University of New Hampshire
Nuclear & Particle Physics Group

The g_2p Experiment: A Measurement of the Proton's Spin Structure Functions 2021 Status Update

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Hall A Collaboration Meeting

January 22, 2021

Essential Quantities in *ep* Scattering

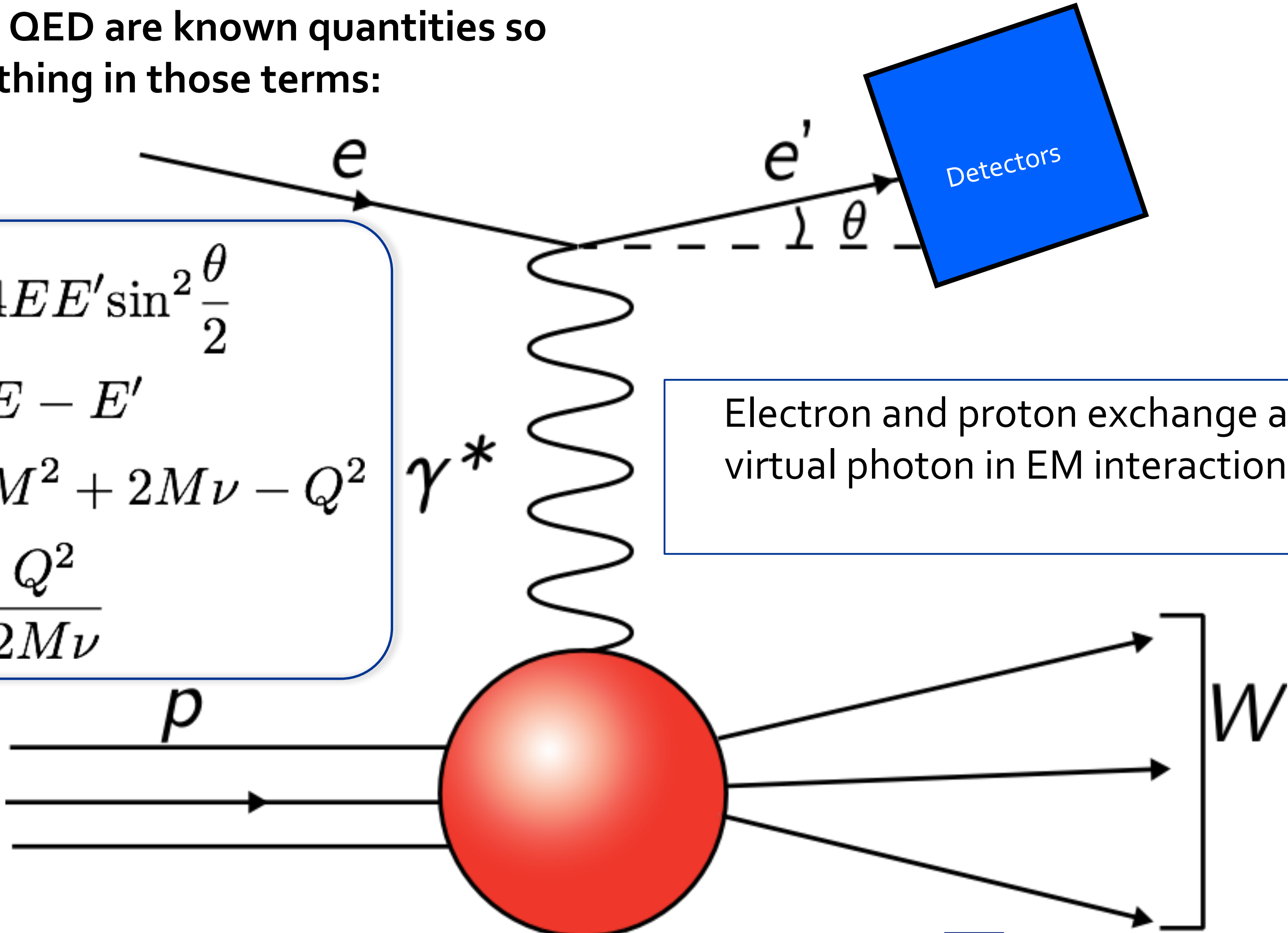
Electron and QED are known quantities so define everything in those terms:

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

$$\nu = E - E'$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$x = \frac{Q^2}{2M\nu}$$



Electron and proton exchange a virtual photon in EM interaction

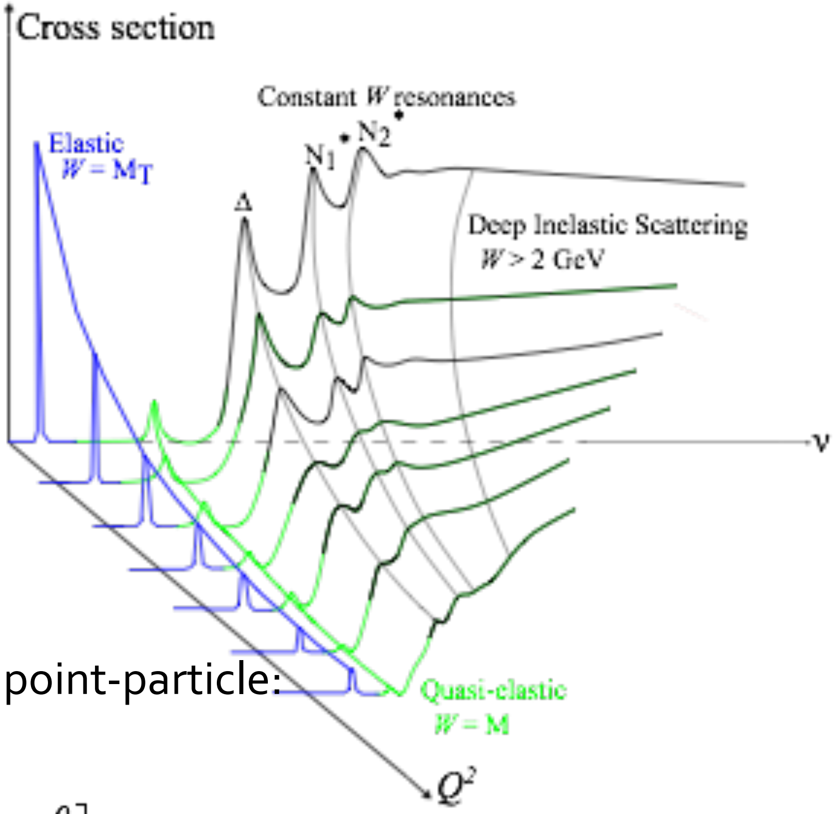
Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

Elastic scattering: target remains in the ground state after interaction

$$E'_{\mathrm{elas}} = \frac{E}{1 + \frac{2E}{M}\sin^2\frac{\theta}{2}}$$

Mott cross section describes scattering from point-particle:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4\,E^2\,\sin^4\frac{\theta}{2}}\cos^2\frac{\theta}{2}$$



Rosenbluth cross section describes deviation from point-particle:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}\left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

G_E and G_M related to charge and current distributions

Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

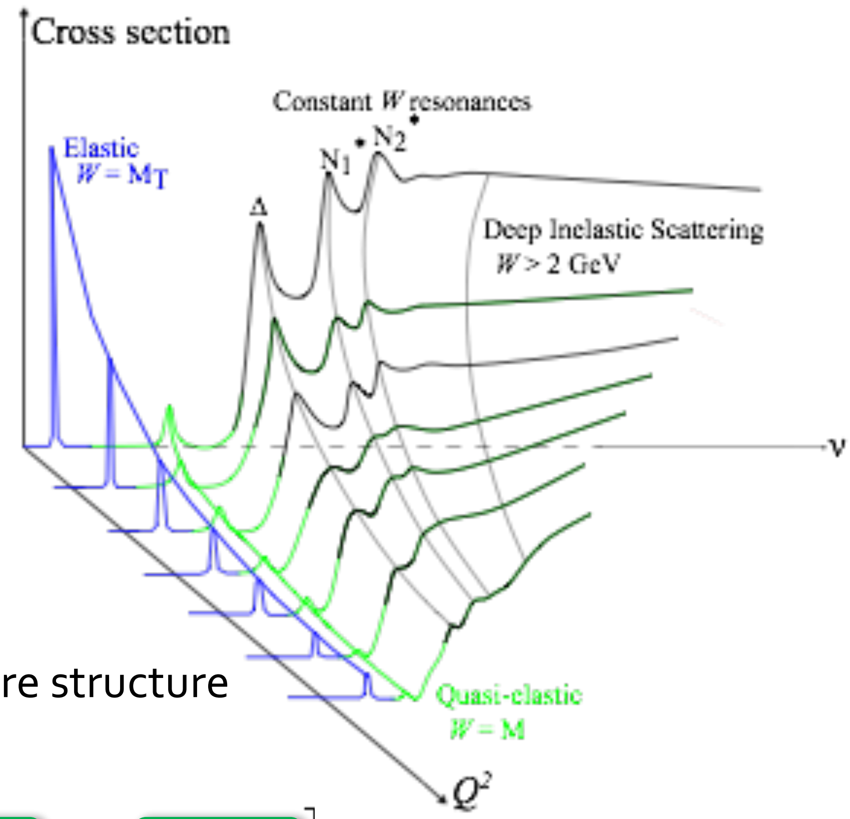
Inelastic scattering: Target is in excited state after interaction

Structure Functions:

Inclusive *unpolarized* cross sections

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

F_1 and F_2 related to quark/gluon distribution



Adding a *polarized* beam and target adds two more structure functions

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

g_1 and g_2 related to spin distribution

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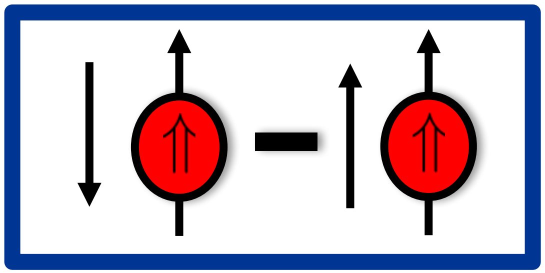
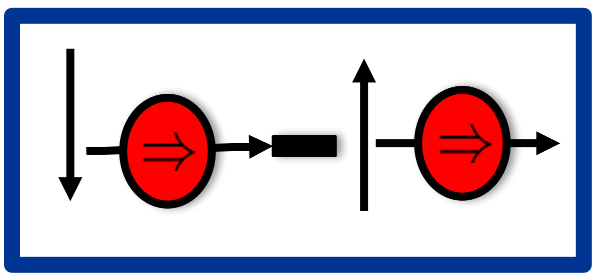
Extracting Spin Structure by Looking at Cross Section Differences

Inclusive *polarized* cross sections



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

Parallel



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

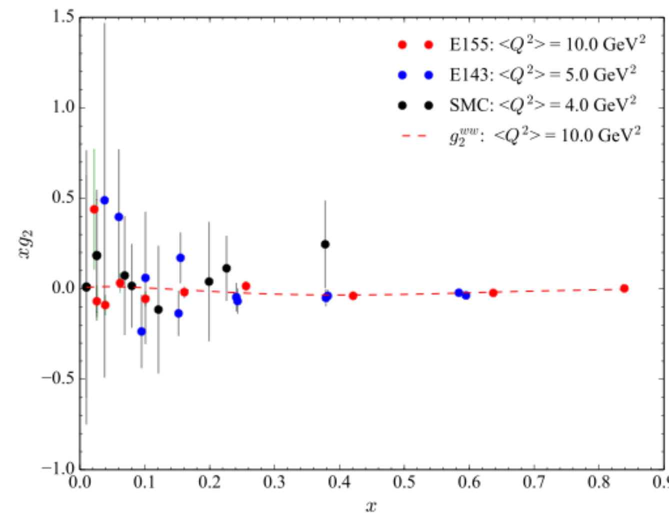
Perpendicular

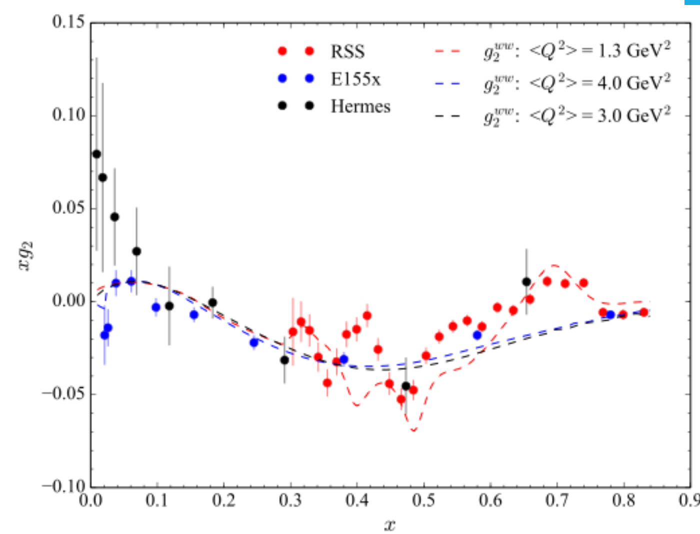
Two equations, two unknowns…

Motivation:

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

- Measurements at Jefferson Lab:
  - RSS – medium Q^2 (1-2 GeV^2) (published)
  - SANE – high Q^2 (2-6 GeV^2) (analysis)
  - **g_2p – low Q^2 (0.02-0.20 GeV^2) (analysis)**
- **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
  - Study finite size effects of the proton
- **g_2p experiment ran spring 2012 in Hall A**



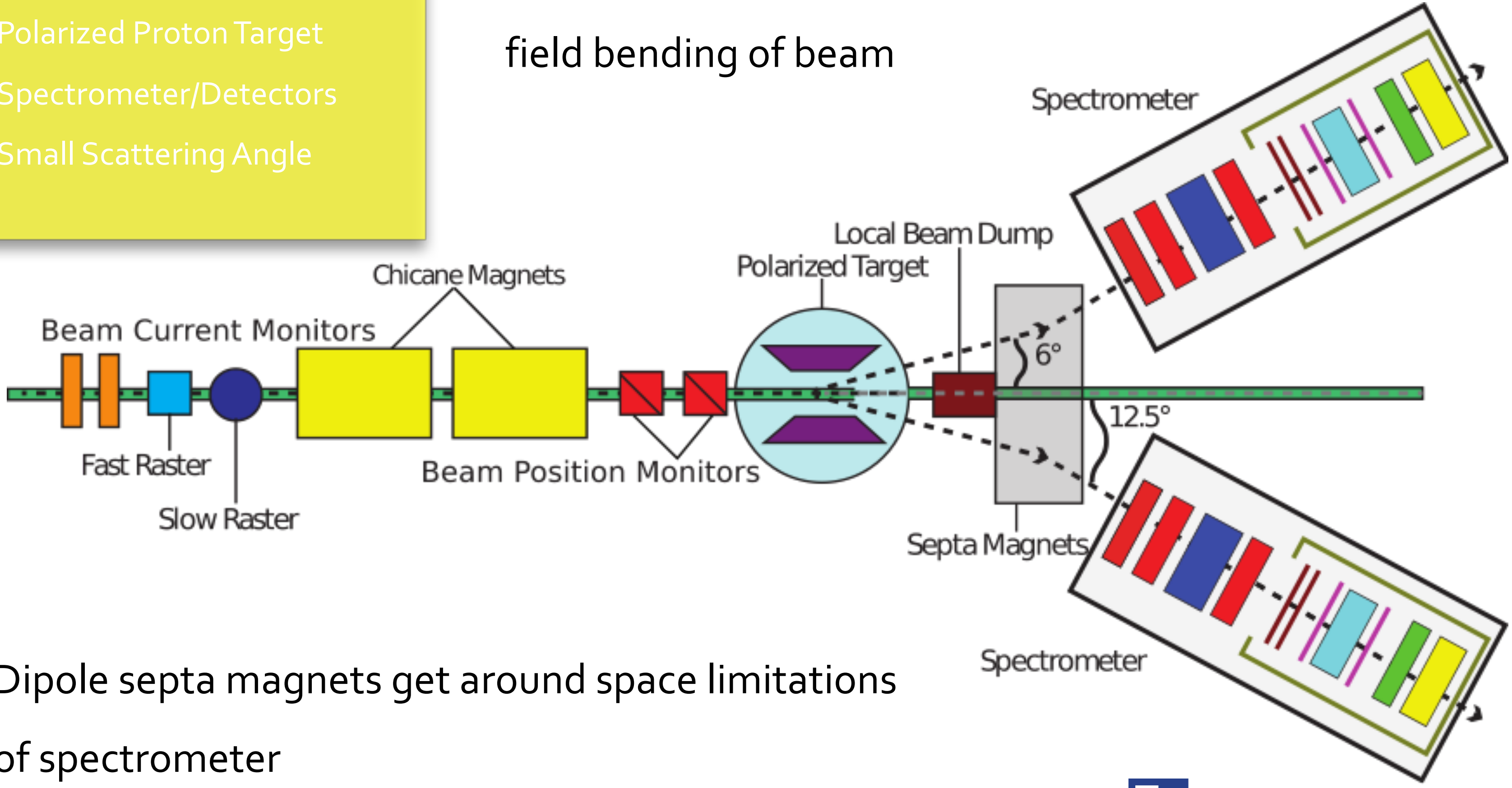


Hall A Experimental Setup:

Measuring g_2^p

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

- 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:

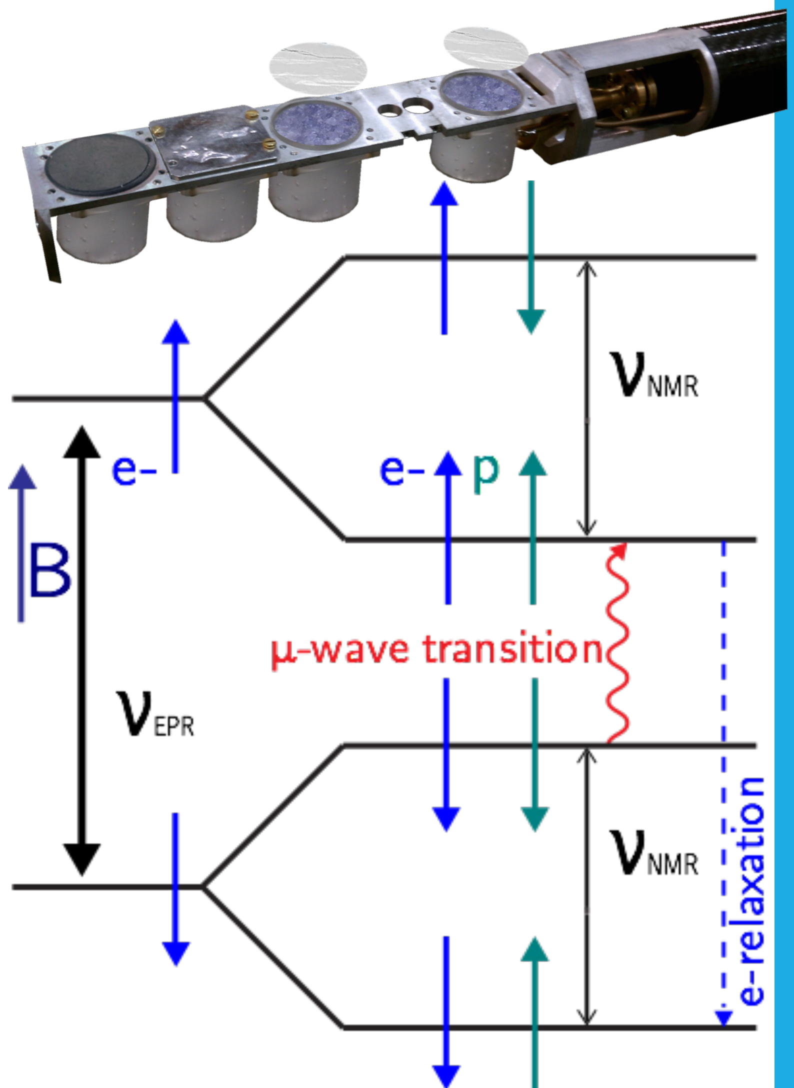
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

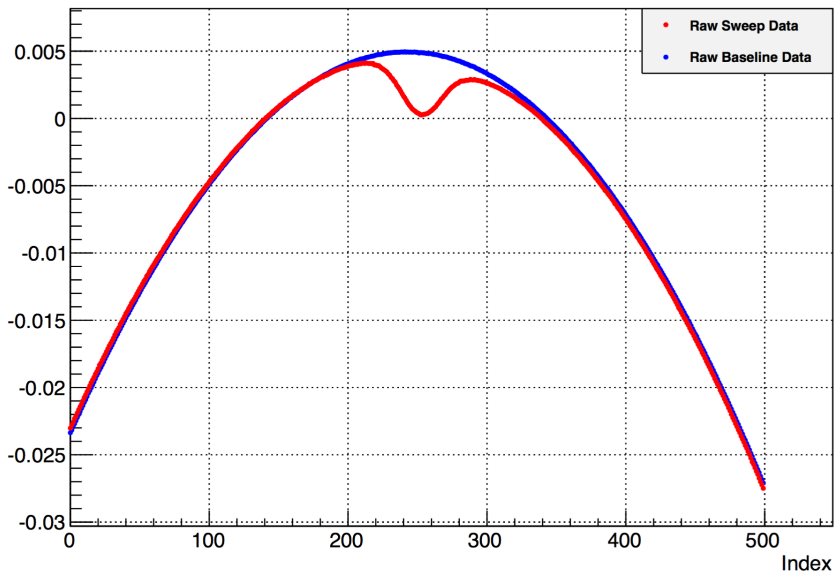
- Large μ_e (~660μ_p) creates large electron polarization (~99% at 5T/1K)

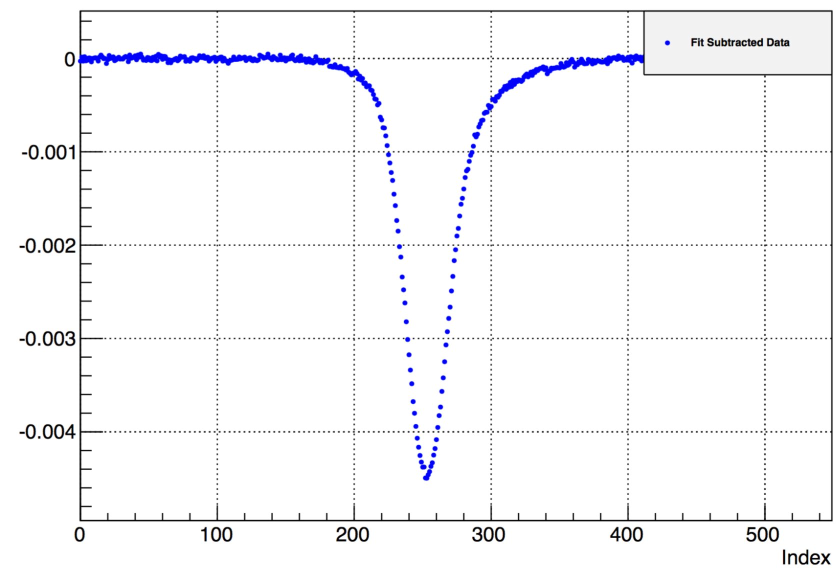
Enhancing initial polarization:

- 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

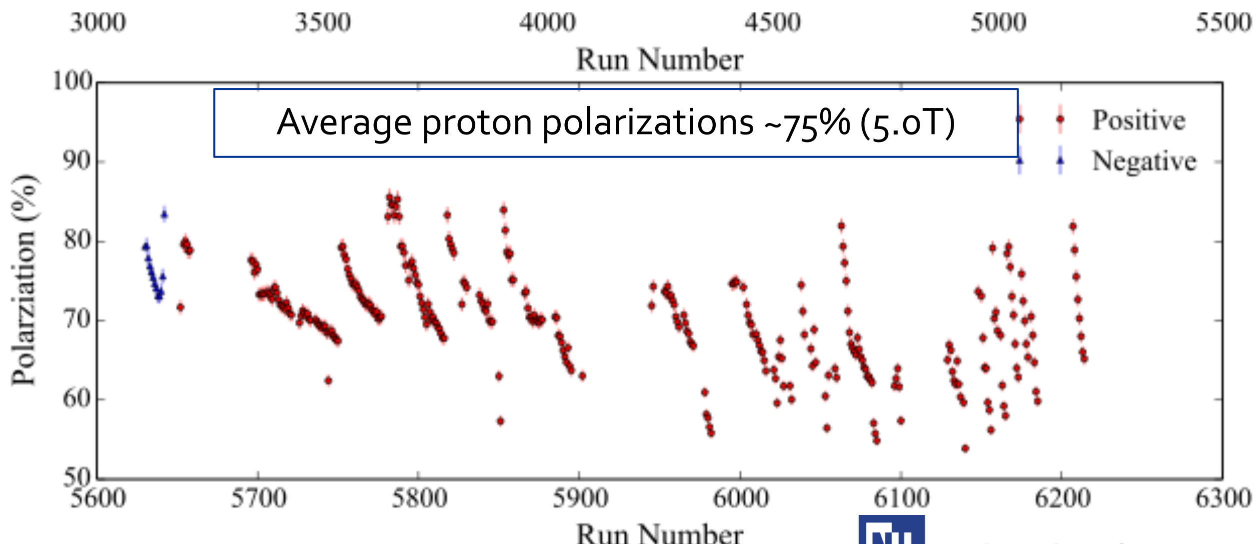


Proton Polarization Measured with Q-Meter





- LRC circuit where proton spin's couple with and change inductance



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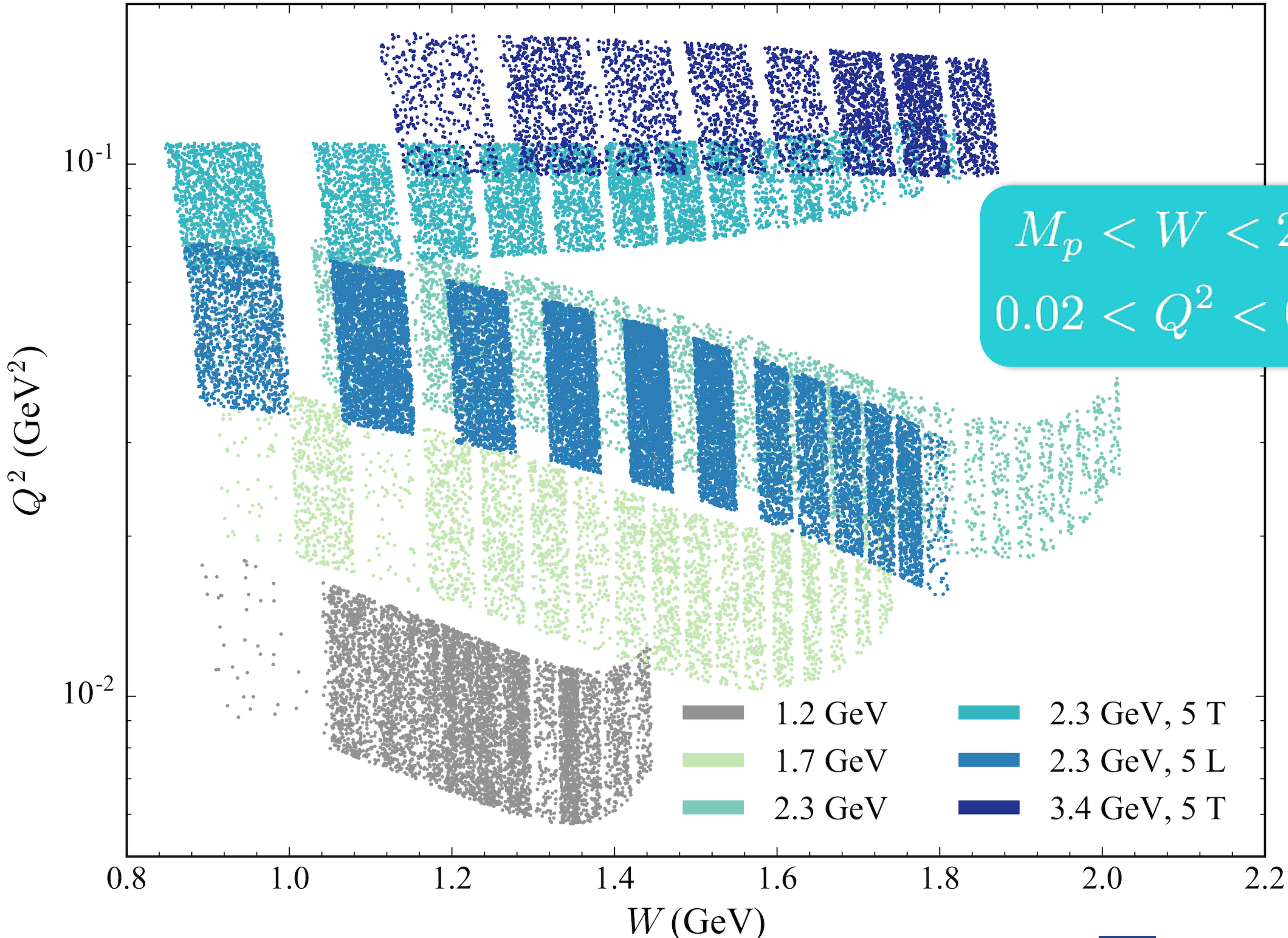
T. Badman (2013) TN #08: http://hallaweb.jlab.org/experiment/g2p/collaborators/toby/technotes/target.pdf

g_2p Kinematic Coverage



$M_p < W < 2\,\mathrm{GeV}$

$0.02 < Q^2 < 0.20\,\mathrm{GeV}^2$

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MEASURING $g_{1,2}$ from data

What can we measure?

1. Helicity dependent asymmetries
2. Unpolarized cross sections
3. Polarized cross sections

1.

$$A_\perp = \frac{\frac{d^2\sigma}{d\Omega dE'}(\downarrow\Rightarrow - \uparrow\Rightarrow)}{\frac{d^2\sigma}{d\Omega dE'}(\downarrow\Rightarrow + \uparrow\Rightarrow)}$$

2.

$$\sigma_0 = \frac{1}{2}\frac{d^2\sigma}{d\Omega dE'}(\downarrow\Rightarrow + \uparrow\Rightarrow)$$

3.

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

Similar equation for parallel polarized cross section

Why do it this way?

- Asymmetries are easy to measure
- Lots of data on unpolarized cross sections so models are a possibility

Need to be mindful of contributions from scattering from anything other than protons

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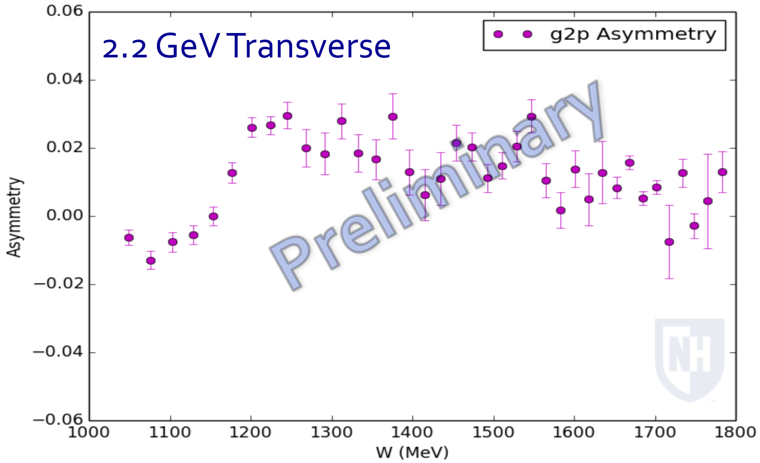
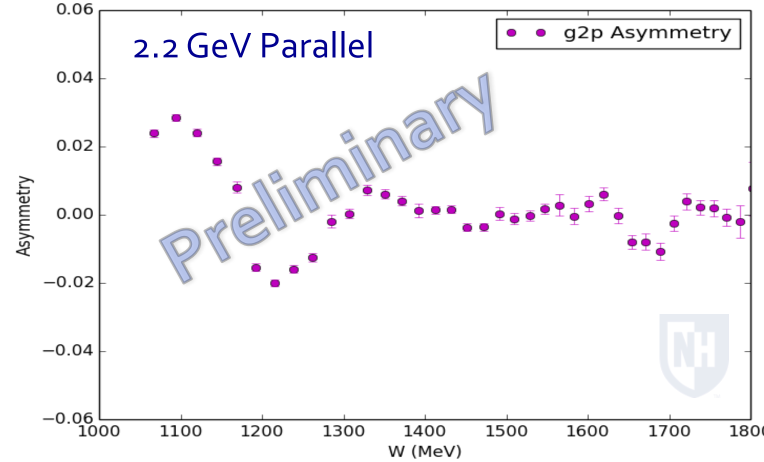
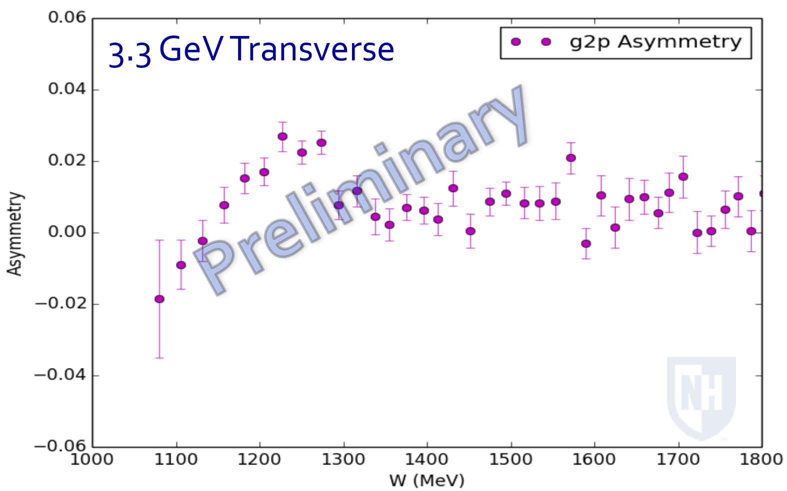
5T Proton Asymmetries







Raw Counts:

$$Y_\pm = \frac{N_\pm}{LT_\pm Q_\pm}$$

Measured Asymmetries:

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

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

dilution factor (f)

beam/target pol ($P_t \cdot P_b$)

Combine both HRS for best statistics!

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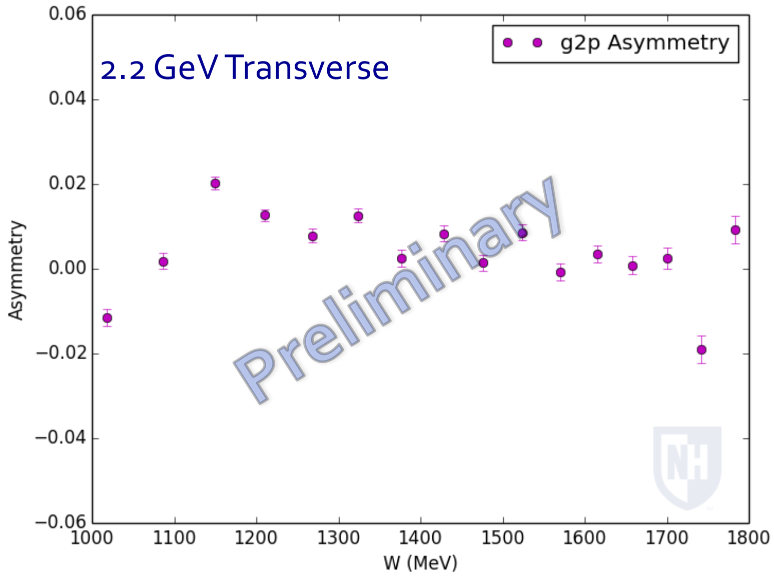
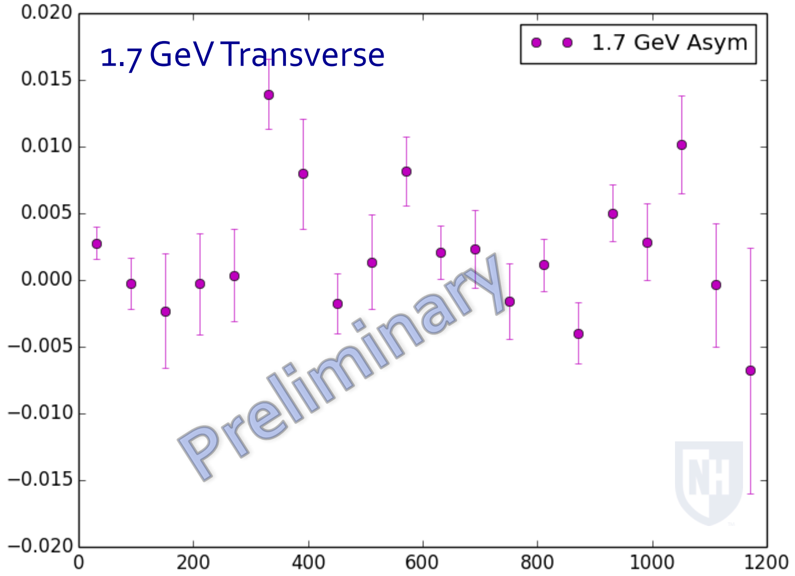
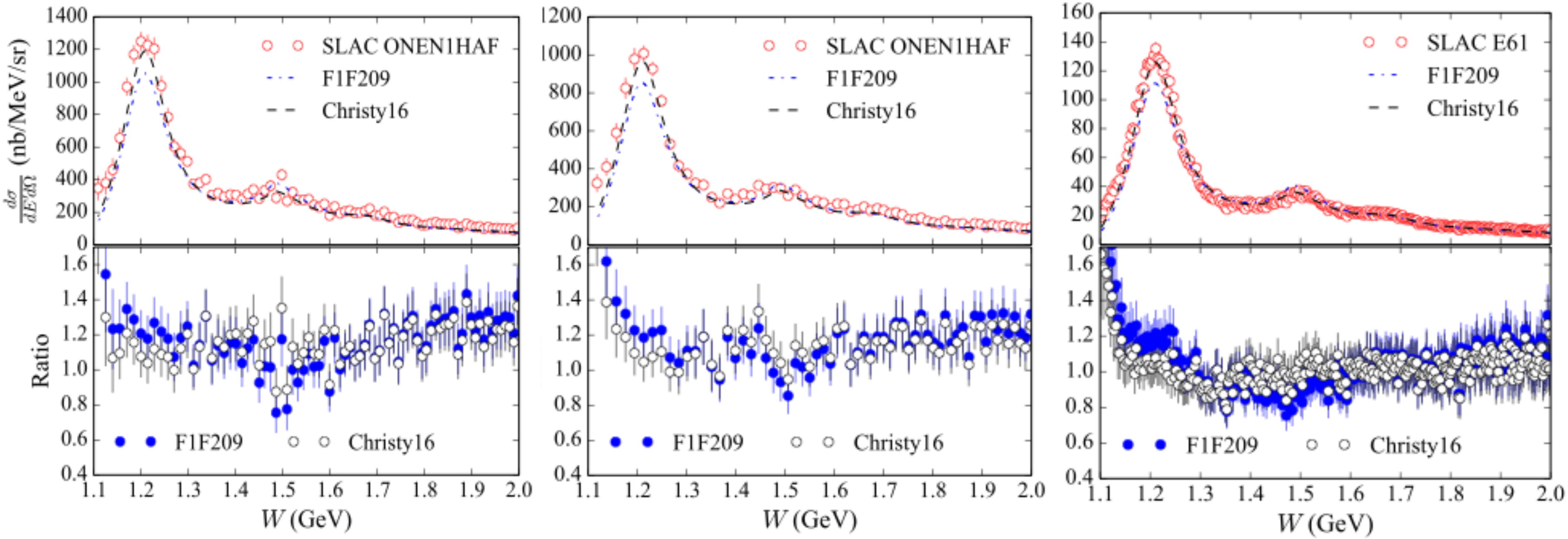
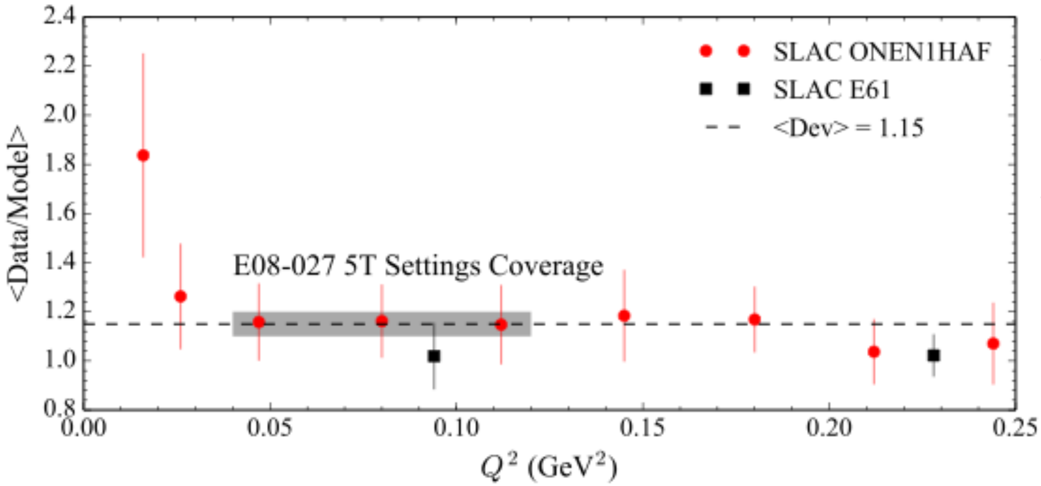
2.5T Proton Asymmetries





Model Cross Section

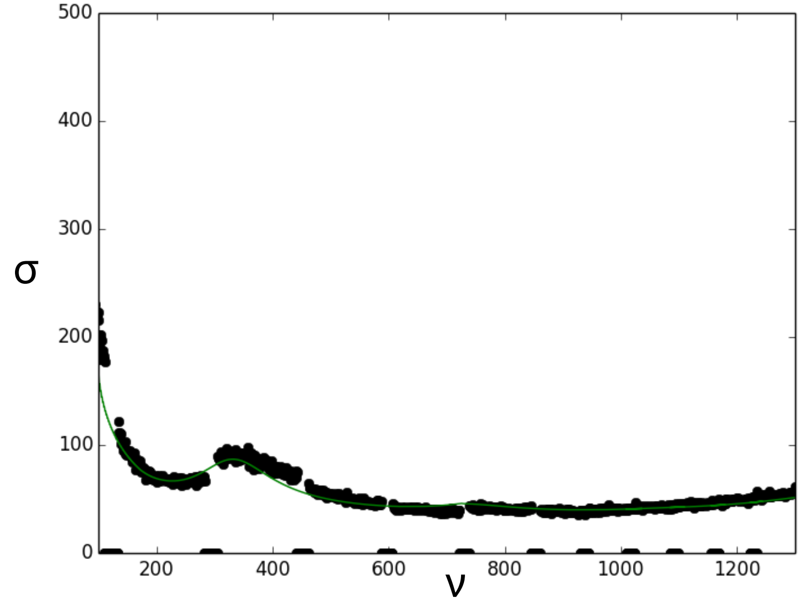


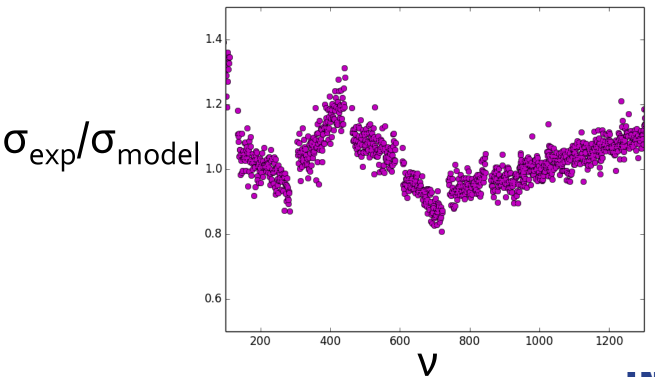


- Use proton model for unpolarized cross section
- Does a good job of reproducing data at E08-027 kinematics

Model Cross Section

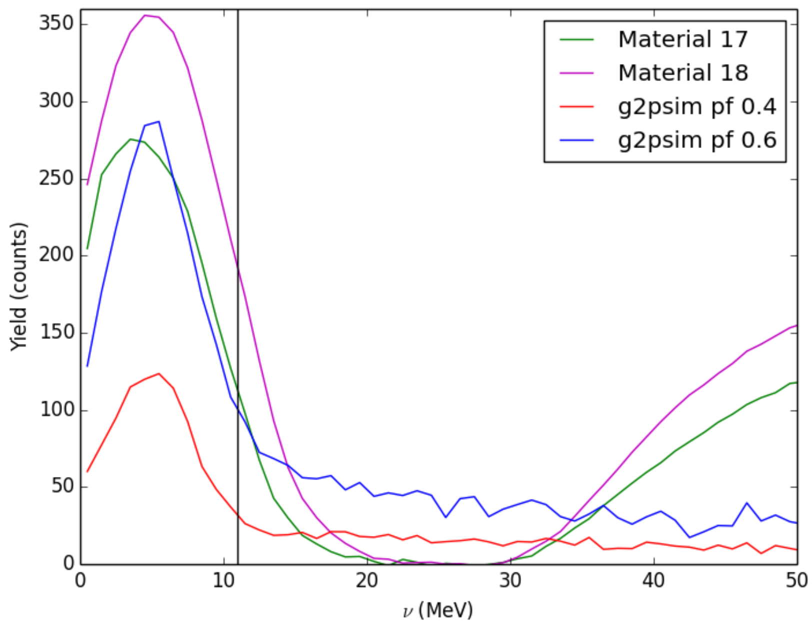
- Direct comparison to g2p Longitudinal cross section yields very similar comparison results
- Acceptance complications at the transverse settings make it preferable to use the model cross section for final results despite the relatively large associated systematic



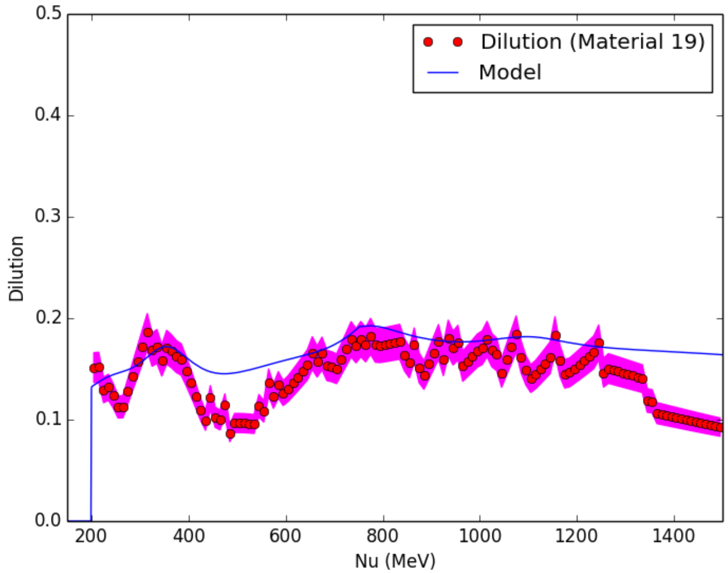


Packing Fraction & Dilution Analysis

- Packing fraction describes how much material is in the target cell, important for calculating dilution factor
- Previous packing fraction and dilution analysis yielded unrealistic results, in February I concluded a lengthy re-analysis of both
- Packing Fraction Analysis re-done with Oscar Rondon's method from RSS



- Dilution approximates how much of data comes from other materials
- $f = \frac{\sigma_{Proton}}{\sigma_{Prod}} = 1 - \frac{Y_N + Y_{He} + Y_{Al}}{Y_{Prod}}$
- Acceptance effects on edge of momentum settings and BPM calibration issues complicated this analysis



Extracting the Spin Structure Functions

Model driven procedure for unmeasured part

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

$$K_1 = \frac{MQ^2}{4\alpha}\frac{y}{(1-y)(2-y)}$$

$$K_2 = \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}.$$

Adjusting to a constant Q^2

$$\delta_{\text{evolve}} = g_{1,2}^{\text{mod}}(x_{\text{data}}, Q^2_{\text{data}}) - g_{1,2}^{\text{mod}}(x_{\text{const}}, Q^2_{\text{const}}),$$

$$x_{\text{const}} = Q^2_{\text{const}}/(W^2 - M^2 + Q^2_{\text{const}}),$$

Small effect at the transverse settings

Model driven procedure for unmeasured part

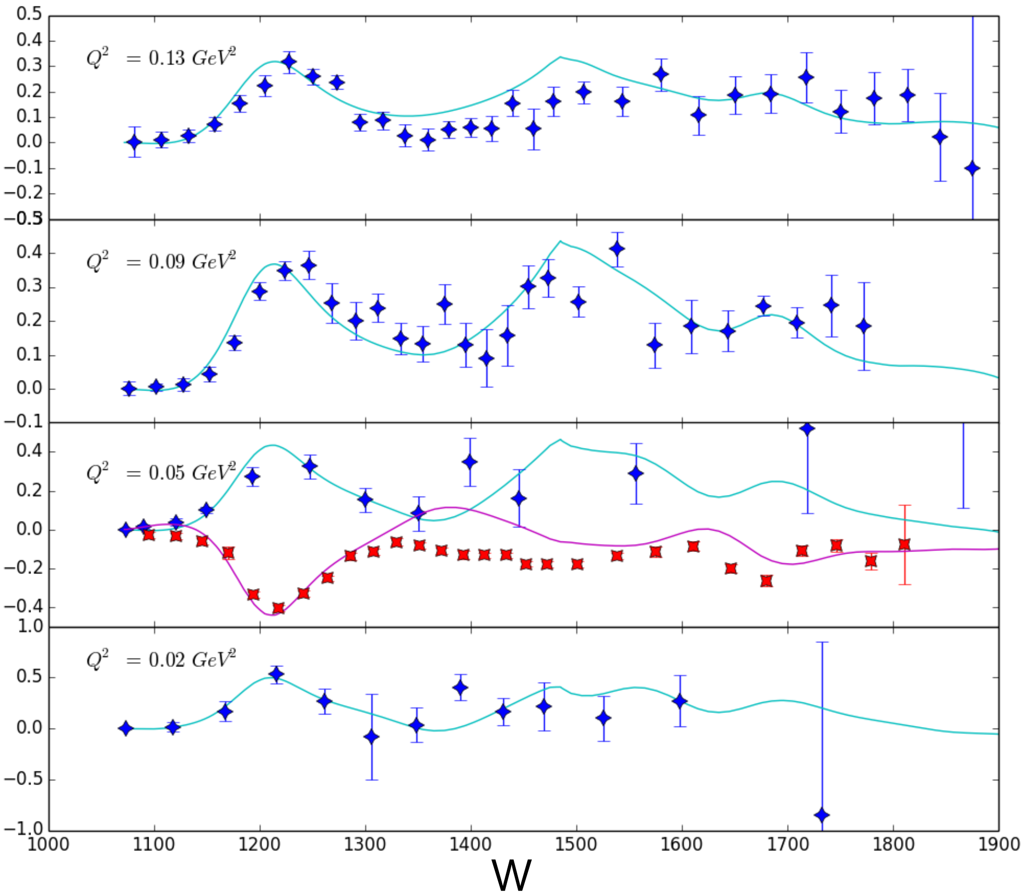
$$g_1(x,Q^2) = K_1\left[\Delta\sigma_{\parallel}\left(1 + \frac{1}{K_2}\tan\frac{\theta}{2}\right)\right] + \frac{2g_2(x,Q^2)}{K_2 y}\tan\frac{\theta}{2}$$

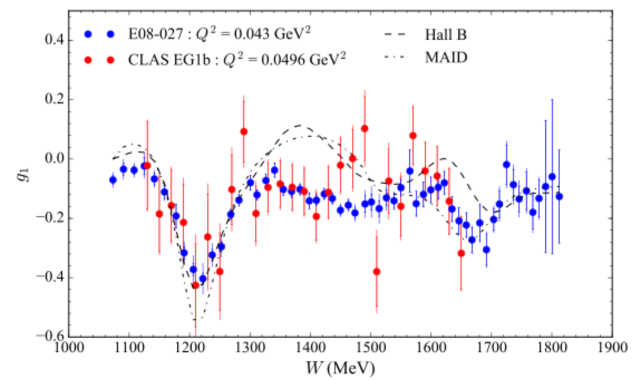
$$K_1 = \frac{MQ^2}{4\alpha}\frac{y}{(1-y)(2-y)}$$

$$K_2 = \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}.$$

Structure Function Results

Blue Stars – g_2 (Transverse Setting)
Red Xs – g_1 (Longitudinal Setting)



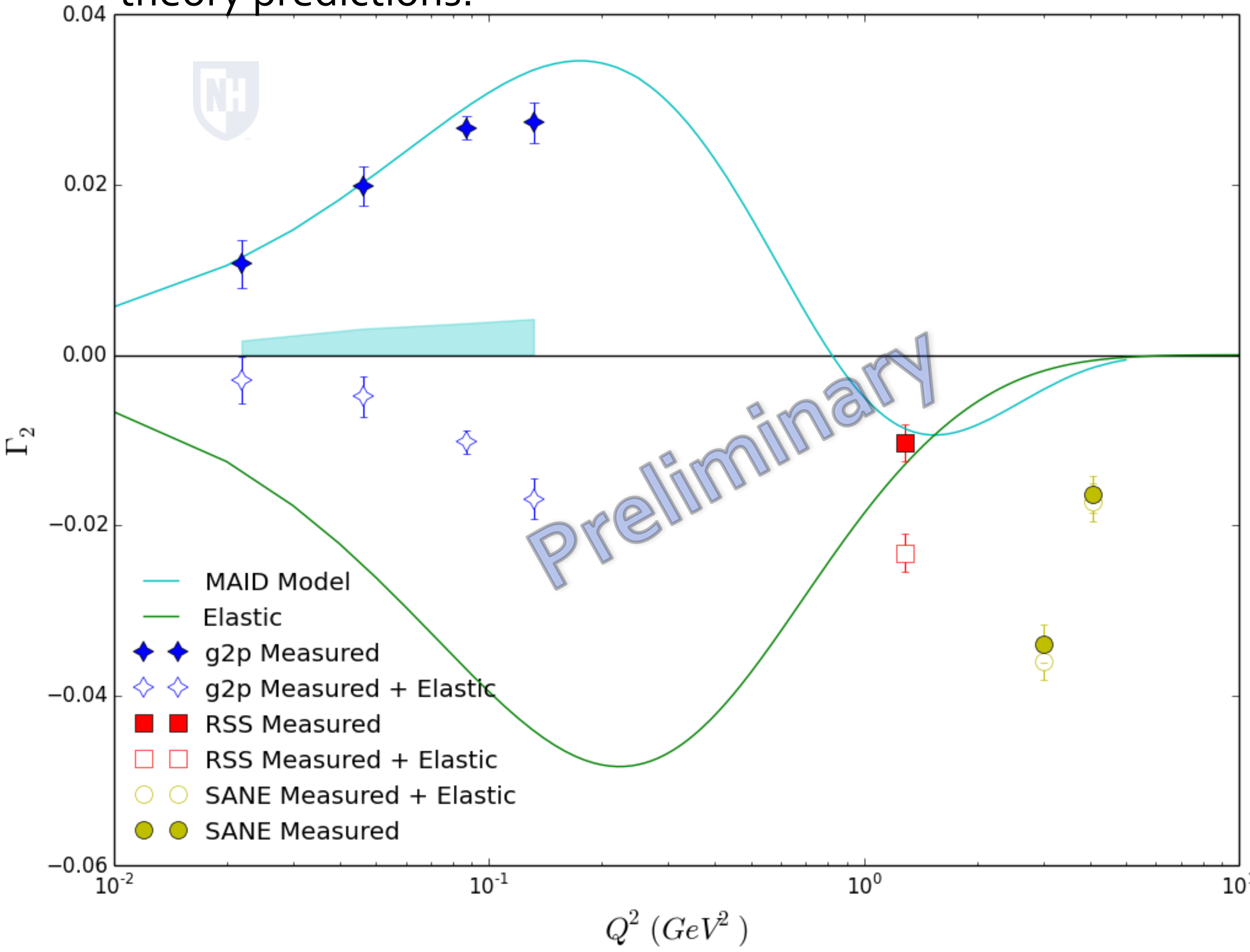


- E08-027 data is consistent with previously published data from CLAS
- But with much better statistics!!

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

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

Moments provide a useful quantity that can be related back to theory predictions!



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

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

Distance between Measured+elastic and zero can be taken as measurement of this hard to measure region if BC sum rule is followed

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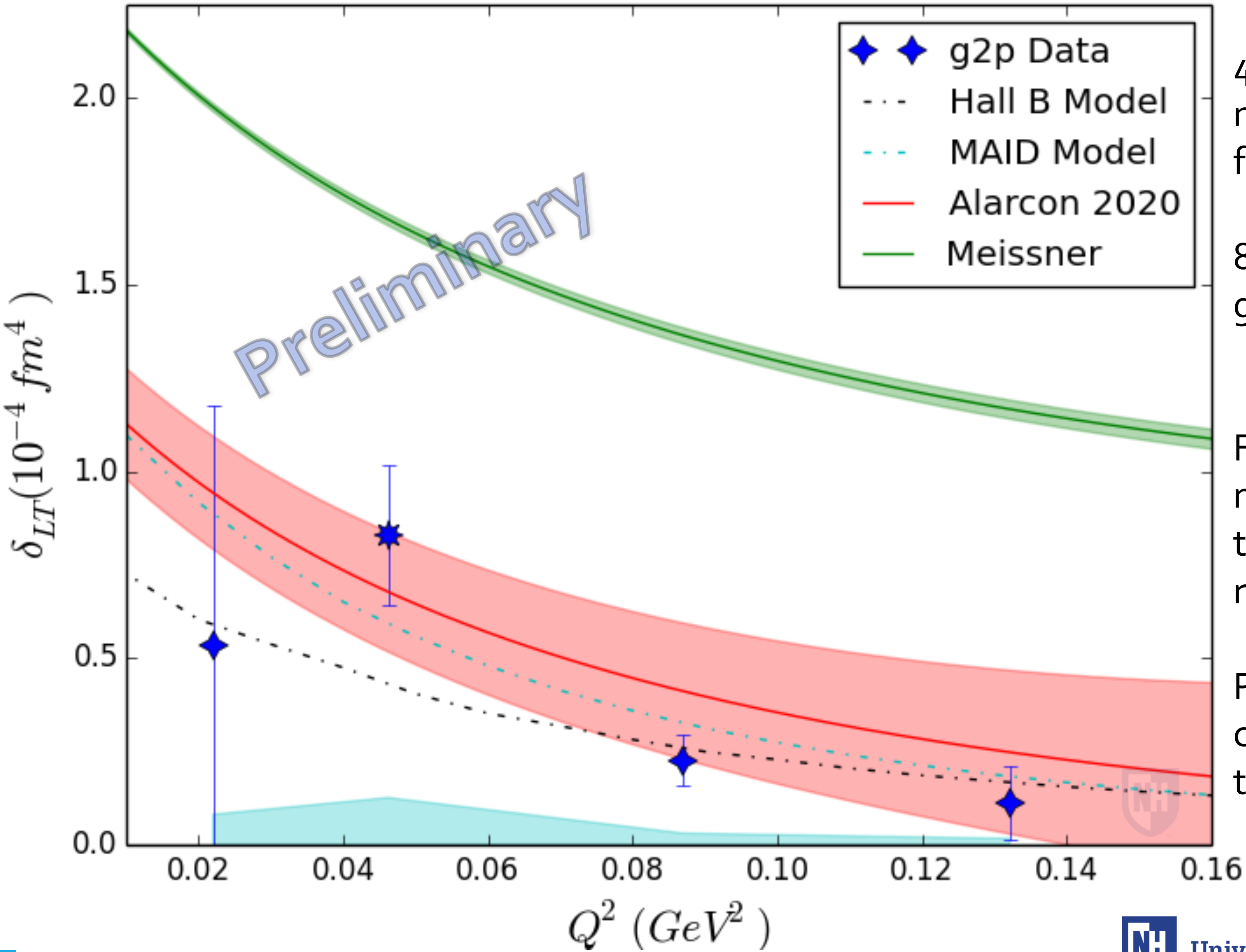
Transverse-Longitudinal Spin Polarizability

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



4 pt star – g2 measured with g1 from Hall B model

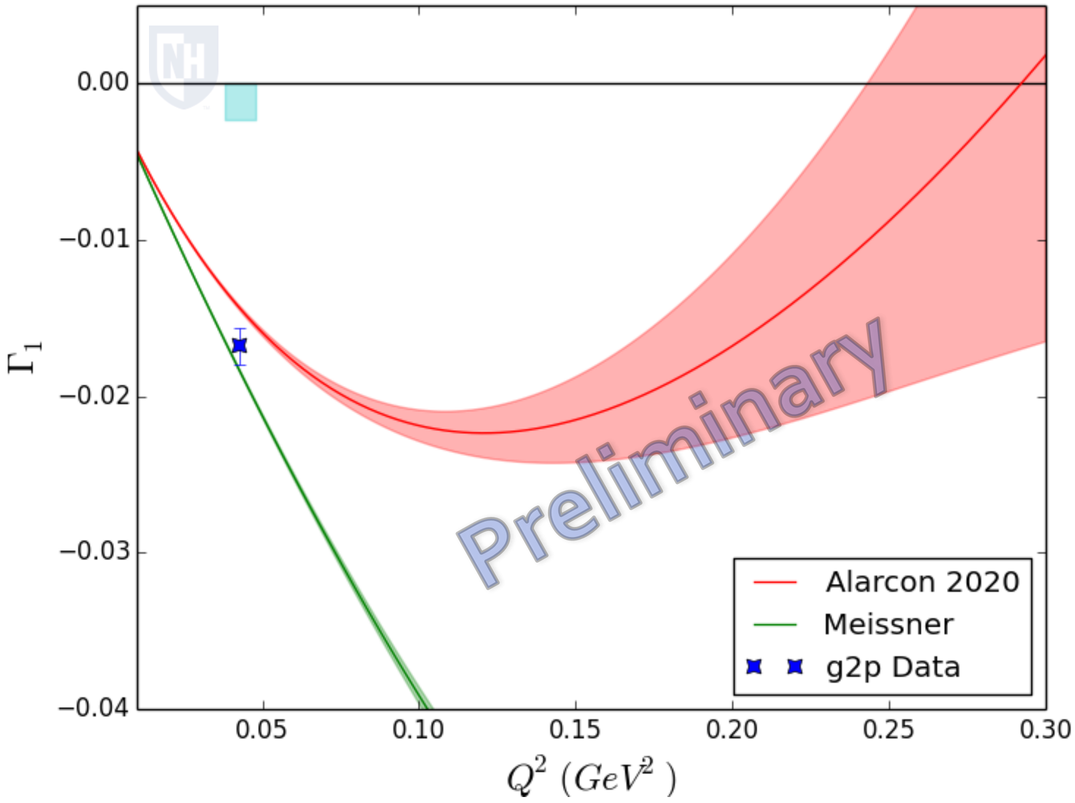
8 pt star – g1 and g2 both measured

First ever measurement of this quantity in this region!

Possible test of chiral perturbation theory

First Moment of $g_1(x,Q^2)$

$$\Gamma_1(Q^2) = \int_0^{x_{\rm th}} g_1(x,Q^2)dx$$



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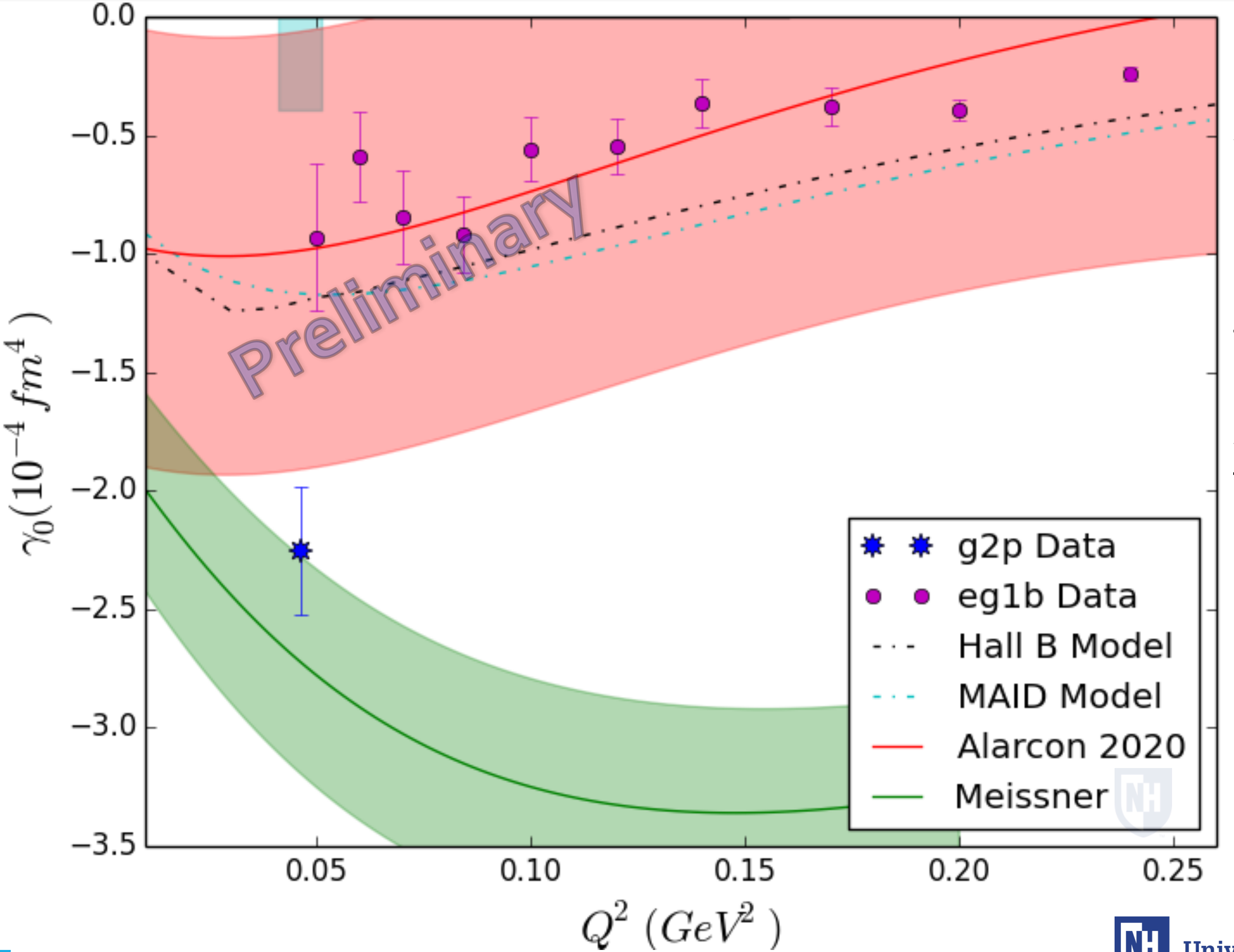
Generalized Forward Spin Polarizability

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}} x^2 g_1(x,Q^2) - \frac{4M^2}{Q^2}x^4 g_2(x,Q^2)dx$$



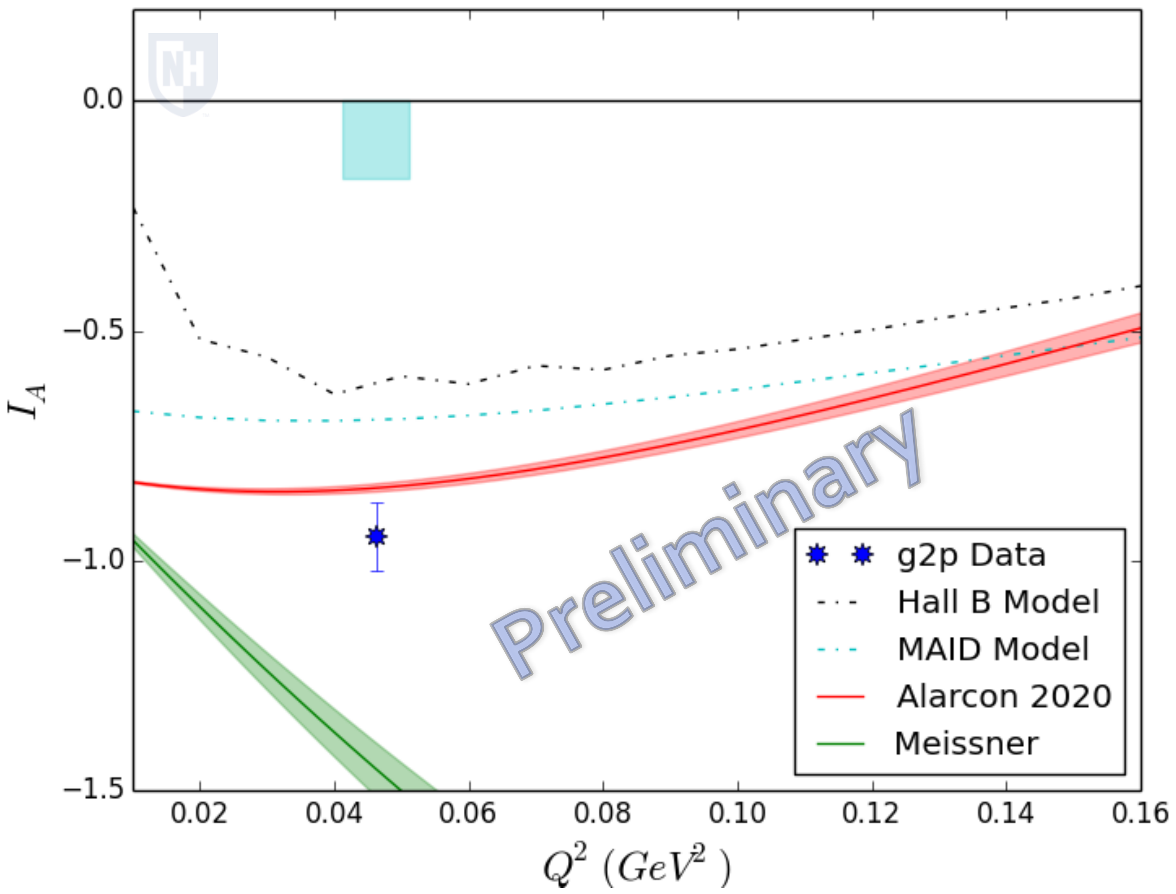
Strong disagreement with eg1b data

g_2^p data includes measured data for g_2…

And goes closer to threshold

Gerasimov-Drell-Hearn Sum Rule

$$I_A = \frac{2M^2}{Q^2}\int_0^{x_{th}} g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x,Q^2)dx$$



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Conclusion

- Experimental measurements of proton structure are key to understanding the proton!
- The g_2p experiment was a precision measurement of proton g_2 in low Q^2 region **for the first time!**
- Since the Hall A summer meeting, an analysis of the 1.7 GeV data and a comparison of our Longitudinal cross section to the Bosted-Christy model has been completed, as well as a thorough analysis of the moment results
- Analysis is now **complete**! We are in the process of writing a publication with the intention of submitting to Physical Review Letters in the coming months.

Acknowledgements

g2p Analysis Team

Spokespeople:
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Don Crabb
Karl Slifer

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