Nucleon g_2 Structure Function at Large x: Probing Color Forces

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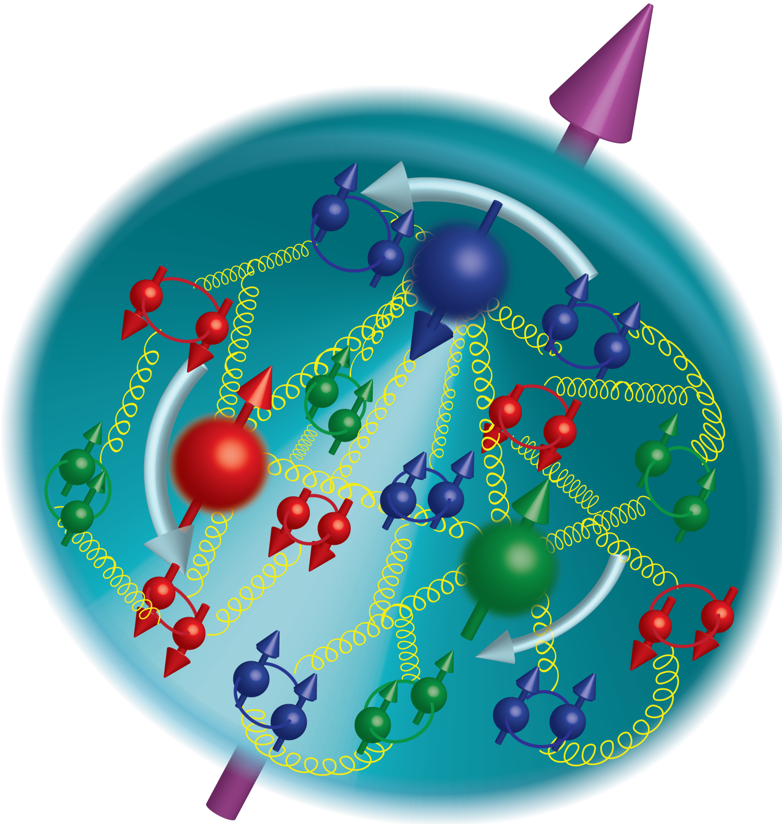
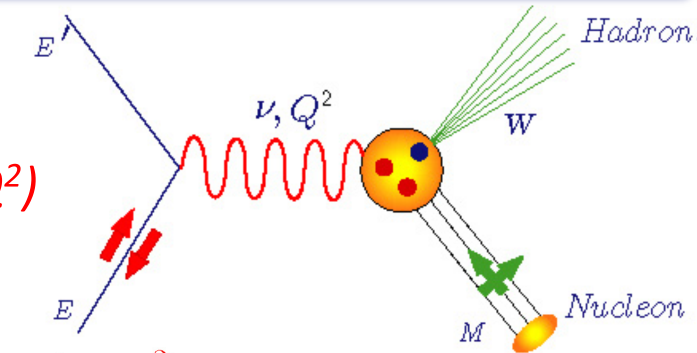
Outline:

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



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

First moments

$$\int_{thr}^{\infty}\left[\frac{\sigma_{3/2}-\sigma_{1/2}}{\nu}\right]d\nu = \frac{2\pi^2\alpha}{M^2}\kappa^2$$

GDH Sum Rule

$I_{GDH}(0)$

Generalized GDH Integral

$I_{GDH}(Q^2)$

$$\int_0^1 [g_1^p(x,Q^2) - g_1^n(x,Q^2)]\, dx = \frac{1}{6}g_A$$

Bjorken Sum Rule

Γ_1^{p-n}

Chiral Perturbation Theory

$$-\frac{\kappa^2}{8M^2}Q^2 + cQ^4 + O(Q^6)$$

Operator product Expansion

Bjorken result for (p-n) at finite Q^2

$$\sum_{\tau=2,4\ldots}\frac{\mu_\tau(Q^2)}{Q^{\tau-2}}$$

Burkhardt-Cottingham sum rule

$\Gamma_2(Q^2)=0$

$$\int_0^1 g_2(x,Q^2)dx = 0$$

Higher moments

Spin Polarizabilities

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

Higher twists & color Polarizabilities

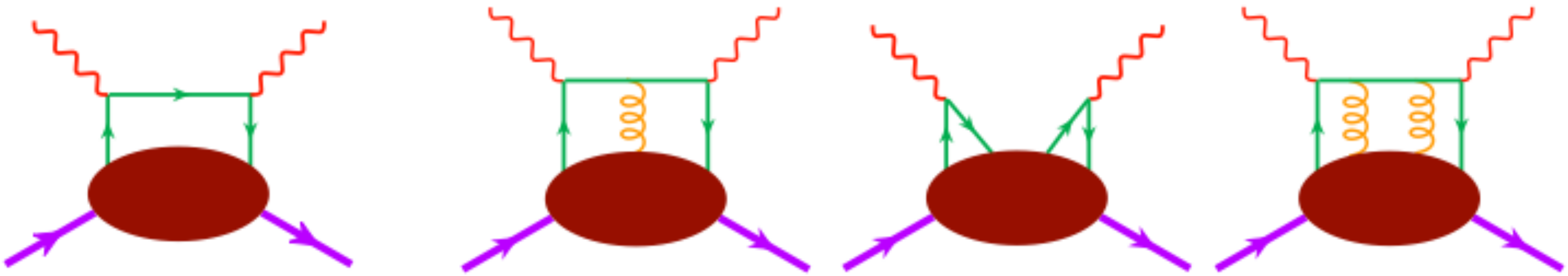
$d_2(Q^2), f_2(Q^2)$

0 ← 1 Q^2 10 ∞

χPT Lattice QCD OPE pQCD

MODELS DSE AdS/CFT

Moments of Structure Functions: Probing Color Forces



$\tau = 2$

single quark scattering

$\tau > 2$

qq and qg correlations

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

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

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

Moment of spin structure function g_1

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

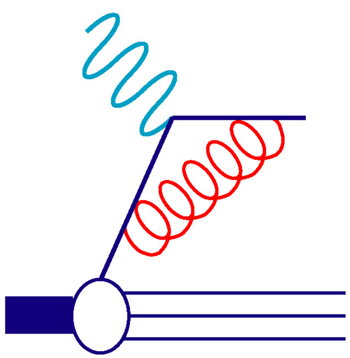
leading twist (μ_2)

higher twist

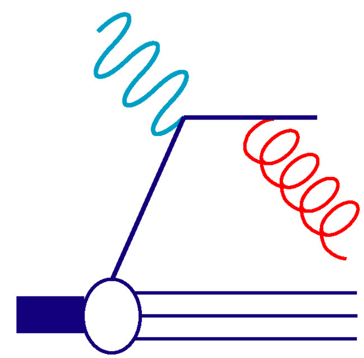
$$\mu_2^{p,n}(Q^2) = (\pm \frac{1}{12} g_A + \frac{1}{36} a_8) + \frac{1}{9}\Delta\Sigma$$ + pQCD corrections

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

$\Delta\Sigma$ = singlet axial charge



$$g_A = \Delta u - \Delta d$$
$$a_8 = \Delta u + \Delta d - 2\Delta s$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$



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

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

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

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

- $f_2(Q^2)$ → 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):

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

Transversity

q-*g* correlations

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

"Color Polarizabilities"

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

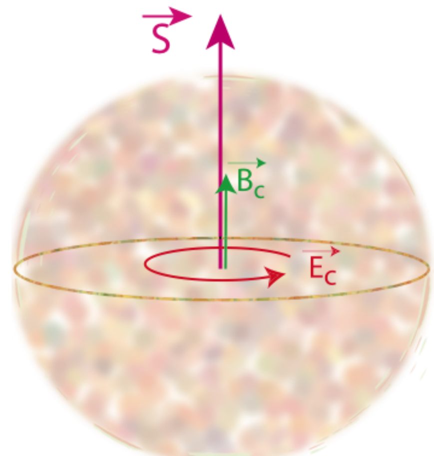
How does the gluon field respond when a nucleon is polarized ?

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

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



$$d_2 = (\chi_E + 2\chi_B)/4$$
$$f_2 = \chi_E - \chi_B$$

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:

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

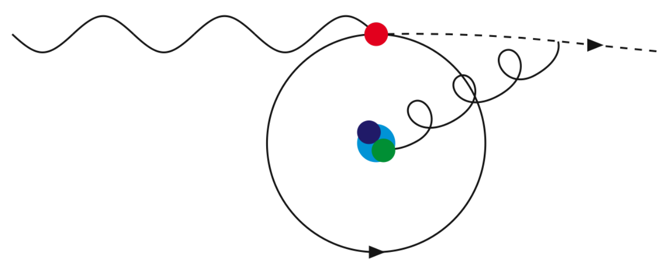
$$= -\frac{1}{2P^+}\langle P, S|\bar{q}(B^x - E^y)\gamma^+ q|P, S\rangle$$

$$= -M^2 d_2$$

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

Average Color Lorentz Force (M. Burkardt)

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



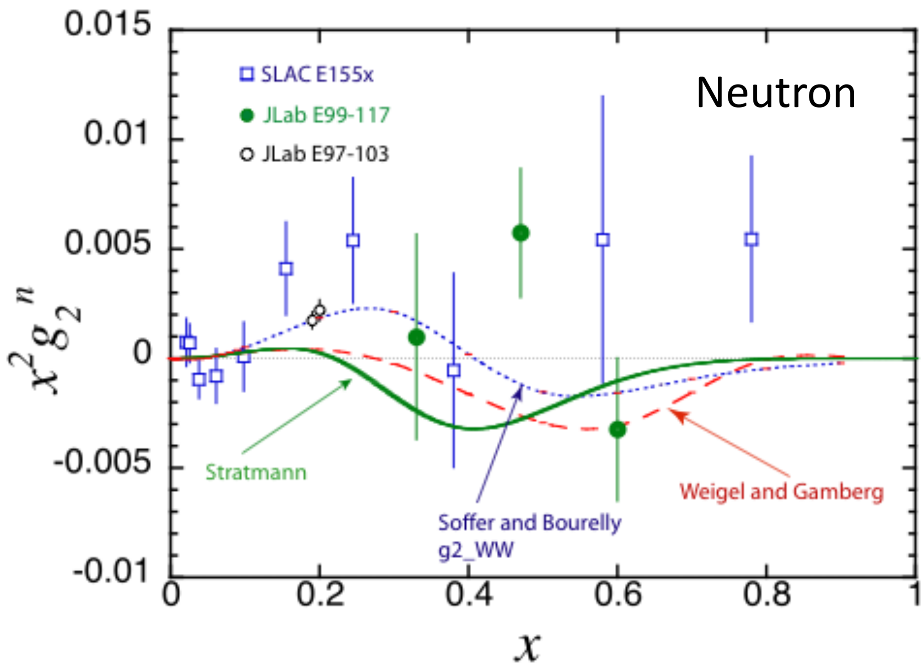
$\hookrightarrow$ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

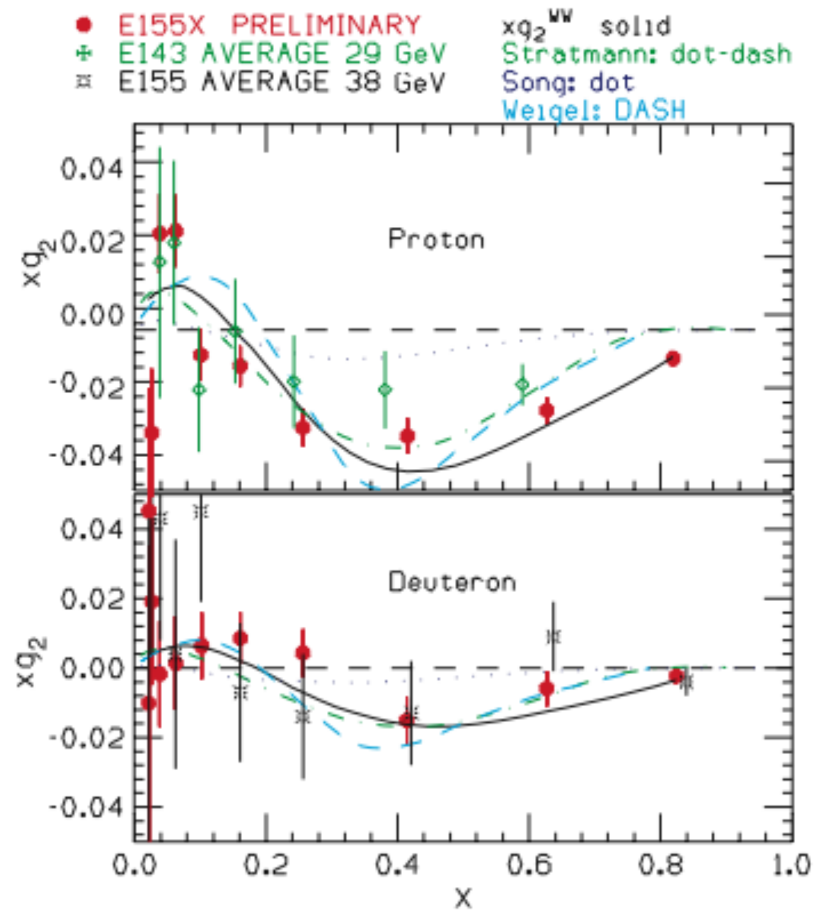
$\langle F^y(0) \rangle = -M^2 d_2$ (rest frame; $S^x = 1$)

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

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

Earlier nucleon world results of g_2



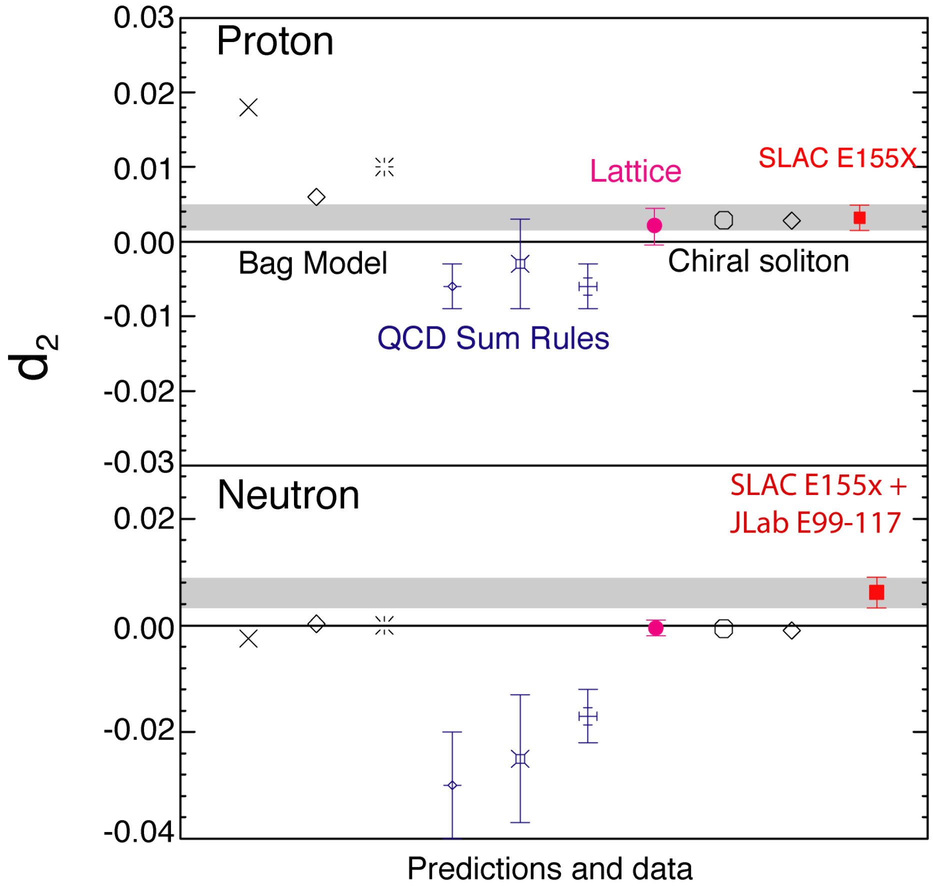


- SLAC E155x (proton and deuteron)
- JLab E99-117(helium-3), A_1^n in DIS
- Jlab E97-103 (helium 3) Q^2 dependence below 1 GeV^2

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

Posik, Flay, Parno et al.,
Phys.Rev.Lett. 113 (2014) 2, 022002
Phys.Lett. B744 (2015) 309-314

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

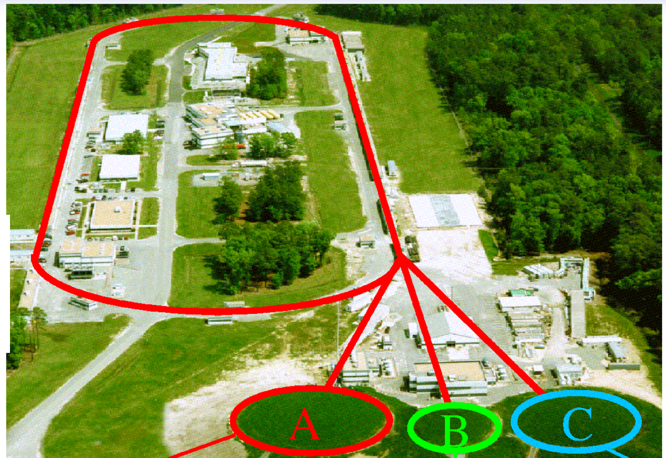
Students:
W. Armstrong, H. Kang, A. Liyanage, J. Maxwell, J. Mulholland

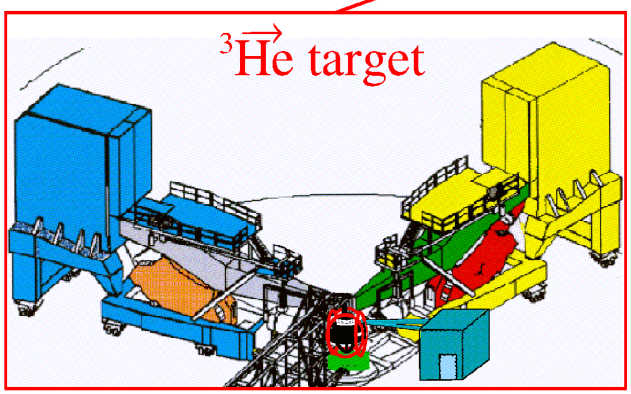
and the Hall C collaboration

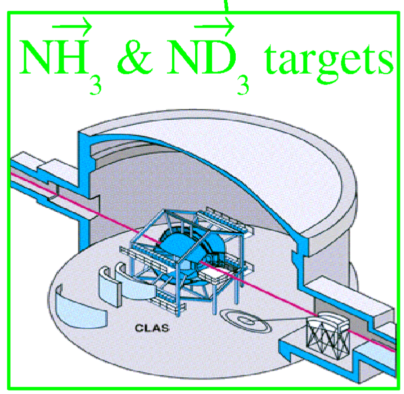
Analysis close to completion:
Preliminary results

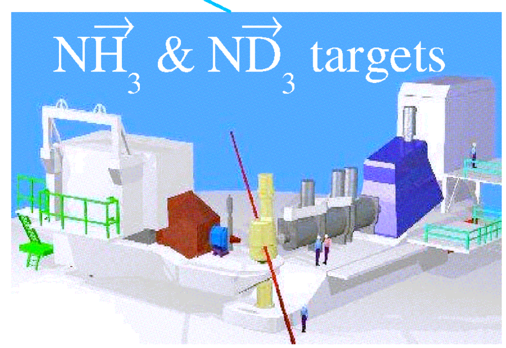
Jefferson Lab Polarized DIS experiments at 6 GeV

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









HallA: two HRS'

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

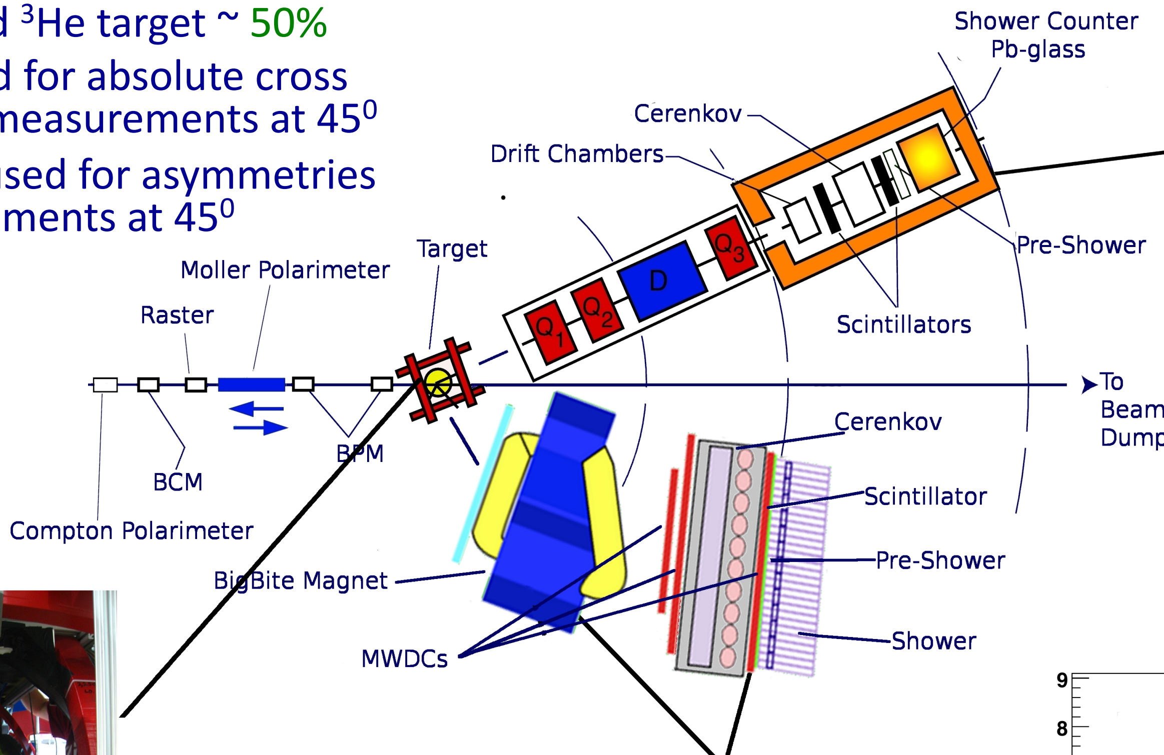
Hall B:CLAS

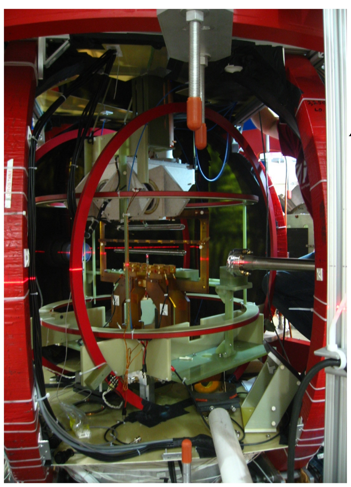
Hall C: HMS+SOS

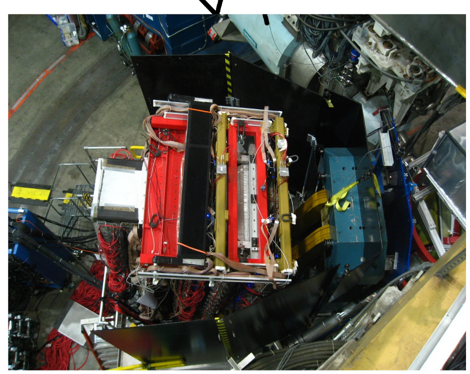
Luminosity up to 10^{35} (cm^{-2} s^{-1})

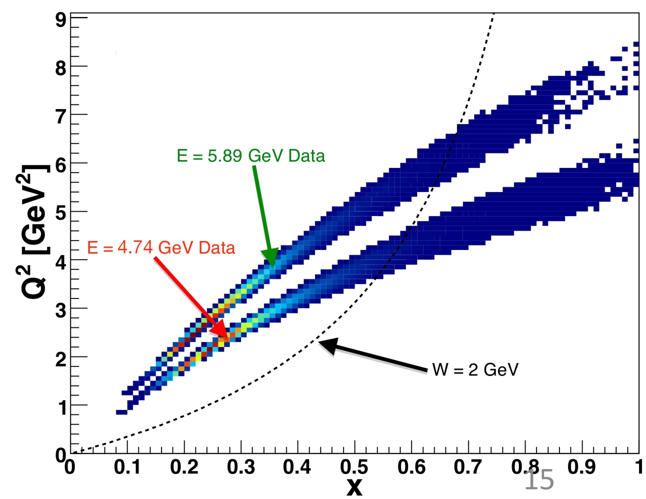
The JLab E06-014 (d_2^n) Experiment

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

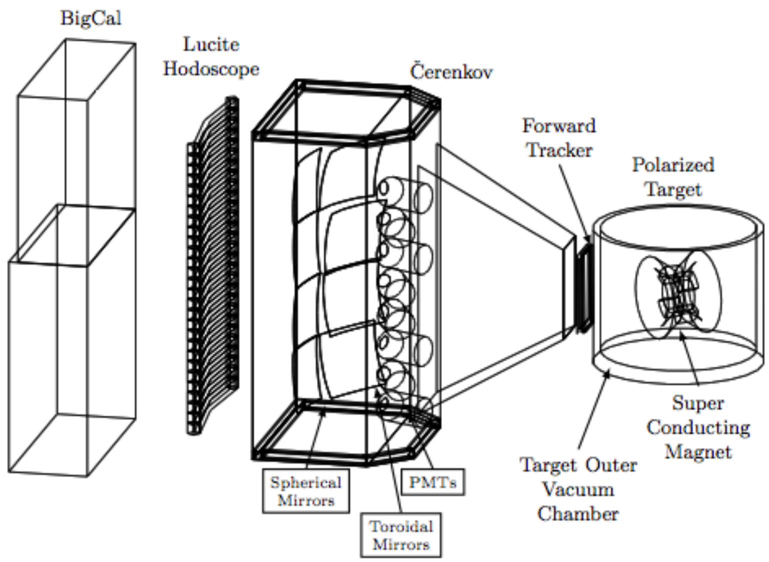


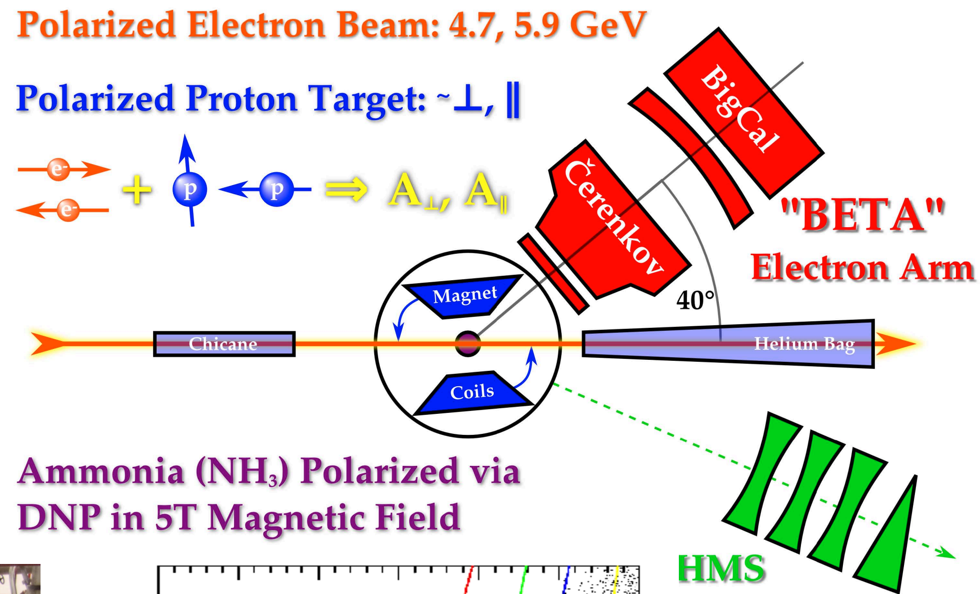


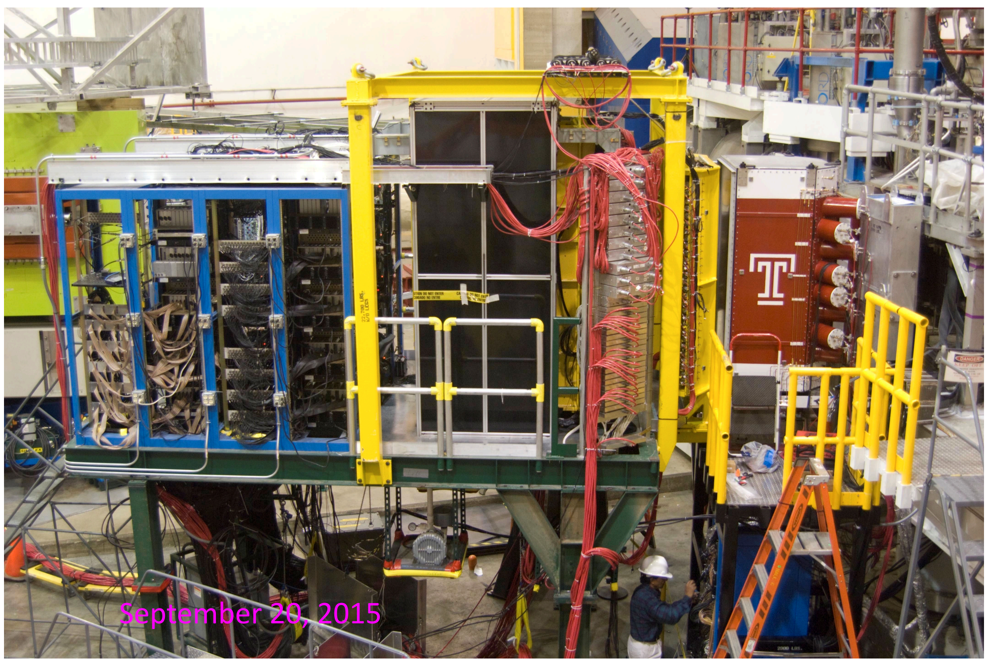


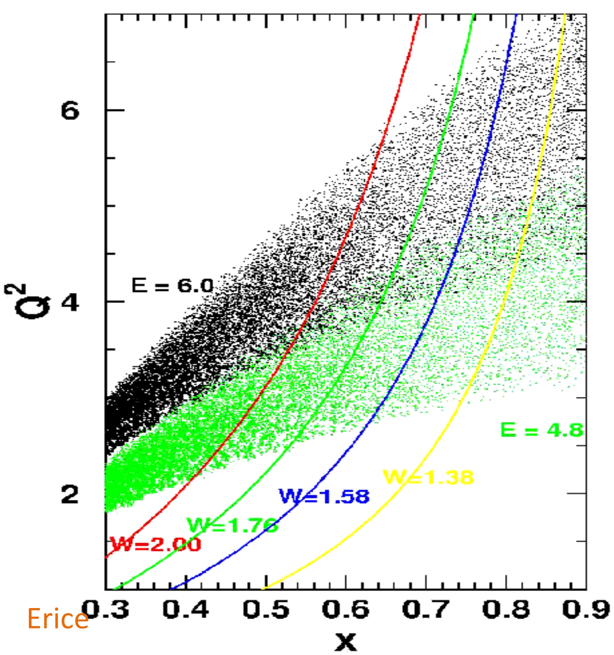


Spin Asymmetries of the Nucleon Experiment (SANE)

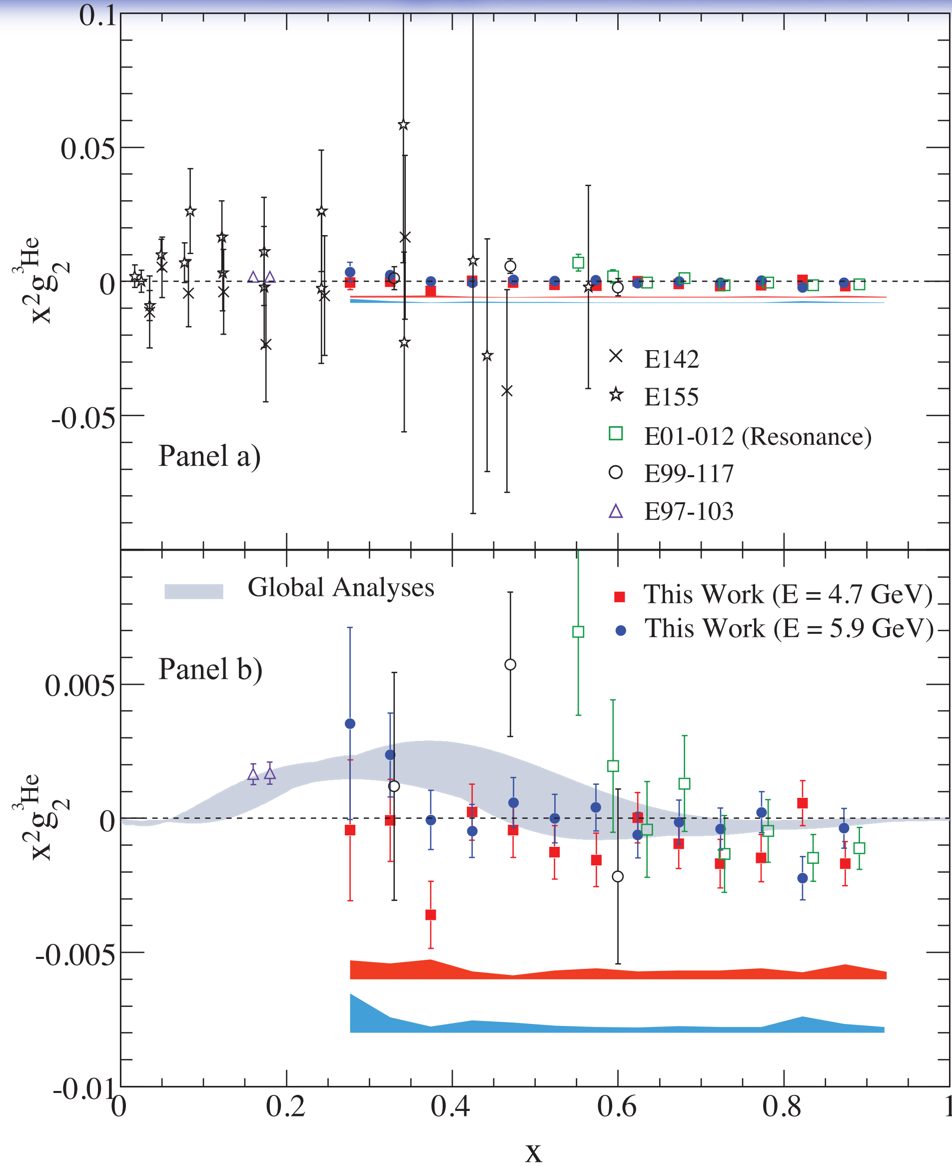








^{3}He g_2 structure function

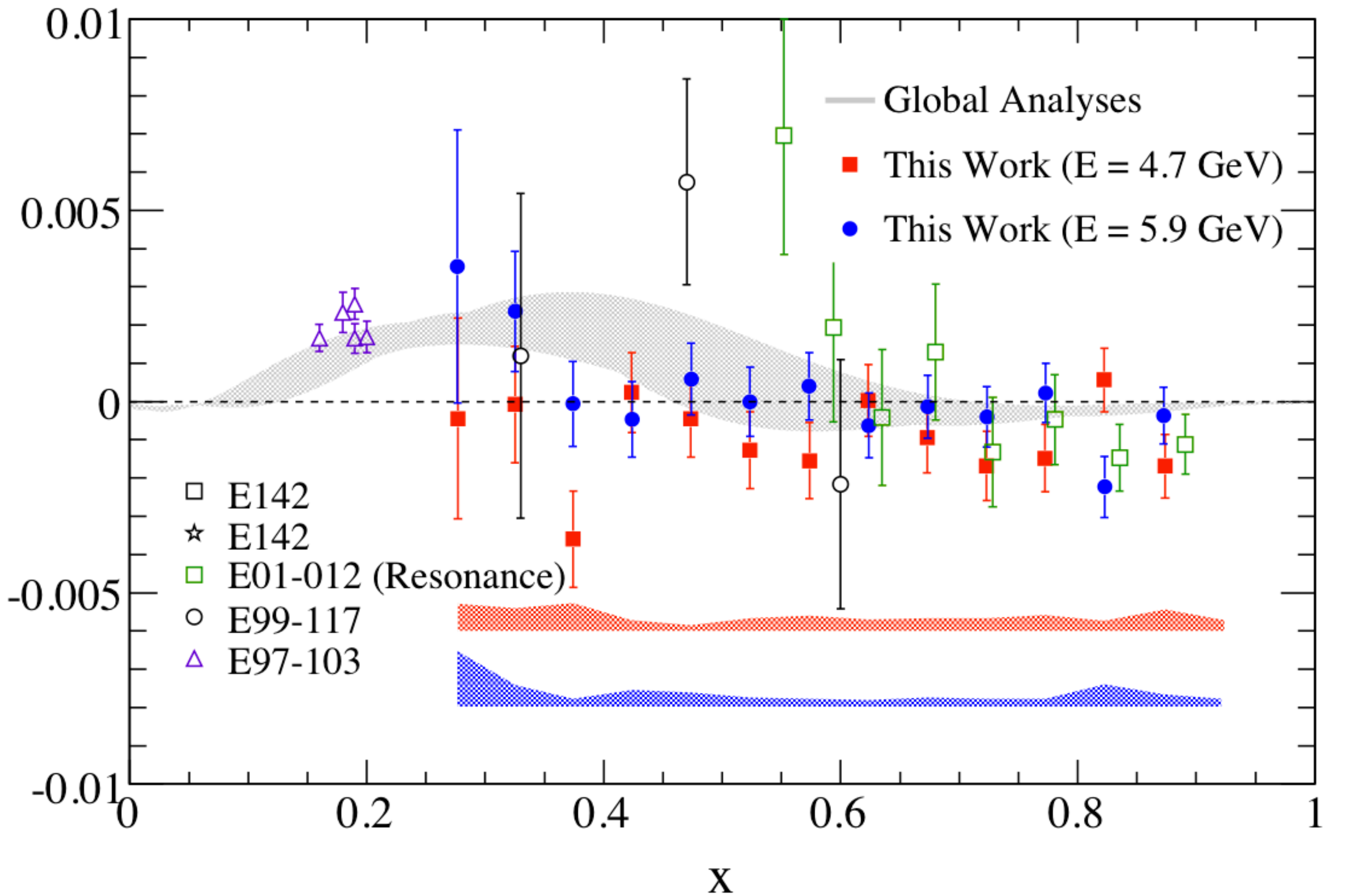


M. Posik, D. Flay, D. Parno et al.

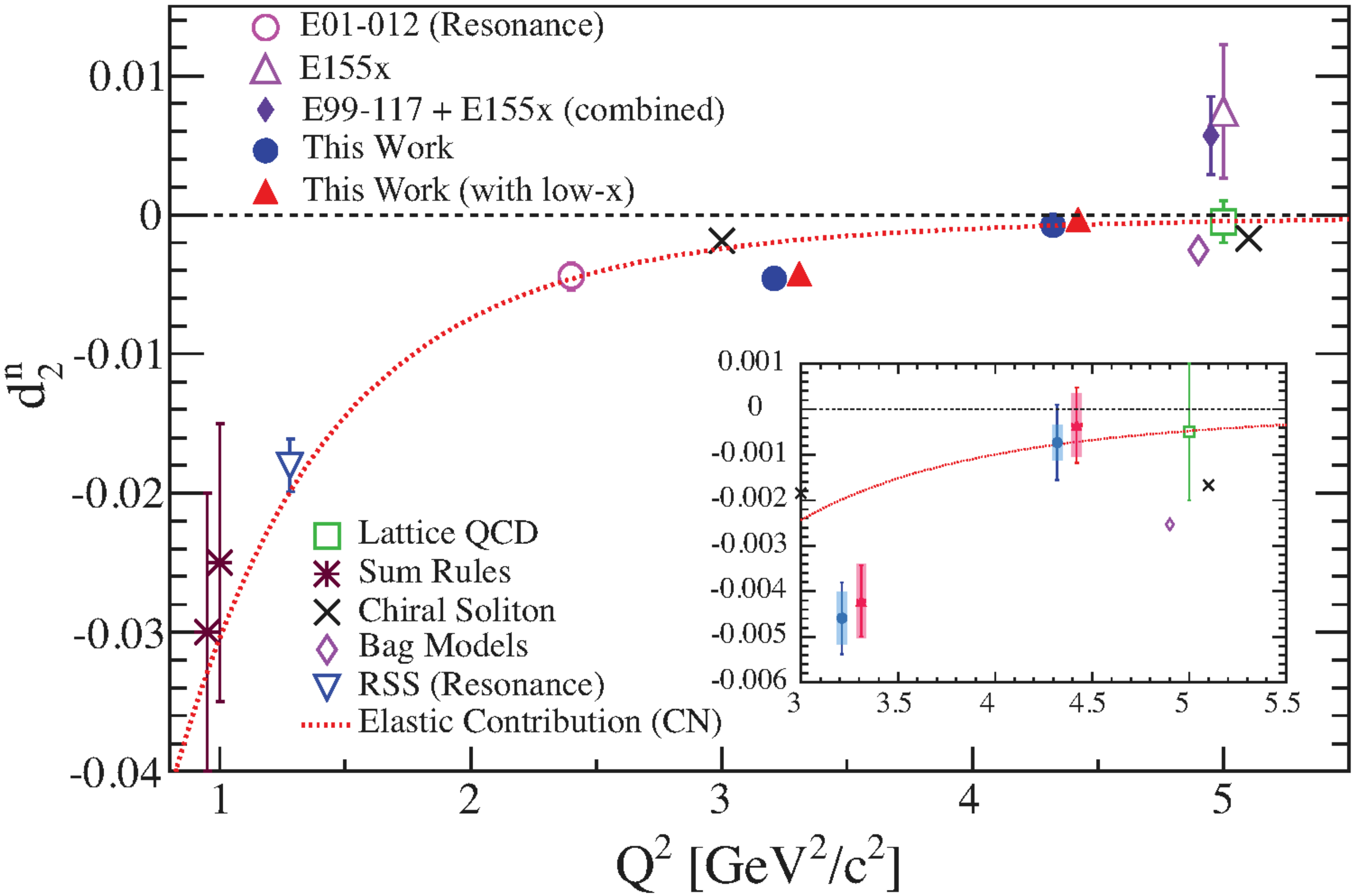
Phys.Rev.Lett. 113 (2014) 2, 022002

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

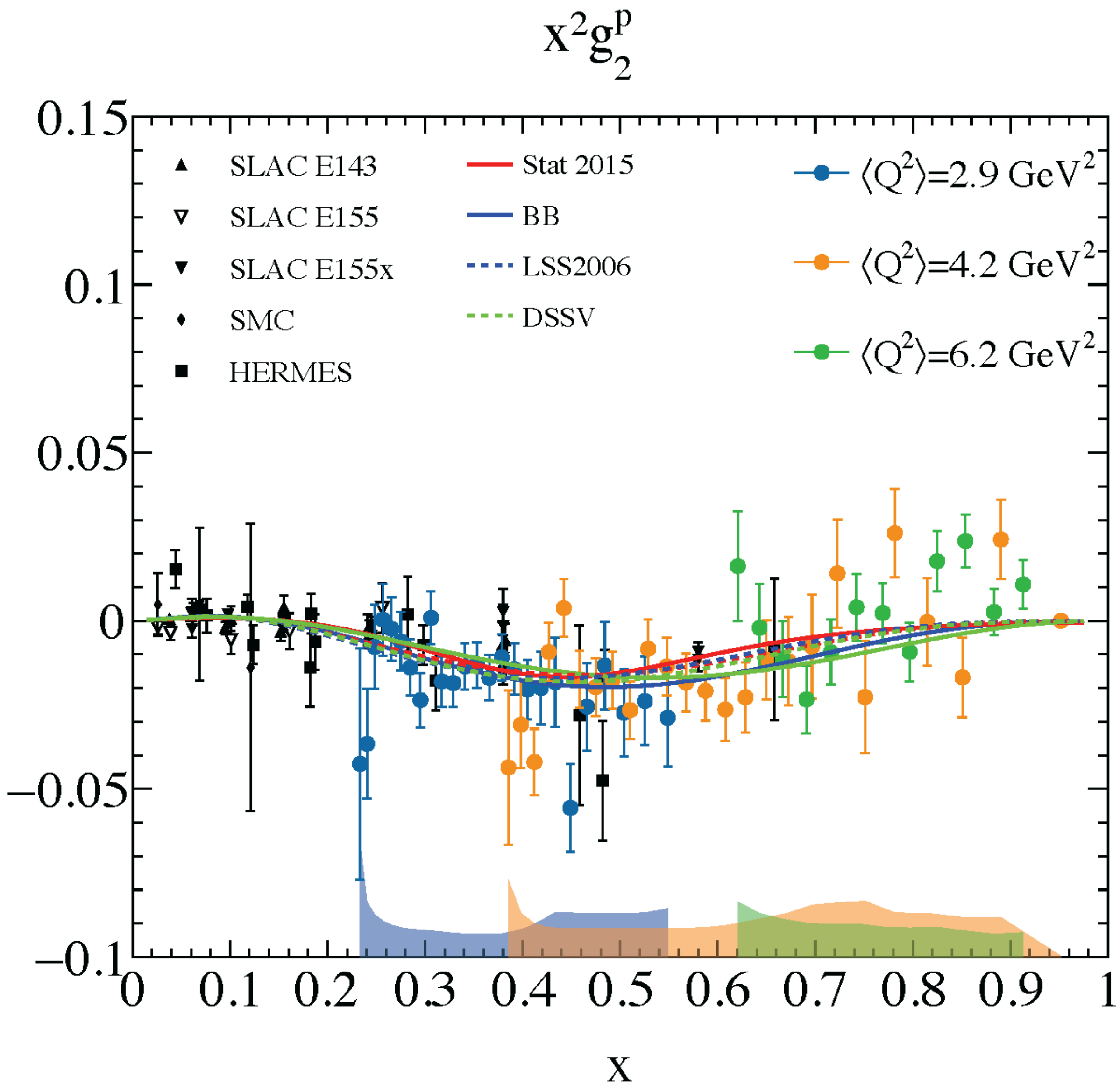
^3He g_2 structure function



d_2^n results compared to calculations



Proton g_2 spin structure function (SANE)



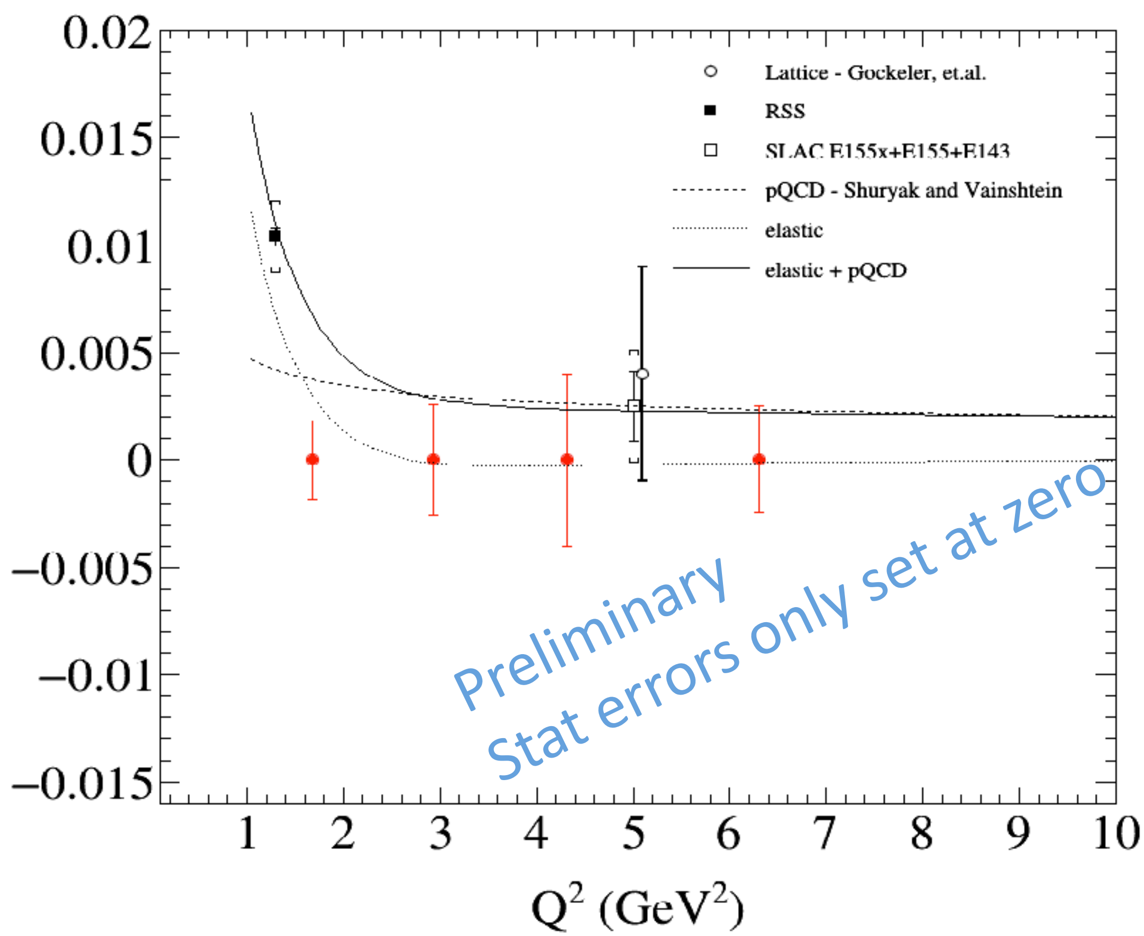
- Beta proton data
  - DIS and Resonance data
  - $g2^{WW}$ curves using g_1 at $Q^2 = 4\ GeV^2$
  - E'> 0.6 GeV
  - More data at $Q^2 = 1.6\ GeV^2$

(W. Armstrong)

Proton d_2 compared to calculations

- Nachtmann moments are needed to get twist-3 free of target mass corrections

(W. Armstrong)



$$d_2(Q^2) = \int_0^1 dx \xi^2 \left(2\frac{\xi}{x} g_1 + 3(1 - \frac{\xi^2 M^2}{2Q^2}) g_2 \right)$$

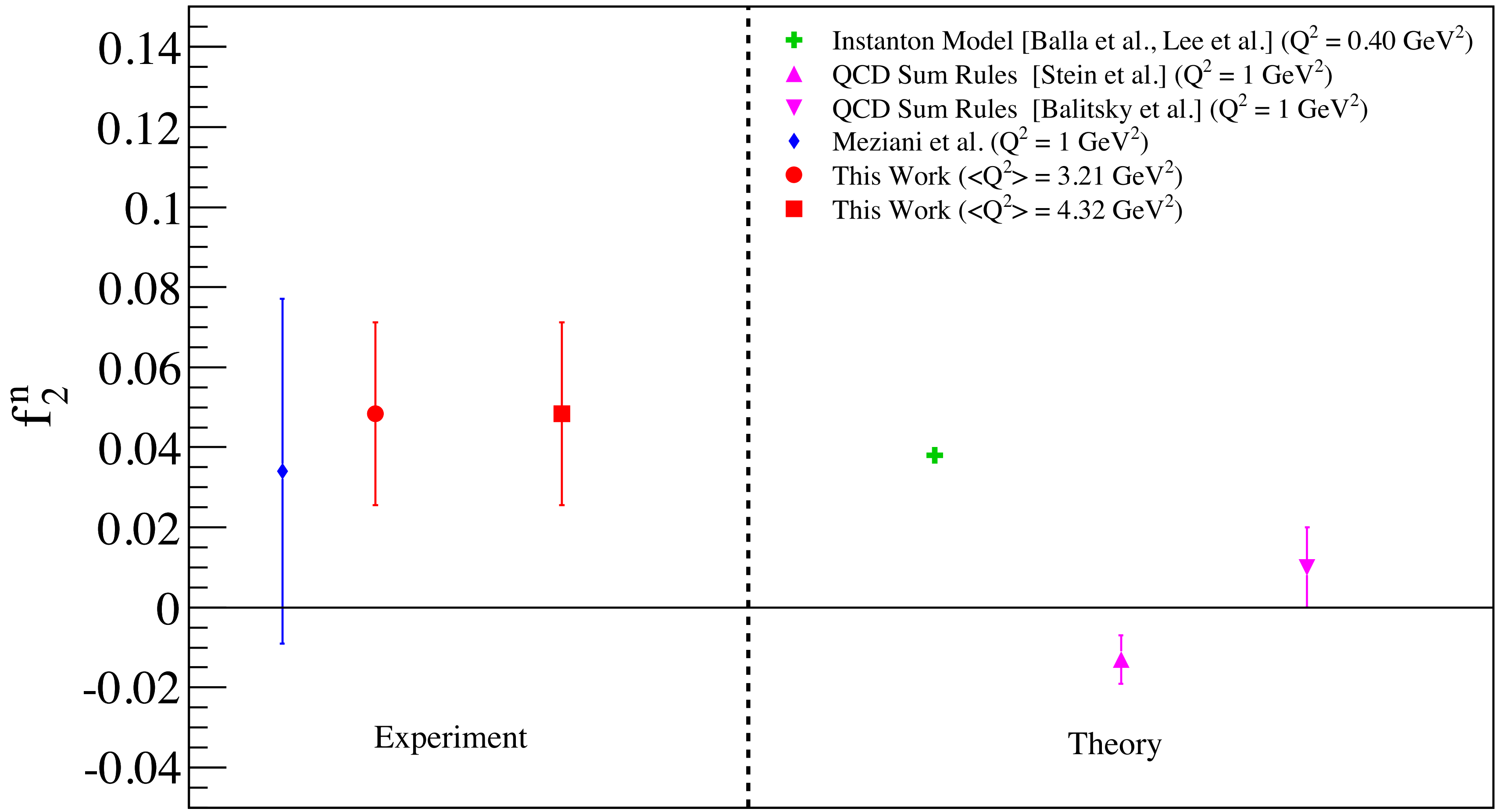
Flavor separated color forces

Table: Flavor separated color forces.

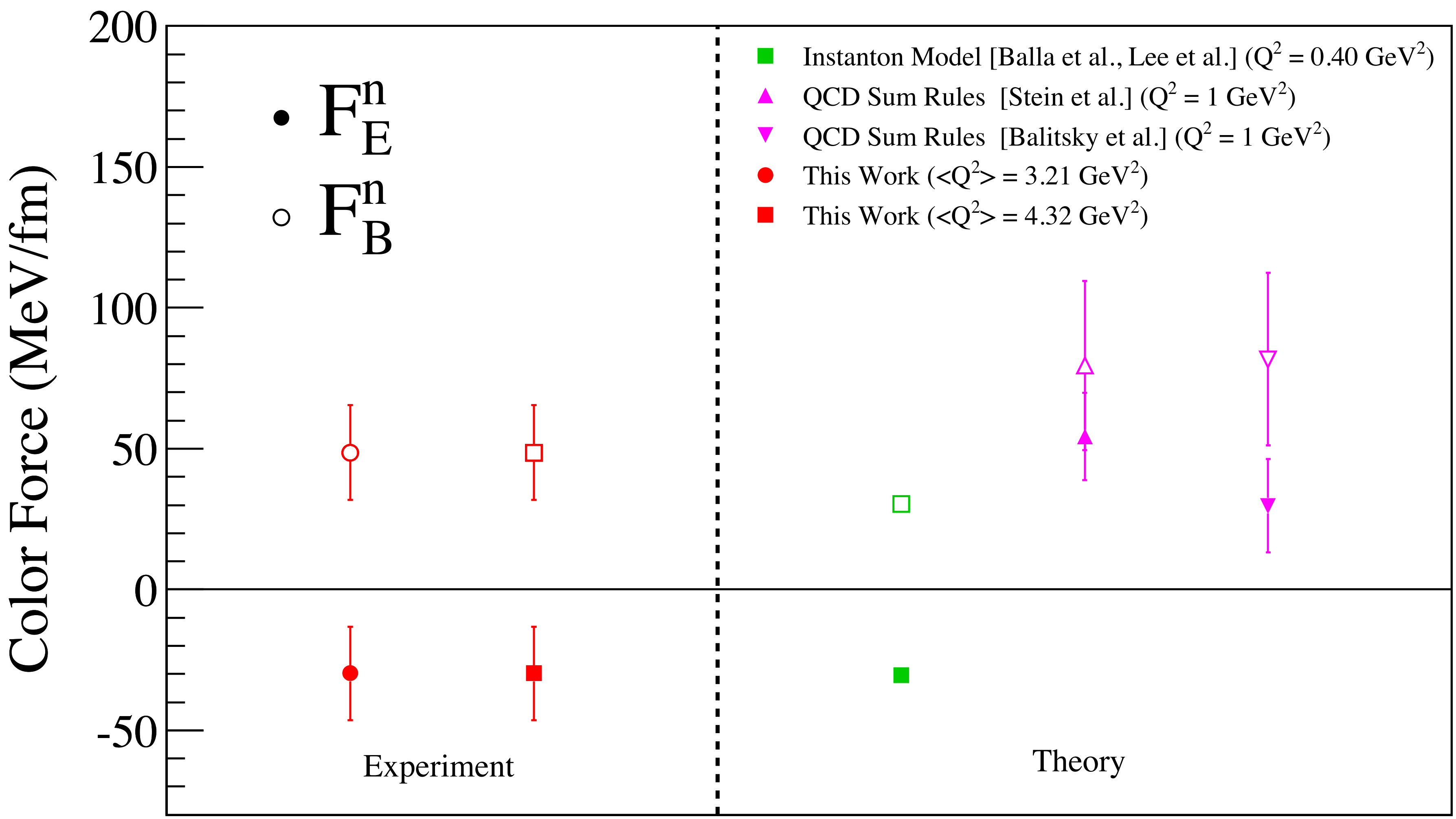
d_2^p Input	d_2^n Input	F^u (MeV/fm)	F^d (MeV/fm)
E155	E155	$-26.22 \pm 44.54_{stat}$	$-151.96 \pm 103.13_{stat}$
LQCD	LQCD	$-45.48 \pm 54.10_{stat}$	$21.40 \pm 34.78_{stat}$
E155	E0-6014(3)	$-91.01 \pm 36.63_{stat} \pm 4.39_{sys}$	$107.23 \pm 19.20_{stat} \pm 17.55_{sys}$
E155	E0-6014(4)	$-70.36 \pm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

Will finalize the SANE proton results …

Extraction of Twist-4 f_2



Color Electric and Mgnetic Components



Need d_2 and f_2 to perform the Electric and Magnetic components separations

Virtual-Photon Nucleon Asymmetry A_1

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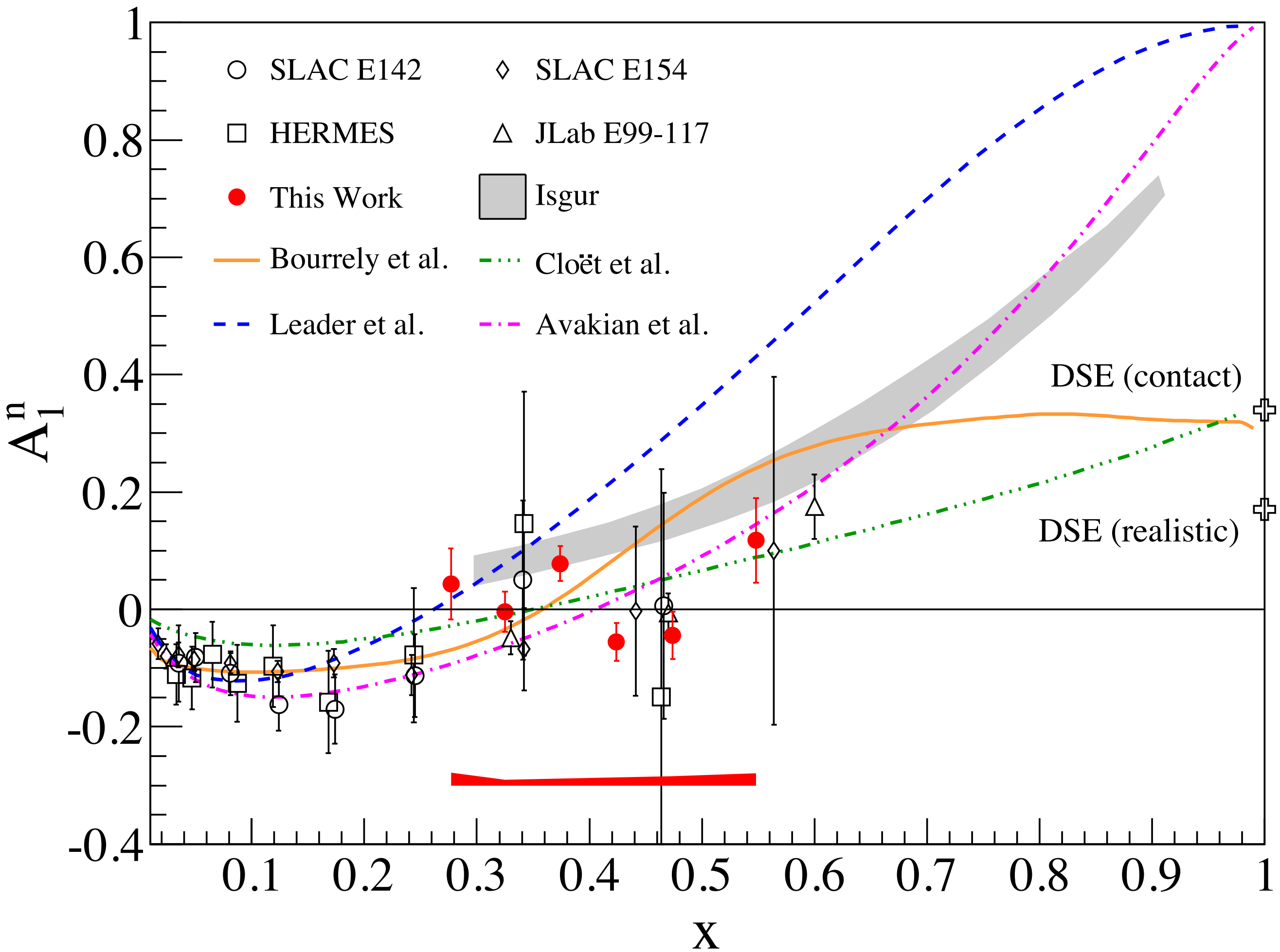
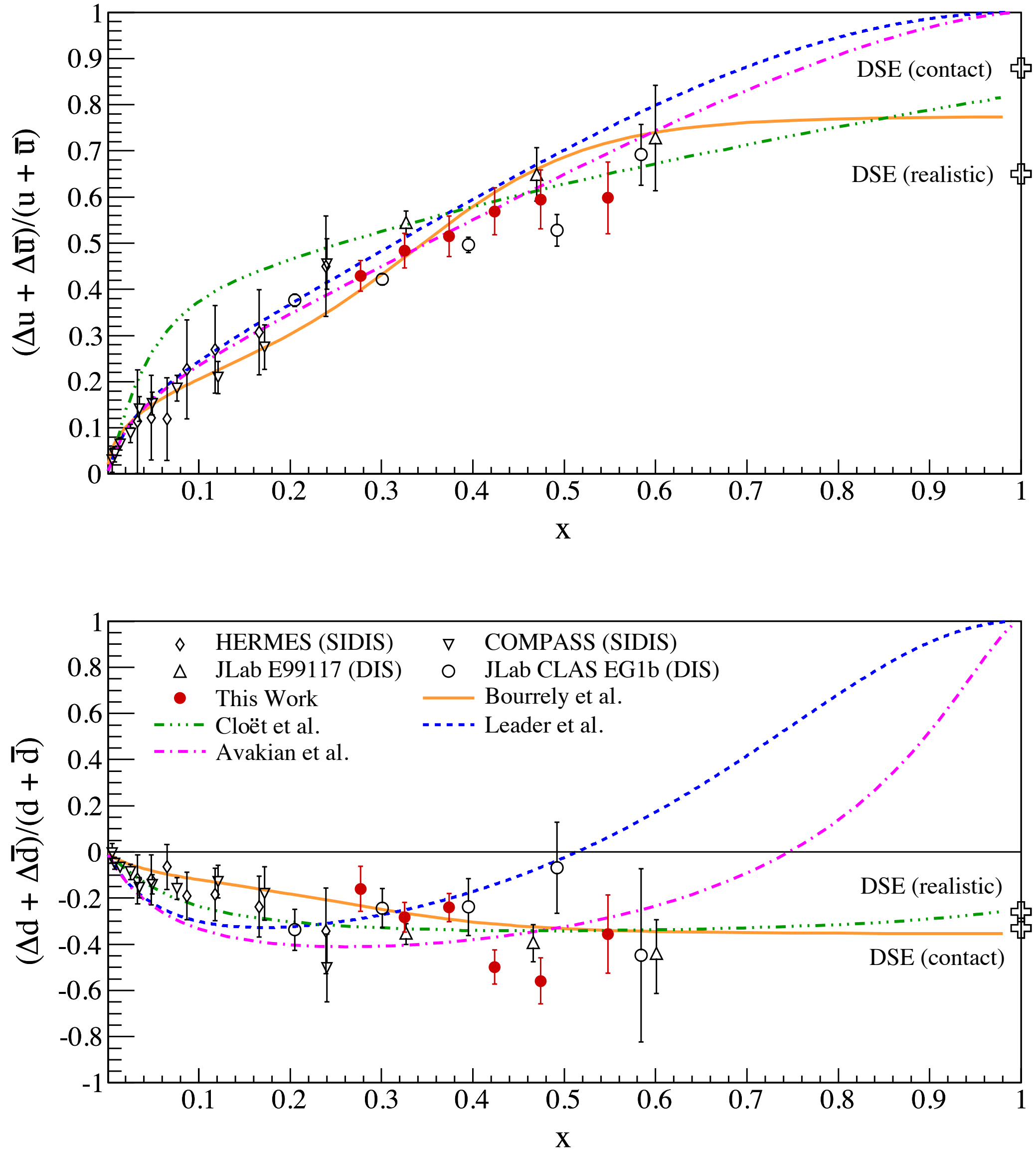


Flavor decomposition



Summary

- The neutron was measured with precision and found consistent with Lattice and in contrast with previous results.
- The proton d_2 is measured with reasonable precision and found to be consistent with Lattice QCD calculations and consistent with the SLAC data around 5 GeV^2. The results need to be finalized.
- Using the proton and neutron data a preliminary flavor decomposition of the color forces is carried out.
- The helicity contribution of the up and down quarks at large x still exhibits a behavior consistent with quark models and not pQCD predictions.
- This program will be pursued at JLab 11 GeV for higher precision and greater Q^2 and x coverage.