g2p2 Experiment Preparations

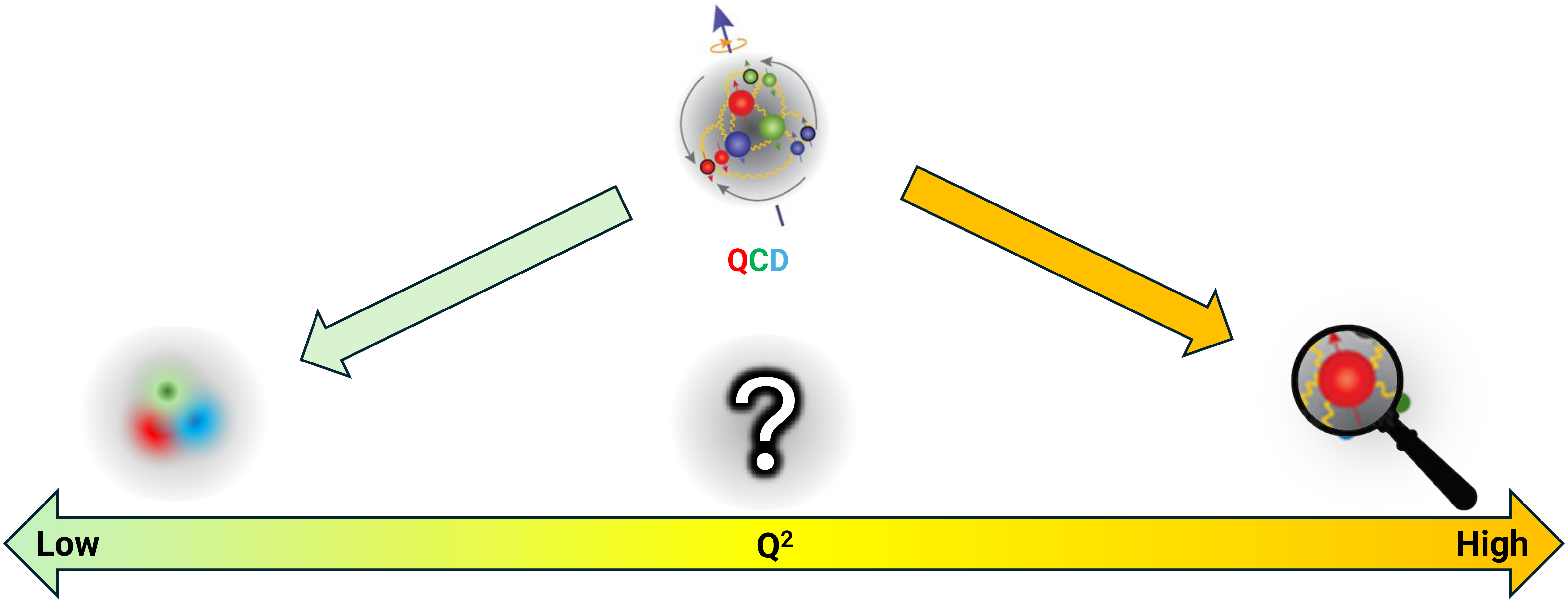
Tensor SIDIS Workshop

6/5/26

David Ruth

NM STATE

Jefferson Lab



- 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 / F_2 structure functions describe quark-gluon distribution:

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

- In a spin-½ polarized system, g_1/g_2 describe the spin distribution :

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

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

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

$\overline{g_2}$ - Never measured for the proton!

Twist-3

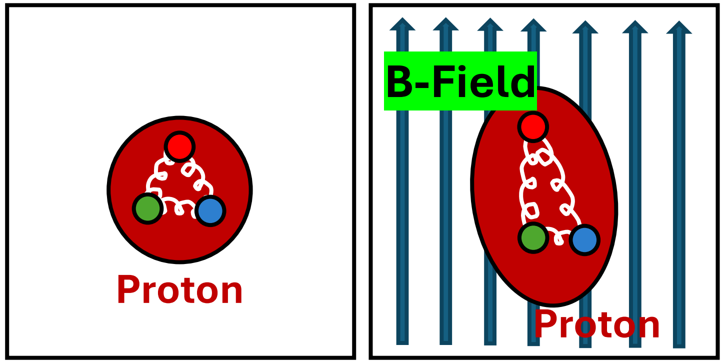
Function of g_1

- **Benchmarking (Lattice) QCD:**

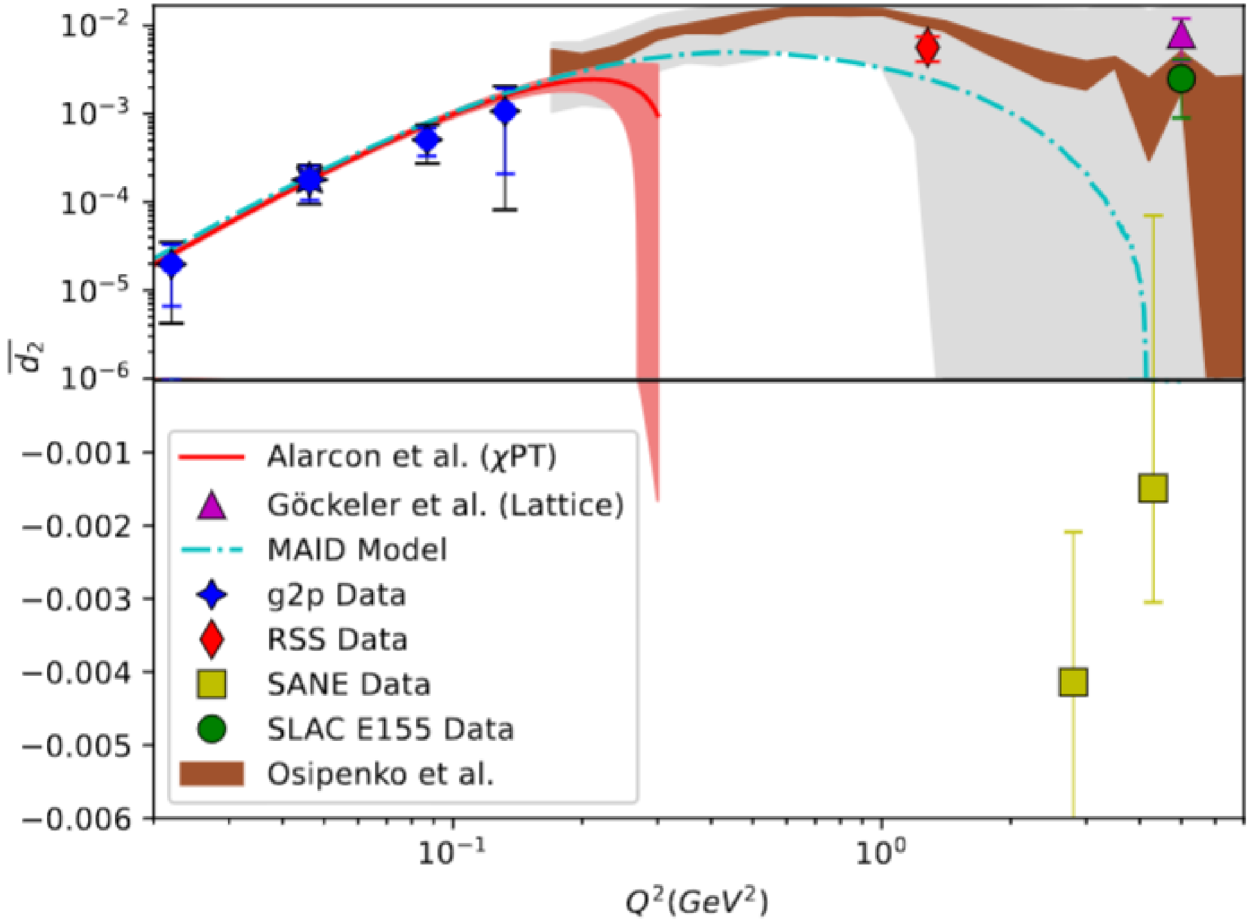
Weighted integrals (moments) of the spin structure functions can be directly calculated by effective theories:

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

Polarizabilities describe nucleon's ensemble response to an external field



“Color Polarizability” 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: color polarizability / “color Lorentz force”
- Interesting differences in existing data motivate further study
- **Upcoming lattice predictions** in this region need experimental benchmark!

g_2 is the perfect quantity to study the transition regime…

- Examine quark-gluon correlations ✅
- Study interaction dependent (twist-3) effects ✅
- Benchmark Lattice QCD ✅
- However…

$g_2(x, Q^2)$

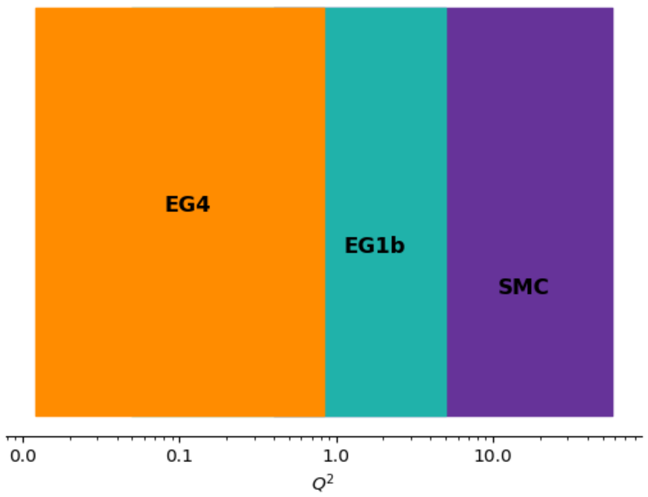
$\overline{g_2}$

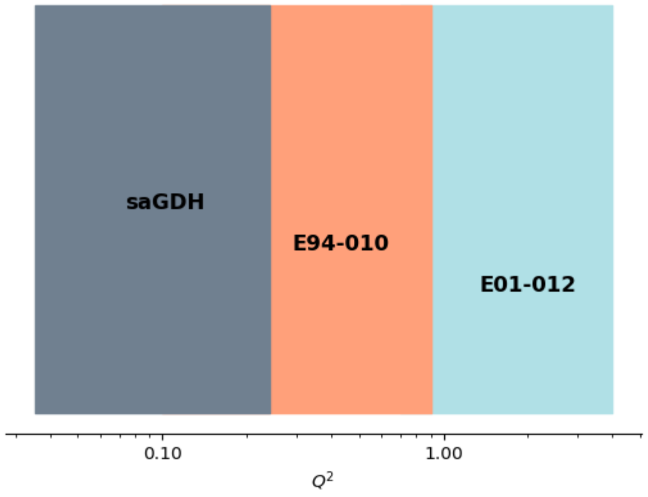
d_2

Proton

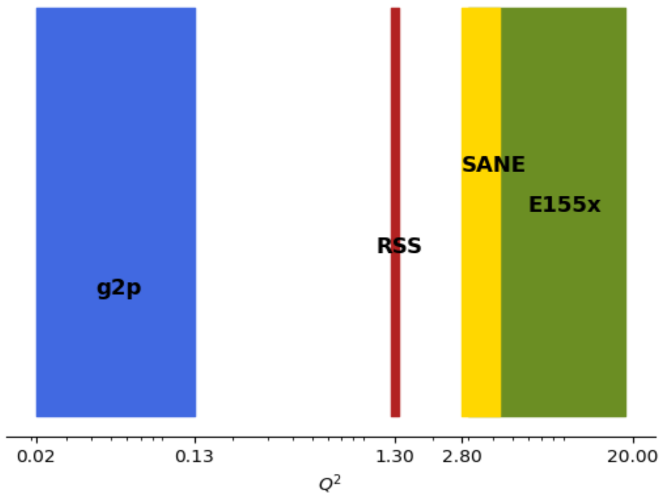
Neutron

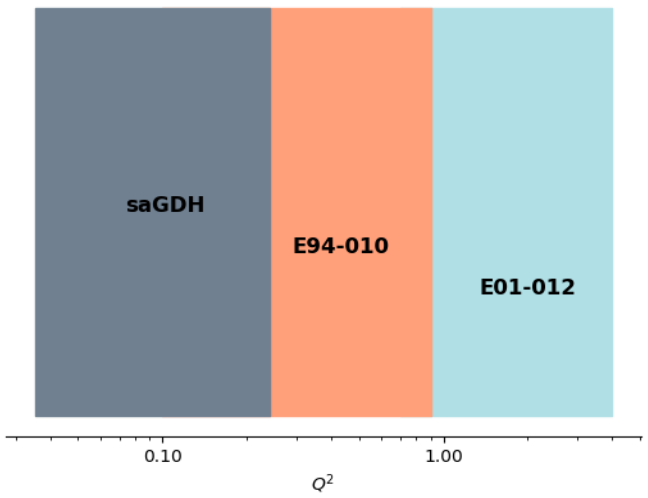
g_1



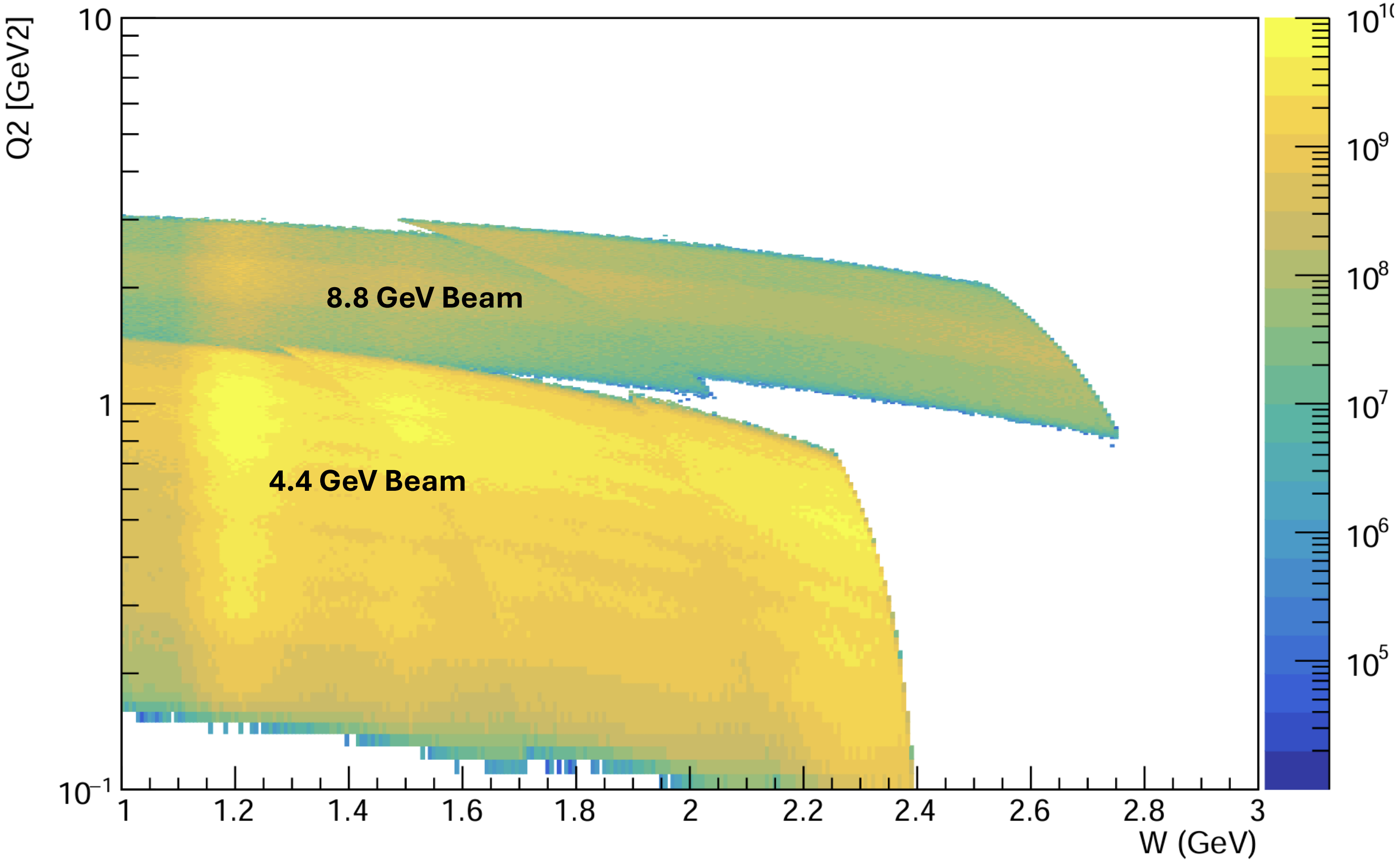


g_2



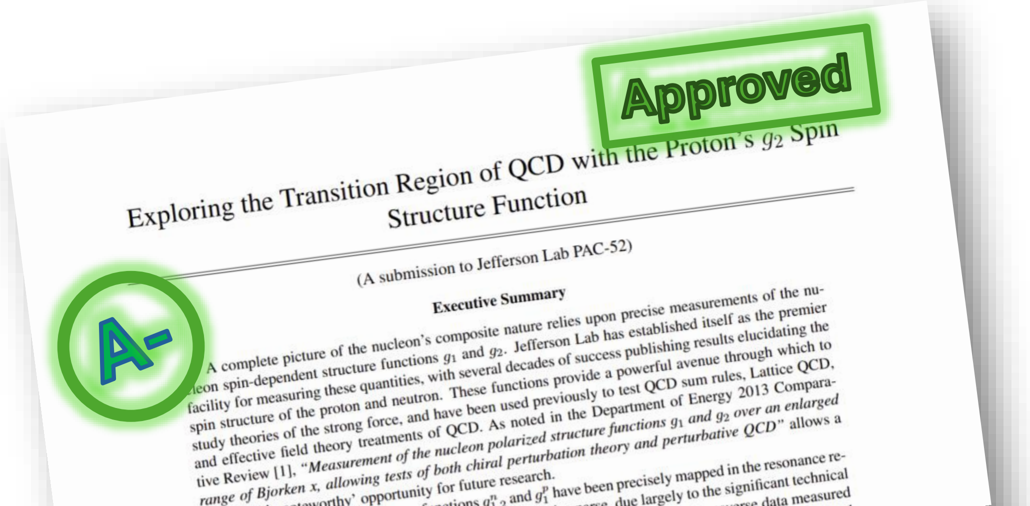


g2p2 Experiment (**E12-24-002**)



26 PAC Days

- 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
- Collect the first transition region measurement of the proton's g_2, and extract its moments and higher twist effects



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

(A submission to Jefferson Lab PAC-52)

Executive Summary

A complete picture of the nucleon's composite nature relies upon precise measurements of the nucleon spin-dependent structure functions g_1 and g_2. Jefferson Lab has established itself as the premier facility for measuring these quantities, with several decades of success publishing results elucidating the spin structure of the proton and neutron. These functions provide a powerful avenue through which to study theories of the strong force, and have been used previously to test QCD sum rules, Lattice QCD, and effective field theory treatments of QCD. As noted in the Department of Energy 2013 Comparative 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 'noteworthy' opportunity for future research.

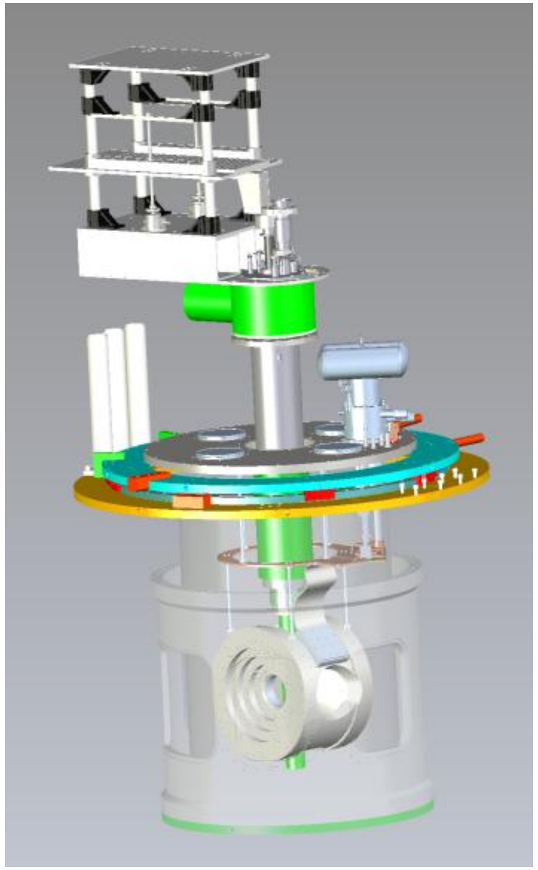
... and g_1^p have been precisely mapped in the resonance re... due largely to the significant technical ... data measured

Synergy with Tensor Experiments

- Hall C Experimental setup shares many equipment needs:
  - ➢**Solid Polarized DNP Target**
  - ➢**Slow Raster**
  - ➢**Low Current Beamline Instrumentation**

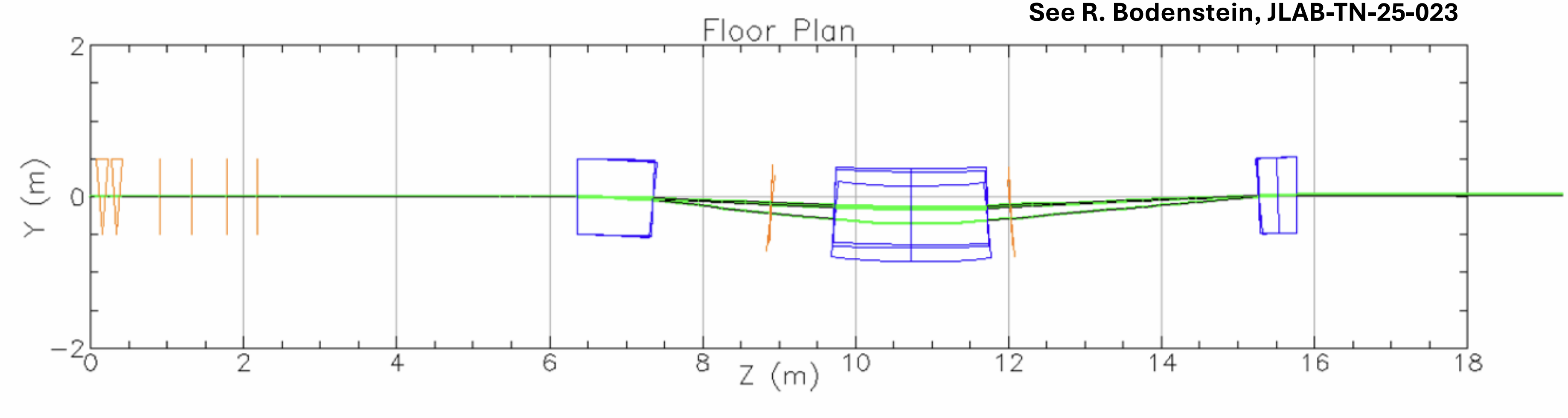
- Differences:
  - ➢~~**Tensor Enhancement Techniques**~~
  - ➢**Chicane Magnets**
  - ➢**Transverse Target Field**
  - ➢**Beamline revision to include pivot**

- Seems likely to be scheduled for run period after b_1/A_{zz}
- **Makes sense to collaborate on building the target, etc.**
- **Potential for shared ERR**



Chicane Magnet

See R. Bodenstein, JLAB-TN-25-023



- The transverse target field needs pre-bending of the beam
- Chicane design (J. Benesch) would replace two existing 1m dipoles
- Further BMAD optimization performed by R. Bodenstein
- **High Priority: designs/drawings for the chicane and hoist-included beamline**

g_2 Extraction Method

- Measure Asymmetry and Cross Section:

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

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

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

Spin-Dependent Effects

Unpolarized Scattering

- Form Polarized XS Difference:

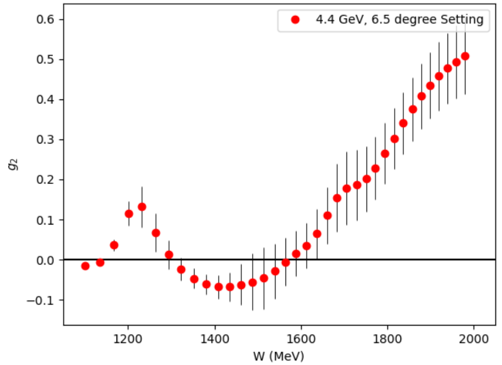
$$\Delta\sigma_{\perp} = 2A_{\perp}^{exp}\sigma_0$$

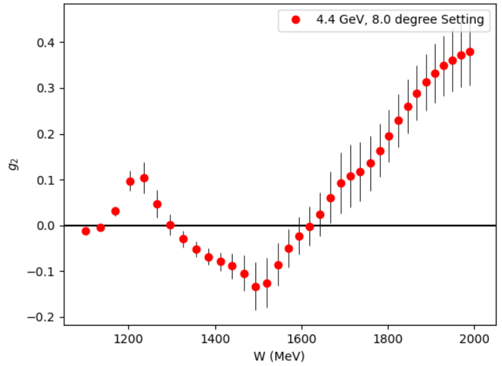
- Extract g_2

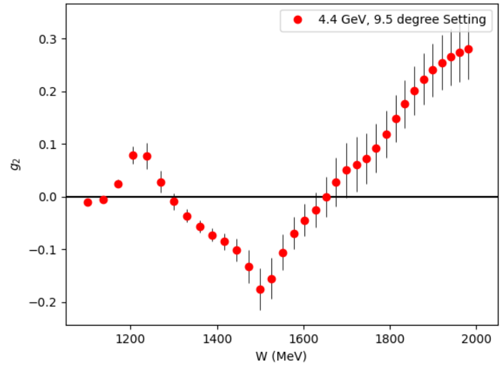
Input from Hall B Data

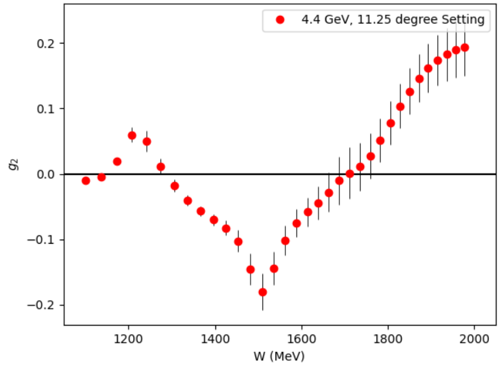
$$g_2(x, Q^2) = \frac{K_1 y}{2}\left[\Delta\sigma_{\perp}\left(K_2 + \tan\frac{\theta}{2}\right)\right] + \frac{g_1(x, Q^2)y}{2}$$

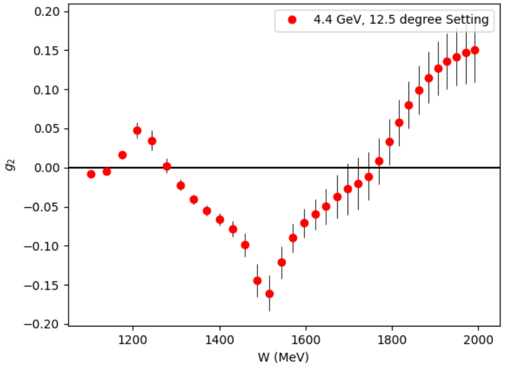
Projected g_2 Uncertainties

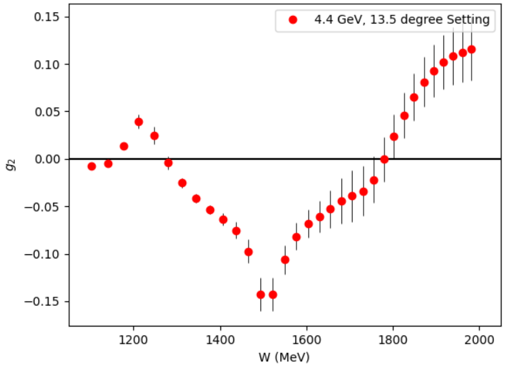


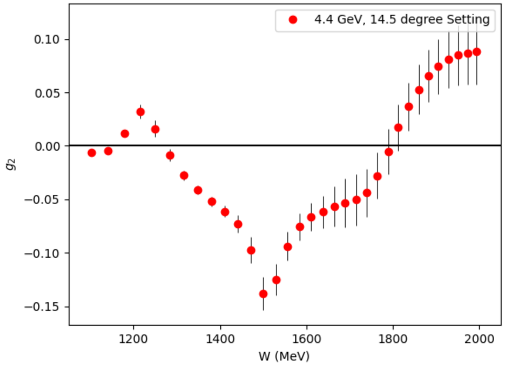


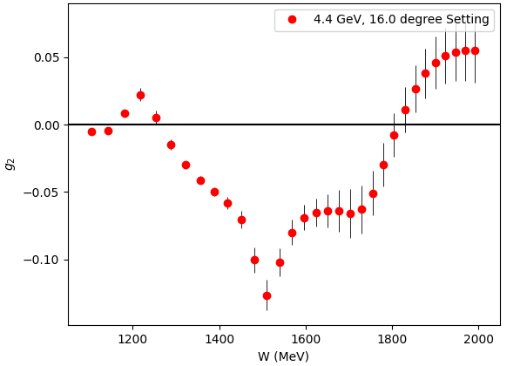




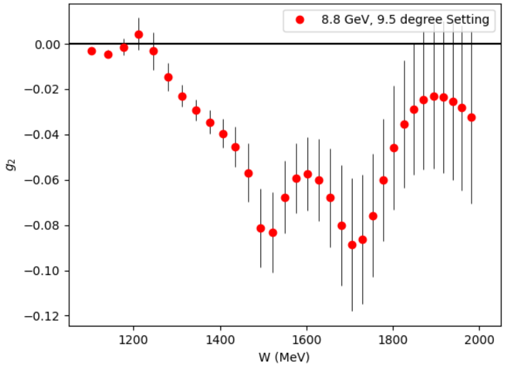


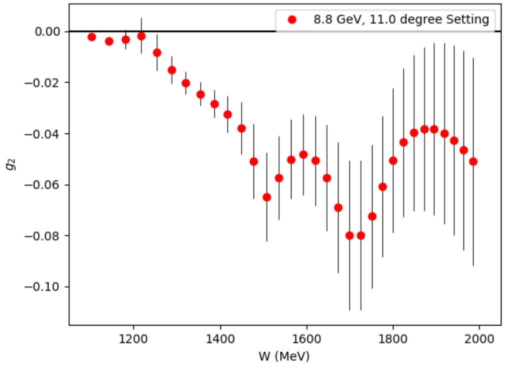






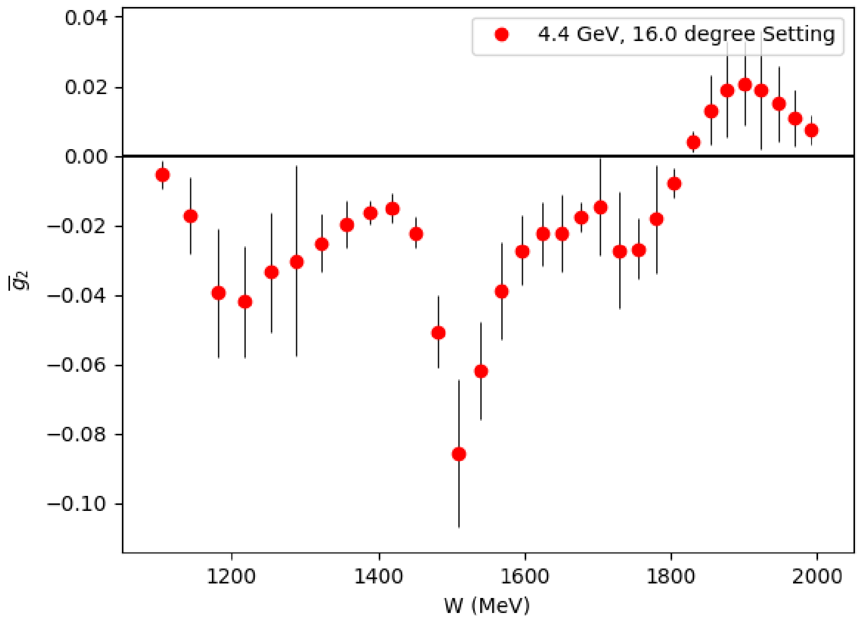
Covers almost the entire transition region





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

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



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

Small

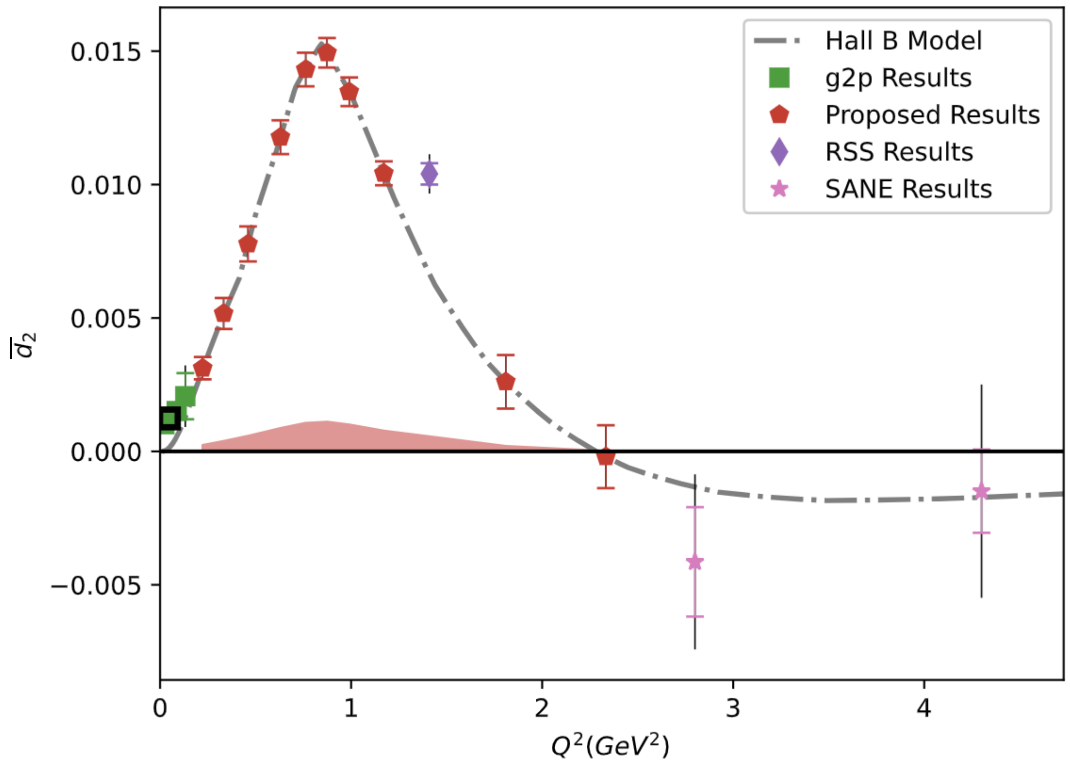
Utilize CLAS Hall B Results for g_1 in same regime

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

- Direct extraction of Twist 3 effects **in the regime they contribute most significantly**
- Can also be used to study *Dynamical Mass Generation*

World First Extraction of this quantity

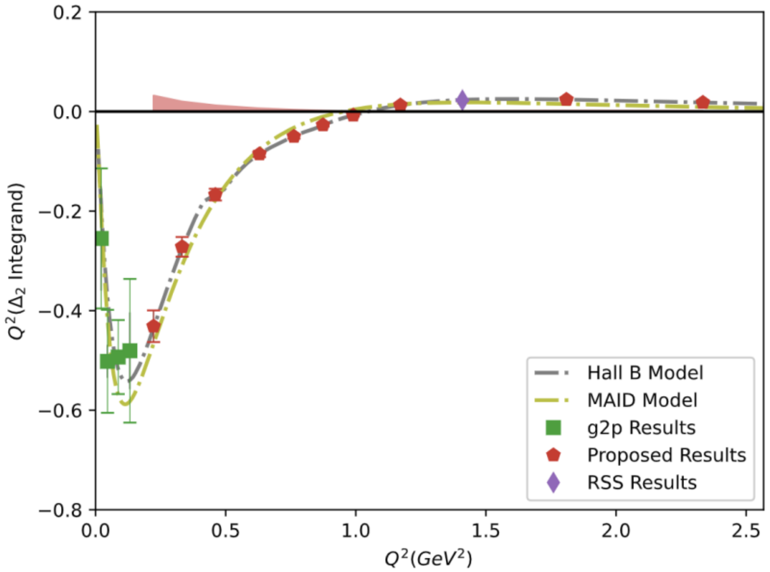
Projected $\overline{d_2}$ Uncertainties



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

New Lattice calculations expected *in next few years!*

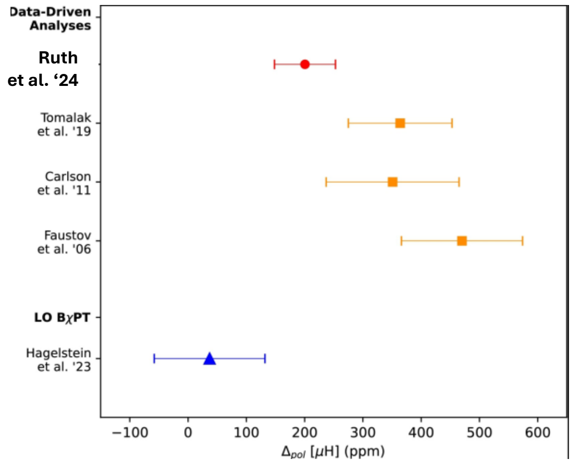
Hyperfine Splitting Impact



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

- 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}!

Δ_{pol}



Preparing for ERR

- **Major Requirements (guess):**
  - Proving the transverse target will be operational in time
  - Designs and drawings for beamline revision outlined by D. Gaskell
  - Proving the beamline instruments can run at 85 nA

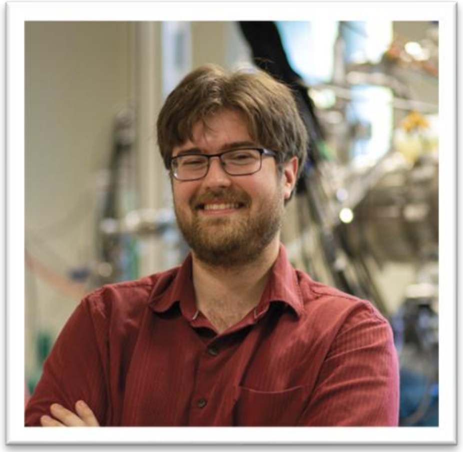
- Collaboration is ready to send students to help build the target
- Need support from the lab to complete beamline design work + drawings
- **Hall C / Target Group Review Late 2027**

Thanks to the Collaboration!

Jian-Ping Chen

Nathaly Santiesteban

Karl Slifer



David Ruth

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R. Bodenstein
D. Higinbotham
M. Jones
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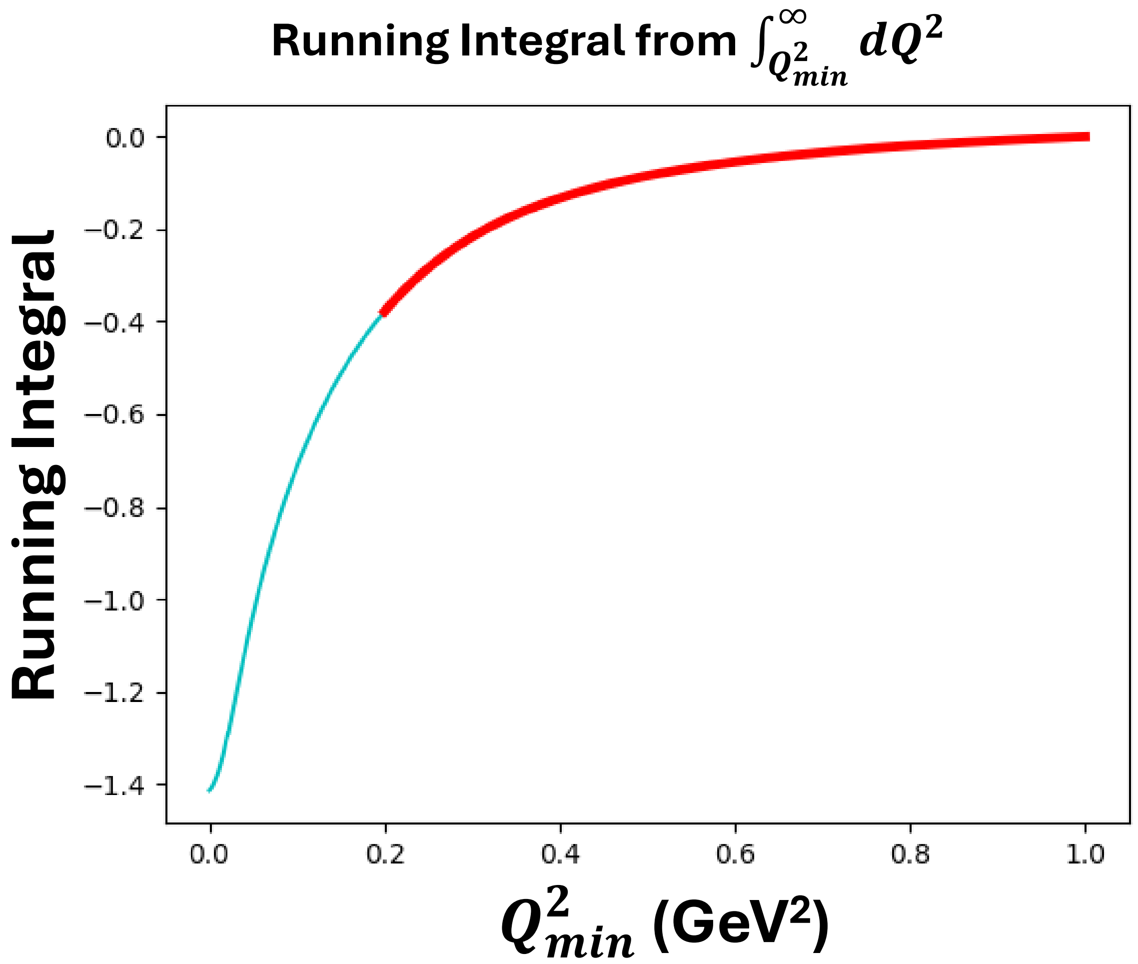
Backup Slides

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!

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	11	7.213	2.3	0	0.5	33.3
		5.321		0	0.8	19.0
	14	7.213	3.44	0	0.1	101.8
		5.321		0	0.2	31.6

Overhead

- **Total: 12.7 Overhead Days (305.5)**

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	4	24.0
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

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

- “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])

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!