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

-

C12-24-002
Jefferson Lab PAC 53
6/16/2025

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Experiment Overview

Hall: C

Goal Observables:

- g_2 Spin Structure Function
- $\overline{d_2}$ Polarizability
- Δ_2 Hydrogen Hyperfine Splitting Contribution
- $\overline{g_2}$ Twist 3 Effects
- g_T PDF

Needed Equipment:

- Solid Transversely-Polarized Target
- Chicane Magnet
- Beamline Instrumentation

Detectors: SHMS

Beam Current: 85 nA

Beam Energies: 4.4 GeV, 8.8 GeV

Target Material: NH_3 (Ammonia)

Q^2 Range: 0.22 – 2.2 GeV^2

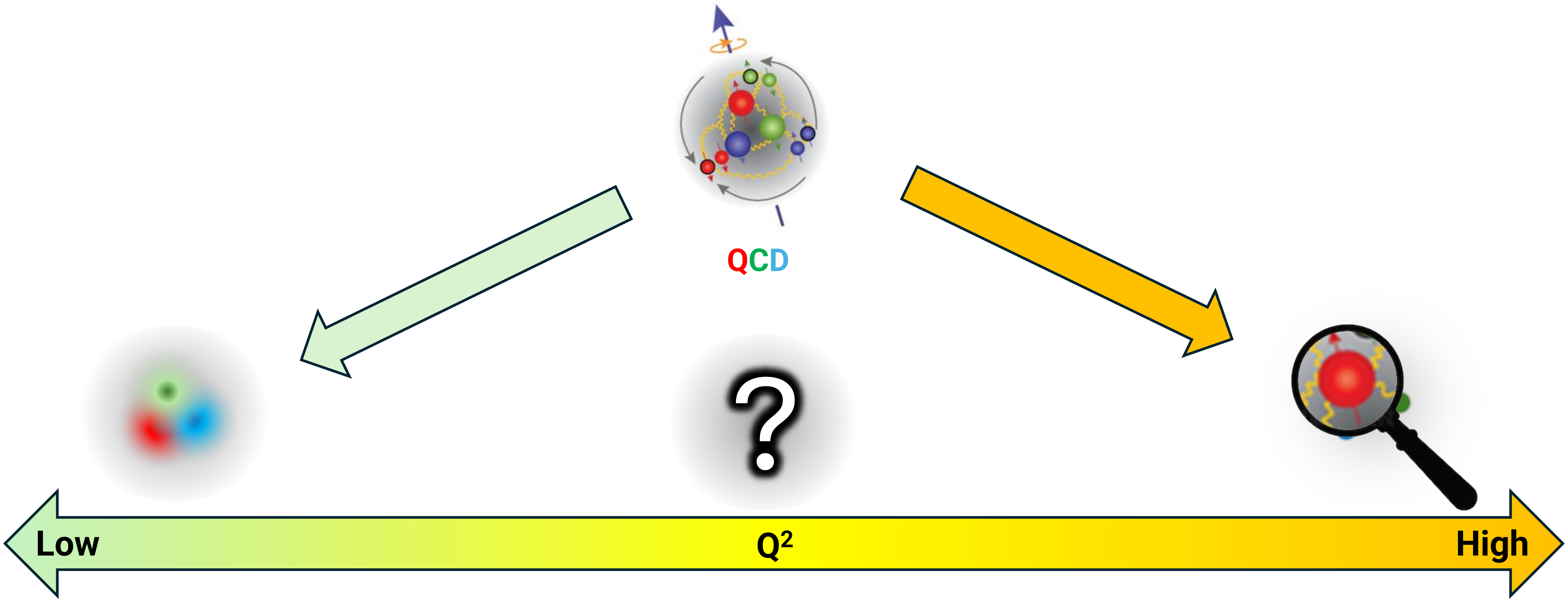
W Range: 1078 – 2400 MeV

Requested Days: 26

Current Status: C2 (Conditional Approval)

PAC52 Report Conditions:

- "The impact of this new setup on the detector resolution and its subsequent effect on the physics results has not been thoroughly addressed. **A full Monte Carlo simulation** of the new setup and detector is needed." **(✅ Complete)**



- 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:**

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

Small

Function of g_1

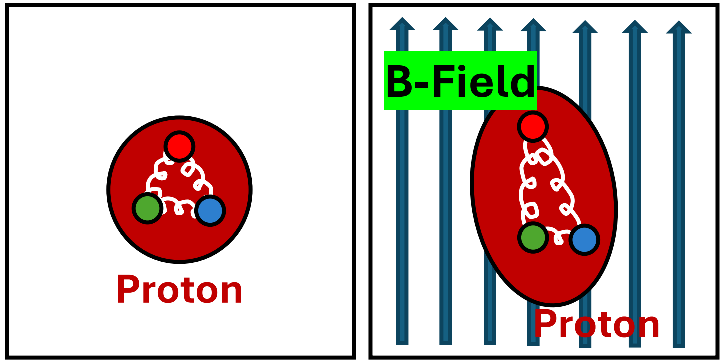
Twist-3

- **Benchmarking (Lattice) QCD:**

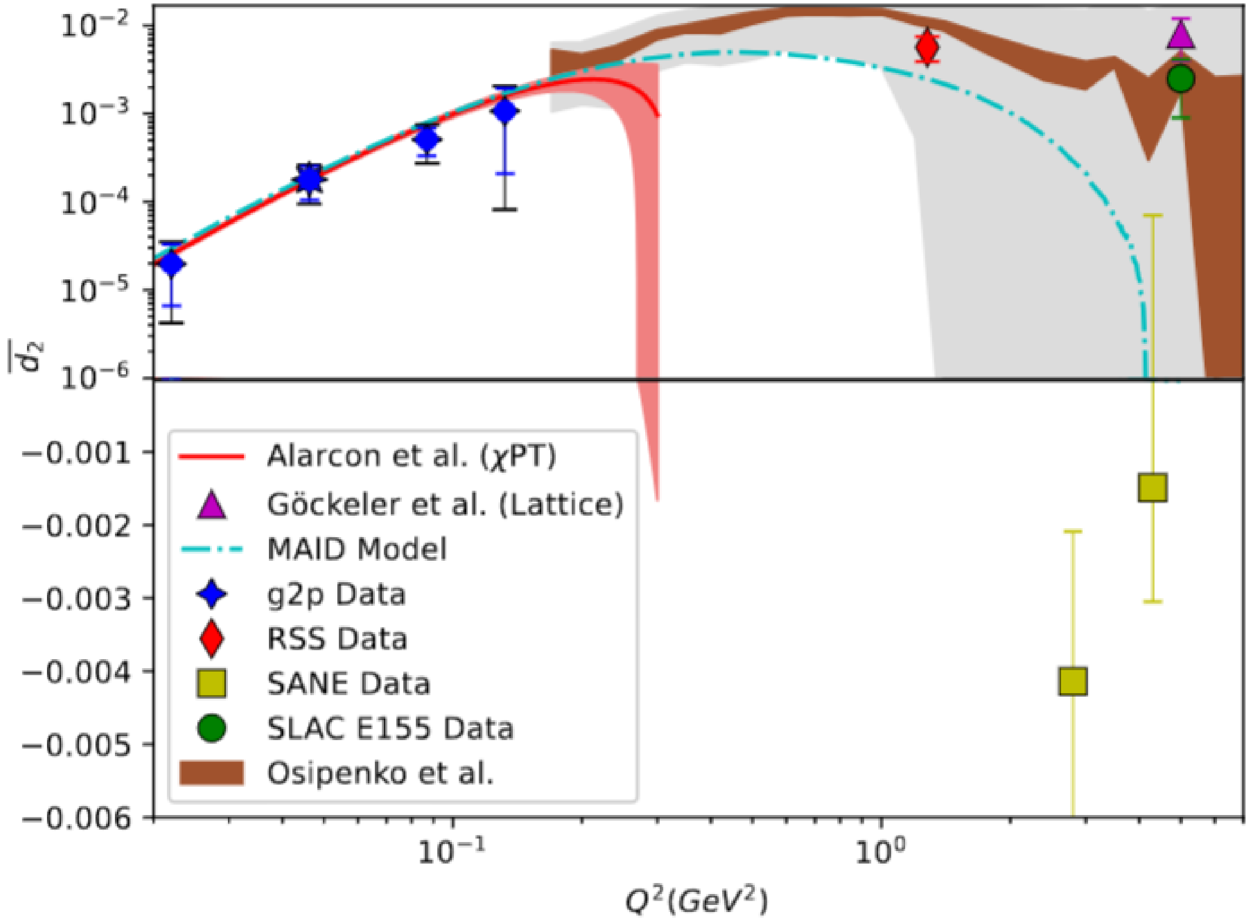
Weighted integrals (moments) of the spin structure functions can be directly calculated by effective theories:

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

Polarizabilities describe nucleon's ensemble response to an external field



"Color Polarizability" d_2



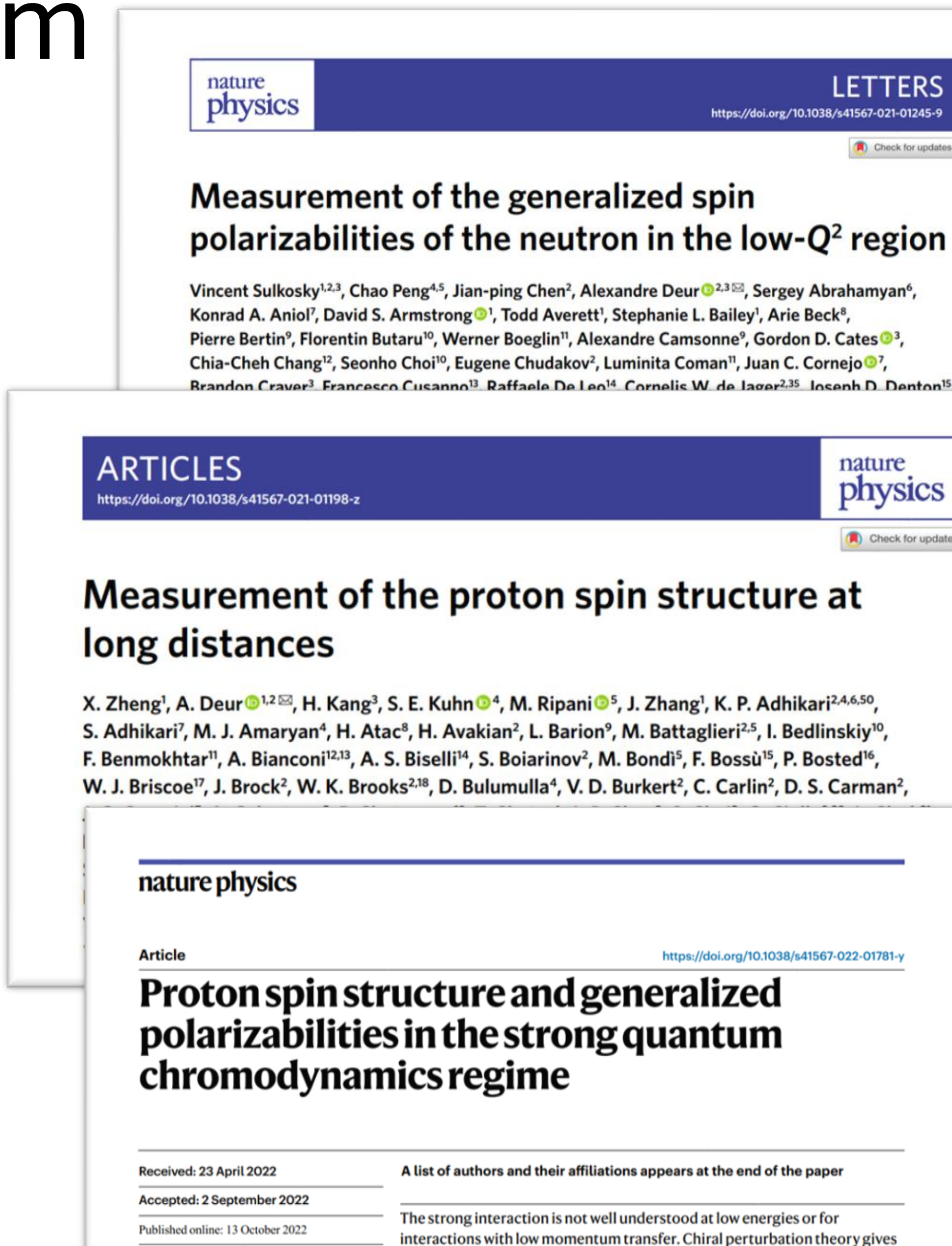
$$\overline{d_2} = \int_0^{x_{th}} x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

- 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!

Recent Successful JLab Program

- **Highly** successful program to measure SSF
- 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], ...

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

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

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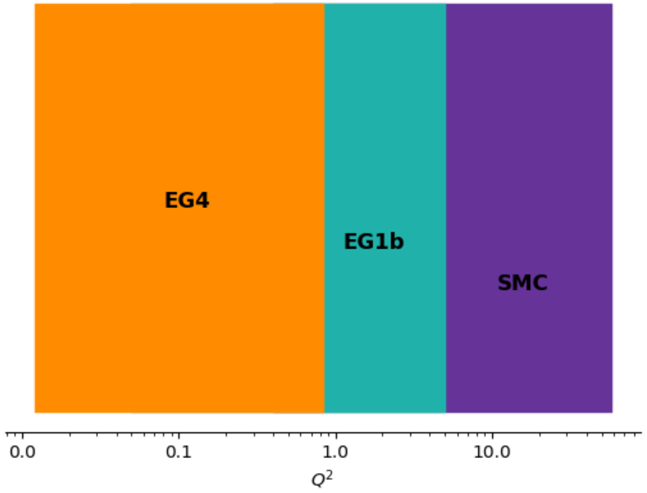
A list of authors and their affiliations appears at the end of the paper

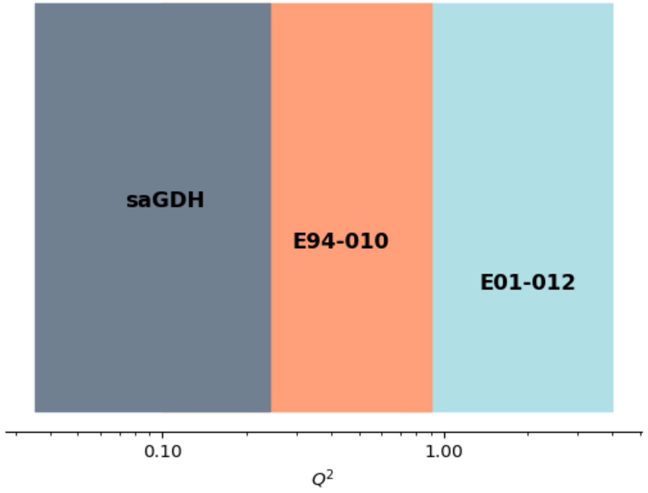
The strong interaction is not well understood at low energies or for interactions with low momentum transfer. Chiral perturbation theory gives

Proton

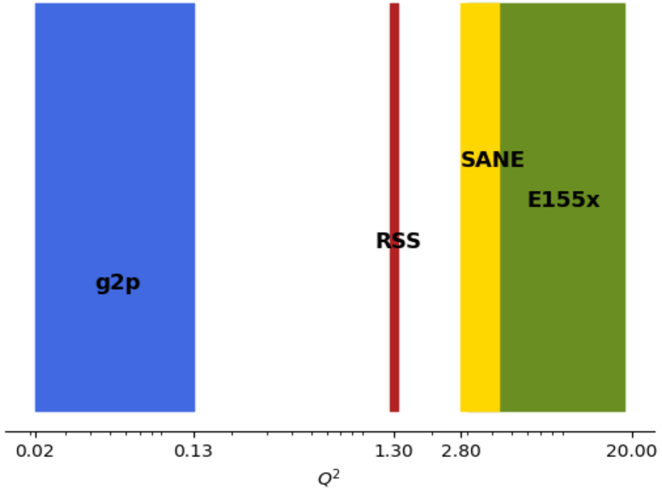
Neutron

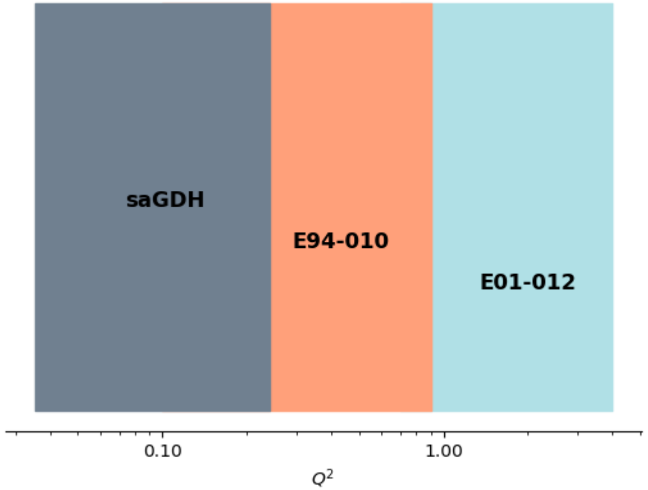
g_1





g_2





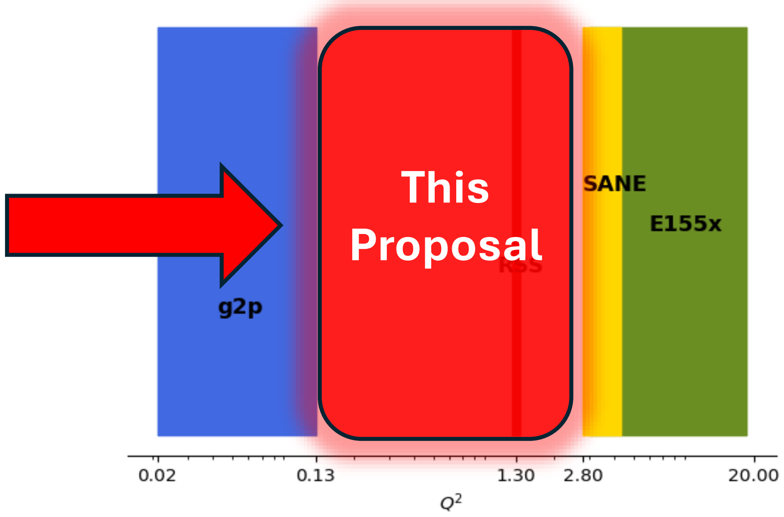
Should be Easier than 3 previous Hall A/C measurements at JLab:

- **<u>Much higher rates</u>** than the higher Q^2 experiments
- **<u>Smaller out-of-plane angle</u>** than the low Q^2 data

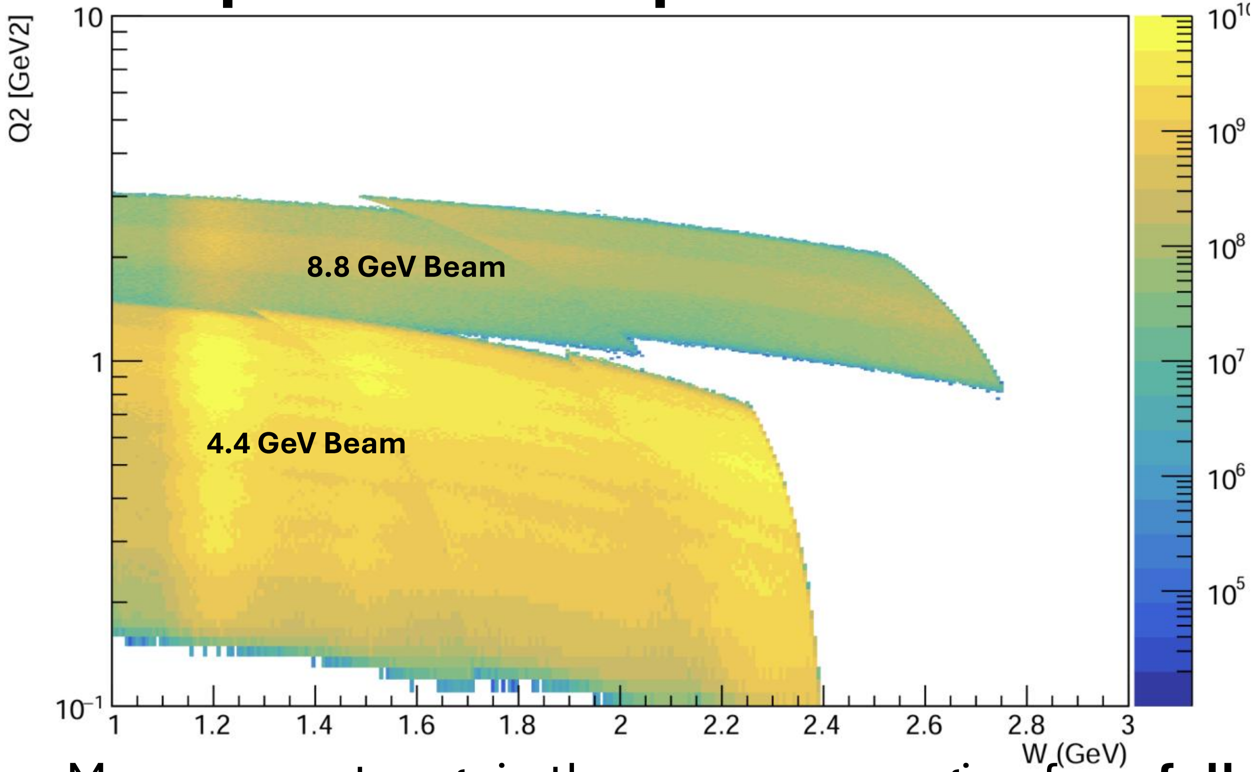
Transition Region g_2 has Strong scientific motivation:

- **<u>Needed</u> as a Benchmark for Lattice QCD**
- **Unique Sensitivity to Twist-3 Effects**

g_2

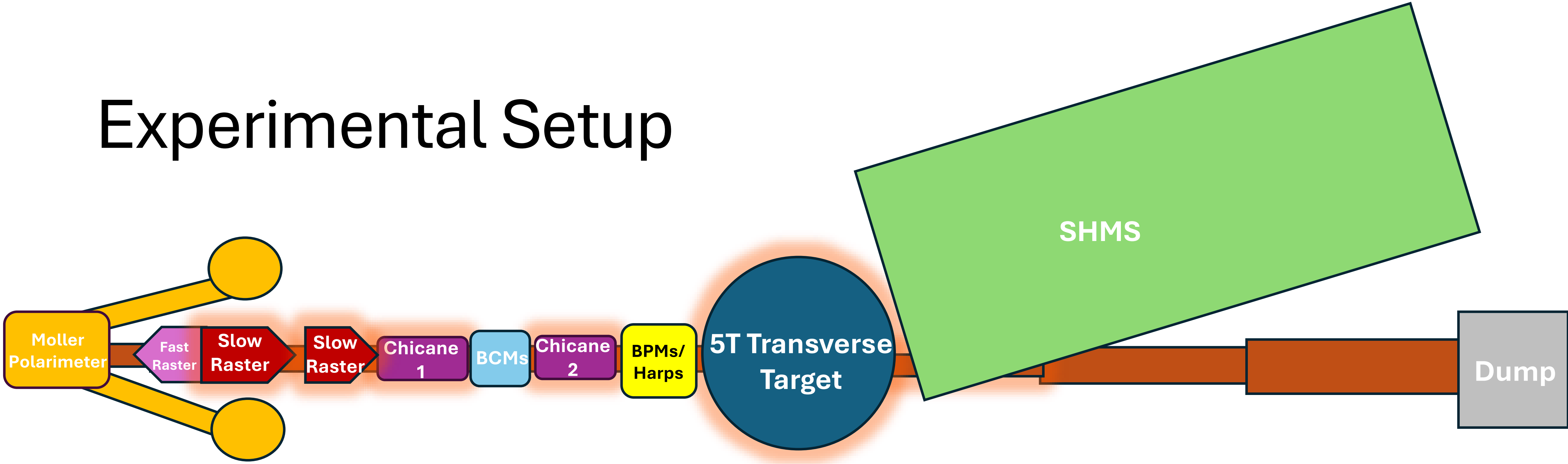


Proposed Experiment



- Measure proton g_2 in the resonance region for **<u>a full order of magnitude in Q^2 range</u>** 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

Experimental Setup



Standard equipment package, plus:

- 5T polarized target
- Chicane Magnet
- Low current beamline configuration
- Slow Raster

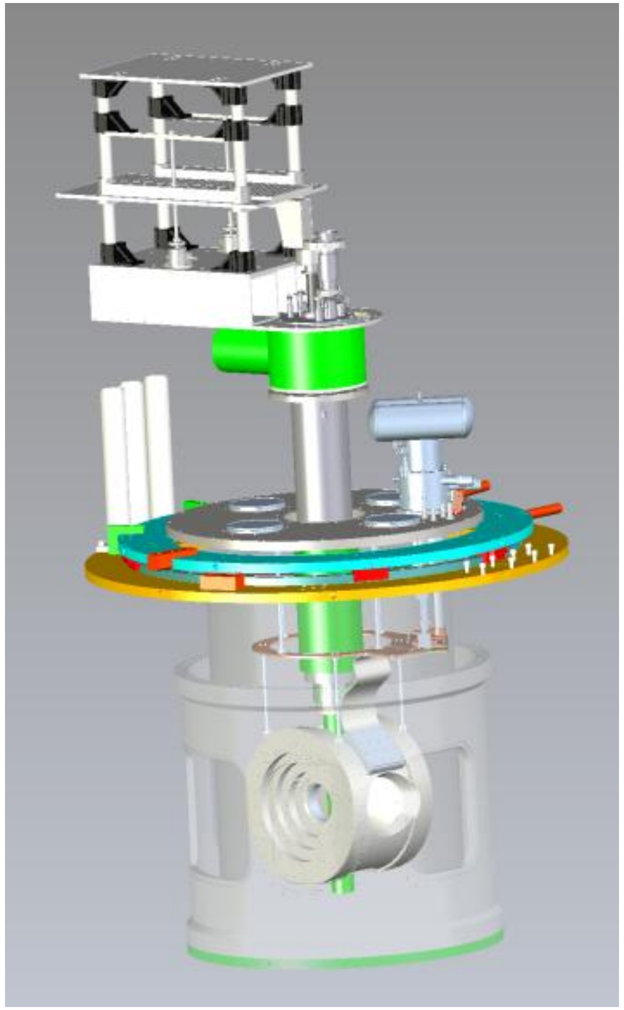
Nearly identical to the successful setup for previous Hall A/C experiments RSS, EG4, g2p

Polarized Target

- NH_3 (Ammonia) target
- Transversely Polarized with Dynamic Nuclear Polarization (DNP)

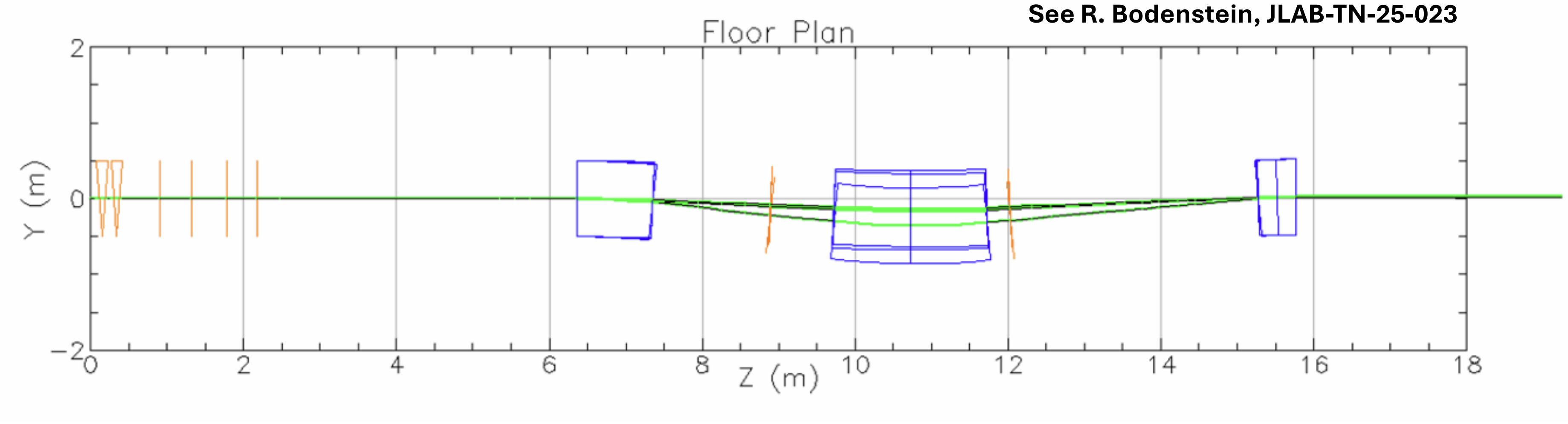
- Since previous experiments:
  - New Target Group magnet **more optimized for transverse running!**

- Several polarized target experiments already approved in Hall C – possibility for



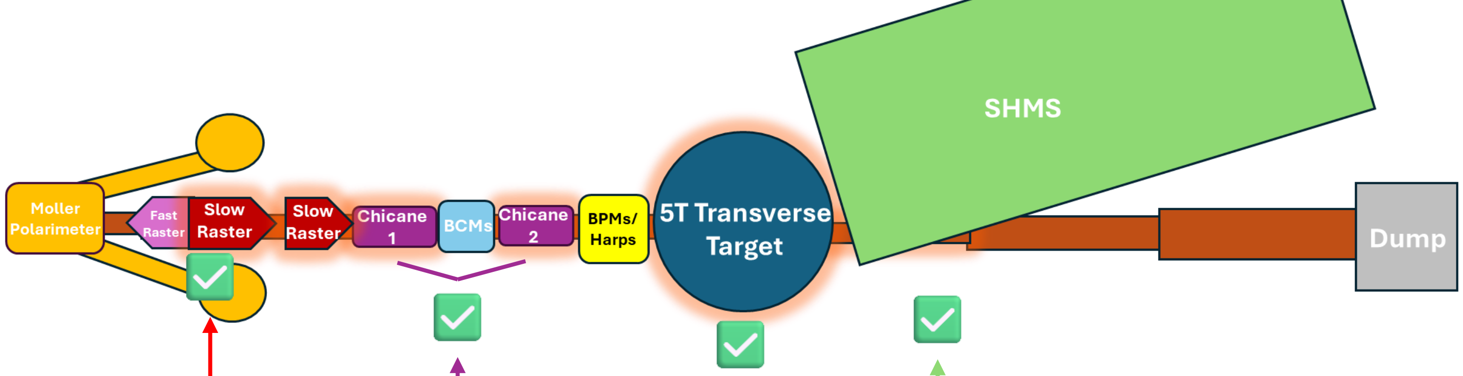
Chicane Magnet

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
- Chicane will be needed for SoLID and any other experiment with transverse polarized target

Simulation Study



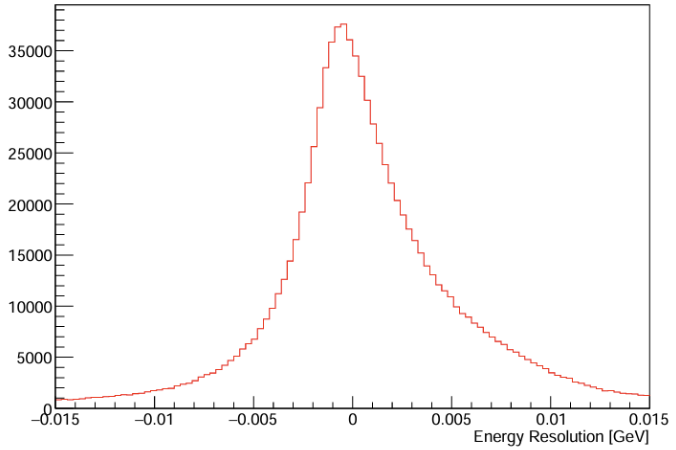
- **Monte-Carlo simulation performed with all effects included & accounted for:**
  - **Raster**
  - **Chicane**
  - **Target Field**
  - **Spectrometer Optics**
- Transverse target field calculation:
  - Field Map
  - Iterative Runge-Kutta procedure
- Chicane optimization: BMAD and Optim
- Standard Hall C analysis cuts
- Systematic impact on observable **now included**

All following plots are for the **worst case** kinematic setting at the lowest Q^2.

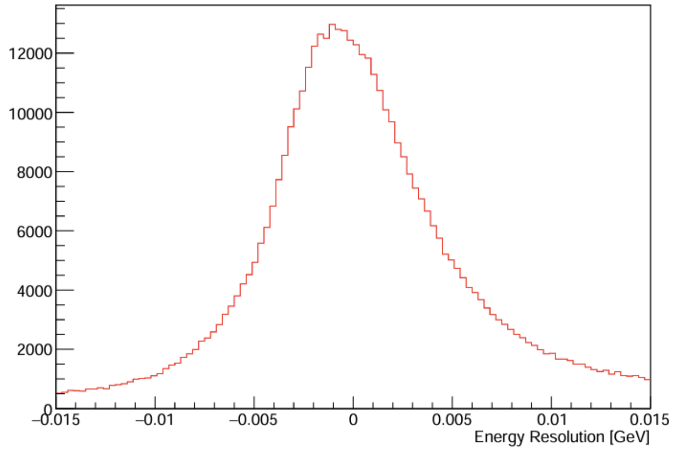
Target field/chicane effects are smaller for all other settings.

Thanks to Jefferson Lab Staff Scientists
Dave Gaskell, Jay Benesch, and Ryan Bodenstein for their help!

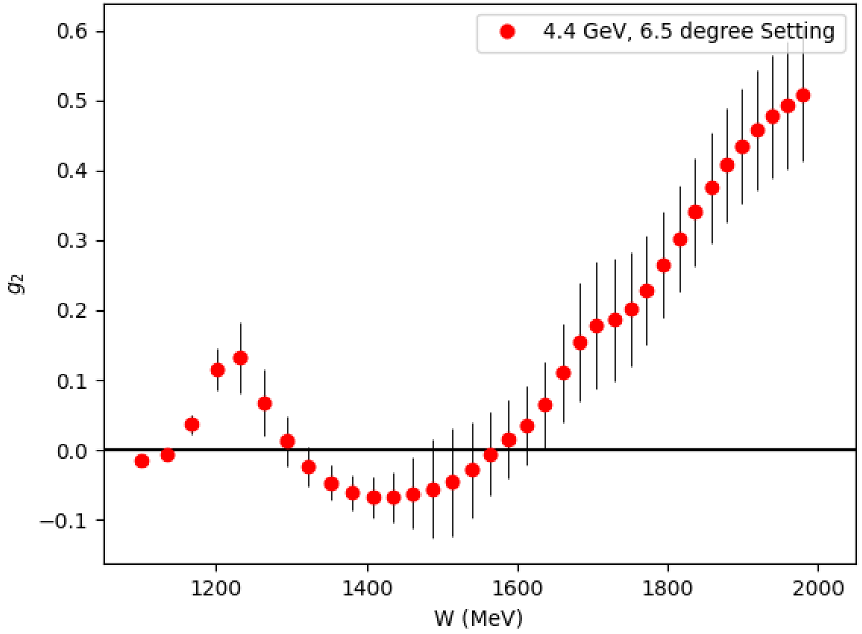
Resolutions



Without Target Field/Chicane



With Target Field/Chicane

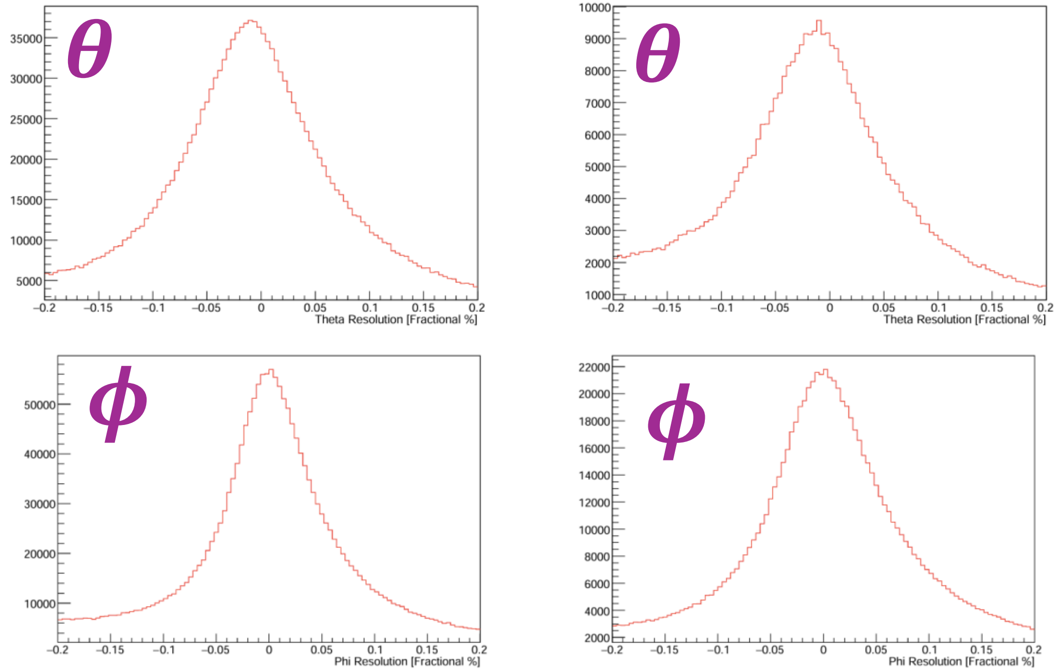


Planned Bin Size: > 30 MeV

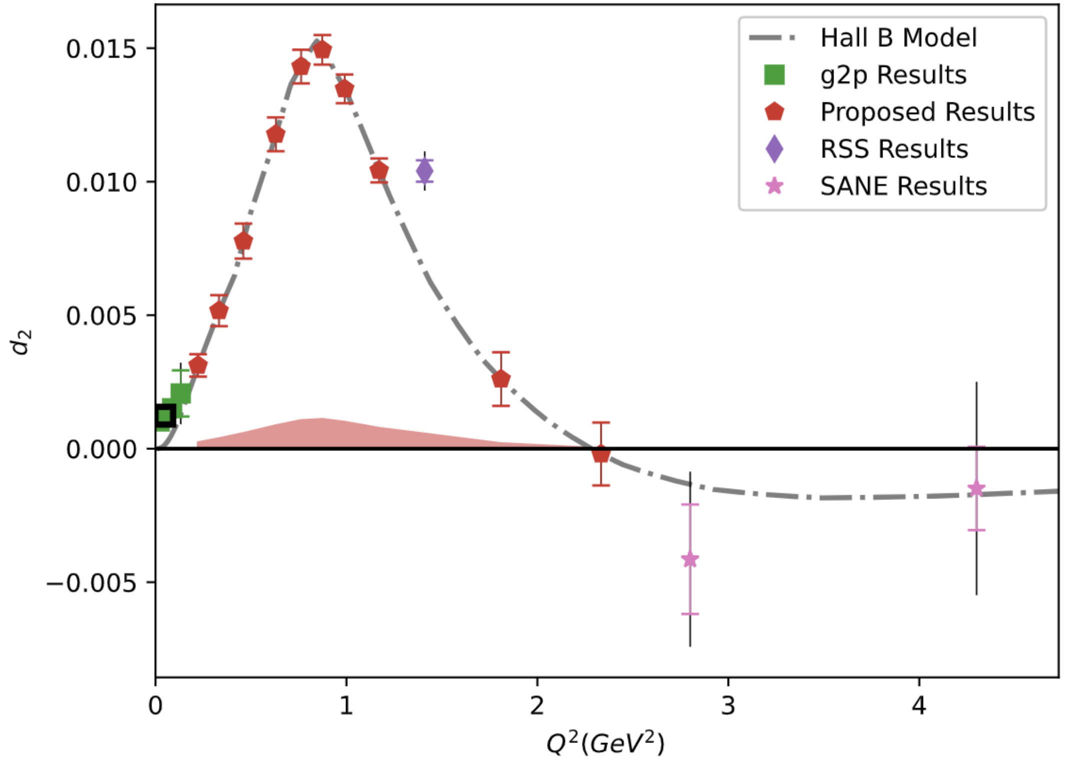
Resolution w/ Target: 10-20 MeV

- **There should be no issue resolving the resonances of g_2p**

Resolutions



Without Target Field/Chicane **With Target Field/Chicane**

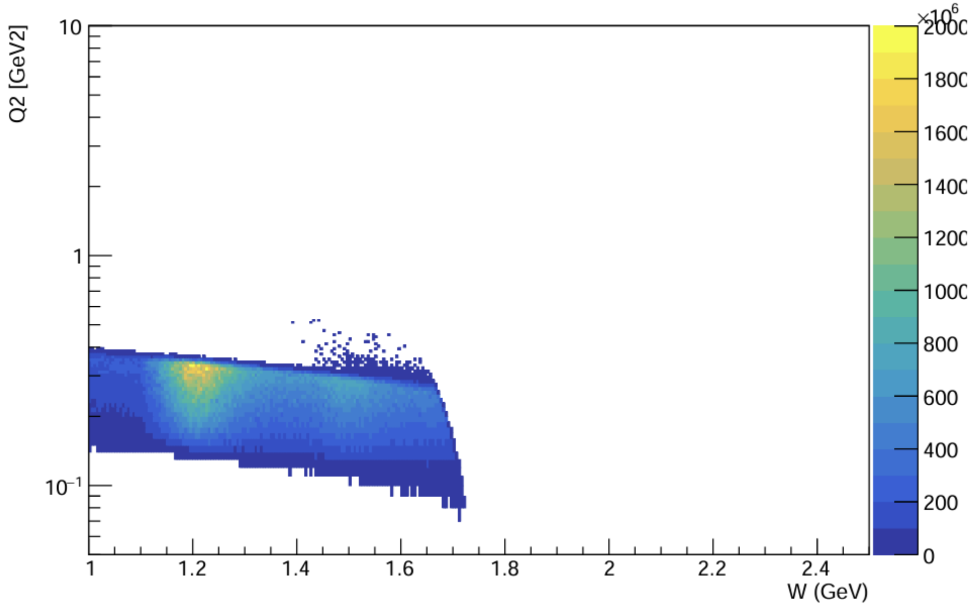


Planned Scattering Angle Bin Size: ~1.0 - 2.5°

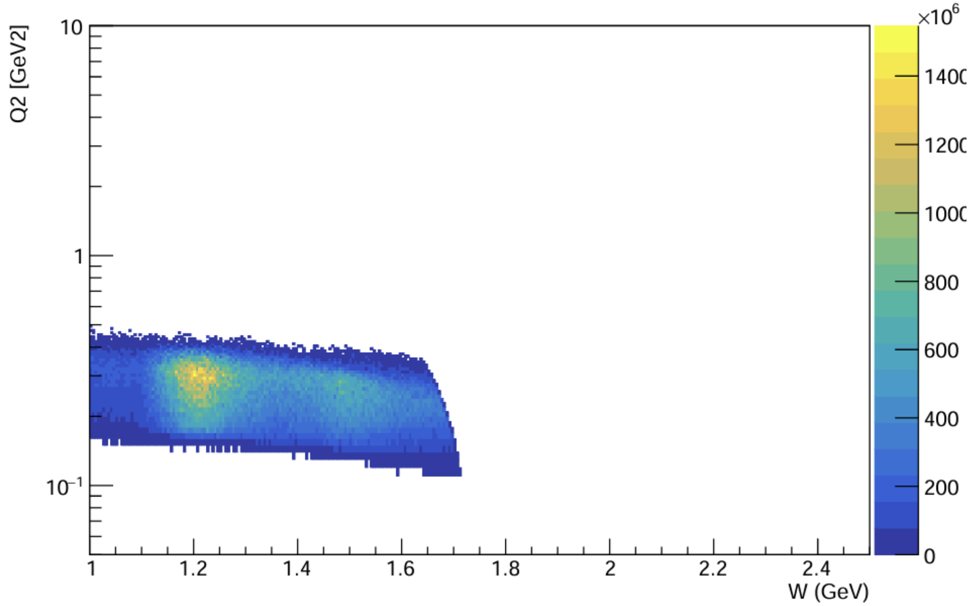
Resolution w/ Target: ~0.96°

- **<u>There should be no issue resolving the features of the moments</u>**

Impact on Coverage



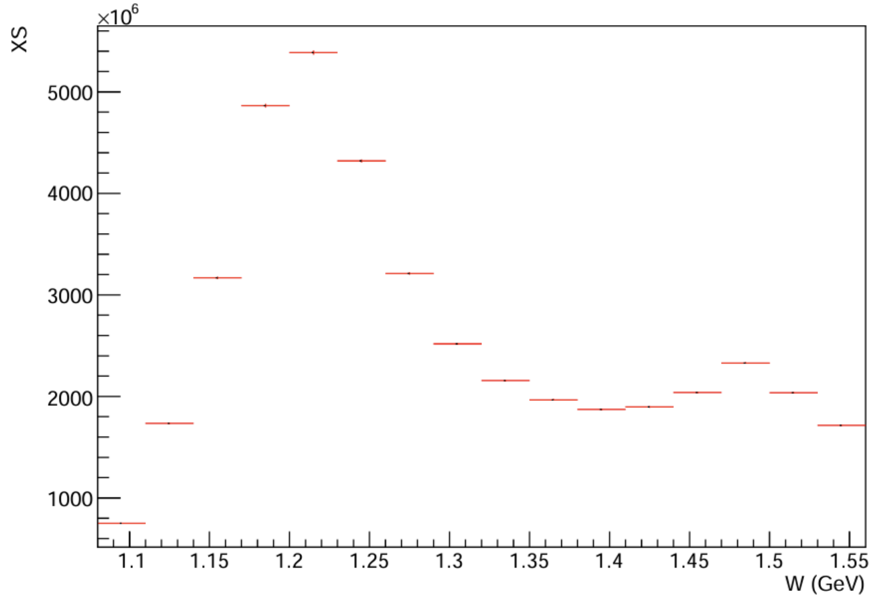
Without Target Field/Chicane



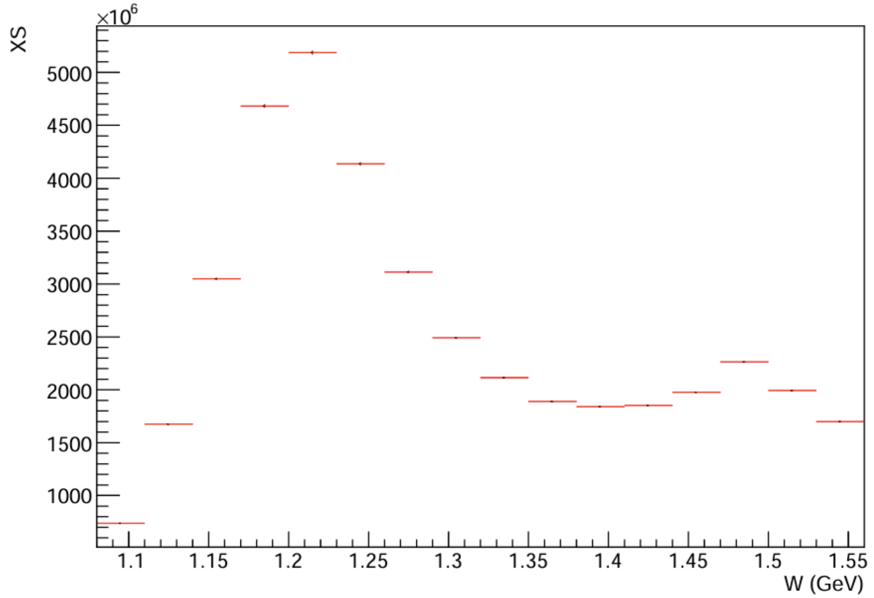
With Target Field/Chicane

- **<u>Effects on the kinematic coverage are small and well-understood</u>**

Systematic Impact



Without Target Field/Chicane



With Target Field/Chicane

- <u>**Around a 2% or less effect from the resolution on the XS**</u>
- **Included in new systematics calculation**

Simulation Conclusions

- **PAC52 Conditional:** "The impact of this new setup on the detector resolution and its subsequent effect on the physics results has not been thoroughly addressed. **A full Monte Carlo simulation** of the new setup and detector is needed." **(✅ Complete)**
- Resolutions enlarged by the target field and are close to the desired bin size, so a full simulation was indeed necessary
- We have fulfilled PAC52's condition and the impact of the target and chicane is now **well understood and accounted for**

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

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

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...

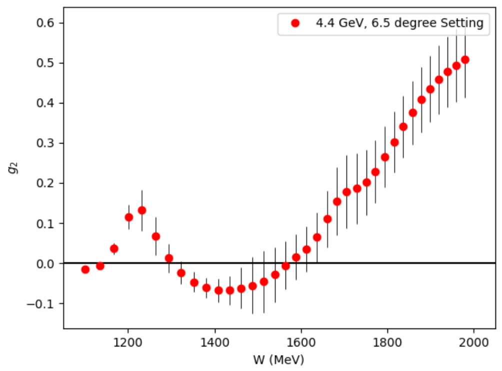
covering a **full order of magnitude** of the transition region!

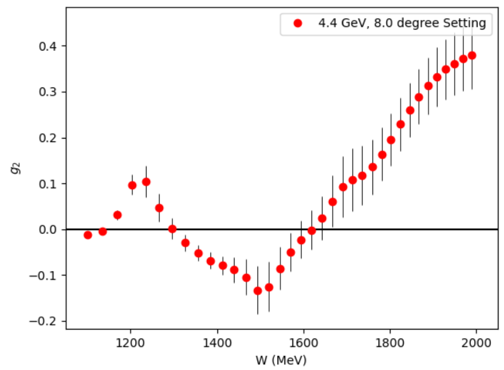
Projected Systematics

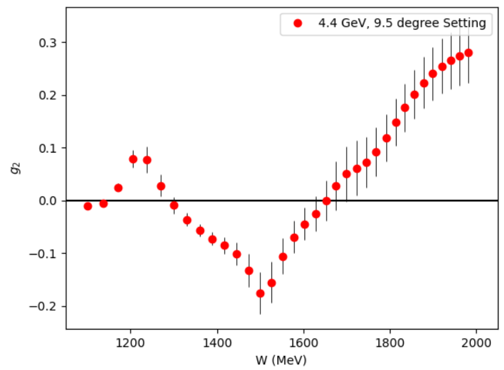
- Dominating systematics are **target polarization** and **acceptance**

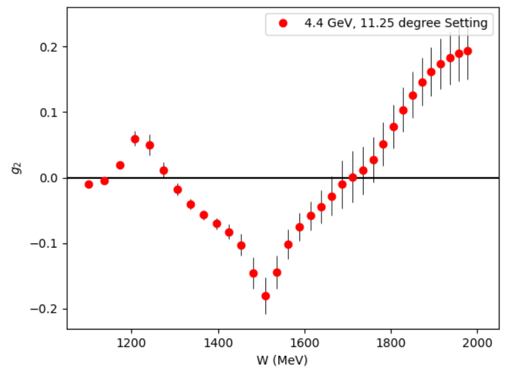
Source	%
Acceptance	4-6
Packing Fraction	3
Charge Determination	1
Tracking Efficiency	1
PID Efficiencies	< 1
Software Cut Efficiency	< 1
Resolution/Simulation	< 2
Energy	0.5
Deadtime	< 1
XS Total	5-7
Target Polarization	5
Beam Polarization	3
Radiative Corrections	3
Parallel Contribution	2
Const Q^2 Adjustment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

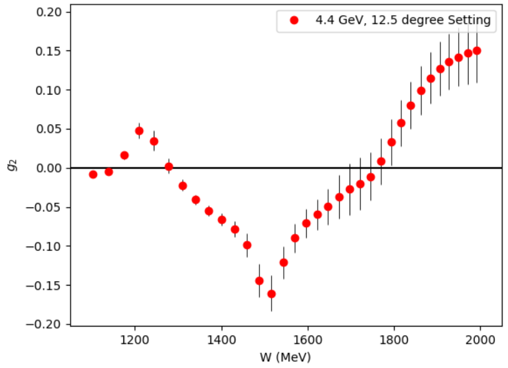
Projected g_2 Uncertainties

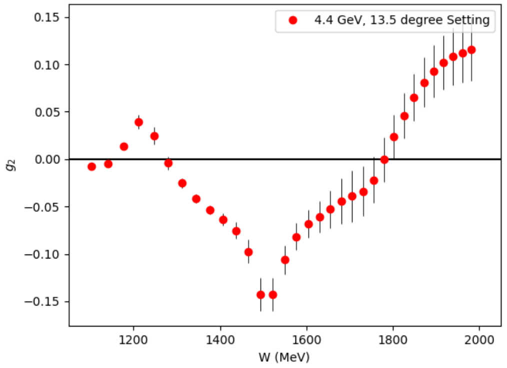


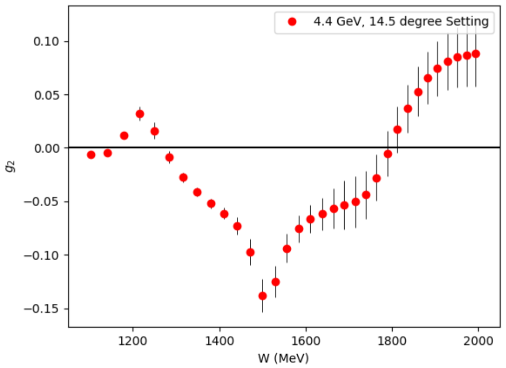


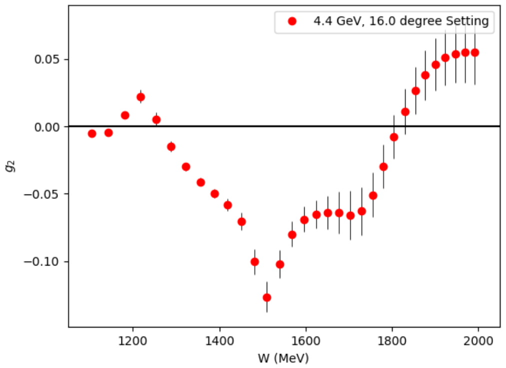




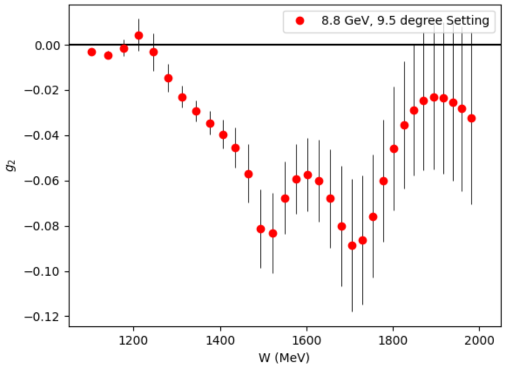


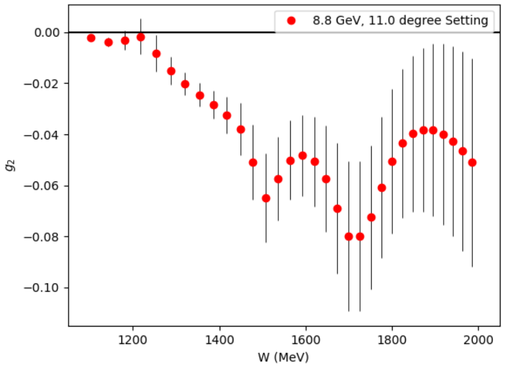






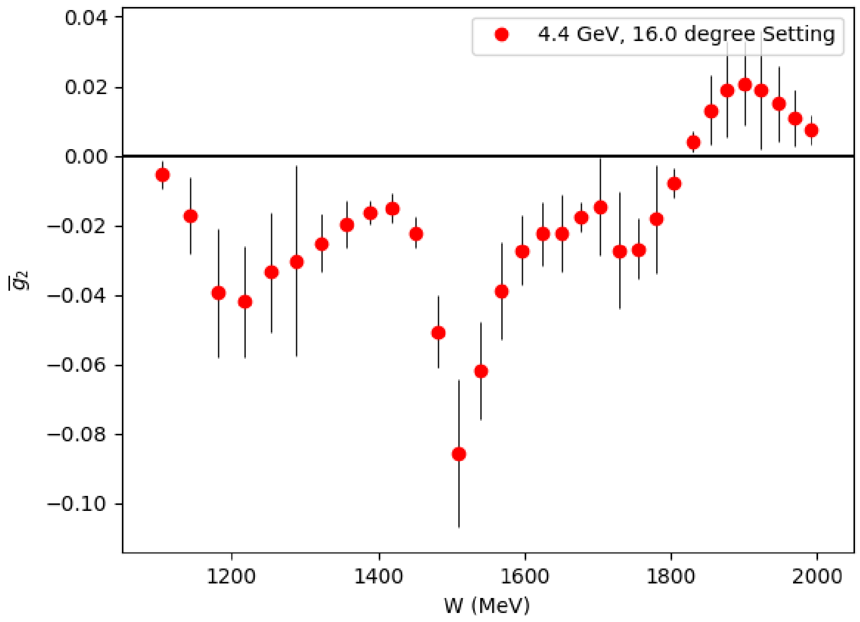
Covers almost the entire transition region





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

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



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

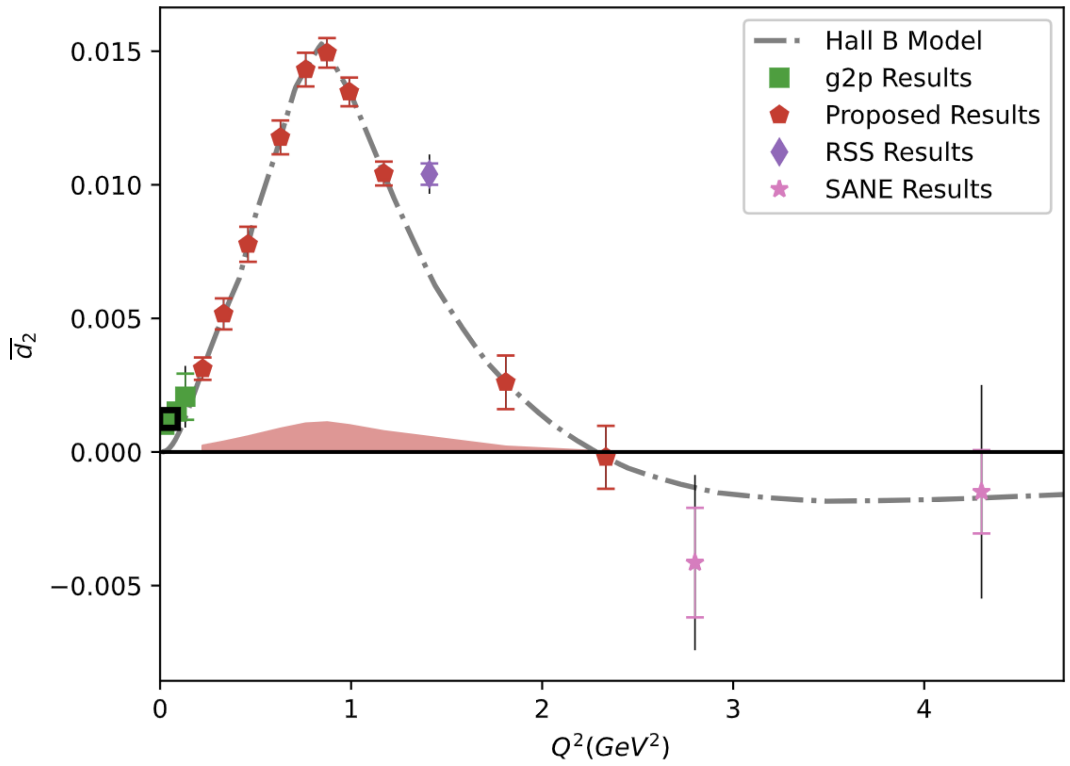
Small

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

Projected $\overline{d_2}$ Uncertainties

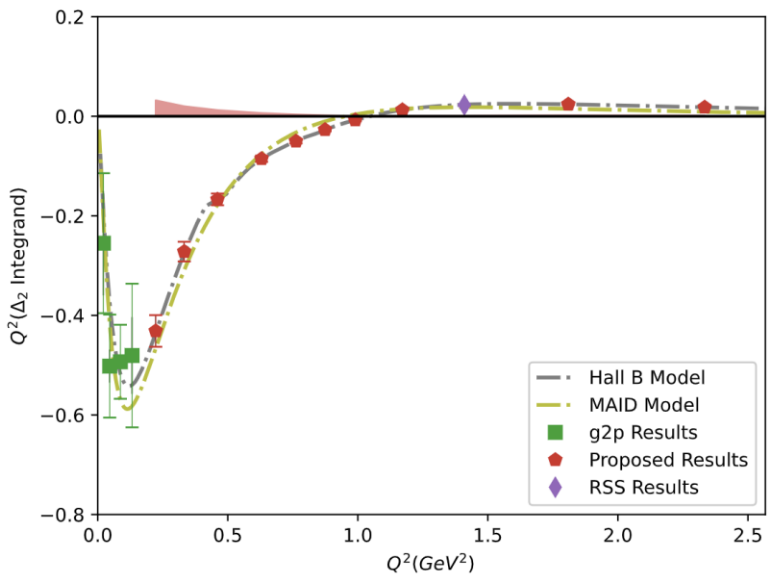


Can benchmark Lattice QCD **in the regime where Perturbative QCD starts failing**

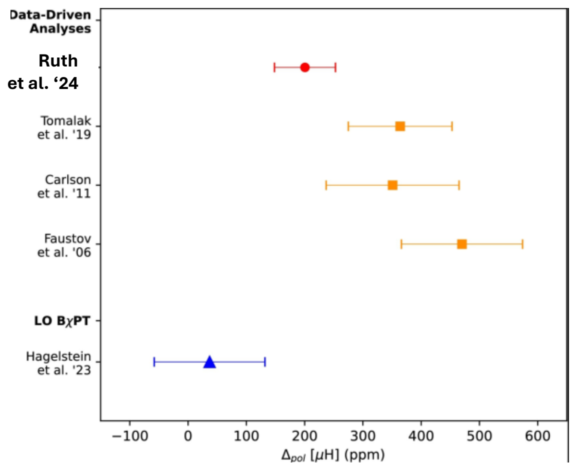
New Lattice calculations expected in next few years!

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

Hyperfine Splitting Impact



Δ_{pol}



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

- 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}!

What do past PACs and theorists have to say…?

“A clear case of ‘low-hanging fruit’ with a wealth of opportunities to address long-standing open questions.”

– PR12-23-007 Theory Report

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

– PR12-24-002 Theory Report

“The PAC recognizes the significant importance of measuring the fundamental proton structure function g_2 for the proton. The presented physics case and the proponents’ approach to the future measurement are solid.”

– PAC52 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 $\overline{d_2}$**

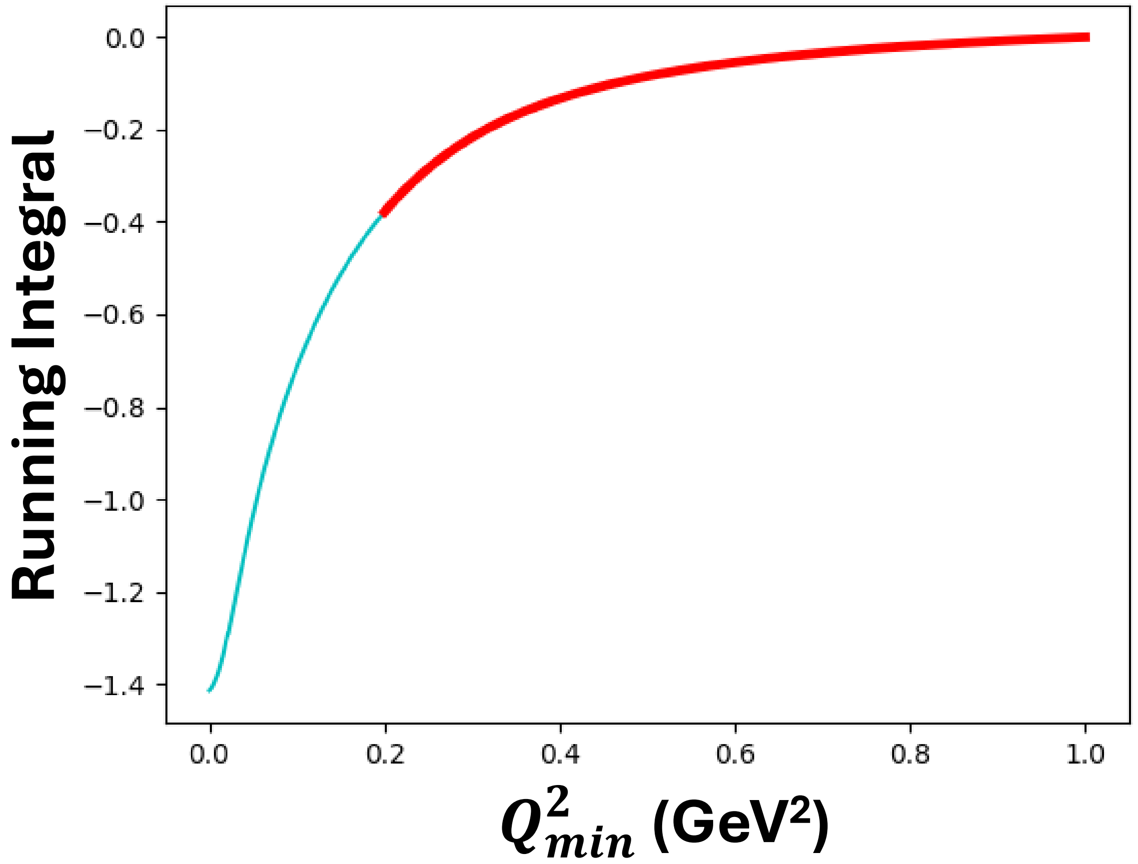
✓ **Study other truncated moments**

Let's make it happen!

Backup Slides

Hyperfine Contribution

Running Integral from $\int_{Q^2_{min}}^{\infty} dQ^2$



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

- 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

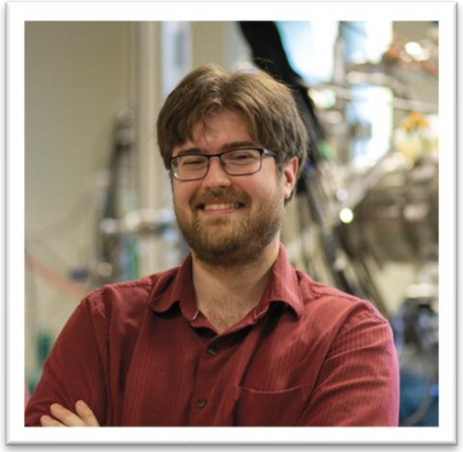
- The transition region accounts for ~30% of the integral!

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

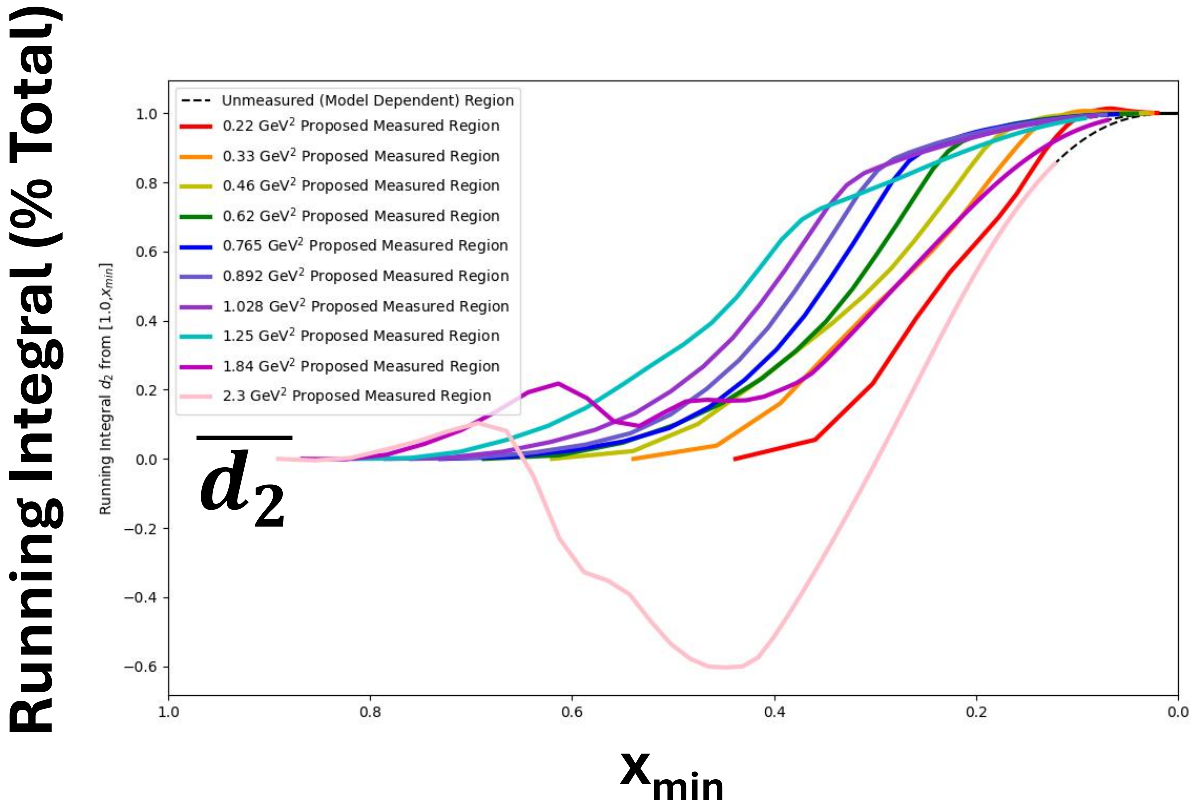
RSS Analysis

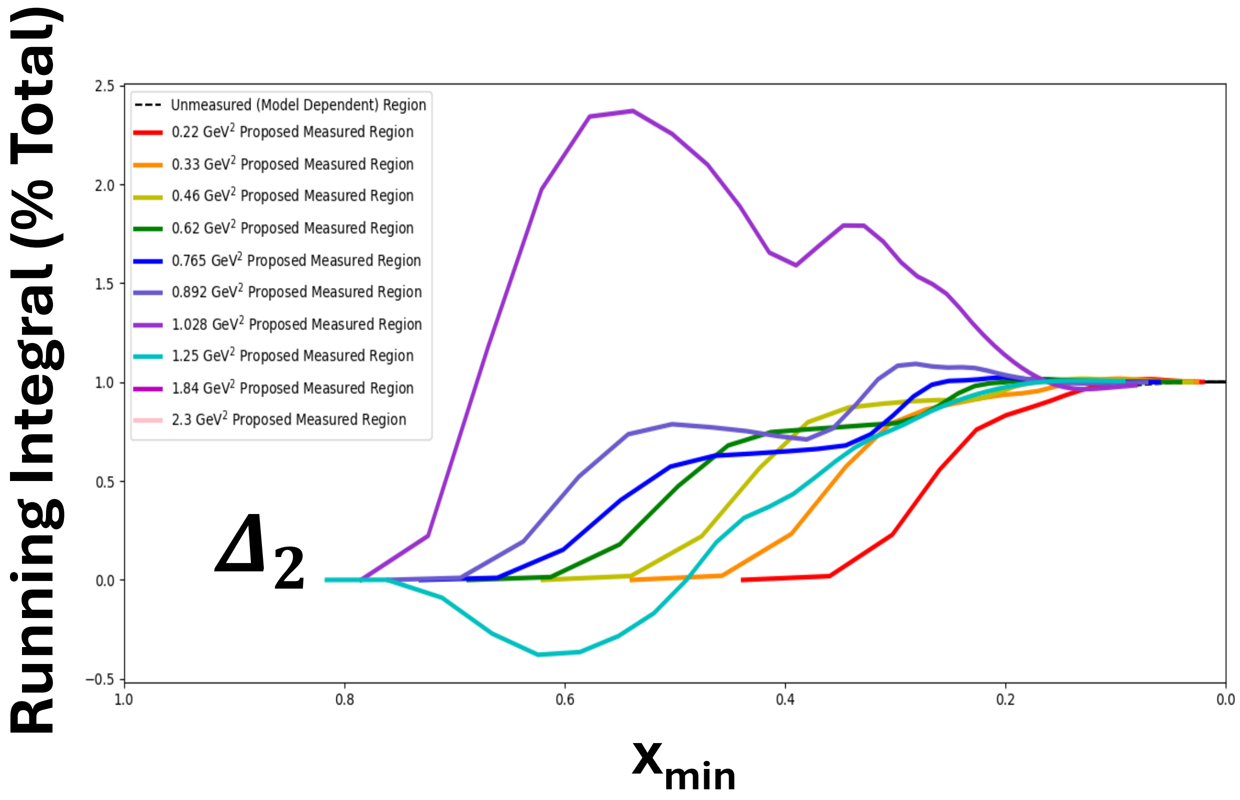
K. Slifer
M. Jones
O. Rondon

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

Running Integrals as % Total Value ($\int_{x_{min}}^{1} dx$)





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

Rates Table

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
4.4	6.5	2.661	0.22	65	25.1	1
4.4	6.5	1.963	0.22	69	18.9	1
4.4	8	3.607	0.33	41	21.4	1.3
4.4	8	2.661	0.33	28	11.5	1.9
4.4	8	1.963	0.33	30	8.3	1.8
4.4	9.5	3.607	0.46	18	9.1	2.3
4.4	9.5	2.661	0.46	14	5.9	3.0
4.4	9.5	1.963	0.46	15	4.3	2.8
4.4	11.2	3.607	0.62	7	3.7	6.0
4.4	11.2	2.661	0.62	6	3.0	6.5
4.4	11.2	1.963	0.62	7	2.2	5.9
4.4	12.5	3.607	0.765	4	2.0	9.1
4.4	12.5	2.661	0.765	4	1.9	8.5
4.4	12.5	1.963	0.765	4	1.5	7.6
4.4	13.5	3.607	0.892	2	1.3	16.5
4.4	13.5	2.661	0.892	3	1.3	13.7
4.4	13.5	1.963	0.892	3	1.1	12.1
4.4	14.5	3.607	1.028	1	0.8	23.2
4.4	14.5	2.661	1.028	2	1.0	17.4
4.4	14.5	1.963	1.028	2	0.8	14.9
4.4	16	3.607	1.250	0	0.4	50.8
4.4	16	2.661	1.250	1	0.6	32.7
4.4	16	1.963	1.250	1	0.5	26.6
8.8	11	7.213	2.3	0	0.5	33.3
8.8	11	5.321	2.3	0	0.8	19.0
8.8	14	7.213	3.44	0	0.1	101.8
8.8	14	5.321	3.44	0	0.2	31.6

Total PAC Days: 13.0

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])

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

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!