Low Q^2 Spin Structure Results from Jefferson Lab

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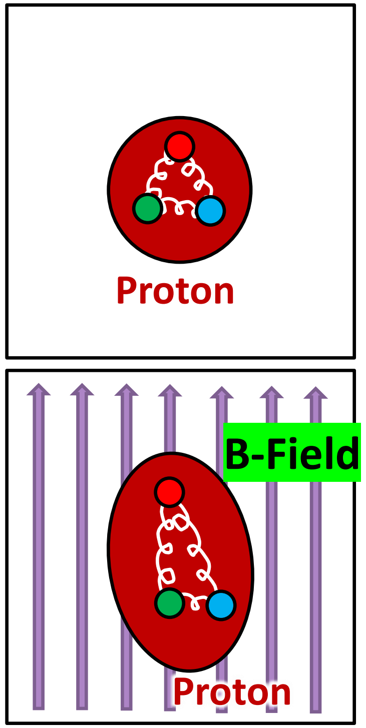
CHIRAL DYNAMICS WORKSHOP 2024

8/30/24

Testing Chiral Perturbation Theory with Polarizabilities

- **How good are our low Q^2 effective theories of QCD?** We need data benchmarks to check…
- χPT and other theoretical calculations can be directly compared to data for **Spin Polarizabilities**
- **Polarizabilities** describe a nucleon's ensemble response to an external field
- **Spin Polarizabilities** can be accessed with sum rule integrals of **Spin Structure Functions** experimentally measured with **Inclusive Electron Scattering**



Spin Structure Functions

- In unpolarized systems, the inclusive electron scattering cross section can be written with F_1 and F_2 structure functions describing the internal dynamics of a nucleon:

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

- In a spin-½ polarized system, two additional structure functions describe the spin structure of the nucleon:

$$\frac{d^2\sigma^{\pm}}{d\Omega dE'} = \sigma_{\text{Mott}}\left[\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) \pm \underline{\gamma g_1(x,Q^2)} \pm \underline{\delta g_2(x,Q^2)}\right]$$

Mostly from longitudinal polarization

Mostly from transverse polarization

Moments of g_1 and g_2 are one of the best options to test effective theories!

Moments & Polarizabilities

Super-convergence Sum Rules

$$I_1(Q^2=0) = \frac{2M^2}{Q^2}\int_0^1 g_1(x,Q^2)dx = \frac{2\pi^2\alpha\kappa^2}{M^2}$$

Gerasimov-Drell-Hearn Sum Rule

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

Burkhardt-Cottingham Sum Rule

Polarizabilities & Higher Moments

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}} x^2[g_1(x,Q^2)+g_2(x,Q^2)]dx$$

Transverse-Longitudinal Spin Polarizability

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}} x^2 g_1(x,Q^2)+\frac{4M^2x^4}{Q^2}g_2(x,Q^2)]dx$$

Generalized Forward Spin Polarizability

$$\overline{d_2} = \int_0^{x_{th}} x^2[2g_1(x,Q^2)+3g_2(x,Q^2)]dx$$

Color Polarizability / Twist-3 Matrix Element

Moments & Polarizabilities

Hyperfine Structure Contributions

$$\Delta_1 = \int_0^\infty \frac{dQ^2}{Q^2}\,[\beta_1(\tau_l)F_2^2 + \frac{8M^2}{Q^2}\int_0^{x_{th}} \widetilde{\beta_1}(x, Q^2)\,g_1(x, Q^2)\,dx$$

$$\Delta_2 = -24M^2 \int_0^\infty \frac{dQ^2}{Q^4}\int_0^{x_{th}} \widetilde{\beta_2}(x, Q^2)\,g_2(x, Q^2)\,dx$$

⇓

$$\Delta_{pol} = \frac{\alpha m_l}{2\pi(1+\kappa)M}(\Delta_1 + \Delta_2)$$

Dominating Source of Hydrogen Hyperfine Splitting Uncertainty!

Thomas Jefferson National Accelerator Facility

- **Jefferson Lab** is a premier facility in Newport News, VA, USA for electron scattering experiments
- 1400 Meter “Racetrack” Linear Accelerator with 4 experimental halls
- Spin polarized electron beam with energy up to **12 GeV**
- Current ranges from 50 nA – 85 uA
- Host to a number of completed experiments measuring **spin structure functions** at low Q^2:
  - E94-010 (Neutron, ⊥/ ∥)
  - EG1b (Proton, ∥)
  - E97-110 [saGDH] (Neutron, ⊥/ ∥)
  - E08-027 [g2p] (Proton, ⊥)
  - E03-006/E06-017 [EG4] (Proton/Neutron, ∥)

General Extraction Procedure

1. Measure inclusively scattered polarized electrons off a longitudinally (∥) or transversely (⊥) polarized target

2. Compare + and – helicity counts for whichever target configurations were used and form **asymmetries**:

$$A_\perp = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}} \qquad A_\parallel = \frac{\sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}}{\sigma^{\uparrow\Uparrow} + \sigma^{\downarrow\Uparrow}}$$

3. Extract an **unpolarized experimental cross section** from the total counts:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{(ps)N}{N_{in}\rho(LT)\epsilon_{det}} \frac{f}{\Delta\Omega\Delta E'\Delta Z}$$

(**Or** use world data for unpolarized part)

4. Combine into **polarized cross section differences**:

$$\Delta\sigma_\perp = 2A_\perp\sigma_0 \qquad \Delta\sigma_\parallel = 2A_\parallel\sigma_0$$

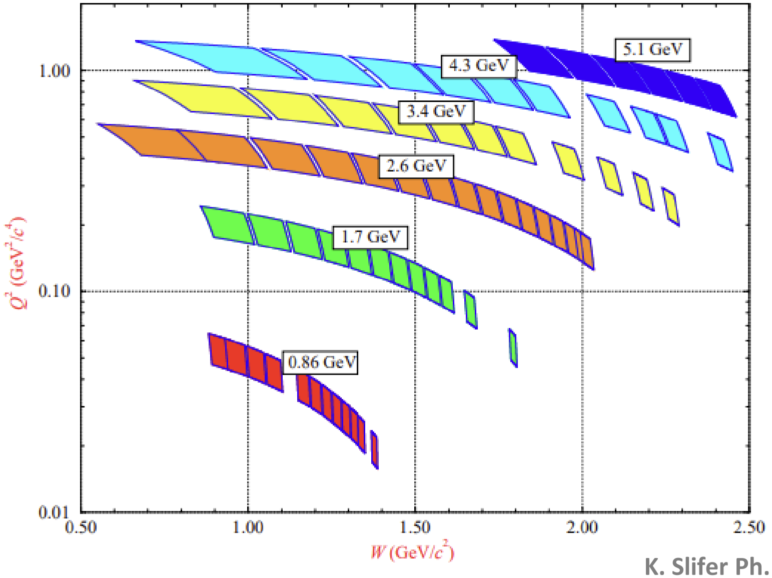
(EG4 directly measured these cross section differences)

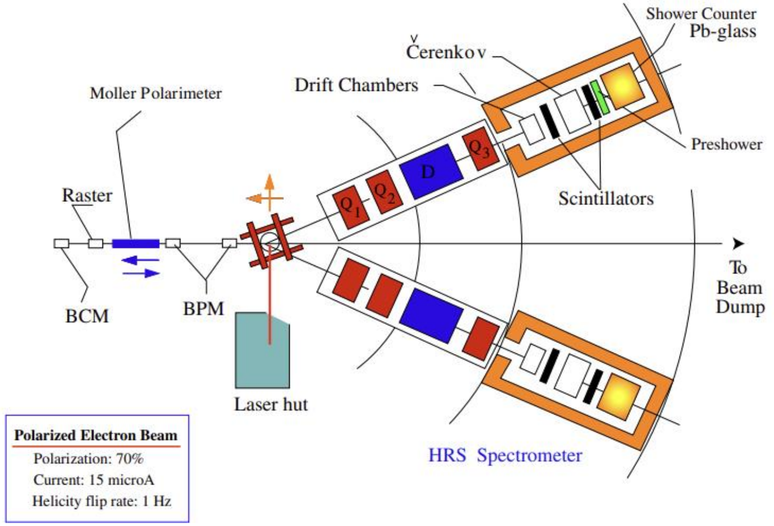
5. Extract **spin structure functions** from:

$$\Delta\sigma_\perp = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\,[\nu g_1(x,Q^2) - 2E g_2(\nu,Q^2)] \qquad \Delta\sigma_\parallel = \frac{4\alpha^2}{M\nu Q^2}\frac{E'}{E}\left[g_1(x,Q^2)\{E + E'^{\cos\theta}\} - \frac{Q^2}{\nu} g_2(\nu,Q^2)\right]$$

E94-010 Experiment

- Ran in 1998 in **Hall A**
- Polarized ^{3}He Target used to extract **neutron** structure functions
- Scattered electrons measured with Hall A High Resolution Spectrometers
- Spins of the two protons in ^{3}He are antialigned in ground state, so spin is dominated by the neutron



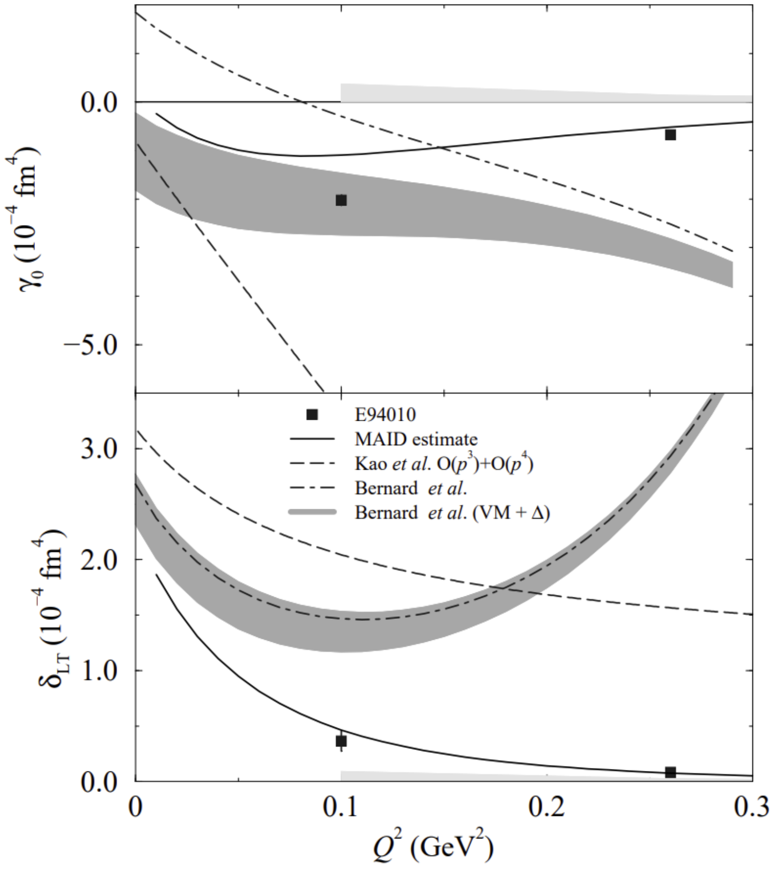


K. Slifer Ph.D. Thesis (2004)

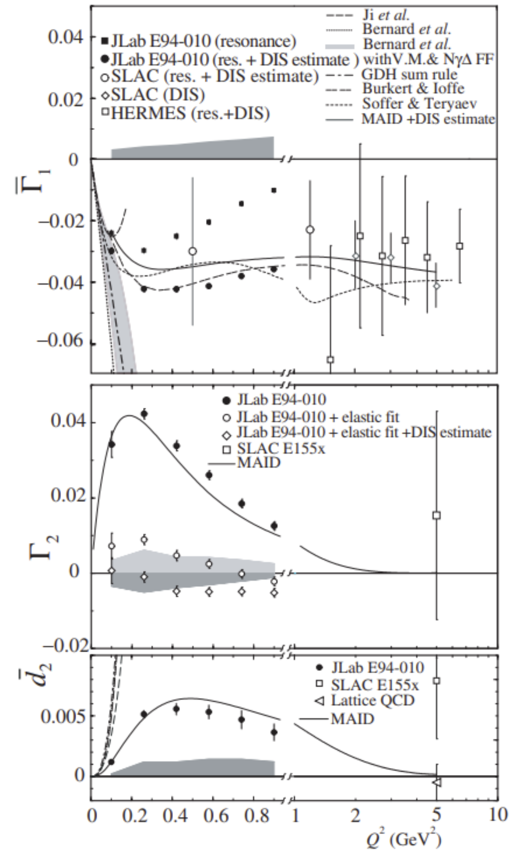
- First look at intermediate to low Q^2 neutron spin structure!

E94-010 Results

M. Amarian et al., Phys. Rev. Lett. 93, 152301 (2008)



M. Amarian et al., Phys. Rev. Lett. 92, 022301 (2004)



- δ_{LT} a benchmark test of **χ**PT due to insensitivity to Δ(1232) resonance
- E94010 results disagreed with **χ**PT at low Q^2 at the time: **“δ_{LT} Puzzle”**
- Γ_2 results found no B.C. Sum Rule violation
- Γ_1 results seem to be converging to GDH slope and agree with Bernard et al. calculation at low Q^2

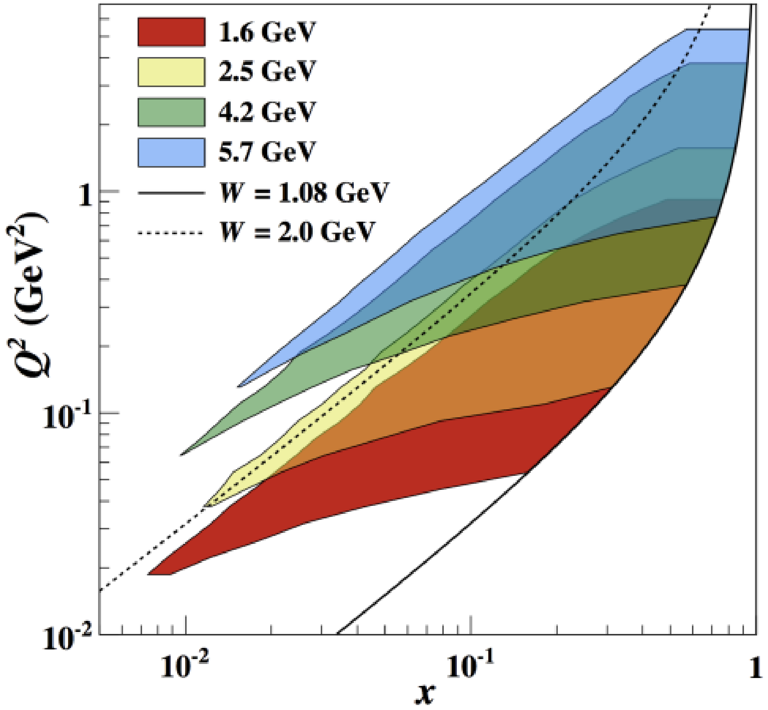
What about the **proton**?

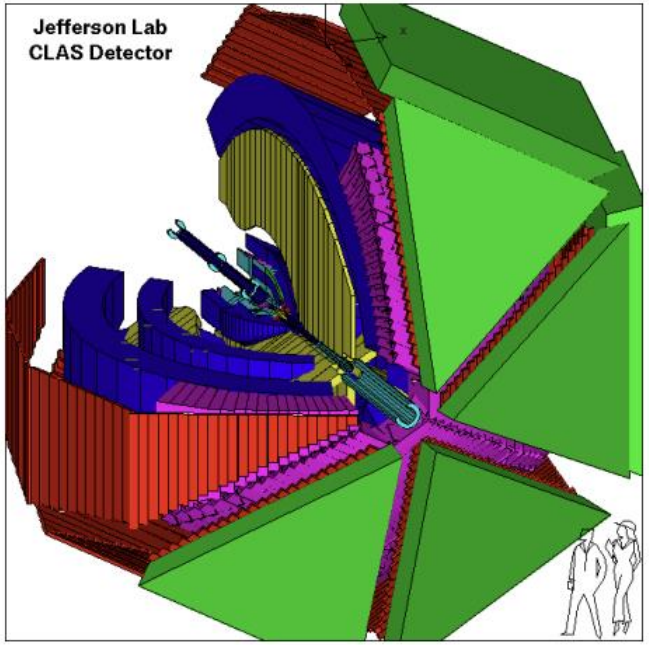
EG1b Experiment

- As for the **proton**, first low Q^2 results from JLab came from the EG1b experiment in **Hall B** which ran in 2000-2001
- **CLAS:** A large acceptance spectrometer based on a six coil toroidal superconducting magnet
- Longitudinally polarized solid Ammonia (NH_3 or ND_3) target
- Polarized with **dynamic nuclear polarization**

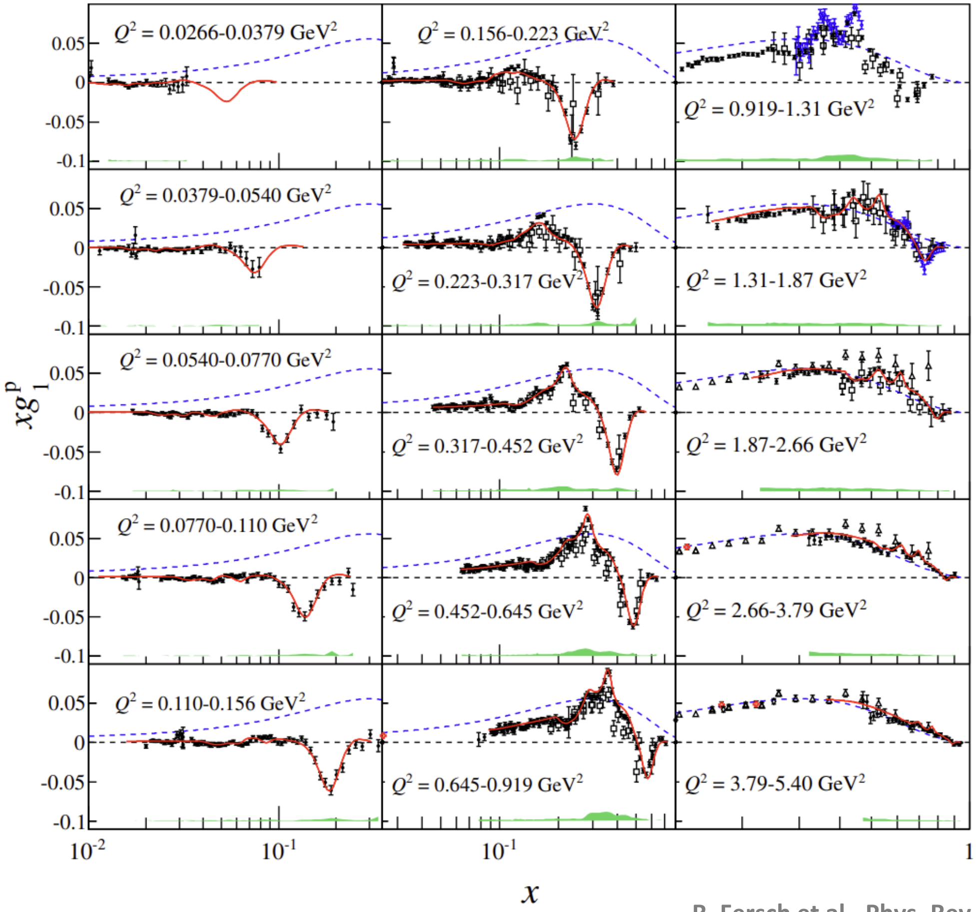
- Full results published in 2017!

R. Fersch et al., Phys. Rev. C 96, 065208 (2017)

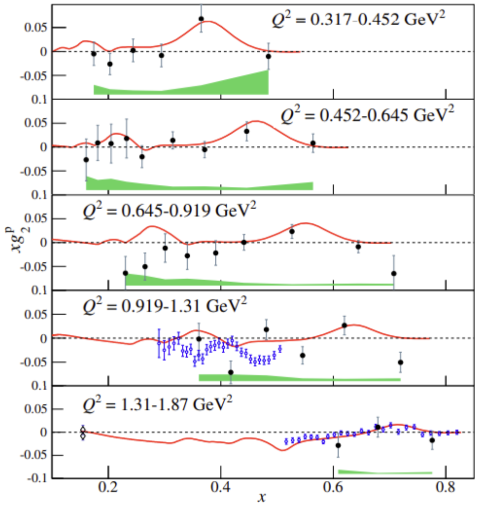




EG1b Structure Function Results



- g_1 measured directly over a very large range with excellent resolution in Q^2
- Primarily resonance region results



R. Fersch et al., Phys. Rev. C 96, 065208 (2017)

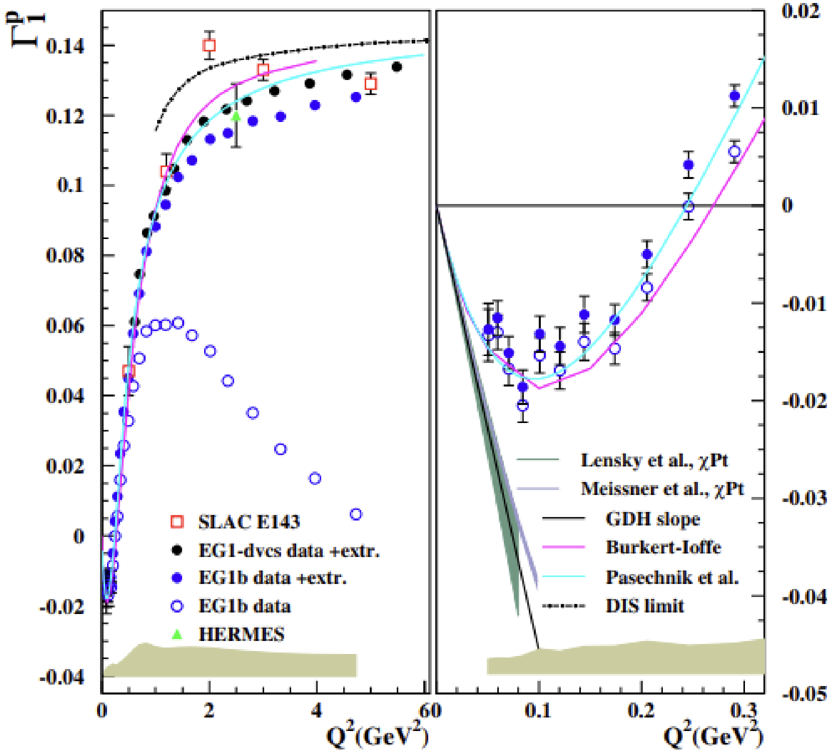
- g_2 calculated with Wandzura-Wilczek relation:

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

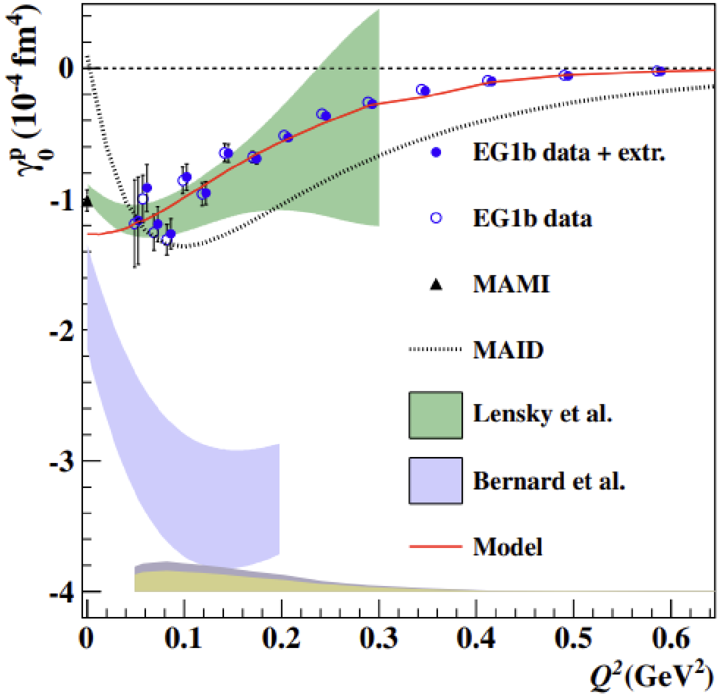
- g_2^{WW} is not trusted at low Q^2 due to higher twist effects

EG1b Moment Results

R. Fersch et al., Phys. Rev. C 96, 065208 (2017)



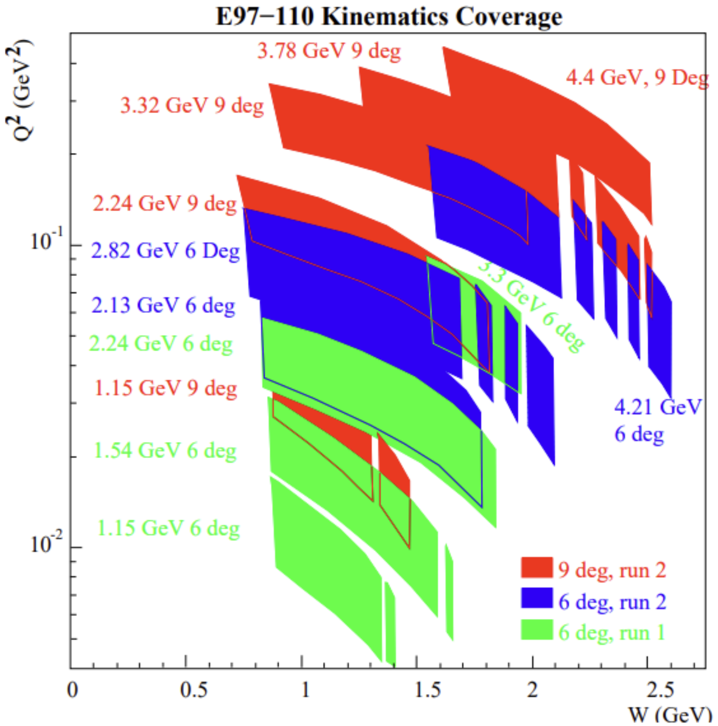
- Γ_1 approaches GDH Slope & **χ**PT predictions
- Difference between **χ**PT calculations for γ_0
- The Bernard et al. calculation represents the leading-order predictions and the subleading corrections are large, so a true comparison is difficult without more analysis

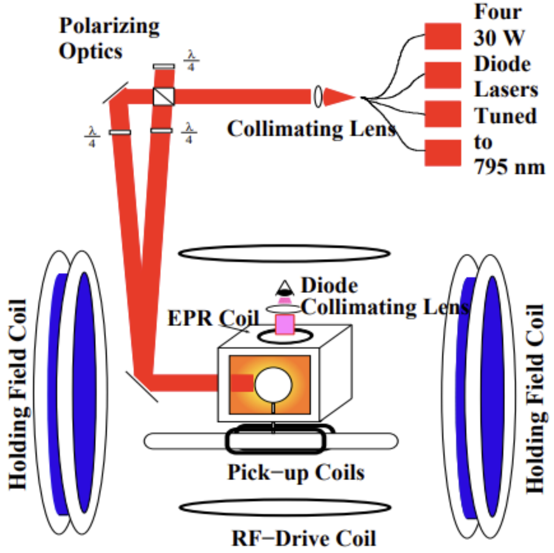


Can we go to even smaller Q^2 with the **neutron**?

E97-110 Experiment (Small-Angle GDH)

- **Neutron** (^{3}He) target with both longitudinal and transverse polarization through spin-exchange optical pumping
- Due to small scattering angle, covers almost an order of magnitude lower in Q^2 than E94-010
- Ran in **Hall A** in 2003, published in *Nature Physics* in 2021
- Septum magnet allows small scattering angles down to 6 degrees with the Hall A High Resolution Spectrometers

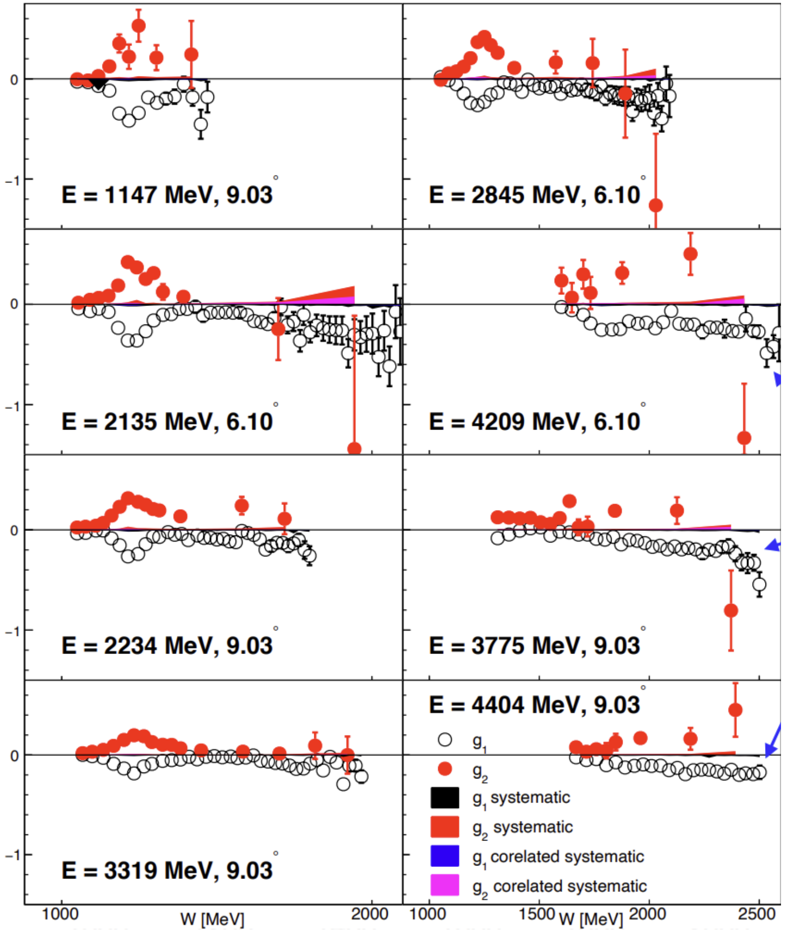




V. Sulkosky Ph.D. Thesis (2007)

Small-Angle GDH Results (SSF)

A. Deur Hadron24, Dalian, China, 08/07/2024

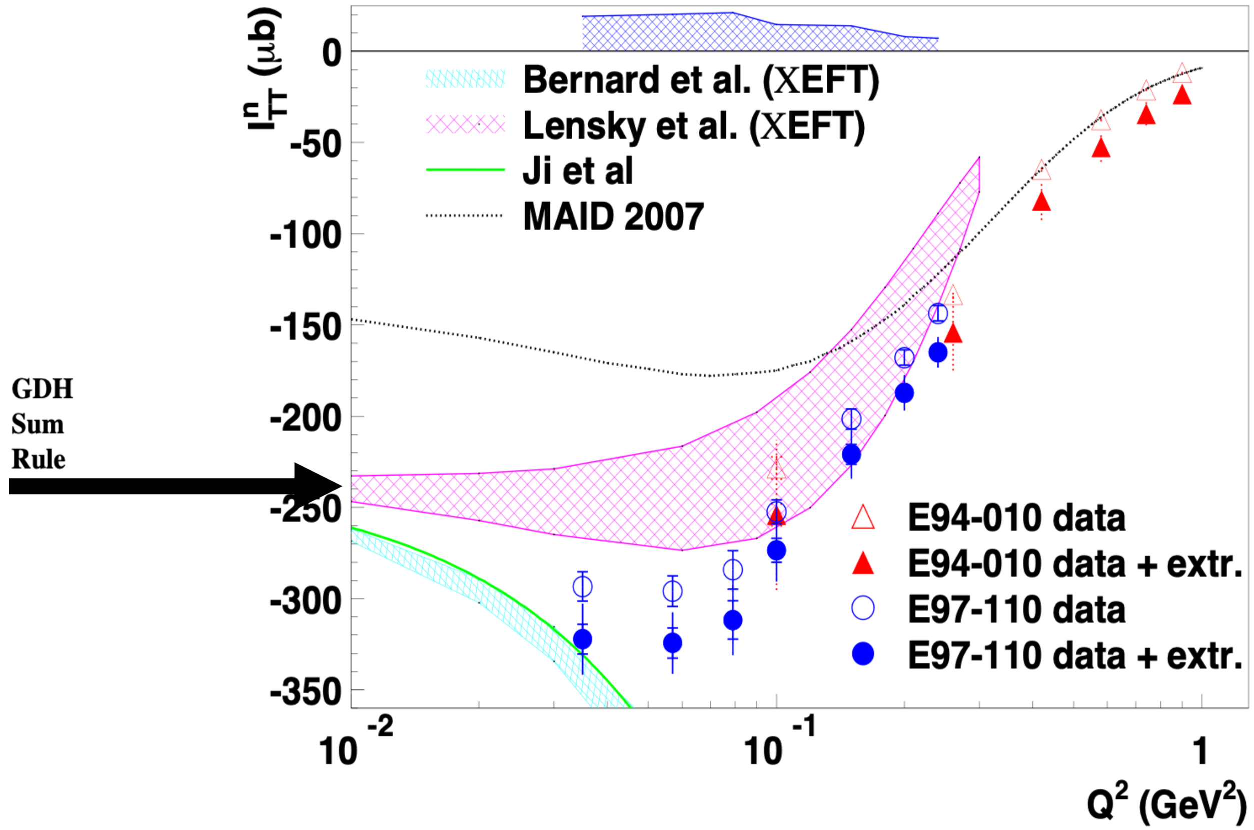


- As before, assume proton contributions cancel, so ^{3}He SSF are dominated by Neutron

- g_1 and g_2 are approximately equal and opposite

Small-Angle GDH – GDH Sum Rule

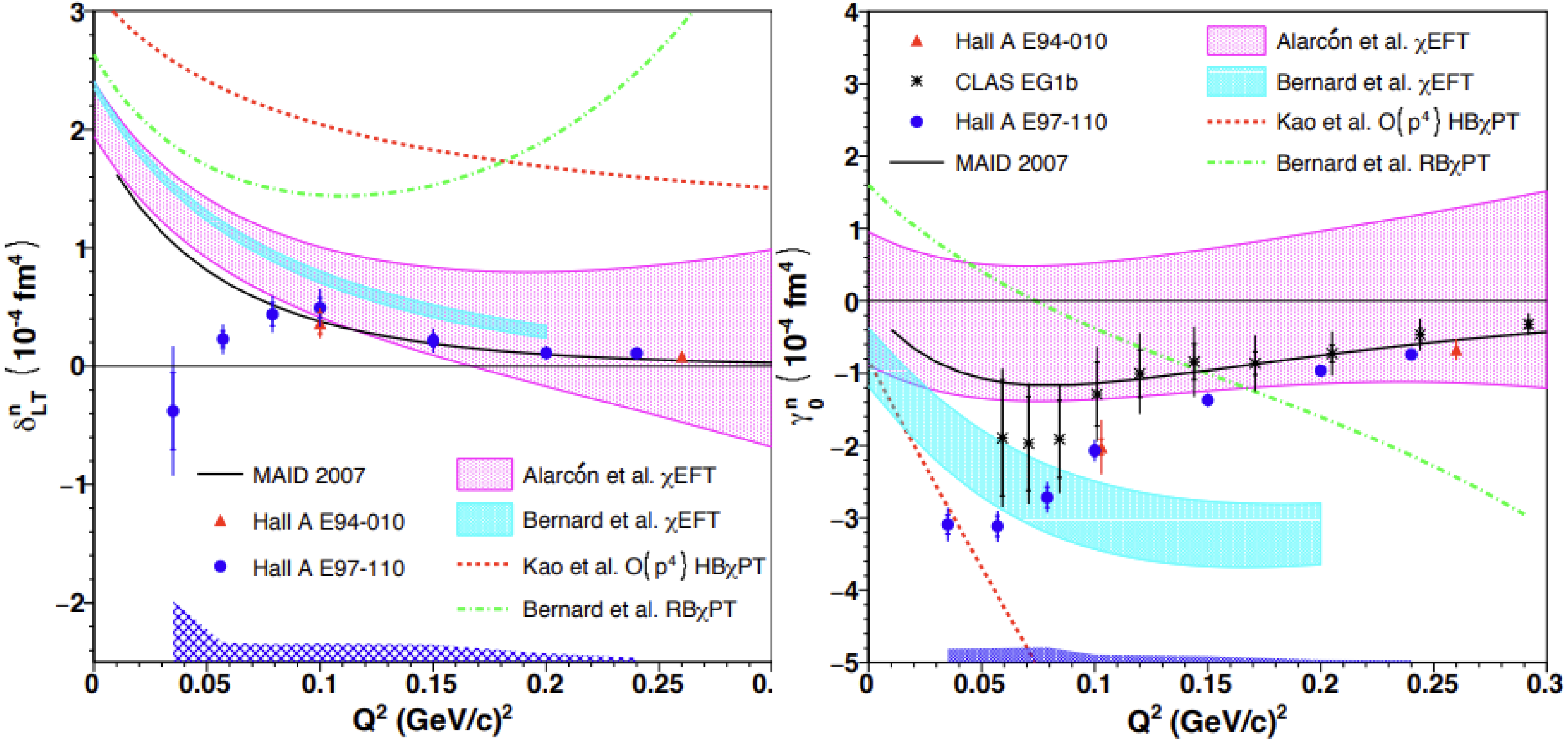
A. Deur low-Q 2023, 18 May 2023, courtesy J.P. Chen



- Agrees with older data at high Q^2
- Agrees with the Lensky at al. calculation **only** at high Q^2
- Agrees with the Bernard et al. calculation **only** at lowest Q^2
- MAID does not agree with any of the new data

Small-Angle GDH Polarizabilities

V. Sulkosky et al., Nature Physics, Vol. 17 687-692 (2021)

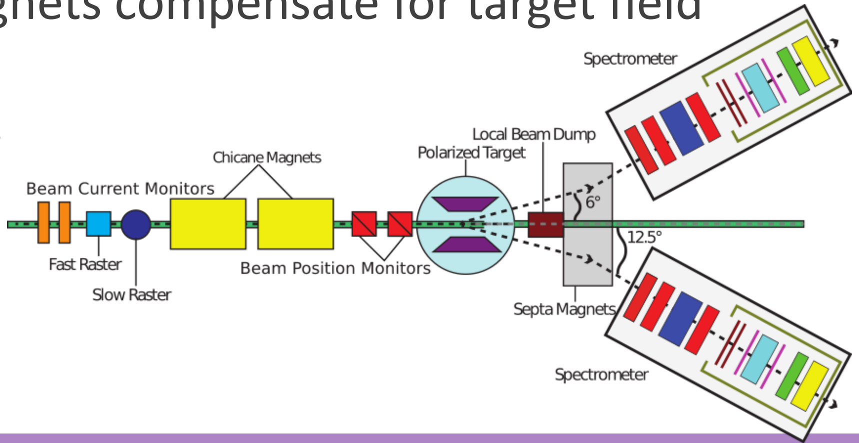


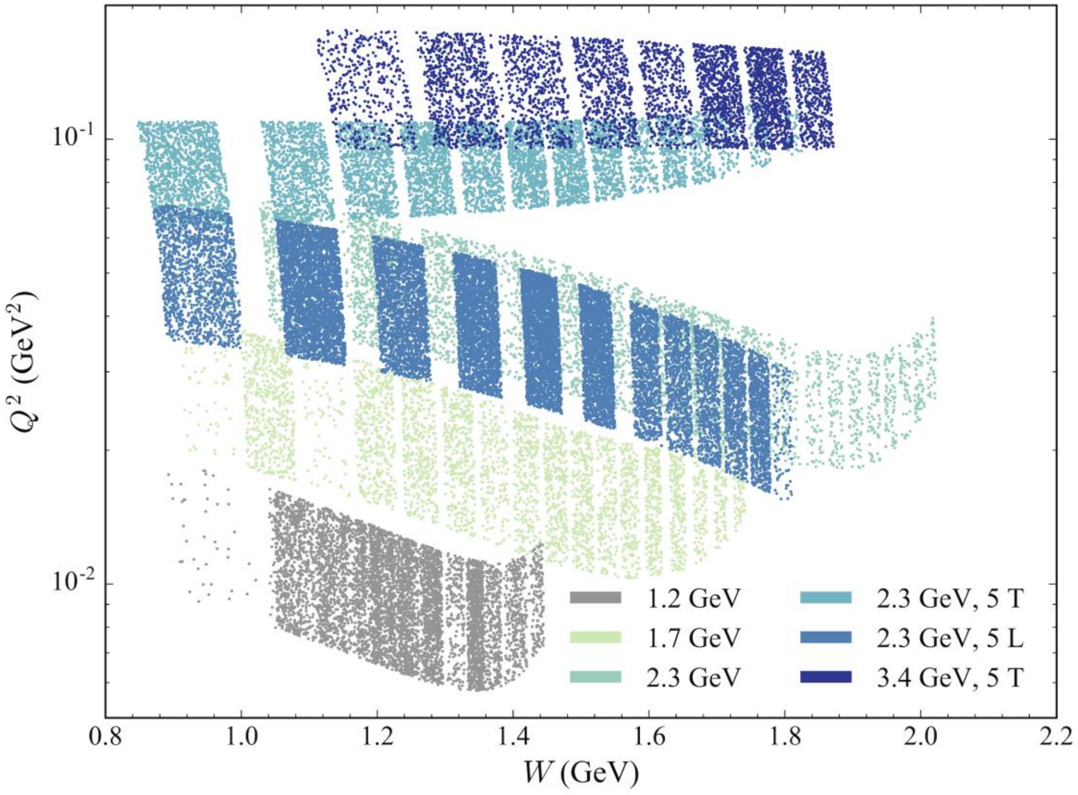
- New calculations explicitly including the Δ(1232) resonance agree better in the regime of E94-010!
- …but the lower Q^2 achieved by E97-110/Small-Angle GDH shows a continuing disagreement for both spin polarizabilities
- The Neutron's **“δ_{LT} Puzzle”** is alive and well

Does the **proton** also have the δ_{LT} Puzzle?

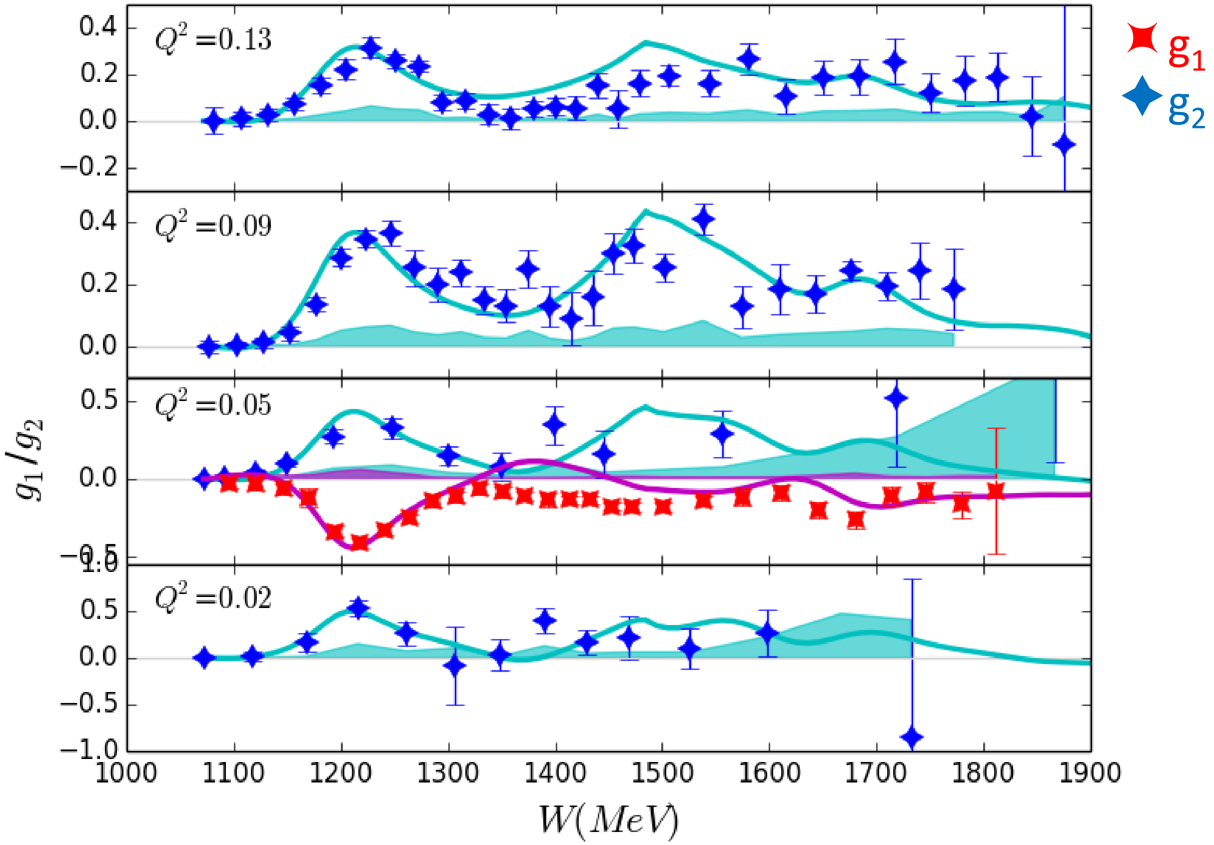
g2p Experiment

- Ran in **Hall A** in 2012
- Published results in *Nature Physics* in 2022
- First low Q^2 g_2 measurement for the **proton**!
- Transversely polarized solid NH_3 target
- Septa magnets allow small scattering angle
- Chicane magnets compensate for target field bending
- Covers Q^2 of 0.01-0.12 GeV^2



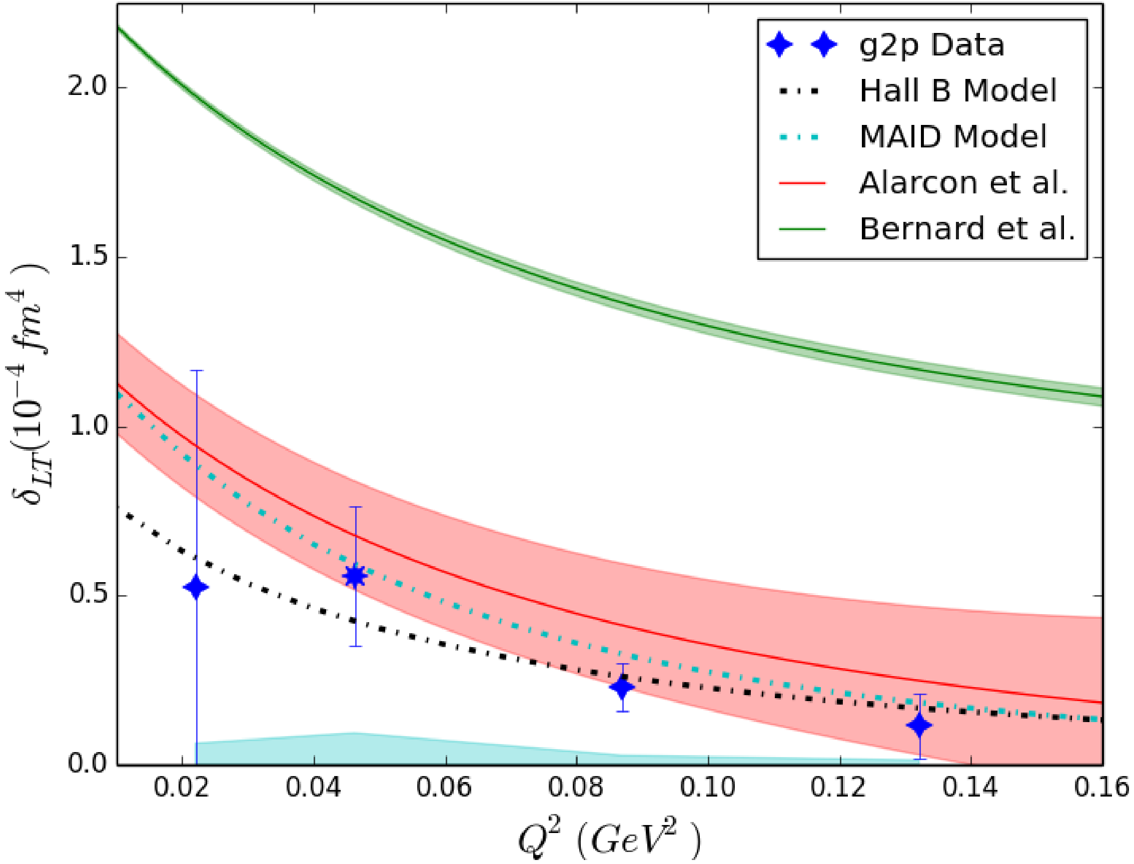


g2p Results (SSF)



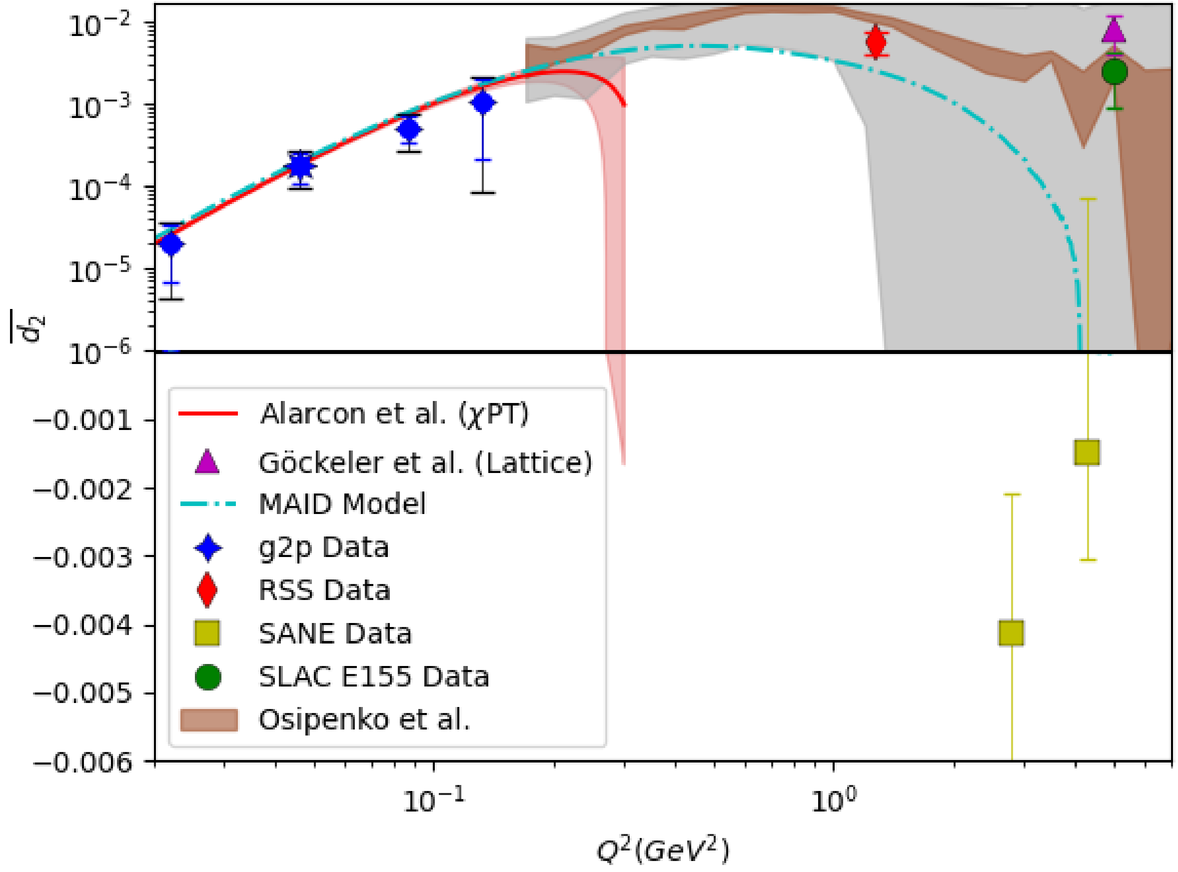
- g_2 results have good precision in the resonance region
- Phenomenological models (Hall B, MAID) agree well with the data over most of the measured range
- The experiment's one g_1 setting has excellent precision and has data down to the pion production threshold
- g_1 result stays negative while models expect a small positive result near threshold, but data is compatible with a positive result within error bars

g2p Results ($\boldsymbol{\delta_{LT}}$)



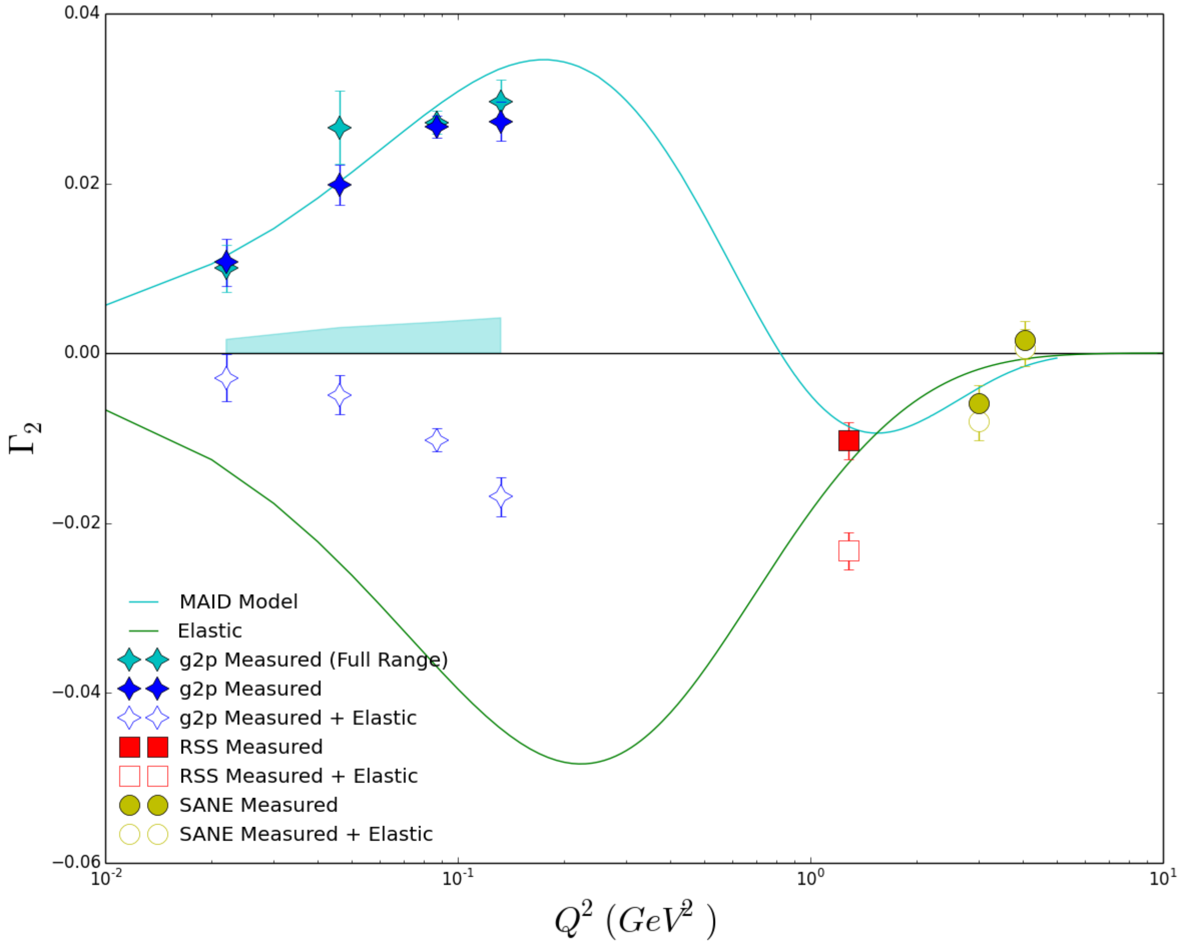
- δ_{LT} results agree very well with Alarcon et al. prediction
- More significant tension with Bernard et al. calculation
- Low Q^2 error bar is due to the strong $1/Q^6$ weighting in the moment
- No sign of a proton **“$\boldsymbol{\delta_{LT}}$ Puzzle”**

g2p Results ($\overline{d_2}$)



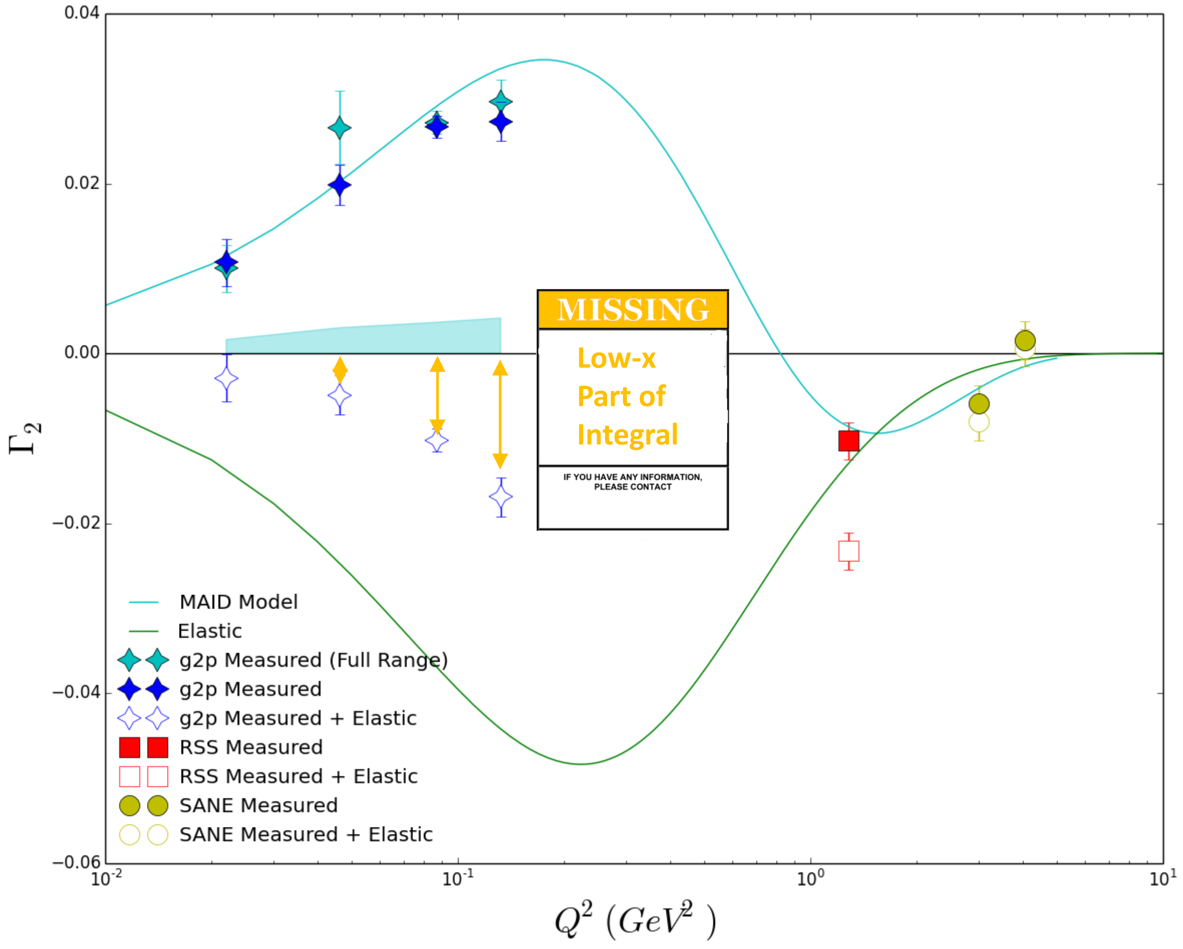
- Agrees very well with Alarcon et al. prediction and phenomenological models
- At low Q^2, the color definition drops out and this is a "pure polarizability"
- Fully positive, in contrast to the negative SANE result at higher Q^2
- Ideal observable to try and understand the full Q^2 spectrum from the EFT regime to the pQCD regime

g2p Results (Γ_2)



- Without the full integral, we can't check B.C. Sum Rule fulfillment…
- Higher Q^2 experiments have used g_2^{WW} to estimate this part, but because it relies on the assumption of Twist-2, it fails by this Q^2
- Instead, the data can be used to access the unmeasurable low-x regime if B.C. Sum Rule is assumed

g2p Results (Γ_2)



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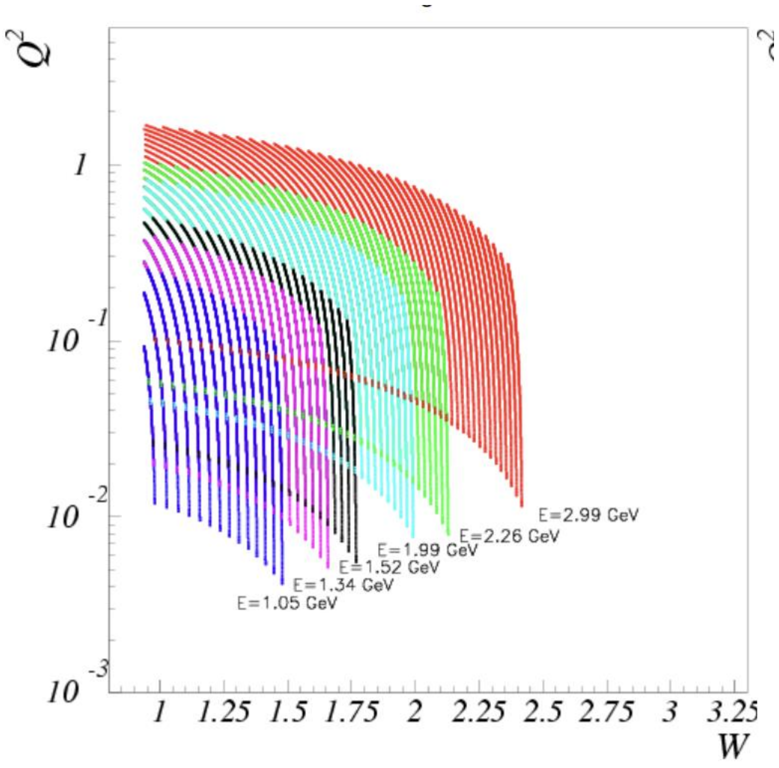
- Instead, the data can be used to access the unmeasurable low-x regime if B.C. Sum Rule is assumed

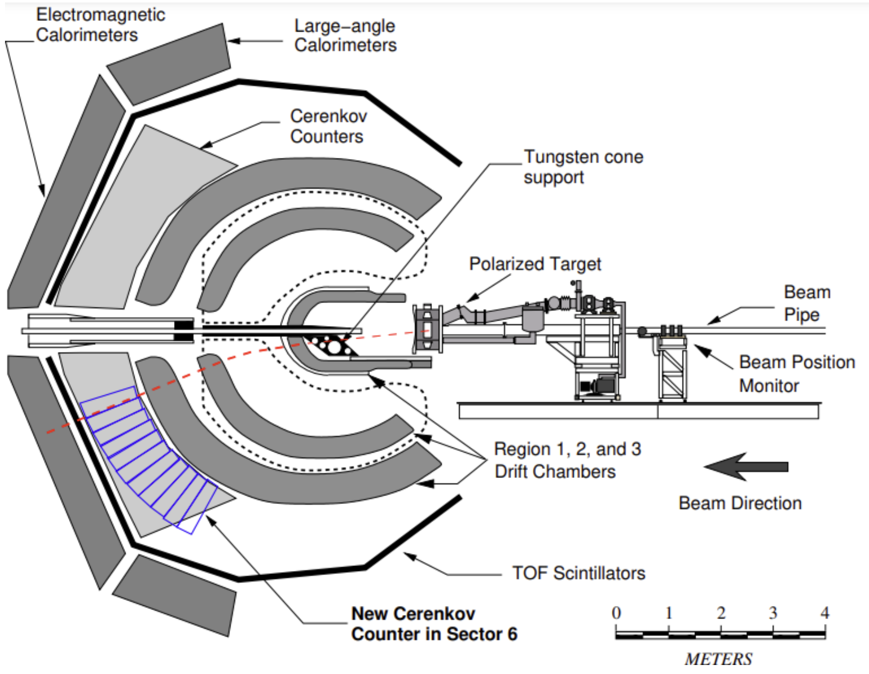
We also need proton g_1 results at this same Q^2…

EG4 Experiment

- Builds on EG1 by going to very low $Q^2 = 0.01\ \mathrm{GeV}^2$
- Ran with CLAS Detector in **Hall B** in 2006
- Longitudinally polarized NH_3 and ND_3 target
- Specialized Cerenkov detector improved efficiency at forward angles, allowing access to lower Q^2
- Excellent precision longitudinal results for both the **proton** and **neutron**
- **Proton** results published in *Nature Physics* in 2021



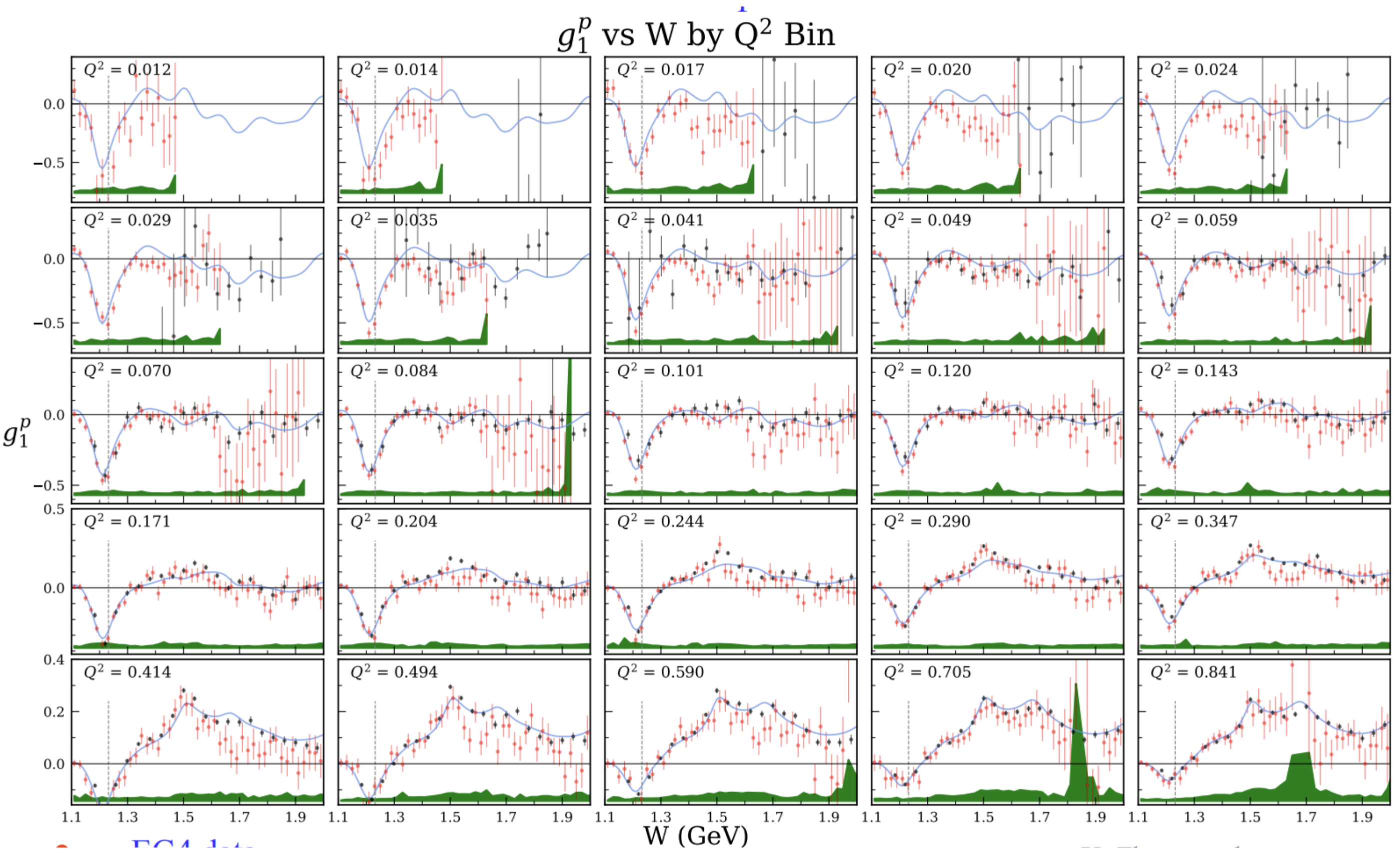
X. Zheng, March 2009, Spin Structure at Long Distance

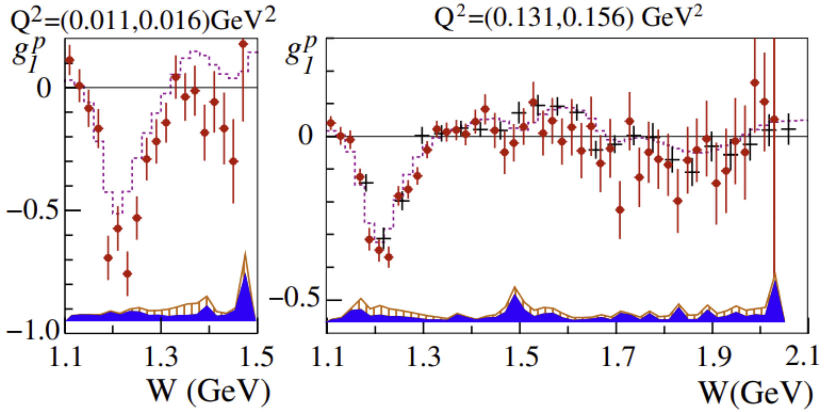


Courtesy X. Zheng

EG4 Results (SSF)

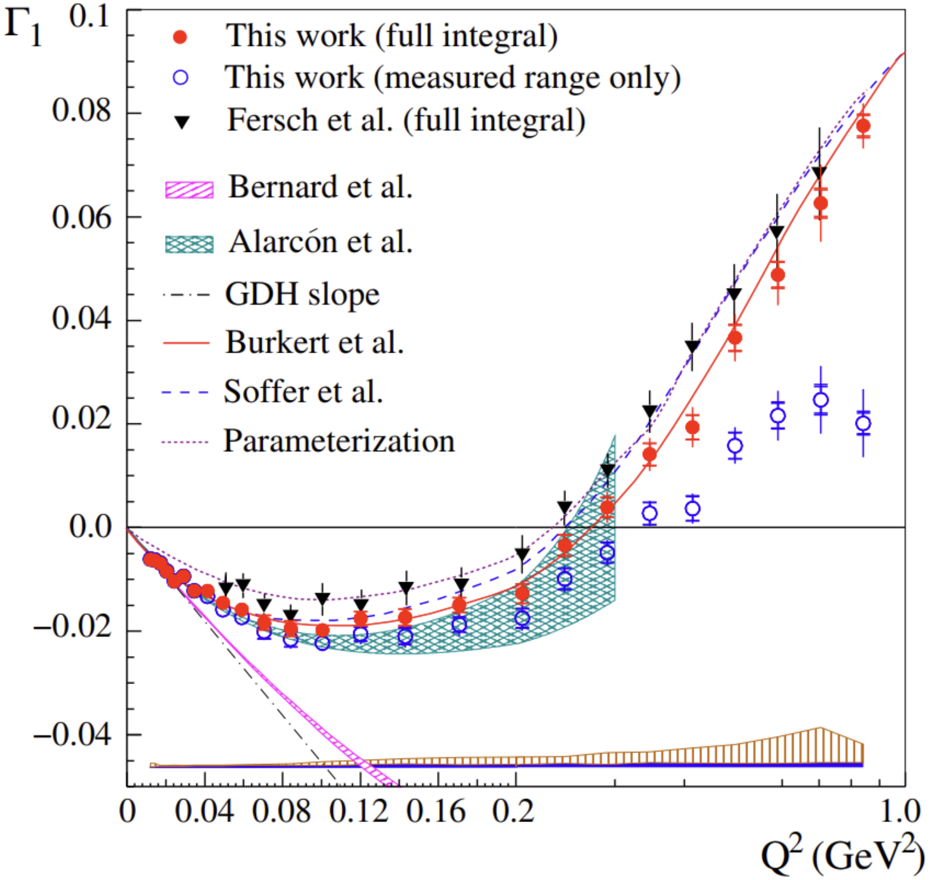
A. Deur Hadron24, Dalian, China, 08/07/2024

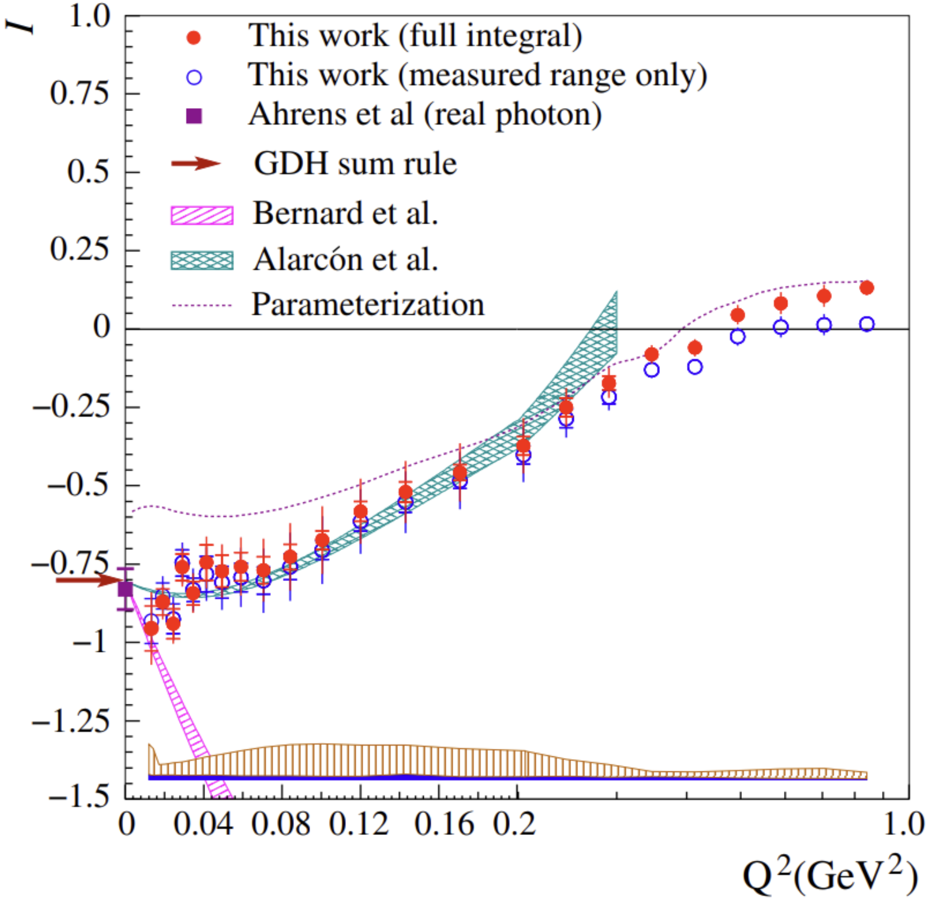




EG4 Results (GDH Sum) [Proton]

X. Zheng et al., Nature Physics 17, 736–

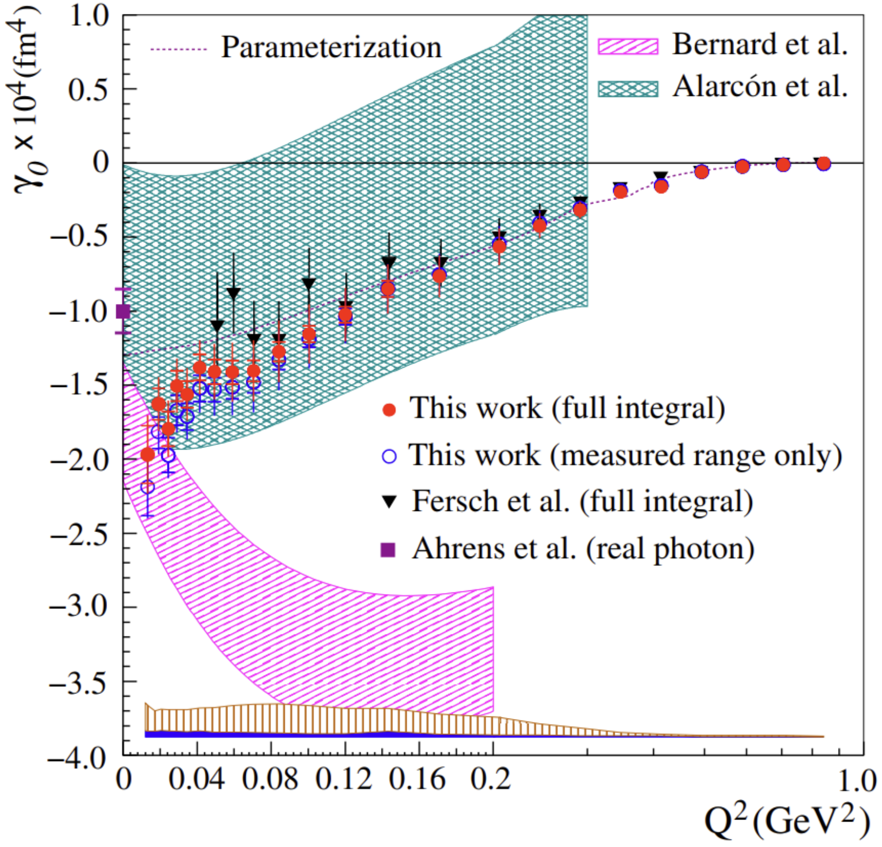




- Agrees well with Alarcon et al. prediction
- Better agreement with Bernard et al. calculation at lowest Q^2
- Seems to converge to the GDH Slope by the lowest Q^2 of the data
- Extrapolation to $Q^2 = 0$ gives $I(0) = -0.798 \pm 0.042$ compared to $I^{GDH} = -0.804$

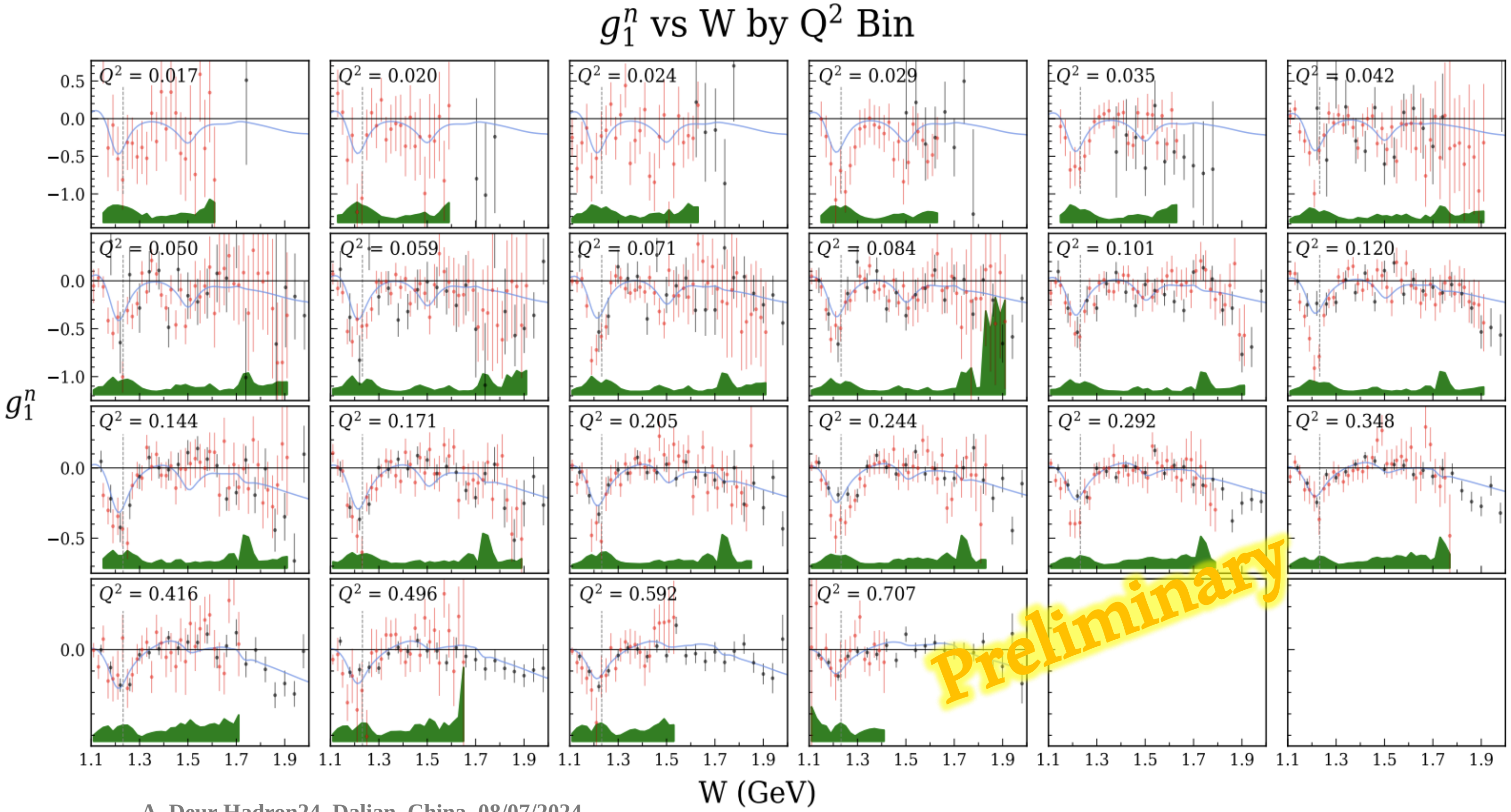
EG4 Results (γ_0) [Proton]

X. Zheng et al., Nature Physics 17, 736–741 (2021)



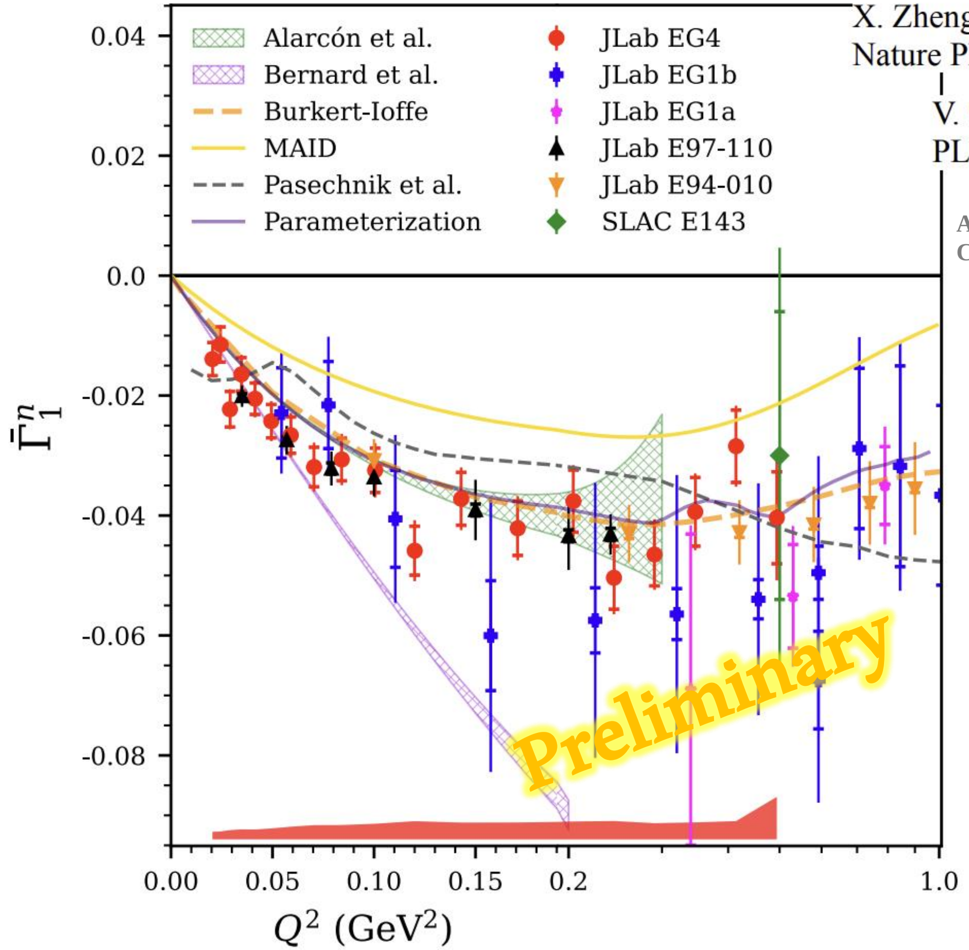
- Most of the range agrees well with Alarcon et al. prediction
- Lowest Q^2 point better agrees with Bernard et al. calculation

EG4 Results [Neutron]



- Neutron results are still preliminary
- Courtesy Darren Upton
- Will be posted on Arxiv soon!

EG4 Results (Γ_1) [Neutron]



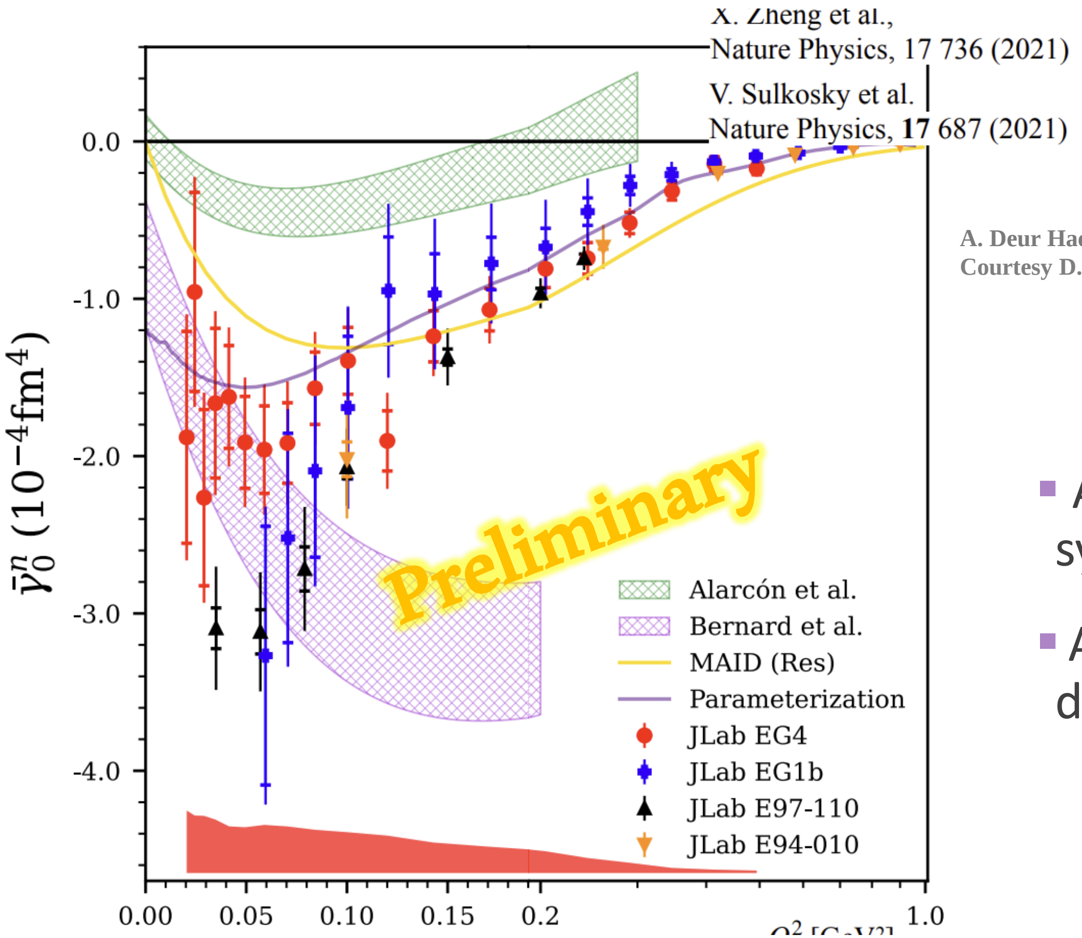
X. Zheng et al.,
Nature Physics, 17 736 (2021)

V. Sulkosky et al.
PLB 805 135428 (2020)

A. Deur Hadron24, Dalian, China, 08/07/2024
Courtesy D. Upton

- Good agreement with E97-110
- Decent agreement with both Bernard and Alarcon calculations at low Q^2, favors Alarcon calculation at higher Q^2

EG4 Results (γ_0) [Neutron]



X. Zheng et al.,
Nature Physics, 17 736 (2021)

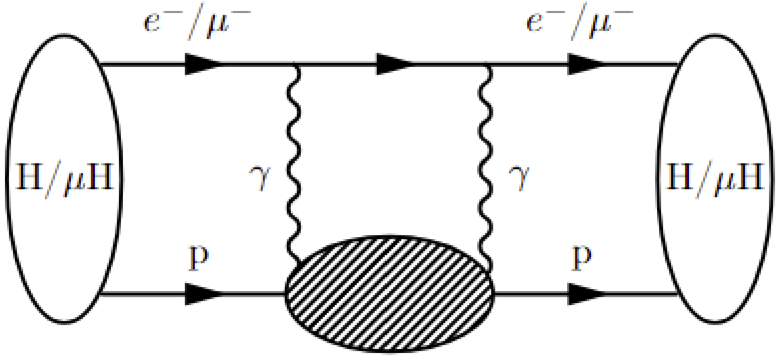
V. Sulkosky et al.
Nature Physics, **17** 687 (2021)

A. Deur Hadron24, Dalian, China, 08/07/2024
Courtesy D. Upton

- At high Q^2, only agrees with EG1b (when considering systematics)
- At low Q^2, agrees with Bernard et al. calculation, and disagrees with E97-110 and Alarcon et al. calculation

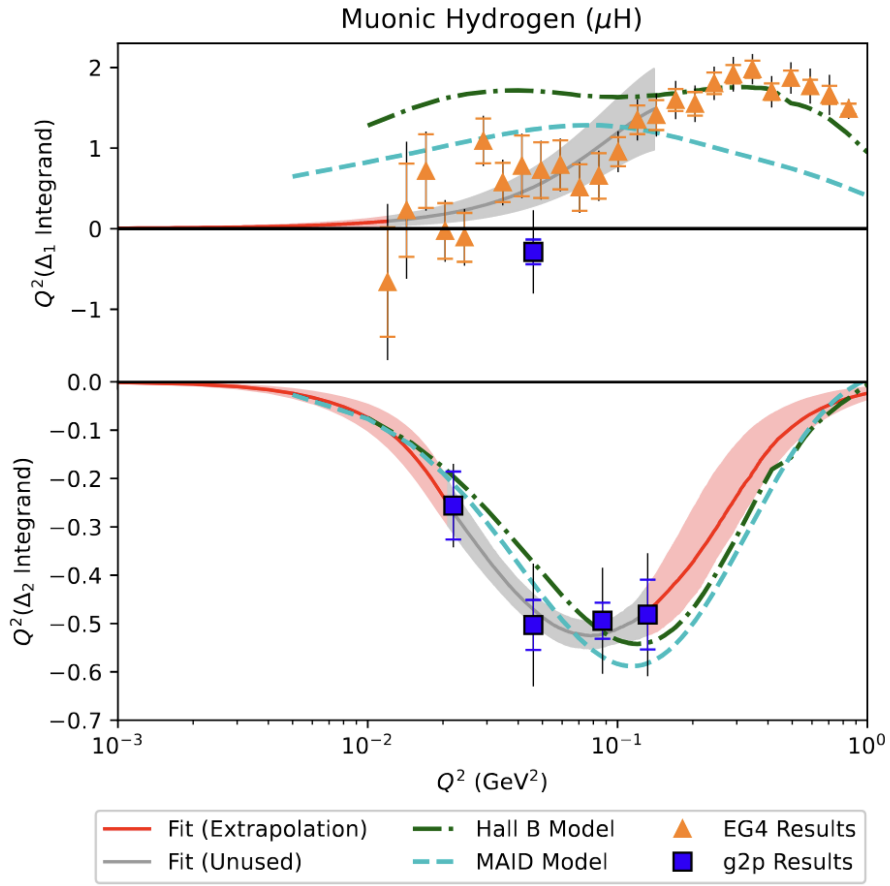
g2p / EG4 Hydrogen Hyperfine Splitting

$$E^{2\gamma}_{nS\text{-HFS}} = \frac{E_{\mathrm{F}}}{n^3}\left(\Delta_{\mathrm{Z}} + \Delta_{\mathrm{recoil}} + \Delta_{\mathrm{pol}}\right)$$

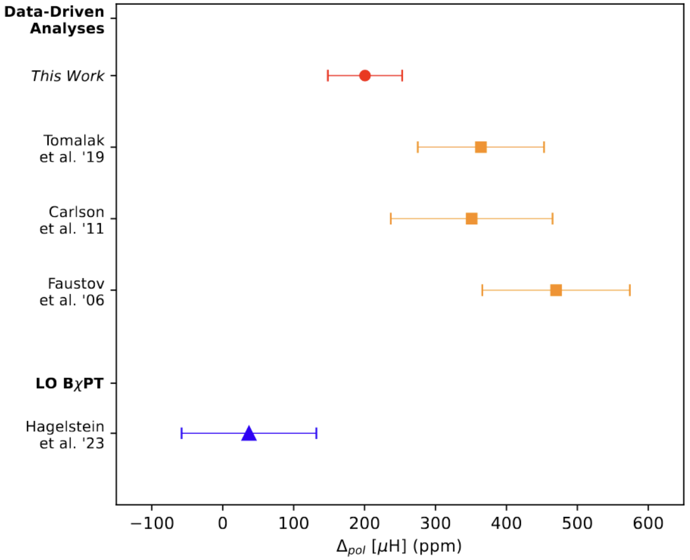


- Hydrogen Hyperfine Splitting – one of the best-measured quantities in physics
- Theoretical uncertainty is a million times larger…. ☹
- Upcoming searches at PSI and FAMU will need precise guidance where to look for the HFS in Muonic Hydrogen!
- Two-Photon Exchange effect dominates HFS uncertainty
- Polarizability effect dominates TPE contribution uncertainty = need g_1 and g_2

g2p / EG4 Hydrogen Hyperfine Splitting



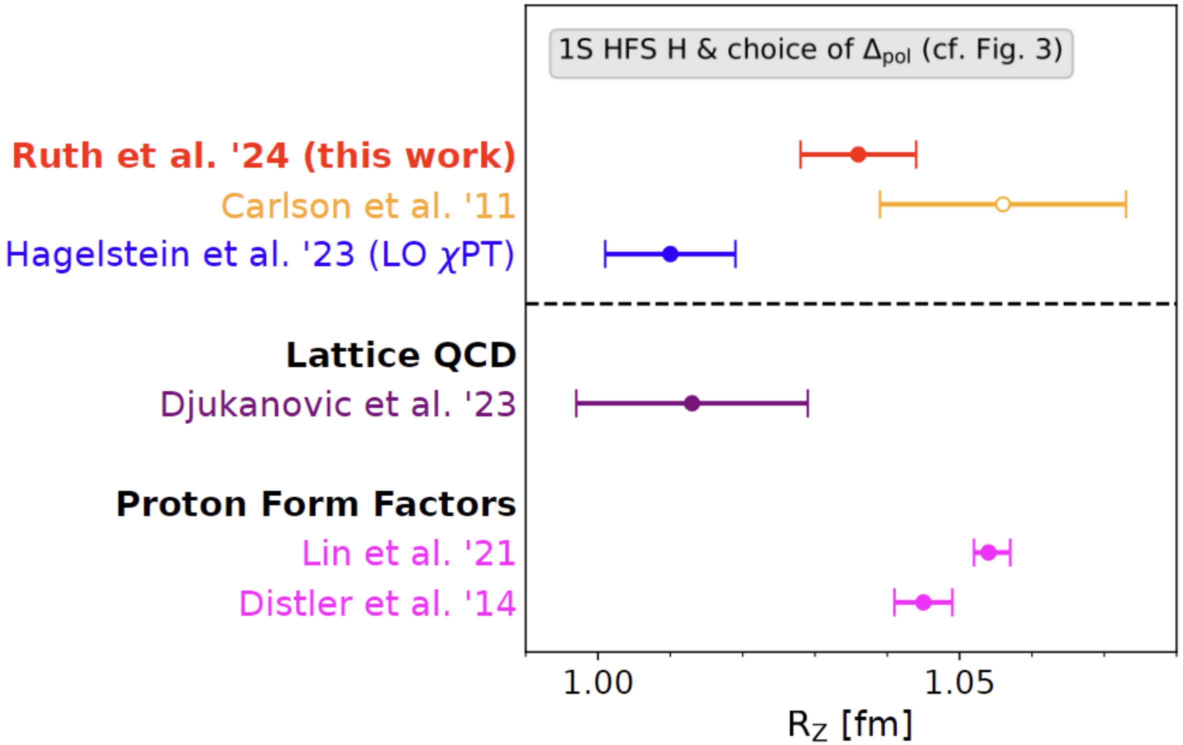
- Use Hall B model for the unmeasured low-x and high Q^2 parts
- Fit the data to extrapolate to $Q^2 = 0$



- New result cuts the data-driven uncertainty in half
- Reduces longstanding tension with χPT dramatically!
- But, still some clear tension remains…

HFS Analysis – Zemach Radius

Courtesy F. Hagelstein



- Using highly precise HFS measurement we can use our $\boldsymbol{\Delta_{pol}}$ to get R_Z:

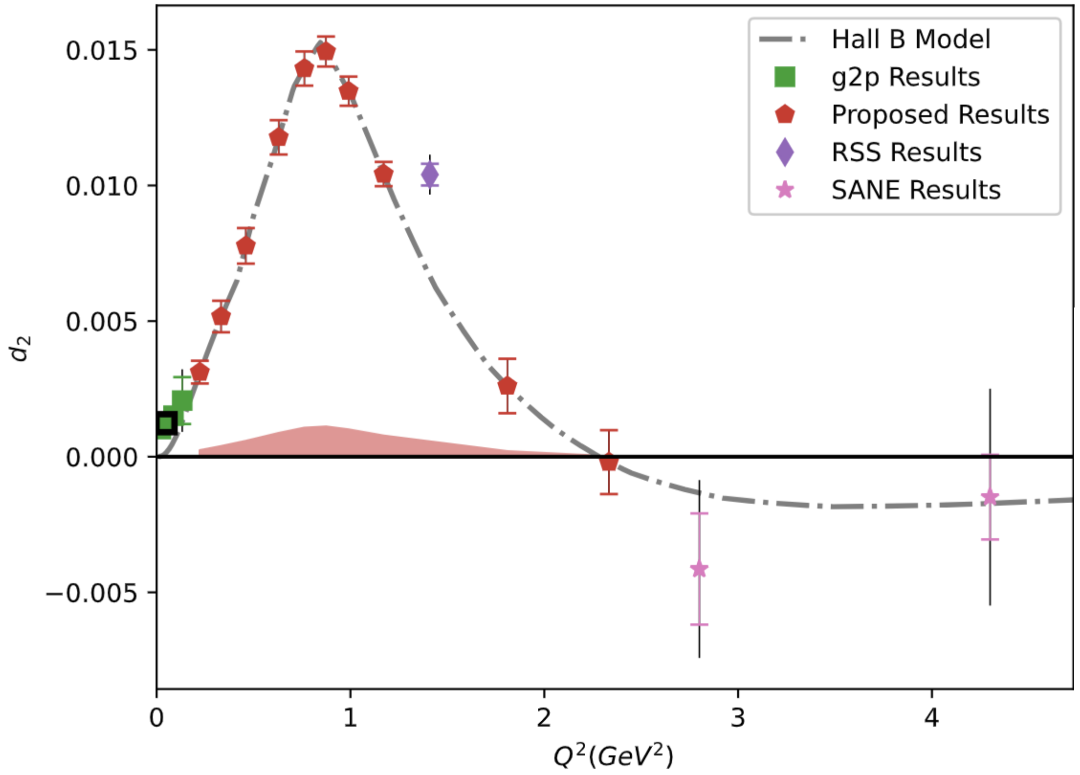
$$R_Z = 1.036(8)\,\mathrm{fm}$$

- Compatible with FF results and Lattice QCD prediction

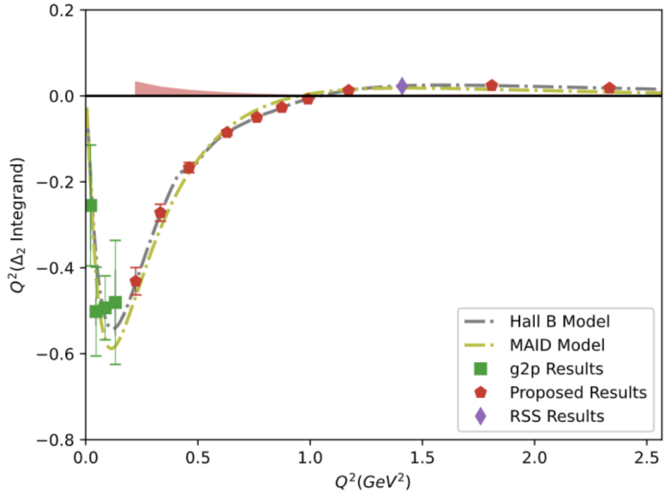
Thanks to HFS Analysis collaborators:
F. Hagelstein, V. Pascalutsa, C. Carlson
A. Deur, S. Kuhn, X. Zheng, M. Ripani
K. Slifer, J.P. Chen

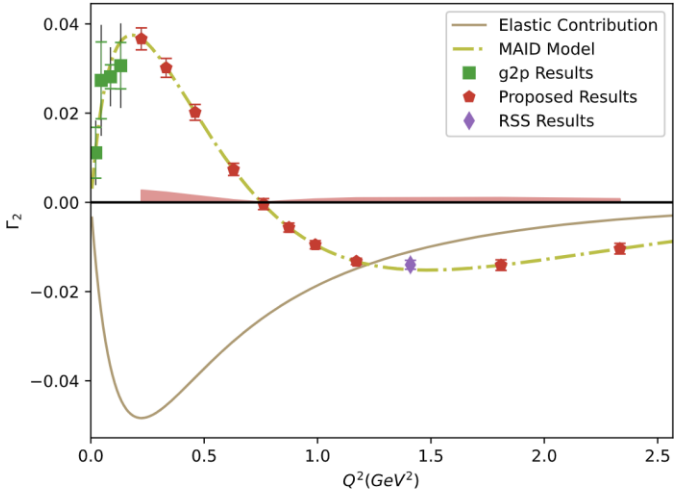
Transition Region g_2p Proposal

PR12-24-002 Projected Uncertainties



- Experiment to measure proton g_2 from 0.22-2.2 GeV^2 proposed to PAC52 in July 2024
- Will fill a major gap in g_2 spectrum, bridging the effective theory regime with the perturbative QCD regime
- **Conditionally Approved (C2)** by PAC52!





Recent Publications

E97-110 Neutron Results (g_1 and g_2):
Sulkosky et al. *Nature Physics.* volume 17, pages687–692 (2021)

EG4 Proton Results (g_1):
Zheng et al. *Nature Physics.* volume 17, pages736-741 (2021)

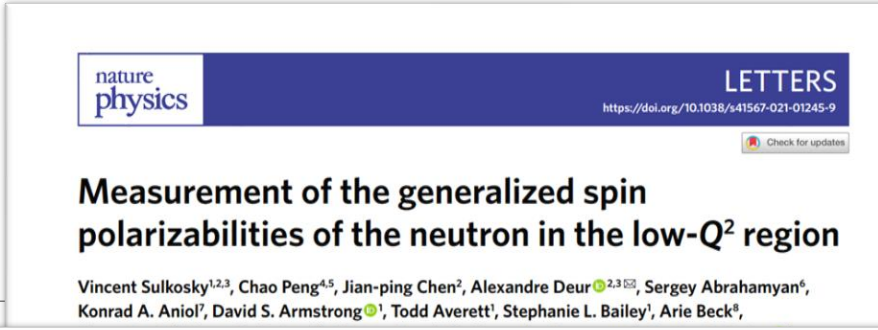
g2p Proton Results (g_2):

Ruth et al. *Nature Physics.* volume 18, pages1441–1446 (2022)

g2p+EG4 Hyperfine Splitting Results:

Under Review at Physics Letters B…

arXiv:2406.18738



nature physics

LETTERS

https://doi.org/10.1038/s41567-021-01245-9

Check for updates

Measurement of the generalized spin polarizabilities of the neutron in the low-Q^2 region

Vincent Sulkosky[1,2,3], Chao Peng[4,5], Jian-ping Chen[2], Alexandre Deur[2,3] ✉, Sergey Abrahamyan[6], Konrad A. Aniol[7], David S. Armstrong[1], Todd Averett[1], Stephanie L. Bailey[1], Arie Beck[8],

ARTICLES

https://doi.org/10.1038/s41567-021-01198-z

nature physic

Check for u

Measurement of the proton spin structure at long distances

X. Zheng[1], A. Deur[1,2] ✉, H. Kang[3], S. E. Kuhn[4], M. Ripani[5], J. Zhang[1], K. P. Adhikari[2,4,6,50], S. Adhikari[7], M. J. Amaryan[4], H. Atac[8], H. Avakian[2], L. Barion[9], M. Battaglieri[2,5], I. Bedlinskiy[10], F. Benmokhtar[11], A. Bianconi[12,13], A. S. Biselli[14], S. Boiarinov[2], M. Bondì[5], F. Bossù[15], P. Bosted[16], W. J. Briscoe[17], J. Brock[2], W. K. Brooks[2,18], D. Bulumulla[4], V. D. Burkert[2], C. Carlin[2], D. S. Carman[2], J. C. Carvajal[7], A. Celentano[5], P. Chatagnon[19], T. Chetry[6], J.-P. Chen[2], S. Choi[3], G. Ciullo[9,20], L. Clark[2

New Spin Structure Constraints on Hyperfine Splitting and Proton Size

David Ruth[a,*], Karl Slifer[a], Jian-Ping Chen[b], Carl E. Carlson[c], Franziska Hagelstein[d,e,f], Vladimir Pascalutsa[d], Alexandre Deur[b], Sebastian Kuhn[g], Marco Ripani[h], Xiaochao Zheng[i], Ryan Zielinski[a], Chao Gu[j]

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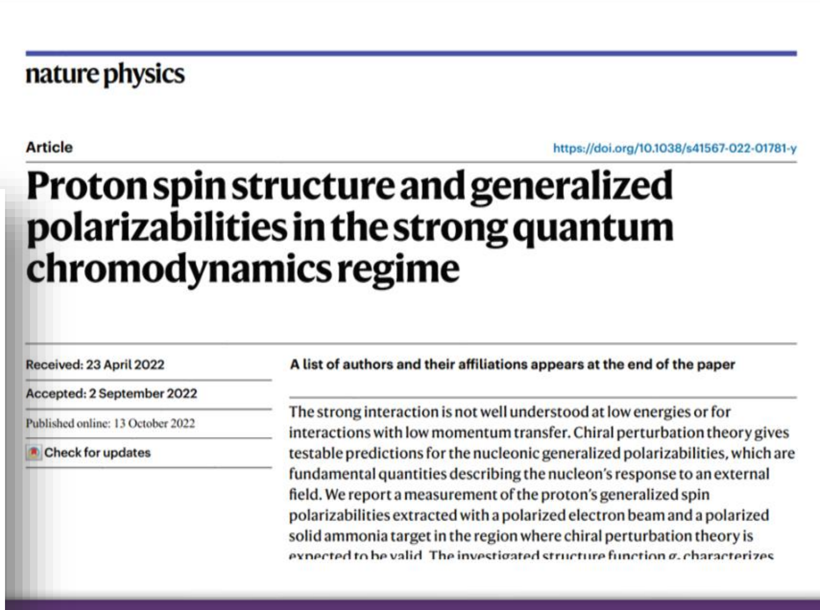

nature physics

Article

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Proton spin structure and generalized polarizabilities in the strong quantum chromodynamics regime

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A list of authors and their affiliations appears at the end of the paper

The strong interaction is not well understood at low energies or for interactions with low momentum transfer. Chiral perturbation theory gives testable predictions for the nucleonic generalized polarizabilities, which are fundamental quantities describing the nucleon's response to an external field. We report a measurement of the proton's generalized spin polarizabilities extracted with a polarized electron beam and a polarized solid ammonia target in the region where chiral perturbation theory is expected to be valid. The investigated structure function g characterizes

State of Comparisons to χPT

- χPT reproduces the data well sometimes and not as well other times
- Still some question on how the two cutting edge χPT calculations compare to each other
- **Hydrogen HFS:** Diminished but still significant tension between data and χPT
- δ_{LT}: No sign of "δ_{LT} Puzzle" for proton, but the puzzle remains at the lowest Q^2 neutron data
- d_2: No tension for proton
- Γ_1/GDH: Good agreement for proton, some tension for neutron
- γ_0: Good agreement for proton, some tension for neutron

Conclusion

- **χ**PT is doing a much better job with the proton than the neutron, though questions still remain about the proton, especially the HFS
- Lattice QCD can also produce many of these quantities – this data provides a benchmark to check these calculations when they are finished
- **Lots** of recently published high precision **spin structure function** and moment data out of JLab, with more on the way
- SSF moments and polarizabilities provide a **crucial benchmark** for testing low Q^2 effective theories!

Thanks!