Overview of JLab Experiments on Nucleon Spin Structure

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The International Spin Physics Symposium

Kyoto, Japan
Oct. 2-7, 2006

Spin Structure Experiments

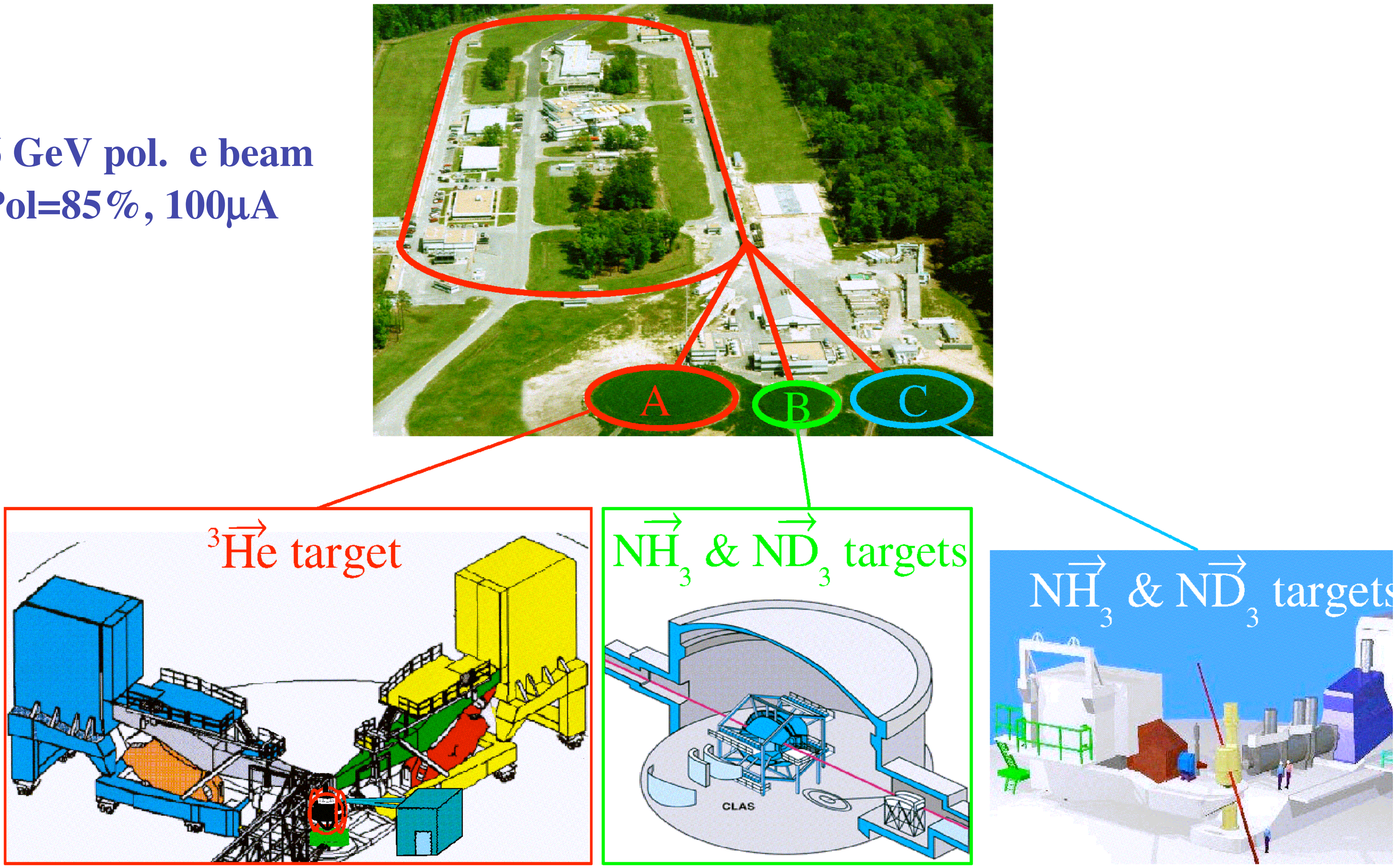
- JLab Hall A: neutron/^{3}He, longitudinal and transverse
  - Generalized GDH, E94-110, Q^2 range 0.1 - 1 GeV^2
  - Small Angle GDH, E97-110, Q^2 range 0.02 – 0.3 GeV^2
  - Spin Duality, E01-012: Q^2 from 1-4 GeV^2
  - A_1^n at high x E99-117: Q^2 from 2.5-5 GeV^2
  - Higher-twist E97-113: g_2^n at Q^2 of 0.5-1.5 GeV^2
  - Semi-inclusive: transversity, flavor decomposition

- JLab Hall B : proton/deuteron, longitudinal
  - EG1a/EG1b, Q^2 range 0.05 - 4 GeV^2
  - EG4: Q^2 range 0.015 – 0.5 GeV^2
  - Semi-inclusive: flavor decomposition

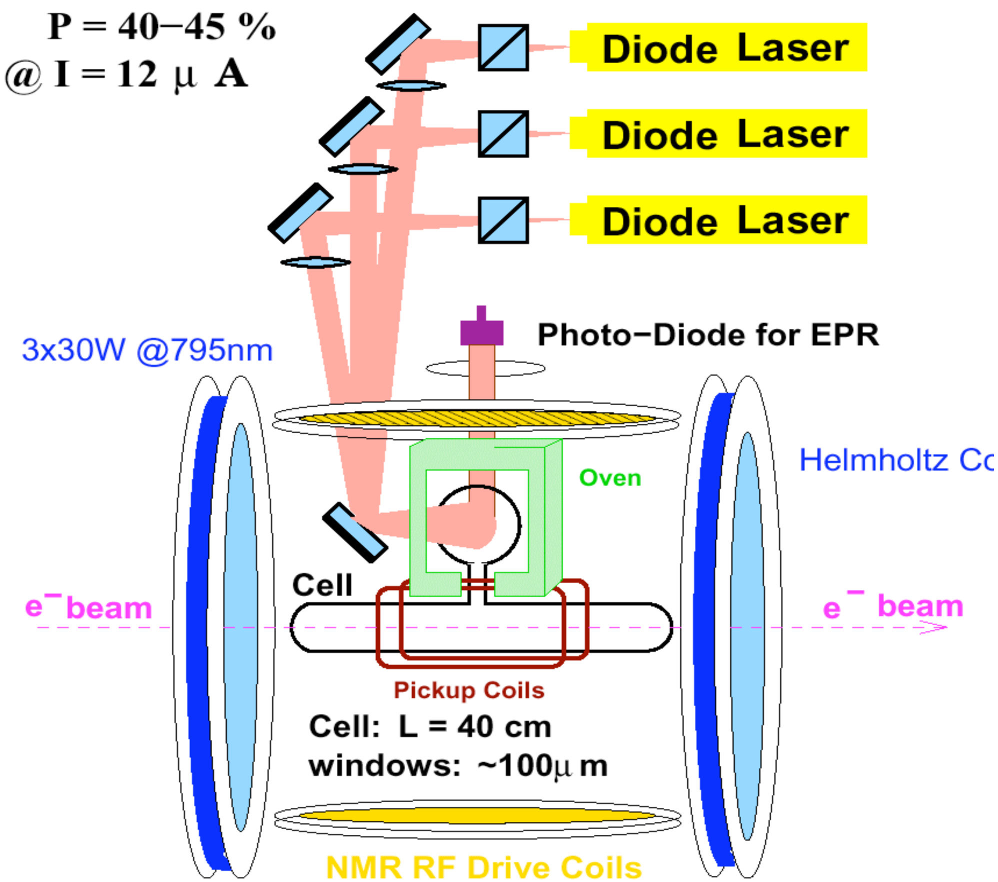
- JLab Hall C: proton/deuteron, longitudinal and transverse
  - RSS: $\langle Q^2 \rangle = 1.3$ GeV^2
  - SANE $2 < Q^2 < 6$ GeV^2
  - Semi-SANE: semi-iclusive with flavor decomposition

Jefferson Lab Experimental Halls

6 GeV pol. e beam
Pol=85%, 100μA



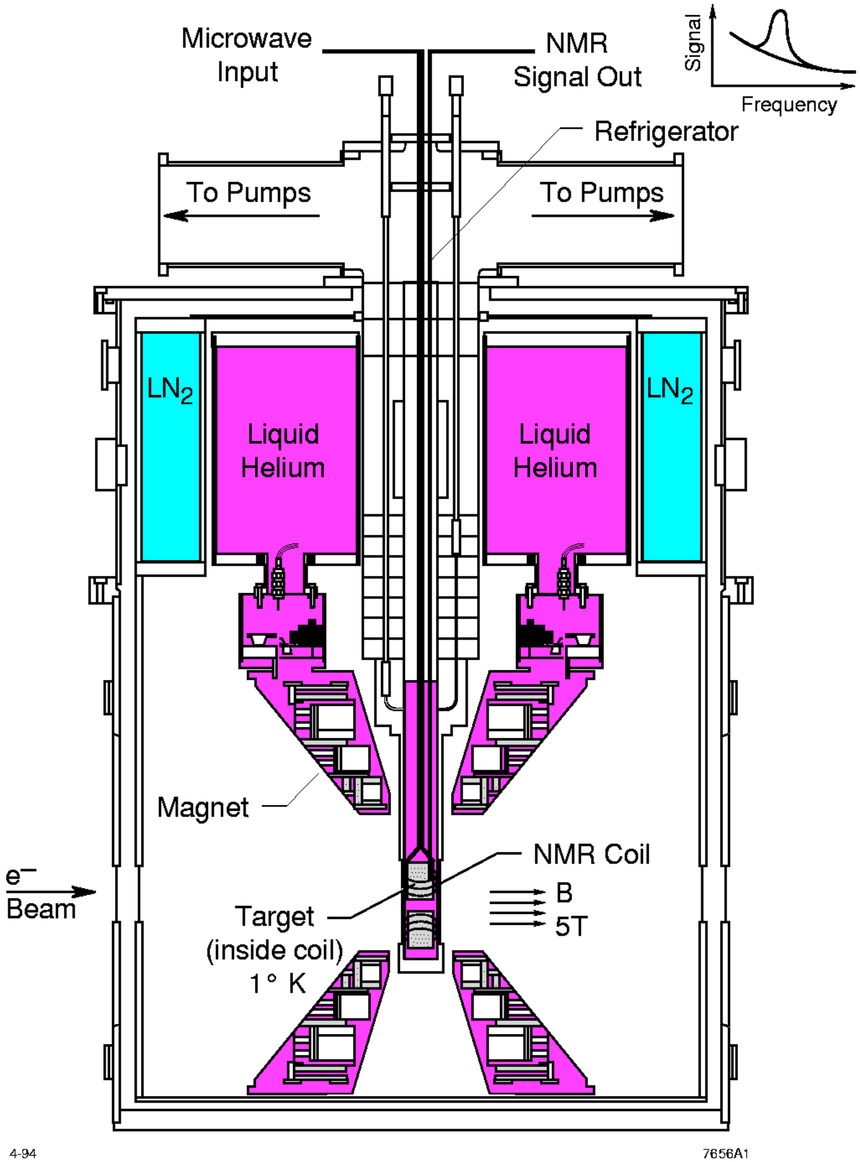
Hall A Polarized ^{3}He Target



- ✓ Longitudinal, transverse and vertical
- ✓ Luminosity=10^{36} ($cm^{-2}s^{-1}$) (best in the world)
- ✓ High in-beam polarization > 50%
- ✓ Effective polarized neutron target
- ✓ 7 completed experiments
  5 approved with 6 GeV
  3 approved with 12 GeV (A/C)

Hall B and C polarized proton/deuterium target

- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization
- In-beam average polarization
  - 70-80% for p
  - 20-30% for d
- Luminosity up to ~ 10^{35} (cm^{-2} s^{-1})



Moments of spin structure functions

GDH Sum Rule
$I_{GDH}(0)$

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

Bjorken Sum Rule
Γ_1^{p-n}

Burkhardt-Cottingham sum rule
$\Gamma_2(Q^2)=0$

First moments

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

Higher twists & color Polarizabilities
$d_2(Q^2), f_2(Q^2)$

Higher moments

0 1 10 ∞

Q^2

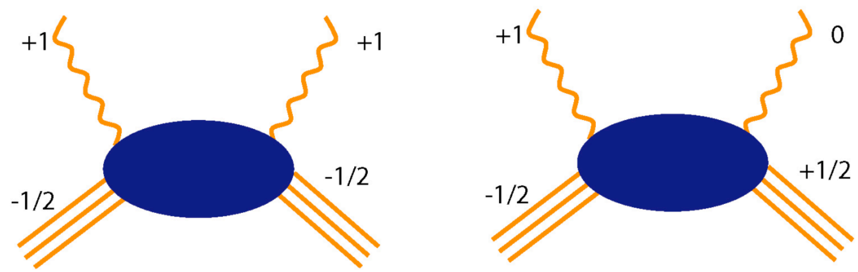
Generalized GDH sum rules

Forward Virtual Compton Scattering Amplitudes

$$S_1(\nu, Q^2), \quad S_2(\nu, Q^2)$$

The spin structure functions $G_{1,2}(\nu, Q^2)$ are proportional to the virtual Compton amplitudes:

$$\mathrm{Im} S_i(\nu, Q^2) = 2\pi G_i(\nu, Q^2)$$



Dispersion Relations

$$S_1(\nu, Q^2) = 4 \int_{Q^2/2M}^{\infty} \frac{\nu' G_1(\nu', Q^2)}{\nu'^2 - \nu^2} d\nu' \qquad \text{(a)}$$

$$S_2(\nu, Q^2) = 4 \int_{Q^2/2M}^{\infty} \frac{\nu' G_2(\nu', Q^2)}{\nu'^2 - \nu^2} d\nu' \qquad \text{(b)}$$

(a) leads to the extended GDH sum rule valid at all Q^2.

(b) leads to the Burkhardt-Cottingham sum rule.

Generalized Gerasimov-Drell-Hearn sum rule

- Many approaches: Anselmino, Ioffe, Burkert, Drechsel, …

- Ji and Osborne, a rigorous generalization of the GDH sum rule

  Forward Virtual-Virtual Compton Scattering Amplitudes: $S_1(Q^2,\nu)$, $S_2(Q^2, \nu)$

  (or alternatively, $g_{TT}(Q^2,\nu)$, $g_{LT}(Q^2,\nu)$)

Calculable quantity → $S_1(0,Q^2)$

Measurable quantity → $G_1(\nu,Q^2)$

$$S_1(0,Q^2) = 4\int_{\frac{Q^2}{2M}} \frac{d\nu}{\nu} G_1(\nu,Q^2)$$

Bernard, Hemmert, Meissner, RBχPT with Δ

Ji, Kao, Osborne; Kao, Spitzenberg, Vanderhaeghen, HBχPT

GDH sum rule and
Chiral Perturbation Theory

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

Operator product Expansion
Bjorken result for (p-n) at

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

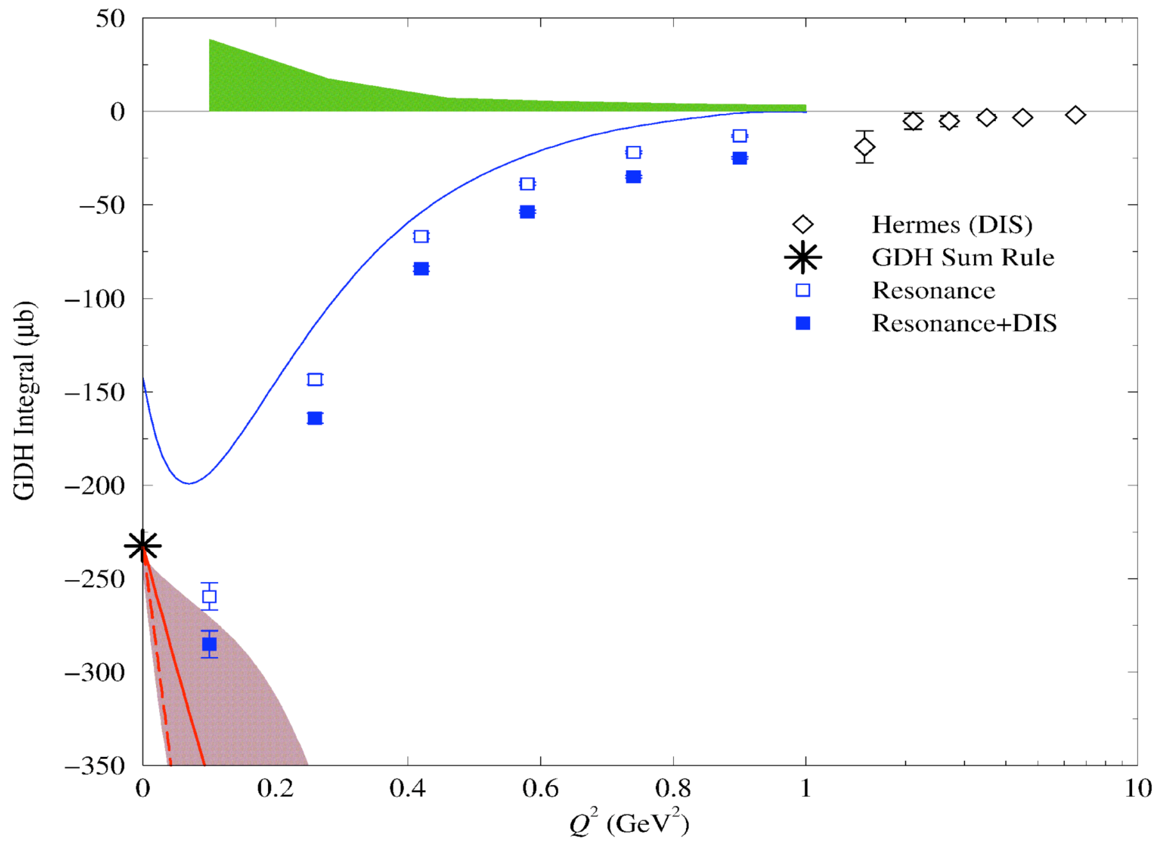
0 1 10 ∞

Neutron Spin Structure and Sum Rules at low Q^2

Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani
PhD Students: A. Deur, P. Djawotho, S. Jensen, I. Kominis, K. Slifer

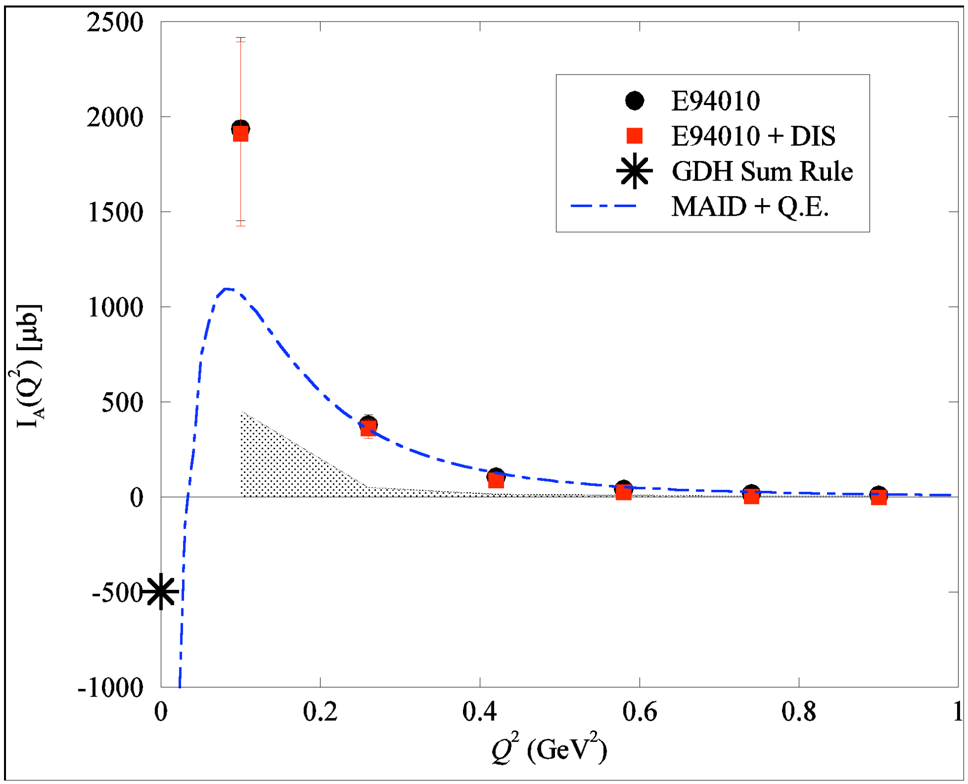
- Q^2 evolution of spin structure moments and sum rules (generalized GDH, Bjorken and B-C sum rules)
- transition from quark-gluon to hadron
- Results published in five PRL/PLB
- New results on ^{3}He

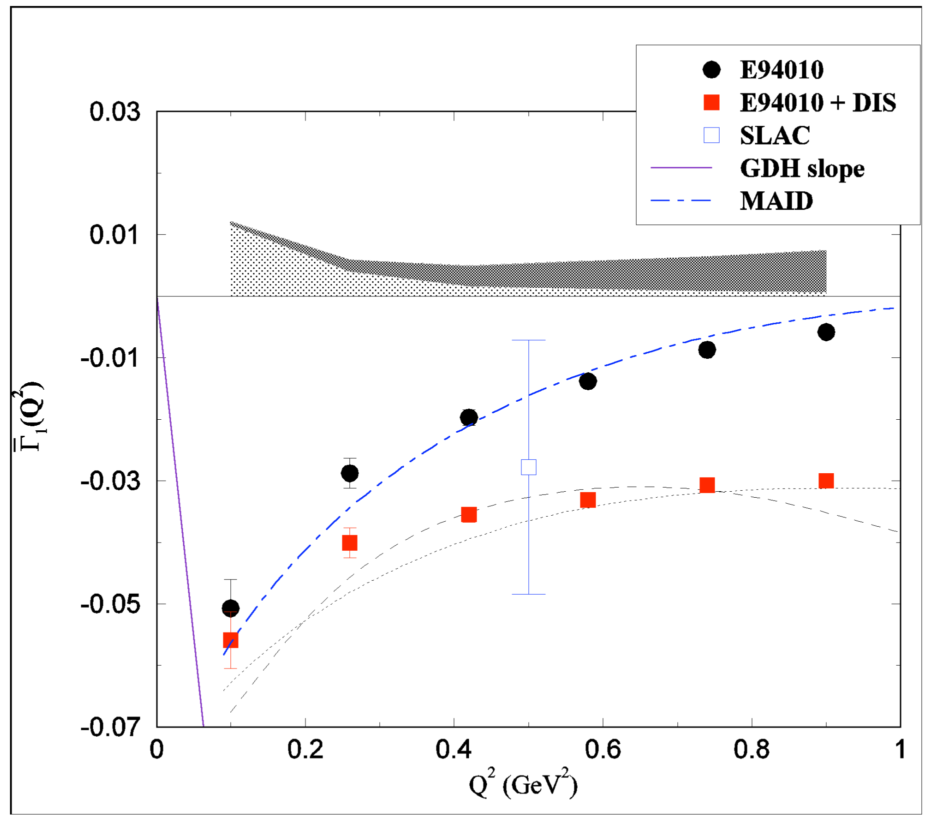
PRL 89 (2002) 242301



New Hall A ^{3}He Results (preliminary)

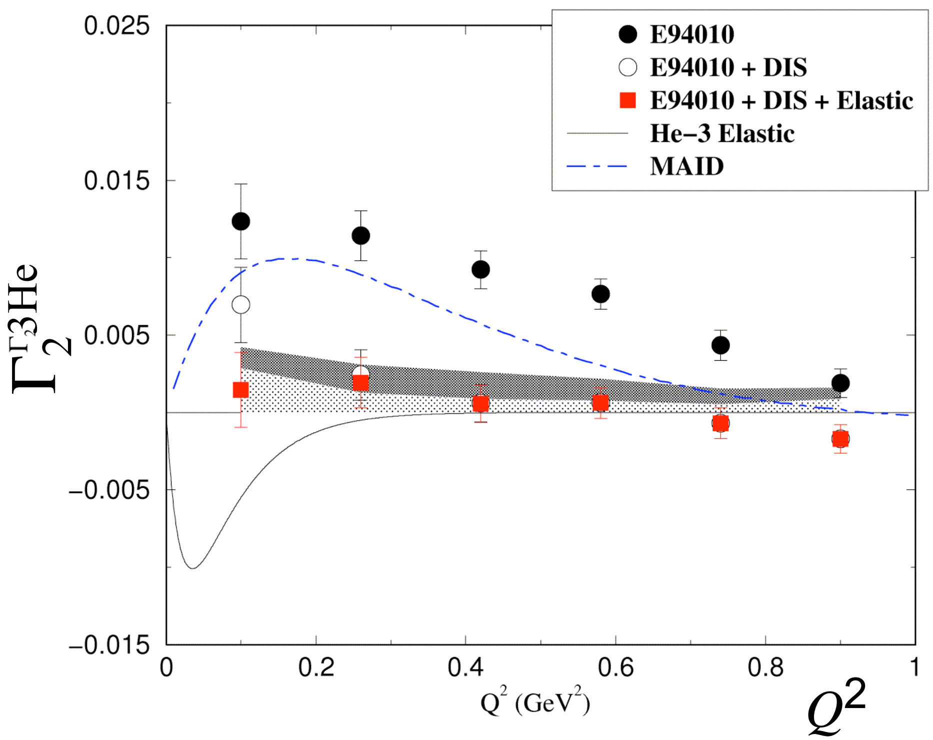
- Q^2 evolution of moments of ^{3}He spin structure functions
- Test Chiral perturbation theory predictions at low Q^2
- Need Chiral PT calculations for ^{3}He, need ^{3}He calculations



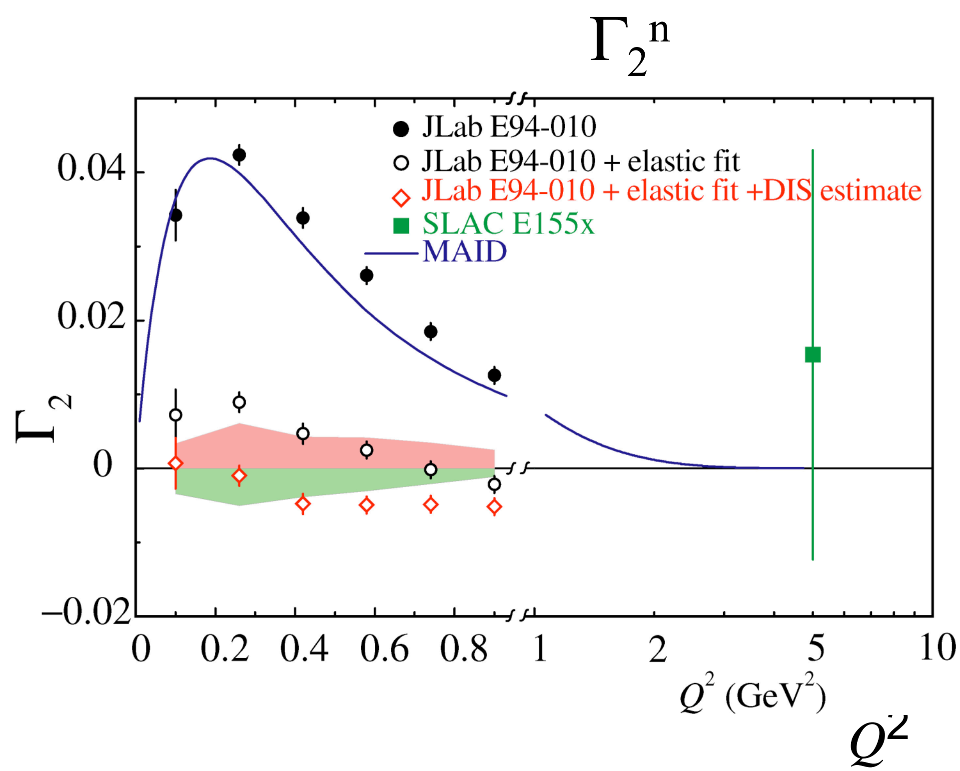


Γ_2 :First Moment of g_2 for ^{3}He and Neutron

- Q^2 evolution of Γ_2^{3He} and Γ_2^n
- B-C sum rule satisfied within uncertainties



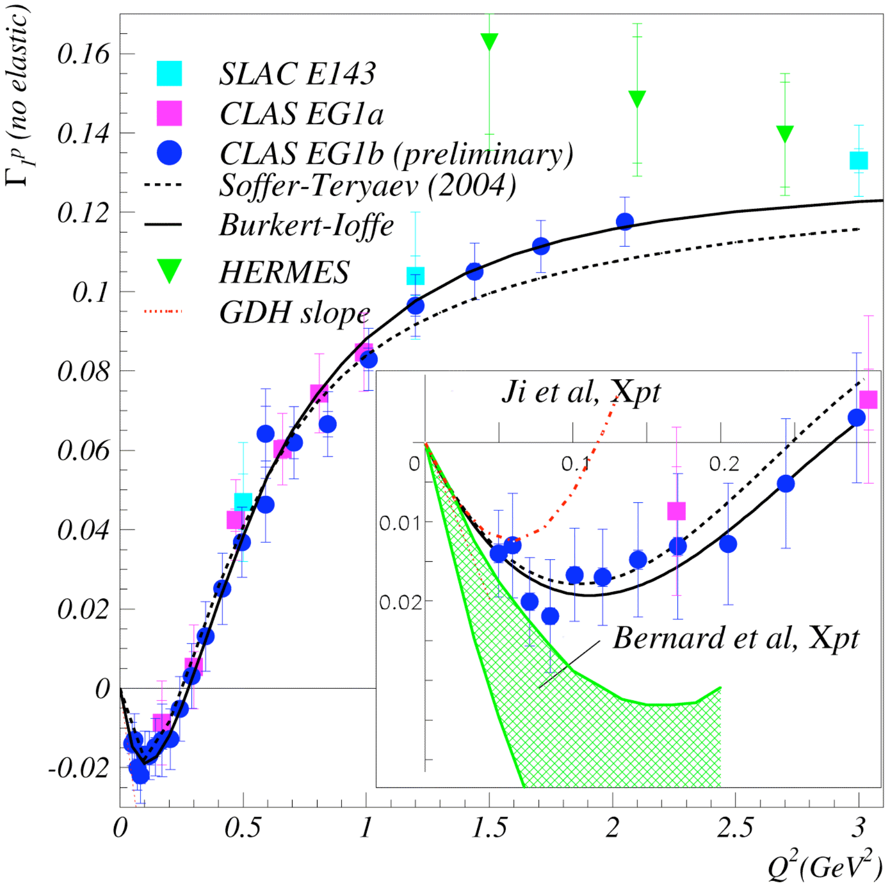
E94-010, preliminary

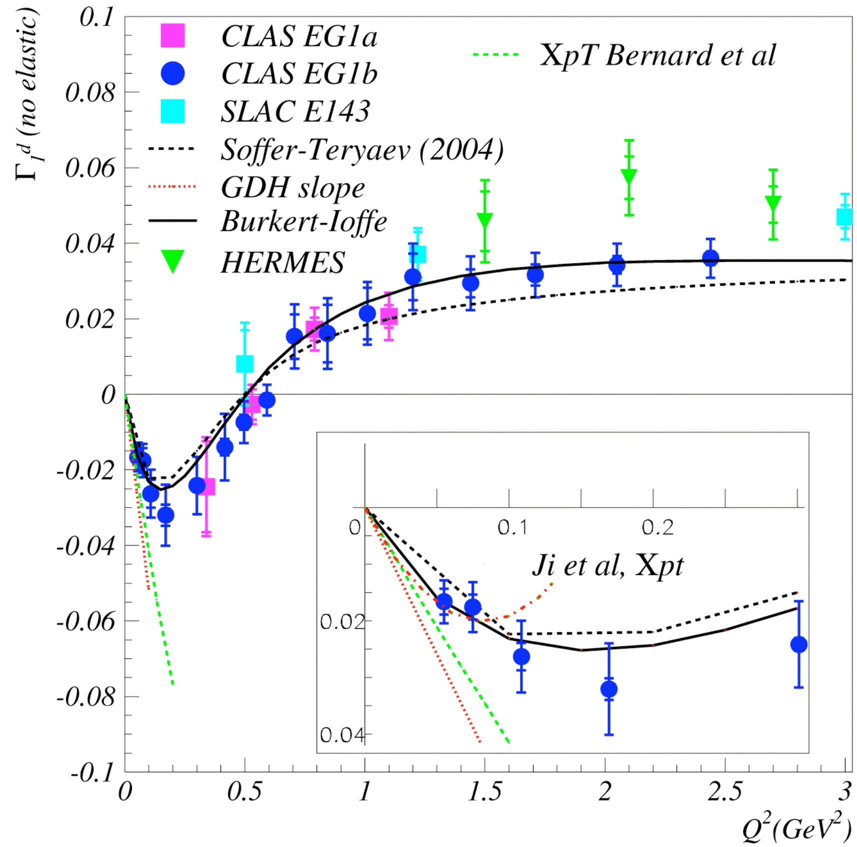


E94-010, PRL 92 (2004) 022301

Hall B EG1b Preliminary Results: Γ_1^p and "Γ_1^d"

Spokespersons: V. Burkert, D. Crabb, G. Dodge, S. Kuhn, R. Minehart, M. Taiuti

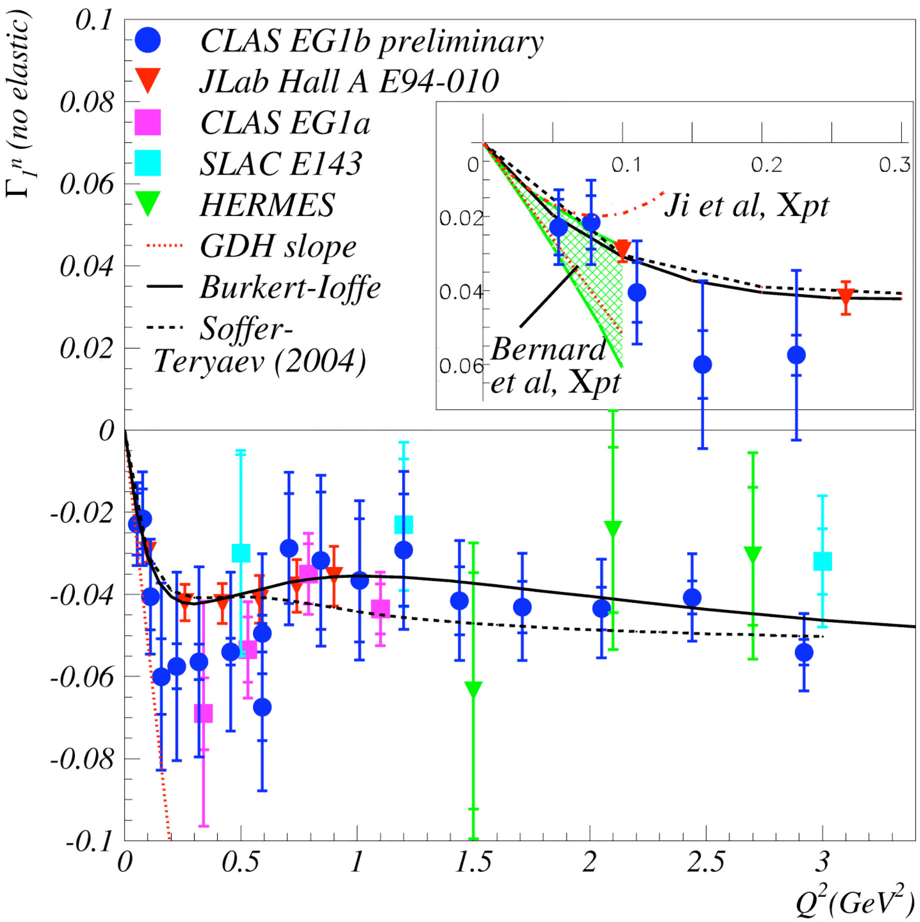




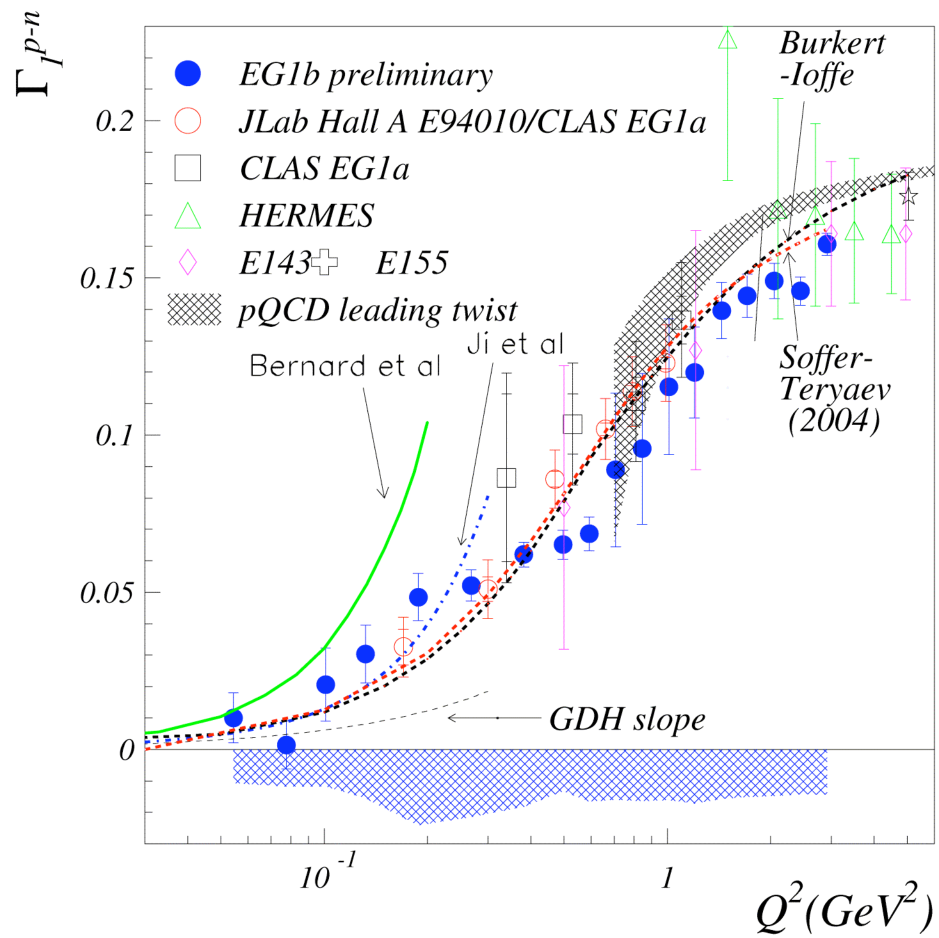
EG1b preliminary and
EG1a, PRL 91: 222002 (2003)

EG1b preliminary and
EG1a, PRC 67, 055204 (2003)

Moments of neutron and proton-neutron

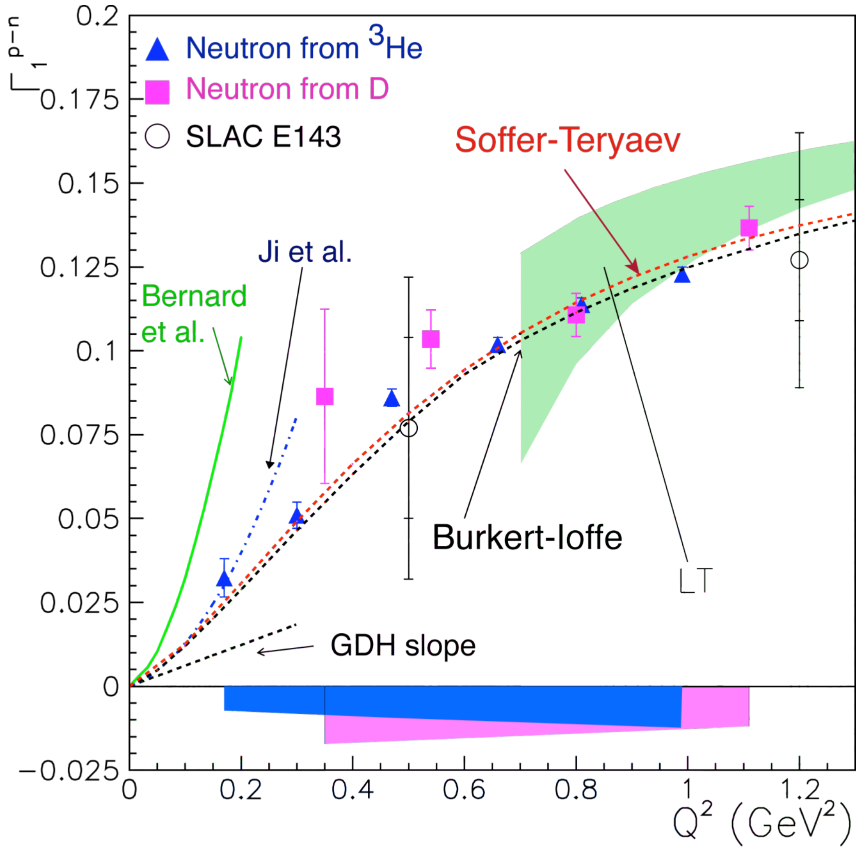


Hall B EG1b preliminary
and Hall A

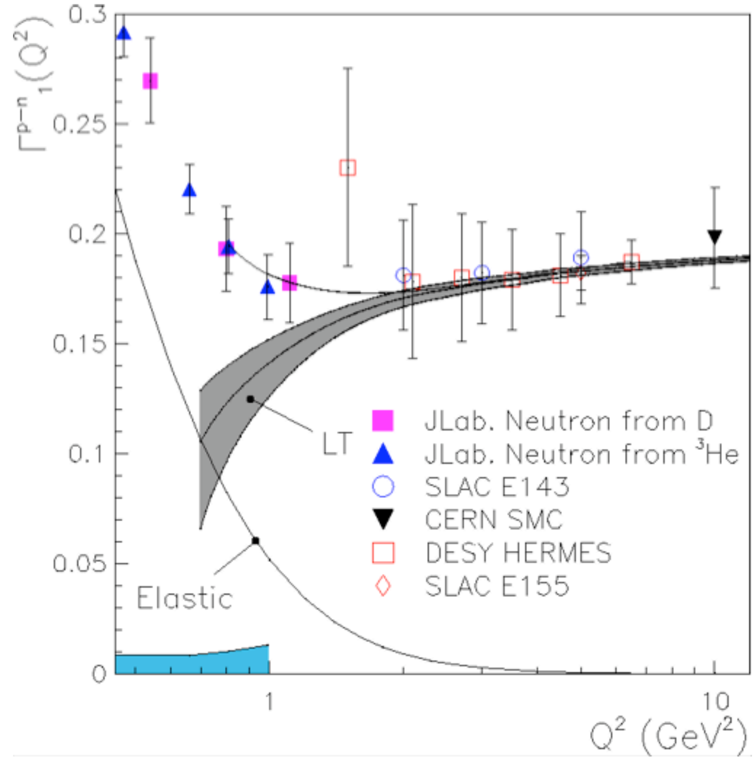


EG1b preliminary and
Hall A + Hall B EG1a: PRL 93 (2004) 212001

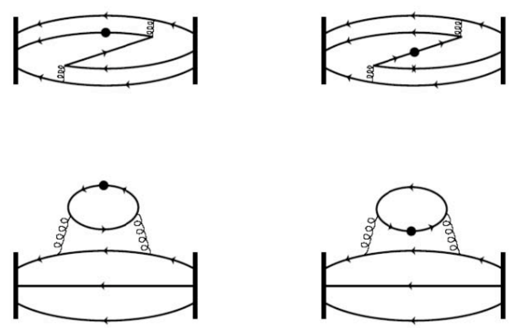
Bjorken Sum Q^2 evolution and higher twists



eg1a + E94-010, A. Deur *et al*. PRL 93, 212001 (2004)



- At low Q^2 good quantity to test Chiral P. T.
  - Little or no contribution from the Delta
- At large Q^2 does not contain non disconnected diagrams. Good to compare to Lattice calculations



f_2^{p-n}=-0.18±0.10

μ_4/M^2=-0.06±0.02

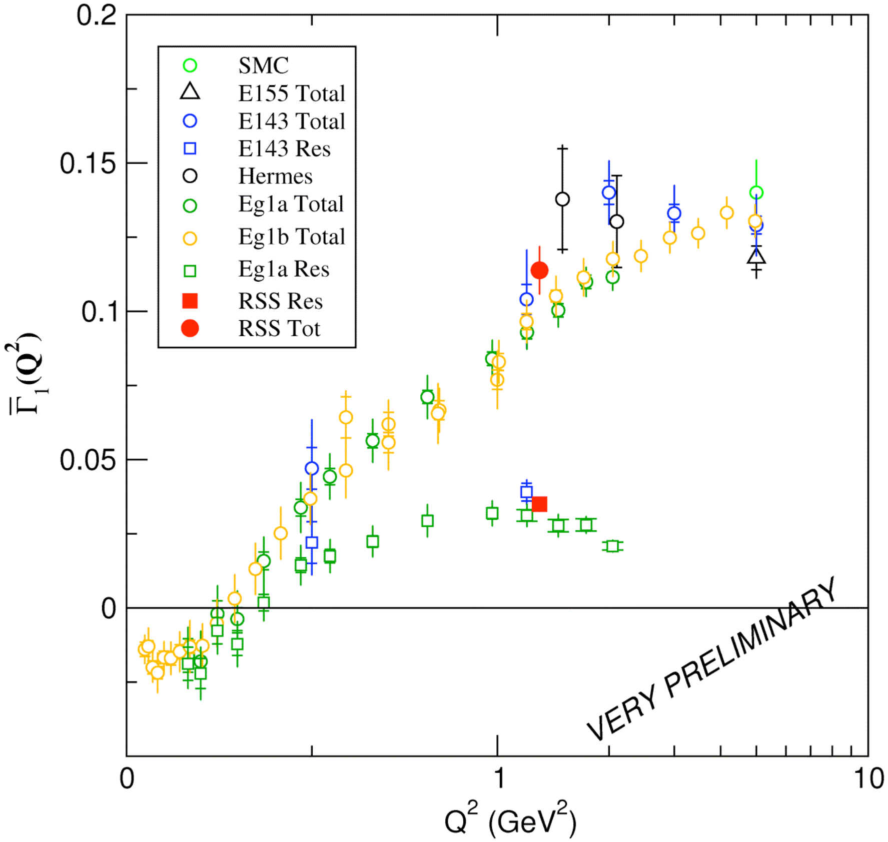
μ_6/M^4=0.09±0.03

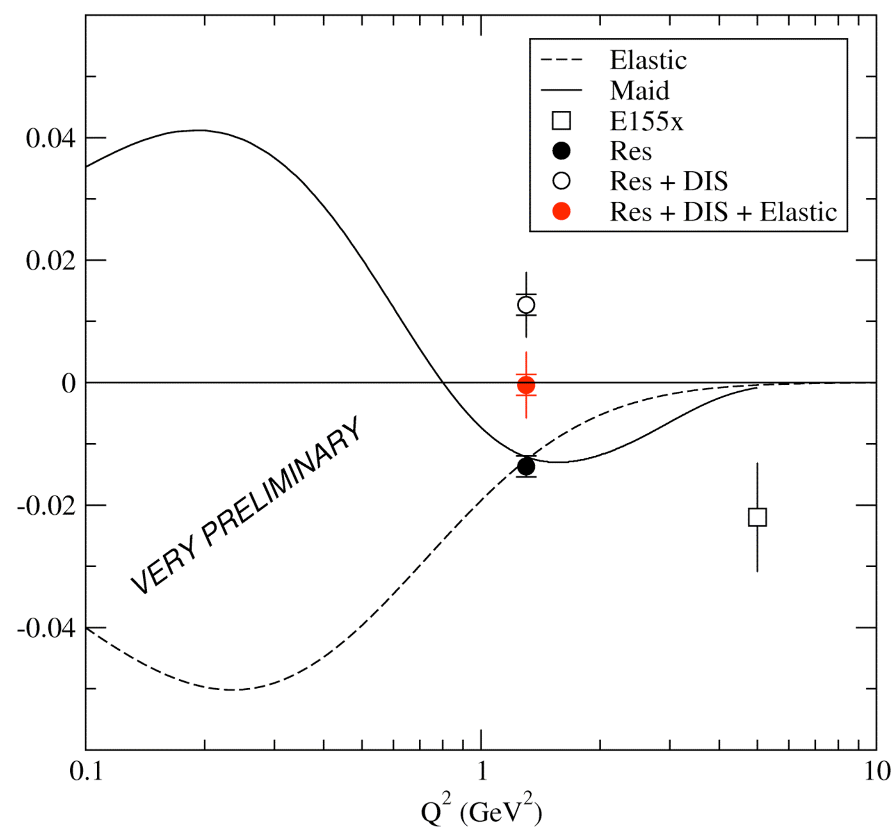
Hall C RSS Preliminary Results on Γ_1^p and Γ_2^p

from K. Slifer (Spokesperons: M. Jones, O. Rondon)

- Q^2=1.3 GeV^2, Γ_1^p consistent with Hall B results
  Γ_2^p satisfies B-C sum rule

Γ_1^p Γ_2^p



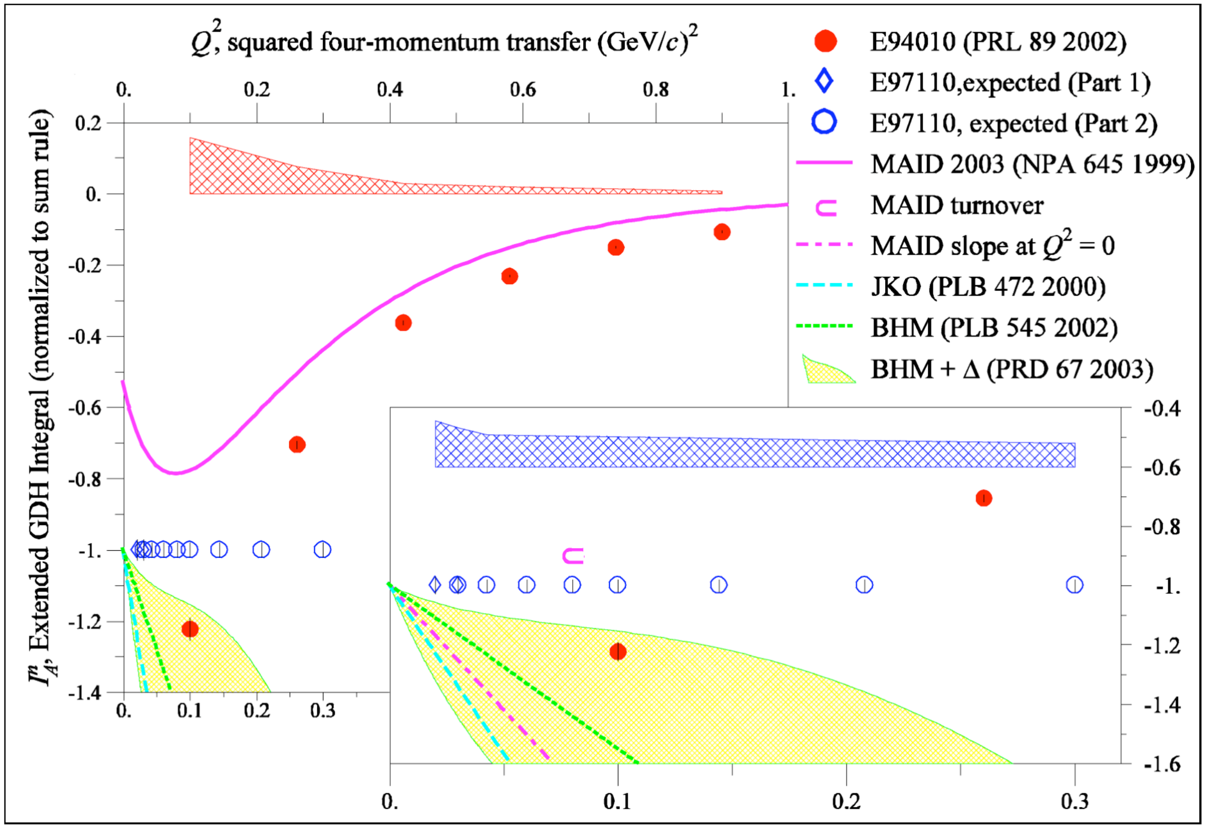


GDH Sum Rule and Spin Structure of ^{3}He and Neutron with Nearly Real Photons

Spokespersons: J. P. Chen, A. Deur, F. Garibaldi

- Measured generalized GDH at Q^2 near zero for ^{3}He and neutron
  - ➥ Slope at $Q^2 \sim 0$

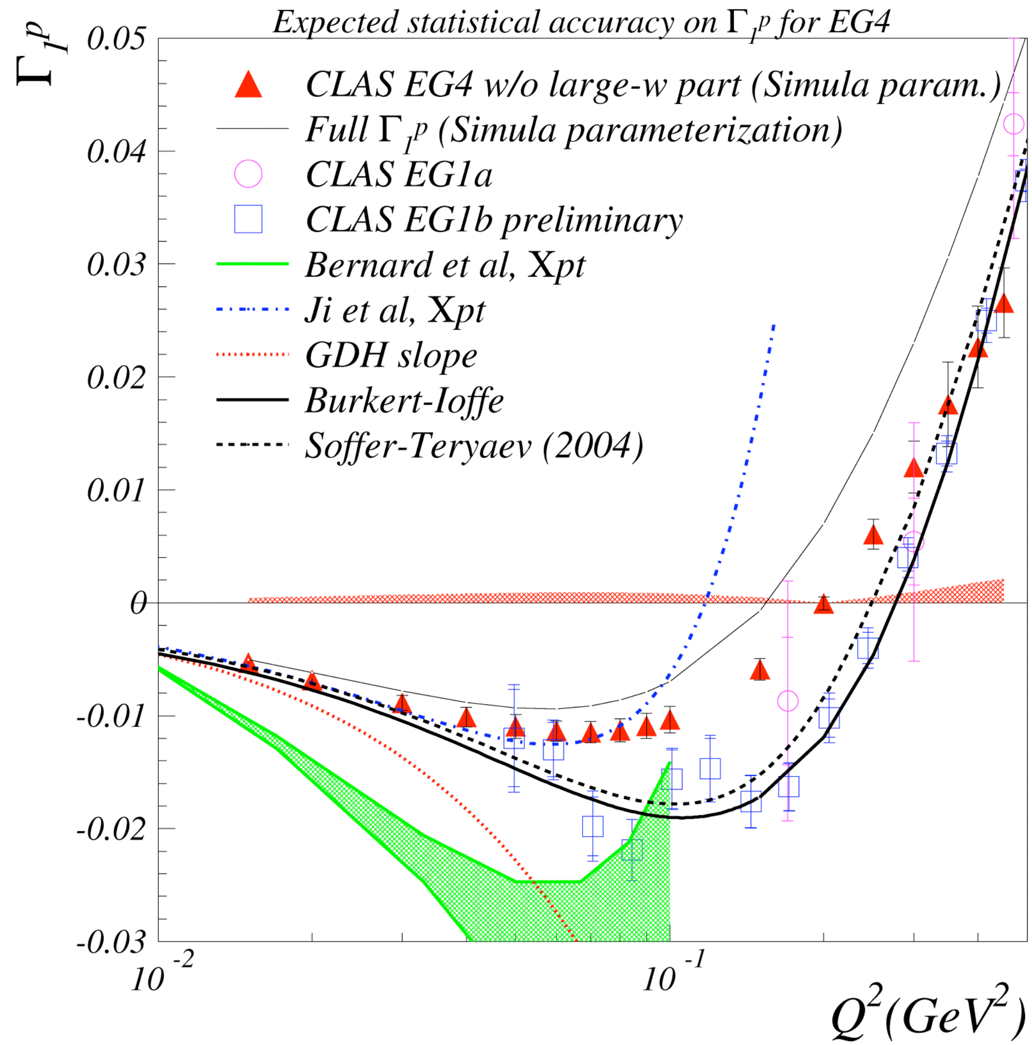
  Benchmark test of χPT
- Data taken in 2003
- Analysis underway
- Need ^{3}He calculations to help neutron extraction



Hall B EG4 Projected Results

Spokespersons: M. Battaglieri, R. De Vita, A. Deur, M. Ripani

- Extend to very low Q^2 of 0.015 GeV^2 both p and d
- Benchmark test of χPT
- Data taking earlier this year.



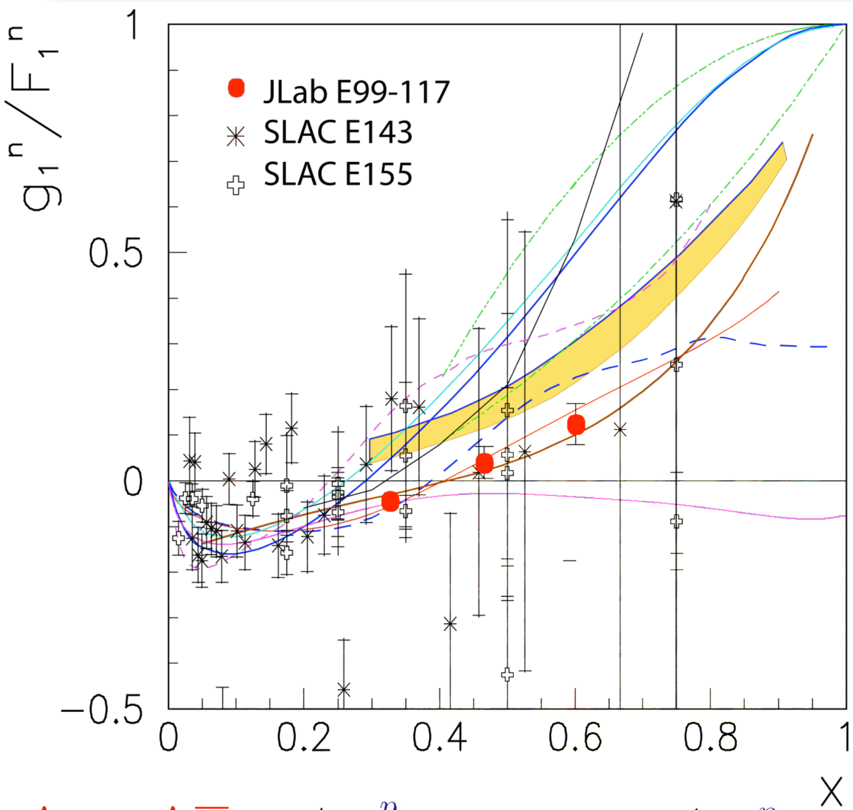
Spin Structure in the Valence Region /Duality

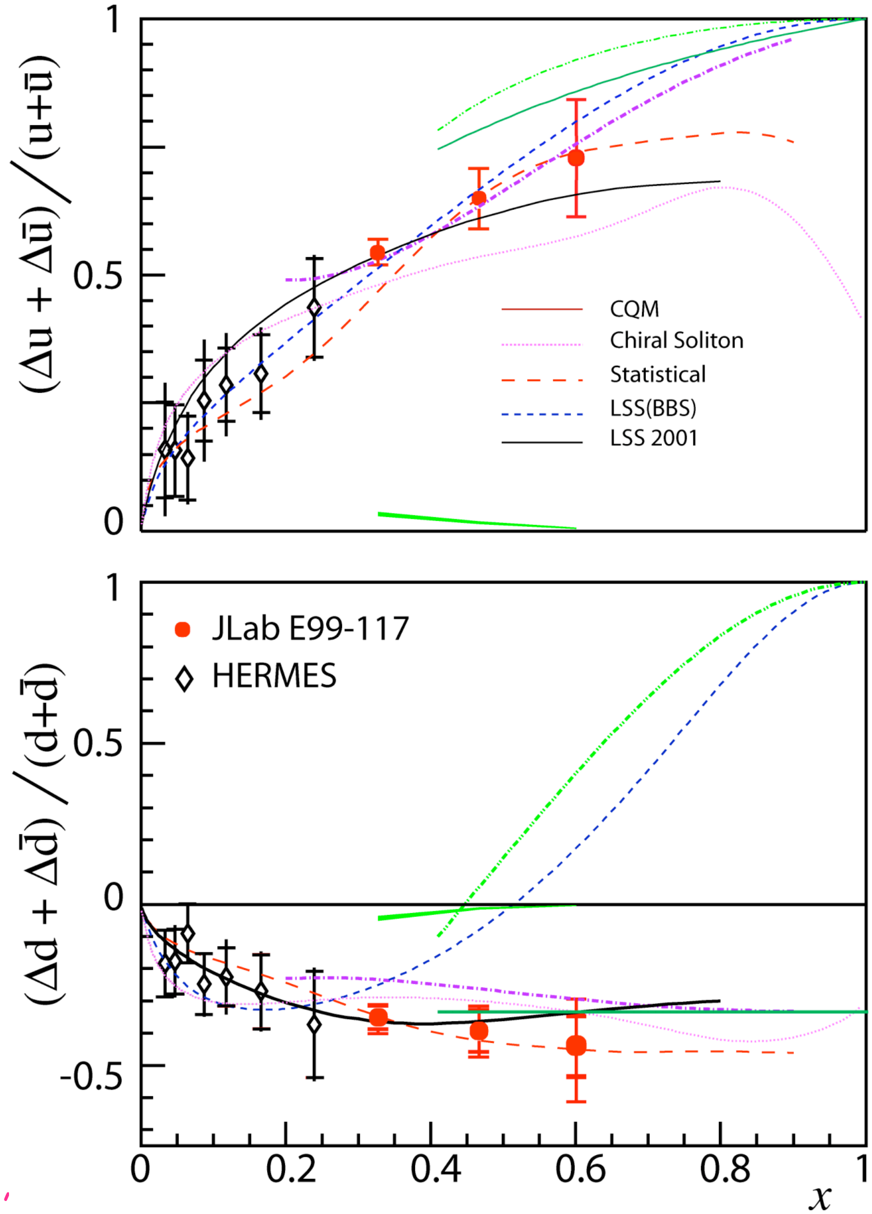
and

Helicity Dependent Parton Distributions

Flavor Decomposition of PDFs at large x, E99-117

X. Zheng et al. PRL 92, 012004 (2004) and **PRC**70, 065270 (2004)





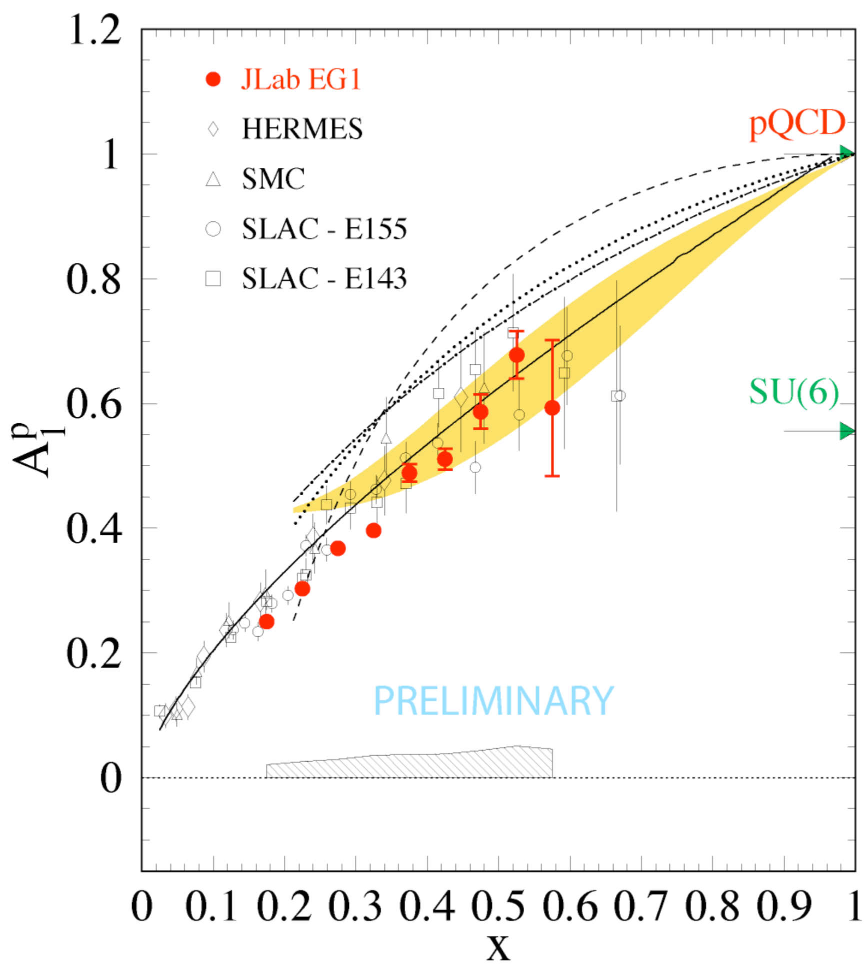
$$\frac{\Delta u + \Delta \overline{u}}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

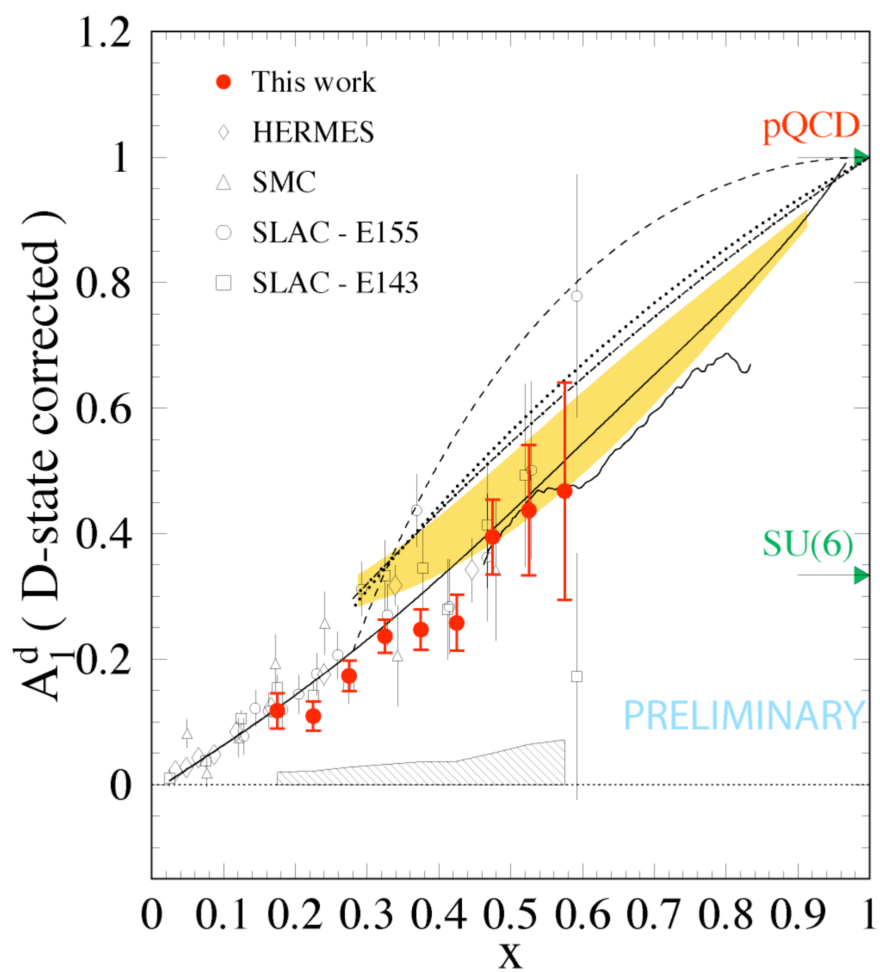
$$\frac{\Delta d + \Delta \overline{d}}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4 + \frac{1}{R^{du}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1 + 4\frac{1}{R^{du}})$$

$$R^{du} = \frac{d + \overline{d}}{u + \overline{u}}$$

$A_1^{p,d}$ From NH_3 and ND_3 in Hall B

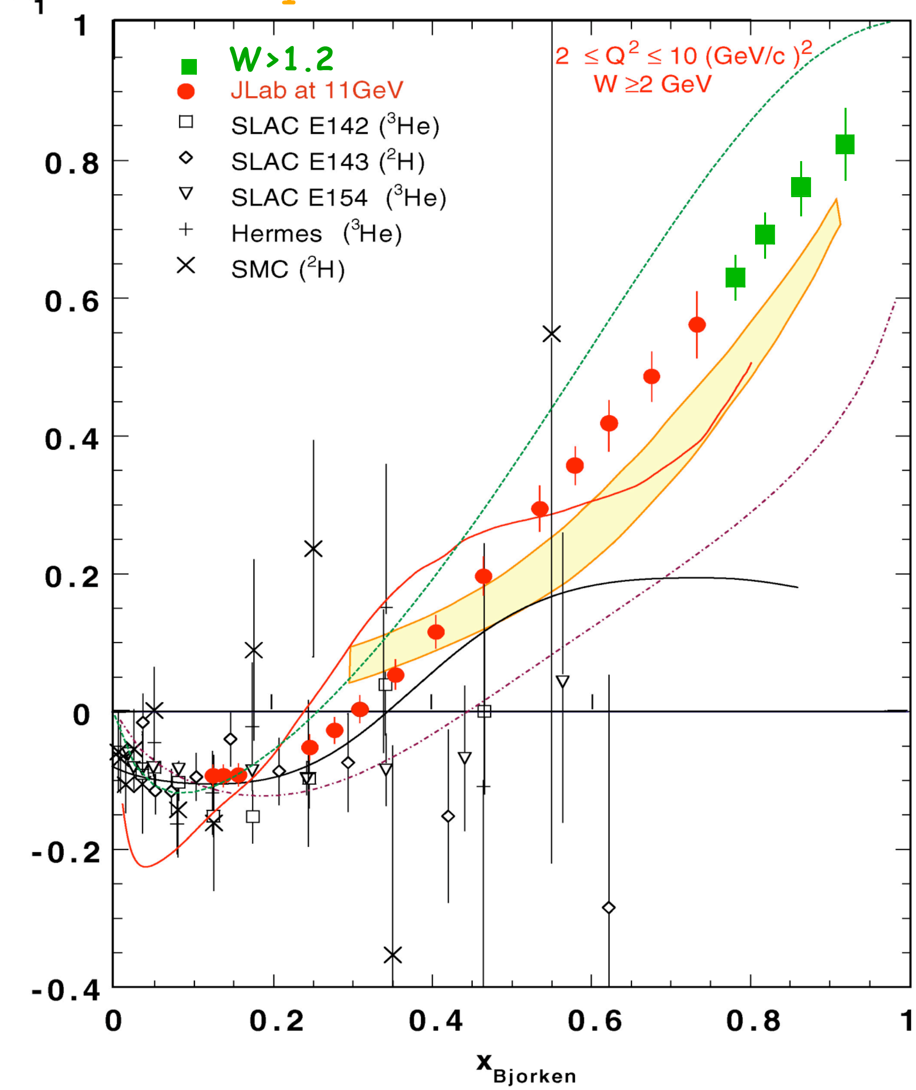
V. Burkert, S. Kuhn R. Mineheart, G. Dodge et al. EG1 collaboration



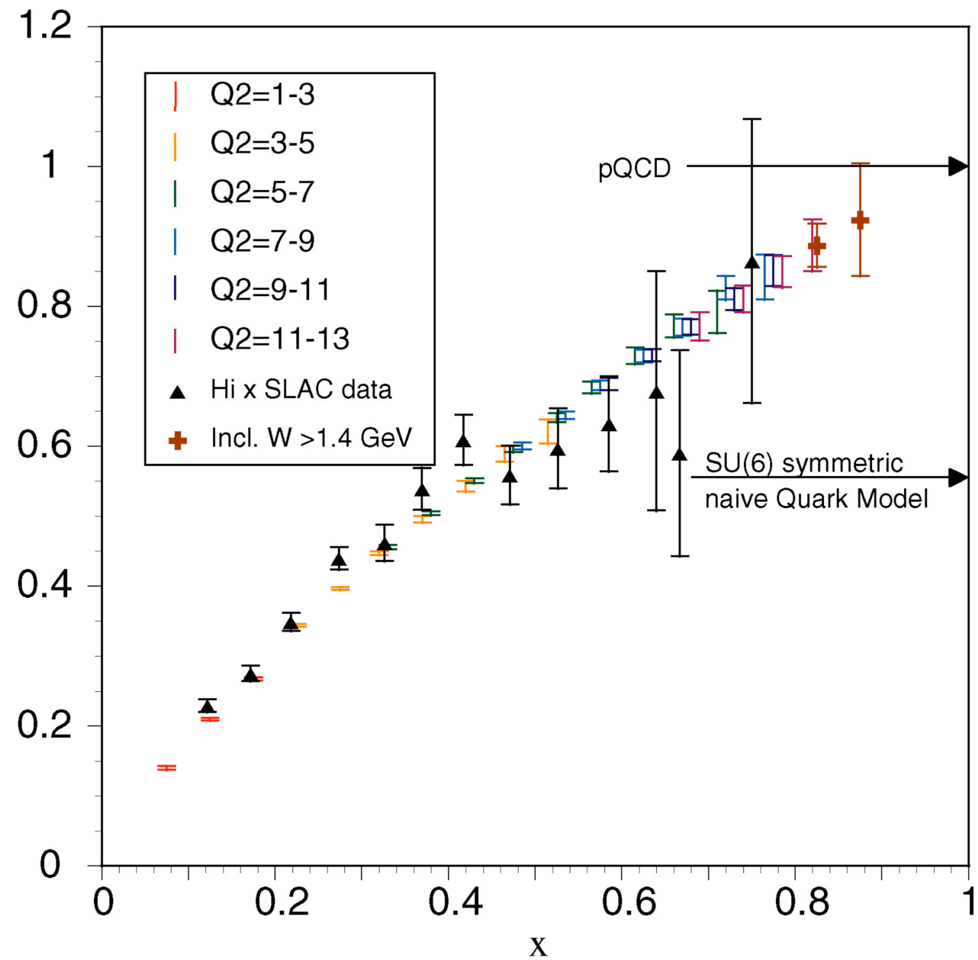


What's possible with 11 GeV beam

A_1^n at 11 GeV

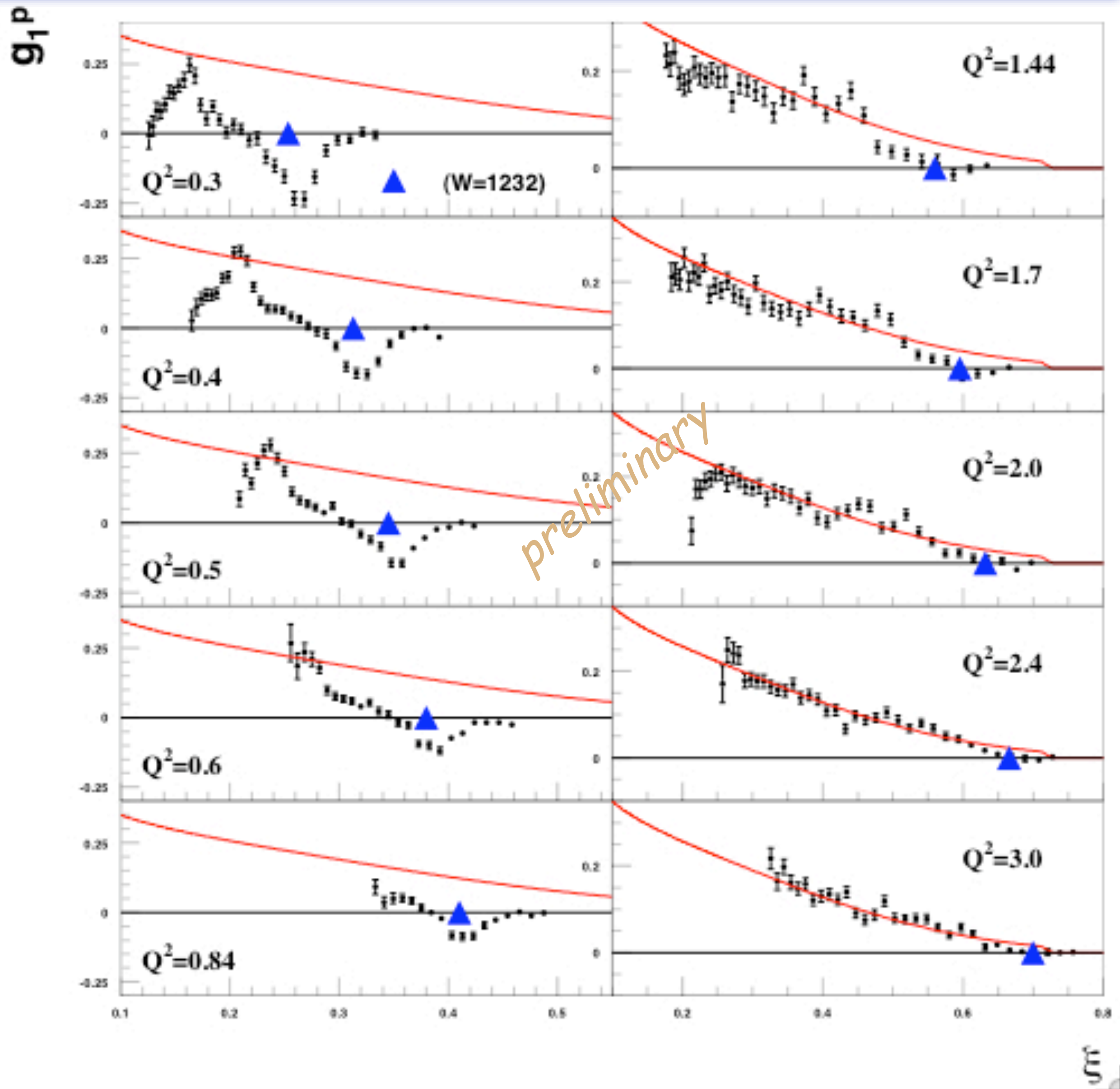


A_1^p at 11 GeV



CLAS data on g1p

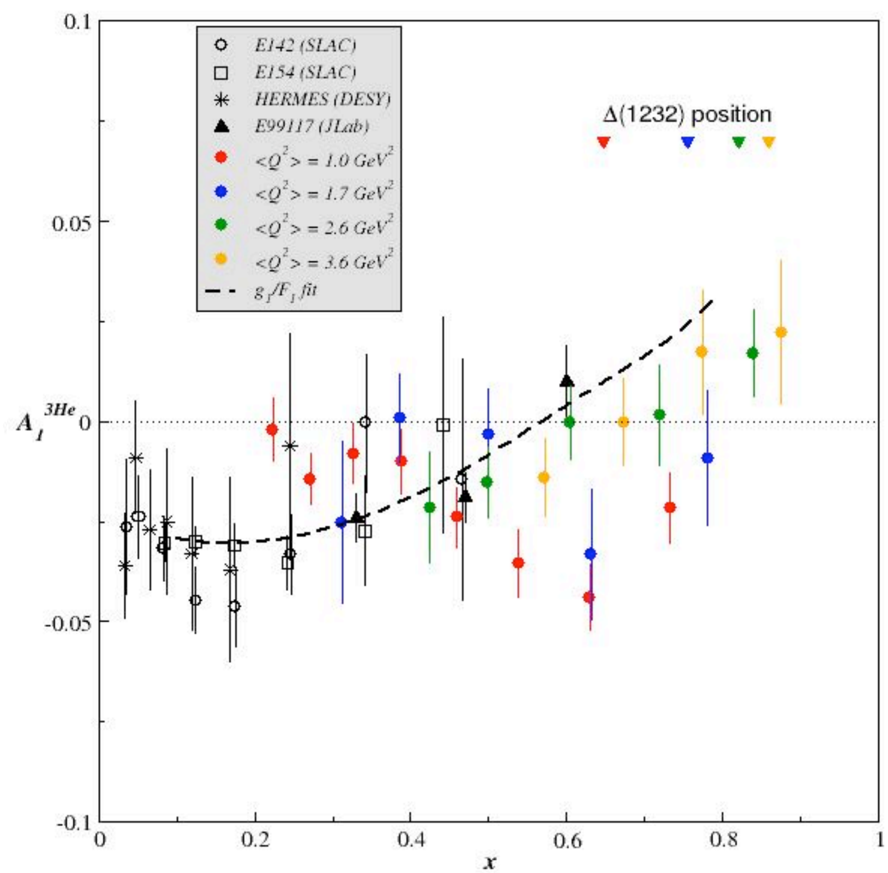
JLab Hall B for g_1^p

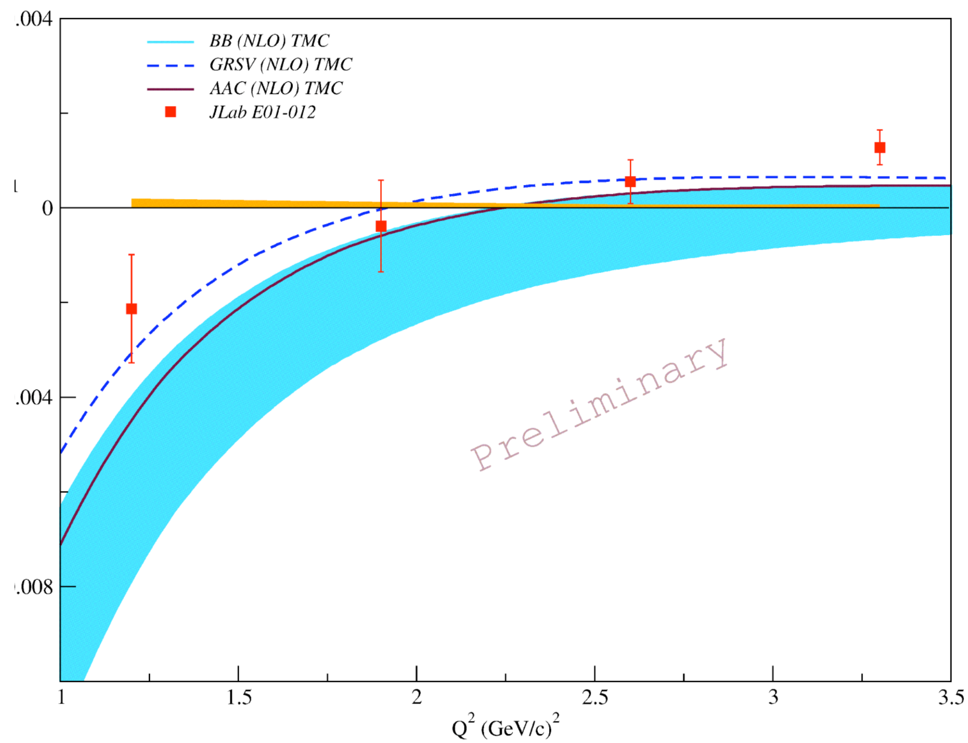


Hall A E01-012 Preliminary Results: Γ_1^n and A_1^{3He}

Spokespersons: N. Liyanage, J. P. Chen, S. Choi, **PhD Student:** P. Solvignon

- g_1/g_2 and A_1/A_2 (^3He/n) in resonance region, $1 < Q^2 < 4$ GeV^2
- Study quark-hadron duality in spin structure





Γ_1^n resonance comparison with pdfs

Higher Moments
Generalized Spin Polarizabilities
and
Quark Gluons Correlations
Color Polarizabilities

Generalized Spin Polarizabilities

- **Consider Spin-flip VVCS amplitudes: $g_{TT}(Q^2,\nu)$, $g_{LT}(Q^2,\nu)$**
  Low-energy expansion, the $O(\nu^3)$ term gives
  generalized forward spin polarizability, γ_0, and
  generalized longitudinal-tranverse spin polarizability, δ_{LT}

$$\gamma_0(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu}\frac{\sigma_{TT}(Q^2,\nu)}{\nu^3}d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) - \frac{4M^2}{Q^2}x^2 g_2(Q^2,x)]dx$$

$$\delta_{LT}(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu}\frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2}d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) + g_2(Q^2,x)dx$$

Neutron Spin Polarizabilities

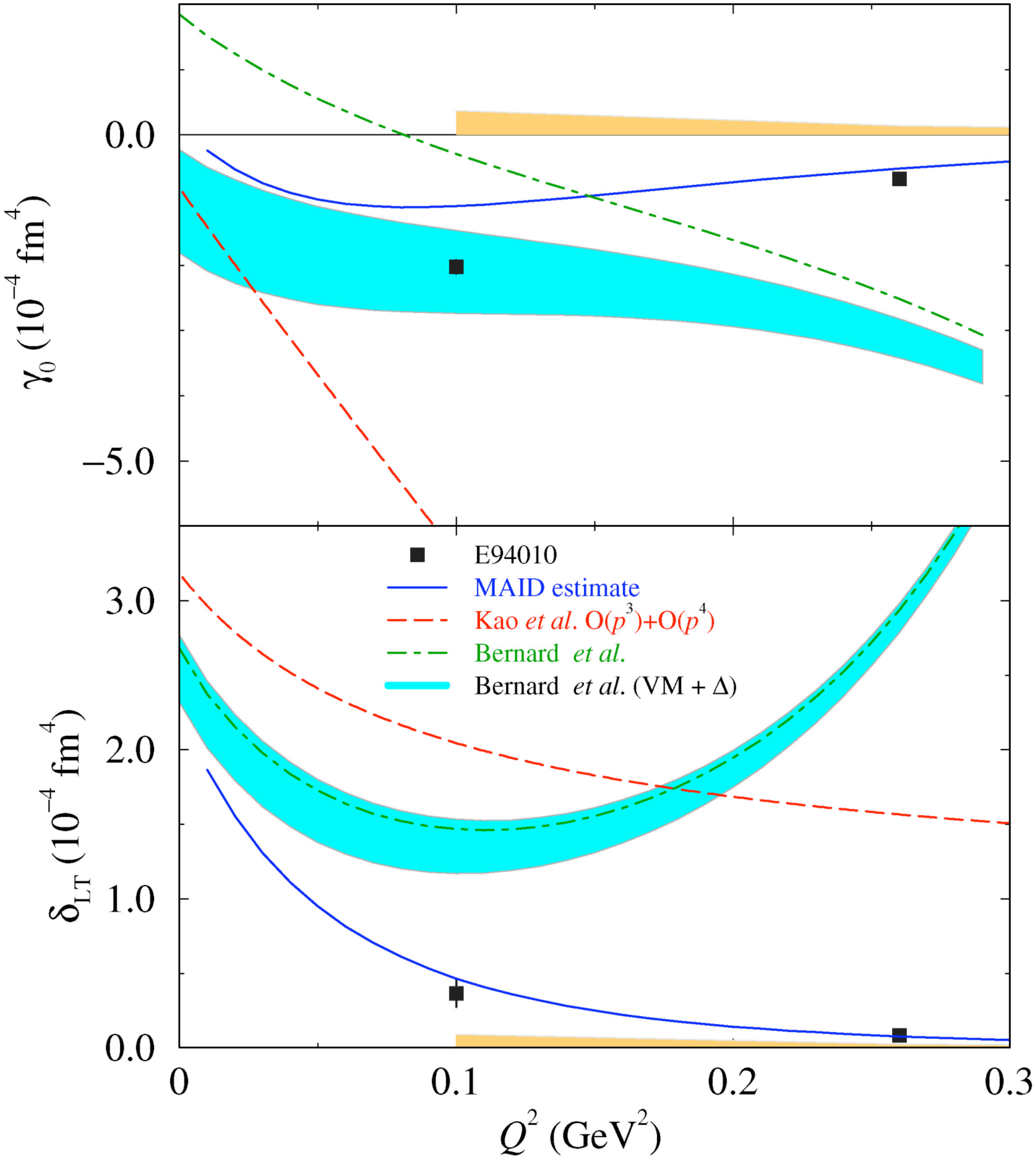
- ChPT expected to work at low Q^2 (up to ~ 0.1 GeV^2?)

  γ_0 sensitive to resonance,

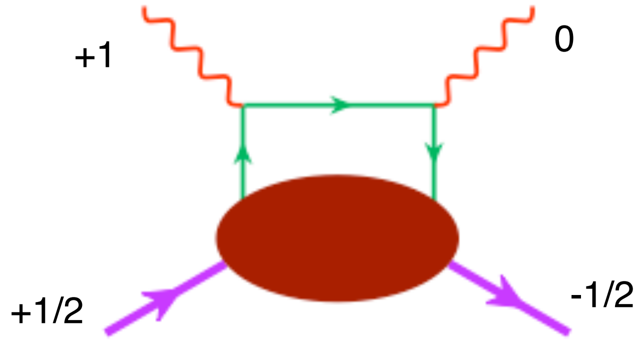
  δ_{LT} insensitive to resonance

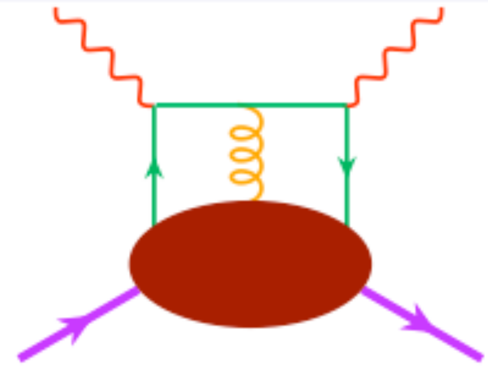
  E94-010 results:

  PRL 93 (2004) 152301
- RB ChPT calculation with resonance for γ_0 agree with data at Q^2=0.1 GeV^2
- Significant disagreement between data and both ChPT calculations for δ_{LT}
- Good agreement with MAID model predictions



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 ($h_T(y,Q^2)$)

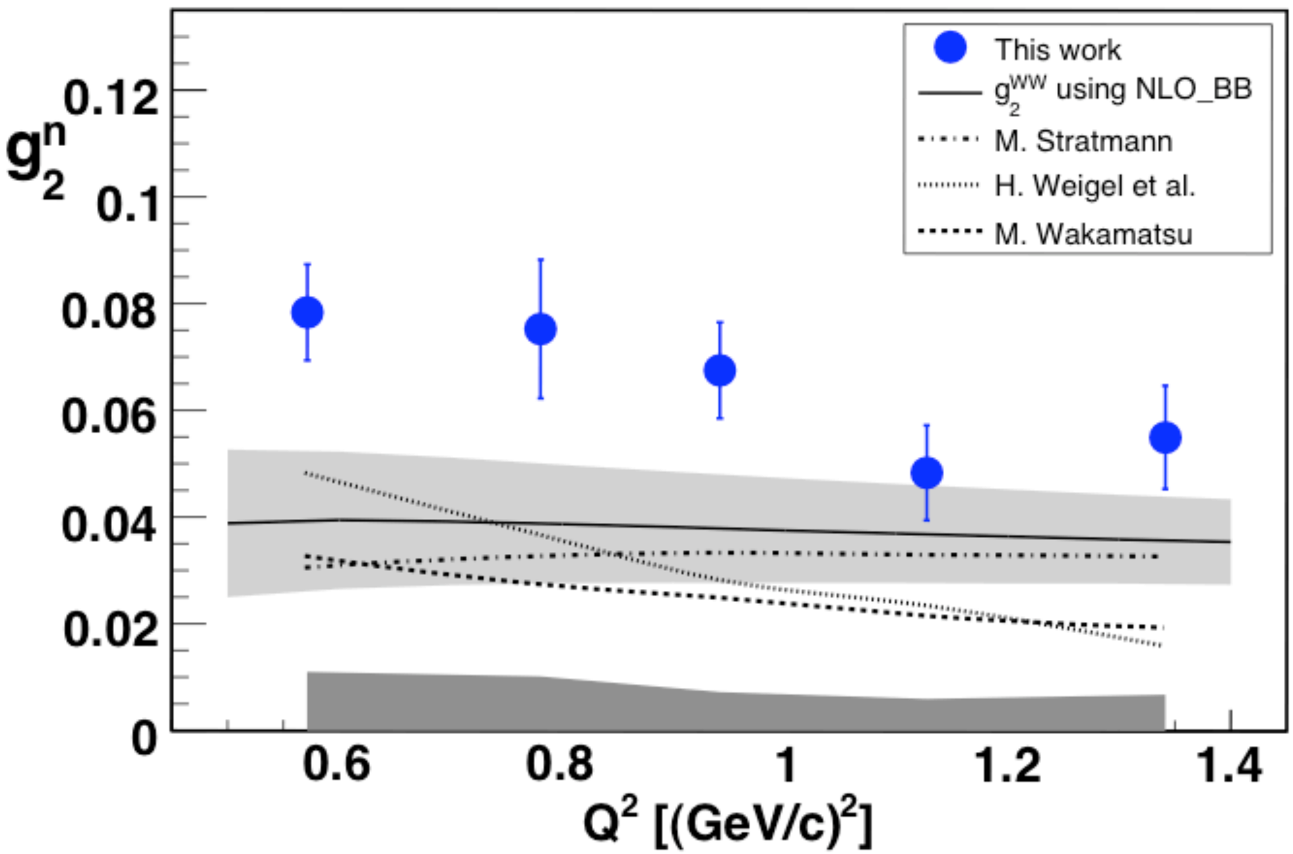
qg correlations ($\xi(y,Q^2)$)

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



d_2: twist-3 matrix element

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

  d_2: twist-3 matrix element

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

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

Color polarizabilities

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

χPT and Model (MAID) at low Q^2

Avoid issue of low-x extrapolation

Color "Polarizabilities"

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

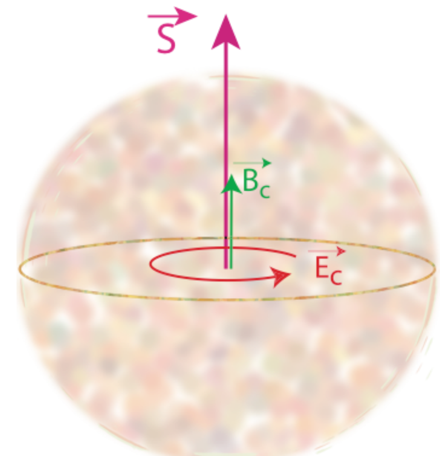
How does the gluon field respond when a nucleon is polarized ?

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

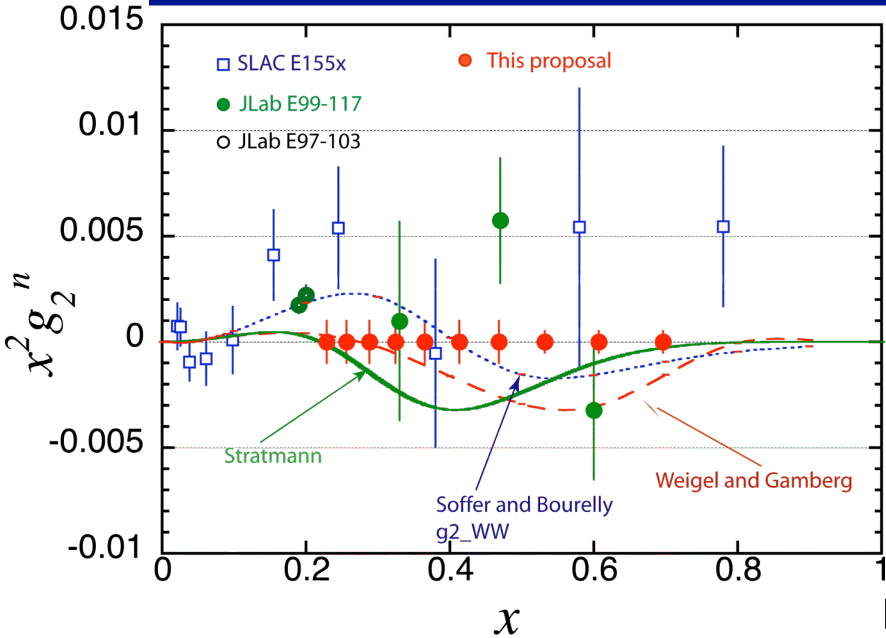
$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{\boldsymbol{E}} \psi$$



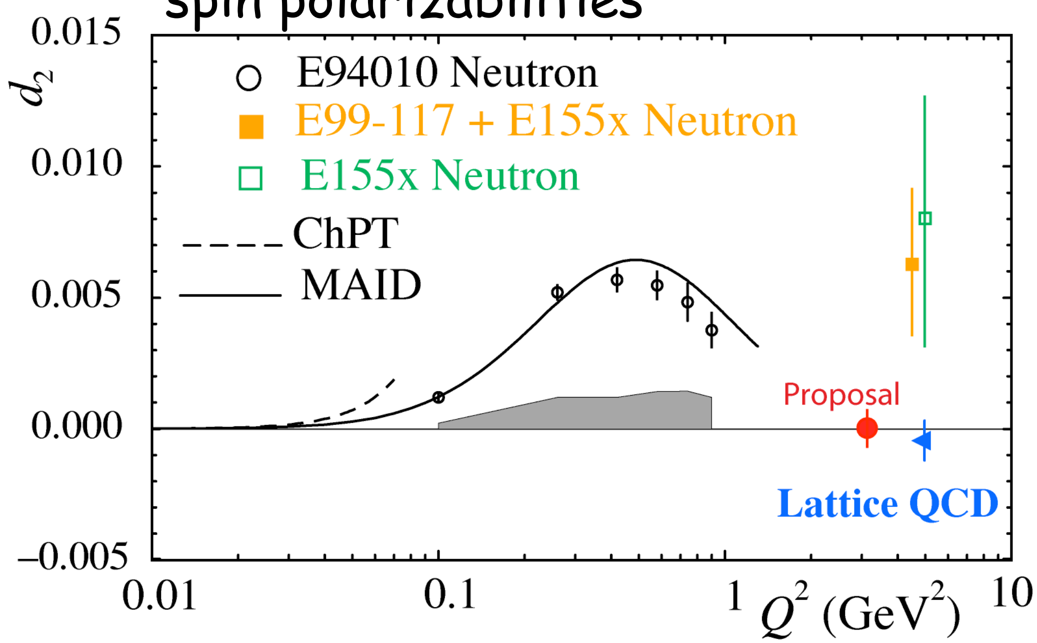
$$d_2 = (\chi_E + 2\chi_B)/8$$
$$f_2 = (\chi_E - \chi_B)/2$$

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

Color Polarizability: d_2^n (Hall A)



- 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

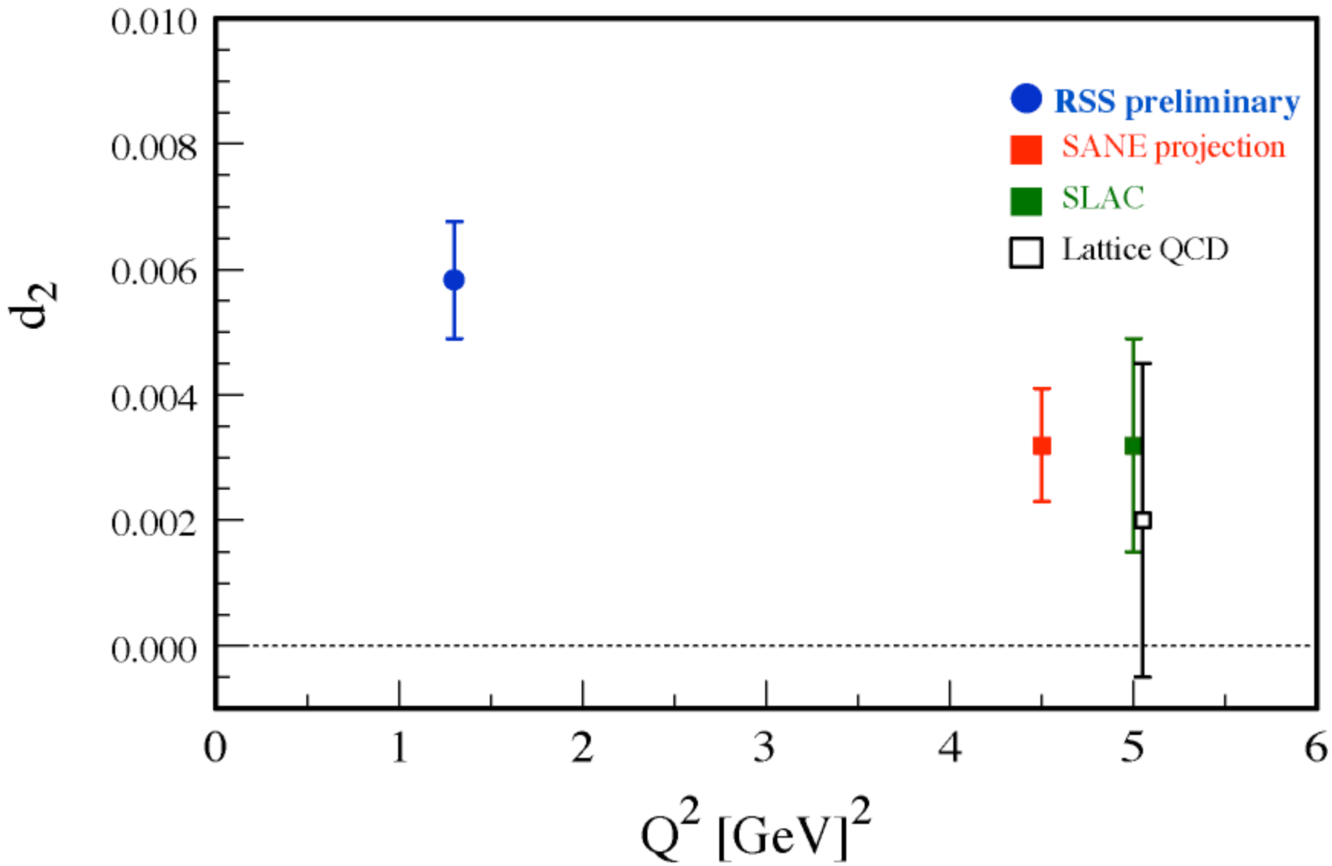


Approved experiment E06-114
Running in Fall 2007

Spokespersons: S. Choi, X. Jiang, Z. Meziani, B. Sawatzky

Color Polarizability: d_2^p (Hall C RSS) and SANE projection

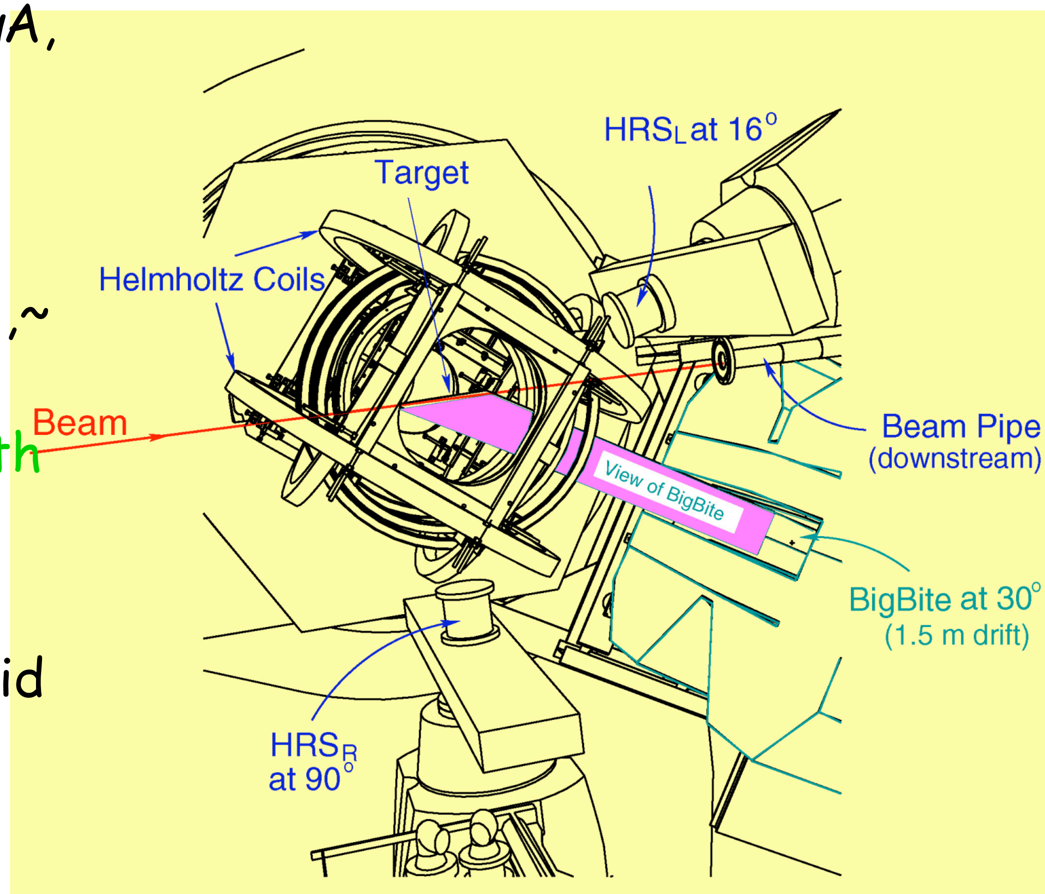
RSS Spokesperons: M. Jones, O Rondon
SANE spokespersons: S. Choi, O. Rondon, Z.-E. Meziani



Jlab Hall A E03-004 / $^3He\ (e,e'\pi^{-/+})X$

Spokespersons: J.-P Chen, X. Jiang & J.-C. Peng

- Beam
  - Polarized (P~80%) e-, 15 μA, helicity flip at 60Hz
- Target
  - Optically pumped Rb+spin exchange ^3He, 50 mg/cm2,~ 40% polarization
  - Transversely polarized with tunable direction
- Electron detection
  - Bigbite spectrometer, Solid angle 60 msr, θ=30 deg
- Charged pion detection
  - HRS spectrometer, θ=16 deg



Conclusion

A very rich program that will extend into the Future
with
the 12 GeV Jefferson Lab Upgrade

(see K. de Jager talk)