Tensor structure of the deuteron and Nuclear structure functions

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Part I

Tensor structure of deuteron in terms of quark and gluon degrees of freedom

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- Motivations, Situation on b_1
- Definition of tensor structure functions (b_1, …, b_4)

Analysis of HERMES data

- Functional form for parametrization
- Obtained tensor-polarized distributions

Polarized proton-deuteron processes

- General formalism for pd Drell-Yan
- Parton model and possible spin asymmetries

Summary and Prospects

Introduction

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 proposal

  No investigation 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

(2) New structure functions

- Tensor structure function b_1

  → (1) Test of our hadron description in another spin

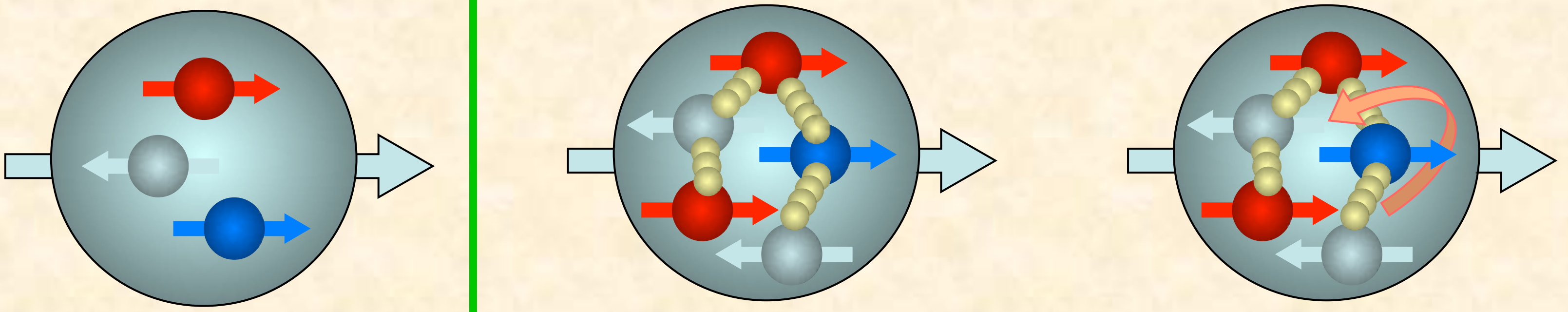
  (2) Description of tensor structure in terems of quark-gluon degrees of freedom

(3) Asymmetries in polarized light-antiquark distributions

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

Nucleon spin

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

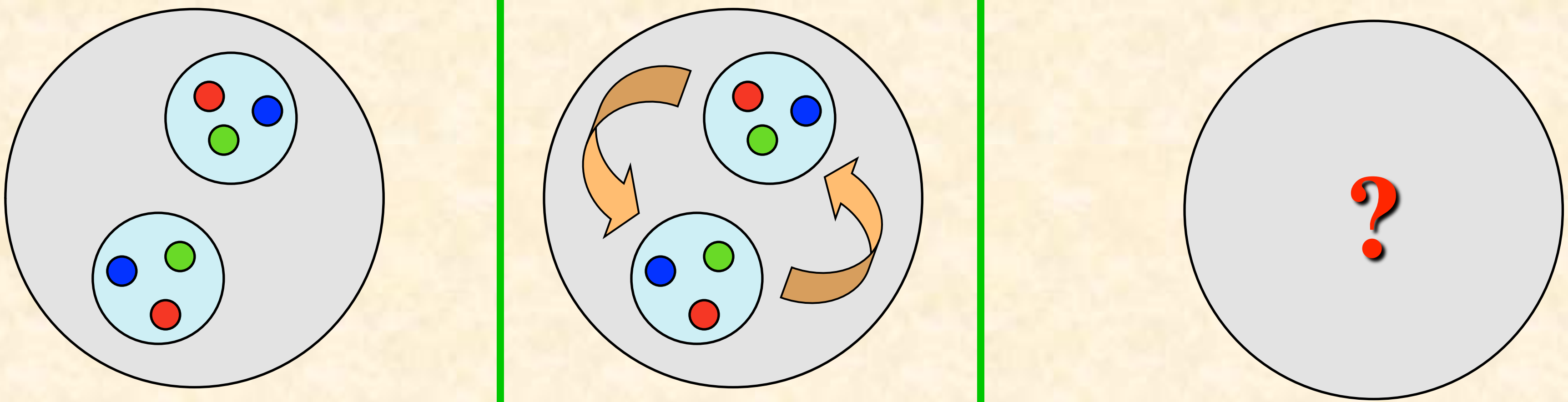


Naïve Quark Model | Sea-quarks and gluons? | Orbital angular momenta ?

"old" standard model

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

Tensor-structure crisis!?



only S wave | S + D waves

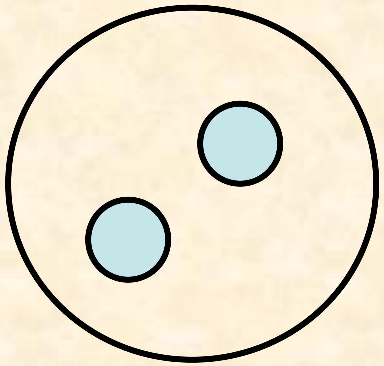
$b_1 = 0$

standard model $b_1 \neq 0$

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

Structure function b_1 in a simple example

Spin-1 particles (deuteron, mesons)



only in S-wave

$b_1 = 0$

$b_1 \neq 0$: New field of high-energy spin physics with orbital angular momenta.

The b_1 probes a dynamical aspect of hadron structure beyond simple expectations of a naive quark model.

→ Description of tensor structure by quark-gluon degrees of freedom

Personal studies

- **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 2010's

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).

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

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

$b_1, \cdots, b_4$ 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 $\sim \frac{M^2}{Q^2}$

Projections to $F_1, F_2, \ldots, b_4$ from W

Calculate $W^{\mu\nu}$ in hadron models $\rightarrow$ need to extract structure functions $b_1, b_2, \cdots$

Projection operators are needed to extract them from the calculated $W^{\mu\nu}$.

For F_1 and F_2, they are well known:

$$F_1 = -\frac{1}{2}\left(g^{\mu\nu} - \frac{\kappa-1}{\kappa}\frac{p^\mu p^\nu}{M^2}\right)W_{\mu\nu}, \quad F_2 = -\frac{x}{\kappa}\left(g^{\mu\nu} - \frac{\kappa-1}{\kappa}\frac{3p^\mu p^\nu}{M^2}\right)W_{\mu\nu}, \quad \kappa = 1 + \frac{Q^2}{\nu^2}$$

Try to obtain projections

in a spin-1 hadron by combinations of

$$g^{\mu\nu}, \quad \frac{p^\mu p^\nu}{M^2}, \; \varepsilon^{\mu\nu\alpha\beta} q_\alpha s_\beta, \ldots$$

Results on a spin-1 hadron

$$F_1 = -\frac{1}{2}\left(g^{\mu\nu} - \frac{\kappa-1}{\kappa}\frac{p^\mu p^\nu}{M^2}\right)\frac{1}{3}\delta_{\lambda_f\lambda_i} W_{\mu\nu}^{\lambda_f\lambda_i}, \qquad F_2 = -\frac{x}{\kappa}\left(g^{\mu\nu} - \frac{\kappa-1}{\kappa}\frac{3p^\mu p^\nu}{M^2}\right)\frac{1}{3}\delta_{\lambda_f\lambda_i} W_{\mu\nu}^{\lambda_f\lambda_i},$$

$$g_1 = -\frac{i}{2\kappa\nu}\epsilon^{\mu\nu\alpha\beta} q_\alpha (s_\beta^{11}\delta_{\lambda_f 1}\delta_{\lambda_i 1} - s_\beta^{10}\delta_{\lambda_f 0}\delta_{\lambda_i 1}) W_{\mu\nu}^{\lambda_f\lambda_i}, \qquad g_2 = \frac{i}{2\kappa\nu}\epsilon^{\mu\nu\alpha\beta} q_\alpha \left(s_\beta^{11}\delta_{\lambda_f 1}\delta_{\lambda_i 1} + \frac{s_\beta^{10}}{\kappa-1}\delta_{\lambda_f 0}\delta_{\lambda_i 1}\right) W_{\mu\nu}^{\lambda_f\lambda_i},$$

$$b_1 = \left[-\frac{1}{2\kappa} g^{\mu\nu}(\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \delta_{\lambda_f 1}\delta_{\lambda_i 0}) + \frac{\kappa-1}{2\kappa^2}\frac{p^\mu p^\nu}{M^2}(\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \delta_{\lambda_f 1}\delta_{\lambda_i 1})\right] W_{\mu\nu}^{\lambda_f\lambda_i},$$

$$b_2 = \frac{x}{\kappa^2}\Big[g^{\mu\nu}\{-\delta_{\lambda_f 0}\delta_{\lambda_i 0} - 2(\kappa-1)\delta_{\lambda_f 1}\delta_{\lambda_i 1} + (2\kappa-1)\delta_{\lambda_f 1}\delta_{\lambda_i 0}\} + \frac{3(\kappa-1)}{\kappa}\frac{p^\mu p^\nu}{M^2}(\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \delta_{\lambda_f 1}\delta_{\lambda_i 1})$$
$$- \frac{4(\kappa-1)}{\sqrt{\kappa}M}\{p^\mu E^\nu(\lambda=1) + p^\nu E^\mu(\lambda=1)\}\delta_{\lambda_f 1}\delta_{\lambda_i 0}\Big] W_{\mu\nu}^{\lambda_f\lambda_i},$$

$$b_3 = \frac{x}{3\kappa^2}\Big[g^{\mu\nu}\Big\{-\delta_{\lambda_f 0}\delta_{\lambda_i 0} + \frac{2(2\kappa^2+2\kappa-1)}{\kappa-1}\delta_{\lambda_f 1}\delta_{\lambda_i 1} - \frac{4\kappa^2+3\kappa-1}{\kappa-1}\delta_{\lambda_f 1}\delta_{\lambda_i 0}\Big\}$$
$$+ \frac{3(\kappa-1)}{\kappa}\frac{p^\mu p^\nu}{M^2}(\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \delta_{\lambda_f 1}\delta_{\lambda_i 1}) - \frac{4(\kappa-1)}{\sqrt{\kappa}M}\{p^\mu E^\nu(\lambda=1) + p^\nu E^\mu(\lambda=1)\}\delta_{\lambda_f 1}\delta_{\lambda_i 0}\Big] W_{\mu\nu}^{\lambda_f\lambda_i},$$

$$b_4 = \frac{x}{3\kappa^2}\Big[g^{\mu\nu}\Big\{-\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \frac{2(\kappa^2+4\kappa+1)}{\kappa-1}\delta_{\lambda_f 1}\delta_{\lambda_i 1} + \frac{2\kappa^2+9\kappa+1}{\kappa-1}\delta_{\lambda_f 1}\delta_{\lambda_i 0}\Big\}$$
$$+ \frac{3(\kappa-1)}{\kappa}\frac{p^\mu p^\nu}{M^2}(\delta_{\lambda_f 0}\delta_{\lambda_i 0} - \delta_{\lambda_f 1}\delta_{\lambda_i 1}) + \frac{4(2\kappa+1)}{\sqrt{\kappa}M}\{p^\mu E^\nu(\lambda=1) + p^\nu E^\mu(\lambda=1)\}\delta_{\lambda_f 1}\delta_{\lambda_i 0}\Big] W_{\mu\nu}^{\lambda_f\lambda_i}, \quad (9)$$

Bjorken scaling limit

$$F_1 = \frac{1}{2x}F_2 = -\frac{1}{2}g^{\mu\nu}\frac{1}{3}\delta_{\lambda_f\lambda_i} W_{\mu\nu}^{\lambda_f\lambda_i}$$

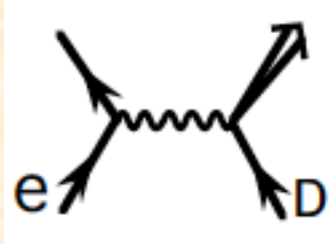
$$g_1 = -\frac{i}{2\nu}\varepsilon^{\mu\nu\alpha\beta} q_\alpha s_\beta \delta_{\lambda_f 1}\delta_{\lambda_i 1} W_{\mu\nu}^{\lambda_f\lambda_i}$$

$$b_1 = \frac{1}{2x}b_2 = \frac{1}{2}g^{\mu\nu}\left(\delta_{\lambda_f 1}\delta_{\lambda_i 1} - \delta_{\lambda_f 0}\delta_{\lambda_i 0}\right) W_{\mu\nu}^{\lambda_f\lambda_i}$$

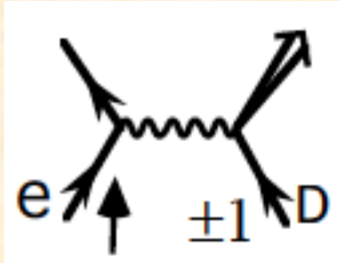
For the details, see
T.-Y. Kimura and SK, PRD 78 (2008) 117505.

Structure Functions

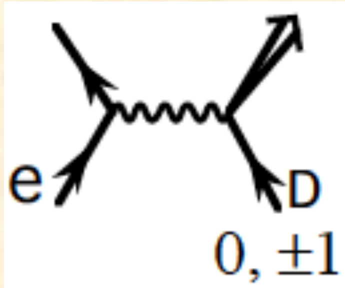
$$F_1 \propto \langle d\sigma \rangle$$



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



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



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

Parton Model

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

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

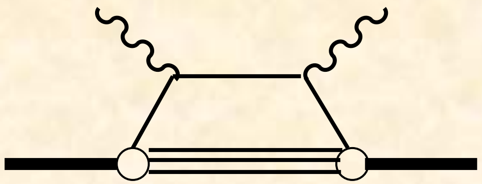
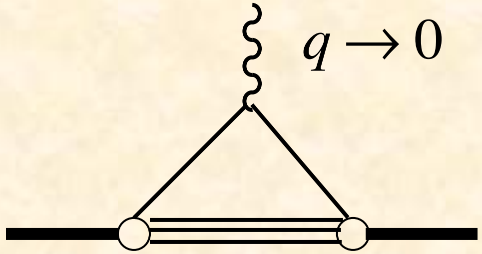
$$\left[q_\uparrow^H\left(x,Q^2\right)\right] \qquad b_1 = \frac{1}{2}\sum_i e_i^2 \left(\delta_T q_i + \delta_T\bar{q}_i\right) \qquad \delta_T q_i = q_i^0 - \frac{q_i^{+1}+q_i^{-1}}{2}$$

Sum rule for b_1

$\int dx\, b_1(x) = \text{dimensionless} \sim QM^2$???

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

M = hadron mass Q = quadrupole moment

$\int dx \Big($  $\Big)$ $\leftrightarrow$ 

$$\int dx\, b_1^D(x) = \int dx\left[\frac{4}{9}\left(\delta u_D + \delta \bar{u}_D\right) + \frac{1}{9}\left(\delta d_D + \delta \bar{d}_D + \delta s_D + \delta \bar{s}_D\right)\right]$$

$$= \frac{5}{9}\int dx\left[\delta u_v(x) + \delta u_v(x)\right] + \frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{\text{sea}}$$

$$\left(\delta Q + \delta \bar{Q}\right)_{\text{sea}} = \int dx\left[5\left(\delta u + \delta \bar{u} + \delta d_D + \delta \bar{d}_D\right) + 2\left(\delta s_D + \delta \bar{s}_D\right)\right]_{\text{sea}}$$

Elastic amplitude in a parton model

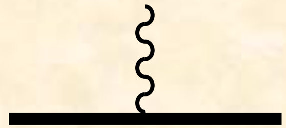
$$\Gamma_{H,H} = \langle p,H | J_0(0) | p,H \rangle = \sum_i e_i \int dx\left[q_{i\uparrow}^H + q_{i\downarrow}^H - \bar{q}_{i\Uparrow}^H - \bar{q}_{i\Downarrow}^H\right]$$

$$\frac{1}{2}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] = \sum_i e_i \int dx\left[\delta q_D - \delta \bar{q}_D\right] = \frac{1}{3}\int dx\left[\delta u_v(x) + \delta d_v(x)\right]$$

$$\int dx\, b_1^D(x) = \frac{5}{6}\left[\Gamma_{0,0} - \frac{1}{2}\left(\Gamma_{1,1} + \Gamma_{-1,-1}\right)\right] + \frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{\text{sea}}$$

Macroscopically

$t \to 0$



$$\Gamma_{0,0} = \lim_{t\to 0}\left[F_c(t) - \frac{t}{3M^2} F_Q(t)\right]$$

$$\Gamma_{+1,+1} = \Gamma_{-1,-1} = \lim_{t\to 0}\left[F_c(t) - \frac{t}{6M^2} F_Q(t)\right]$$

Note: $F_Q(t)$ in the unit of $\frac{1}{M^2}$

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

$$\Rightarrow \lim_{t\to 0} -\frac{5}{12}\frac{t}{M^2} F_Q(t)$$

If the sum-rule violation is shown by experiment, it suggests antiquark tensor polarization.

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

Polarized electron-deuteron deep inelastic scattering

Analysis of HERMES data to obtain tensor-polarized quark distributions

S. Kumano, Phys. Rev. D 82 (2010) 017501

Purposes

- Understanding of current situation on tensor-polarized distributions
- Useful for future proposals at JLab, J-PARC, …
- Test of theoretical model estimates
- Description of tensor structure in terms of quark-gluon degrees of freedom
- Understanding of hadron spins with orbital angular momenta

…

HERMES results on b_1

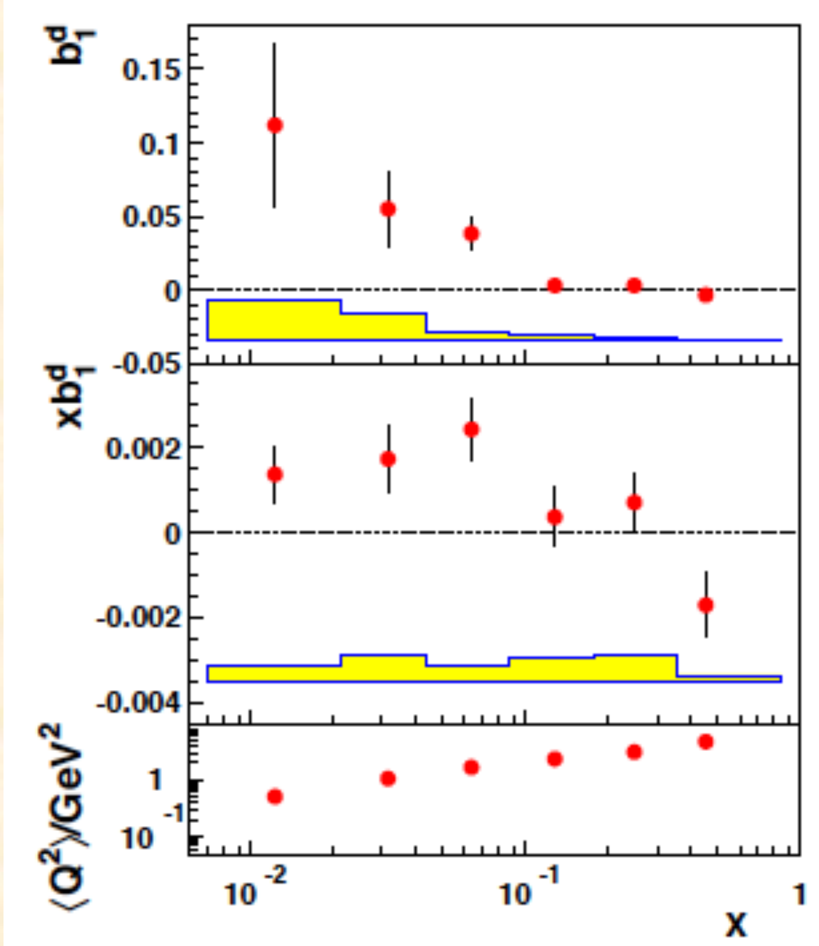
27.6 GeV/c ⇄, 0

positron deuteron

b_1 measurement in the kinematical region

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

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



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

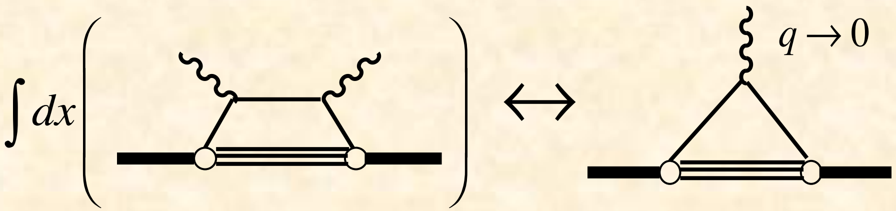
$$\int dx\, b_1^D(x) = \lim_{t \to 0} -\frac{5}{12}\frac{t}{M^2} F_Q(t) + \frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{\mathrm{sea}} = 0\ ?$$

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

Drell-Yan experiments probe these antiquark distributions.

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)$^2 \cdot$ (quadrupole moment)

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

Elastic amplitude in a parton model

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

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

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

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

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

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

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

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

Functional form of parametrization

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

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

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

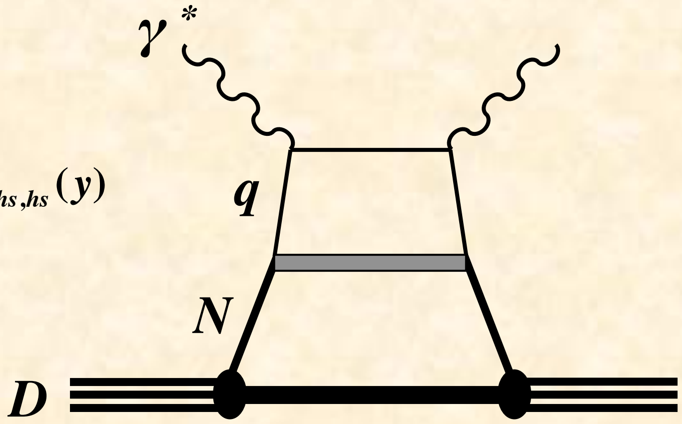
Set 1: $\delta_T\bar{q}^D(x) = 0$ Tensor-polarized antiquark distributions are terminated ($\alpha_{\bar{q}} = 0$),

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

Theoretical background for the parametrization

(1) Tensor-polarized valence quarks: $\int dx\, \delta_T q_v(x) = 0$

(2) Standard convolution approach



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

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

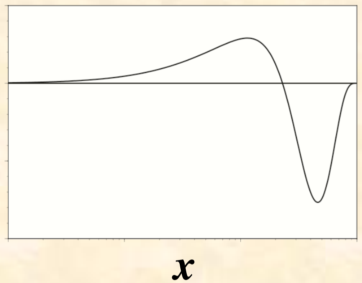
$$\hat{A}_{+\uparrow,+\uparrow} = F_1 - g_1, \qquad \hat{A}_{+\downarrow,+\downarrow} = F_1 + g_1$$

$$b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2} = \int \frac{dy}{y} \sum_s \left[f^0(y) - \frac{f^+(y) + f^-(y)}{2} \right] F_1(x/y) \quad \text{where } f^H(y) \equiv f_\uparrow^H(y) + f_\downarrow^H(y)$$

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

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

$$= \cos\alpha\ \psi_0(p) Y_{00}(\hat{p}) \chi_H + \sin\alpha \sum_{m_L} \langle 2m_L : 1m_S | 1H \rangle \psi_2(p) Y_{2m_L}(\hat{p}) \chi_{m_S}$$

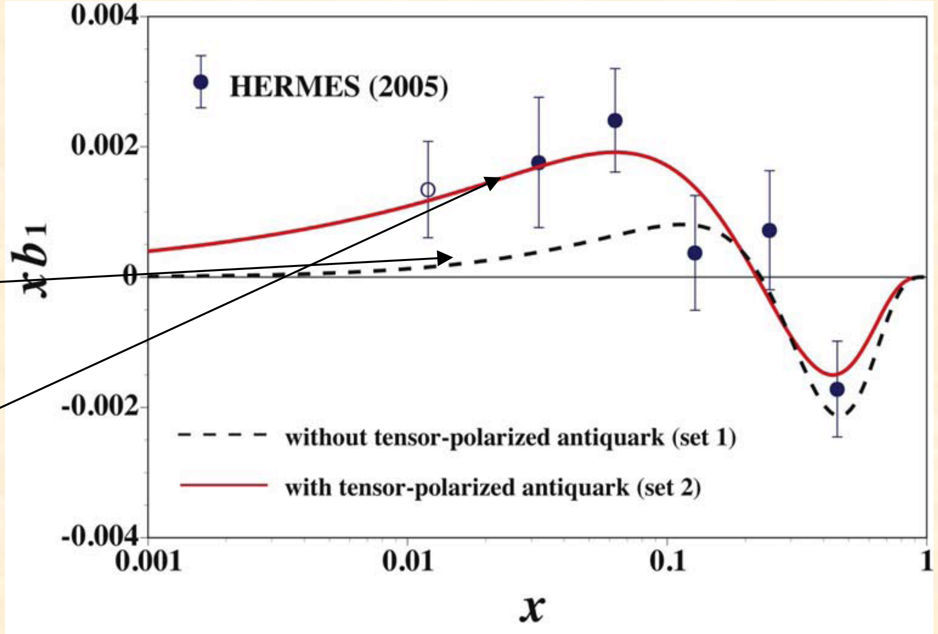


Numerical estimates indicate the oscillatory function with $\int dx\, b_1(x) = 0$.

Results

Two-types of fit results:

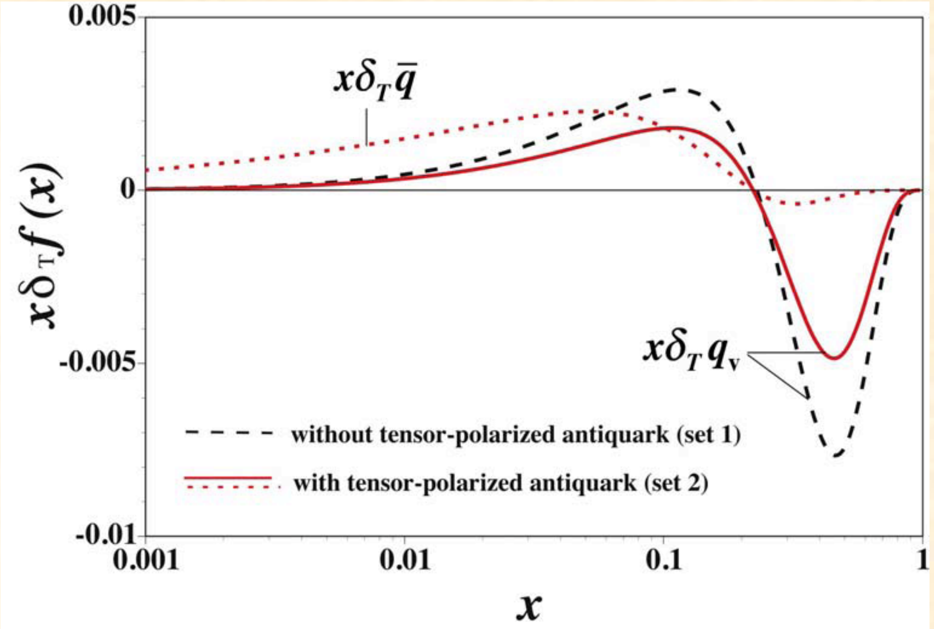
- set-1: χ^2 / d.o.f. = 2.83
  Without $\delta_T \bar{q}$, the fit is not good enough.
- set-2: χ^2 / d.o.f. = 1.57
  With finite $\delta_T \bar{q}$, the fit is reasonably good.



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

(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 submitted at JLab.

More theoretical studies …

Drell-Yan

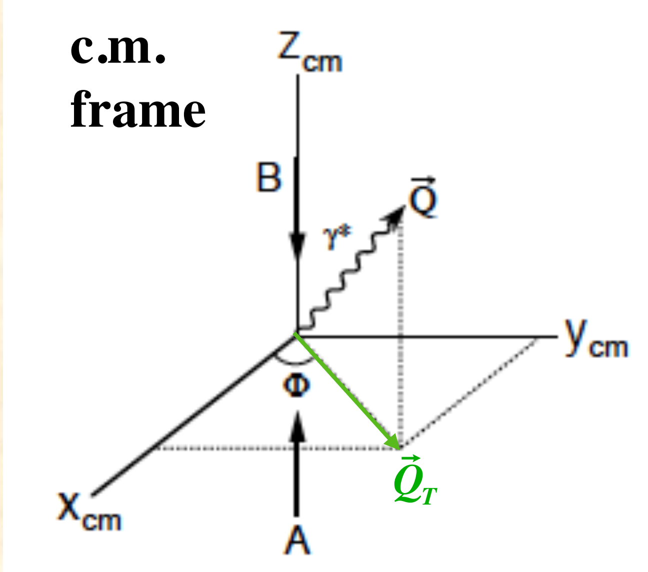
with polarized deuteron

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

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

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

Formalism of *pd* Drell-Yan process



See Ref. PRD59 (1999) 094026.

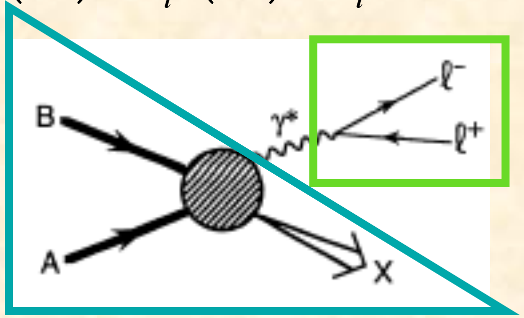
	proton-proton	proton-deuteron
Number of structure functions	48	108
After integration over $\vec{Q}_T$ (or $\vec{Q}_T \to 0$)	11	22
In parton model	3	4

Additional structure functions due to tensor structure

I will briefly explain in the following.

Drell-Yan cross section and hadron tensor

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



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

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

Possible vectors to expand $W^{\mu\nu}$

- $X^\mu = P_A^\mu Q^2 Z \cdot P_B - P_B^\mu Q^2 Z \cdot P_A$
  $\quad + Q^\mu \left(Q \cdot P_B \; Z \cdot P_A - Q \cdot P_A \; Z \cdot P_B\right)$
- $Y^\mu = \varepsilon^{\mu\alpha\beta\gamma} P_{A\alpha} P_{B\beta} Q_\gamma$
- $Z^\mu = P_A^\mu Q \cdot P_B - P_B^\mu Q \cdot P_A$

Q^μ = photon momentum

$Q_T \lesssim \frac{1}{R} \ll$ hard scale, $\quad R$ = hadron size

As $Q_T \to 0$, $X^\mu = Y^\mu \to 0$

Expand $W^{\mu\nu}$ by possible combinations

$$\left(W^{\mu\nu}\right)_{Q_T=0} = -g^{\mu\nu} A - \frac{Z^\mu Z^\nu}{Z^2} B' + Z^{\{\mu} T_A^{\nu\}} C + Z^{\{\mu} T_B^{\nu\}} D + Z^{\{\mu} S_{AT}^{\nu\}} E + Z^{\{\mu} S_{BT}^{\nu\}} F - S_{BT}^\mu S_{BT}^\nu G' - S_{AT}{}^{\{\mu} S_{BT}^{\nu\}} H'$$
$$+ T_A{}^{\{\mu} S_{BT}^{\nu\}} I' + S_{BT}{}^{\{\mu} T_B^{\nu\}} J + Q^\mu Q^\nu K + Q^{\{\mu} Z^{\nu\}} L + Q^{\{\mu} S_{AT}^{\nu\}} M + Q^{\{\mu} S_{BT}^{\nu\}} N + Q^{\{\mu} T_A^{\nu\}} O + Q^{\{\mu} T_B^{\nu\}} P$$

$$T^\mu = \varepsilon^{\mu\alpha\beta\gamma} S_\alpha Z_\beta Q_\gamma \qquad Q^{\{\mu} Z^{\nu\}} \equiv Q^\mu Z^\nu + Q^\nu Z^\mu$$

Use current conservation: $Q_\mu W^{\mu\nu} = 0$

$$\left(W^{\mu\nu}\right)_{Q_T=0} = -\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2}\right)A - \left[\frac{Z^\mu Z^\nu}{Z^2} - \frac{1}{3}\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2}\right)\right]B + Z^{\{\mu}T_A^{\nu\}}C + Z^{\{\mu}T_B^{\nu\}}D + Z^{\{\mu}S_{AT}^{\nu\}}E + Z^{\{\mu}S_{BT}^{\nu\}}F$$

$$-\left[S_{BT}^\mu S_{BT}^\nu - \frac{1}{2}S_{BT}\cdot S_{BT}\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2} - \frac{Z^\mu Z^\nu}{Z^2}\right)\right]G - \left[S_{AT}^{\{\mu}S_{BT}^{\nu\}} - S_{AT}\cdot S_{BT}\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2} - \frac{Z^\mu Z^\nu}{Z^2}\right)\right]H$$

$$+\left[T_A^{\{\mu}S_{BT}^{\nu\}} - T_A\cdot S_{BT}\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2} - \frac{Z^\mu Z^\nu}{Z^2}\right)\right]I + S_{BT}^{\{\mu}T_B^{\nu\}}J$$

The coefficients A, B, ... still contain spin factors in scalar and pseudoscalar forms.

$$A = A_1' + \frac{M_A M_B}{sZ^2}Z\cdot S_A\; Z\cdot S_B A_2 - S_{AT}\cdot S_{BT}A_3 + \frac{8M_B^2\left(Z\cdot S_B\right)^2}{s^2\left(Q\cdot P_B\right)^2}A_4' + \frac{M_B}{Z^2 Q\cdot P_B}Z\cdot S_B\; T_A\cdot S_{BT}A_5$$

$$= A_1 + \frac{1}{4}\lambda_A\lambda_B A_2 + \left|\vec{S}_{AT}\right|\left|\vec{S}_{BT}\right|\cos\left(\phi_A - \phi_B\right)A_3 + \frac{2}{3}\left(2\left|\vec{S}_{BT}\right|^2 - \lambda_B^2\right)A_4 + \lambda_B\left|\vec{S}_{AT}\right|\left|\vec{S}_{BT}\right|\sin\left(\phi_A - \phi_B\right)A_5$$

- $S_A^\mu = \lambda_A P_A^\mu / M_A + S_{AT}^\mu - \delta_-^\mu\left(\lambda_A M_A / P_A^+\right)$
- $S_B^\mu = \lambda_B P_B^\mu / M_B + S_{BT}^\mu - \delta_+^\mu\left(\lambda_B M_B / P_B^-\right)$
- $S_T^\mu = \left(g^{\mu\nu} - \dfrac{Q^\mu Q^\nu}{Q^2} - \dfrac{Z^\mu Z^\nu}{Z^2}\right)S_\nu$
- $T^\mu = \varepsilon^{\mu\alpha\beta\gamma}S_\alpha Z_\beta Q_\gamma$

$a^\mu = [a_-,\, a_+,\, \vec{a}_T],\;\; a_\pm = (a^0 + a^3)/\sqrt{2}$

$\delta_+^\mu = [0,\, 1,\, \vec{0}_T],\;\; \delta_-^\mu = [1,\, 0,\, \vec{0}_T]$

- $\vec{Z} = \left(0, 0, \left|\vec{Z}\right|\right)$
- $\vec{k} = \left|\vec{k}\right|\left(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta\right)$
- $\vec{S}_{AT} = \left|\vec{S}_{AT}\right|\left(\cos\phi_A, \sin\phi_A, 0\right)$
- $\vec{S}_{BT} = \left|\vec{S}_{BT}\right|\left(\cos\phi_B, \sin\phi_B, 0\right)$
- $\vec{T}_A = Q\left|\vec{Z}\right|\left|\vec{S}_{AT}\right|\left(\sin\phi_A, -\cos\phi_A, 0\right)$
- $\vec{T}_B = Q\left|\vec{Z}\right|\left|\vec{S}_{BT}\right|\left(\sin\phi_B, -\cos\phi_B, 0\right)$

Expand B, C, $\cdots$ in the same way $\cdots$

Expand B, C, $\cdots$ in the same way

$$B = B_1 + \frac{Z^\mu Z^\nu}{sZ^2} Z\cdot S_A\ Z\cdot S_B B_2 - S_{AT}\cdot S_{BT} B_3 - \left[\frac{8M_B^2 (Z\cdot S_B)^2}{s^2 (Q\cdot P_B)^2} + \frac{4}{3}S_B^2\right] B_4 + \frac{M_B}{Z^2 Q\cdot P_B} Z\cdot S_B\ T_A\cdot S_{BT} B_5$$

$$= B_1 + \frac{1}{4}\lambda_A\lambda_B B_2 + |\vec{S}_{AT}||\vec{S}_{BT}|\cos(\phi_A - \phi_B) B_3 + \frac{2}{3}\left(2|\vec{S}_{BT}|^2 - \lambda_B^2\right) B_4 + \lambda_B |\vec{S}_{AT}||\vec{S}_{BT}|\sin(\phi_A - \phi_B) B_5$$

$$C = -\frac{1}{QZ^2}\left[C_1 - \left\{\frac{8M_B^2 (Z\cdot S_B)^2}{s^2 (Q\cdot P_B)^2} + \frac{4}{3}S_B^2\right\} C_2\right] = +\frac{1}{Q|\vec{Z}|^2}\left[C_1 + \frac{2}{3}\left(2|\vec{S}_{BT}|^2 - \lambda_B^2\right) C_2\right]$$

$$D = -\frac{1}{QZ^2}\left[D_1 + \frac{M_A M_B}{sZ^2} Z\cdot S_A\ Z\cdot S_B D_2 - S_{AT}\cdot S_{BT} D_3\right] = +\frac{1}{Q|\vec{Z}|^2}\left[D_1 + \frac{1}{4}\lambda_A\lambda_B D_2 + |\vec{S}_{AT}||\vec{S}_{BT}|\cos(\phi_A - \phi_B) D_3\right]$$

$$E = \frac{QM_B}{Z^2 Q\cdot P_B} Z\cdot S_B E_1 = -\frac{1}{|\vec{Z}|}\lambda_B E_1$$

$$F = -\frac{QM_A}{Z^2 Q\cdot P_A} Z\cdot S_A F_1 + \frac{QM_B}{Z^2 Q\cdot P_B} Z\cdot S_B F_2 - \frac{1}{Z^2 Q} T_A\cdot S_{BT} F_3' = -\frac{1}{|\vec{Z}|}\left[\lambda_A F_1 + \lambda_B F_2 + |\vec{S}_{AT}||\vec{S}_{BT}|\sin(\phi_A - \phi_B) F_3\right]$$

$$G = 2G_1,\quad H = H_1,\quad I = -\frac{M_B}{Z^2 Q\cdot P_B} Z\cdot S_B I_1 = \frac{\lambda_B}{Q|\vec{Z}|} I_1,\quad J = -\frac{M_A}{Z^2 Q\cdot P_A} Z\cdot S_A J_1 = \frac{\lambda_A}{Q|\vec{Z}|} J_1$$

Structure functions and cross sections

spin-1/2, spin-1

spin-1 only

$A_1 = W_{0,0}, \quad A_2 = V_{0,0}^{LL}, \quad A_3 = V_{0,0}^{TT}, \quad A_4 = V_{0,0}^{UQ_0}, \quad A_5 = V_{0,0}^{TQ_1},$

$B_1 = W_{2,0}, \quad B_2 = V_{2,0}^{LL}, \quad B_3 = V_{2,0}^{TT}, \quad B_4 = V_{2,0}^{UQ_0}, \quad B_5 = V_{2,0}^{TQ_1},$

$C_1 = U_{2,1}^{TU}, \quad C_2 = U_{2,1}^{TQ_0}, \quad D_1 = U_{2,1}^{UT}, \quad D_2 = U_{2,1}^{LQ_1}, \quad D_3 = U_{2,1}^{TQ_2},$

$E_1 = U_{2,1}^{TL}, \quad F_1 = U_{2,1}^{LT}, \quad F_2 = U_{2,1}^{UQ_1},$

$H_1 = U_{2,2}^{TT}, \quad G_1 = U_{2,2}^{UQ_2}, \quad I_1 = U_{2,2}^{TQ_1}, \quad J_2 = U_{2,2}^{LQ_2}$

W for unpolarized structure functions

V, U for polarized structure functions

$$\int d\Omega\, Y_{L,M} \frac{d\sigma}{d^4Q\, d\Omega} \propto W_{L,M}$$

Q_0 for the term $3\cos^2\theta_B - 1 \sim Y_{20}$

Q_1 $\sin\theta_B \cos\theta_B \sim Y_{21}$

Q_2 $\sin^2\theta_B \sim Y_{22}$

$$\lambda_B = |\vec{S}_B| \cos\theta_B, \quad |\vec{S}_{BT}| = |\vec{S}_B| \sin\theta_B$$

$$\begin{aligned}
\frac{d\sigma}{d^4Q\, d\Omega} = \frac{\alpha^2}{2sQ^2} \Bigg\{ & 2\Bigg[W_{0,0} + \frac{1}{4}\lambda_A\lambda_B V_{0,0}^{LL} + |\vec{S}_{AT}||\vec{S}_{BT}| \cos(\phi_A - \phi_B) V_{0,0}^{TT} + \frac{2}{3}\left(2|\vec{S}_{BT}|^2 - \lambda_B^2\right) V_{0,0}^{UQ_0} + |\vec{S}_{AT}|\lambda_B |\vec{S}_{BT}| \sin(\phi_A - \phi_B) V_{0,0}^{TQ_1} \Bigg] \\
& + \left(\frac{1}{3} - \cos^2\theta\right)\Bigg[W_{2,0} + \frac{1}{4}\lambda_A\lambda_B V_{2,0}^{LL} + |\vec{S}_{AT}||\vec{S}_{BT}| \cos(\phi_A - \phi_B) V_{2,0}^{TT} + \frac{2}{3}\left(2|\vec{S}_{BT}|^2 - \lambda_B^2\right) V_{2,0}^{UQ_0} + |\vec{S}_{AT}|\lambda_B |\vec{S}_{BT}| \sin(\phi_A - \phi_B) V_{2,0}^{TQ_1} \Bigg] \\
& + 2\sin\theta\cos\theta \Bigg[\sin(\phi - \phi_A)|\vec{S}_{AT}| \left(U_{2,1}^{TU} + \frac{2}{3}\left(2|\vec{S}_{BT}|^2 - \lambda_B^2\right) U_{2,1}^{TQ_0} \right) + \sin(\phi - \phi_B)|\vec{S}_{BT}| \left(U_{2,1}^{UT} + \frac{1}{4}\lambda_A\lambda_B U_{2,1}^{LQ_1} \right) \\
& \qquad + \sin(\phi + \phi_A - 2\phi_B)|\vec{S}_{AT}||\vec{S}_{BT}| U_{2,1}^{TQ_2} + \cos(\phi - \phi_A)|\vec{S}_{AT}|\lambda_B U_{2,1}^{TL} + \cos(\phi - \phi_B)|\vec{S}_{BT}| \left(\lambda_A U_{2,1}^{LT} + \lambda_B U_{2,1}^{UQ_1} \right) \Bigg] \\
& + \sin^2\theta \Bigg[\cos(2\phi - 2\phi_B)|\vec{S}_{BT}|^2 U_{2,2}^{UQ_2} + \cos(2\phi - \phi_A - 2\phi_B)|\vec{S}_{AT}||\vec{S}_{BT}| U_{2,2}^{TT} \\
& \qquad + \sin(2\phi - \phi_A - 2\phi_B)|\vec{S}_{AT}|\lambda_B |\vec{S}_{BT}| U_{2,2}^{TQ_1} + \sin(2\phi - 2\phi_B)\lambda_A |\vec{S}_{BT}|^2 U_{2,2}^{LQ_2} \Bigg] \Bigg\}
\end{aligned}$$

Possible spin asymmetries

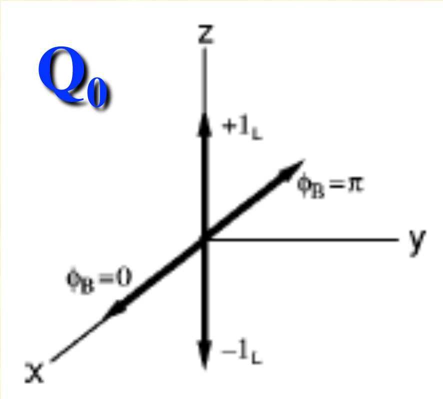
The quadrupole spin asymmetries are new ones in spin-1 hadron reactions.

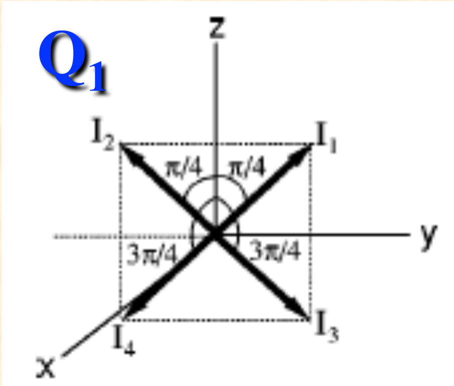
***pp* Drell-Yan** $\langle\sigma\rangle$, A_{LL}, A_{TT}, A_{LT}, A_T

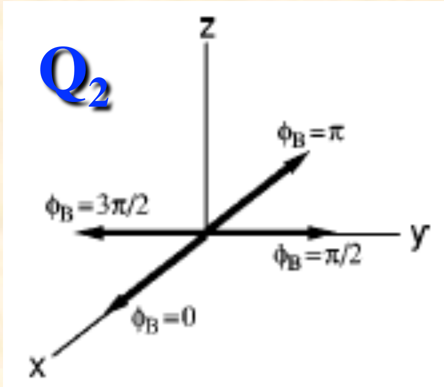
***pd* Drell-Yan** $\langle\sigma\rangle$, A_{LL}, A_{TT}, A_{LT}, A_{TL},

A_{UT}, A_{TU}, A_{UQ_0}, A_{TQ_0}, A_{UQ_1},

A_{LQ_1}, A_{TQ_1}, A_{UQ_2}, A_{LQ_2}, A_{TQ_2}

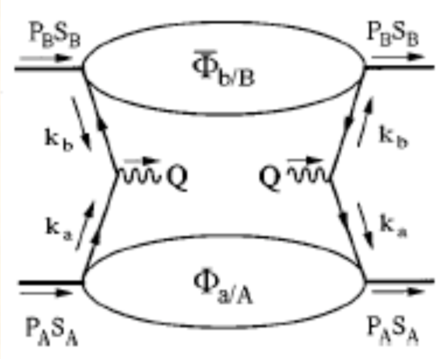






Parton-model analysis

$q(\text{in A}) + \bar{q}(\text{in } B) \to l^+ + l^-$



- $\Phi_{a/A}(P_AS_A;k_a)_{ij} \equiv \int \frac{d^4\xi}{(2\pi)^4} e^{ik_a\cdot\xi} \langle P_AS_A | \bar{\psi}_j^{(a)}(0)\, \psi_i^{(a)}(\xi) | P_AS_A \rangle$
- $\bar{\Phi}_{\bar{a}/B}(P_BS_B;k_{\bar{a}})_{ij} \equiv \int \frac{d^4\xi}{(2\pi)^4} e^{ik_{\bar{a}}\cdot\xi} \langle P_BS_B | \psi_i^{(a)}(0)\, \bar{\psi}_j^{(a)}(\xi) | P_AS_A \rangle$
- $W^{\mu\nu} = \frac{1}{3}\sum_{a,b} \delta_{b\bar{a}} e_a^2 \int d^4k_a d^4k_b \delta^4(k_a + k_b - Q) \mathrm{Tr}\left[\Phi_{a/A}(P_AS_A;k_a)\gamma^\mu \bar{\Phi}_{b/B}(P_BS_B;k_b)\gamma^\nu\right]$

$$= -\frac{1}{3}\sum_{a,b} \delta_{b\bar{a}} e_a^2 \int d^2\vec{k}_{aT} d^2\vec{k}_{bT} \delta^4(\vec{k}_{aT} + \vec{k}_{bT} - \vec{Q}_T)$$

$$\times\Big\{\left(\Phi_{a/A}[\gamma^+]\bar{\Phi}_{b/B}[\gamma^-] + \Phi_{a/A}[\gamma^+\gamma_5]\bar{\Phi}_{b/B}[\gamma^-\gamma_5]\right) g_T^{\mu\nu}$$

$$+\Phi_{a/A}[i\sigma^{i+}\gamma_5]\bar{\Phi}_{b/B}[i\sigma^{j-}\gamma_5]\left(g_{Ti}^{\{\mu} g_{Tj}^{\nu\}} - g_{Tij} g_T^{\mu\nu}\right)\Big\} + O\left(\frac{1}{Q}\right)$$

$(\Phi_{a/A})_{ij}(\gamma^\mu)_{jk}(\bar{\Phi}_{b/B})_{kl}(\gamma^\nu)_{li}$

We use Fierz transformation for $(\gamma^\mu)_{jk}(\gamma^\nu)_{li}$ so that the index summations are taken separately in hadrons A and B.

$$4(\gamma^\mu)_{jk}(\gamma^\nu)_{li} = \left[1_{ji}1_{lk} + (i\gamma_5)_{ji}(i\gamma_5)_{lk} - (\gamma^\alpha)_{ji}(\gamma_\alpha)_{lk} - (\gamma^\alpha\gamma_5)_{ji}(\gamma_\alpha\gamma_5)_{lk} + \frac{1}{2}(i\sigma_{\alpha\beta}\gamma_5)_{ji}(i\sigma^{\alpha\beta}\gamma_5)_{lk}\right] g^{\mu\nu}$$
$$+(\gamma^{\{\mu})_{jk}(\gamma^{\nu\}})_{li} + (\gamma^{\{\mu}\gamma_5)_{ji}(\gamma^{\nu\}}\gamma_5)_{lk} + (i\sigma^{\alpha\{\mu}\gamma_5)_{ji}(i\sigma^{\nu\}}\gamma_5)_{lk}$$

$$\Phi_{a/A}[\Gamma] \equiv \frac{1}{2}\int dk^- \mathrm{Tr}\left[\Gamma\Phi_{a/A}\right]$$

$$\bar{\Phi}_{b/B}[\Gamma] \equiv \frac{1}{2}\int dk^+ \mathrm{Tr}\left[\Gamma\bar{\Phi}_{b/B}\right]$$

We express Φ in terms of parton distributions.

The details are in PRD60 (1999) 054018.

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

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

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

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

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

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

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

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

Summary on *pd* Drell-Yan

- 108 (48) structure functions exist in the *pd* (*pp*) Drell-Yan
- 22 (11) structure functions by the $\vec{Q}_T$ integration or by the $\vec{Q}_T \to 0$ limit
- New polarized structure functions $\to$ associated with the tensor structure
- Tensor polarizations and spin asymmetries
- Only 4 structure functions are finite in the parton model
- The tensor distributions δq and $\delta \bar{q}$ can be measured by A_{UQ_0}
- The *pd* Drell-Yan suitable for measuring $\delta \bar{q}$
- Future experimental possibilities: J-PARC, COMPASS, $\cdots$
- Numerical analysis has not been done about feasibility at J-PARC, etc.

Future prospects

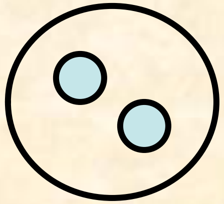
From nucleon-spin crisis to a possible "*tensor-structure crisis*"

→ Jefferson Lab PAC-38 proposal, PR12-11-110

Unpolarized quark distribution in a tensor-polarized deuteron:

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

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



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

See SK, PRD 82 (2010) 017501 for recent information.

Unpolarized proton+ Tensor polarized deuteron

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

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

Polarized proton-deuteron Drell-Yan
(Theory) Some
(Experiment) None → J-PARC?

Unique advantage of J-PARC ($\delta\bar{q}$ measurement)

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

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

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

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
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

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

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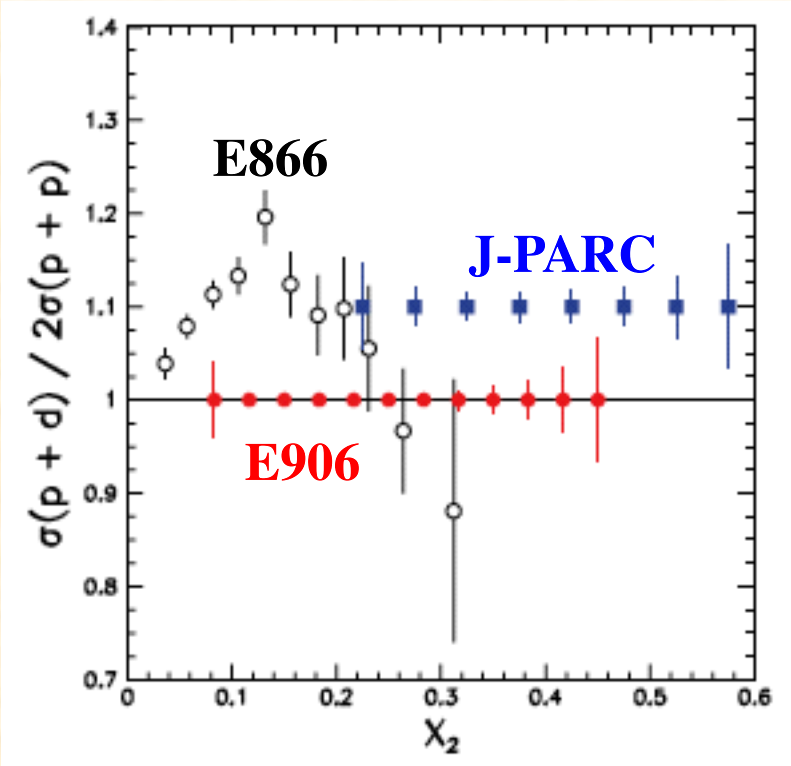
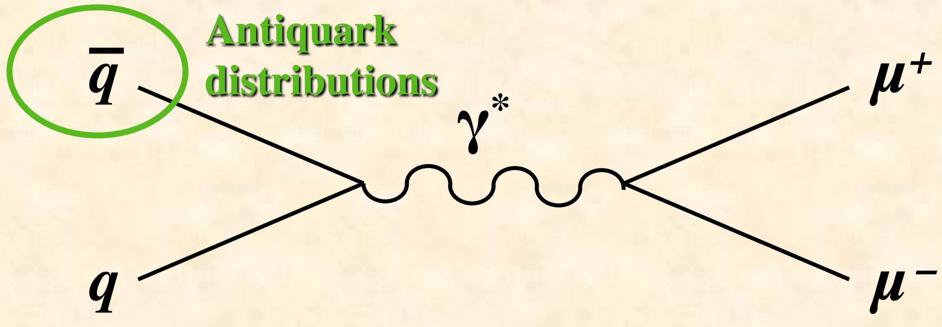
Seonho Choi, Hoyoung Kang, Hyekoo Kang, Yoomin Oh
Seoul National University, Seoul 151-747 Korea

It will be resubmitted after some revisions.

Possibility of Drell-Yan at J-PARC and other hadron facilcities





Drell-Yan: $p+p \rightarrow \mu^+\mu^- + X,\ \ p+d \rightarrow \mu^+\mu^- + X$

$$\frac{\sigma_{DY}(pd)}{2\sigma_{DY}(pp)} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

E866: existing measurements by the Fermilab-E866

E906: expected measurements by the Fermilab-E906

J-PARC: proposal

→ **It should be possible to use polarized proton-deuteron Drell-Yan processes to measure the tensor polarized distributions.**
(Note: Proton-beam polarization is not needed.)

Part II

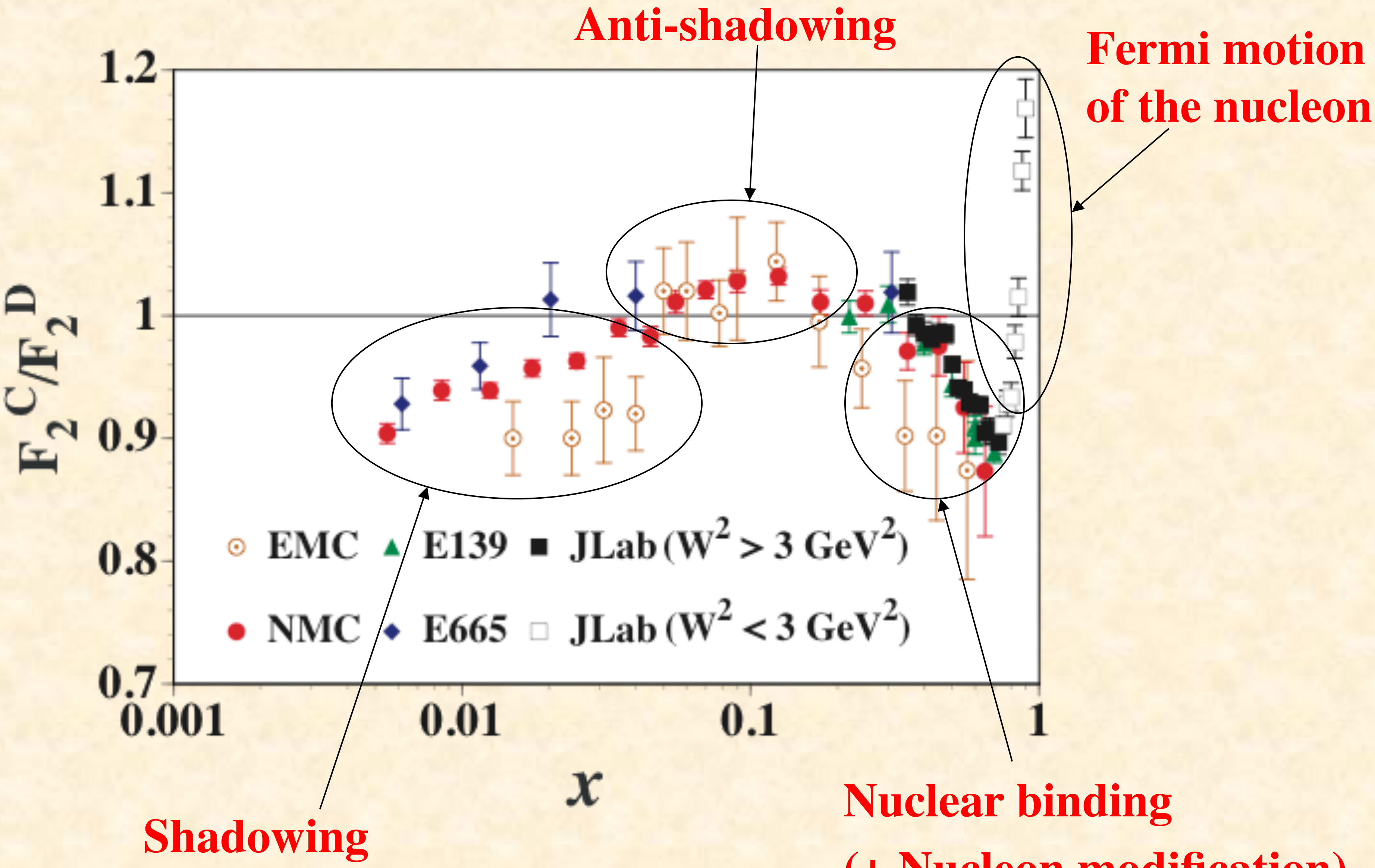
Nuclear structure functions

Clustering aspect of nuclear structure functions

Motivated by a large x-slope of ^{9}Be $\left|\dfrac{d(F_2^{^9Be}/F_2^D)}{dx}\right|$

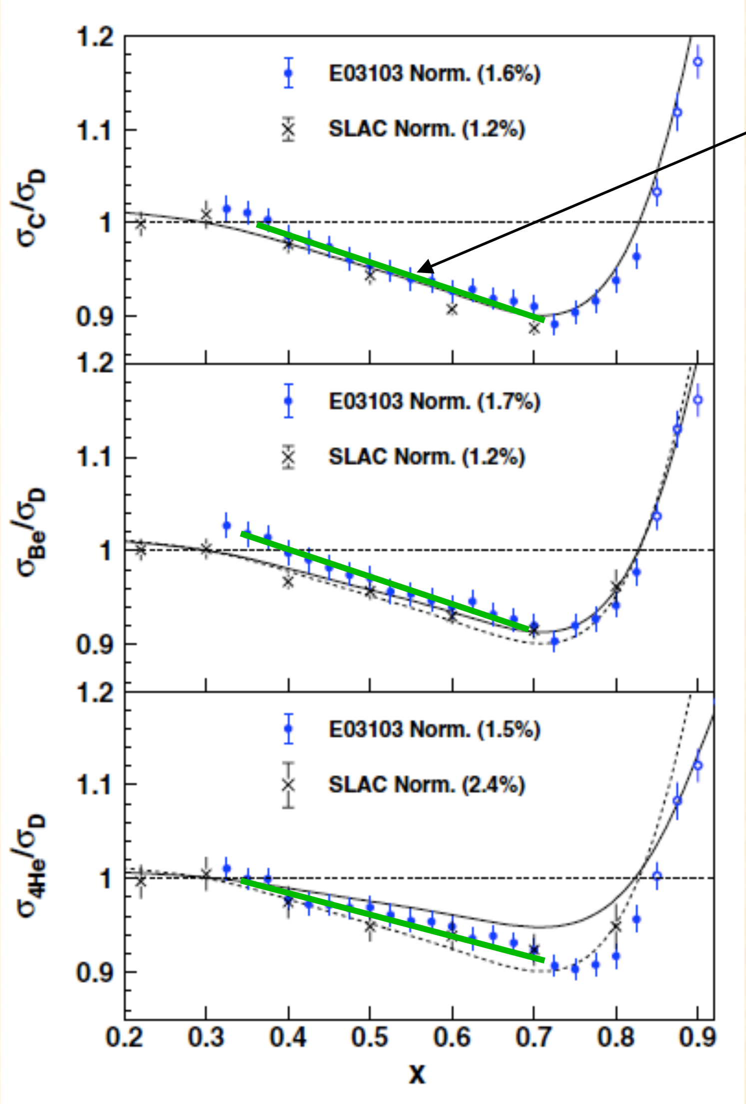
M. Hirai, S. Kumano, K. Saito, and T. Watanabe
Phys. Rev. C83 (2011) 035202.

Nuclear modifications of structure function F_2



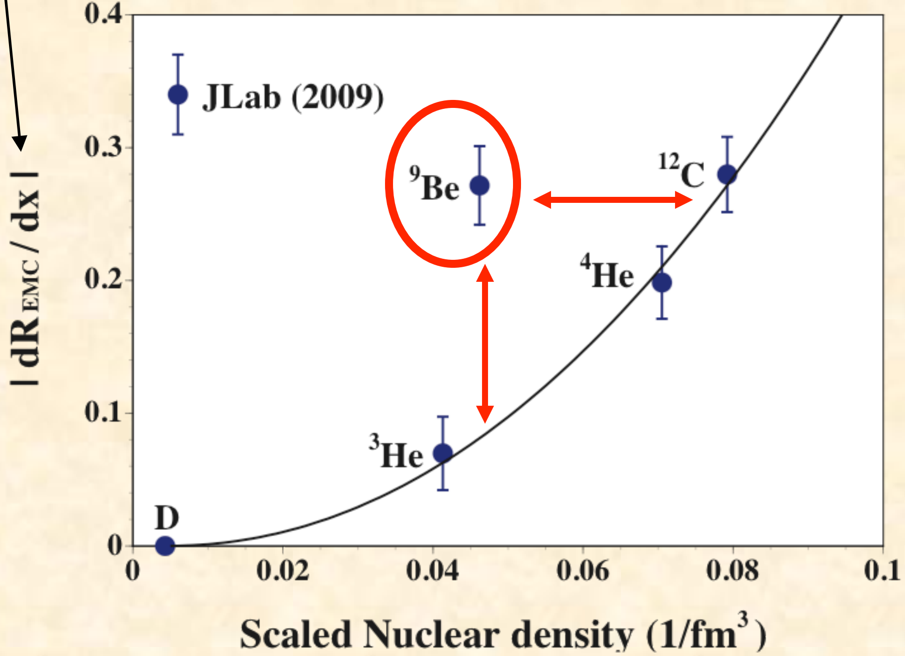
JLab “anomaly” on ^{9}Be

J. Seely *et al.*,
Phys. Rev. Lett. 103 (2009) 202301.



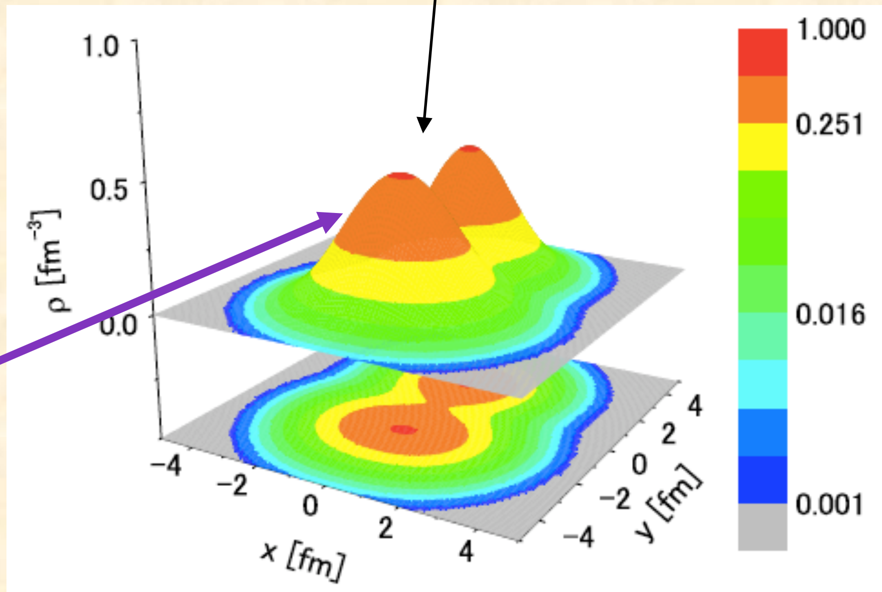
Slope: $\frac{dR_{EMC}}{dx}$, $R_{EMC} = \frac{\sigma_A}{\sigma_D}$

^{9}Be anomaly = EMC slope is too large
to be estimated from its nuclear density



Purpose

Typical nuclear clustering



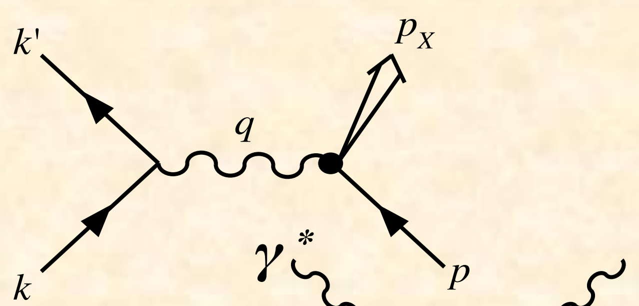
A theoretical-model density with cluster structure for ^{9}Be

High-density regions
= Something new?
(Nucleon modifications,
Short-range correlations, …)

A signature of nuclear clustering in high-energy processes, particularly in structure functions of deep inelastic scattering.

→ Internal nucleon modifications, Short-range correlations, …

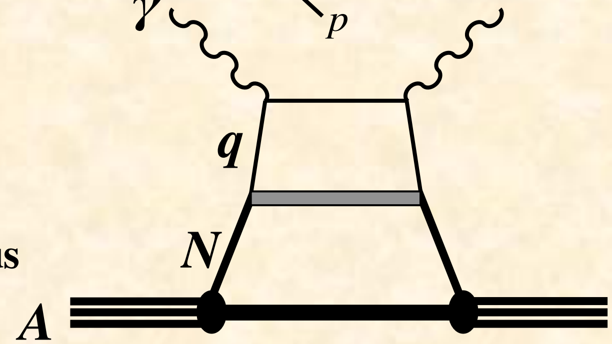
Convolution formalism



Charged-lepton deep inelastic scattering from a nucleus

$d\sigma \sim L^{\mu\nu} W^A_{\mu\nu}$, $L^{\mu\nu}$ = Lepton tensor,

Hadron tensor: $W_{\mu\nu} = \dfrac{1}{4\pi}\int d^4\xi\, e^{iq\cdot\xi} \langle p | \left[J^{em}_\mu(\xi), J^{em}_\nu(0) \right] | p \rangle$



Convolution: $W^A_{\mu\nu}(p_A, q) = \int d^4 p\, S(p)\, W^N_{\mu\nu}(p_N, q)$

$S(p)$ = Spectral function = nucleon momentum distribution in a nucleus

In a simple model: $S(p_N) = |\phi(\vec{p}_N)|^2\, \delta\left(p^0_N - M_A + \sqrt{M^2_{A-1} + \vec{p}^{\,2}_N} \right)$

F_2 needs to be projected out from $W_{\mu\nu}$ by the projection operator $\hat{P}^{\mu\nu}_2 = -\dfrac{M^2_N \nu}{2\tilde{p}^2}\left(g^{\mu\nu} - \dfrac{3\tilde{p}^\mu \tilde{p}^\nu}{\tilde{p}^2} \right)$:

$$W_{\mu\nu} = -F_1 \frac{1}{M_N}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) + F_2 \frac{\tilde{p}_\mu \tilde{p}_\nu}{M^2_N \nu}, \quad \tilde{p}_\mu = p_\mu - \frac{p\cdot q}{q^2} q_\mu; \qquad \hat{P}^{\mu\nu}_2 W_{\mu\nu} = F_2$$

$$F^A_2(x, Q^2) = \hat{P}^{\mu\nu}_2(A) W^A_{\mu\nu}(p_A, q) = \int d^4 p\, S(p)\, \hat{P}^{\mu\nu}_2(A) W^N_{\mu\nu}(p_N, q)$$

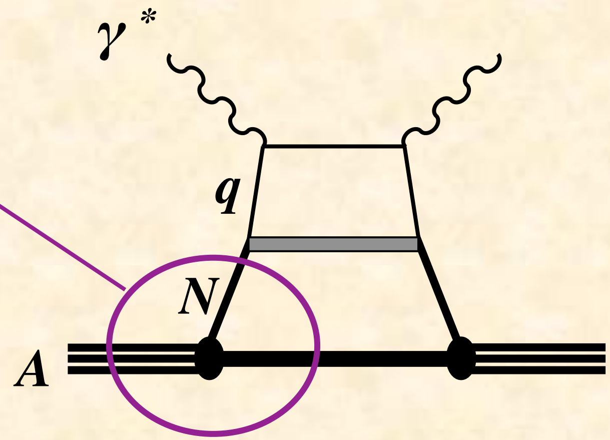
We obtain $F^A_2(x, Q^2) = \int dy\, f(y) F^N_2(x/y, Q^2)$, $\quad f(y) = \int d^3 p_N\, y\, \delta\left(y - \dfrac{p_N\cdot q}{M_N \nu} \right) |\phi(\vec{p}_N)|^2$

$f(y)$ = lightcone momentum distribution for a nucleon

$$y = \frac{p_N\cdot q}{M_N \nu} = \frac{p^0_N \nu - \vec{p}_N \cdot \vec{q}}{M_N \nu} \simeq \frac{p_N \cdot q}{p_A\cdot q / A} \simeq \frac{p^+_N}{p^+_A / A} \simeq \text{lightcone momentum fraction}, \quad p^\pm = \frac{p^0 \pm p^3}{\sqrt{2}}$$

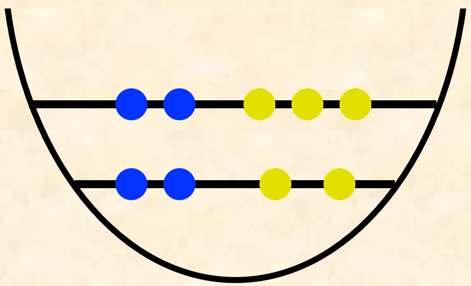
M. Ericson and SK, Phys. Rev. C 67 (2003) 022201.
including Q^2 / M^2_N effects.

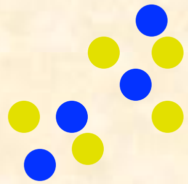
Two theoretical models



$$F_2^A(x,Q^2) = \int dy\, f(y) F_2^N(x/y,Q^2), \quad f(y) = \int d^3p_N\, y\, \delta\left(y - \frac{p_N \cdot q}{M_N \nu}\right) \rho(p_N)$$

Nuclear density $\rho(p_N)$ is calculated by
(1) Simple shell model
(2) Anti-symmetrized molecular dynamics (AMD)





AMD: variational method with effective NN potentials

Simple shell model

$$\psi_{nlm}(r,\theta,\phi) = R_{nl}(r) Y_{lm}(\theta,\phi)$$

$$R_{nl}(r) = \sqrt{\frac{2\kappa^{2\ell+3}(n-1)!}{[\Gamma(n+\ell+1/2)]^3}}\, r^\ell e^{-\frac{1}{2}\kappa^2 r^2} L_{n-1}^{\ell+1/2}(\kappa^2 r^2)$$

$$\kappa^2 \equiv M_N \omega, \qquad V = \frac{1}{2} M_N \omega^2 r^2$$

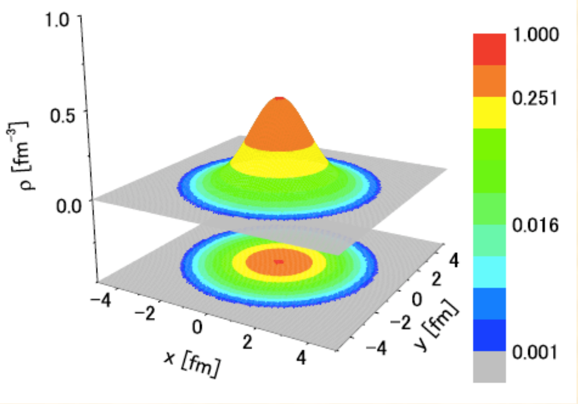
Slater determinant: $$\left|\Phi(\vec{r}_1,\vec{r}_2,\cdots,\vec{r}_A)\right\rangle = \frac{1}{\sqrt{A!}} \begin{vmatrix} \varphi_1(\vec{r}_1) & \varphi_1(\vec{r}_2) & \cdots & \varphi_1(\vec{r}_A) \\ \varphi_2(\vec{r}_1) & \varphi_2(\vec{r}_2) & \cdots & \varphi_2(\vec{r}_A) \\ . & . & \cdots & . \\ \varphi_A(\vec{r}_1) & \varphi_A(\vec{r}_2) & \cdots & \varphi_A(\vec{r}_A) \end{vmatrix}$$

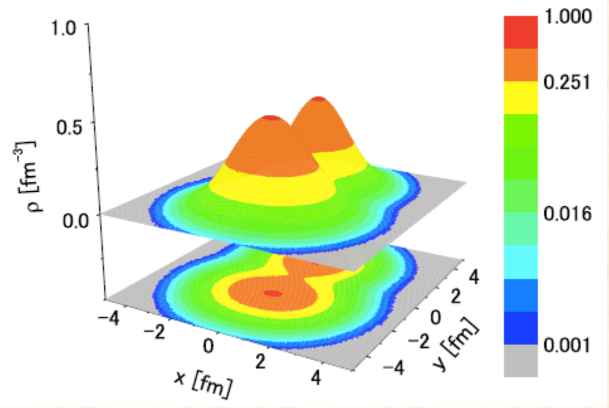
Single-particle wave function: $$\varphi_i(\vec{r}_j) = \left(\frac{2\nu}{\pi}\right)^{3/4} \exp\left[-\nu\left(\vec{r}_j - \frac{\vec{Z}_i}{\sqrt{\nu}}\right)^2\right]$$

Parameters are determined by a variational method with effective NN potentials.

Cluster structure in ^9Be

Density distributions
in ^4He and ^9Be
by AMD





^4He

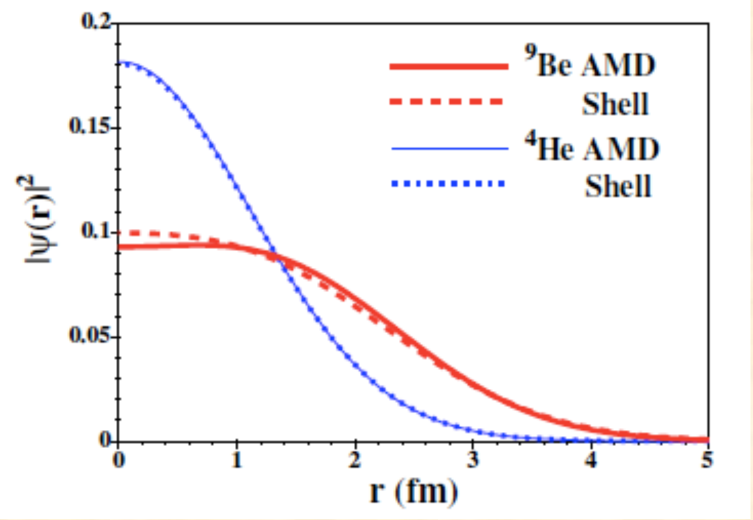
^9Be (~ ^4He + ^4He + n)

Two models:

(1) Shell model

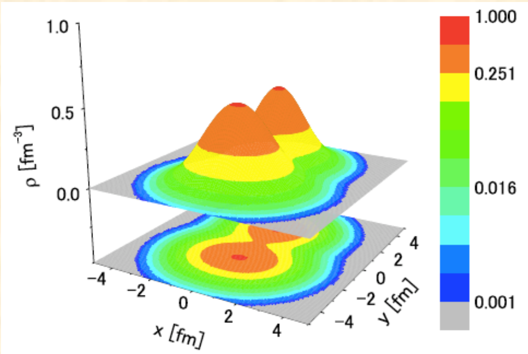
(2) AMD (antisymmetrized molecular dynamics) to describe clustering structure

Space (r) distributions

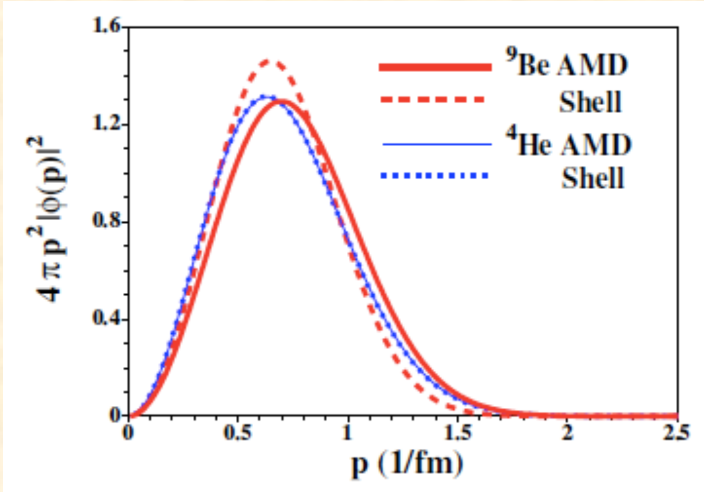


However, if the densities are averaged over the polar and azimuthal angles, differences from shell structure are not so obvious although there are some differences in ^9Be in comparison with ^4He.

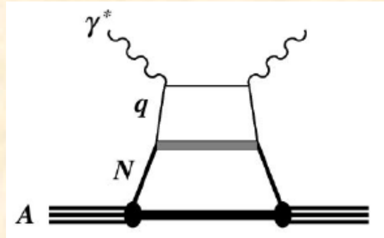
EMC effect



Momentum (p) distributions

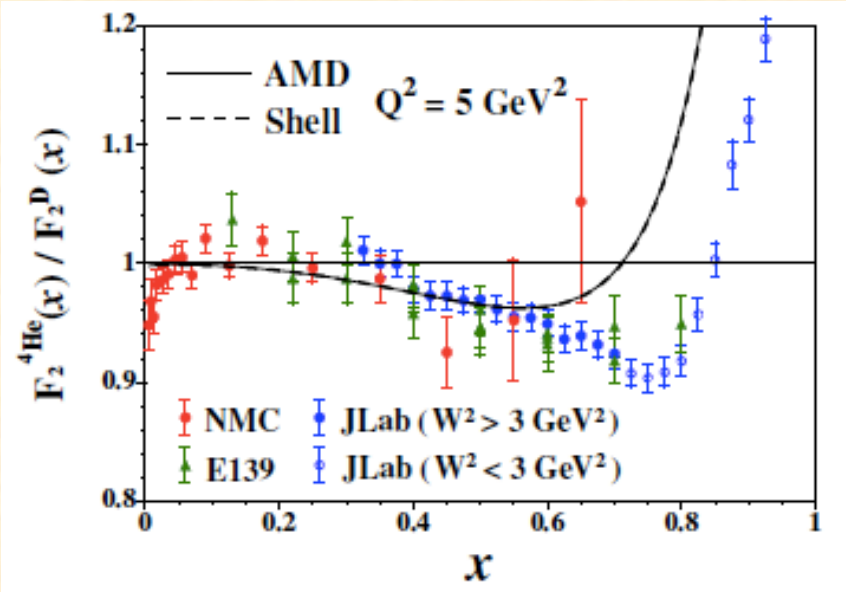


Convolution model

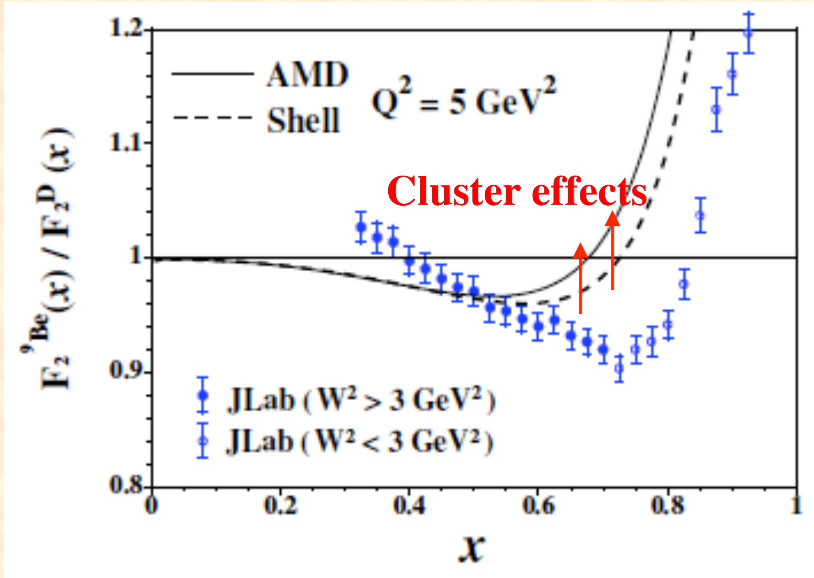


$$F_2^A(x, Q^2) = \int_x^A dy\, f(y)\, F_2^N(x/y, Q^2)$$

^{4}He



^{9}Be

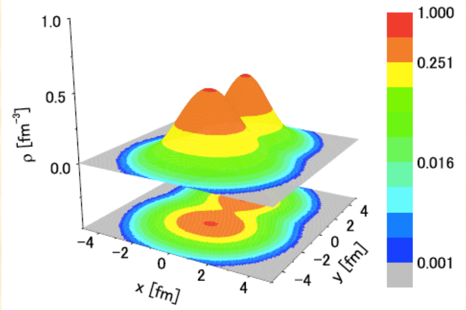


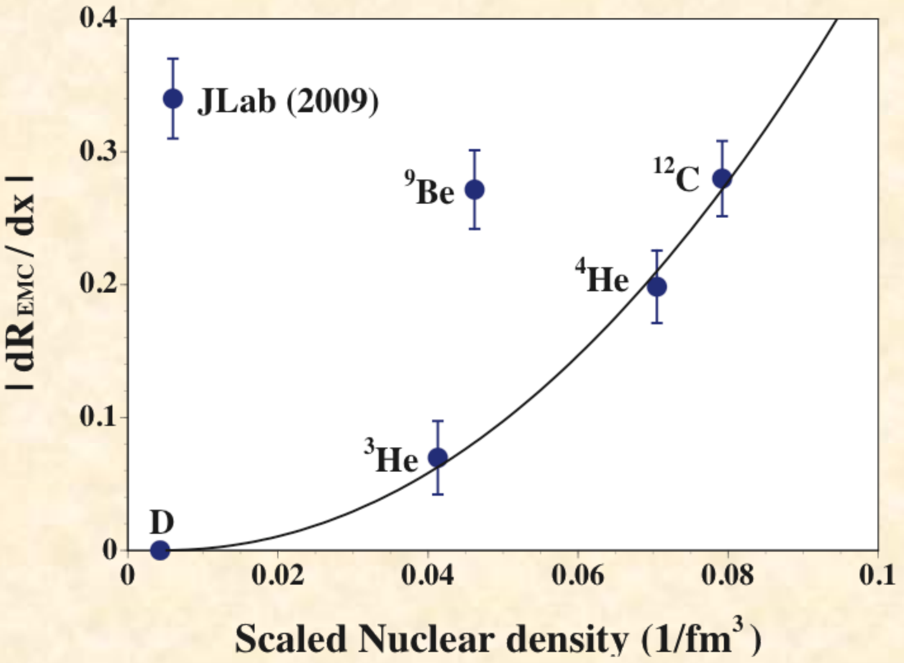
It seems that the mean conventional part cannot explain the large modification of ^{9}Be.

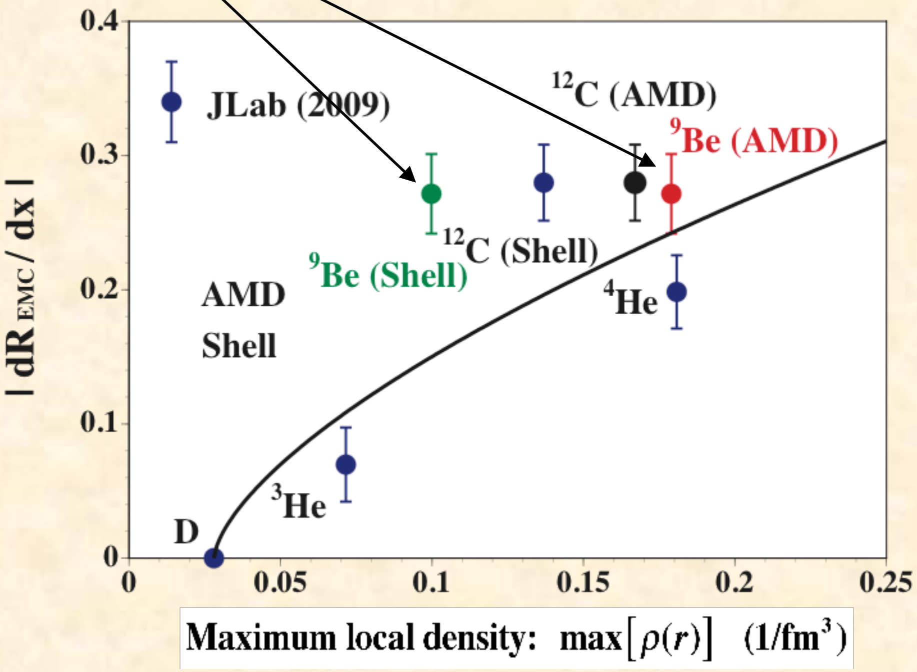
→ Plot the data by the maximum local density created by the cluster formation in ^{9}Be.

EMC slopes plotted by maximum local densities

The ^{9}Be anomaly can be explained by the high-densities, which are created by clustering in the ^{9}Be nucleus.







Original figure → Plotted by the maximum local densities

Our results indicate

$F_2^A =$ (mean part) + (part created by large densities due to cluster formation)

Convolution model indicates clustering effects are small in this term.

JLab data could be related to this effect due to the nuclear cluster.

Prospects

JLab proposal to measure structure functions of other light nuclei.

Jefferson Lab PAC-35 proposal, PR12-10-008 (2009)

Jefferson Lab Experiment E1210008

Detailed studies of the nuclear dependence of F2 in light nuclei.

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Summary on cluster effects in ^{9}Be

1. We developed a convolution formalism with clustering structure.

2. We showed density differences between shell and AMD models in nuclei (^{4}He, ^{9}Be, ^{12}C).
   Nuclear clustering produce high-momentum components.

3. Clustering effects on F_2^A by comparing shell and AMD model calculations; however, the effects are not large.

4. The JLab ^{9}Be anomaly can be "explained" if nuclear modifications are shown by maximum local densities of the AMD not by the ones of the shell model.
   → a clear signature of clustering effects in high-energy processes

5. More investigations at JLab after 12-GeV upgrade (~2014)

Nuclear modifications of $R = F_L / F_T$ at large x

Ref. M. Ericson and SK, Phys. Rev. C 67 (2003) 022201.

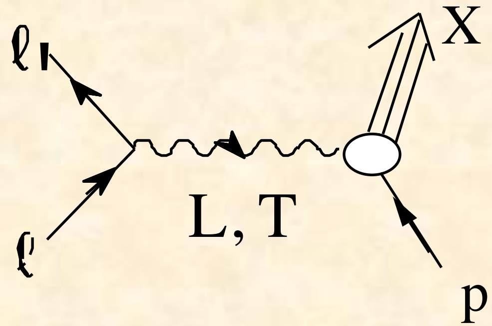
Nuclear effect on $R = F_L / F_T$ by HERMES

HERMES, K. Ackerstaff *el al.*, PL B 475 (2000) 386;

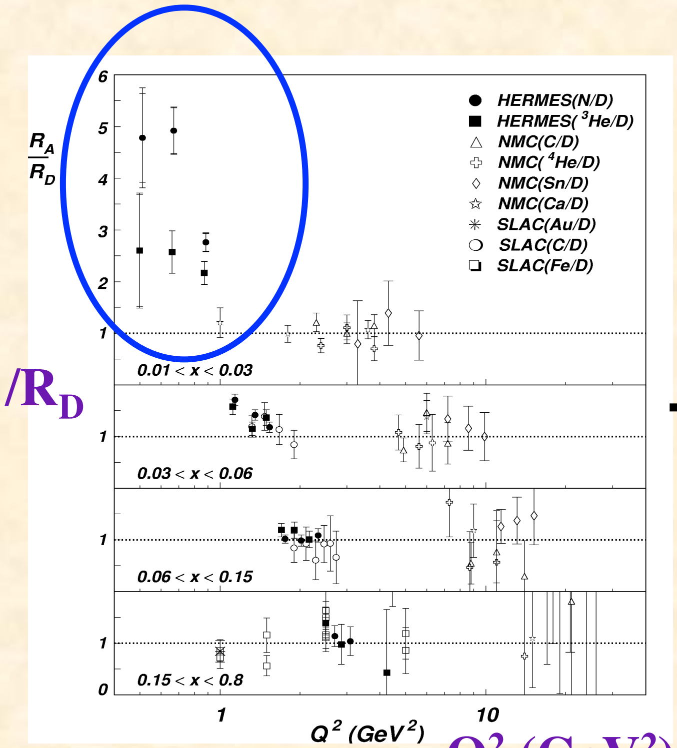
Erratum, PL B567 (2003) 339 [hep-ex/0210067; hep-ex/0210068].

Longitudinal and transverse components $W_\lambda = \varepsilon_\lambda^{\mu\,*}\, \varepsilon_\lambda^{\nu}\, W_{\mu,\nu}$

$$W_T = \frac{1}{2}\,(W_{\lambda=+1} + W_{\lambda=-1}) = W_1 \qquad W_L = W_{\lambda=0} = \left(1 + \frac{\nu^2}{Q^2}\right) W_2 - W_1$$

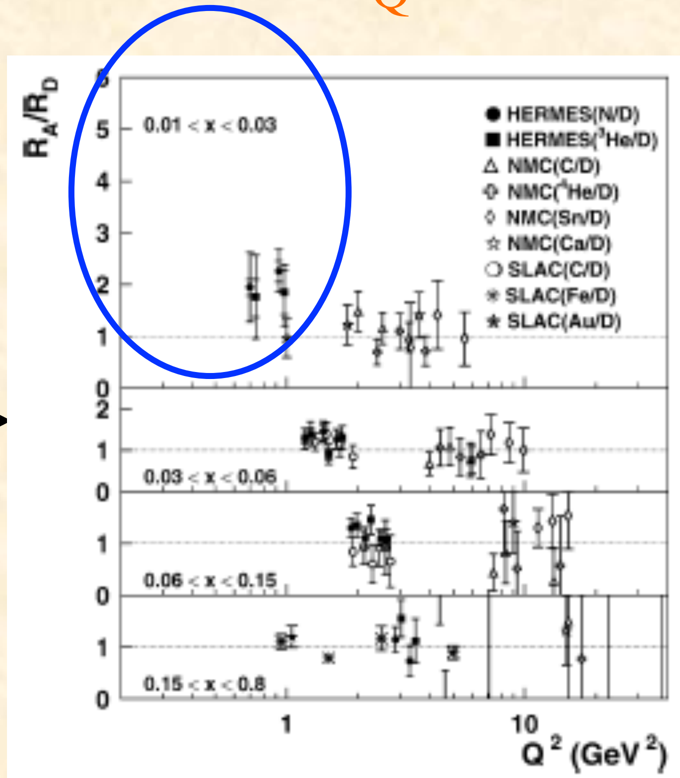


R_A / R_D



Q^2 (GeV^2)

(2000)



(2003)

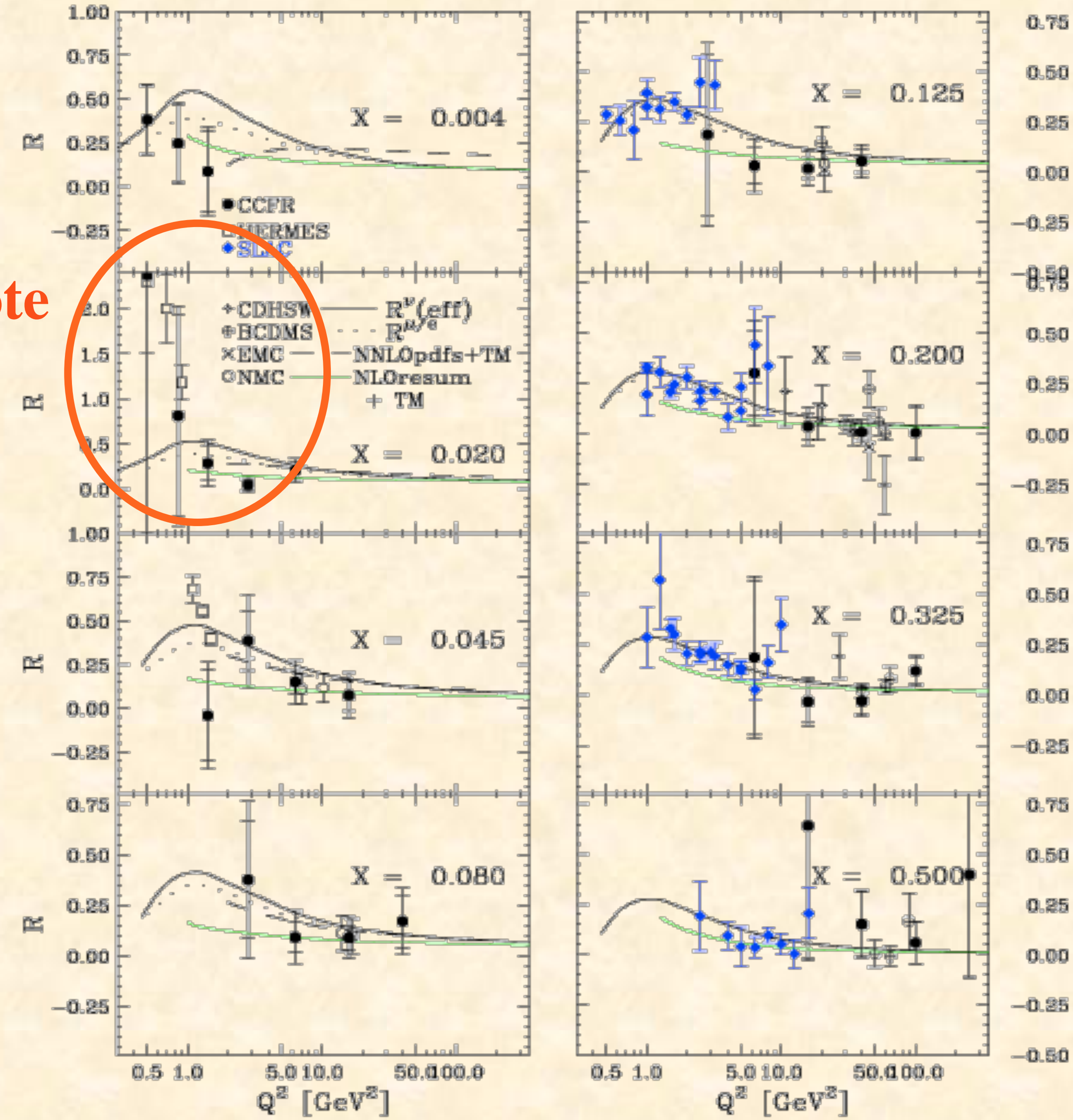
Nuclear effects on *R* by CCFR/NuTeV

U.-K. Yang *et al.*, PRL 87 (2001) 251802.

● CCFR　　□ HERMES

● SLAC

note



No significant deviation is measured from the nucleon case ( ).

↓

No large nuclear modification of *R* is observed in ν+Fe!

(note: CCF/NuTeV target is Fe)

M. Ericson and SK, Phys. Rev. C 67 (2003) 022201

- Submitted (Nov. 30, 2002) just after the HERMES correction paper (Oct. 31, 2002).
- Nuclear modifications of transverse-longitudinal ratio do exist in medium and large-x regions, although the modifications do not seem to exist at small x within experimental errors according to the revised HERMES paper.
- Mechanisms

(1) Transverse nucleon motion

→ T-L admixture of nucleon structure functions.

(2) Binding and Fermi-motion effects in the spectral function.

Formalism

$$W_{\mu\nu}^{A,N} = -W_1^{A,N}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) + W_2^{A,N}\frac{1}{M_N^2}\tilde{p}_\mu^{A,N}\tilde{p}_\nu^{A,N} \qquad \tilde{p}_\mu = p_\mu - \frac{p\cdot q}{q^2}q_\mu$$

$$F_1 = M_N W_1,\quad F_2 = \nu W_2,\quad F_L = \frac{Q^2}{\nu}W_L = \left(1+\frac{Q^2}{\nu^2}\right)F_2 - 2xF_1$$

Projection operators of W_1^A and W_2^A

$$\hat{P}_1^{\mu\nu} = -\frac{1}{2}\left(g^{\mu\nu} - \frac{\tilde{p}_A^\mu \tilde{p}_A^\nu}{\tilde{p}^2}\right),\quad \hat{P}_2^{\mu\nu} = -\frac{p_A^2}{2\tilde{p}_A^2}\left(g^{\mu\nu} - \frac{3\tilde{p}_A^\mu \tilde{p}_A^\nu}{\tilde{p}^2}\right) \qquad \hat{P}_{1,2}^{\mu\nu}W_{\mu\nu}^A = W_{1,2}^A$$

Convolution: $W_{\mu\nu}^A(p_A,q) = \int d^4p\, S(p)\, W_{\mu\nu}^N(p_N,q)$

$$W_{1,2}^A(p_A,q) = \int d^4p\, S(p)\,\hat{P}_{1,2}^{\mu\nu}W_{\mu\nu}^N(p_N,q)$$

Longitudinal and transverse components $\quad W_\lambda^{A,N} = \varepsilon_\lambda^{\mu*}\varepsilon_\lambda^\nu W_{\mu\nu}^{A,N}$

$$W_T^{A,N} = \frac{1}{2}(W_{\lambda=+1}^{A,N} + W_{\lambda=-1}^{A,N}) = W_1^{A,N} \qquad W_L^{A,N} = W_{\lambda=0}^{A,N} = \left(1+\frac{\nu_{A,N}^2}{Q^2}\right)W_2^{A,N} - W_1^{A,N}$$

$$\nu_A^2 = \nu^2 = \frac{(p_N\cdot q)^2}{p_N^2}$$

Formalism (continued)

Scaling variables: $x_A = \dfrac{Q^2}{2p_A\cdot q} = \dfrac{M_N}{M_A}x, \quad x_N = \dfrac{Q^2}{2p_N\cdot q} = \dfrac{x}{z}, \quad x = \dfrac{Q^2}{2M_A\nu}, \quad z = \dfrac{p_N\cdot q}{M_A\nu}$

Longitudinal structure functions F_1 and F_2 : $F_L^{A,N} = \left(1 + \dfrac{Q^2}{\nu_{A,N}^2}\right)F_2^{A,N} - 2x_{A,N}F_1^{A,N}$

Transverse-longitudinal ratio: $R_{\mathrm{A,N}} = \dfrac{F_L^{A,N}}{2x_{A,N}F_1^{A,N}}$

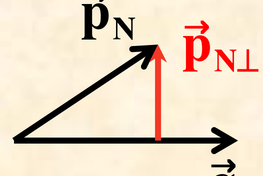
Calculating $W_{1,2}^A = \hat{P}_{1,2}^{\mu\nu}\, W_{\mu\nu}^A = \hat{P}_{1,2}^{\mu\nu}\int d^4p_N\, S(p_N)\, W_{\mu\nu}^N$,

$$2\,x_A\,F_1^A = \int d^4p_N\, S(p_N)\, z\,\frac{M_N}{\sqrt{p_N^2}}\left[\left(1 + \frac{\vec{p}_{N\perp}^{\,2}}{2\,\tilde{\vec{p}}_N^{\,2}}\right)2\,x_N\,F_1^N(x_N, Q^2) + \frac{\vec{p}_{N\perp}^{\,2}}{2\,\tilde{\vec{p}}_N^{\,2}}\,F_L^N(x_N, Q^2)\right]$$

$$F_L^A = \int d^4p_N\, S(p_N)\, z\,\frac{M_N}{\sqrt{p_N^2}}\left[\left(1 + \frac{\vec{p}_{N\perp}^{\,2}}{\tilde{\vec{p}}_N^{\,2}}\right)F_L^N(x_N, Q^2) + \frac{\vec{p}_{N\perp}^{\,2}}{\tilde{\vec{p}}_N^{\,2}}\,2\,x_N\,F_1^N(x_N, Q^2)\right]$$

Transverse-longitudinal admixture

$$\frac{\vec{p}_{N\perp}^{\,2}}{\tilde{\vec{p}}_N^{\,2}} = \frac{4\,x_N^2\,\vec{p}_{N\perp}^{\,2}}{Q^2(1 + 4\,x_N^2\,p_N^2/Q^2)} \approx \frac{4\,x_N^2\,\vec{p}_{N\perp}^{\,2}}{Q^2}$$

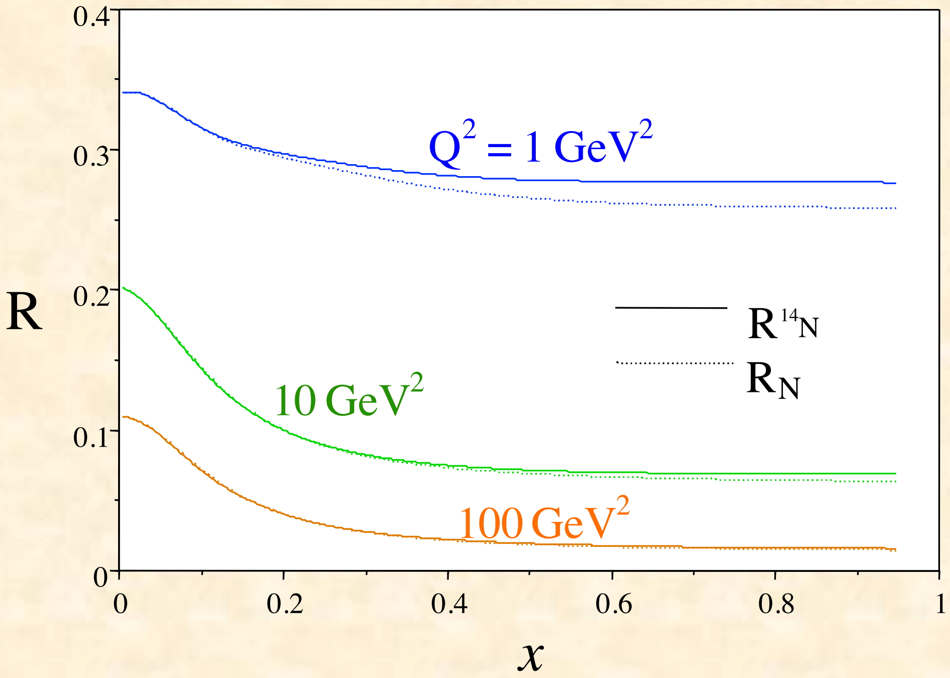


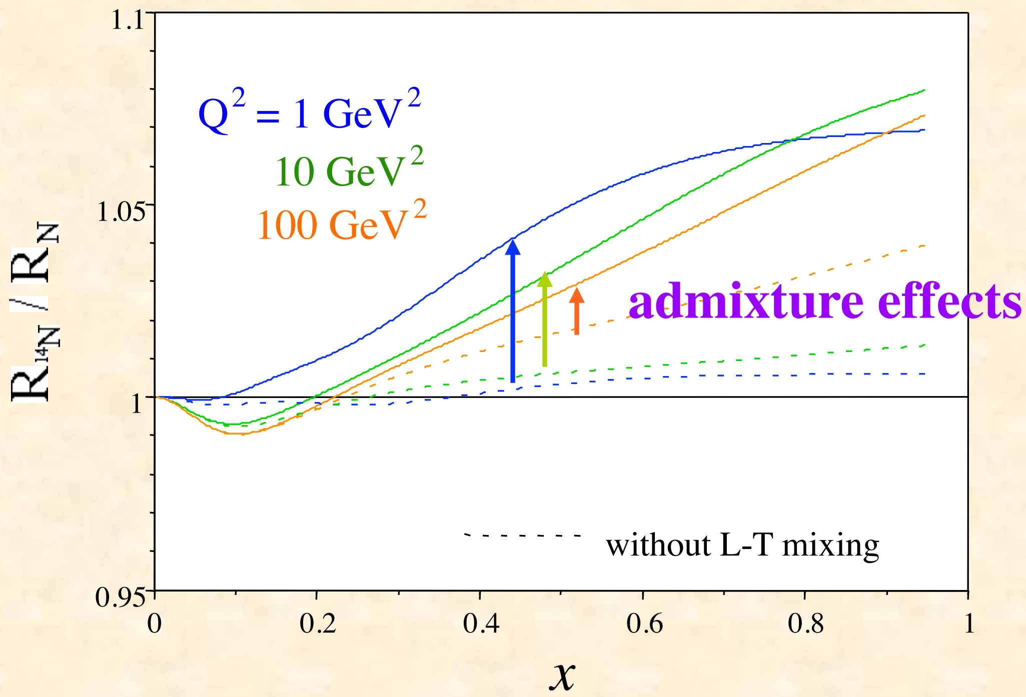
Results

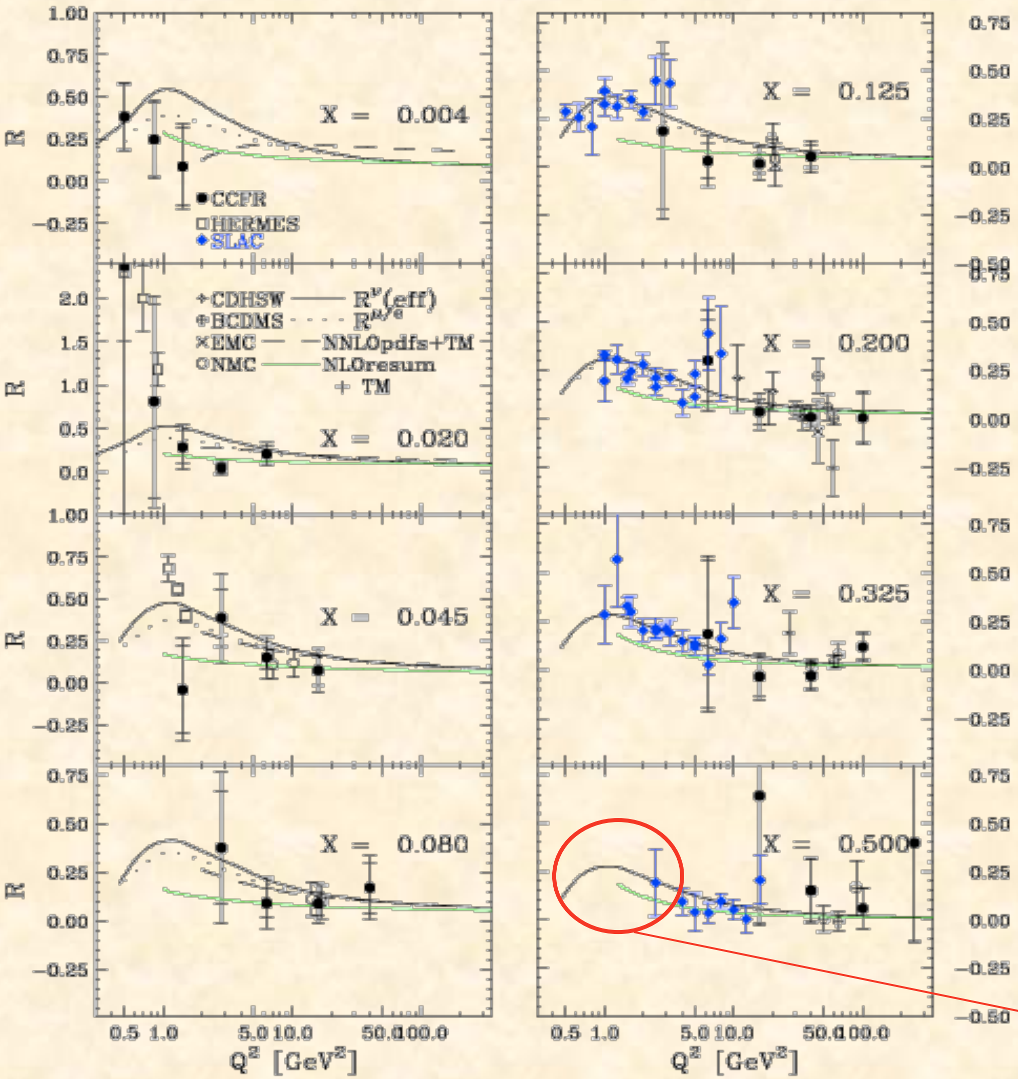
- Spectral function $\quad (M_{A-i} = M_A - M_N - \varepsilon_i)$

$$S(p_N) = \sum_i \left| \phi(\vec{p}_N) \right|^2 \delta\left(p_N^0 - M_A + \sqrt{M_{A-i}^2 + \vec{p}_N^{\,2}}\right) \quad \text{for } {}^{14}N$$

- Transverse-longitudinal ratio: R_{1990}
- F_2^N (PDFs): MRST98-LO







After the HERMES (CCFR/NuTeV) re-analysis, people tend to lose interest in the nuclear effect on R.
However, we claim that nuclear modification should exist in medium and large-*x* regions.

Physical origins

- **transverse-longitudinal admixture due to the transverse Fermi motion**
- **binding and Fermi motion effects in the spectral function**

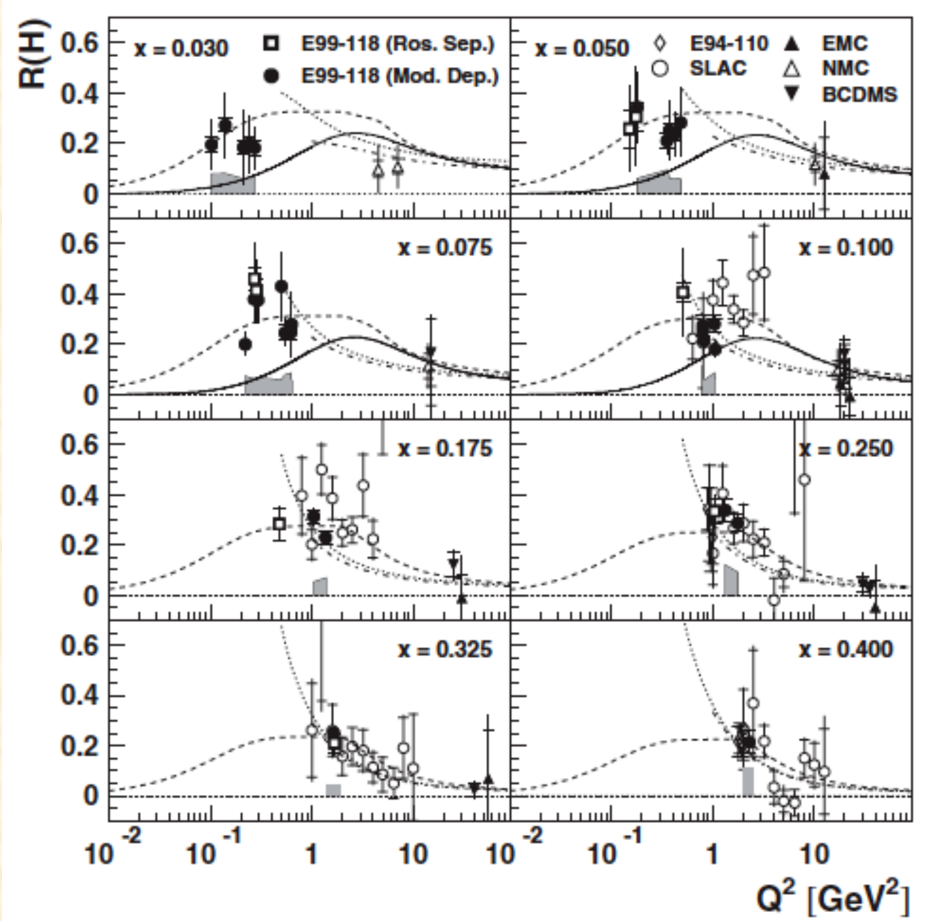
In the kinematical region of our prediction, data does not exist.
Need future experimental investigations at
JLab, EIC, ν factory, …

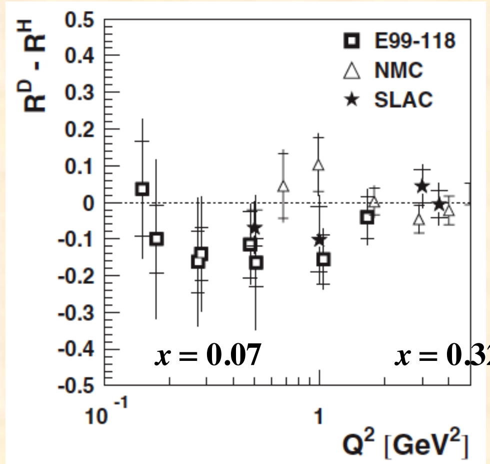
JLab measurements in 2007

- V. Tvaskis *et al.*, PRL 98 (2007) 142301.
- Lingyan Zhu (Hampton Univ), personal communications (2009).

——— Badelek, Kwiecinski, Stasto (1997)
- - - - - - - - E99-118
-·-·-·-·-· MRST-2004
.... GRV-1995

$E_e = 2.301,\ 3.419,\ 5.648$ GeV
$0.007 < x < 0.55,\ \ 0.06 < Q^2 < 2.8\ \text{GeV}^2$
proton, deuteron





Q^2 (GeV^2)	x	R^H	Stat.	Syst.	$R^D - R^H$	Stat.	Syst.
0.150	0.041	0.259	0.074	0.153	0.036	0.131	0.136
0.175	0.050	0.307	0.056	0.188	−0.100	0.091	0.196
0.273	0.077	0.460	0.049	0.132	−0.162	0.084	0.153
0.283	0.081	0.414	0.045	0.117	−0.141	0.071	0.138
0.476	0.156	0.283	0.063	0.025	−0.115	0.091	0.061
0.508	0.091	0.406	0.038	0.168	−0.164	0.065	0.172
1.045	0.200	0.335	0.048	0.041	−0.155	0.068	0.046
1.670	0.320	0.211	0.038	0.021	−0.040	0.057	0.051

Almost same for *p* an *d*, but at $0.04 < x < 0.32$.

→ In any case, nuclear modifications should be small for the deuteron.

→ Importance of future JLab measurements for heavier nuclei, <u>especially at large *x* (>0.4)</u>.

Effects on NuTeV $\sin^2\theta_W$ anomaly due to nuclear modification differences between u_v and d_v

(1) S. Kumano, Phys. Rev. D66 (2002) 111301.

Charge and baryon-number conservations indicate that there should exist a difference between nuclear modifications of $u_v(x)$ and $d_v(x)$.

(2) M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. D71 (2005) 113007.

Global analysis for the difference between nuclear modifications of $u_v(x)$ and $d_v(x)$. → Could be the origin of the NuTeV anamaly but with large erros.

$\sin^2\theta_W$ anomaly

Others: $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = 0.2227 \pm 0.0004$

NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013\ (\mathrm{stat}) \pm 0.0009\ (\mathrm{syst})$

Paschos-Wolfenstein (PW) relation

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_W$$

NuTeV target: ^{56}Fe ($Z = 26$, $N = 30$)
not isoscalar nucleus

N = isoscalar nucleon

⟶ nuclear effects should be carefully taken into account

Charged current (CC) cross sections for νA and $\bar{\nu} A$:

$$\frac{d\sigma_{CC}^{\nu A}}{dx\,dy} = \sigma_0\, x\, [\, d^A(x) + s^A(x) + \{\bar{u}^A(x) + \bar{c}^A(x)\}\,(1-y)^2]$$

$$\frac{d\sigma_{CC}^{\bar{\nu} A}}{dx\,dy} = \sigma_0\, x\, [\, \bar{d}^A(x) + \bar{s}^A(x) + \{u^A(x) + c^A(x)\}\,(1-y)^2]$$

where $\sigma_0 = G_F^2\, s / \pi$

Neutral current (NC):

$$\frac{d\sigma_{NC}^{\nu A}}{dx\,dy} = \sigma_0\, x\, [\, \{u_L^2 + u_R^2\,(1-y)^2\}\{u^A(x) + c^A(x)\}$$
$$+ \{u_R^2 + u_L^2\,(1-y)^2\}\{\bar{u}^A(x) + \bar{c}^A(x)\}$$
$$+ \{d_L^2 + d_R^2\,(1-y)^2\}\{d^A(x) + s^A(x)\}$$
$$+ \{d_R^2 + d_L^2\,(1-y)^2\}\{\bar{d}^A(x) + \bar{s}^A(x)\}$$

$$\frac{d\sigma_{NC}^{\bar{\nu} A}}{dx\,dy} = \frac{d\sigma_{NC}^{\nu A}}{dx\,dy}\ (L \leftrightarrow R)$$

$$u_L = +\frac{1}{2} - \frac{2}{3}\sin\theta_W^2\,,\quad u_R = -\frac{2}{3}\sin\theta_W^2$$

$$d_L = -\frac{1}{2} + \frac{1}{3}\sin\theta_W^2\,,\quad u_R = +\frac{1}{3}\sin\theta_W^2$$

$$R_A^- = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}} = \frac{\{1-(1-y)^2\}\,[\,(u_L^2 - u_R^2)\{u_v^A(x) + c_v^A(x)\} + (d_L^2 - d_R^2)\{d_v^A(x) + s_v^A(x)\}]}{d_v^A(x) + s_v^A(x) - (1-y)^2\{u_v^A(x) + c_v^A(x)\}}$$

$$q_v^A \equiv q^A - \bar{q}^A$$

(1) Difference between nuclear modifications of u_V and d_V: $\varepsilon_v(x) = \dfrac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}$

Nuclear effects are in the weight functions: w_{u_v} and w_{d_v}

$$u_v^A(x) = w_{u_v}(x)\,\frac{Z\,u_v(x) + N\,d_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x)\,\frac{Z\,d_v(x) + N\,u_v(x)}{A}$$

(2) Neutron excess: $\varepsilon_n(x) = \dfrac{N-Z}{A}\,\dfrac{u_V(x) - d_V(x)}{u_V(x) + d_V(x)}$

$$q_v(x) \equiv q(x) - \bar{q}(x)$$

(3) Strange, Charm: $\varepsilon_s(x)$, $\varepsilon_c(x) = \dfrac{2\,s_v^A(x) \quad \text{or} \quad 2\,c_v^A(x)}{[w_{uv}(x) + w_{dv}(x)][u_V(x) + d_V(x)]}$

$$R_A^- = \frac{(\frac{1}{2} - \sin^2\theta_W)\,\{1 + \varepsilon_v(x)\,\varepsilon_n(x)\} + \frac{1}{3}\sin^2\theta_W\,\{\varepsilon_v(x) + \varepsilon_n(x)\} + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\,\varepsilon_s(x) + (\frac{1}{2} - \frac{4}{3}\sin^2\theta_W)\,\varepsilon_c(x)}{1 + \varepsilon_v(x)\,\varepsilon_n(x) + \frac{1+(1-y)^2}{1-(1-y)^2}\,\{\varepsilon_v(x) + \varepsilon_n(x)\} + \frac{2\{\varepsilon_s(x) - (1-y)^2\,\varepsilon_c(x)\}}{1-(1-y)^2}}$$

Expand in $\varepsilon_v, \varepsilon_n, \varepsilon_s, \varepsilon_c \ll 1$

We investigate this term. (→ $O(\varepsilon_v)$)

$$\mathbf{R_A^- = \frac{1}{2} - \sin^2\theta_W + O(\varepsilon_v) + O(\varepsilon_n) + O(\varepsilon_s) + O(\varepsilon_c)}$$

$\varepsilon_v(x)$ effects on $\sin^2\theta_W$

2002 version

SK, Phys. Rev. D66 (2002) 111301.

Constraints of baryon number and charge

$$Z = \int dx\, A \sum_q e_q (q^A - \bar{q}^A) = \int dx\, \frac{A}{3} (2 u_v^A - d_v^A)$$

$$A = \int dx\, A \sum_q \frac{1}{3} (q^A - \bar{q}^A) = \int dx\, \frac{A}{3} (u_v^A + d_v^A)$$

→ (A) $\int dx\, (u_v + d_v)\, [\, \Delta w_v + w_v\, \varepsilon_v(x)\, \varepsilon_n(x)\,] = 0$

(B) $\int dx\, (u_v + d_v)\, [\, \Delta w_v \{1 - 3\, \varepsilon_n(x)\} - w_v\, \varepsilon_v(x)\, \{3 - \varepsilon_n(x)\}\,] = 0$

where $w_v = \dfrac{w_{u_v} + w_{d_v}}{2}$, $\Delta w_v = w_v - 1$

Prescription 1. Neglect $O(\varepsilon^2)$, then integrand (B) = 0

$$\varepsilon_V^{(1)}(x) = -\frac{N - Z}{A}\, \frac{u_V(x) - d_V(x)}{u_V(x) + d_V(x)}\, \frac{\Delta w_V(x)}{w_V(x)}$$

Prescription 2. χ^2 analysis of NPDFs

$$\varepsilon_V^{(2)}(x) = \frac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}$$

→ **We discuss this point in the following.**

Global analysis of F_2 and Drell-Yan data for $\varepsilon_v(x)$

$$u_v^A(x) = w_{u_v}(x,A)\,\frac{Z\,u_v(x) + N\,d_v(x)}{A}$$

$$d_v^A(x) = w_{d_v}(x,A)\,\frac{Z\,d_v(x) + N\,u_v(x)}{A}$$

$$\bar{q}^A(x) = w_{\bar{q}}(x,A)\,\bar{q}(x), \quad g^A(x) = w_g(x,A)\,g(x)$$

in the NPDF analysis

$$w_{uv} = 1 + (1-1/A^{1/3})\,\frac{a_{uv}+b_v x+c_v x^2+d_v x^3}{(1-x)^{\beta_v}}$$

$$w_{dv} = 1 + (1-1/A^{1/3})\,\frac{a_{dv}+b_v x+c_v x^2+d_v x^3}{(1-x)^{\beta_v}}$$

in the current analysis

$$w_{uv} + w_{dv} = 1 + (1-1/A^{1/3})\,\frac{a_v+b_v x+c_v x^2+d_v x^3}{(1-x)^{\beta_v}}$$

$$w_{uv} - w_{dv} = 1 + (1-1/A^{1/3})\,\frac{a_v'+b_v' x+c_v' x^2+d_v' x^3}{(1-x)^{\beta_v}}$$

2004 version

Analysis result for $\varepsilon_v(x)$

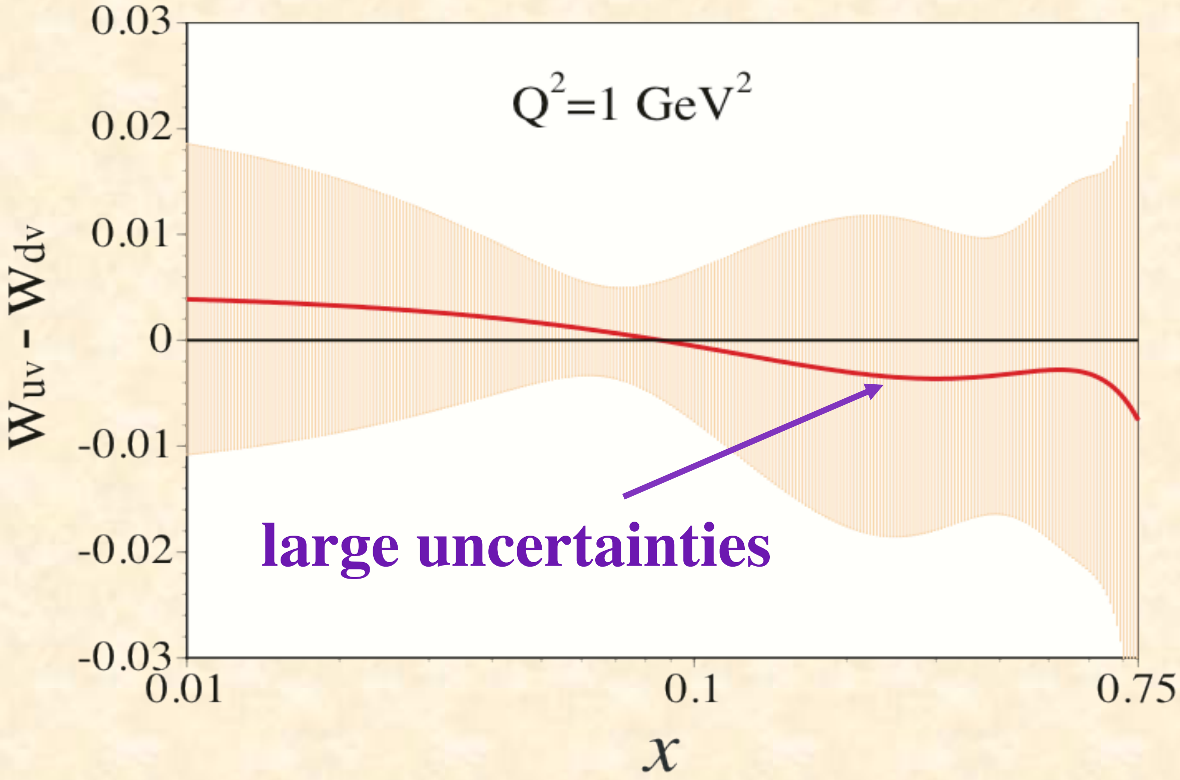
$$\varepsilon_v(x) = \frac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}$$

$$R_{\bar{A}} = \frac{1}{2} - \sin^2\theta_W - \varepsilon_v(x) \left\{ \left(\frac{1}{2} - \sin^2\theta_W\right) \frac{1+(1-y)^2}{1-(1-y)^2} - \frac{1}{3}\sin^2\theta_W \right\} + O(\varepsilon_v^2)$$

$$w_{uv} - w_{dv} = 1 + (1-1/A^{1/3}) \frac{a'_v + b'_v x + c'_v x^2 + d'_v x^3}{(1-x)^{\beta_v}}$$

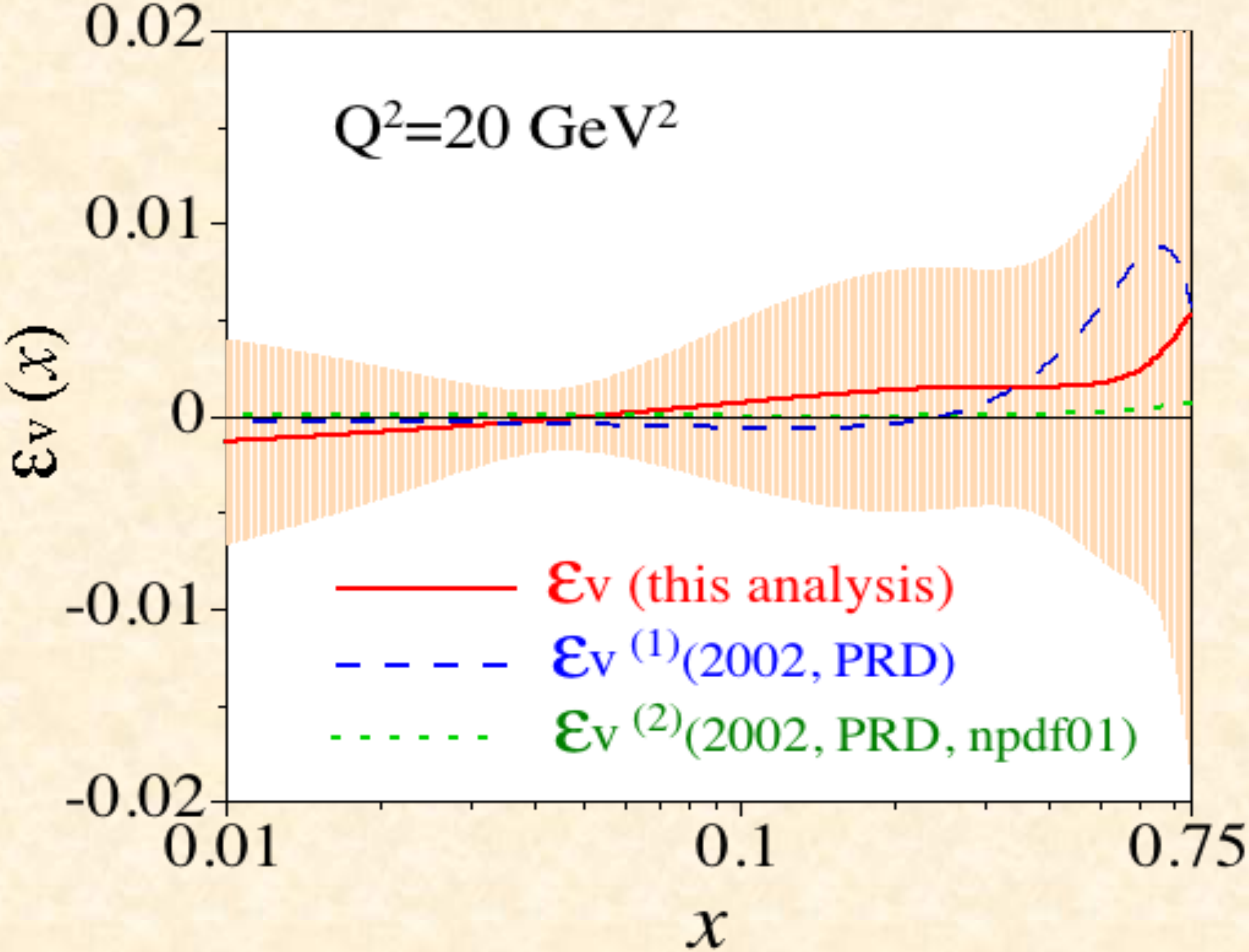
a'_v, b'_v, c'_v, d'_v are determined by the analysis

M. Hirai, SK, T.-H. Nagai, Phys. Rev. D71 (2005) 113007.



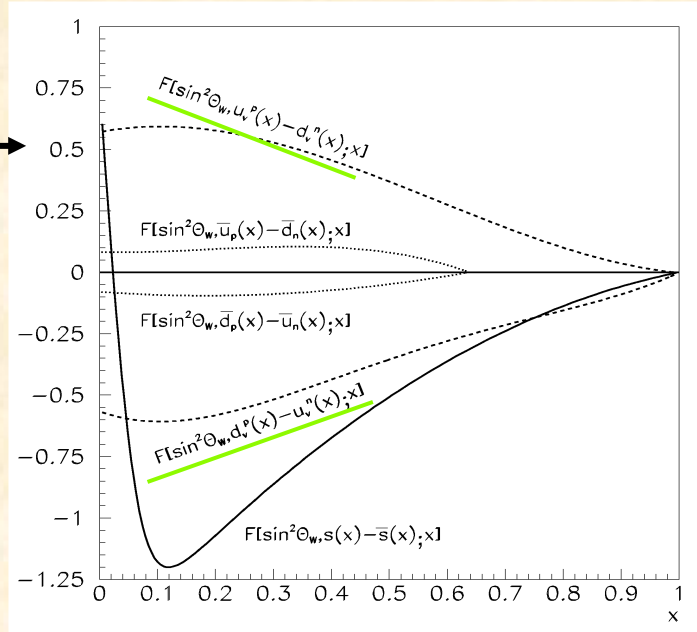
It is very difficult to determine the difference between nuclear modifications of u_v and d_v distributions at this stage.

Comparison with the 2002 results



NuTeV kinematics

G. P. Zeller et al. Phys. Rev. D65 (2002) 111103. →



x

PDFs ↔ NuTeV PDFs (*)

$$x u_V^A = w_{u_V} \frac{Z\, x u_V + N\, x d_V}{A} = \frac{Z\, u^*_{Vp} + N\, u^*_{Vn}}{A}$$

$$x d_V^A = w_{d_V} \frac{Z\, x d_V + N\, x u_V}{A} = \frac{Z\, d^*_{Vp} + N\, d^*_{Vn}}{A}$$

$$\rightarrow\ u^*_{Vp} = w_{u_V} x u_V,\ u^*_{Vn} = w_{u_V} x d_V,\ d^*_{Vp} = w_{d_V} x d_V,\ d^*_{Vn} = w_{d_V} x u_V$$

$$\rightarrow\ \delta u^*_V = u^*_{Vp} - d^*_{Vn} = -\varepsilon_V\,(w_{u_V} + w_{d_V})\, x u_V$$

$$\delta d^*_V = d^*_{Vp} - u^*_{Vn} = +\varepsilon_V\,(w_{u_V} + w_{d_V})\, x d_V$$

$$\Delta \sin^2\theta_W = -\int dx\, \{ F[\delta u^*_V, x]\, \delta u^*_V + F[\delta d^*_V, x]\, \delta d^*_V \}$$

$$= 0.0004 \pm 0.0015$$

at Q^2=20 GeV^2

Summary on NuTeV $\sin^2\theta_W$

(1) χ^2 analysis for the difference between nuclear modifications of u_v and d_v distributions.

It is very difficult to determine it at this stage.

(2) Effect on NuTeV $\sin^2\theta_W$

$\Delta(\sin^2\theta_W) = 0.0004 \pm 0.0015$ (with a large error)

The End

The End