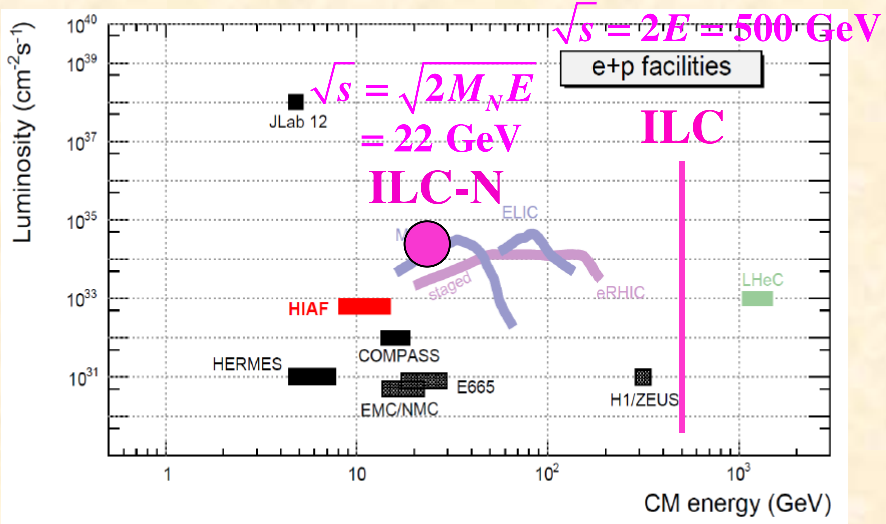


5 – 250 GeV electron beams
for fixed target experiments

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.

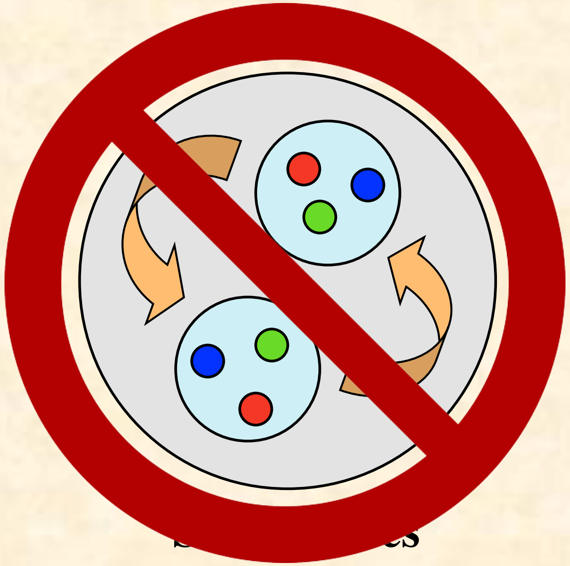
ILC-N is better than on-going COMPASS
but it is in competition with EIC in 2025 !



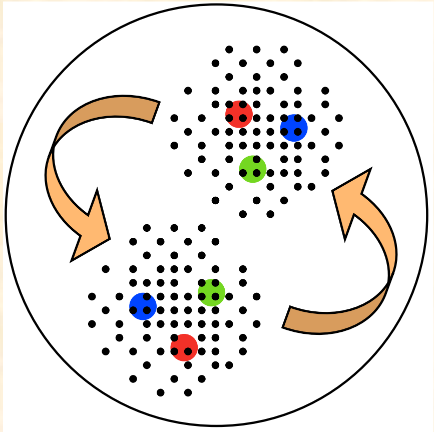
Summary III

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:

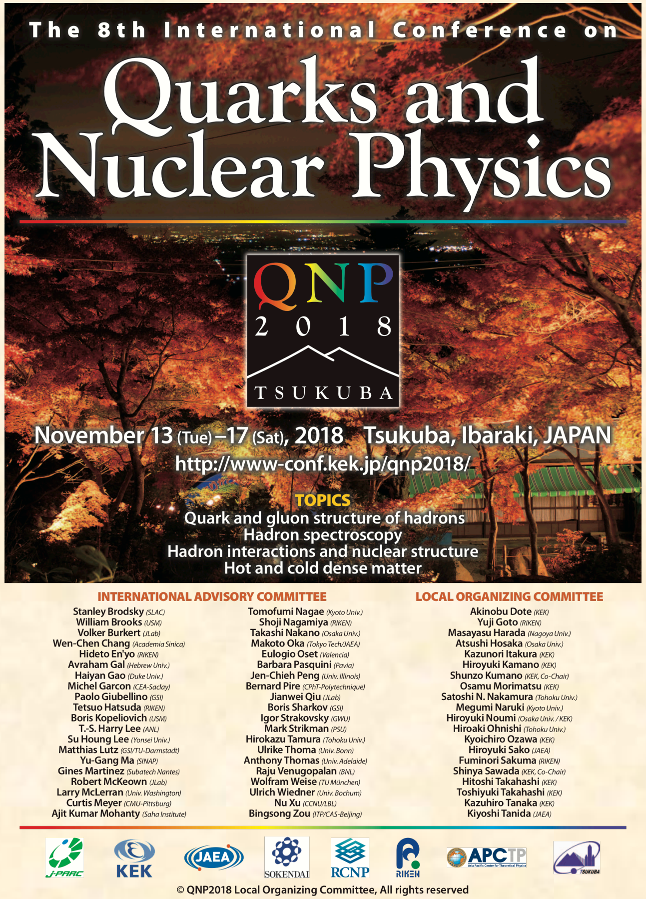
- heavy quark physics, exotics, N*, ...

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 8th International Conference on
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QNP
2 0 1 8
TSUKUBA

November 13 (Tue) – 17 (Sat), 2018 Tsukuba, Ibaraki, JAPAN
http://www-conf.kek.jp/qnp2018/

TOPICS
Quark and gluon structure of hadrons
Hadron spectroscopy
Hadron interactions and nuclear structure
Hot and cold dense matter

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