DIS on tensor-polarized deuteron

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Next-generation nuclear physics with JLab12 and EIC
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Ref. SK, J. Phys. Conf. Ser. 543 (2014) 1, 012001 (arXiv:1407.3852)

February 12, 2016

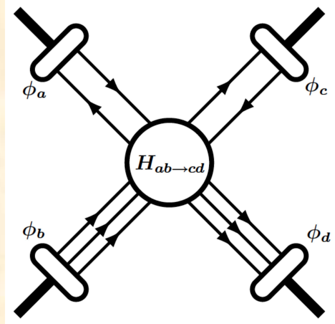
Interesting project
at 12 GeV and EIC

Comment on
Hard production of hyperons

(1) W.-C. Chang, S. Kumano, and T. Sekihara
Phys. Rev. D 93 (2016) 034006 (arXiv:1512.06647).

(2) H. Kawamura, S. Kumano, T. Sekihara,
Phys. Rev. D 88 (2013) 034010 (arXiv:1307.0362).

Constituent-counting rule in perturbative QCD: Hard exclusive processes $a + b \to c + d$



Consider the hard exclusive hadron reaction $a + b \to c + d$

$$M_{ab\to cd} = \int d[x_a]d[x_b]d[x_c]d[x_d]\phi_c([x_c])\phi_d([x_d])H_M([x_a],[x_b],[x_c],[x_d],Q^2)\phi_a([x_a])\phi_b([x_b])$$

ϕ_p = proton distribution amplitude, H_M = hard amplitude (calculated in pQCD)

Rule for estimating $M_{ab\to cd}$

(1) Feynman diagram: Draw leading and connected Feynman diagram by connecting $n/2$ quark lines by gluons.

(2) Gluon propagators: The factor $1/P^2$ is assigned for each gluon propagator.

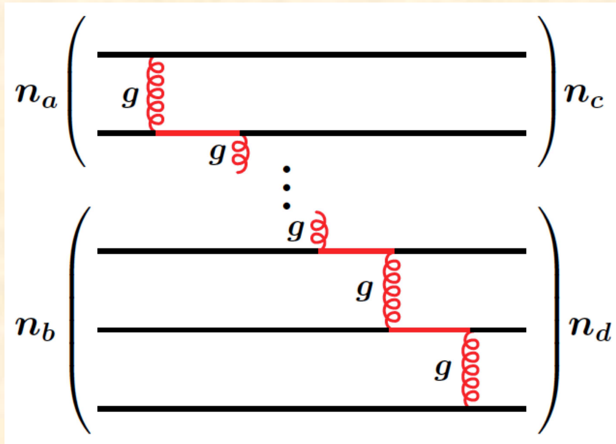
There are $n/2-1$ gluon propagators $\sim 1/(P^2)^{n/2-1}$.

(3) Quark propagators: The factor $1/P$ is assigned for each quark propagator.

There are $n/2-2$ gluon propagators $\sim 1/(P)^{n/2-2}$.

(4) External quarks: The factor $\sqrt{P}$ is assigned for each external quark.

There are n gluon propagators $\sim (\sqrt{P})^n$.



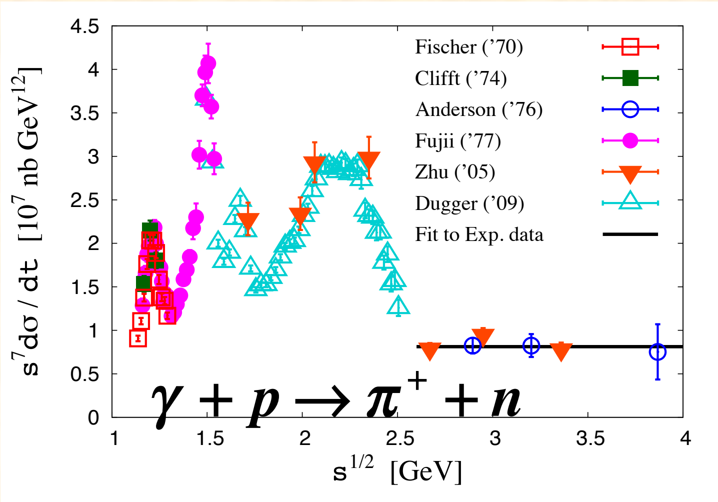
$$M_{ab\to cd} \sim \frac{1}{(P^2)^{n/2-1}}\frac{1}{(P)^{n/2-2}}(\sqrt{P})^n = \frac{(P)^{n/2}}{(P)^{n-2}(P)^{n/2-2}} = \frac{1}{(P)^{n-4}} \sim \frac{1}{s^{n/2-2}}$$

Cross section: $$\frac{d\sigma_{ab\to cd}}{dt} \simeq \frac{1}{16\pi^2}\overline{\sum_{spol}}|M_{ab\to cd}|^2 \sim \frac{1}{s^{n-2}}$$

Constituent-counting rule, Transition from hadron degrees of freedom to quark-gluon ones

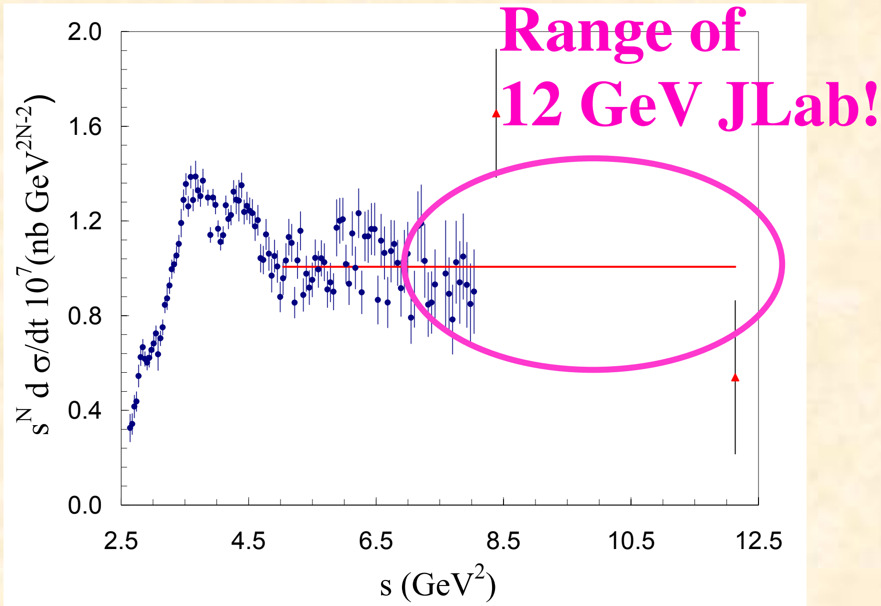
Typical current situation

- Transition from hadron d.o.f to quark d.o.f.
- (Looks like) Constituent-counting scaling



JLab: L.Y. Zhu *et al.*, PRL 91, 022003 (2003); PRC 71, 044603 (2005);
W. Chen *et al.*, PRL 103, 012301 (2009).

R. A. Schumacher and M. M. Sargsian, PRC 83 (2011) 025207

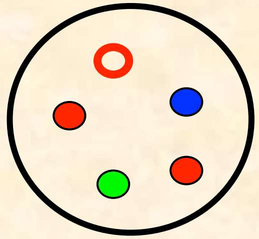


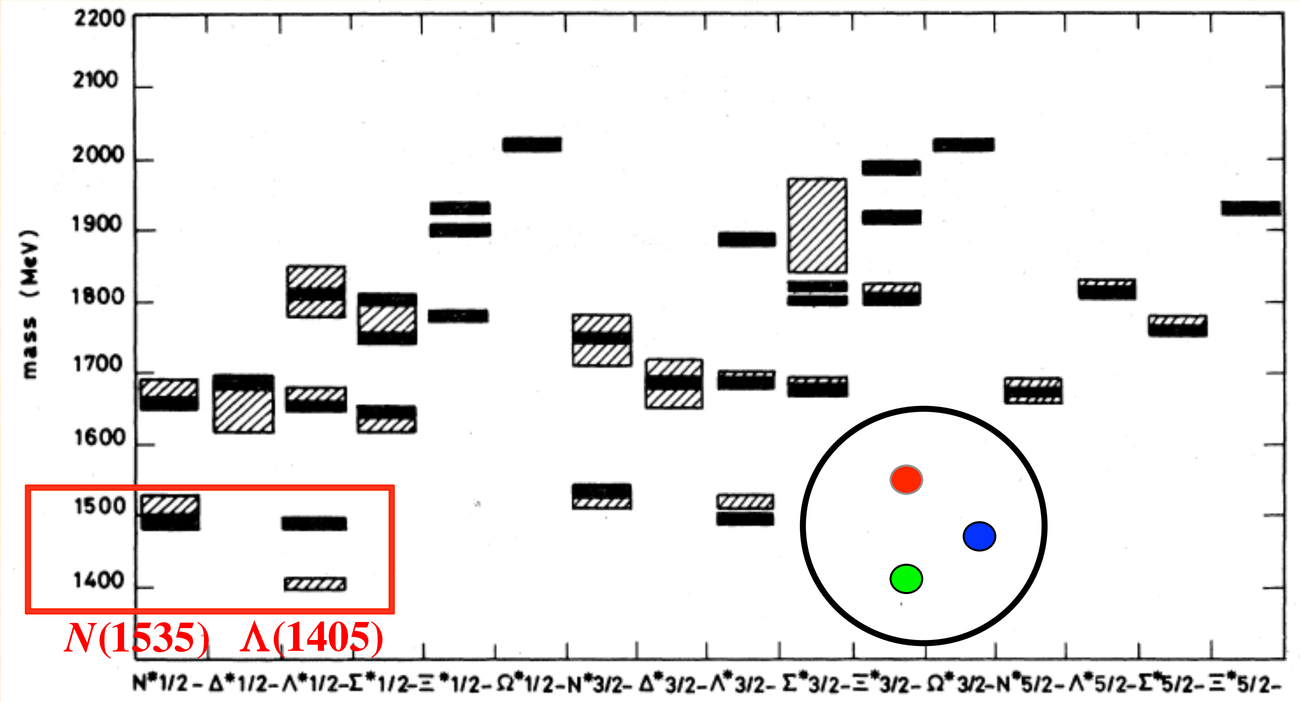
BNL: C. White it et al., PRD 49 (1994) 58.

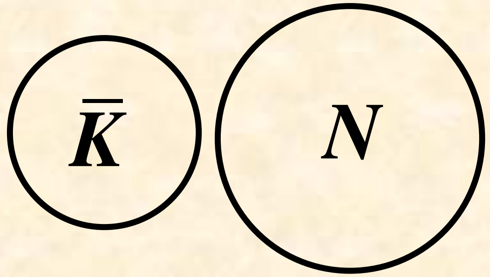
No.	Interaction	Cross section E838	Cross section E755	n-2 ($\frac{d\sigma}{dt} \sim 1/s^{n-2}$)
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	0.9 ± 0.9	≥ 3.9
5	$\pi^+ p \to p\rho^+$	214 ± 30	3.4 ± 0.7	8.3 ± 0.5
6	$\pi^- p \to p\rho^-$	99 ± 13	1.3 ± 0.6	8.7 ± 1.0
13	$\pi^+ p \to \pi^+ \Delta^+$	45 ± 10	2.0 ± 0.6	6.2 ± 0.8
15	$\pi^- p \to \pi^+ \Delta^-$	24 ± 5	≤ 0.12	≥ 10.1
17	$pp \to pp$	3300 ± 40	48 ± 5	9.1 ± 0.2
18	$\bar{p}p \to p\bar{p}$	75 ± 8	≤ 2.1	≥ 7.5

$\Lambda(1405)$: exotic hadron?

Negative-parity baryons
N. Isgur and G. Karl,
PRD 18 (1978) 4187.







Our proposal:

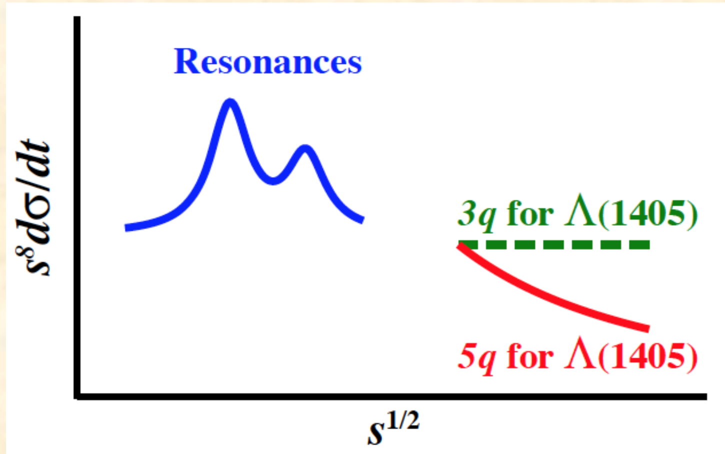
Exotic hadron production

$\pi^- + p \to K^0 + \Lambda(1405)$: J-PARC, COMPASS?

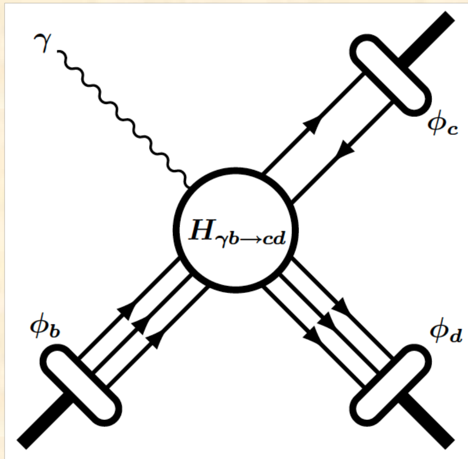
$\gamma + p \to K^+ + \Lambda(1405)$: JLab

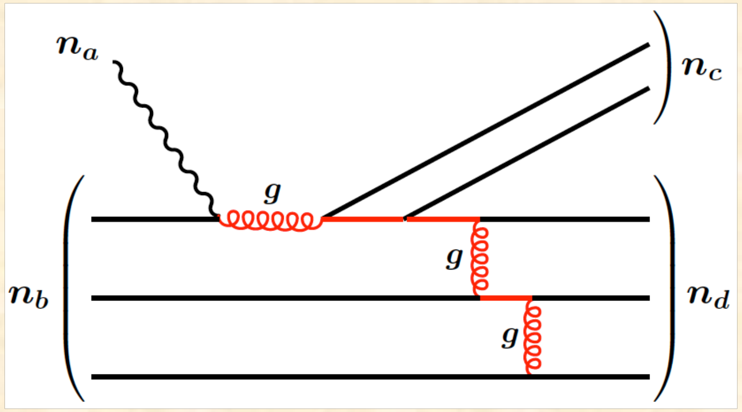
Most spectra agree with the ones by a 3*q*-picture

- **Only $\Lambda(1405)$ deviates from the measurement.**
- **Difficult to understand the small mass of $\Lambda(1405)$ in comparison with $N(1535)$.**
  $\to \bar{K}N$ molecure or penta-quark ($qqqq\bar{q}$)?



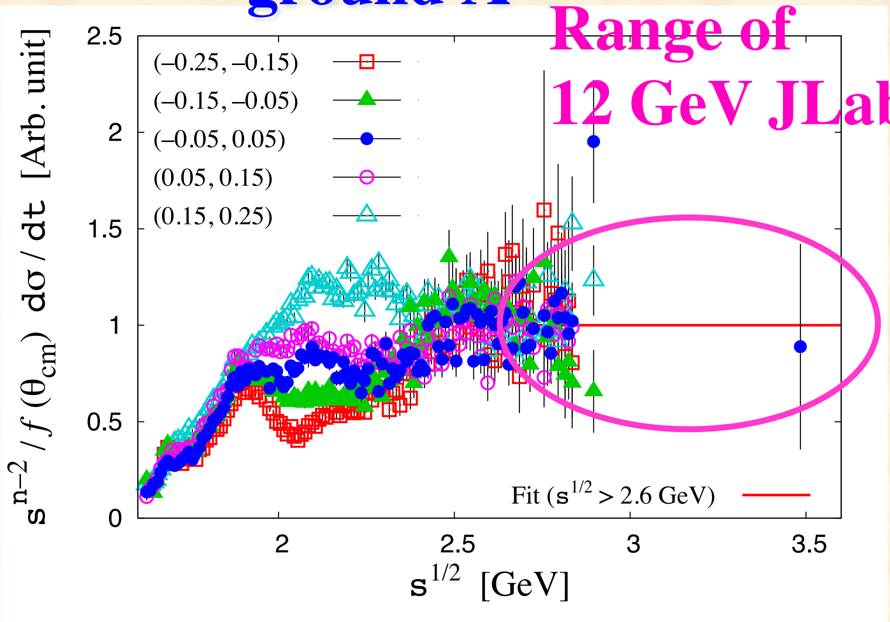
JLab hyperon productions



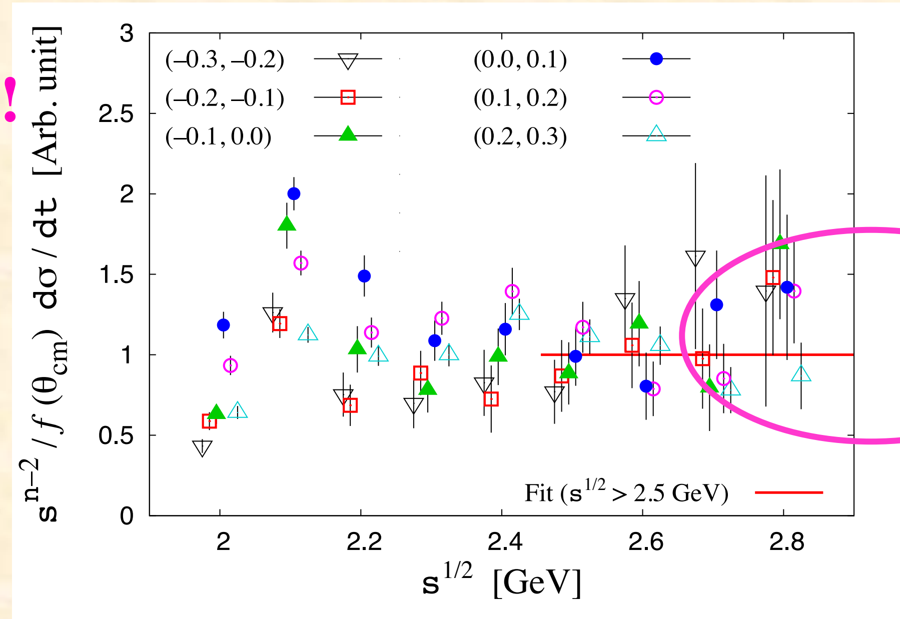


ground Λ

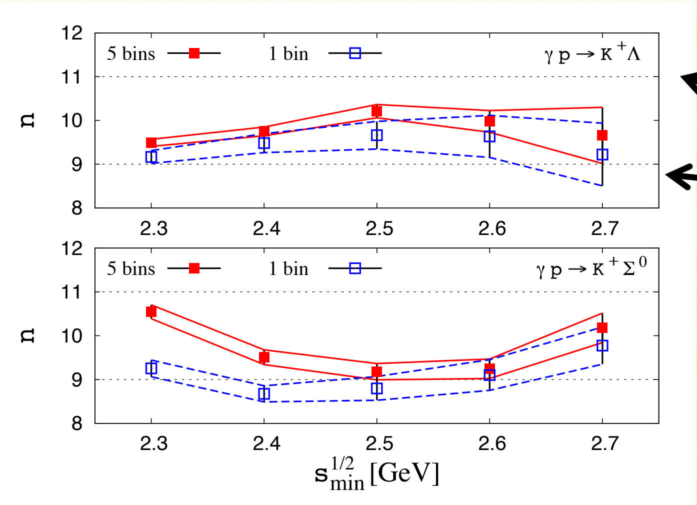
Range of 12 GeV JLab!



Λ(1405)

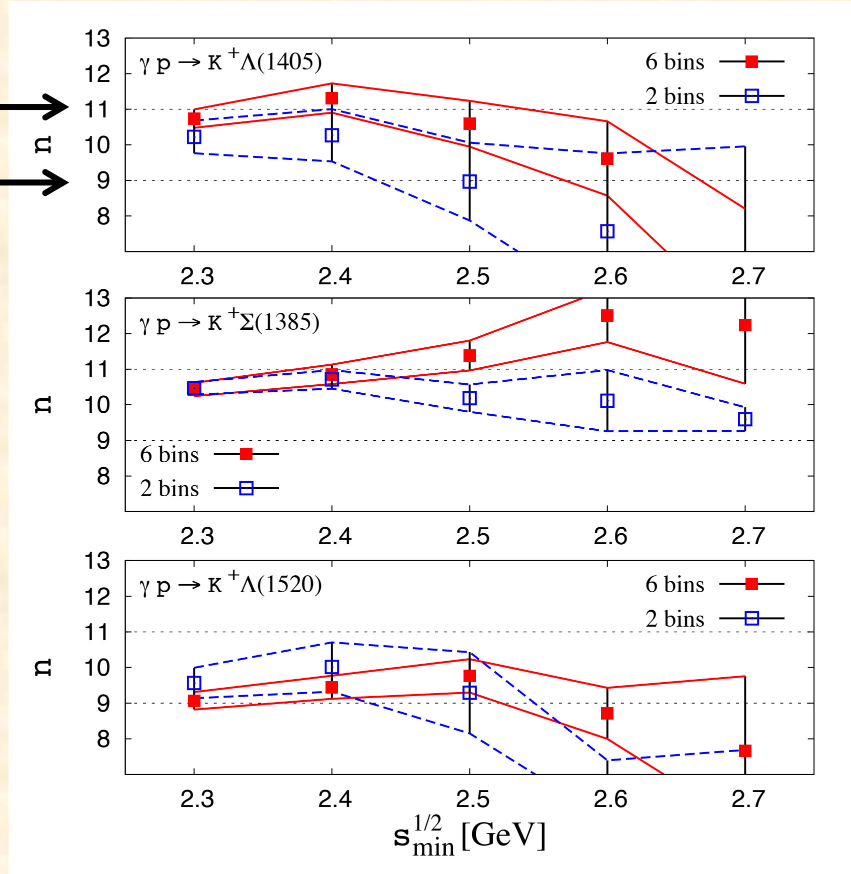


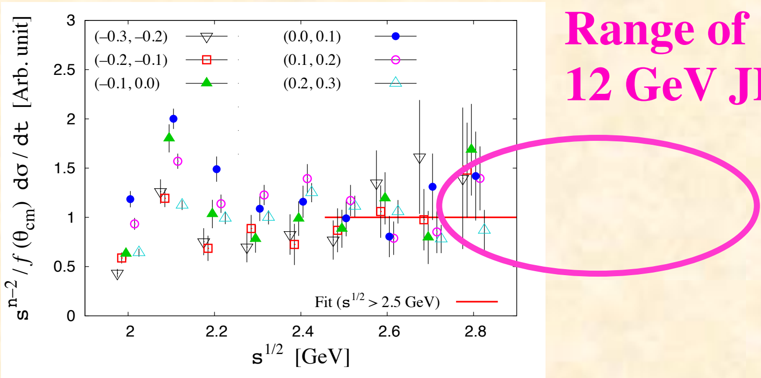
JLab hyperon productions including Λ(1405)



$n_\Lambda = 5$

$n_\Lambda = 3$





Range of
12 GeV JLab!

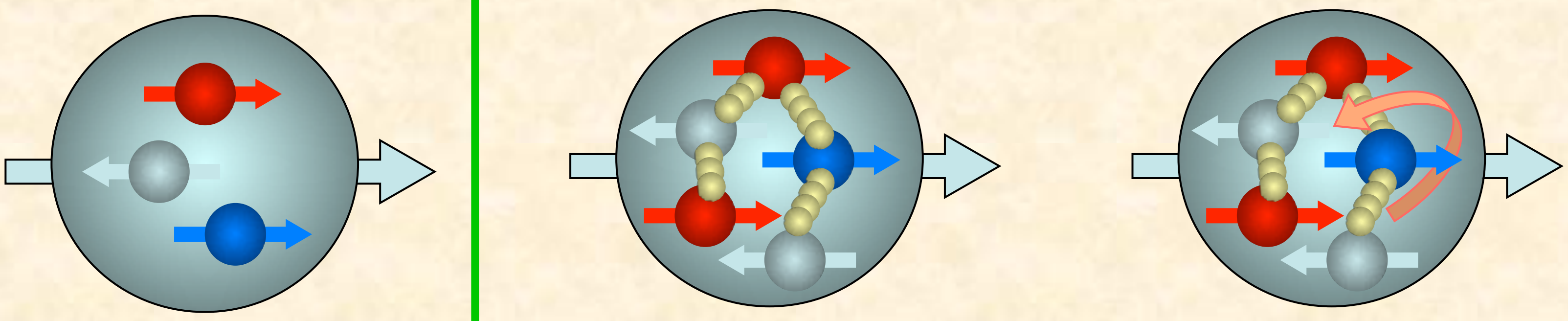
- Λ. Λ(1520) and Σ seem to be consistent with ordinary baryons with $n = 3$.
- Λ(1405) looks penta-quark at low energies but $n \sim 3$ at high energies???
- Σ(1385) : $n = 5$???

$\rightarrow$ In order to clarify the nature of Λ(1405) $\left[qqq,\ \bar{K}N,\ qqqq\bar{q}\right]$,
the JLab 12-GeV experiment plays an important role!

Tensor structure of the deuteron

Nucleon spin

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

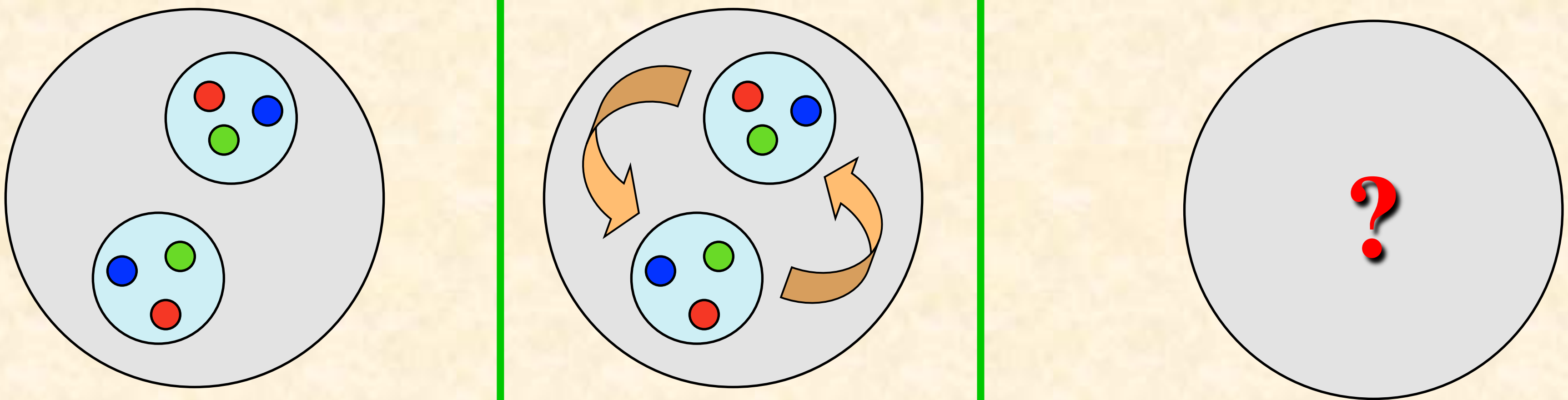


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure crisis!?



only S wave: $b_1 = 0$

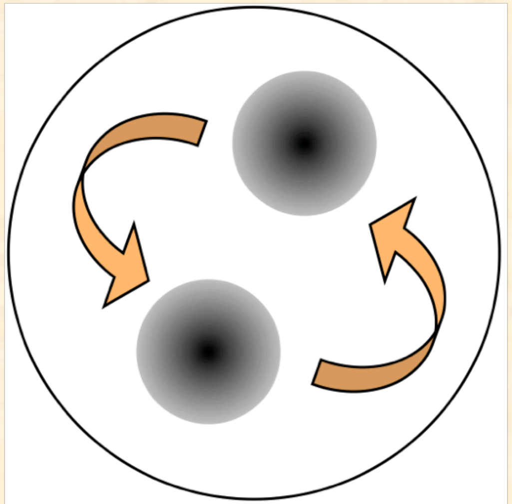
S + D waves: standard model $b_1 \neq 0$

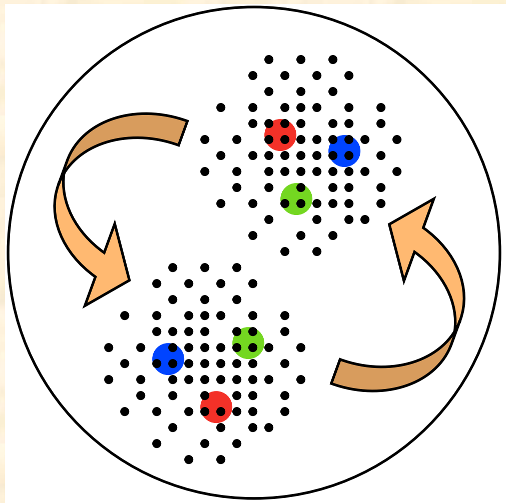
$b_1^{\text{experiment}} \neq b_1^{\text{“standard model”}}$

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.





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 (J-PARC, RHIC, COMPASS, GSI, …) experiment ?**

Purposes of studying polarized deuteron reactions

(1) Neutron information

- **Polarized PDFs in the neutron**
  (Note: There are contributions from b_1 to longitudinal spin asymmetry A_1^{ed}.)

(2) New structure functions

- **Tensor structure function b_1**
  $\rightarrow$ **(1) Test of our hadron description in another spin**
  (2) Description of tensor structure by quark-gluon degrees of freedom

(3) Asymmetries in polarized light-antiquark distributions

- $\Delta\bar{u} \,/\, \Delta\bar{d}$, $\Delta_T\bar{u} \,/\, \Delta_T\bar{d}$

Status

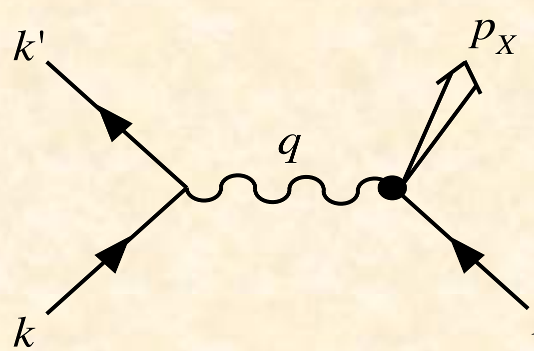
- $e + \vec{d} \rightarrow e' + X$

  Theoretical studies: some
  Experimental measurements: HERMES
  Future experimental measurements: JLab

- $p + \vec{d} \rightarrow \mu^+\mu^- + X$

  Theoretical studies: a few papers
  Experimental measurements: none (Fermilab, hadron facilities, ...)

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



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

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

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

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

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

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.]

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

spin-1/2, spin-1

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

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.

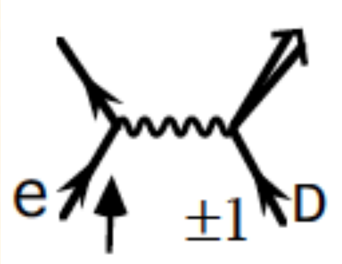
$2xb_1 = b_2$ in the scaling limit $\sim O(1)$

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

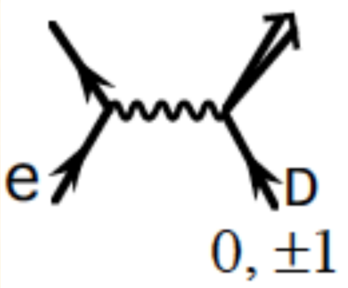
Structure Functions

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

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



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



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

Parton Model

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

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

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

Personal studies on tensor structure of the deuteron

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

JLab experiment ~2019, Fermilab pd Drell-Yan?

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)

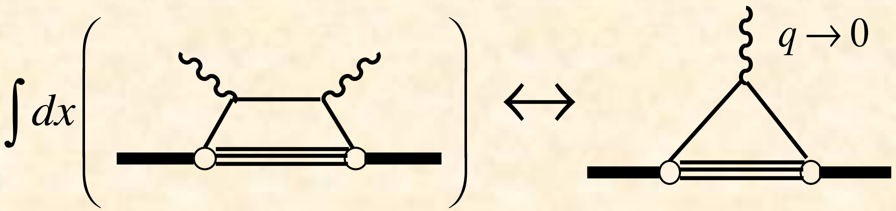
Future possibilities
at JLab, J-PARC, RHIC, …

↓

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

Constraint on valence-tensor polarization (sum rule)

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



Intuitive derivation without calculation:

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

$=$ (mass)^2 · (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

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

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

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

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

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

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

Similarity to the Gottfried sum rule

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

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

(Gottfried sum rule)

$$F_2^{\mu p}(x)_{\text{LO}} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$
$$F_2^{\mu n}(x)_{\text{LO}} = x\left[\frac{4}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]_n$$
$$= x\left[\frac{4}{9}\{d(x)+\bar{d}(x)\} + \frac{1}{9}\{u(x)+\bar{u}(x)\} + \frac{1}{9}\{s(x)+\bar{s}(x)\}\right]$$
$$\frac{1}{x}\left[F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}\right] = \frac{3}{9}\{u(x)+\bar{u}(x)\} - \frac{3}{9}\{d(x)+\bar{d}(x)\}$$
$$\int_0^1 \frac{dx}{x}\left[F_2^{\mu p}(x)_{\text{LO}} - F_2^{\mu n}(x)_{\text{LO}}\right] = \int_0^1 dx\left[\frac{1}{3}\{u_v(x)+2\bar{u}(x)\} - \frac{1}{3}\{d_v(x)+2\bar{d}(x)\}\right]$$
$$= \frac{2}{3} - \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$

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

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

Extrapolating the NMC data, they obtained

$$S_G = 0.235 \pm 0.026$$

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

$$\int_0^1 \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x) - \bar{d}(x)\right]$$
$$\int dx\, b_1^D(x) = -\frac{5}{6}\lim_{t\to 0} tF_Q(t) + \frac{1}{18}\int dx\left[8\delta_T \bar{u}^D + 2\delta_T \bar{d}^D + \delta_T \bar{s}^D\right]$$

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

Standard convolution approach

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

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

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

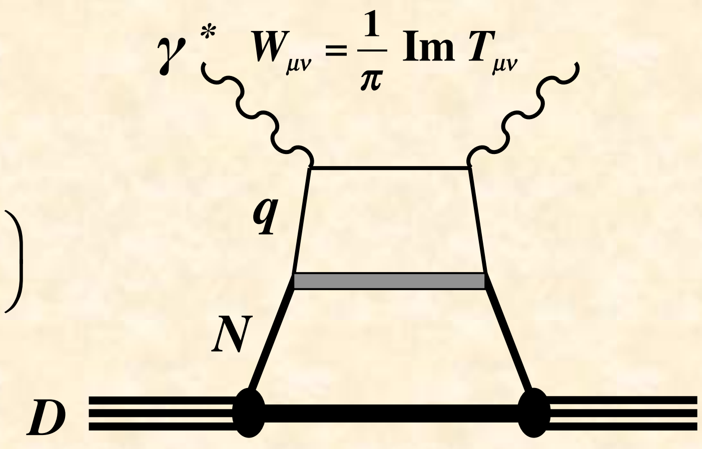
Momentum distribution: $f^H(y) = \int d^3p \left|\phi^H(\vec{p})\right|^2 \delta\left(y - \frac{E + p_z}{M}\right)$

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

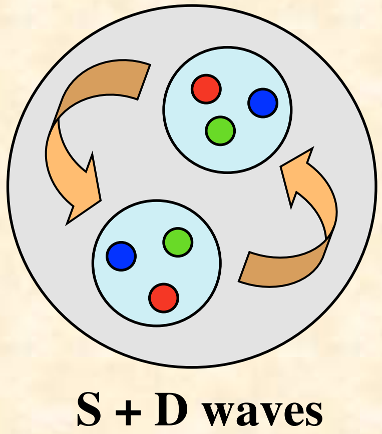
D-state admixture: $\phi^H(\vec{p}) = \phi_{\ell=0}^H(\vec{p}) + \phi_{\ell=2}^H(\vec{p})$

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

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



Standard model of the deuteron



Comparison with HERMES data

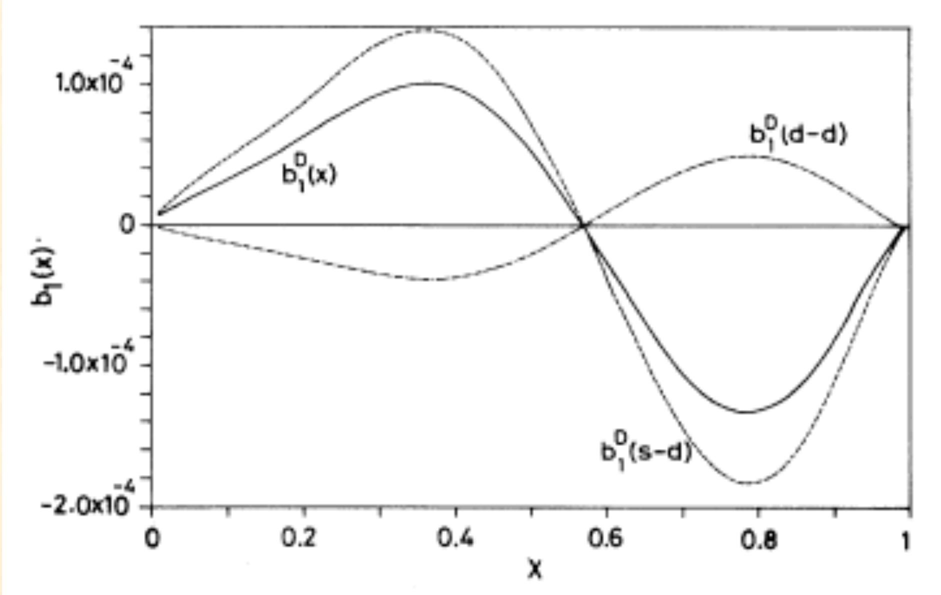
H. Khan and P. Hoodbhoy,
PRC44 (1991) 1219.

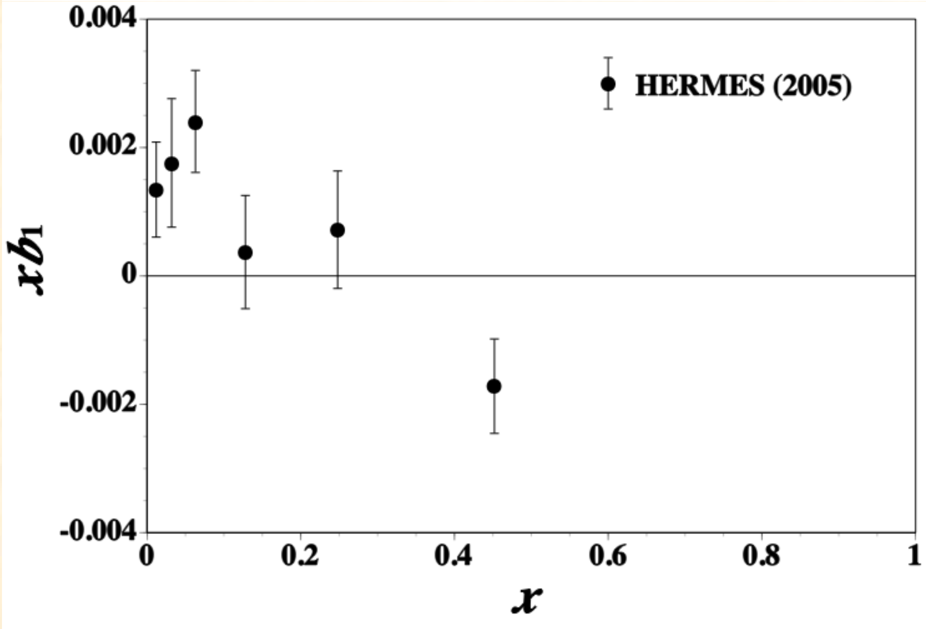
$xb_1 \sim 10^{-3}$

↕ Order of magnitude difference

$xb_1 \sim 10^{-2}$ in HERMES data

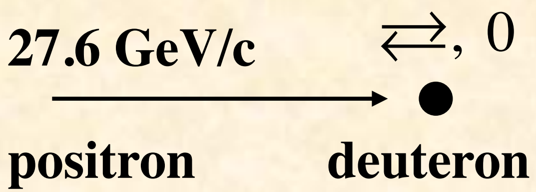
Standard convolution model does not work for the deuteron tensor structure!?





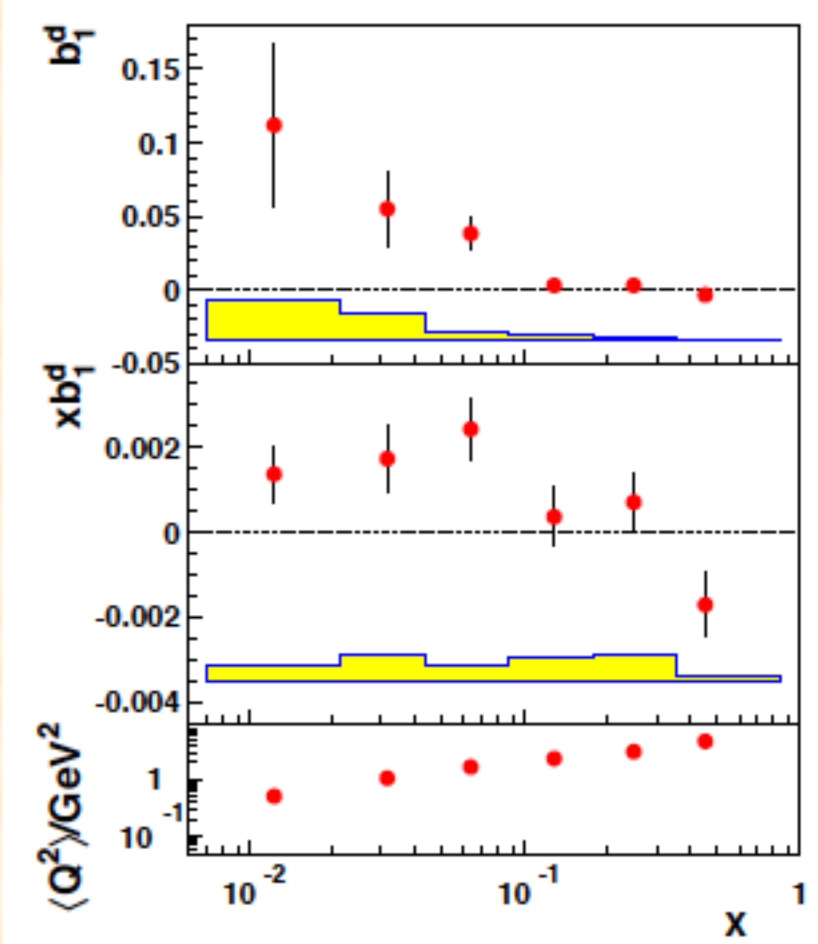
HERMES measurements on b_1

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



b_1 measurements in the kinematical region

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



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

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.

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

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

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

Two types of analyses

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

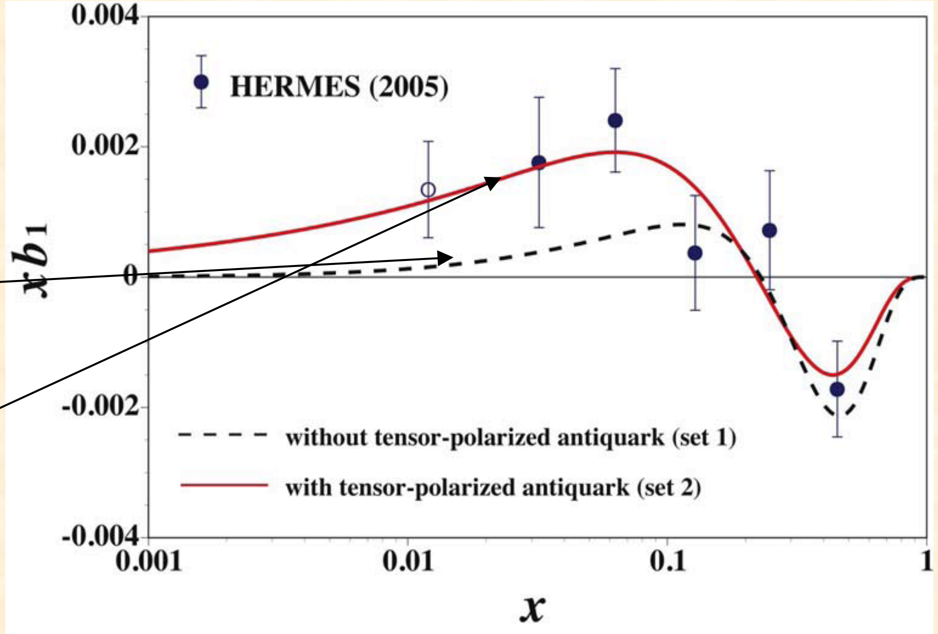
Set 2: $\delta_T \bar{q}^D(x) \neq 0$ Finite tensor-polarized antiquark distributions are allowed ($\alpha_{\bar{q}} \neq 0$).

Results

SK, PRD 82 (2010) 017501

Two-types of fit results:

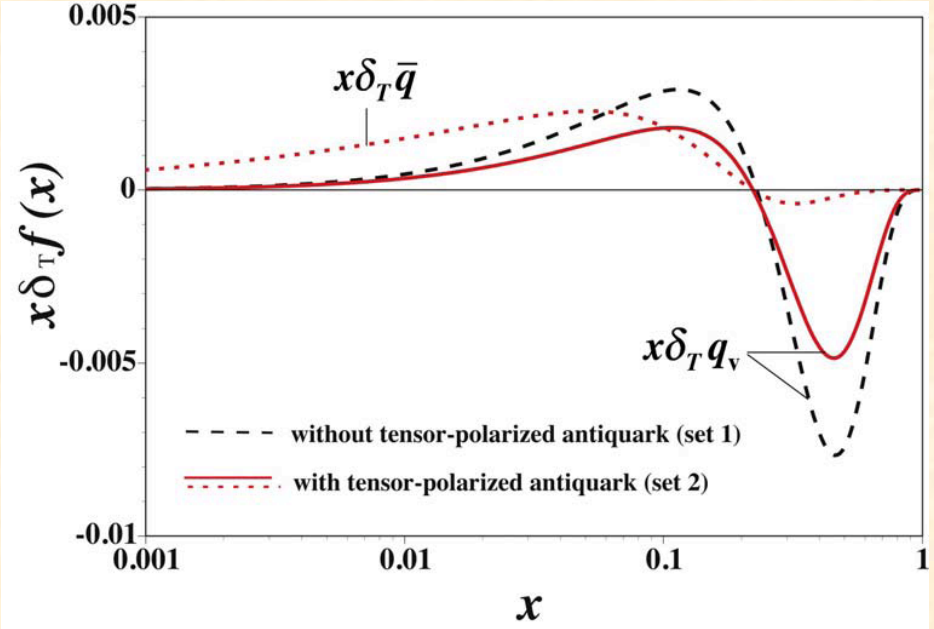
- set-1: $\chi^2 / \text{d.o.f.} = 2.83$
  Without $\delta_T q$, the fit is not good enough.
- set-2: $\chi^2 / \text{d.o.f.} = 1.57$
  With finite $\delta_T q$, the fit is reasonably good.



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:

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

Summary for spin-1 structure

(1) The tensor-polarized distributions: $\delta_T q(x)$, $\delta_T \bar{q}(x)$
were obtained from the HERMES data on b_1.

(2) Finite tensor polarization was obtained
for antiquarks: $\int dx \delta_T \bar{q}(x) \neq 0$.

Physics mechanism of $\delta_T \bar{q}(x)$?

Prospects

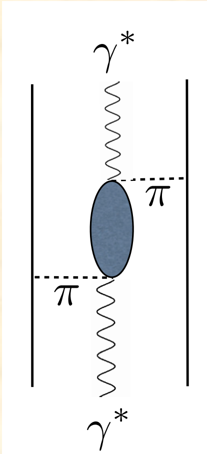
Future experimental possibilities
at JLab, EIC, J-PARC, RHIC, COMPASS, GSI, …

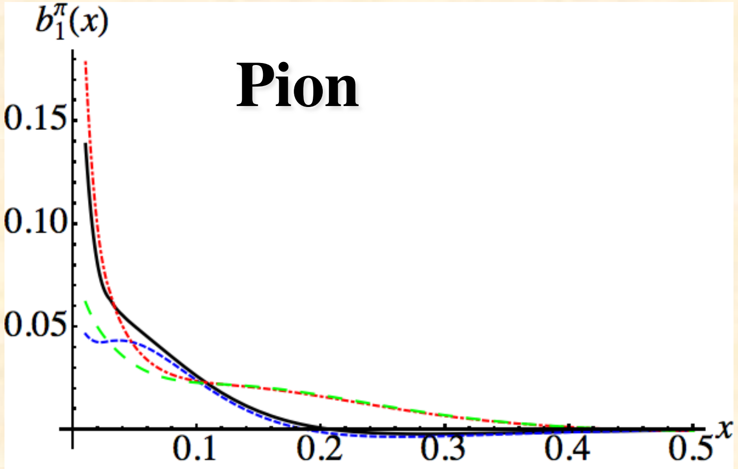
Experimental proposal was approved at JLab.

More theoretical studies …

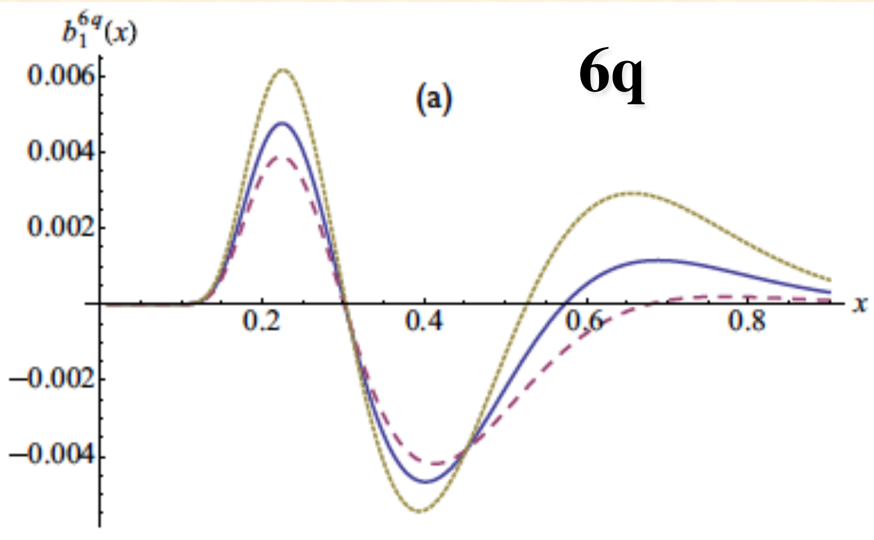
Recent work: Pion, Hidden-color, Six-quark

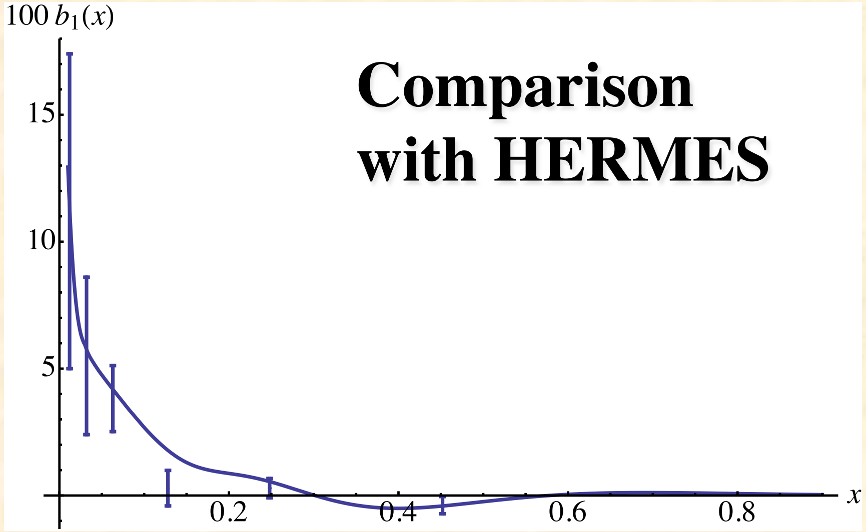
G. A. Miller,
PRC 89 (2014) 045203.





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





Prospects for tensor-polarized distributions

- **Lepton facilities:** $e+\vec{d} \rightarrow e' + X$ **: JLab experiment PR12-11-110**

  approved! 2019?~

  (Co-spokespersons: J.-P. Chen, P. Solvignon, N. Kalantarians, O. Rondon, K. Slifer *et al.*)

- **Hadron facilities:** $p+\vec{d} \rightarrow \mu^+\mu^- + X$ **: Fermilab experiment?**

  under consideration for a proposal

  (pereonal communcations with Xiaodong Jiang (Los Alamos), Dustin Keller (JLab))

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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C. Keith, S. Wood, J. Zhang
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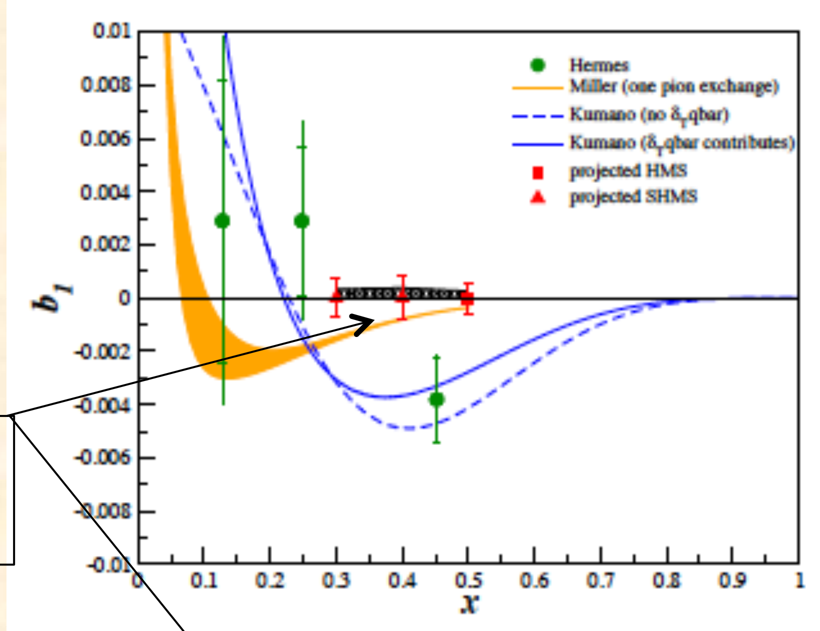
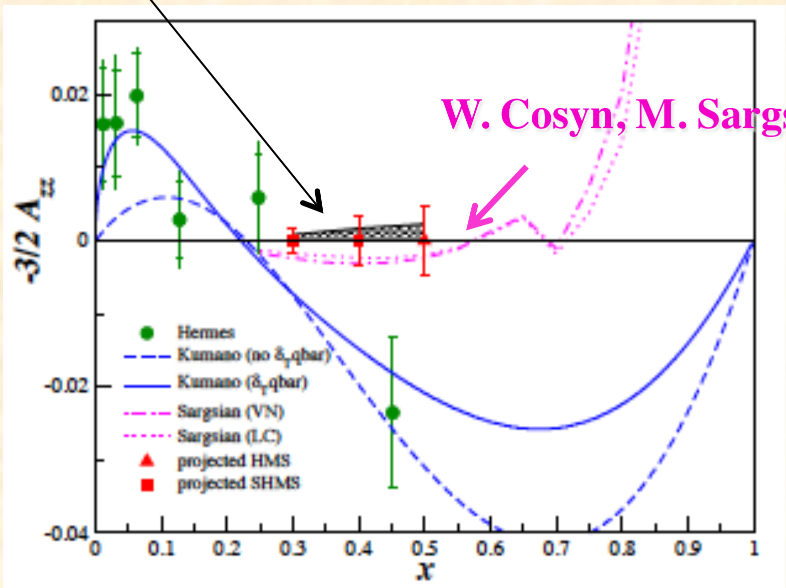
Seoul National University, Seoul 151-747 Korea

Approved!

Expected errors by JLab





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

Tensor structure at hadron facility: *pd* Drell-Yan

- **General formalism for polarized Drell-Yan processes with spin-1/2 and spin-1 hadrons**

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

- **Parton-model analysis of polarized Drell-Yan processes with spin-1/2 and spin-1 hadrons**

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

- **An application: Possible extraction of polarized light-antiquark distributions from Drell-Yan**

  SK and M. Miyama, Phys. Lett. B497 (2000) 149.

Comments on the situation

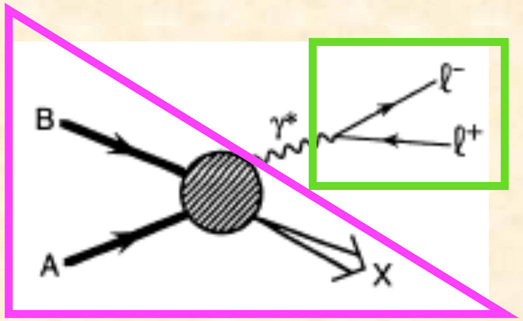
- There was a feasibility study for polarized deuteron beam at RHIC:
  E. D. Courant, BNL-report (1998).
- No actual experimental progress with hadron facilities.
- Possibilities: Fermilab, J-PARC, COMPASS, U70, GSI-FAIR, RHIC, …

Drell-Yan cross section and hadron tensor

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

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

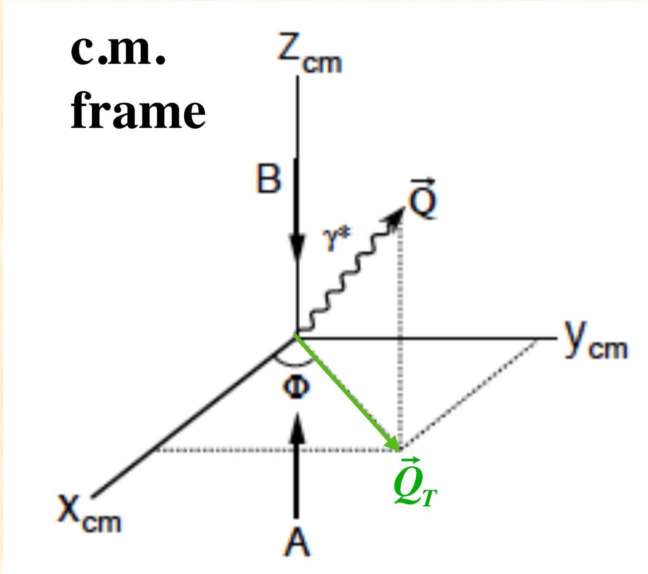
$$\frac{d\sigma}{d^4 Q d\Omega} = \frac{\alpha^2}{2sQ^4} L_{\mu\nu} W^{\mu\nu} \qquad W^{\mu\nu} \equiv \int \frac{d^4\xi}{(2\pi)^4} e^{iQ\cdot\xi} \langle P_A S_A P_B S_B | J^\mu(0) J^\nu(\xi) | P_A S_A P_B S_B \rangle$$



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

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

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

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

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

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

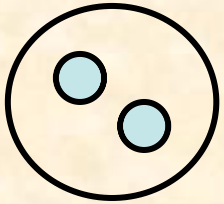
$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A)\delta_T\bar{q}_a(x_B)}{\sum_a e_a^2 q_a(x_A)\bar{q}_a(x_B)}$$

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

Summary From nucleon-spin crisis to a possible "*tensor-structure crisis*"

Unpolarized quark distribution in a tensor-polarized deuteron:

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



only in S-wave $\delta_T q = 0$

Spin asymmetry in $p + \vec{d} \to \mu^+ \mu^- + X$

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

Polarized proton-deuteron Drell-Yan
(Theory) Some
(Experiment) None → hadron facilities

1st measurement of b_1 ($\delta_T q$):
(HERMES) A. Airapetian et al., PRL 95 (2005) 242001.

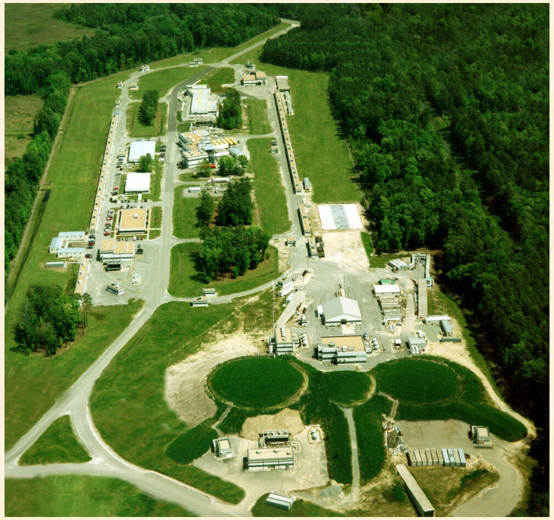
→ JLab experiment, PR12-11-110

$$\int dx\, b_1^D(x) = -\frac{5}{24} \lim_{t\to 0} t F_Q(t) + \frac{1}{9} \int dx \left(4\delta_T \bar{u} + \delta_T \bar{d} + \delta_T \bar{s} \right)$$

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

We need more theoretical studies on mechanisms of tensor polarization in the parton level.

Experimental possibilities



Approved experiment! (2019~)

© JLab

Feasibility under investigation

© Fermilab

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

© BNL

© J-PARC

© GSI

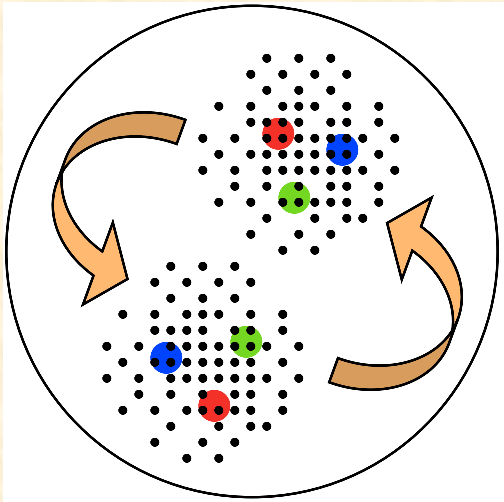
© CERN-COMPASS

© IHEP, Russia

Summary on this talk

Spin-1 structure function of the deuteron

- tensor structure in quark-gluon degrees of freedom
- exotic signature in nuclear physics
- new spin structure
- ···



The End

The End