University of New Hampshire
Nuclear & Particle Physics Group

A Measurement of the Proton's Spin Structure Functions in the Strong-QCD Regime
2022 Summer Status Update

David Ruth

Hall A Collaboration Meeting

June 16th, 2022

Acknowledgements

g2p Collaboration

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(The Jefferson Lab Hall A g2p Collaboration)

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Acknowledgements

g2p Analysis Team

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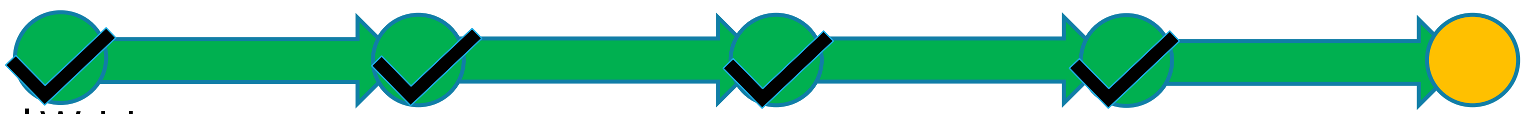
1. Experiment Background
    - First low Q^2 measurement of transverse proton spin structure
    - Dynamic Nuclear Polarized (DNP) Target
    - Model Cross Section & Experimental Asymmetry
2. Publication Progress



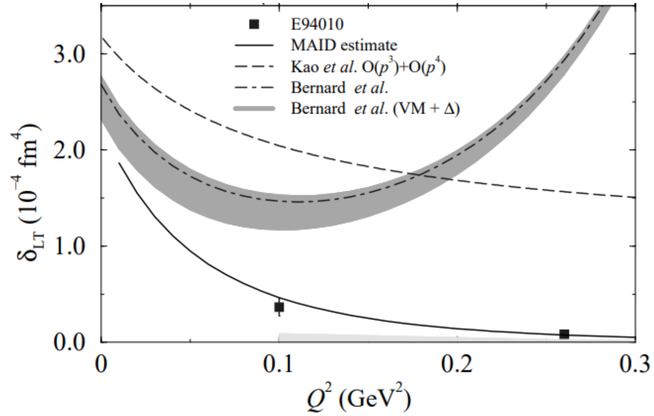
3. Results
    - g_2 structure function
    - δ_{LT} Transverse-Longitudinal Spin Polarizability
    - d_2 Matrix Element
    - Other results in preparation: g_1, Γ_2

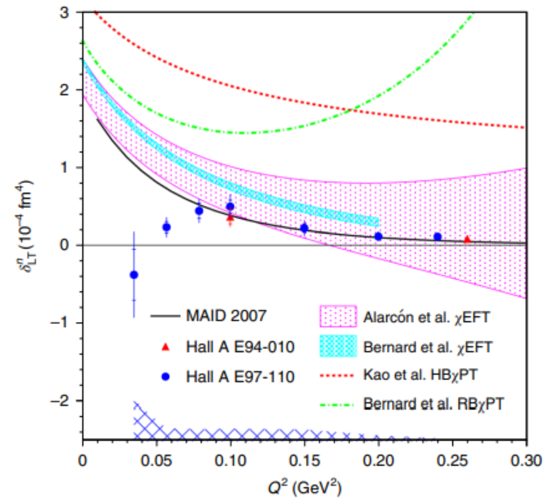
Motivation: Measure a fundamental spin observable (g_2) in the region $0.02 < Q^2 < 0.20$ GeV² for the first time

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

g_1 and g_2 related to spin distribution

- Both structure functions measured over broad kinematic range for neutron: Small-Angle GDH, E94010 at Jefferson Lab
- g1 measured for proton: EG4, EG1b, RSS, SANE
- No g2 data in the very low Q^2 region for the proton!
- Neutron Moment δ_{LT} disagrees with χPT in low Q^2 region, important to test for the proton
- **Low Q^2 is difficult**:
  - Electrons strongly influenced by target field
  - Strong kinematic dependence on observables
- **Low Q^2 is useful**:
  - Test predictions of Chiral Perturbation Theory (χPT)
  - Test sum rules and measure moments of g_2





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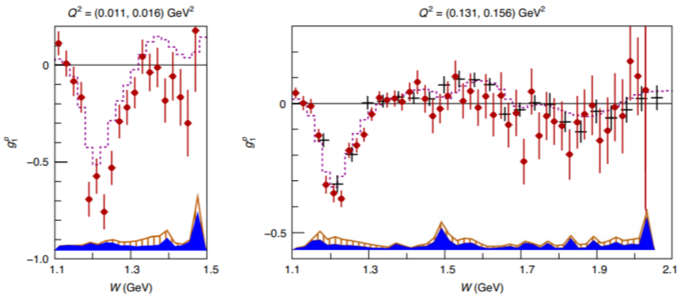
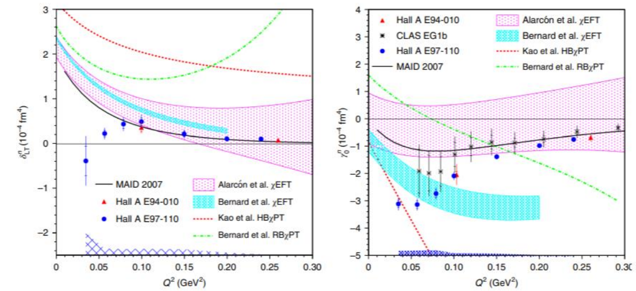
Recent Spin Structure Studies

- EG4: Published in Nature Physics in April 2021
  - Low+Medium Q^2 measurement of g_1 and longitudinal moments for Proton
- Small-Angle GDH: Published in Nature Physics in May 2021
  - Low Q^2 measurement of g_1 and g_2 for Neutron
- New χPT Calculations: Bernard et. al calculation in 2013 gave closer agreement to results of E94010
- Alarcon et. al calculation has been updated several times, most recently in 2020
- These calculations disagree at low Q^2 for the proton, showing that there are unanswered questions about QCD in the chiral domain



X. Zheng et al. Nature Physics 17, 736-741



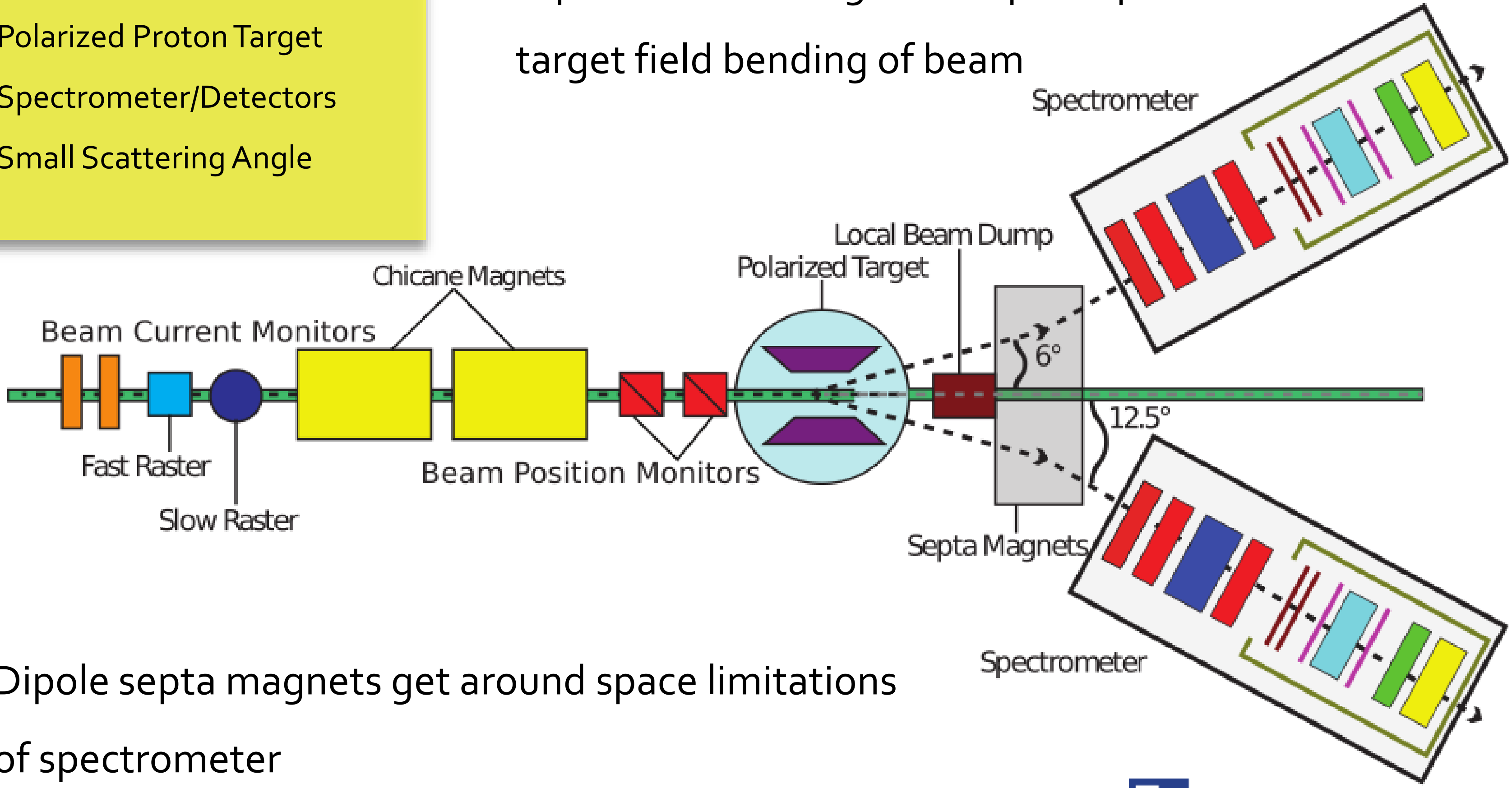
V. Sulkosky et al. Nature Physics 17, 687-692

Hall A Experimental Setup:

Measuring g_2^p

- Electron Beam
- Polarized Proton Target
- Spectrometer/Detectors
- Small Scattering Angle

- g2p experiment ran spring 2012 in Hall A
- Transverse polarized NH_3 target (2.5/5.0T)
- Dipole chicane magnets help compensate for target field bending of beam



- Dipole septa magnets get around space limitations of spectrometer

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Polarized Protons Created with Dynamic Nuclear Polarization (DNP)

Creating initial polarization:

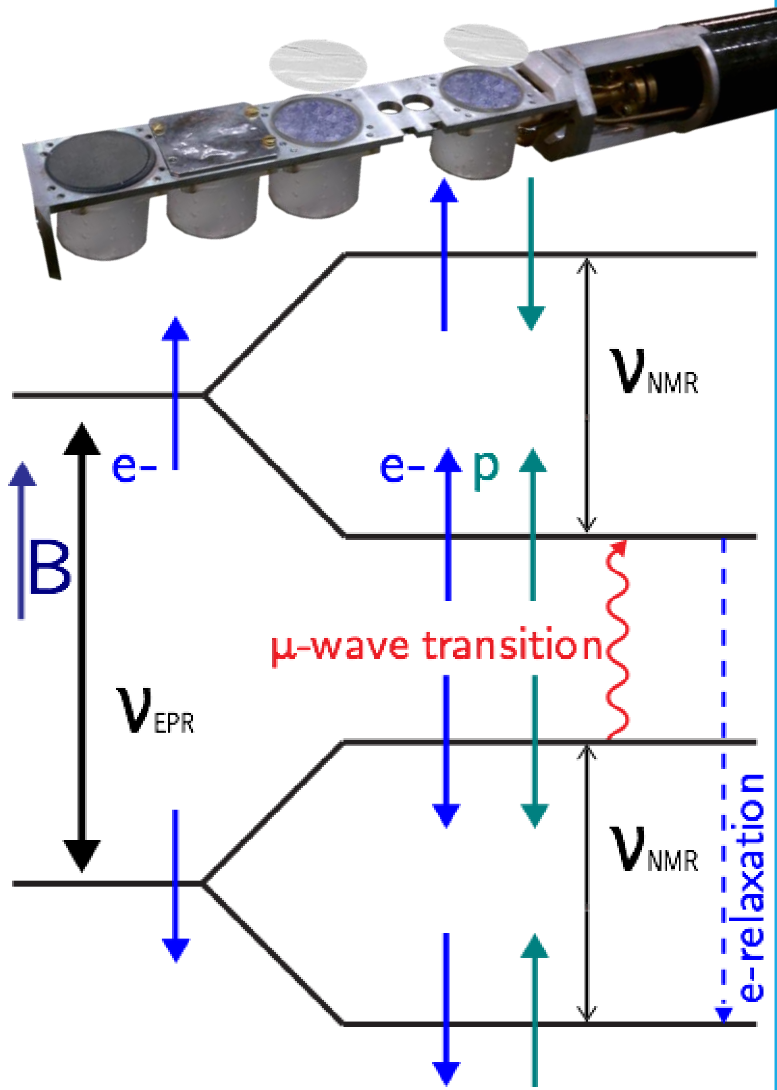
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

$$P_{\mathrm{TE}} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}}$$

- Large μ_e (~660μ_p) creates large electron polarization (~99% at 5T/1K)

Enhancing initial polarization:

- Proton pol. much smaller (~0.5% 5T) at TE
- *ep* spin coupling and microwaves drive pol.
- Electrons relax much quicker than protons so polarization is sustained



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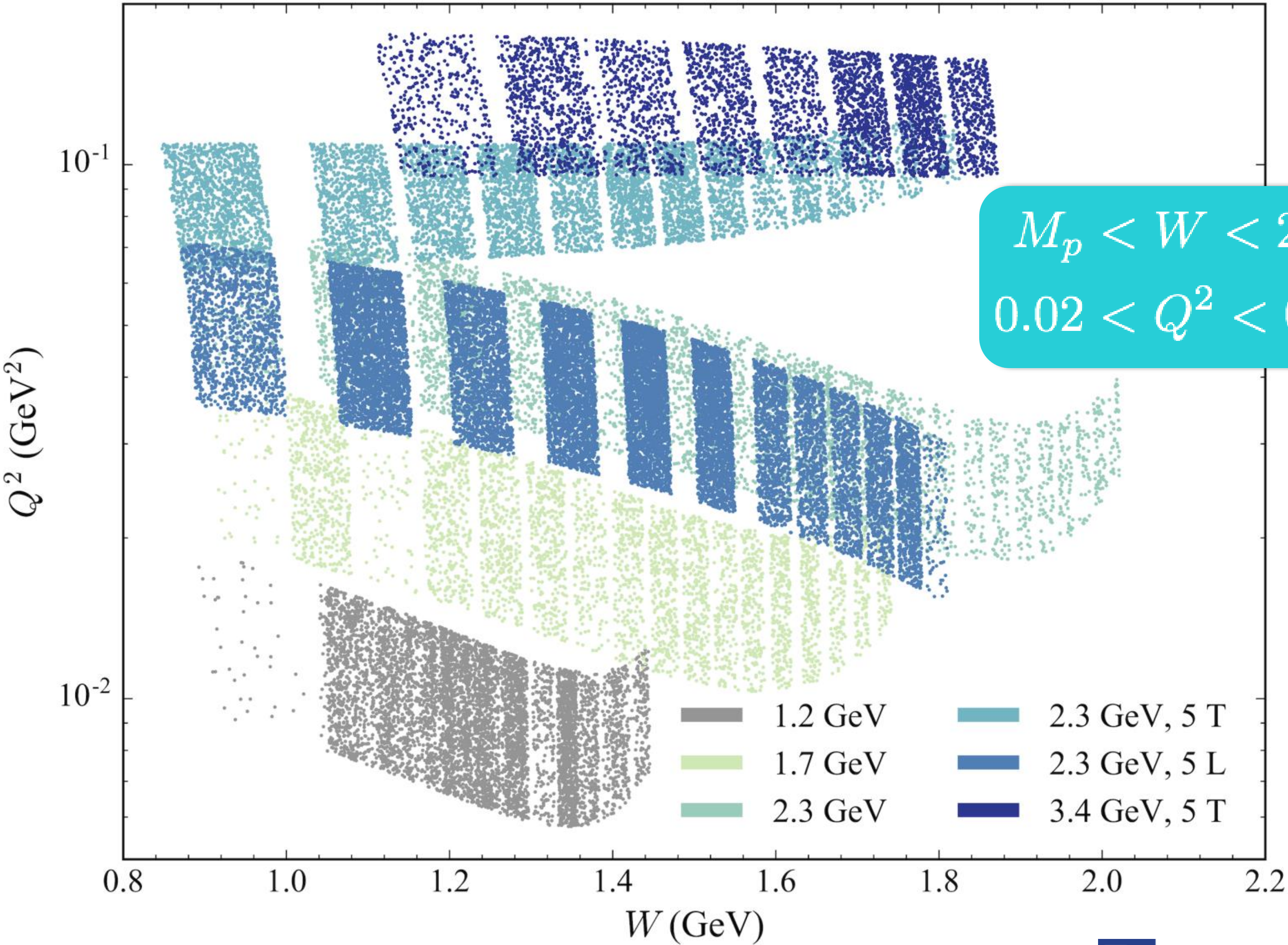
g_2p Kinematic Coverage



$$M_p < W < 2\,\text{GeV}$$
$$0.02 < Q^2 < 0.20\,\text{GeV}^2$$

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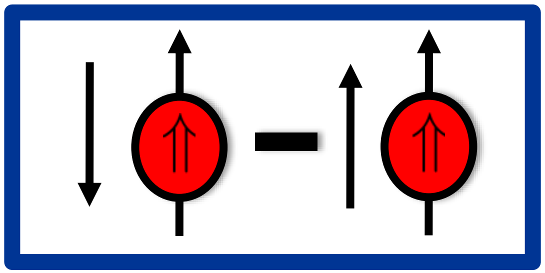
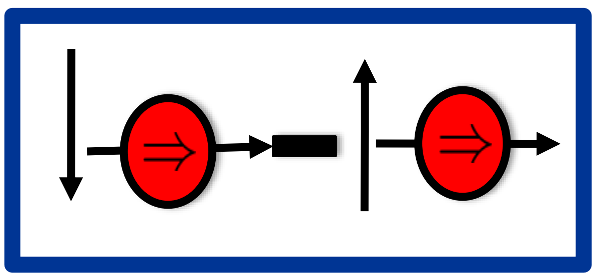
Extracting Spin Structure by Looking at Cross Section Differences

Inclusive *polarized* cross sections



Parallel

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



Perpendicular

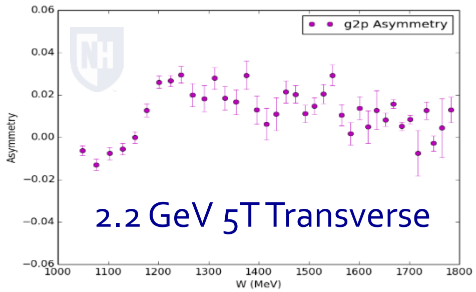
$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\left[\nu g_1(x,Q^2) + 2Eg_2(\nu,Q^2)\right]$$

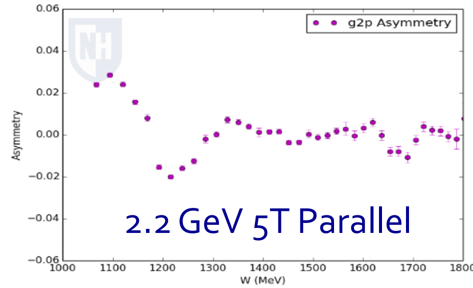
$$\Delta\sigma_\perp = \frac{d^2\sigma}{d\Omega dE'}(\downarrow\rightarrow - \uparrow\rightarrow) = 2\cdot \boxed{A_\perp}\boxed{\sigma_0}$$

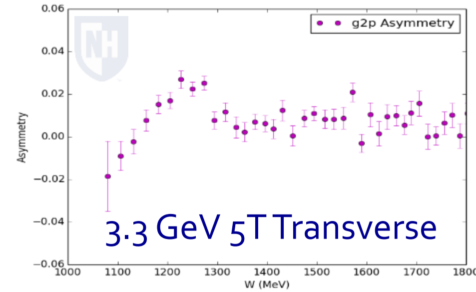
From Model

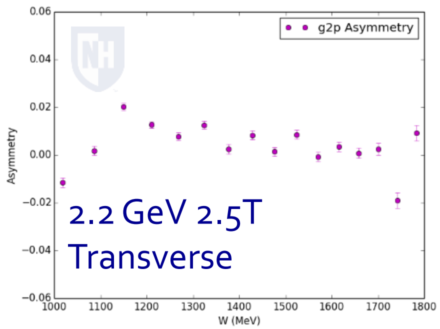
From Data

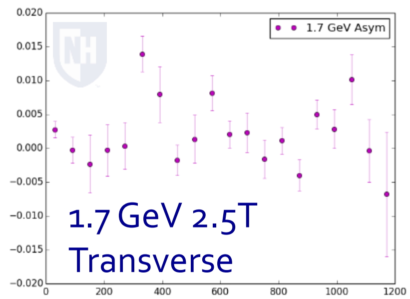
Asymmetries











Measured Asymmetries:

$$A^{\text{meas}} = \frac{Y_+ - Y_-}{Y_+ + Y_-},$$

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

dilution factor

beam/target pol

Raw Counts:

$$Y_\pm = \frac{N_\pm}{L T_\pm Q_\pm}$$

Combine both HRS for best statistics!

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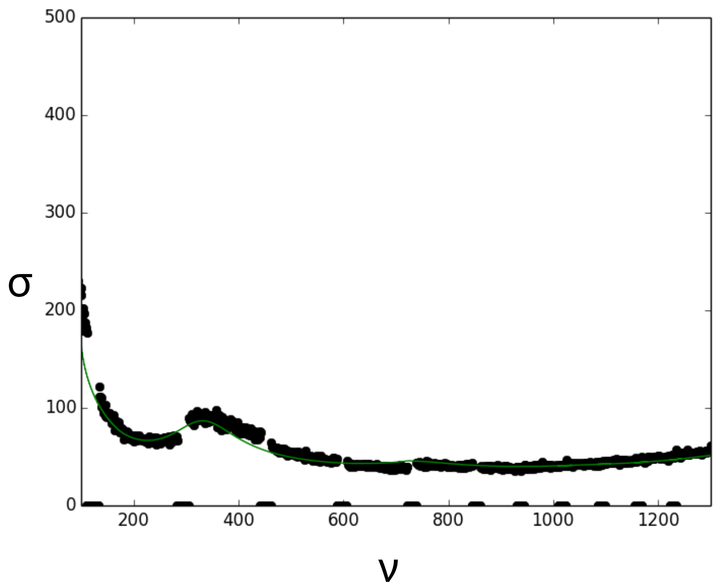
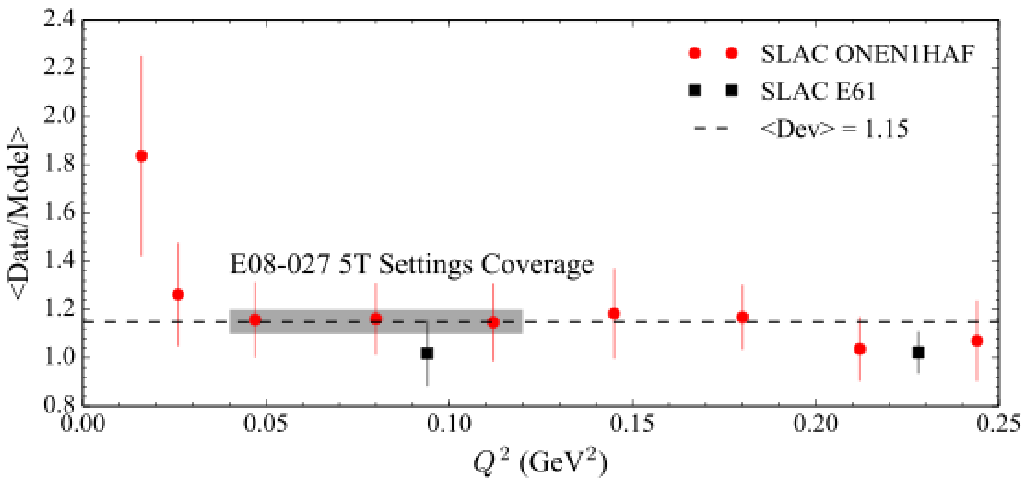
Model Cross Section



- g2p data has good agreement with Bosted-Christy Model if a scaling of 1.15 is used
- We investigated this scaling in depth and determined its impact on the moments is less than 6%
- Transverse acceptance forces us to use model cross section



- Bosted-Christy model in this region is based on E61, while g2p and onen1haf require a similar scaling factor
- However all three experiments agree within error

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Extraction & Model Scaling Factor Impact

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

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

Input from Hall B model

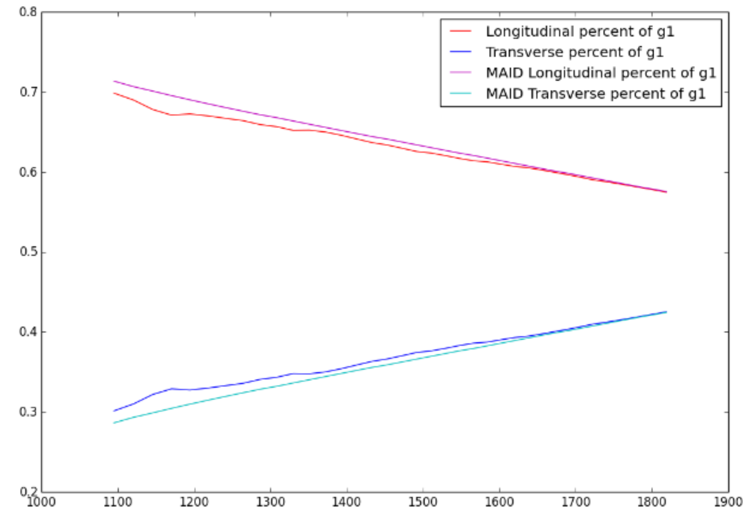
Combination of data & Bosted model

- Scaling factor is on Bosted-Christy XS
- Hall B has different systematics
- Input term is a significant part of the SSF: ~30%

- Propagate through Bosted-Christy with scaling of 1.0 vs scaling of 1.15 for Longitudinal setting
- Everything else stays the same
- Form a 'zeroeth order' and 'second order' moment:

$$M_0 = \int g_1 dx \qquad M_2 = \int x^2 g_1 dx$$

- Zeroeth order difference is suppressed by Hall B term
- 2^{nd} order difference is further suppressed by x^2 weighting
- Highest difference is ~6%



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First publication under peer review!

- Our first paper, highlighting the transverse results, has been submitted to Nature Physics
- Paper is in peer review and we have received mostly very supportive comments from the reviewers, we are revising and hope to have an editor decision soon!
- Thank you to all who helped us prepare the draft for submission!

The Proton Spin Structure Function g_2 and Generalized Polarizabilities in the Strong QCD Regime

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Under Review

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- All the Hall A technical staff and accelerator operators
- Jose Manuel Alarcón
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- Eric Christy
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- Hermann Krebs
- Sebastian Kuhn
- Vadim Lensky
- Ulf-G.Meißner
- Vladimir Pascalutsa

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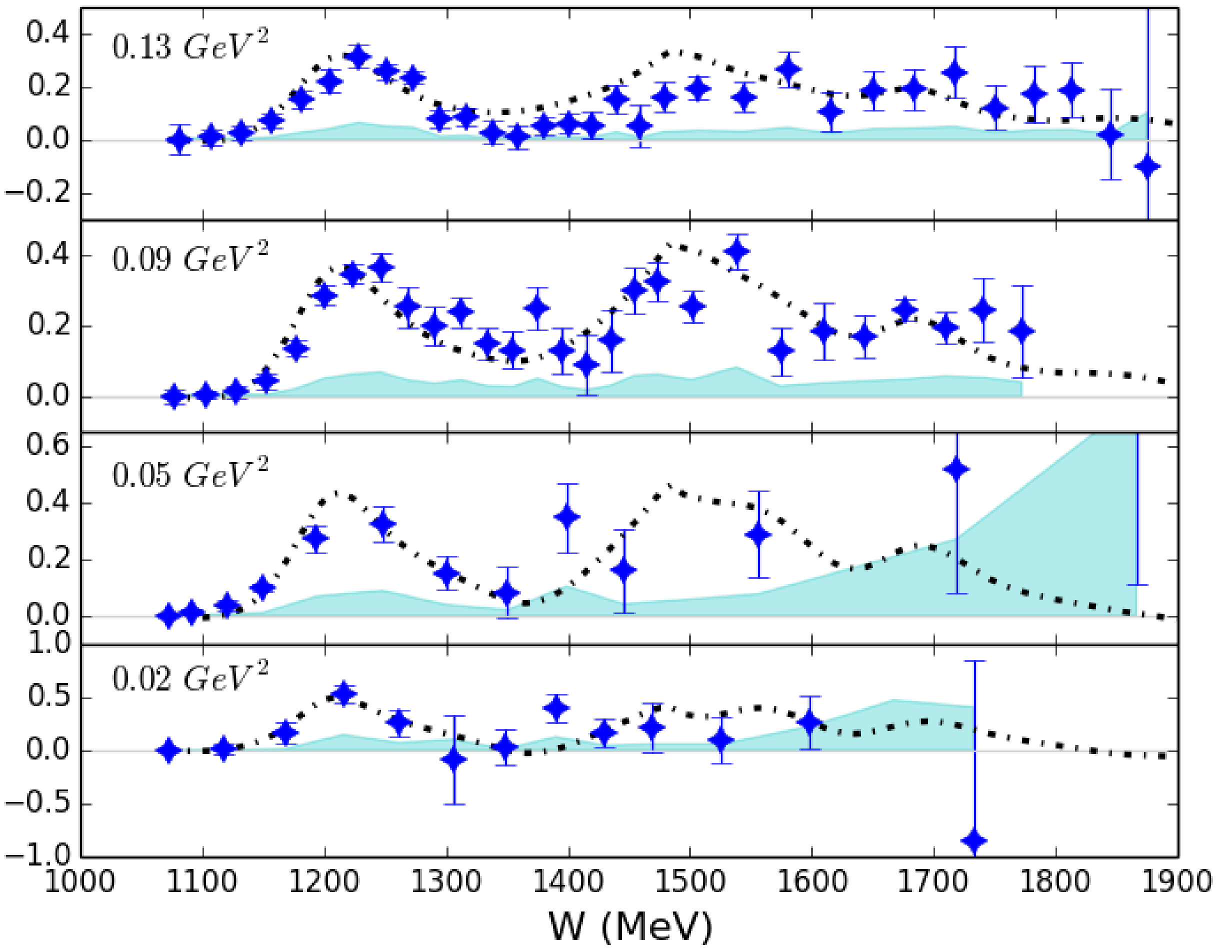
g_2 Structure Function Results



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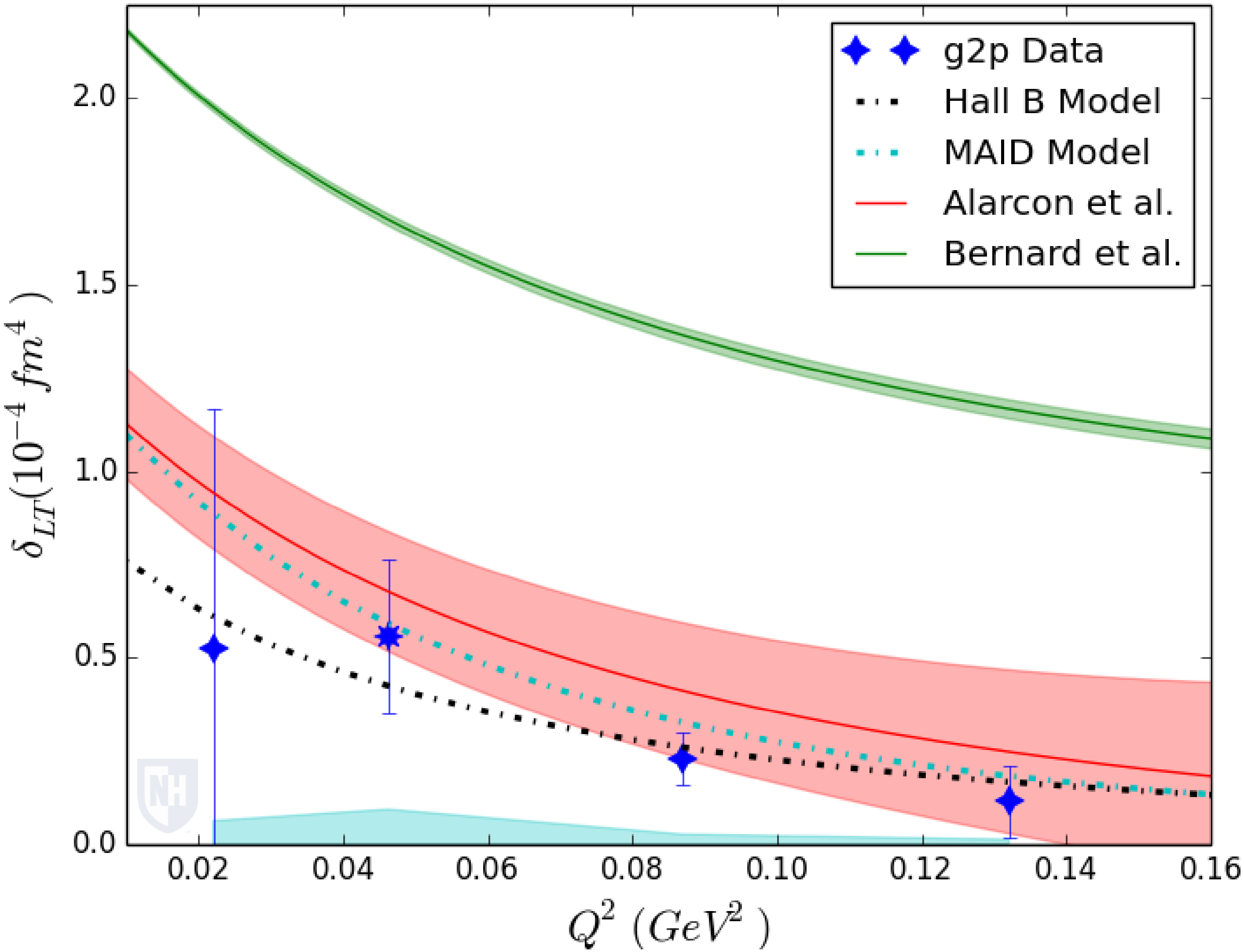
Transverse-Longitudinal Spin Polarizability

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

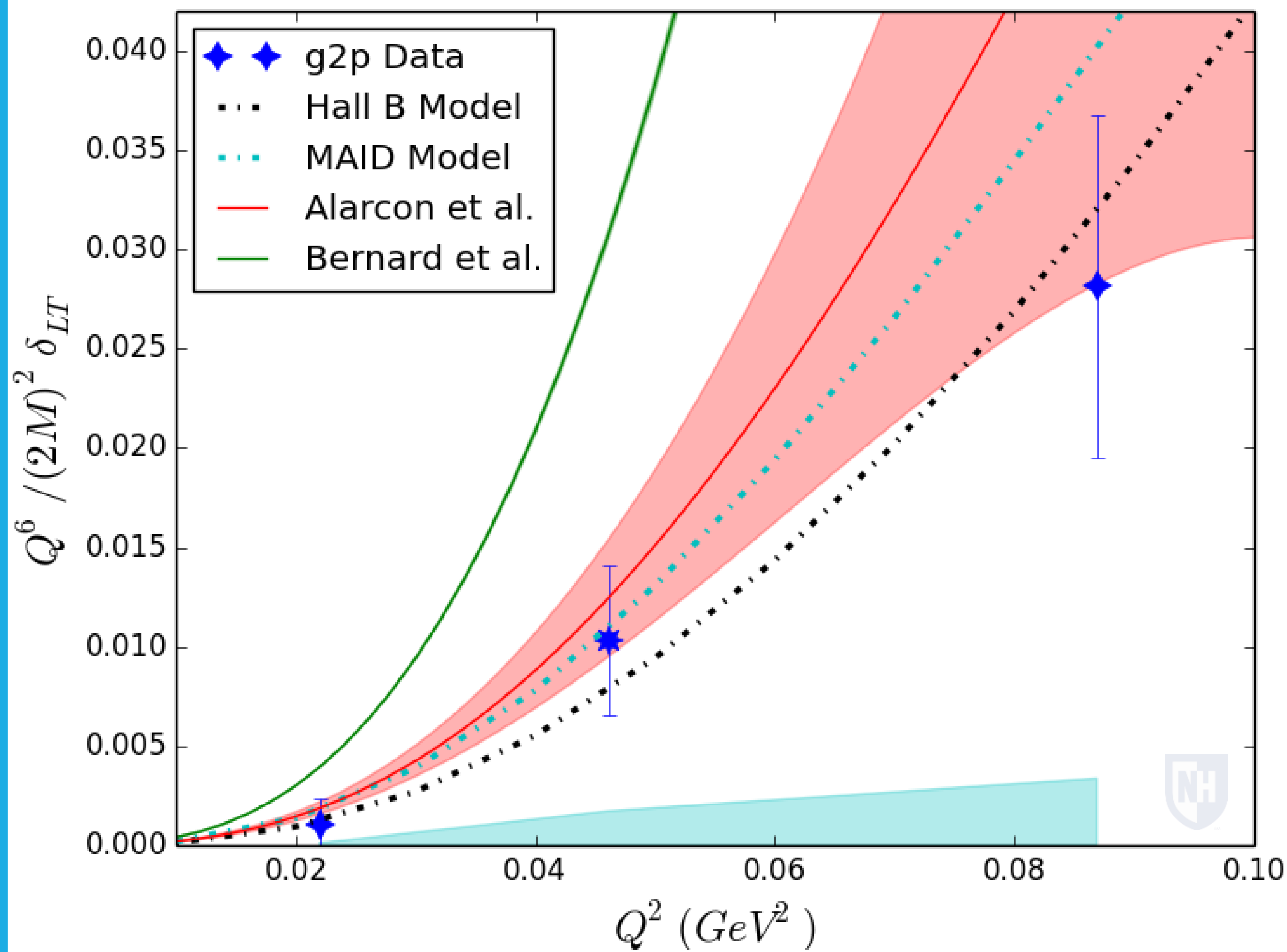


First ever measurement of this quantity in this region!

New benchmark for χPT and other calculations

Transverse-Longitudinal Spin Polarizability

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

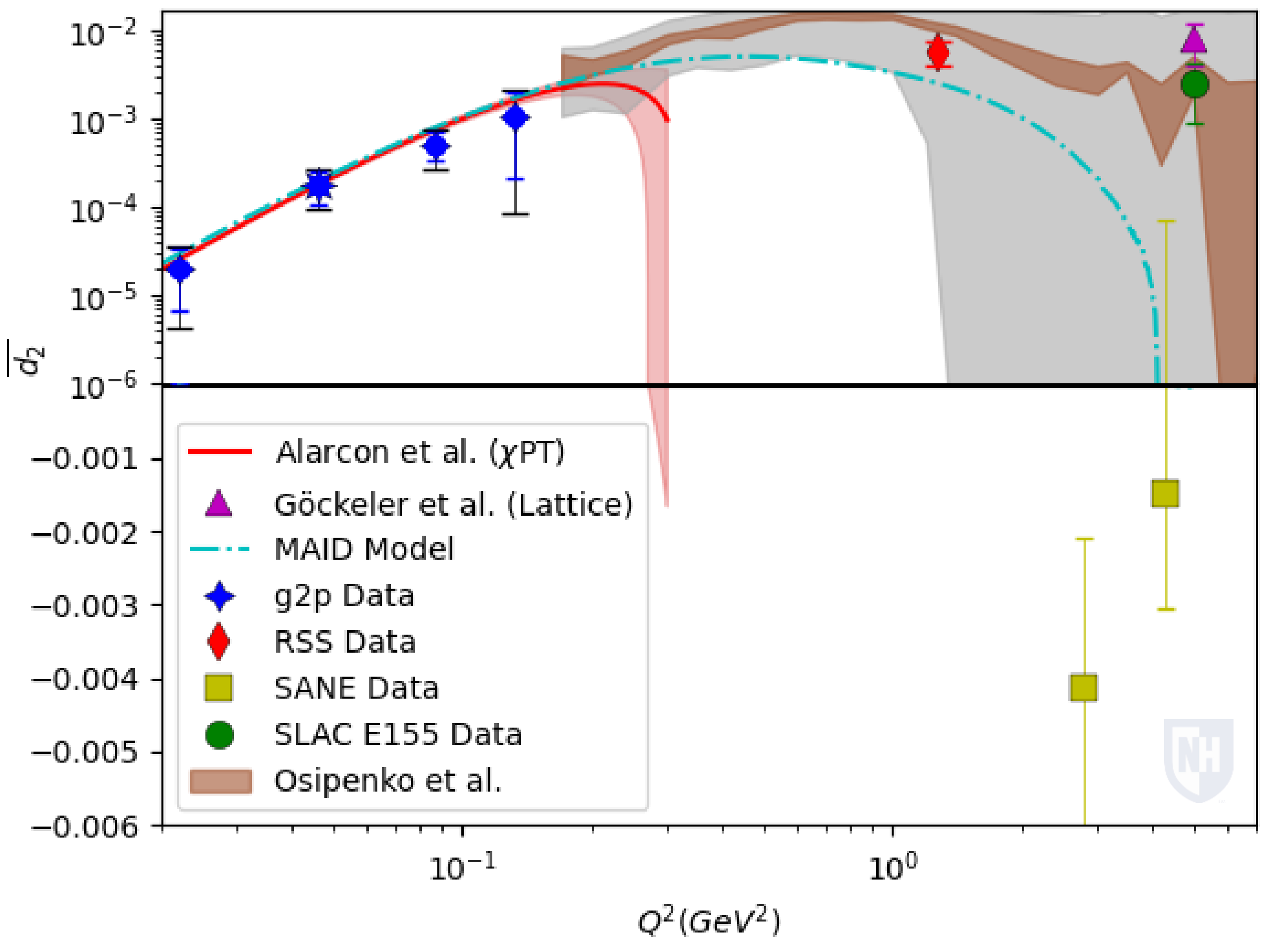


Highlights low Q^2 results

Forms a unitless quantity

d2 Matrix Element

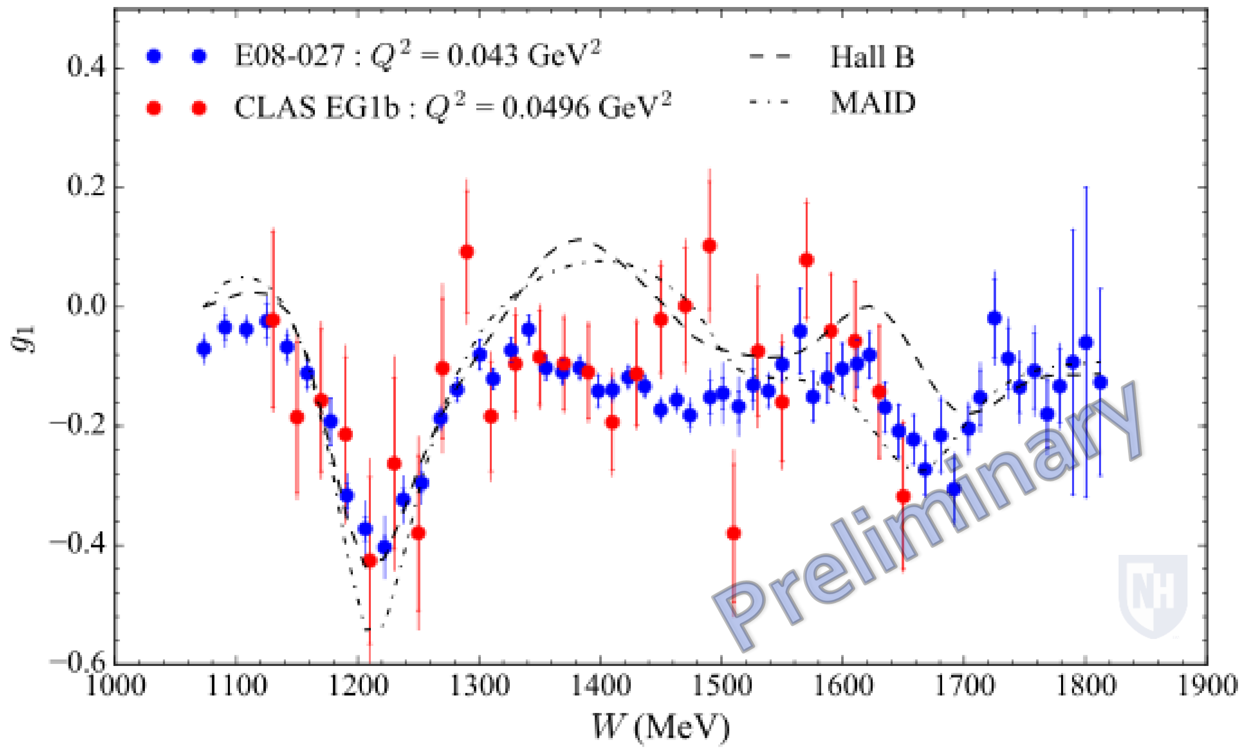
$$\overline{d_2} = \int_0^{x_{th}} x^2[2\, g_1(x,Q^2) + 3\, g_2(x,Q^2)]dx$$



Data agrees well with Chiral Perturbation Theory calculation

Moment is an interesting way to probe quark-gluon correlations at low Q²

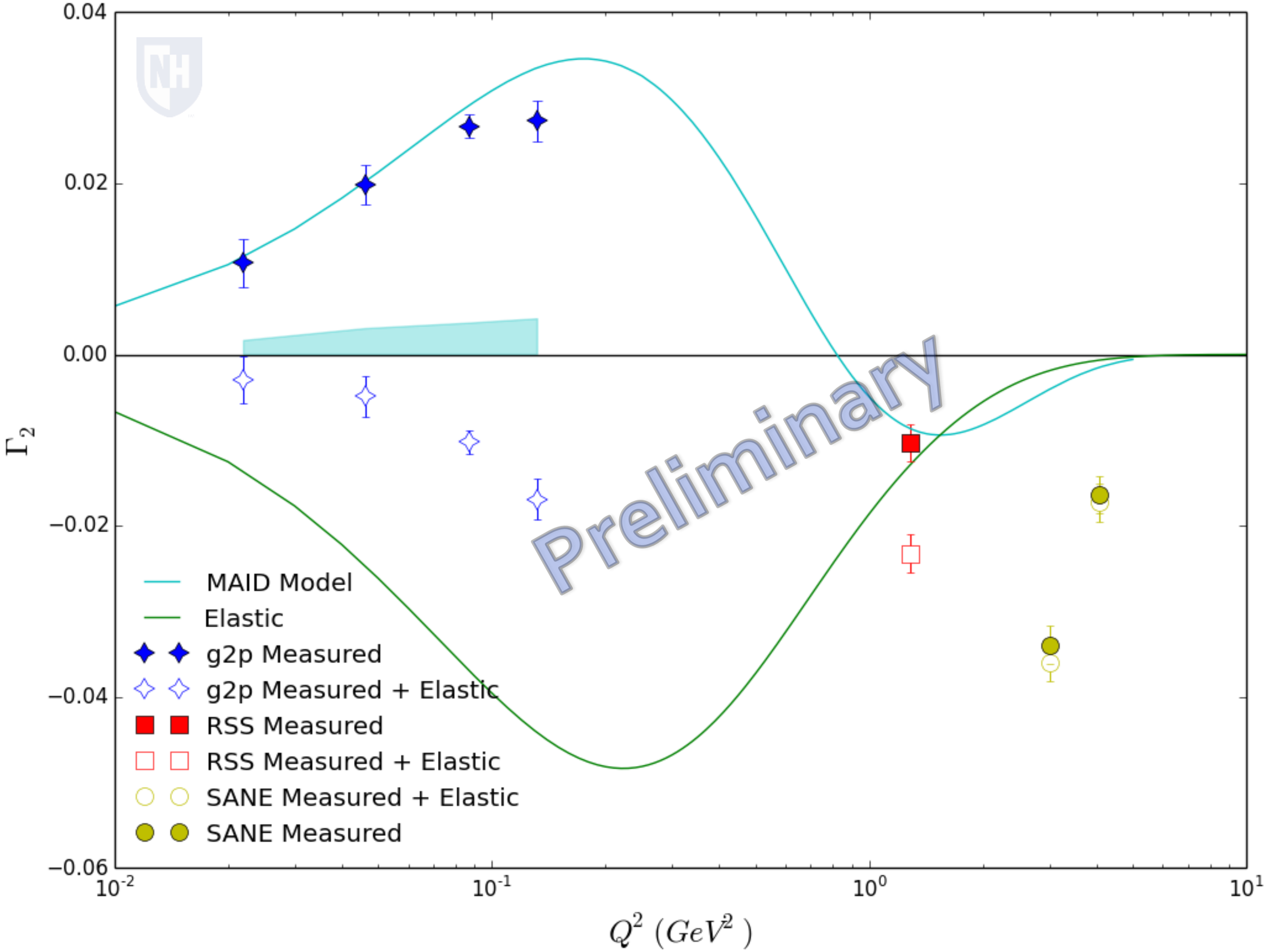
Other Results: g1 Structure Function



- E08-027 data is consistent with previously published data from CLAS
- But with much better statistics!!
- Interesting differences near pion production threshold

Other Results: First Moment of $g_2(x,Q^2)$

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



Q^2 (GeV^2)	Lowest x_{bj}
0.13	0.059
0.09	0.043
0.05	0.029
0.02	0.010

Burkhardt-Cottingham Sum rule says this moment should be zero everywhere…

Unmeasured, low x part difficult to calculate accurately at low Q^2

Conclusion

- The g2p experiment was a precision measurement of proton g_2 in low Q^2 region **for the first time!**
- Analysis is **complete**!
- First publication is **under peer review at Nature Physics!**
- Four more publications in preparation!

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