New Constraints on Proton Size from Spin Structure Data

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Based on current work with D. Ruth, K. Slifer, J.-P. Chen, F. Hagelstein, V. Pascalutsa, A. Deur, S. Kuhn, M. Ripani, X. Zheng, R. Zielinski, & C. Gu.
Also ancient papers with Nazaryan & Griffioen, PRL 2006, CJP 2007, LNP 2008, PRA 2008, 2011

Motivation

- General: find the proton structure effects on the hyperfine splitting (HFS) in hydrogen, both μH and *e*H.

- More specific:

  - Take advantage of excellent new input data

  - Get more accurate prediction of splitting to help in setting up new experiments

  - Get a new measure of the average separation between magnetic and electric material in the proton, the Zemach radius. (Titular motivation)

- Talk will be mostly about how the calculation is done. Will show new results, both for HFS and Zemach radius.

New input data

- For our calculation, input data includes the spin-dependent proton structure functions g_1 and g_2, measured in polarized inelastic ep scattering

- Functions of W (total CM ep energy) and Q^2 (photon off-shell mass).

- Previously, no g_2 data at all. Now g2p JLab experiment 84 data points, at 4 different Q^2 (Ruth et al., 2022)

- And wonderfully extended set of g_1 data from JLab EG4. 1085 data points, at 25 values of Q^2, range $\approx [0.01, 1.0]$ GeV^2 (Zheng et al., 2021)

For information, the old data

- No old data at all for g_2.
  Wilczek-Wandzura relation could give part of g_2
  and there were data fits (!)

- JLab EG1b g_1 data, available in 2005
  1124 data points at 27 values of Q^2
  range $\approx [0.05, 5.0]$ GeV^2
  (publication Fersch et al., 2017)

- SLAC E155 g_1 data, 24 data points, $Q^2 > 1.2$ GeV^2
  (Anthony et al., 2000)

- Actual data for g_2 and good lower Q^2 g_1 data creates opportunity for much improved calculational result

New planned experiments

- CREMA, FAMU, & JPARC propose measurement of HFS in ground state μH

- 1S μH splitting is about 182.636 meV
  or wavelength ≈ 6.8 μm (infrared)
  or frequency ≈ 44.2 THz

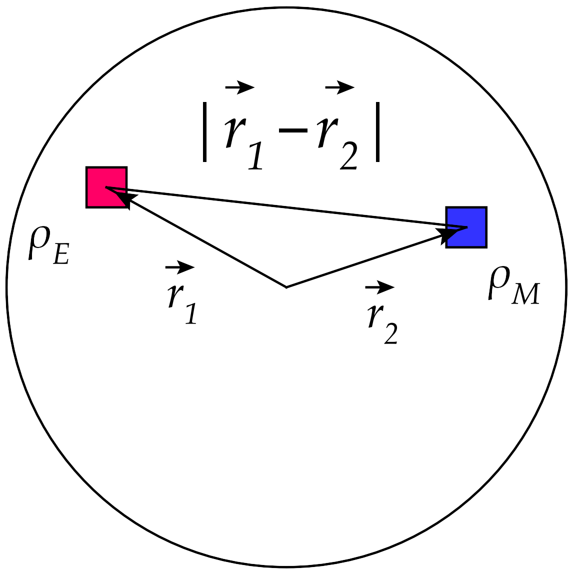
- Worry about time to run experiment:
  Have laser, frequency width ≈ 100 MHz

- Say spread of prediction is about 0.16 meV (can do better!)
  ➔ spread of frequency prediction is ≈ 40 GHz
  ➔ need ≈ 400 frequency settings of laser to scan HFS region.

Planned experiments run time

- From talks: need 1.4 hour to get 4σ signal above background, and 1 hour to change laser frequency.
- 2.4 hours × 400 = 960 hours ≈ 8 weeks   (@ 5 days/week)
  Ugh: other groups want the PSI (CREMA's location) also
- ∴ want good theoretical help to reduce the laser scan width
- Anticipate fractional experimental uncertainty upon completion better than 100 MHz/44.2 THz ≈ 2 ppm
- Current best μH HFS splitting measurement is from CREMA (Science, 2013) and is 22.8089 (51) meV for the 2S state, or ≈ 220 ppm.
- For comparison,
  $E_{\mathrm{1S,HFS}}(eH) = h \times 1420.405\,751\,768\,(2)$ MHz or 1.4 ppt

Coming soon: Zemach radius



- Is average separation of magnetic and electric material in proton

$$r_Z = \int d^3r_1 \; d^3r_2 \; \rho_E(\vec{r}_1) \, |\vec{r}_1 - \vec{r}_2| \, \rho_M(\vec{r}_2)$$

- Nonrelativistically same as

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

- Can obtain from form factors, or by “reverse engineering” from coming work on HFS

Side note

- NR, form factors are Fourier transforms of charge or magnetic densities.

- Relativistically, form factors defined from matrix element of electromagnetic current,

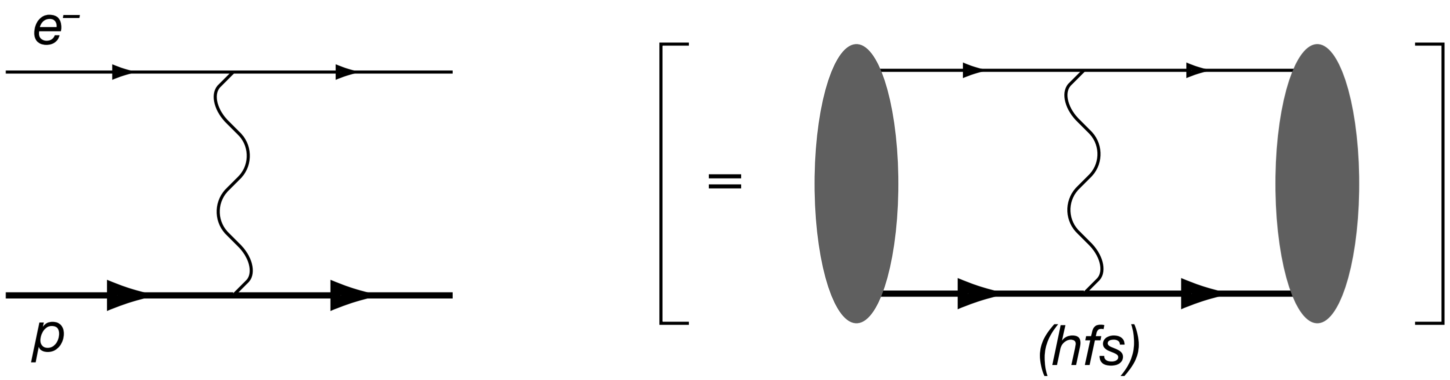
$$\langle p', s' | J_\mu | p, s \rangle = \bar{u}(p', s') \left[\gamma_\mu F_1 + i \sigma_{\mu\nu} q^\nu \frac{F_2}{2m_p} \right] u(p, s)$$

(with $G_M = F_1 + F_2$; $\quad G_E = F_1 - (Q^2/4m_p^2) F_2$)

- Provably same in NR limit, but not in general.
Coming results define r_Z from form factor expression.

The calculation: lowest order

- H-atom, S-state, spin-dependent splitting
  UG textbook calculation!



- Get $$E_F^p = \frac{8\pi}{3}\frac{\mu_B \mu_p}{a_B^3} = \frac{8\pi}{3}(m_r\alpha)^3 \mu_B \mu_p$$

- $\mu_B = e/(2m_\ell)$ Bohr magneton
  $\mu_p = (1+\kappa_p)\, e/(2m_p)$ exact magnetic moment for proton

- “Fermi energy” ; Can evaluate to about 10-figure accuracy

- Alternate writings, $$E_F^p = \frac{8\alpha^4}{3}\frac{m_\ell^2(1+\kappa_p)}{m_p(1+m_\ell/m_p)^3} = \frac{16\alpha^2}{3}\frac{\mu_p}{\mu_B}\frac{R_\infty}{(1+m_\ell/m_p)^3}$$

Next need corrections

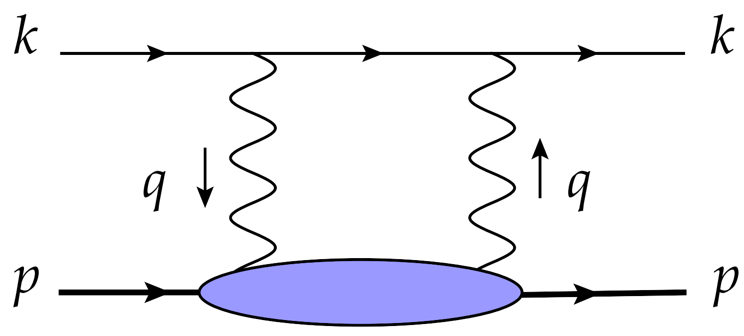
- Write as

$$E^p_{HFS} = E^p_F \left(1 + \Delta_{QED} + \Delta_S + \text{some smaller corrections}\right)$$

- Δ_{QED} well calculated

- "some smaller corrections" won't be discussed here

- Δ_S = structure dependent corrections,
  here meaning corrections from 2-γ exchange,



- Conventionally separate as

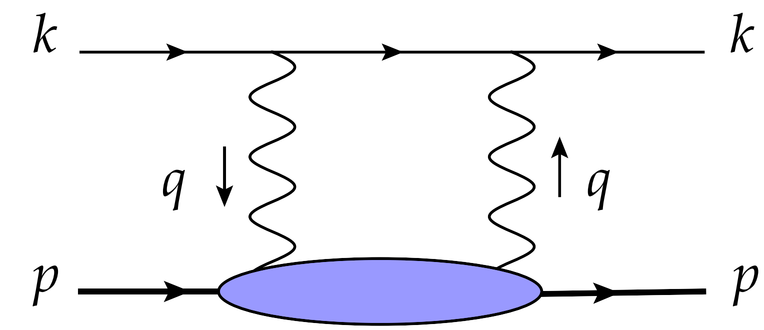
$$\Delta_S = \Delta_Z + \Delta_R + \Delta_{pol}$$

NR elastic "Zemach" | Rel. elastic Corrections | Polarizability corrections

To be discussed

- How do we get the 2γ corrections from ep scattering data? (General answer: dispersion relations)
- Believe unsubtracted dispersion relation o.k. Can be discussed if needed.
- Effect of new data.

2γ corrections



- Not calculable *ab initio*.
  But lower part is forward Compton scattering of off-shell photons, algebraically gotten from

$$T_{\mu\nu}(q,p,S) = \frac{i}{2\pi m_p} \int d^4\xi \; e^{iq\cdot\xi} \langle pS \big| \; T j_\mu(\xi) j_\nu(0) \big| pS \rangle$$

- Spin dependence is in the antisymmetric part

$$T^A_{\mu\nu} = \frac{i}{m_p} \epsilon_{\mu\nu\alpha\beta} q^\alpha \left[H_1(\nu,Q^2)\, S^\beta + H_2(\nu,Q^2) \frac{p\cdot q\, S^\beta - S\cdot q\, p^\beta}{p\cdot q} \right]$$

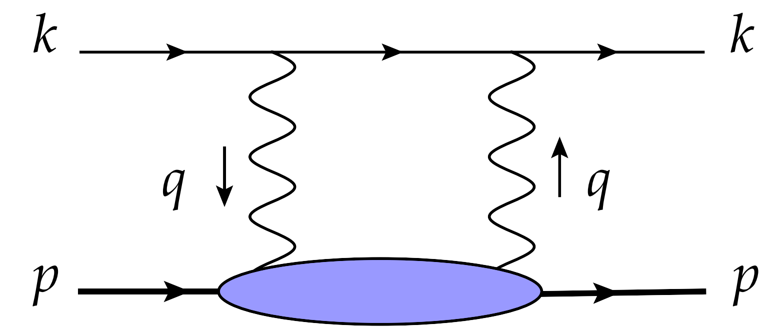
Some use $S_{1,2} = 4\pi^2 \alpha H_{1,2}$

- Imaginary part of above is related to polarized inelastic ep scattering, with

$$\operatorname{Im} H_1(\nu,Q^2) = \frac{1}{\nu}\, g_1(\nu,Q^2) \qquad \text{and} \qquad \operatorname{Im} H_2(\nu,Q^2) = \frac{m_p}{\nu^2}\, g_2(\nu,Q^2)$$

- Emphasize: g_1 and g_2 are measured at SLAC, HERMES, JLab,…

2γ corrections



- Combine electron part of diagram with Compton bottom, and energy from 2γ exchange

$$\Delta_{\rm pol} = \left.\frac{E_{2\gamma}}{E_F}\right|_{\rm inel} = \frac{2\alpha m_e}{(1+\kappa_p)\pi^3 m_p}$$
$$\times \int \frac{d^4Q}{(Q^4+4m_e^2Q_0^2)Q^2}\left\{(2Q^2+Q_0^2)H_1^{\rm inel}(iQ_0,Q^2) - 3Q^2Q_0^2H_2^{\rm inel}(iQ_0,Q^2)\right\}$$

- (Wick rotated). Great, but don't know $H_{1,2}$ from data.

- But do know Im parts, and if no subtraction, simple Cauchy (dispersion relation) gives

$$H_1^{\rm inel}(\nu,Q^2) = \frac{1}{\pi}\int_{\nu_{th}^2}^{\infty} d\nu'^2\,\frac{{\rm Im}\,H_1(\nu',Q^2)}{\nu'^2-\nu^2}$$

and similarly for H_2.

Do some integrals analytically, getting

- $$\Delta_{\text{pol}} = \frac{\alpha m_\ell}{2(1+\kappa_p)\pi m_p}(\Delta_1 + \Delta_2)$$

- $$\Delta_1 = \int_0^\infty \frac{dQ^2}{Q^2} \left\{ \beta_1\left(\frac{Q^2}{4m_\ell^2}\right) F_2^2(Q^2) + 4m_p \int_{\nu_{th}}^\infty \frac{d\nu}{\nu^2} \tilde{\beta}_1\left(Q^2, \nu, m_\ell\right) g_1(\nu, Q^2) \right\}$$

- $$\Delta_2 = -12m_p \int_0^\infty \frac{dQ^2}{Q^2} \int_{\nu_{th}}^\infty \frac{d\nu}{\nu^2} \tilde{\beta}_2\left(Q^2, \nu, m_\ell\right) g_2(\nu, Q^2)$$

  - $\beta_1(\tau) = -3\tau + 2\tau^2 + 2(2-\tau)\sqrt{\tau(\tau+1)}$

  - $\tilde{\beta}_1$ and $\tilde{\beta}_2$ are known kinematic weighting functions.

Comments

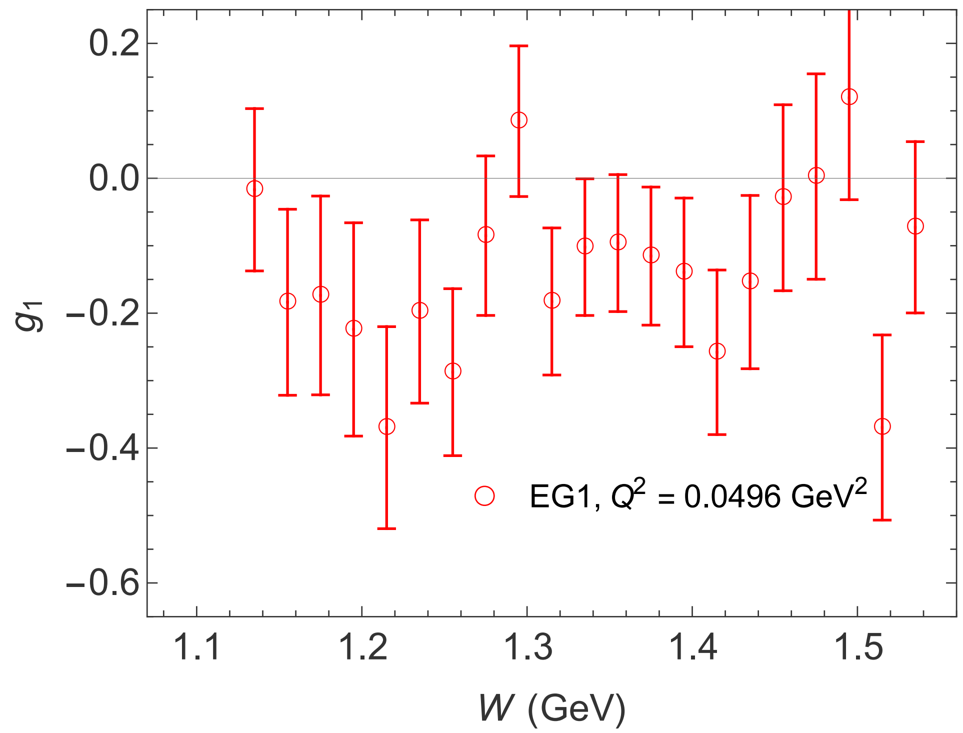
- Early history: begun by Iddings (1965),
  finalized by Drell and Sullivan (1967),
  put in present notation by de Rafael (1971).
  No spin-dependent data existed,
  no nonzero evaluation for > 30 years,
  until Faustov and Martynenko (2002),
  then modern era starts

- Someone added something: the F_2^2 term. Not inelastic.
  (Put in here, taken out somewhere else.)
  Thought convenient in 1967, still here in 2024..

- Δ_1 term as written finite in $m_e \to 0$ limit, because of known sum rule, $4m_p \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu^2} g_1(\nu,0) = -\kappa_p^2$ (DHGHY)

Effect of new data, g_1

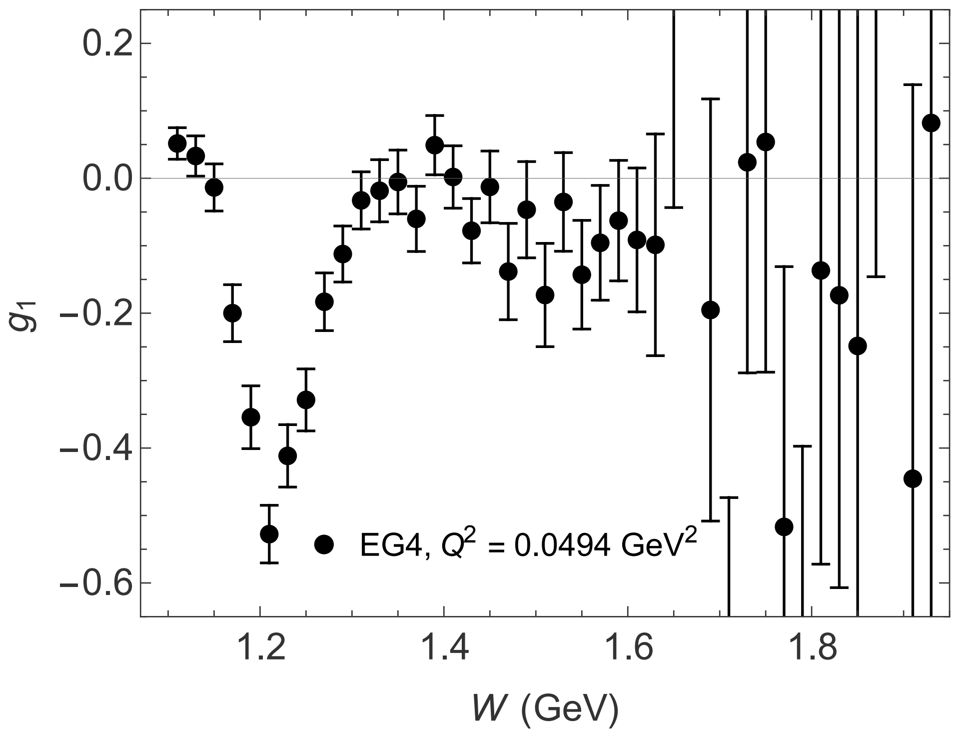
- One set of plots



- 2005 data

Effect of new data, g_1

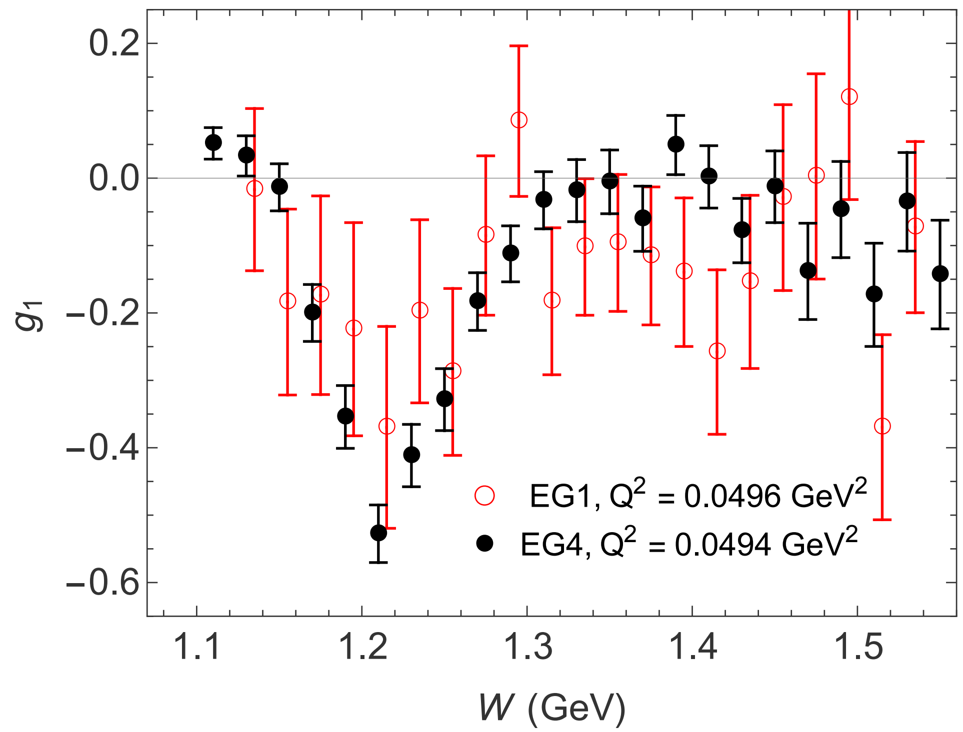
- One set of plots



- 2022 data

Effect of new data, g_1

- One set of plots



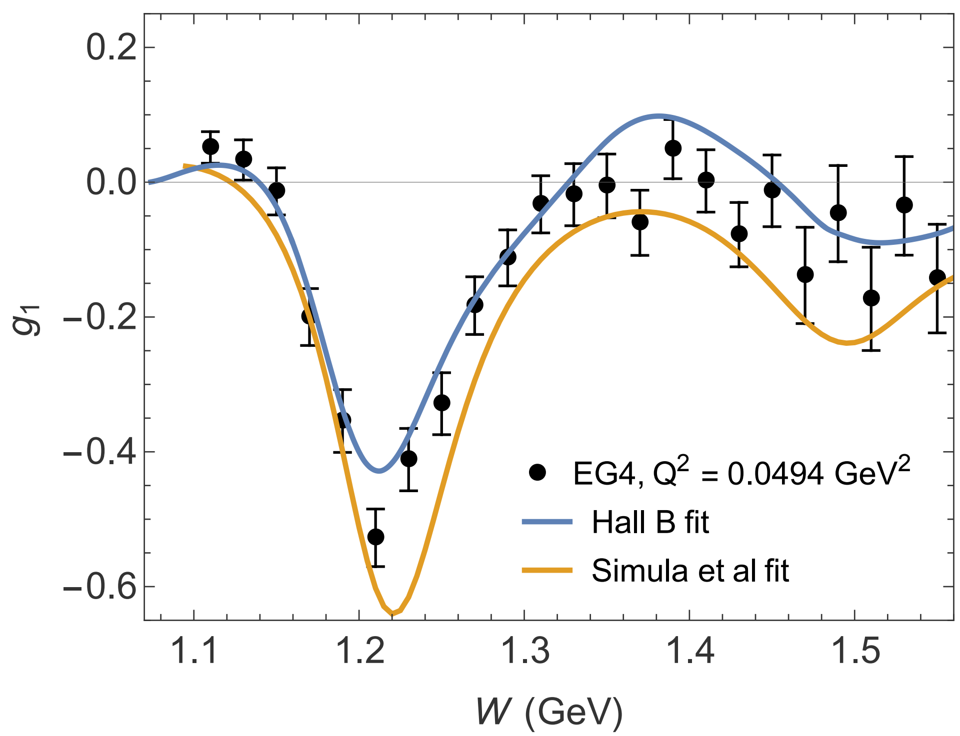
- together

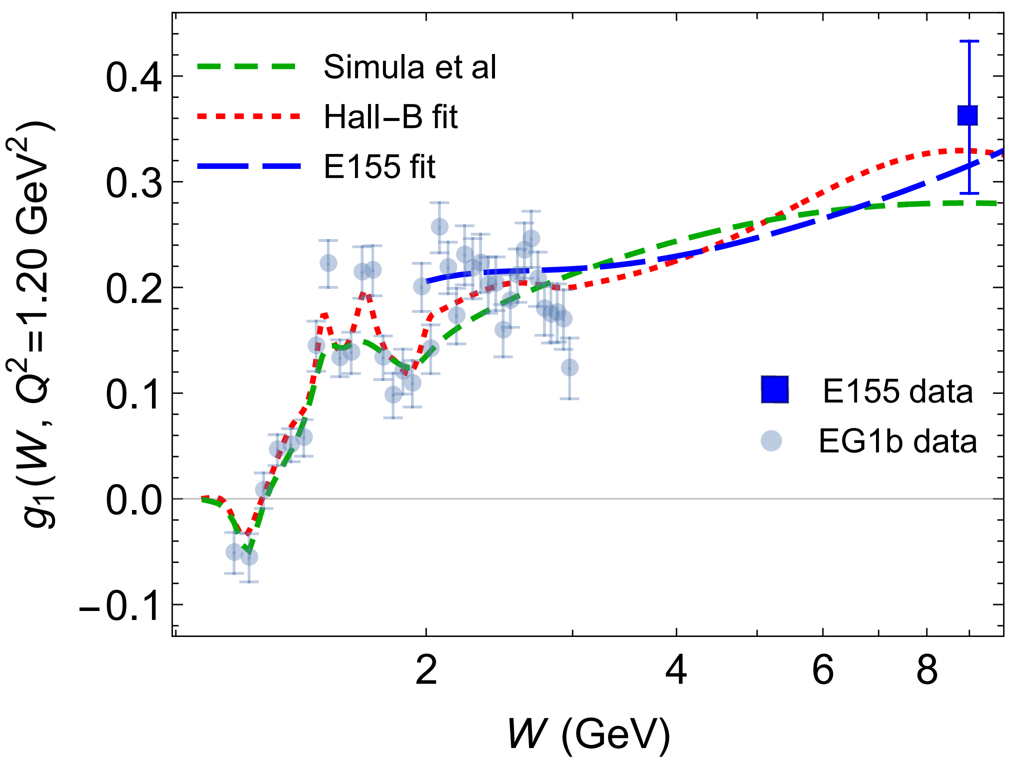
- Effect on error limits:
  new: $\Delta_1(eH, \text{data only}) = 4.72 \pm 1.02$
  old: $\Delta_1(eH, \text{data only}) = x.xx \pm 2.69$

Completion of Δ_1 calculation

- More comments on Δ_1 before going to g_2
- ∃ noticeable contributions from outside the data region. Need model or fit to extrapolate. Have fit of Simula et al (PRD, 2002) and
fit of Hall B collaboration (unpub., ca. 2016) and
fit of E155 (PLB, 2000, high Q^2, high W only).
- Hall B fits best where we have comparison data

Some fit comparisons





- Generally good agreement among the three fits in scaling region (high Q^2, high W).
- Hall B closer in data region. (They did have EG1b data.)
- We use the Hall B fit for the fill-in contributions (higher W for Q^2in data region, and Q^2 above and below data region).

Δ_1 results today

- $\Delta_1(eH)$ = 4.71 ± 1.02 from data
  + 1.60 ± … high W fill-in, data region
  + 0.12 ± … low Q^2
  + 0.34 ± … high Q^2

  = 6.78 ± 1.02_{data} ± $0.23_{\text{fill-in}}$

- Old $\Delta_1(eH)$ = 8.85 ± 2.78

- About -1 unit from newer data and about -1 from updated fill-in choice.

Modern Δ_2, short version

- Thanks to g2p JLab experiment, have data where there was none before
- $\Delta_2(eH) = -1.20_{\text{data}} \pm 0.16_{\text{data}} + \text{fill-in}$
  $= -1.98 \pm 0.16_{\text{data}} \pm 0.38_{\text{fill-in}}$
- Old $\Delta_2(eH) = -0.57 \pm 0.57$
- Big difference from having data.
- Wilczek-Wandzura close to old value, not to data.

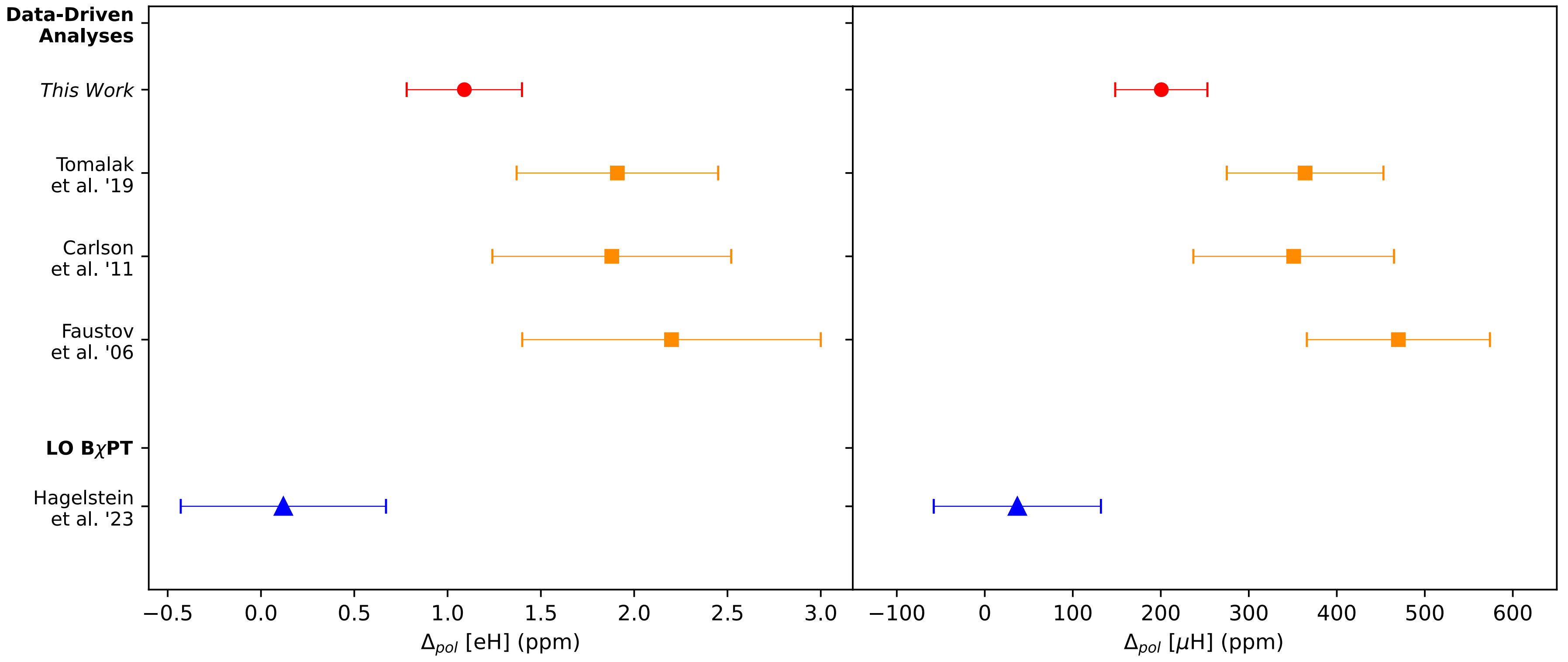
Δ_{pol} results

- Reminders: $$\Delta_{\text{pol}} = \frac{\alpha m_\ell}{2(1+\kappa_p)\pi m_p}(\Delta_1 + \Delta_2)$$

$$E^p_{HFS} = E^p_F \left(1 + \Delta_{QED} + \Delta_Z + \Delta_R + \Delta_{\text{pol}} + \text{some smaller corrections}\right)$$

- New results: $\Delta_{\text{pol}}(eH) = 1.09 \pm 0.31$ ppm

  $\Delta_{\text{pol}}(\mu H) = 200.6 \pm 52.4$ ppm



More results

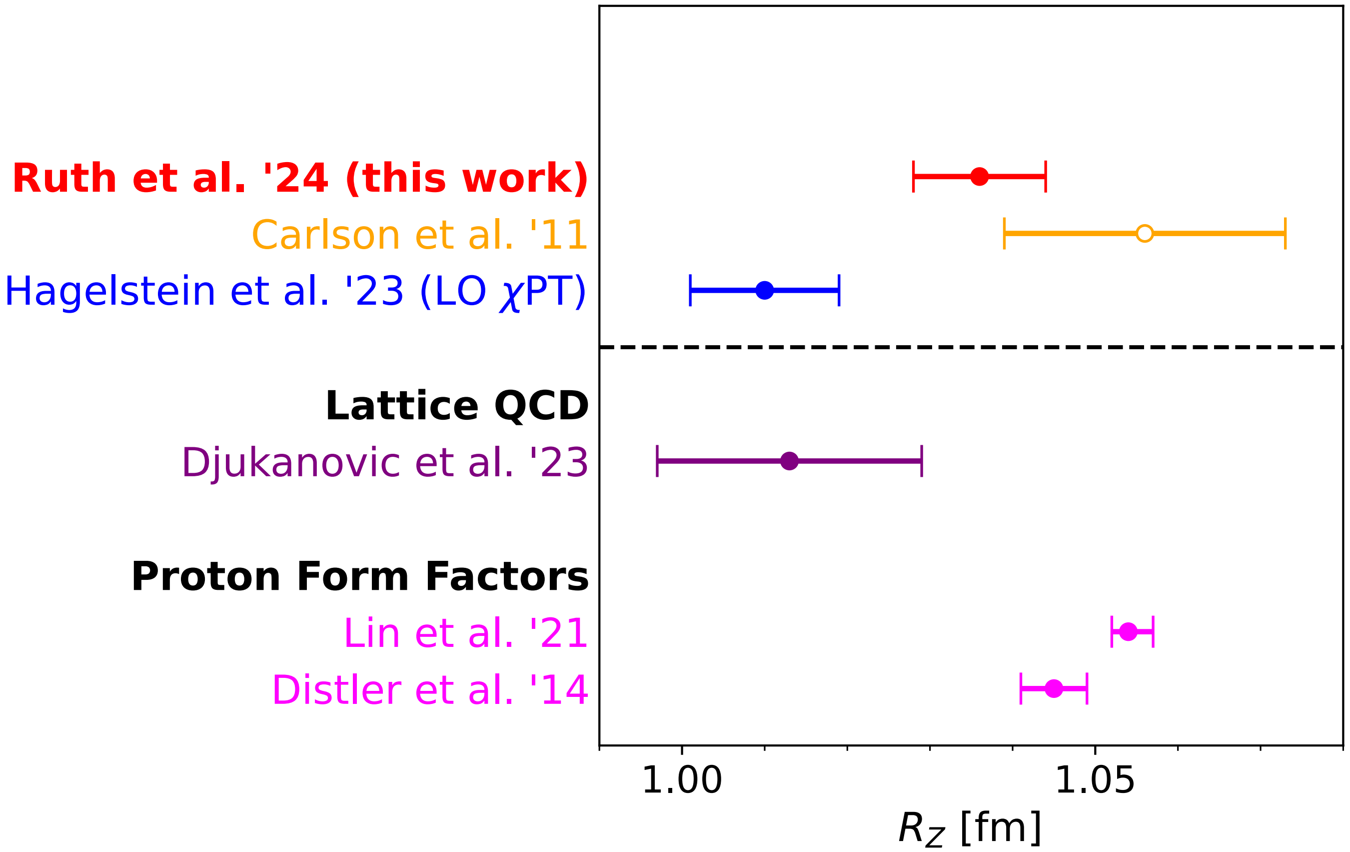
- Want also Δ_Z and Δ_R
- Δ_Z is big (magnitude about 7000 ppm for μ case), and varies with choice of form factors.
- If focusing on muon case, one way to do better is to use electron experimental data and calculation of Δ_R (a smaller term, about 900 ppm) to obtain the Zemach radius.
- Then use Zemach radius so determined to find HFS for μH

Zemach radius

- Reminder: $r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa_p} - 1\right]$

$$\Delta_Z = -2\alpha\, m_{r\ell}\, r_Z$$

- "Reverse engineering": $r_Z = 1.036(8)$ fm



- More comparisons,

  $r_Z = \{1.080, 1.091, 1.069, 1.049, 1.025\}$

  for AMT, AS, Kelly, FW, dipole

Muon results

- Use this r_Z and work out other corrections to find overall HFS for μH.

- Specifically need recoil term, which is a relativistic correction, dependent on $G_E, G_M, \& F_2$. Surprisingly steady at about 931 ppm.

- $$E^{\text{th.}}_{1S\text{-HFS}}(\mu\text{H}) = 182.636\,(16)\,\text{meV}$$

Note

- Further improveable method of Tomalak and of Peset and Pineda (2018). They realized that the experimental $E^p_{HFS}(eH)$ is known to 12 figures and the bulk of the μH calculation just scales with the $m_{r\mu}/m_{re}$ mass ratio, known to 10 figures. Just need to calculate the smaller pieces that don't scale this way, leading to a final result with smaller overall uncertainty. Will see again ready soon. Relatively modern number obtained this way already available in Antognini et al (2022). Error bar (8).

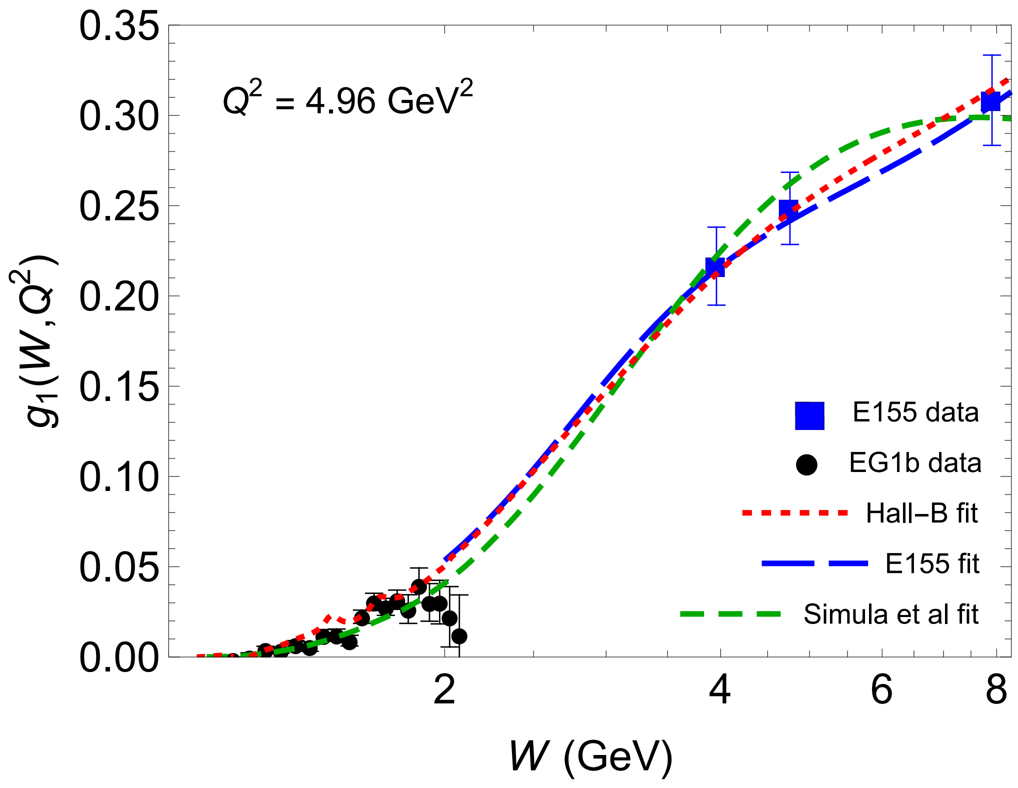
Summary

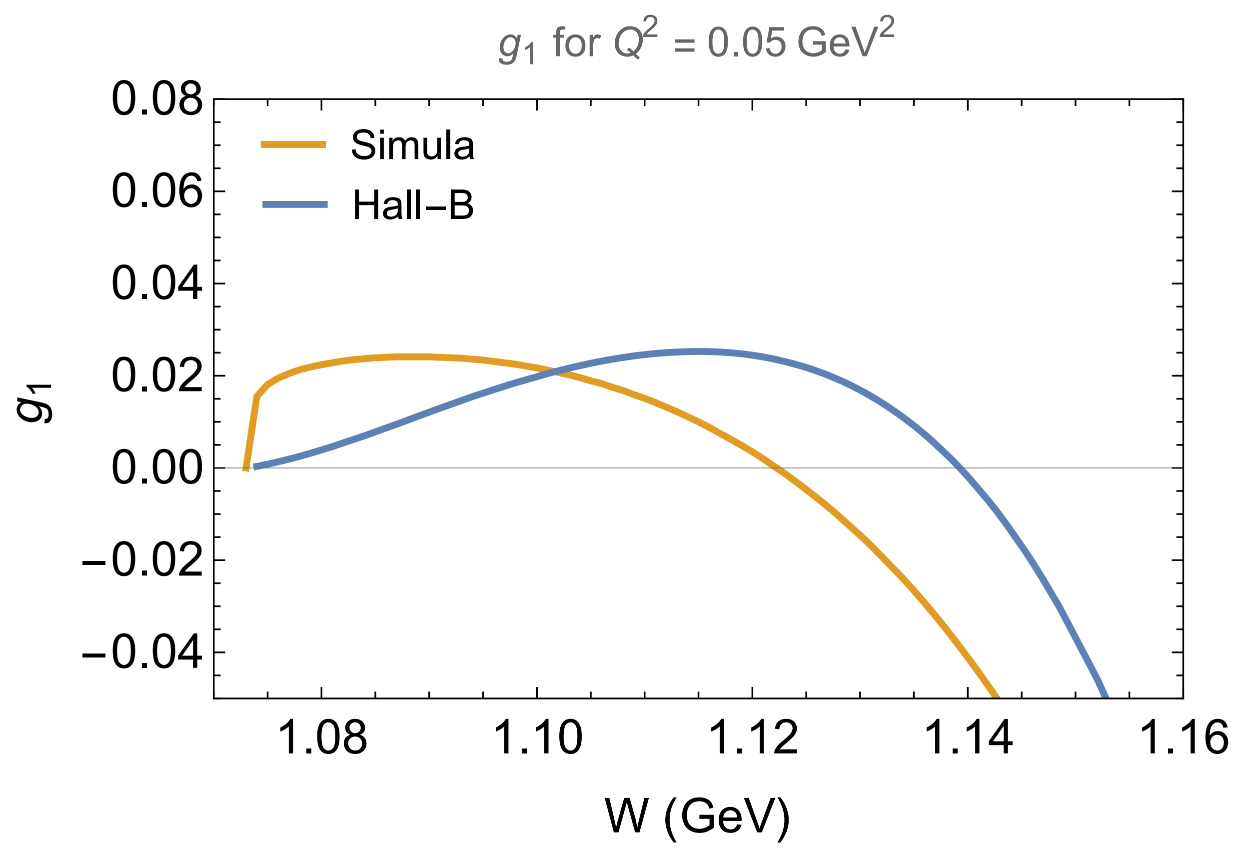
- Dispersive calculation, assuming no subtractions are needed, is complete, well defined, and unambiguous.
- Gets value of HFS using spin-dependent ep scattering data as input.
- New data reduces uncertainty limits in calculated HFS by more than factor 2.
- Result already useful for pinning down starting point of laser settings in new μH HFS measurements.
- Also have an improved (Zemach) radius determination.
- Can still do somewhat better.
- EFT calculations not much mentioned in this talk, but there is a “tension” that requires resolution.

Beyond the end

More fit comparisons

- Scaling region; near threshold W.



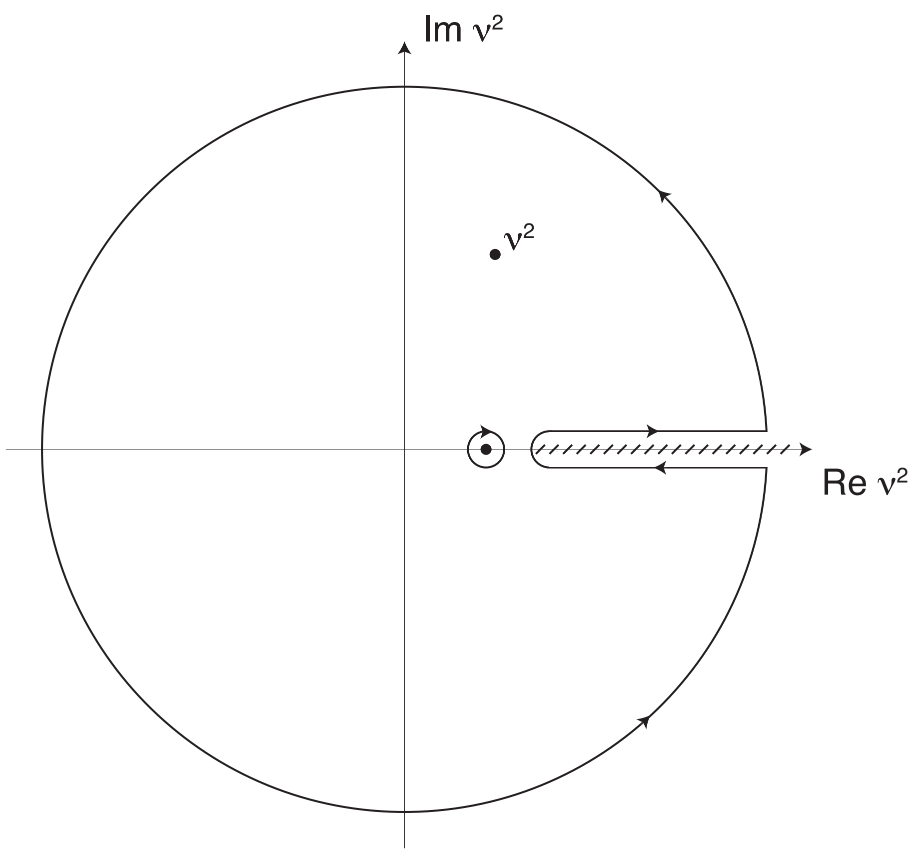


Unsubtracted dispersion relation (DR)?

- Was once openly discussed (< 2006, say), now seems generally thought o.k.

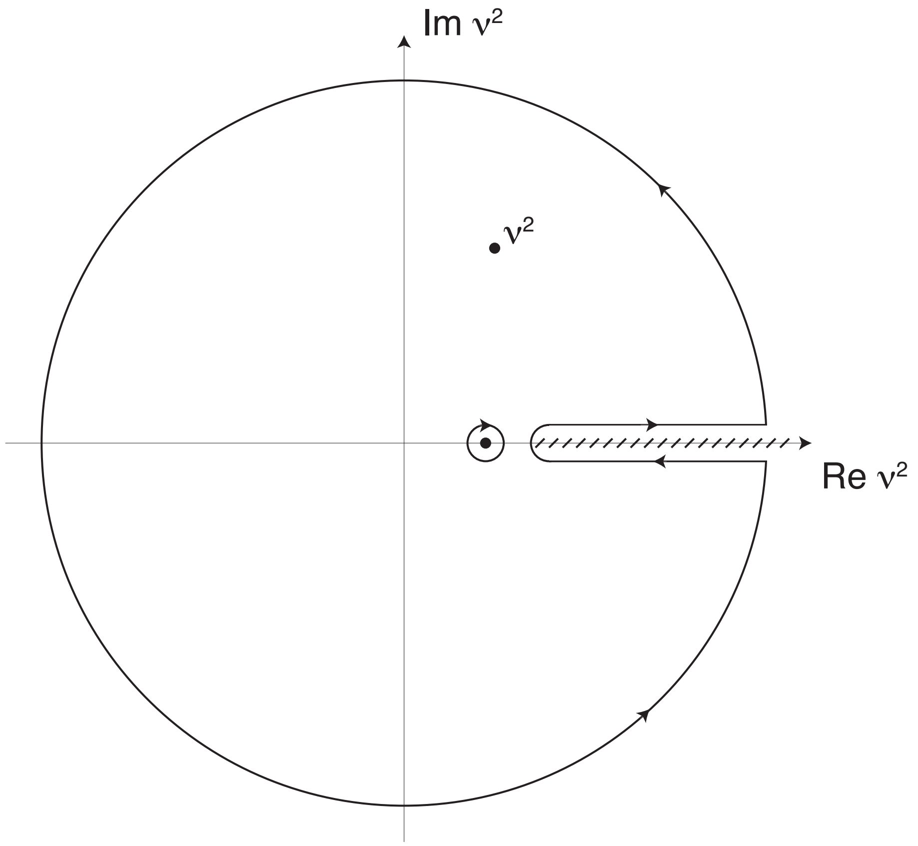
- DR comes from Cauchy integral formula applied with some contour (closed integration path)

$$H_1(\nu, Q^2) = \frac{1}{2\pi i} \oint \frac{H_1(\nu', Q^2)}{\nu'^2 - \nu^2} d\nu'^2$$



- (DR in ν (or ν^2) with Q^2 fixed)

Dispersion relation



- Work into

$$H_1(\nu,Q^2) = \frac{\text{Res } H_1(\nu,Q^2)\Big|_{el}}{\nu_{el}^2-\nu^2} + \frac{1}{\pi}\int_{cut}\frac{\text{Im}\, H_1(\nu',Q^2)}{\nu'^2-\nu^2}d\nu'^2 + \frac{1}{2\pi i}\int_{|\nu'|=\infty}\frac{H_1(\nu',Q^2)}{\nu'^2-\nu^2}d\nu'^2$$

- Drop the $|\nu| = \infty$ term. O.k. if H_1 falls at high ν.

- Can view as standard or as dramatic assumption.

H_1

- The elastic term can be worked out, sticking on-shell form factors at the γp vertices,

$$H_1^{el} = \frac{2m_p}{\pi}\left(\frac{Q^2F_1(Q^2)G_M(Q^2)}{(Q^2-i\epsilon)^2-4m_p^2\nu^2} - \frac{F_2^2(Q^2)}{4m_p^2}\right)$$

- The second term does not fall with ν at fixed Q^2.

- Unsubtracted DR fails for H_1^{el} alone. Overall success requires exact cancelation between elastic and inelastic contributions.

- (In case of interest: $H_2^{el} = -\frac{2m_p}{\pi}\frac{m_p\nu F_2(Q^2)G_M(Q^2)}{(Q^2-i\epsilon)^2-4m_p^2\nu^2}$.)

But then,

- Free quarks if there is at least one large momentum scale. So at high ν, Compton amplitude for proton should be sum of Compton amplitudes for free quarks, which have zero F_2 .

- Regge theory suggests H_1 must fall with ν. See Abarbanel and Nussinov (1967), who show $H_1 \sim \nu^{\alpha-1}$ with $\alpha < 1$.*

- Very similar DR derivation gives GDH sum rule, which is checked experimentally and works, within current experimental uncertainty.

- GDH sum rule also checked in LO and NLO order perturbation theory in QED. Appears to work.

*Footnote 16 of this paper reads: For an indication of the lengthy details involved one may see M. Gell-Mann, M. L. Goldberger, and F. .E Low, Rev. Mod. Phys. 36, 640 (1964).

Resolution?

- In modern times, authors who use experimental scattering data and DR to calculate the 2γ corrections assume an unsubtracted DR works for all of H_1 .
- Reevaluation always possible.
- Proceed to next topic, comparison of data driven evaluations of HFS to evaluations using BχPT to obtain $H_{1,2}$.
- See if subtraction comments come into play.

Side note: how good need we be?

- New measurements of HFS in μH in 1S state are planned.

- May measure to 0.1 ppm (as fraction of Fermi energy). But need theory prediction to help determine starting point of laser frequency scan.

- From 2018 conference at MITP (Mainz), want theory prediction to 25 ppm or better. Better is what we should look for.

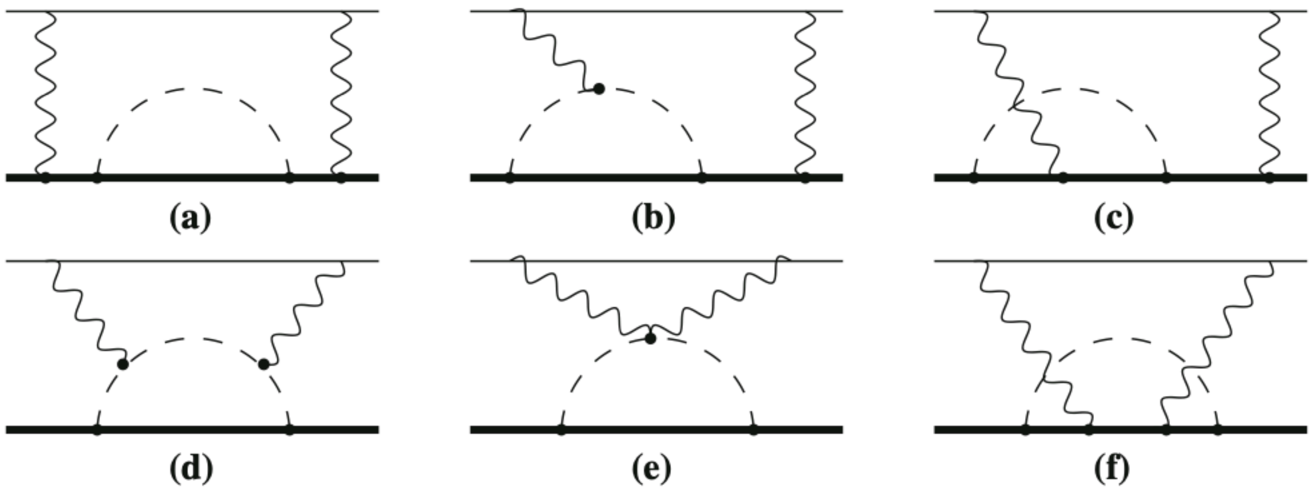
- Believe state of art for HFS in 1S μH is from Antognini, Hagelstein, Pascalutsa (2022),

$$E_{\text{HFS}}^{\text{1S}} = 182.634(8)\ \text{meV}$$

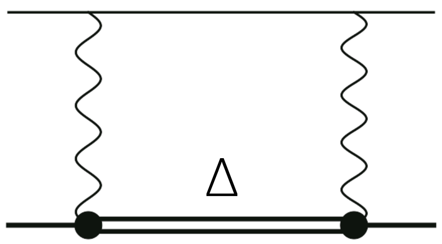
or 44 ppm.

Application of BχPT

- Using chiral perturbation theory, one can calculate beyond the elastic case diagrams like



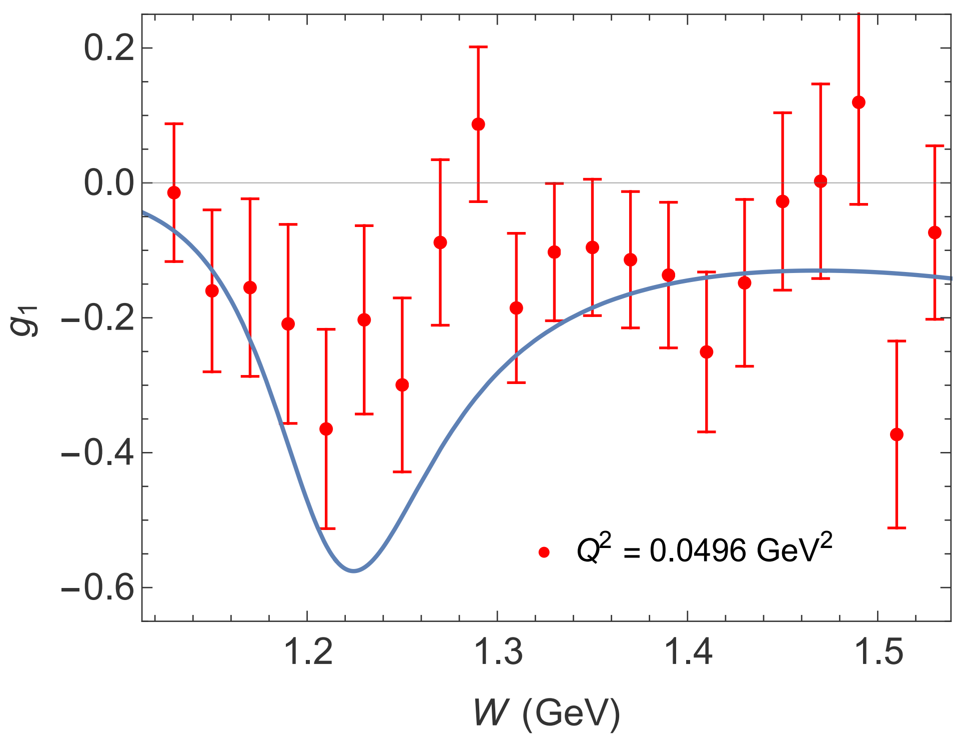
- Or diagrams where there is a Δ-baryon on the hadronic leg,

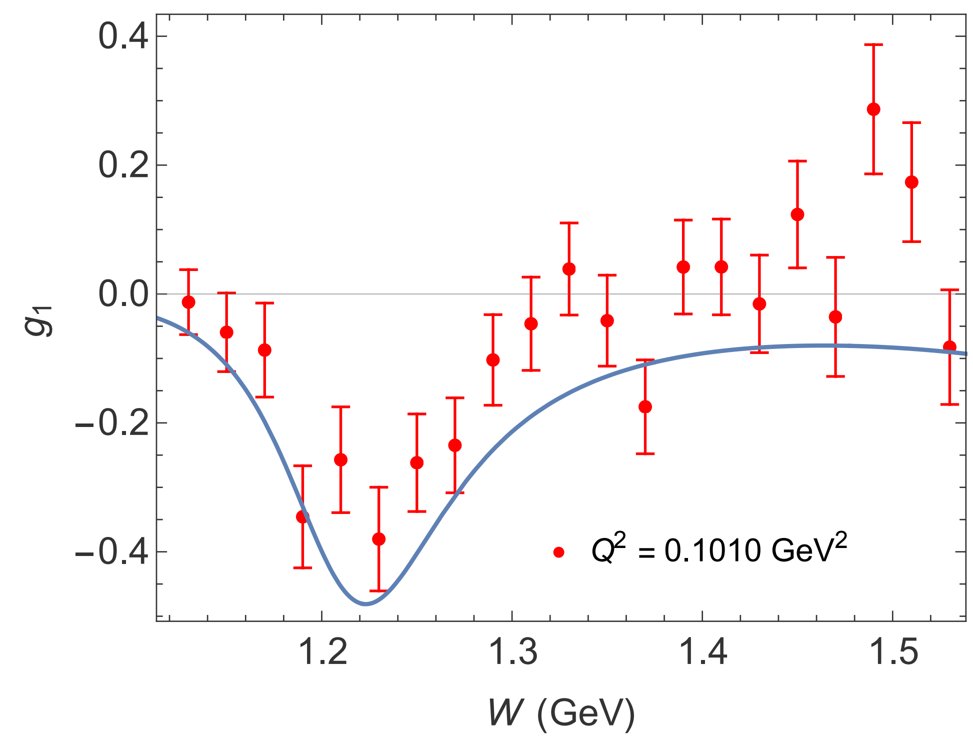


- These can be used to calculate $H_{1,2}$, at low Q^2 and CM energy W not too far from threshold. Also can get $\gamma^* N \to \pi N$ or $\gamma^* N \to \Delta$ and from them obtain $g_{1,2}$ at similarly low kinematics.

g_1 comparison

- Compare g_1 from BχPT (blue lines) to actual JLab data





- Plots are "unofficial": Made by me* and involve spreading Δ pole out using Lorentzian of same total area.

*With greatest thanks to Pascalutsa and Hagelstein for providing code for their gamma N -> pi N

- O.k. This won't explain difference in Δ_{pol} results.

Non-pole terms

- Non-pole means ν independent terms in $H_{1,2}$.
- Recall elastic $H_1^{el} = \frac{2m_p}{\pi}\left(\frac{Q^2F_1(Q^2)G_M(Q^2)}{(Q^2-i\epsilon)^2-4m_p^2\nu^2} - \frac{F_2^2(Q^2)}{4m_p^2}\right)$.
- The BχPT results for H_1 with π-N and Δ intermediate states also have non-pole terms.
- To calculate energies for the non-pole terms, cannot use the DR (at least not un-subtracted ones), but can use the expressions on slide 7, which were before any Cauchy trickery was used

Pole and non-pole

- One part: The Δ contribution to μH HFS for 2S state*

$$E_{pol}^{HFS} = -40.69\,\mu\text{eV} \qquad \text{pole}$$
$$= 39.54\,\mu\text{eV} \qquad \text{non-pole}$$
$$= -1.15\,\mu\text{eV} \qquad \text{total}$$

- Lot of cancellation.

- But from asymptotic freedom, or from Regge analysis, or from success of DHG sum rule, expect zero non-pole term. Totality, from elastic and resonances and inelastic terms, needs to add to zero for the ν independent terms.

- Something to talk about.

*from Hagelstein (2016)

One point

- How should one deal with non-zero non-pole terms that result from partial information, when one knows that the non-pole terms are zero when one has complete information?

Δ_{pol} with newest $g_{1,2}$

- Defer to David Ruth (next after next talk).
- Except for comment on handling regions outside the data range.
- Mostly, because of the kinematic factors, the need is for data at low Q^2 and low ν (or W near threshold), and this is where the data is.
- Again, mostly, where there is no data and we use models or interpolations, the contributions to $\Delta_{1,2}$ are not great and the accruing uncertainty is not great.

Δ_{pol} with newest $g_{1,2}$

- An exception may be the very low Q^2 region, where there is no data. For the 2003 data, this was $Q^2 < 0.0452$ GeV^2.

- And there may be a problem when comparing to χPT.

- What we did: reminder

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

with
$$B_1(Q^2) = \frac{4}{9}\int_0^{x_{\rm th}} dx\,\beta_1(\tau)g_1(x,Q^2) \ .$$

- For very low Q^2 we used

$$B_1(Q^2) = -\frac{\kappa_p^2}{8m_p^2}Q^2 + c_{1B}Q^4 = -\frac{\kappa_p^2}{8m_p^2}Q^2 + 4.94\,Q^4/\text{GeV}^4$$

got by fitting to data $Q^2 < 0.3$ GeV^2

Δ_{pol} with newest $g_{1,2}$

- The region $Q^2 < 0.0492$ GeV^2 contributed about 15% of Δ_1 and (by our estimate) 30% of the uncertainty.

- Use standard expansion for the form factor,

$$F_2(Q^2) = \kappa_p \left(1 - \frac{1}{6} R^2_{Pauli} Q^2 + \ldots \right)$$

- Get Integrand =

$$\frac{9}{4} \frac{1}{Q^2} \left(F_2^2 + \frac{8m_p^2}{Q^2} B_1 \right) = -\frac{3}{4} \kappa_p^2 R^2_{Pauli} + 8 m_p^2 c_{1B}$$

- And $\Delta_1(0 \to Q^2_{low\,data}) \approx$ Integrand $\cdot\, Q^2_{low\,data} \approx 1.35$

Δ_{pol} with newest $g_{1,2}$

- χPT has knowledge of g_1 at low Q^2, and can do the integrals. Do good approximation by expanding the β_1 function for low Q^2.

- Work for a while to get Integrand =

$$-\frac{3}{4}\kappa_p^2 R_{Pauli}^2 + 8m_p^2 c_1 - \frac{5m_p^2}{4\alpha}\gamma_0 + \mathcal{O}(Q^2),$$

- Where $\gamma_0 = \frac{2\alpha}{m_p^2}\int \frac{d\nu}{\nu^4} g_1(\nu,0)$

and c_1 came from

$$I(Q^2) \equiv 4m_p \int \frac{d\nu}{\nu^2} g_1(\nu, Q^2) = -\kappa_p^2 + c_1 Q^2 + \mathcal{O}(Q^4)$$

Δ_{pol} with newest $g_{1,2}$

- Value for known, and doing integrals to get c_1, find

  $$\Delta_1(0 \rightarrow Q^2_{low\,data}) \approx \text{Integrand} \cdot Q^2_{low\,data} \approx -0.45$$

  thanks again to F. Haglestein et al.

- Not even same sign!

- Corresponding numbers for μ are ≈ 0.86 and -0.20

- Remembering $\Delta_{\text{pol}} = \dfrac{\alpha m_\mu}{2(1+\kappa_p)\pi m_p}(\Delta_1 + \Delta_2)$, difference gives about 50 ppm or about 15% of discrepancy.

- More to talk about!