The Polarized Structure Function $g_2(x,Q^2)$

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بسم الله الرحمن الرحيم

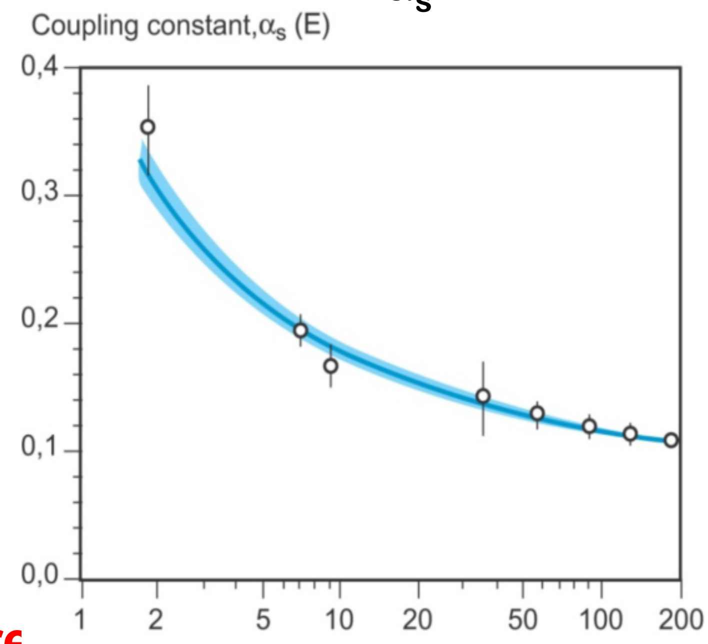
Strong Interaction and QCD

- Strong interaction, running coupling ~1
  -- QCD: accepted theory for strong interaction
  -- asymptotic freedom (2004 Nobel)
  perturbation calculation works at high energy
  -- interaction significant at intermediate energy
  quark-gluon correlations
  -- interaction strong at low energy (nucleon size)
  confinement

❖ theoretical tools:
pQCD, OPE, Lattice QCD, …

- A major challenge in fundamental physics:
  Understand QCD in strong interaction region
  → Study and understand nucleon structure

α_s



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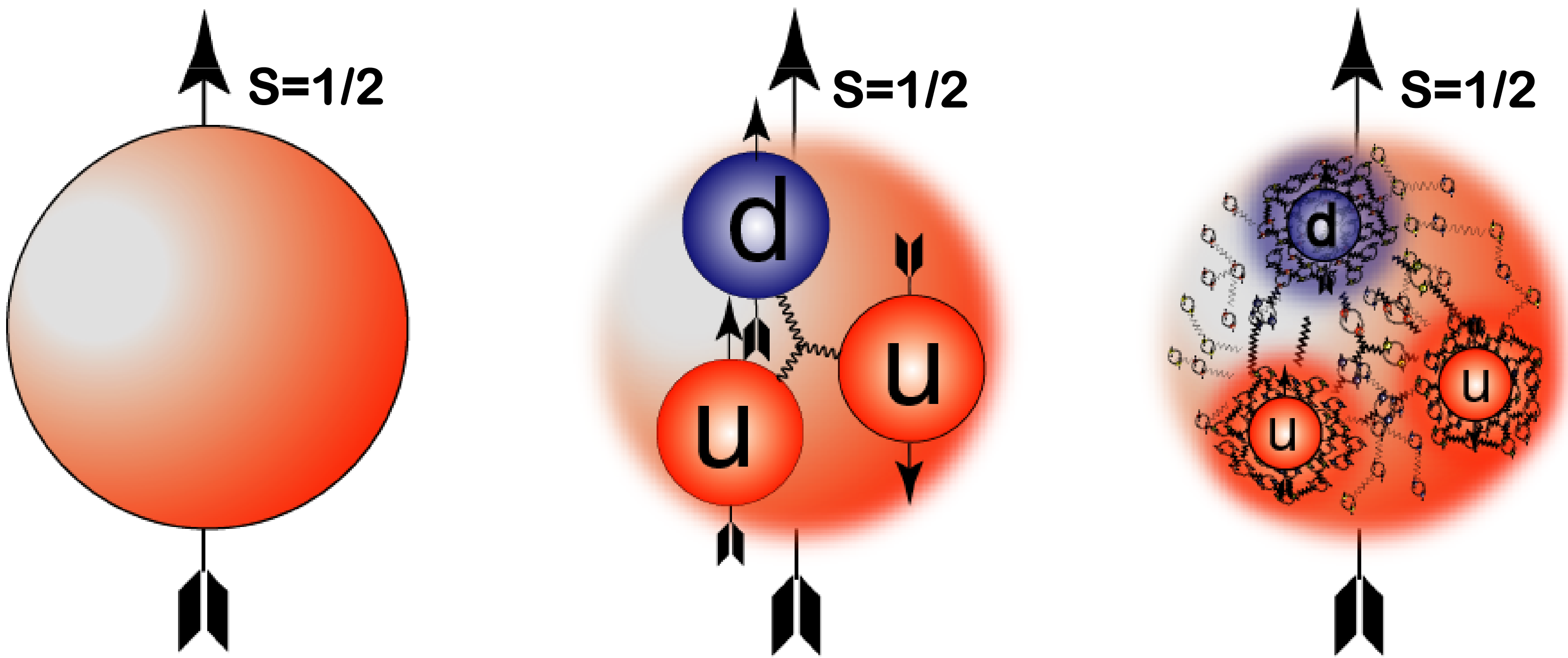
What we "see" changes with spatial resolution

>1 fm
Nucleons

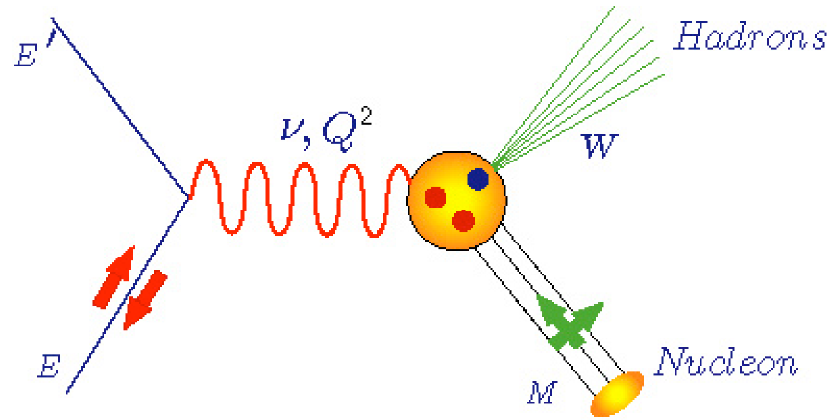
0.1 — 1 fm
Constituent quarks and glue

< 0.1 fm
"bare" quarks and glue



Nucleon Structure and Sum Rules

- 3 valence quarks carry ~50% of the nucleon momentum
- Spin=1/2, quarks contribute ~30% — Spin Sum Rule
- Axial charge — Bjorken Sum Rule
- Polarizabilities (Spin, Color)

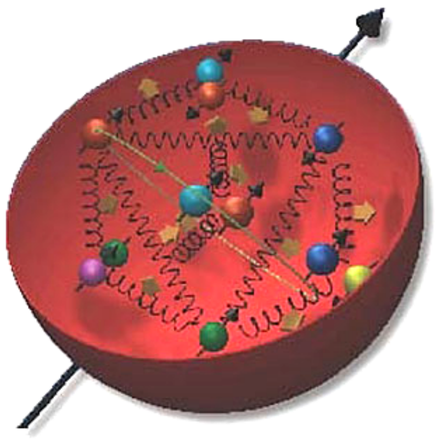


Three Decades of Spin Structure

- 1980s: EMC (CERN) + early SLAC
- Quark contribution to proton is very small

$\Delta\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$! " spin crisis"

- Violation of Ellis- Jaff Sum Rule



Three Decades of Spin Structure

- **1990s: SLAC, SMC(CERN), HERMES(DESY)**

$$\boxed{\Delta\Sigma = 20-30\%}$$

- **The rest = gluon and quark orbital angular momentum**

$$\boxed{1/2 = (1/2)\Delta\Sigma + L_q + \Delta G + L_g}$$

Three Decades of Spin Structure

- 2000s: COMPASS(CERN), HERMESS, RHIC-Spin, JLab,…

$\Delta\Sigma \approx 30\%$

ΔG probably small

Orbital angular momentum probably significiant

Transversity

Transverse-momentum dependent distribution

Generalized Parton Distributions

Much more work to do at next decade

Longitudinal Spin

Spin in Valence (high-x) Region

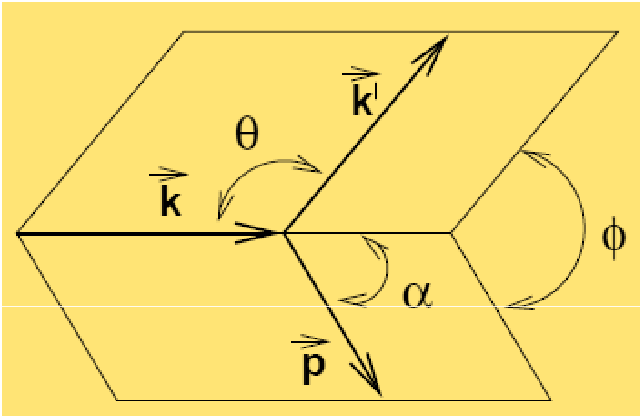
Moments of Spin Structure Functions

Spin Sum Rules

Some fundamental relations

- The spin structure of the nucleon in Inclusive DIS scattering

Longitudinally electron in lab frame



definition of scattering & polarization angles

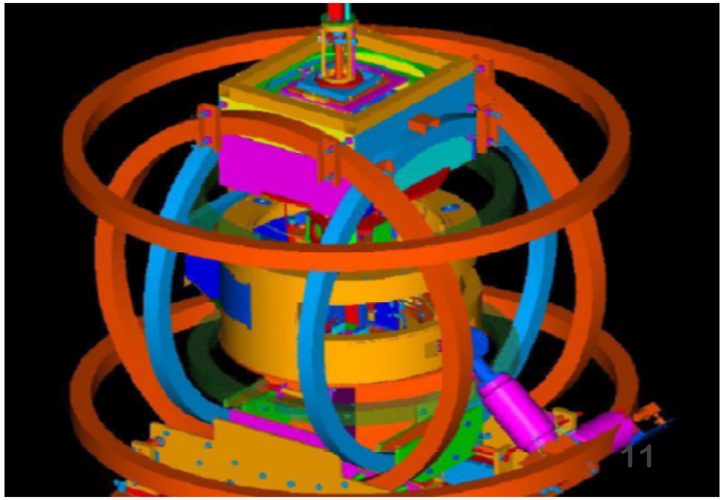
The cross section difference between target polarized along $\alpha, \alpha+\pi$

$$\frac{d^3(\sigma(\alpha)-\sigma(\alpha+\pi))}{dx\ dy\ d\phi} = \frac{e^4}{4\pi^2 Q^2}\left\{cos(\alpha)\left\{\left(1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right)\ g_1(x,Q^2)-\frac{y}{2}\gamma^2 g_2(x,Q^2)\right\}\ -\right.$$

$$\left. sin(\alpha)cos(\phi)\sqrt{\gamma^2\left(1-y-\frac{y^2}{4}\gamma^2\right)}\left\{\frac{y}{2}\ g_1(x,Q^2)+g_2(x,Q^2)\right\}\right\}\ .$$

Transverse Spin

g_2 Structure Function and Moments
Burkhardt - Cottingham Sum Rule
Color Polarizability d_2



Transversity

- **Three twist-2 quark distributions:**

Momentum distributions: $q(x,Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$

Longitudinal spin distributions: $\Delta q(x,Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$

Transversity distributions: $\delta q(x,Q^2) = q^{\perp}(x) - q_{T}(x)$

$$f(x) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS|\bar{\psi}(0)\gamma^+\psi(0,\xi^-,0_\perp)|PS\rangle$$

$$\Delta f(x) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS|\bar{\psi}(0)\gamma^+\gamma_5\psi(0,\xi^-,0_\perp)|PS\rangle$$

$$\Delta_T f(x) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle PS|\bar{\psi}(0)\gamma^+\gamma^1\gamma_5\psi(0,\xi^-,0_\perp)|PS\rangle$$

Spin structure functions

- Quark component of the nucleon helicity is much smaller than the naive QPM predictions
- $g_1(x,Q^2)$, $g_2(x,Q^2)$ are important tools for testing QCD, models of nucleon structure, and sum rules
- g_1 is dominant when the target is polarized along the beam direction
- g_2 is dominant when longitudinally polarized leptons scatter from transversely polarized nucleons
- g_2: central to knowledge of nucleon structure but remained unmeasured at low Q^2 and still have limited statistical precision
- Properties of g_2 have been established using OPE within QCD

g_2 and Quark-Gluon Correlations

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- a twist-2 term (Wandzura & Wilczek, 1977):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(x,Q^2)\frac{dy}{y}$$

- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 1992):

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M}\boxed{h_T(y,Q^2)} + \boxed{\xi(y,Q^2)}\right]\frac{dy}{y}$$

Transversity

q-g correlations

- **$g_2 - g_2^{WW}$: a clean way to access twist-3 contribution**
  quantify q-g correlations

- expression of Wandzura-Wilczek($g_2^{tw.2}$)

can be derived from the OPE Sum rules for g_1 & g_2

at fixed Q^2

$$\boxed{\int_0^1 x^n g_1(x, Q^2)dx = \frac{a_n}{2}, \quad n = 0, 2, 4, \ldots,}$$

$$\boxed{\int_0^1 x^n g_2(x, Q^2)dx = \frac{1}{2}\frac{n}{n+1}(d_n - a_n), \quad n = 2, 4, \ldots}$$

by keeping a_n(twist-2) and neglecting the d_n(twist-3) matrix elements

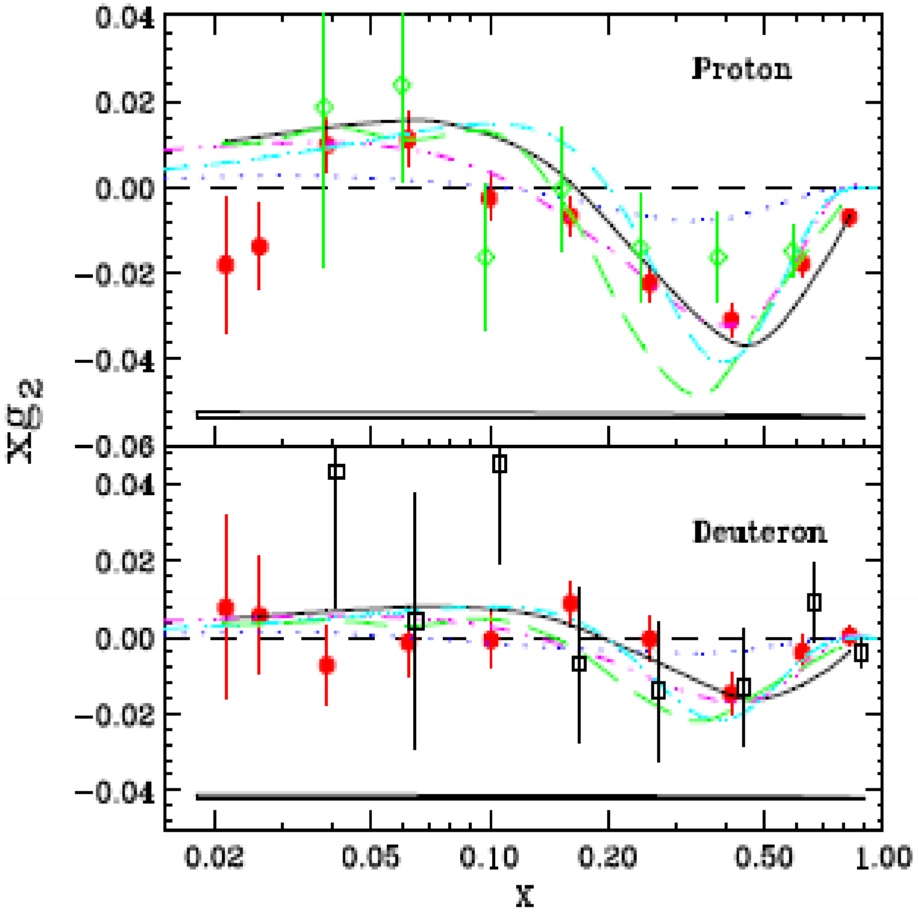
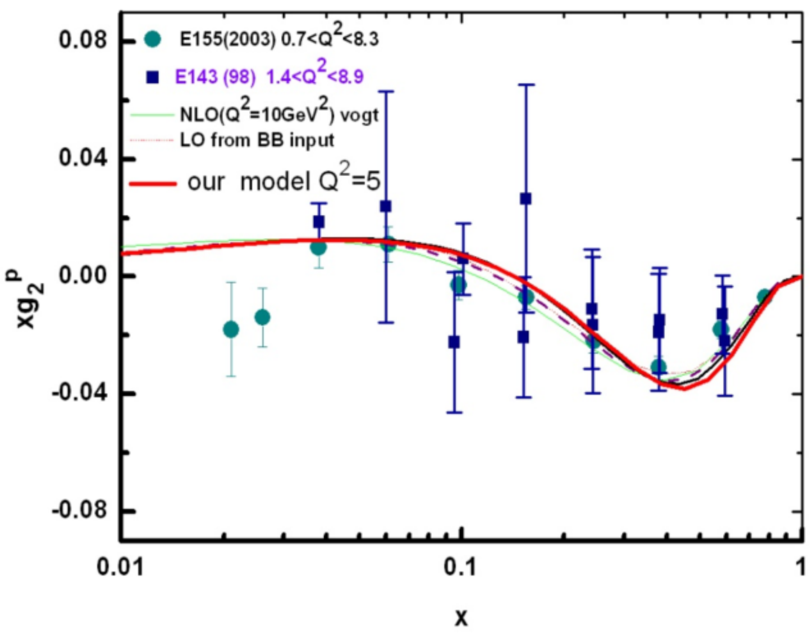
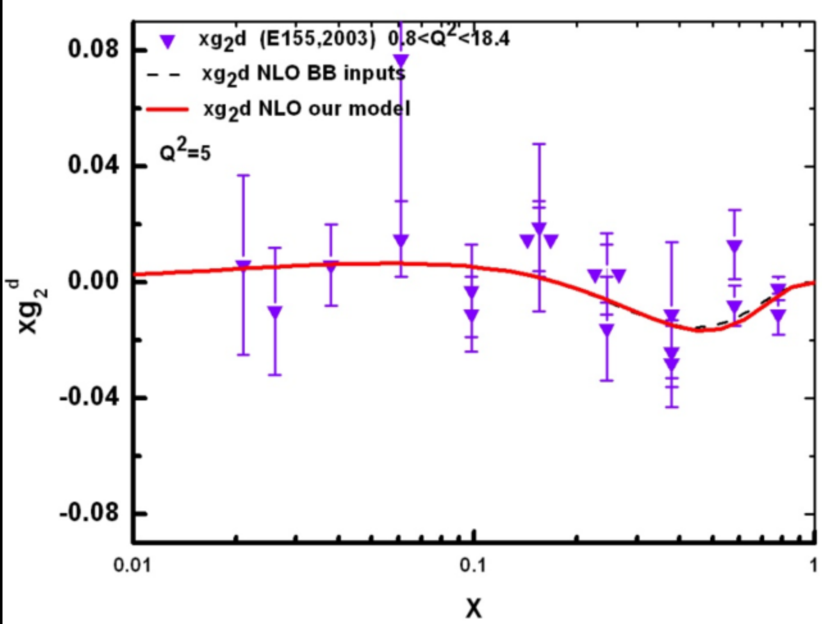
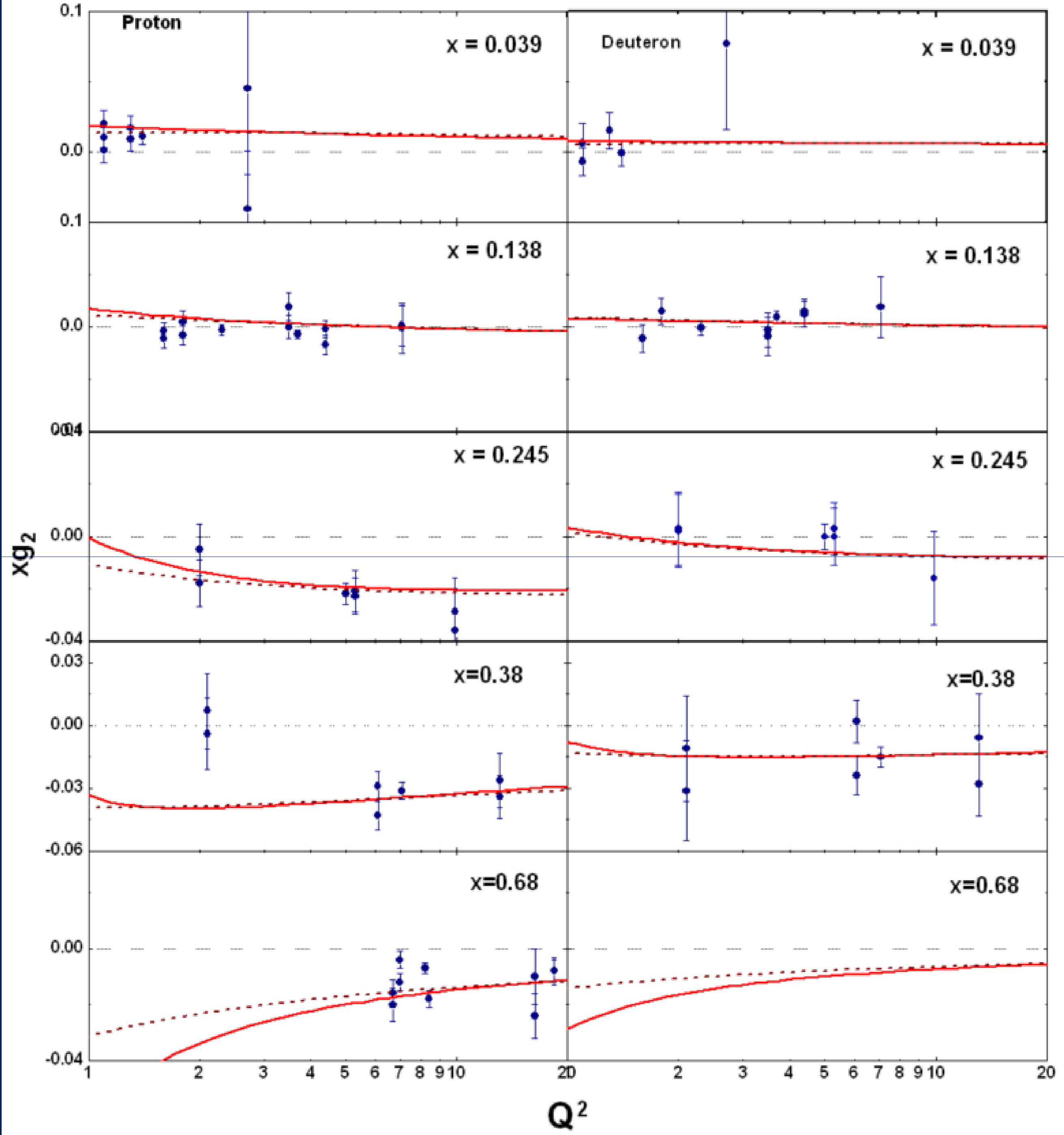


Figure 2: Q^2 averaged (0.8–8.2 GeV^2) xg_2 from E155x (solid circle), E143 (open diamond) and E155 (open square). Error bars are statistical. Also shown is g_2^{WW} (solid line) at the average Q^2 of E155x. Curves are the bag model calculations of Stratmann[30] (dash-dot) and Song[31] (dot) and the chiral soliton models of Weigel and Gamberg[32] (short dash) and Wakamatsu[33] (long dash). *Reproduced from [26].*



Our result for g_2^p, g_2^d




Proton
Deuteron
x = 0.039
x = 0.138
x = 0.245
x=0.38
x=0.68
xg2
Q2
0.1
0.0
0.04
0.00
-0.04
0.03
-0.03
-0.06
1
2
3
4
5
6
7
8
9
10
20

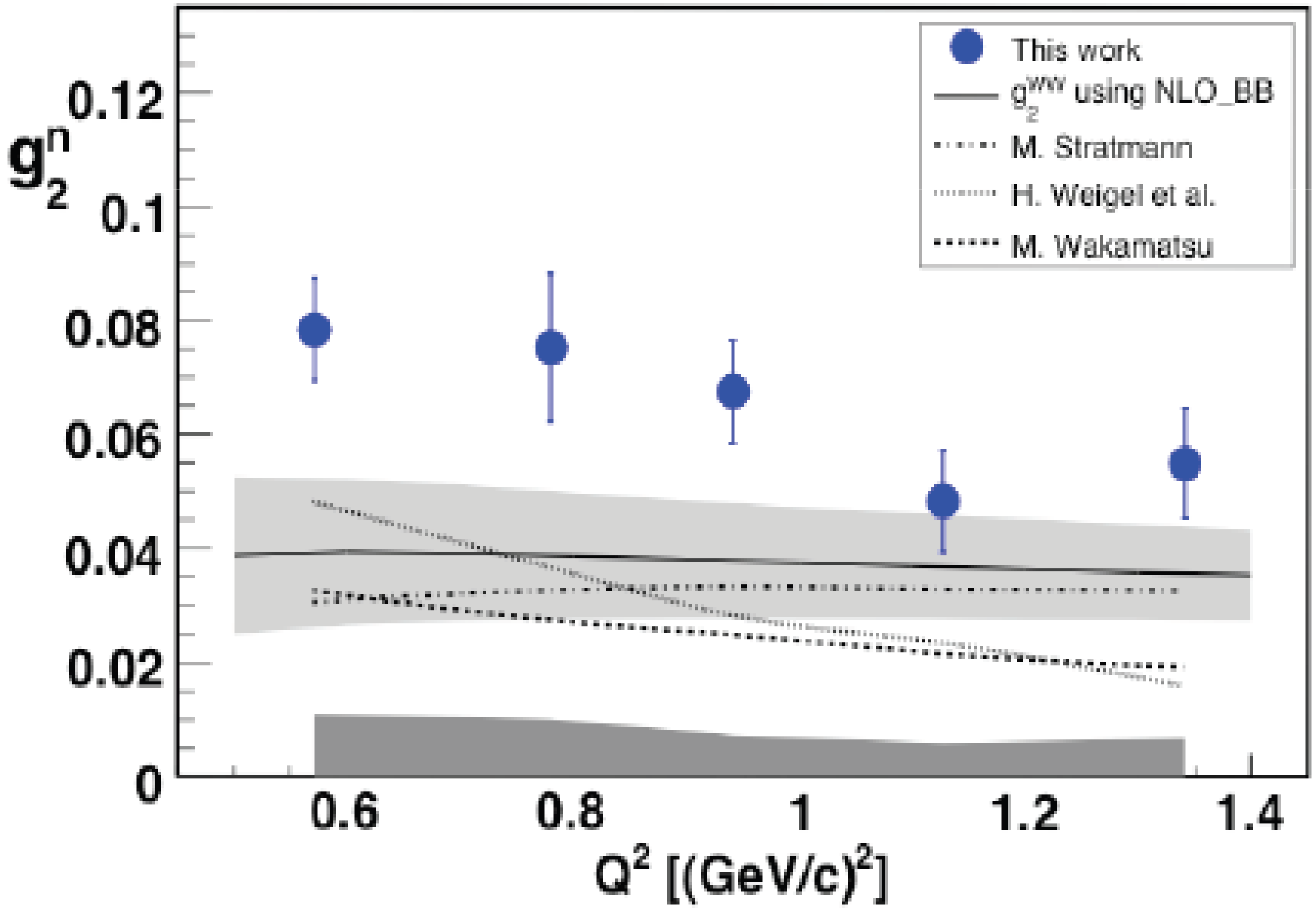
Q^2 dependence below 1 GeV^2

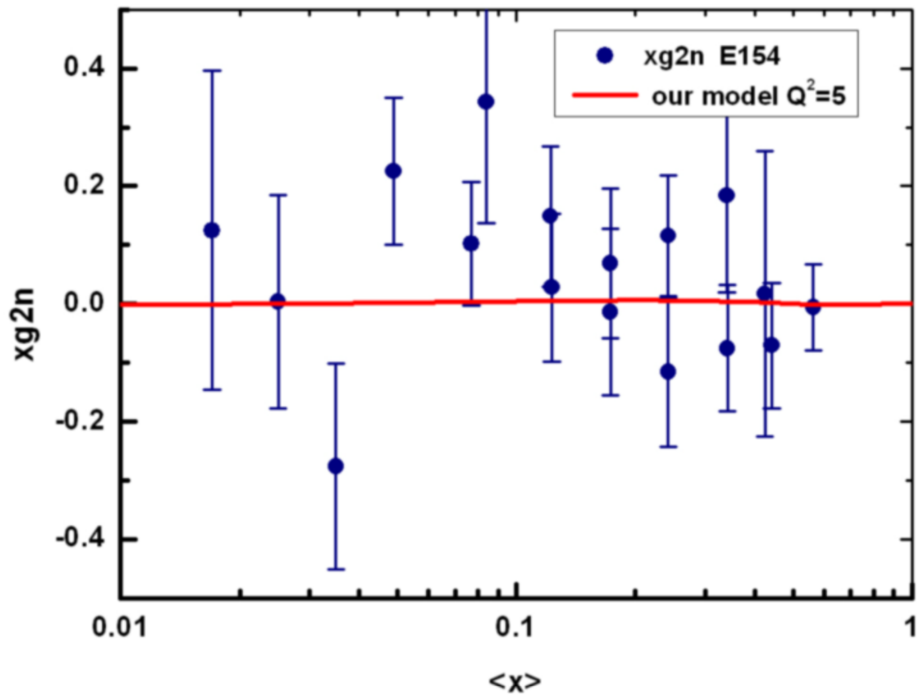
JLab E97-103 (^3He) DIS, Q^2 dependence mainly below 1.4 GeV^2

Spokespersons: T. Averett and W. Korsch

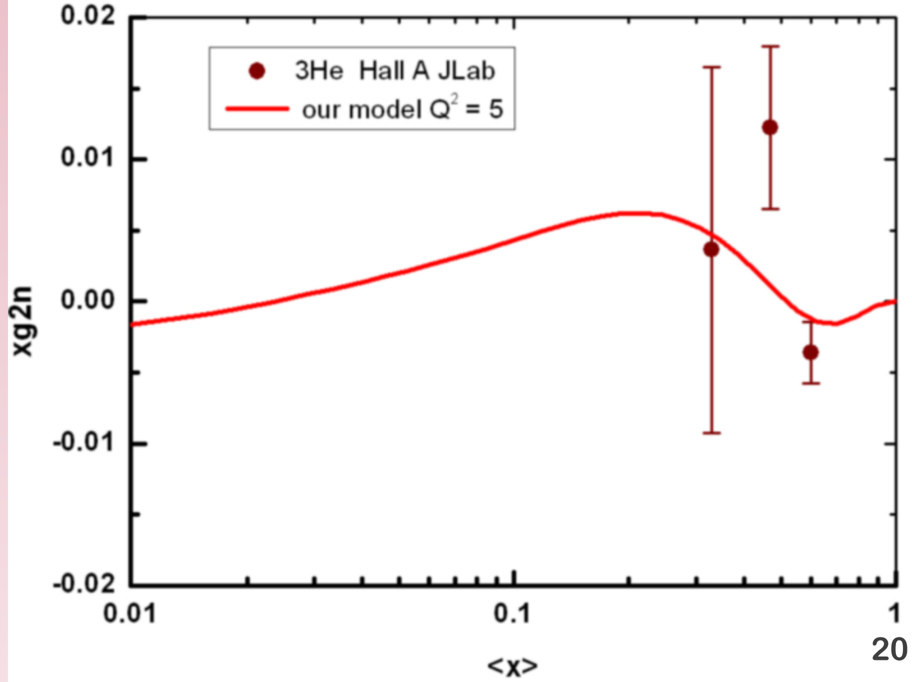
Student: K. Kramer

Phys. Rev. Lett. 95:142002, 2005.





Our result for g_2^n



Moments of Structure Functions (continued)

➡ $a_2(Q^2) \equiv 2\int_0^1 \mathrm{d}x\, x^2\, g_1^{\mathrm{twist}-2}(x,Q^2)$ → target mass correction term

➡ $d_2(Q^2)$ → dynamical twist-3 matrix element

$$\boxed{d_2(Q^2) = \int_0^1 dx\, x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]}$$

➡ $f_2(Q^2)$ → dynamical twist-4 matrix element

$$\boxed{f_2 M^2 S^\mu = \frac{1}{2}\sum_q e_q^2 < N|\bar{\psi}_q g \tilde{F}^{\mu\nu}\gamma_\nu \psi_q|N >}$$

Color Polarizability: d_2 (twist-3)

- 2^{nd} moment of g_2-g_2^{WW}

$d_2(Q^2) \longrightarrow$ dynamical twist-3 matrix element

$$d_2(Q^2) = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$
$$= \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

d_2 and g_2-g_2^{WW}: clean access of higher twist (twist-3) effect: q-g correlations

Color Polarizability

Color Polarizabilities χ_E, χ_B are linear of d_2 , f_2

$$\boxed{d_2 = \frac{1}{8}(\chi_E + 2\chi_B)}$$

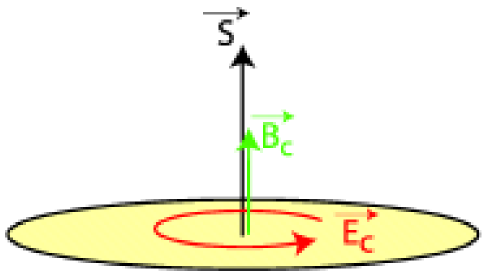
$$\boxed{f_2 = (\chi_E - \chi_B)/2}$$

Provide a benchmark test of Lattice QCD at high Q^2

at high Q^2, d_2 measure include

color field by target spin

Polarized Nucleon



Induced Color
Magnetic and Electric Fields

$$\mathbf{B}_C \sim \chi_B \mathbf{S}$$
$$\mathbf{E}_C \sim \chi_E \mathbf{S}$$

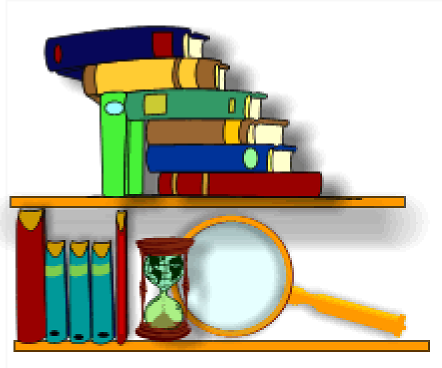
Summary

- Spin structure study full of surprises and puzzles
- Past experiments on the neutron and proton suggest that the twist-3 and twist-4 are small but finite.
- Precision measurements of g1 and g2 in the range $1 < Q^2 < 4$ GeV^2 are crucial for an improved extraction of the
  - ⇨ Average color Lorentz force
  - ⇨ "Color polarizabilities"
- We need greater Q^2 and x coverage, to have a better interpretation of g_2s behavior and interesting physics.

CONCLUSION

- The behaviour of $g_2(x,Q^2)$ is more complicated in comparison with the other structure functions.
- Within experimental precision, specially in DIS region, the g_2 data are well described by the twist-2 contribution, g_2^{WW}.
- Twist-3 matrix elements are extracted and compared to theoretical predictions.
- More precise data on g_2 are needed to make any conclusions regarding possible twist-3.
- *PSFs* at low Q^2 have physical interpretation. $g_2(x)$ provides access to q-g correlations in the nucleon. The x^2 moment of $\overline{g}_2(x)$ can be considered as an average transverse force on quarks in DIS scattering.

References



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   coupling?, JHEP(2009)


Thank you for
attention
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