Proton spin structure functions and polarizability contribution to Hyperfine Splitting in muonic hydrogen

David Ruth

PREN/μASTI Workshop 2023

6/27/2023

A big thanks to the whole g2p collaboration!

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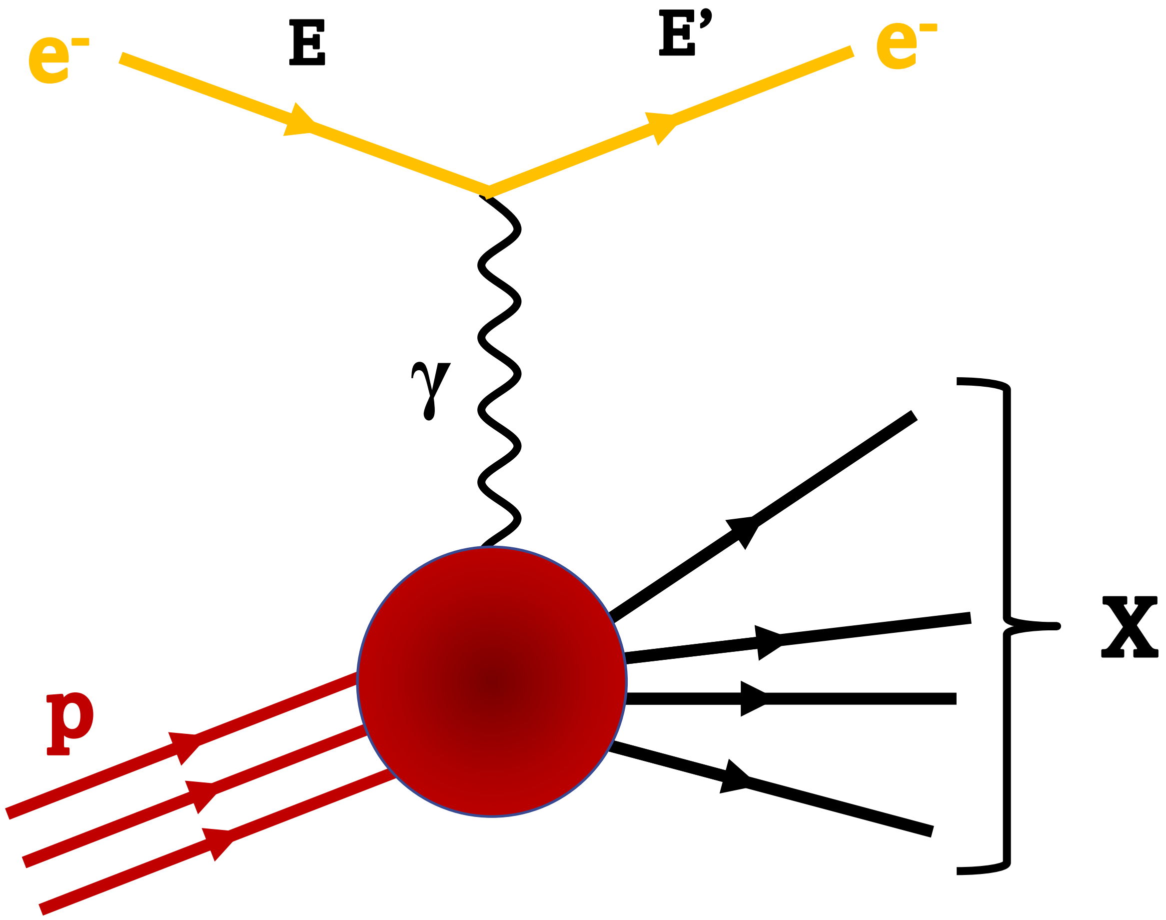
Electron-Proton Scattering Formulation

Goal: study the proton's spin structure and understand QCD in the regime where quark-gluon correlations are significant

Inclusive electron scattering measurement



$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

$$\nu = E - E'$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$x = \frac{Q^2}{2M\nu}$$

Cross section can be decomposed into Form Factors & Structure Functions

Elastic Scattering: target remains in ground state

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

Form factors G_e and G_m describe electric and magnetic distribution

Inelastic Scattering: target is excited by interaction

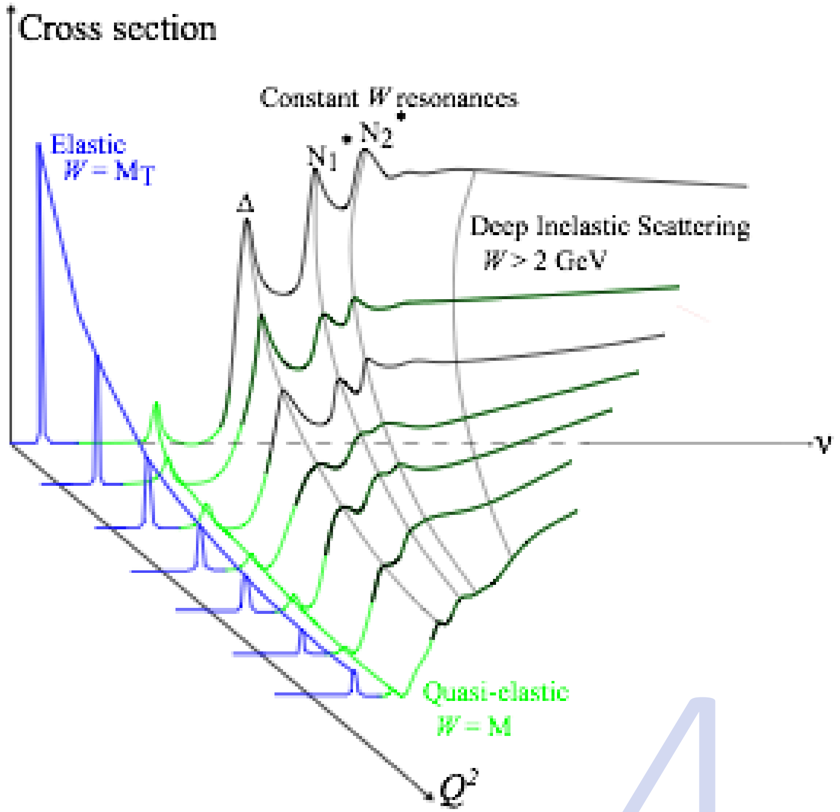
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Structure functions F_1 and F_2 describe quark-gluon distribution

Inelastic Scattering with polarized beam & target:

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

g_1 and g_2 describe spin distribution & quark-gluon correlations

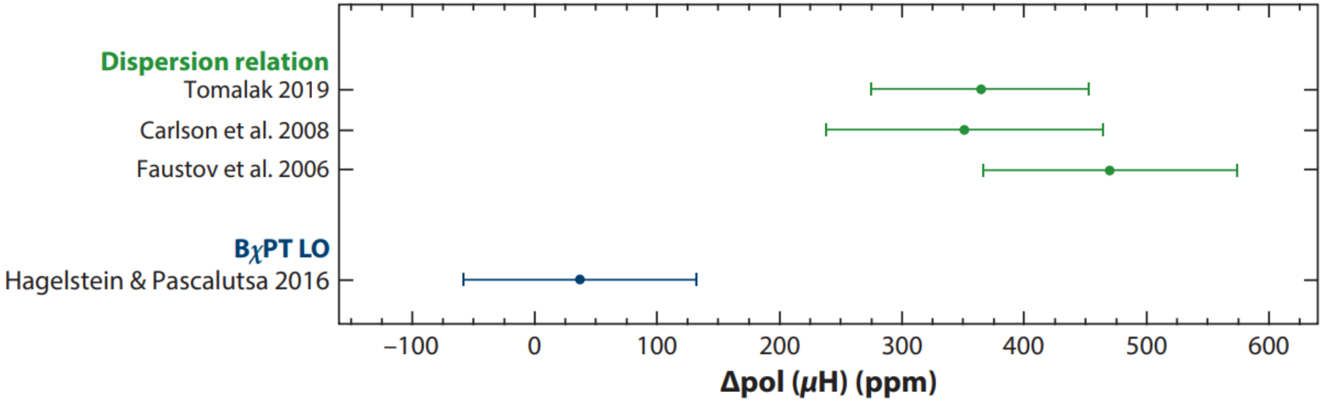


Proton Spin Structure contributes to Hyperfine Splitting of Hydrogen

- See Carl Carlson's previous talk…

- Uncertainty in theoretical calculations of Hyperfine splitting is presently dominated by proton structure term

- Requires experimental constraint from spin structure functions!



A. Antognini, F. Hagelstein, and V. Pascalutsa (2022)

$$E^{2\gamma}_{nS-hfs} = \frac{E_F}{n^3}\left(\Delta_Z + \Delta_{recoil} + \boldsymbol{\Delta_{pol}}\right)$$

$$\Delta_{pol} = \frac{\alpha m_l}{\pi g_p M_p}(\Delta_1 + \Delta_2)$$

$$\Delta_1 = \frac{9}{4}\int_0^\infty \frac{dQ^2}{Q^2}\left[\left(\frac{G_M(Q^2) + G_E^2(Q^2)}{1+\tau}\right)^2 + \frac{8M_p^2}{Q^2}\int_0^{x_{th}} \widetilde{\beta_1}(x, Q^2)\,\boldsymbol{g_1(x, Q^2)}\,dx\right]$$

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

Kinematic weighting for muonic hydrogen

$$\widetilde{\beta_1}(Q^2) = \frac{x^2\beta_1(\tau) - \left(\frac{m_l}{m_p}\right)^2 \beta_1(\tau_l)}{x^2 - \left(\frac{m_l}{m_p}\right)^2}$$

$$\tau = \frac{\upsilon^2}{Q^2}$$

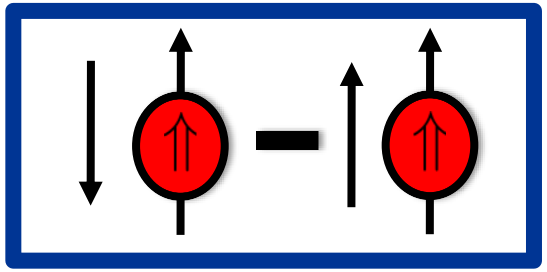
$$\widetilde{\beta_2}(Q^2) = \frac{x^2[\beta_2(\tau) - \beta_2(\tau_l)]}{x^2 - \left(\frac{m_l}{m_p}\right)^2}$$

$$\tau_l = \frac{Q^2}{4m_l^2}$$

$$\beta_1(Q^2) = \frac{4}{9}\left(-3\tau + 2\tau^2 + 2(2-\tau)\sqrt{\tau(\tau+1)}\right)$$

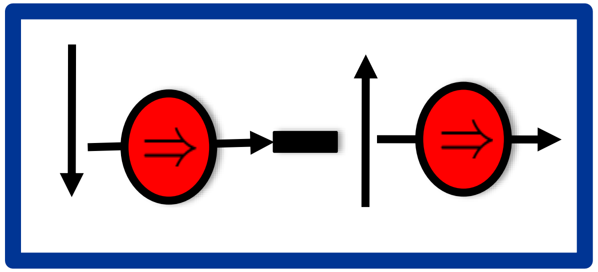
$$\beta_2(Q^2) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)}$$

Extracting structure functions



$\Delta\boldsymbol{\sigma}_{\parallel}$

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'}{E}\left[g_1(x,Q^2)\{E+E'\cos\theta\} - \frac{Q^2}{\nu}g_2(\nu,Q^2)\right]$$



$\Delta\boldsymbol{\sigma}_{\perp}$

$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\left[\nu g_1(x,Q^2) + 2Eg_2(\nu,Q^2)\right]$$

Can solve for the structure functions

$\Delta\boldsymbol{\sigma}_{\parallel}$ dominated by g_1

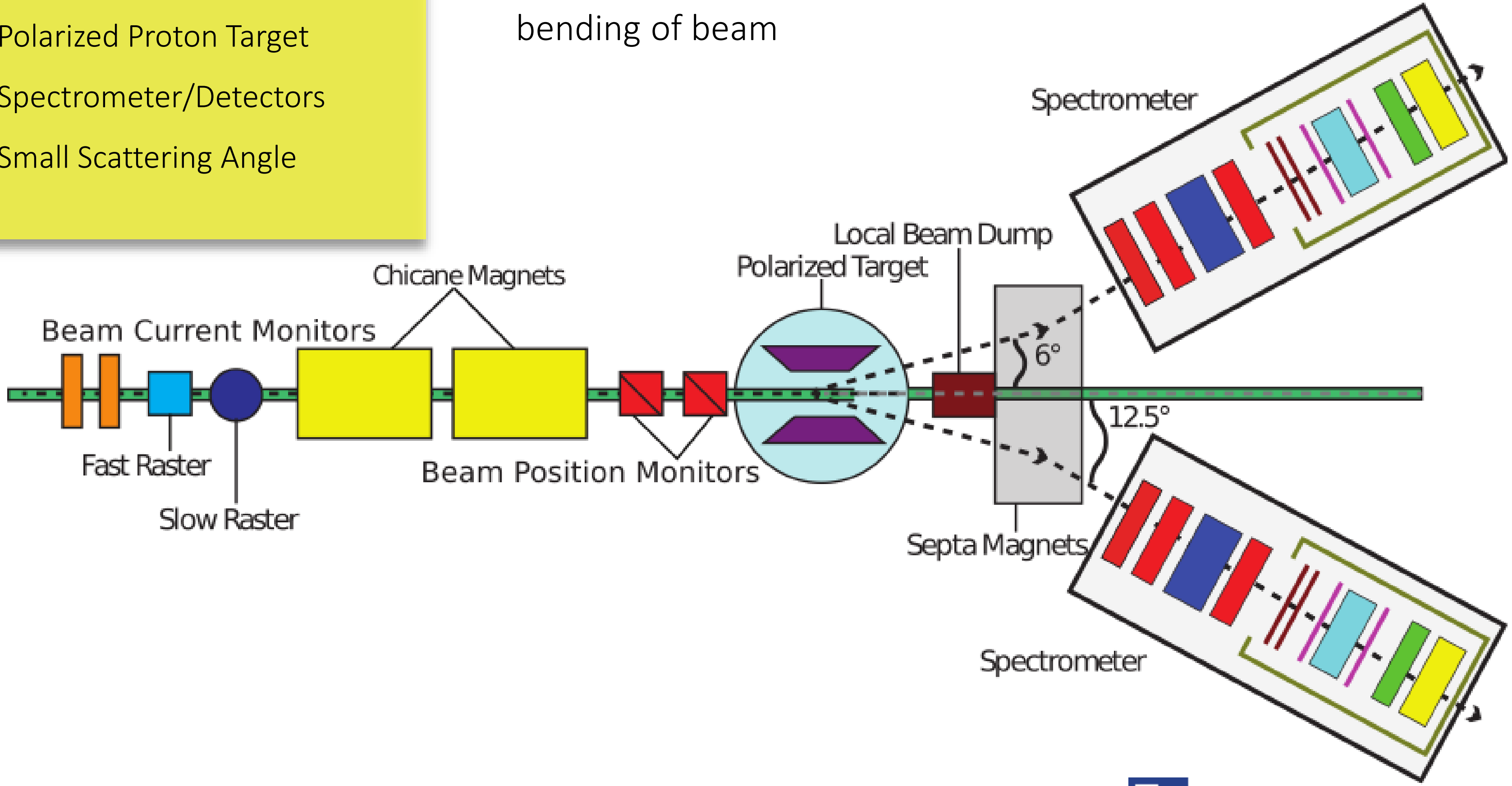
$\Delta\boldsymbol{\sigma}_{\perp}$ dominated by g_2

Hall A Experimental Setup:

Measuring g_2^p

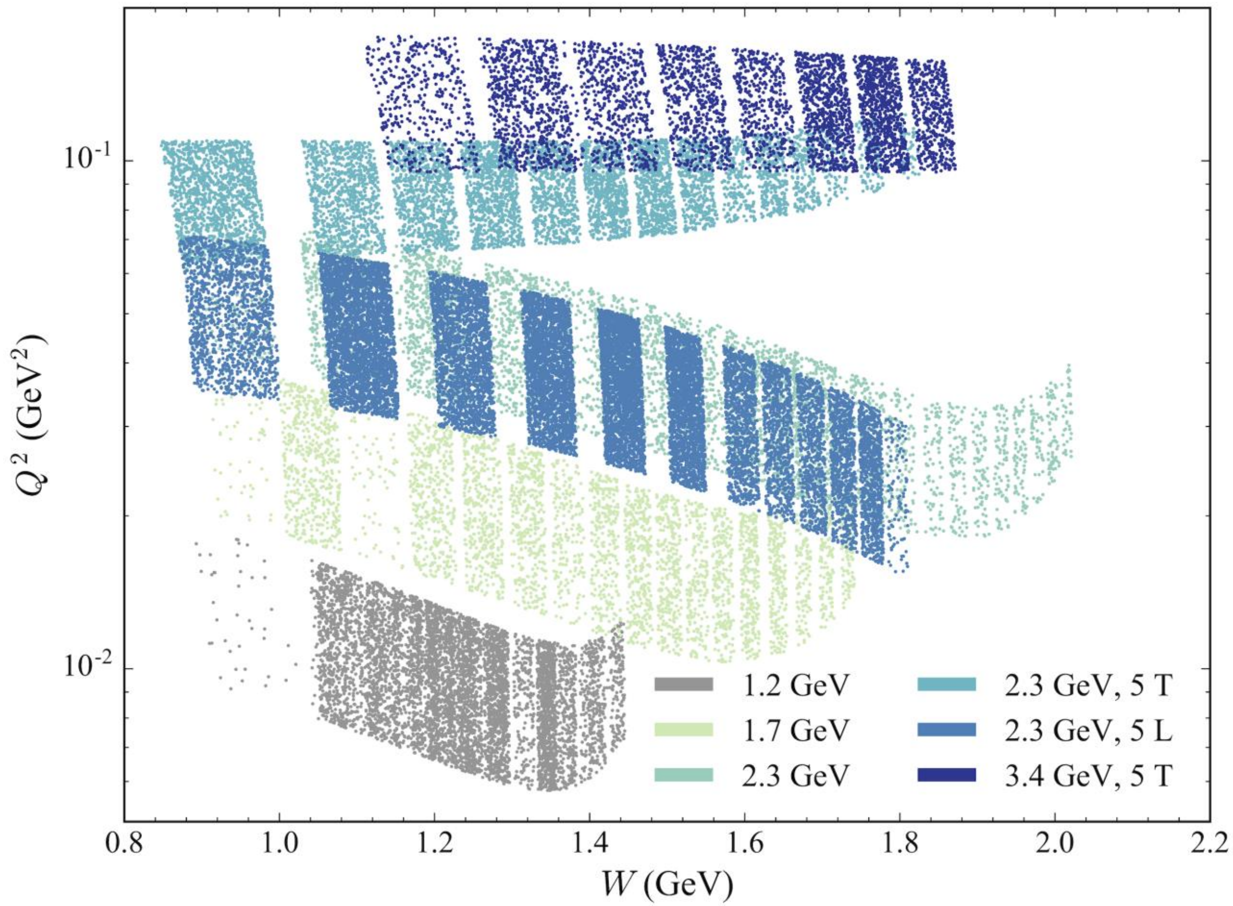
- Electron Beam
- Polarized Proton Target
- Spectrometer/Detectors
- Small Scattering Angle

- g2p experiment ran spring 2012 at Jefferson Lab in Hall A
- Transverse polarized NH_3 target (2.5/5.0T)
- Dipole chicane magnets help compensate for target field bending of beam



University of New Hampshire

Kinematic Settings



5 Transverse settings and 1 Longitudinal setting

1.2 GeV setting only used for radiative corrections

2.2 GeV 5T Longitudinal & 2.2 GeV 2.5T Transverse fall at almost the same Q^2 and so can be used together

Forming polarized cross section differences

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

Form with an asymmetry and an unpolarized cross section

Lots of unpolarized world data for the proton, so the models are very good

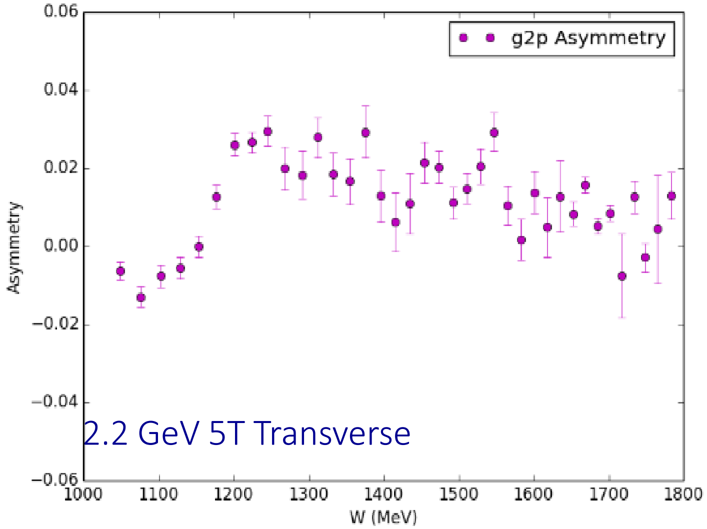
Asymmetries are easy because they cancel many quantities:

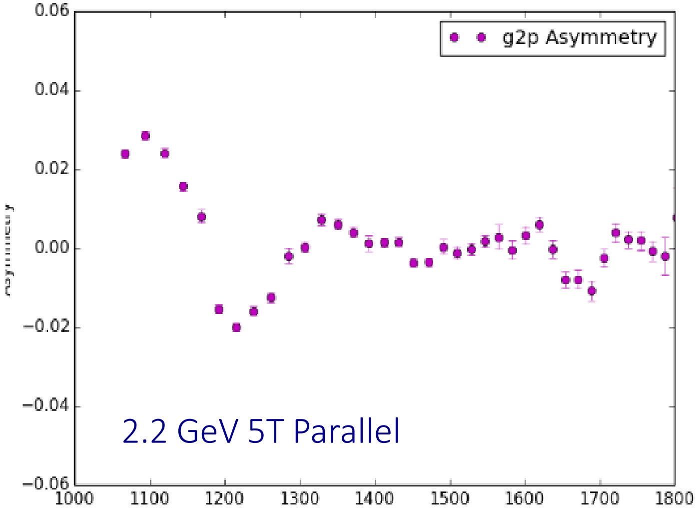
$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}}$$

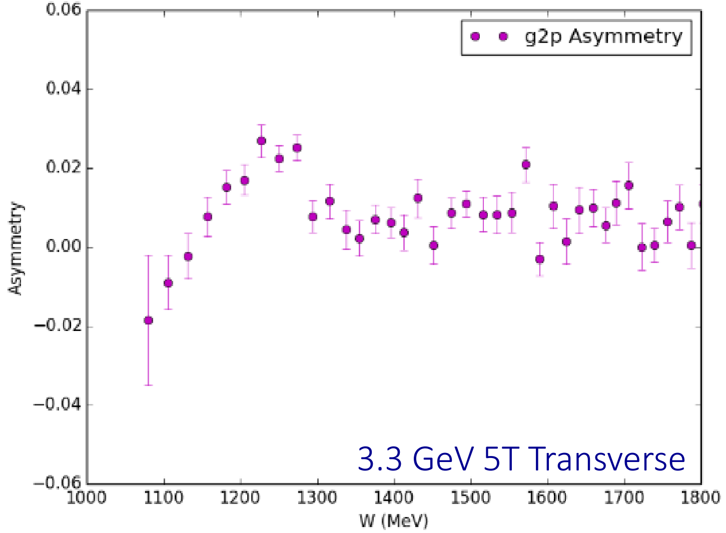
$$A^{\text{meas}} = \frac{Y_+ - Y_-}{Y_+ + Y_-}, \qquad Y_{\pm} = \frac{N_{\pm}}{LT_{\pm}Q_{\pm}}$$

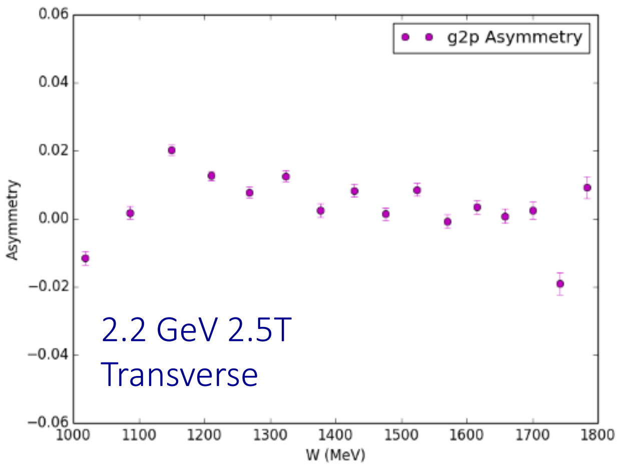
$$A^{\text{exp}} = \frac{1}{f \cdot P_t \cdot P_b} A^{\text{raw}}$$

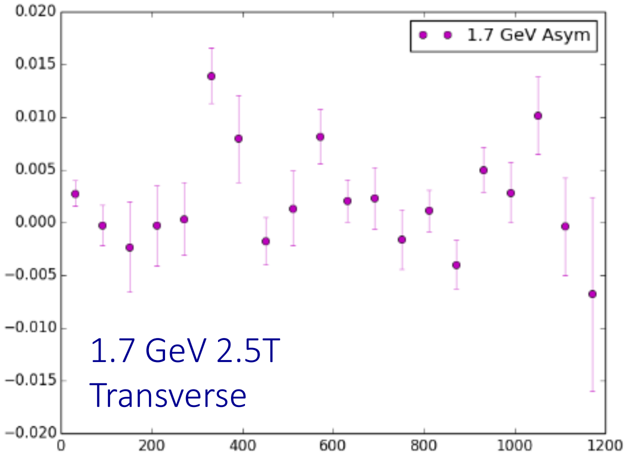
Asymmetry Results





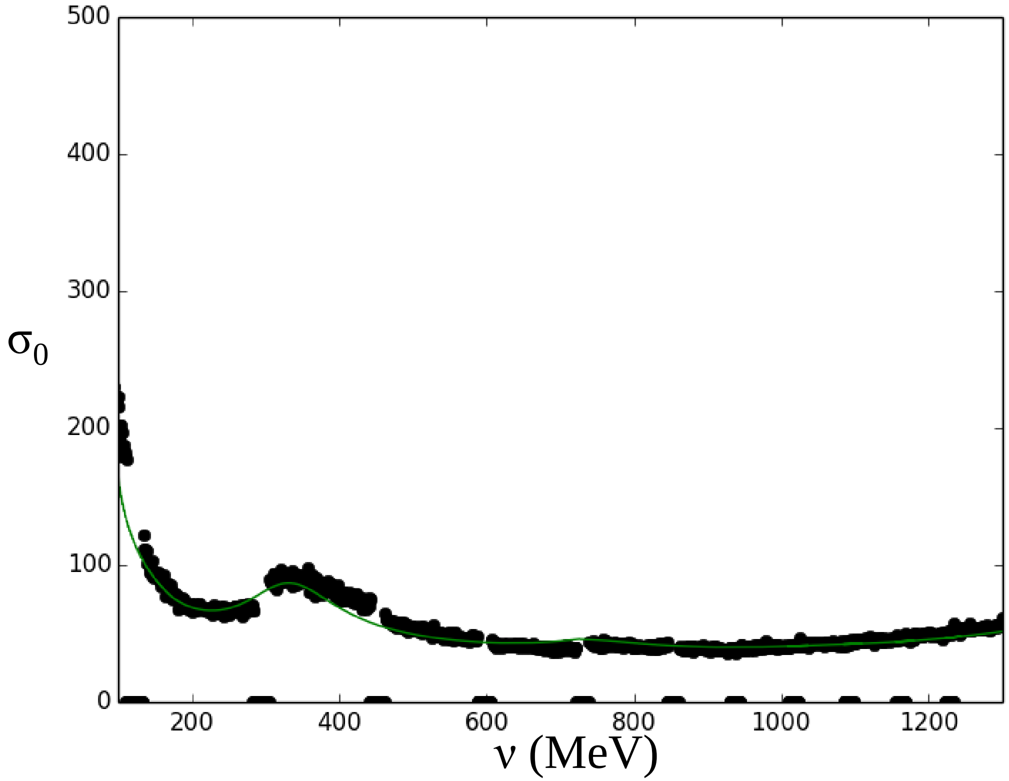






LHRS and RHRS combined for better statistics

Unpolarized Cross Section



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

Acceptance issues on the edge of transverse momentum settings made the unpolarized cross section extraction challenging, with large associated systematics

Instead, use a model unpolarized cross section

Bosted-Christy model used, shows good agreement with our longitudinal setting cross section in the resonance region

Extraction of Structure Functions

$$g_1(x,Q^2) = K_1\left[\Delta\sigma_{\parallel}\left(1+\frac{1}{K_2}\tan\frac{\theta}{2}\right)\right] + \frac{2\,g_2(x,Q^2)}{K_2 y}\tan\frac{\theta}{2}$$

$$g_2(x,Q^2) = \frac{K_1 y}{2}\left[\Delta\sigma_{\perp}\left(K_2+\tan\frac{\theta}{2}\right)\right] + \frac{g_1(x,Q^2)\,y}{2}$$

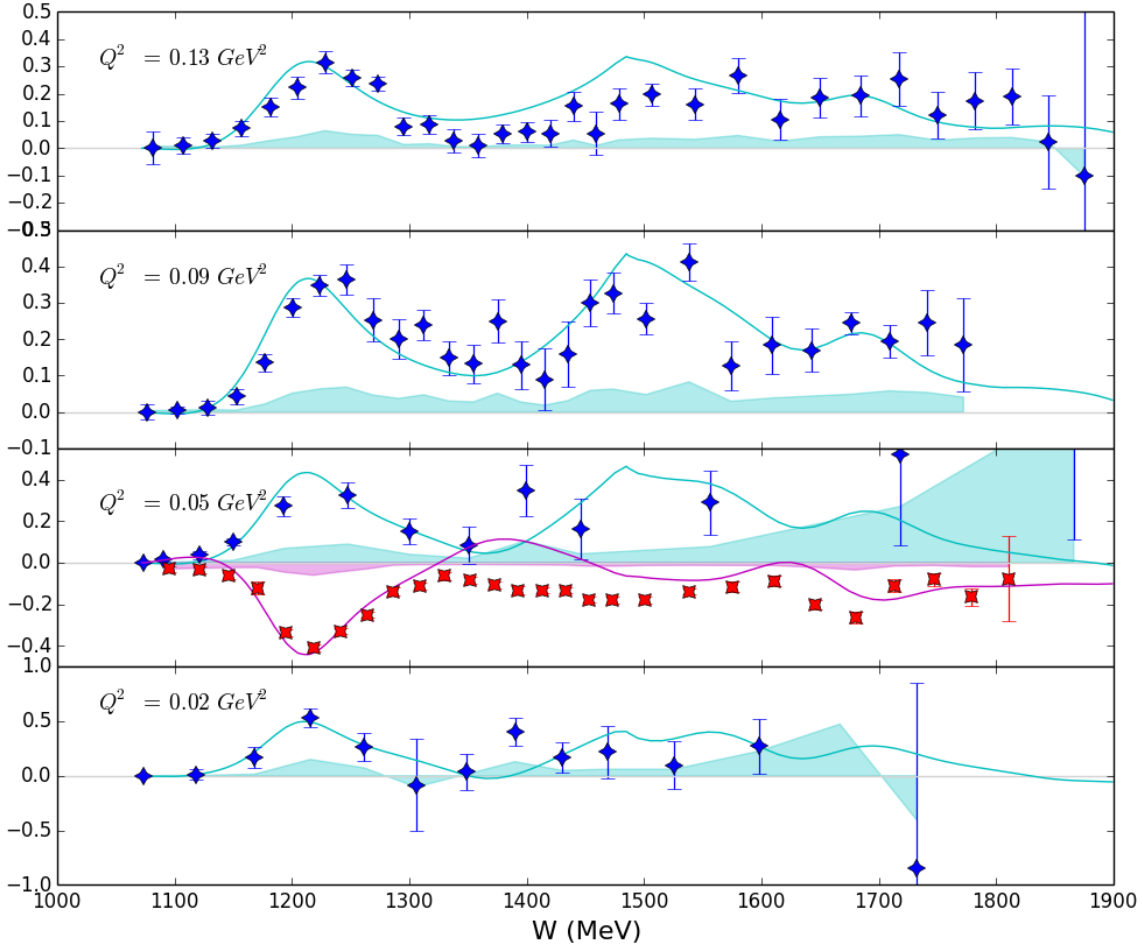
Input from Hall B model

Combination of data & Bosted model

CLAS Hall B model used as g_1 input for most settings

For 0.045 GeV^2 setting, we have both polarized XS differences, so we can form g_1 and g_2 from data

Structure Function Results

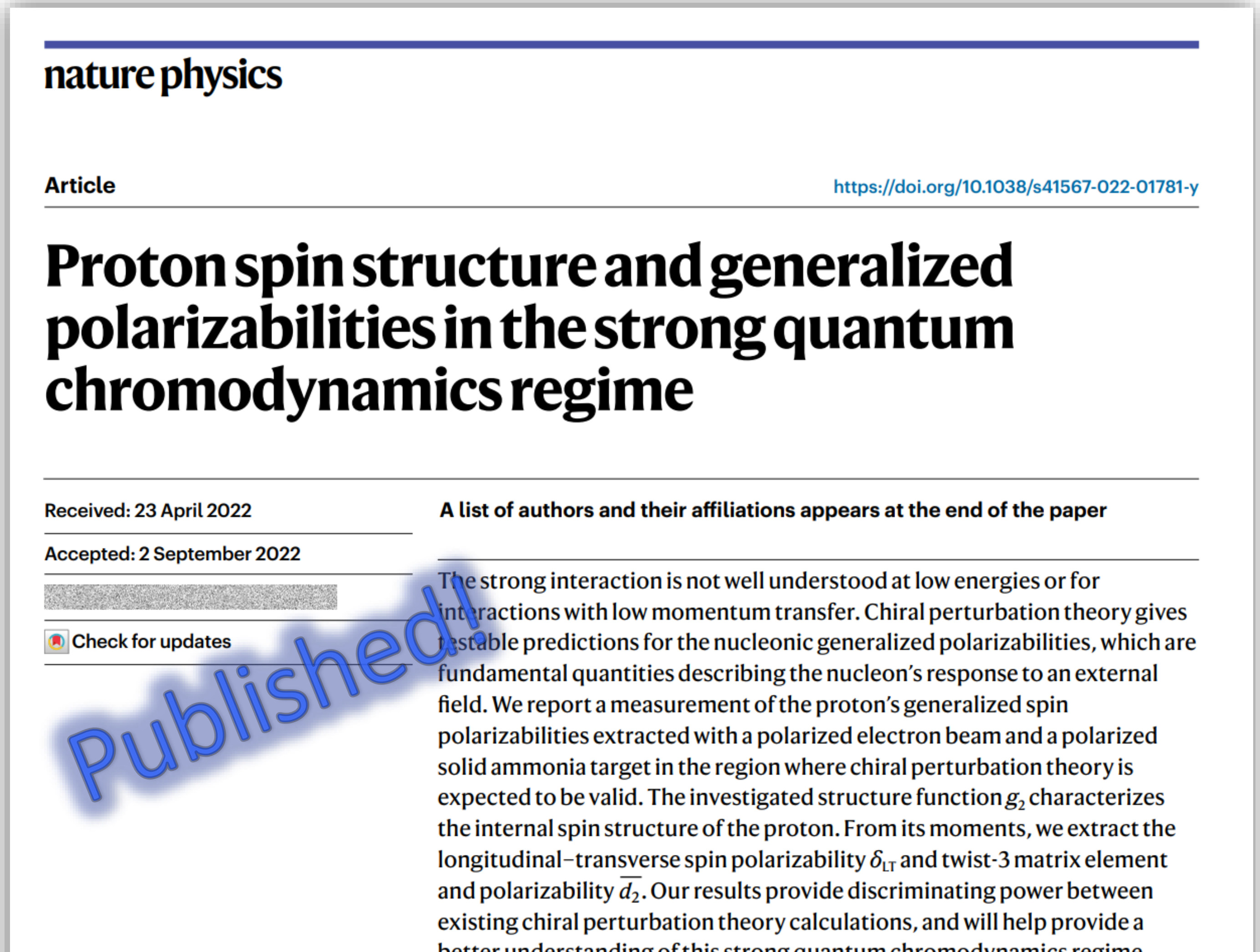


Blue stars: g_2

Red stars: g_1

g_1 data has very good statistics and goes very close to pion production threshold

First publication released in October!


nature physics

Article https://doi.org/10.1038/s41567-022-01781-y

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

Received: 23 April 2022

Accepted: 2 September 2022

Check for updates

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_2 characterizes the internal spin structure of the proton. From its moments, we extract the longitudinal–transverse spin polarizability δ_{LT} and twist-3 matrix element and polarizability $\overline{d_2}$. Our results provide discriminating power between existing chiral perturbation theory calculations, and will help provide a

First publication released October 2022 in **Nature Physics!**

Highlights g_2 results as well as the δ_{LT} and $\overline{d_2}$ moments

https://www.nature.com/articles/s41567-022-01781-y

Δ_1 Results (Muonic Hydrogen)

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See X. Zheng et al (Nature Physics 2021) and R. Fersch et al (PRC 2017)
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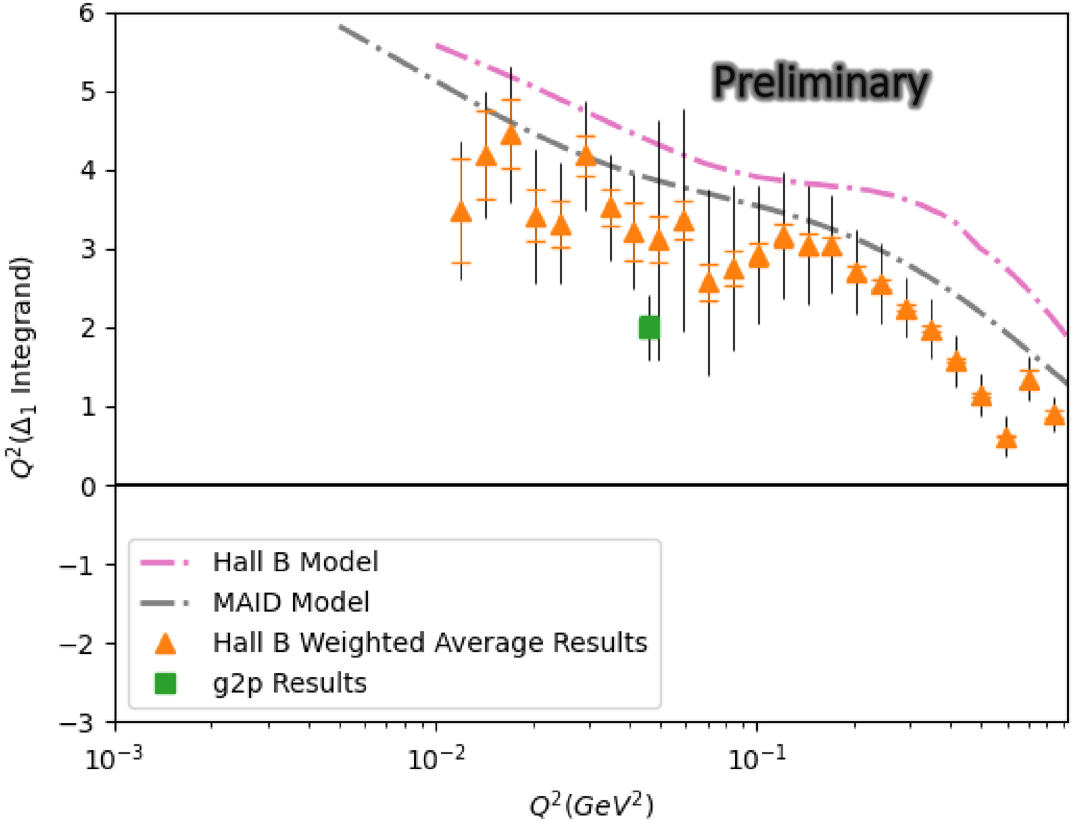
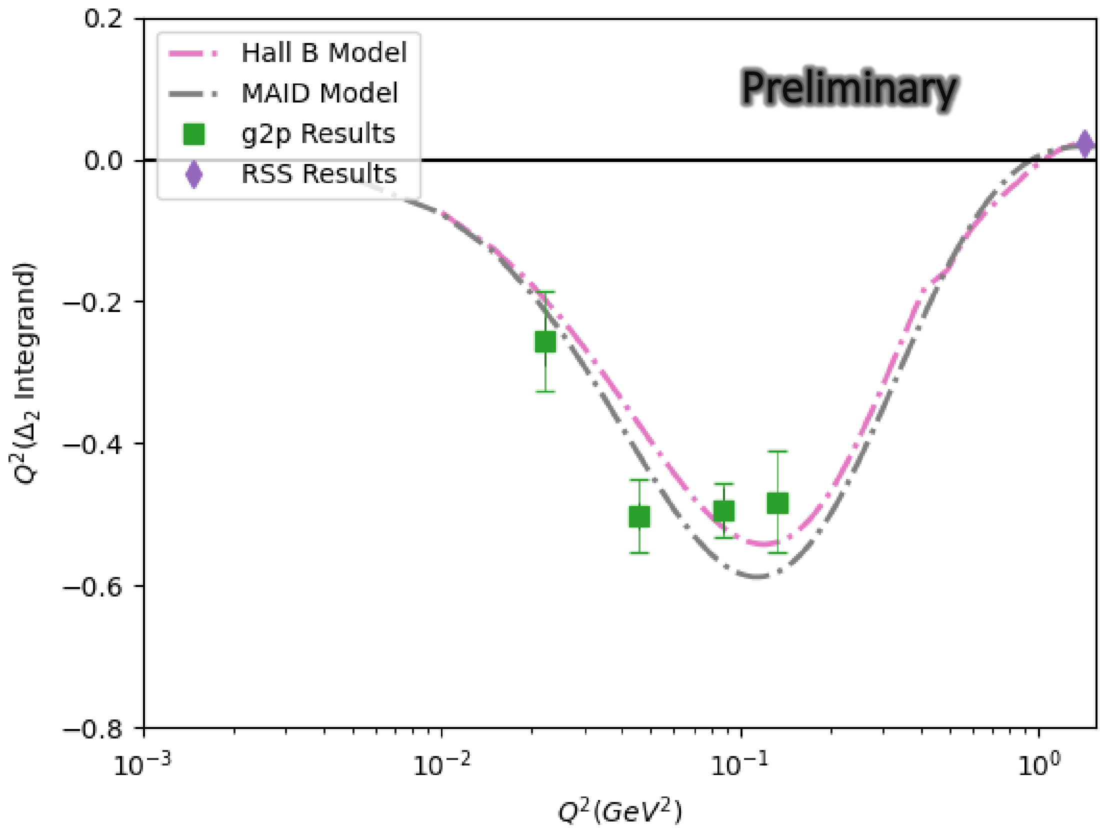


- New data from g2p and other Jefferson Lab experiments constrains Δ_1 above $Q^2 = 0.01$ GeV^2

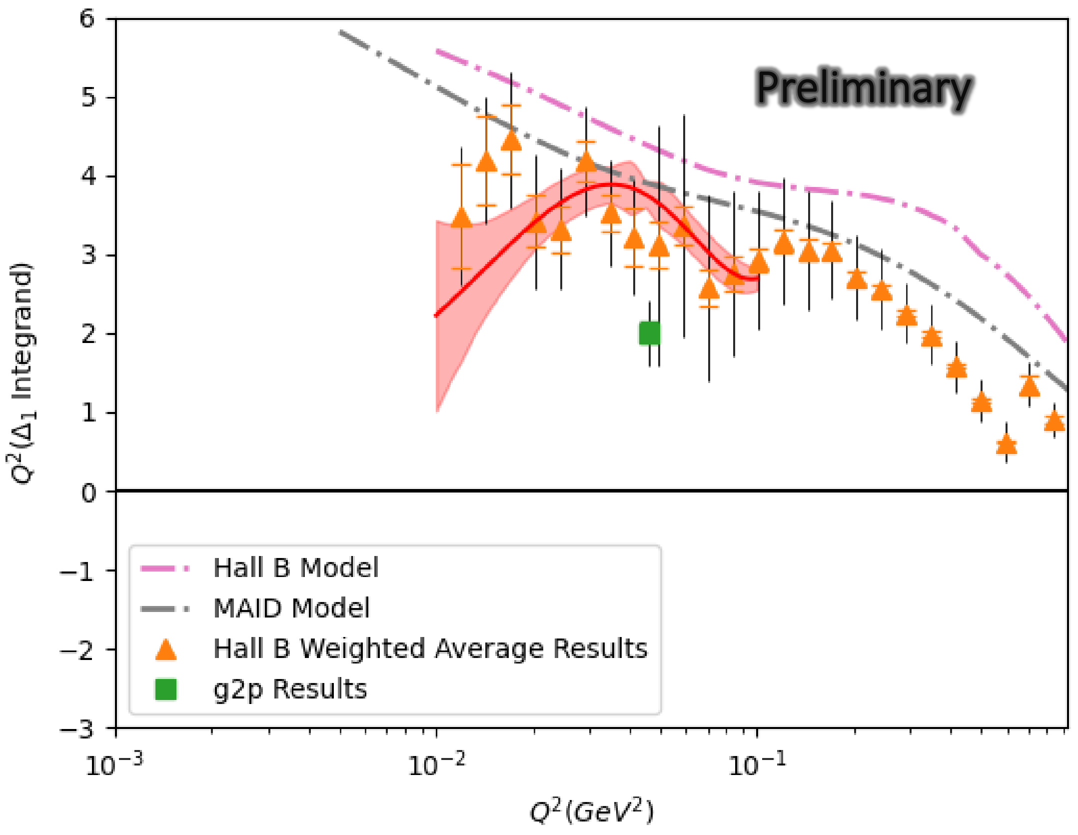
Δ_2 Results (Muonic Hydrogen)

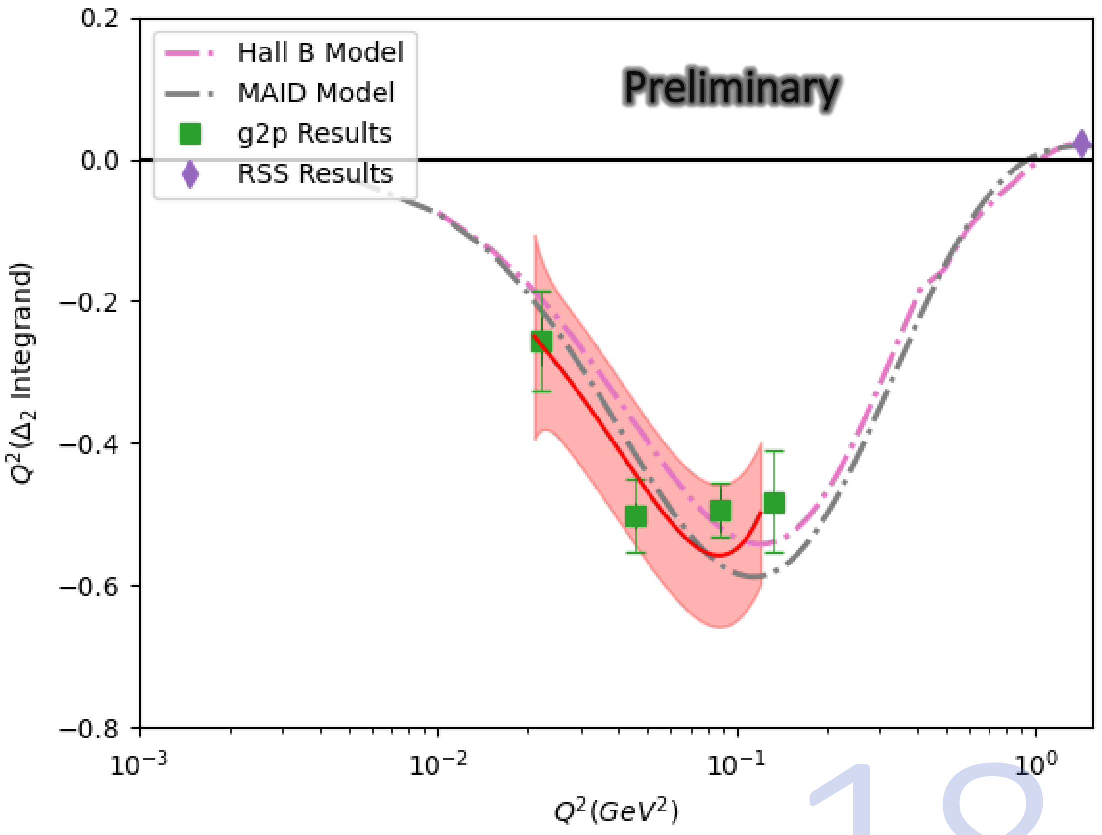
RSS Data constructed from F. Wesselman, K. Slifer, S. Tajima et al (PRL 2007)



- First ever experimental results for this quantity!
- Q^2 both above and below g2p contributes strongly to Δ_2

$\Delta_{1,2}$ Results (Fits)





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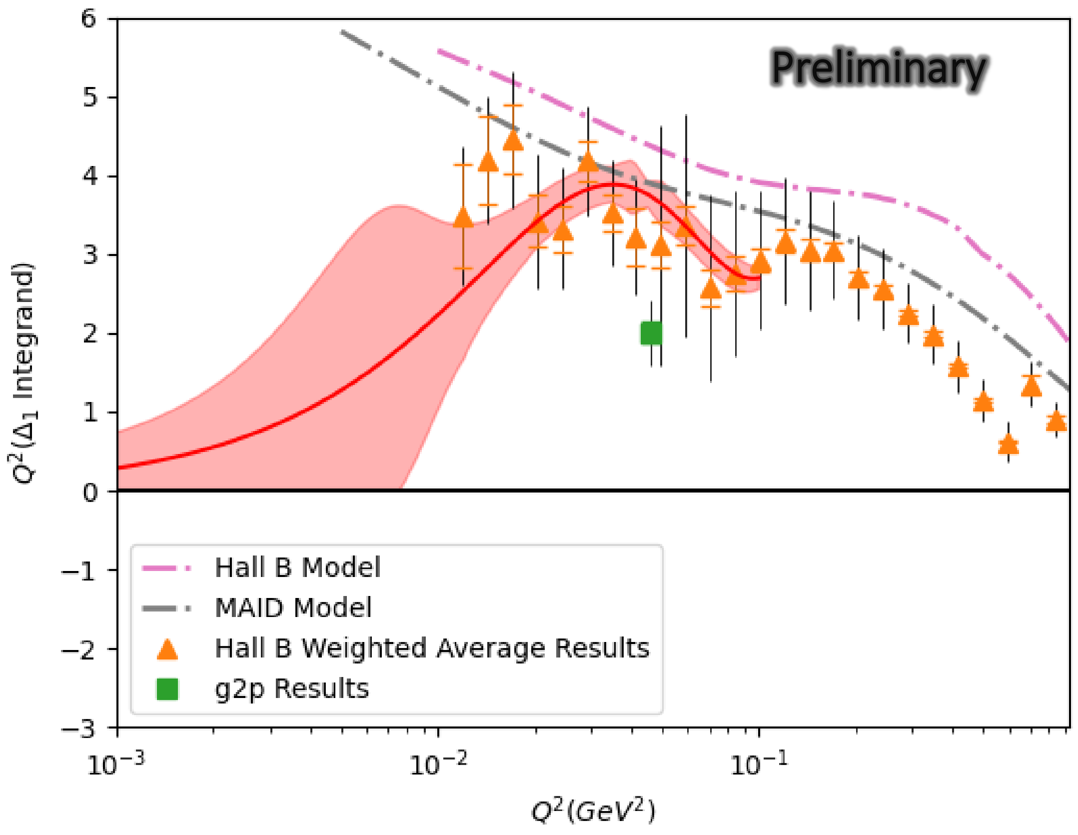
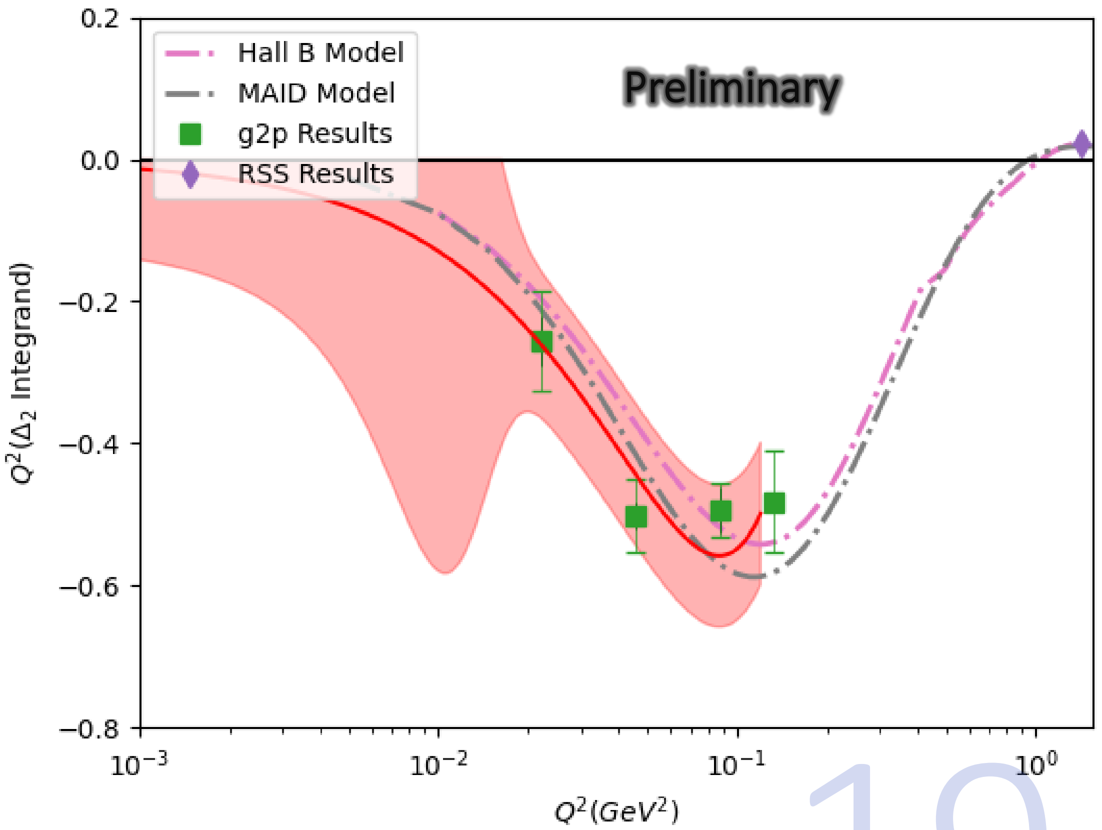




Low Q^2 Limit

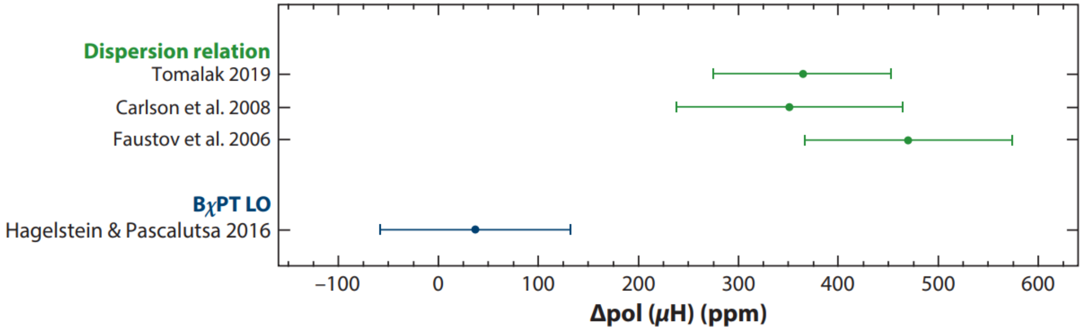
- Franziska Hagelstein and Vladimir Pascalutsa working with us to determine a constraint at Q^2 of 0
- Possible options include using static polarizability predictions to determine a value for the Deltas at $Q^2=0$, attempting to employ MAID's lowest Q^2 prediction
- Without such a constraint, the large extrapolation error bar shown combined with $1/Q^4$ weighting means the error below $Q^2=0.01$ is impossibly large
- Proceeding integrals are performed from $Q^2=0.01$ up

Muonic Hydrogen Hyperfine Contribution Results

- Integrate data where possible, and MAID above the region of the data
- Results does NOT include integral contribution below $Q^2 = 0.01\ GeV^2$

- $\Delta_1 = 12.44 \pm 3.65$
- $\Delta_2 = -1.38 \pm 0.23$
- $\Delta_{pol} = 516.502 \pm 170.92$ ppm

$$\Delta_{pol} = \frac{\alpha m_l}{\pi g_p M_p}(\Delta_1 + \Delta_2)$$



A. Antognini, F. Hagelstein, and V. Pascalutsa (2022)

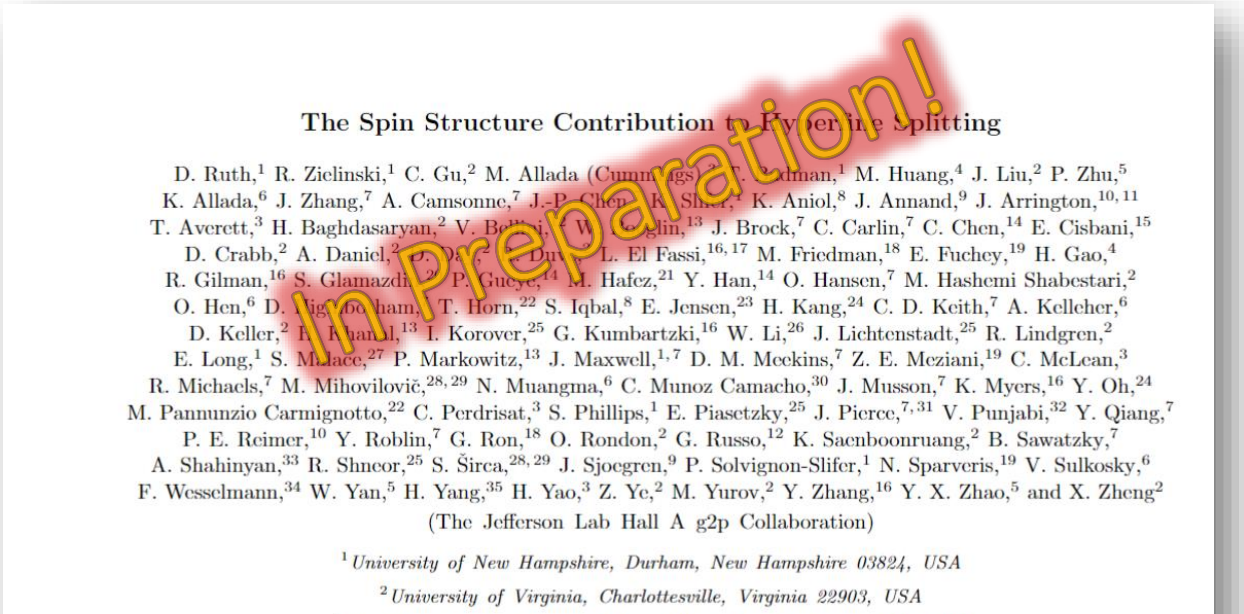
- Previous data-driven approaches were largely based on higher Q^2 data which relies on the assumption of leading twist
- However, this new result is compatible within error bars of these previous approaches
- Still unexplained tension with BχPT result

Hyperfine Structure Publication in preparataion

Paper is in preparation with the hope of submitting soon

Highlights polarizability contributions shown on previous slides

Any feedback or suggestions welcomed!!



The Spin Structure Contribution to Hyperfine Splitting

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Acknowledgements

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Chao Gu
Toby Badman
Melissa Cummings
Min Huang
Jie Liu
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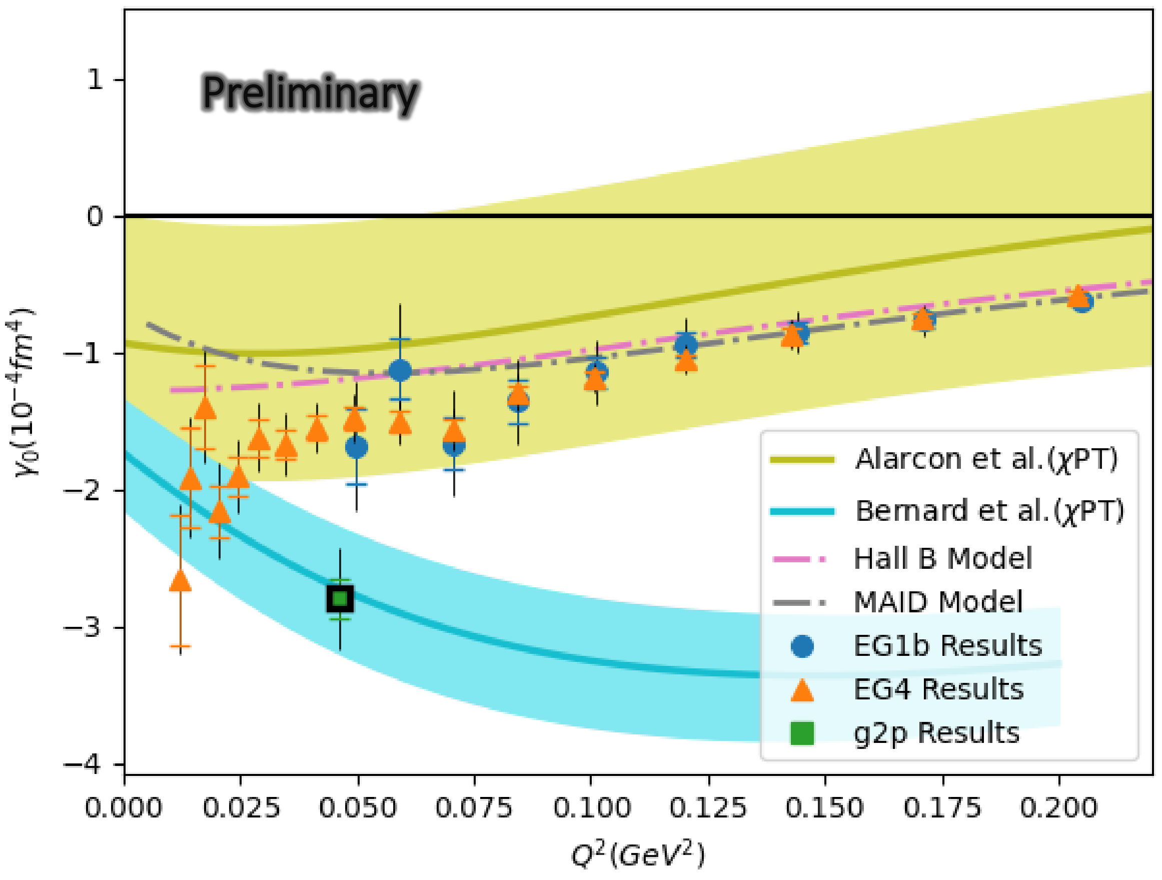
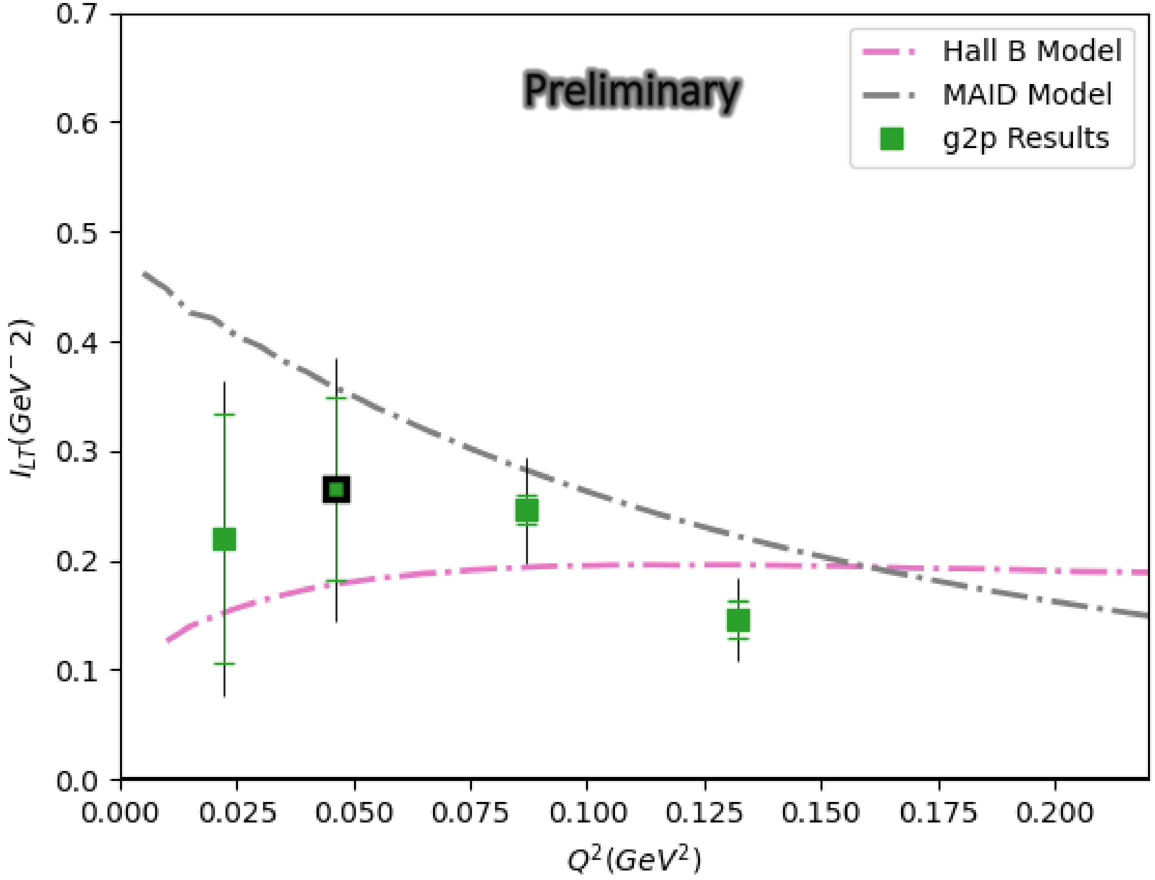
Extra Slide: Gamma0



Extra Slide: Schwinger Sum Rule



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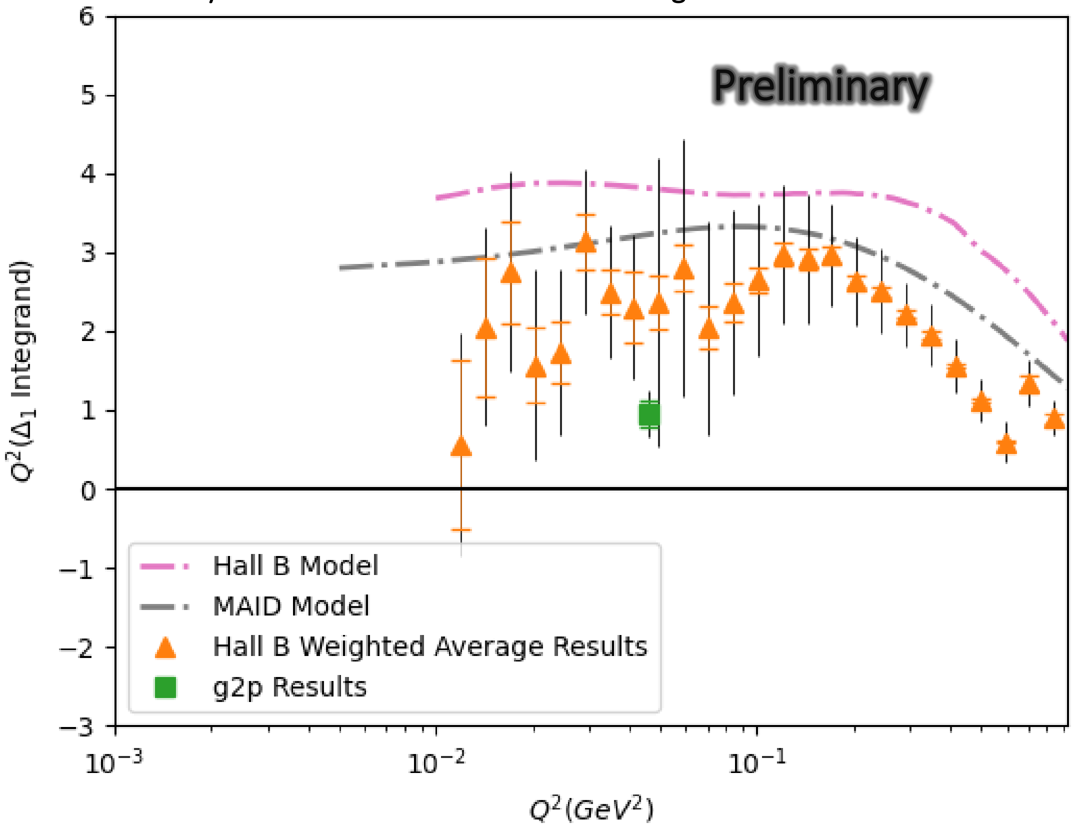

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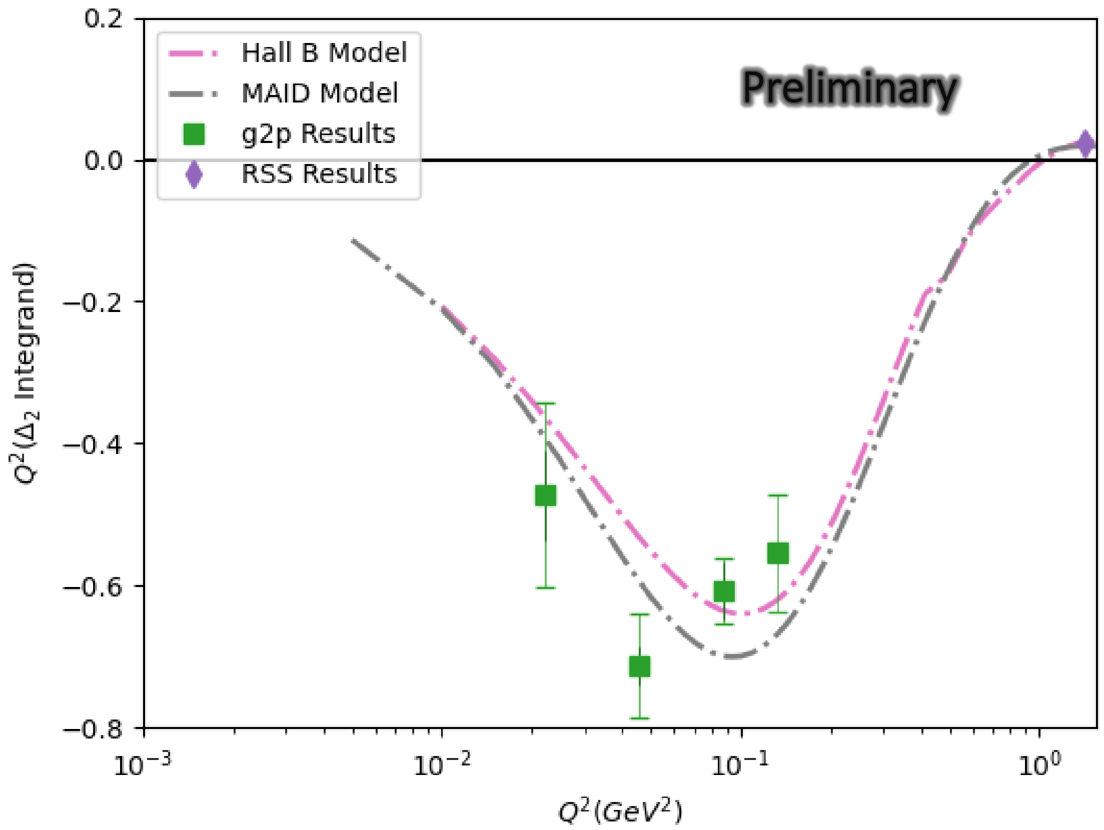

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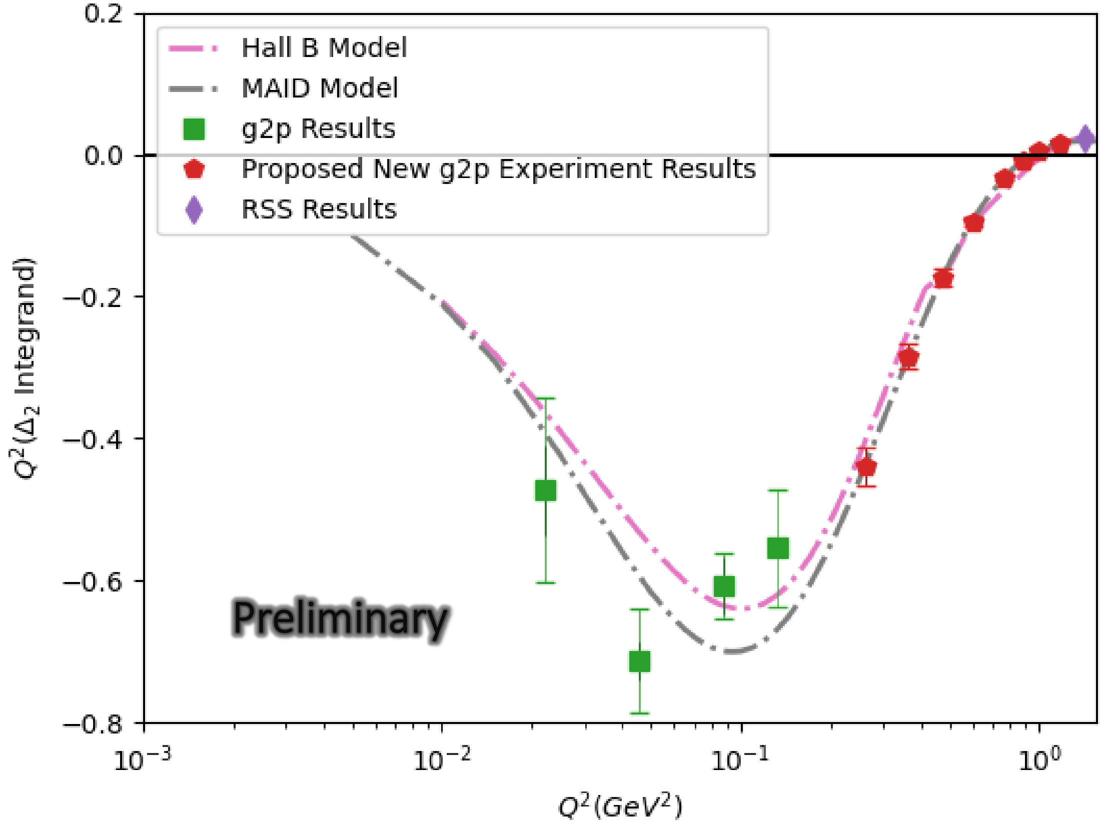
- Q^2 both above and below g2p contributes strongly to Δ_2

Proposal in Progress to Measure another relevant region of Δ_2



- In preparation for JLab PAC deadline next week with Karl Slifer, Jian-Ping Chen, and Nathaly Santiesteban
- Intend to propose transverse polarized target experiment in Hall C for $0.27\ GeV^2 < Q^2 < 1.1\ GeV^2$
- Please let us know if you are interested in being part of the proposal!!

Δ_1 Results (Fits)