Nucleon Spin Structure from Confinement to Asymptotic Freedom

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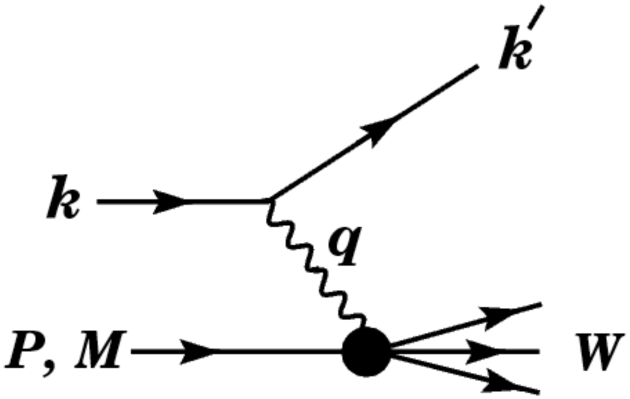
INTRODUCTION

The nucleon structure functions F_1, F_2, g_1 and g_2 depend on two Lorentz invariants. Although well-defined over all kinematics, their interpretation varies with momentum-transfer scale. They have been actively measured over several decades at a number of labs around the world.

Inelastic Scattering



Lorentz invariants:

$\nu = p \cdot q/M = (E - E')_{\rm lab}$

$Q^2 = -q \cdot q = (4EE' \sin^2 \frac{\theta}{2})_{\rm lab}$

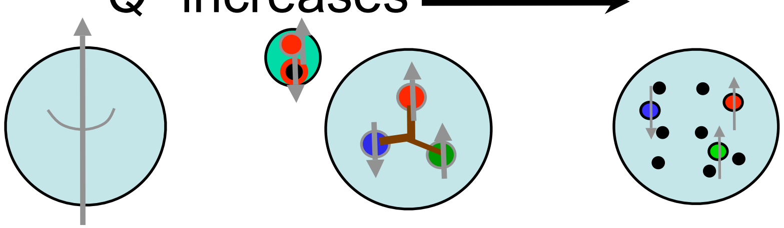
$x = -q \cdot q/2p \cdot q = (Q^2/2M\nu)_{\rm lab}$

$y = p \cdot q/p \cdot k = (\nu/E)_{\rm lab}$

$W^2 = (p+q)^2 = (M^2 + 2M\nu - Q^2)_{\rm lab}$

$s = (k+p)^2 = (2EM + M^2)_{\rm lab}$

Q^2 increases →



Unpolarized Cross Section:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\frac{y}{2}F_1 + \frac{\xi}{2xy}F_2\right]$$

Polarized Cross Section:

$$\frac{d^2\Delta\sigma}{dx dQ^2} = \frac{8\pi\alpha^2 y}{Q^4}[\cos\alpha\{(\xi + \frac{y}{2})g_1 - \frac{\gamma y}{2}g_2\} - \sin\alpha\cos\phi\{\frac{y}{2}g_1 + g_2\}]$$

α = polar angle of target spin wrt the beam axis

ϕ = azimuthal spin angle wrt the scattering plane

$\alpha = 0°$ (longitudinal); $\alpha = 90°, \phi = 0°$ (transverse).

$\gamma^2 = 4M^2x^2/Q^2 = Q^2/\nu^2$

$\xi = 1 - y - \gamma y^2/4$

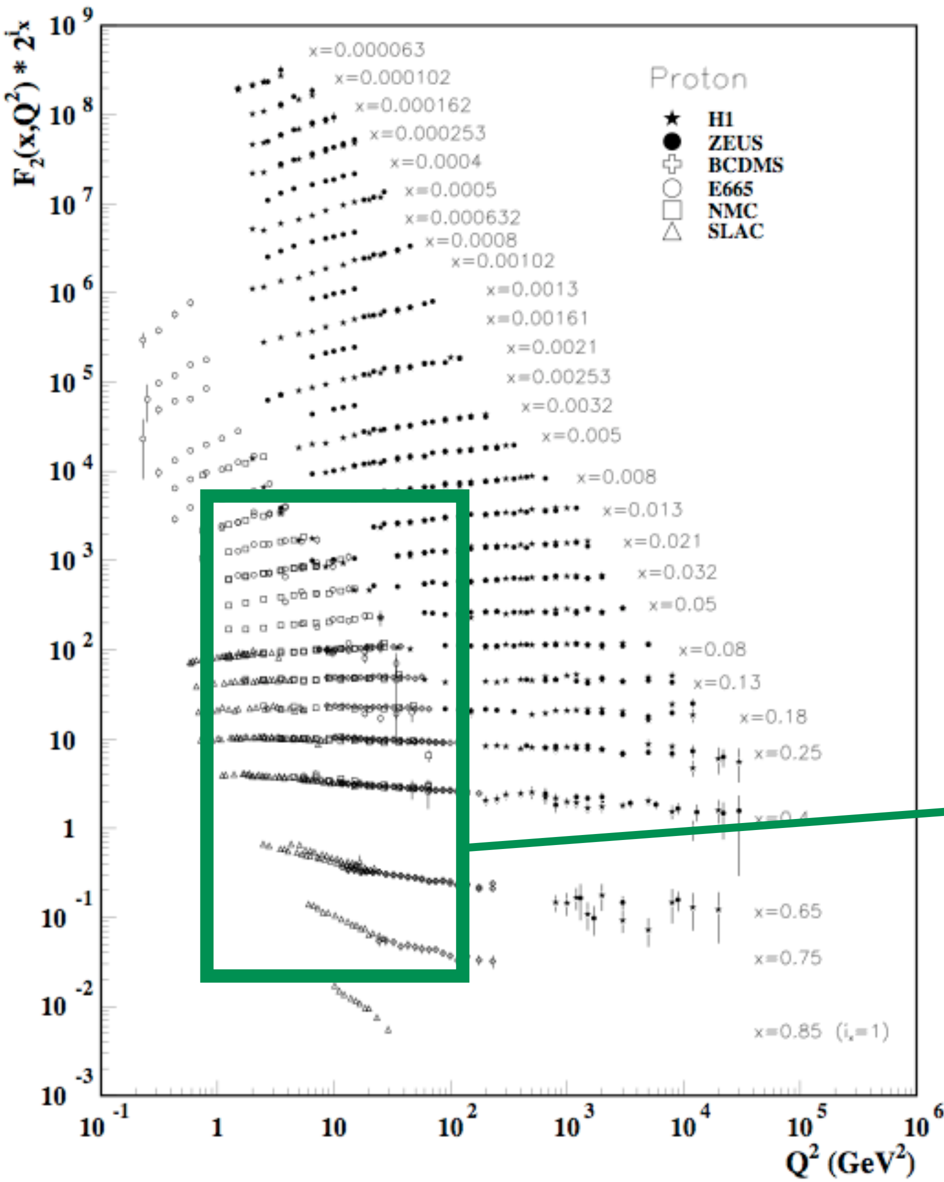
Parton Model:

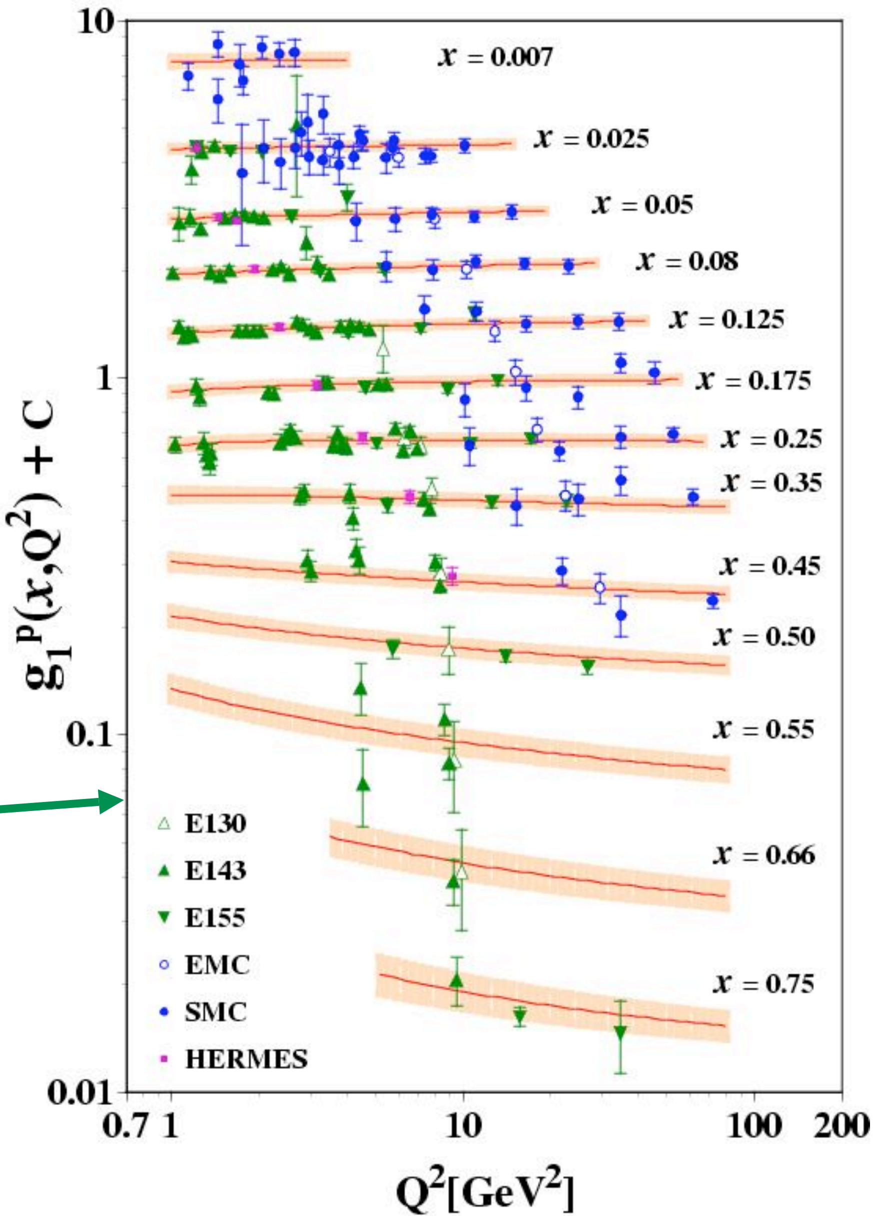
$F_1(x,Q^2) = \frac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) + q^\downarrow(x) + \bar{q}^\uparrow(x) + \bar{q}^\downarrow(x))$

$F_2(x,Q^2) = 2xF_1(x,Q^2)$

$g_1(x,Q^2) = \frac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) - q^\downarrow(x) + \bar{q}^\uparrow(x) - \bar{q}^\downarrow(x))$

$F_2^p(x,Q^2)$ and $g_1^p(x,Q^2)$





Integrals over *x*

Gottfried Sum Rule

0.235(26) at Q^2=4 GeV^2

$$\Phi_1^{p,n}(Q^2) = \int_0^1 F_1^{p,n}(x,Q^2)dx$$

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$$

$$\Phi_1^p - \Phi_1^n = \frac{1}{6}[u_v - d_v + 2\bar{u} - 2\bar{d}]$$

Bjorken Sum Rule

0.176(7) at Q^2=5 GeV^2

$$\Gamma_1^{p,n}(Q^2) = \int_0^1 g_1^{p,n}(x,Q^2)dx$$

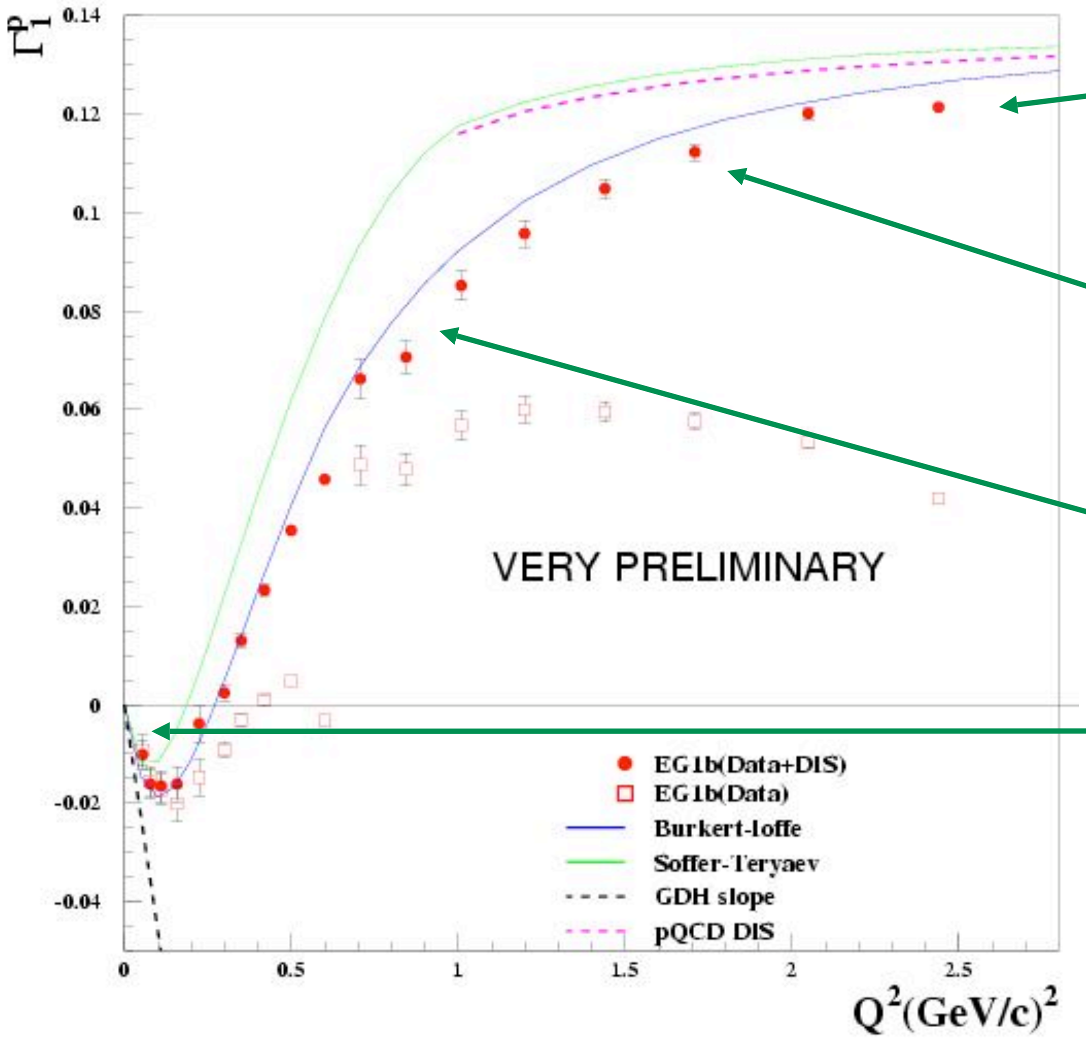
$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}[\Delta u_v - \Delta d_v + 2\Delta\bar{u} - 2\Delta\bar{d}]$$

Complicating Factor

$$\Delta C_{NS}^{\bar{M}S} = 1 - \frac{\alpha_S}{\pi} - 3.583\left(\frac{\alpha_S}{\pi}\right)^2 - 20.215\left(\frac{\alpha_S}{\pi}\right)^3 + \ldots$$

Regions of Q^2



scaling: $\ln Q^2$

higher twist: $(1/Q^2)^n$

no nice expansion

χPT: $(Q^2)^n$

The Q^2 Map

• Infinite Q^2	Parton Model, PDF(x)
• Large Q^2	DIS, pQCD, PDF(x,log(Q^2))
• Medium Q^2	Higher twist, target mass correct.
• Low Q^2	Resonances (complexity)
• Tiny Q^2	Chiral perturbation theory
• Zero Q^2	Real photons

- Complexity, as measured by γ_0, δ_{LT}, d_2 and Γ_1, disappears rapidly at high and low Q^2

The Major Spin Contributors

- CERN
  - EMC, SMC, COMPASS
- SLAC
  - E80, E130, E142, E143, E154, E155
- DESY
  - HERMES
- Jefferson Lab
  - Hall A, Hall B (CLAS), Hall C
- Brookhaven National Lab (RHIC)
  - STAR, PHENIX

EXPERIMENTS

Jefferson Lab's Hall B (CLAS) is one of the current experiments that is significantly improving our knowledge of g_1 in the range $0.01<Q^2<3.5$ GeV^2, where perturbative QCD breaks down.

Spin Structure with CLAS

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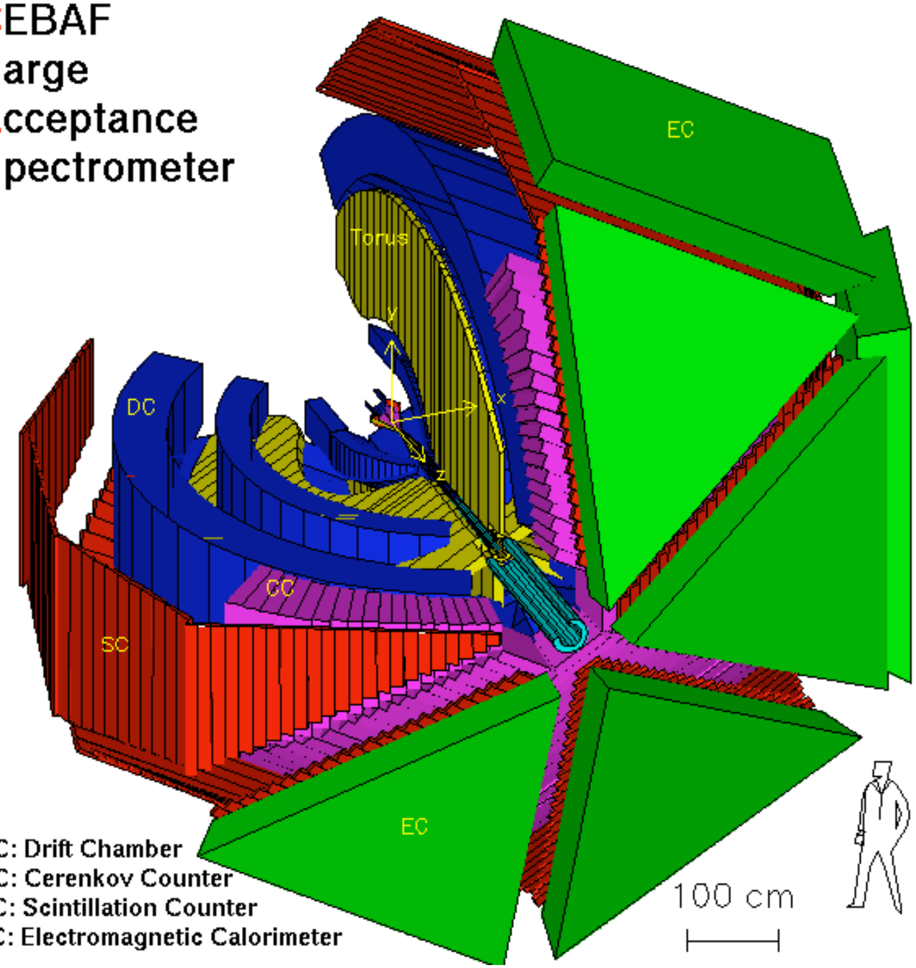
- Long-standing program in Hall-B at JLab to measure longitudinal double spin asymmetries $A_{||}$ on $^{15}NH_3$ and $^{15}ND_3$
- EG1: $0.05<Q^2<3.5$ GeV^2
  - data (2001); anal (2008)
- EG4: $0.01<Q^2<1$ GeV^2
  - data (2006); anal (2009)
- EG1-DVCS: $1<Q^2<3.5$
  - data (2009); anal (2010)
- EG12: $0.5<Q^2<7$ GeV^2
  - data (2012?); anal (2014)

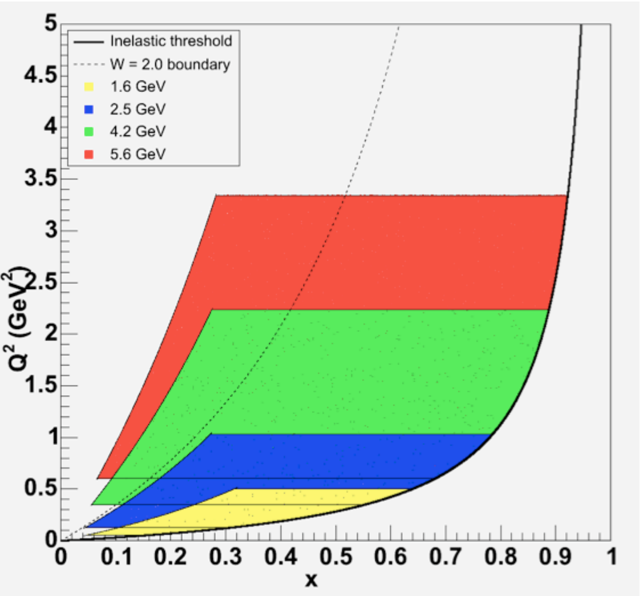
CEBAF
Large
Acceptance
Spectrometer



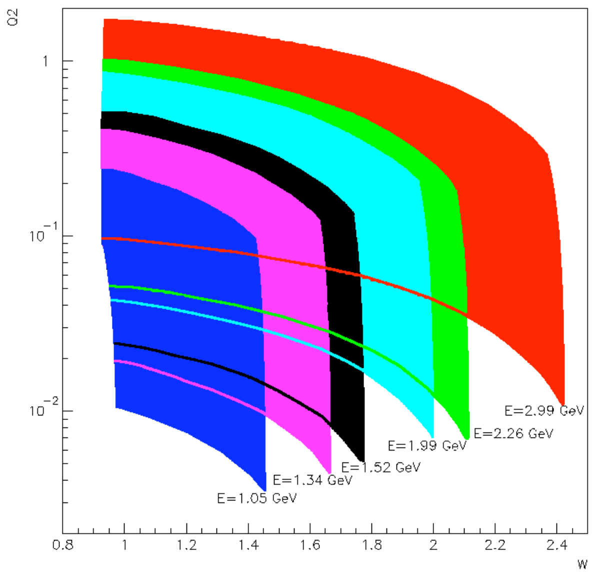
DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter

Kinematics

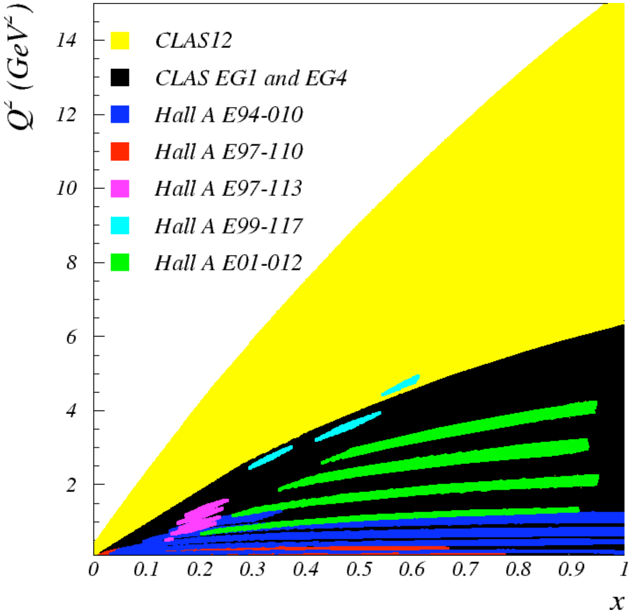
EG1



EG4



EG12



EG1-DVCS (red)

- Overlapping colors correspond to different beam energies
- CLAS measures a large range in x at each fixed Q^2
- Different E_{beam} for fixed (x,Q^2) allows separation of A_1 & A_2

Formalism

$$A_{\parallel} = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow}}$$

$$A_{\parallel} = D(A_1 + \eta A_2)$$

We can extract A_1 using a model for A_2 (small), or g_1 using a model for g_2 (small)

We can extract A_1 and A_2 from $A_{||}$ at multiple values of $\eta(E_{beam})$

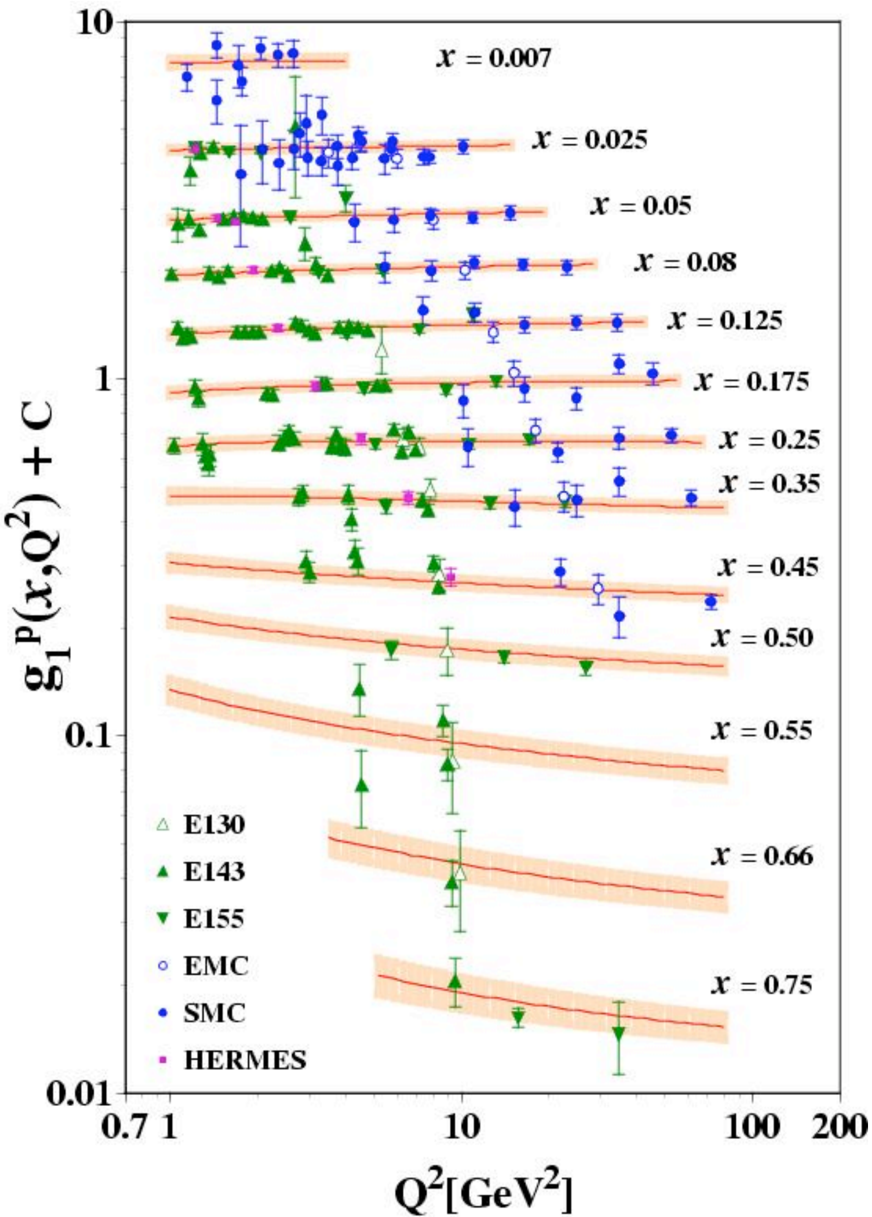
$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

$$= \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

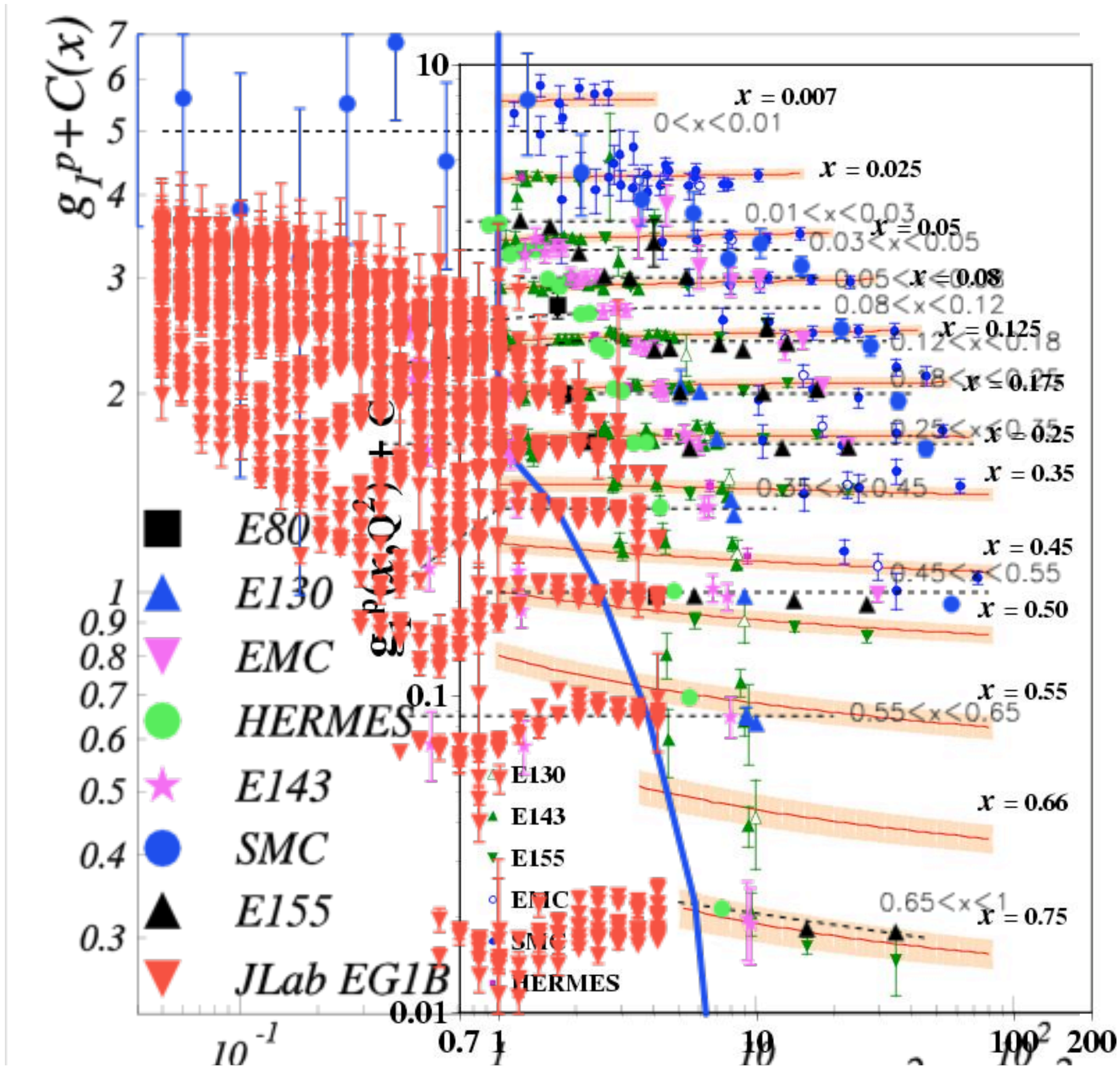
$$A_2 = \frac{2\sigma_{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

$$= \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

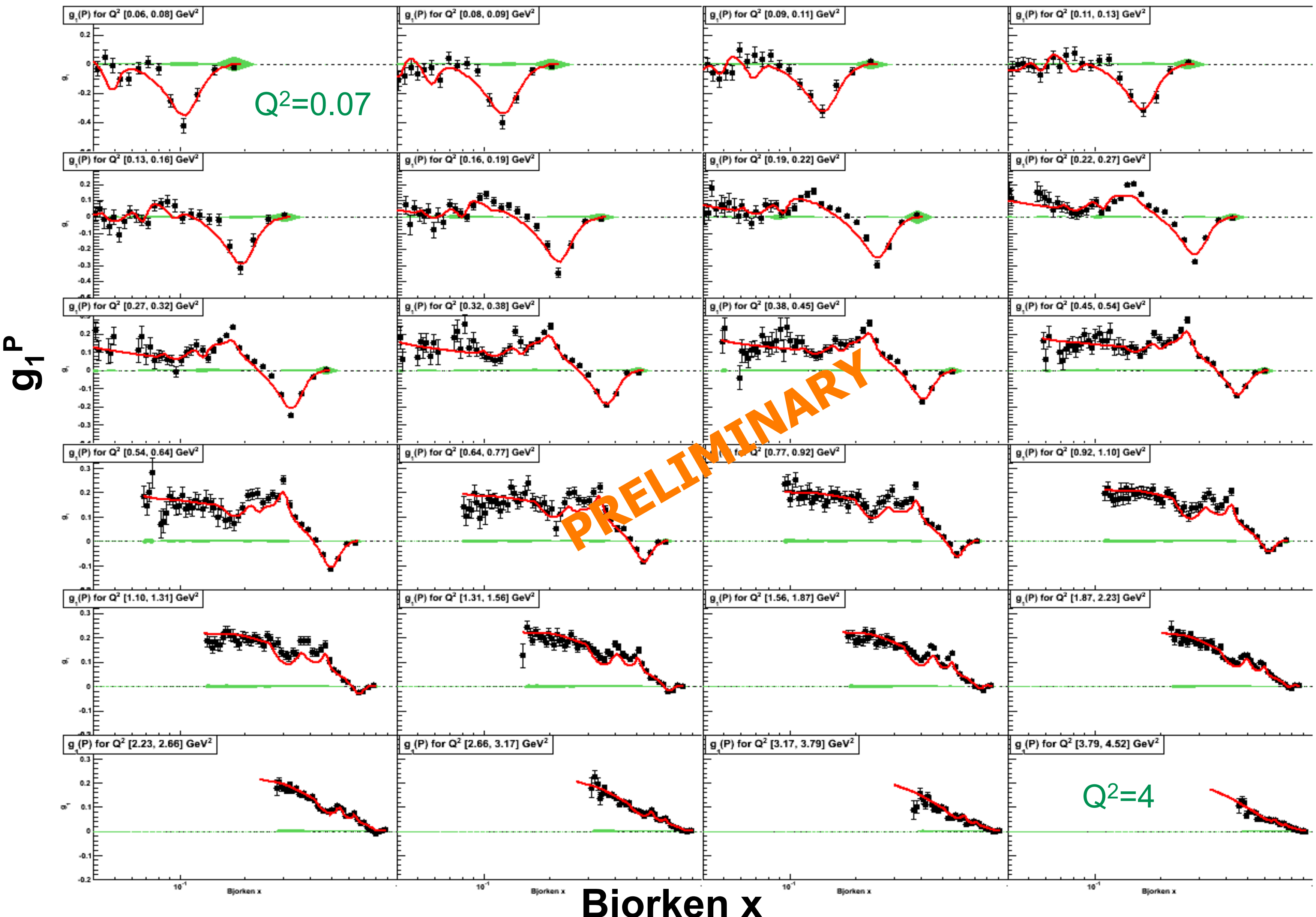
$g_1^p(x,Q^2)$ before CLAS



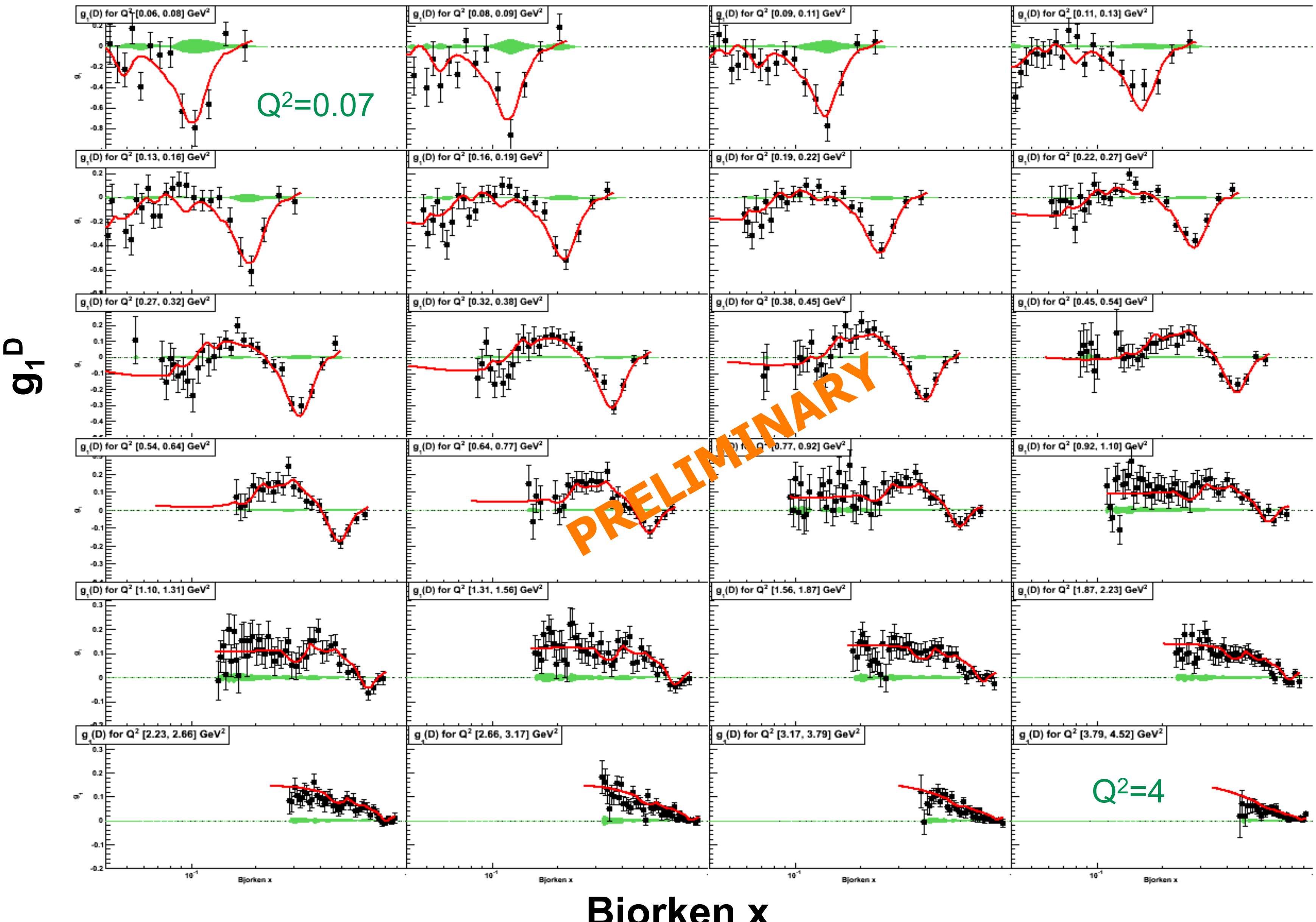
$g_1^p(x,Q^2)$ with JLab CLAS



EG1b g_1^p


g1(P) for Q2 [0.06, 0.08] GeV2
g1(P) for Q2 [0.08, 0.09] GeV2
g1(P) for Q2 [0.09, 0.11] GeV2
g1(P) for Q2 [0.11, 0.13] GeV2
Q2=0.07
g1(P) for Q2 [0.13, 0.16] GeV2
g1(P) for Q2 [0.16, 0.19] GeV2
g1(P) for Q2 [0.19, 0.22] GeV2
g1(P) for Q2 [0.22, 0.27] GeV2
g1(P) for Q2 [0.27, 0.32] GeV2
g1(P) for Q2 [0.32, 0.38] GeV2
g1(P) for Q2 [0.38, 0.45] GeV2
g1(P) for Q2 [0.45, 0.54] GeV2
g1(P) for Q2 [0.54, 0.64] GeV2
g1(P) for Q2 [0.64, 0.77] GeV2
g1(P) for Q2 [0.77, 0.92] GeV2
g1(P) for Q2 [0.92, 1.10] GeV2
g1(P) for Q2 [1.10, 1.31] GeV2
g1(P) for Q2 [1.31, 1.56] GeV2
g1(P) for Q2 [1.56, 1.87] GeV2
g1(P) for Q2 [1.87, 2.23] GeV2
g1(P) for Q2 [2.23, 2.66] GeV2
g1(P) for Q2 [2.66, 3.17] GeV2
g1(P) for Q2 [3.17, 3.79] GeV2
g1(P) for Q2 [3.79, 4.52] GeV2
Q2=4
PRELIMINARY
g1P
Bjorken x

EG1b g_1^d


g1(D) for Q² [0.06, 0.08] GeV²
g1(D) for Q² [0.08, 0.09] GeV²
g1(D) for Q² [0.09, 0.11] GeV²
g1(D) for Q² [0.11, 0.13] GeV²
g1(D) for Q² [0.13, 0.16] GeV²
g1(D) for Q² [0.16, 0.19] GeV²
g1(D) for Q² [0.19, 0.22] GeV²
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g1(D) for Q² [0.45, 0.54] GeV²
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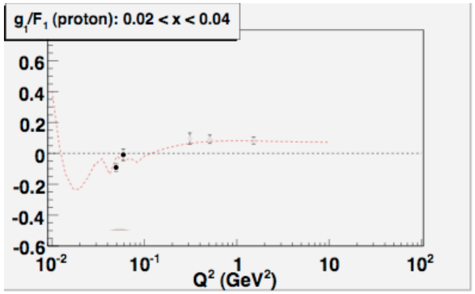
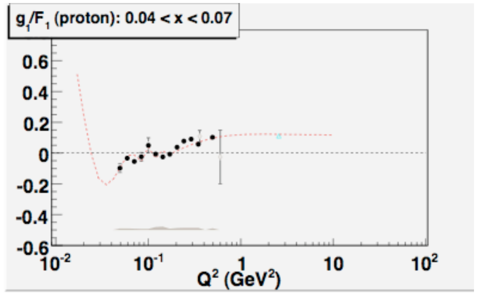
g1(D) for Q² [0.92, 1.10] GeV²
g1(D) for Q² [1.10, 1.31] GeV²
g1(D) for Q² [1.31, 1.56] GeV²
g1(D) for Q² [1.56, 1.87] GeV²
g1(D) for Q² [1.87, 2.23] GeV²
g1(D) for Q² [2.23, 2.66] GeV²
g1(D) for Q² [2.66, 3.17] GeV²
g1(D) for Q² [3.17, 3.79] GeV²
g1(D) for Q² [3.79, 4.52] GeV²
Q²=0.07
Q²=4
PRELIMINARY
g1D
Bjorken x

A_1

The virtual photon asymmetry A_1 (approximately g_1/F_1) should scale with Q^2 if g_1 and F_1 evolve identically. It is very sensitive to resonance structure at moderate Q^2 and to PDFs at high x.

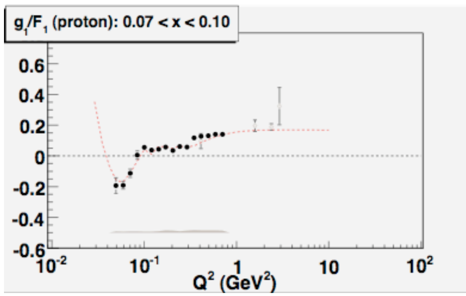
EG1b g_1^p/F_1^p vs. Q^2

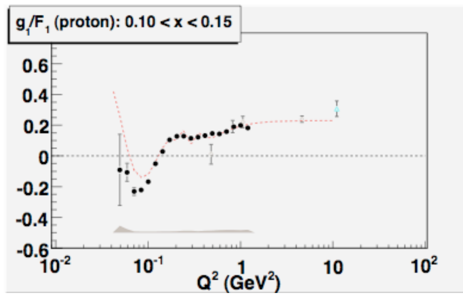


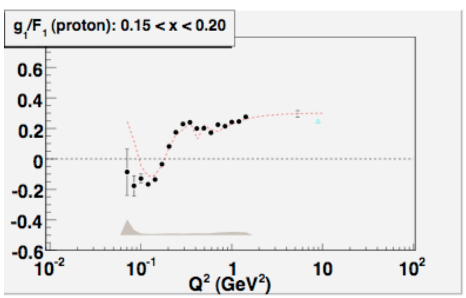


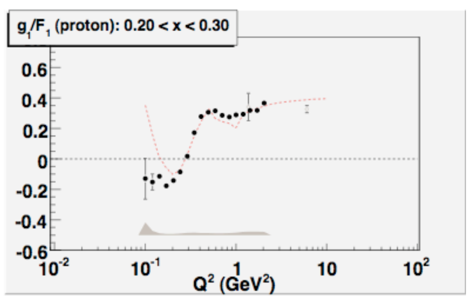
Scaling starts at:

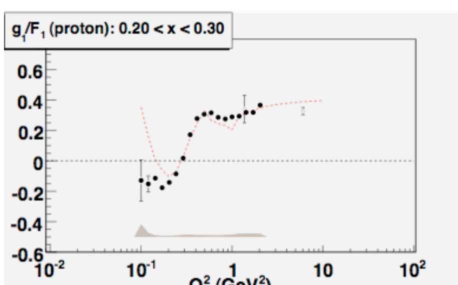
x	Q^2
0.085	0.1
0.125	0.2
0.175	0.3
0.250	0.6
0.350	0.8
0.500	1.0

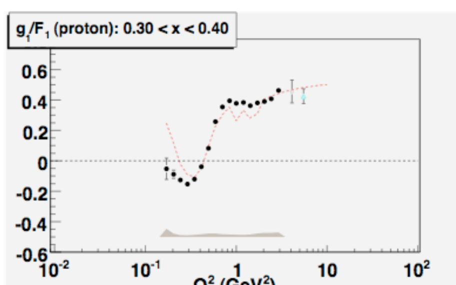


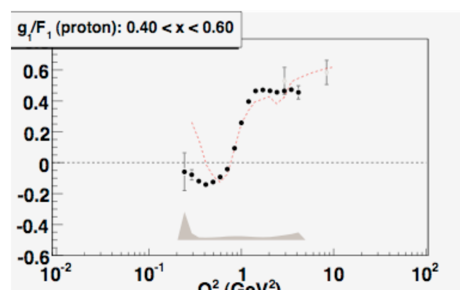








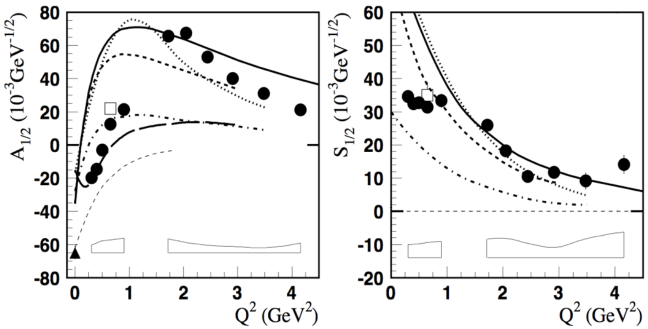




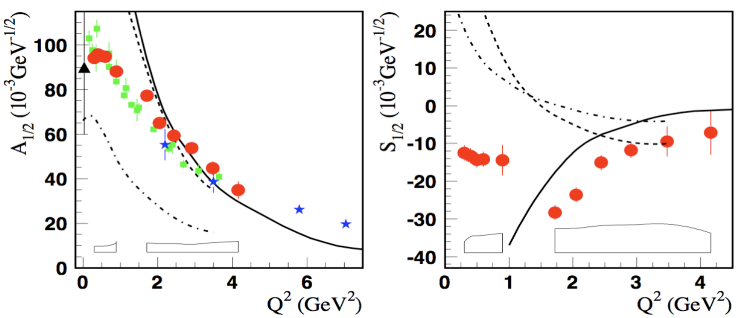
Modeling the Resonance Region

Burkert arXiv:0908.3507

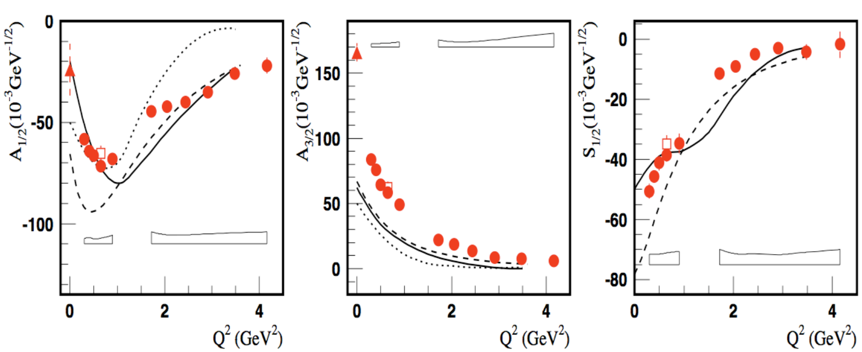
$$A_1 = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$



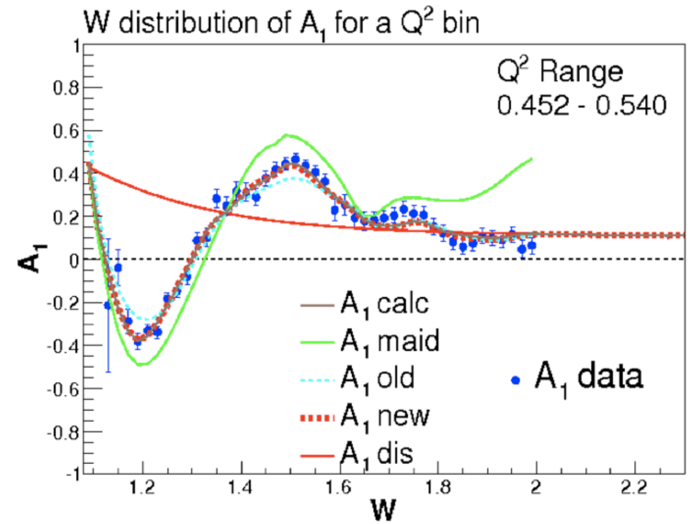
P_{11}



S_{11}



D_{13}



- Resonances induce huge variations in A_1 compared to the smooth deep-inelastic behavior (red)
- The world's collected wisdom on resonance structure, encoded in MAID (green) does not describe the data well

A_1 Data from EG1

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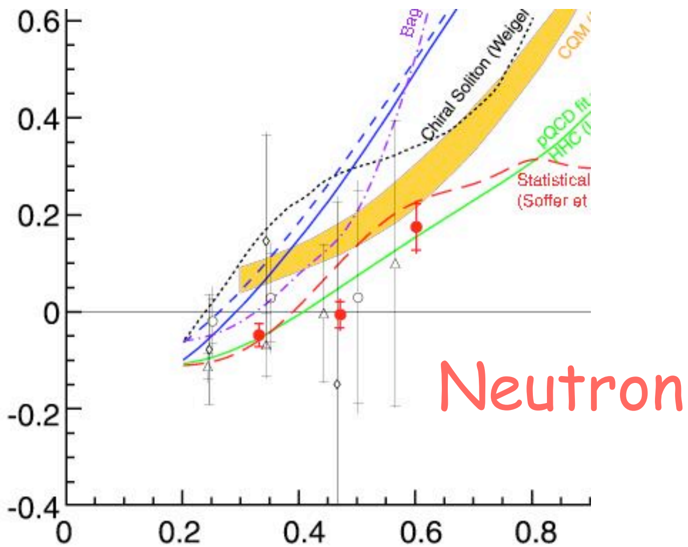
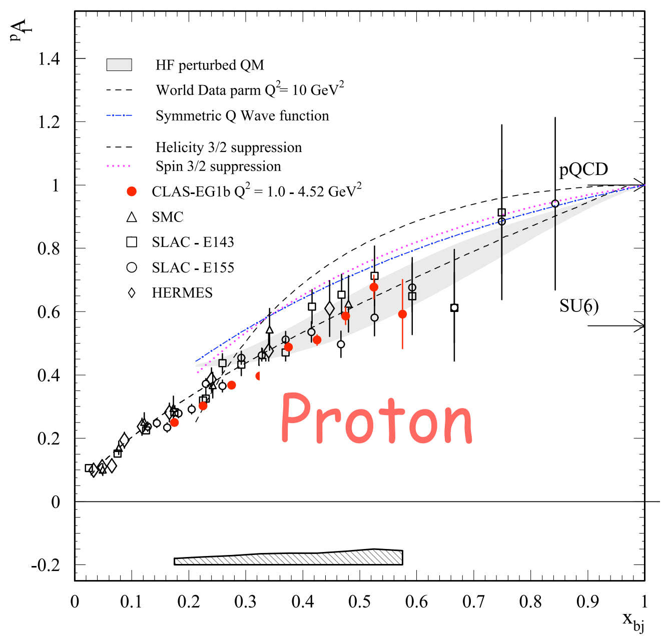
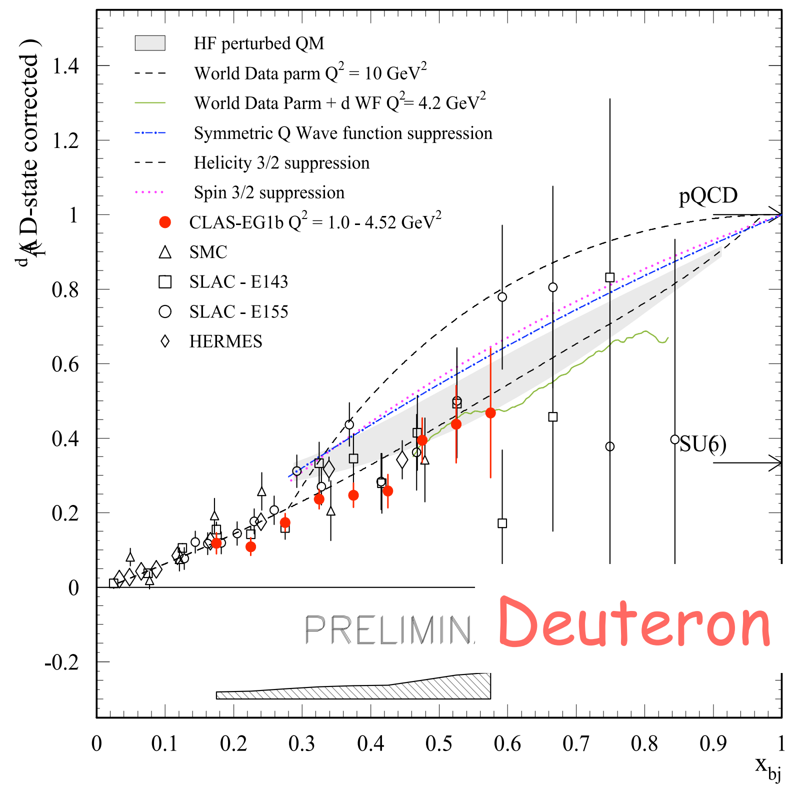


$\sim g_1/F_1$

Close and Melnitchouk, PRC **68**, 035210 (2003)

Isgur, PRD **59**, 034013 (2003)



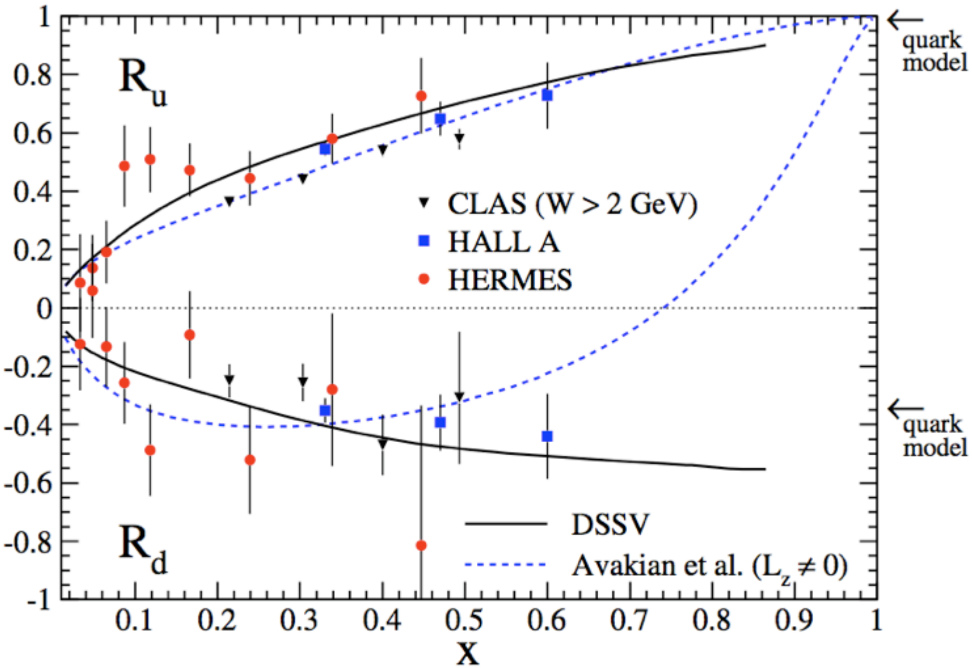


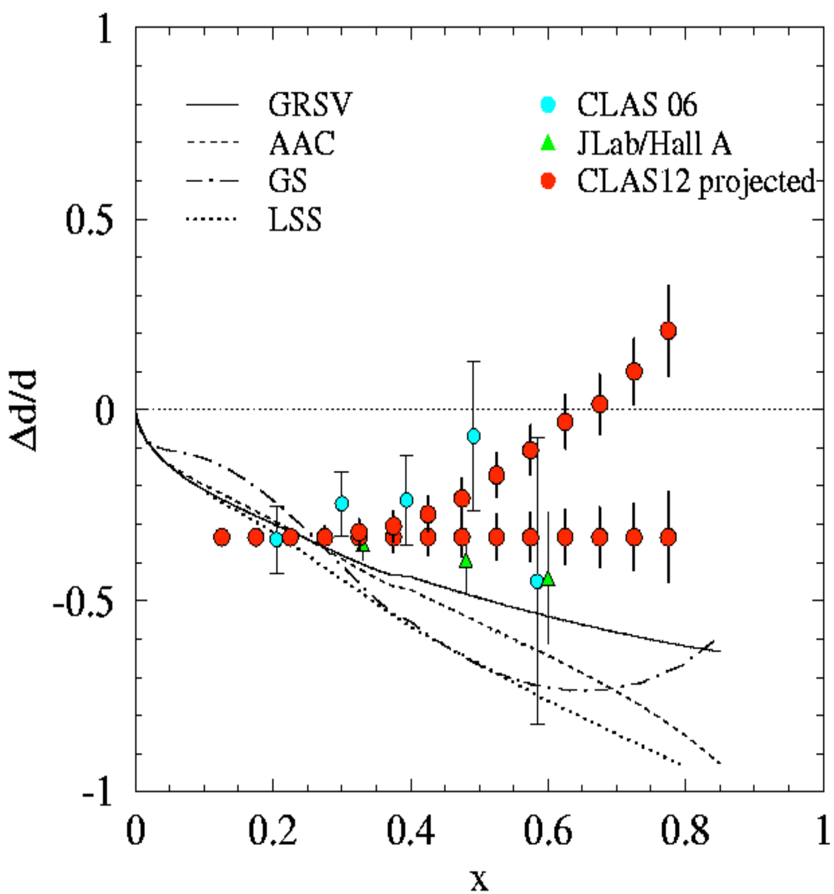
Quark polarization in the valence limit

$$A_1(x,Q^2) = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)}$$

Simulated Data for EG12
Extracted from A_1^p, A_1^d and d/u

$R_u = \Delta u/u$; $R_d = \Delta d/d$

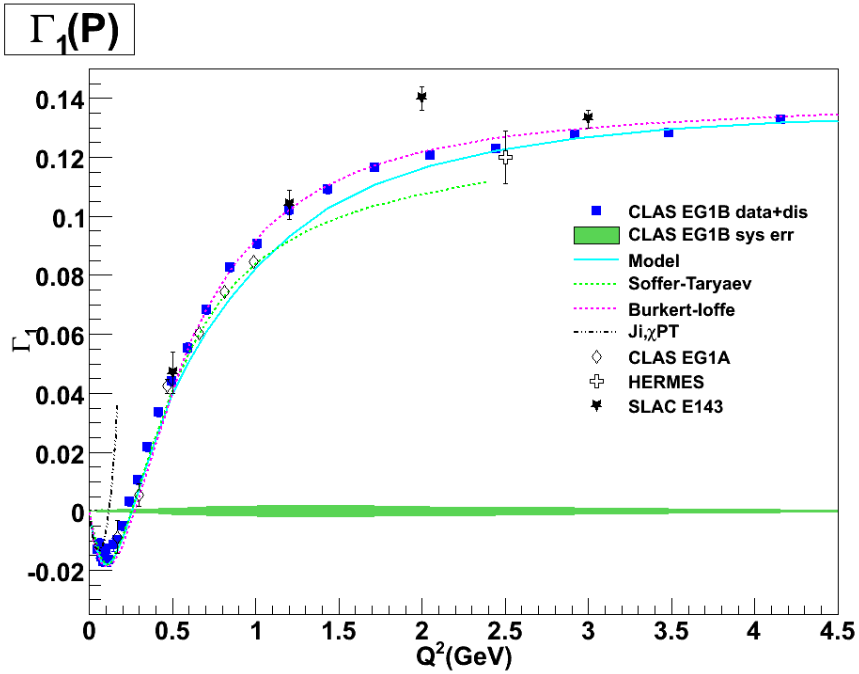


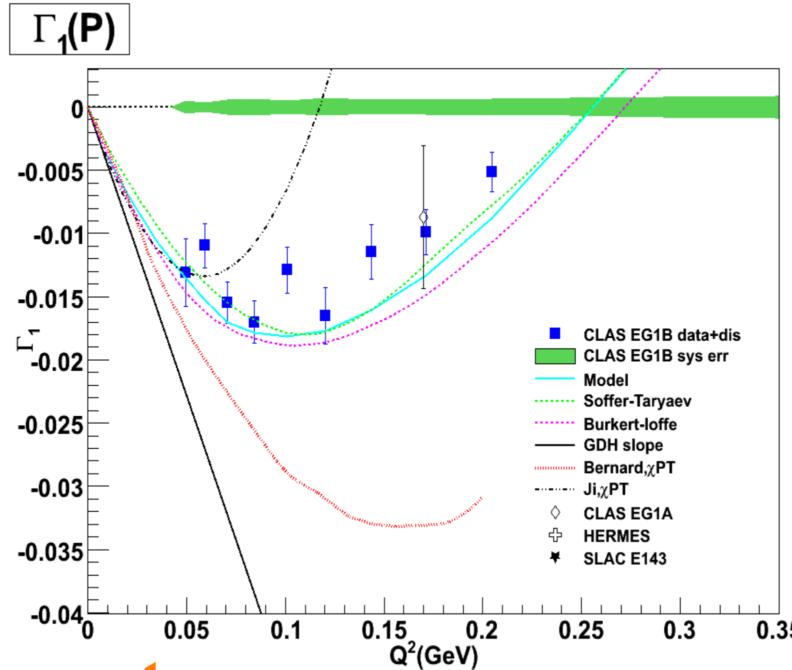


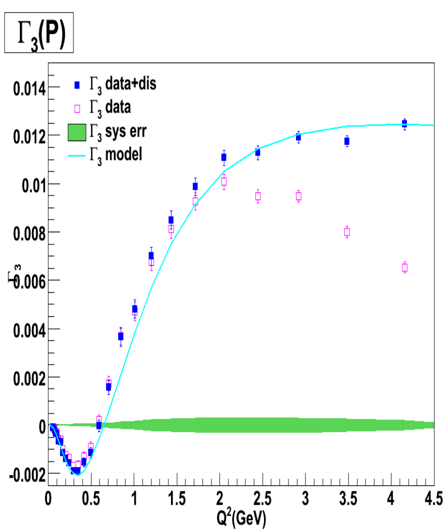
Moments

Accurate moments of structure functions (x-weighted integrals) can now be constructed from experimental data over a wide range of Q^2. These directly show the changing landscape with momentum transfer, and are often easier to compare with theoretical calculations.

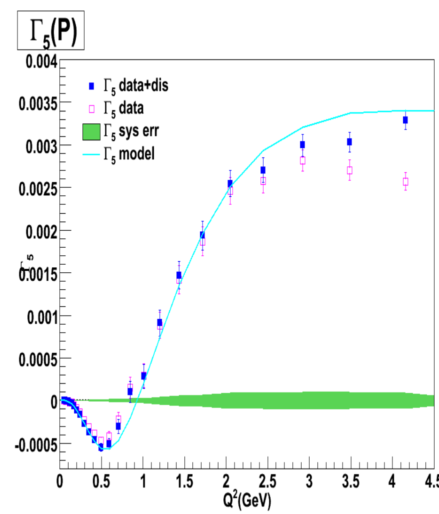
EG1b $\Gamma^p_{1,3,5}$



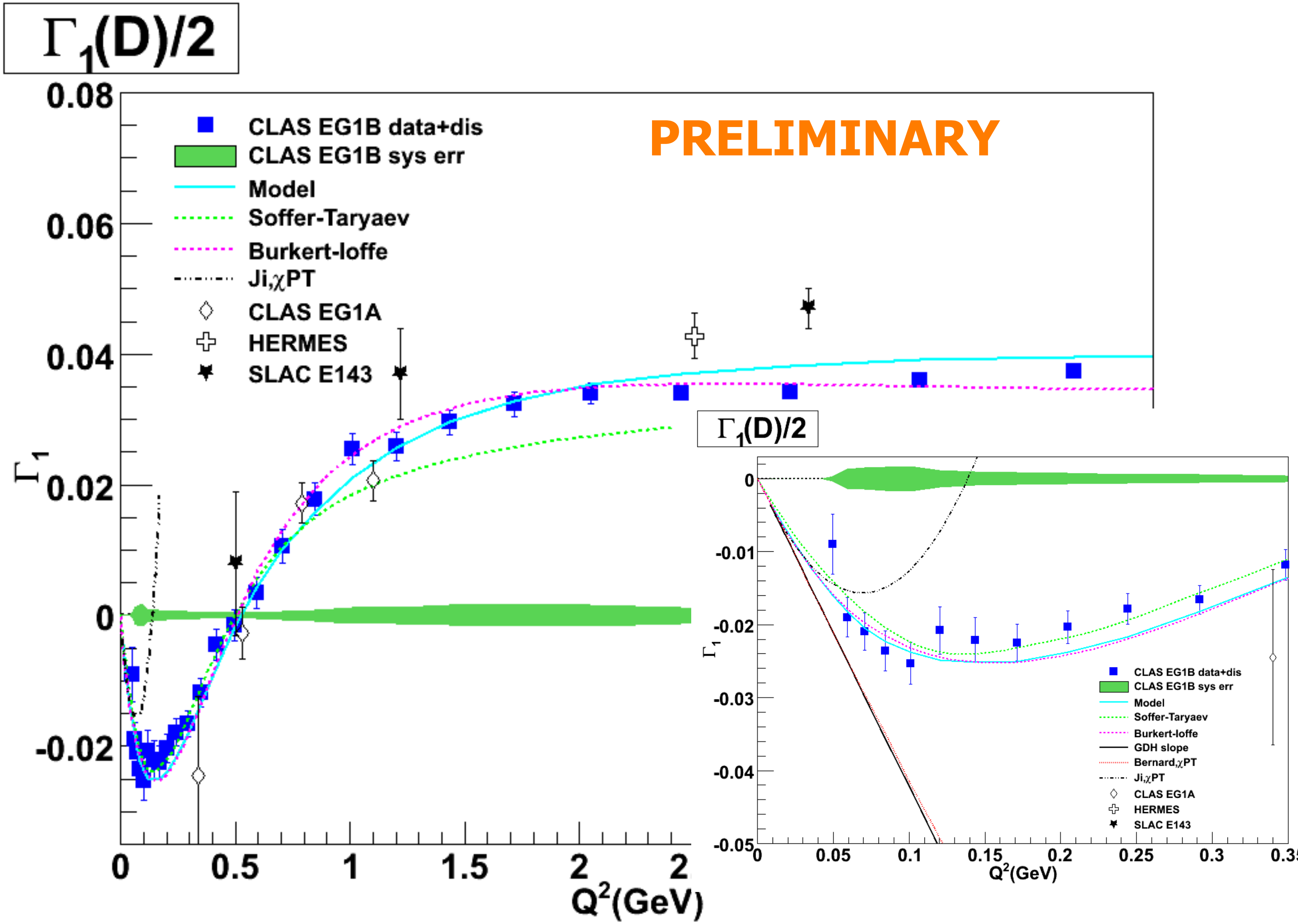




PRELIMINARY



EG1b Γ_1^d



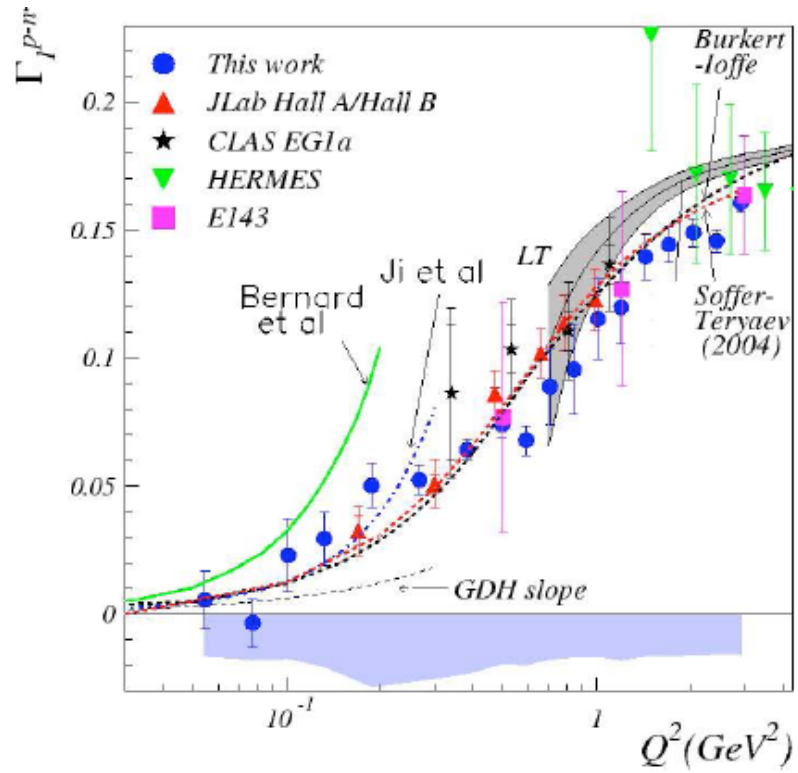
Higher Twist

The Operator Product Expansion of QCD sorts quark-gluon correlations into higher twists, which fall off inversely with powers of Q^2. Measurements at intermediate Q^2 have been able to extract these higher-twist coefficients d_2 and f_2 and the related color electric and magnetic susceptibilities.

Bjorken Sum & Higher Twist

$$\Gamma_1^{(n)} = \int_0^1 x^n g_1(x,Q^2)dx = \frac{a_n}{2}, \quad n=0,2,4,\ldots,$$

$$\Gamma_2^{(n)} = \int_0^1 x^n g_2(x,Q^2)dx = \frac{1}{2}\frac{n}{n+1}(d_n - a_n), \quad n=2,4,\ldots,$$



Bjorken Sum Rule:

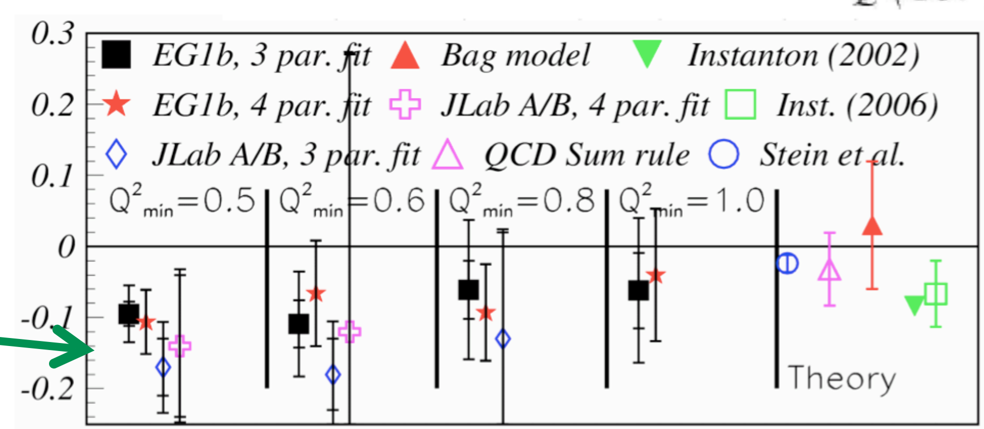
CLAS: Deur

$$\Gamma_1^{p-n} = \frac{g_A}{6}\left[1 - \frac{\alpha_s}{\pi} - 3.58\left(\frac{\alpha_s}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s}{\pi}\right)^3\right] + \frac{\mu_4^{p-n}}{Q^2} + \ldots$$

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

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

Fit Γ_1^{p-n} to powers of $1/Q^2$ and extract f_2^{p-n}

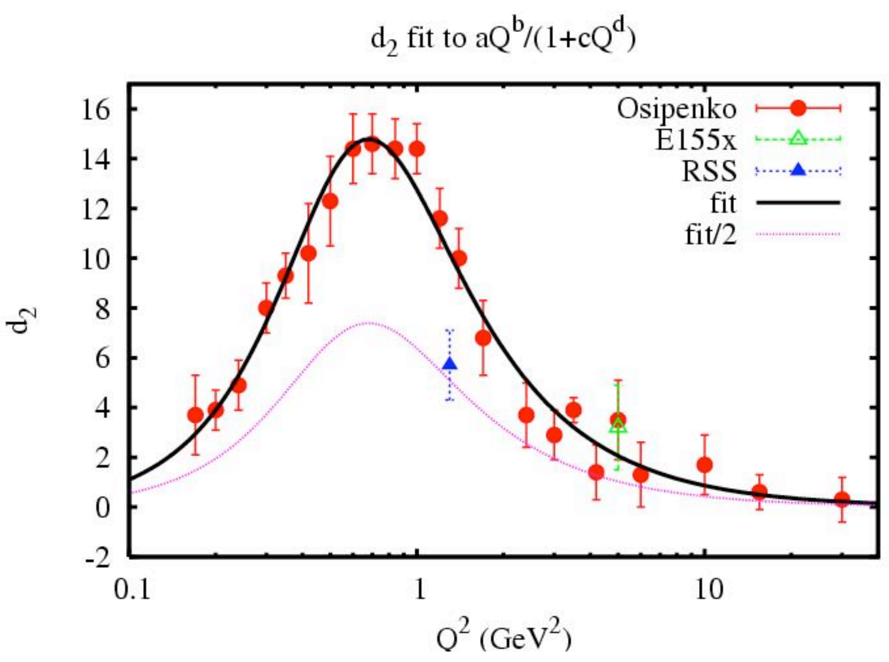


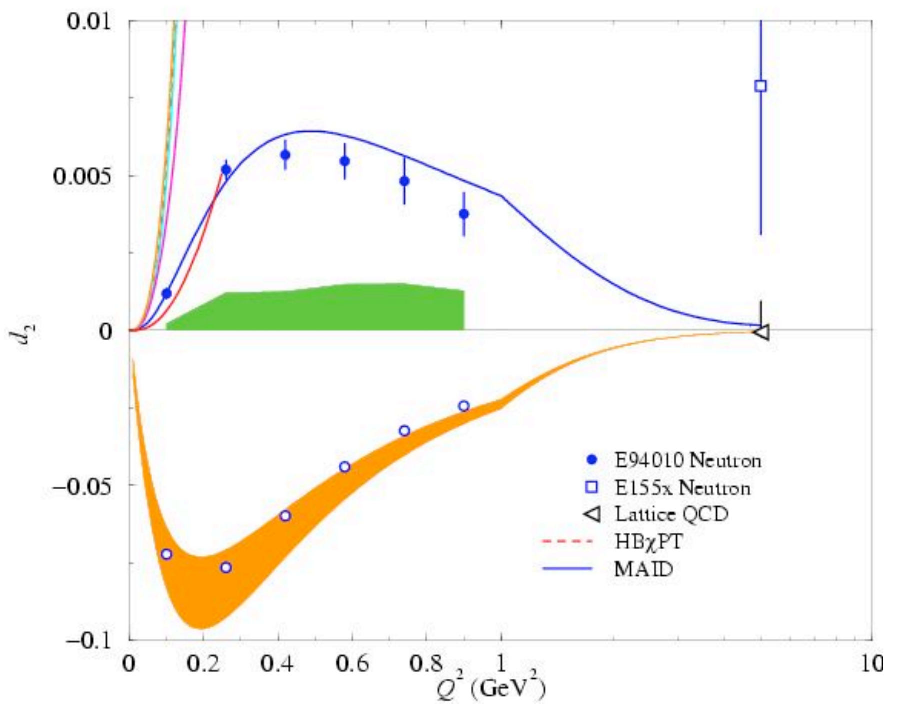
Higher Twist d_2

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

CLAS EG1 (proton)
Osipenko, PRD71(05)054007
Model-dependent determination

Hall A (neutron)
E94-010
Amarian, PRL92(04)022301





Nachtmann Moments

CLAS, Osipenko

PLB609(05)259

$$M_1(Q^2) = \int_0^1 dx \frac{\xi^2}{x^2}\left\{g_1(x,Q^2)\left(\frac{x}{\xi} - \frac{1}{9}\frac{M^2 x\xi}{Q^2}\right) - g_2(x,Q^2)\frac{4}{3}\frac{M^2x^2}{Q^2}\right\},$$

$$\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$$

$$M_1(Q^2) = \mu_2(Q^2) + \frac{\mu_4(Q^2)}{Q^2} + \frac{\mu_6(Q^2)}{Q^4} + \cdots$$

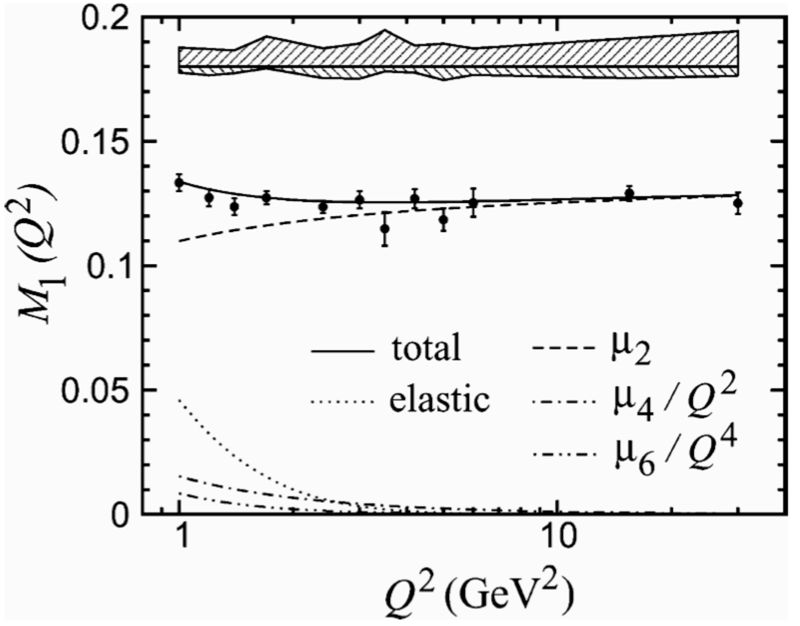
$$\mu_4(Q^2) = 4f_2(Q^2)/9M^2$$

$$f_2 = 0.039 \pm 0.022(\text{stat}) \pm^{0.000}_{0.018}(\text{sys}) \pm 0.030(\text{low } x) \pm^{0.007}_{0.011}(\alpha_s),$$

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

$$\chi_E = \frac{2}{3}(2d_2 + f_2)$$

$$\chi_B = \frac{1}{3}(4d_2 - f_2)$$



$$\chi_E = 0.026 \pm 0.015(\text{stat}) \pm^{0.021}_{0.024}(\text{sys}),$$

$$\chi_B = -0.013 \mp 0.007(\text{stat}) \mp^{0.010}_{0.012}(\text{sys})$$

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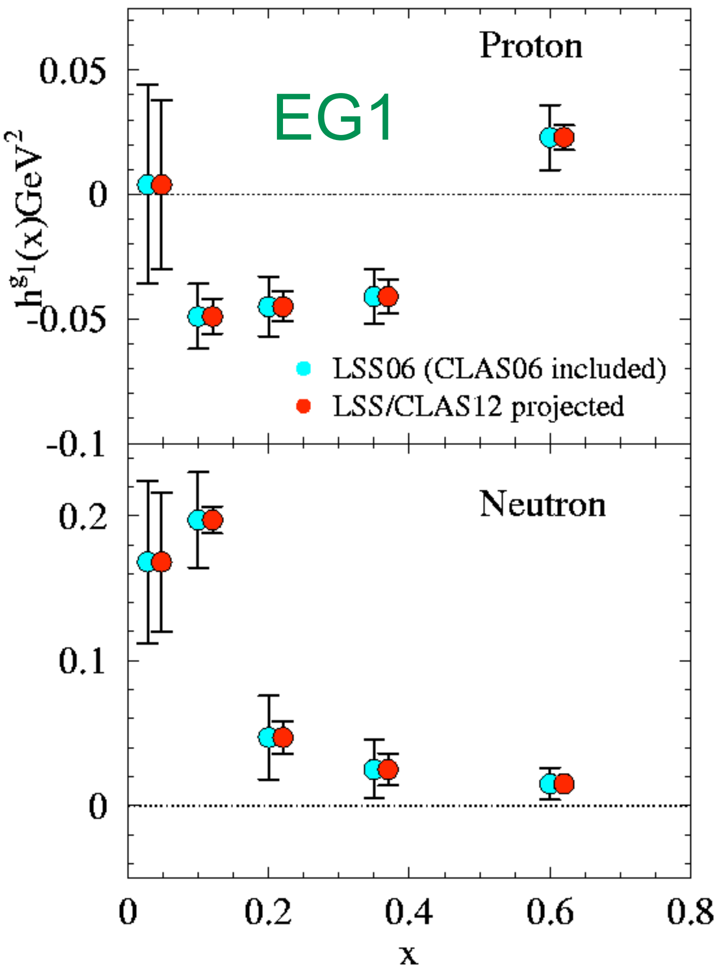
Higher Twist from g_1 in CLAS

$$\left[\frac{g_1(x,Q^2)}{F_1(x,Q^2)}\right]_{\rm exp} F_1(x,Q^2)_{\rm exp} = g_1(x,Q^2)_{\rm exp} = g_1(x,Q^2)_{LT} + h^{g_1}(x)/Q^2$$



$$1 < Q^2 < 5 \text{ GeV}^2, \quad 2 < W < 3.5 \text{ GeV}$$

$$\int_0^1 dx h^{g_1}(x) = \frac{4}{9} M^2 (d_2 + f_2)$$

- F_1 from NMC fit to F_2 and 1998 SLAC fit to R
- g_1 (leading twist) from NLO fit at high Q^2
- h from fit to all data, especially CLAS in the pre-asymptotic region
- d_2: twist-3, f_2: twist-4

Leader, Sidorov, Stamenov, EPJST **162**(08)19

Color Polarizability

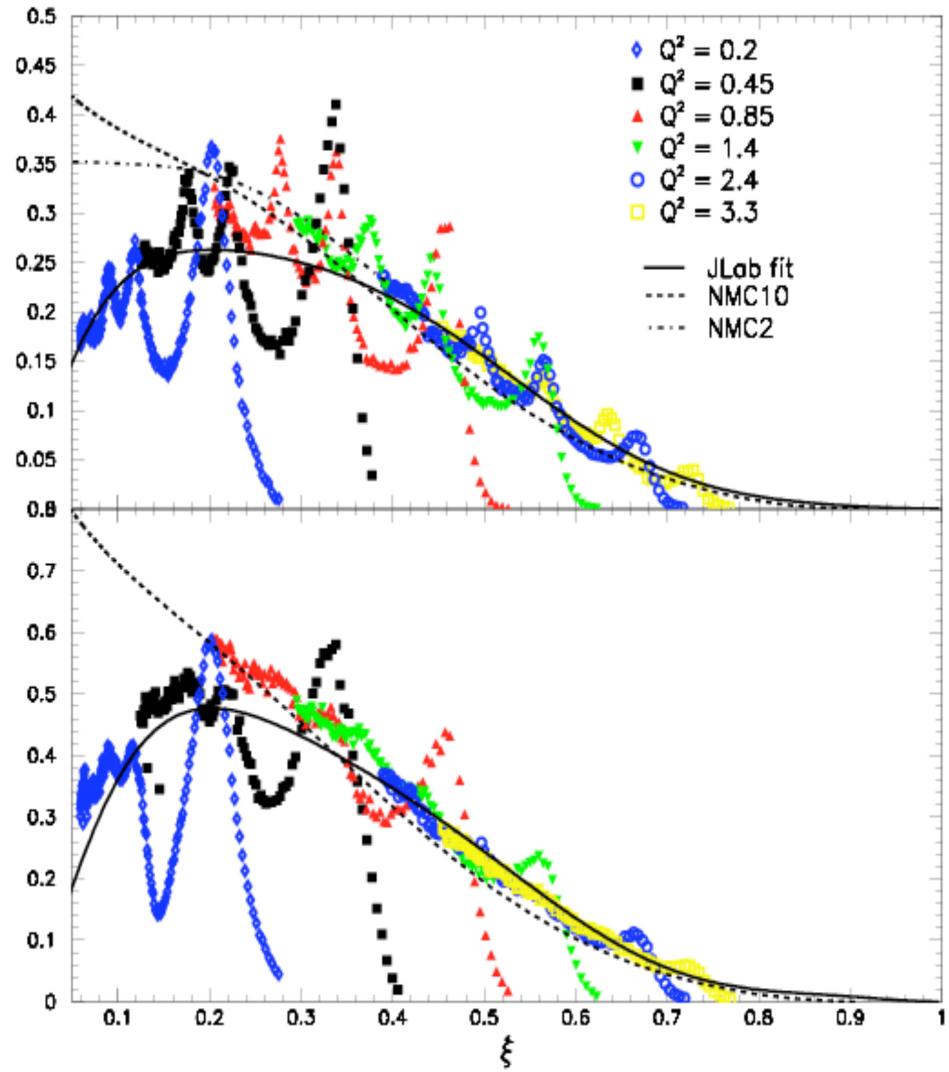
- Osipenko, CLAS, proton, PLB609(05)249
  - f_2 = 0.039(39) χ_E = 0.026(27) χ_B = -0.013(13)
- E94-010, Hall A, neutron
  - f_2 = 0.034(43) χ_E = 0.033(29) χ_B = -0.001(16)
- Deur, CLAS, Bjorken (p-n)
  - f_2 = -0.101(74) χ_E = -0.077(50) χ_B = 0.024(28)
- More accurate determinations are needed.

Duality

When structure functions are averaged over resonance peaks and valleys, they behave just like deep-inelastic scattering extrapolated into the resonance region. Local duality (one resonance region) and global duality (all resonances) tend to hold to 10% above Q^2=2 GeV^2, except for the polarized Δ resonance.

Duality

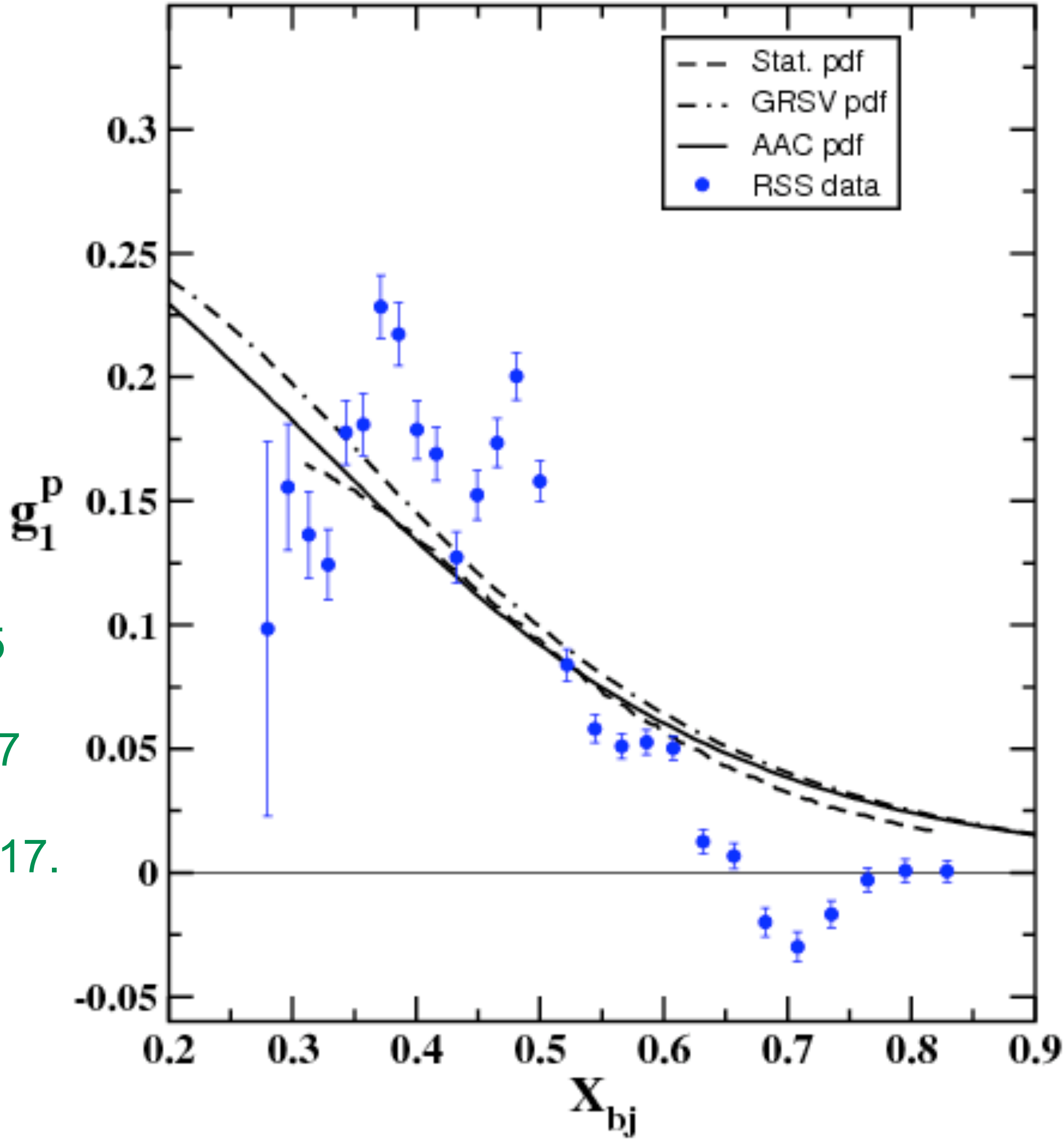
Hall C
PRL85(00)1182
Global duality to 10%
Local duality to 10%
W=1.232, 1.535, 1.680 GeV



Duality - structure functions averaged over resonances behave according to DIS systematics
Global - all resonances
Local - one resonance

Polarized Duality

Hall C
RSS, Wesselmann, Slifer
Q^2=1.379 GeV^2
Target Mass Corrections
applied to PDFs
No duality for Δ
PRL98(07)132003



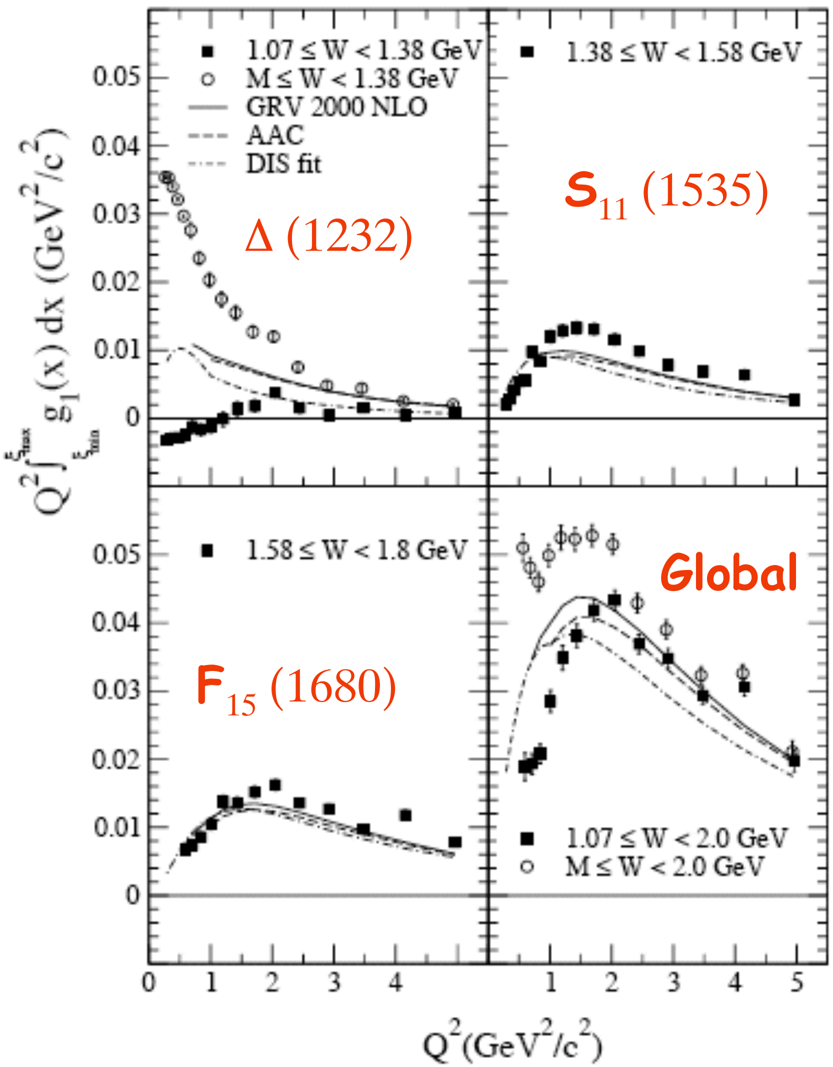
GRSV: Phys. Rev. D 53, (1996) 4775

BSB : Eur. Phys. J. C 41, (2005) 327

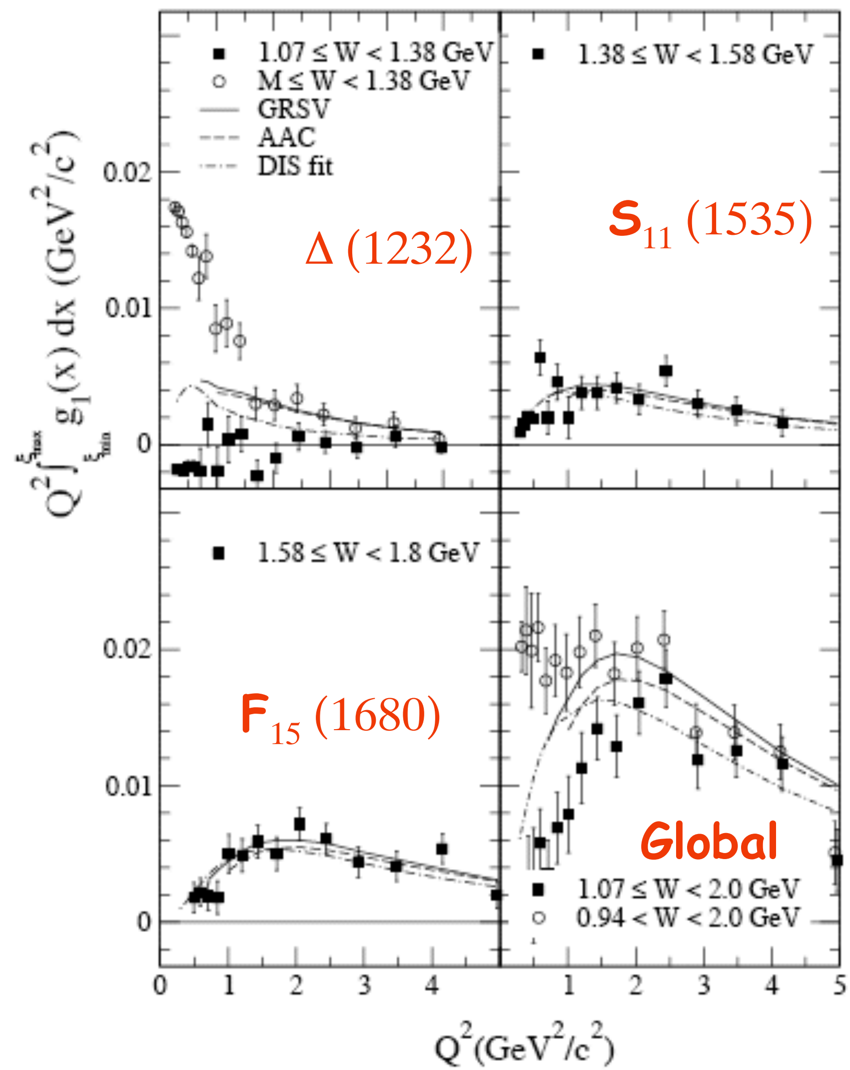
AAC : Phys. Rev. D 62, (2000) 034017.

Duality at CLAS (EG1)

Proton



Deuteron



g_2

The structure function g_2 in pQCD can be expressed as a convolution of g_1. Deviations from this Wandzura-Wilczek form measures higher twist. The Burkhardt-Cottingham sum rule states that the first moment of g_2 is zero. Precise data are now available to evaluate this claim.

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RSS g_2^p

Wandzura-Wilczek

$$g_2^{WW} = -g_1 + \int_x^1 \frac{g_1}{y} dy$$

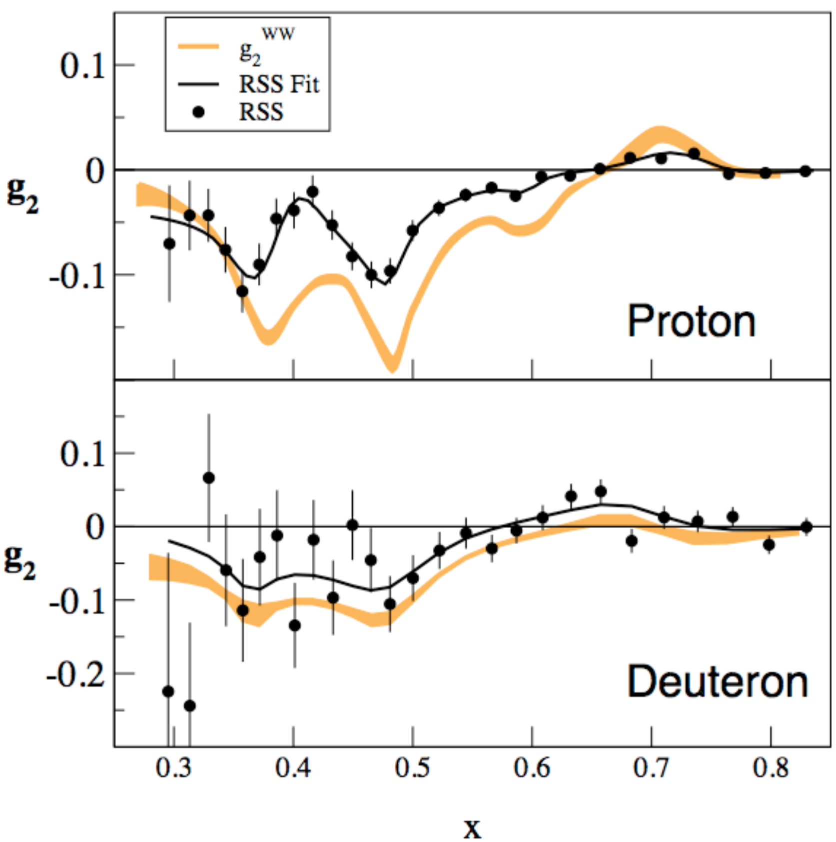
$$g_2 = g_2^{WW} + \overline{g}_2$$

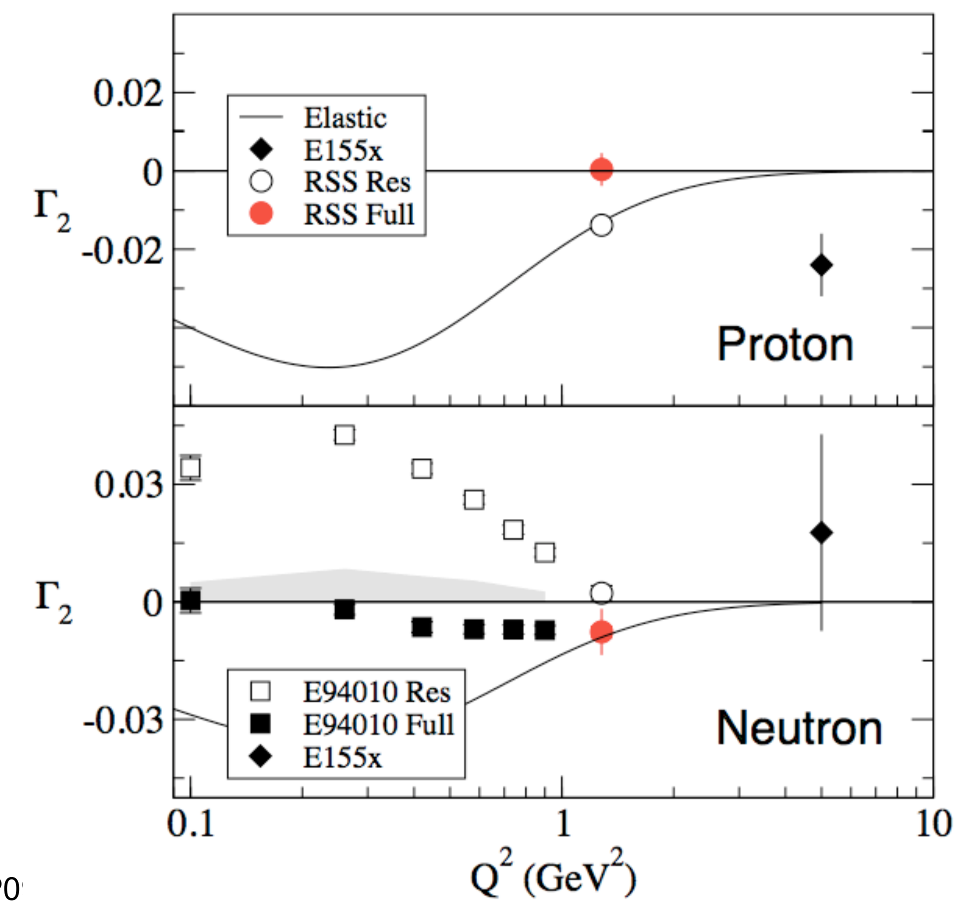
Q^2=1.28 GeV^2

Burkhardt-Cottingham Sum Rule

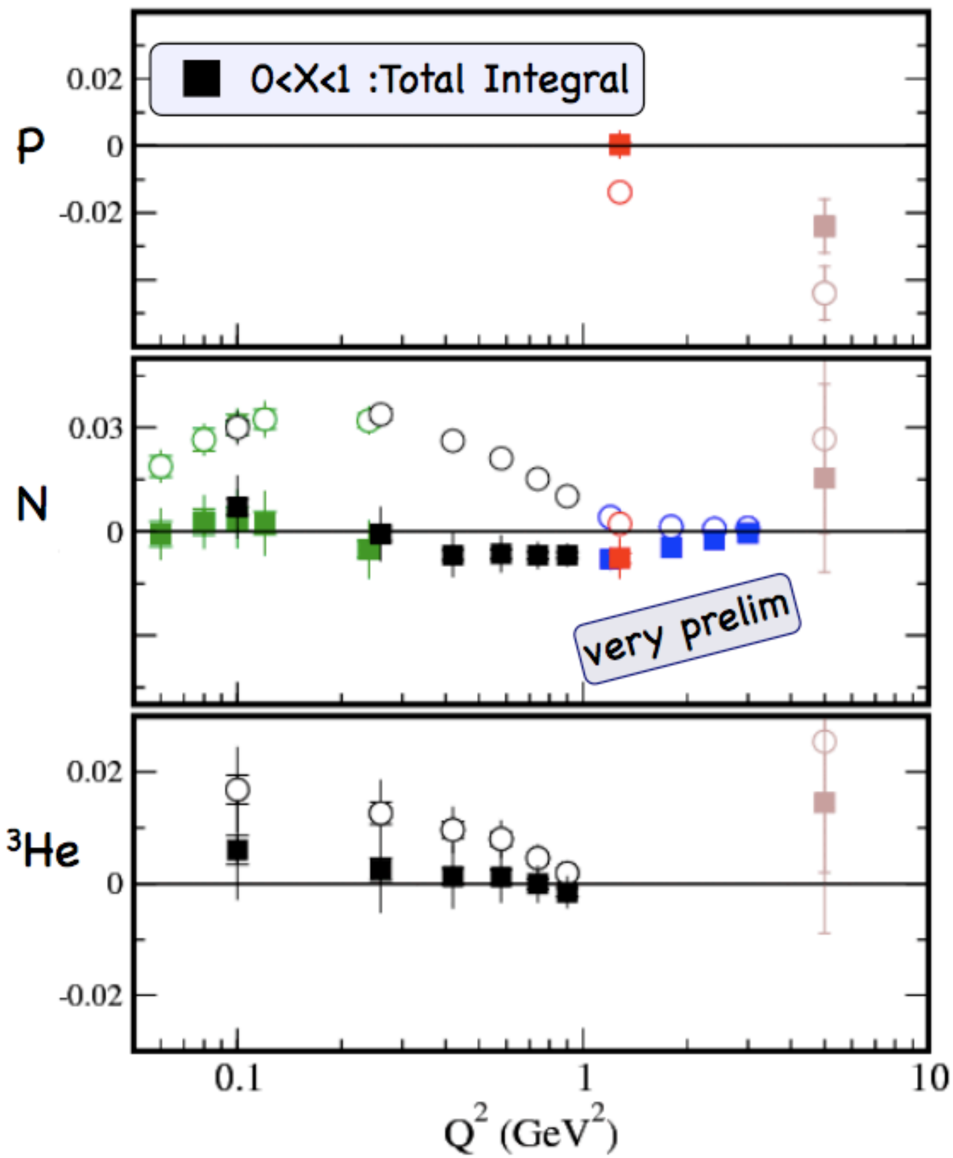
$$\Gamma_2 = \int_0^1 g_2(x,Q^2)dx = 0$$

Hall C: Slifer et al. arXiv:0812.0031





Burkhardt Cottingham Sum



- Plot: K. Slifer
- Open points: Measured
- Solid points: Corrected for unmeasured regions and elastic contribution
- Green: Hall A E97-110
- Blue: Hall A E01-012
- Red: Hall C RSS
- Black: Hall A E94-010
- Brown: SLAC E155

Burkhardt & Cottingham, Ann. Phys. **56**(70)453

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

Spin Polarizabilities

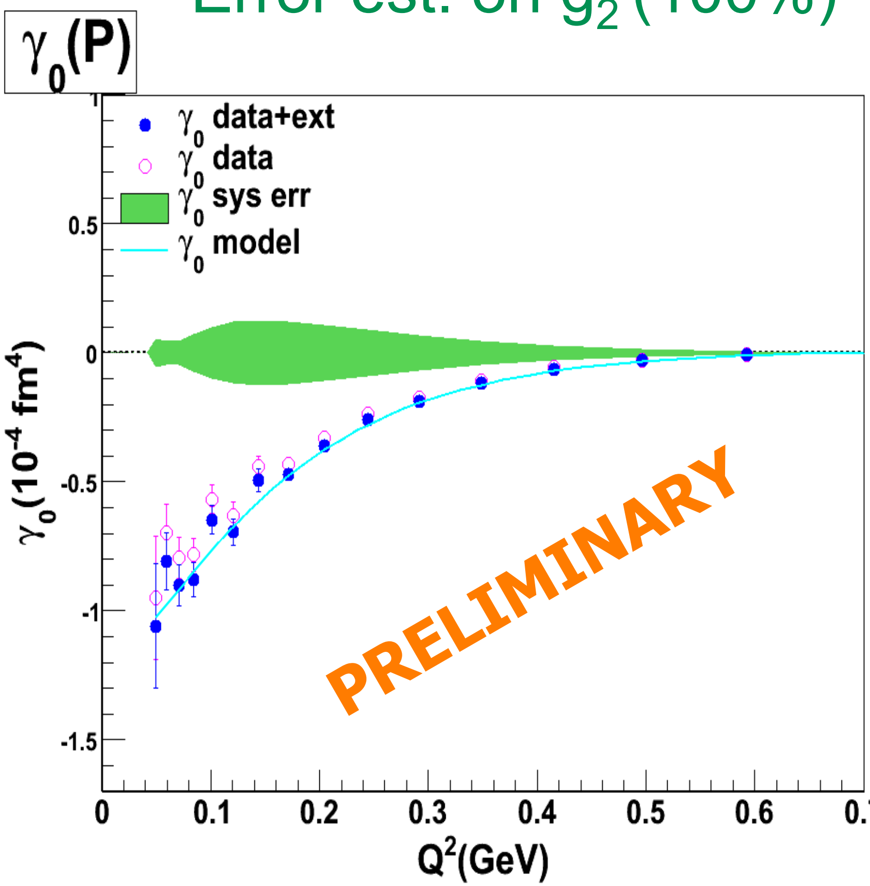
The spin polarizability can be expressed in terms of moments of g_1 and g_2. How this evolves at low Q^2 from the real photon point provides a rigorous test of chiral perturbation theory.

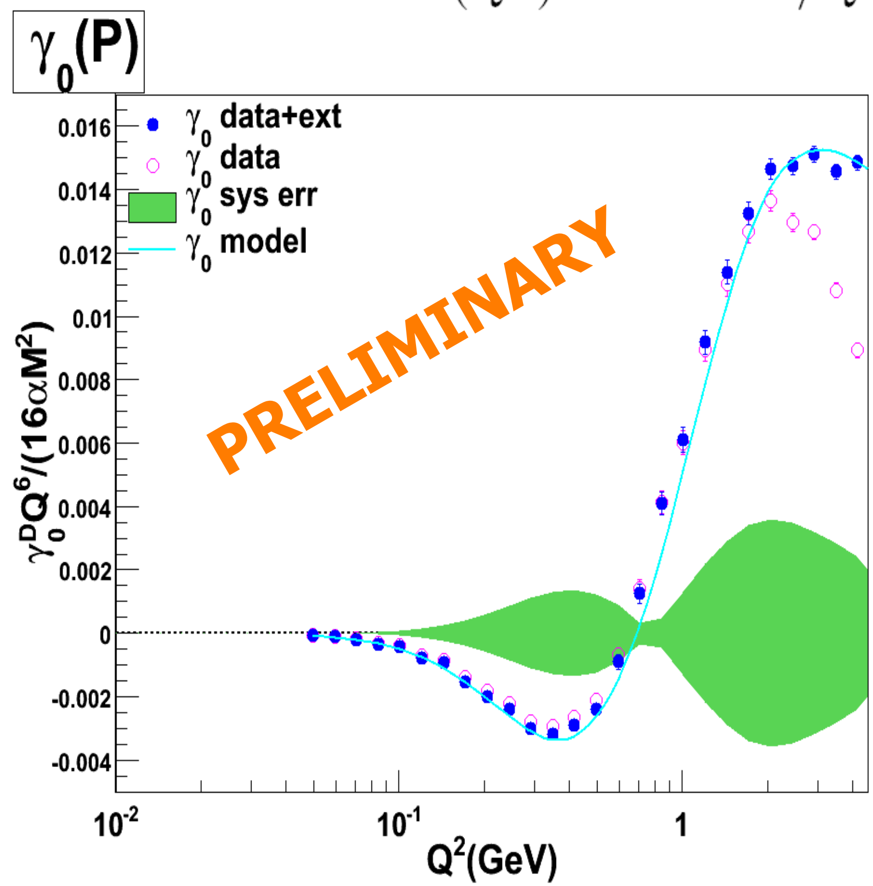
EG1b γ_0^p

$$\gamma_0(Q^2) = C(Q^2)\int_0^{x_0} x^2\left\{g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x,Q^2)\right\} dx$$

Error est. on g_2 (100%)

$$C(Q^2) = 16\alpha M^2/Q^6$$



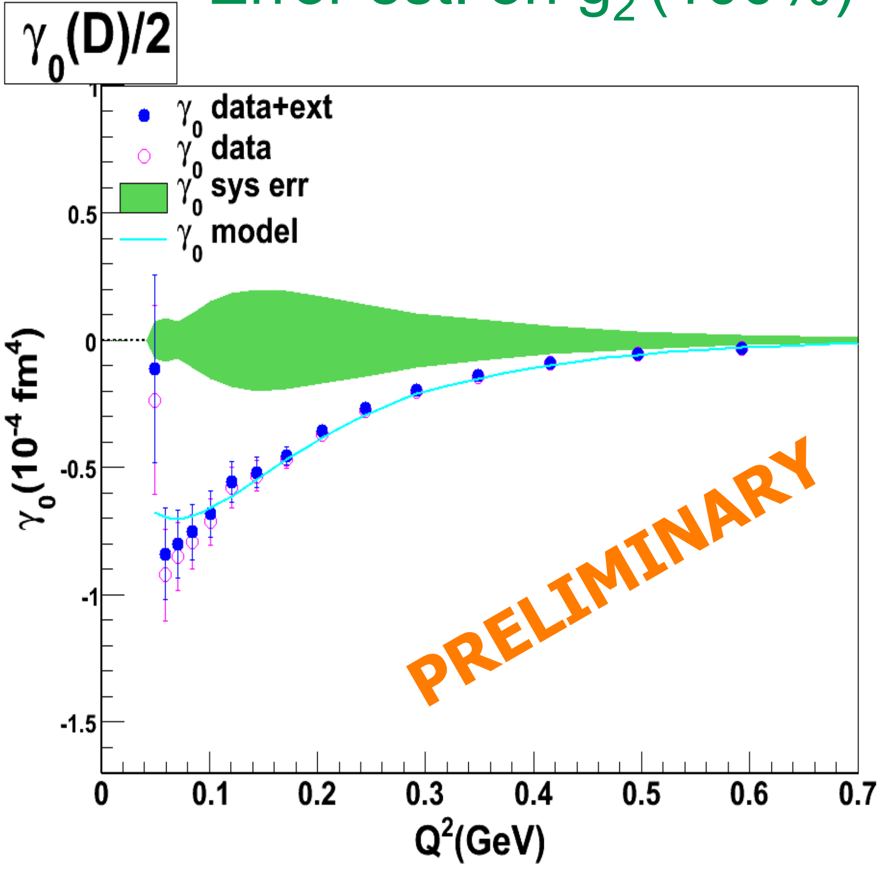


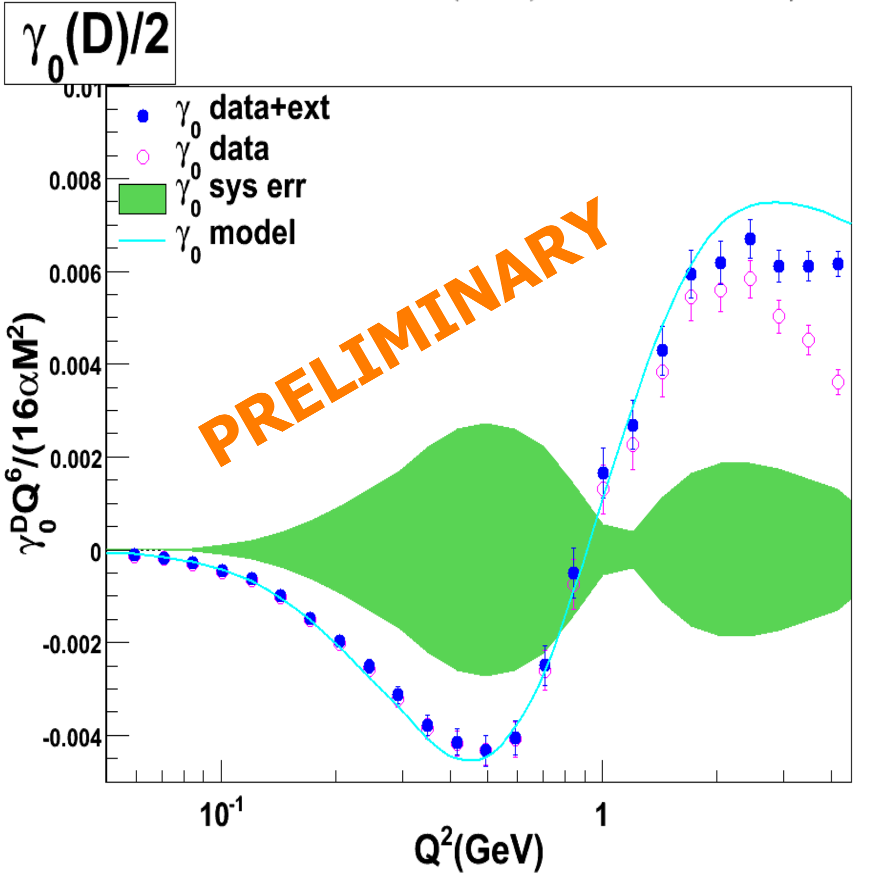
EG1b γ_0^d

$$\gamma_0(Q^2) = C(Q^2)\int_0^{x_0} x^2 \left\{ g_1(x,Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x,Q^2) \right\} dx$$

$$C(Q^2) = 16\alpha M^2/Q^6$$

Error est. on g_2 (100%)

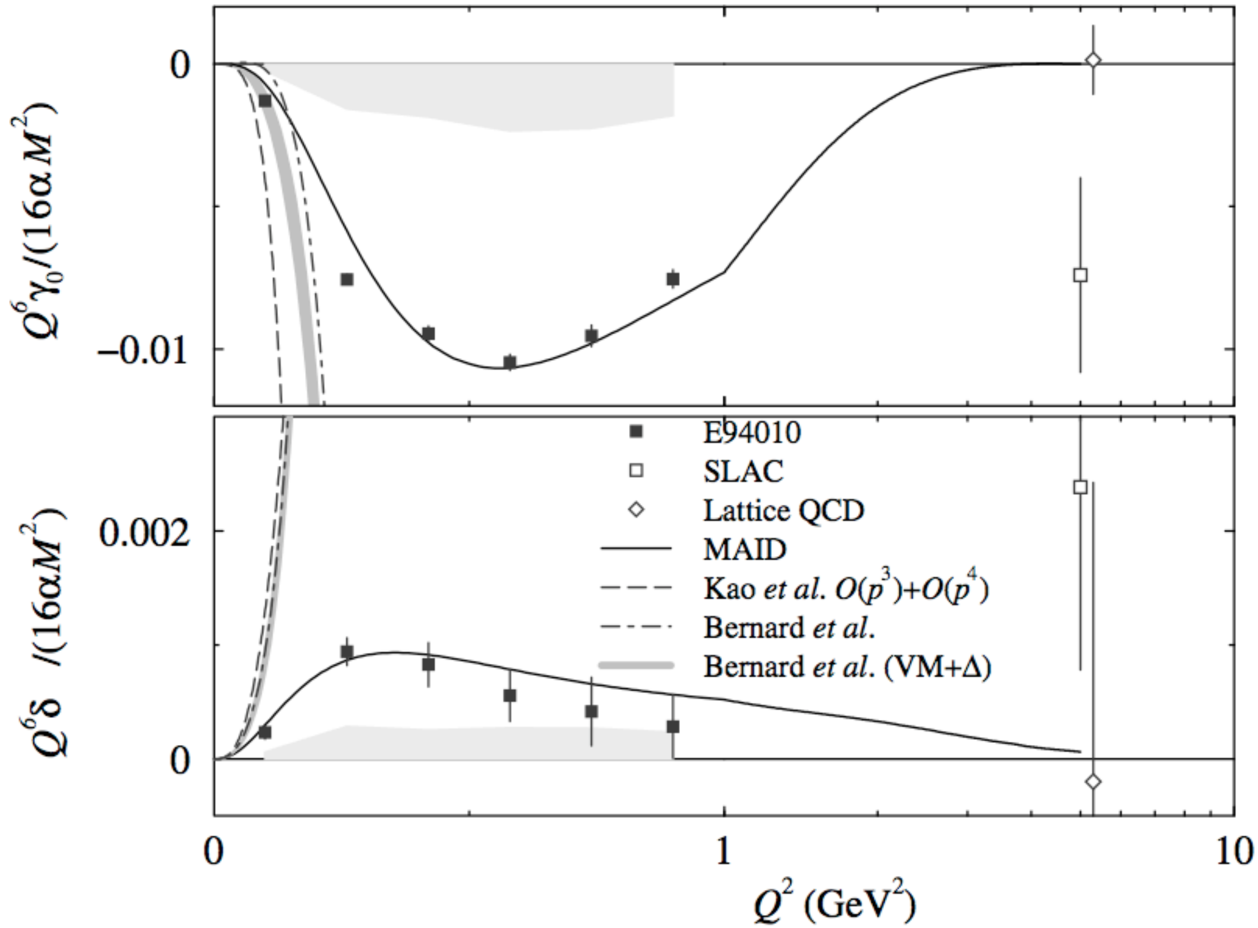




^{3}He Polarizabilities

$$\delta_{LT}(Q^2) = \left(\frac{1}{2\pi^2}\right) \int_{\nu_0}^{\infty} \frac{K(\nu, Q^2)}{\nu} \frac{\sigma_{LT}(\nu, Q^2)}{Q\nu^2} d\nu$$
$$= \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 [g_1(x, Q^2) + g_2(x, Q^2)] dx$$

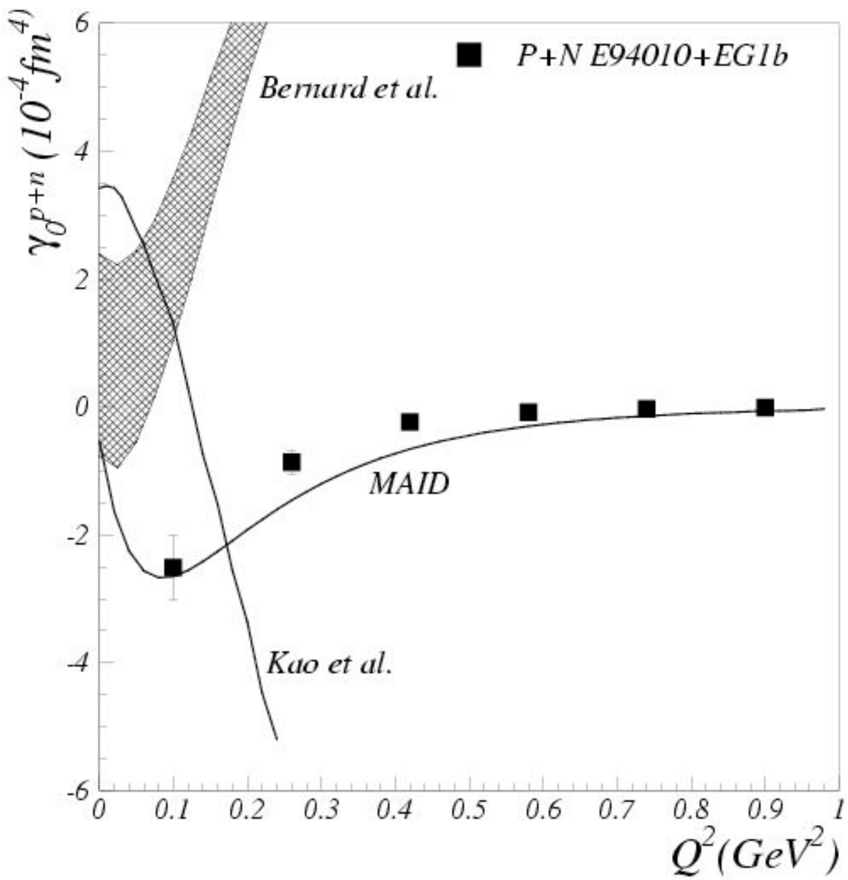
Hall A
Amarian,
PRL93(04)1152301

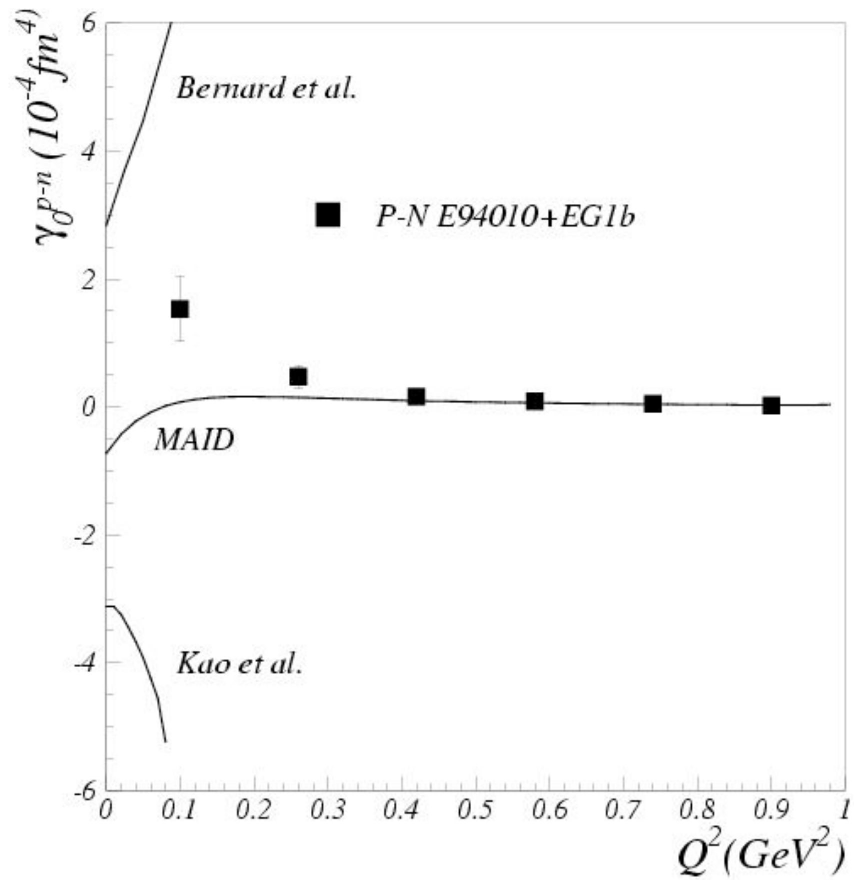


γ_0^{p-n} and γ_0^{p+n}

A Deur
CLAS + Hall A

For isovector (p-n) case
Δ contribution cancels





The GDH Sum Rule

At low Q^2, the evolution of the first moment of g_1 should be proportional to Q^2 and to the square of the anomalous magnetic moment of the nucleon. Data are now available to test this.

Global Properties

Energy-Weighted Sum Rule

$$S(F) = \Sigma_a (E_a - E_0) |\langle a|F|0\rangle|^2 = \langle 0|[F,[H,F]]|0\rangle$$

GDH Sum Rule

$$\int_{k_\pi}^{\infty} \frac{dk}{k} \Delta\sigma^{\gamma N}(k) = \frac{2\pi^2 \alpha \kappa^2}{M^2}$$

$$\Delta\sigma^{\gamma N} = \sigma_{3/2}^{\gamma N} - \sigma_{1/2}^{\gamma N}$$

Sum over excited states is tied to property of ground state

CLAS Moments $\Gamma_1^{p,d}$

$$\Gamma_1^{p,d}(Q^2) = \int_0^1 g_1^{p,d}(x, Q^2)dx \qquad \Gamma_1(Q^2) = aQ^2 + bQ^4 + cQ^6 + dQ^8$$

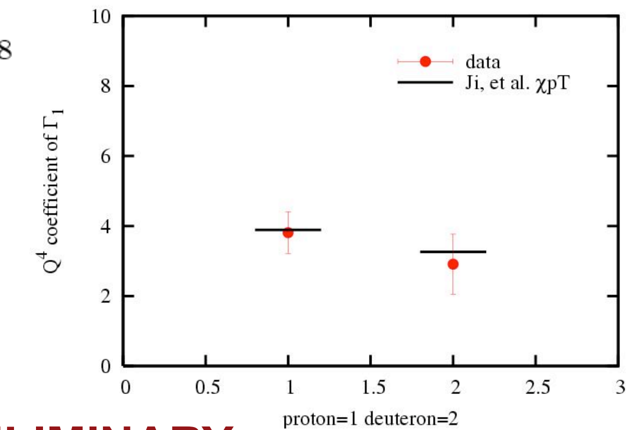
low Q^2 fit

$$\Gamma_1^d(Q^2) = (1 - 1.5\omega_D)\left\{\Gamma_1^p(Q^2) + \Gamma_1^n(Q^2)\right\}$$

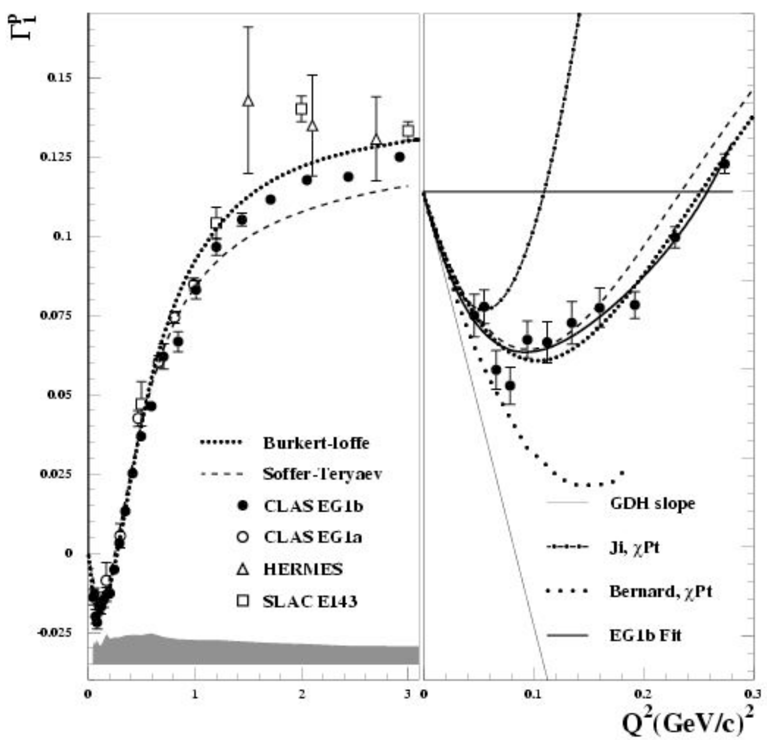
$$\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2}Q^2 + 3.89Q^4 + \ldots$$

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

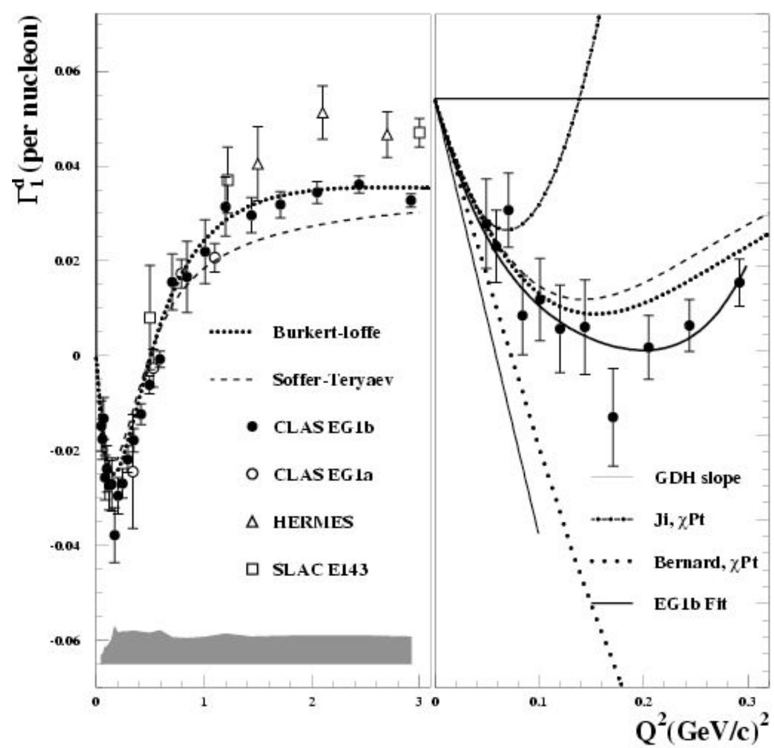
GDH + χpT



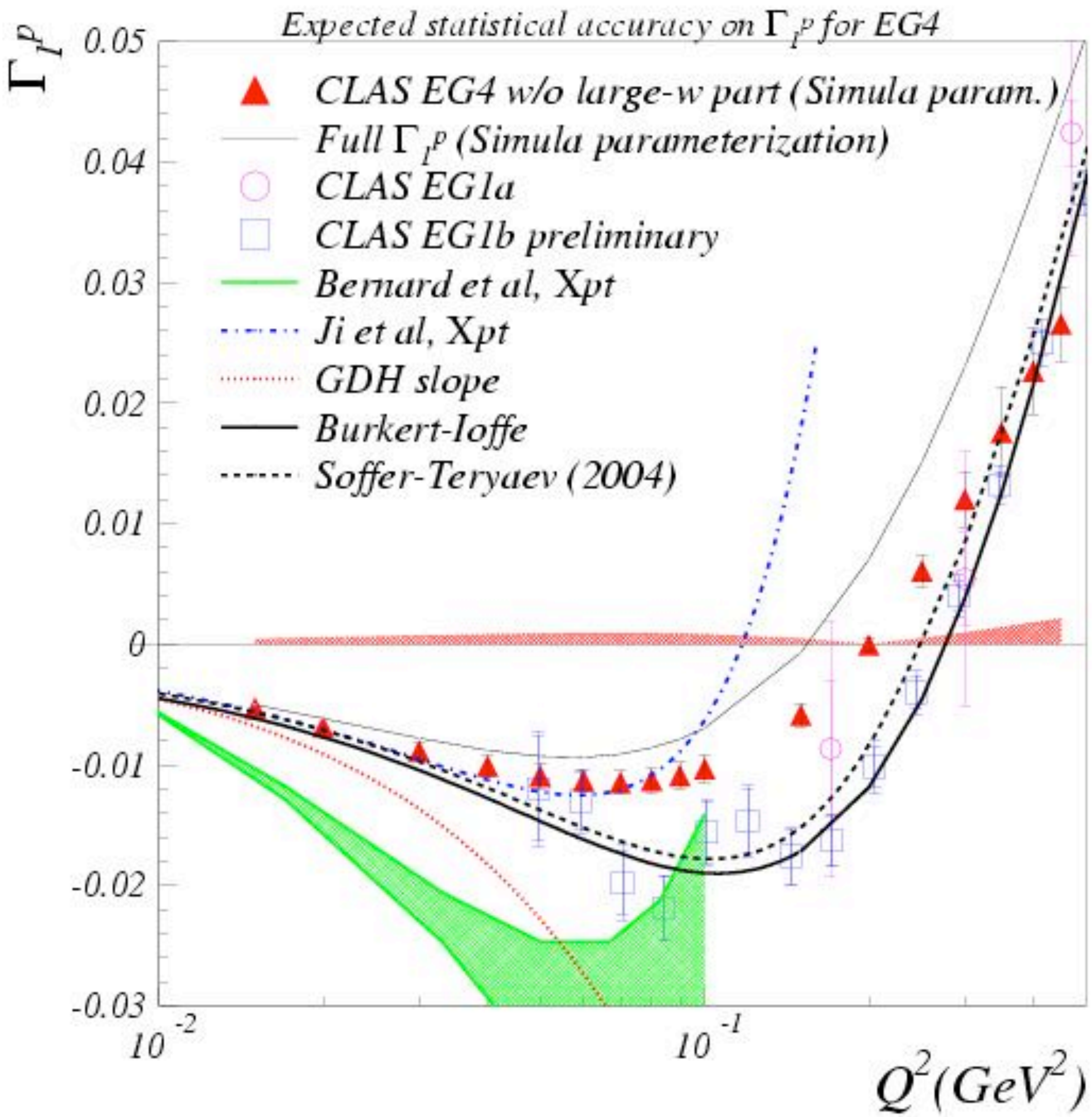
PRELIMINARY



PRELIMINARY



EG4 Γ_1^p Expected



The Spin Crisis

Where does the spin of the nucleon come from? Only a quarter comes from the quark spins. The rest must be gluon polarization and orbital angular momentum; both of these are hard to measure. However, data are becoming available that suggest the gluon polarization is small.

The Spin Puzzle

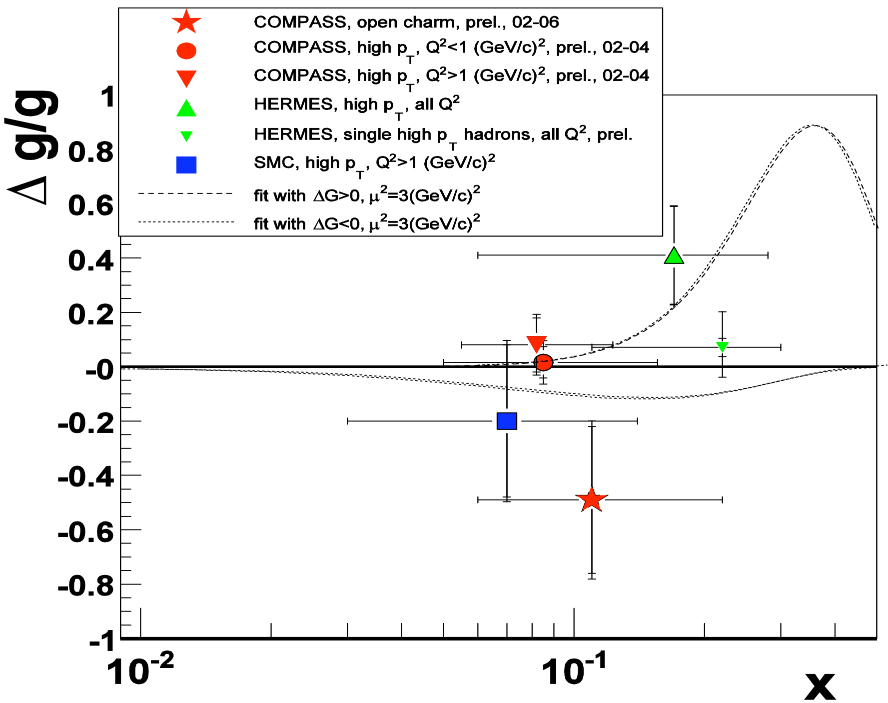
$$\frac{1}{2} = \frac{\Delta\Sigma}{2} + \Delta G + L_z$$

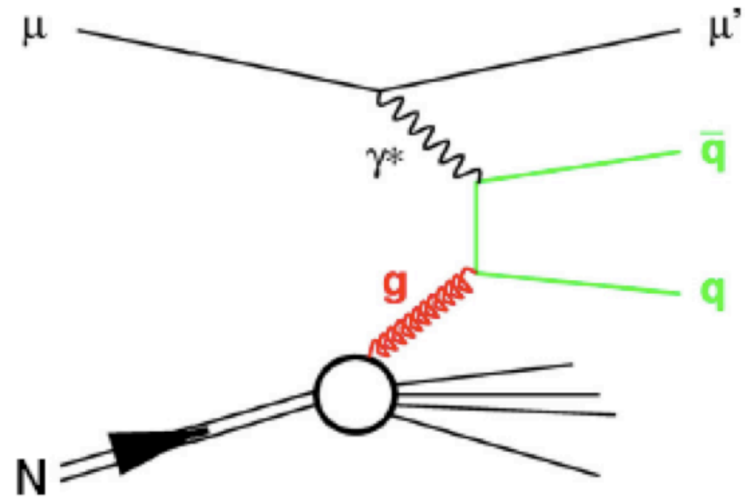
Known

Could be constrained by QCD evolution but this requires an understanding of higher twist at moderate Q^2. Direct measures through photon-gluon fusion and pp reactions.

Transverse momentum dependent distributions and generalized parton distributions
are sensitive to quark orbital angular momentum

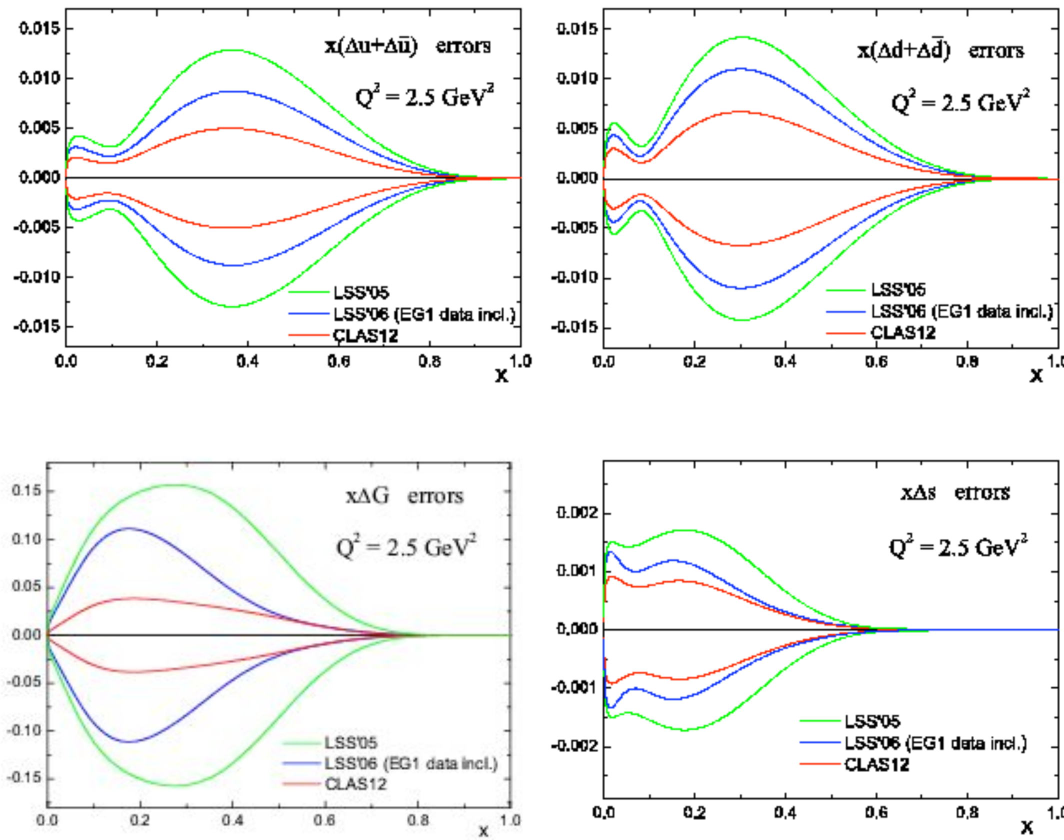
Δg





Photon-gluon fusion measurements show
a relatively small polarized gluon distribution.

PDFs and CLAS



- Error envelopes for PDFs from LSS05 global analysis (green)
- CLAS EG1 data significantly improve errors on Δu, Δd, Δx and ΔG (blue)
- CLAS EG12 (12 GeV upgrade) will especially improve ΔG (red)

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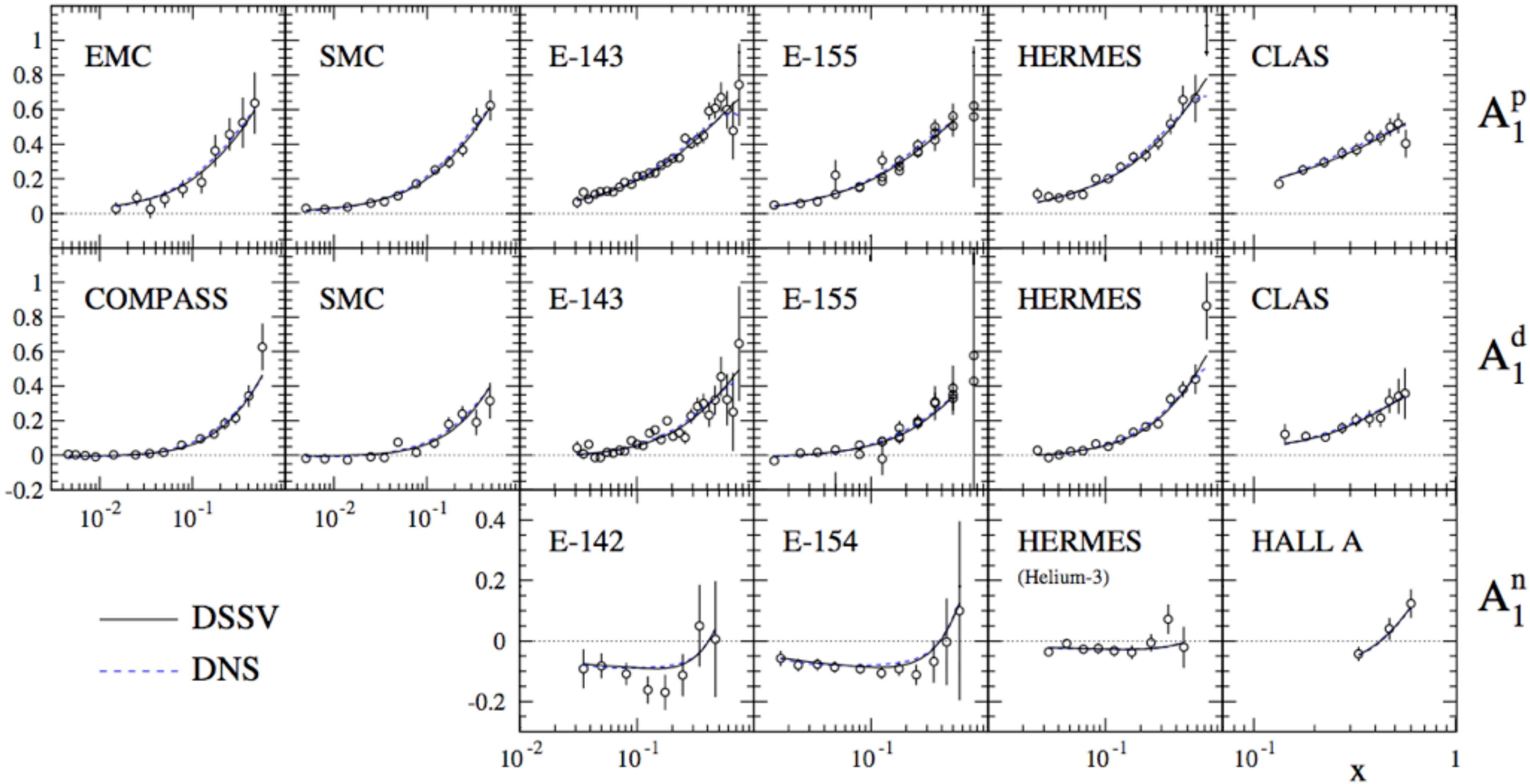
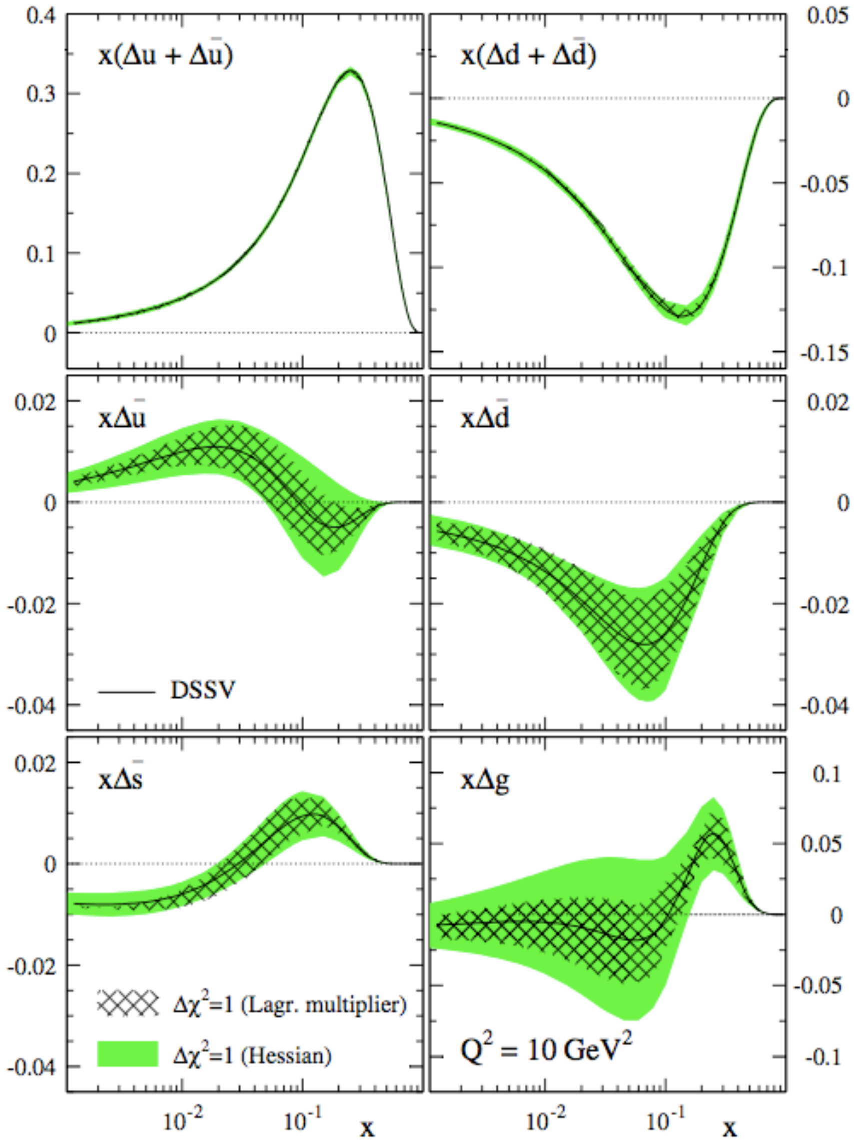
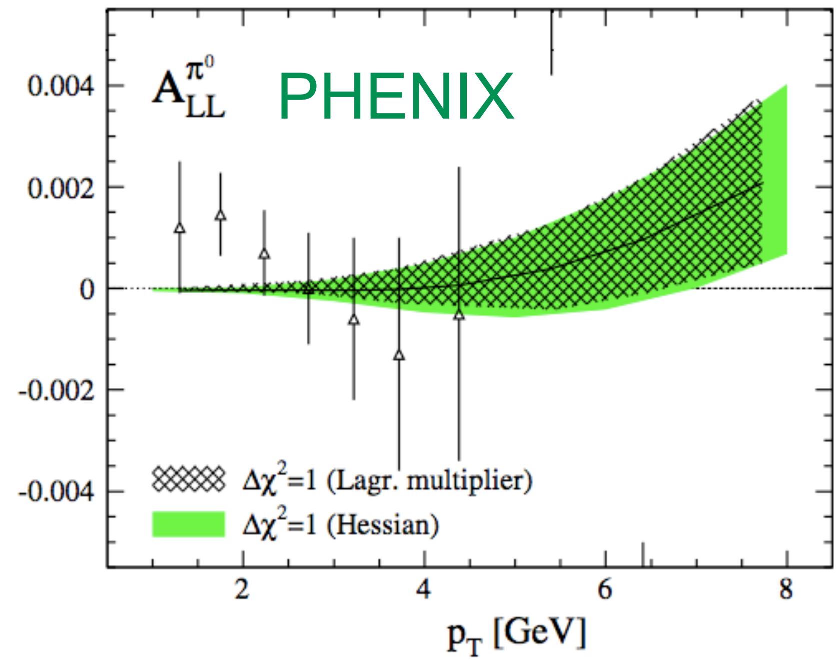
NLO Fits to A_1



DeFlorian, Sassot, Stratmann & Vogelsang (DSSV) PRD80(09)034030

Polarized PDFs





Double polarized
pp scattering occurs through
qq, qg or gg scattering.
Later two are sensitive to Δg

DSSV PDFs

x range in Eq. (35)	Q^2 [GeV^2]	$\Delta u + \Delta \bar{u}$	$\Delta d + \Delta \bar{d}$	$\Delta \bar{u}$	$\Delta \bar{d}$	$\Delta \bar{s}$	Δg	$\Delta \Sigma$
0.001–1.0	1	0.809	−0.417	0.034	−0.089	−0.006	−0.118	0.381
	4	0.798	−0.417	0.030	−0.090	−0.006	−0.035	0.369
	10	0.793	−0.416	0.028	−0.089	−0.006	0.013	0.366
	100	0.785	−0.412	0.026	−0.088	−0.005	0.117	0.363
0.0–1.0	1	0.817	−0.453	0.037	−0.112	−0.055	−0.118	0.255
	4	0.814	−0.456	0.036	−0.114	−0.056	−0.096	0.245
	10	0.813	−0.458	0.036	−0.115	−0.057	−0.084	0.242
	100	0.812	−0.459	0.036	−0.116	−0.058	−0.058	0.238

- Significant contributions from x<0.001
- ΔG vanishes with increasing Q^2
- $1/2 = (1/2)\Delta\Sigma + \Delta G + L_z$ implies:
- At Q^2=4 GeV^2, L_z = 0.474 (large)
- Errors on ΔG are still very large

Orbital Angular Momentum

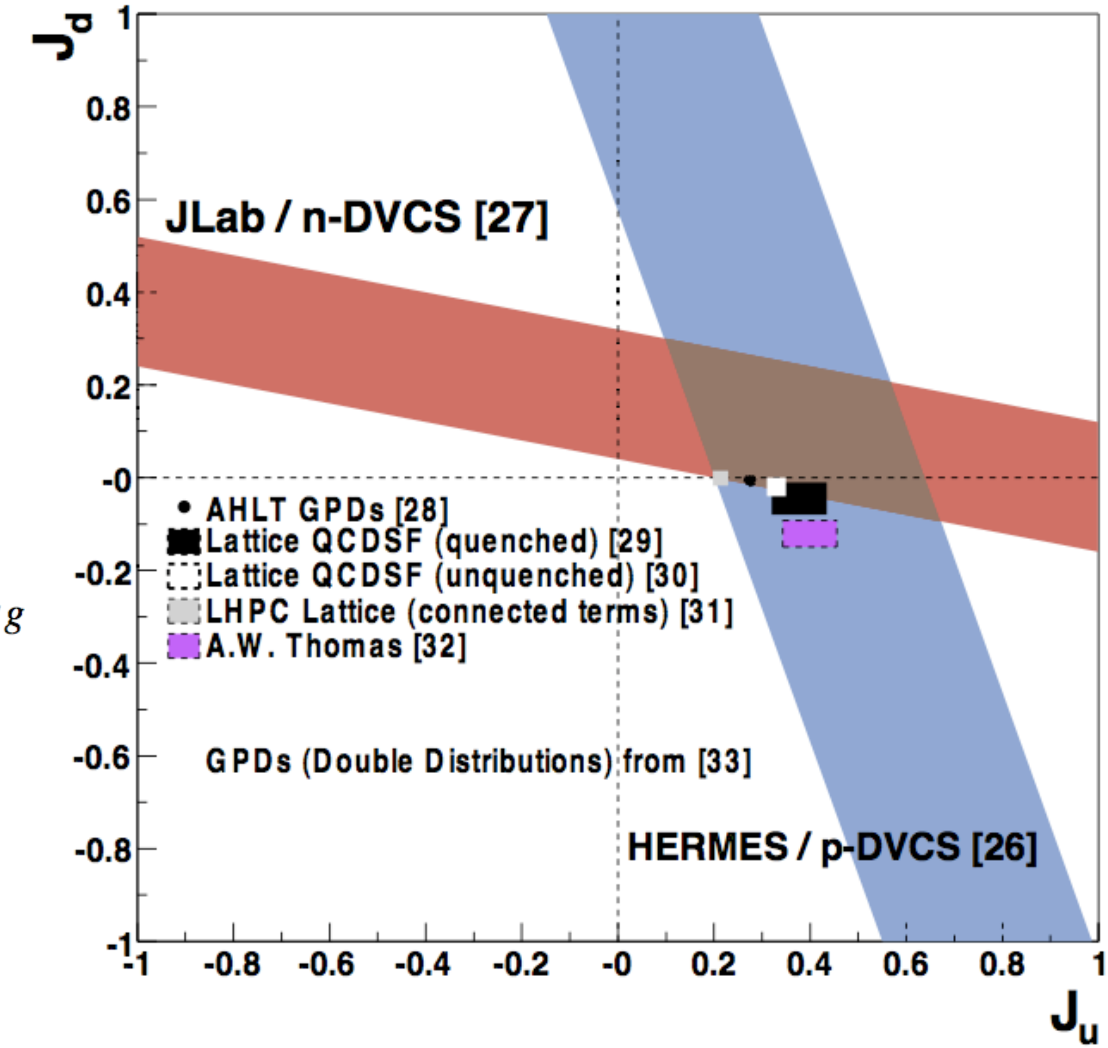
Plot: Voutier, arXiv:0802.2499
[27] Mazouz et al., PRL**99**(07)2425
[26] Airapetian et al., arXiv:0802.2499

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$

$$J_g = L_g + \Delta g$$

$$J_q(x) = \frac{1}{2}x[q(x) + E_q(x)]$$



OAM accessed through GPDs via deeply virtual Compton scattering

HYPERFINE

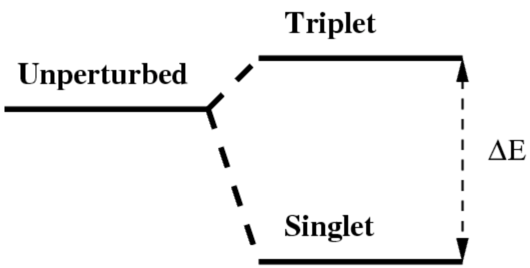
The 21 cm line in hydrogen (ground-state hyperfine splitting) has been measured to 13 digits of accuracy. Theoretical calculations are limited to parts per million because of the nuclear physics that depends on g_1 and g_2. Recent data improves this calculation.

Hydrogen Hyperfine Splitting

Carlson, Nazaryan, Griffioen, PRA**78**(08)022517

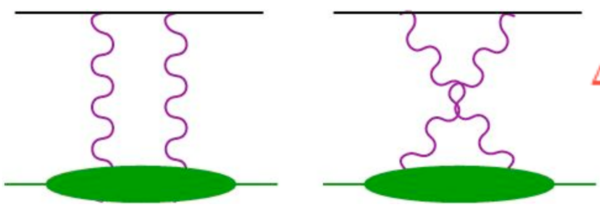
$$E_{\rm HFS}(e^- p) = 1.42040575177667(9)\,{\rm GHz} = (1+\Delta_{QED}+\Delta_R^p+\Delta_S)E_F^p$$

$$\Delta_S = \Delta_Z + \Delta_{\rm pol} \qquad \delta_Z^{\rm rad} = \frac{\alpha}{3\pi}\left[2\ln\frac{\Lambda^2}{m^2} - \frac{4111}{420}\right]$$



Zemach: $\Delta_Z = -2\alpha m_e \langle r\rangle_Z (1+\delta_Z^{\rm rad})$

$$\langle r\rangle_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa} - 1\right]$$



$\Delta_S = -38.62(16)$ ppm $\quad \Delta_Z = -41.0(5)$ ppm

$\Delta_{\rm pol} = 2.38(58)$ ppm

$$\Delta_{\rm pol} = \frac{\alpha m_e}{2\pi(1+\kappa)M}(\Delta_1+\Delta_2) = (0.2264798\ {\rm ppm})(\Delta_1+\Delta_2)$$

$$\tau = \nu^2/Q^2$$

$$\Delta_1 = \frac{9}{4}\int_0^\infty \frac{dQ^2}{Q^2}\left\{F_2^2(Q^2) + \frac{8m_p^2}{Q^2}B_1(Q^2)\right\} = 8.85(278)$$

$$\Delta_2 = -24m_p^2\int_0^\infty \frac{dQ^2}{Q^4}B_2(Q^2). = -0.57(57)$$

$$B_1 = \int_0^{x_{\rm th}} dx\,\beta(\tau)g_1(x,Q^2)\,,$$

$$B_2 = \int_0^{x_{\rm th}} dx\,\beta_2(\tau)g_2(x,Q^2)\,,$$

$$\beta(\tau) = \frac{4}{9}\left(-3\tau+2\tau^2+2(2-\tau)\sqrt{\tau(\tau+1)}\right)$$

$$\beta_2(\tau) = 1+2\tau-2\sqrt{\tau(\tau+1)}\,,$$

$\Delta_{\rm pol}$ = 1.88(64) ppm from CLAS

COMMENSURATE SCALING

The QCD is scale-independent BOTH at high Q^2 and low Q^2. By defining an effective coupling constant consistent with the form from NLO pQCD, the relationship of these constants can be calculated.

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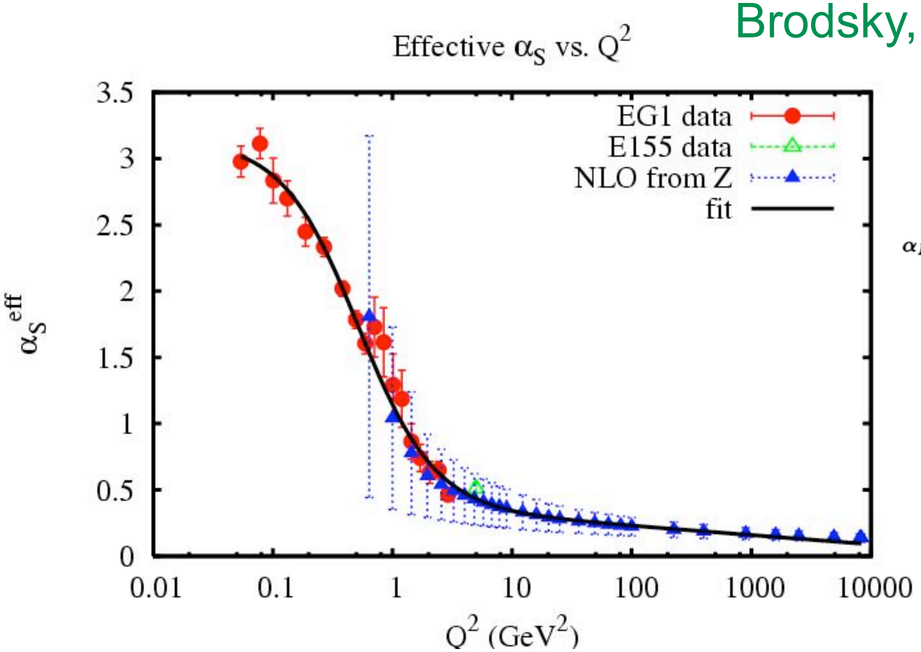
Commensurate Scaling

Brodsky, Lu, PRD**51**(95)3652; Deur, PLB**650**(07)244



$$\int_0^1 dx\,[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{1}{3}\left|\frac{g_A}{g_V}\right|\left[1 - \frac{\alpha_{g_1}(Q)}{\pi}\right]$$

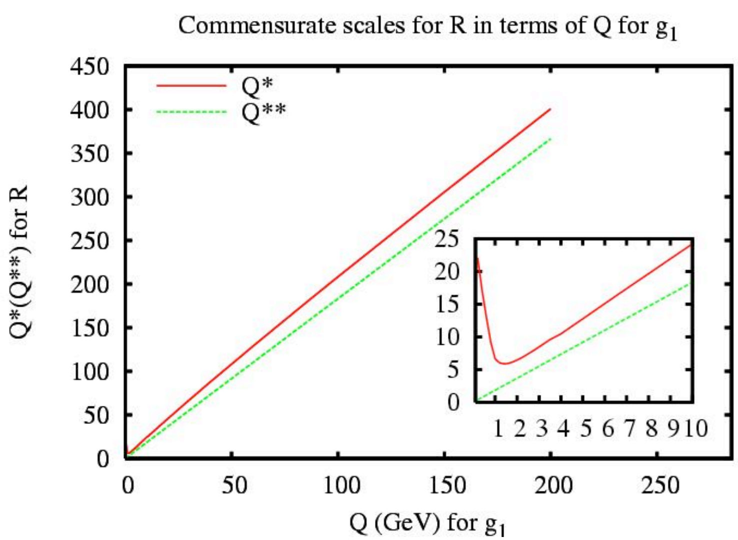
$$R(Q) \equiv 3\sum_f Q_f^2\left[1 + \frac{\alpha_R(Q)}{\pi}\right]$$

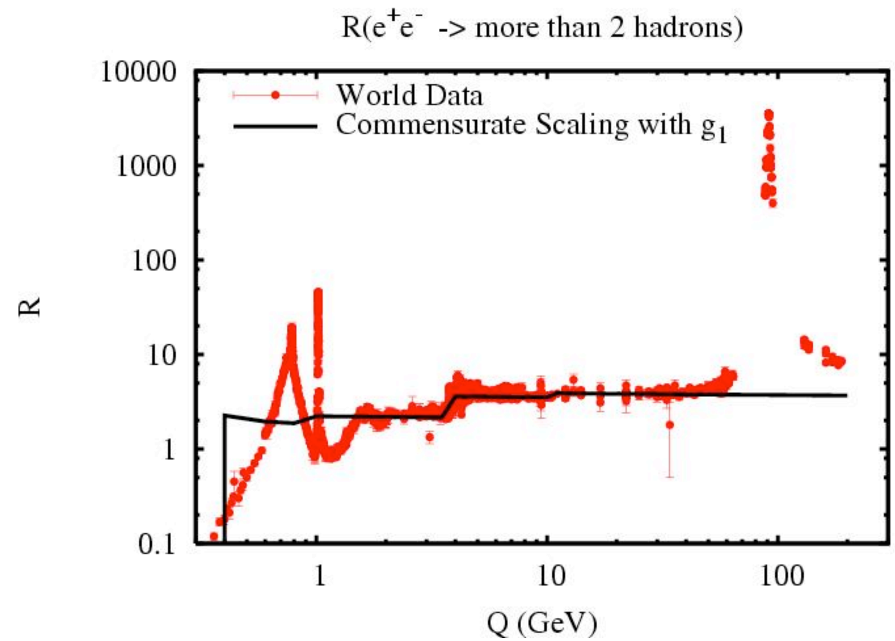
$\alpha_R(Q)$ in terms of $\alpha_{g_1}(Q)$.

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{g_1}(Q^*)}{\pi} + \frac{3}{4}C_F\left(\frac{\alpha_{g_1}(Q^{**})}{\pi}\right)^2 + \left[\frac{9}{16}C_F^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right)\frac{d^{abc}d^{abc}}{C_F N}\frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right]\left(\frac{\alpha_{g_1}(Q^{***})}{\pi}\right)^3,$$

$$\ln(Q^*/Q) = -\frac{7}{4} + 2\zeta_3 + \left(-\frac{11}{96} - \frac{7}{3}\zeta_3 + 2\zeta_3^2 + \frac{\pi^2}{24}\right)\left(\frac{11}{3}C_A - \frac{2}{3}f\right)\frac{\alpha_{g_1}(Q)}{\pi},$$

$$\ln(Q^{**}/Q) = -\frac{233}{216} + \frac{64}{9}\zeta_3 - \frac{20}{3}\zeta_5 + \left(-\frac{13}{54} + \frac{2}{9}\zeta_3\right)\frac{C_A}{C_F}.$$





CONCLUSIONS

Although much is known, there is still much to be learned about nucleon spin that will keep us busy for at least another decade.

Conclusions

- What's still missing:
  - high x: $A_1^{p,d}$ for polarized PDFs (CLAS12)
  - g_2^p (transverse target); SANE (Hall C) covers $Q^2>1$ GeV^2; nobody's measuring $Q^2<1$ GeV^2
  - low Q^2 evolution of $g_1^{p,d}$ (EG4)
  - gluon spin: evolution for $1< Q^2<10$ (CLAS12); direct measurements?
  - orbital angular momentum (GPD experiments)
- What's gained:
  - understanding three regions
    - Q^2 near 0 (χPT)
    - Q^2 from 0.1-10 GeV^2 (TMC, higher twists, resonances, the transition)
    - Q^2 near infinity (pQCD)