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

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Nikhef Colloquium
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Inelastic Scattering

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:

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

\[\alpha = \text{polar angle of target spin wrt the beam axis}\]
\[\phi = \text{azimuthal spin angle wrt the scattering plane}\]
\[\gamma^2 = 4M^2x^2/Q^2 = Q^2/\nu^2\]
\[\xi = 1 - y - \gamma y^2/4\]

Parton Model:
\[F_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 (q^+(x) + ar{q}^+(x) + \bar{q}^+(x))\]
\[F_2(x, Q^2) = 2x F_1(x, Q^2)\]
\[g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 (q^+(x) - q^+(x) + ar{q}^+(x) - ar{q}^+(x))\]
\[g_2(x, Q^2) = 0\]

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

\[Q^2 \text{ increases}\]
$g_1(x, Q^2)$

- $g_1$ DIS measured for $p$, $d$ and $^{3}\text{He}$
- CERN/HERA/SLAC
- (AAC: hep-ph0603213) 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
\[ \frac{1}{2} = \frac{\Delta \Sigma}{2} + \Delta G + L_z \]

<table>
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<td>$0.50 \pm 1.27$</td>
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</table>
• 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
Our tendency is to go from inclusive to exclusive reactions

\[ f(x, Q^2) \quad f(x, Q^2, p_\perp) \]

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

\[ S(F) = \sum_a (E_a - E_0) |<a|F|0>|^2 = <0|[F,[H,F]|0> \]

GDH Sum Rule

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

\[ \Delta \sigma^{\gamma N} = \sigma^{\gamma N}_{3/2} - \sigma^{\gamma N}_{1/2} \]

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

Gottfried Sum Rule

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

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

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

Bjorken Sum Rule

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

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

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

Complicating Factor

\[ \Delta C_{\overline{MS}}^{NS} = 1 - \frac{\alpha_s}{\pi} - 3.583 \left( \frac{\alpha_s}{\pi} \right)^2 - 20.215 \left( \frac{\alpha_s}{\pi} \right)^3 + \ldots \]
Regions of $Q^2$

- Scaling: $\ln Q^2$
- Higher twist: $(1/Q^2)^n$
- $\chi$PT: $(Q^2)^n$
- No nice expansion

$\Gamma^p$

$Q^2(\text{GeV}/c)^2$
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
• Electron beams up to 5.7 GeV with >80% longitudinal polarization
• Beam currents of 1-50 nA in Hall B
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

\[
A_{||} = \frac{\sigma_{\uparrow \uparrow} - \sigma_{\uparrow \uparrow}}{\sigma_{\uparrow \uparrow} + \sigma_{\uparrow \uparrow}}
\]

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

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

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

\[
A_1 = \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{F_1(x, Q^2)}
\]

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

\[
A_2 = \frac{\gamma [g_1(x, Q^2) + g_2(x, Q^2)]}{F_1(x, Q^2)}
\]

We can extract \( A_1 \) and \( A_2 \) from \( A_{||} \) at multiple values of \( \eta(E_{\text{beam}}) \)
• Overlapping colors correspond to different beam energies
• CLAS measures a large range in x at each fixed $Q^2$
• Different $E_{\text{beam}}$ for fixed $(x, Q^2)$ allows separation of $A_1$ & $A_2$
- At low $Q^2$ the $\Delta$ 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
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).
• 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 $A_2$

- 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

Close and Melnitchouk, PRC 68, 035210 (2003)

\[ W > 2; \quad Q^2 > 1 \]

Proton

Deuteron
Quark polarization in the valence limit

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

EG1 Existing Data

Simulated Data for EG12
Extracted from \( A_1^p, A_1^d \) and \( d/u \)
Duality

Proton

global

$\Delta (1232)$

$S_{11} (1535)$

$F_{15} (1680)$

Deuteron

global

$\Delta (1232)$

$S_{11} (1535)$

$F_{15} (1680)$
Higher Twist from $g_1$

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

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

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

- $F_1$ 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
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:

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

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

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

Fit \( \Gamma_1^{p-n} \) to powers of \( 1/Q^2 \) and extract \( f_2^{p-n} \)
Commensurate Scaling

\[ \int_0^1 dx \left[ g_{1p}^e(x, Q^2) - g_{1n}^e(x, Q^2) \right] = \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left( 1 - \frac{\alpha_{g_1}(Q)}{\pi} \right) \]

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

\[ \frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{g_1}(Q^*^*)}{\pi} + \frac{3}{4} C_F \left( \frac{\alpha_{g_1}(Q^*^**)}{\pi} \right)^2 \]

\[ + \left[ \frac{9}{16} C_F^2 + \left( \frac{11}{3} \frac{\alpha_{g_1}(Q^*^**)}{\pi} \right) \frac{\alpha_{g_1}(Q^*^*)}{\pi} \right] \left( \frac{\alpha_{g_1}(Q^*^*)}{\pi} \right)^2 \]

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

\[ \ln \left( \frac{Q^*/Q}{Q^*^*/Q} \right) = -\frac{233}{216} + 64 \zeta_3 + \frac{22}{3} \zeta_3^2 + \left( -\frac{13}{54} + \frac{2}{9} \zeta_3 \right) \frac{C_A}{C_F} \]

\[ R(e^+e^- \rightarrow \text{more than 2 hadrons}) \]

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Nikhef
\[ \Gamma_1^{p,d}(Q^2) = \int_0^1 g_1^{p,d}(x, Q^2) dx \]
\[ \Gamma_1(Q^2) = aQ^2 + bQ^4 + cQ^6 + dQ^8 \]
\[ \Gamma_1^d(Q^2) = (1 - 1.5 \omega_D) \{ \Gamma_1^p(Q^2) + \Gamma_1^n(Q^2) \} \]
\[ \Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2} Q^2 + 3.89Q^4 + \ldots \]
\[ \Gamma_1^n(Q^2) = -\frac{\kappa_n^2}{8M^2} Q^2 + 3.15Q^4 + \ldots \]

**PRELIMINARY**

**Moments \( \Gamma_1^{p,d} \)**

**low \( Q^2 \) fit**

**GDH + \( \chi pT \)**
Low $Q^2$ Fits of $\Gamma_1$

\[ \Gamma_1^n(Q^2) = a \Gamma_1^n(Q^2) + b \Gamma_1^n(Q^2) + c \Gamma_1^n(Q^2) + d \Gamma_1^n(Q^2) \]

$a$ fixed by GDH
$b$ compared to $\chi$PT

\[ \chi_{PT} \]

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

Amarian et al., PRL92(04)022301

\[ \gamma_0(Q^2) = \frac{4e^2 M^2}{\pi Q^6} \int_0^{x_0} dx \, x^2 \left\{ g_1(x, Q^2) - \gamma^2 g_2(x, Q^2) \right\} \]
$\gamma_0$ 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, PRL94(05)022001,169902(E).
- \( E_{\text{hfs}}(e^- p) = E_p (1 + \Delta_{\text{QED}} + \Delta^p_R + \Delta S + \Delta^p_{\text{hvp}} + \Delta^p_{\mu\text{vp}} + \Delta^p_{\text{weak}}) = 1.4204057517667(9) \text{ GHz} \)
- \( \Delta_{\text{QED}} = 1136.09(14) \text{ ppm} \left( \frac{\alpha}{2\pi} + \ldots \right) \)
- \( \Delta^p_R = 5.86(15) \text{ ppm} \) (recoil)
- \( \Delta^p_{\text{hvp}} = 0.01 \text{ ppm} \) (hadronic vacuum polarization)
- \( \Delta^p_{\mu\text{vp}} = 0.07 \text{ ppm} \) (muonic vacuum polarization)
- \( \Delta^p_{\text{weak}} = 0.06 \text{ ppm} \) (weak interaction)
- \( \Delta S = -38.62(16) \text{ ppm} \) (nucleon structure; deduced)
- \( \Delta S \) is the largest uncertainty in theoretical calculation of \( E_{\text{hfs}}(e^- p) \)
Hydrogen Hyperfine Splitting

\[ E_{\text{HFS}}(e^-p) = 1.4204057517667(9)\text{GHz} = (1 + \Delta_{QED} + \Delta_{p} + \Delta_{S}) E_{F}^{p} \]

\[ \Delta_{S} = \Delta_{Z} + \Delta_{\text{pol}} \]

\[ \delta_{Z}^{\text{rad}} = \frac{\alpha}{3\pi} \left[ 2 \ln \frac{\Lambda^2}{m^2} - \frac{4111}{420} \right] \]

Zemach: \[ \Delta_{Z} = -2\alpha m_{e} \langle r \rangle_{Z} (1 + \delta_{Z}^{\text{rad}}) \]

\[ \langle r \rangle_{Z} = -\frac{4}{\pi} \int_{0}^{\infty} \frac{dQ}{Q^2} \left[ G_{E}(Q^2) \frac{G_{M}(Q^2)}{1 + \kappa} - 1 \right] \]

\[ \Delta_{S} = -38.62(16) \text{ ppm} \quad \Delta_{Z} = -41.0(5) \text{ ppm} \quad \Delta_{\text{pol}} = 2.38(58) \text{ ppm} \]

\[ \Delta_{\text{pol}} = \frac{\alpha m_{e}}{2\pi(1 + \kappa) M} (\Delta_{1} + \Delta_{2}) = (0.2264798 \text{ ppm}) (\Delta_{1} + \Delta_{2}) \]

\[ \Delta_{1} = \frac{9}{4} \int_{0}^{\infty} \frac{dQ^2}{Q^2} \left\{ F_{2}^{2}(Q^2) + \frac{8m_{p}^2}{Q^2} B_{1}(Q^2) \right\} \]

\[ \Delta_{2} = -24m_{p}^2 \int_{0}^{\infty} \frac{dQ^2}{Q^4} B_{2}(Q^2). \]

\[ \tau = \nu^2 / Q^2 \]

\[ B_{1} = \int_{0}^{\infty} dx \beta(\tau) g_{1}(x, Q^2), \]

\[ B_{2} = \int_{0}^{\infty} dx \beta_{2}(\tau) g_{2}(x, Q^2), \]

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

\[ \beta_{2}(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau + 1)}, \]
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 $B_2 = \int \beta_2 g_2 dx$

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

$\Delta_{\text{pol}} = (1.3 \pm 0.3) \text{ ppm}$
(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 $Q^2$

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

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

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

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

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

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

$$
\delta_{LT}(Q^2) = \left( \frac{1}{2\pi^2} \right) \int_{\nu_0}^\infty \frac{K(\nu, Q^2)}{\nu} \frac{\sigma_{LT}(\nu, Q^2)}{\nu Q^2} \, d\nu
\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 [g_1(x, Q^2) + g_2(x, Q^2)] \, dx
$$
\[ \Delta_2[0, Q_1^2] = 3m_p^2 Q_1^2 (\gamma_0 - \delta_{LT}) / 2\alpha \]

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

\[ \gamma_0 = -1.01 \times 10^{-4} \text{ fm}^4 \text{ (photons)} \]

\[ r_P = 0.878(15) \text{ fm (Kelly)} \]

\[ c_1 = 2.95 - 3.89 \text{ (fits/} \chi^2 \text{PT)} \]

\[ \delta_{LT} = 1.35 \times 10^{-4} \text{ fm}^4 \text{ (MAID)} \]

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

\[ \Delta_2[0,0.05] = -0.40(05) [g_2^{WW}] \]

\[ -1.4 \text{ [MAID]} \]

\[ -0.24 \text{ [EG1 Model]} \]

\[ \Delta_1 + \Delta_2 = 5.91 \pm 1.06 \]

\[ \Delta_{pol} = 1.34 \pm 0.24 \text{ ppm} \]
Various estimates change $\Delta_{\text{pol}}$ up or down within the quoted errors. New data at low $Q^2$ are needed to improve this.

$$\Delta_1[0,0.05] = [-0.75r_p^2\kappa_p^2 + 18m_p^2b]0.05 = 0.32$$
$G_{Ep}$ & $G_{Mp}$

Friedrich and Walcher, EPJA17(2003)607
The diversity of fits reflects an inaccurate knowledge of the form factors at low $Q^2$. 

G. Ron et al., nucl-ex 0706.0128
Hall A
Zemach: \[ \Delta_Z = -2\alpha m_e \langle r \rangle_Z (1 + \delta_{\text{rad}}^Z) \]

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

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<th>Reference</th>
<th>( r_Z ) (fm)</th>
<th>( \Delta_Z ) (ppm)</th>
<th>( \Delta_S - \Delta_Z - \Delta_{\text{pol}} ) (ppm)</th>
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<td>Kelly</td>
<td>1.069(13)</td>
<td>-41.01</td>
<td>1.11</td>
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<tr>
<td>Sick</td>
<td>1.086(12)</td>
<td>-41.67</td>
<td>1.77</td>
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<td>-40.20</td>
<td>0.30</td>
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<td>Dipole</td>
<td>1.025</td>
<td>-39.32</td>
<td>-0.58</td>
</tr>
</tbody>
</table>

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

Expected statistical accuracy on $\Gamma_p$ for EG4

- CLAS EG4 w/o large-w part (Simula param.)
- Full $\Gamma_p$ (Simula parameterization)
- CLAS EG1a
- CLAS EG1b preliminary
- Bernard et al, Xpt
- Ji et al, Xpt
- GDH slope
- Burkert-Ioffe
- Soffer-Teryaev (2004)
In Conclusion

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

- significantly improve global PDF fits to $\Delta u$, $\Delta d$, $\Delta s$ and $\Delta G$
- precisely determine higher twists
- rigorously probe duality over a wide $Q^2$ range
- quantitatively test $\chi$PT calculations at low $Q^2$
- accurately yield the polarizability correction to hydrogen hyperfine splittings
• 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