The Proton's Spin Structure & Polarizabilities in the Strong QCD Regime

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A big thanks to the whole g2p collaboration!

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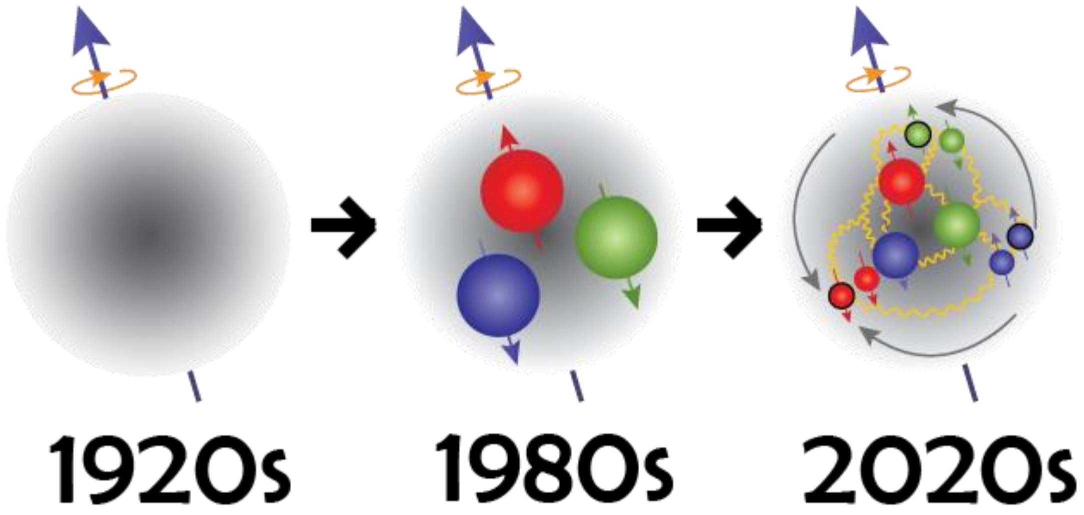
Goal: Measure a fundamental proton spin observable at low Q^2 for the first time



- Proton spin structure can be probed with a **structure function**
- Polarizabilities: a fundamental property which characterizes a nucleon's response to an external field
- Low Q^2 = Strong QCD
- Effective theories such as chiral perturbation theory describe QCD in this regime, but leading predictions disagree with each other & with nucleon data

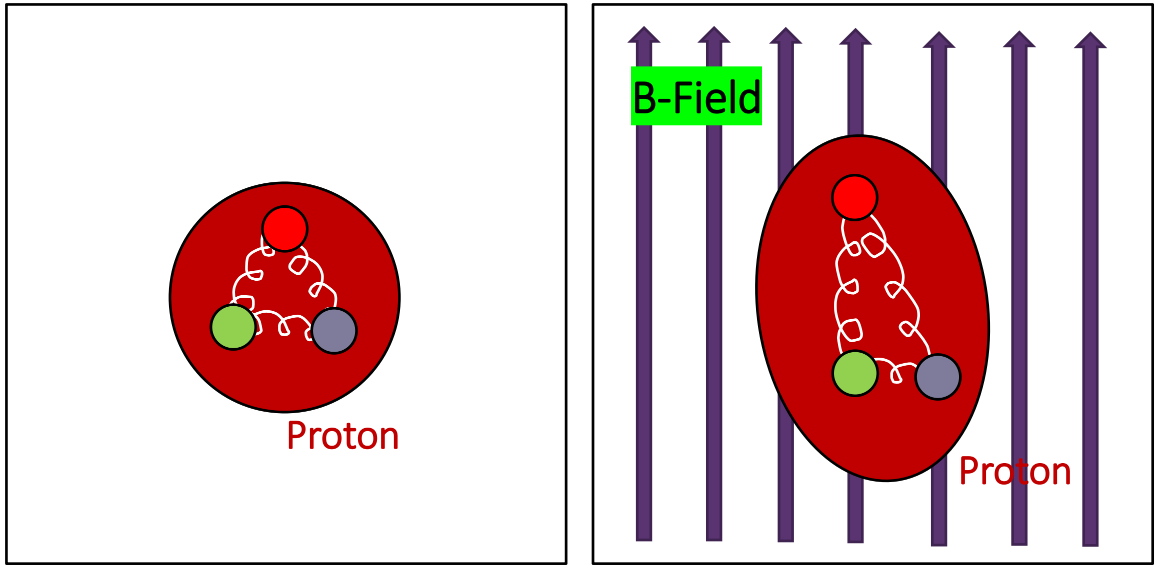
Polarizabilities show nucleonic response to external fields!

In an external field, all constituent particles are effected

Rather than trying to write equations of motion for each particle in the proton, a **polarizability** measures the collective response

Since constituents are beholden to strong force, polarizabilities are a direct consequence of QCD

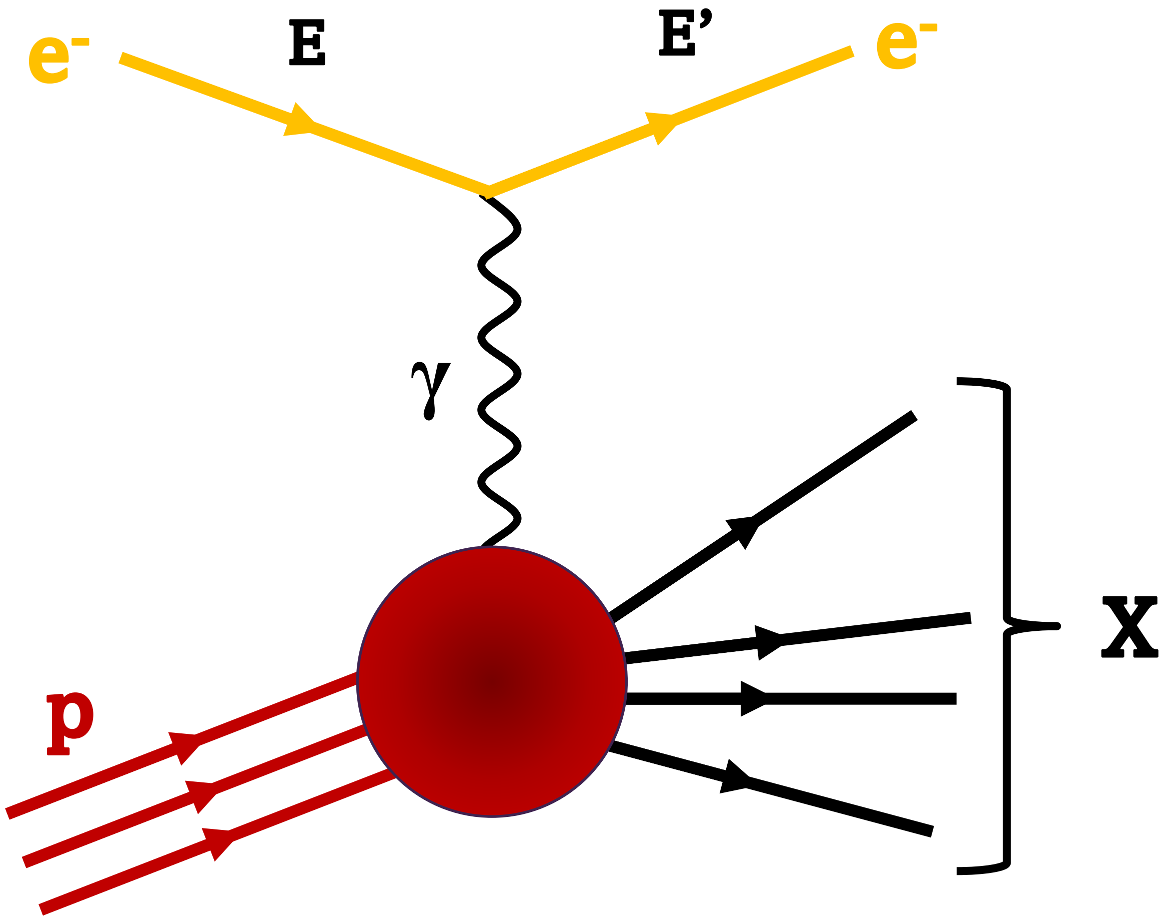
Essential nucleon property which can be predicted by effective theories of QCD!



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

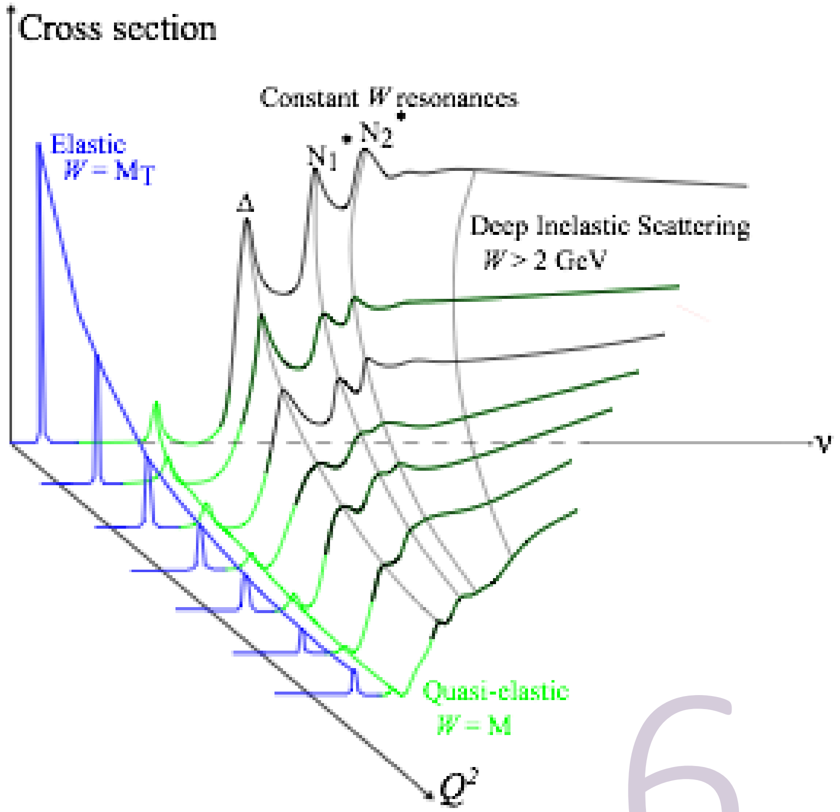
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\text{Mott}}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Structure functions F_1 and F_2 describe quark-gluon distribution

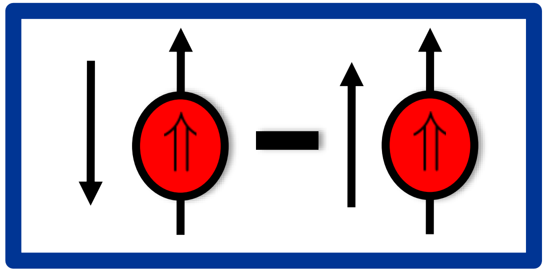
Inelastic Scattering <u>with polarized beam & target:</u>

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

g_1 and g_2 describe spin distribution & quark-gluon correlations

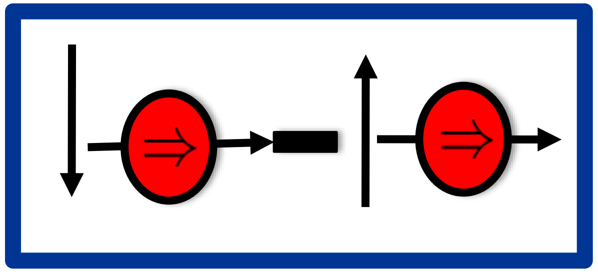


Extracting structure functions



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

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



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

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

Can solve for the structure functions

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

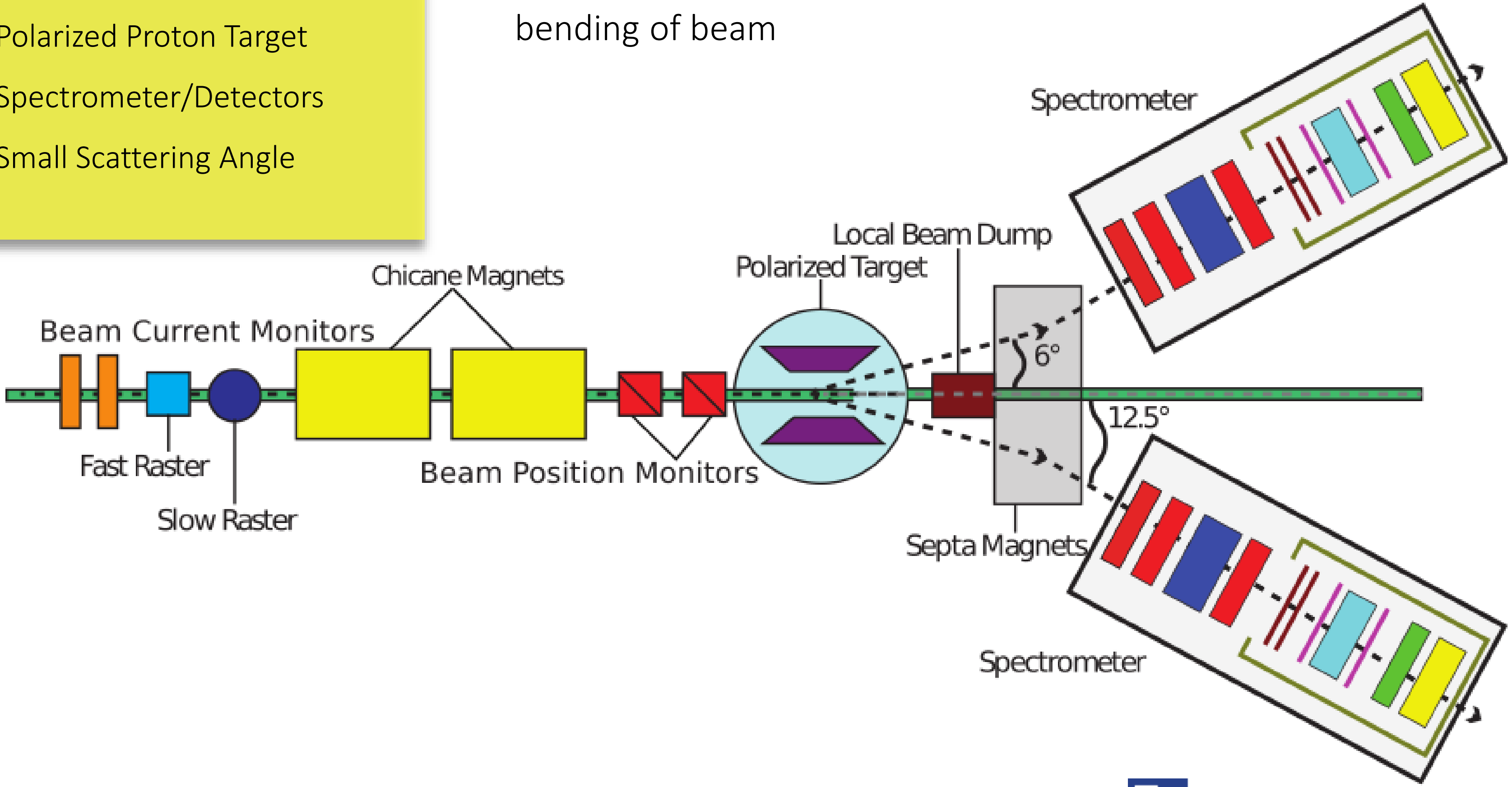
$\Delta\boldsymbol{\sigma}_{\perp}$ dominated by g_2

Hall A Experimental Setup:

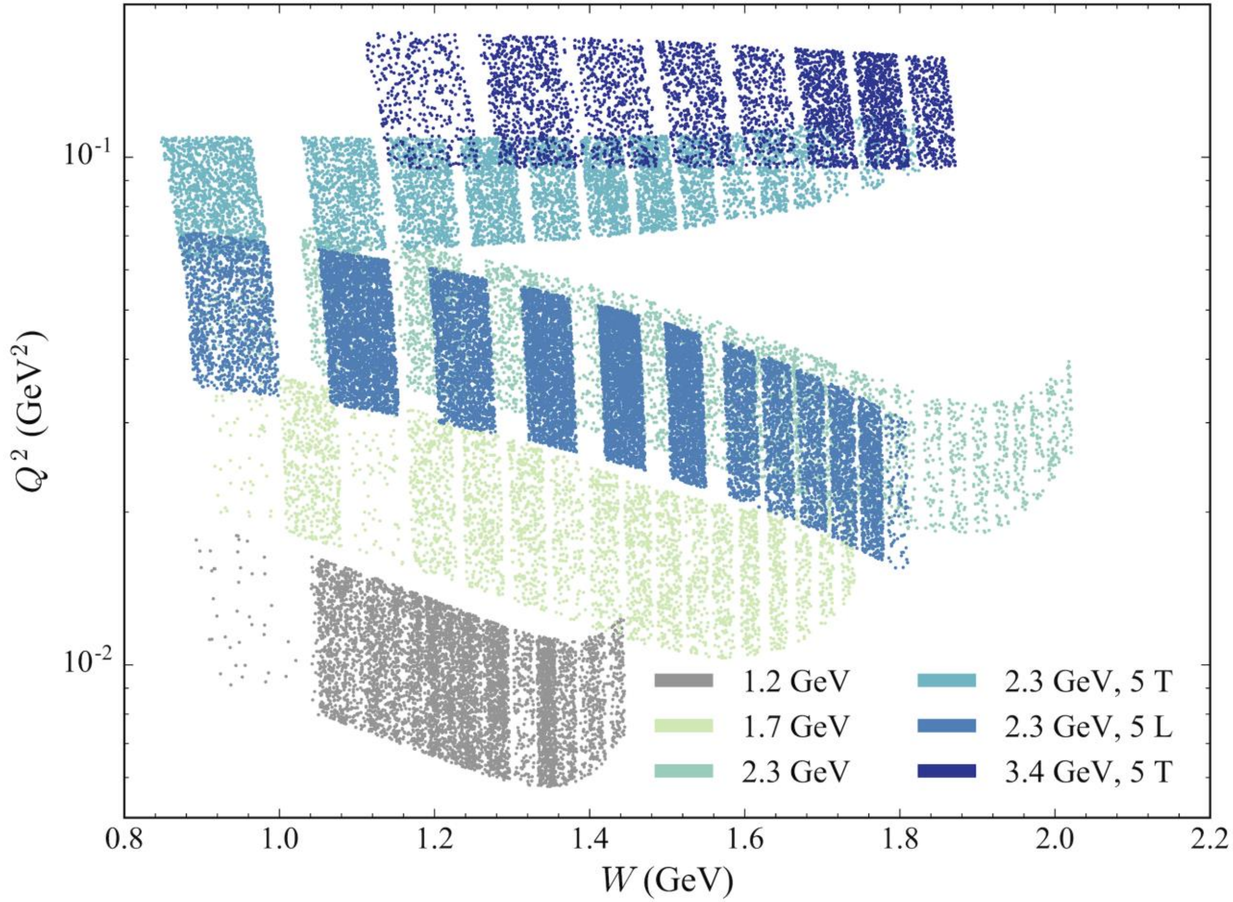
Measuring g_2^p

- 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



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

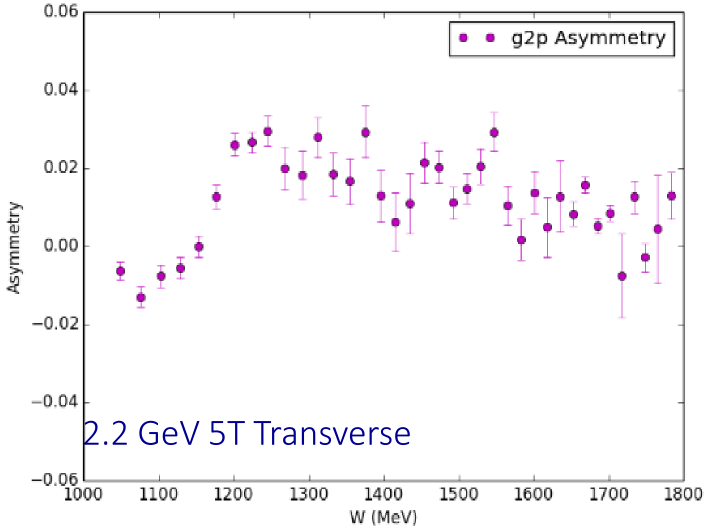
Asymmetries are easy because they cancel many quantities:

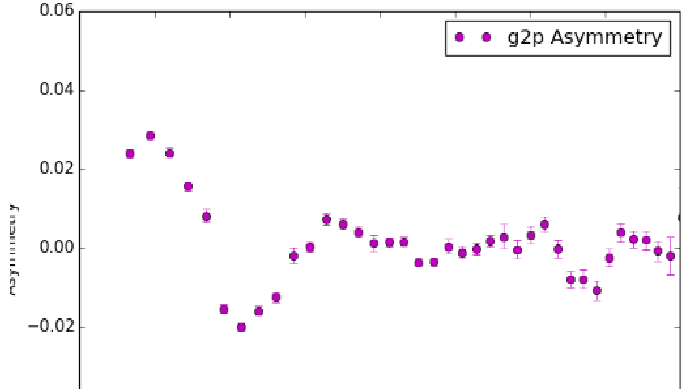
$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}}$$

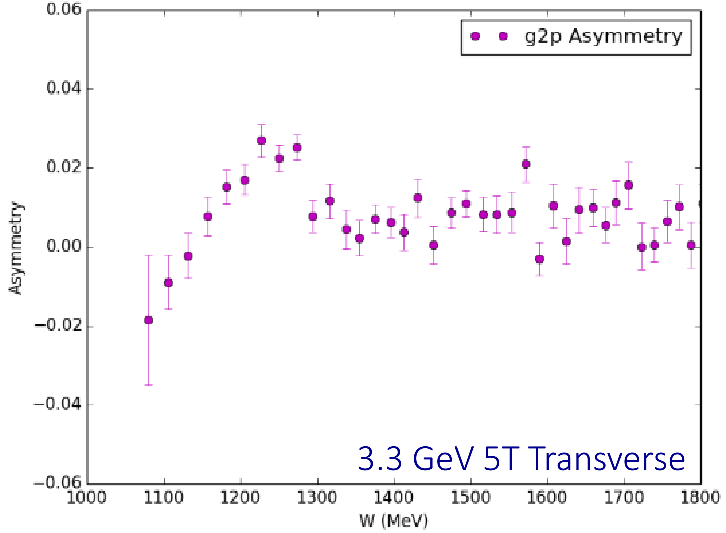
$$A^{\rm meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}, \qquad Y_{\pm} = \frac{N_{\pm}}{LT_{\pm}Q_{\pm}}$$

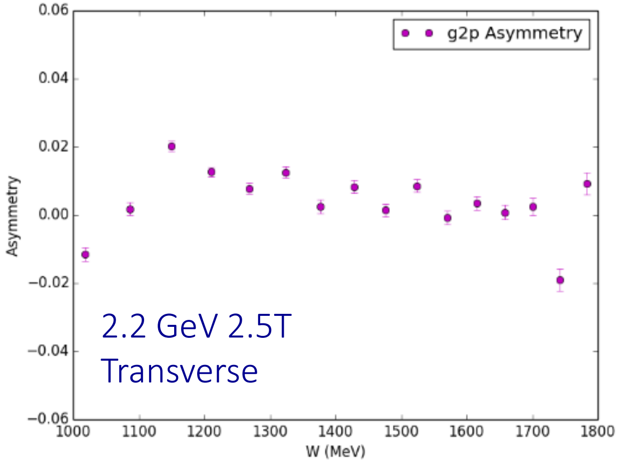
$$A^{\rm exp} = \frac{1}{f \cdot P_t \cdot P_b} A^{\rm raw}$$

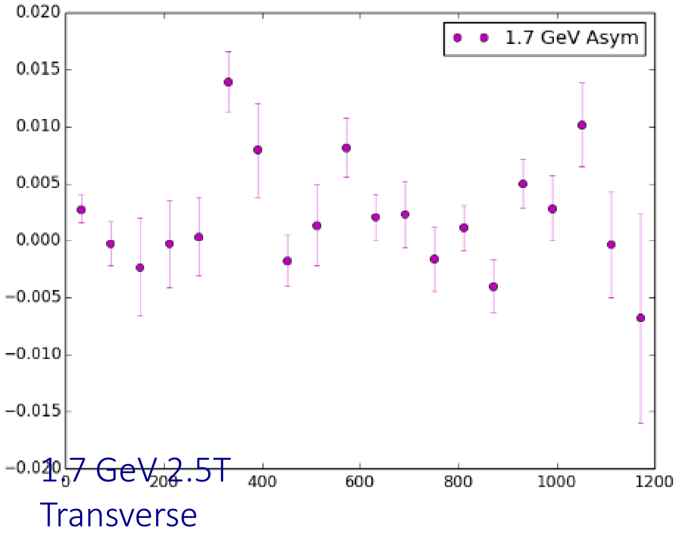
Asymmetry Results





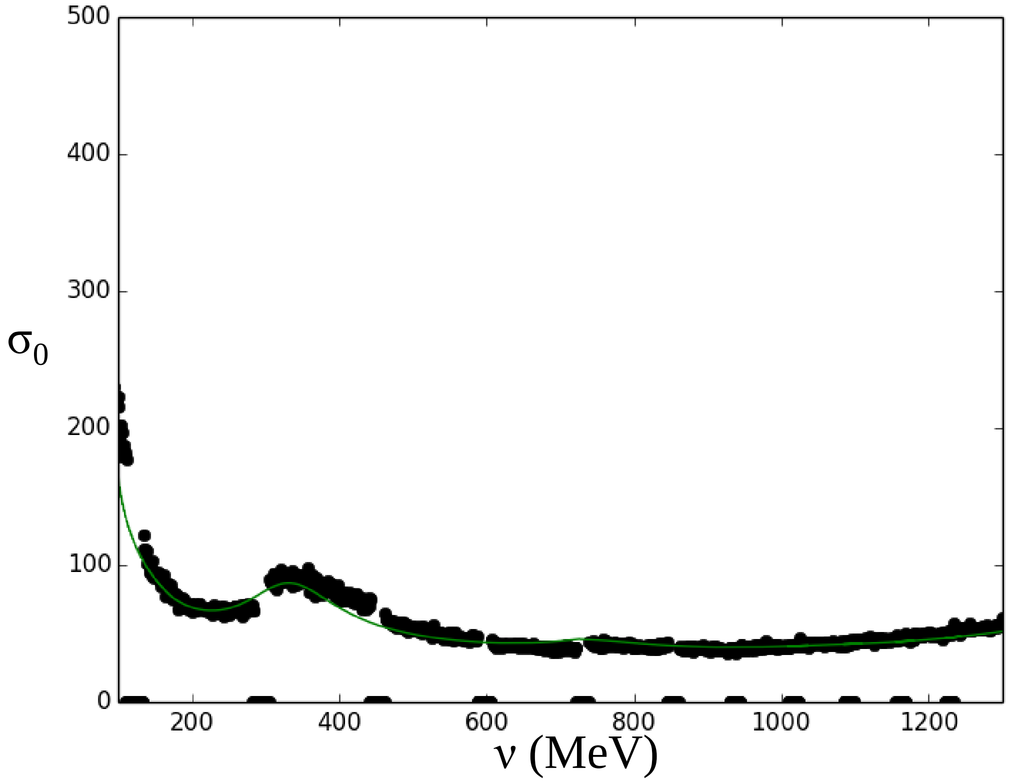






LHRS and RHRS combined for better statistics

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

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

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

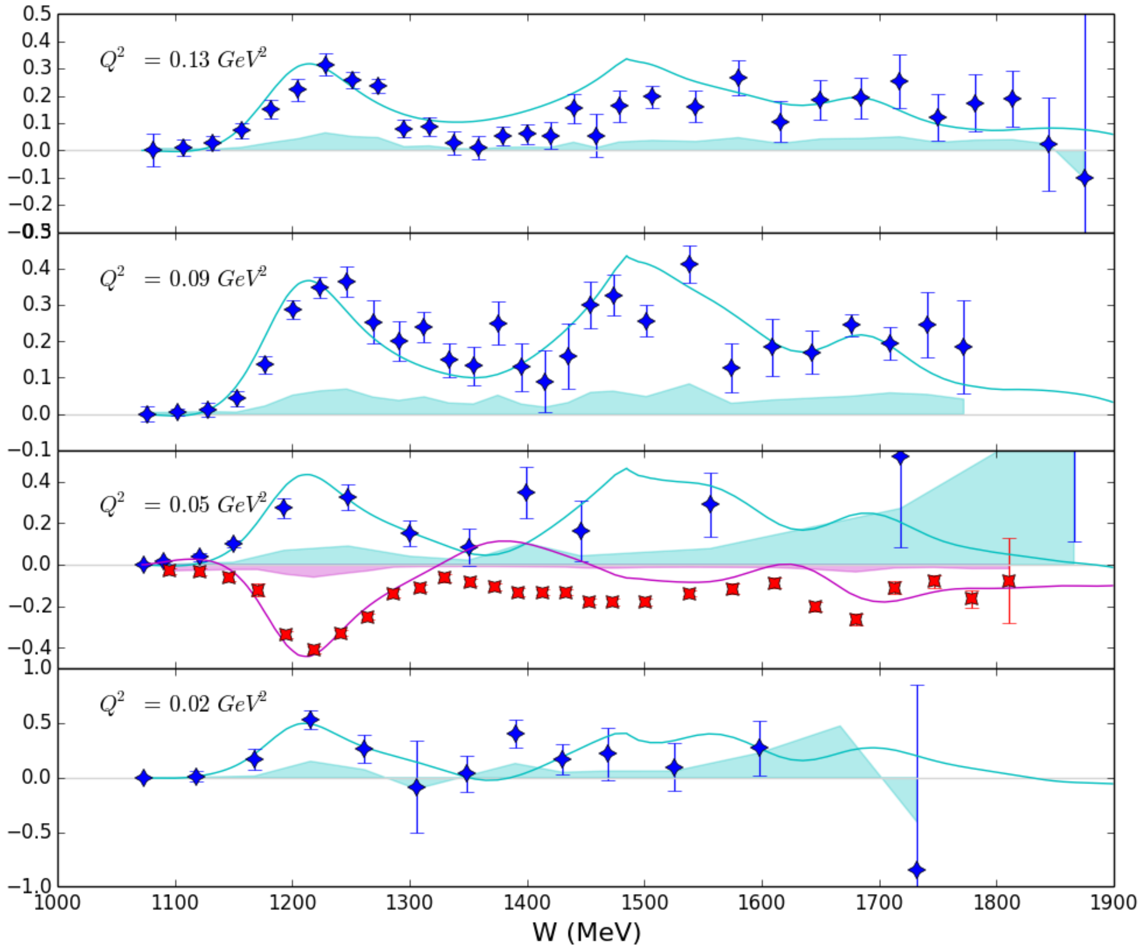
Input from Hall B model

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

Burkhardt-Cottingham Sum Rule

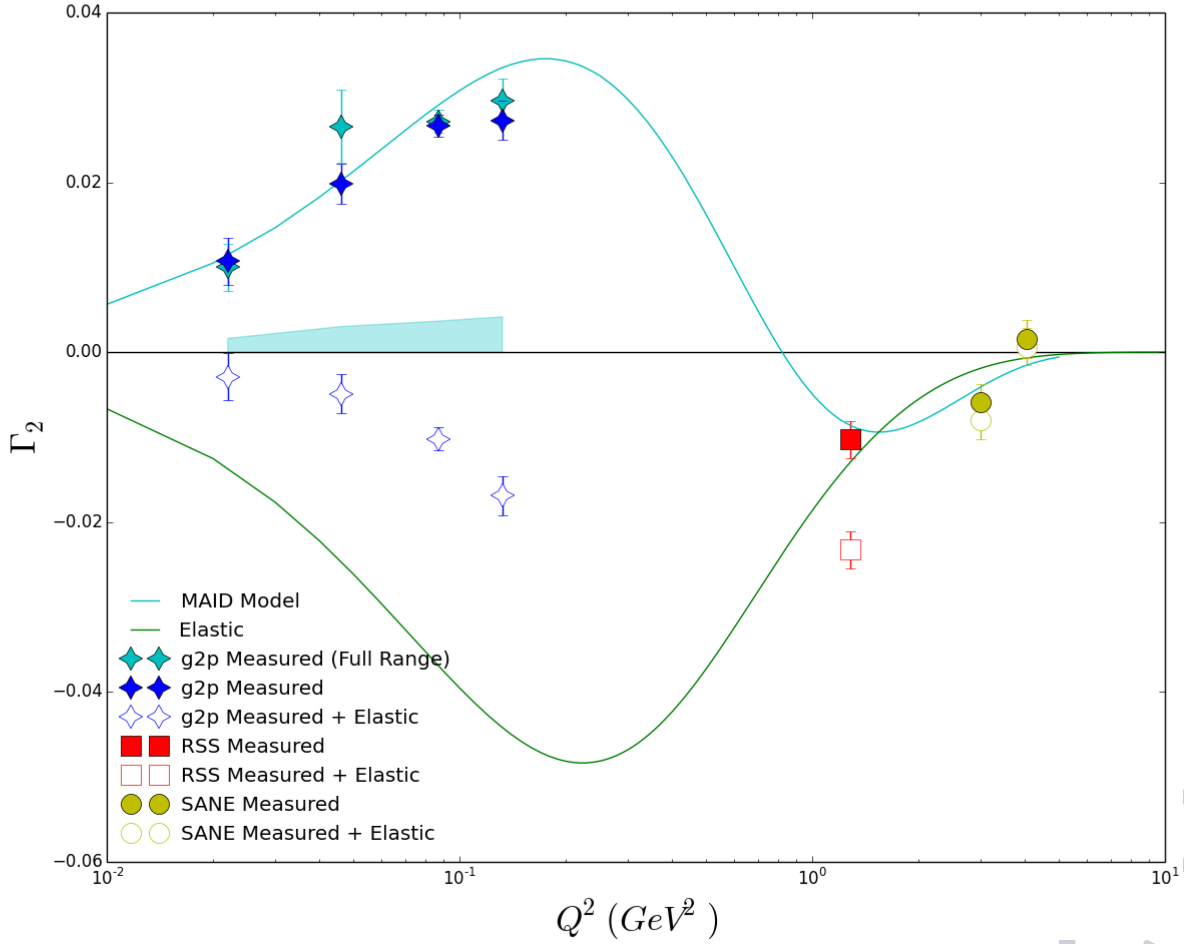
$$\Gamma_2 = \int_0^{x_{th}} g_2(x, Q^2)\,dx$$

At high Q^2, unmeasured low x_{bj} part is estimated with Wandzura-Wilczek g_2^{WW}

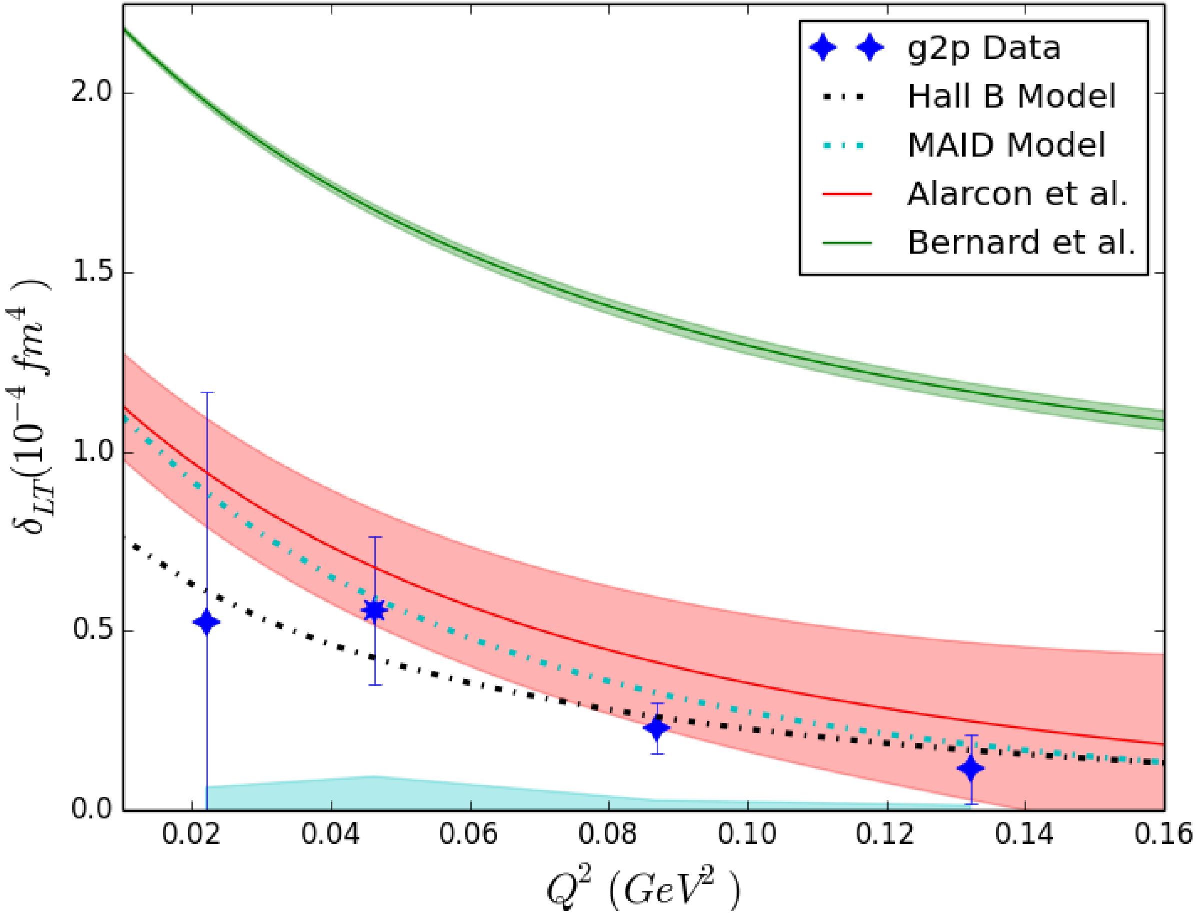
This method is not viable at low Q^2

However, lowest point approaches x coverage down to 0.001, so good fulfillment of B.C. sum rule

Need full estimate of unmeasured region to check agreement with the sum rule



Transverse-Longitudinal Spin Polarizability



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

A benchmark test of χPT because it was expected to be insensitive to the contribution of the Δ-resonance

Heavy Q^2 weighting causes lowest point to appear to have a large statistical error

Strong disagreement between theory and data for the neutron, but g2p results much closer for the proton

However, two different calculations disagree

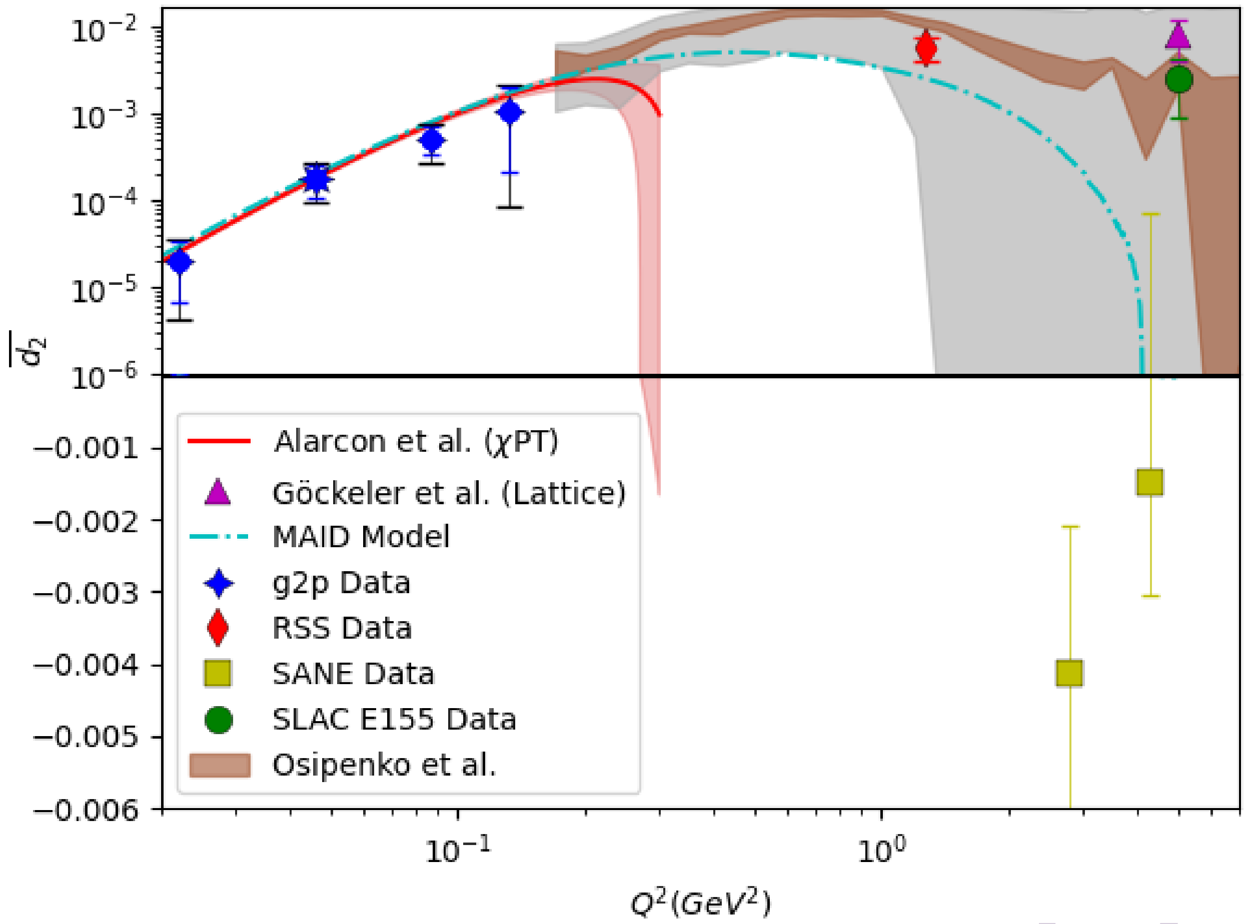
$\overline{d_2}$ Moment (Twist-3 Local Operator)

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

At high Q^2, moment becomes the d_2 matrix element, which is identified with a color polarizability. At low Q^2, it is a “pure polarizability”

Data agrees well with χPT calculation

Must vanish at Q^2 = 0 and ∞, giving it power in mapping the transition from the perturbative to non-perturbative regimes of QCD



First publication released in October!

nature physics

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

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Check for updates

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

Published!

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 better understanding of this strong quantum chromodynamics regime

First publication released <u>October 2022</u> in **Nature Physics!**

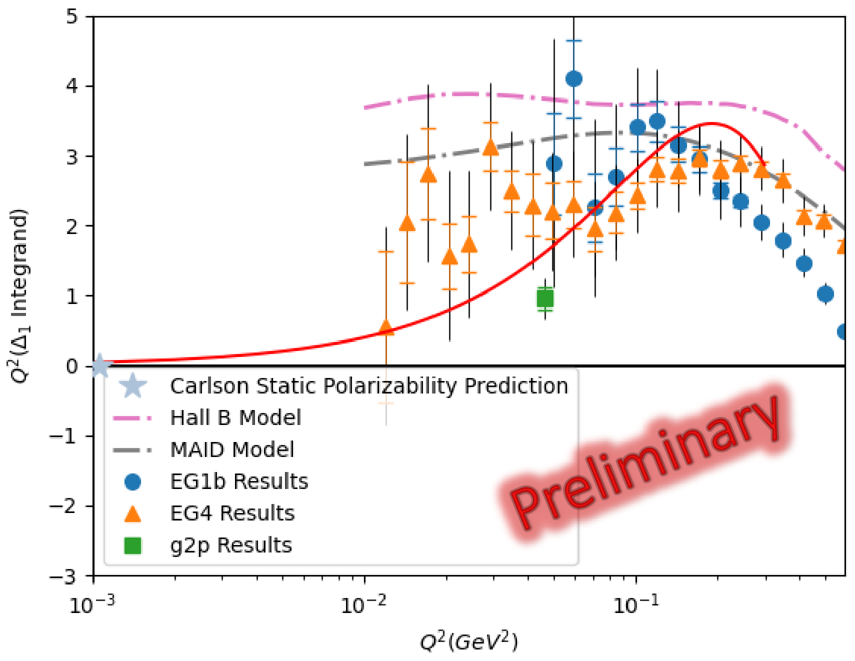
Highlights g_2 results as well as the δ_{LT} and $\overline{d_2}$ moments

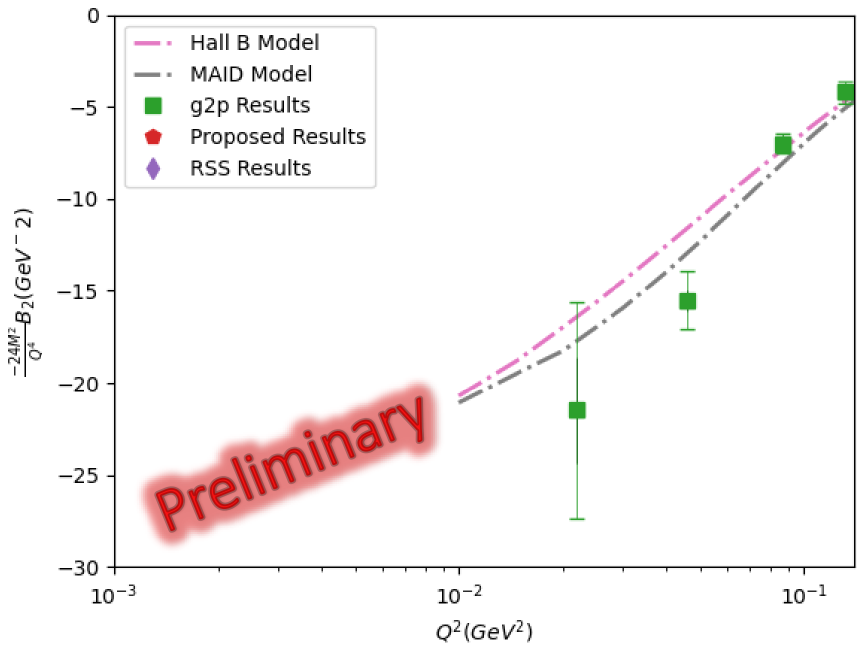
https://www.nature.com/articles/s41567-022-01781-y

Hyperfine Structure Analysis In Progress...

Hyperfine interaction of the hydrogen atom experimentally measured more than 1e6 times more precisely than current theory calculations

Biggest uncertainty in modern theory calculations comes from the polarizabilities!





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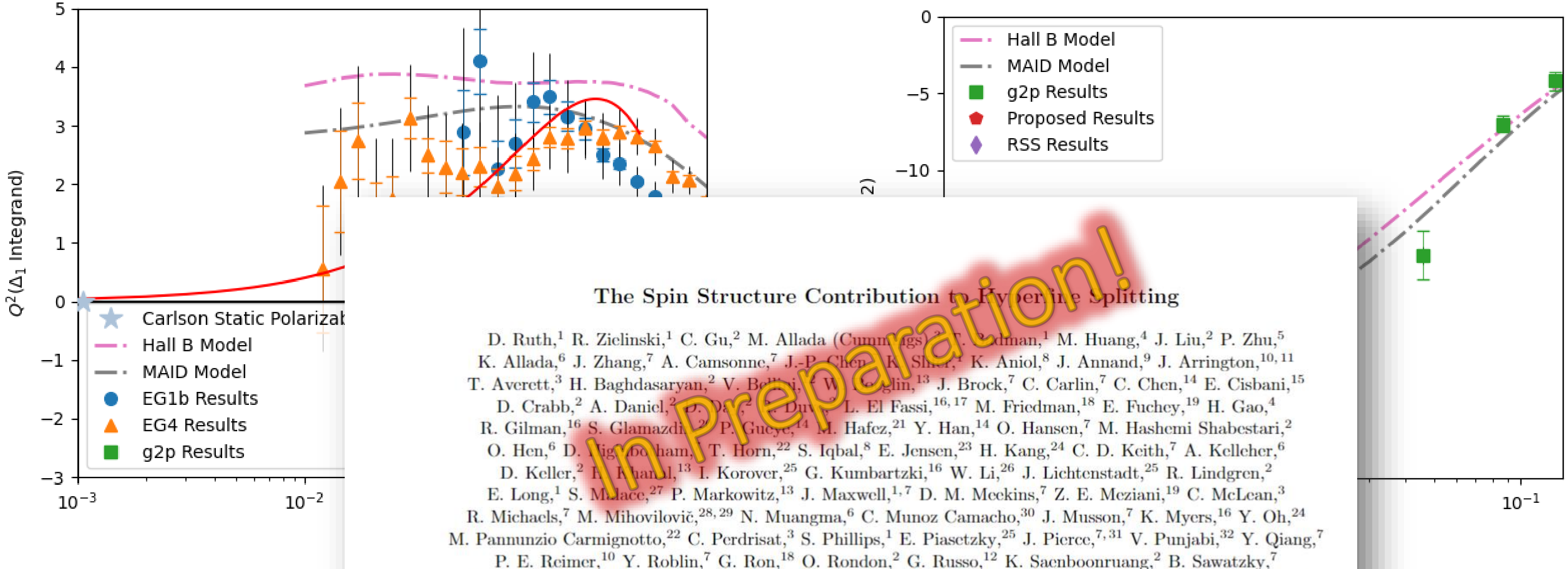

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References

R. Zielinski, The g2p Experiment: A Measurement of the Proton's Spin Structure Functions, Ph.D. thesis, University of New Hampshire (2017), arXiv:1708.08297 [nucl-ex].

C. Gu. The Spin Structure of the Proton at Low Q2: A Measurement of the Structure Function g2p. PhD thesis, University of Virginia, 2016.

X. Zheng, A. Deur, H. Kang, et al., Nature Physics, 17, 736 (2021).

V. Sulkosky, C. Peng, J. Chen, et al., Nature Physics, 17, 687 (2021).

J. M. Alarcón, F. Hagelstein, V. Lensky, and V. Pascalutsa, Phys. Rev. D, 102, 114026 (2020).

V. Bernard, E. Epelbaum, H. Krebs, and U.-G. Meissner, Phys. Rev. D, 87, 054032 (2013).

M. E. Christy and P. E. Bosted, Phys. Rev. C, 81, 055213 (2010).

J. Alcorn et al. Basic Instrumentation for Hall A at Jefferson Lab. Nucl. Instrum. Meth., A522:294–346, 2004.