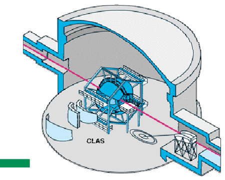

A Nucleon Observed: Of QCD, Higher Twist, and Hydrogen Hyperfine Splittings

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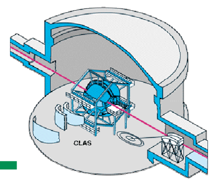
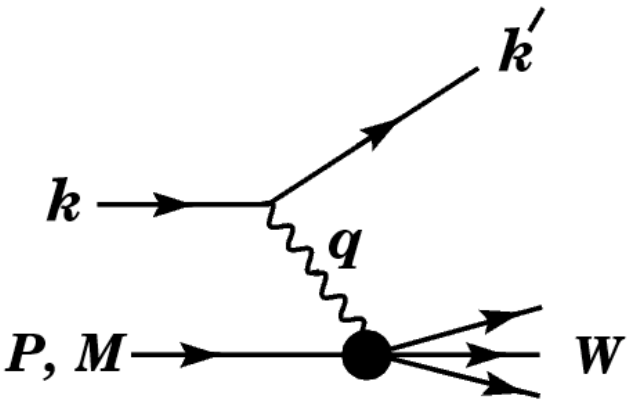
Nikhef Colloquium

4 September 2007

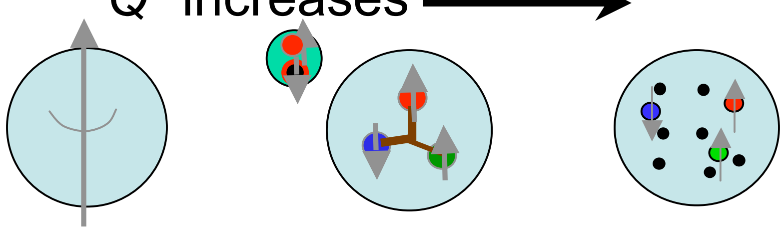
Inelastic Scattering





Lorentz invariants:

$\nu = p \cdot q/M = (E - E')_{\rm lab}$
$Q^2 = -q \cdot q = (4EE' \sin^2 \frac{\theta}{2})_{\rm lab}$
$x = -q \cdot q/2p \cdot q = (Q^2/2M\nu)_{\rm lab}$
$y = p \cdot q/p \cdot k = (\nu/E)_{\rm lab}$
$W^2 = (p+q)^2 = (M^2 + 2M\nu - Q^2)_{\rm lab}$
$s = (k+p)^2 = (2EM + M^2)_{\rm lab}$



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:

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

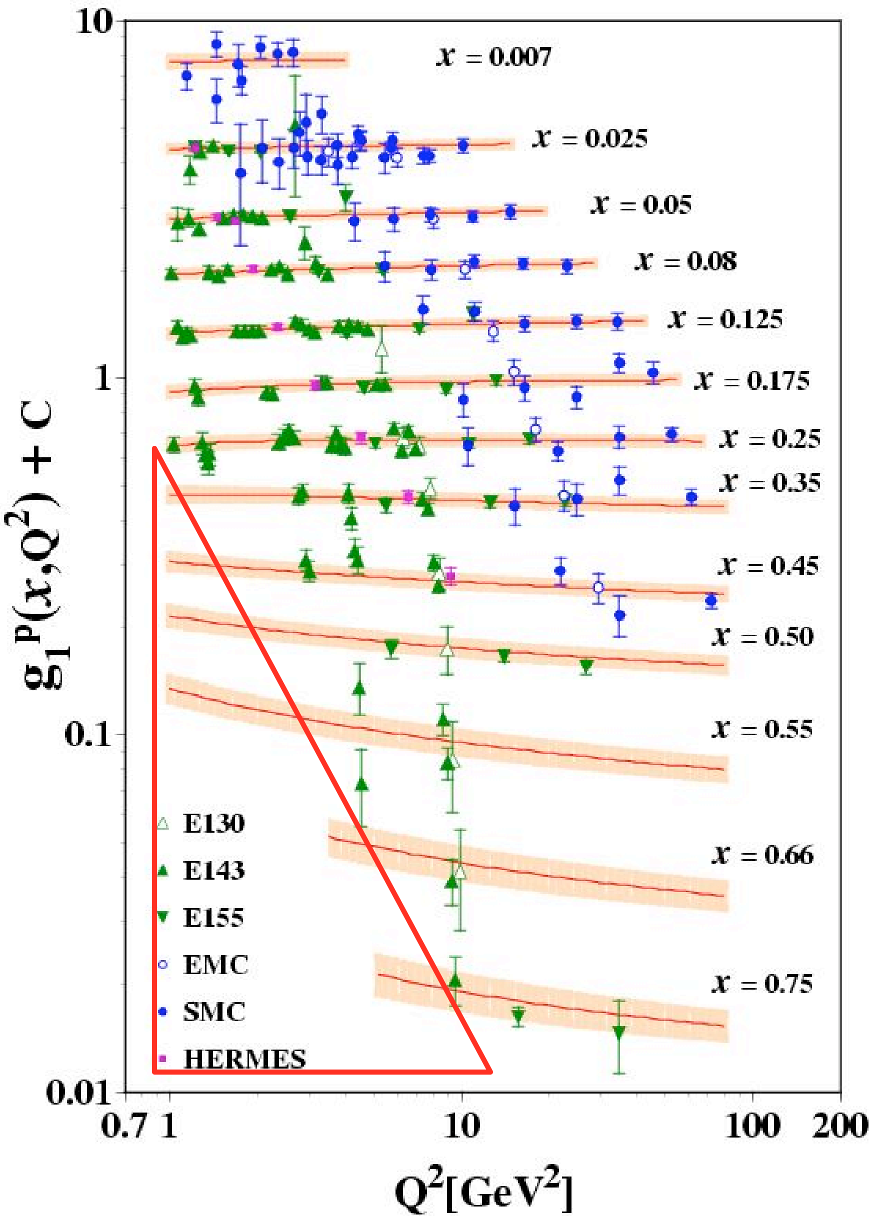
α = polar angle of target spin wrt the beam axis
ϕ = azimuthal spin angle wrt the scattering plane
$\alpha = 0°$ (longitudinal); $\alpha = 90°, \phi = 0°$ (transverse).
$\gamma^2 = 4M^2x^2/Q^2 = Q^2/\nu^2$
$\xi = 1 - y - \gamma y^2/4$

Parton Model:

$F_1(x, Q^2) = \frac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) + q^\downarrow(x) + \bar{q}^\uparrow(x) + \bar{q}^\downarrow(x))$
$F_2(x, Q^2) = 2xF_1(x, Q^2)$
$g_1(x, Q^2) = \frac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) - q^\downarrow(x) + \bar{q}^\uparrow(x) - \bar{q}^\downarrow(x))$
$g_2(x, Q^2) = 0$

$g_1(x,Q^2)$

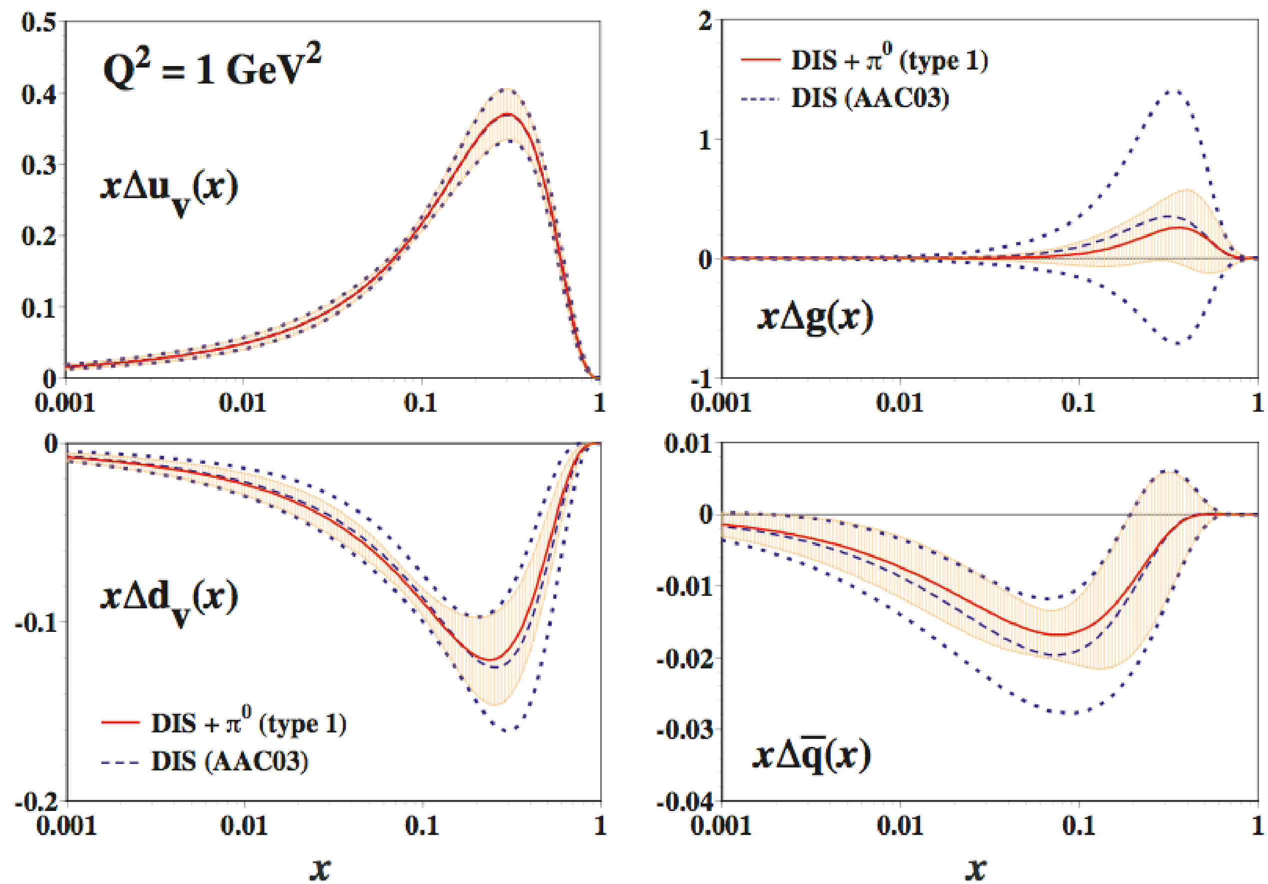
- g_1 DIS measured for p, d and ^{3}He
- CERN/HERA/SLAC
- (AAC: hepph0603213) NLO fits to extract quark and gluon distributions
- Notice the hole at high *x* and Q^2<10 GeV^2
- CLAS12 DIS coverage (red)
- CLAS 6 covers this triangle in the resonance region



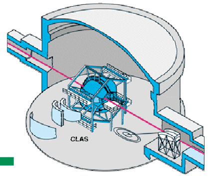
NLO Fits

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

	$\Delta\bar{q}$	Δg	$\Delta\Sigma$
Type 1	-0.05 ± 0.01	0.31 ± 0.32	0.27 ± 0.07
Type 2	-0.06 ± 0.02	0.47 ± 1.08	0.25 ± 0.10
AAC03	-0.06 ± 0.02	0.50 ± 1.27	0.21 ± 0.14



A Nucleon Observed



- We’ve measured quite a lot about the proton in the last 50 years since Hofstadter observed its charge distribution
  “Messen ist wissen” -- E. W. von Siemens
- The proton has proved to be quite complex
  “Il y a science des choses simples, et art des choses compliquées.” -- Paul Valéry
- There’s still a lot more work to be done
  “Great art is never produced for its own sake. It is too difficult to be worth the effort” -- George Bernard Shaw

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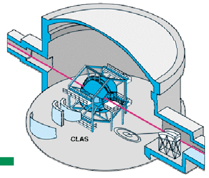
Toward Fewer Variables



Our tendency is to go from inclusive to exclusive reactions

$\boxed{f(x, Q^2)}$ $\boxed{f(x, Q^2, p_\perp)}$

Our tendency is to go from low resolution (Q^2) to high

Σ of constituents resolved constituents

Our tendency is to go from holism to reductionism

Much of his talk is about going in the other direction:

$$\int f(x, Q^2, p_\perp) dp_\perp \rightarrow f(x, Q^2)$$

$$\int f(x, Q^2) dx \rightarrow f(Q^2)$$

$$\int f(Q^2) dQ^2 \rightarrow \text{hyperfine splitting}$$

Global Properties

Energy-Weighted Sum Rule

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

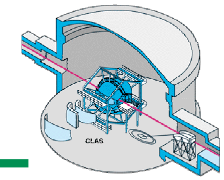
GDH Sum Rule

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

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

Sum over excited states is tied to properties of the ground state

At High Energy



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

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

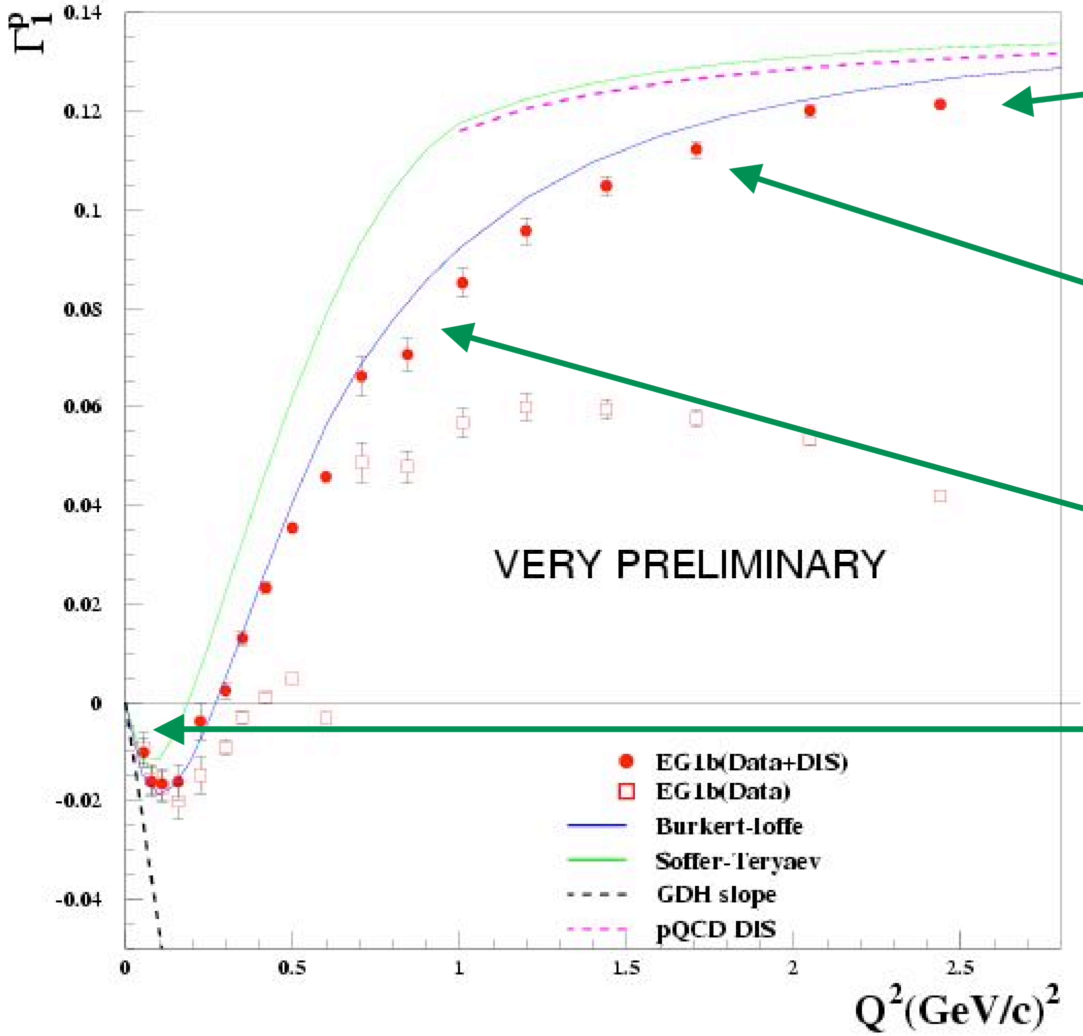
$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

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

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



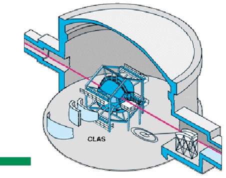
scaling: $\ln Q^2$

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

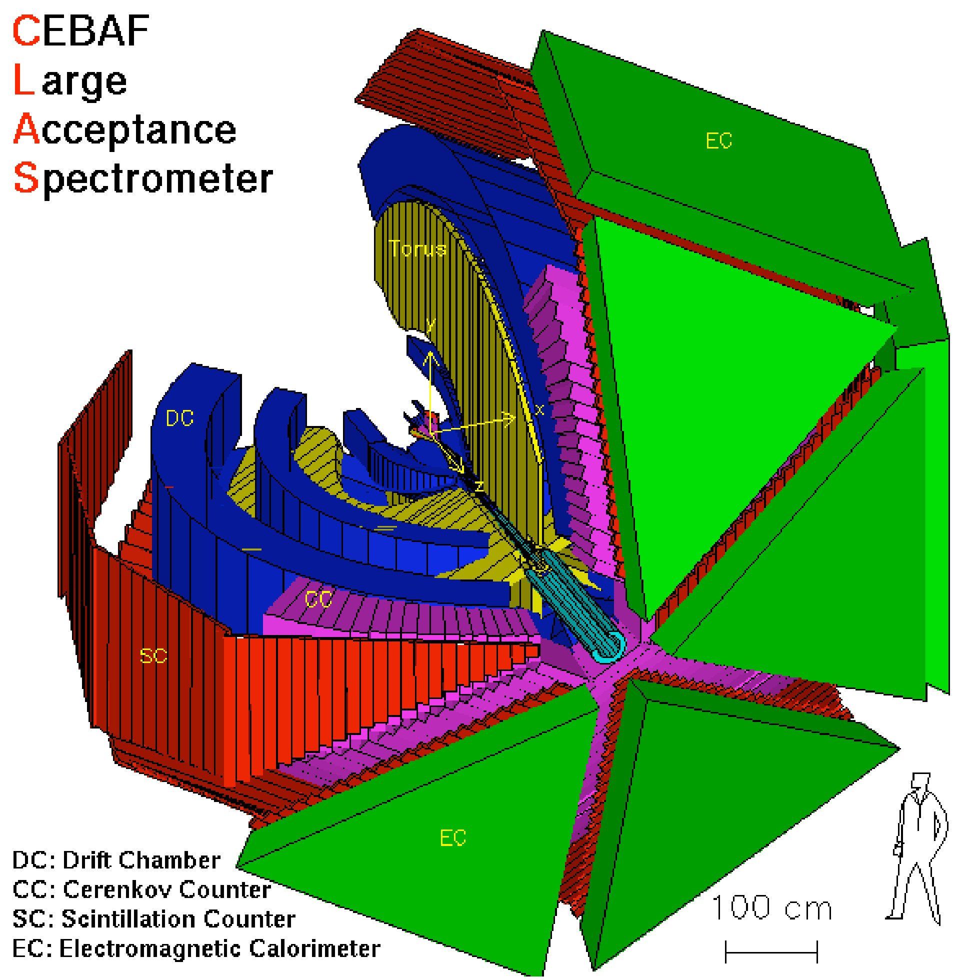
no nice expansion

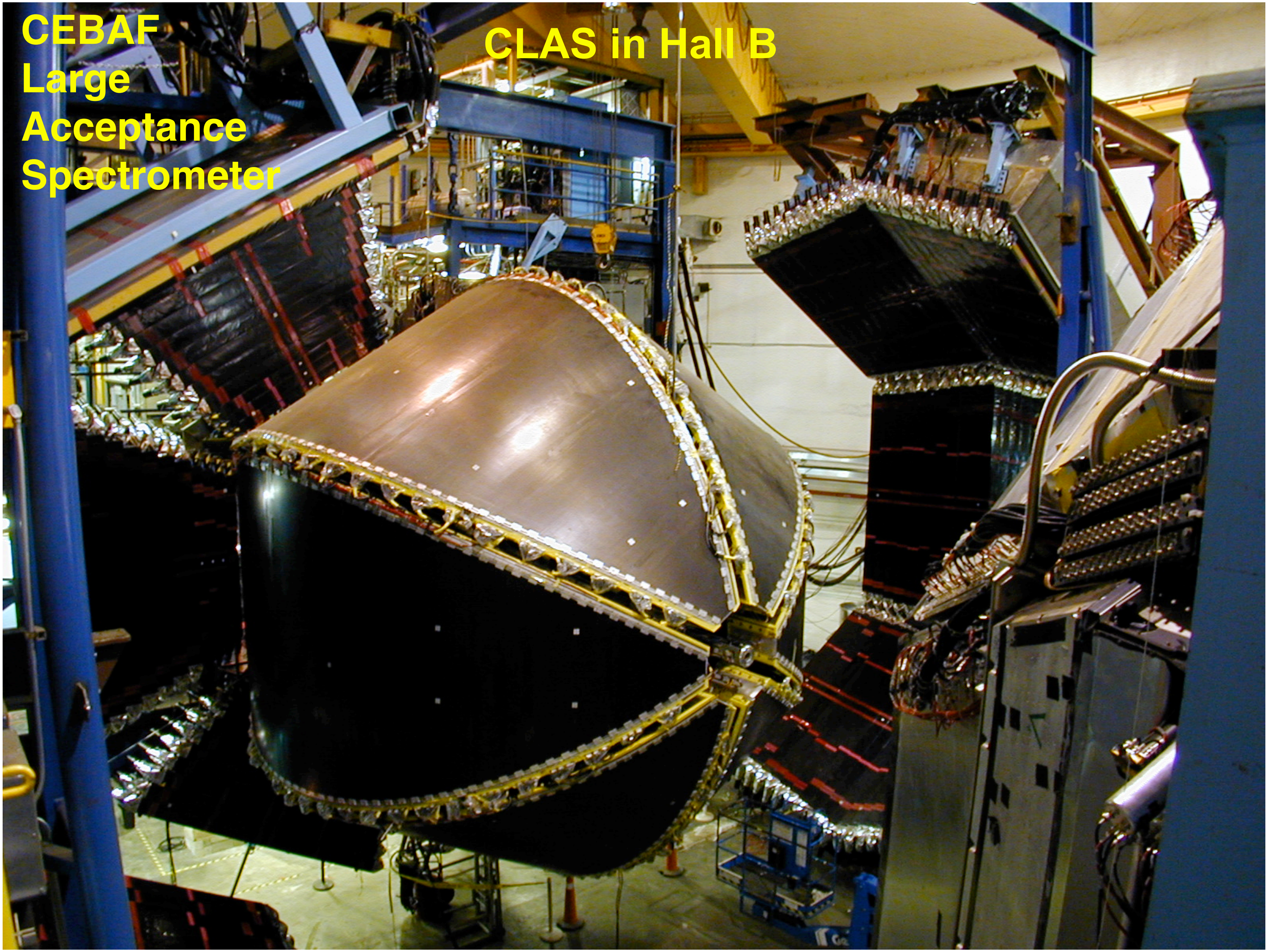
χPT: $(Q^2)^n$

Spin Structure with CLAS

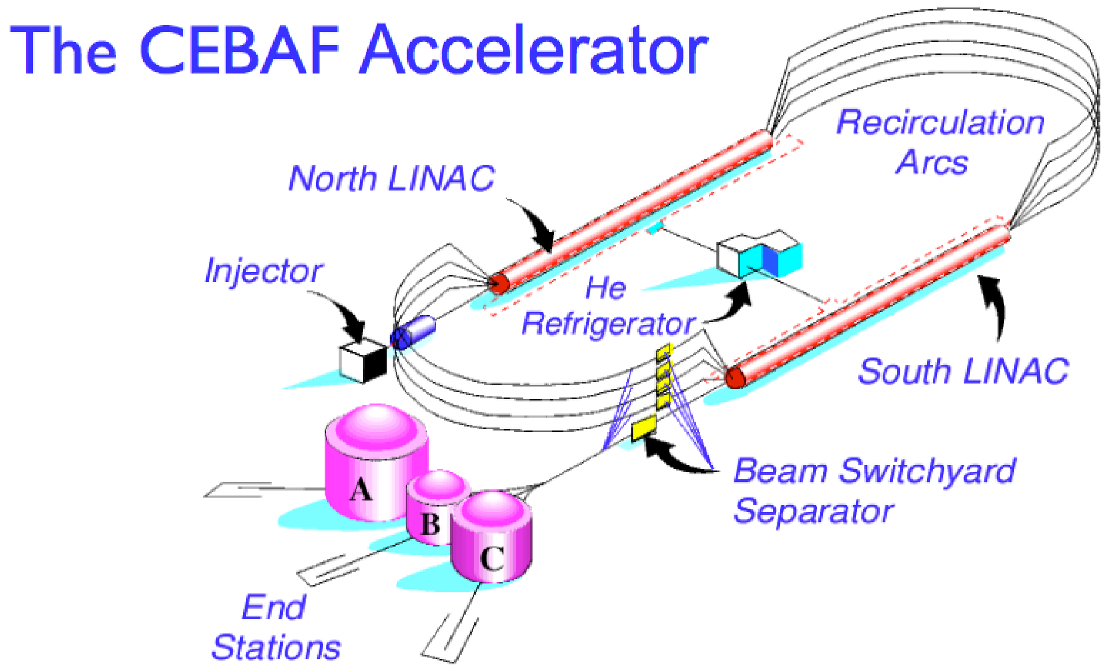


- Long-standing program in Hall-B at JLab to measure longitudinal double spin asymmetries $A_{||}$ on $^{15}NH_3$ and $^{15}ND_3$
- EG1: $0.05<Q^2<3.5$ GeV^2
  - data (2001); anal (2007)
- EG4: $0.01<Q^2<1$ GeV^2
  - data (2006); anal (2008)
- EG12: $0.5<Q^2<7$ GeV^2
  - data (2012?); anal (2014)




CEBAF
Large
Acceptance
Spectrometer
CLAS in Hall B

CEBAF Accelerator



- Electron beams up to 5.7 GeV with >80% longitudinal polarization
- Beam currents of 1-50 nA in Hall B

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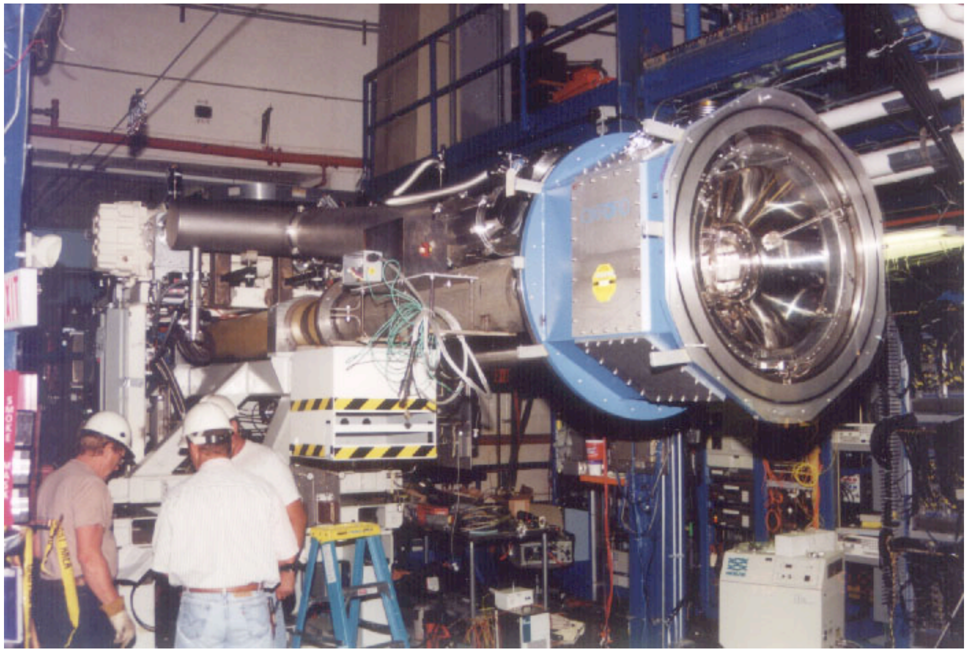
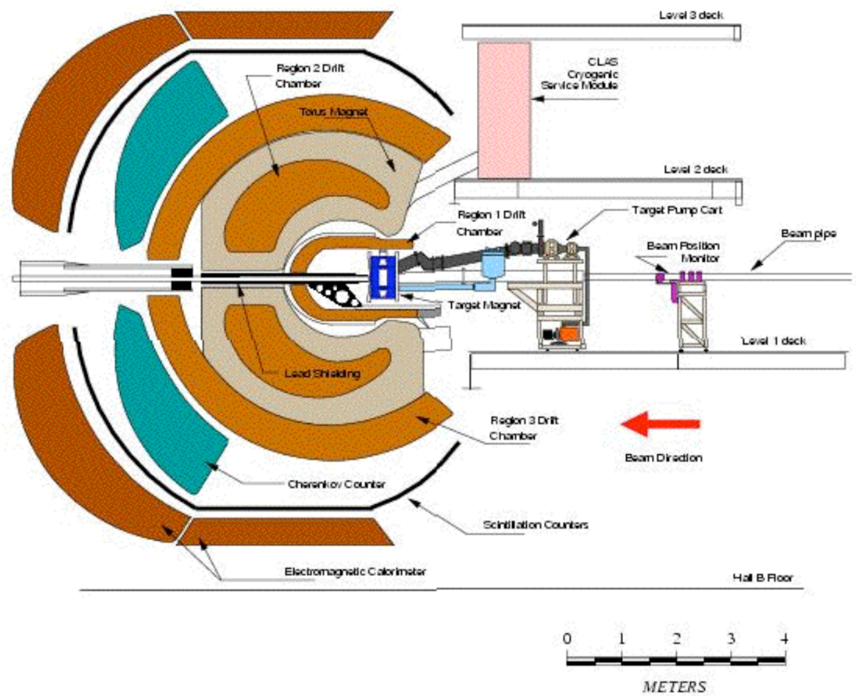
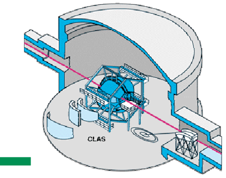
Polarized Target





- Dynamic nuclear polarization of NH_3 and ND_3
- Polarizations of 70-80% for p and 20-30% for d
- Luminosity 10^{35} $cm^{-2}s^{-1}$

Formalism



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

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

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

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

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

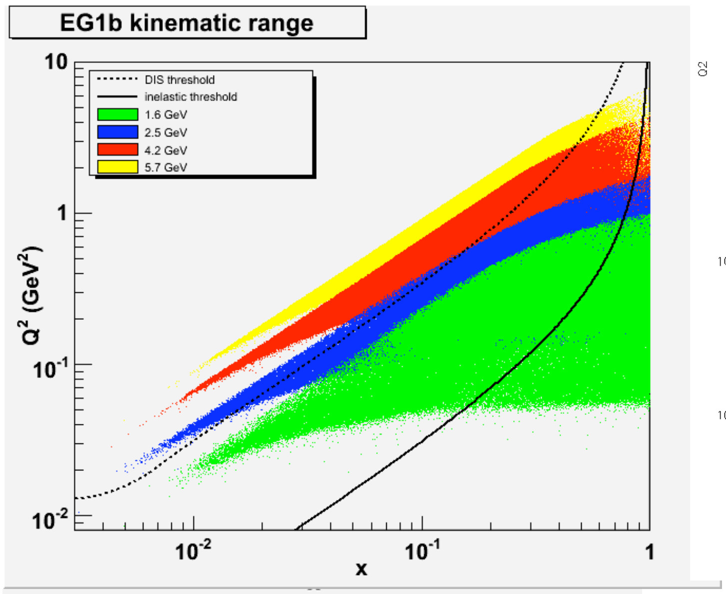
$$A_2 = \frac{2\sigma_{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

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

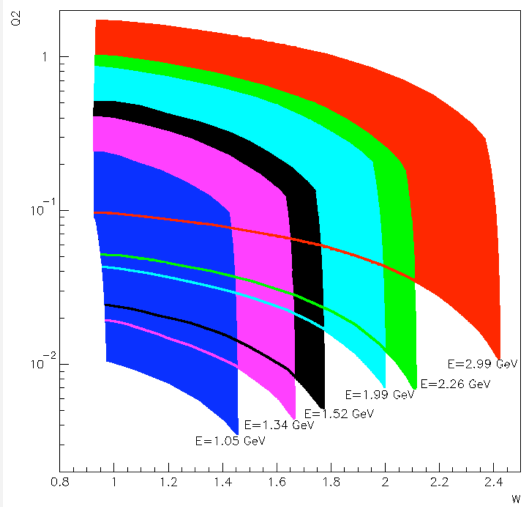
$$= \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

Kinematics

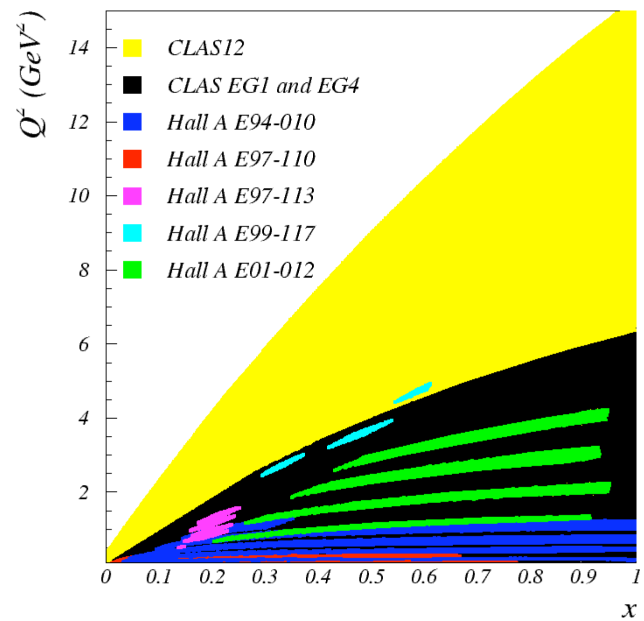
EG1



EG4



EG12



- 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

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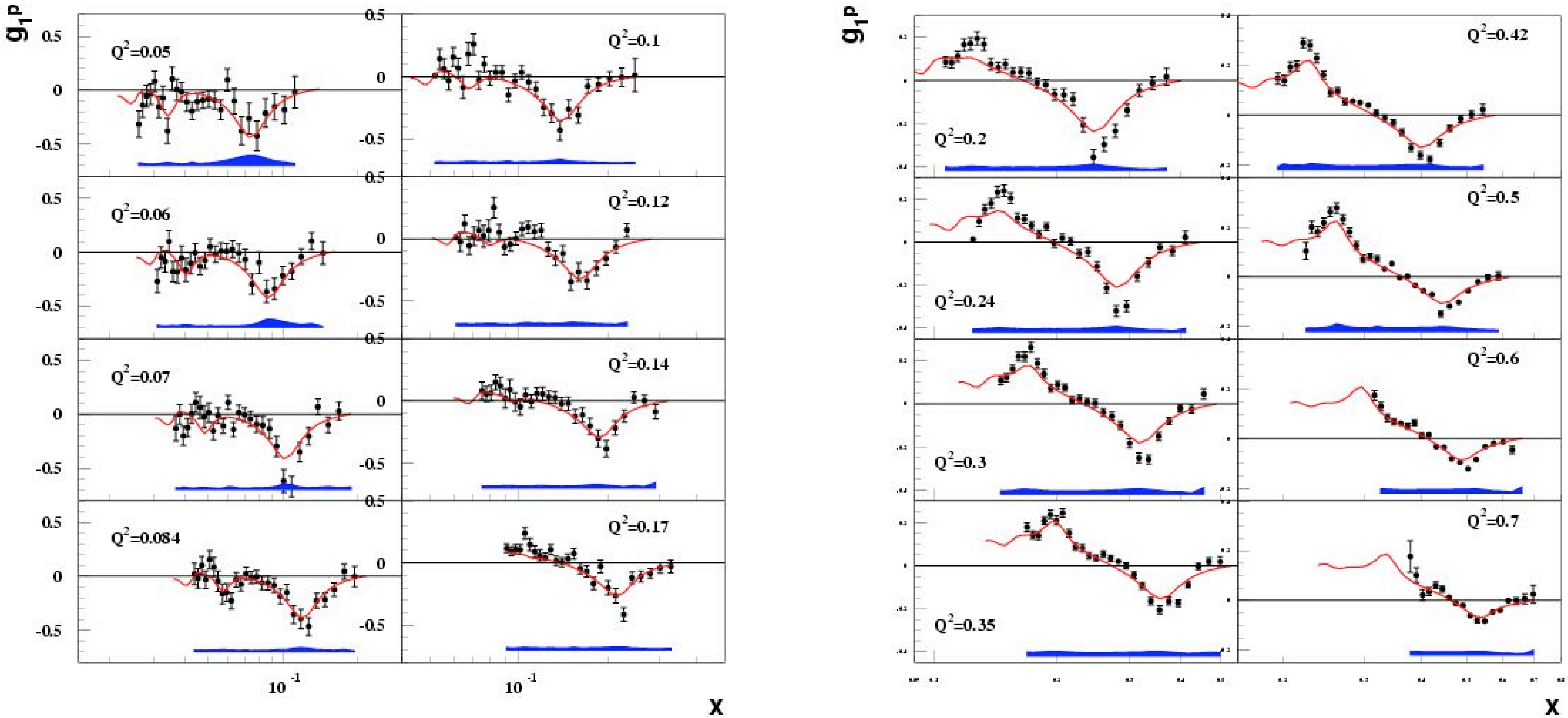
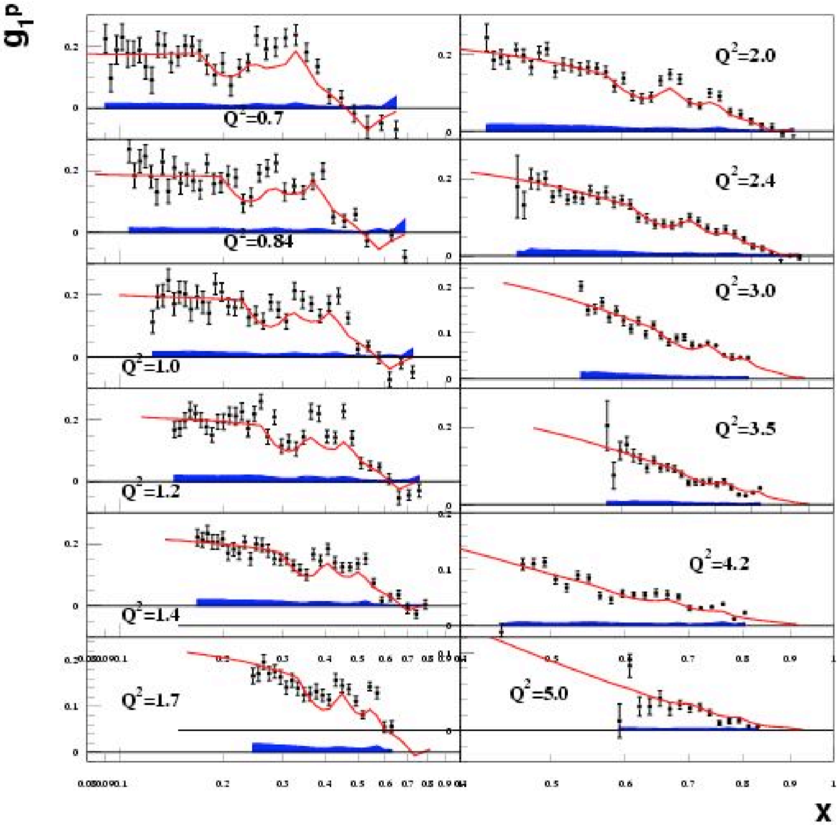
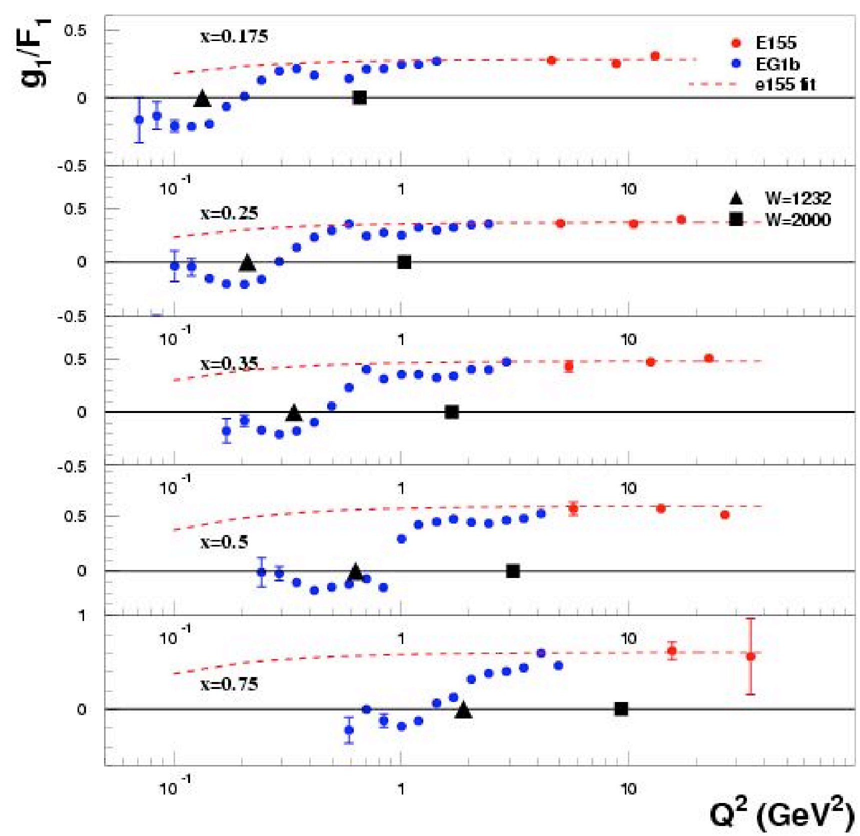
EG1 g_1^p (Q^2<0.7)



- At low Q^2 the Δ resonance drives g_1 negative
- Extensive x-range at fixed Q^2 allows integration over x
- Red curve is the EG1 model used for radiative corrections

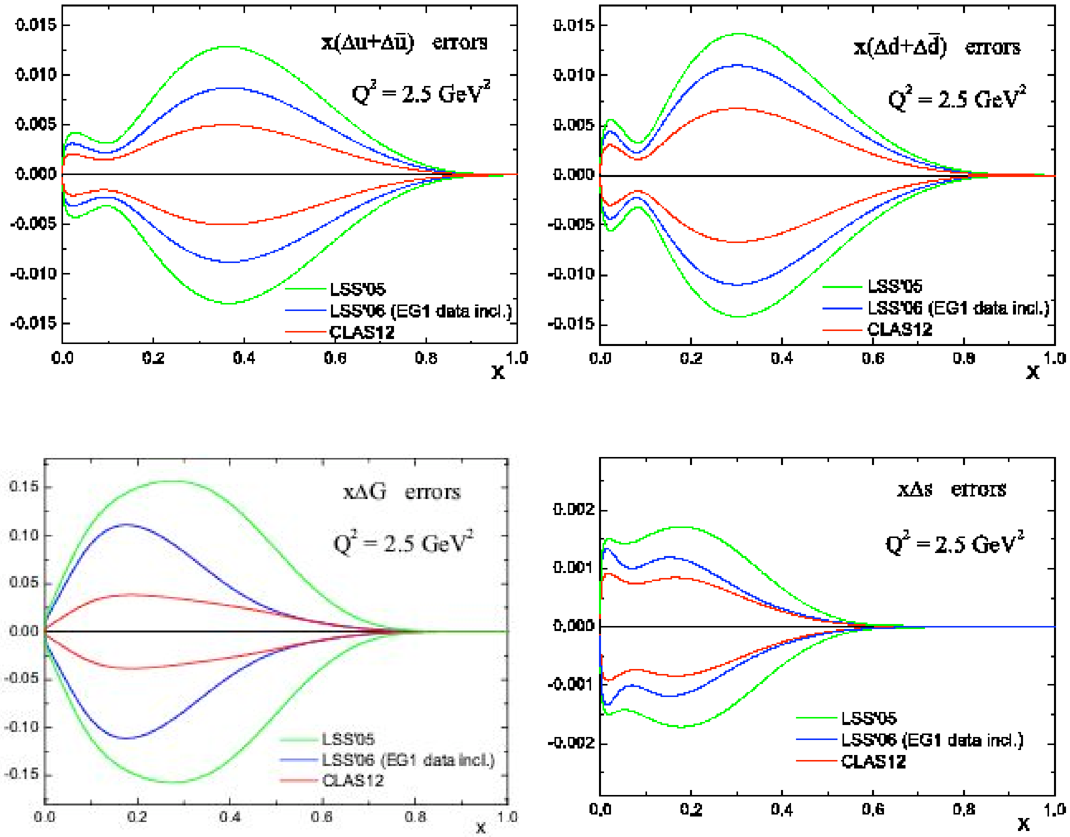
EG1 g_1^p (Q^2>0.7) & g_1/F_1





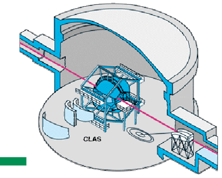
- At higher Q^2, g_1 becomes positive everywhere
- g_1/F_1 falls far below the DIS extrapolation at low Q^2
- Red curve is the EG1 model (dashed: DIS extrapolation)

PDFs and CLAS



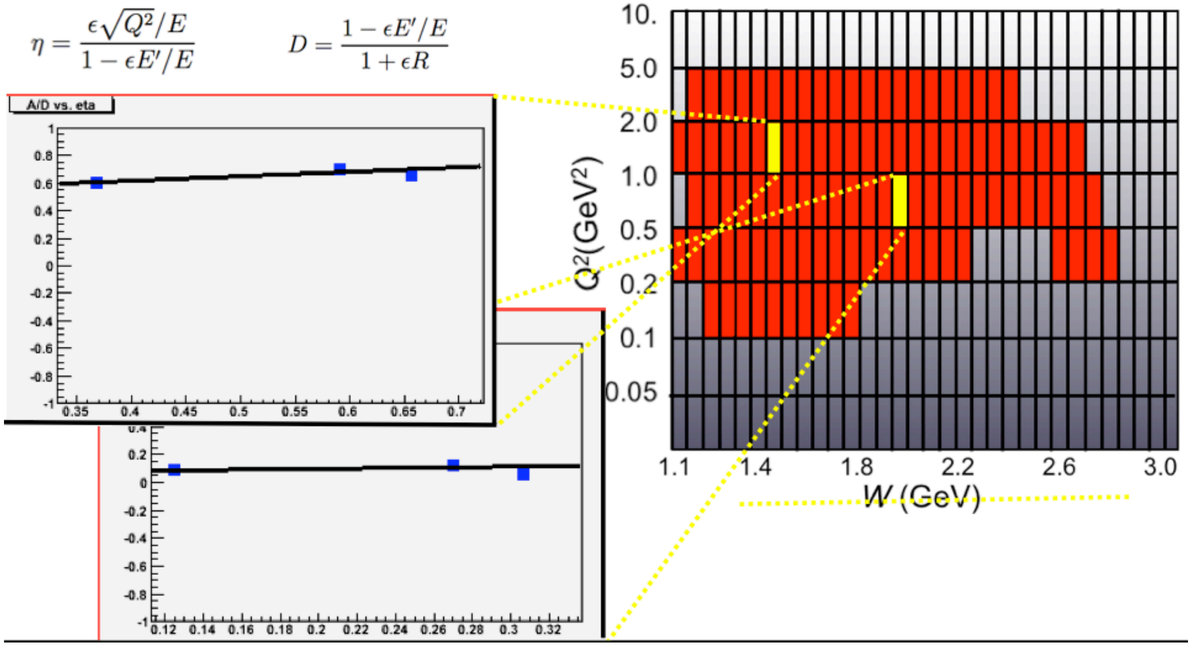
- Error envelopes for PDFs from LSS05 global analysis (green)
- CLAS EG1 data significantly improve errors on Δu, Δd, Δx and ΔG (blue)
- CLAS EG12 (12 GeV upgrade) will especially improve ΔG (red)

EG1 Extraction of A_2

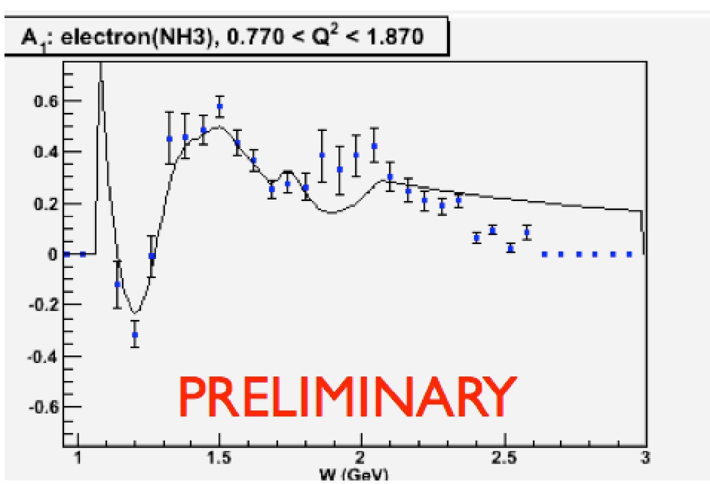


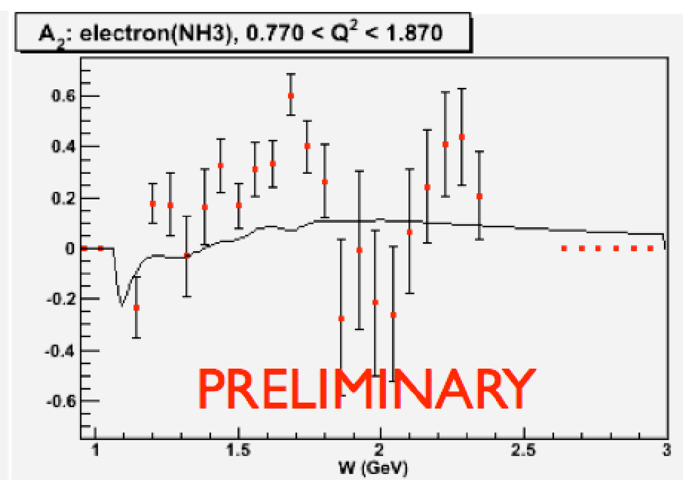
$$A_{\|} = D(A_1 + \eta A_2)$$

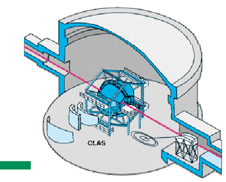
$$\eta = \frac{\epsilon\sqrt{Q^2}/E}{1-\epsilon E'/E} \qquad D = \frac{1-\epsilon E'/E}{1+\epsilon R}$$



- Analysis is in progress to obtain both A_1 and A_2 from the EG1 data
- Intercept gives A_1
- Slope gives A_2
- A_2 is larger than EG1 model (MAID, AO) as is Hall C RSS experiment



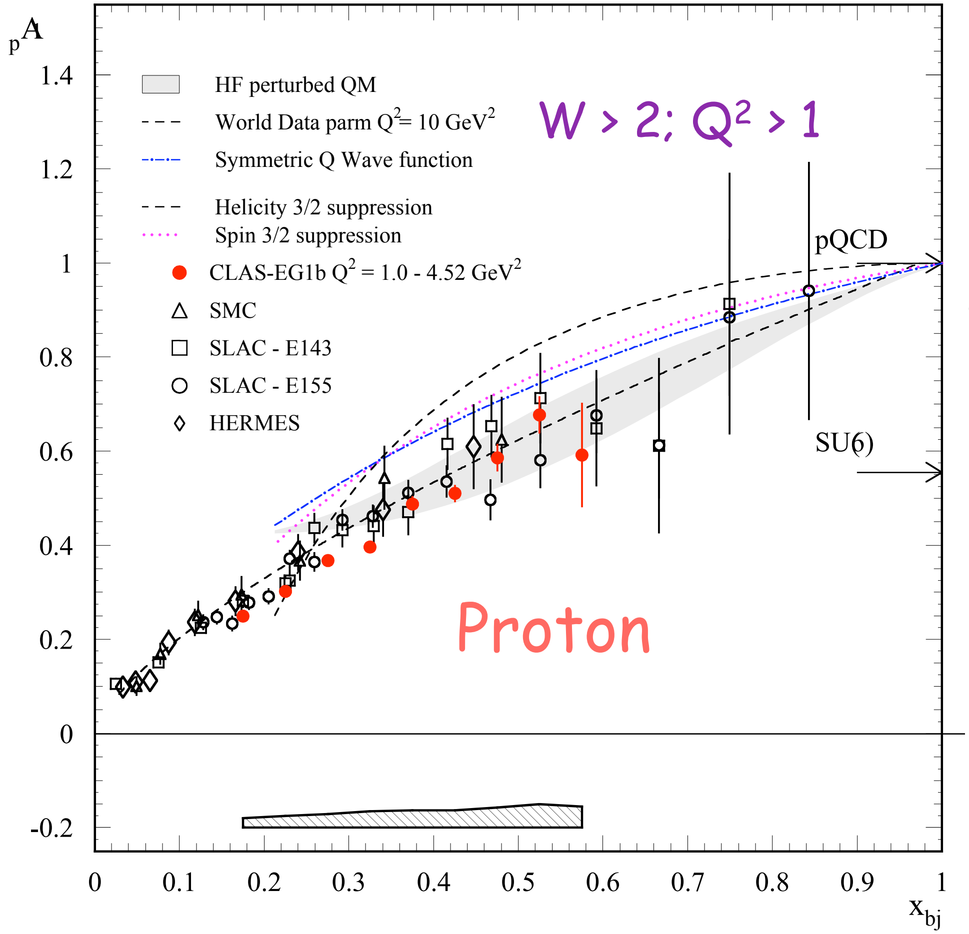


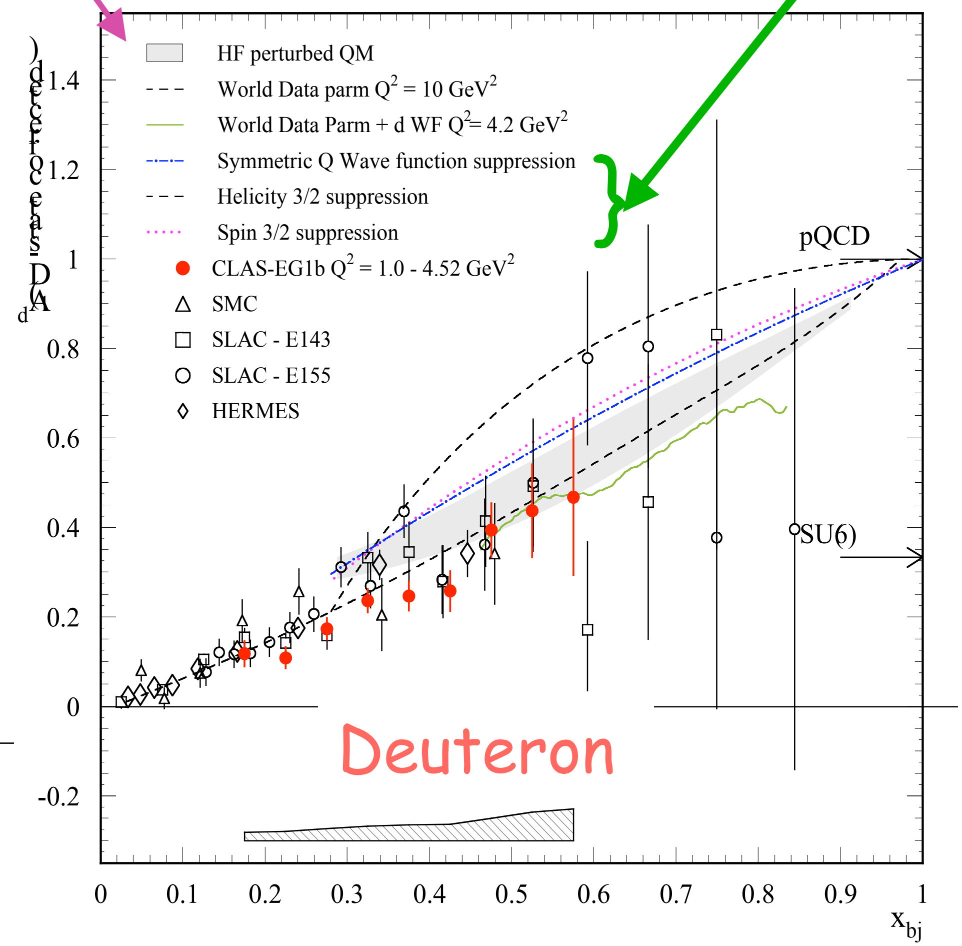


A_1 Data from EG1

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

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





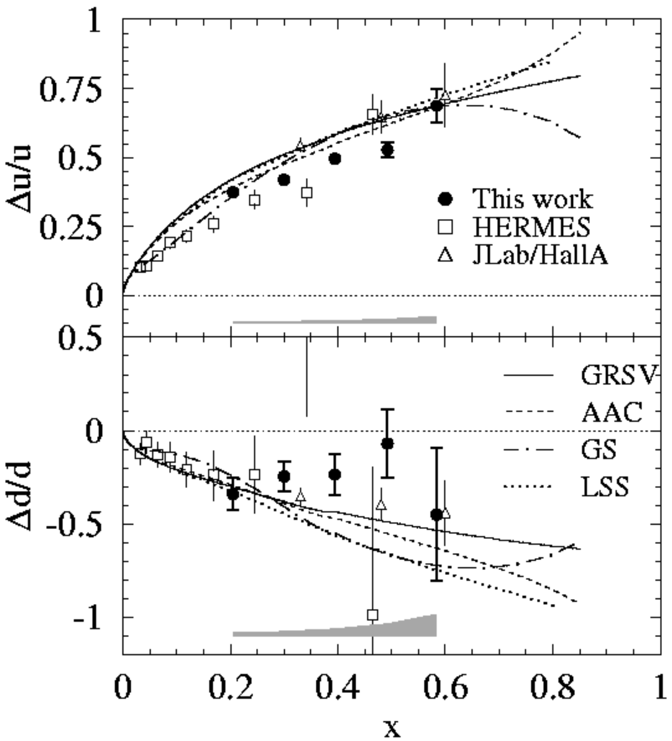
Quark polarization in the valence limit

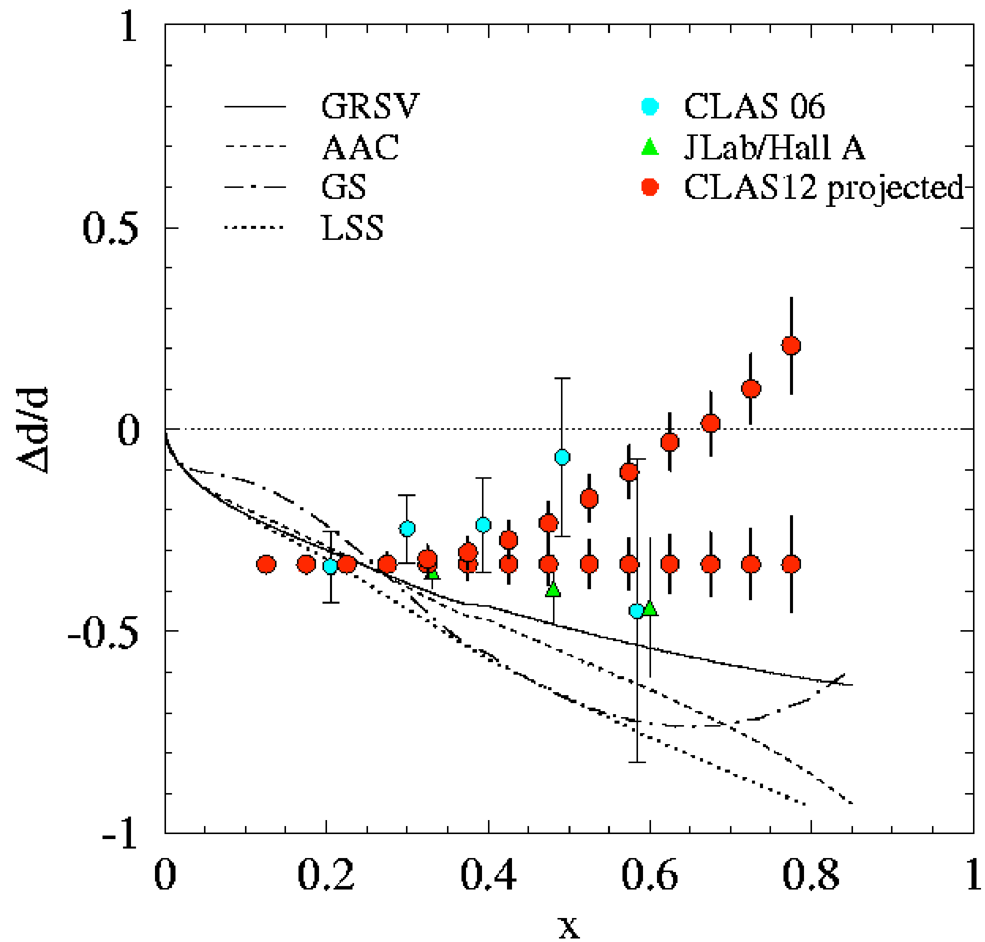
$$A_1(x, Q^2) = \frac{\sum e_i^2 \Delta q_i(x, Q^2)}{\sum e_i^2 q_i(x, Q^2)}$$

Simulated Data for EG12

Extracted from A_1^p, A_1^d and d/u

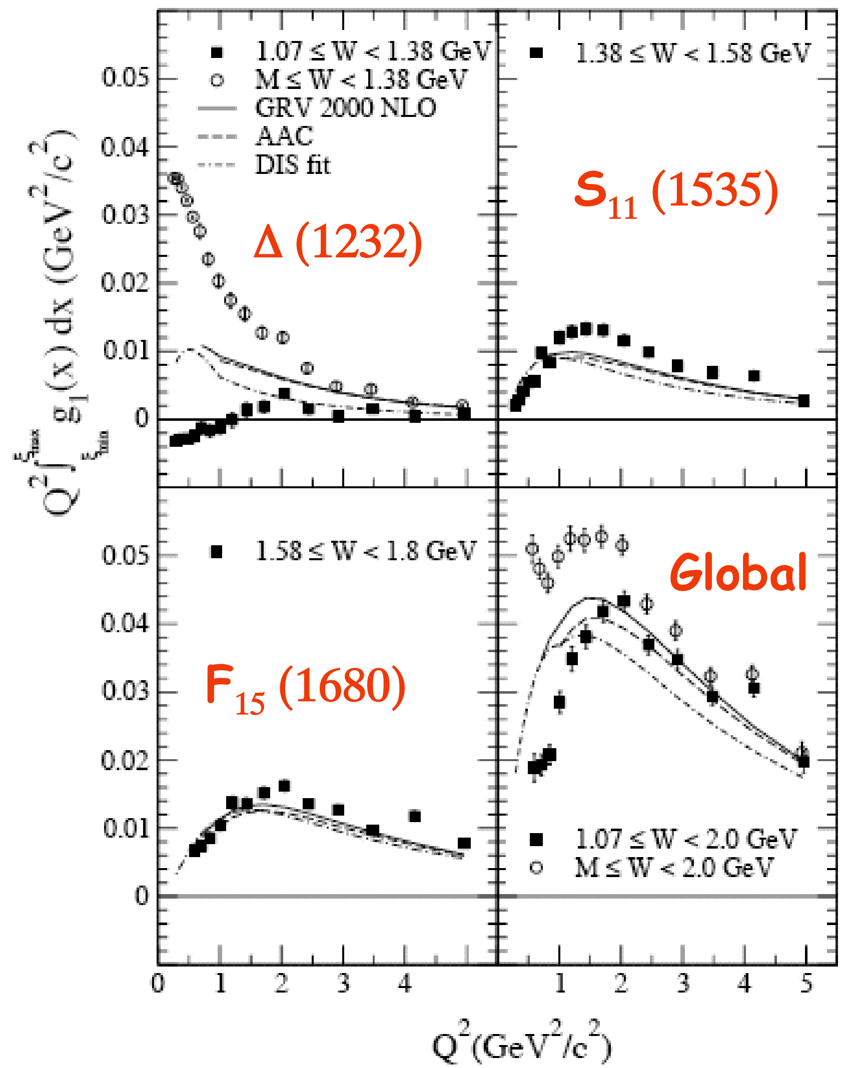
EG1 Existing Data



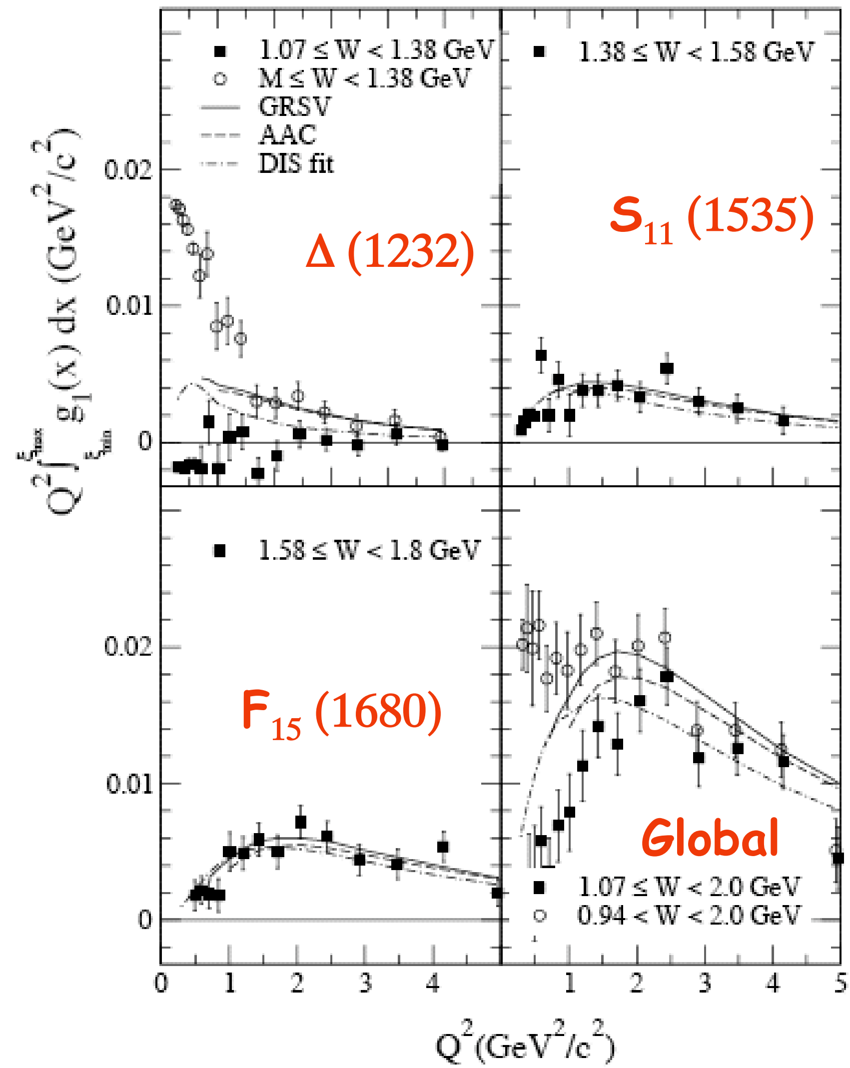


Duality

Proton

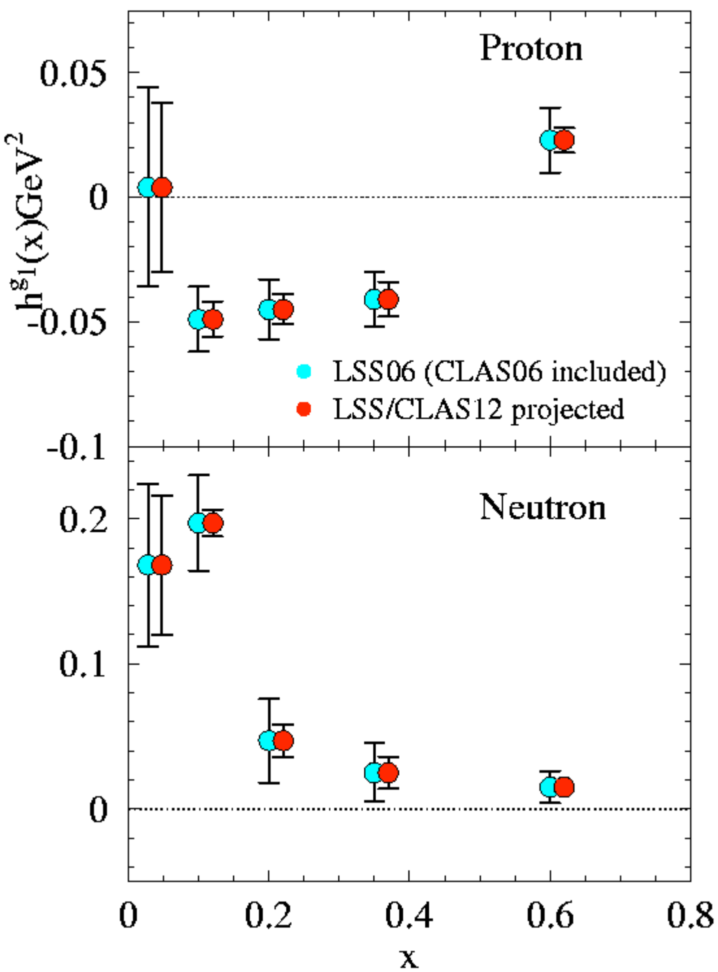


Deuteron



Higher Twist from g_1

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



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

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

- 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

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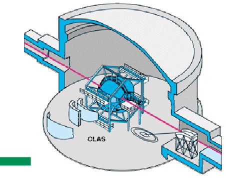
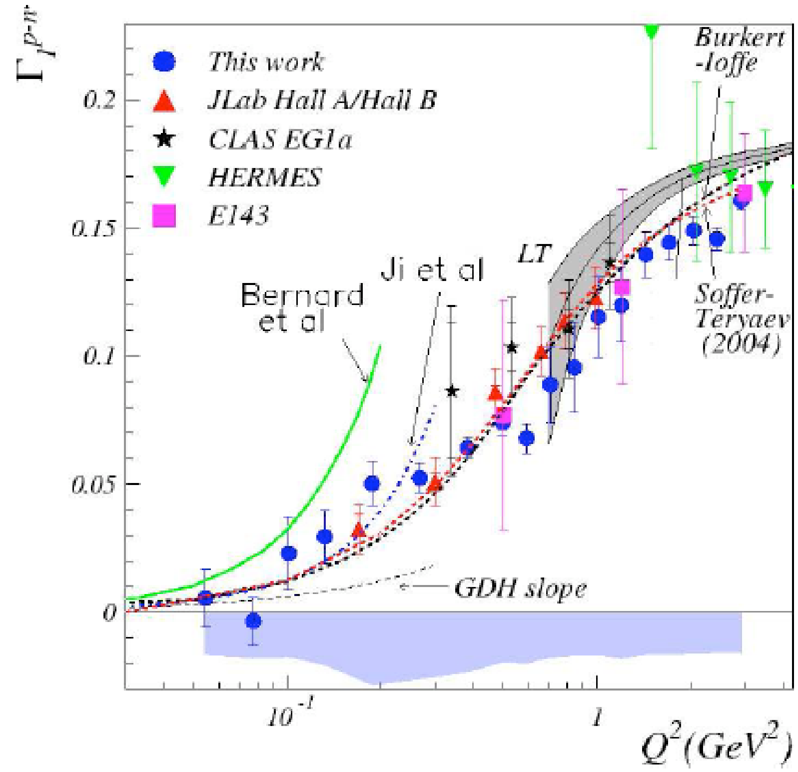
Bjorken Sum & Higher Twist



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

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



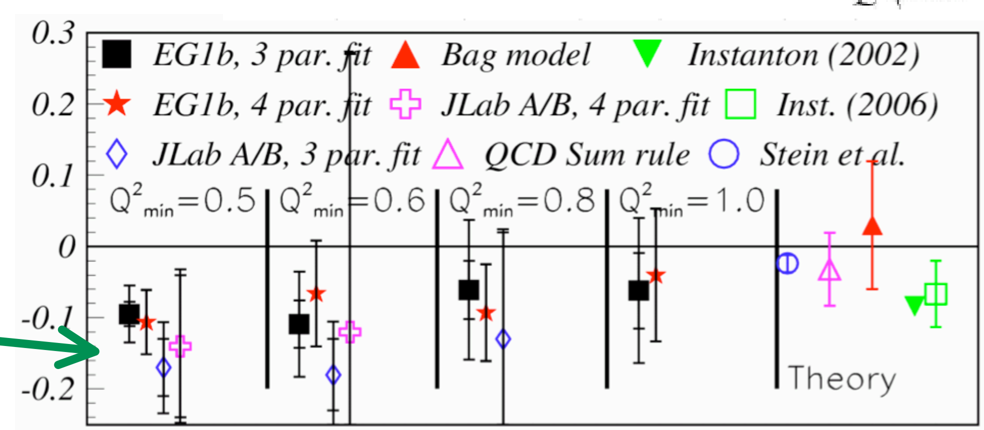
Bjorken Sum Rule:

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

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

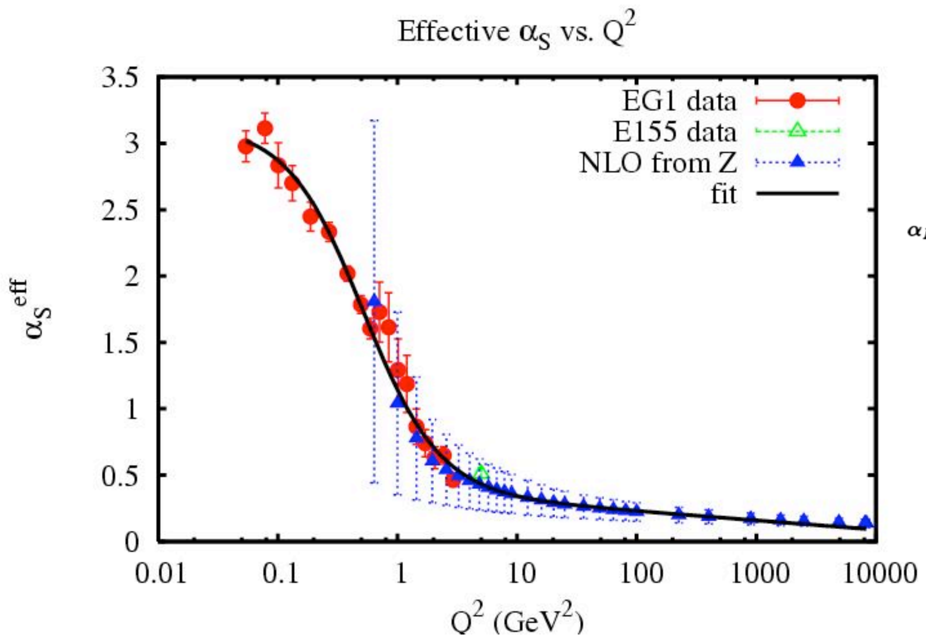
$$d_2^{p-n} = \int_0^1 dx\, x^2\left(2g_1^{p-n} + 3g_2^{p-n}\right)$$

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



Commensurate Scaling

Brodsky, Lu, PRD51(95)3652



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

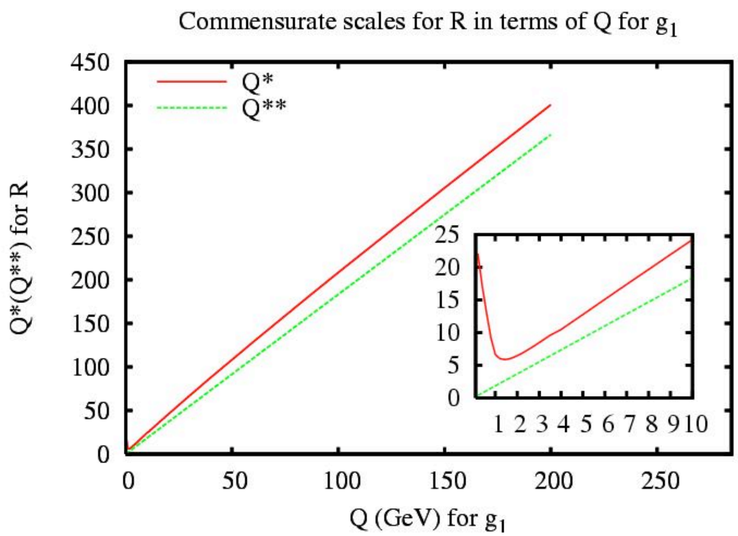
$$R(Q) \equiv 3\sum_f Q_f^2\left[1 + \frac{\alpha_R(Q)}{\pi}\right]$$

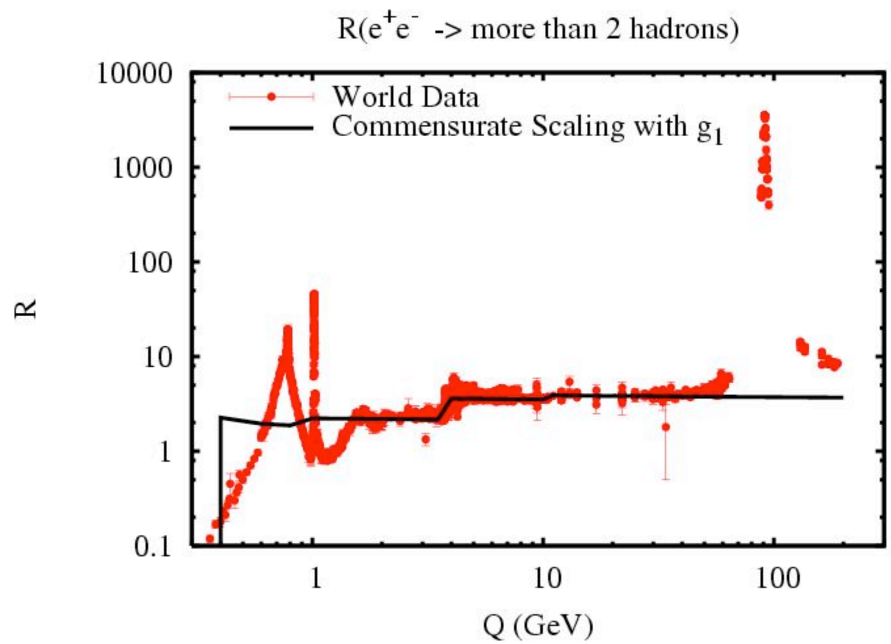
$\alpha_R(Q)$ in terms of $\alpha_{g_1}(Q)$.

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

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

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





Moments $\Gamma_1^{p,d}$

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

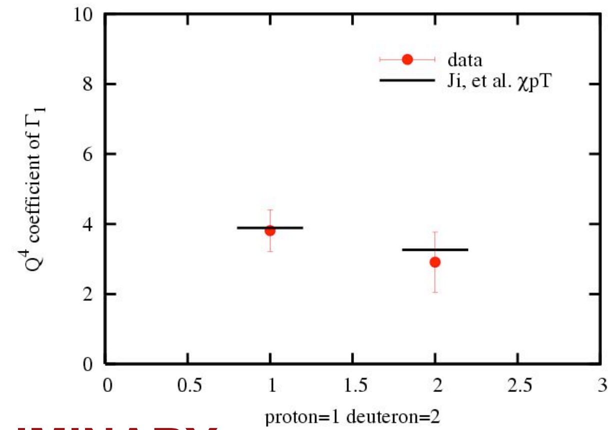
$$\Gamma_1^d(Q^2) = (1-1.5\omega_D)\left\{\Gamma_1^p(Q^2)+\Gamma_1^n(Q^2)\right\}$$

low Q^2 fit

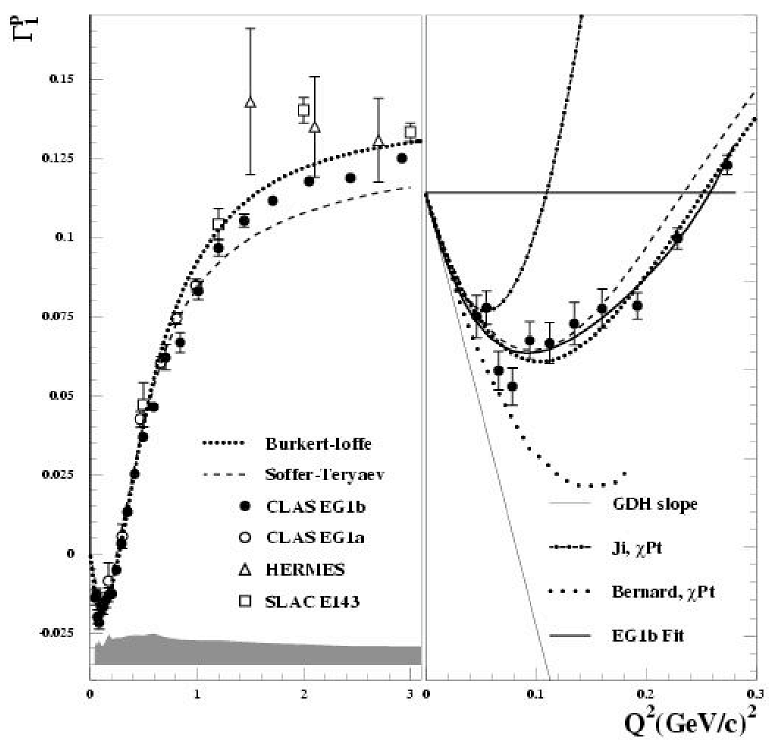
$$\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2}Q^2 + 3.89Q^4 + \ldots$$

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

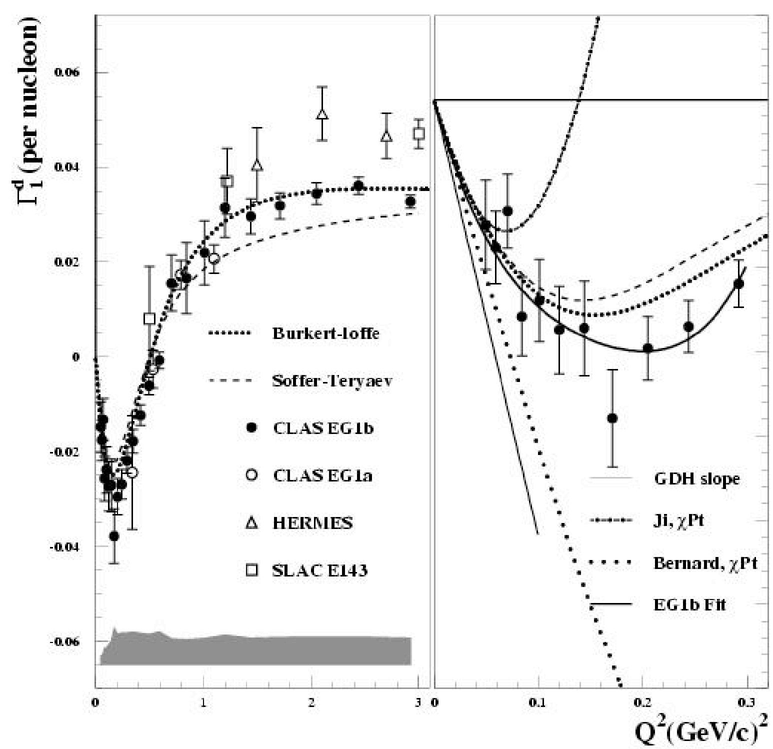
GDH + χpT



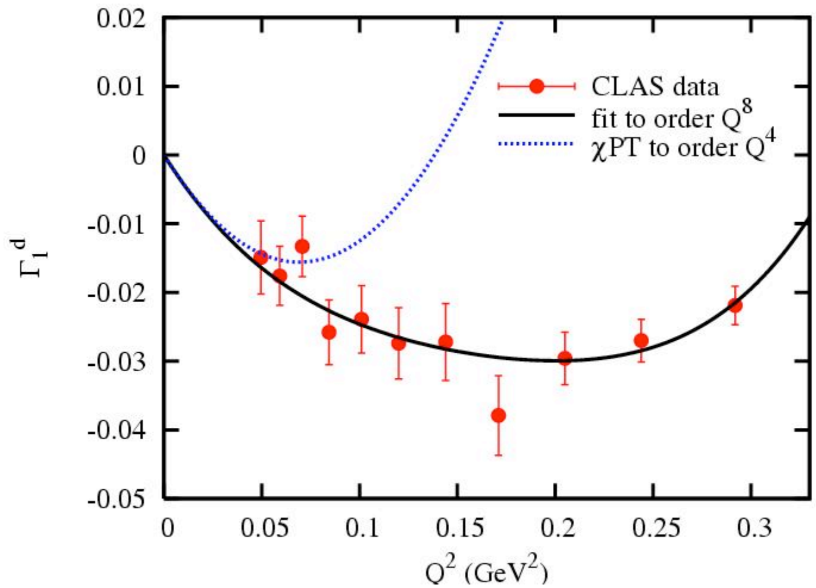
PRELIMINARY

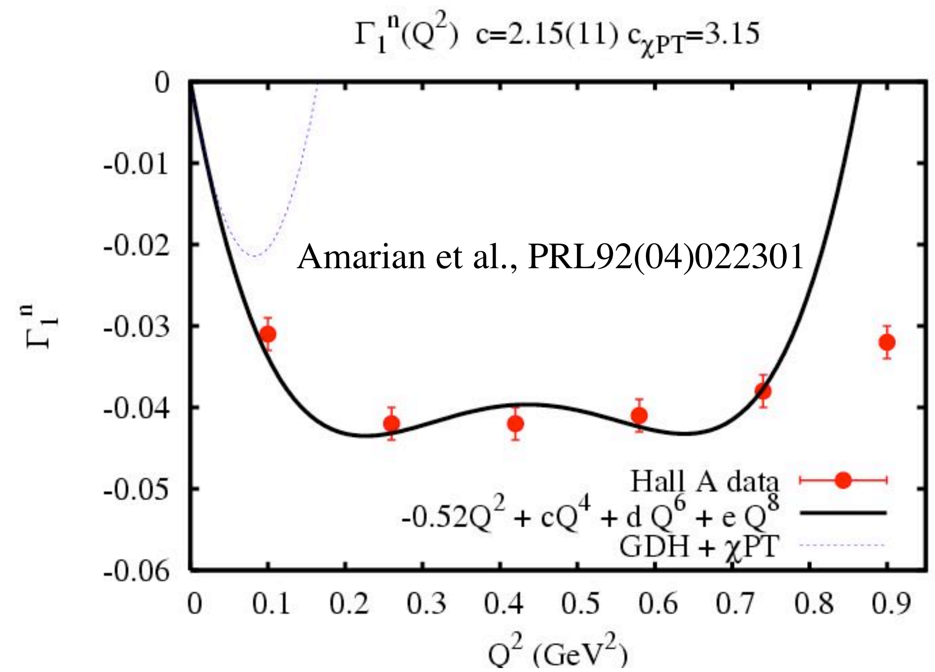


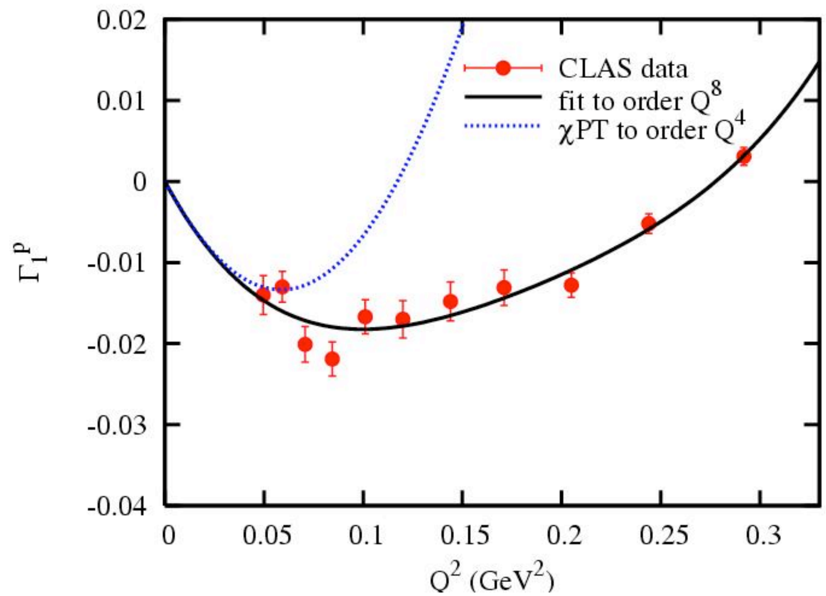
PRELIMINARY



Low Q^2 Fits of Γ_1







χPT X. D. Ji, C. W. Kao and J. Osborne, Phys. Lett. B **472**, 1 (2000) [arXiv:hep-ph/9910256].

fit to $aQ^2 + bQ^4 + cQ^6 + dQ^8$

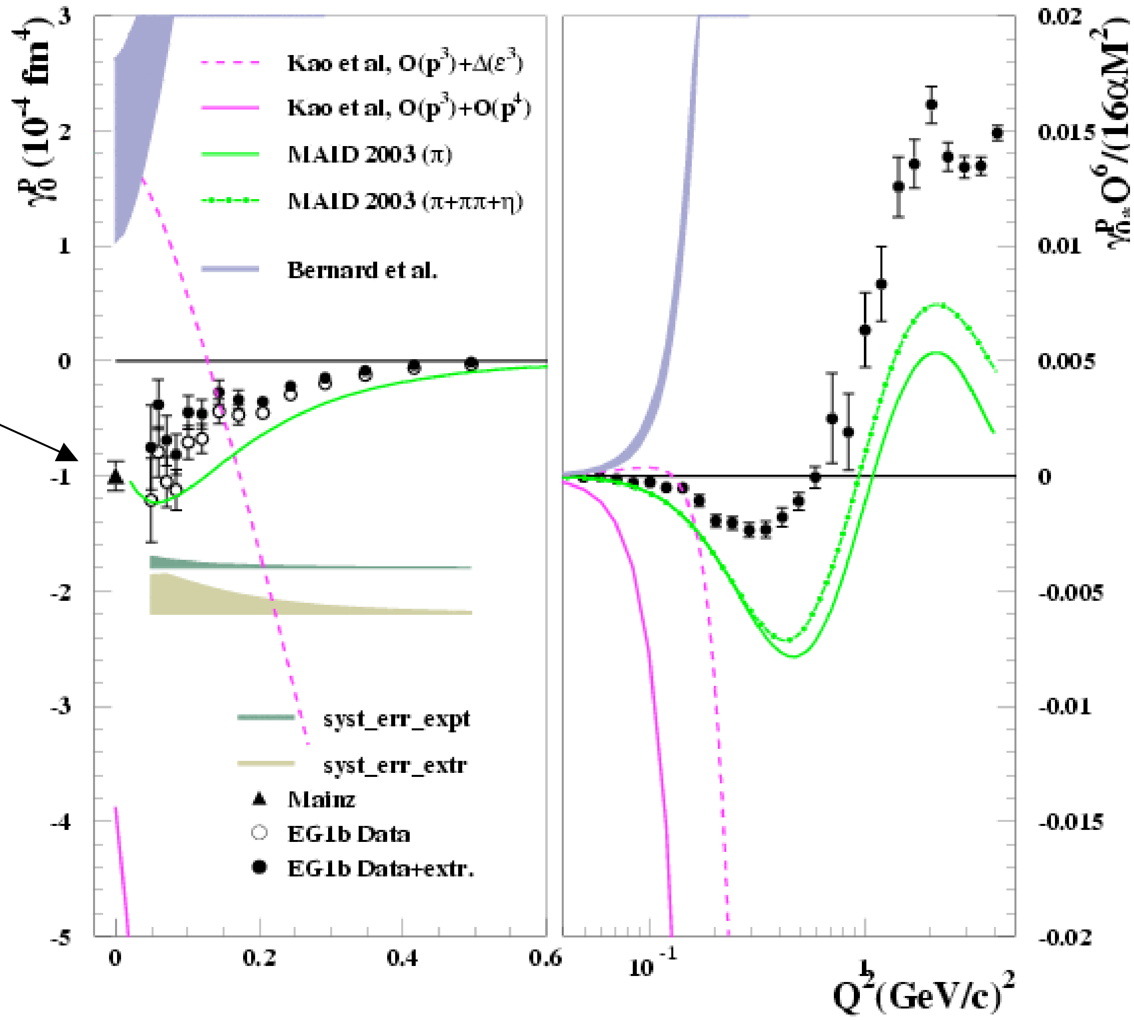
a fixed by GDH
b compared to χPT

Forward Spin Polarizability

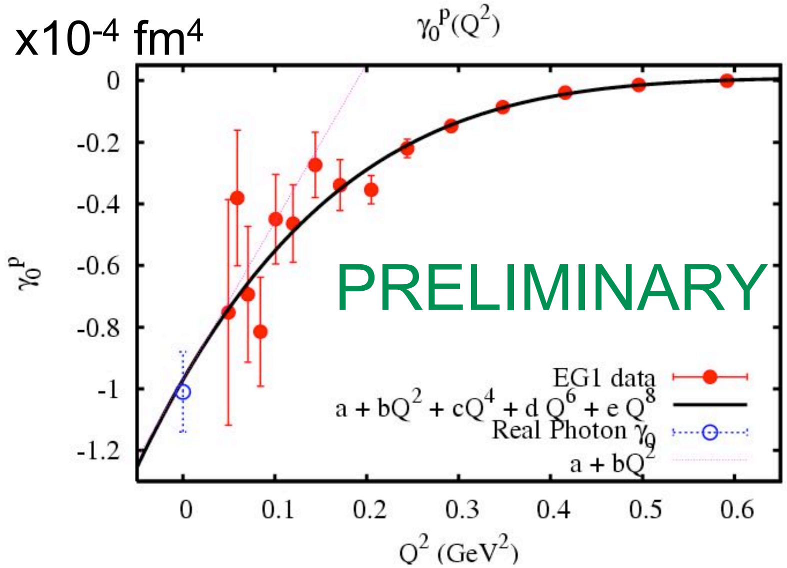
$$\gamma_0(Q^2) = \frac{4e^2M^2}{\pi Q^6}\int_0^{x_0} dx\, x^2 \left\{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)\right\}$$

PRELIMINARY

real photon point



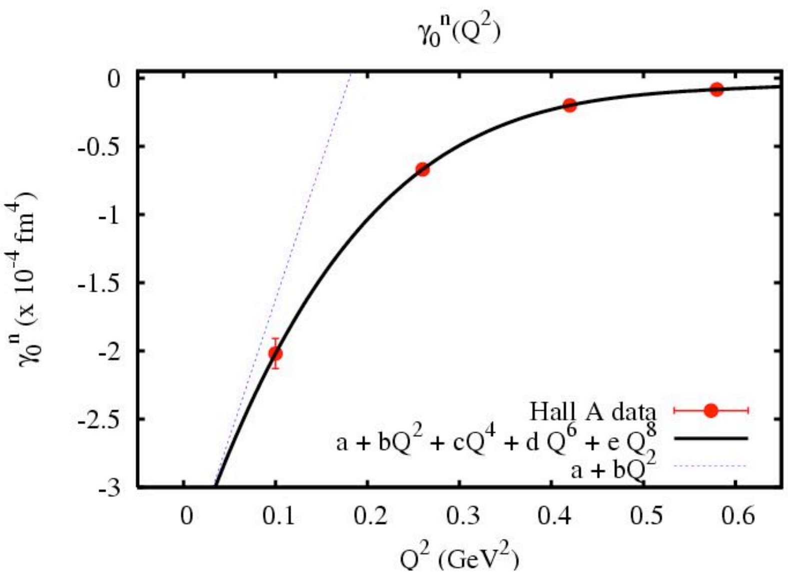
γ_0 Fits at Low Q^2



a = -0.97(11)

b = 5.13(94)

Prok et al., CLAS EG1

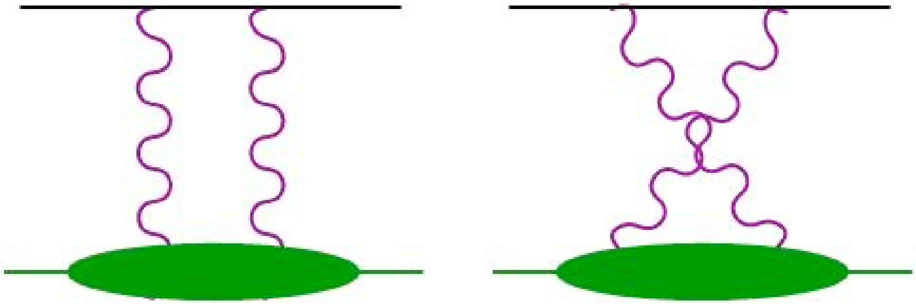


a = -3.643(1)

b = 20.180(8)

Amarian et al., PRL93(04)152301

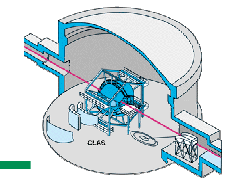
Hydrogen Hyperfine Splitting



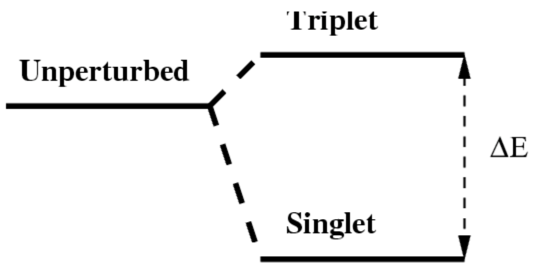
Proton Feynman diagrams for the proton polarizability term in the hydrogen hyperfine splitting.

- see Brodsky, Carlson, Hiller and Hwang, PRL**94**(05)022001,169902(E).
- $E_{\rm hfs}(e^-p) = E_F^p(1+\Delta_{\rm QED}+\Delta_R^p+\Delta_S+\Delta_{\rm hvp}^p+\Delta_{\mu{\rm vp}}^p+\Delta_{\rm weak}^p) = 1.4204057517667(9)\,{\rm GHz}$
- $\Delta_{\rm QED} = 1136.09(14)$ ppm ($\frac{\alpha}{2\pi} + \ldots$)
- $\Delta_R^p = 5.86(15)$ ppm (recoil)
- $\Delta_{\rm hvp}^p = 0.01$ ppm (hadronic vacuum polarization)
- $\Delta_{\mu{\rm vp}}^p = 0.07$ ppm (muonic vacuum polarization)
- $\Delta_{\rm weak}^p = 0.06$ ppm (weak interaction)
- $\Delta_S = -38.62(16)$ ppm (nucleon structure; deduced)
- Δ_S is the largest uncertainty in theoretical calculation of $E_{\rm hfs}(e^-p)$

Hydrogen Hyperfine Splitting



$$E_{\rm HFS}(e^- p) = 1.420405751 7667(9)\,{\rm GHz} = (1+\Delta_{QED}+\Delta_R^p+\Delta_S)E_F^p$$



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

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 $\Delta_Z = -41.0(5)$ ppm $\Delta_{\rm pol} = 2.38(58)$ ppm

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

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

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

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

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

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

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

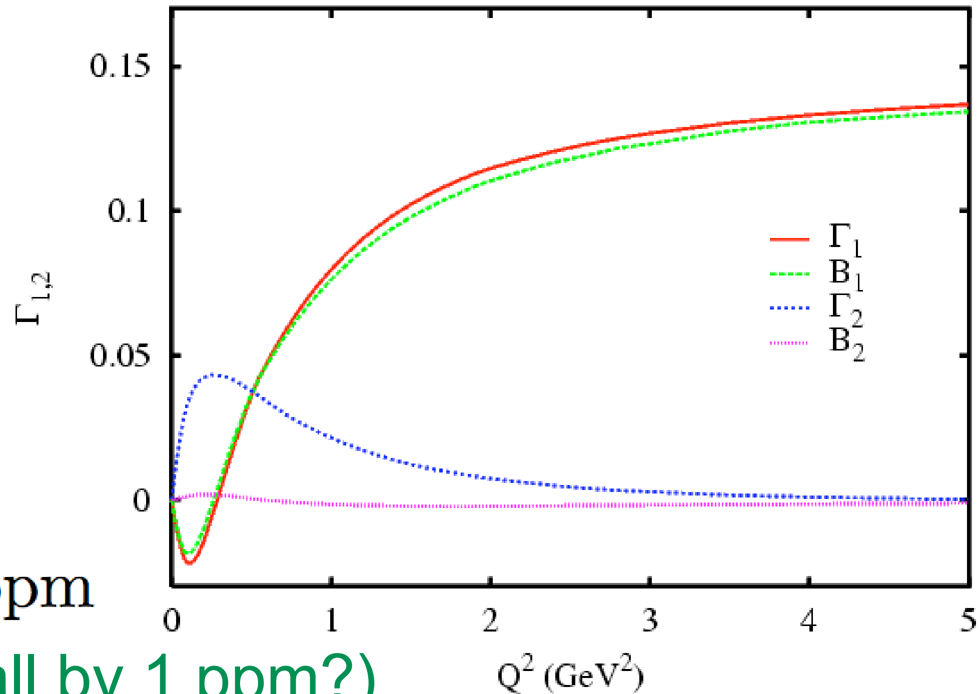
$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)}\,,$$

$\Delta_{1,2}$ from $g_{1,2}$

Comparisons between $\Gamma_1 = \int g_1 dx$ and $B_1 = \int \beta_1 g_1 dx$
and between $\Gamma_2 = \int g_2 dx$ and $B_2 = \int \beta_2 g_2 dx$

PRL**96**,163001

- $B_1 \approx \Gamma_1$
- $B_2 \approx 0$
- Experimentally, errors on Γ_1 are understood; we exploit this fact.
- $\Gamma_2 = \int g_2 dx \neq 0$ at low Q^2.

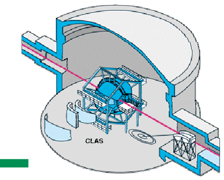


$$\Delta_{\rm pol} = (1.3 \pm 0.3)\ \rm ppm$$

(from EG1: too small by 1 ppm?)

Nucleon structure is the largest uncertainty in calculating HFS.
Better g_1, g_2, G_M, G_E data at low Q^2 required to resolve discrepancy.

Moments at Low Q^2



$$\Gamma_{1,2}^{(N)}(Q^2) = \int_0^{x_{\rm th}} x^N g_{1,2}(x,Q^2)dx$$

$$\Gamma_{1,2}^{(N)} \sim (Q^2)^{N+1}$$

$$\gamma_0(Q^2) = \frac{16\alpha m_p^2}{Q^6}\int_0^{x_{\rm th}} x^2\left(g_1 - \frac{4m_p^2x^2}{Q^2}g_2\right)dx$$

$$\Gamma_1^{(2)} \;\rightarrow\; \gamma_0 Q^6/(16\alpha m_p^2)$$

$$\Gamma_1^{(0)} = -\kappa_p^2 Q^2/(8m_p^2) + c_1 Q^4 + \ldots$$

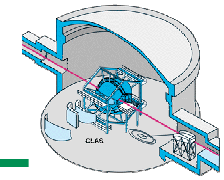
$$B_1 = \Gamma_1^{(0)} - 10m_p^2\Gamma_1^{(2)}/(9Q^2) + \ldots.$$

$$\Delta_1[0,Q_1^2] = \left\{-\frac{3}{4}r_P^2\kappa_p^2 + 18m_p^2c_1 - \frac{5m_p^2}{4\alpha}\gamma_0\right\}Q_1^2$$

$$\Delta_2[0,Q_1^2] = 3m_p^2Q_1^2(\gamma_0 - \delta_{LT})/2\alpha$$

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

Δ_{pol}



$$\Delta_2[0, Q_1^2] = 3m_p^2 Q_1^2(\gamma_0 - \delta_{LT})/2\alpha$$

$$\Delta_1[0, Q_1^2] = \left\{ -\frac{3}{4} r_P^2 \kappa_p^2 + 18 m_p^2 c_1 - \frac{5m_p^2}{4\alpha}\gamma_0 \right\} Q_1^2$$

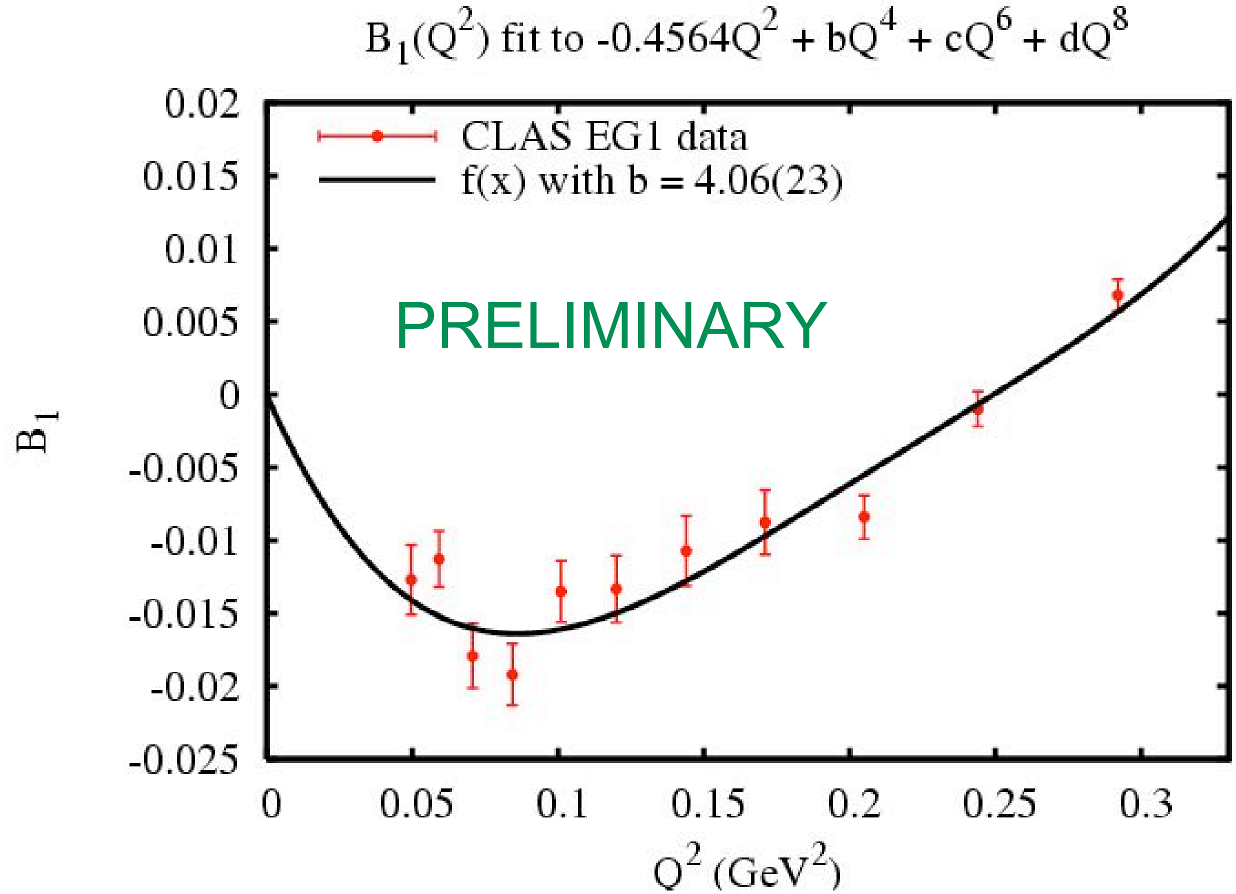
term	Q^2 (GeV^2)	from	Kelly's F_2
Δ_1	[0,0.05]	F_2 and g_1	0.45 ± 0.30
	[0.05,20]	F_2	7.01 ± 0.22
		g_1	-1.10 ± 0.55
	[20,∞]	F_2	0.00
		g_1	0.12 ± 0.01
total Δ_1			6.48 ± 0.89
Δ_2	[0,0.05]	g_2	-0.24 ± 0.24
	[0.05,20]	g_2	-0.33 ± 0.33
	[20,∞]	g_2	0.00
total Δ_2			-0.57 ± 0.57
$\Delta_1 + \Delta_2$			5.91 ± 1.06
Δ_{pol}			1.34 ± 0.24 ppm

γ_0 = -1.01x10^{-4} fm^4 (photons)
r_P = 0.878(15) fm (Kelly)
c_1 = 2.95-3.89 (fits/χPT)
δ_{LT} = 1.35x10^{-4} fm^4 (MAID)

$$g_2 = g_2^{WW} \rightarrow \Gamma_2^{(N)} = -N\Gamma_1^{(N)}/(N+1)$$

Δ_2[0,0.05] =
-0.40(05) [g_2^{WW}]
-1.4 [MAID]
-0.24 [EG1 Model]

B_1 from CLAS

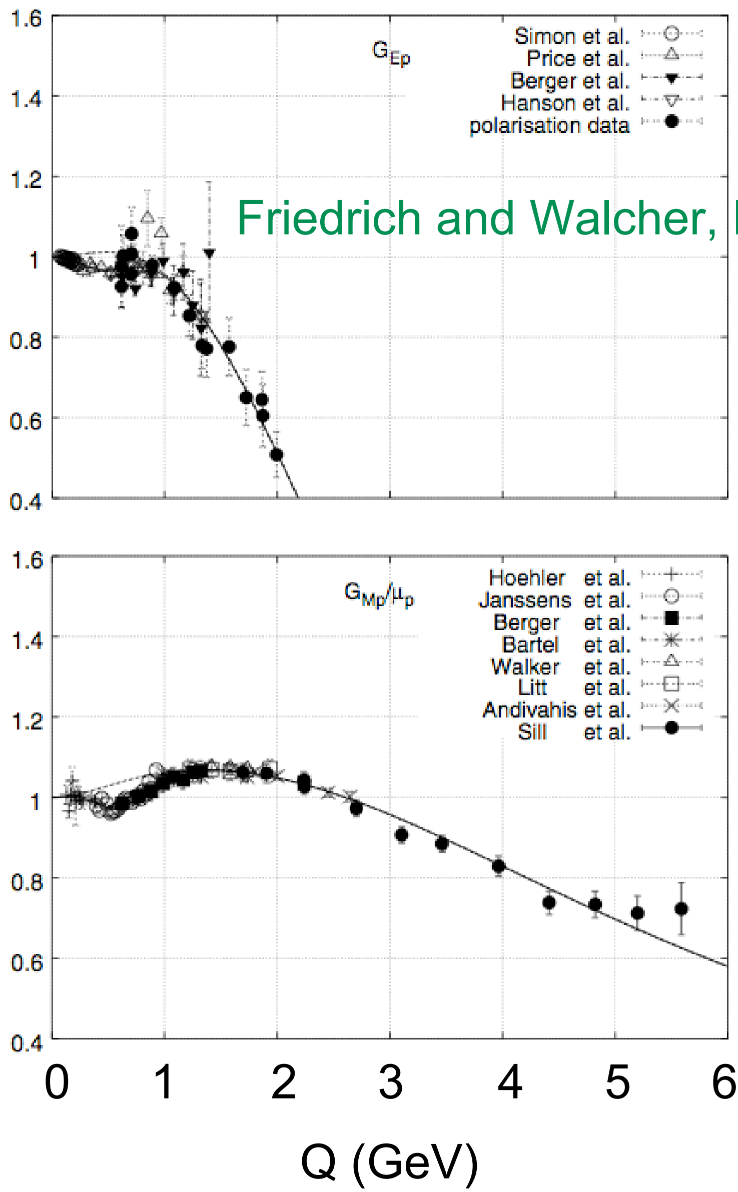


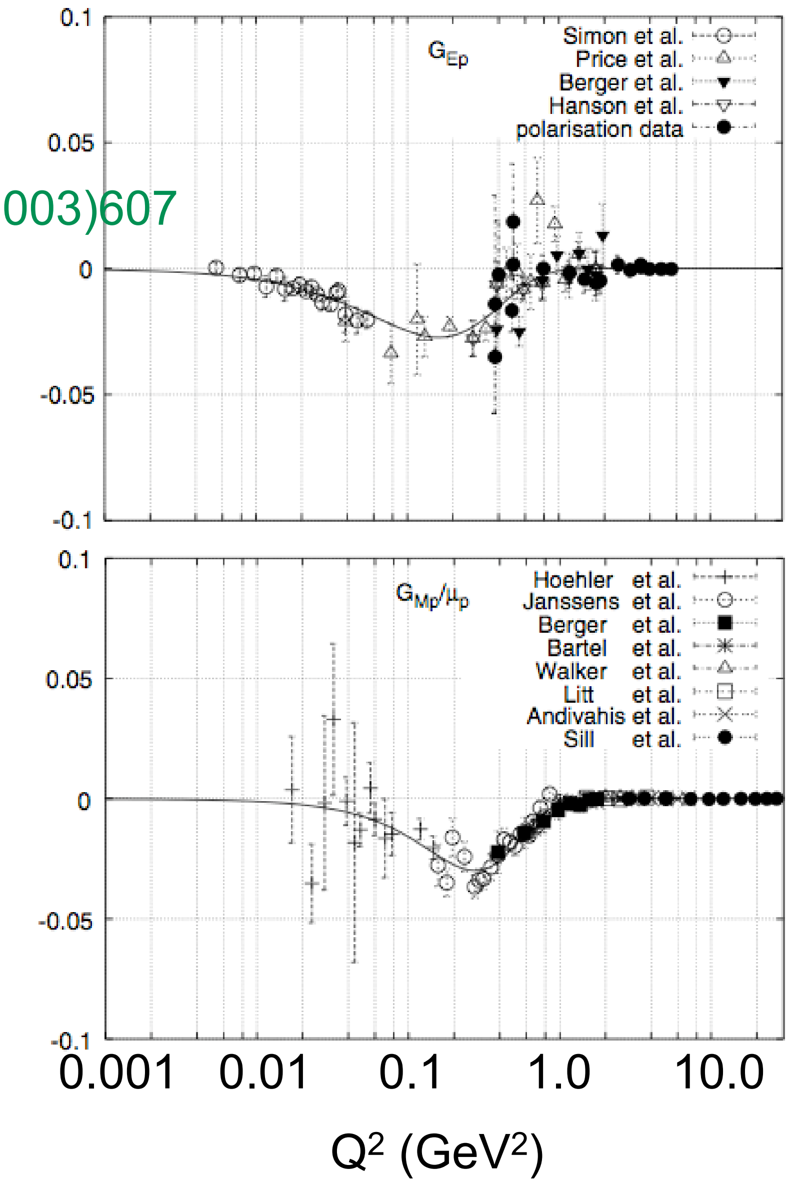
Various estimates change Δ_{pol} up or down within the quoted errors. New data at low Q^2 are needed to improve this.

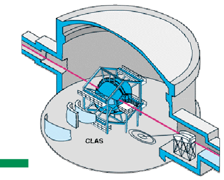
$$\Delta_1[0,0.05] = [-0.75 r_P^2 \kappa_p^2 + 18 m_p^2 b]0.05 = 0.32$$

G_{Ep} & G_{Mp}

Friedrich and Walcher, EPJA17(2003)607



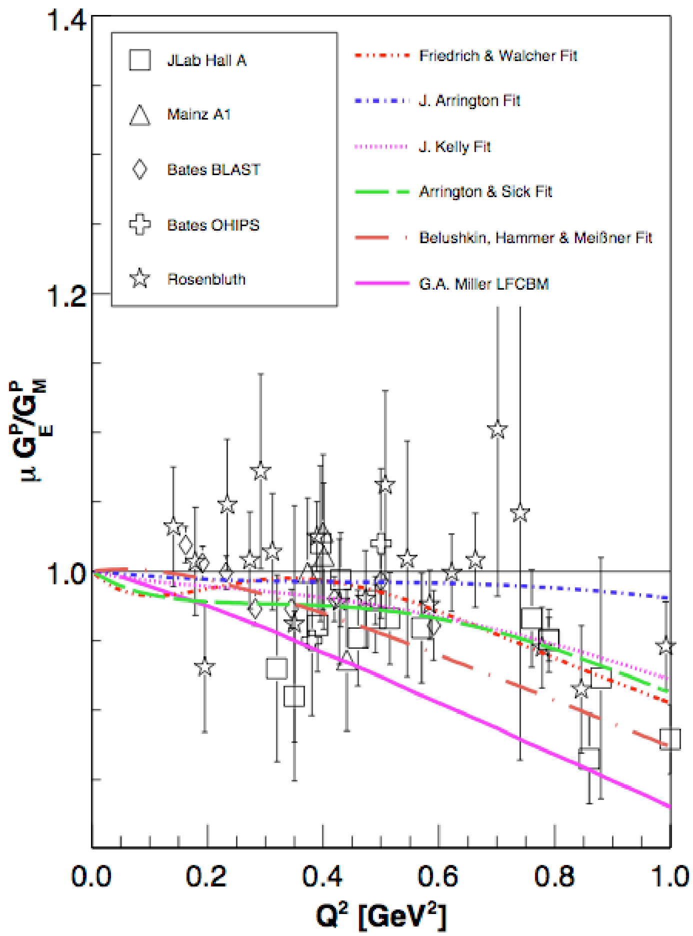


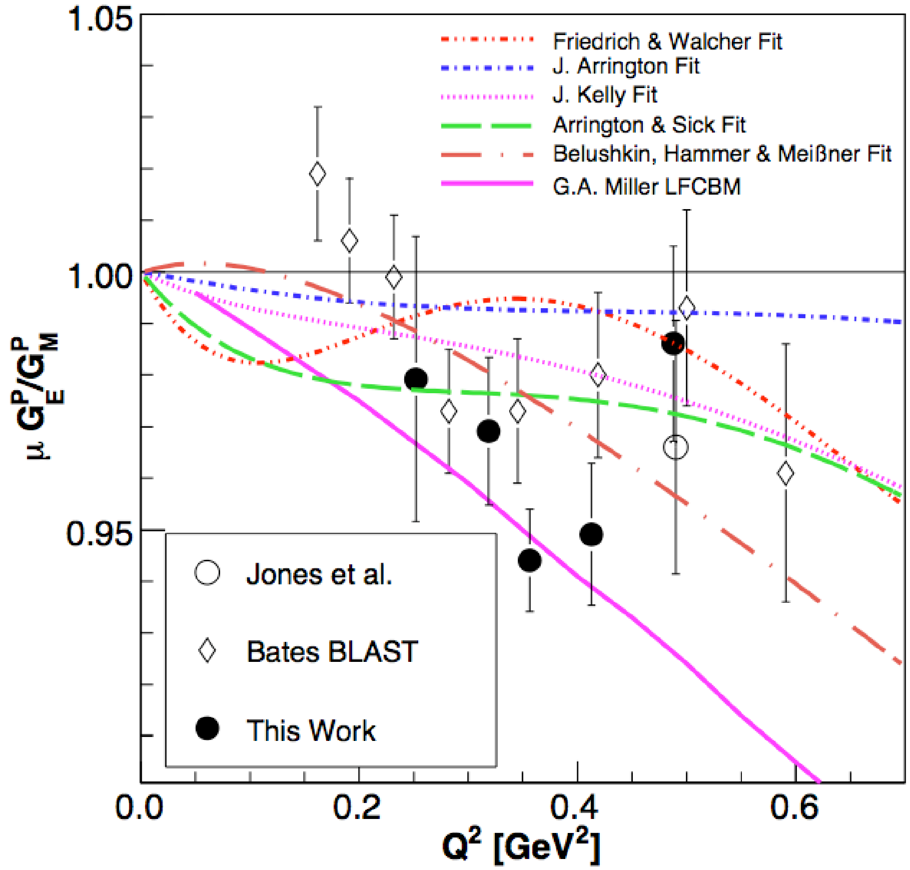


$\mu G_{Ep}/G_{Mp}$

G. Ron et al., nucl-ex 0706.0128

Hall A





The diversity of fits reflects an inaccurate knowledge of the form factors at low Q^2

Zemach Radius

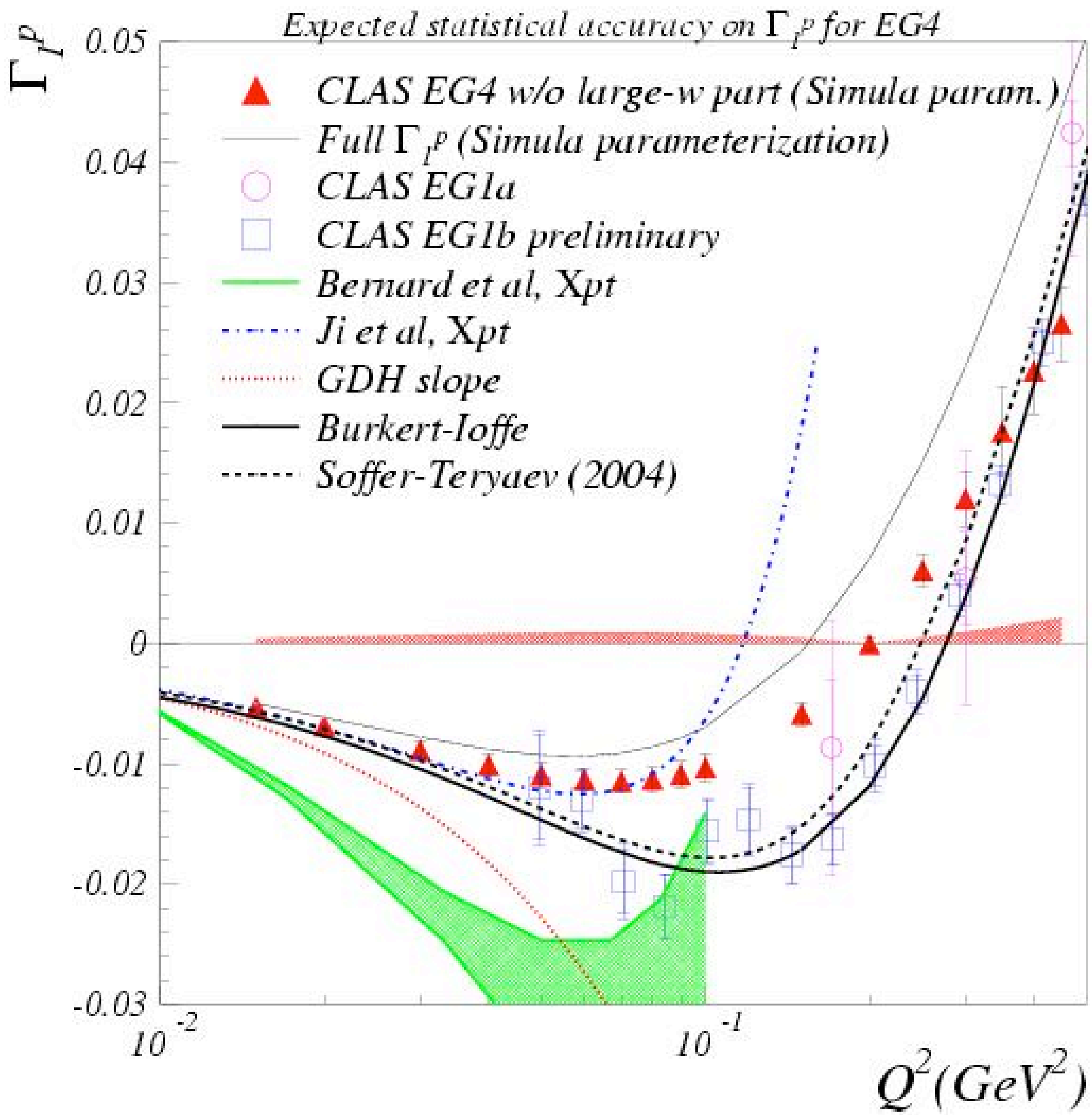
Zemach: $\Delta_Z = -2\alpha m_e \langle r \rangle_Z (1 + \delta_Z^{\text{rad}})$

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

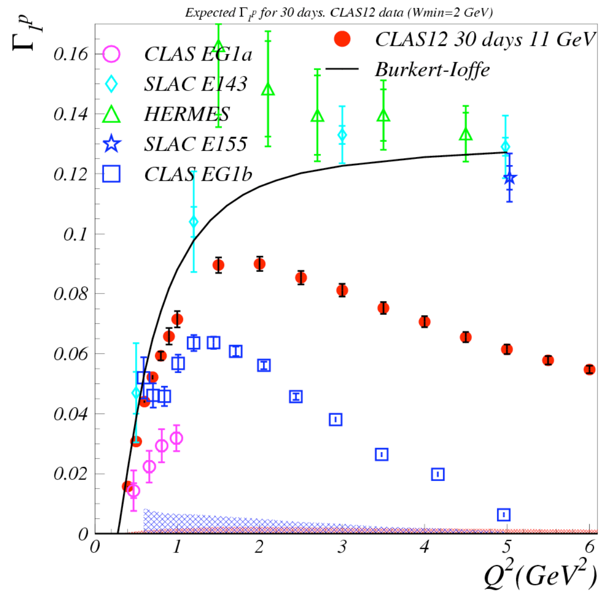
Reference	r_Z (fm)	Δ_Z (ppm)	$\Delta_S - \Delta_Z - \Delta_{pol}$ (ppm)
Kelly	1.069(13)	-41.01	1.11
Sick	1.086(12)	-41.67	1.77
Friedrich	1.048	-40.20	0.30
Dipole	1.025	-39.32	-0.58

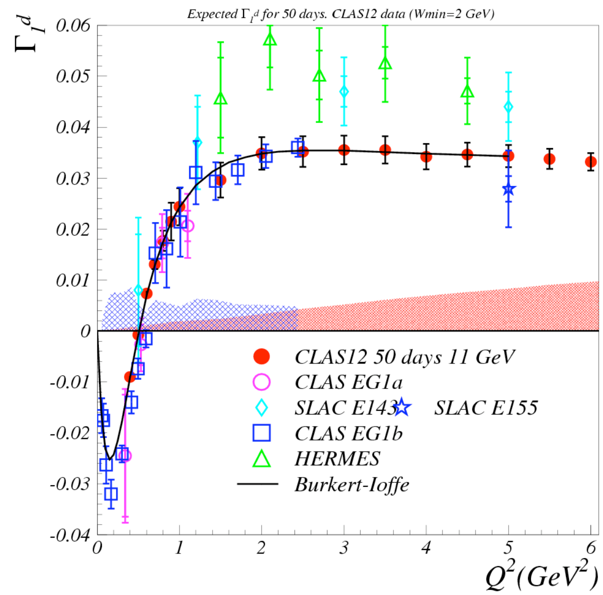
Quoted errors on S,Z and pol are 0.16, 0.49, and 0.24 ppm respectively.
Quoted error on S-Z-pol is 0.57 ppm.
Largest uncertainty in hyperfine splitting comes from low Q^2 form factors!

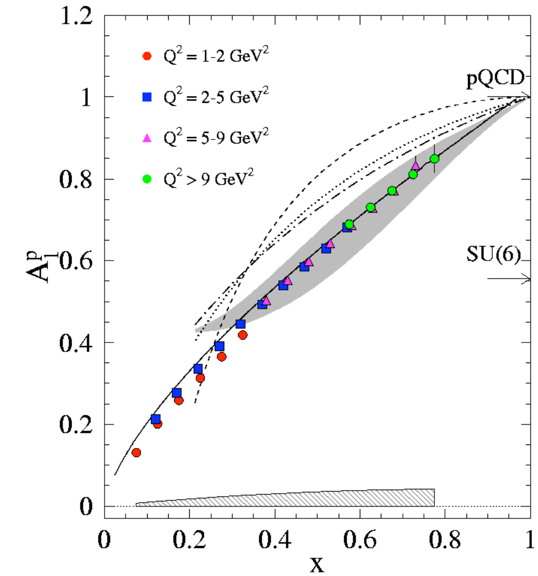
EG4 Expectations

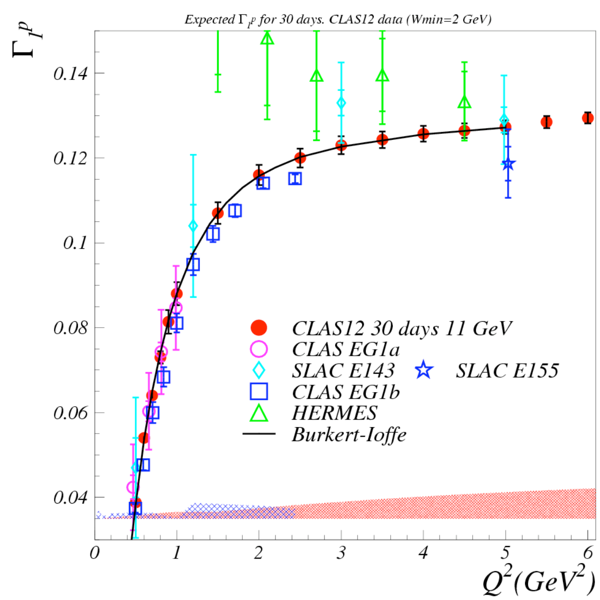


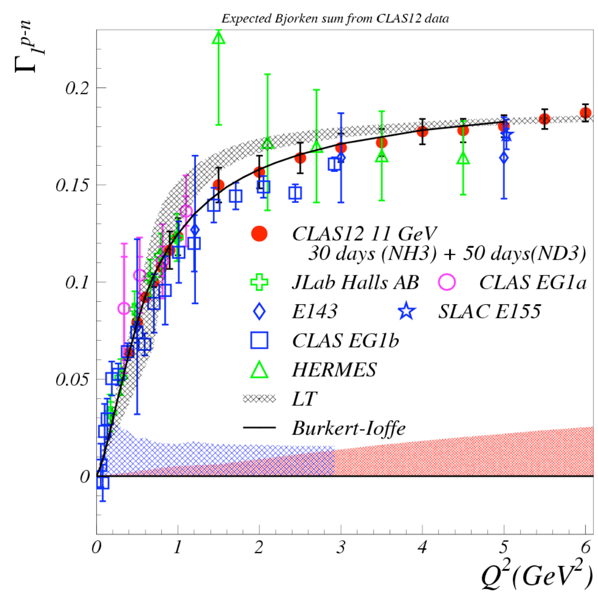
EG12 Expectations

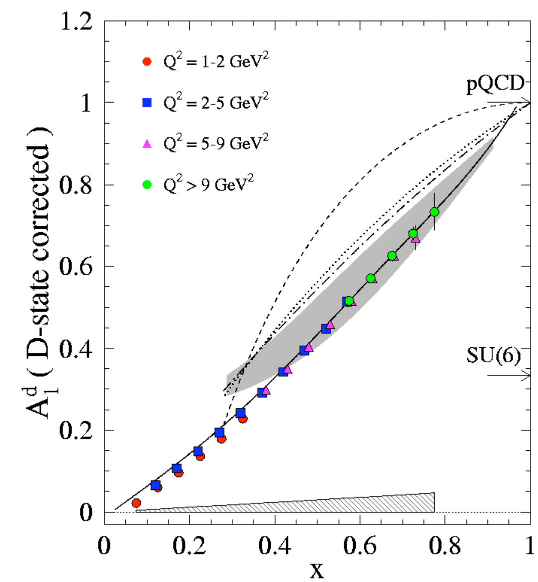










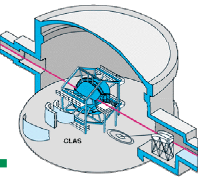


In Conclusion

CLAS, past, present and future, provides high-quality $A_{||}$ data over a large and continuous range in x and Q^2 that

- significantly improve global PDF fits to Δu, Δd, Δs and ΔG
- precisely determine higher twists
- rigorously probe duality over a wide Q^2 range
- quantitatively test χPT calculations at low Q^2
- accurately yield the polarizability correction to hydrogen hyperfine splittings

Postscript



- Our patchwork understanding of the nucleon is not elegant and still incomplete

  "If you are out to describe the truth, leave elegance to the tailor" -- A. Einstein

- After 50 years the nucleon still captures our interest

  "La nature, pour nous hommes, et plus en profondeur qu'en surface." -- Paul Cézanne

- The nucleon, boring on the surface, has a rich internal life

  "o sweet spontaneous
  earth how often
  has the naugty thumb
  of science prodded
  thy
  beauty
  thou answerest
  them only with
  spring" -- e e cummings