University of New Hampshire
Nuclear & Particle Physics Group

The g_2p Experiment: A Measurement of the Proton's Spin Structure Functions 2020 Status Update

David Ruth

Hall A Collaboration Meeting

January 30, 2020

Some Slides & Figures by Ryan Zielinski

Essential Quantities in *ep* Scattering

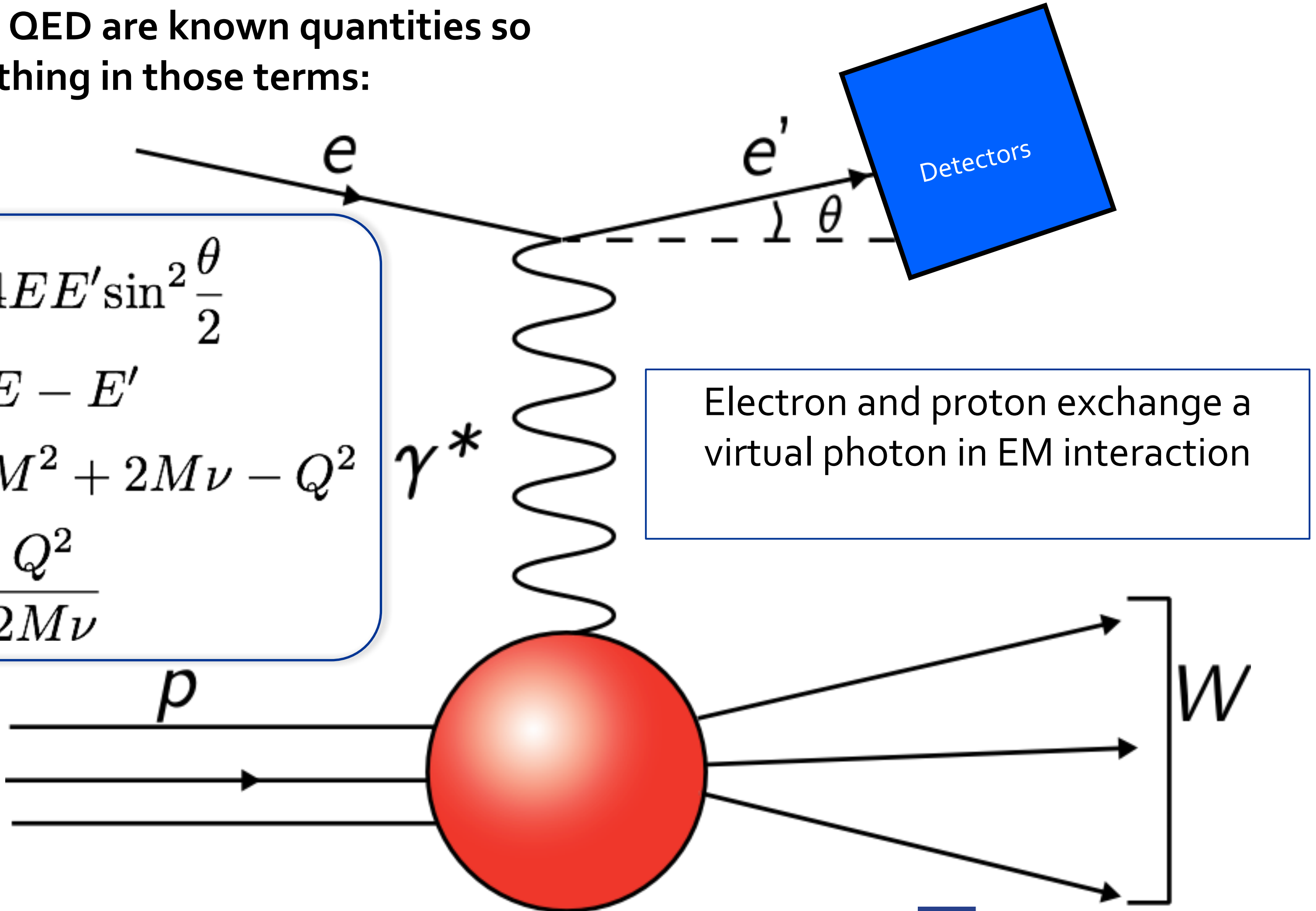
Electron and QED are known quantities so define everything in those terms:

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

$$\nu = E - E'$$

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

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

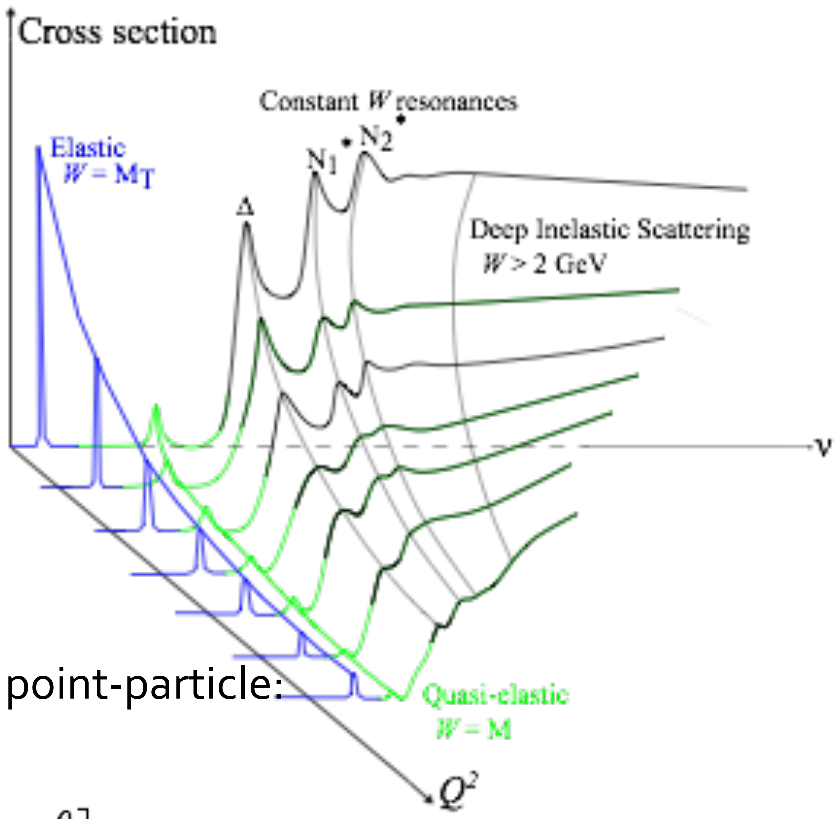


Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

Elastic scattering: target remains in the ground state after interaction

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

Mott cross section describes scattering from point-particle:



Rosenbluth cross section describes deviation from point-particle:

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

G_E and G_M related to charge and current distributions

Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

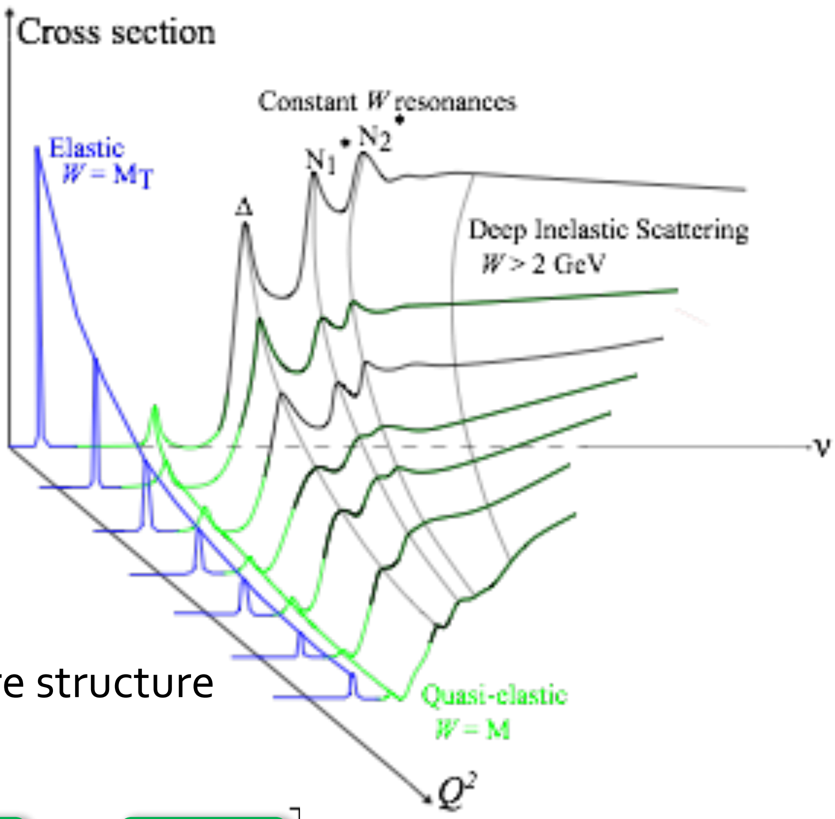
Inelastic scattering: Target is in excited state after interaction

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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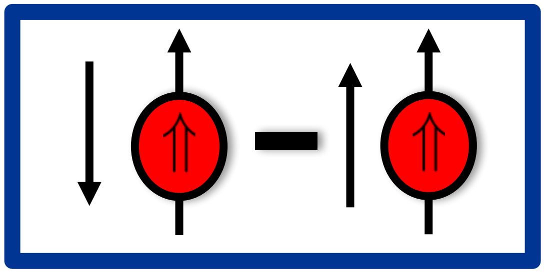
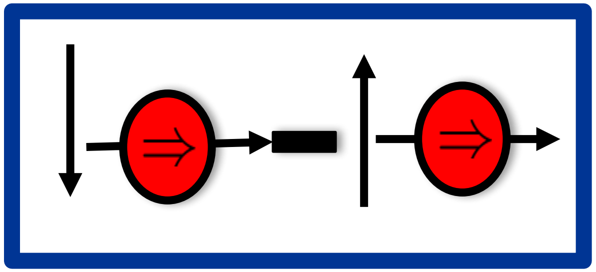
Extracting Spin Structure by Looking at Cross Section Differences



Parallel

Inclusive *polarized* cross sections

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



Perpendicular

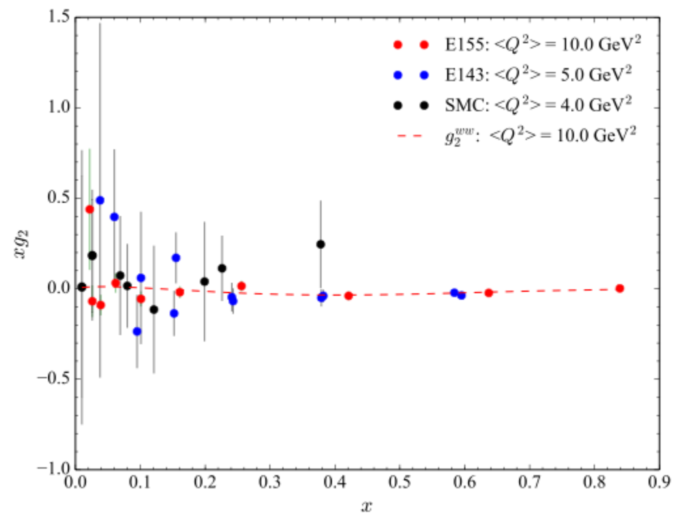
$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\left[\nu g_1(x,Q^2) + 2E g_2(\nu,Q^2)\right]$$

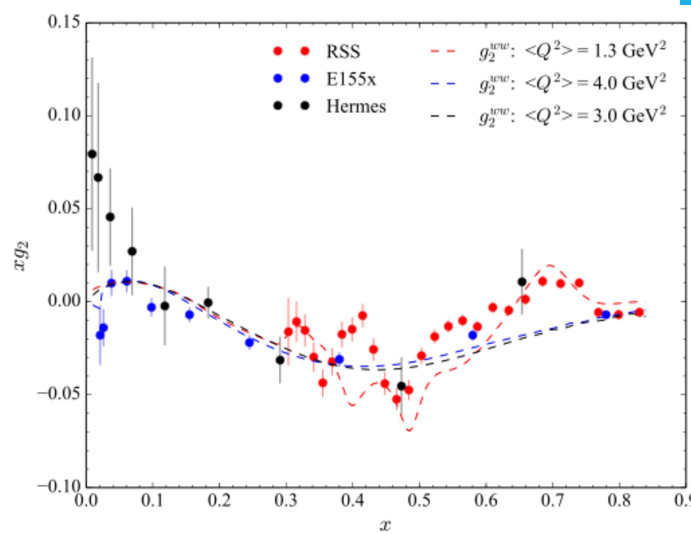
Two equations, two unknowns…

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**





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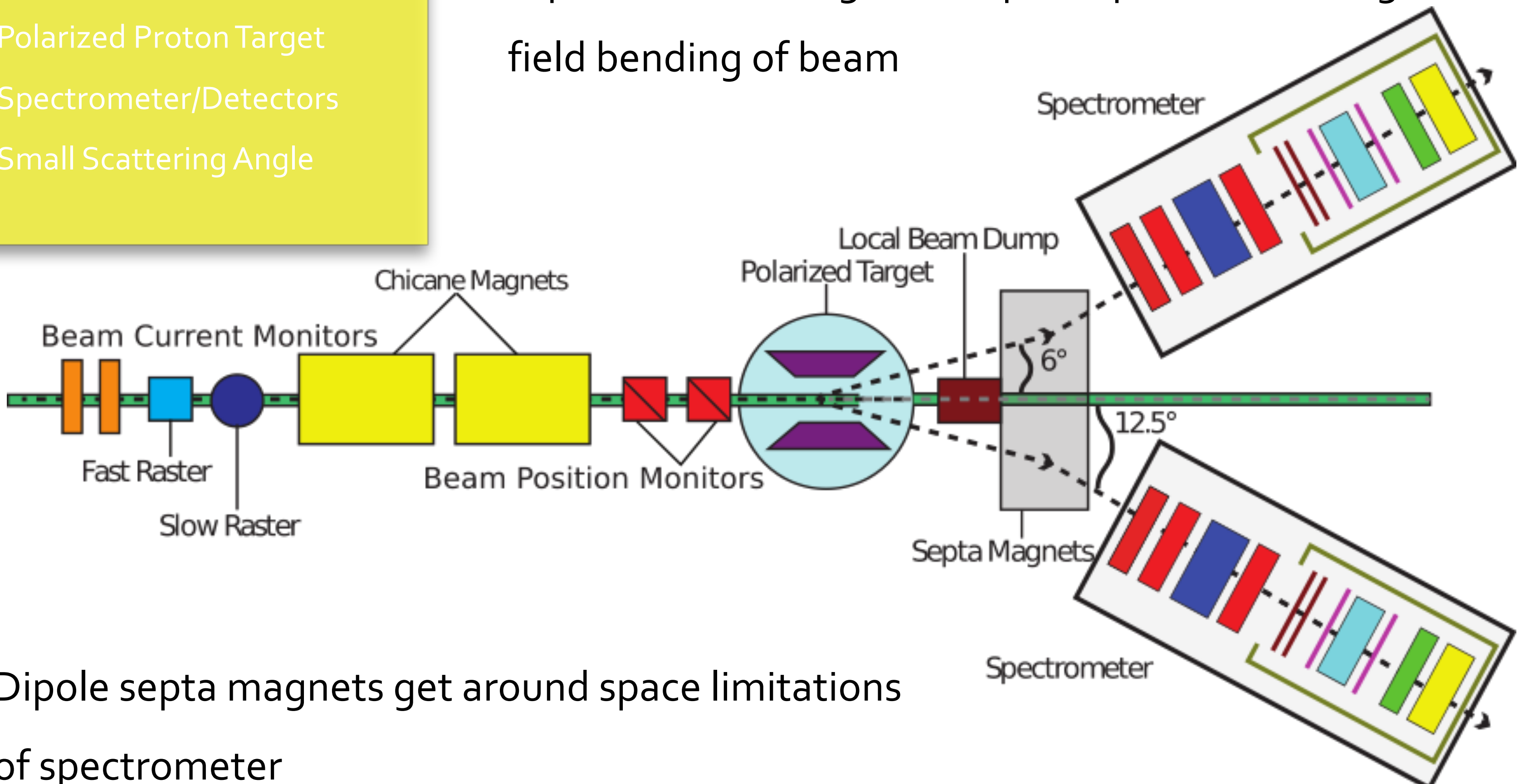
Hall A Experimental Setup:

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

Polarized Protons Created with Dynamic Nuclear Polarization (DNP)

Creating initial polarization:

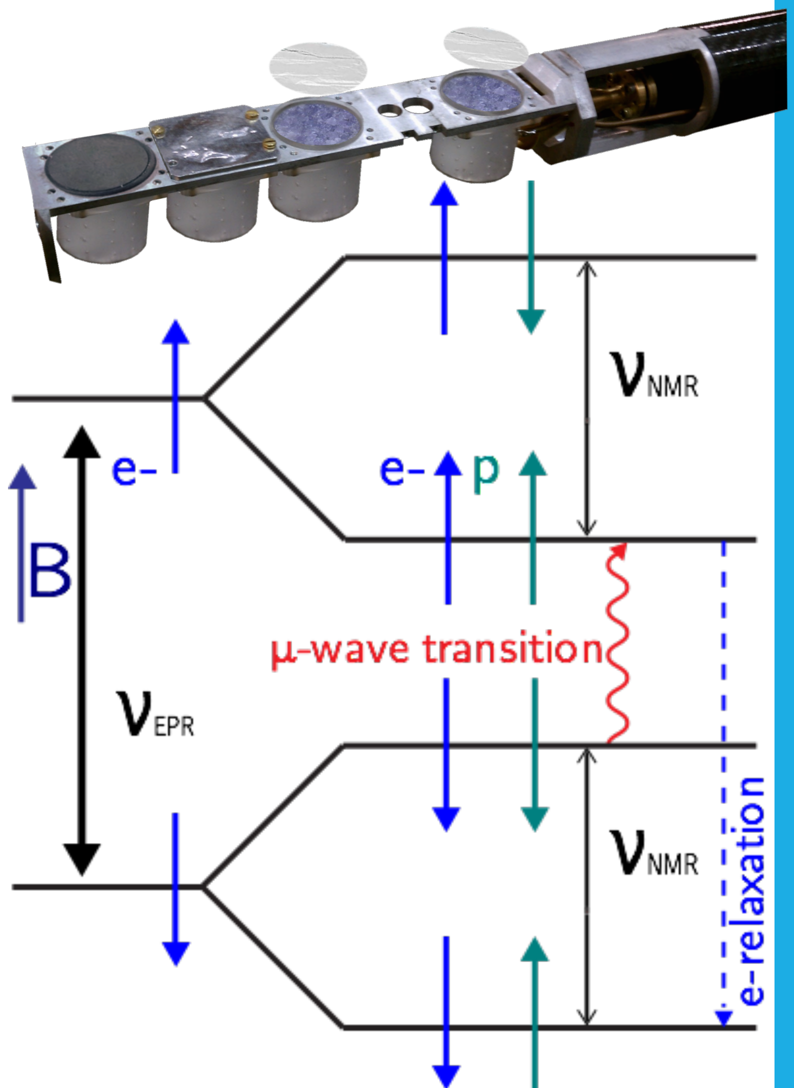
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

- 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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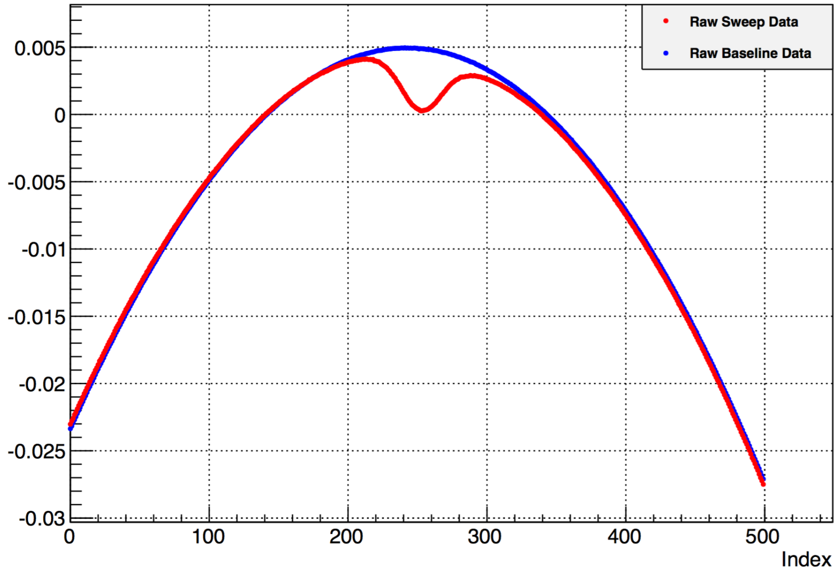
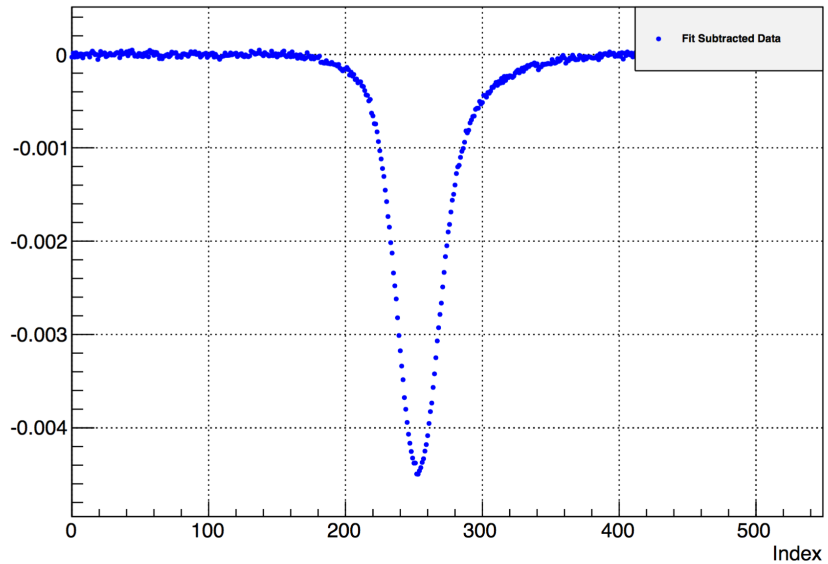
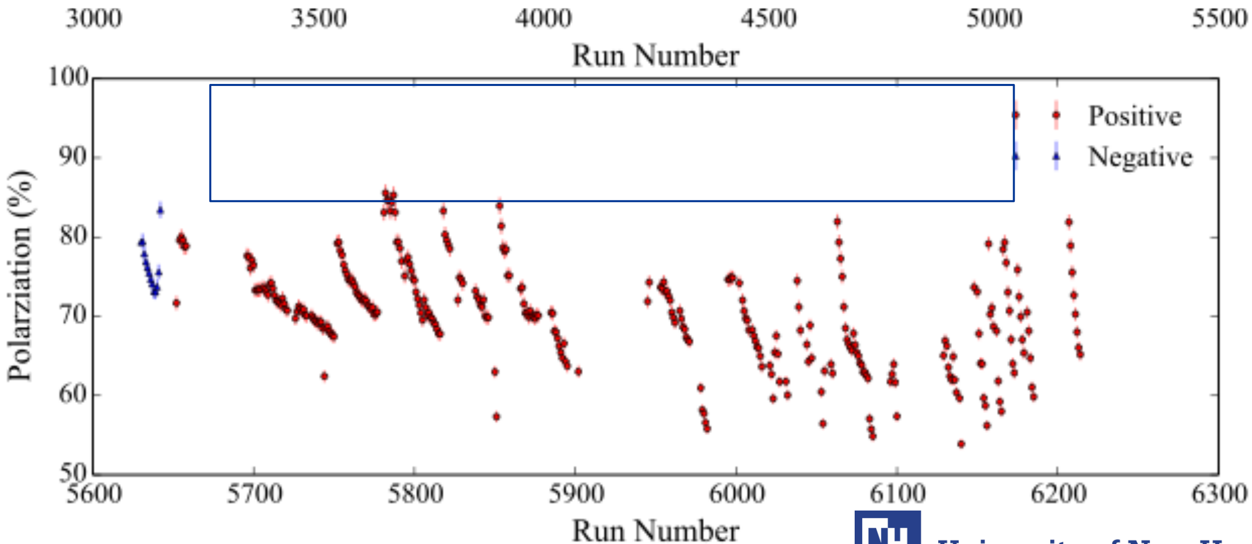
Proton Polarization Measured with Q-Meter





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



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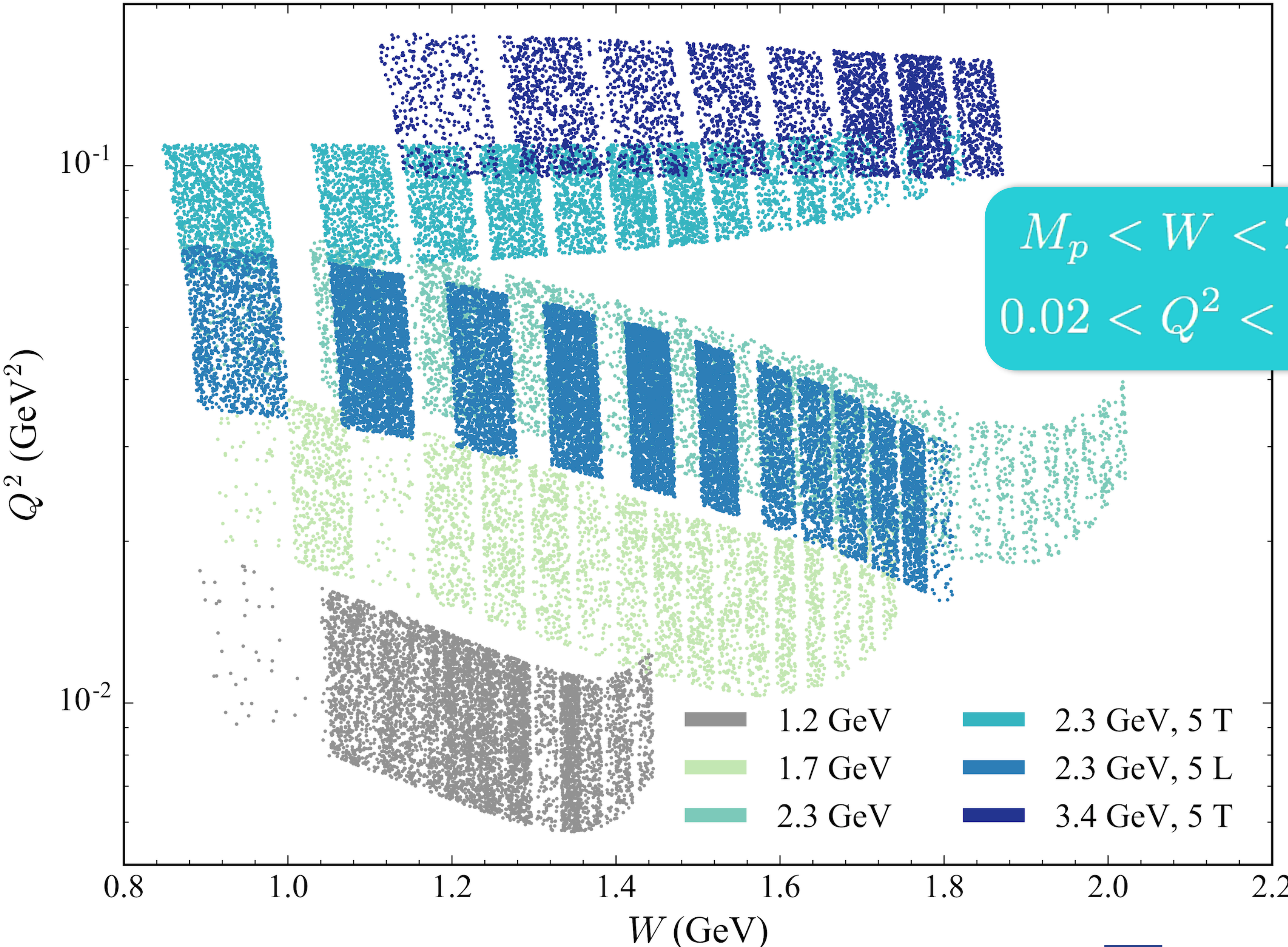
T. Badman (2013) TN #08: http://hallaweb.jlab.org/experiment/g2p/collaborators/toby/technotes/target.pdf

g_2p Kinematic Coverage



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

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

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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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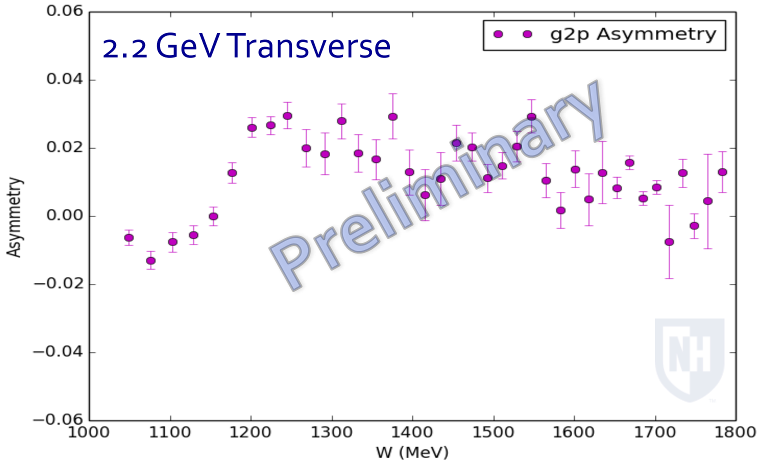
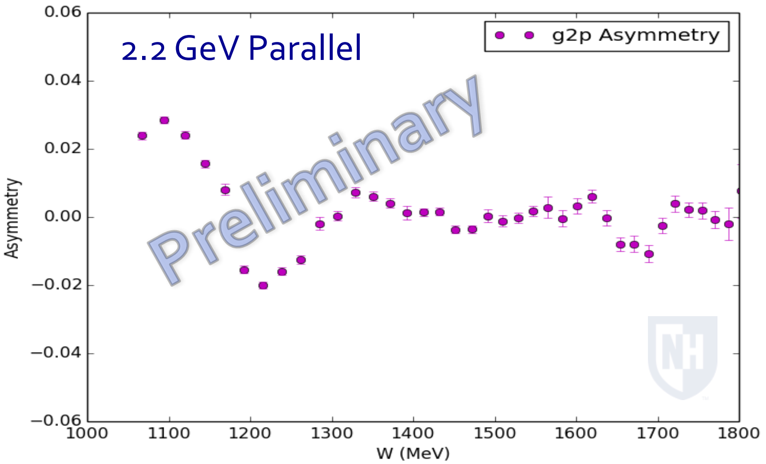
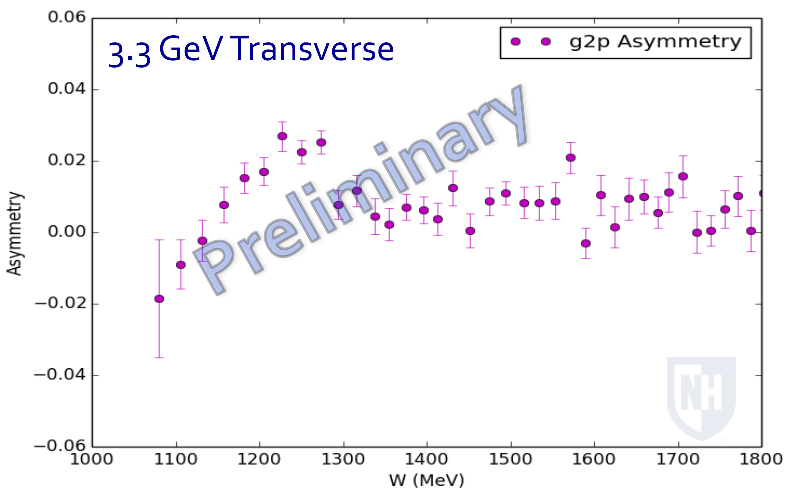
5T Proton Asymmetries







Raw Counts: $$Y_{\pm} = \frac{N_{\pm}}{LT_{\pm}Q_{\pm}}$$

Measured Asymmetries:

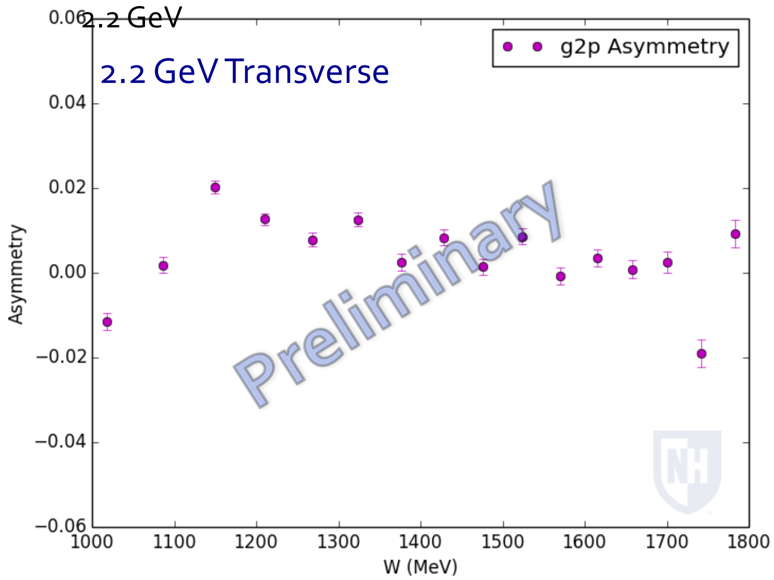
$$A^{\text{raw}} = \frac{Y_+ - Y_-}{Y_+ + Y_-},$$

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

dilution factor (f)

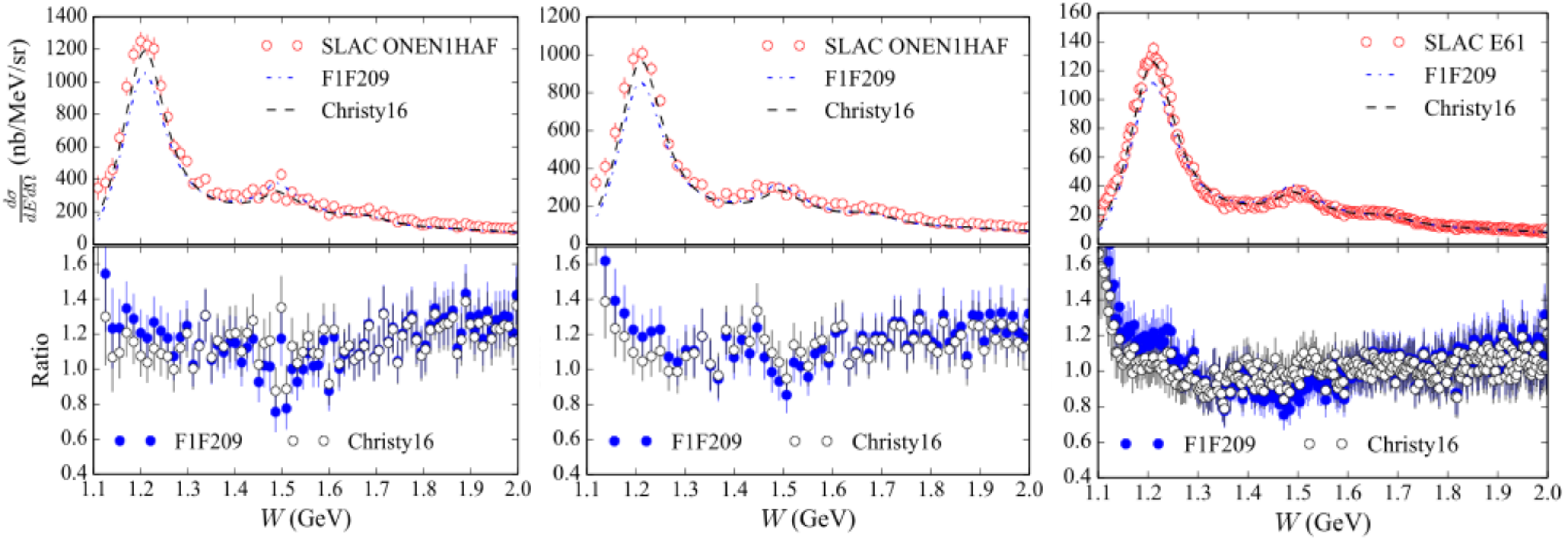
beam/target pol ($P_t \cdot P_b$)

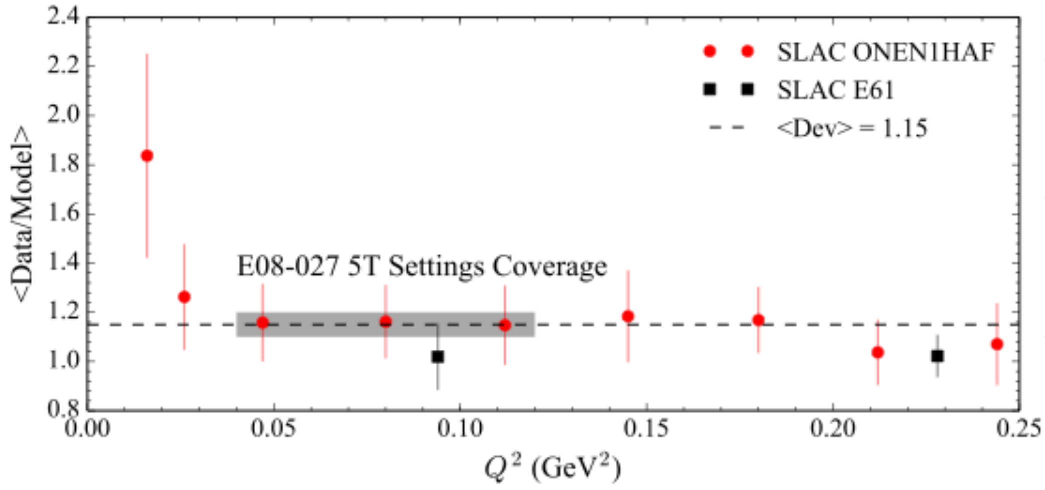
2.5T Proton Asymmetries



2.5T Data exists at 1.7 GeV and 1.1 GeV energy settings, but has large systematics that complicate analysis and will not be focused in initial publications

Model Cross Section





- Use proton model for unpolarized cross section
- Does a good job of reproducing data at E08-027 kinematics
- Working on comparison to g2p data to lower associated systematic

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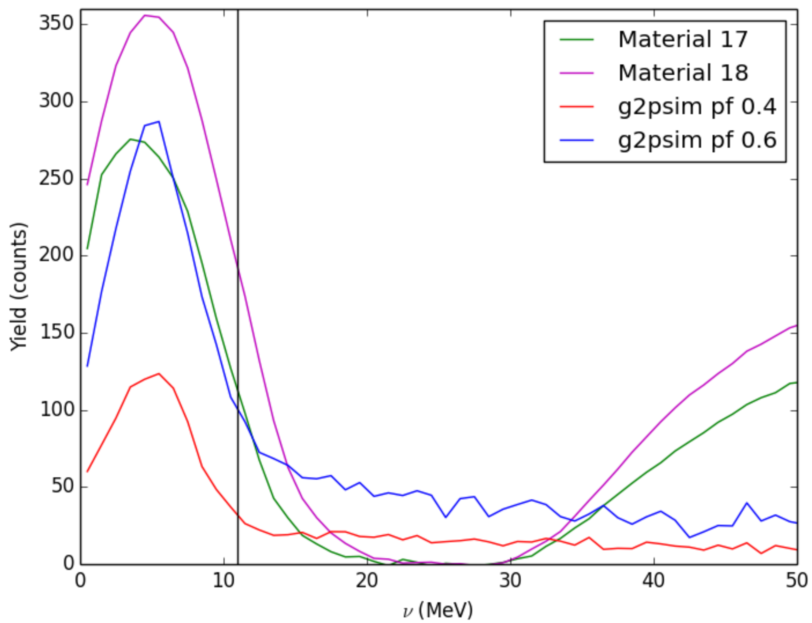
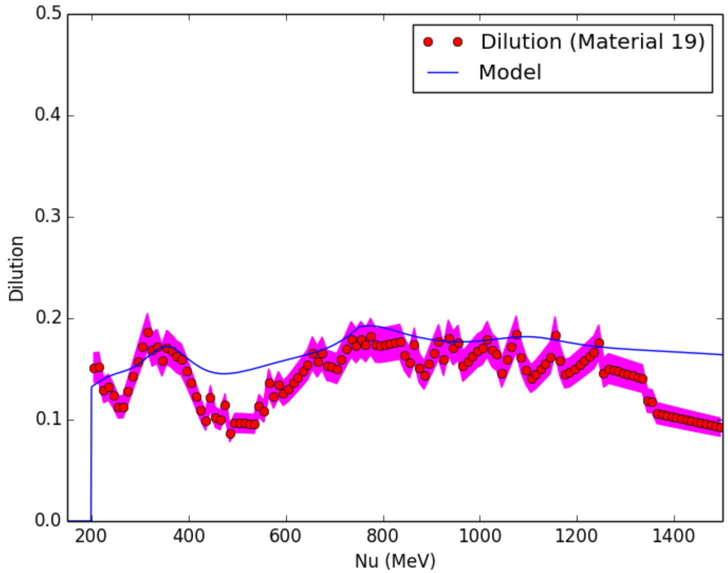
Packing Fraction & Dilution Analysis

- 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





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Extracting the Spin Structure Functions : g_2

Model driven procedure for unmeasured part

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

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

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

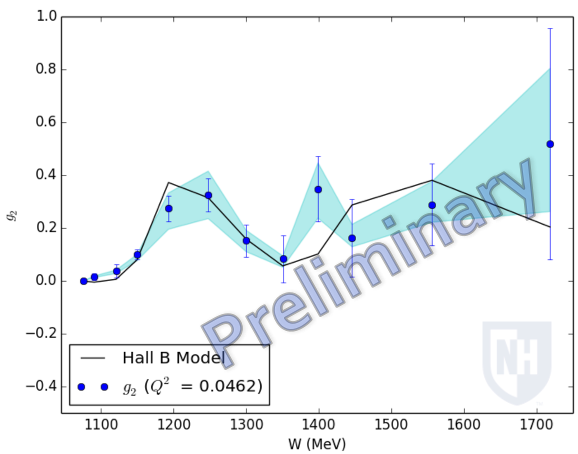
Adjusting to a constant Q^2

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

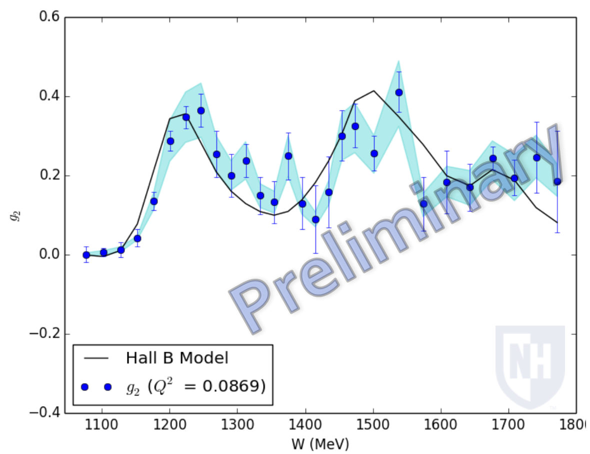
$$x_{\text{const}} = Q^2_{\text{const}}/(W^2 - M^2 + Q^2_{\text{const}}),$$

Small effect at the transverse settings

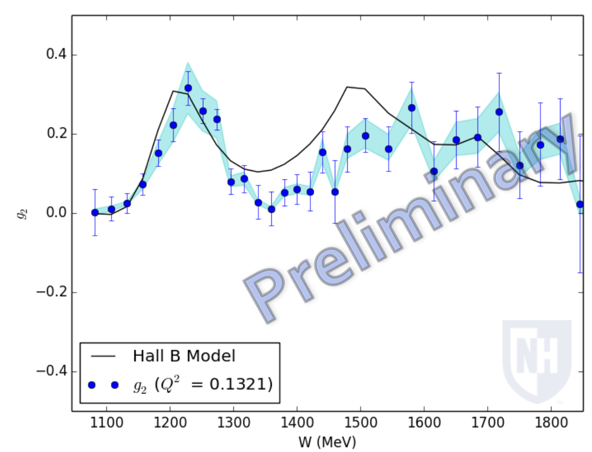
2.5T 2254 MeV Transverse



5T 2254 MeV Transverse



5T 3351 MeV Transverse



Final systematics may be slightly smaller, we are still trying to reduce the unpolarized model systematic with an XS comparison to our data

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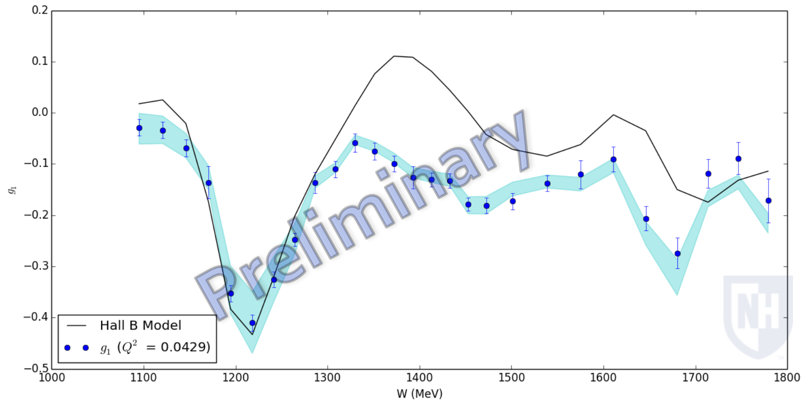
Extracting the Spin Structure Functions: g_1

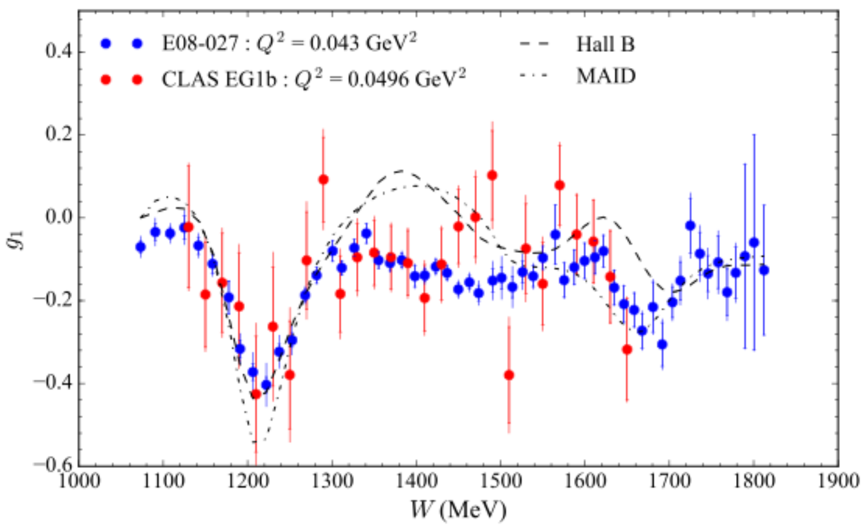


Model driven procedure for unmeasured p

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

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

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



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

http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

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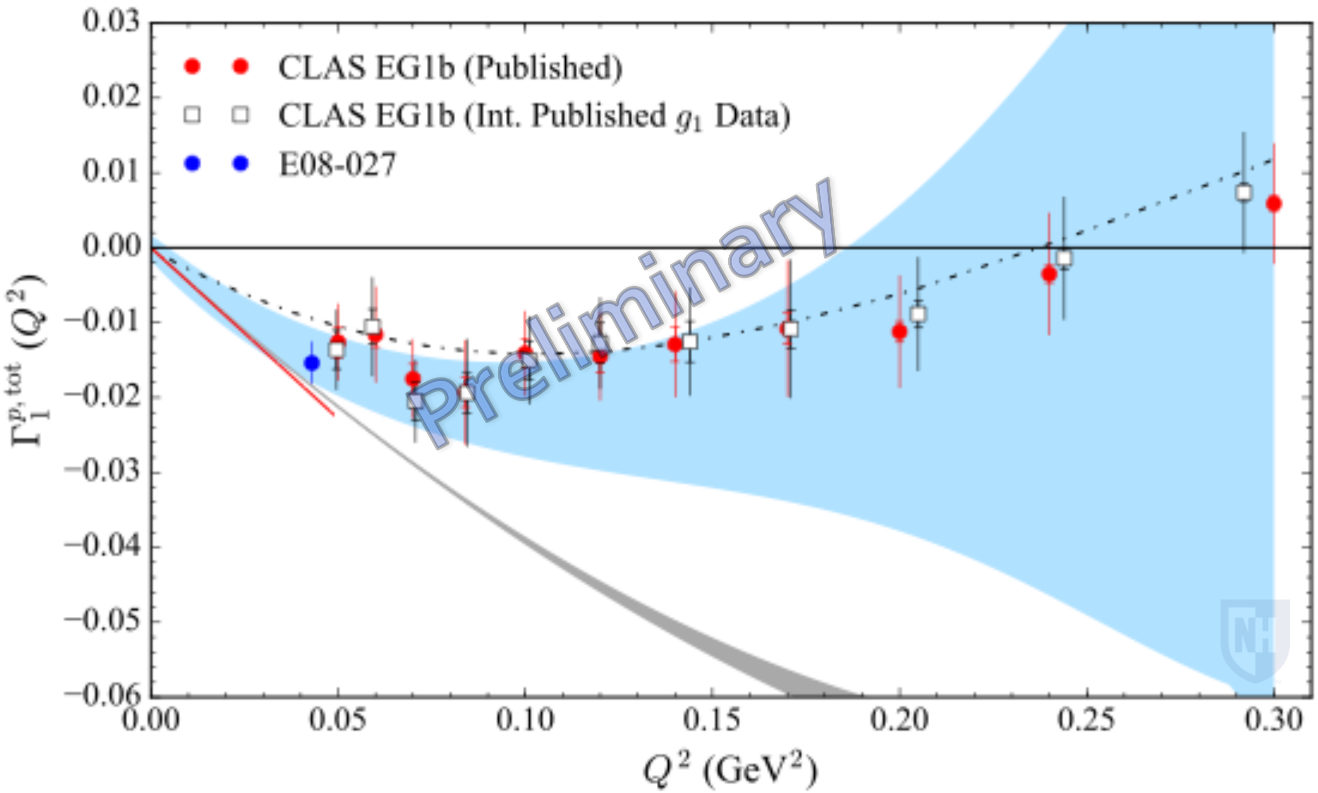
First Moment of $g_1(x,Q^2)$

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

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



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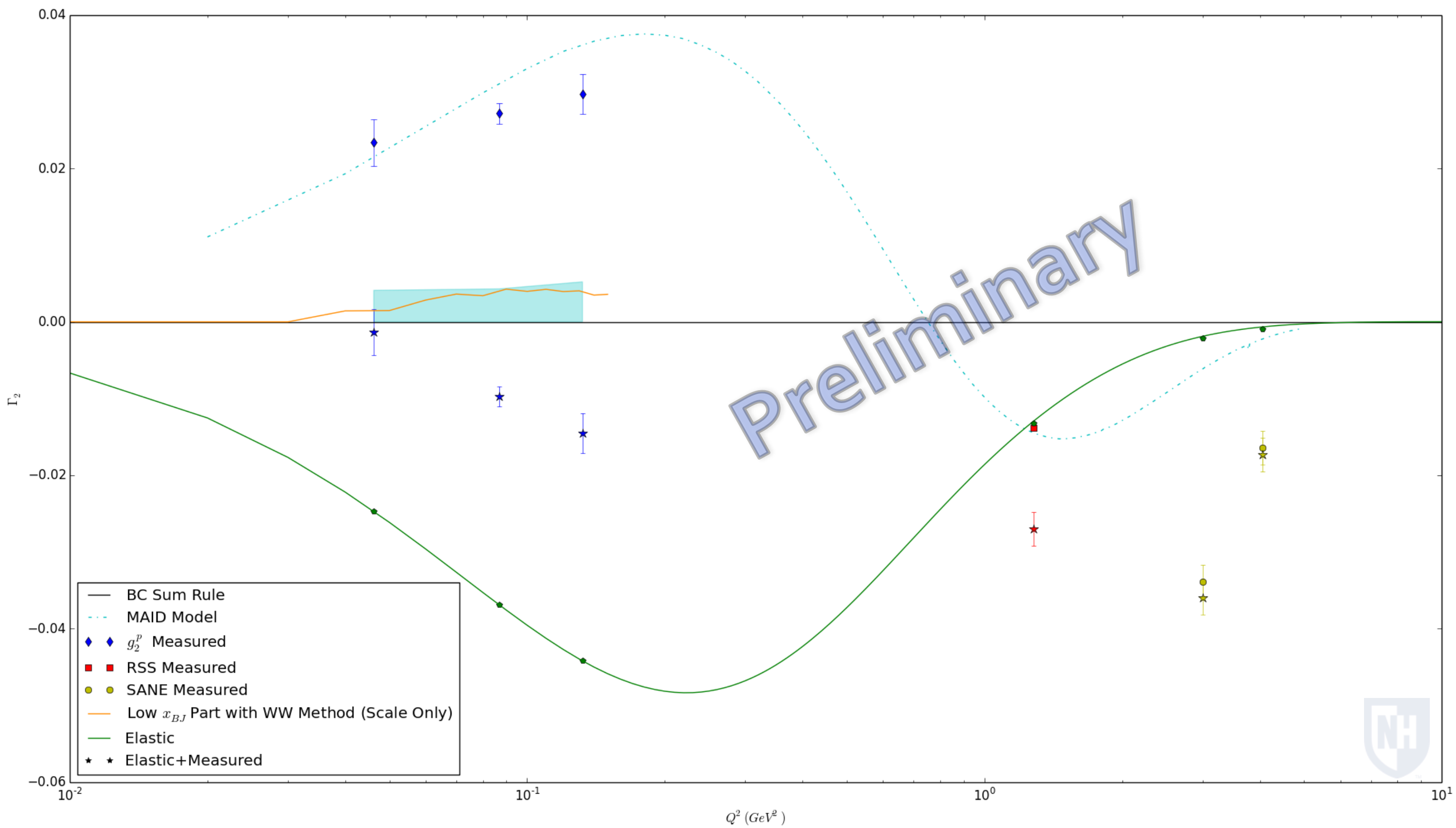
K.V. Dharmawardane (2006) *et al.* https://doi.org/10.1016/j.physletb.2006.08.011

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

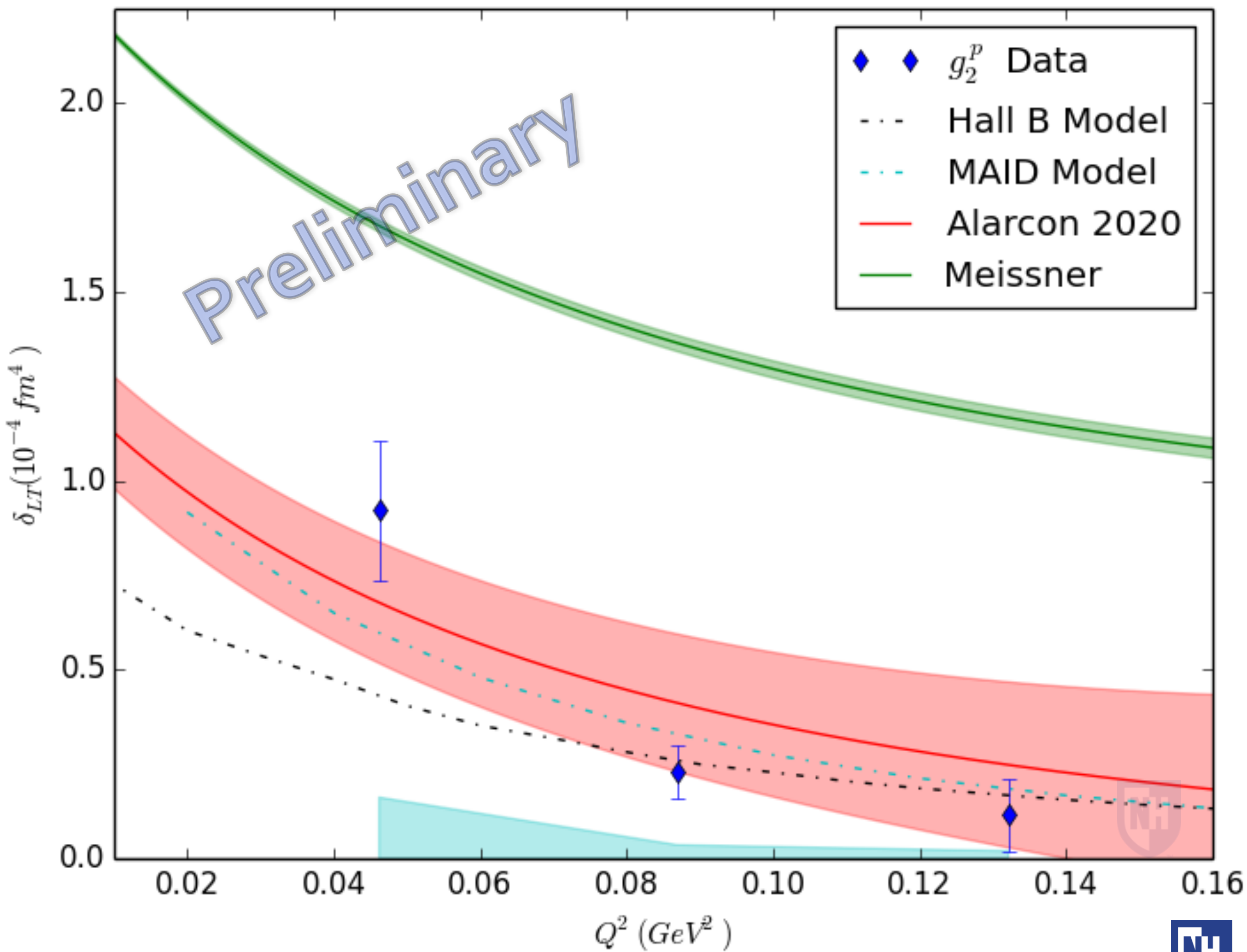
$$\Gamma_2 = \int_0^{x_{th}} g_2(x, Q^2)dx$$

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

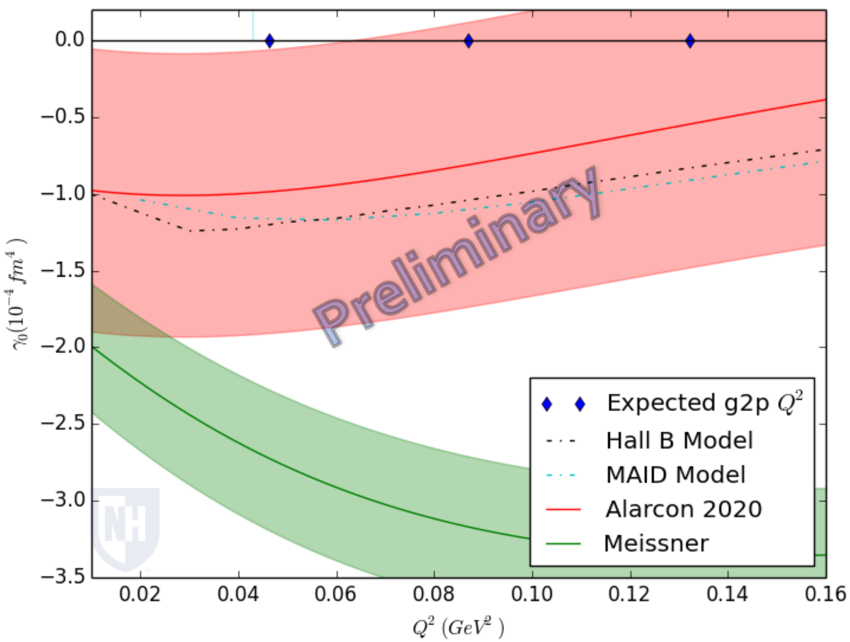


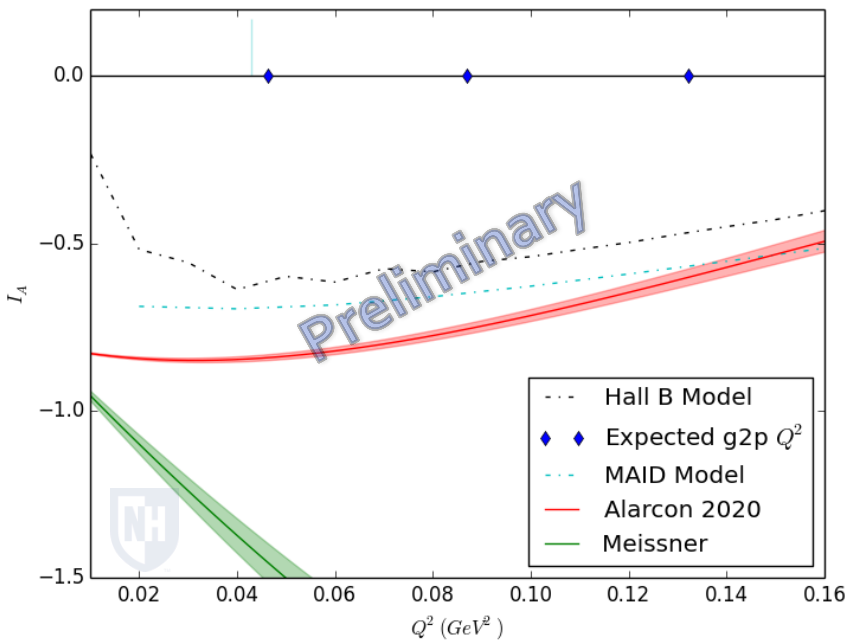
Transverse-Longitudinal Spin Polarizability

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



Other In Progress Moments





$$\gamma_0 = \frac{16\alpha m_p^2(\hbar c)^4}{Q^6}\int_0^{x_{th}} x^2\left[g_1(x,Q^2) + \frac{4m_p^2x^2}{Q^2}g_2(x,Q^2)\right]dx$$

$$I_A = \frac{2m_p^2}{Q^2}\int_0^{x_{th}} \left[g_1(x,Q^2) + \frac{4m_p^2x^2}{Q^2}g_2(x,Q^2)\right]dx$$

Future Work

- Attempt to decrease unpolarized model systematic with a direct comparison to g2p cross sections
- Method for propagating radiative corrections systematic to the moments may be changed slightly

- Will soon produce final plots for a number of other moments, including Γ_1, γ_0, I_A, Δ_2, as well as higher order moments, including $\overline{\gamma_0}$ and $\overline{\delta_{LT}}$

… that's it!

Conclusions

- 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!**
- Some indication that 1.7 GeV data may be useable as well, this may be revisited as an additional data point once the analysis of the shown settings is completed
- Structure Function results and Moment results for the four highest energy settings of the experiment will likely be finalized in **a matter of weeks**

Acknowledgements

g2p Analysis Team

Spokespeople:
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