Nucleon g_2 Structure Function Measurement at Large x and Color Forces

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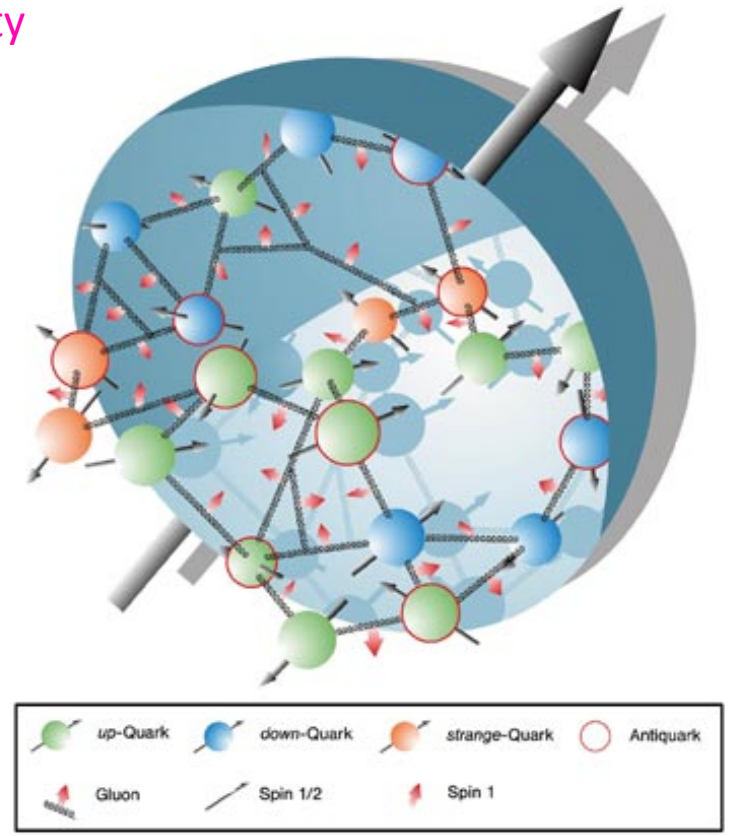
Outline:

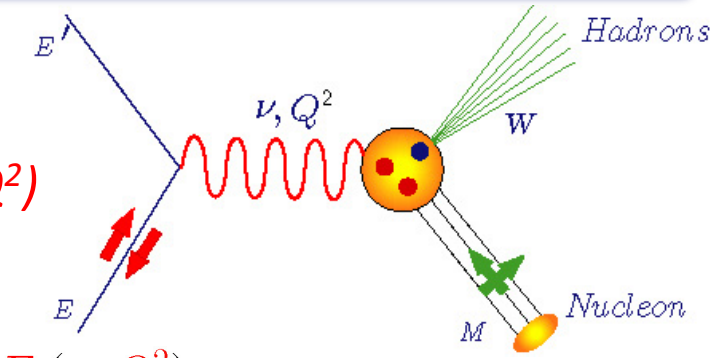
- Introduction
- Quark-gluon correlations and color forces
- JLab d2n and SANE experiments
- Experimental results
- Summary



Courtesy of CERN Courier

On behalf of the d2n and the SANE collaborations

Inclusive Deep Inelastic Scattering: 1-D View



- 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

  $g_1(x,Q^2)$ *(parton model interpretation)*

  $g_2(x,Q^2)$ *(quark-gluon correlations)*

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 $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

Moments of spin structure functions

Gerasimov-Drell-Hearn Sum Rule
$I_{GDH}(0)$

Generalized GDH Integral
$I_{GDH}(Q^2)$

Bjorken Sum Rule
Γ_1^{p-n}

Burkhardt-Cottingham sum rule
$\Gamma_2(Q^2)$

Spin Polarizabilities
$\gamma_0(Q^2), \delta_{LT}(Q^2)$

Higher twists & color forces/polarizabilities
$d_2(Q^2), f_2(Q^2)$

0 — 1 — 10 — ∞

Q^2

Lattice QCD

pQCD

χPT

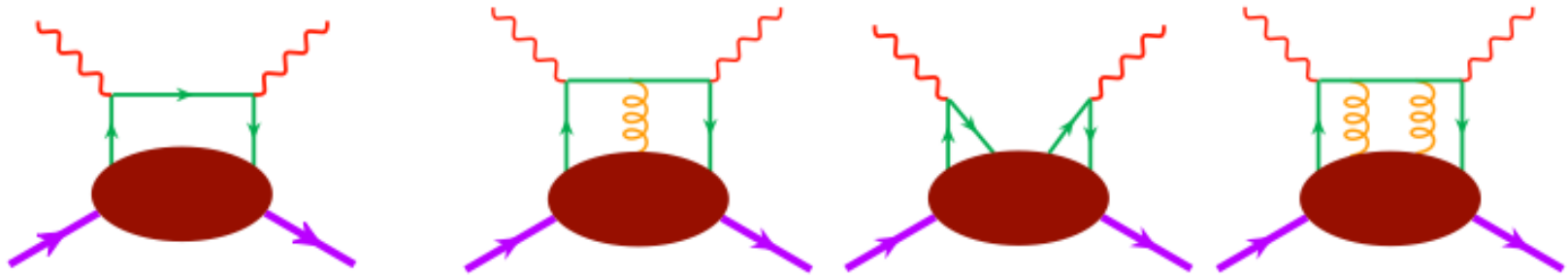
OPE

MODELS

DSE

AdS/CFT

Moments of Structure Functions: Probing Color Forces



$\tau = 2$

single quark scattering

$\tau > 2$

qq and qg correlations

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

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

$\tau \equiv \mathrm{twist} \equiv \mathrm{operator\ dimension} - \mathrm{spin}$

Moment of spin structure function g_1

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\, dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

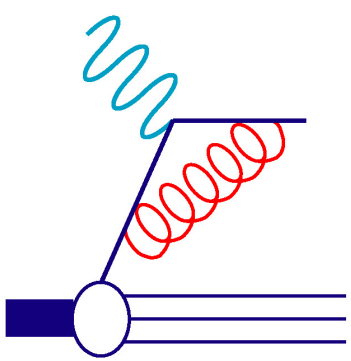
leading twist

higher twist

$$\mu_2^{p,n}(Q^2) = (\pm \frac{1}{12} g_A + \frac{1}{36} a_8) + \frac{1}{9}\Delta\Sigma$$ + pQCD corrections

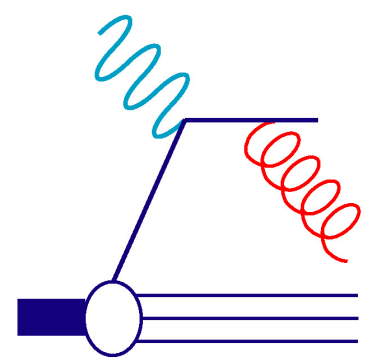
$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

$\Delta\Sigma$ = singlet axial charge



$$\begin{aligned} g_A &= \Delta u - \Delta d \\ a_8 &= \Delta u + \Delta d - 2\Delta s \\ \Delta\Sigma &= \Delta u + \Delta d + \Delta s \end{aligned}$$

pQCD radiative corrections



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

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

$$d_2(Q^2) = \int_0^1 dx x^2 \bar{g}_2(x,Q^2)$$

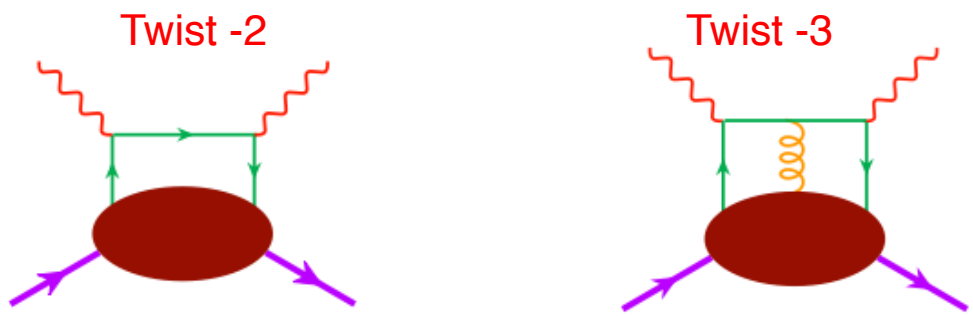
$$\frac{1}{2}\langle N|\bar{\psi}\gamma^{\{\alpha}g\tilde{G}^{\beta\}\gamma}\psi|N\rangle = d_2\left(p^{\{\alpha}p^{\beta\}}S^{\gamma} - p^{\gamma}p^{\{\beta}S^{\gamma\}}\right)$$

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

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

$$\frac{1}{2}\langle N|\bar{\psi}\gamma_{\alpha}g\tilde{G}^{\beta\alpha}\psi|N\rangle = f_2 S^{\beta}$$

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

$$\boxed{d_2 = 3\int_0^1 dx x^2 \bar{g}_2(x) = \int_0^1 dx x^2 \left[3g_2(x) + 2g_1(x)\right]}$$

"Color Polarizabilities"

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

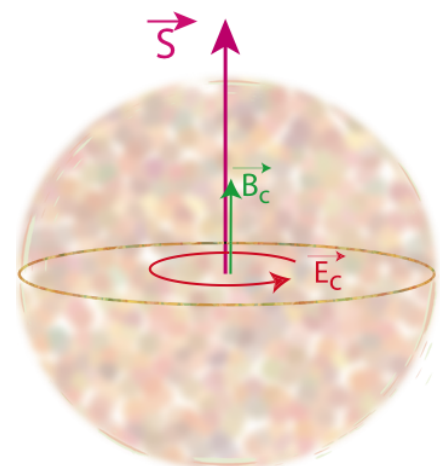
How does the gluon field respond when a nucleon is polarized ?

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

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



$$\boxed{\begin{aligned} d_2 &= (\chi_E + 2\chi_B)/4 \\ f_2 &= \chi_E - \chi_B \end{aligned}}$$

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

Lorentz Color Force (M. Burkardt)

Consider a charge e moving near speed of light ($\vec{v} = (0, 0, -1)$) along the $-\hat{z}$ direction. The electromagnetic Lorentz force is written as:

$$F^y = e\left[\vec{E} \times \vec{v}\vec{B}\right]^y = e(E^y - B^x) = -e\sqrt(2)F^{+y}$$

Color Lorentz force reads:

$$F^y = -\frac{\sqrt{2}}{2P^+}\langle P, S|\bar{q}G^{+y}\gamma^+ q|P, S\rangle$$

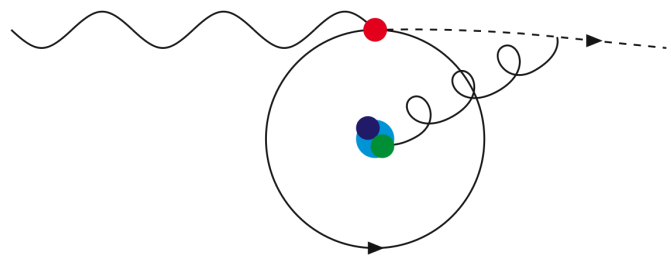
$$= -\frac{1}{2P^+}\langle P, S|\bar{q}(B^x - E^y)\gamma^+ q|P, S\rangle$$

$$= -M^2 d_2$$

M. Burkardt, Phys. Rev. D 88, 114502 (2013) and
Nucl. Phys. A 735, 185 (2004).

Average Color Lorentz Force (M. Burkardt)

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



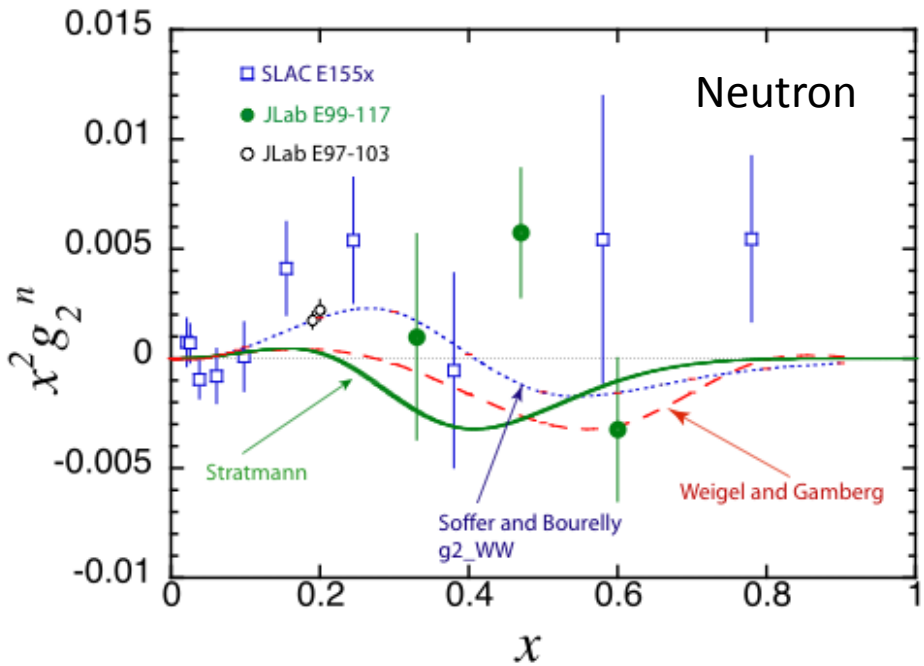
$\hookrightarrow$ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

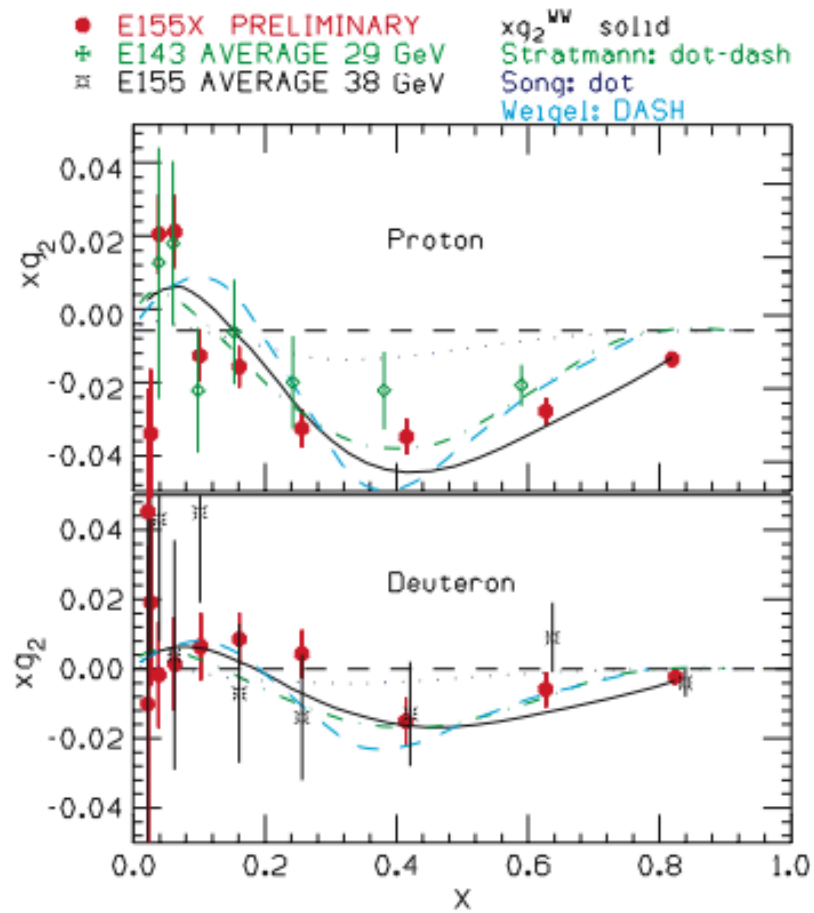
$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

$$F_E{}^y(0) = -\frac{M^2}{4} \chi_E = -\frac{M^2}{4} \left[\frac{2}{3} (2d_2 + f_2) \right]$$

$$F_B{}^y(0) = -\frac{M^2}{2} \chi_B = -\frac{M^2}{2} \left[\frac{1}{3} (4d_2 - f_2) \right]$$

Earlier nucleon world results of g_2



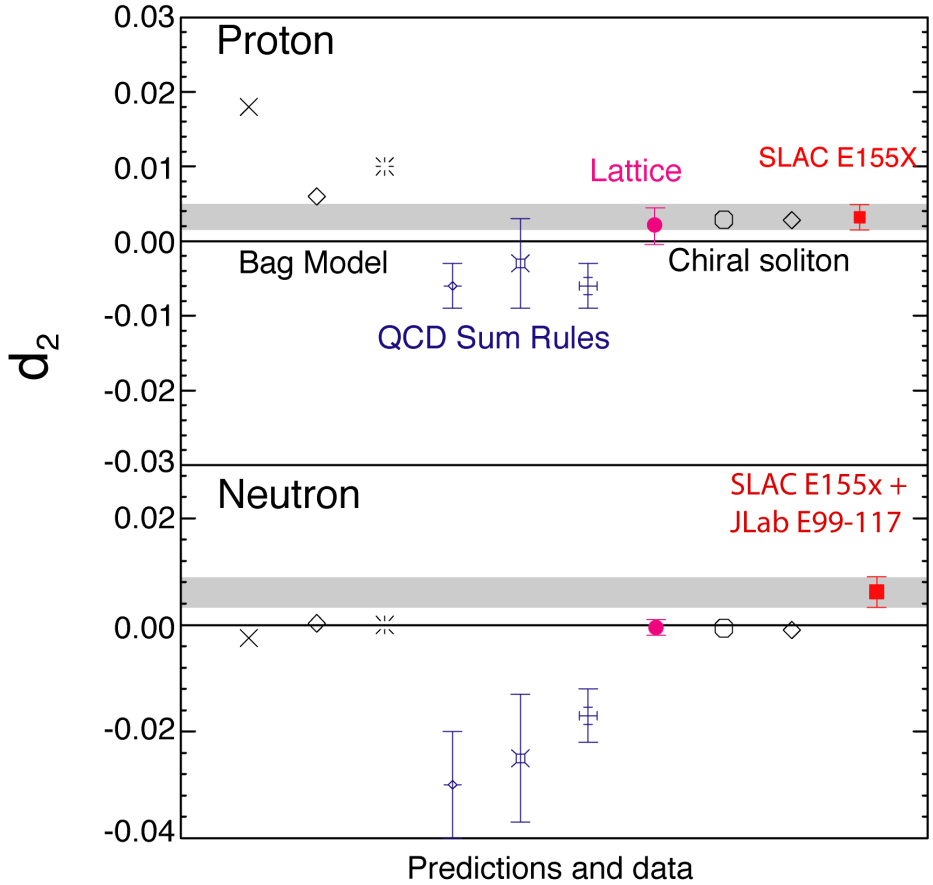


- SLAC E155x (proton and deuteron)
- JLab E99-117(helium-3), A_1^n in DIS
- Jlab E97-103 (helium 3) Q^2 dependence below 1 GeV^2

SLAC E155x (proton and deuteron)

Recent work on g_2: V. Braun et al. Phys. Rev. D83 (2011) 094023

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)

Two Jefferson lab experiments dedicated to measure the g_2 structure function

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 and Z.-E. M

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

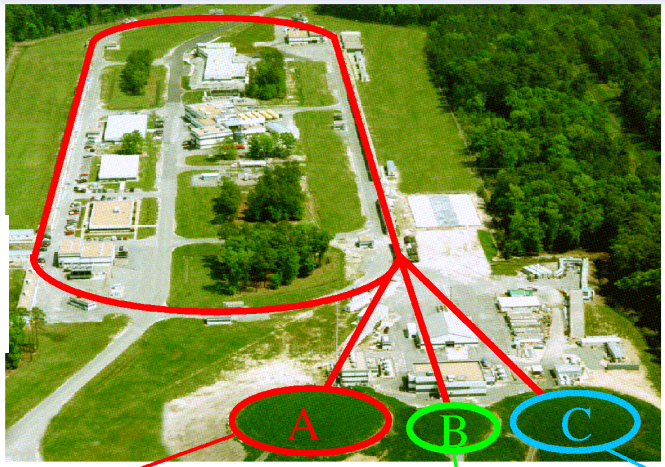
and the Hall C collaboration

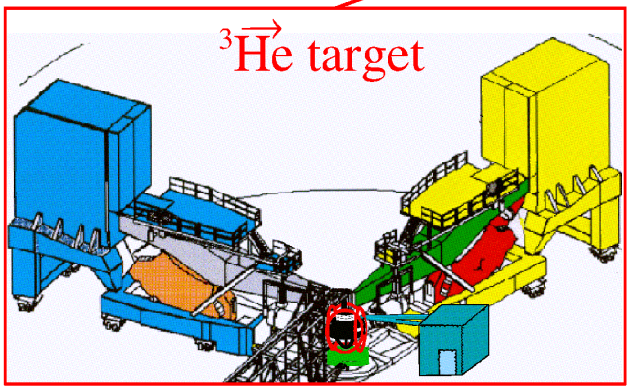
Posik, Flay, Parno et al. Arxiv: 1404.4003v2
Submitted to PRL

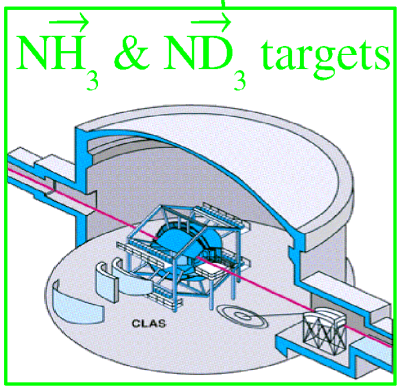
Analysis close to completion

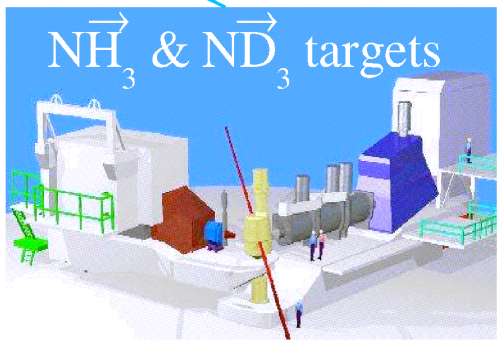
Jefferson Lab Polarized DIS experiments at 6 GeV

6 GeV pol. e beam
Pol=85%, 100mA









HallA: two HRS'

Luminosity~10^{36} (cm^{-2} s^{-1})

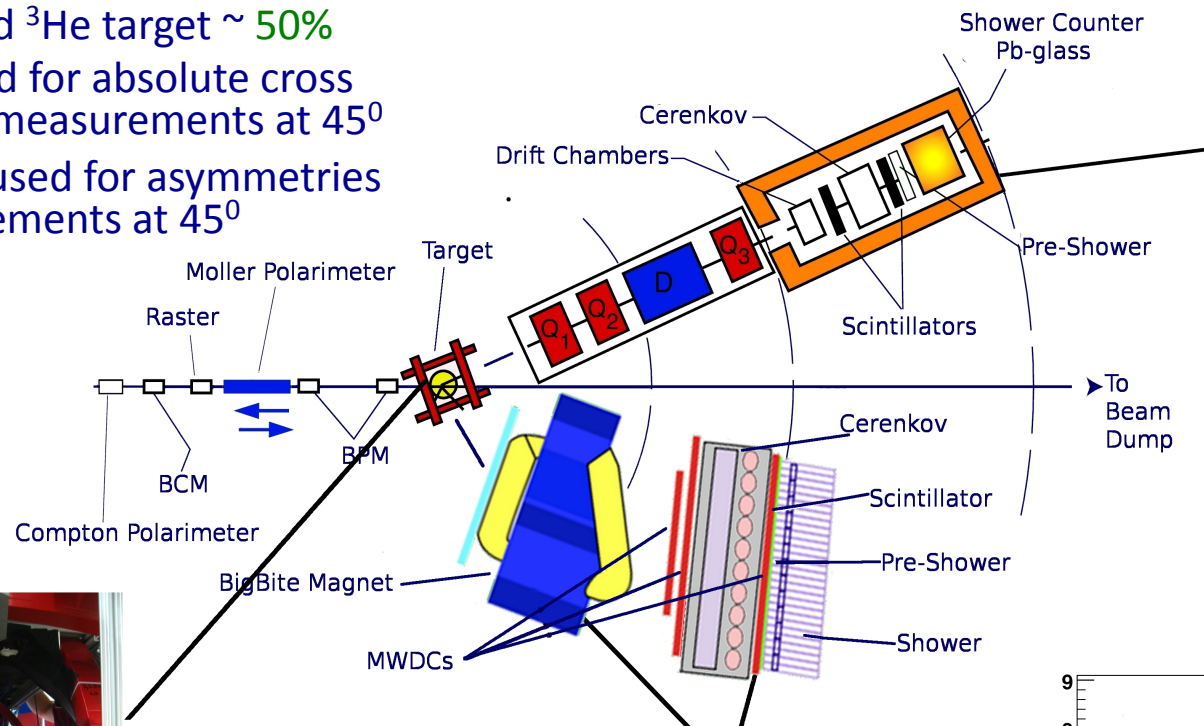
Hall B:CLAS

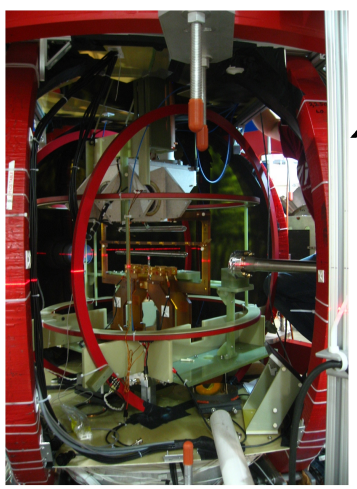
Hall C: HMS+SOS

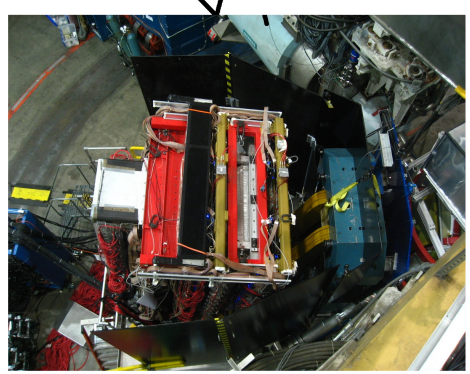
Luminosity up to 10^{35} (cm^{-2} s^{-1})

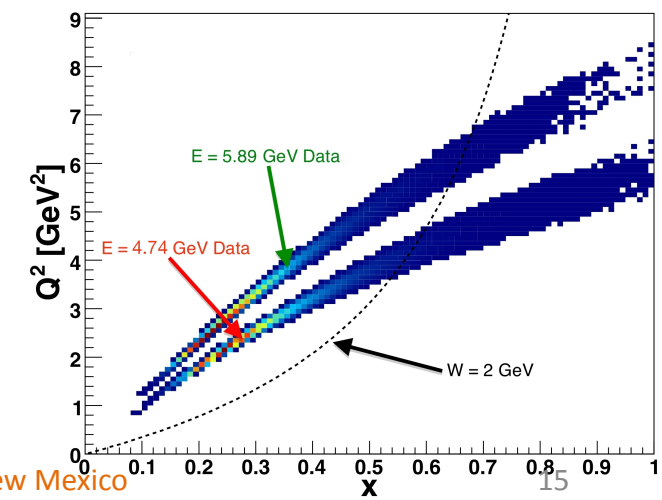
The JLab E06-014 (d_2^n) Experiment

- Polarized electron beam: E=4.74, 5.89 GeV, polarization ~ 71%
- Polarized ^{3}He target ~ 50%
- HRS used for absolute cross section measurements at 45^0
- Bigbite used for asymmetries measurements at 45^0

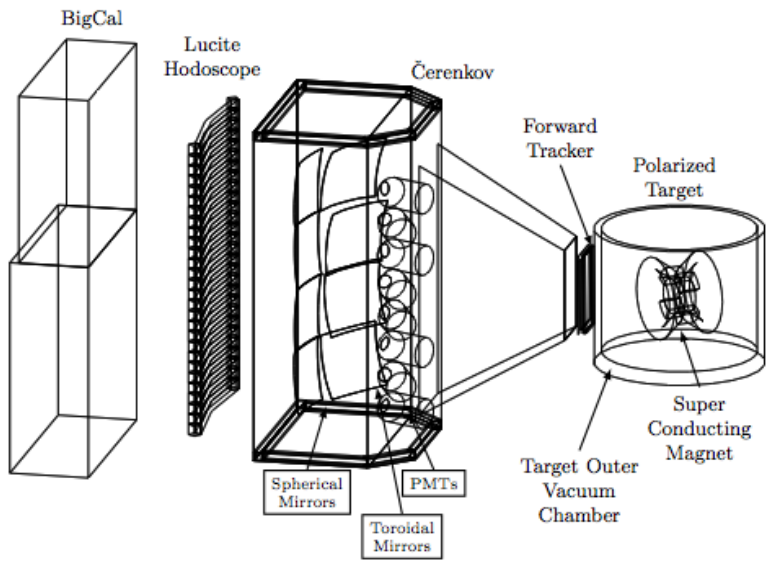


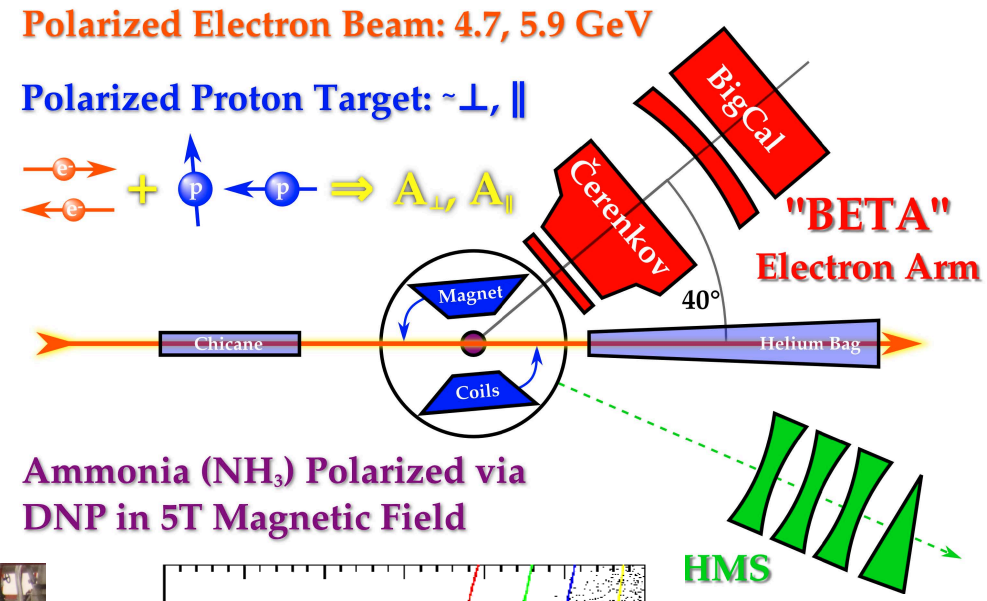


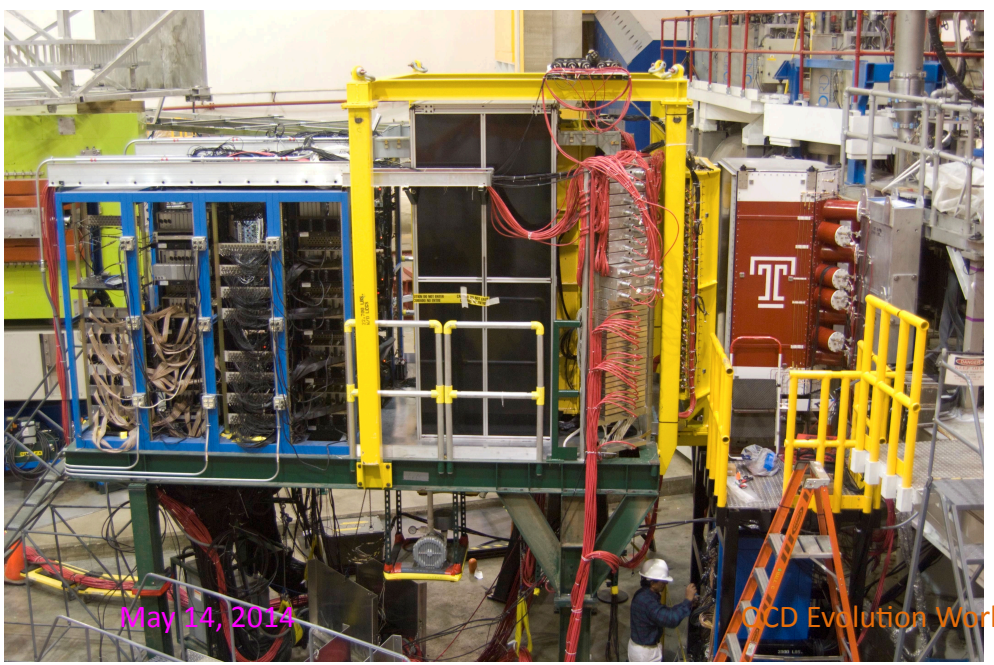


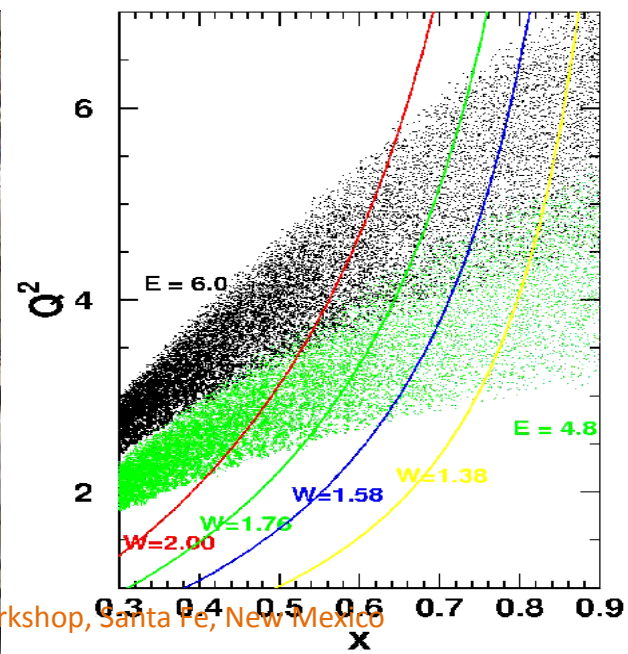


Spin Asymmetries of the Nucleon Experiment (SANE)

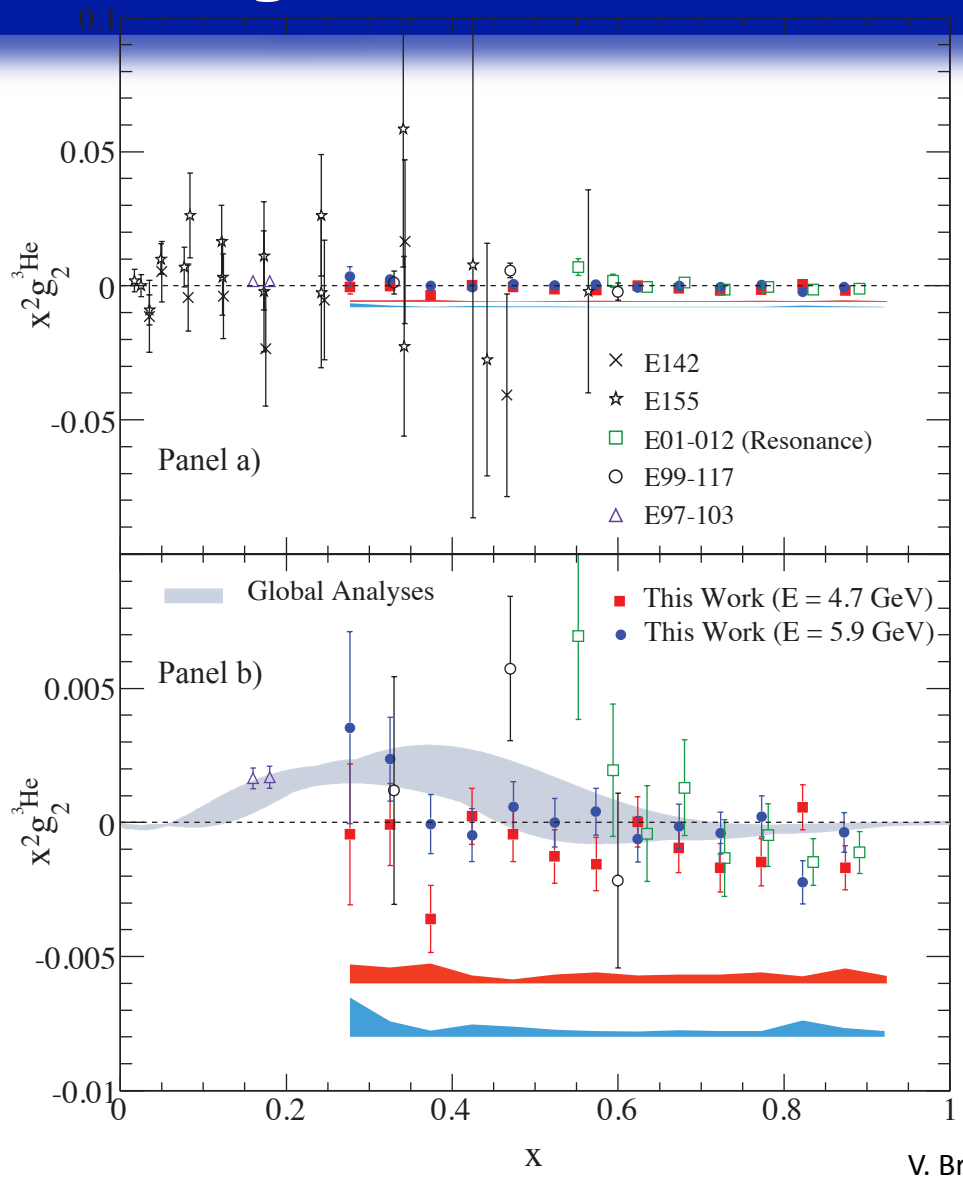








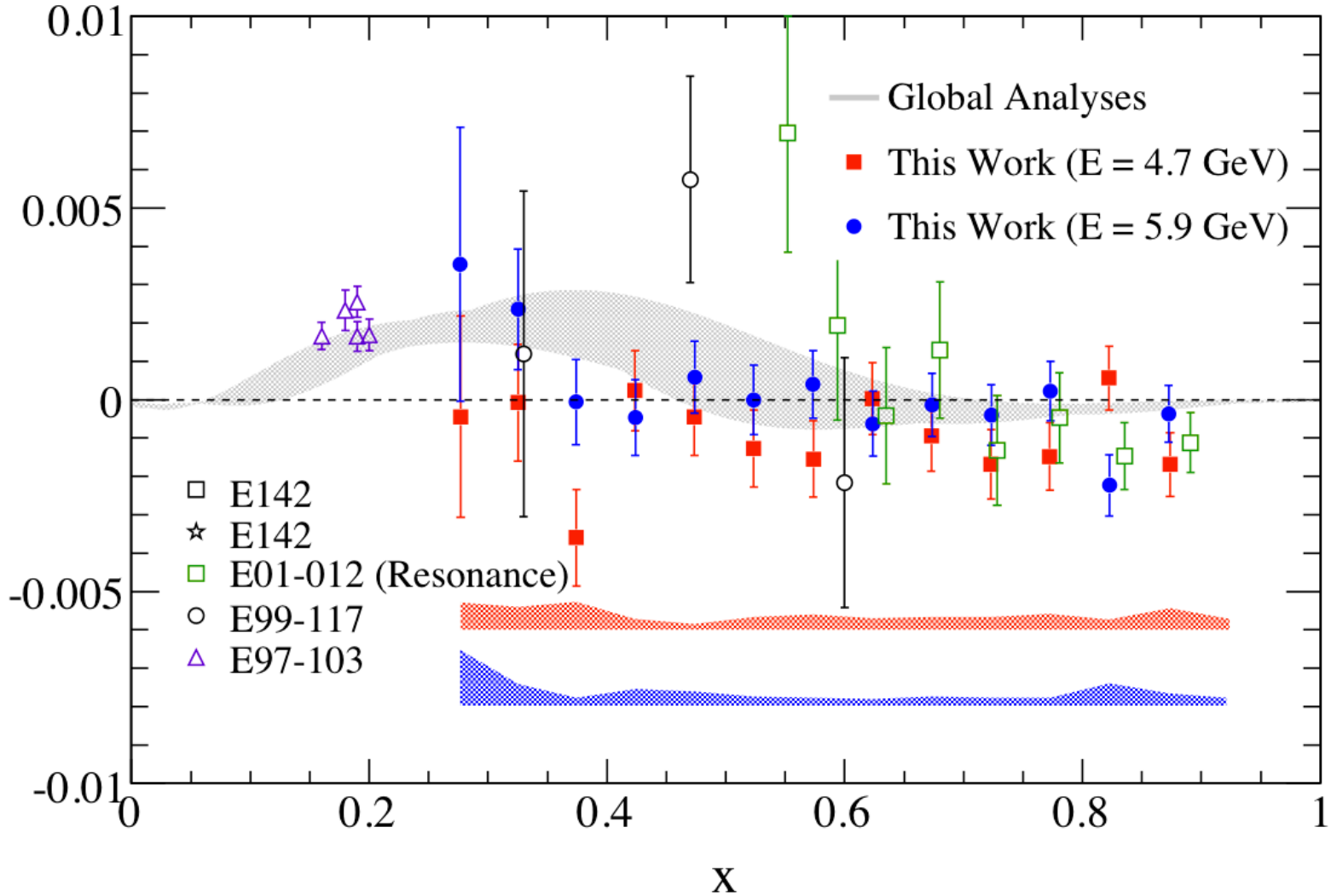
^{3}He g_2 structure function



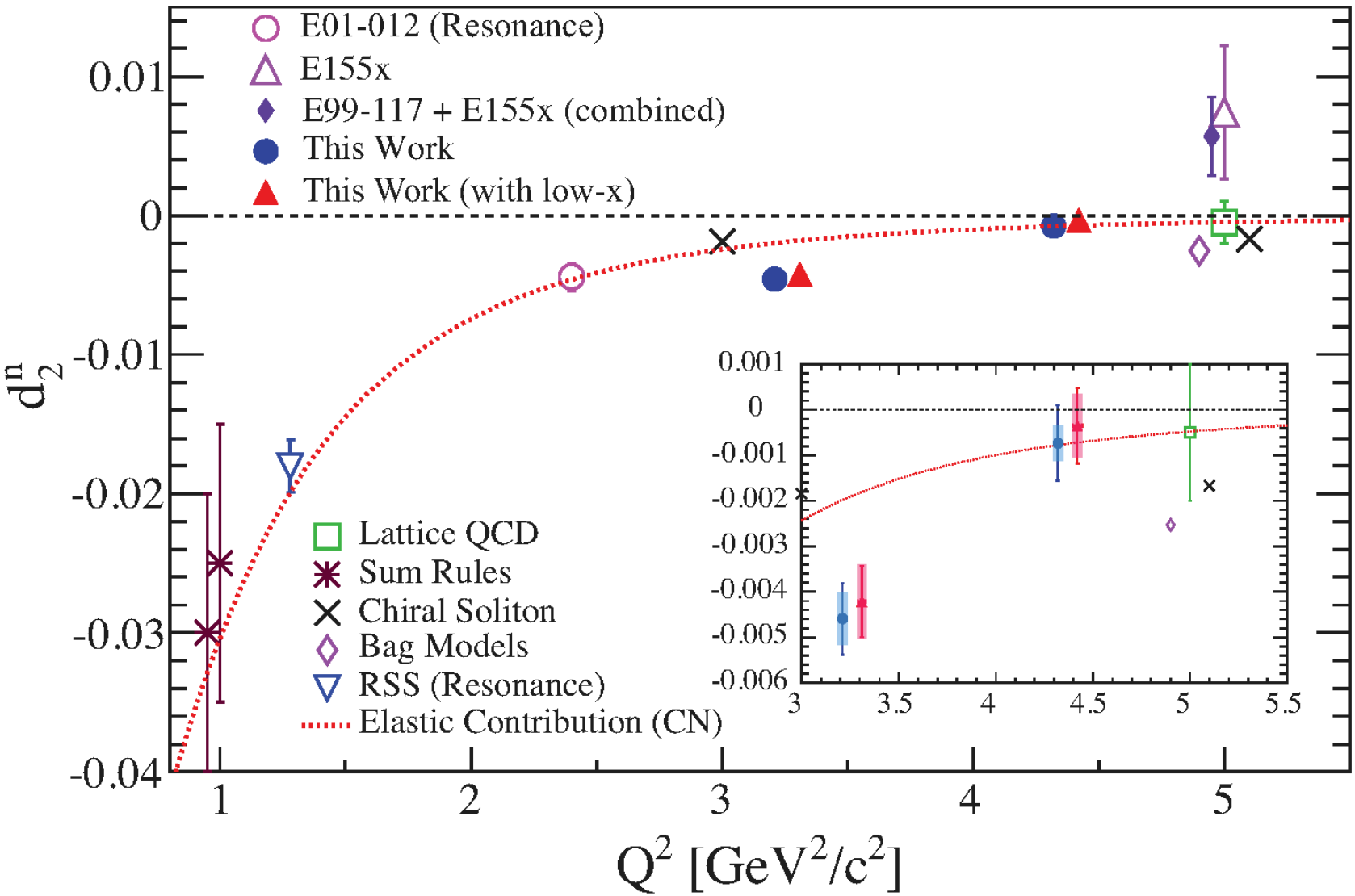
M. Posik, D. Flay, D. Parno et al.
Arxiv: 1404.4003v2
Submitted to PRL

V. Braun et al. Nucl. Phys. B603 (2001) 69-124

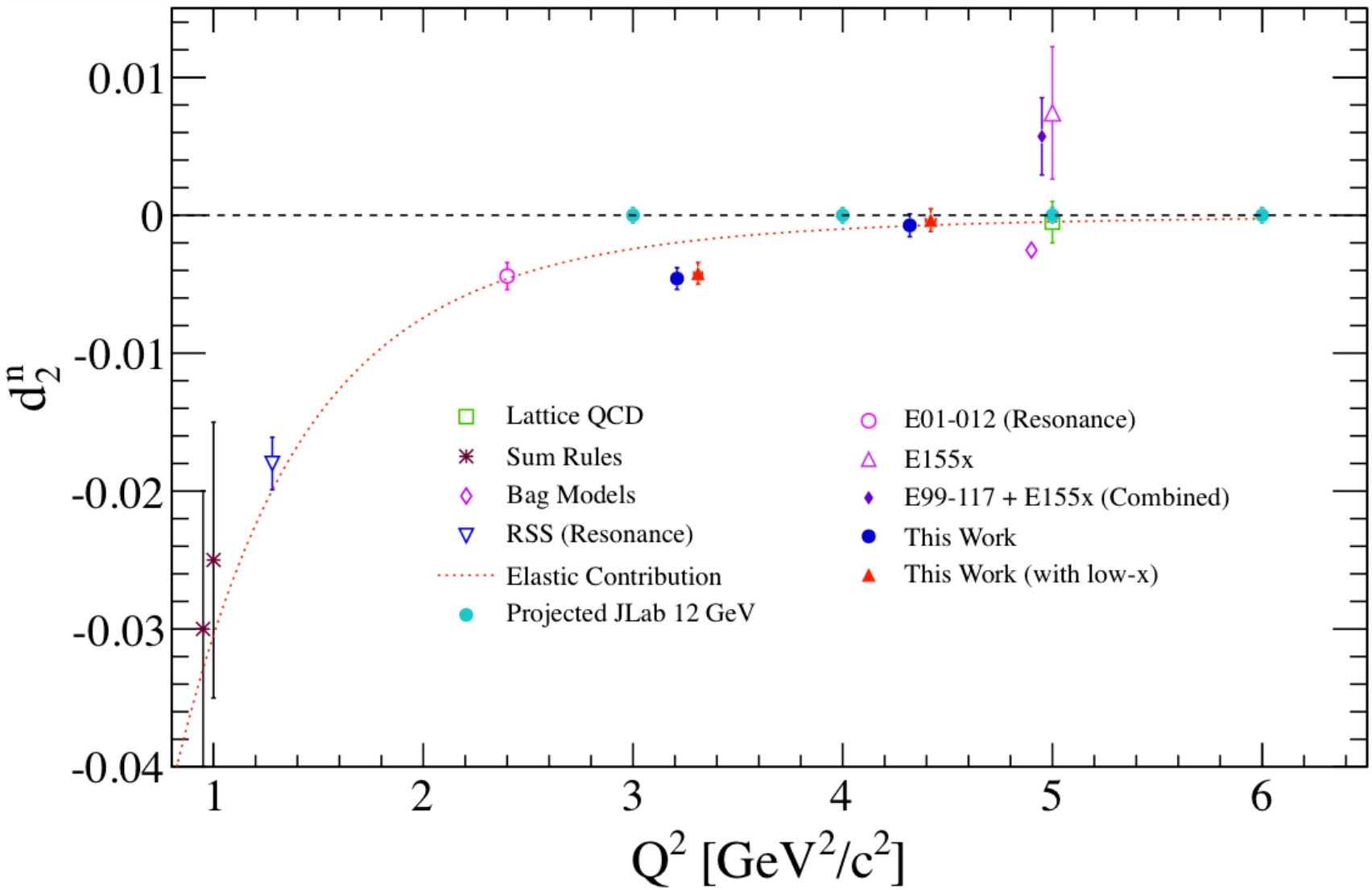
^{3}He g_2 structure function



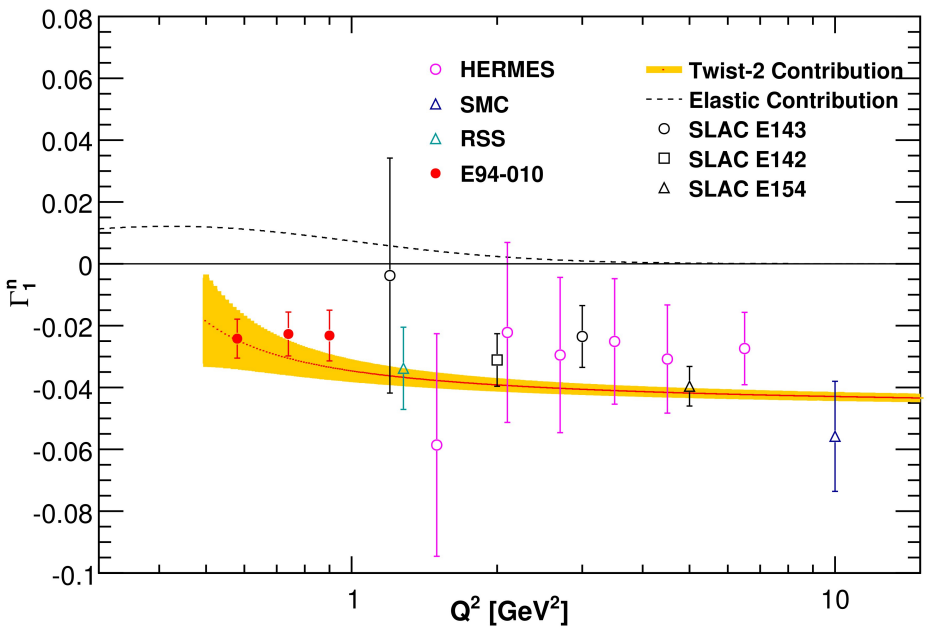
d_2^n results compared to calculations

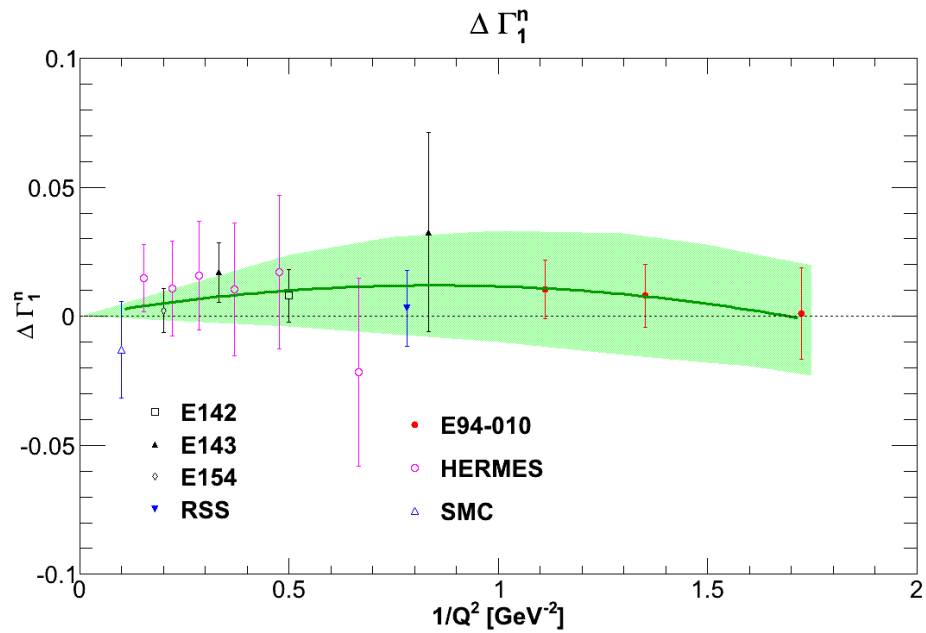


JLab 12 projection of d_2^n Planned in Hall C



Extraction of the twist-4 matrix element





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

$\langle Q^2 \rangle$ (GeV^2)	f_2^n	Stat.	Syst.
3.21	0.07623	0.00079	0.04014
4.32	0.07329	0.00083	0.04013

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

Color forces in the neutron

Group	Q^2 (GeV$^2/c^2$)	$f_2^n \times 10^{-3}$	F_E (MeV/fm)	F_B (MeV/fm)
E06-014	3.21	$76.23 \pm 0.79 \pm 40.1$	$-51.85 \pm 1.32 \pm 29.90$	$66.64 \pm 2.43 \pm 30.00$
E06-014	4.32	$73.29 \pm 0.83 \pm 40.1$	$-54.18 \pm 1.37 \pm 29.90$	$55.39 \pm 2.53 \pm 30.00$
Instanton	0.40	38.0	-30.41	30.41
QCD sum rule	1	-13.0 ± 6.0	54.25 ± 15.52	79.52 ± 30.06
QCD sum rule	1	10.0 ± 10.0	29.73 ± 16.62	81.75 ± 30.64

- The electric and magnetic average color forces in the neutron are about equal and opposite
- A new measurement of the proton is needed to perform a flavor tagging of the force.
- A lattice calculation of f_2 is still missing?!

Flavor separated color forces

Table: Flavor separated color forces.

d_2^p Input	d_2^n Input	F^u (MeV/fm)	F^d (MeV/fm)
E155	E155	-26.22$\pm$44.54$_{stat}$	-151.96$\pm$103.13$_{stat}$
LQCD	LQCD	-45.48$\pm$54.10$_{stat}$	21.40$\pm$34.78$_{stat}$
E155	E0-6014(3)	-91.01$\pm$36.63$_{stat}$ $\pm$4.39$_{sys}$	107.23$\pm$19.20$_{stat}$ $\pm$17.55$_{sys}$
E155	E0-6014(4)	-70.36$\pm$36.65$_{stat}$ $\pm$3.69$_{sys}$	24.61$\pm$19.96$_{stat}$ $\pm$14.77$_{sys}$
LQCD	E0-6014(3)	-65.33$\pm$53.67$_{stat}$ $\pm$4.39$_{sys}$	100.81$\pm$21.56$_{stat}$ $\pm$17.55$_{sys}$
LQCD	E0-6014(4)	-44.68$\pm$53.69$_{stat}$ $\pm$3.69$_{sys}$	18.19$\pm$22.24$_{stat}$ $\pm$14.77$_{sys}$

Waiting for the new proton results …

Summary

- The neutron d_2 is measured with precision and found to be consistent with Lattice QCD calculations.
- The proton d_2 is also measured with precision and the results will be available soon.
- The Lorentz electric and magnetic color forces in the neutron are determined and found to be equal and opposite in sign.
- Together with the proton the flavor decomposition of the color forces will be carried out.
- This program will be pursued at JLab 11 GeV for higher precision and greater Q^2 and x coverage.

A_1^n results from the d_2^n experiment