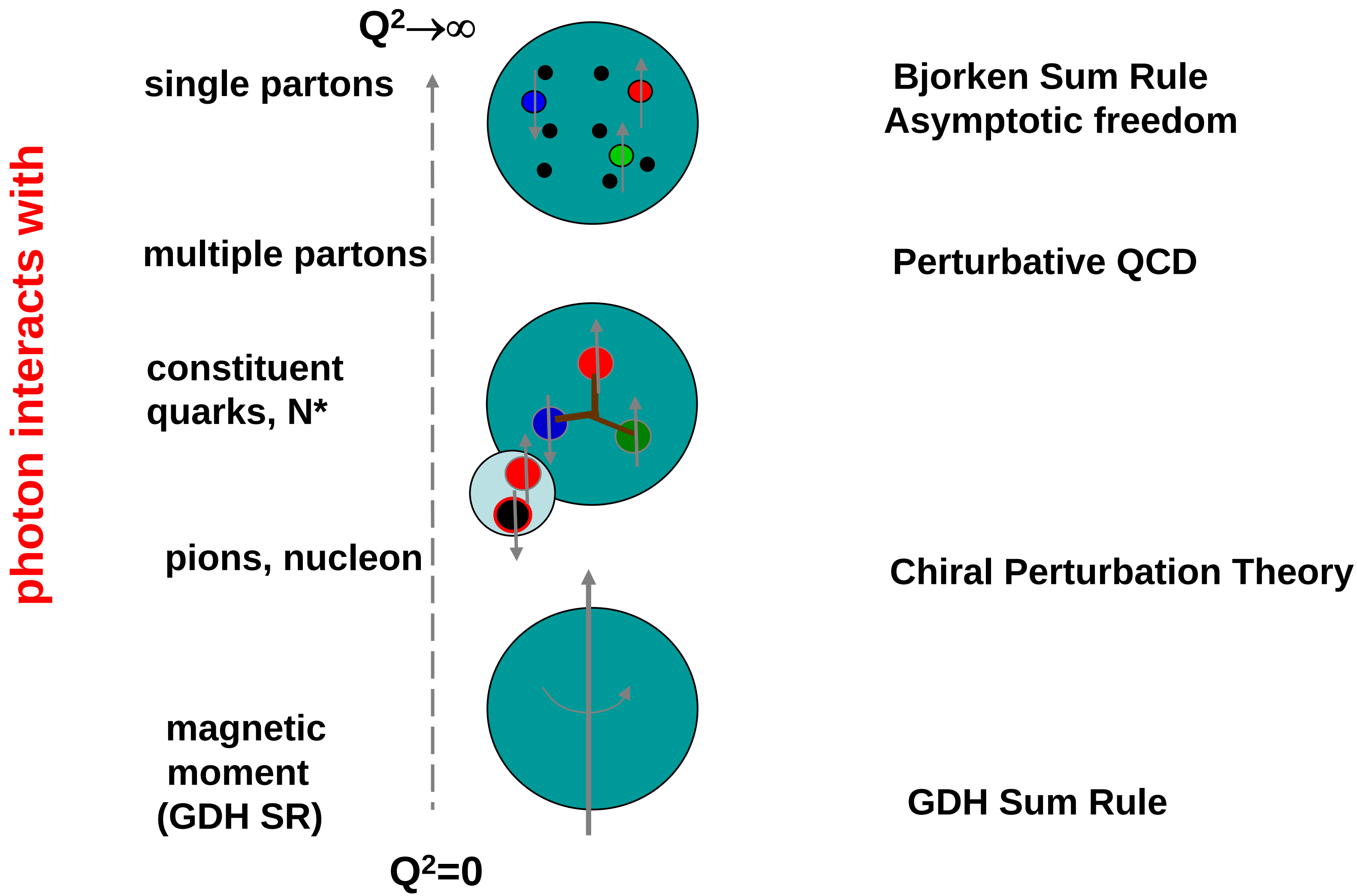
Overview of Jefferson Lab's Spin Physics Programme

- Introduction
- Experimental Setup
- Asymmetry Measurement
- Moments of Structure Functions
- Outlook

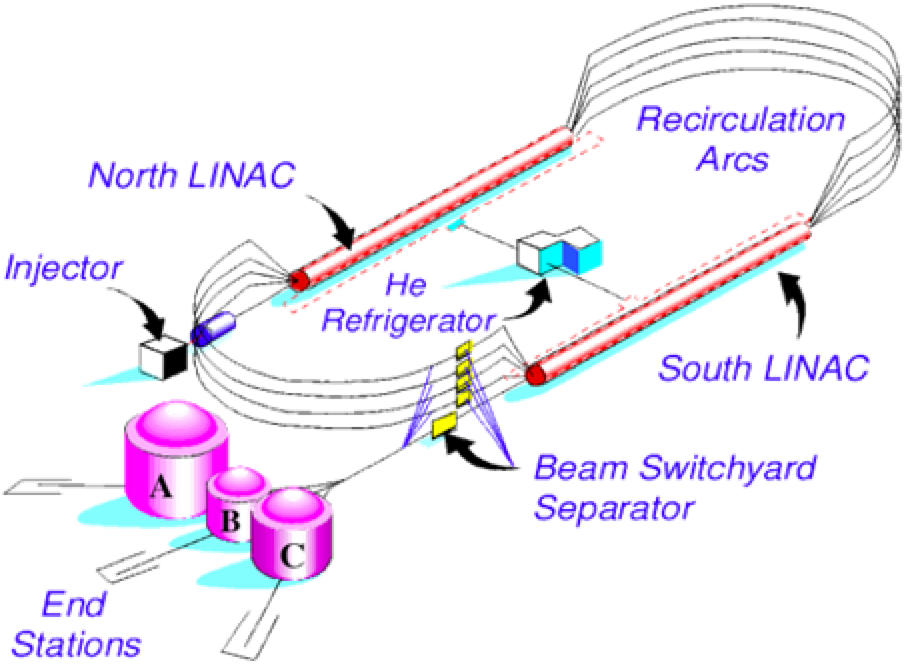
Spin structure vs distance scale



The CEBAF Accelerator

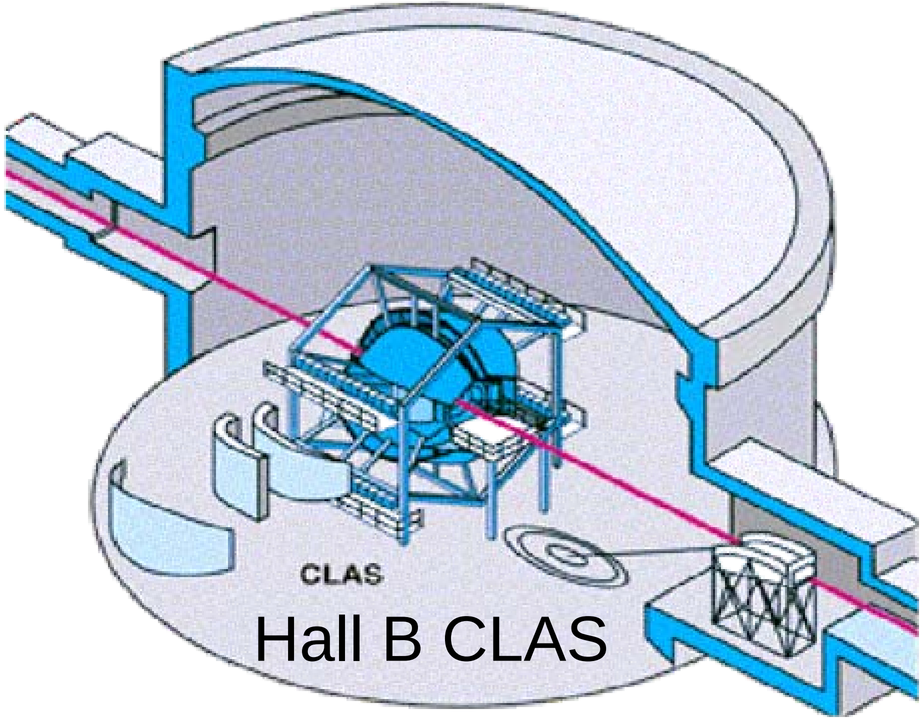
Electron beam

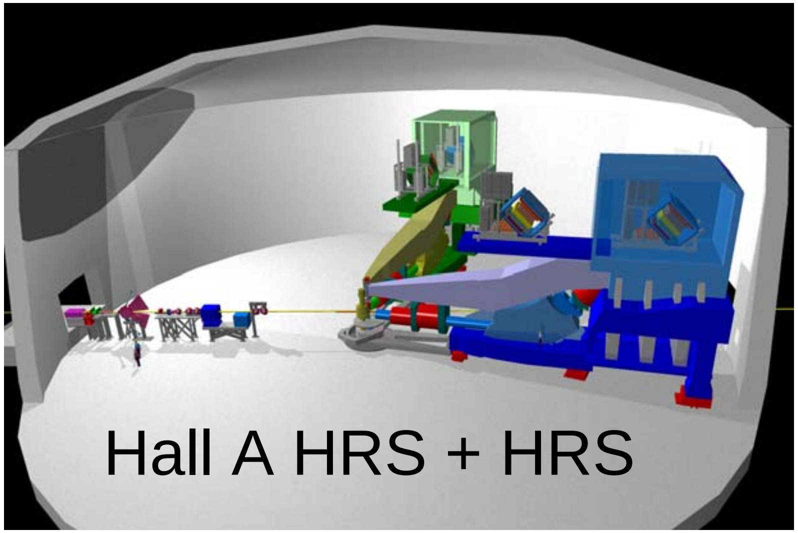
- Energy up to 5.7 GeV
- Current 1 - 100 µA (Hall B 50 nA)
- Polarization > 0.8



Experimental Halls

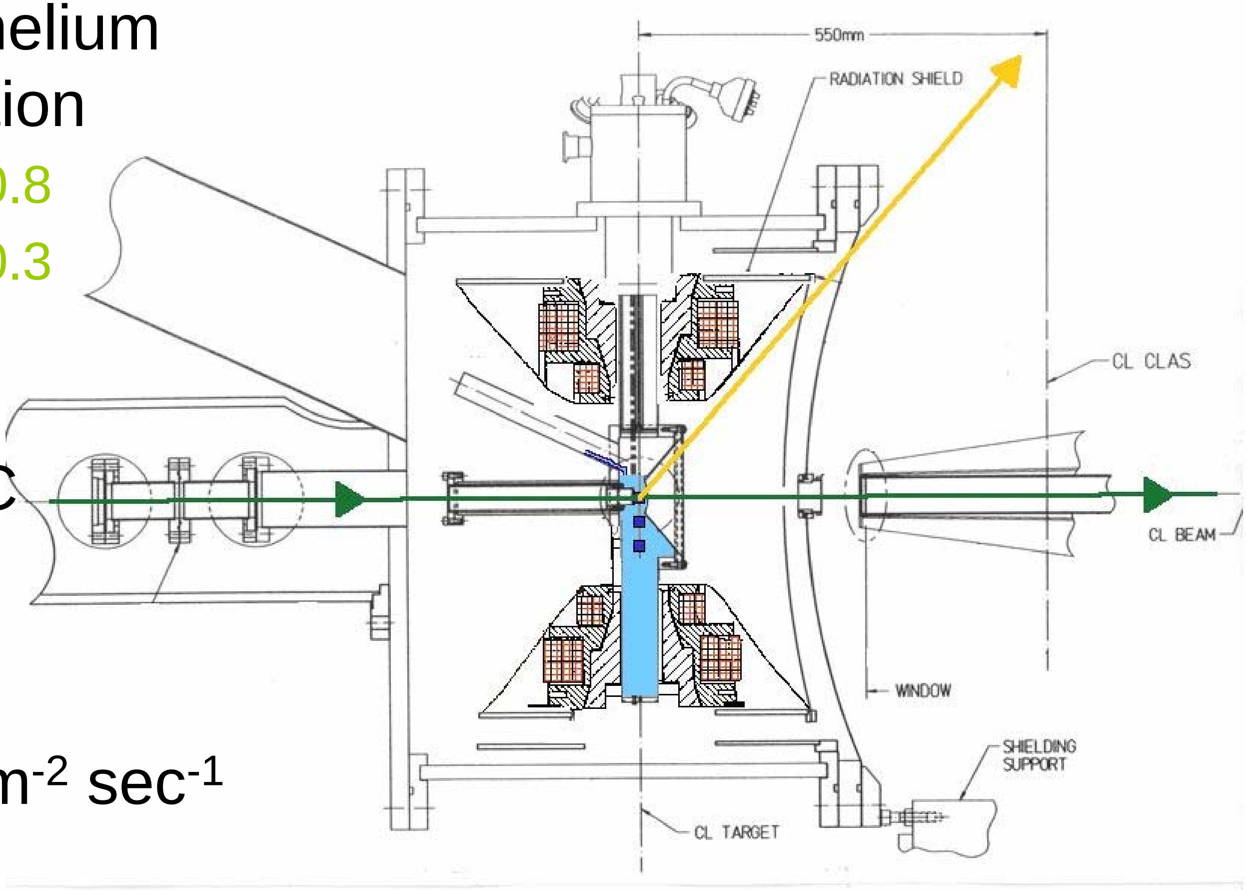
Polarized Targets:
H_2 and D_2 (Hall B + C)
^{3}He (Hall A)





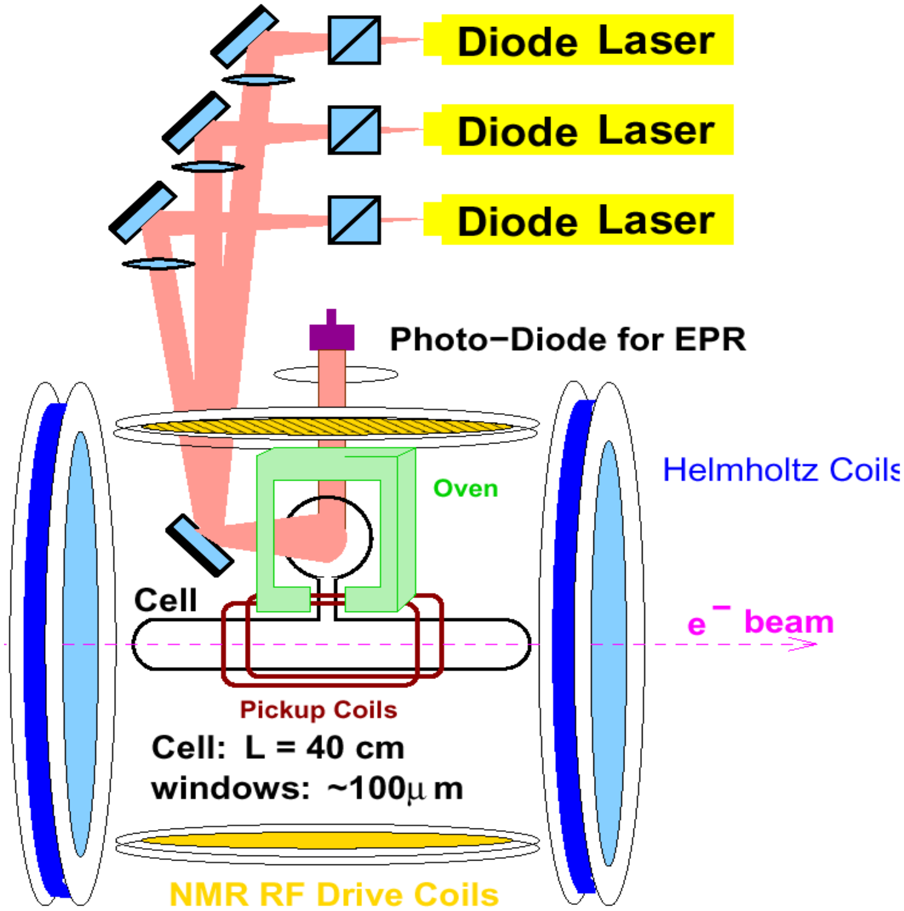
Polarized Targets in Halls B & C

- Dynamically polarized targets of solid (deuterated) ammonia
- 5 Tesla magnetic field
- 140 GHz polarizing microwaves
- 1 Kelvin superfluid helium
- Longitudinal polariztion
  $P_1 < 0.9$ $P_{1\,ave} = 0.7 - 0.8$
  $P_2 < 0.4$ $P_{2\,ave} = 0.2 - 0.3$
  measured by NMR
- Also transverse polarization in Hall C
- Current
  3 nA in Hall B
  100 nA in Hall C
- Luminosity < 10^{35} cm^{-2} sec^{-1}

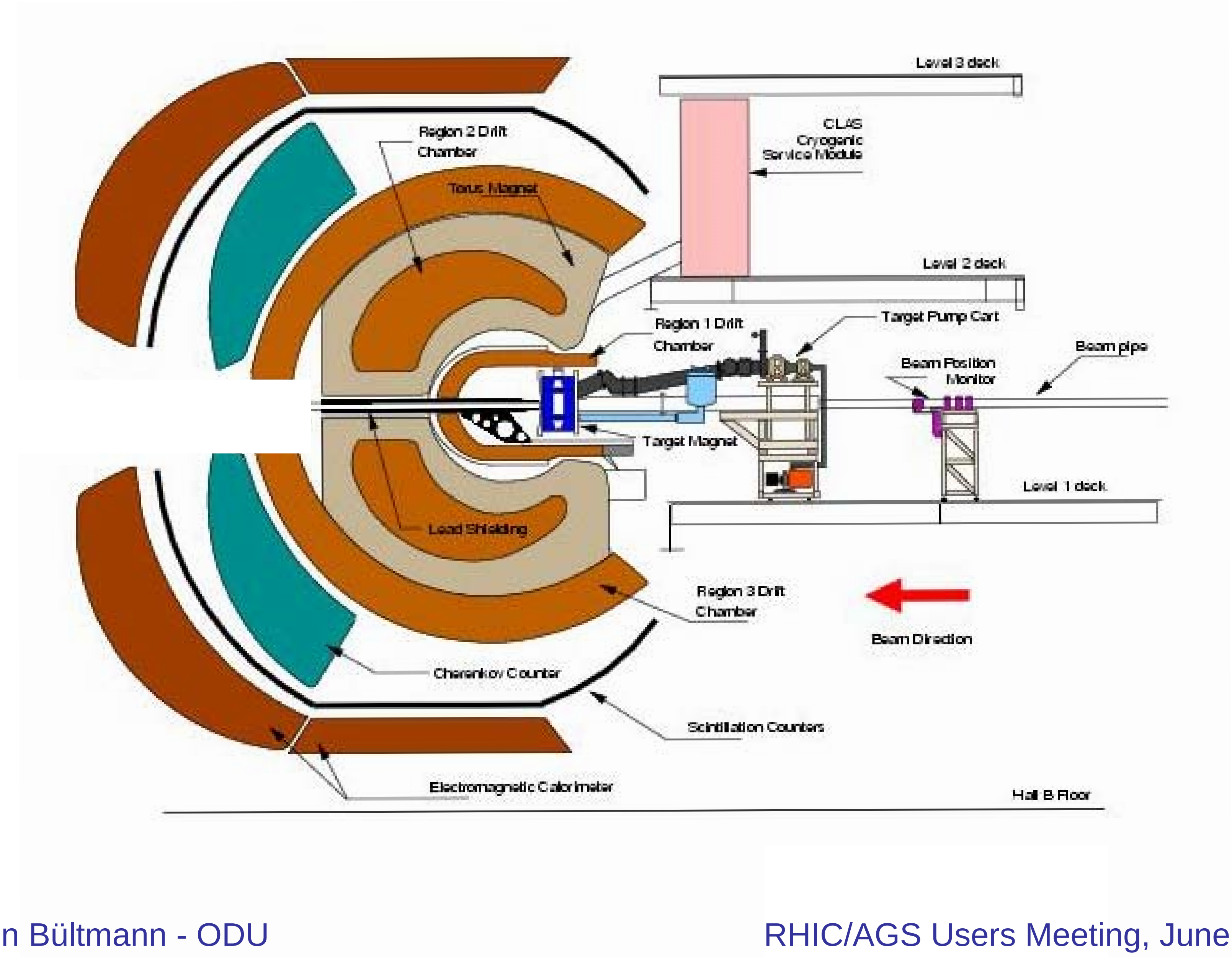


Polarized Target in Hall A

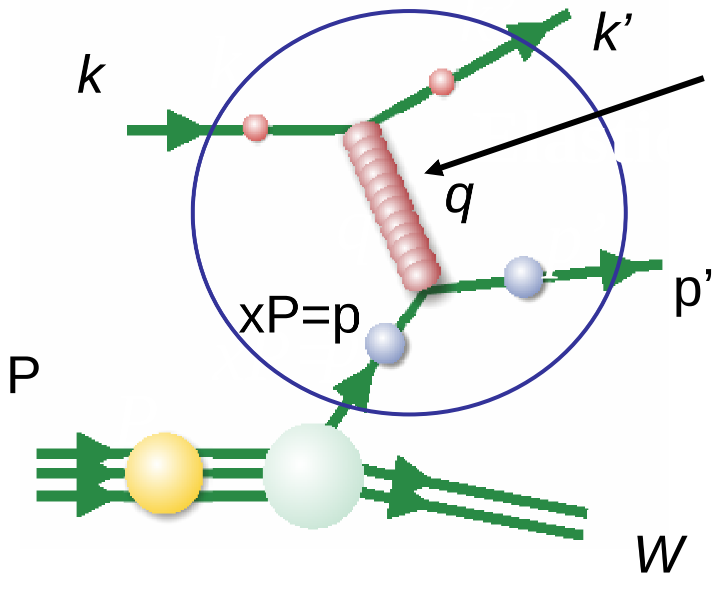
- Polarized ^{3}He gas target
- Optical pumping and spin exchange
- Longitudinal and transverse polarization
  $P_3 < 0.5$ $P_{1\ ave} = 0.4$
  measured by NMR and EPR
- Current 12 µA
- Luminosity < 10^{36} cm^{-2} sec^{-1}



CLAS Detector in Hall B



DIS of lepton off nucleon



Virtual photon scatters off parton

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

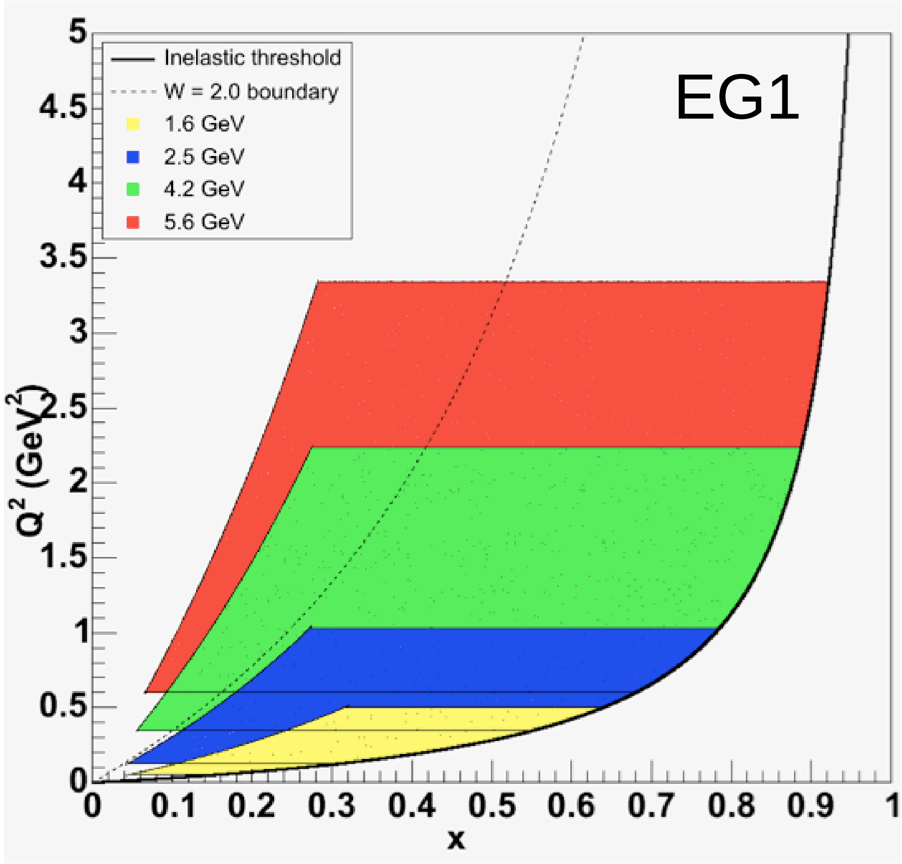
$$W^2 = M^2 + 2M\nu - Q^2$$

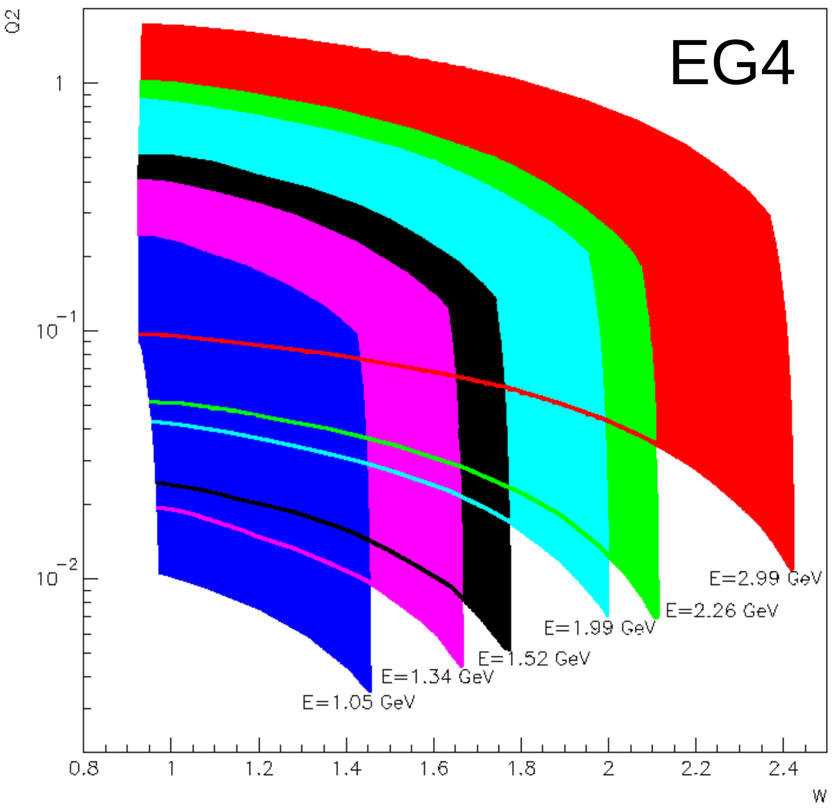
$$x = \frac{Q^2}{2M\nu}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

Kinematic Coverage

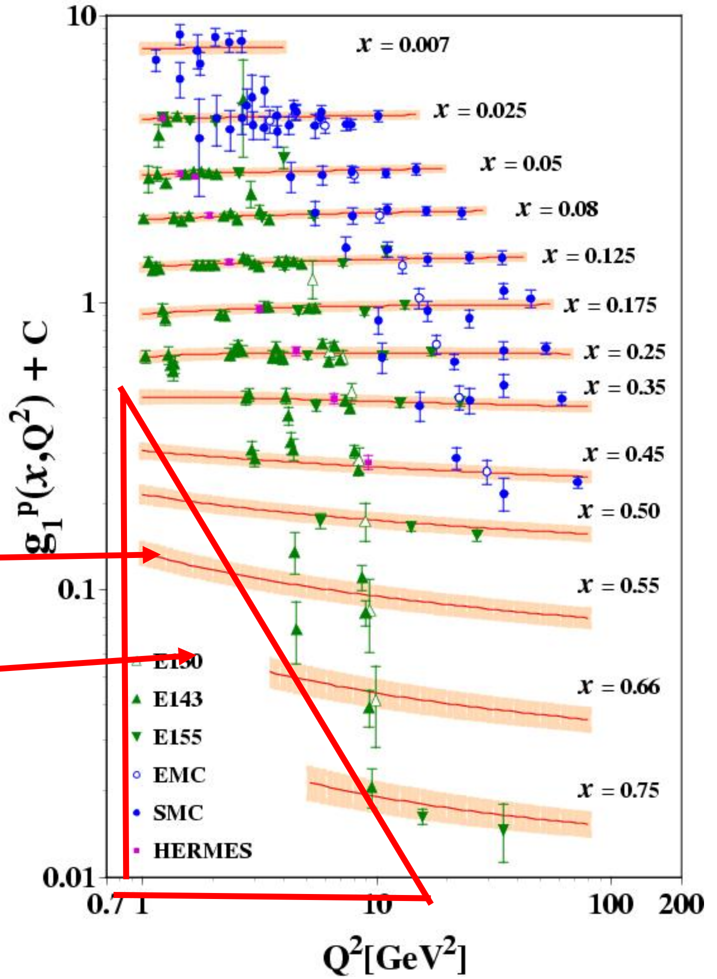




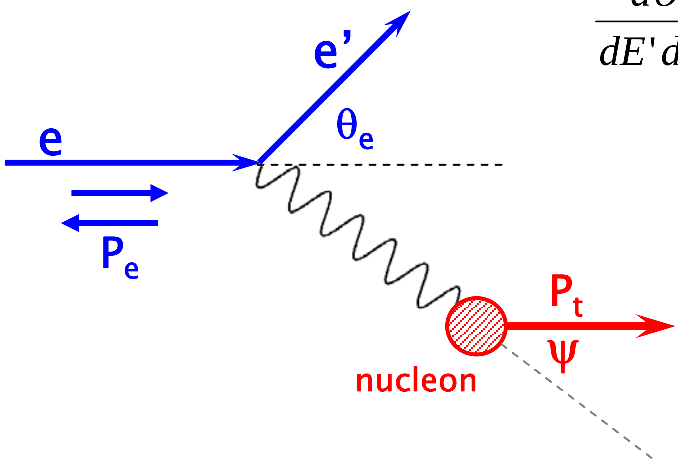
Status of $g_1(x,Q^2)$

$$g_1(x,Q^2)_{\text{pQCD}} = \frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

- Existing data mostly for DIS and low *x*
- Remaining
  - ΔG (RHIC, COMPASS)
  - ΔL (COMPASS, HERMES, Jlab)
  - Transversity (HERMES, Jlab, RHIC)
  - Large *x* precision measurements (Jlab)
  - Measurement in non-perturbative region (Jlab)



Asymmetry Measurement



$$\frac{d\sigma}{dE'\,d\Omega} = \Gamma_v \left[\sigma_T + \varepsilon\sigma_L + P_e P_t \left(\sqrt{1-\varepsilon^2}\, \mathbf{A_1}\, \sigma_T \cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}\, \mathbf{A_2}\, \sigma_T \sin\psi \right) \right]$$

$$\mathbf{A_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \qquad \mathbf{A_2} = \frac{\sigma_{LT'}}{\sigma_T}$$

the asymmetries A_1 and A_2 can be extracted by varying the direction of the nucleon polarization

$$A^{\parallel} = D\left(A_1 + \eta A_2\right)$$
$$A^{\perp} = d\left(A_1 + \zeta A_2\right)$$

where D, η, d, ξ are function of Q^2, W, E_0, R

the structure functions g_1 and g_2 are linear combination of A_1 and A_2

$$g_1(x,Q^2) = \frac{Q^2}{Q^2 + 4M^2x^2}\left(A_1 + \frac{2Mx}{\sqrt{Q^2}}A_2\right)F_1\left(x,Q^2\right)$$

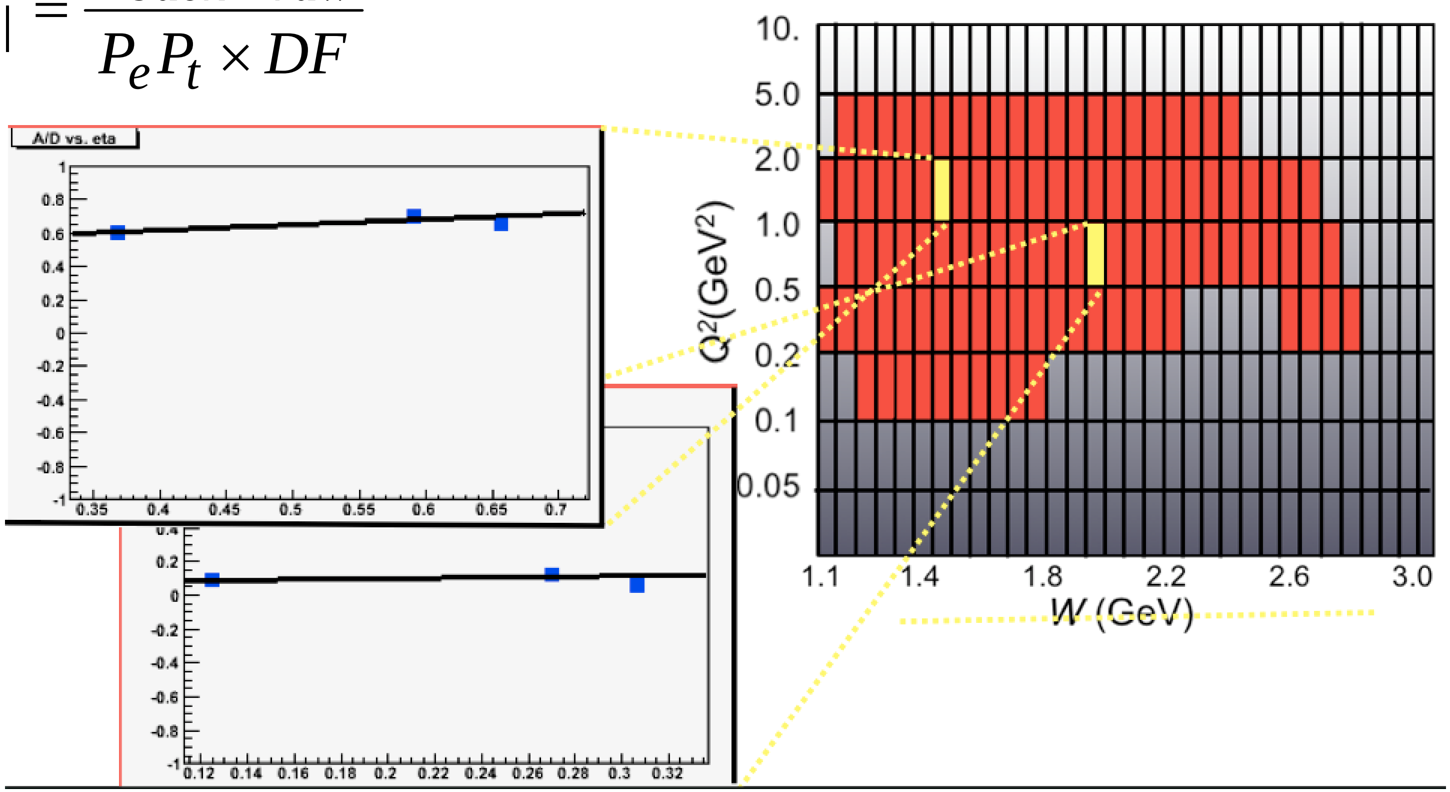
$$g_2(x,Q^2) = \frac{Q^2}{Q^2 + 4M^2x^2}\left(\frac{\sqrt{Q^2}}{2Mx}A_2 - A_1\right)F_1\left(x,Q^2\right)$$

Asymmetry Measurement

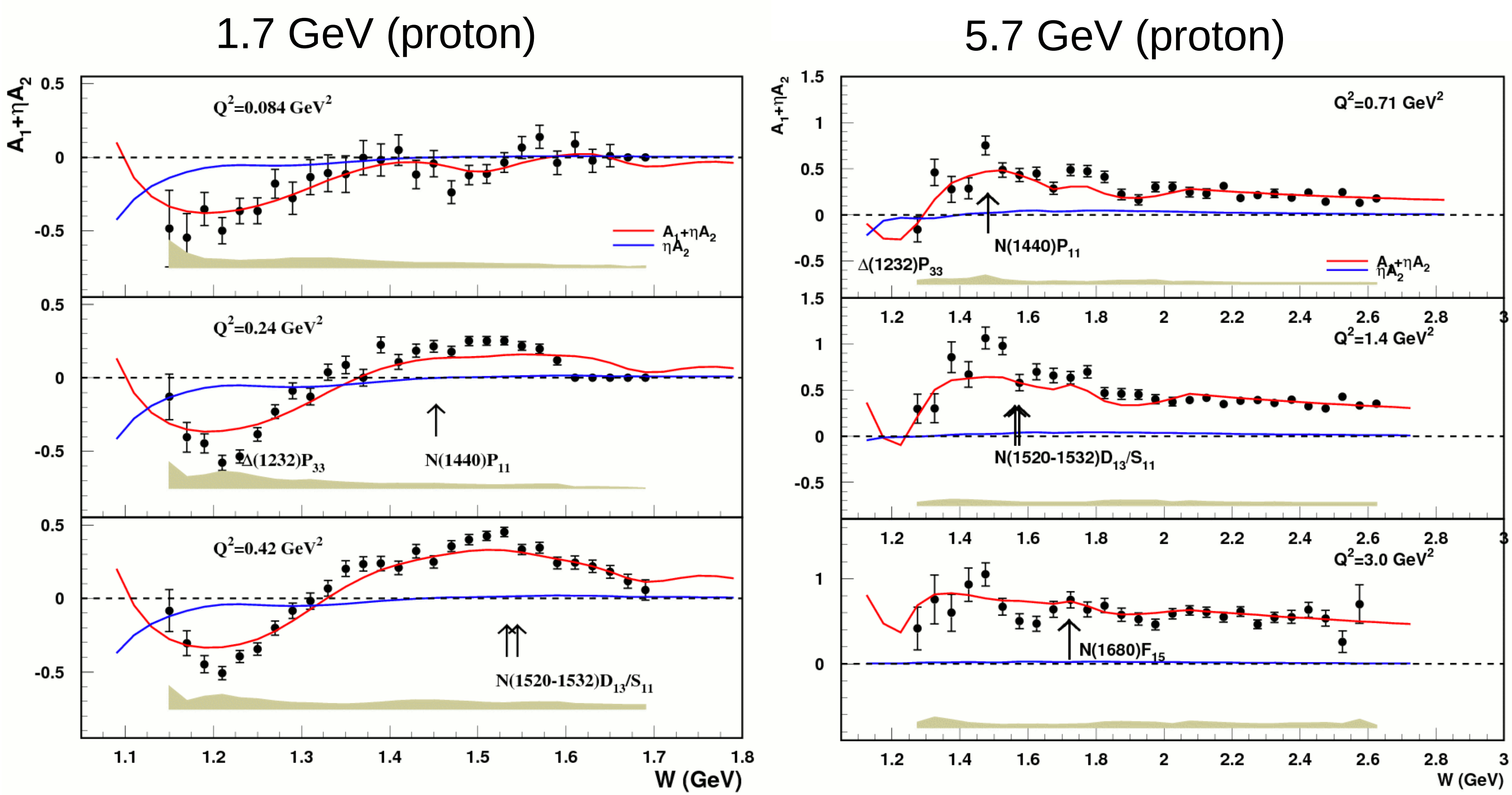
Simultaneous extraction of A_1 and A_2 from measured asymmetry

$$A_{\|} = D\,(A_1 + \eta A_2) \quad \text{with } \eta = \frac{\varepsilon\sqrt{Q^2}}{E - \varepsilon E'} \quad \text{and } D = \frac{1 - \varepsilon E'/E}{1 + \varepsilon R}$$

$$A_{\|} = \frac{C_{back} A_{raw}}{P_e P_t \times DF}$$



$A_1+\eta A_2$ for proton

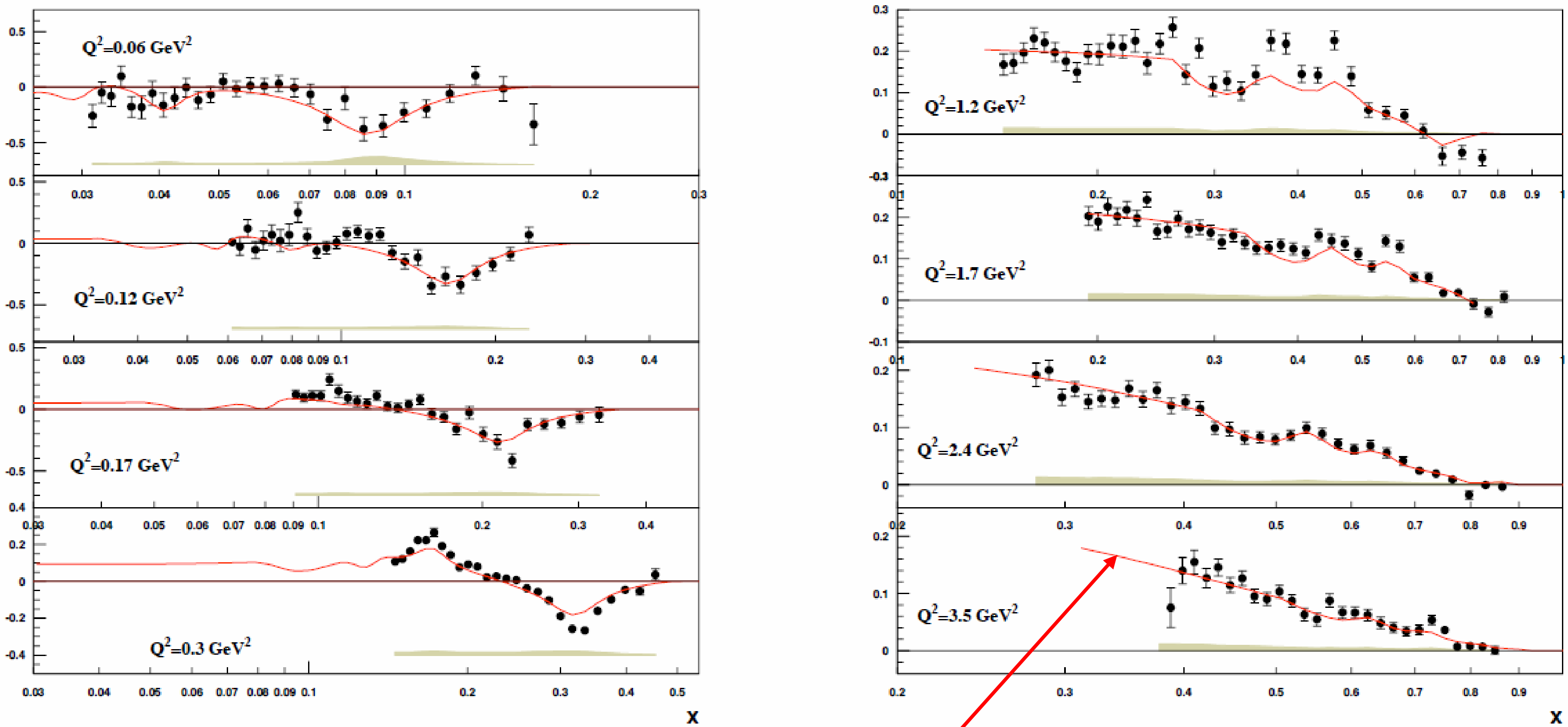


Parametrization of previous world data (including CLAS) by
S. Kuhn , L. Stuart, et al. including “AO” and “MAID2000” for resonance region
Blue solid line = Estimated contribution from A_2 to $A_1+\eta A_2$

$g_1(x,Q^2)$ for the proton

1.7 GeV (proton)

5.7 GeV (proton)



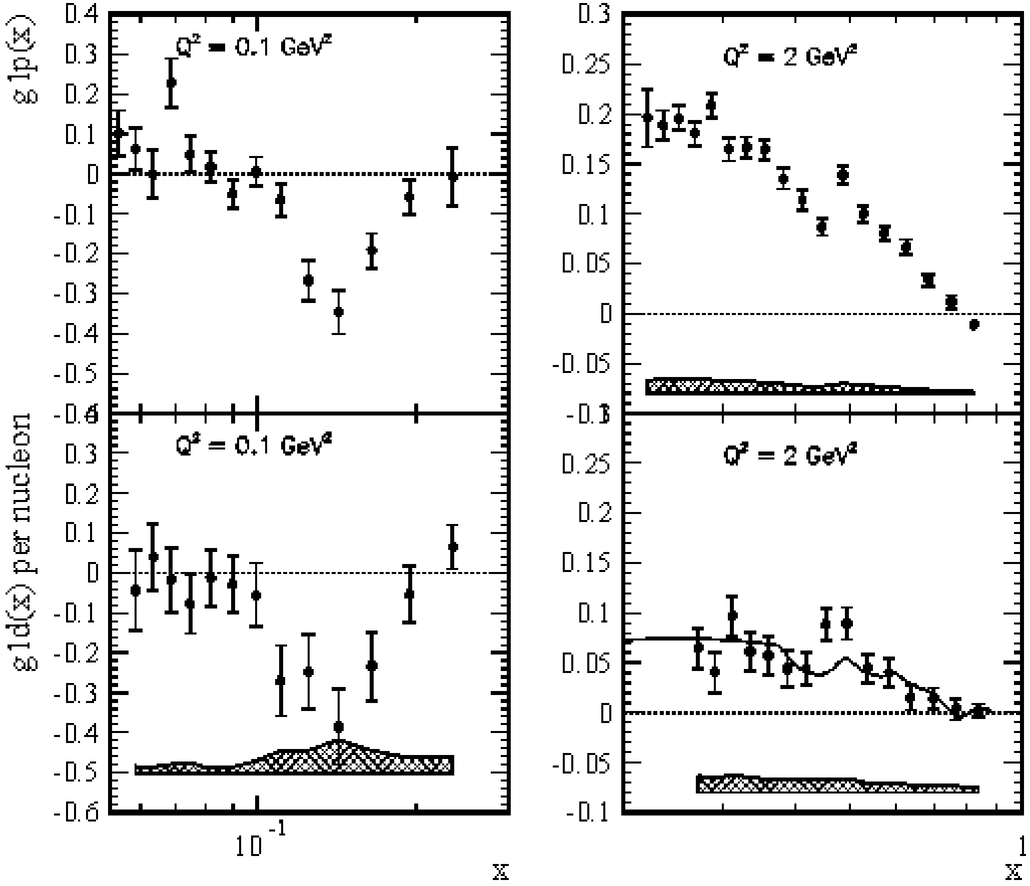
$$g_1(x,Q^2) = \frac{F_1}{1+°^2}\left[(A_1+´\, A_2)+(°-´)A_2\right]$$

Parameterization of previous world data (including CLAS)

Proton/Deuteron Comparison

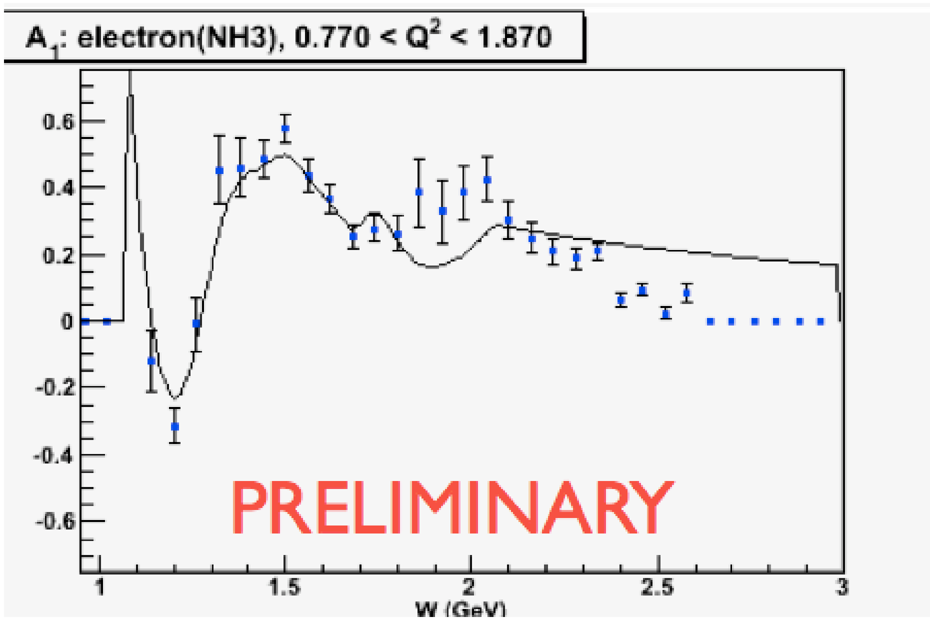
In the ¢(1232) region and at low Q^2, $g_1^d/2$ is consistent with g_1^p

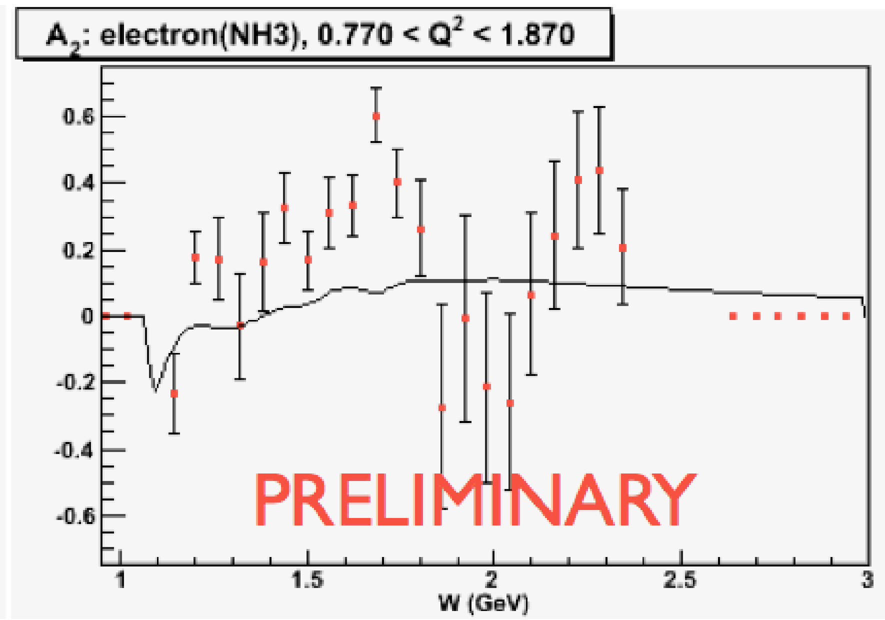
At high Q^2, g_1^p is significantly larger than $g_1^d/2$, indicating a negative contribution from the neutron



Asymmetry Measurement

- Very preliminary result
- A_2 is larger than previously used EG1 model, basing on MAID and AO
- Same result reported by RSS experiment from JLab Hall C (2007)

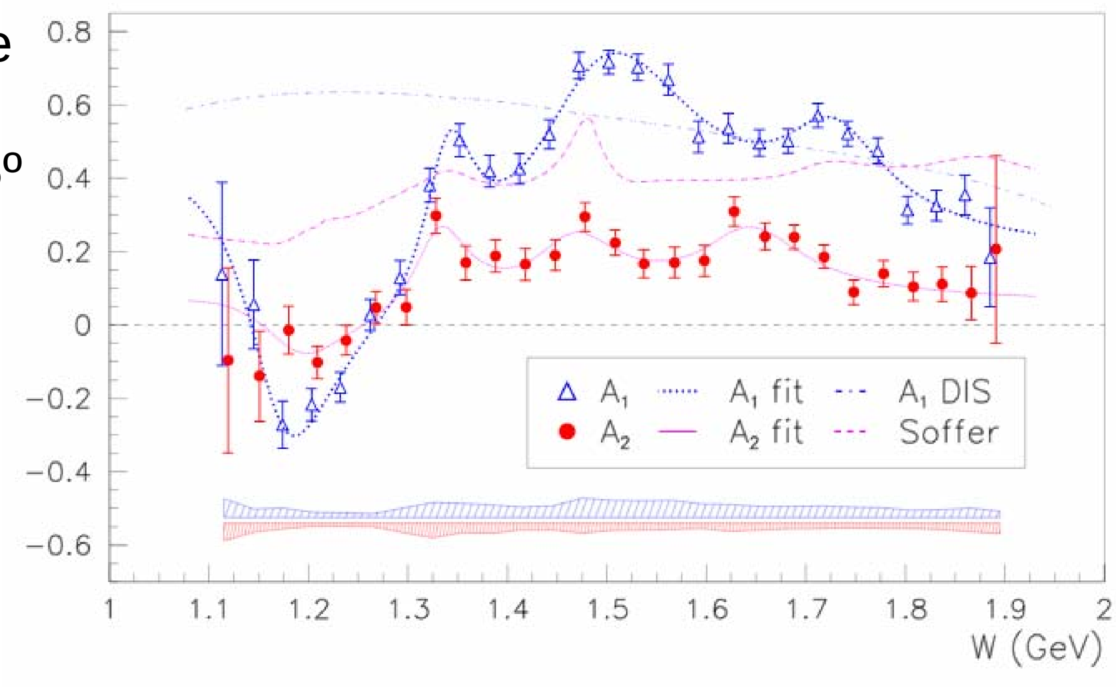




Asymmetry Measurement in Hall C (RSS)

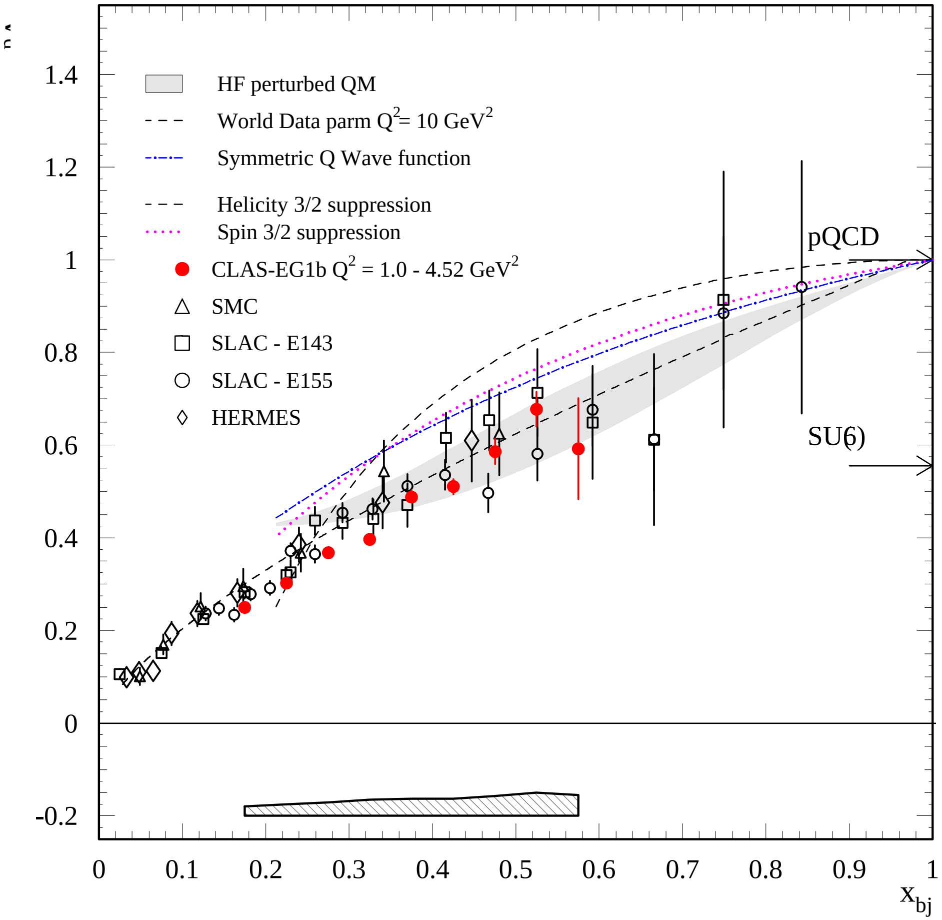
- Polarized longitudinal and transverse ammonia target
- 100 nA electron beam
- Both polarizations average between 0.6 and 0.7
- HMS spectrometer at 13.5º
- 160 million events

Q^2 range from 0.8 to 1.4 GeV^2/c^2

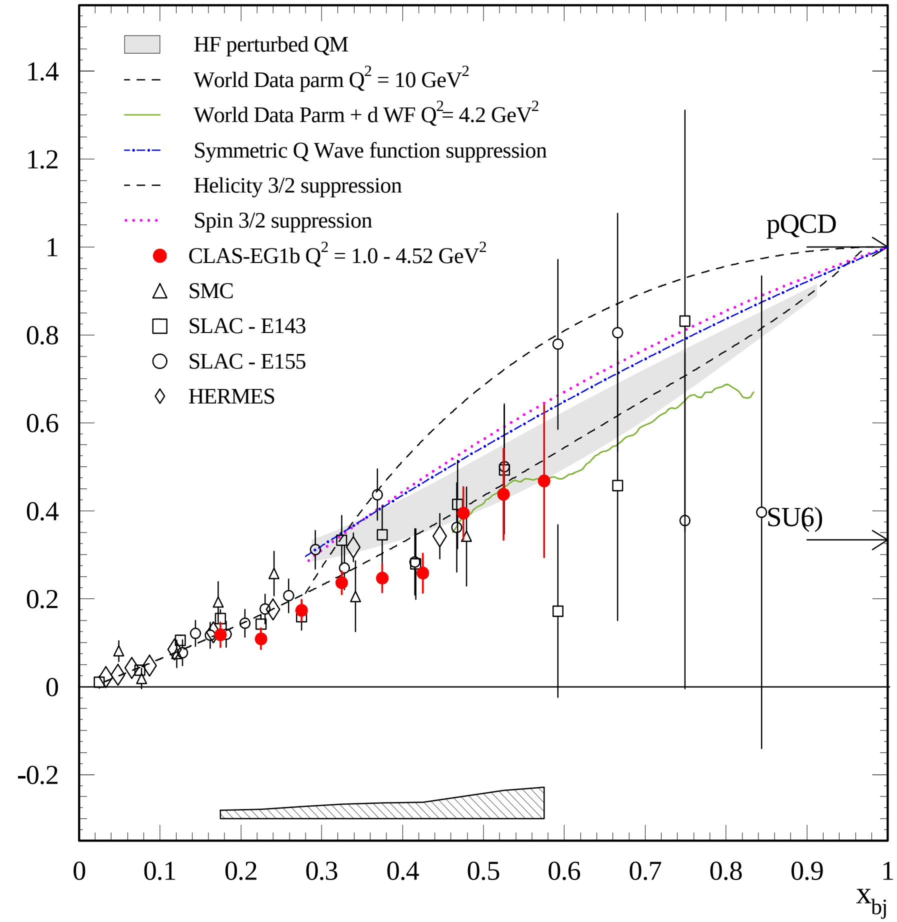


Asymmetry A_1

Proton



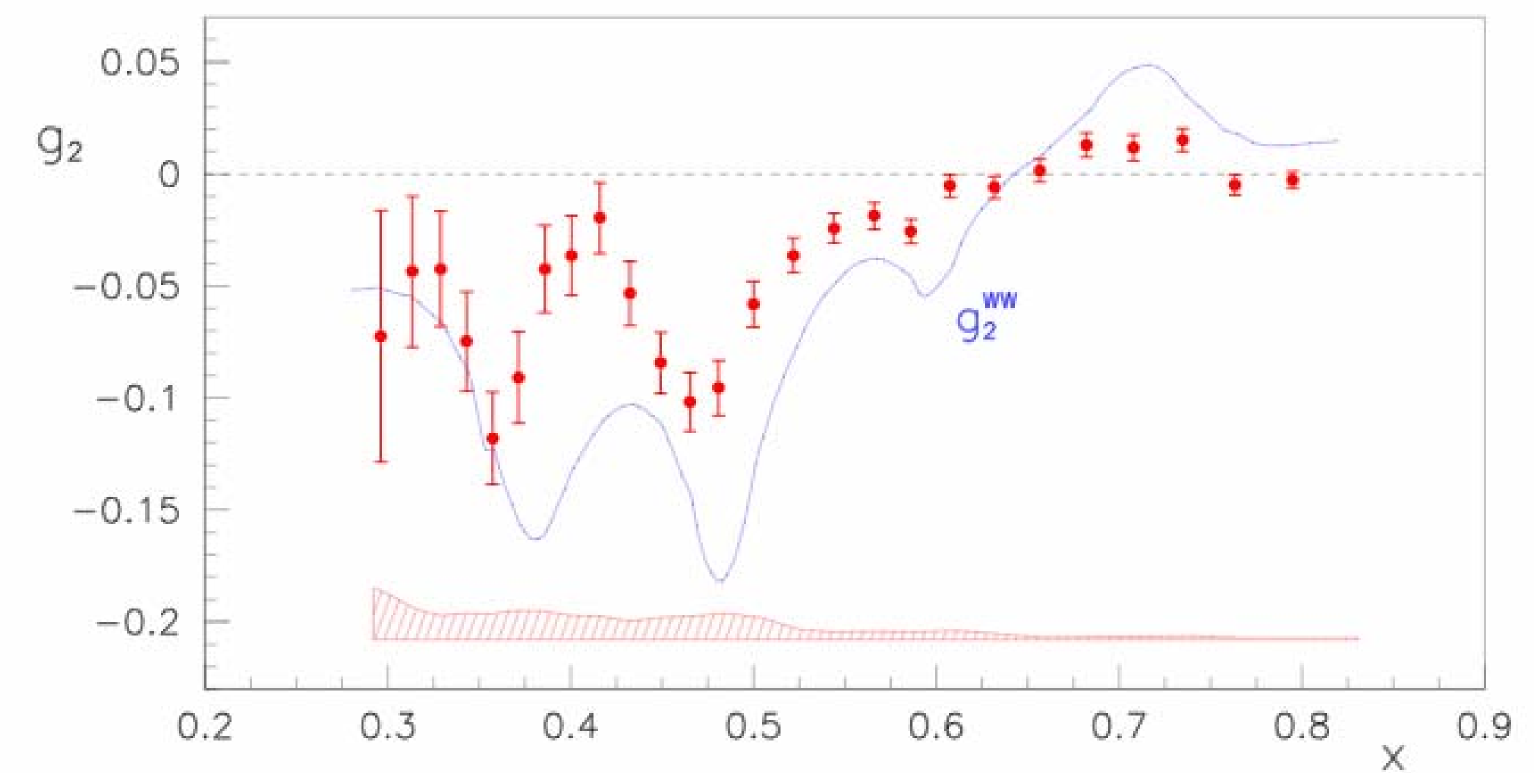
Deuteron



g_2 from Hall C (RSS)

Twist-2 Wandzura-Wilcek approximation

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



g_2 from Hall C (RSS)

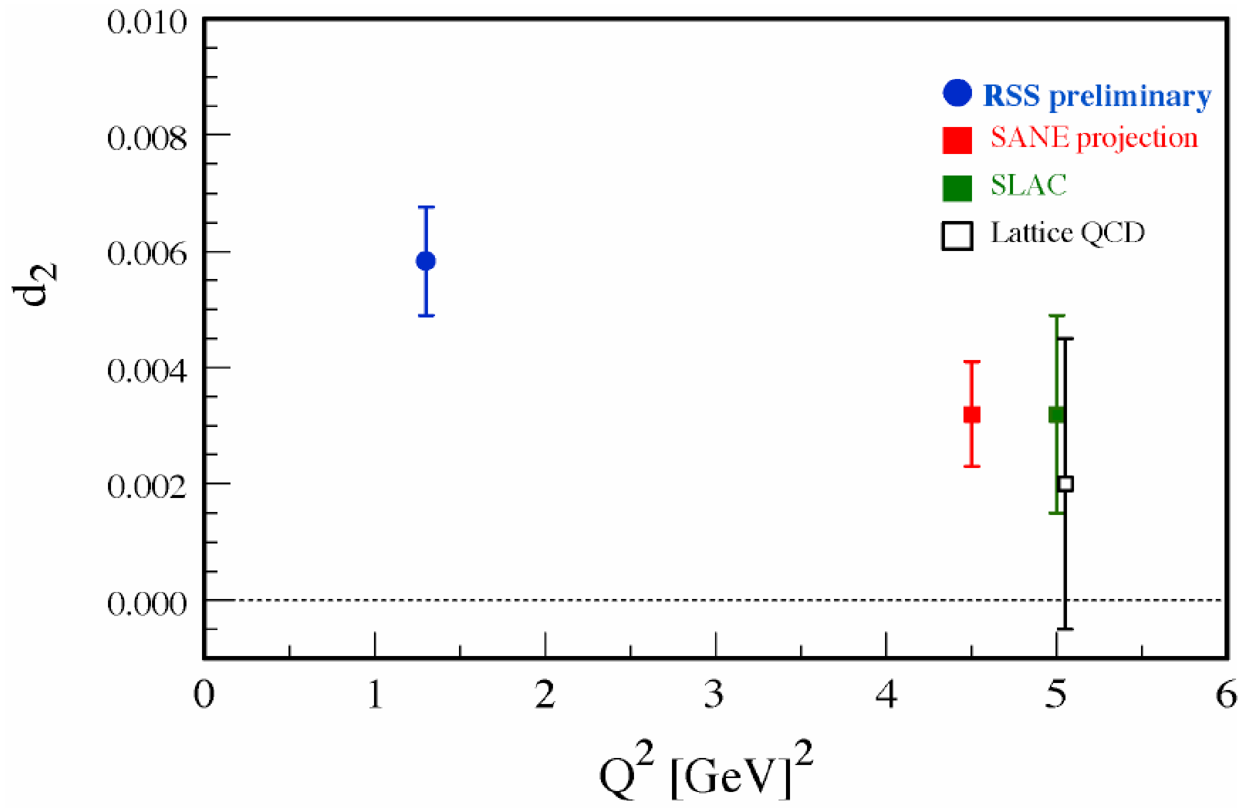
Twist-3 matrix element d_2 representing quark-gluon correlation

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

$d_2 = 0.0057 \pm 0.0009$ *stat.* ± 0.0007 *sys.* for $0.29 < x < 0.84$

$d_2 = 0.0029$
at $Q^2 = 5$ GeV$^2/c^2$

Compared to SLAC
$d_2 = 0.0032 \pm 0.0017$

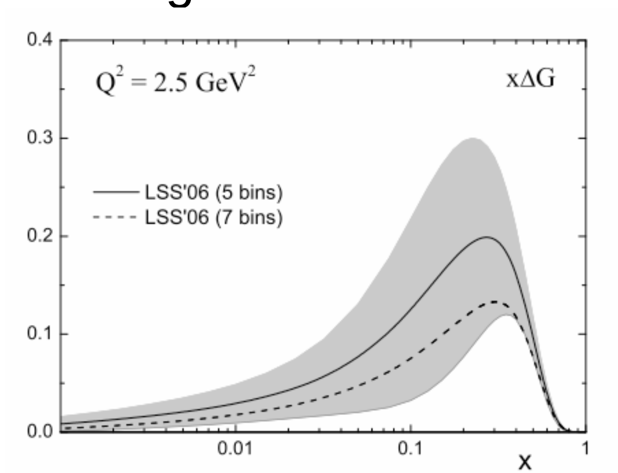


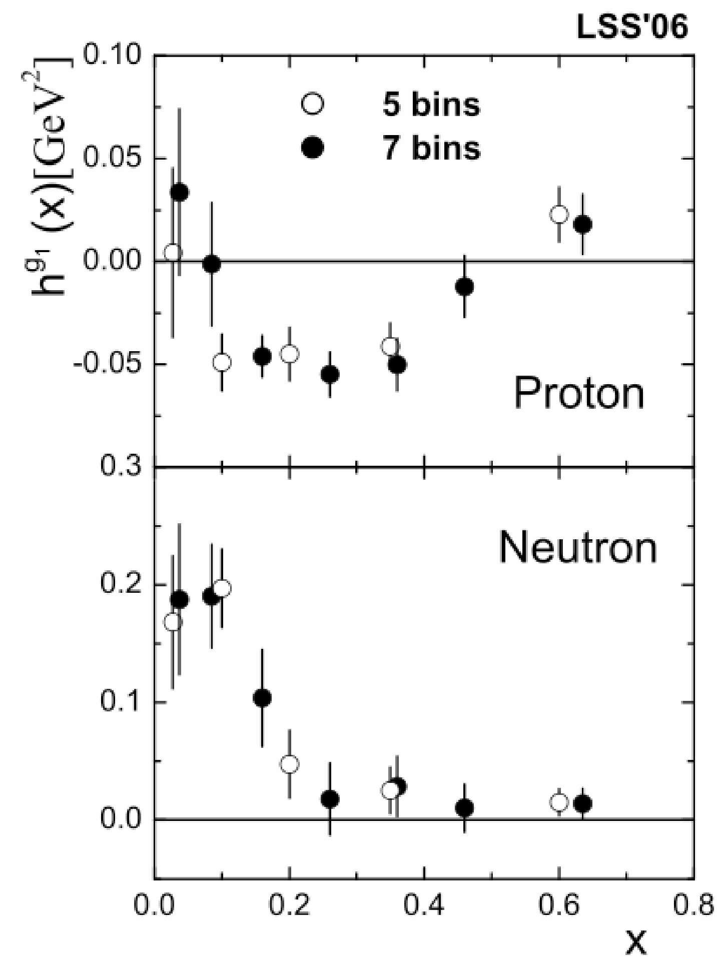
Polarized PDF's

$$g_1(x,Q^2)_{\rm LT} \;=\; g_1(x,Q^2)_{\rm pQCD} + h^{\rm TMC}(x,Q^2)/Q^2 + \mathcal{O}(M^4/Q^4)$$

$$g_1(x,Q^2)_{\rm HT} = h(x,Q^2)/Q^2 + \mathcal{O}(\Lambda^4/Q^4)$$

- Inclusion of large amount of low-Q^2 data from CLAS EG1 by Leader, Siderov, and Stamenov
- Simultaneous extraction of polarized parton densities and higher twist corrections



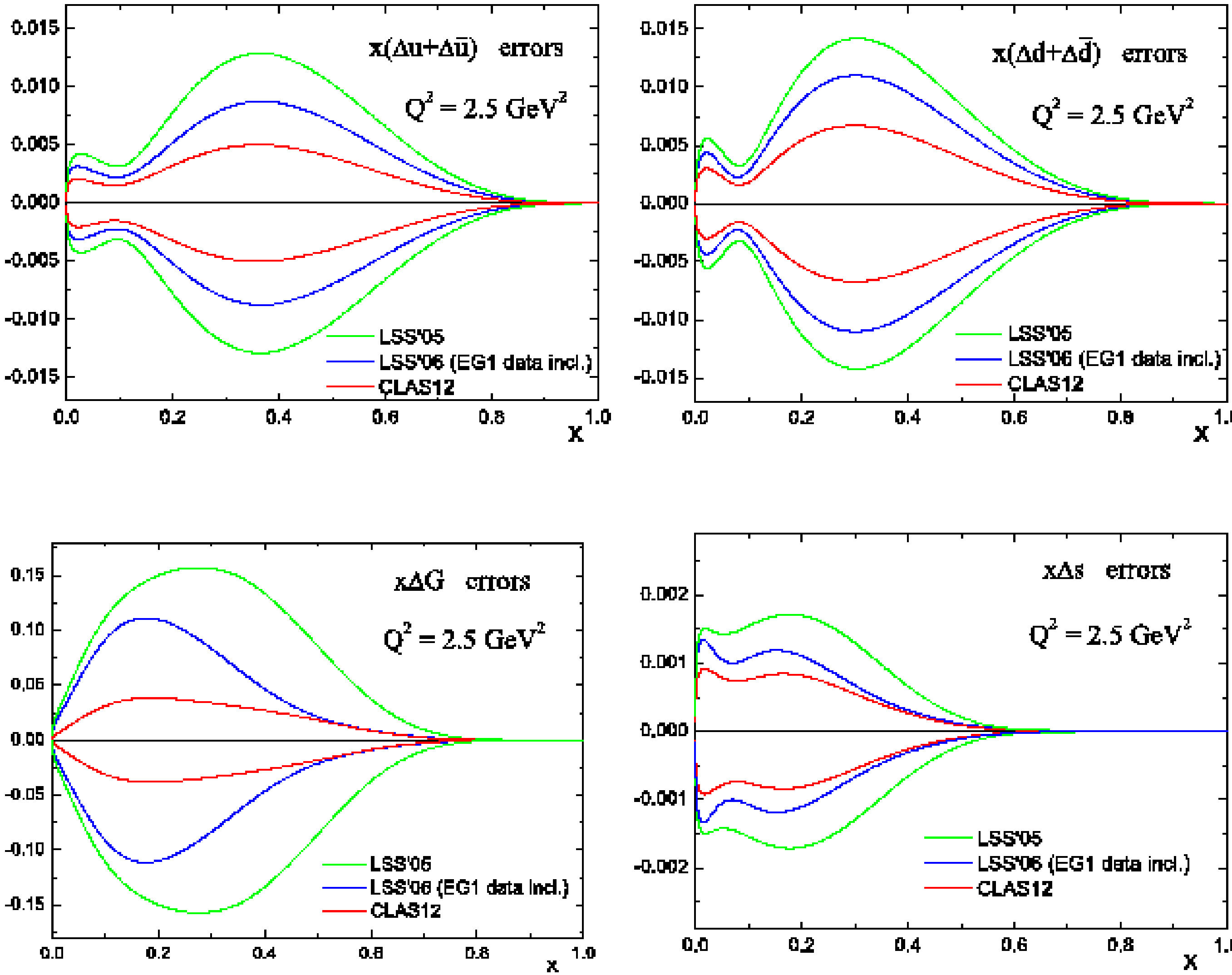


Polarized PDF's

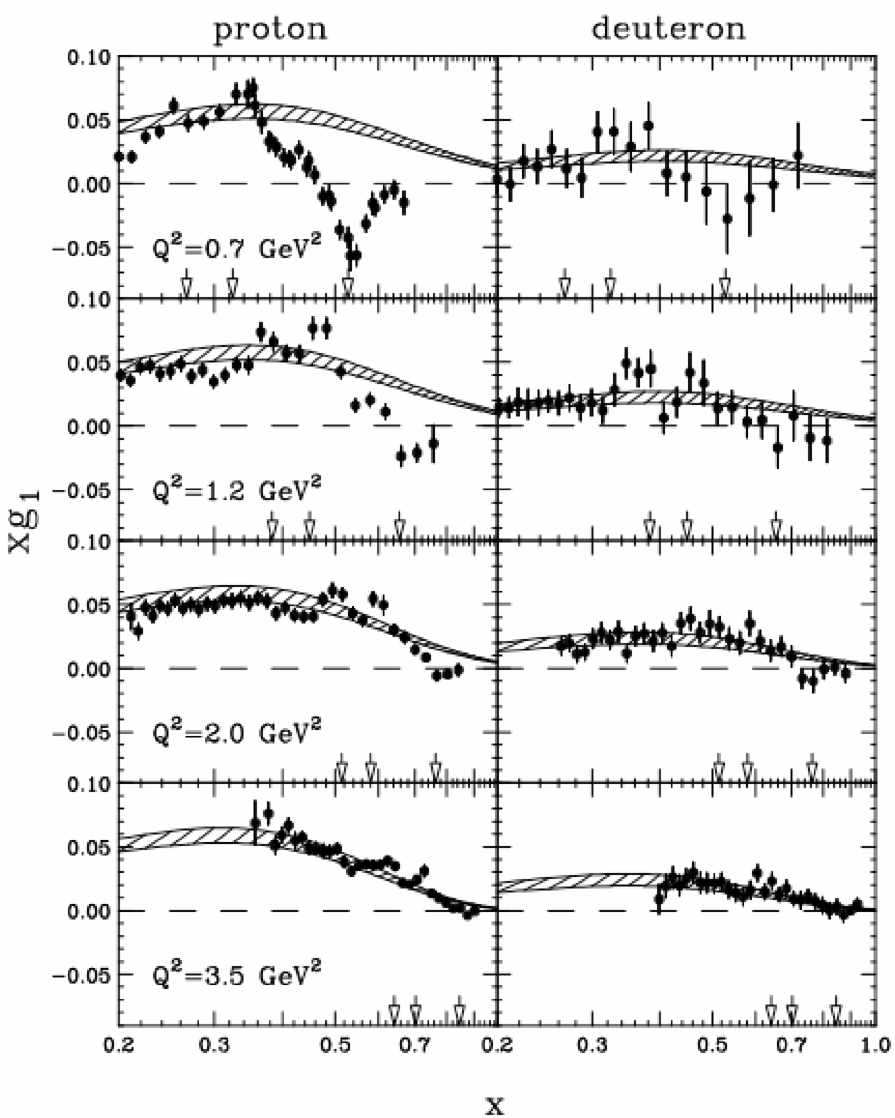
Error envelopes

- LSS05
- LSS06 (EG1)
- CLAS12

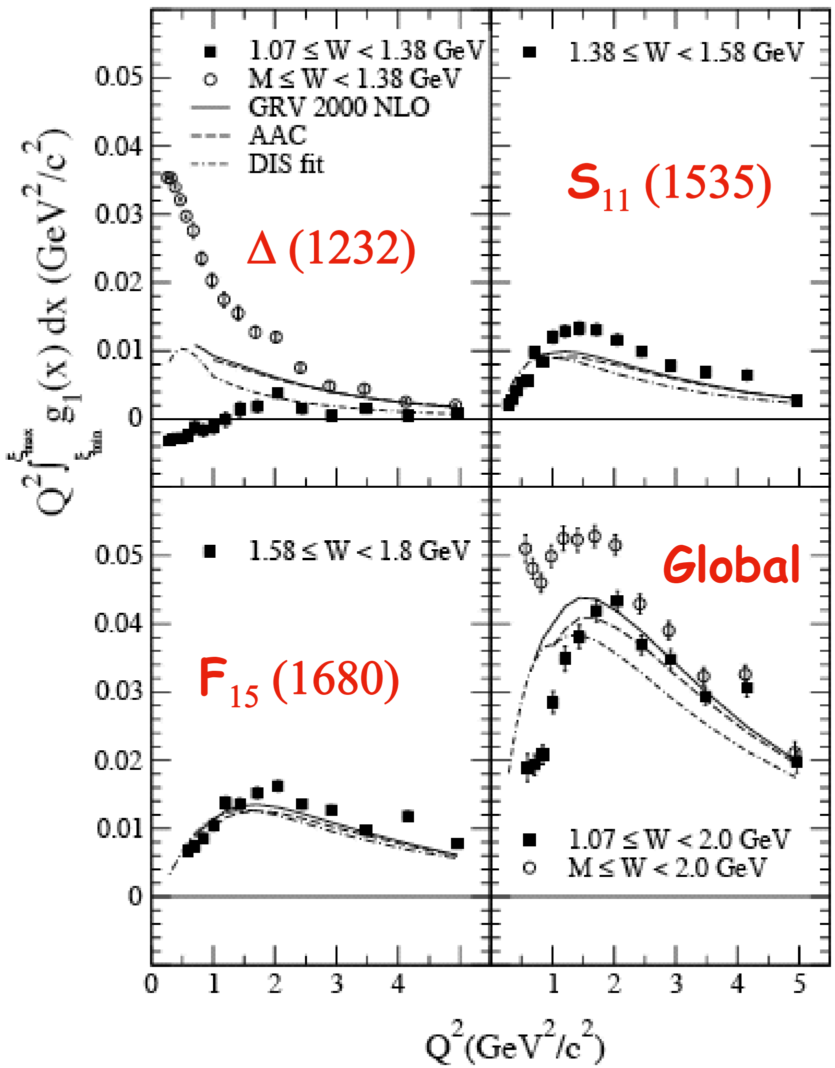
overall improved by EG1 data



Test of Quark-Hadron Duality



Proton

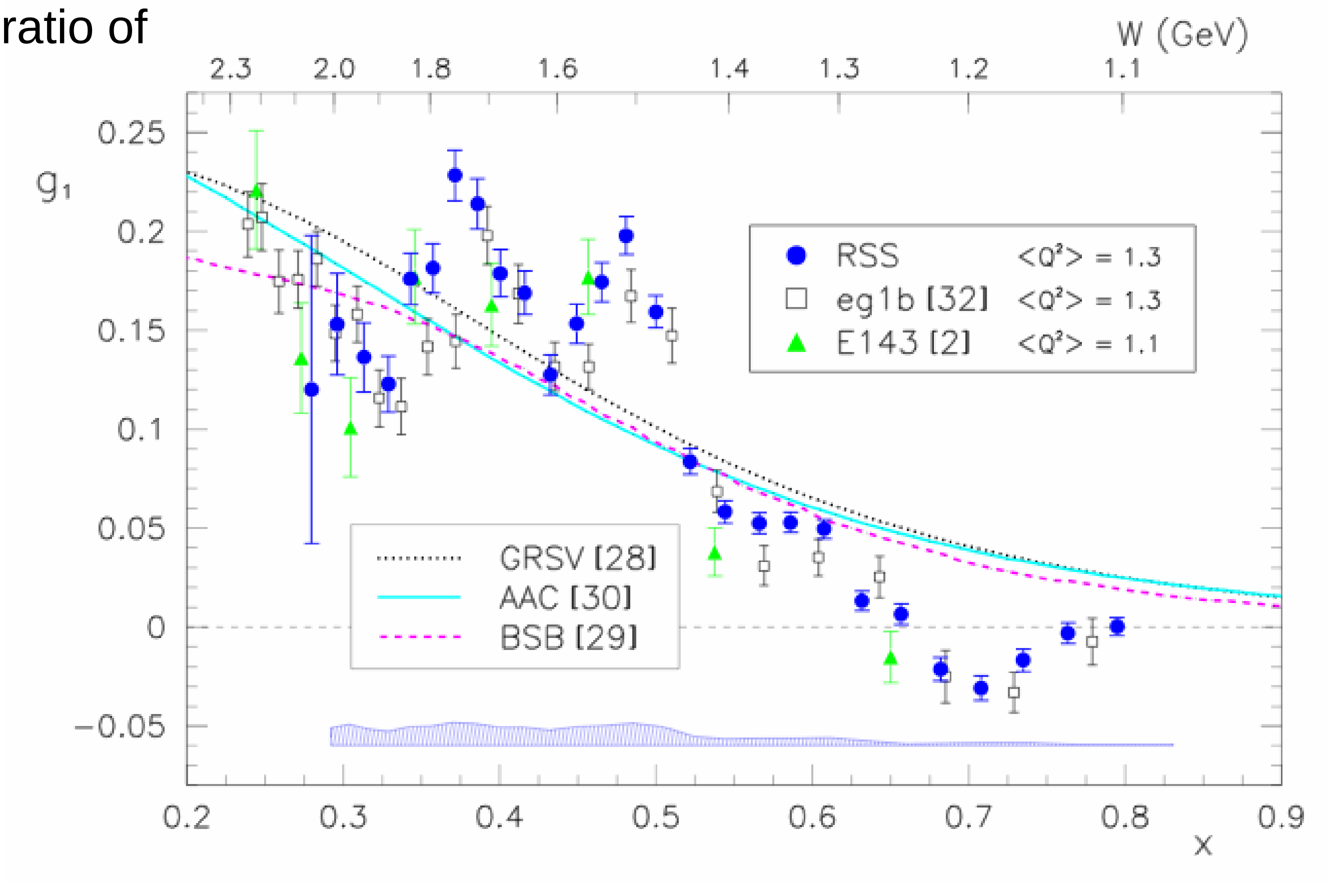


g_1 from Hall C (RSS)

Integration over resonance region
1.09 GeV < W < 1.91 GeV
of NLO PDFs and comparison with measurement gives a ratio of
1.17 ± 0.08

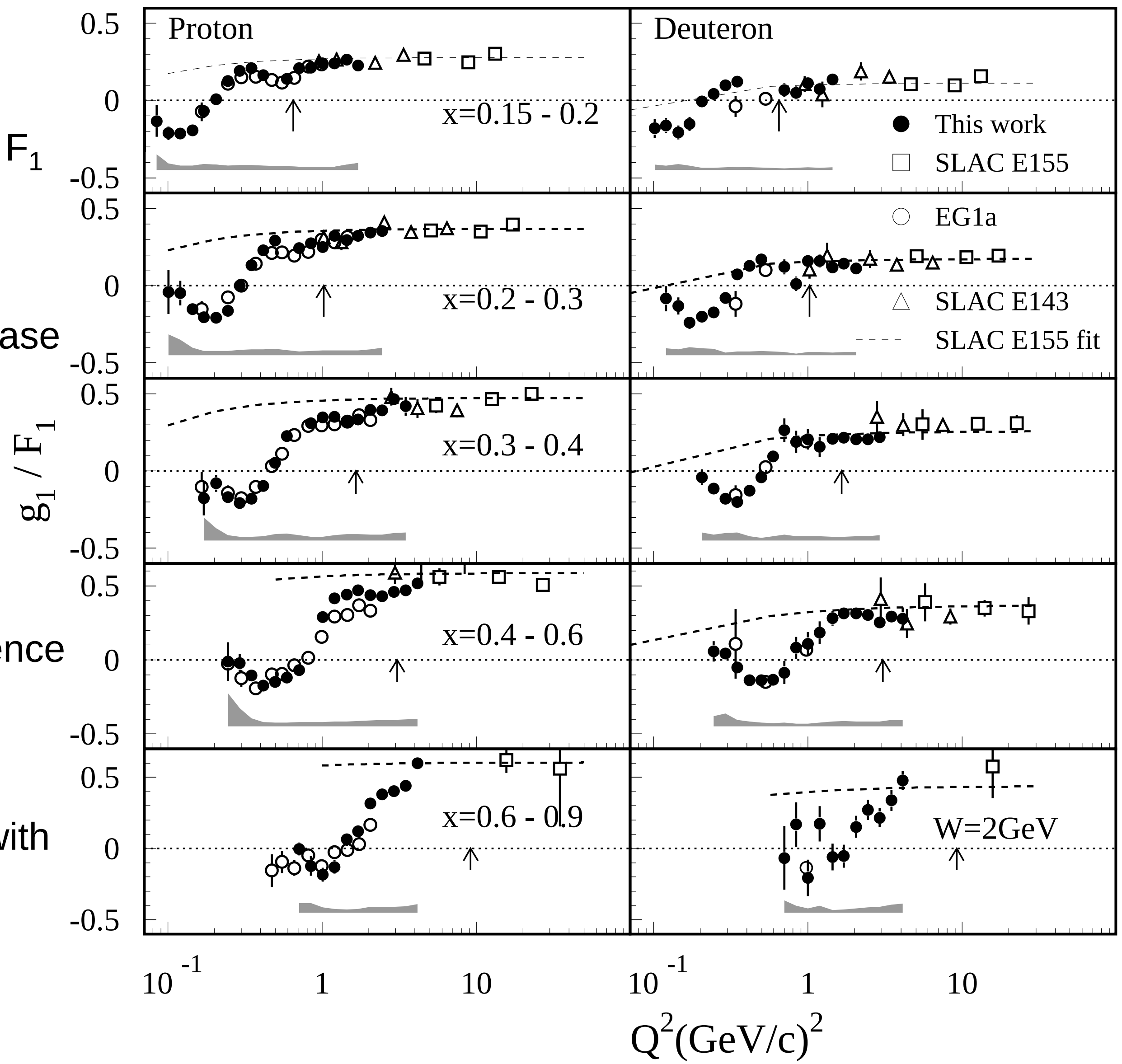
Global duality only at 2 sigma level
Local duality not observed

Q^2 range from 0.8 to 1.4 GeV$^2/c^2$



Q^2 dependence of g_1/F_1

- Q^2 dependence of g_1 at fixed x is very similar to F_1 in the DIS region
- EG1 data show a decrease in g_1/F_1 even in the DIS region
- Resonance region
  - ➔ different Q^2 dependence
  - ➔ goes negative at Δ
- High Q^2 results agree with SLAC data

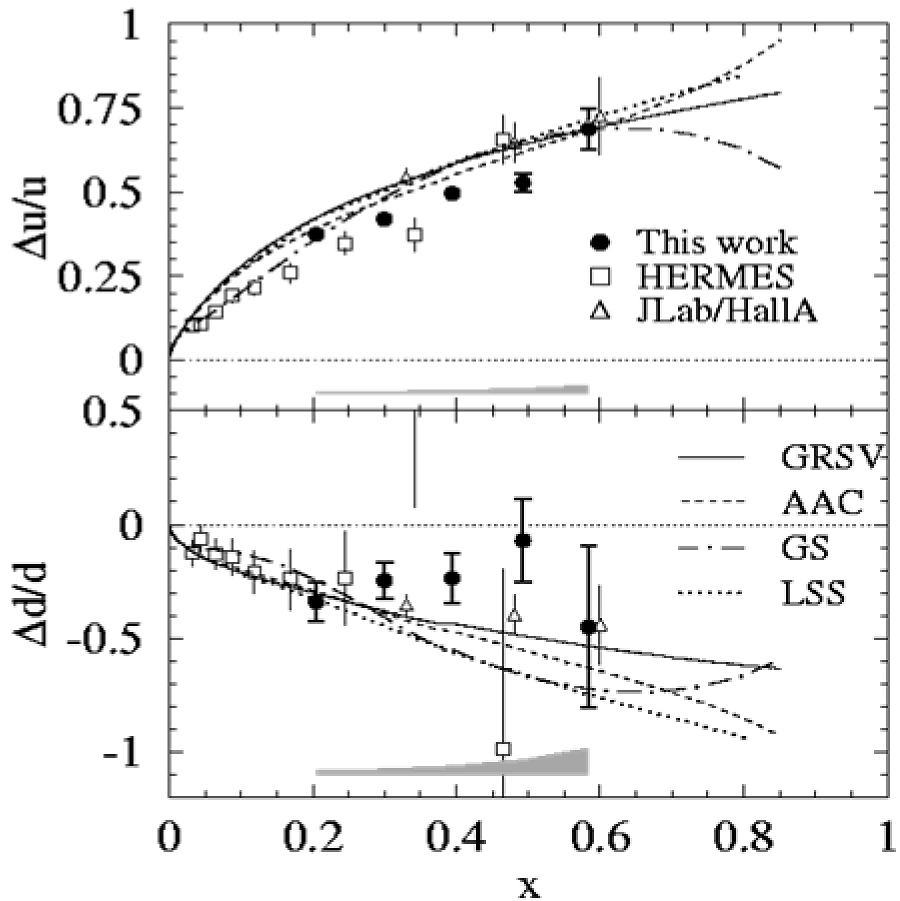


Quark polarization in the valence region

Assuming the naïve parton model with no sea contribution, quark polarizations in the valence region can be estimated directly from the data:

¢u/u = $[5g_1^p-2g_1^d/(1-1.5w_D)]/[5F_1^p-2F_1^d]$

¢d/d = $[8g_1^d/(1-1.5w_D)-5g_1^p]/[8F_1^d-5F_1^p]$



¢u /u ! 1 as x ! 1

Consistent with pQCD and QM

Disagrees with SU(6)

¢d /d < 0 up to the highest *x* ~0.6

Consistent with Hyperfine Perturbed QM

Disagrees with pQCD w/o orbital angular momentum

Moments and Sum Rules

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)\,dx$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

QPM →

$$\Gamma_1^p = \frac{1}{2}\left(\frac{4}{9}\Delta U + \frac{1}{9}\Delta D + \frac{1}{9}\Delta S\right) =$$

$$\Gamma_1^n = \frac{1}{2}\left(\frac{1}{9}\Delta U + \frac{4}{9}\Delta D + \frac{1}{9}\Delta S\right) =$$

Ellis-Jaffe Sum Rule

$$\Gamma_1^p = \frac{3}{36} a_3 + \frac{1}{36} a_8 + \frac{4}{36} a_0 = 0.186 + \text{QCD corr}$$

$$\Gamma_1^n = -\frac{3}{36} a_3 + \frac{1}{36} a_8 + \frac{4}{36} a_0 = -0.025 + \text{QCD corr}$$

Bjorken Sum Rule (pre QCD) $\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + Q^2$ evolution

GDH Sum Rule

$$I_{GDH} = \frac{M^2}{8\alpha\pi^2} \int_{thr}^{\infty} \left(\sigma_{1/2} - \sigma_{3/2}\right) \frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

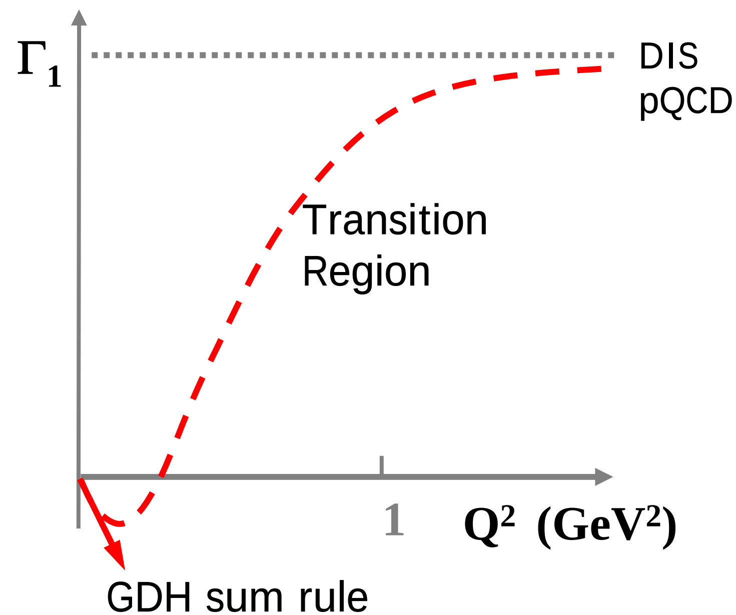
- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties. Recent measurements at Bonn and Mainz, ongoing efforts at other labs

- based on very general principles, as gauge invariance, dispersion relation, low energy theorem

- at finite Q^2 can be related to the integral of the spin structure function g_1

$$\Gamma_1 = \int g_1\left(x, Q^2\right) dx \xrightarrow[Q^2 \to 0]{} \frac{Q^2}{2M^2} I_{GDH}$$

- strong variation of nucleon spin properties as a function of Q^2



Generalized GDH Integral

A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude S_1 to the nucleon structure function G_1

X.Ji et al., Phys.Lett.B472 (2000) 1

$S_1(0,Q^2)$

$$I_{GDH}(Q^2) = \frac{16\pi\alpha}{Q^2}\int_{x_0}^{\infty} dx\, g_1(x,Q^2)$$

Calculable (for $I_{GDH}(Q^2)$) — Measurable (for the integral)

$Q^2 < 0.1$ GeV^2 → **GDH sum rule and Chiral Perturbation Theory**

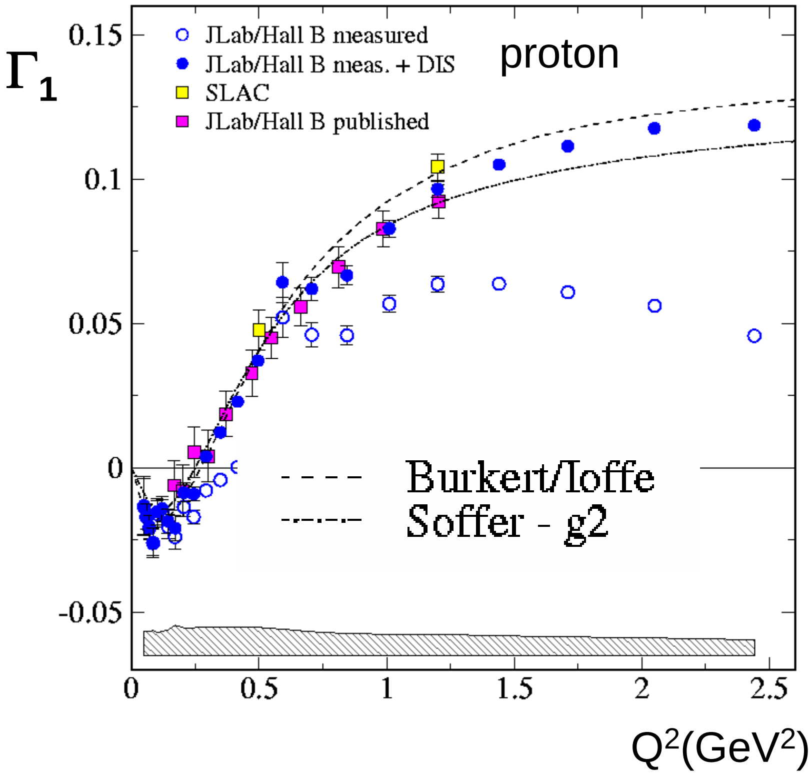
$$-\frac{\kappa^2}{M^2} + cQ^2 + O(Q^4)$$

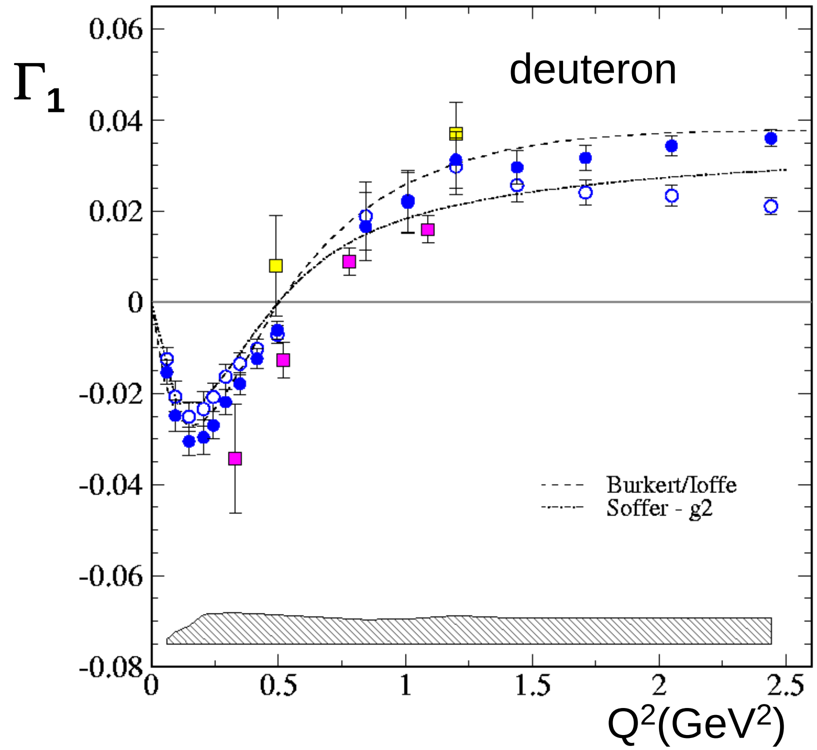
$0.1 < Q^2 < 0.5$ GeV^2 → **Lattice?**

$Q^2 > 0.5$ GeV^2 → **Ellis-Jaffe Sum rule and Operator Product Expansion**

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

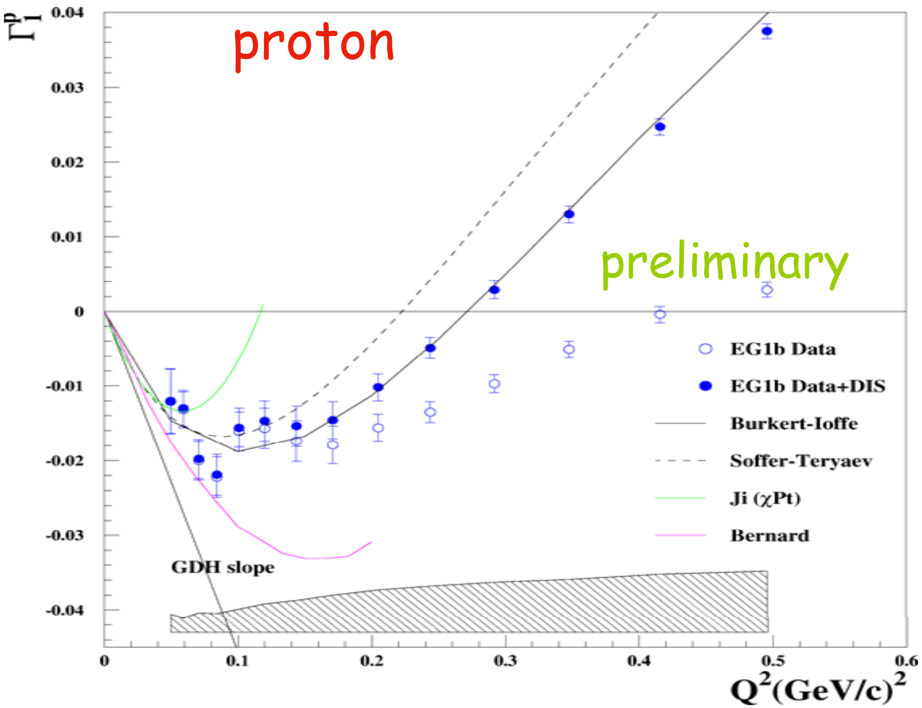
Γ_1 for the proton and deuteron

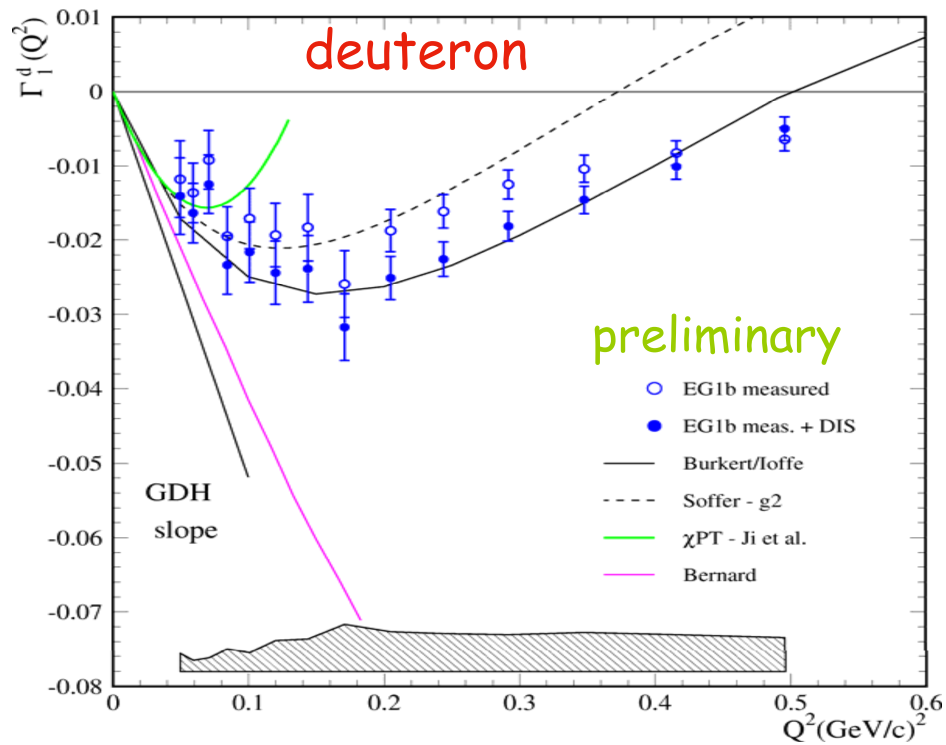




- X_{min}=0.001, x$_{max}$= pion production threshold
- shows strong Q^2 dependence varying from negative to positive values as Q^2 increases

Low Q^2 behavior of Γ_1 - χPT

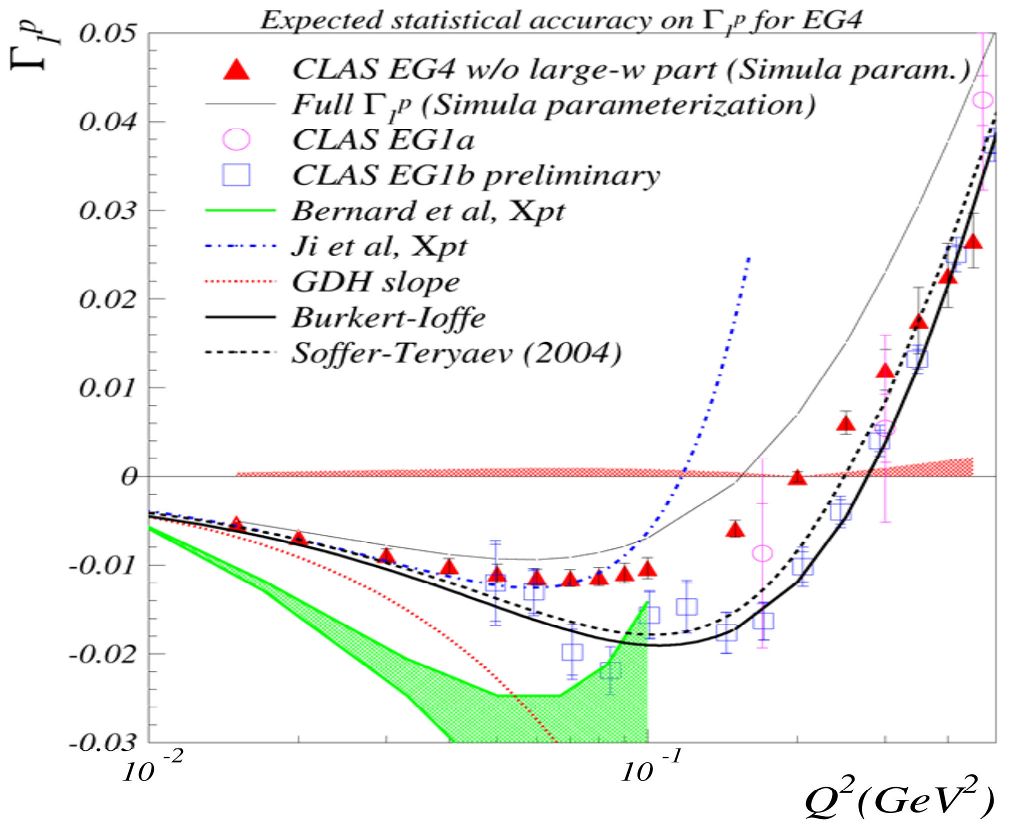




$$\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2}Q^2 + 3.89Q^4 + \ldots$$

$$\Gamma_1^n(Q^2) = -\frac{\kappa_n^2}{8M^2}Q^2 + 3.15Q^4 + \ldots.$$

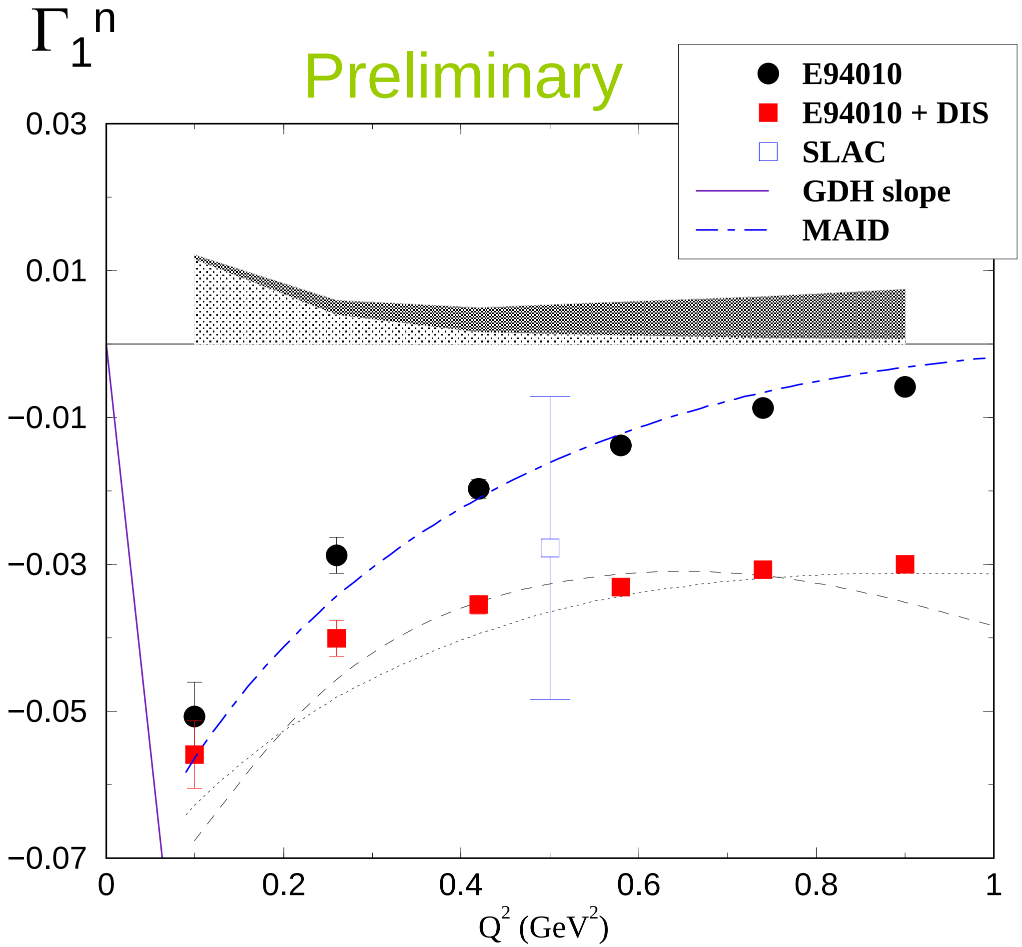
EG4 projection



- Extends to very low Q^2 of 0.015 GeV^2 both proton and deuteron
- Data taken earlier this year

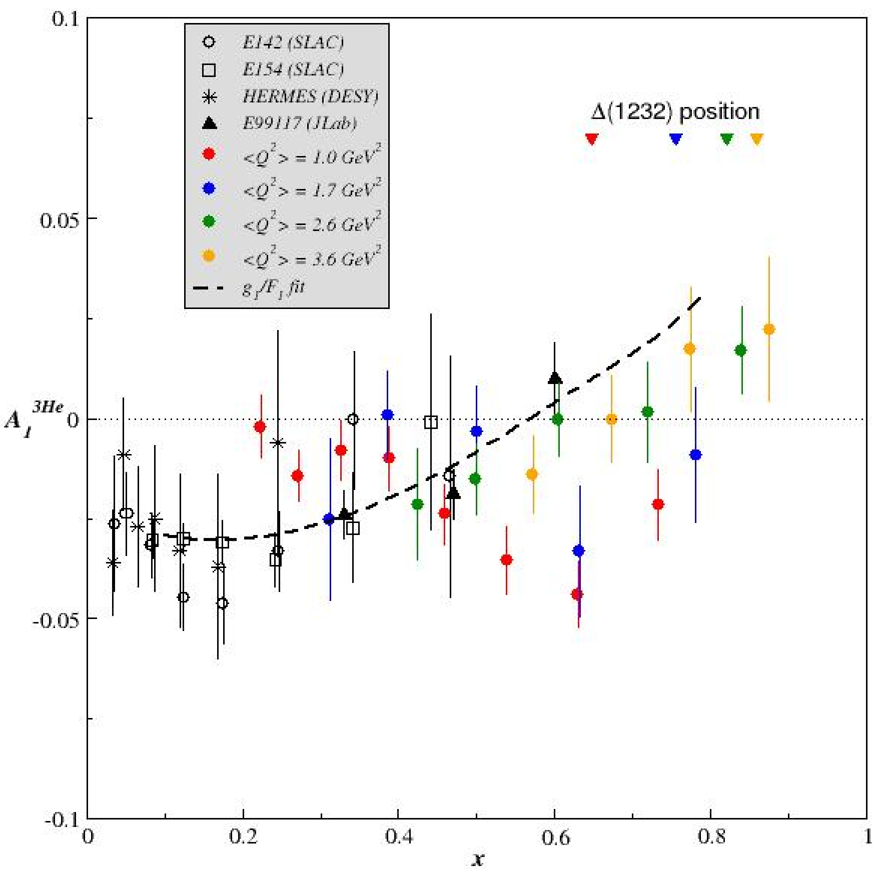
Hall A Measurement on ^{3}He

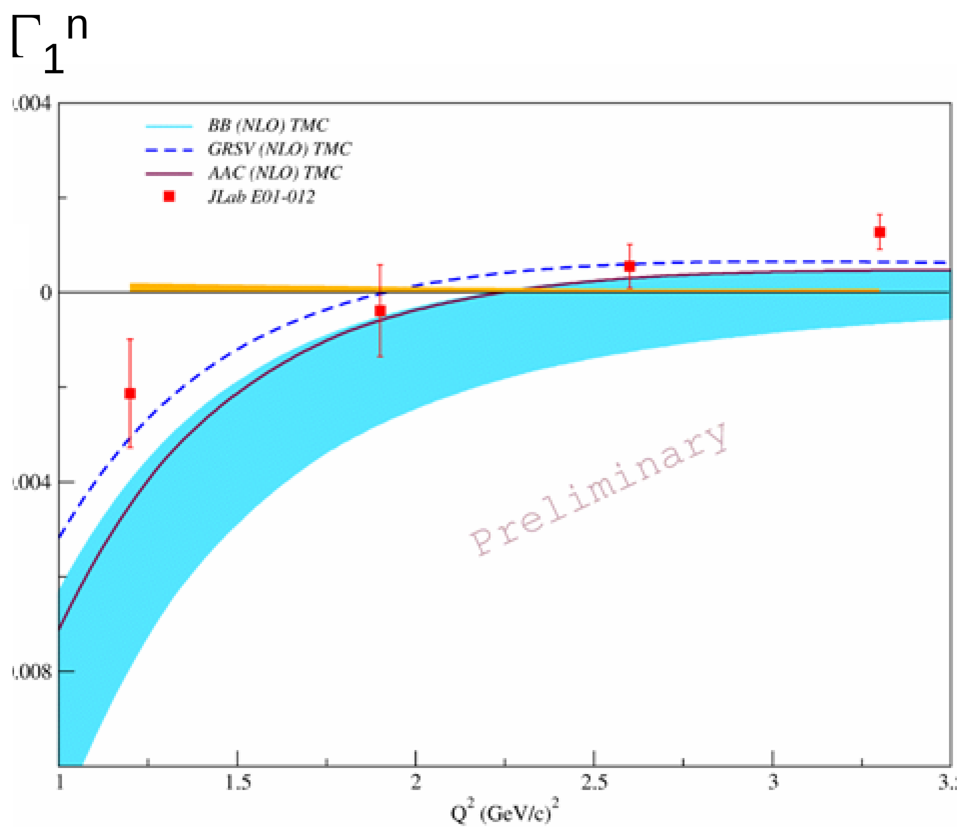
E94-110
Q^2 range 0.1 - 1 GeV^2



Hall A Measurement on ^{3}He E01-012

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

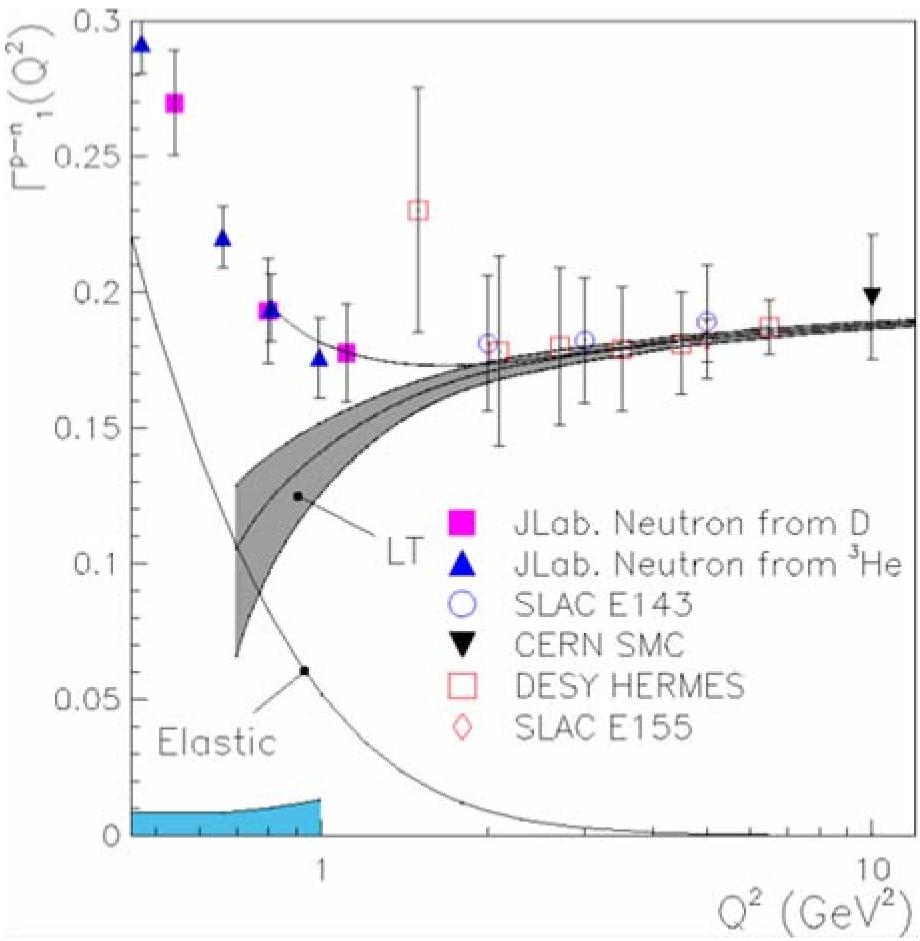




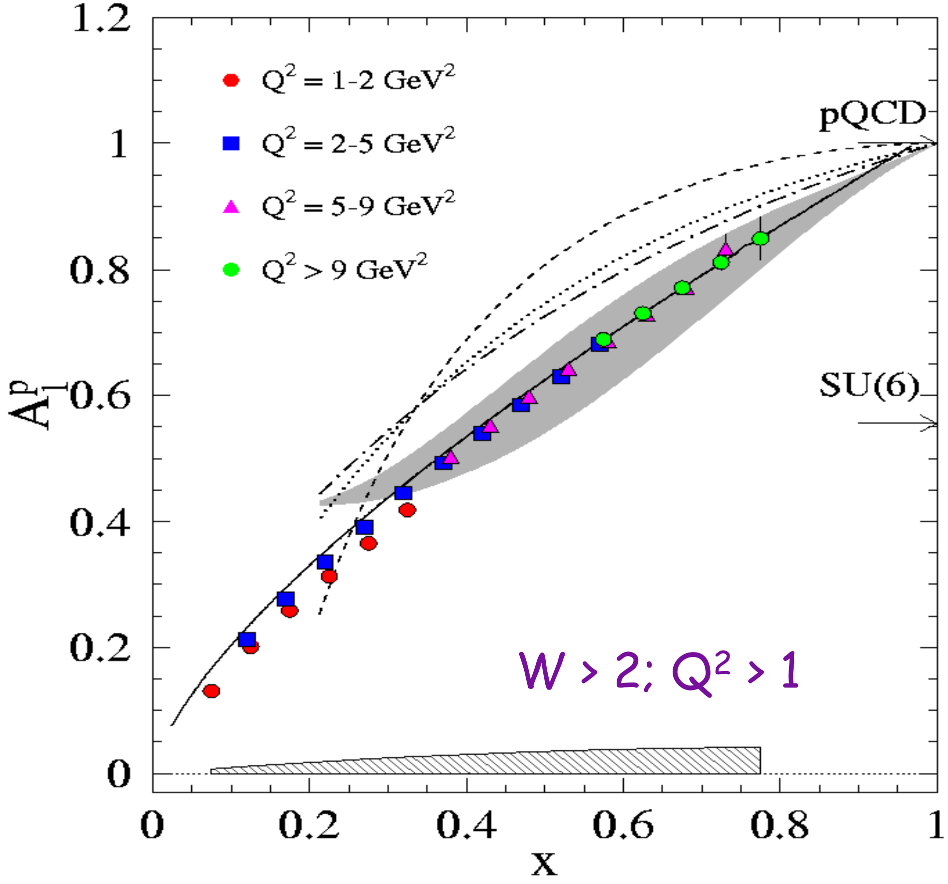
Bjorken Sum Q^2 Evolution

Combined data from EG1a and Hall A E94-010

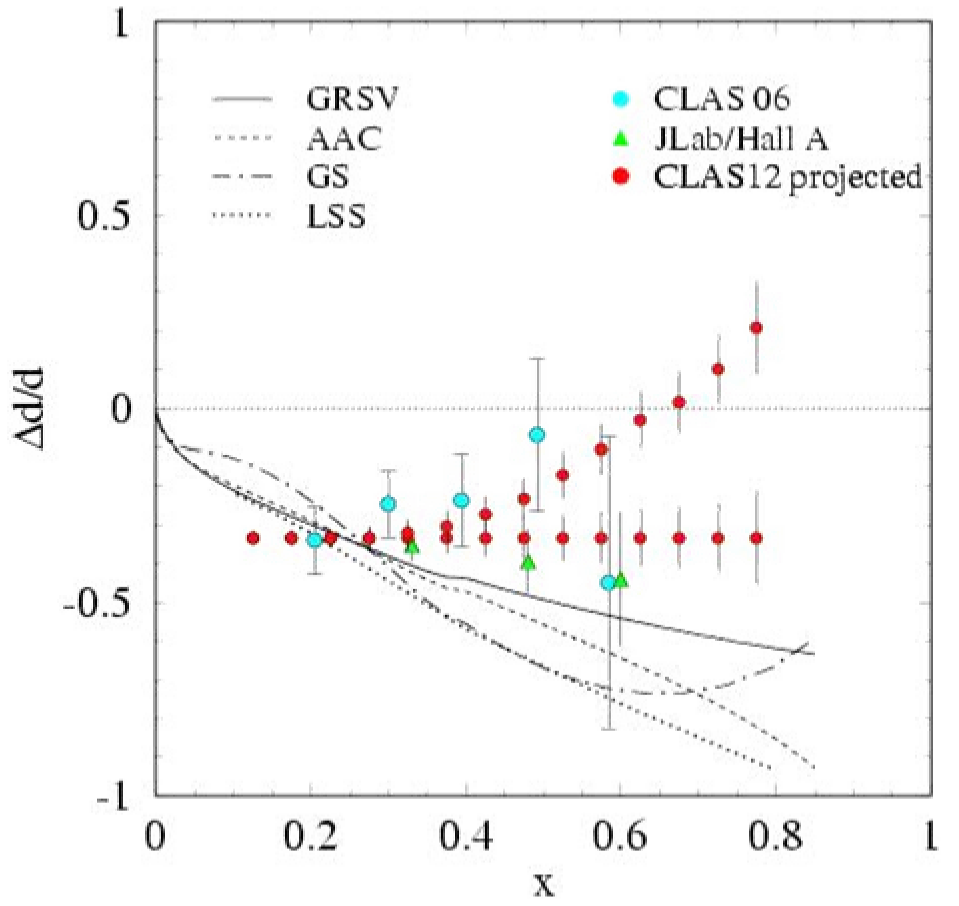
A. Deur, et al., PRL 93, 212001 (2004)



JLab Upgrade: EG12 projections



Allows access to higher x values



Summary

- **A wealth of new data on the nucleon spin structure in the non-perturbative regime has been produced at Jefferson Lab as part of a broad spin physics program, still in progress**
- **These measurements provide new information for understanding the transition between hadronic and partonic degrees of freedom by investigating spin structure functions, related sum rules and moments, asymmetries, …**
- **A new measurement to cover the very low momentum transfer region and provide a bridge to the GDH sum rule at the photon point has just been completed recently**
- **12 GeV program at Jlab will offer the opportunity to extend these measurements into new kinematic regions**