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

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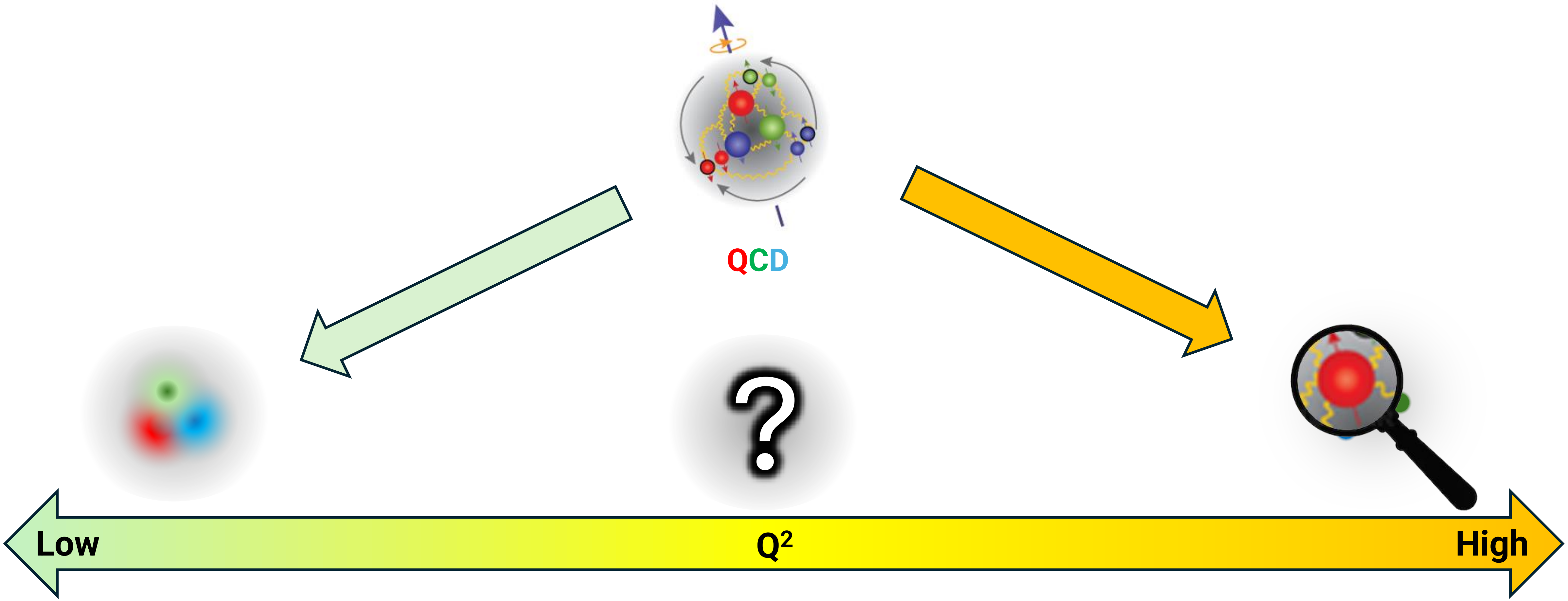
PR12-24-002
Jefferson Lab PAC 52
7/8/2024

David Ruth, Jian-Ping Chen, Nathaly Santiesteban, Karl Slifer



- 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:

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

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

$$\frac{d^2\sigma^{\pm}}{d\Omega dE'} = \sigma_{\text{Mott}}\left[\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) \pm \underbrace{\gamma g_1(x,Q^2)}_{\text{Nucleon Spin Structure}} \pm \underbrace{\delta g_2(x,Q^2)}_{\text{Quark-Gluon Correlations}}\right]$$

g_2 Structure Function enables direct tests of QCD and higher twist

- **Higher Twist:**

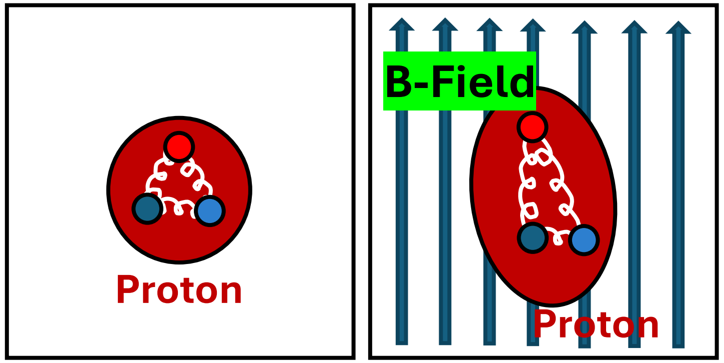
$$g_2(x,Q^2) = \underbrace{g_2^{WW}(x,Q^2)}_{\text{Function of } g_1} - \int_x^1 \frac{\partial}{\partial y}\left[\overbrace{\frac{m_q}{M} h_T(y,Q^2)}^{\text{Small}} + \underbrace{\zeta(y,Q^2)}_{\text{Twist-3}}\right]\frac{dy}{y}$$

- **Benchmarking (Lattice) QCD:**

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

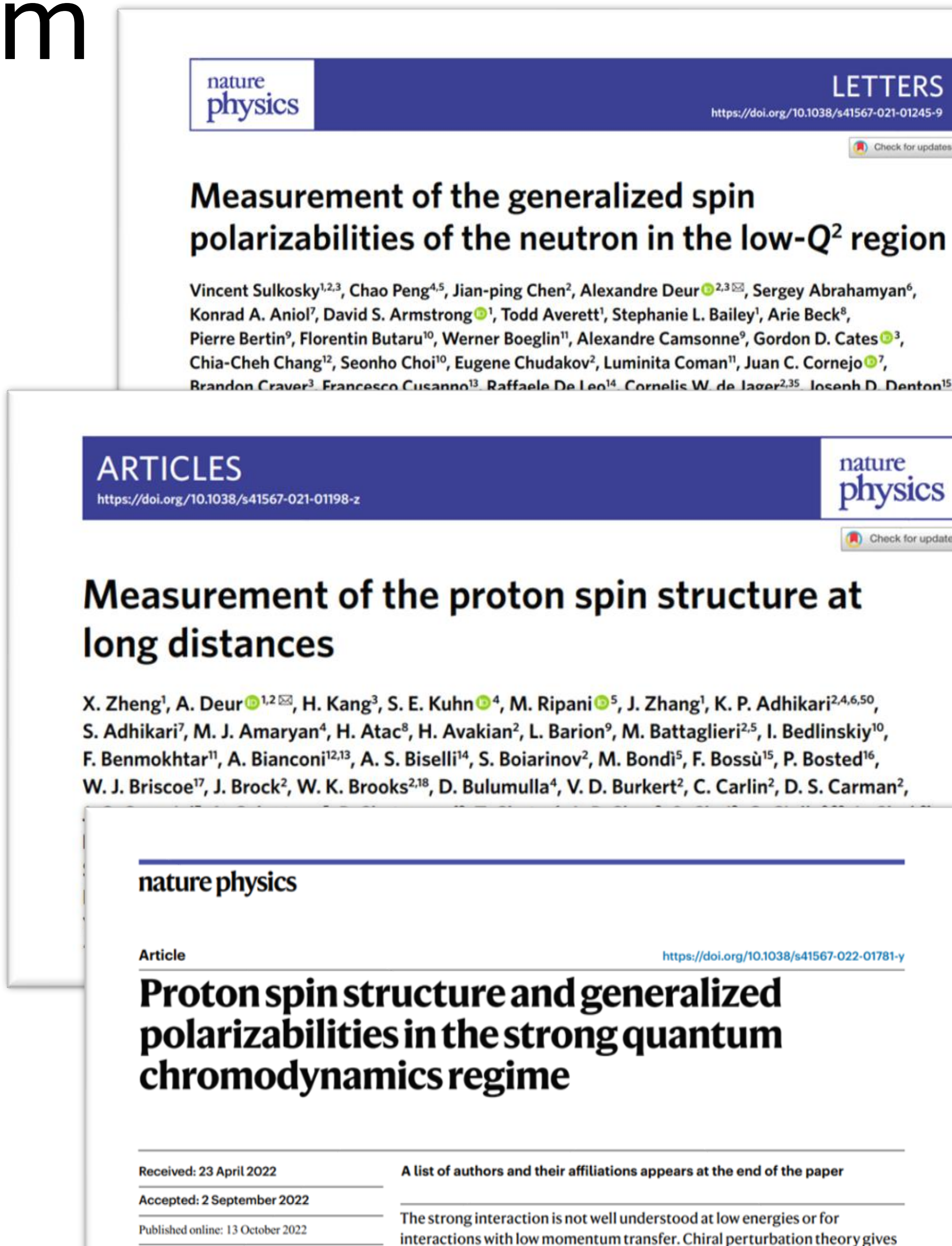
$$\overline{d_2} = \int_0^{x_{th}} x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

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



Recent Successful JLab Program

- 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
- 2007 JLab Review: DOE Milestone to "measure g_1 and g_2 over an enlarged range of x and Q^2"



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

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], Pierre Bertin[9], Florentin Butaru[10], Werner Boeglin[11], Alexandre Camsonne[9], Gordon D. Cates[3], Chia-Cheh Chang[12], Seonho Choi[10], Eugene Chudakov[2], Luminita Coman[11], Juan C. Cornejo[7], Brandon Craver[3], Francesco Cusanno[13], Raffaele De Leo[14], Cornelis W. de Jager[2,35], Joseph D. Denton[15]

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

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],

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
Published online: 13 October 2022

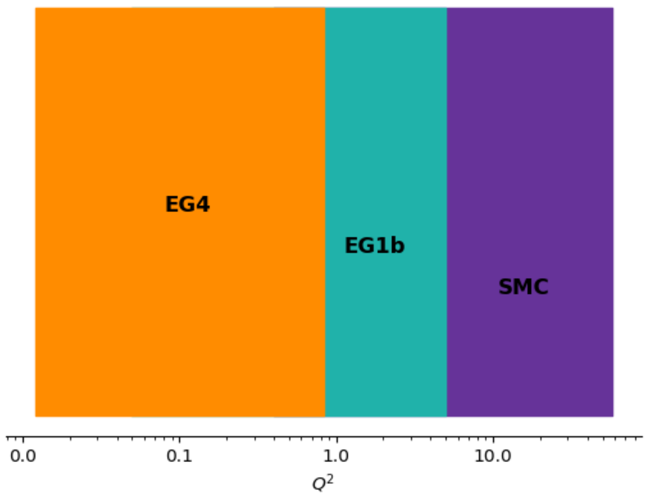
A list of authors and their affiliations appears at the end of the paper

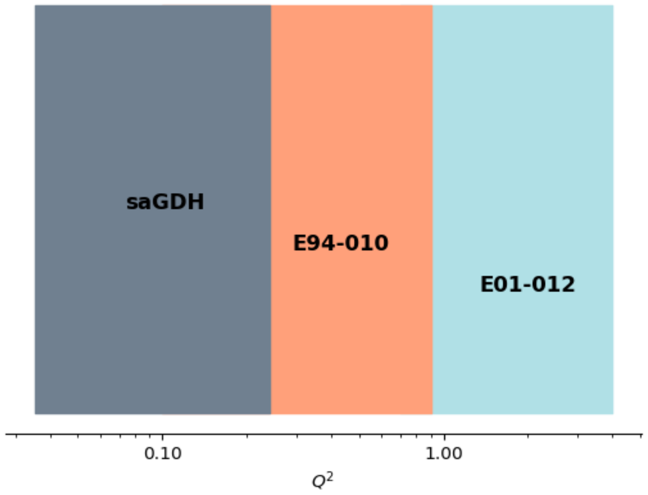
The strong interaction is not well understood at low energies or for interactions with low momentum transfer. Chiral perturbation theory gives

Existing Coverage

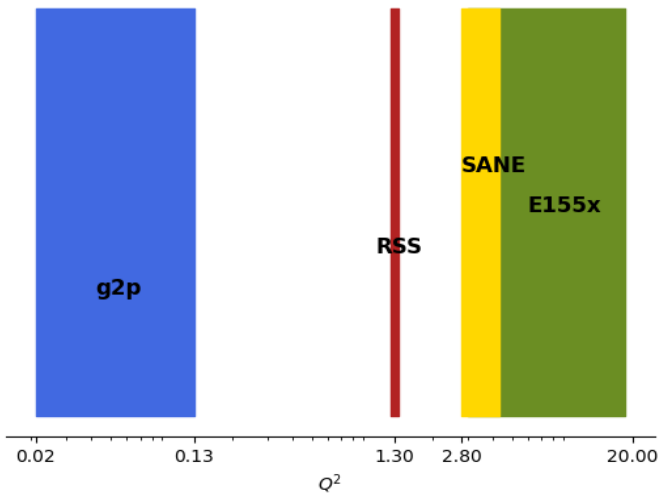
Proton | Neutron

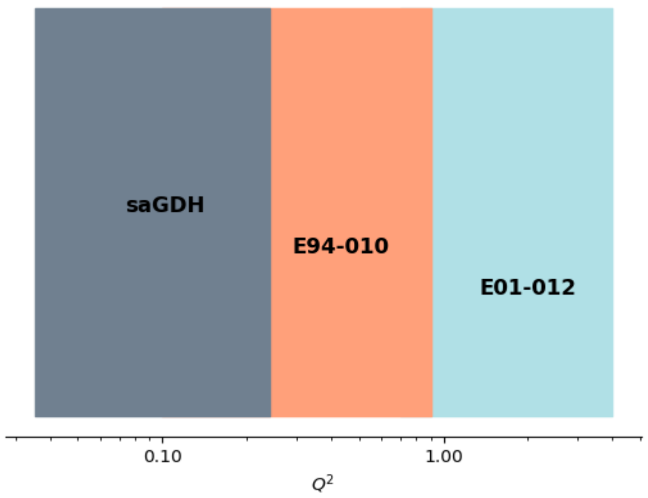
g_1





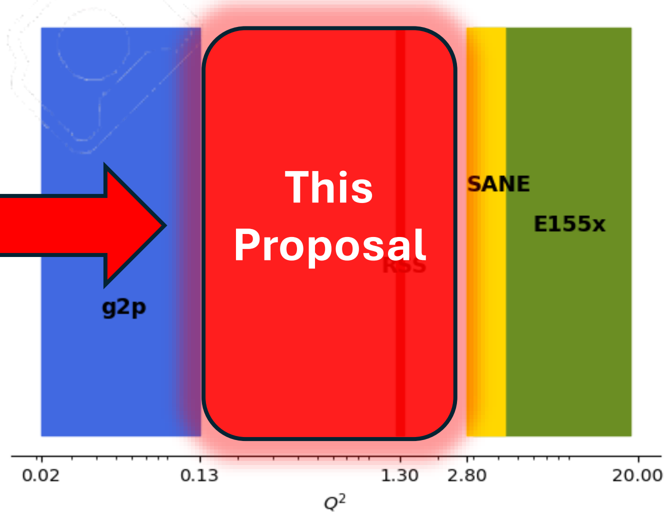
g_2





"Low Hanging Fruit"

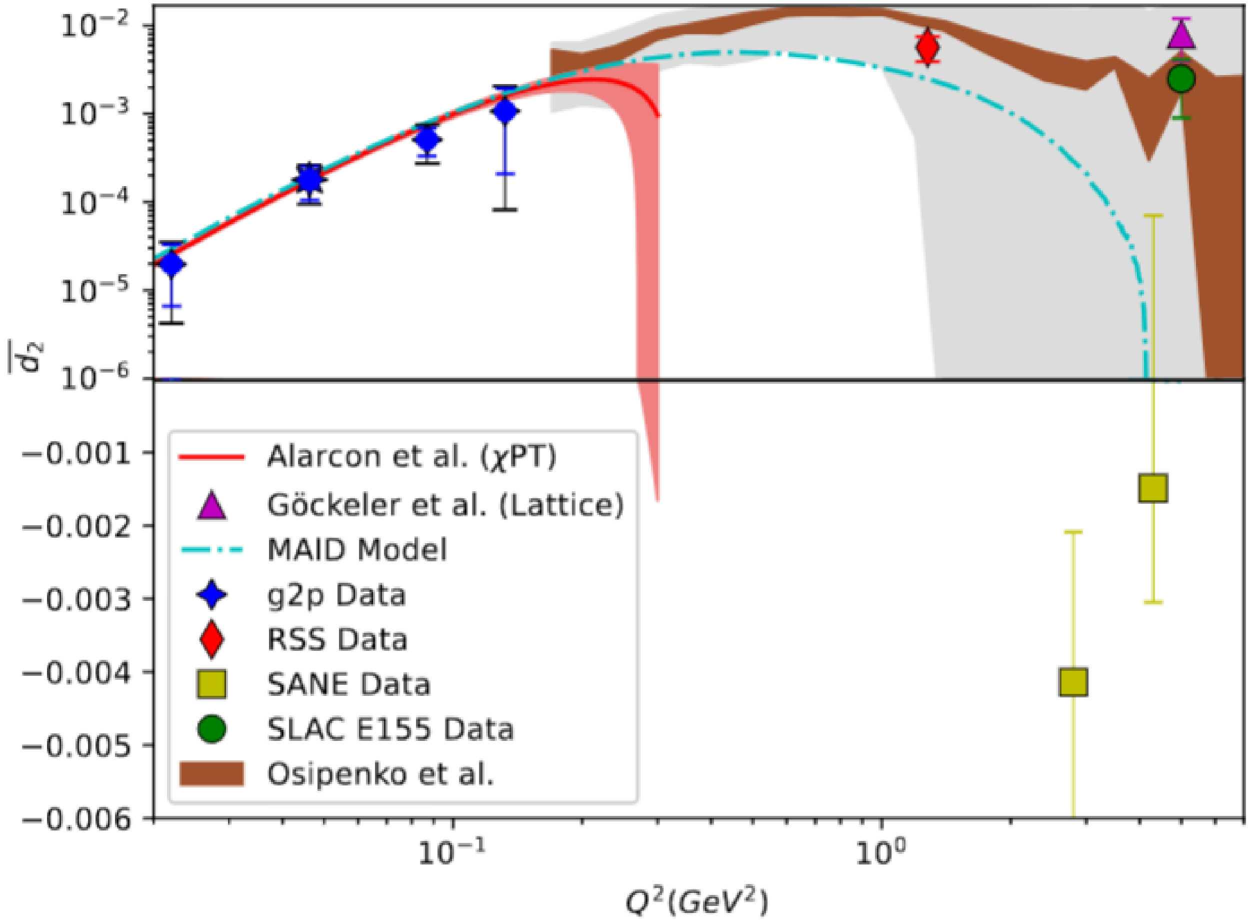
- **<u>Much higher rates</u>** than the higher Q^2 experiments
- **<u>No need for a septum magnet</u>** as was used in the low Q^2 g2p experiment in Hall A
- **<u>Smaller out-of-plane angle</u>** than the low Q^2 data



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>**

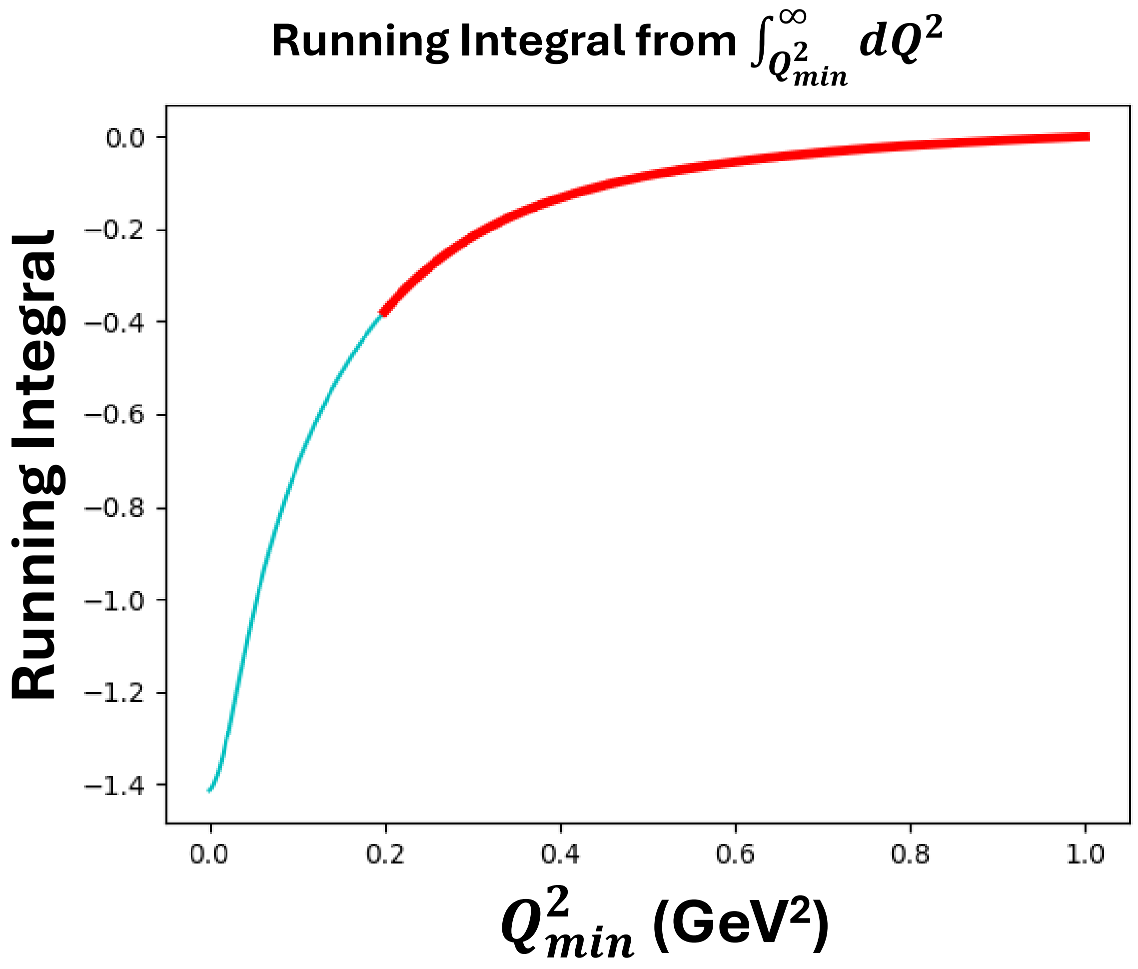
“Color Polarizability” $\overline{d_2}$



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

- 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

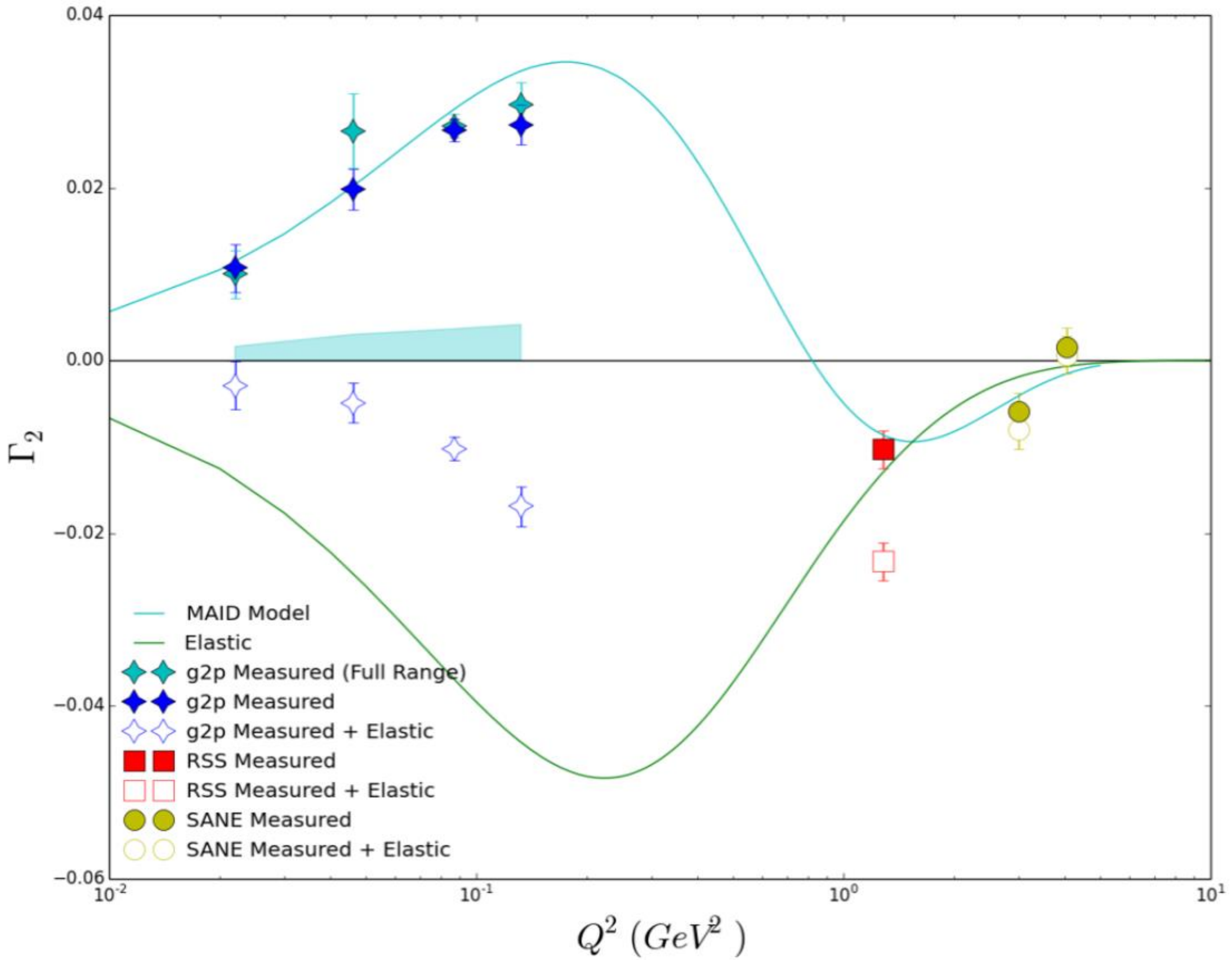


$$\Delta_2 = -24M_p^2 \int_0^{\infty} \frac{dQ^2}{Q^4} \int_0^{x_{th}} \widetilde{\beta_2}(x, Q^2) g_2(x, Q^2) dx$$

- 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!

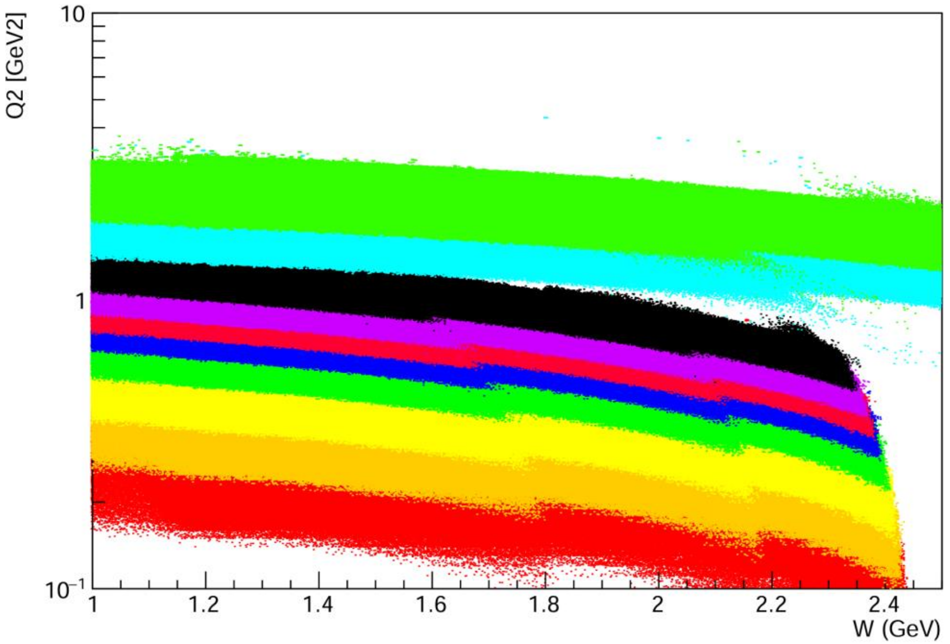
Γ_2 Moment & Burkhardt-Cottingham (BC) Sum rule

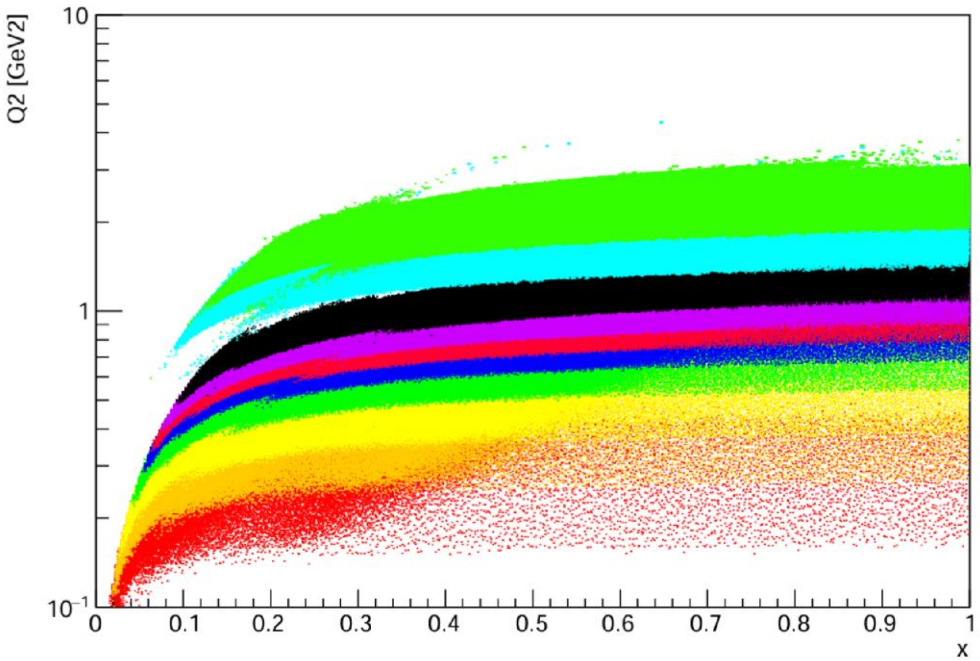


$$\boxed{\Gamma_2 = \int_0^{x_{th}} g_2(x, Q^2)\,dx = 0}$$

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

Proposed Experiment





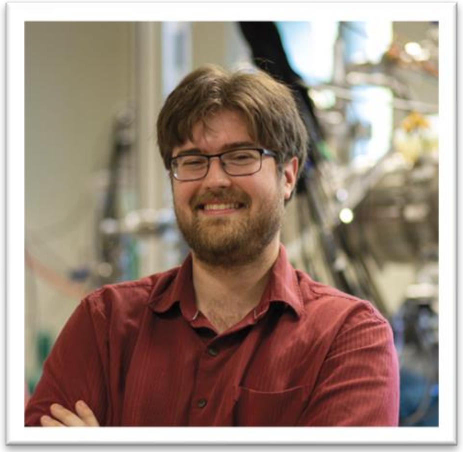
- Measure proton g_2 in the resonance region for **a full order of magnitude in Q^2 range** from 0.2 GeV^2 - 2.2 GeV^2
- Use a transversely polarized NH_3 target and the SHMS spectrometer in Hall C
- Low current (85 nA) beam at 4.4 and 8.8 GeV beam energies
- Collect the first transition region measurement of the proton's g_2, and extract its moments and higher twist effects

Collaboration

Jian-Ping Chen

Nathaly Santiesteban

Karl Slifer



David Ruth

g2p Analysis

D. Ruth
J.P. Chen
K. Slifer

SANE Analysis

W. Armstrong
J. Maxwell
Z.E. Meziani
M. Jones

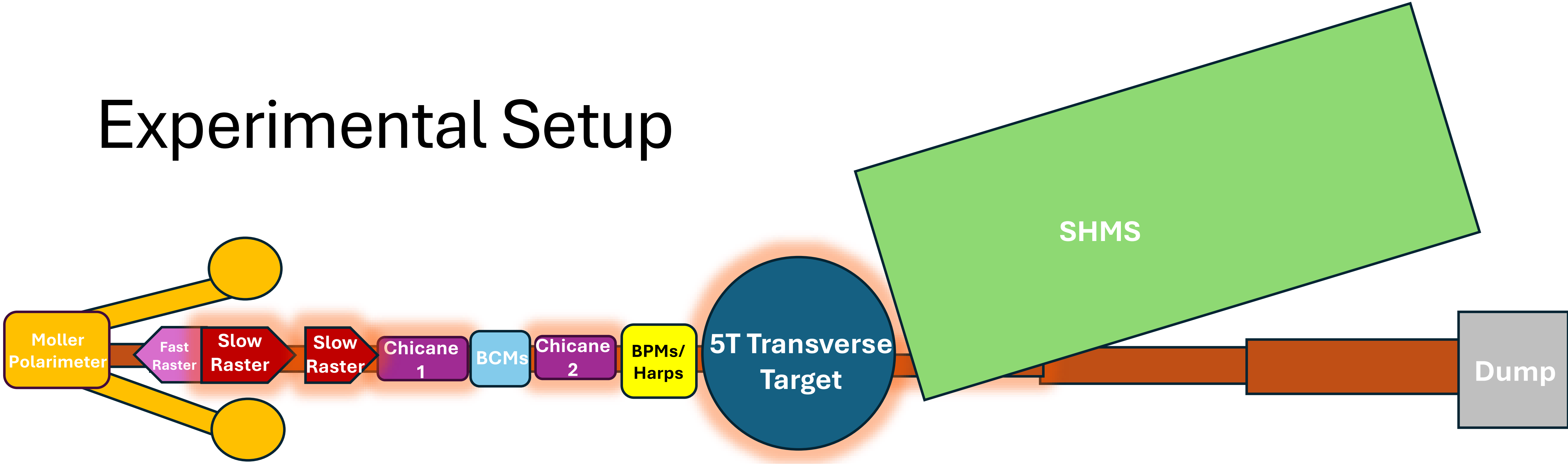
RSS Analysis

K. Slifer
M. Jones
O. Rondon

Polarized Target Experts

K. Slifer, A. Arora, M. Farooq, N. Santiesteban, H. Chinchay, Z. Wolters, O. Olokunboyo, A. Zec, E. Long, J.P. Chen, D. Ruth, C. Keith, J. Maxwell. D. Meekins, J. Brock, D. Keller, I. Fernando, S. Covrig Dusa

Experimental Setup

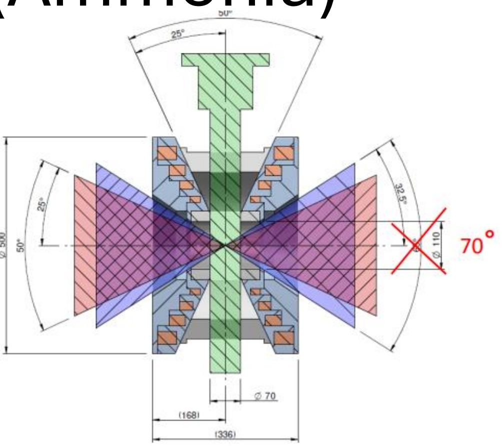


Standard equipment package, plus:

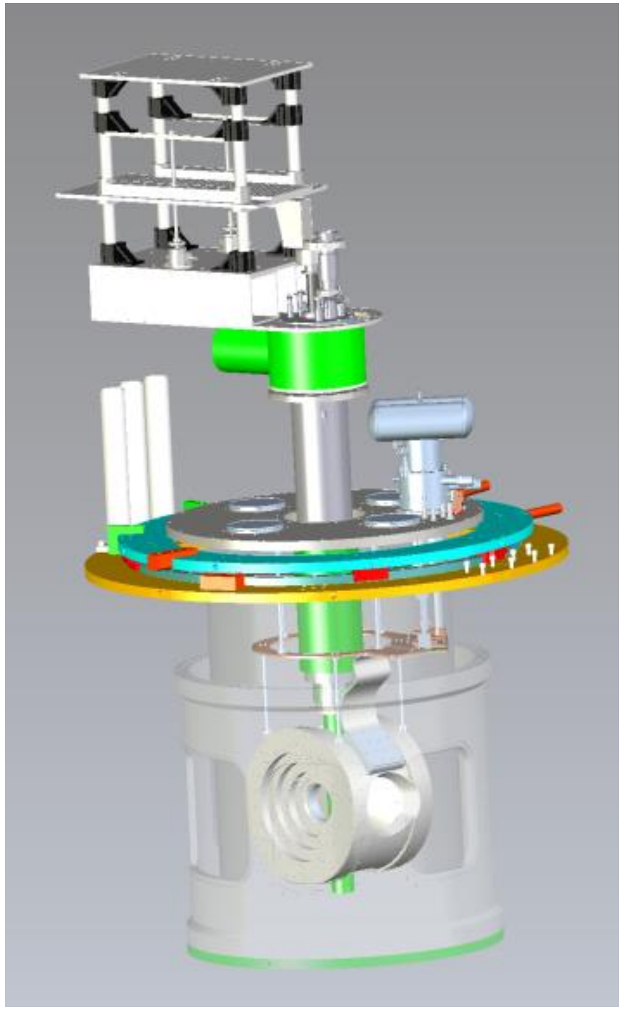
- Installation of the target group's 5T polarized target
- Commissioning of Dr. Jay Benesch's new chicane magnet design
- Configuration of the beamline to operate at low current (85 nA)
- Installation of the slow raster
- Installation of the smaller exit beampipe for small angle SHMS measurements

Polarized Target

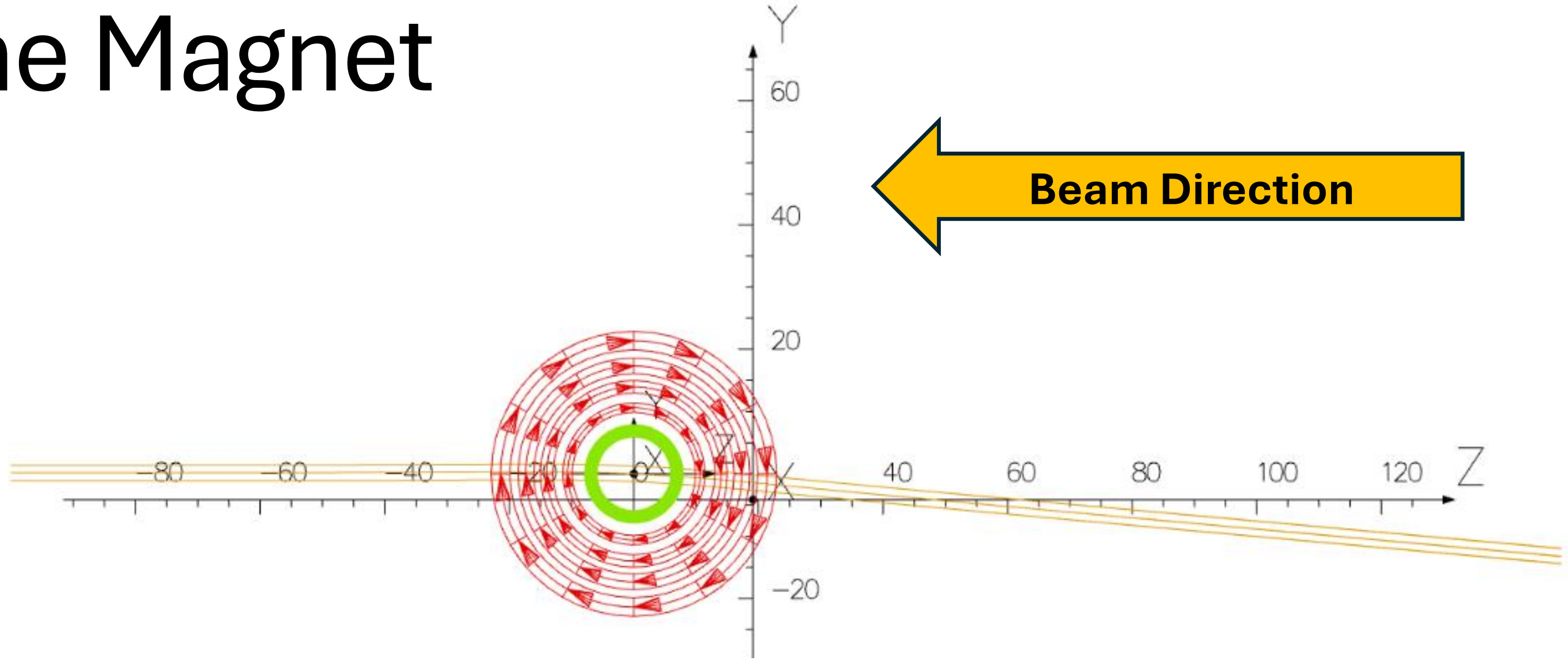
- Target group has new polarized target magnet capable of improving performance from the g2p run
- Helmholtz-configuration magnet is optimized for running with transverse field and acceptance appropriate for the desired kinematics (± 25°)
- Run will require a polarized NH_3 (Ammonia) target
- Several polarized target experiments already approved in Hall C – possibility for cooperation on scheduling



Cross-section through the magnet showing the beam and cold finger access diameters (in mm) and



Chicane Magnet



- The transverse target field necessitates a pre-bending of the beam to locate the beam at the center of the target and within the area of the hall dump
- Dr. Jay Benesch has worked on a new design which would replace two of the existing 1m dipoles and satisfy the needs of this proposal
- **<u>New</u>** installation will need to be commissioned, and is needed for SoLID and any other experiment with transverse polarized target

g_2 Extraction Method

- Measure Asymmetry and Cross Section:

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

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

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

- Form Polarized XS Difference:

Spin-Dependent Effects

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

Unpolarized Scattering

- Extract g_2

Input from Hall B Data

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

Beam Time Required

Source	Time (PAC Days)
$Q^2 = 0.22\ GeV^2$	0.1
$Q^2 = 0.33\ GeV^2$	0.2
$Q^2 = 0.46\ GeV^2$	0.3
$Q^2 = 0.62\ GeV^2$	0.8
$Q^2 = 0.77\ GeV^2$	1.1
$Q^2 = 0.89\ GeV^2$	1.8
$Q^2 = 1.03\ GeV^2$	2.3
$Q^2 = 1.25\ GeV^2$	4.6
$Q^2 = 1.84\ GeV^2$	0.9
$Q^2 = 2.2\ GeV^2$	0.9
Total Physics Days	**13**
Overhead Days	13

Only

26 Days

To measure 10 Q^2 settings of g_2 with high precision...

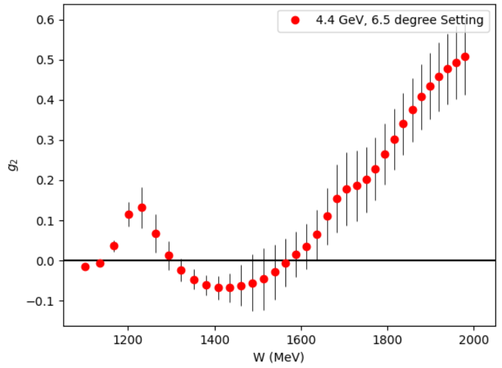
covering a **full order of magnitude** of the transition region!

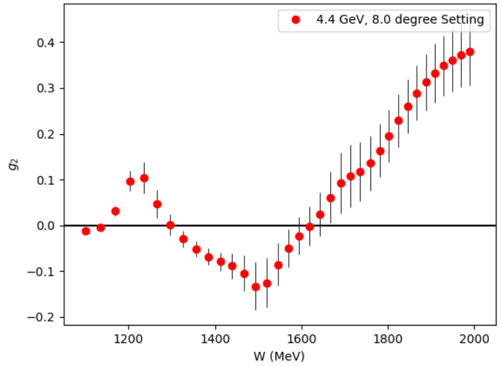
Projected Systematics

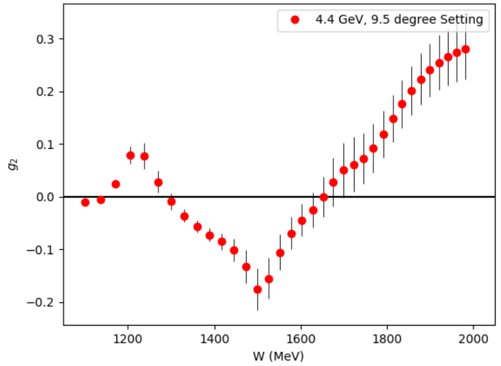
- Dominating systematics are **target polarization** and **acceptance**

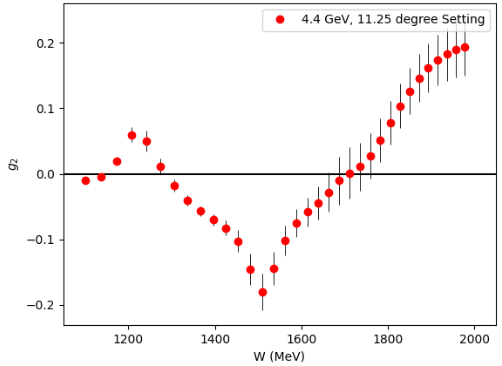
Source	%
Acceptance	4-6
Packing Fraction	3
Charge Determination	1
Tracking Efficiency	1
PID Efficiencies	< 1
Software Cut Efficiency	< 1
Energy	0.5
Deadtime	< 1
XS Total	5-7
Target Polarization	5
Beam Polarization	3
Radiative Corrections	3
Parallel Contribution	2
Const Q^2 Adjustment	< 1
S.F. Total	8.5-9.8

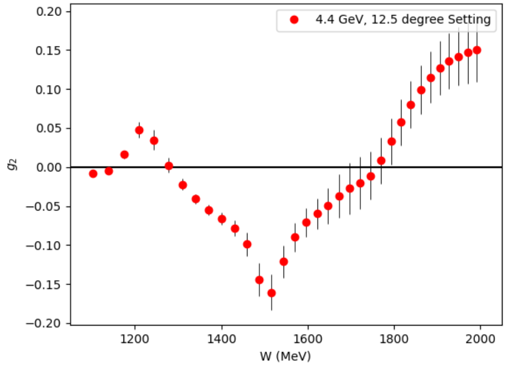
Projected g_2 Uncertainties

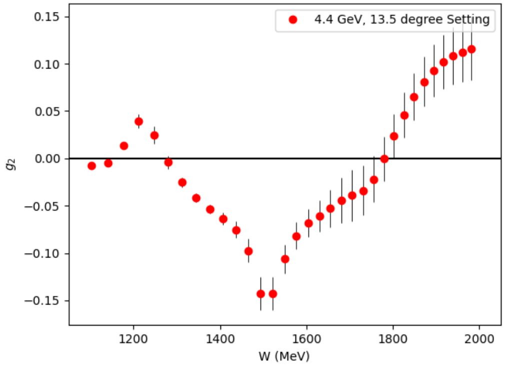


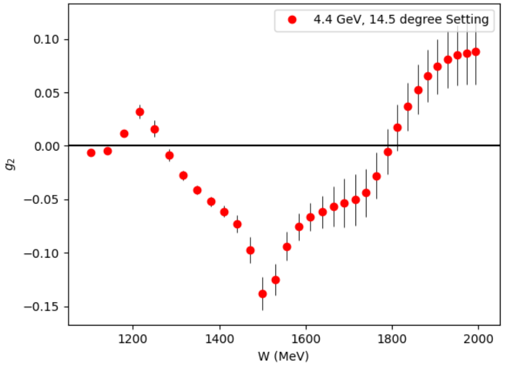


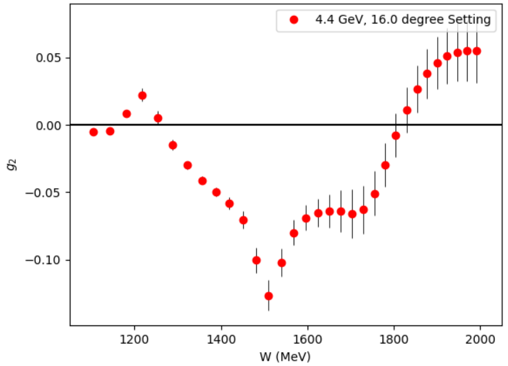




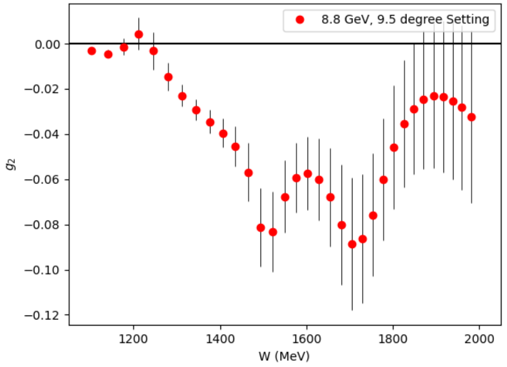


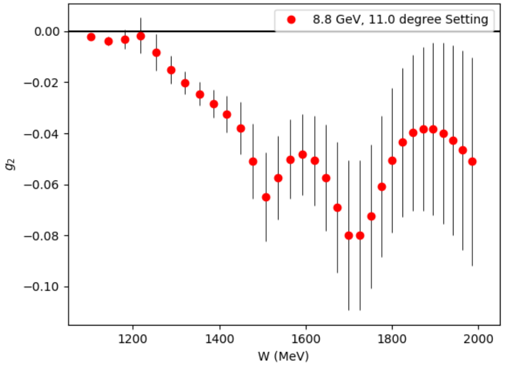






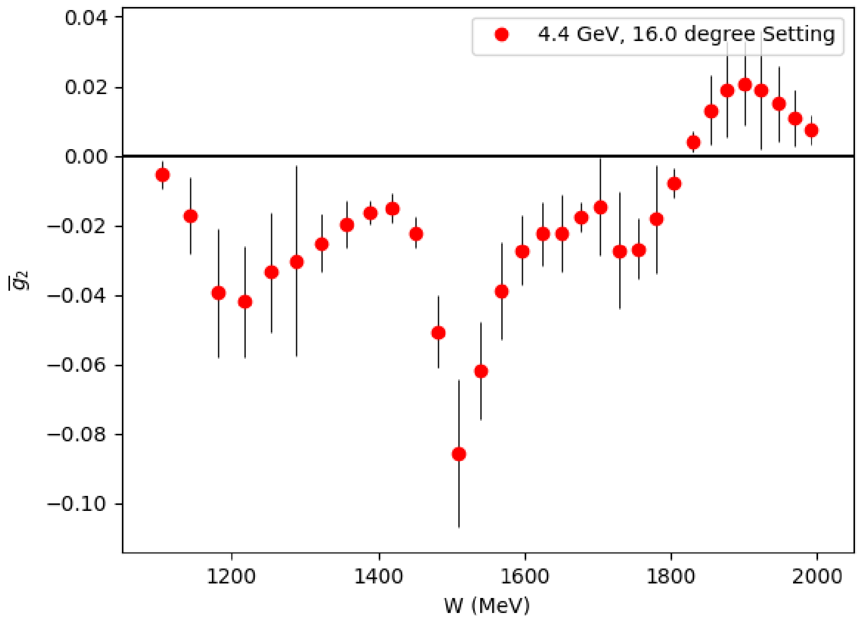
Covers almost the entire transition region





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

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



Small

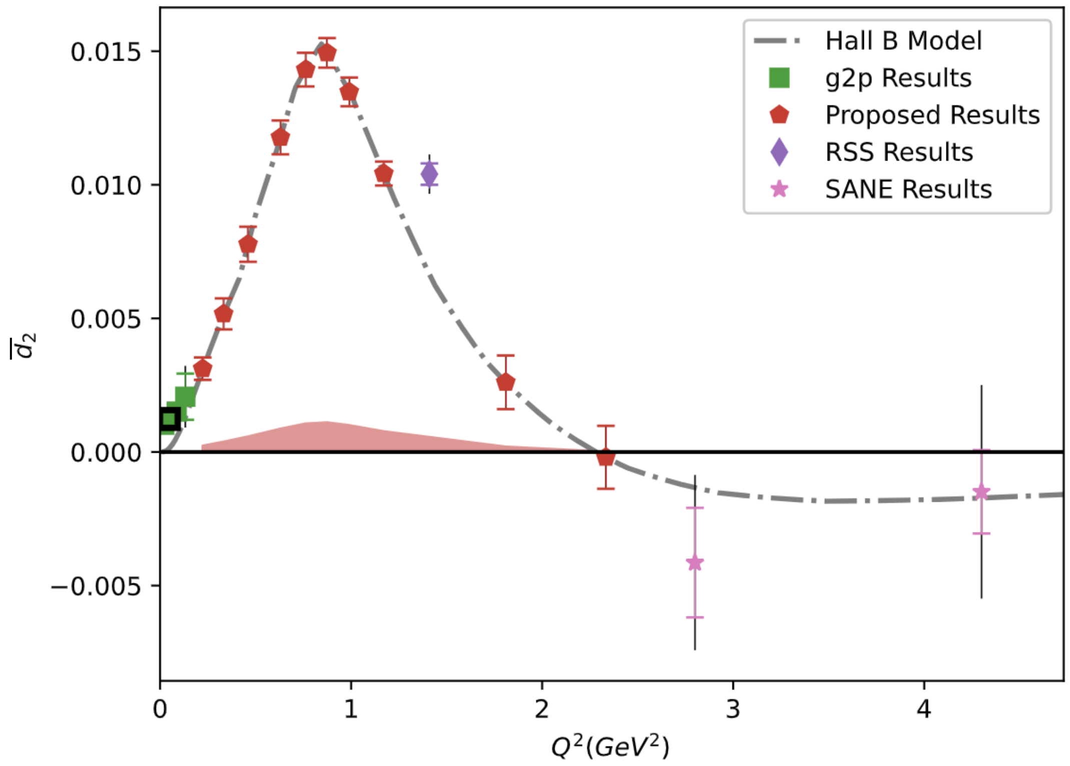
$$g_2(x,Q^2) = \underbrace{g_2^{WW}(x,Q^2)}_{} - \int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \underbrace{\zeta(y,Q^2)}_{}\right]\frac{dy}{y}$$

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**

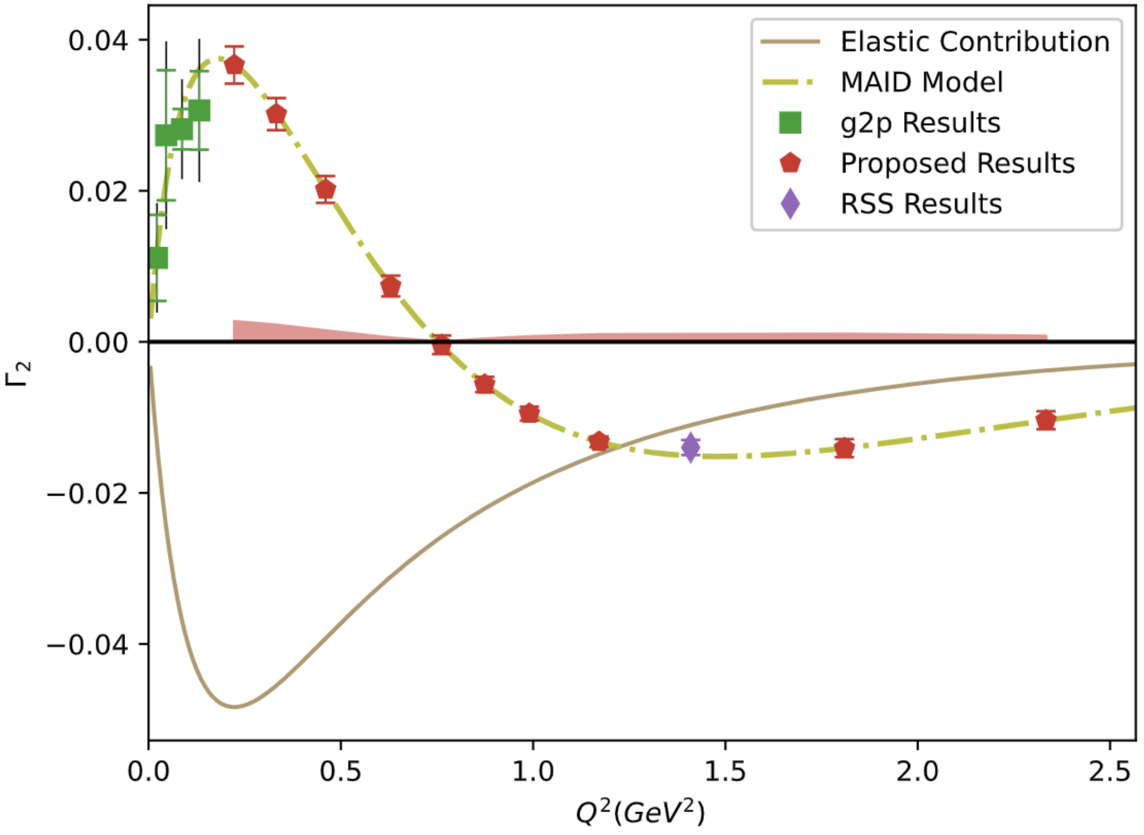
New Lattice calculations expected in next few years!

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

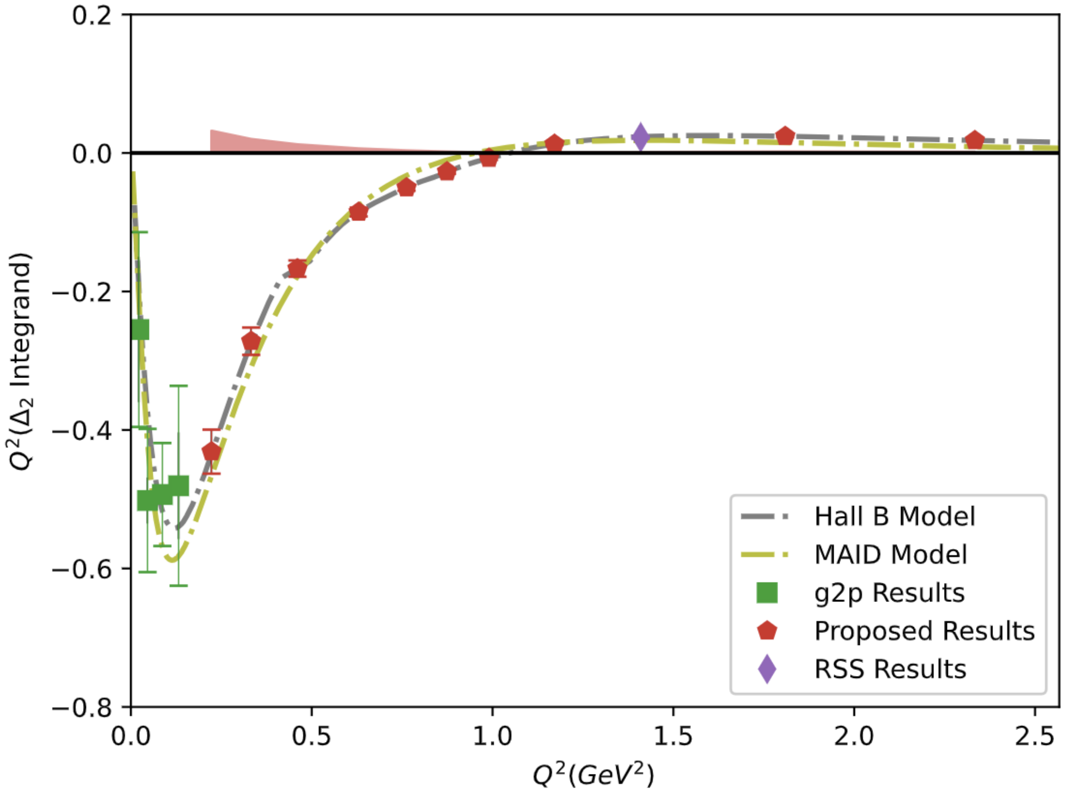
Projected Γ_2 Uncertainties

- 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!

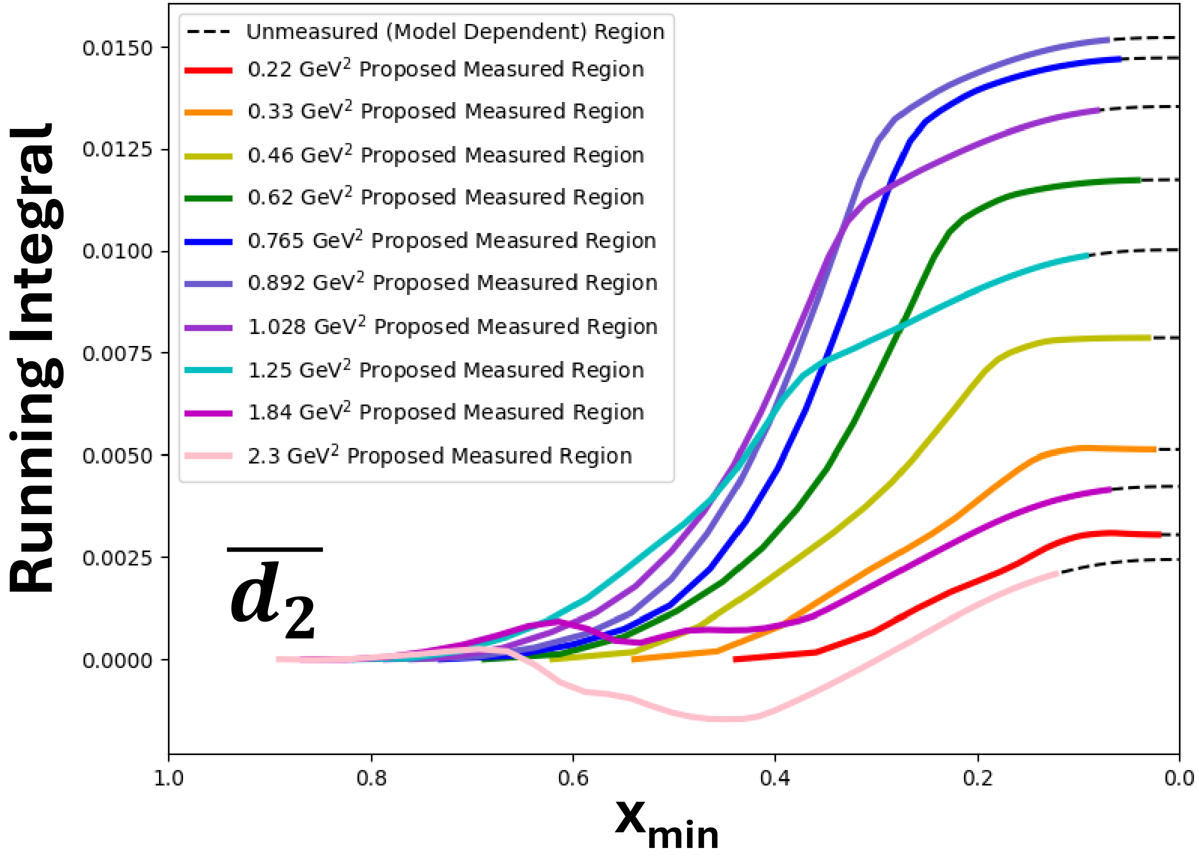


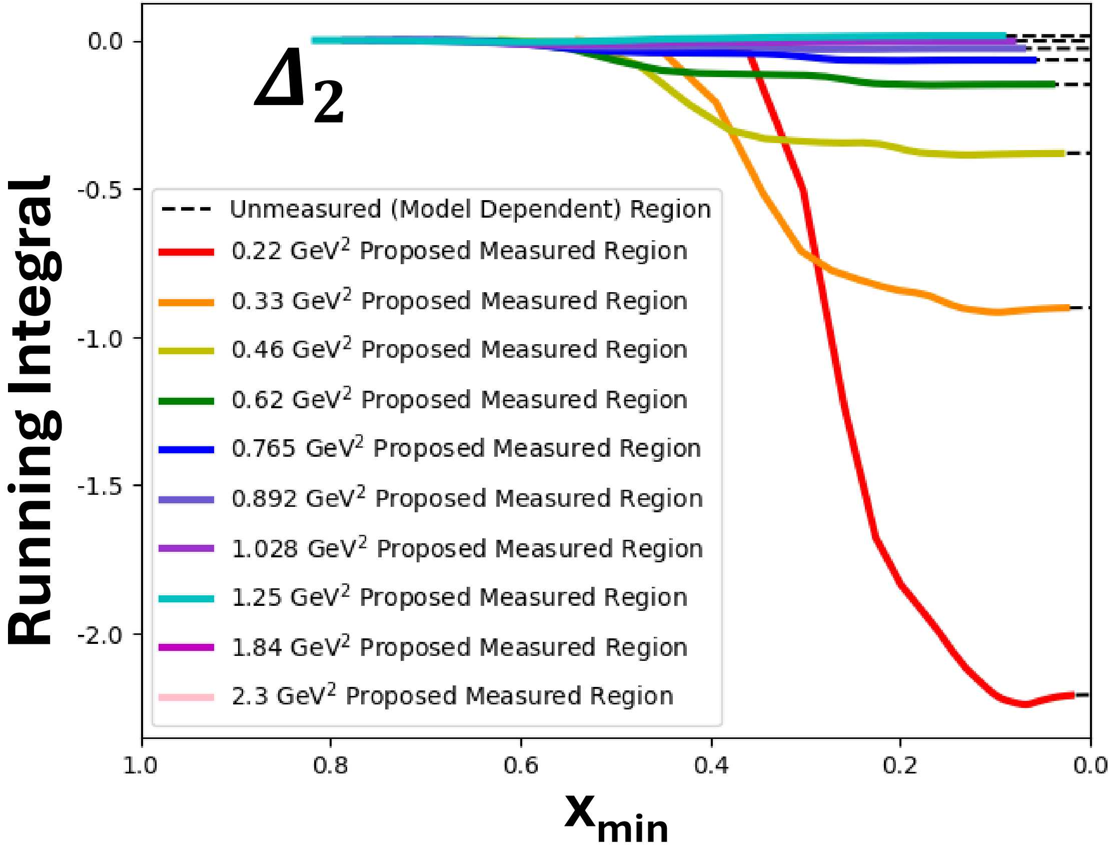
Projected Δ_2 Uncertainties



- Transition region accounts for **30% of $\boldsymbol{\Delta_2}$**
- 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}!

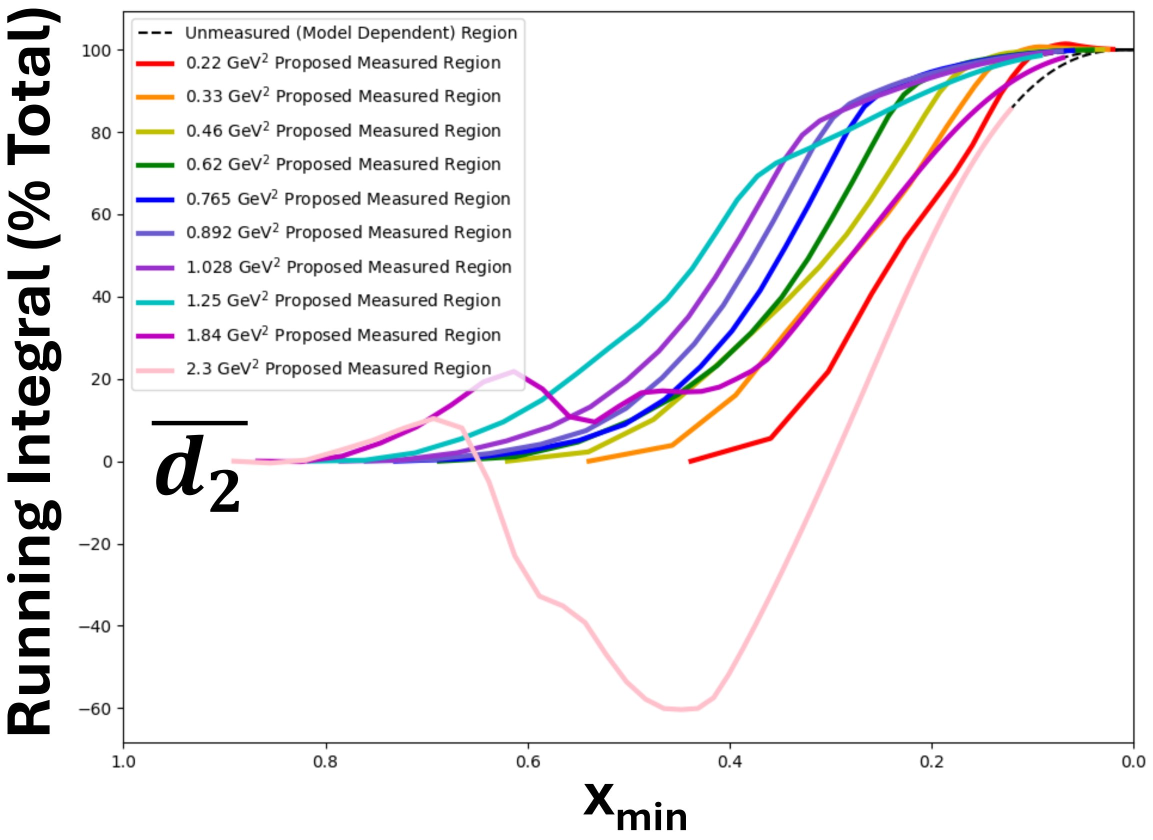
Running Integrals from $\int_{x_{min}}^{x_{th}} dx$

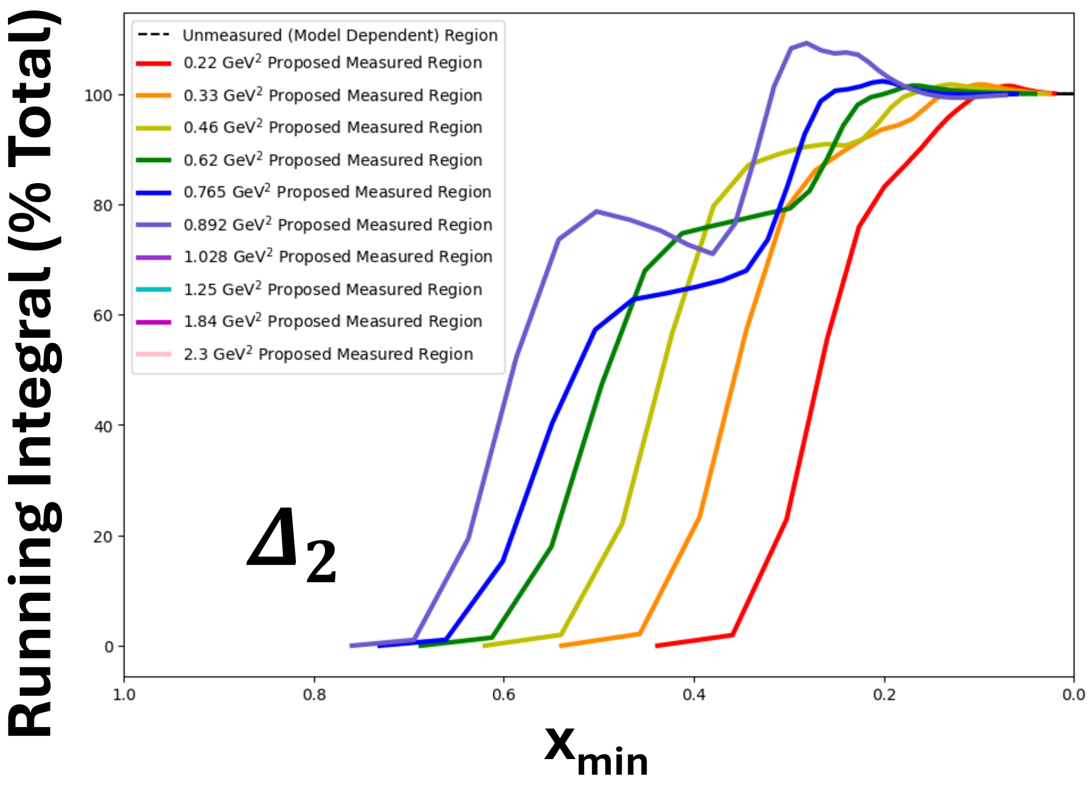




- Integrals are saturated in the measured region (flat slope)
- Therefore, **the low-x regime is irrelevant to these integrals**

Running Integrals as % Total Value ($\int_{x_{min}}^{x_{th}} dx$)





- Integrals are saturated in the measured region (flat slope)
- Therefore, **the low-x regime is irrelevant to these integrals**

What do the theorists have to say…?

"A clear case of 'low-hanging fruit' with a wealth of opportunities to address long-standing open questions."

"The measurement will be very important for future efforts to understand the proton's structure and the transition between parton and hadron descriptions of QCD dynamics"

– PR12-23-007 Theory Report

"[g_2] measurements over a range of Q2 are needed for a comprehensive understanding of the transition from perturbative to nonperturbative QCD"

"Scientifically sound, with a clear rationale and a well-designed experimental plan"

– PR12-24-002 Theory Report

Summary

- In 26 PAC Days, we will measure and publish fundamental observable g_2 across an order of magnitude range of the transition region $Q^2 = 0.22 – 2.2\ GeV^2$ 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**

Backup Slides

Rates Table

Total PAC Days: 13.0

E_0 (GeV)	Scattering Angle (deg)	P_0 (GeV)	Target Q^2 (GeV^2)	Proton Rate (Hz)	Rate (kHz)	Time (h)
4.4	6.5	3.607	0.22	77	40.0	1
		2.661		65	25.1	1
		1.963		69	18.9	1
	8	3.607	0.33	41	21.4	1.3
		2.661		28	11.5	1.9
		1.963		30	8.3	1.8
	9.5	3.607	0.46	18	9.1	2.3
		2.661		14	5.9	3.0
		1.963		15	4.3	2.8
	11.2	3.607	0.62	7	3.7	6.0
		2.661		6	3.0	6.5
		1.963		7	2.2	5.9
	12.5	3.607	0.765	4	2.0	9.1
		2.661		4	1.9	8.5
		1.963		4	1.5	7.6
	13.5	3.607	0.892	2	1.3	16.5
		2.661		3	1.3	13.7
		1.963		3	1.1	12.1
	14.5	3.607	1.028	1	0.8	23.2
		2.661		2	1.0	17.4
		1.963		2	0.8	14.9
	16	3.607	1.250	0	0.4	50.8
		2.661		1	0.6	32.7
		1.963		1	0.5	26.6
8.8	9.5	7.213	1.8	0	1.3	12.9
		5.321		0	1.6	9.3
	11	7.213	2.3	0	0.5	14.3
		5.321		0	0.8	8.2

Overhead

- **Total: 13.0 Overhead Days**

Overhead	Number	Time Per (hr)	(hr)
Target Anneal	26	2.0	52.0
Beamline Survey	10	8.0	80.0
Target Swap	2	4.0	8.0
Target T.E.	6	2.25	13.5
Target Field Ramp	10	1.0	10.0
Carbon, Dummy, Empty runs	28	0.5	14.0
Pass Change	2	4.0	8.0
Momentum Change	28	0.5	14.0
Moller Measurement	10(+1 shift)	4.0(+8.0)	48.0
Pair-Symmetric Background	2	4.0	8.0
Optics Calibration	2	16.0	32.0
BCM Calibration	2	4.0	8.0

Burkhardt-Cottingham Sum Rule

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

- "Superconvergence" Sum Rule for an amplitude whose imaginary part is g_2
- Assuming convergent dispersion relations for $g_2(\nu)$ and $\nu g_2(\nu)$, arises naturally from subtraction of VVCS amplitudes:
  - $Im\ S_2(\nu, Q^2) = \frac{2\pi}{\nu^2 M} g_2(x, Q^2)$
  - $S_2(\nu, Q^2) = \frac{2}{\pi} \int_{\nu_{th}}^{\infty} \frac{\nu\ Im\ S_2}{\nu'^2 - \nu^2} d\nu'$
  - $\nu S_2(\nu, Q^2) = \frac{2}{\pi} \int_{\nu_{th}}^{\infty} \frac{\nu' Im\ S_2}{\nu'^2 - \nu^2} d\nu'$
- B.C. Integral converges to 0 in both QED and Perturbative QCD, and follows from Wandzura-Wilczek relation (Altarelli et al [1994], R. L. Jaffe [1990 Review])

Reliability of the Chicane

- Chicane is a <u>new</u> installation, not a refurbishment of the old chicane
- Design is fundamentally similar to numerous similar projects by the JLab staff, nothing untested or uncertain about it
- Dr. Benesch is the longest serving member of the TAC and has designed resistive and superconducting magnets since 1976
- Design is “Proof of Principle” only in sense that mm scale refinements still need to be made
- Staff scientists are very confident that chicane will be carefully built and tested and will work well, but will need some time to commission

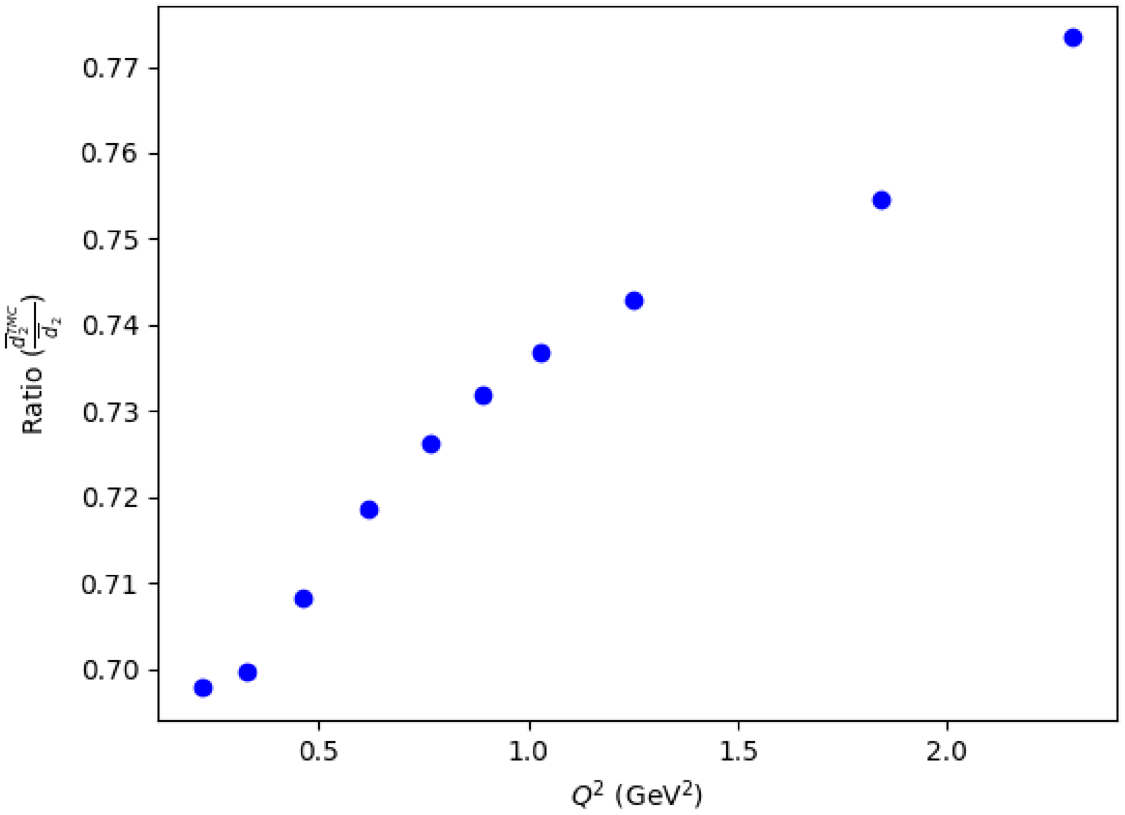
Target Mass Corrections

- Target Mass Corrections irrelevant for a purely experimental quantity like g_2
- But are needed to compare moments to theory
- Use Nachtmann Moments instead of Cornwall-Norton:

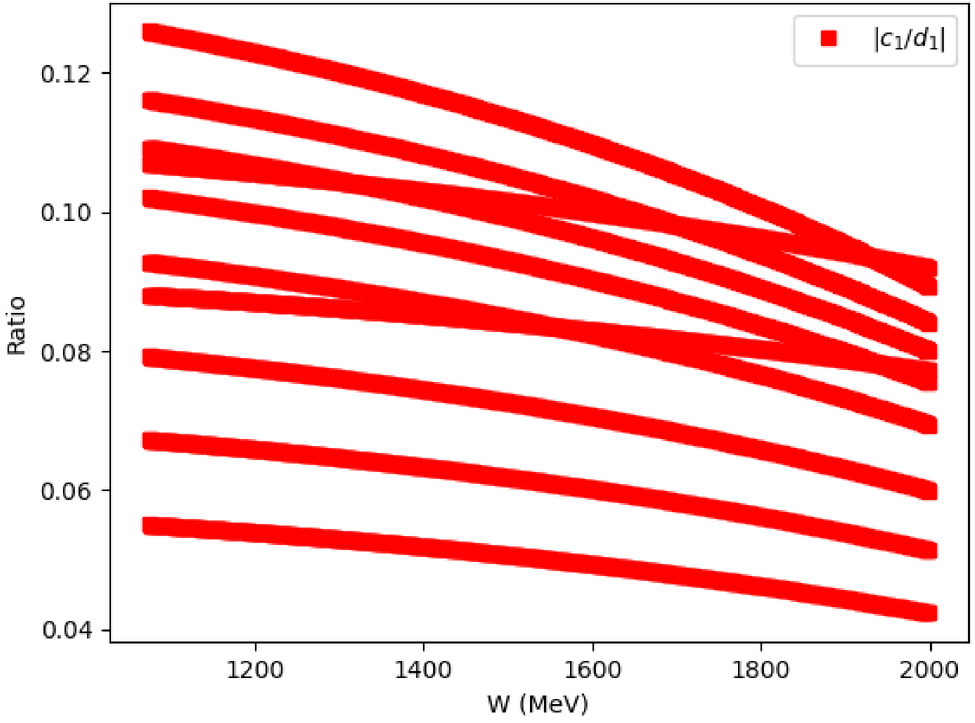
$$M_2^{(n)}(Q^2) = \int_0^1 dx \frac{\xi^{n+1}}{x^2}\left\{\frac{x}{\xi} g_1(x,Q^2) + \left[\frac{n}{n-1}\frac{x^2}{\xi^2} - \frac{n}{n+1} y^2 x^2\right] g_2(x,Q^2)\right\}, \quad (n = 3, 5, \ldots),$$

$$\xi = \frac{2x}{1+\sqrt{1+4y^2x^2}}.$$

$$2M_2^{(3)} = \text{Nachtmann Moment of } \overline{d_2}$$



Sensitivity to $\Delta\sigma_{\|}$



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

88-96% of g_2
From this proposal

4-12% of g_2
From Hall B Data which has its own (small) systematics

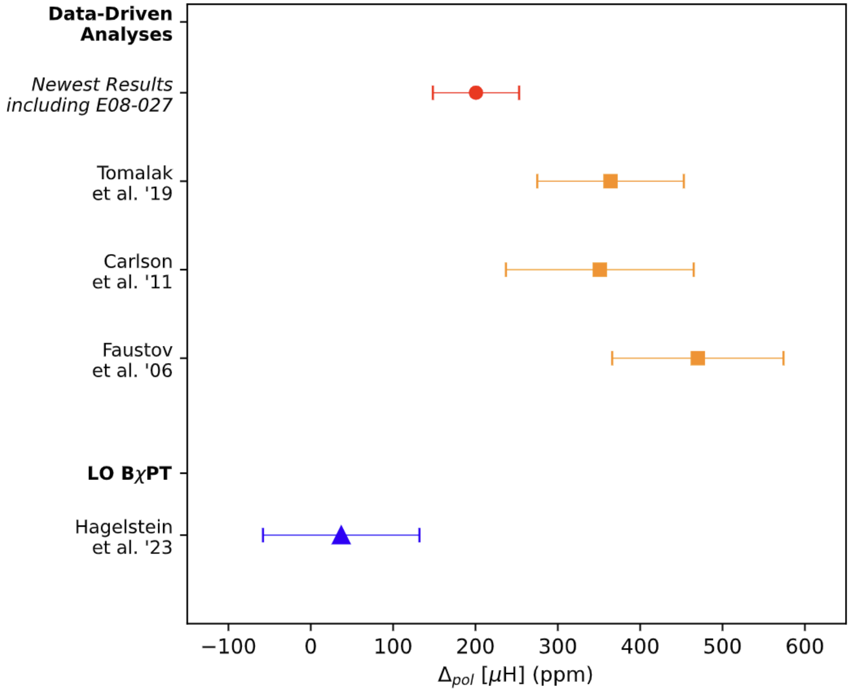
Multiple Scattering

- TAC Question if Multiple Scattering in the target could expand the beam spot enough to hit the exit beampipe (6 mm clearance)

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{p} z \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

- Using g2p values for x/X_0, and the proposal beam energies for p (z = charge number = 1 for electrons) we obtain:
- The beam will take 12.684 m to expand by 6mm, being well out of the small diameter pipe (3.3 m length)
- Less than 0.0008% of the beam will interact with the pipe, so **this background is negligible**

Hyperfine Details



Contribution	Value	% Total Value	Uncertainty	% Total Uncertainty
2γ HFS Contributions (Proposal Eq. 13)				
Δ_Z	-7703 ppm	86%	± 15 ppm	10%
Δ_{recoil}	931 ppm	10%	± 13 ppm	9%
$\boldsymbol{\Delta_{\mathrm{pol}}}$	**351 ppm**	**4%**	**± 112 ppm**	**81%**
Δ_{pol} Contributions (Proposal Eq. 14)				
Δ_1	5.69	67%	±1.04	72%
$\boldsymbol{\Delta_2}$	**-1.40**	**33%**	**± 0.41**	**28%**
Δ_2 Contributions (Proposal Eq. 15)				
Extrapolation ($Q^2 < 0.02$ GeV^2)	-0.20	14%	±0.10	25%
Data ($0.02 \leq Q^2 \leq 0.2$ GeV^2)	-0.78	56%	±0.19	46%
Extrapolation ($\mathbf{Q^2 > 0.2}$ GeV^2)	**-0.42**	**30%**	**± 0.12**	**29%**
PR12-24-002 ($0.2 < \mathbf{Q^2} < 2.2$ GeV^2)	**-0.41**	**30%**	**± 0.02**	**5%**

g2p (E08-027) Data helped to reduce tension significantly by being more negative than expected...

Will transition region data do the same and eliminate the tension? We need to know