CIPANP2009

Nucleon g_2 Structure Function and Quark-Gluon Correlations

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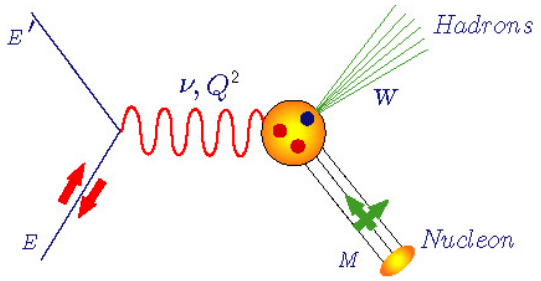
May 30, 2009

CIPANP-2009

Outline

- Quark-gluon correlations: Average Color Lorentz force, Color polarizabitiies
  - Nucleon g_2 and g_1 spin structure functions
  - Twist-3 d_2 and twist-4 f_2 matrix elements
  - d_2^n (E06-114 in Hall A) and SANE (E07-003 in Hall C) experiments at Jefferson Lab
  - Future prospects

Spin Structure Functions



- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$

U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$

Q^2 : Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

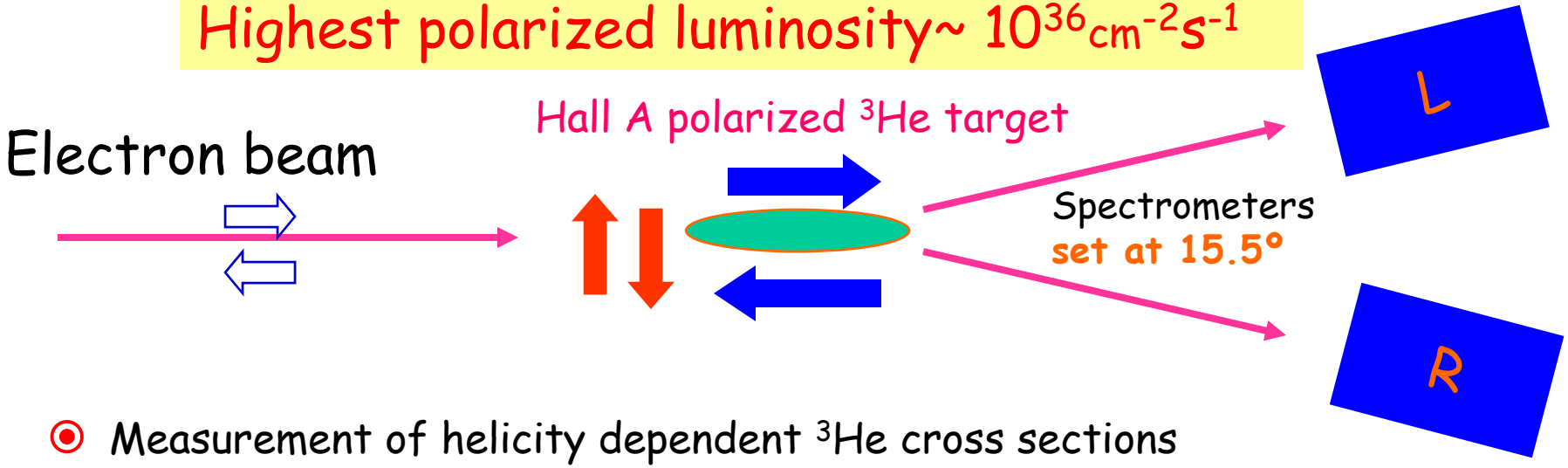
T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

Example of a standard setup in Hall A

Polarized beam
- Energy: 0.86-5.1 GeV
- Polarization: > 70%
- Average Current: 5 to 15 μA

Hall A polarized ^{3}He target
- Pressure ~ 10 atm
- Polarization average: 35%
- Length: 40 cm with 100 μm thickness

Highest polarized luminosity~ $10^{36}cm^{-2}s^{-1}$



- Measurement of helicity dependent ^{3}He cross sections
- Extract g_1 and g_2 spin structure functions of ^{3}He
- Extract moments of spin structure functions of ^{3}He and Neutron

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):

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

Transversity

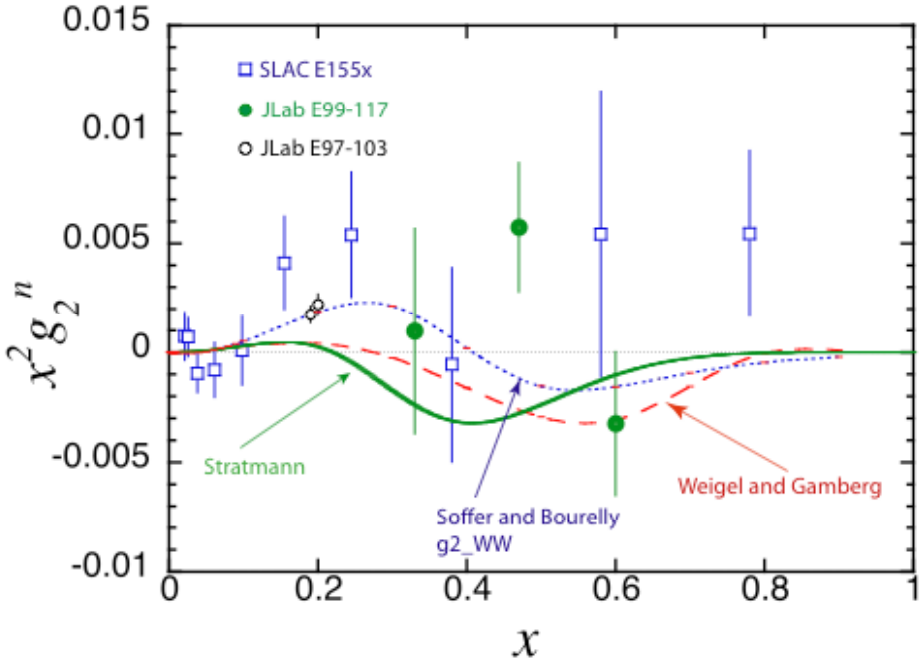
q-g correlations

Quark-Gluon Correlations

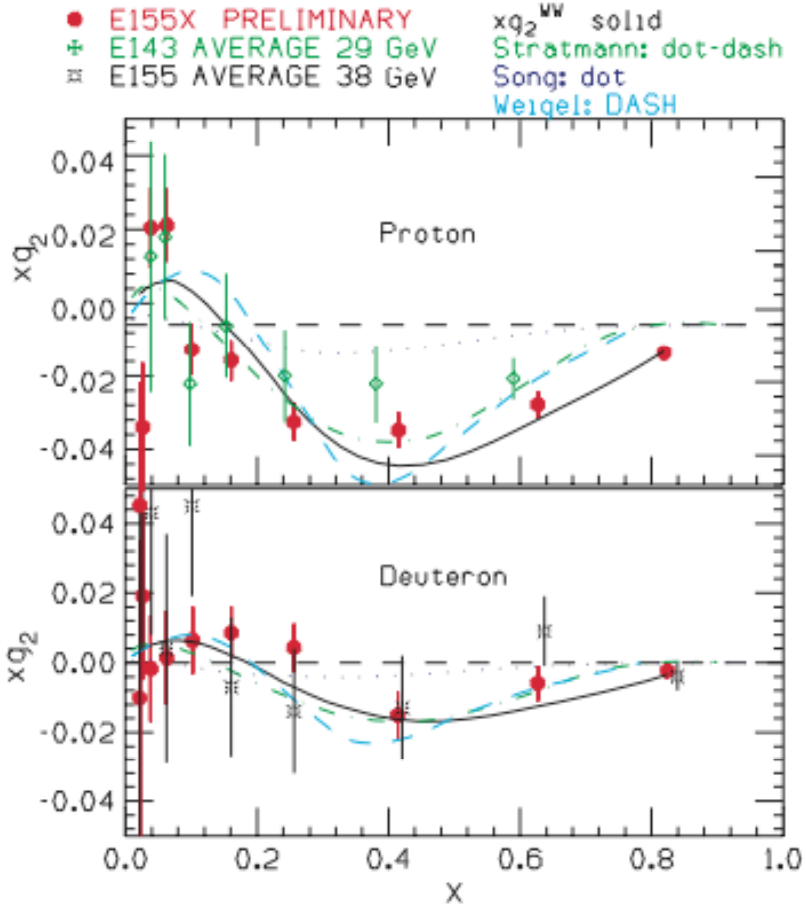
- How did we investigate them?
  - By direct comparison of g_2 to g_2^{WW} to observe deviations
  - As for any other nucleon structure function it is hard to have ab-initio calculation of g_2.
  - Quark models are can be useful to gain insight
- Second moment of g_2 offers another avenue of investigation
  - Moments of $\overline{g_2}$ can be calculated using lattice QCD since they correspond to specific matrix elements of quark and gluon field operators
  - These matrix elements have a physical interpretation
    - Average Color Lorentz Force (M. Burkhardt)
    - "Color polarizabilities" (X. Ji, Stein et al.)

Nucleon world results of g_2

Neutron



Proton and Deuteron



- SLAC E155x (proton and deuteron)
- JLab E99-117(helium-3), A_1^n in DIS
- Jlab E97-103 (helium 3) DIS, Q^2 dependence mainly below 1.4 GeV^2

SLAC E155x (proton and deuteron)

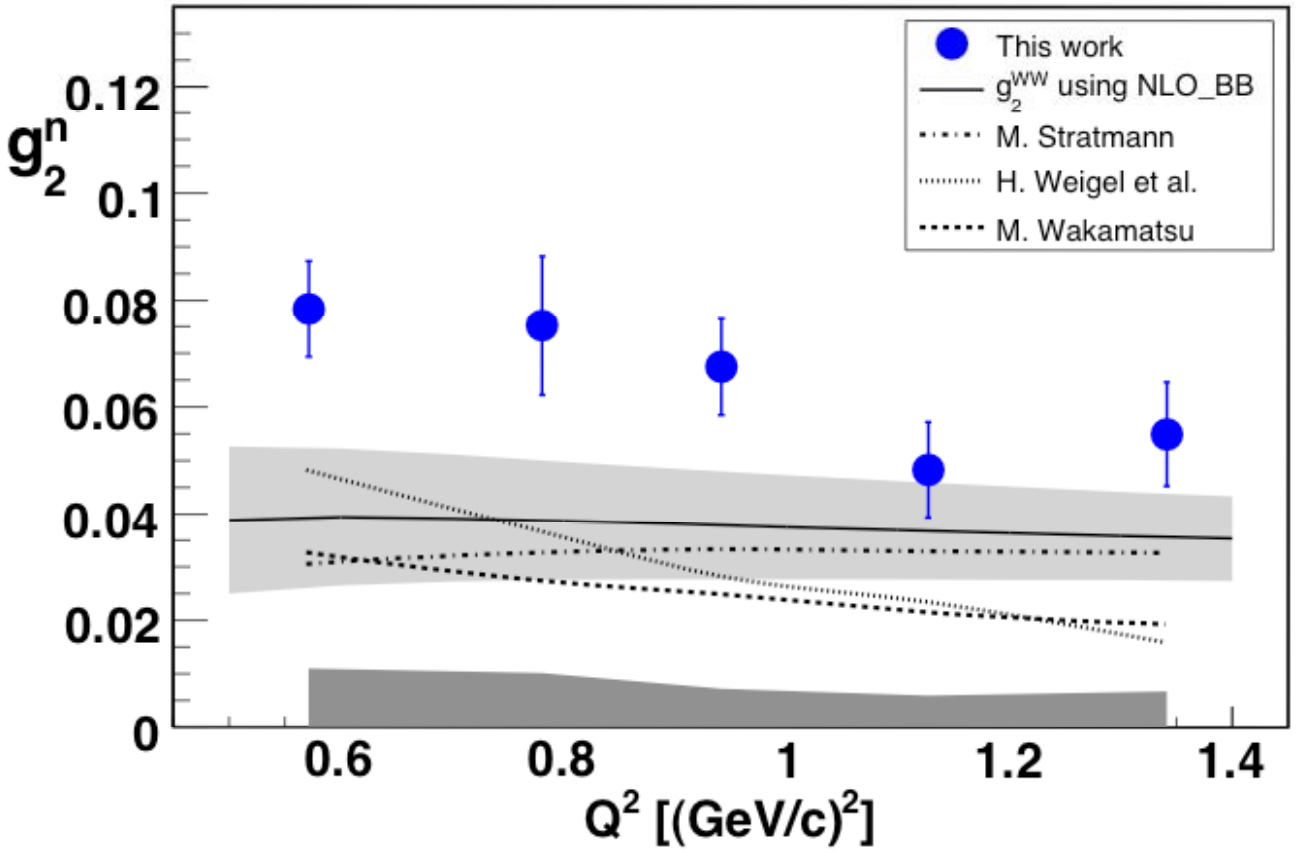
Q^2 dependence below 1 GeV^2

JLab E97-103 (helium 3) 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.



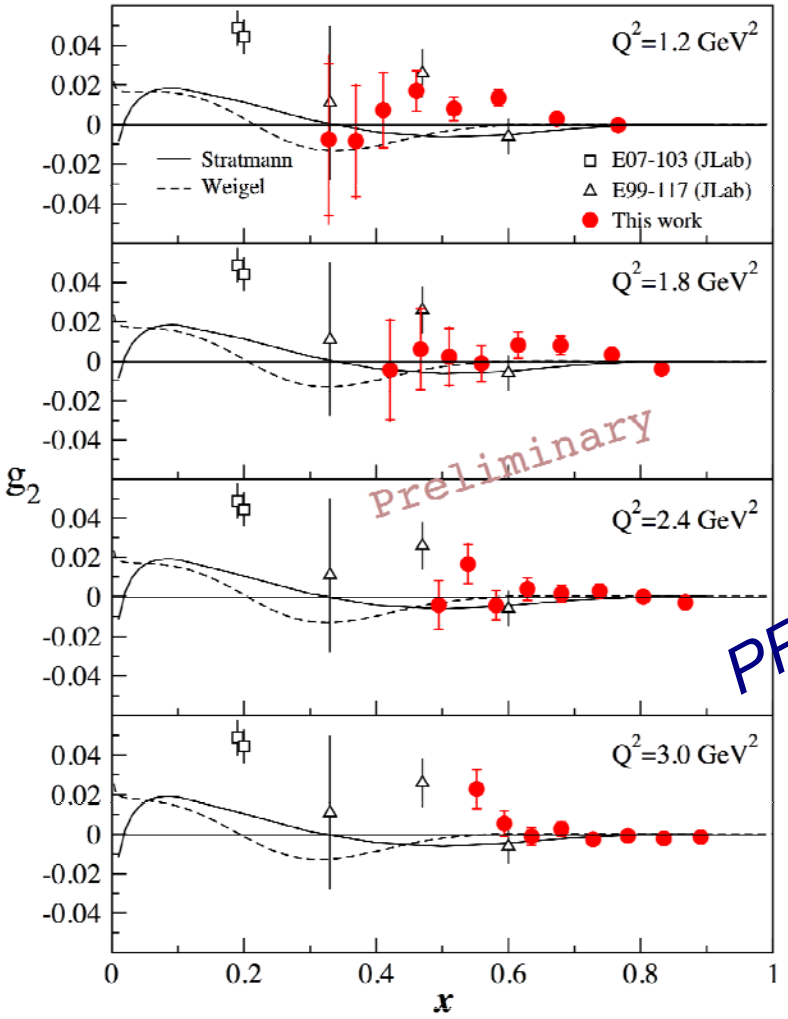
$x^2 g_2{}^{^3He}$ at constant Q^2

JLab Experiment E01-012

Phys.Rev.Lett. 101:182502, 2008.

Spokespersons: J.P Chen, Seonho Choi and N. Liyanage

Thesis student: P. Solvignon



PRELIMINAR

Statistical errors only

Moments of Structure Functions

$$d_2(Q^2) = 3\int_0^1 x^2 \left(g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right) dx$$

$$d_2 S^{[\mu} P^{\{\nu]} P^{\lambda\}} = \frac{1}{8}\sum_q \langle P,S|\bar{\psi}_q \; g\bar{F}^{\{\mu\nu}\gamma^{\lambda\}}\psi_q|P,S\rangle$$

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

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

"Color Polarizabilities"

X.Ji 95, E. Stein et al. 95

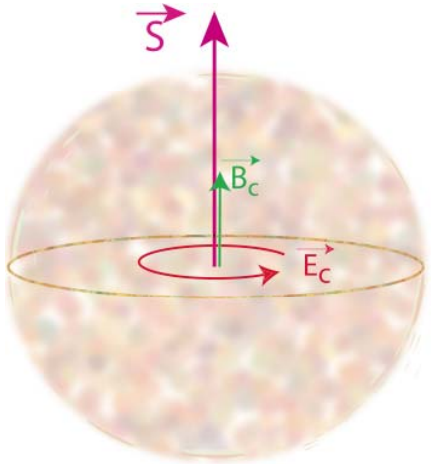
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E}\, 2M^2 \vec{S} = \langle PS|\vec{O}_{B,E}|PS\rangle$$

where $\vec{O}_B = \psi^\dagger g\vec{B}\psi$

$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g\vec{E}\psi$



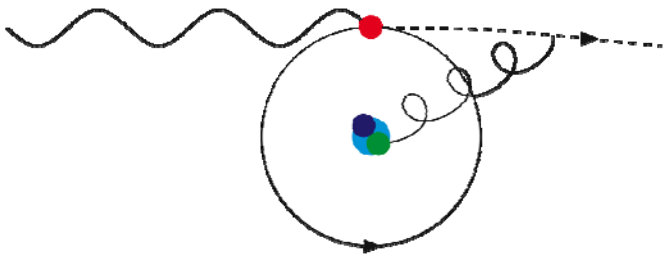
$$d_2 = (\chi_E + 2\chi_B)/8$$

$$f_2 = (\chi_E - \chi_B)/2$$

d_2 and f_2 represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

Average Color Lorentz Force (M. Burkardt)

$$\int dx x^2 \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \left\langle P,S \left| \bar{q}(0) g G^{+y}(0) \gamma^+ q(0) \right| P,S \right\rangle$$



↪ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

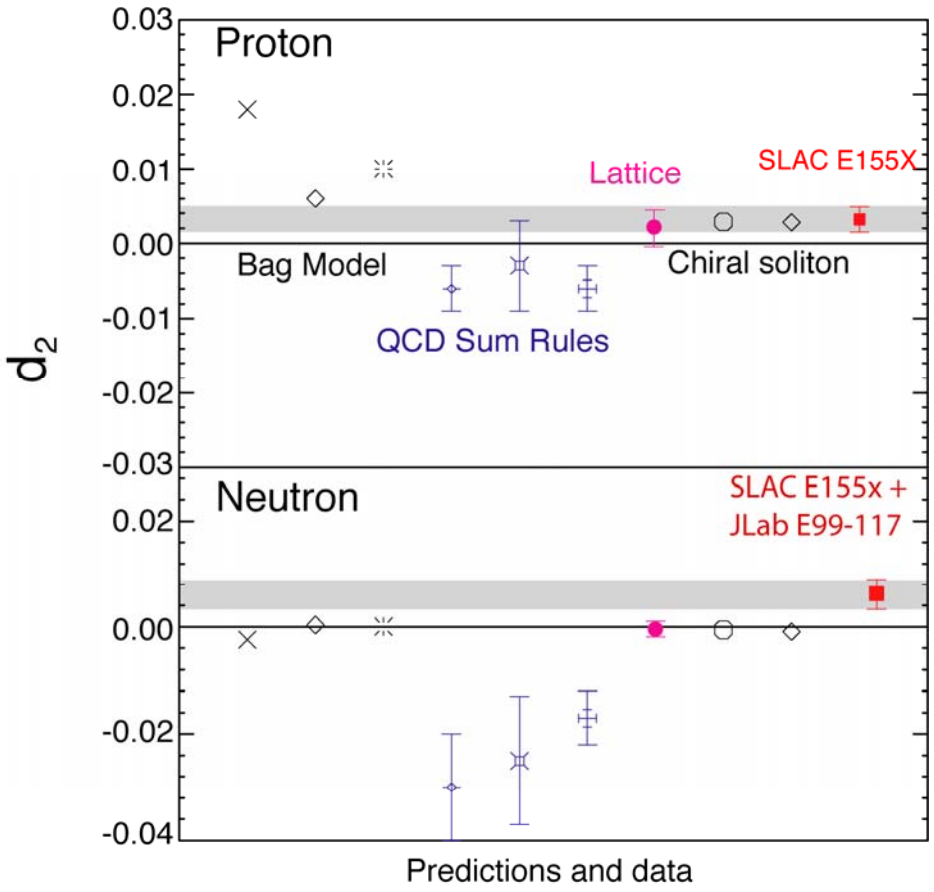
$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

- Interpretation of d_2 with the transverse FSI force in DIS also consistent with $\langle k_\perp^y \rangle \equiv \int_0^1 dx \int \mathrm{d}^2 k_\perp \, k_\perp^2 f_{1T}^\perp(x, k_\perp^2)$ in SIDIS (Qiu, Sterman)

$$\langle k_\perp^y \rangle = -\frac{1}{2p^+} \left\langle P, S \left| \bar{q}(0) \int_0^\infty dx^- g G^{+y}(x^-) \gamma^+ q(0) \right| P, S \right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

Models and Lattice evaluations of d_2



Quark Bag Models

M.Stratmann, Z.Phys.C60,763(1993).
X.Song,Phys.Rev.D54,1955(1996).
X.Ji and P.Unrau, Phys.Lett.B333,228(1994).

Chiral Soliton Model

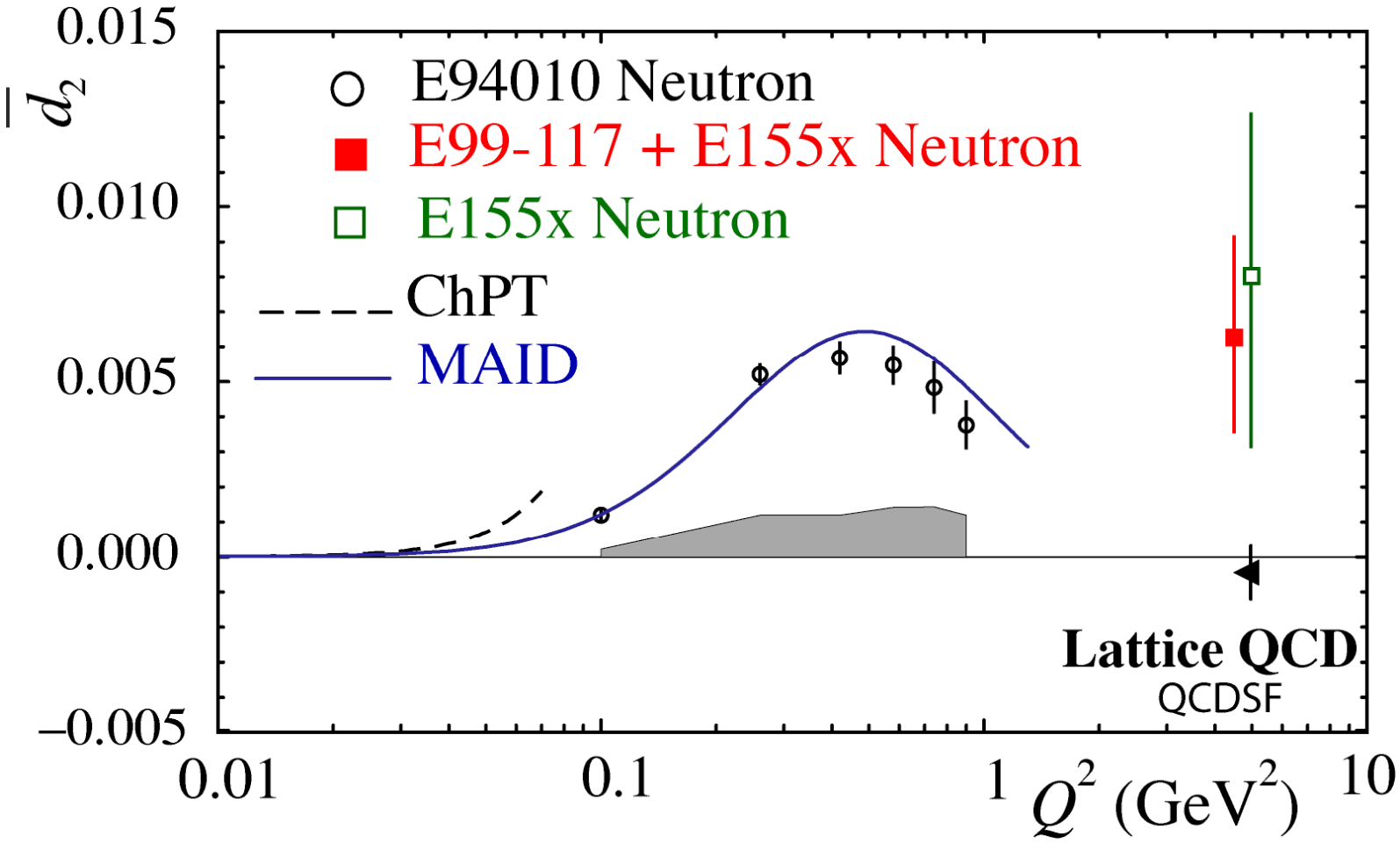
H.Weigel and L.Gamberg,
Nucl. Phys. A680, 48 (2000).
M.Wakamatsu, Phys. Lett. B487,118(2000).

Lattice QCD

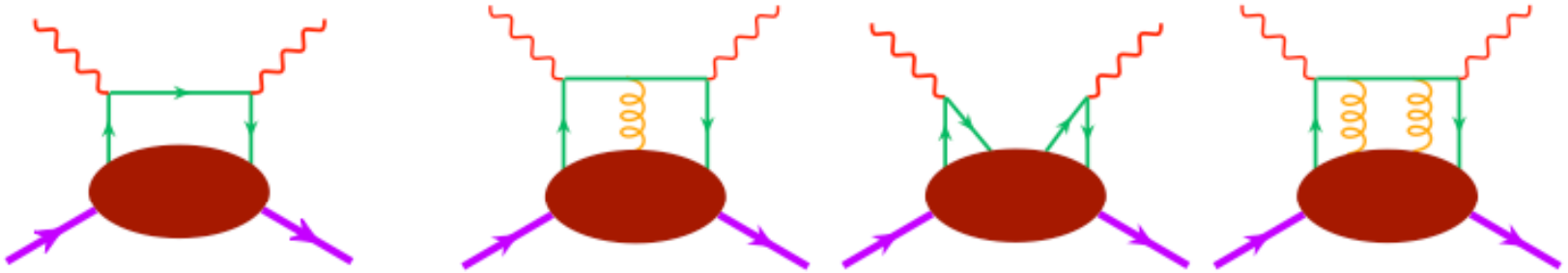
M.Gockeler et al.,

Phys.Rev.D72:054507,(2005)

Q^2 evolution of the neutron "d_2"



Moments of Structure Functions (continued)



$\tau = 2$

$\tau > 2$

single quark scattering

qq and qg correlations

$$\Gamma_1(Q^2) \equiv \int_0^1 \mathrm{d}x\, g_1(x,Q^2)$$

$$= \Gamma_1^{\text{twist}-2}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)$$

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

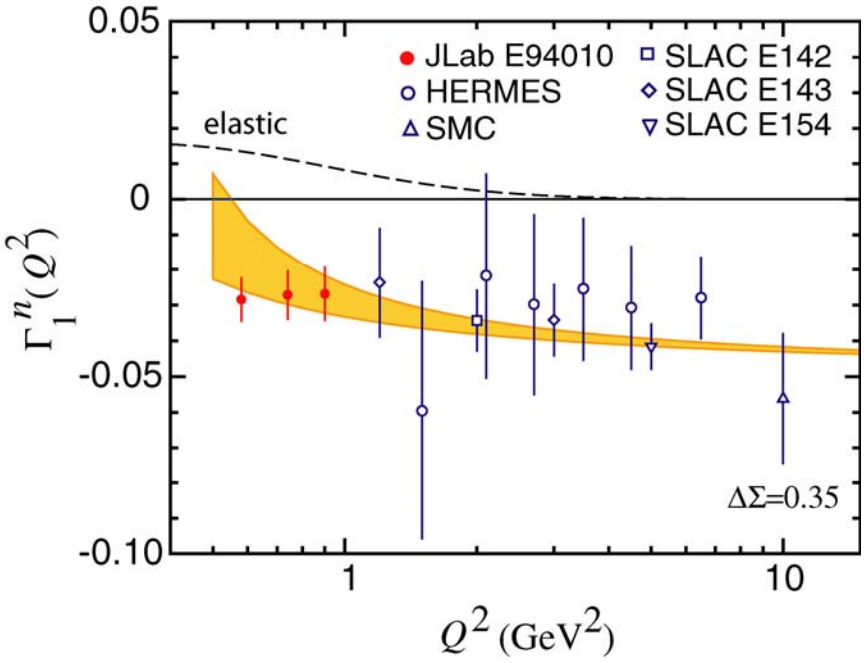
$$d_2(Q^2) = \int_0^1 dx\, x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]$$

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

$$f_2(Q^2) = \frac{1}{2}\int_0^1 dx\, x^2 \left[7g_1(x,Q^2) + 12g_2(x,Q^2) - 9g_3(x,Q^2)\right]$$

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

Twist-4 neutron matrix element f_2



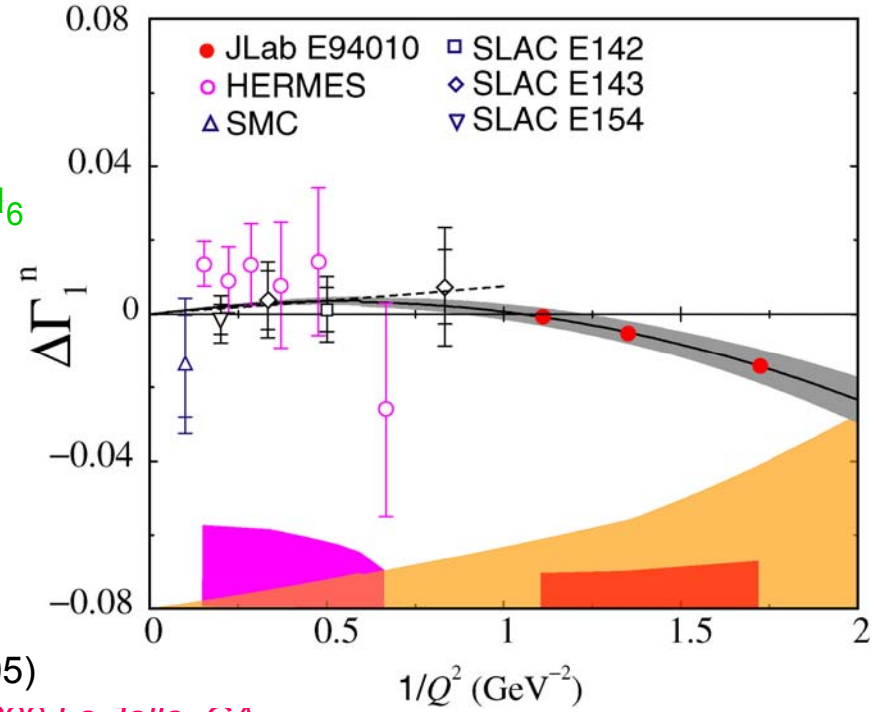
$$\Delta\Gamma_1^n(Q^2) \equiv \Gamma_1^n(Q^2) - \mu_2^n(Q^2) = \frac{\mu_4^n(Q^2)}{Q^2} + \frac{\mu_6^n(Q^2)}{Q^4} + \mathcal{O}\left(\frac{1}{Q^6}\right)$$

$$\mu_4^n = \frac{1}{9}M^2\left(a_2^n + 4d_2^n + 4f_2^n\right)$$

$$f_2^n = 0.033 \pm 0.005\ ,\ \mu_6^n = (-0.019 \pm 0.002)M^4$$

$$f_2^n = 0.034 \pm 0.043\ ,\ \mu_6^n = (-0.019 \pm 0.017)M^4$$

Adding $1/Q^6$ term gives the same f_2 and μ_6 with $\mu_8 = (0.00 \pm 0.03)M^2$

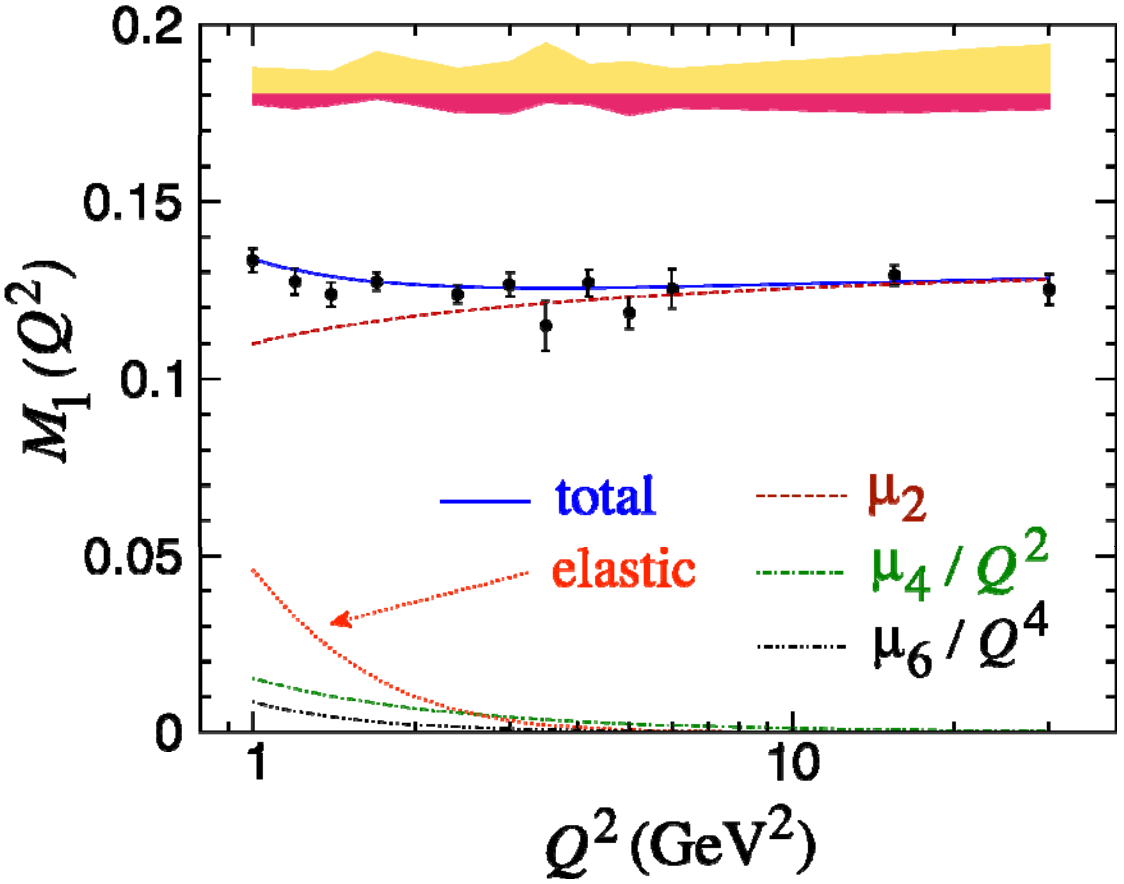


Z.-E. M, W. Melnitchouk et al., Phys. Lett. B613,148 (2005)

Determination of f_2 for the proton

World data + EG1a data: R. Fatemi et al., PRL, 91 22200 (2003)

Osipenko et al. Phys. Lett. B 609, 258 (2005)



$f_2 = 0.039^{+0.037}_{-0.043}$

$\mu_6/M^4 = 0.011^{+0.017}_{-0.013}$

Hall A d_2^n and Hall C SANE experiments

Neutron and Proton

Spokespeople:
B. Sawatzky, S. Choi, X. Jiang and Z.-E.M

Students:
D. Flay, D. Parno, M. Posik

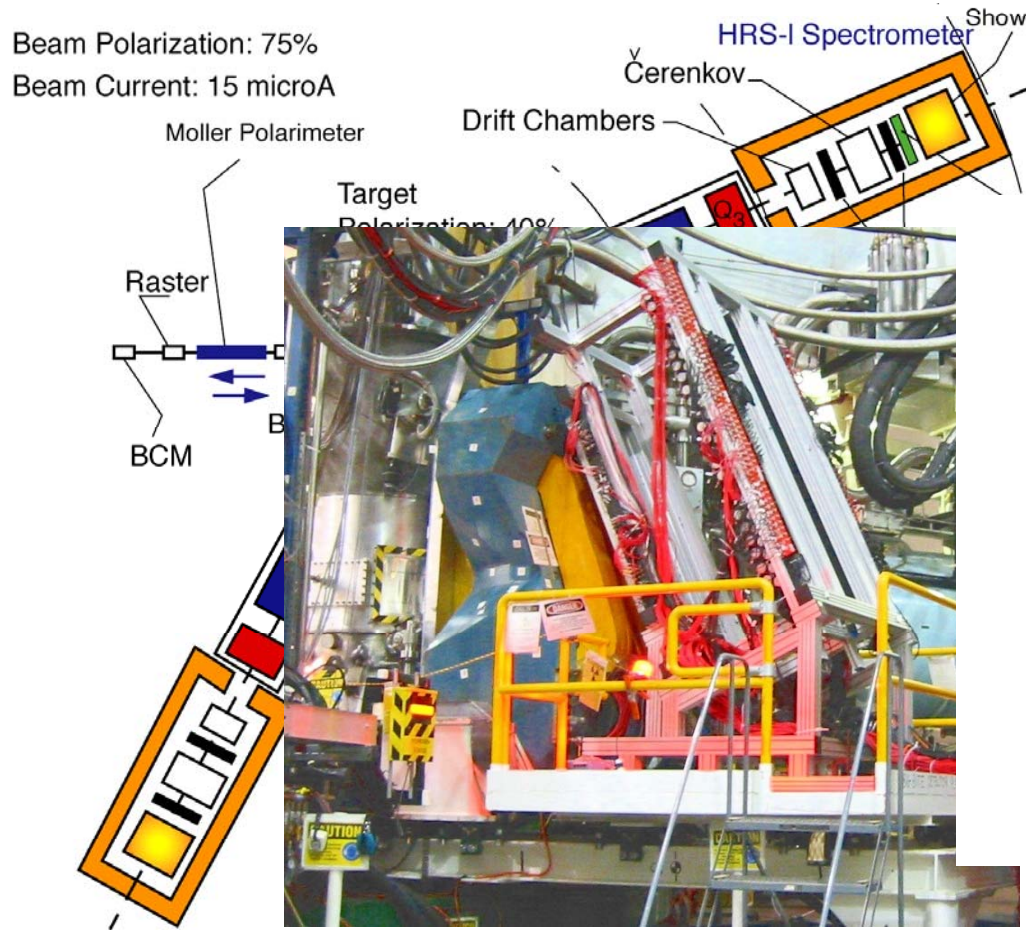
and the Hall A collaboration

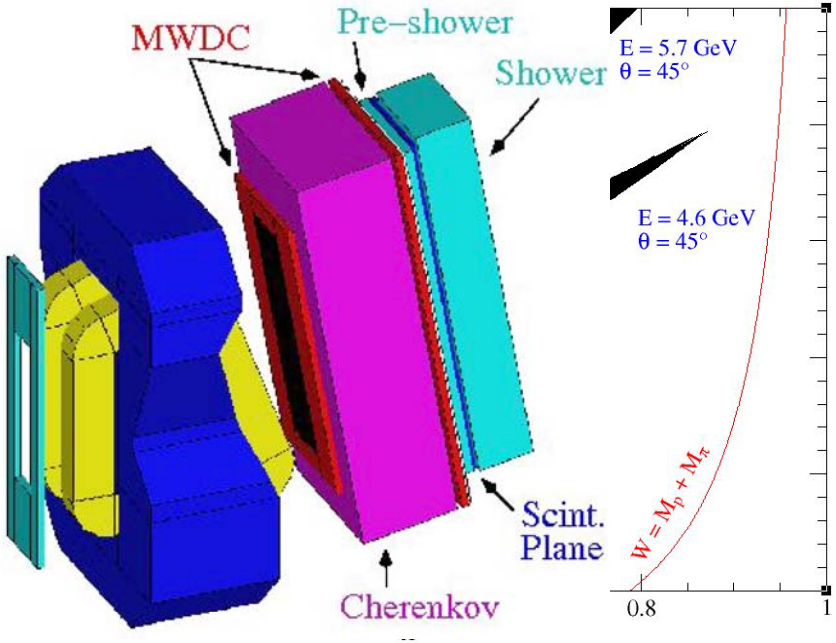
Spokespeople:
O. Rondon, S. Choi, M. Jones,, Z.-E. M

Students:
W. Armstrong, H. Kang, A. Liyanage, J. Maxwell, J. Mulholland

and the Hall C collaboration

Experiment E06-114 (d_2^n) in Hall A



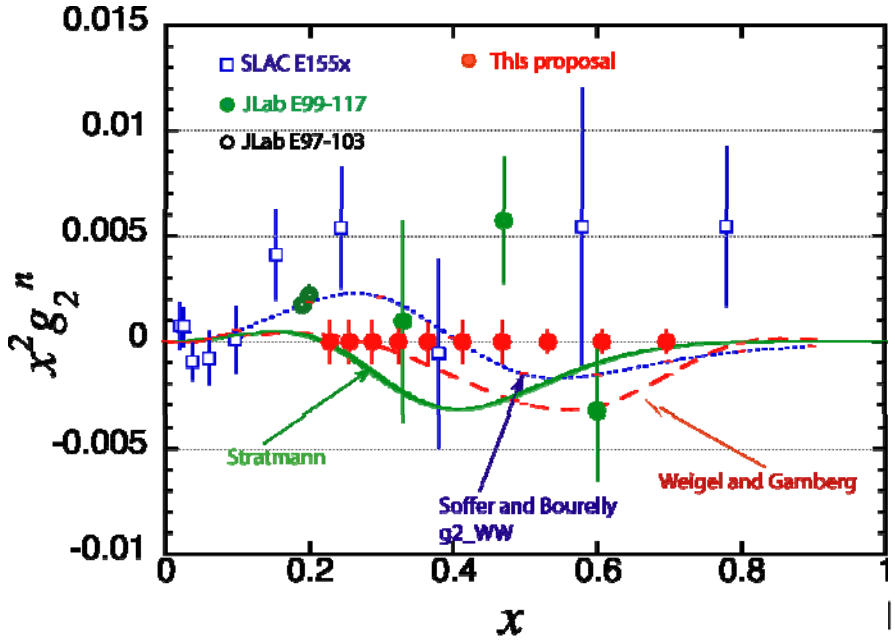


Two beam energies 4.6 and 5.7 GeV
(4 pass, 5 pass)

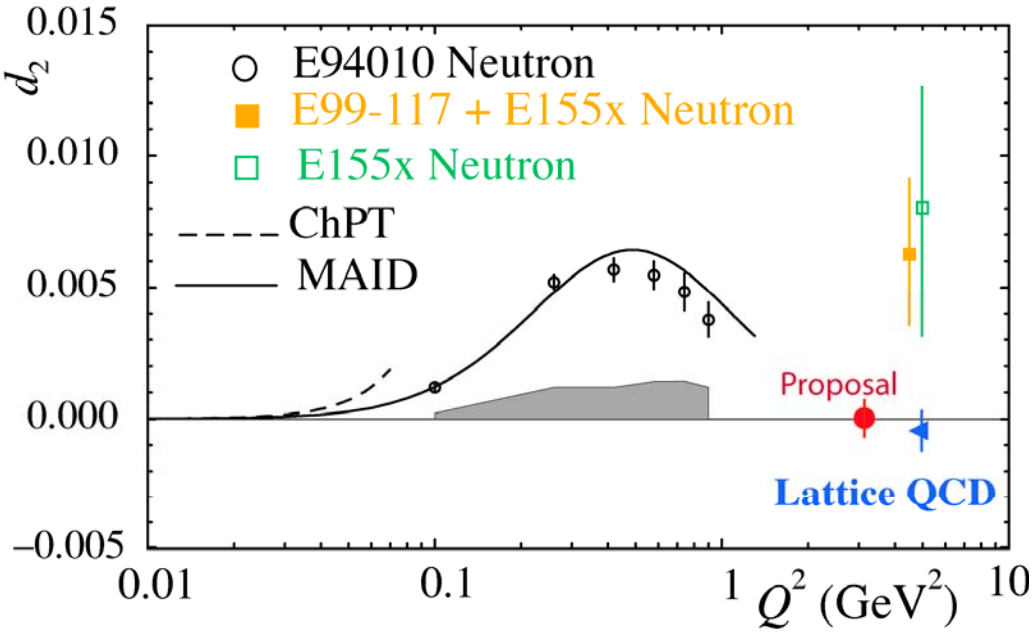
BigBite fixed at single scattering angle (θ=45°)
(data divided into 10 bins during analysis)

Experiment ran Jan.-Mar. 09

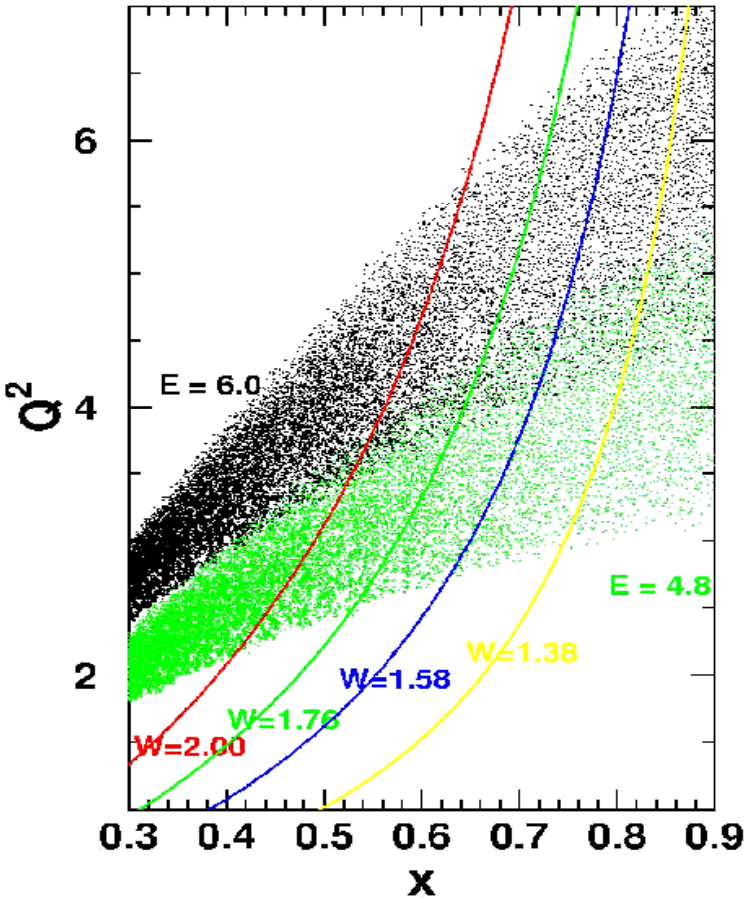
Expected precision in Experiment E06-114

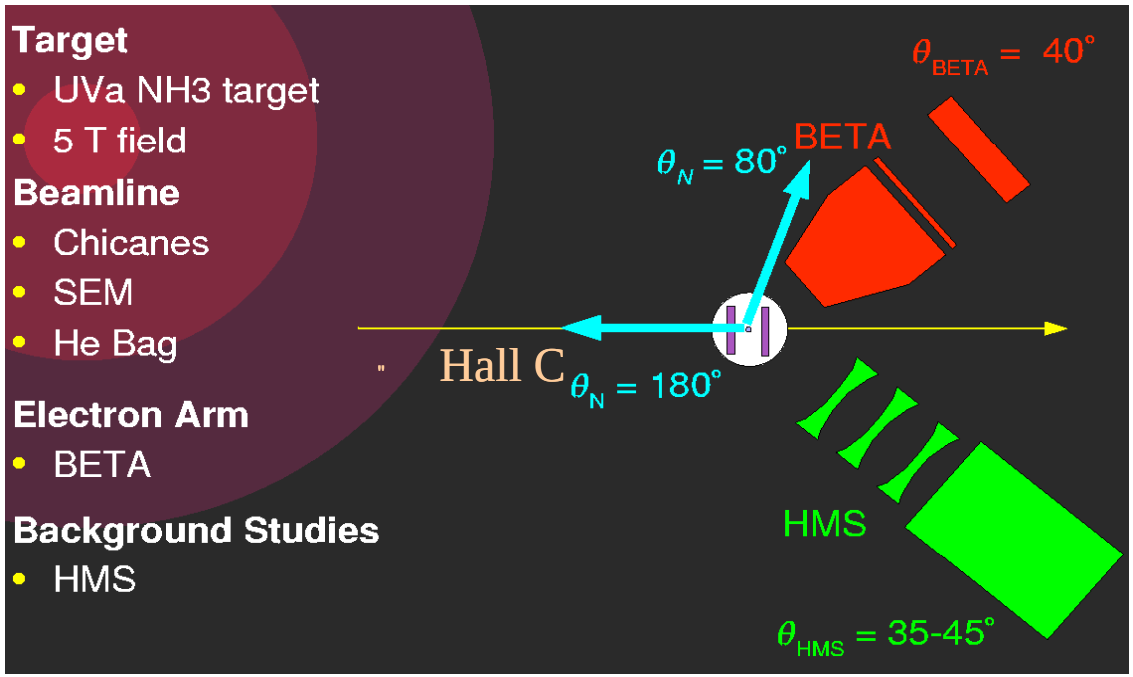


- At large Q^2, d_2 coincides with the reduced twist-3 matrix element of gluon and quark operators
- At low Q^2, d_2 is related to the spin polarizabilities



SANE experiment in Hall C





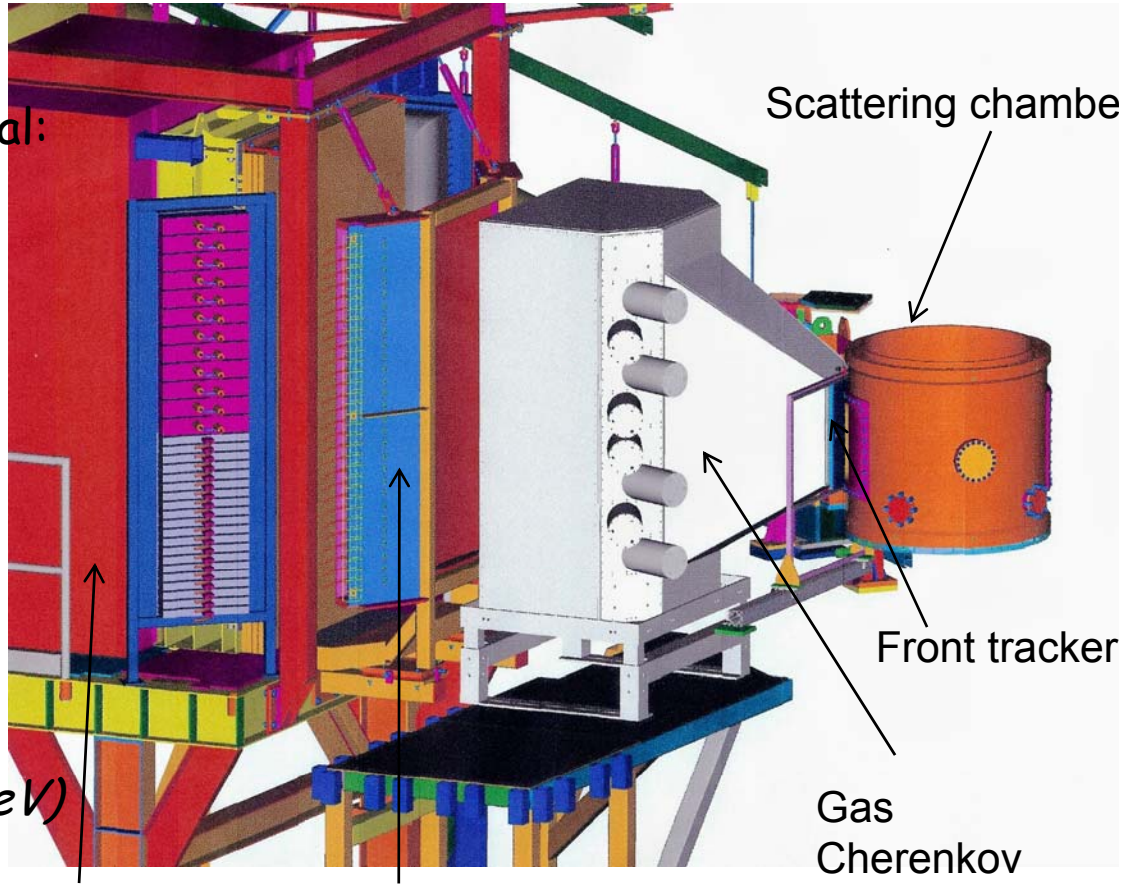
- Two beam energies:
  - **6.0 GeV (black)**
  - **4.8 GeV (green)**

- CEBAF polarized beam
  - 85 nA
  - 75% beam polarization

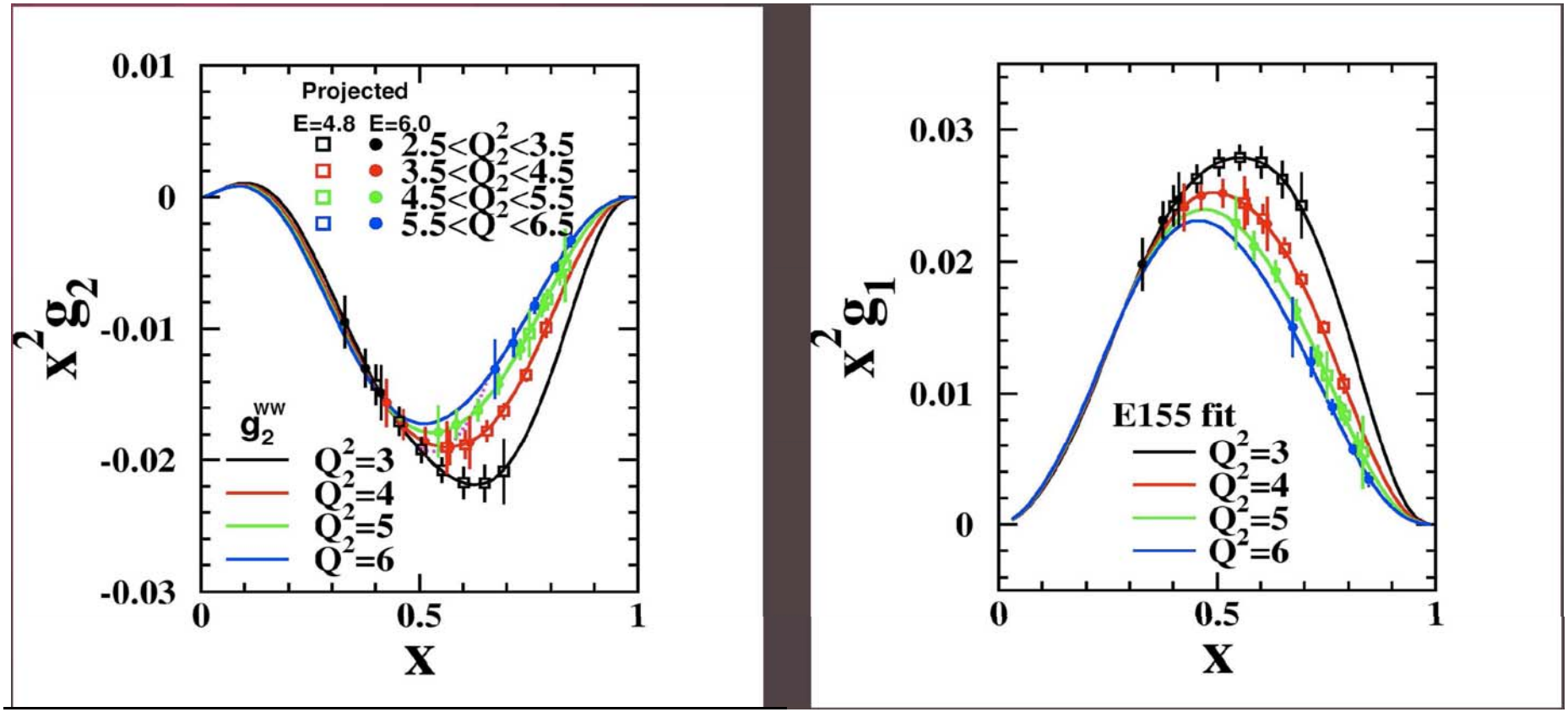
Experiment Ran January-March 09

BETA detector

- Three subsystems:
  - Lead glass calorimeter BigCal: Energy Measurement
  - Gas Cherenkov: e- identification
  - Lucite hodoscope: tracking
  - Front tracker: tracking
- Target field sweeps low *E* background
- Characteristics
  - Effective solid angle (with cuts) = 0.194 sr
  - Energy resolution 5%/$\sqrt{E(GeV)}$
  - *angular resolution = 2°*
  - *1000:1 pion rejection*

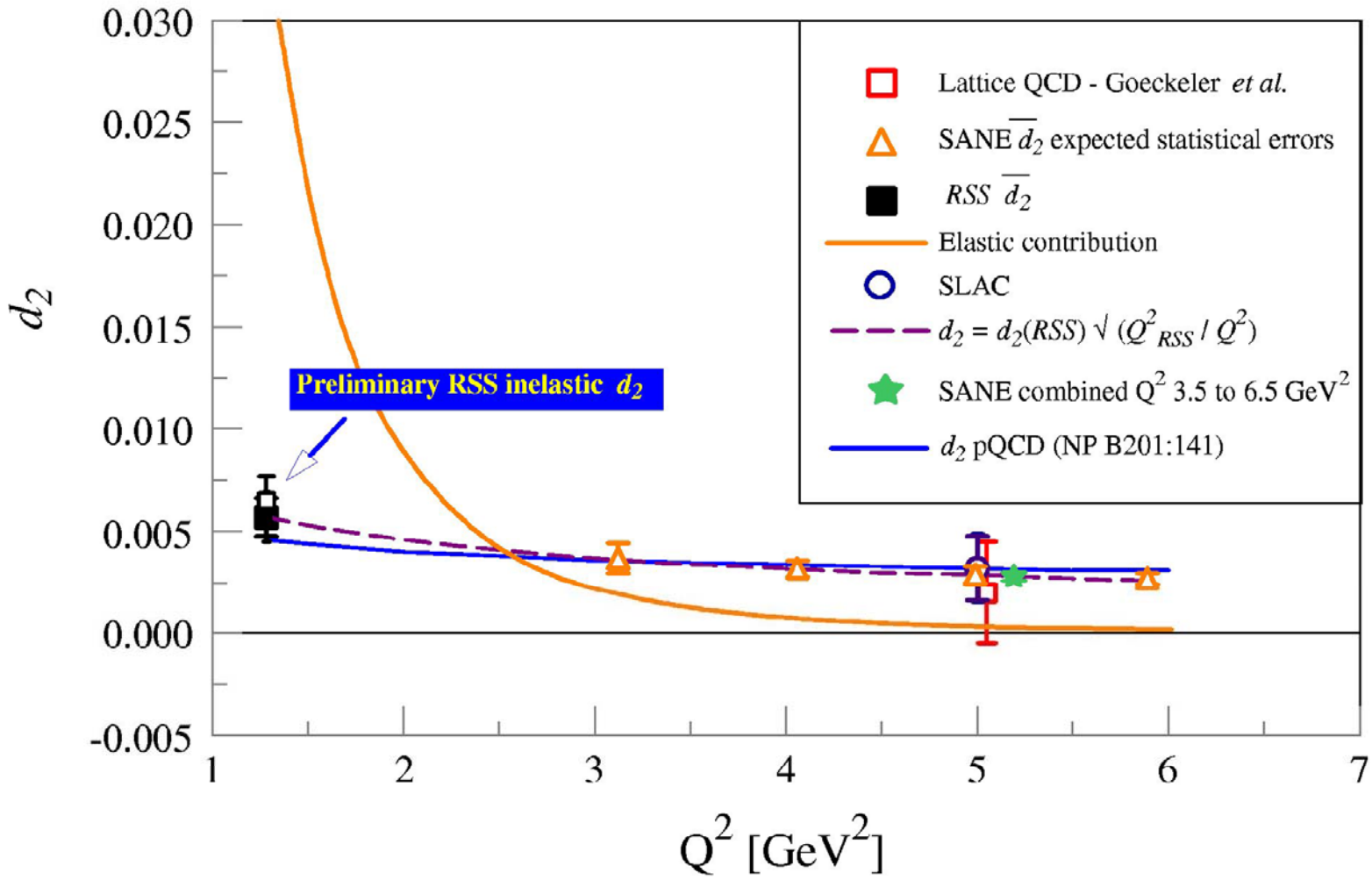


SANE experiment g_2, g_1 projected errors



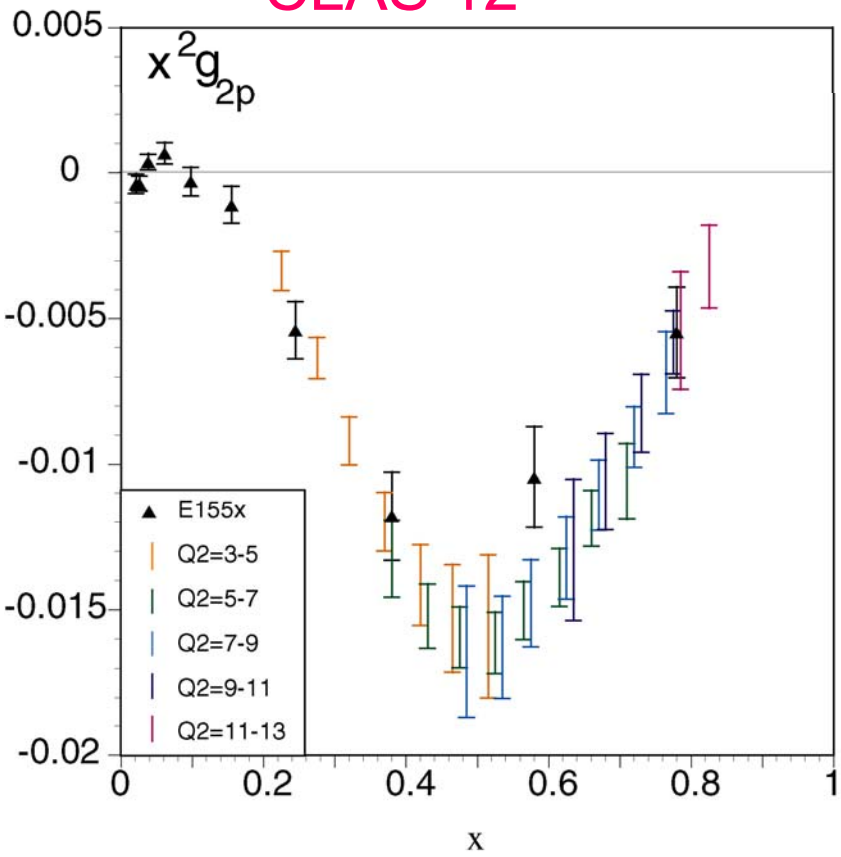
d_2^p RSS and SANE d_2^p projection in Hall C

RSS spokesperons: M. Jones, O. Rondon
SANE spokespersons: S. Choi, M. Jones, O. Rondon, Z.-E. M

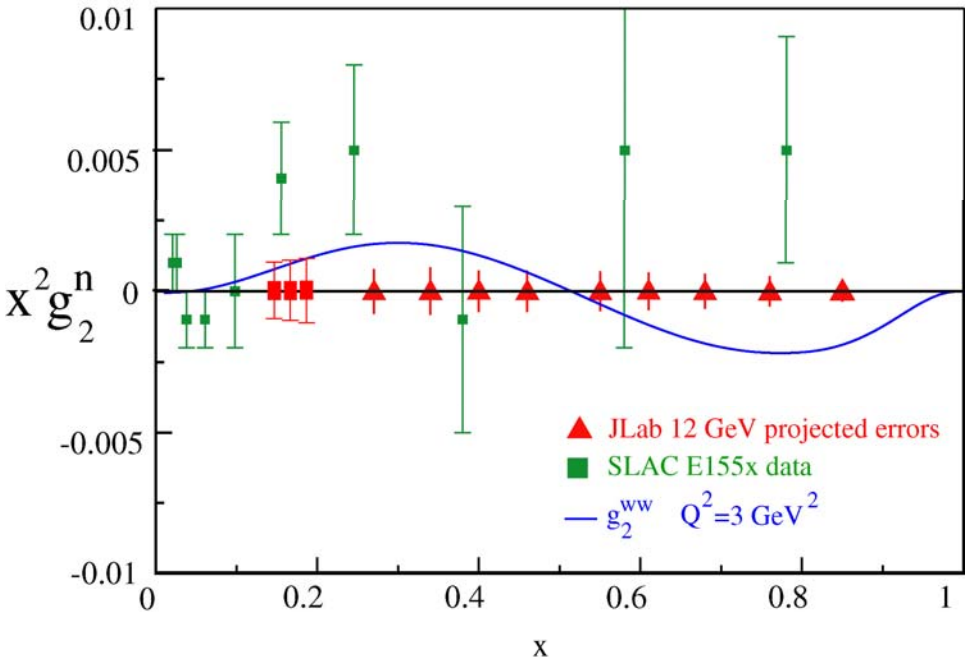


g_2 at JLab with 11 GeV

CLAS 12



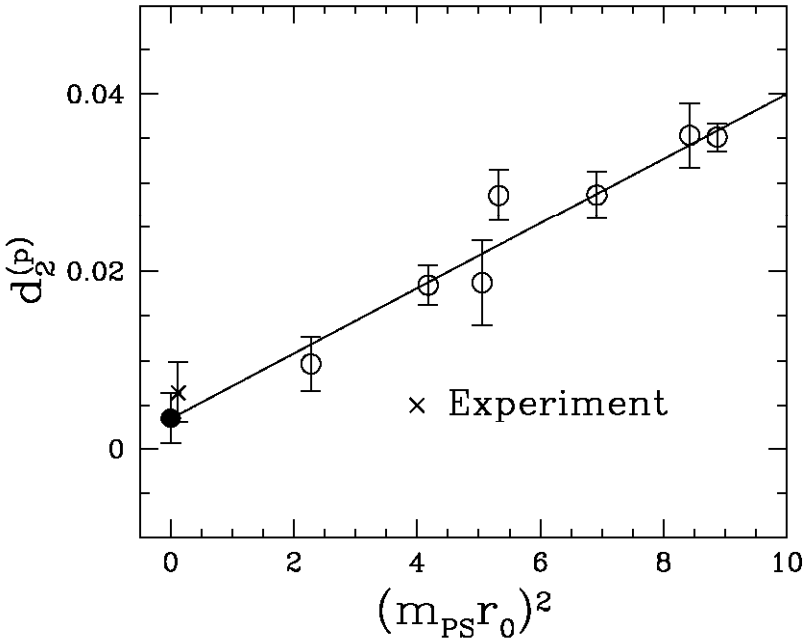
Hall C HMS/SHMS

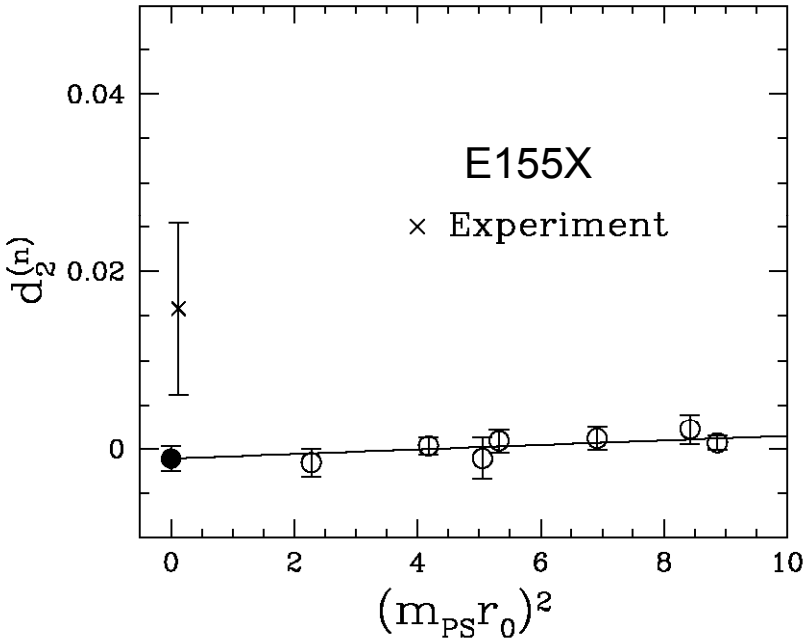


Summary

- Past experiments on the neutron and proton suggest that the twist-3 and twist-4 are small but finite.
- Precision measurements of g_1 and g_2 in the range $1 < Q^2 < 4$ GeV^2 are crucial for an improved extraction of the
  - Average color Lorentz force
  - "Color polarizabilities"
- In the next year or two we will have results from two recently ran experiments at Jefferson Lab, SANE in Hall C (proton) and E06-14 in Hall A (neutron).
- The non-singlet combination ($d_2^p - d_2^n$) should provide a benchmark test for present lattice QCD calculations since no disconnected diagrams are needed.
- This program will be pursued at JLab 11 GeV for higher precision and greater Q^2 and x coverage.

QCDSF Collaboration Lattice Calculations



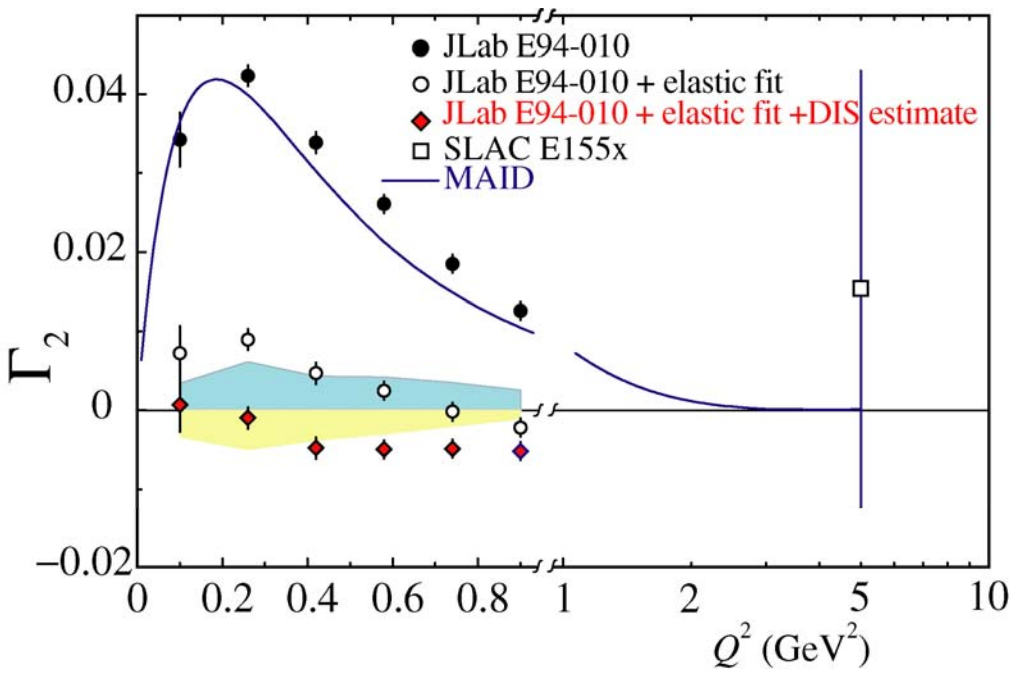


hep-lat/0506017

M. G\"ockeler, R. Horsley, D. Pleiter, P.E.L. Rakow, A. Sch\"afer, G. Schierholz, H. St\"uben, J.M. Zanotti

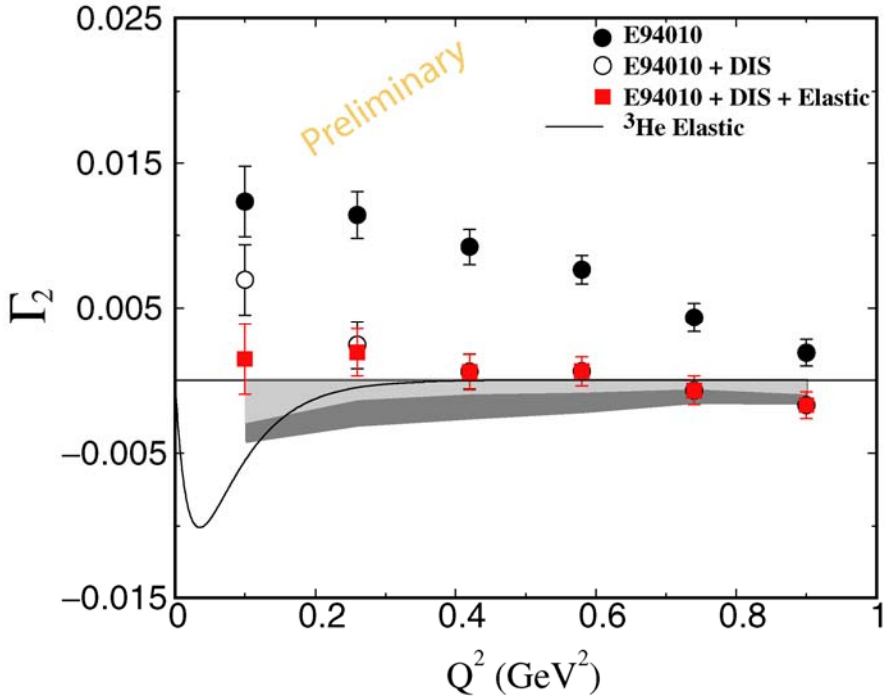
E94-010 B-C sum rule; results

Neutron



M. Amarian et al., Phys. Rev. Lett. 92, 022301 (2004)

^{3}He

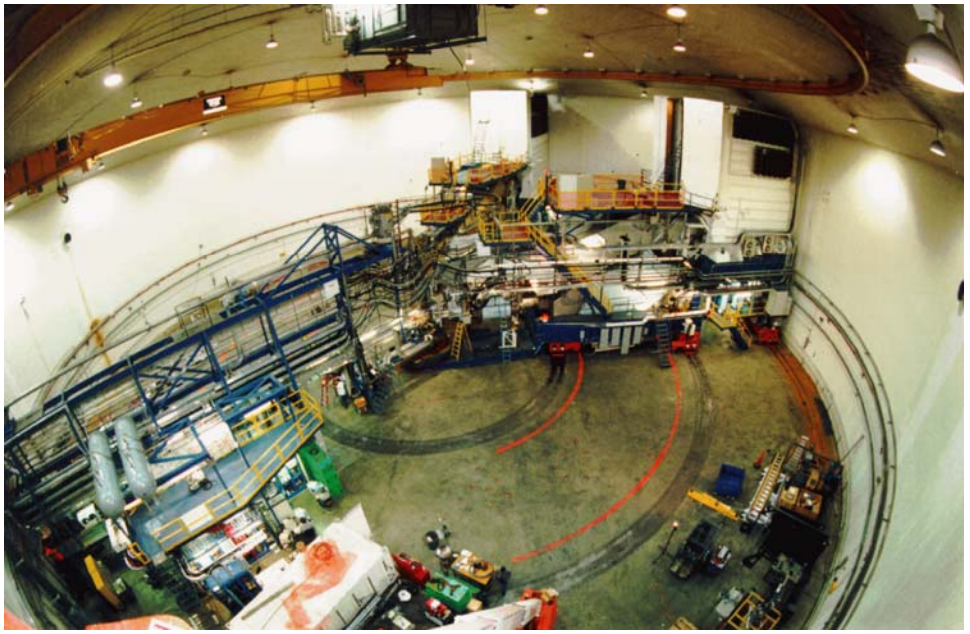


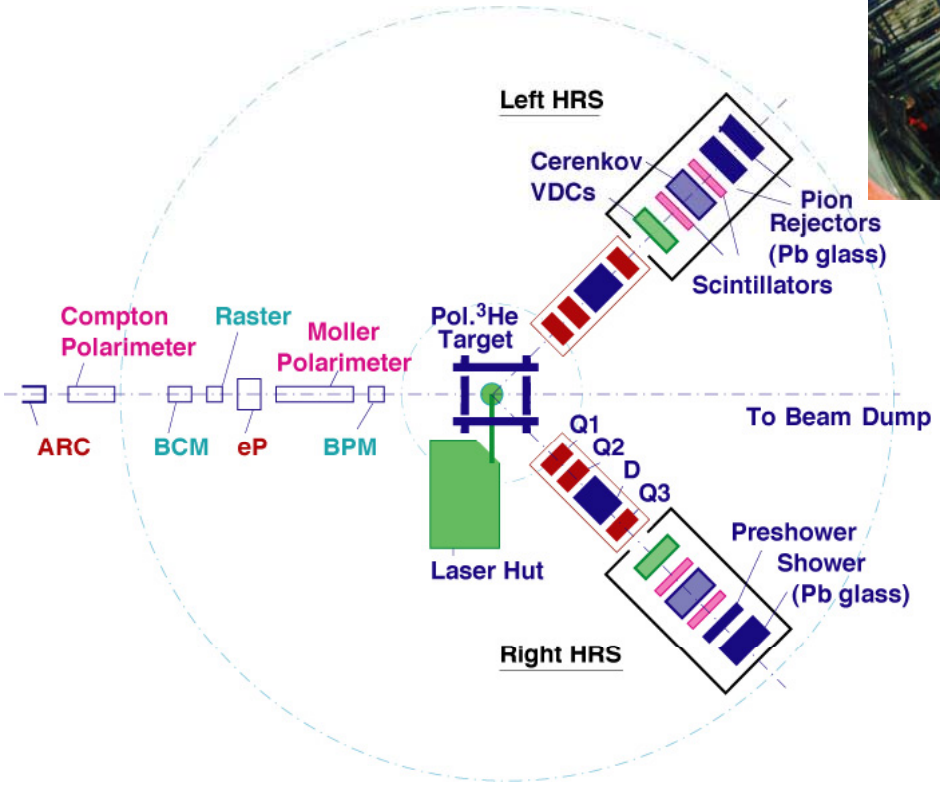
M. Amarian et al., in preparation

Jlab Hall A Experimental Setup

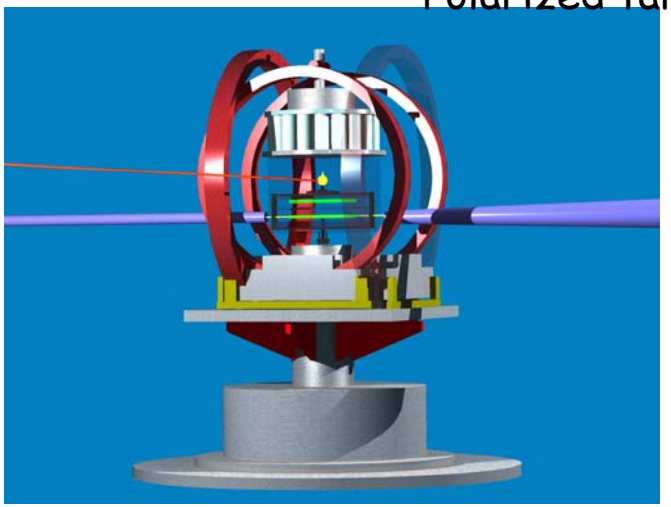
75-80% polarized beam at 15μA

35-40% polarized target in beam

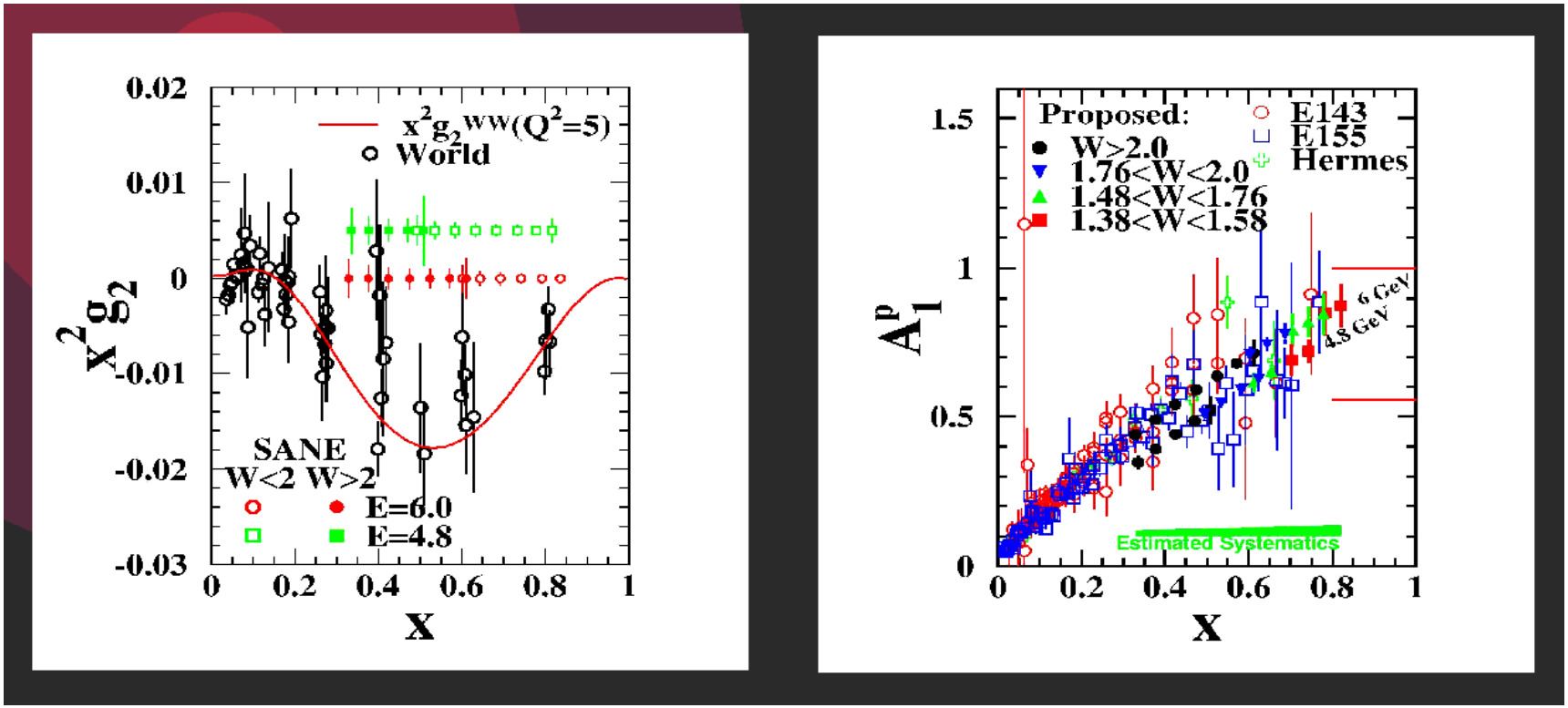




Polarized target



Proton g_2 and A_1



- DIS data up to $x = 0.6$; Resonances measured down to $W = 1.38$ GeV
- g_2 measured in region of most sensitivity for d_2