Exploring the Transition Region of QCD with the Proton's g_2 Structure Function

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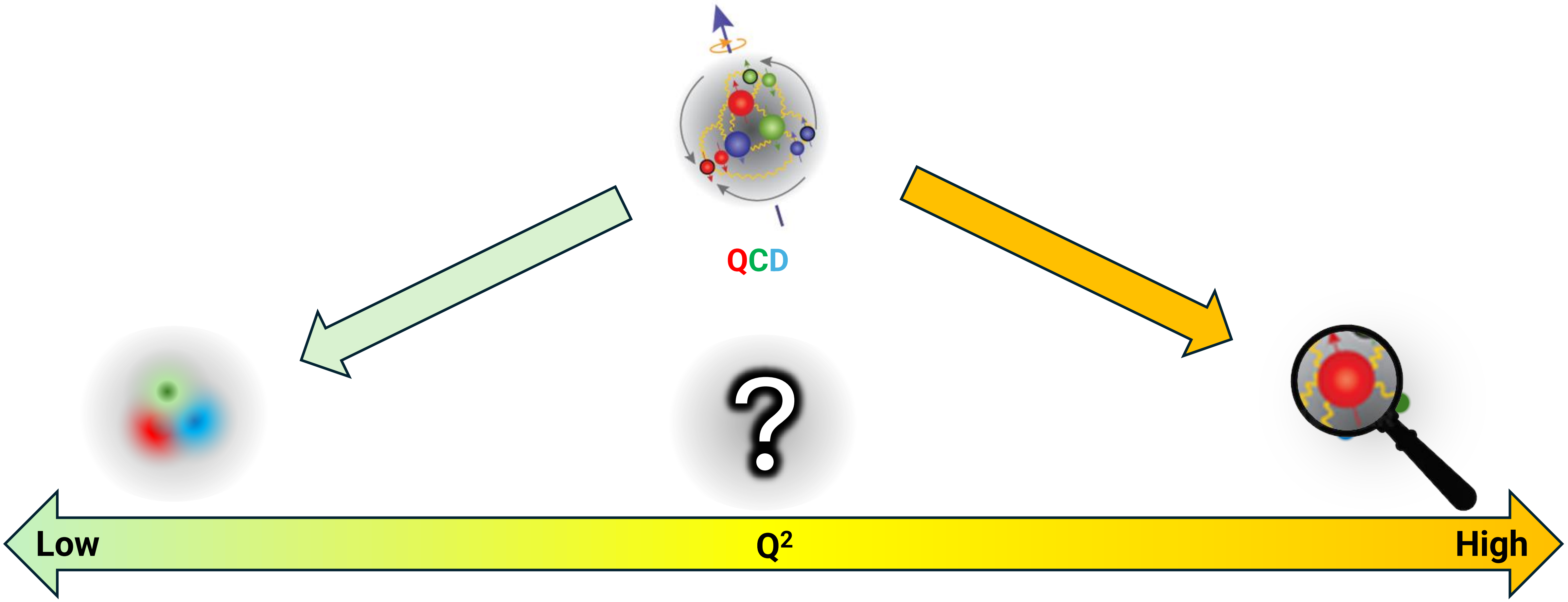
APS Topical Group on Hadronic Physics
14 March, 2025

David Ruth



- Partons Combine to Form Nucleon
- Confinement
- Effective Theories: χPT
- Can't use Twist Approx.

- Quark/Gluon Correlations
- Lattice QCD
- Higher Twists

- Individual Partons
- Asymptotic Freedom
- Perturbative QCD
- Leading Twist

How to study QCD and higher twist in the transition region?

- In unpolarized systems, F_1 and F_2 structure functions describe the quark-gluon distribution of a hadron in inelastic scattering:

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

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

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

Nucleon Spin Structure ($\gamma g_1(x,Q^2)$)

Quark-Gluon Correlations ($\delta g_2(x,Q^2)$)

g_2 Structure Function enables direct tests of QCD and higher twist

- **Higher Twist:**

Small

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) - \int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

Function of g_1

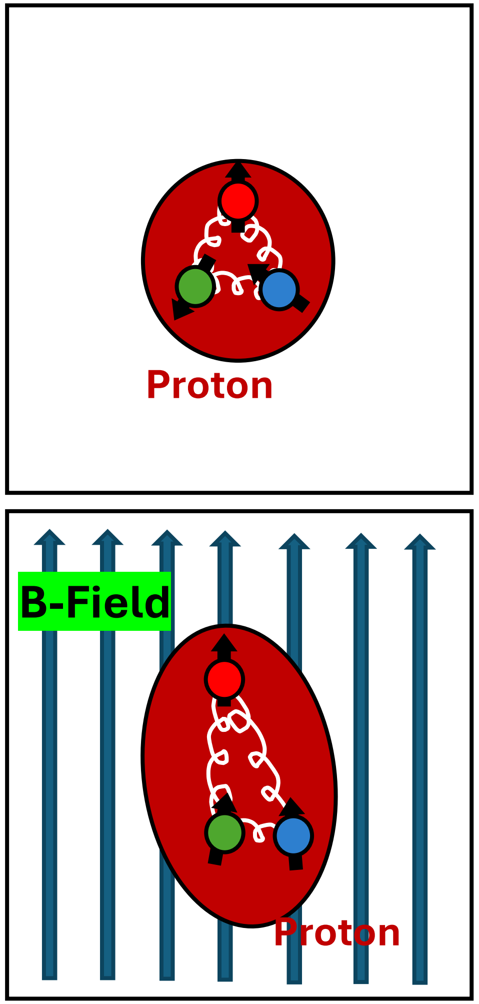
Twist-3

- **Benchmarking (Lattice) QCD:**

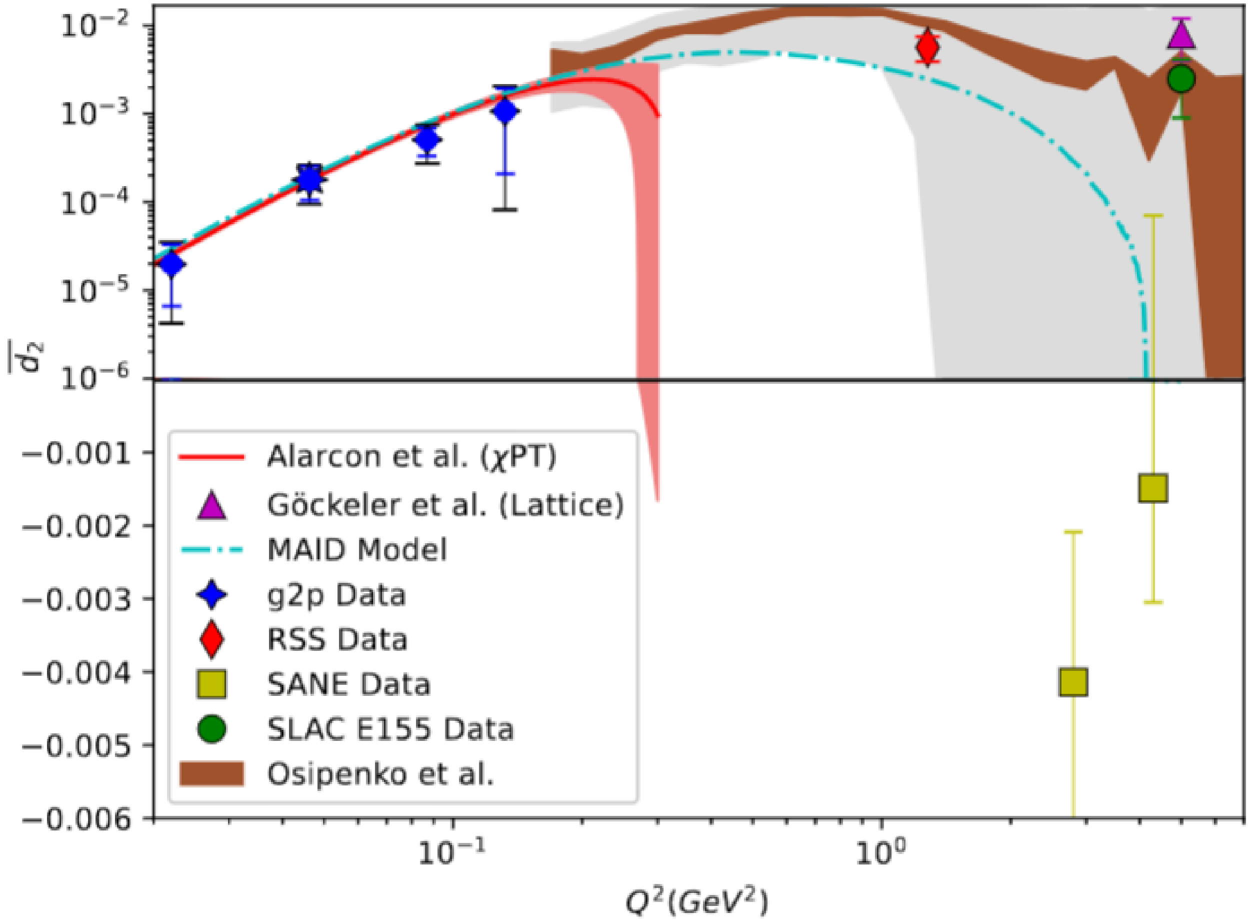
Weighted integrals (moments) of the spin structure functions can be directly calculated by effective theories:

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

These polarizabilities describe the nucleon's ensemble response to an external field



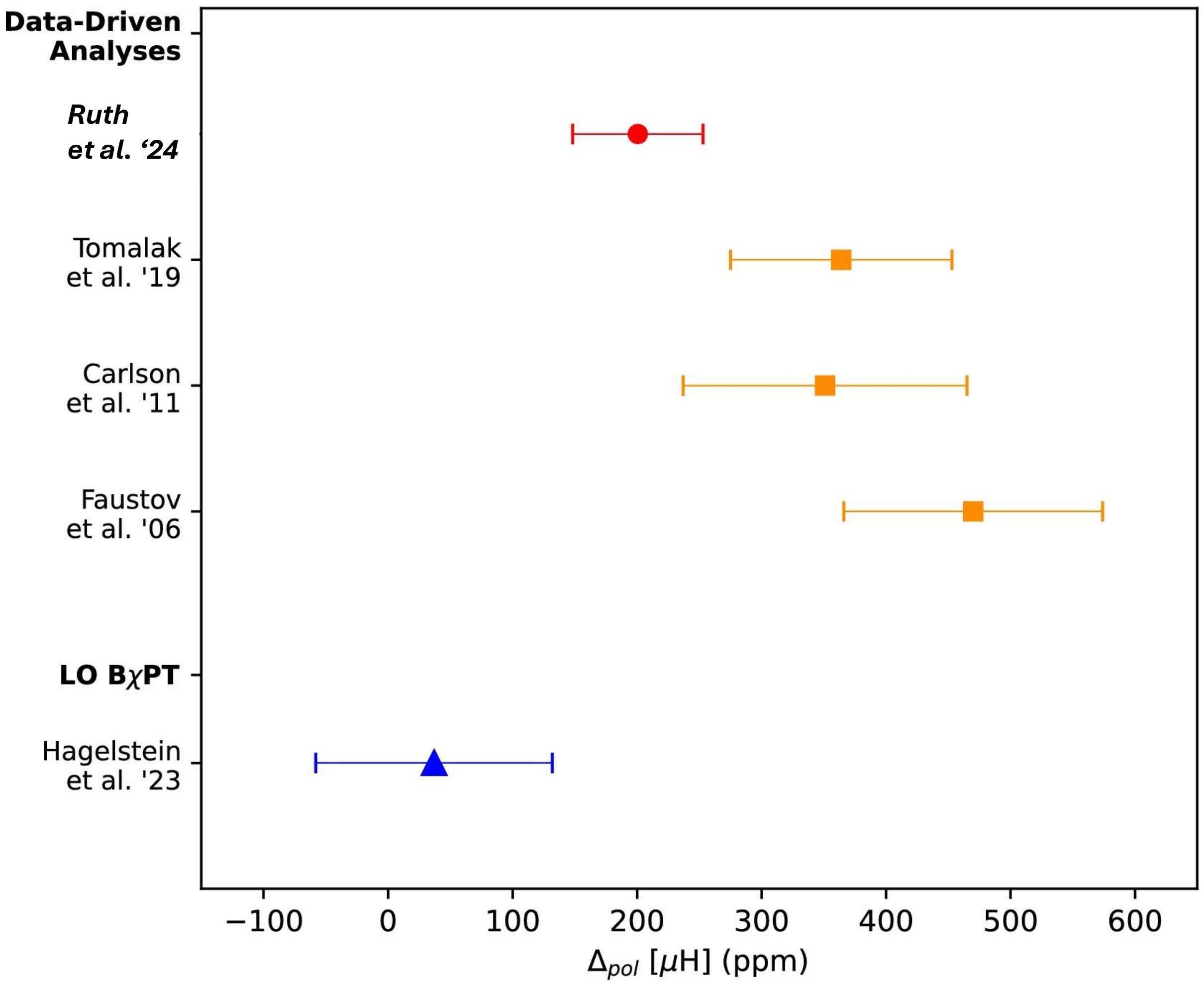
"Color Polarizability" d_2



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

- At high Q^2, identified as a color polarizability or "color Lorentz force"
- Interesting negative result from SANE motivates further study at high Q^2
- Maxima and zero crossing of d_2 are in the unmeasured region
- Upcoming lattice predictions in this region need an experimental benchmark!

Hyperfine Contribution



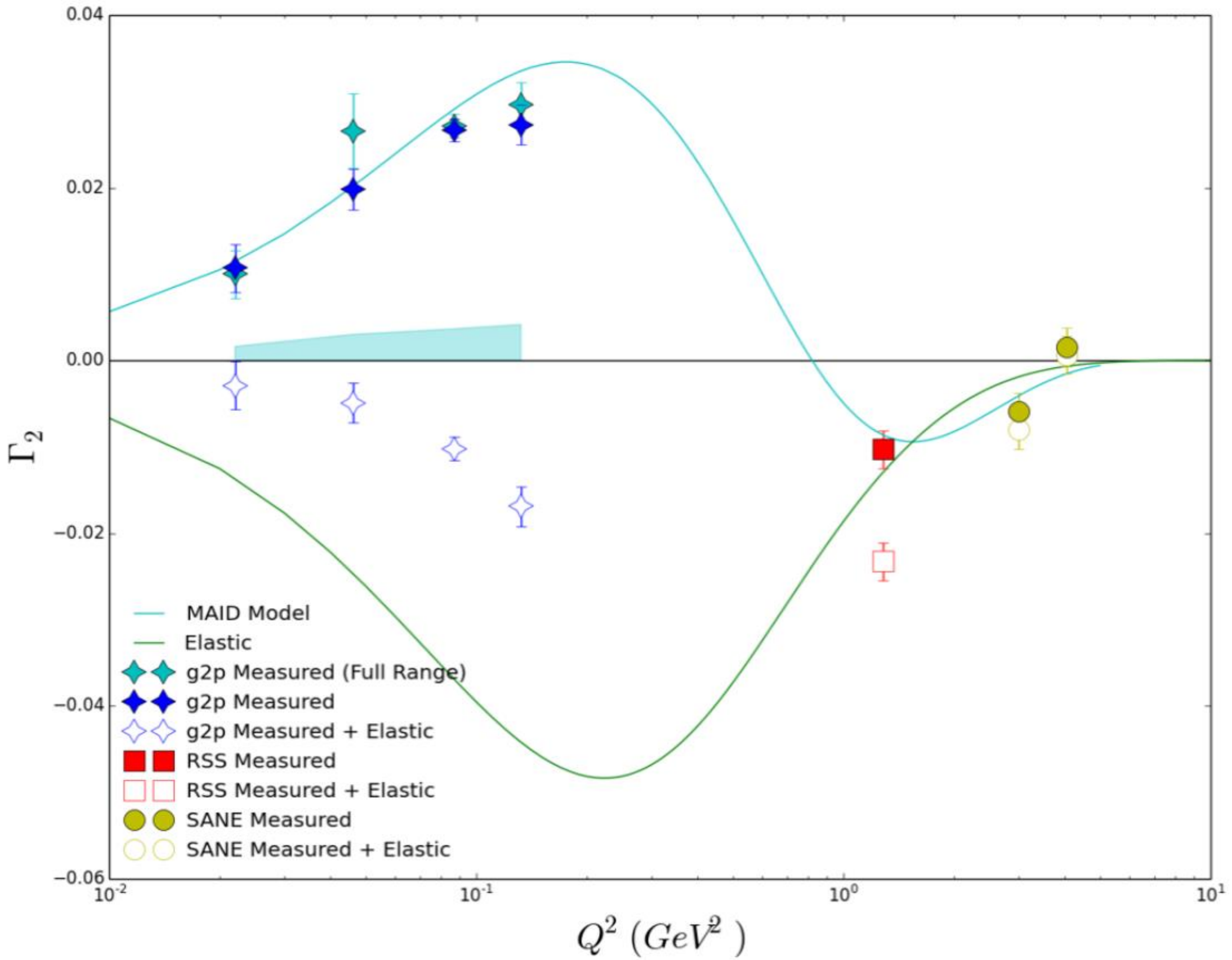
$$\Delta_{pol} = \frac{\alpha\, m_l}{2\pi\,(1+\,\kappa_P)M_p}(\Delta_1 + \Delta_2)$$

$$\Delta_2 = -24M_p^2 \int_0^{\infty} \frac{dQ^2}{Q^4} \int_0^{x_{th}} \widetilde{\beta_2}(x, Q^2)\mathrm{g}_2(\mathrm{x}, \mathrm{Q}^2)\,dx$$

- The leading error in theoretical calculations of the hydrogen HFS comes from these spin-structure function dependent integrals!
- The subject of an ongoing tension between theory and experiment

- The transition region accounts for ~30% of the integral!

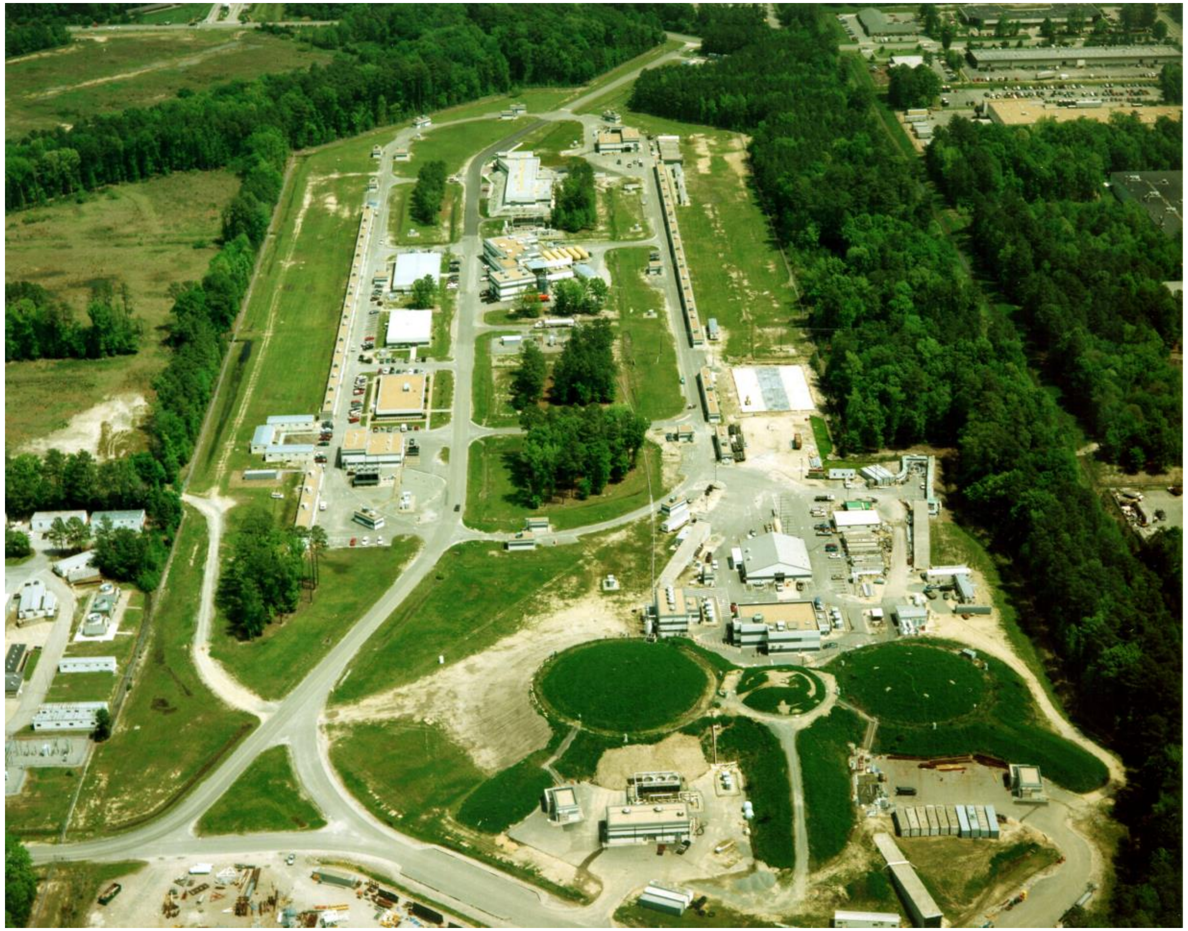
Γ_2 Moment & Burkhardt-Cottingham (BC) Sum rule



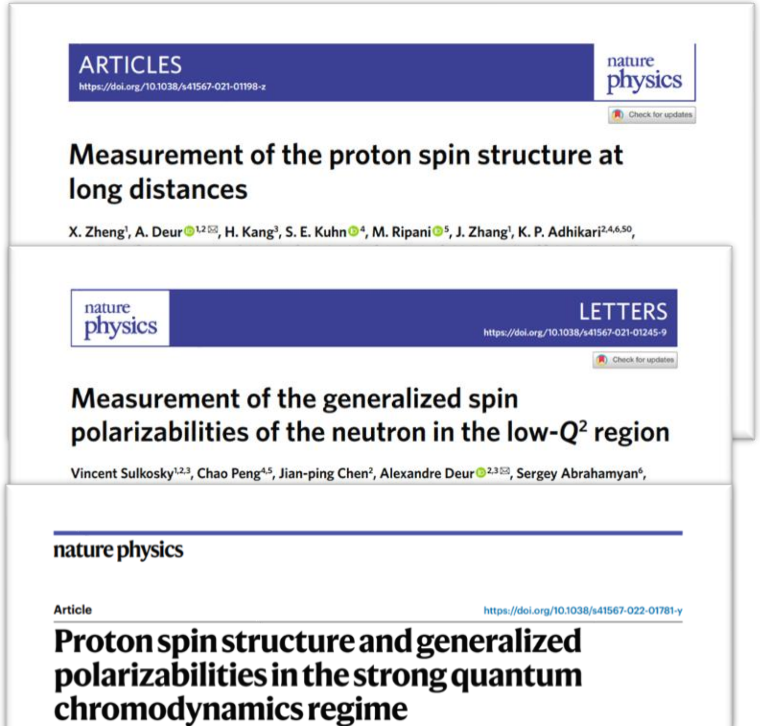
$$\Gamma_2 = \int_0^{x_{th}} g_2(x, Q^2)\,dx = 0$$

- Resonance part of moment crosses zero in transition region
- More transition data needed to understand low-x contribution as leading twist starts to fail

Highly Successful Program Measuring SSF at the Thomas Jefferson National Accelerator



- JLab has led a highly successful program to measure the spin structure functions (SSF) for both nucleons over a broad kinematic range
- Three different experiments published recent SSF results in Nature Physics
- DOE Milestone to "measure g_1 and g_2 over an enlarged range of x and Q^2"



ARTICLES
https://doi.org/10.1038/s41567-021-01198-z
nature physics
Check for updates

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],

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],

nature physics

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

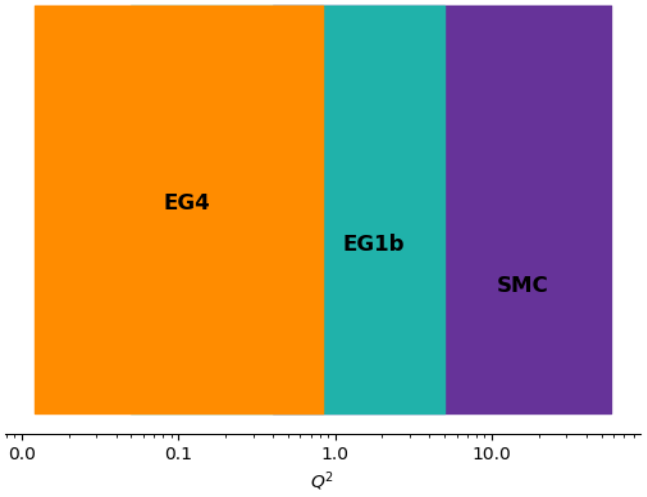
Proton spin structure and generalized polarizabilities in the strong quantum chromodynamics regime

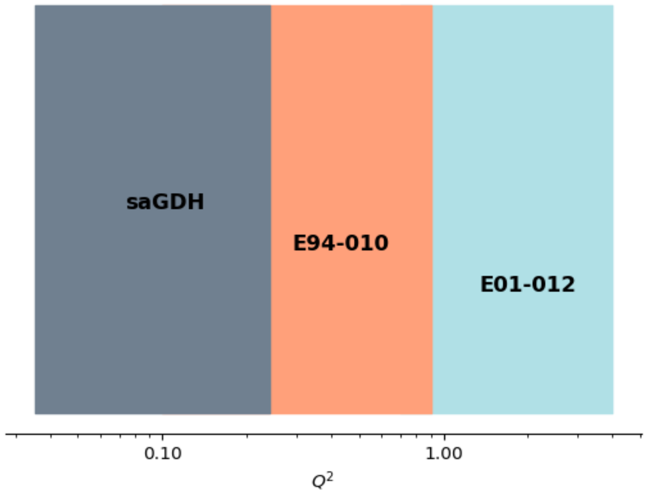
Existing Coverage

Proton

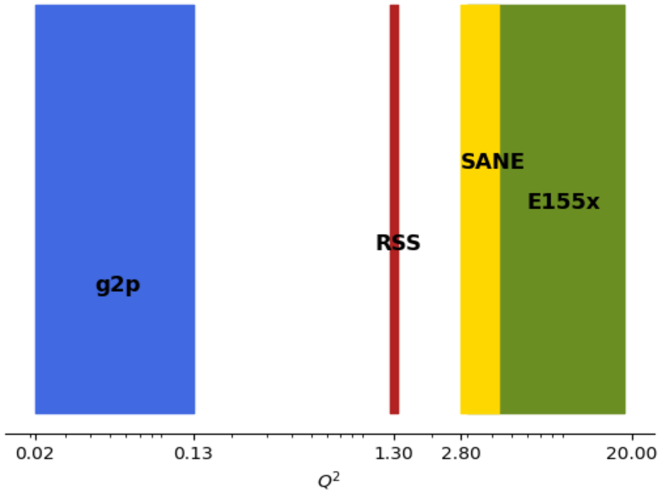
Neutron

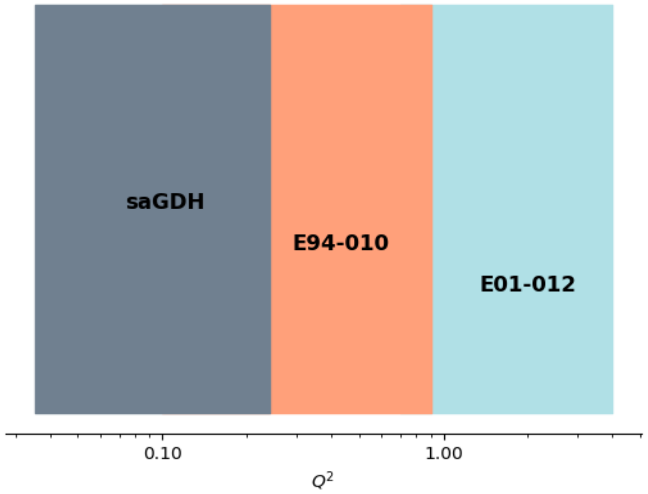
g_1





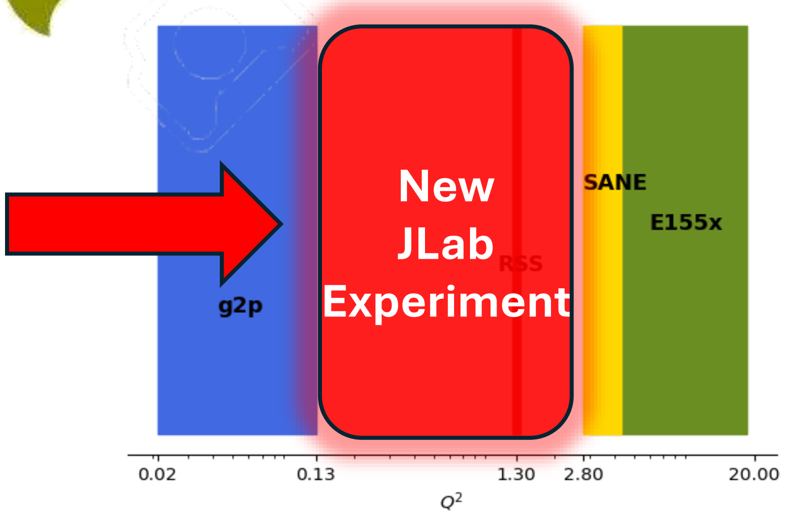
g_2





“Low Hanging Fruit”

- **<u>Much higher rates</u>** than the higher Q^2 experiments
- **<u>No need for a septum magnet</u>** as was used in the low Q^2 g2p experiment in Hall A
- **<u>Smaller out-of-plane angle</u>** than the low Q^2 data

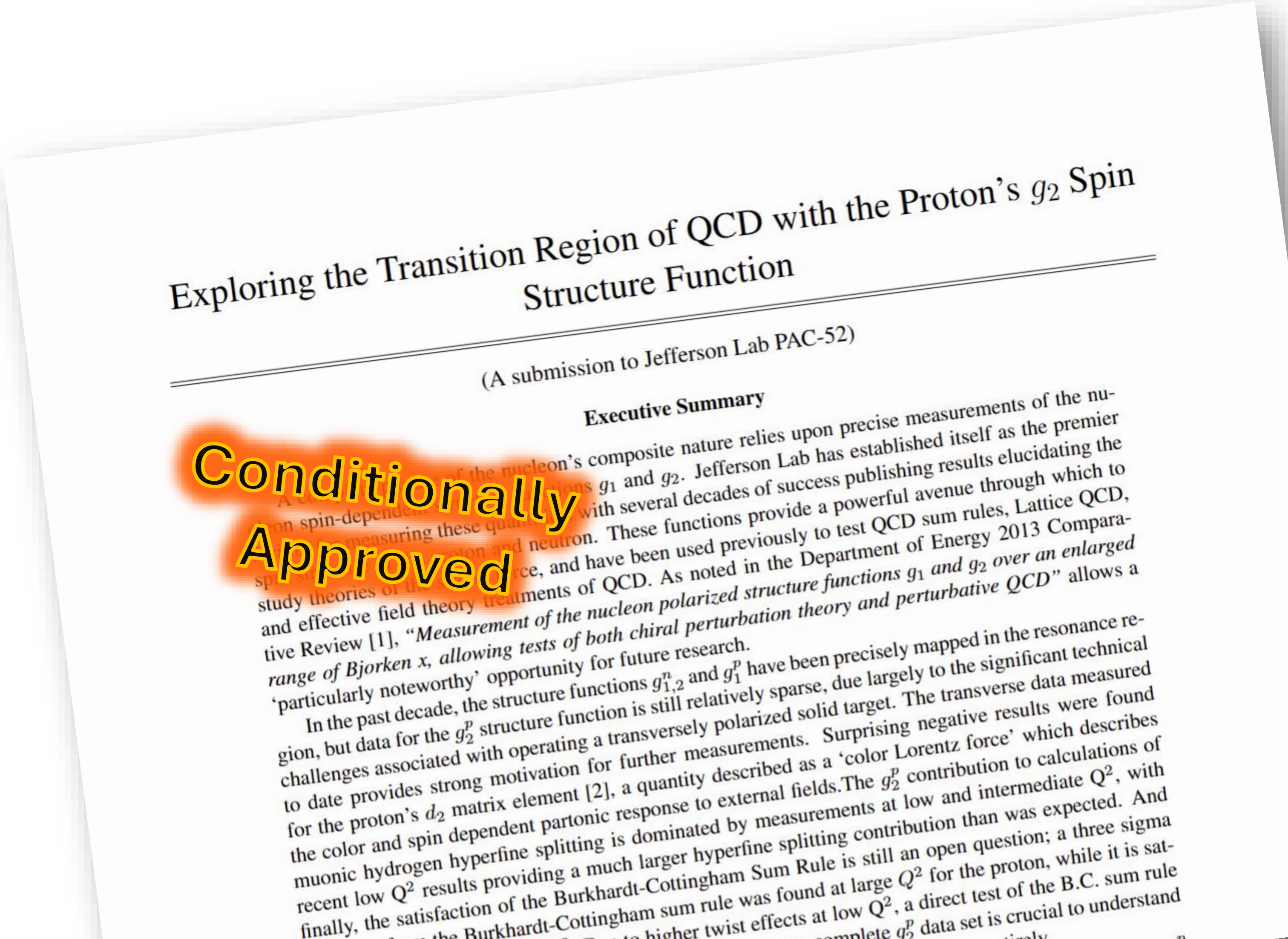


Ripe with scientific motivation:

- **<u>Necessary Benchmark for Lattice QCD</u>**
- **<u>Unique Sensitivity to Twist-3 Effects</u>**
- **<u>Significant contribution to Theoretical Hydrogen Hyperfine Splitting Uncertainty</u>**
- **<u>Study sum rules and transition from perturbative QCD to effective theories</u>**

PR12-24-002 Approved in 2024

- Approved with C2 Status
- Further simulations work was needed to remove the conditional
- We expect the new simulation results will be sufficient to remove the conditional this July



Exploring the Transition Region of QCD with the Proton's g_2 Spin Structure Function

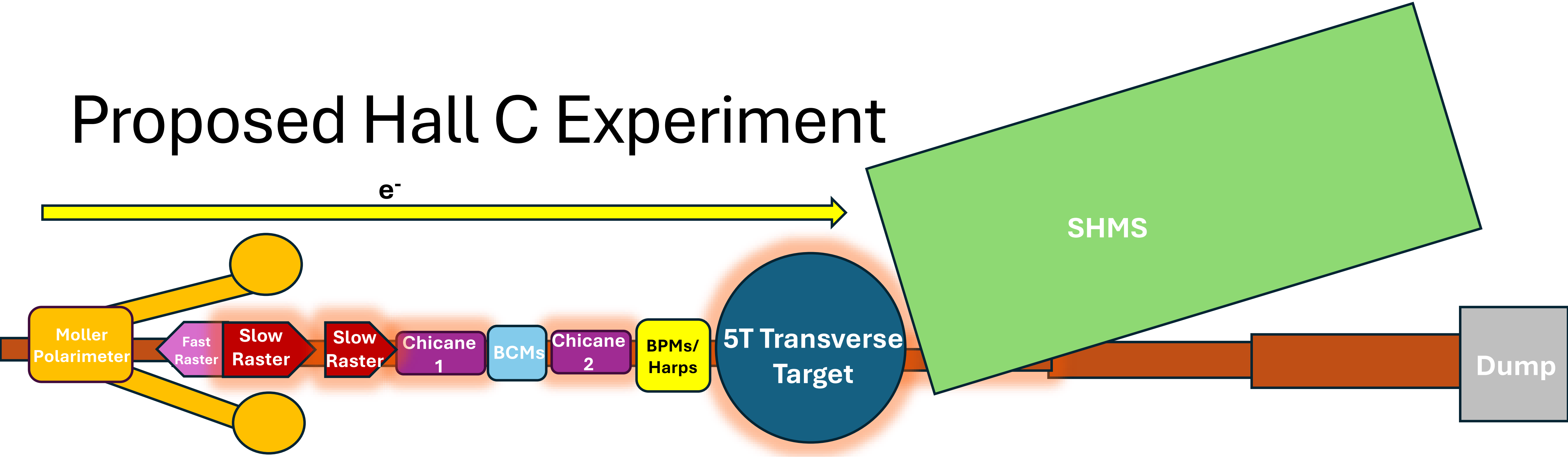
(A submission to Jefferson Lab PAC-52)

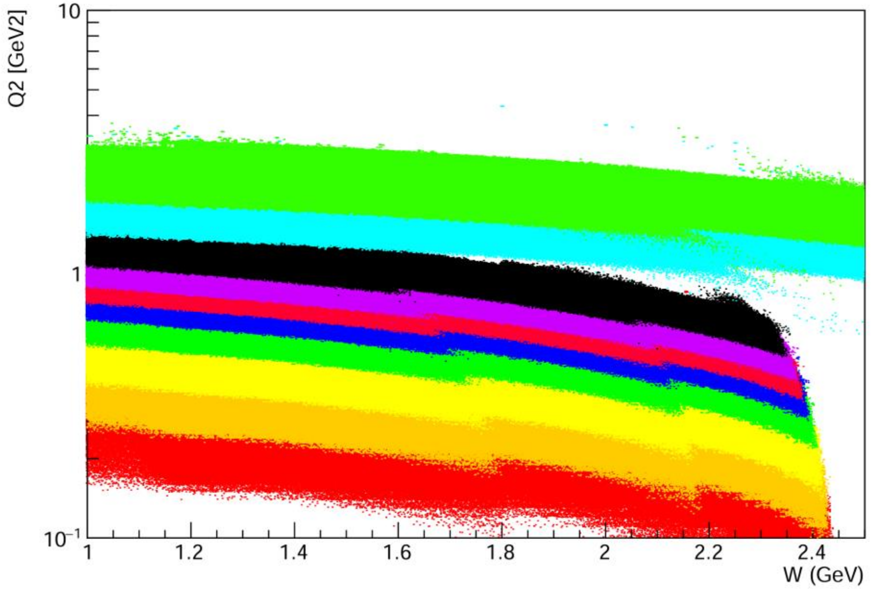
Executive Summary

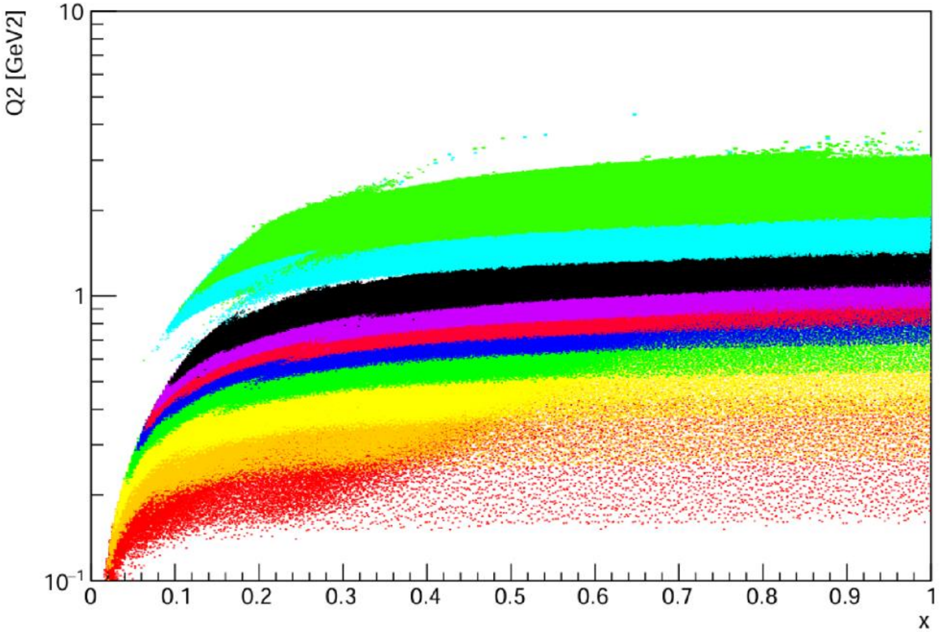
of the nucleon's composite nature relies upon precise measurements of the nu- ions g_1 and g_2. Jefferson Lab has established itself as the premier with several decades of success publishing results elucidating the neutron. These functions provide a powerful avenue through which to ce, and have been used previously to test QCD sum rules, Lattice QCD, study theories of the treatments of QCD. As noted in the Department of Energy 2013 Compara- and effective field theory tive Review [1], "*Measurement of the nucleon polarized structure functions g_1 and g_2 over an enlarged range of Bjorken x, allowing tests of both chiral perturbation theory and perturbative QCD*" allows a 'particularly noteworthy' opportunity for future research.

In the past decade, the structure functions $g^n_{1,2}$ and g^p_1 have been precisely mapped in the resonance re- gion, but data for the g^p_2 structure function is still relatively sparse, due largely to the significant technical challenges associated with operating a transversely polarized solid target. The transverse data measured to date provides strong motivation for further measurements. Surprising negative results were found for the proton's d_2 matrix element [2], a quantity described as a 'color Lorentz force' which describes the color and spin dependent partonic response to external fields.The g^p_2 contribution to calculations of muonic hydrogen hyperfine splitting is dominated by measurements at low and intermediate Q^2, with recent low Q^2 results providing a much larger hyperfine splitting contribution than was expected. And finally, the satisfaction of the Burkhardt-Cottingham Sum Rule is still an open question; a three sigma Burkhardt-Cottingham sum rule was found at large Q^2 for the proton, while it is sat- higher twist effects at low Q^2, a direct test of the B.C. sum rule complete g^p_2 data set is crucial to understand

Proposed Hall C Experiment

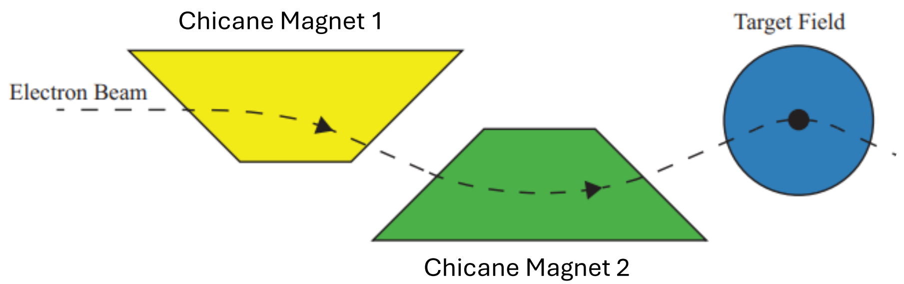


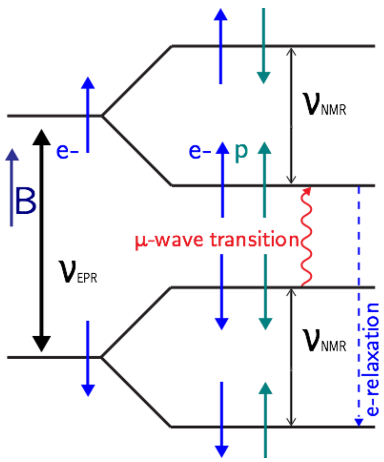


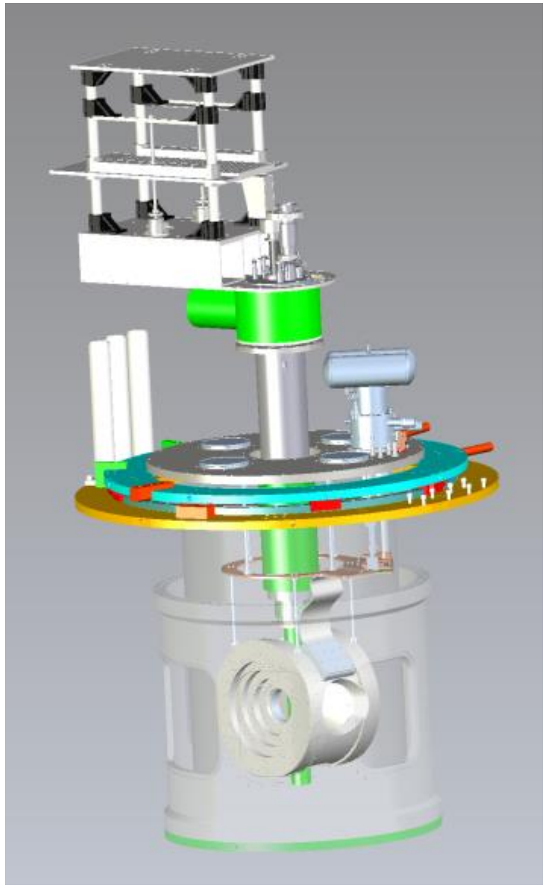


Transverse Polarized Target

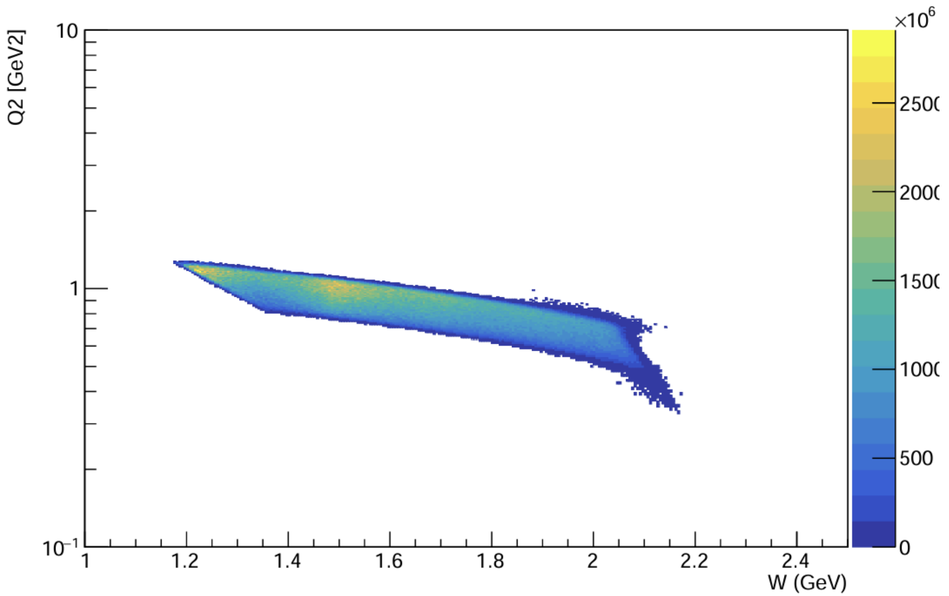
- g_2 Measurement needs a (Transversely) polarized target and polarized beam
- Ammonia (NH_3) target polarized with Dynamic Nuclear Polarization:
  - 5 T magnetic field
  - 1 K temperature
  - Microwaves stimulate easily polarizable electrons to couple with more difficult to polarize protons
- Since target is polarized transverse to the beam direction, we need to "pre-bend" the beam with a chicane magnet



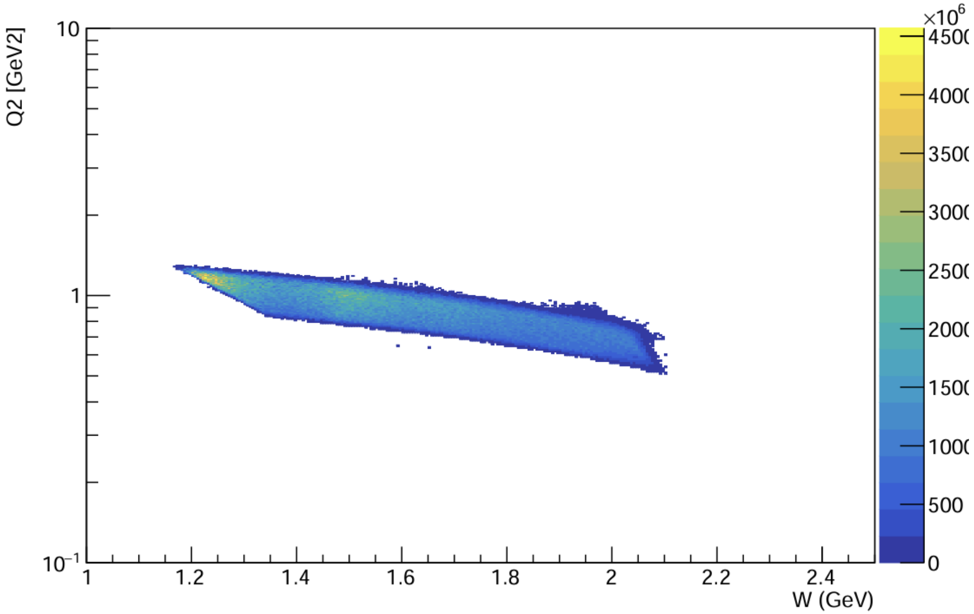




Single-Arm Monte-Carlo Simulation



No target field



With target field and chicane magnets

- Extremely minimal impact on the kinematic coverage
- Equivalent simulation used frequently by other Hall C experiments

- Out-of-plane scattering angle is significant, but has been easily corrected for in previous similar experiments

g_2 Extraction Method

- Measure Asymmetry and Cross Section:

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

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

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

Spin-Dependent Effects

Unpolarized Scattering

- Form Polarized XS Difference:

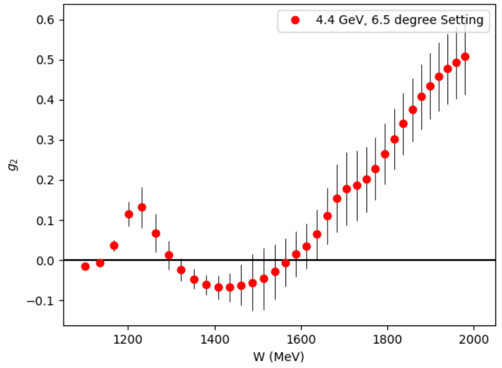
$$\Delta\sigma_{\perp} = 2A_{\perp}^{exp}\sigma_0$$

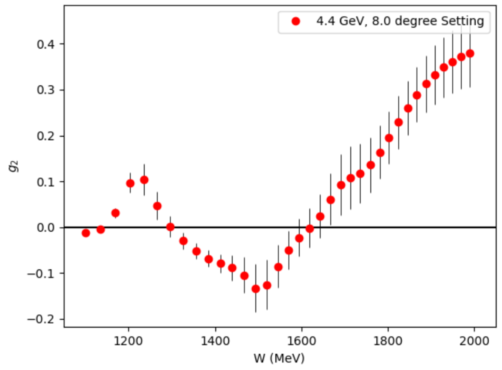
- Extract g_2

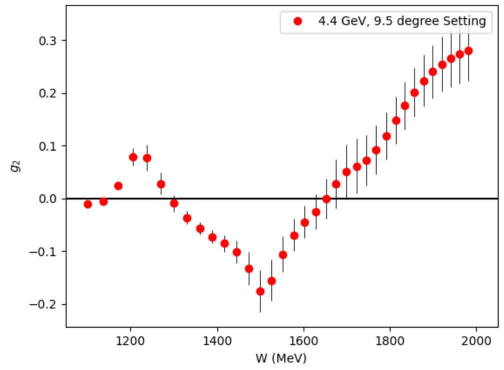
Input from Hall B Data

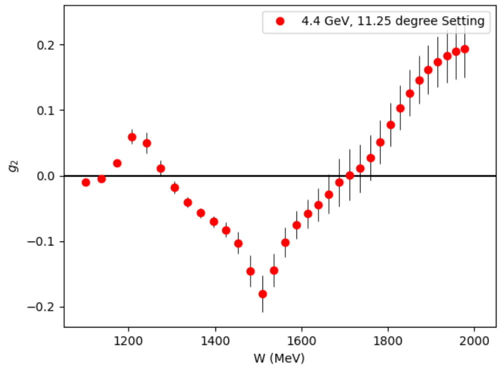
$$g_2(x,Q^2) = \frac{K_1 y}{2}\left[\Delta\sigma_{\perp}\left(K_2 + \tan\frac{\theta}{2}\right)\right] + \frac{g_1(x,Q^2)y}{2}$$

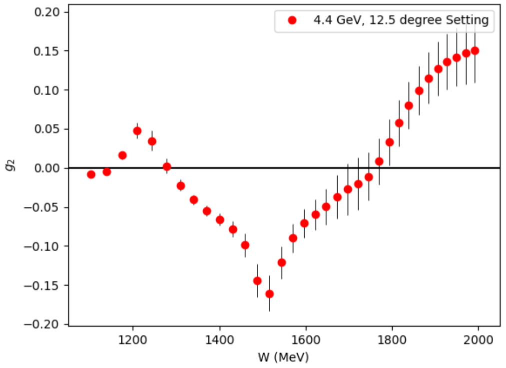
Projected g_2 Uncertainties

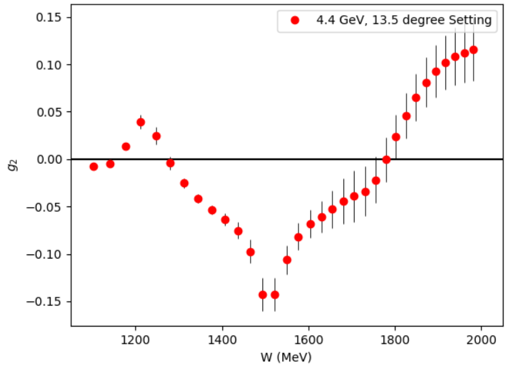


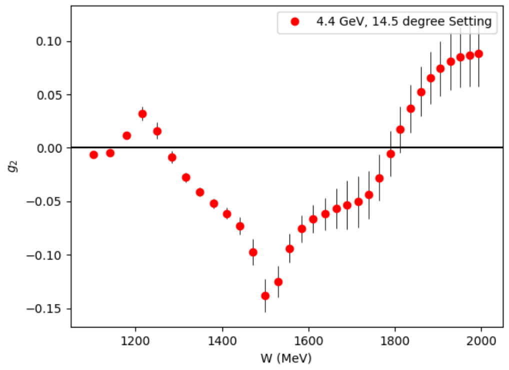


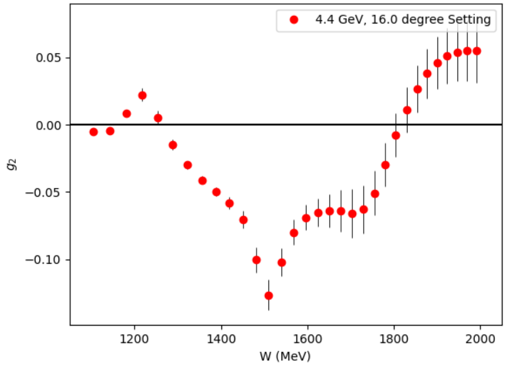




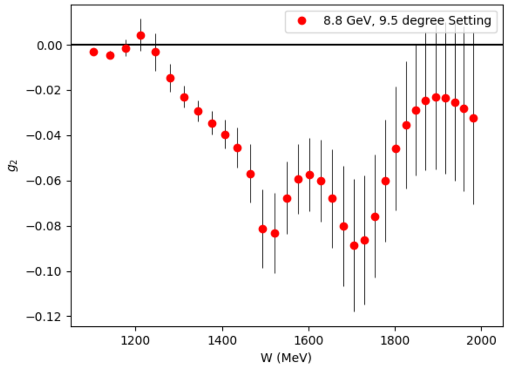


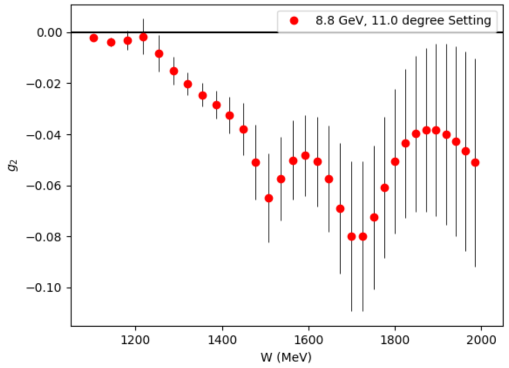






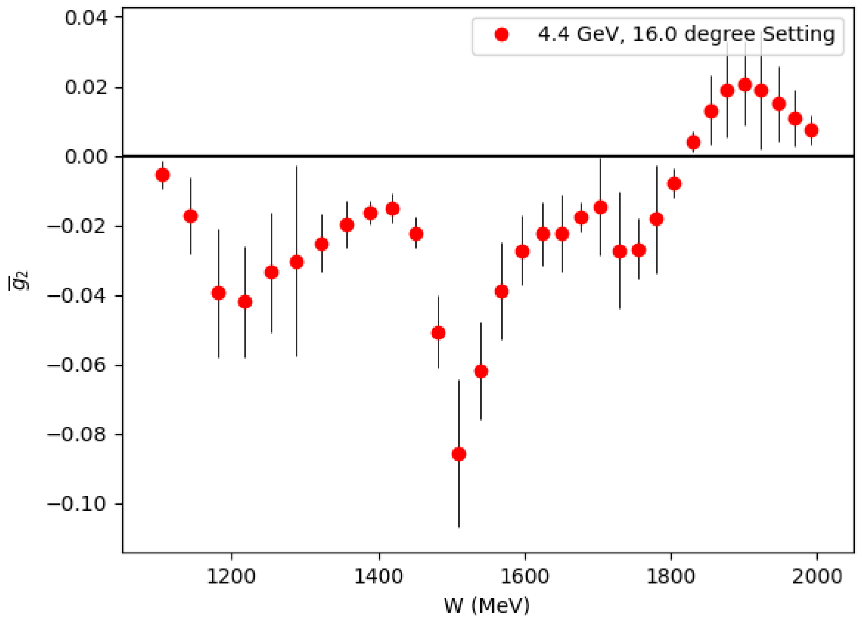
Covers almost the entire transition region





Fills the last major Q^2 spectrum gap for the nucleon spin structure functions

$\overline{g_2}$ (Twist 3 Extraction)



Small

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) - \int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

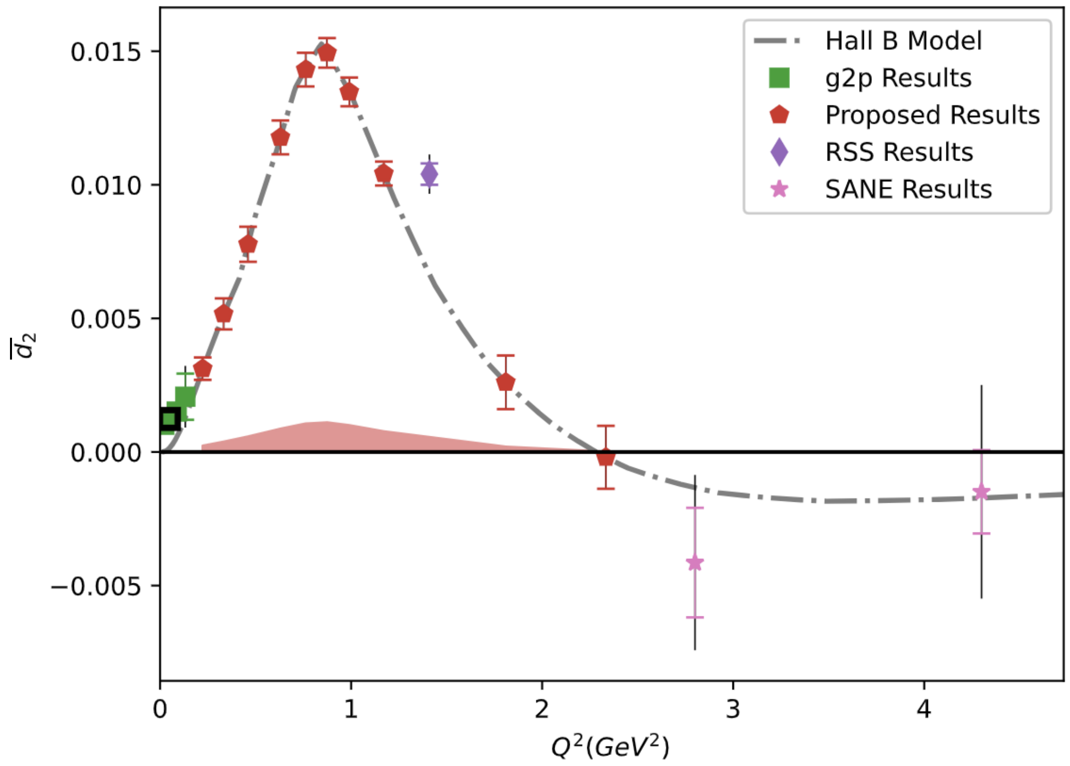
Utilize CLAS Hall B Results for g_1 in same regime

$\overline{g_2}$ **(Twist-3)**

Direct extraction of Twist 3 effects

in the regime they contribute most significantly

Projected $\overline{d_2}$ Uncertainties



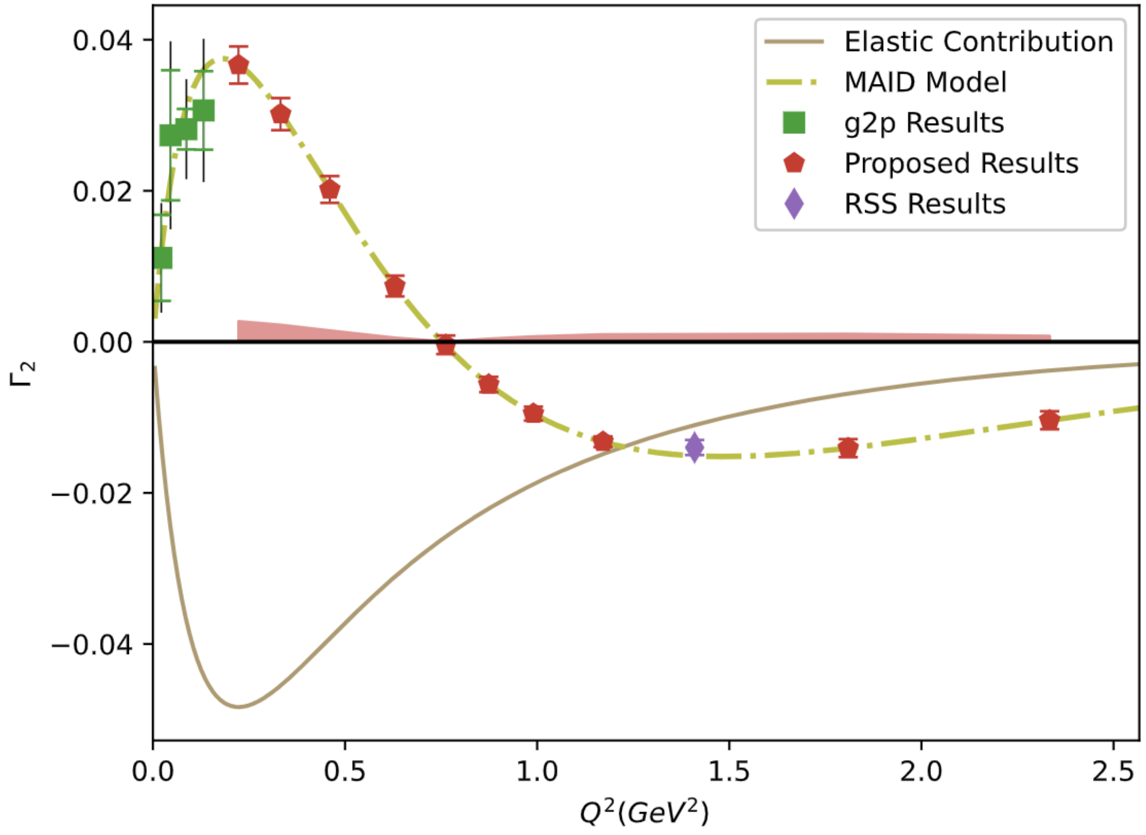
Can benchmark Lattice QCD **in the regime where Perturbative QCD starts failing**

New Lattice calculations expected in next few years!

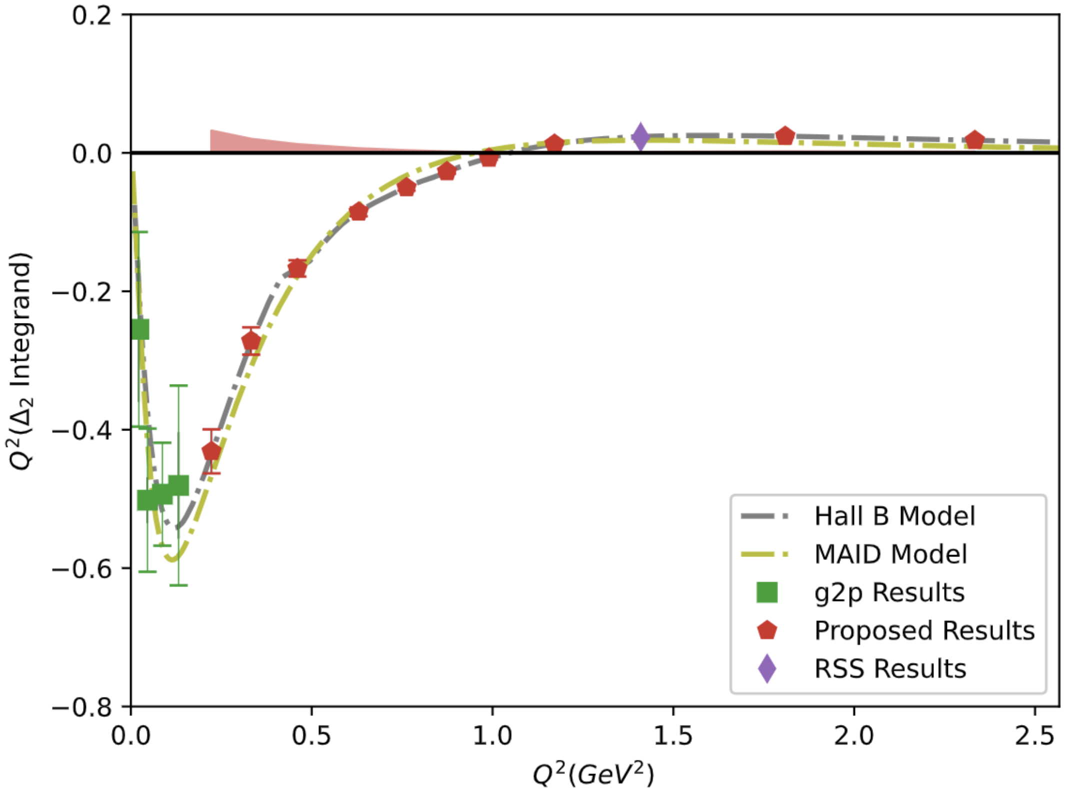
Results should discover maximum and zero crossing of this unique polarizability!

Projected Γ_2 Uncertainties

- Having data in the regime where twist-2 assumption fails helps us better understand the small-x regime
- If B.C. Sum Rule is followed, then we directly measure how the low-x part transitions from g_2^{WW} into a more complex form!

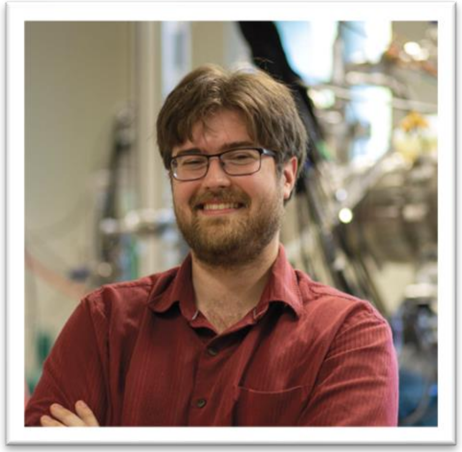


Projected Δ_2 Uncertainties



- Transition region accounts for **30% of Δ_2**
- These results can cut the error in this region to **$^1/_6$ of the current error**
- $\Delta_{pol} = c(\Delta_1 + \Delta_2)$ accounts for **81%** of the current two-photon Hyperfine Splitting uncertainty
- Opportunity to **study or maybe eliminate a long-standing tension** between theory and experiment for Δ_{pol}!

Collaboration



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Conclusion

- g_2 and its moments provide unique power for testing QCD and probing the transition region
- The first experiment measuring g_2 in the transition region (PR12-24-002) has been conditionally approved at Jefferson Lab
- We expect soon the conditional will be removed and we can prepare to run the experiment and:

✓ **Study Twist-3 with $\overline{g_2}$**

✓ **Reduce error on the leading uncertainty in Hydrogen Hyperfine Splitting and study a long-standing tension**

✓ **Fill the last major gap in the nucleon spin structure function Q^2 spectrum**

✓ **Benchmark Lattice QCD with $\overline{d_2}$**

✓ **Enable a better understanding of the B.C. Sum Rule in the nonperturbative regime**

- Further steps towards a continuous QCD are coming soon!