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Nuclear & Particle Physics Group

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

David Ruth

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Acknowledgements

g2p Analysis Team

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Special thanks again to Ryan Zielinski for allowing me to adapt some of his slides and figures for this presentation.

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Essential Quantities in *ep* Scattering

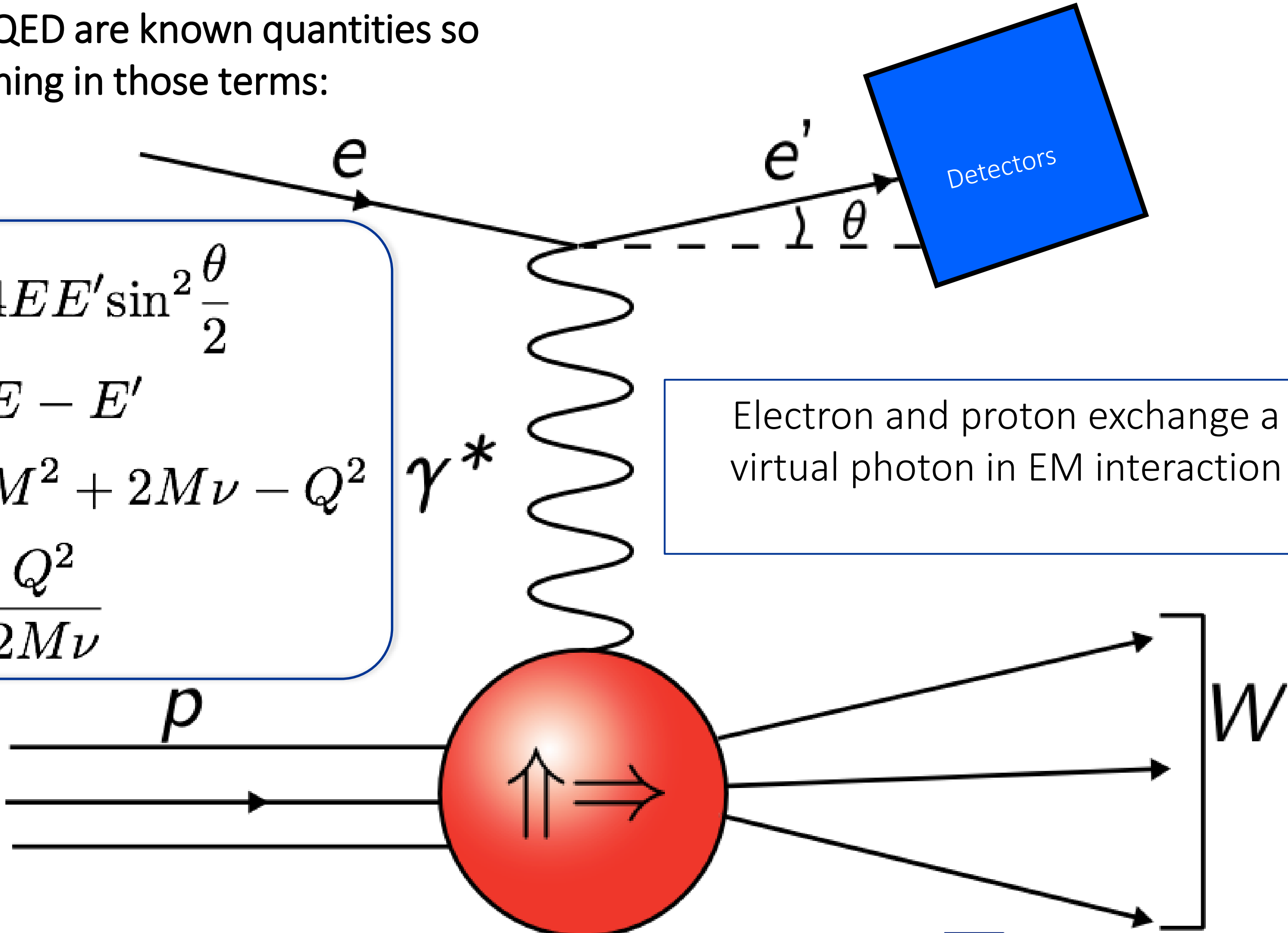
Electron and QED are known quantities so define everything in those terms:

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

$$\nu = E - E'$$

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

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



Electron and proton exchange a virtual photon in EM interaction

Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

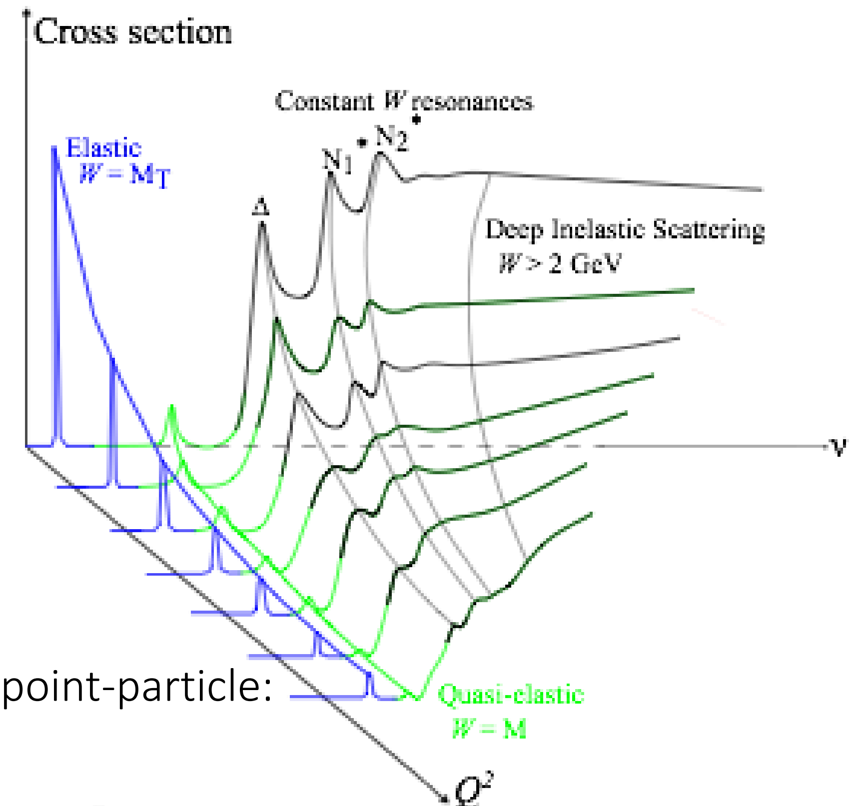
Elastic scattering: target remains in the ground state after interaction

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

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:



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

G_E and G_M related to charge and current distributions

Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

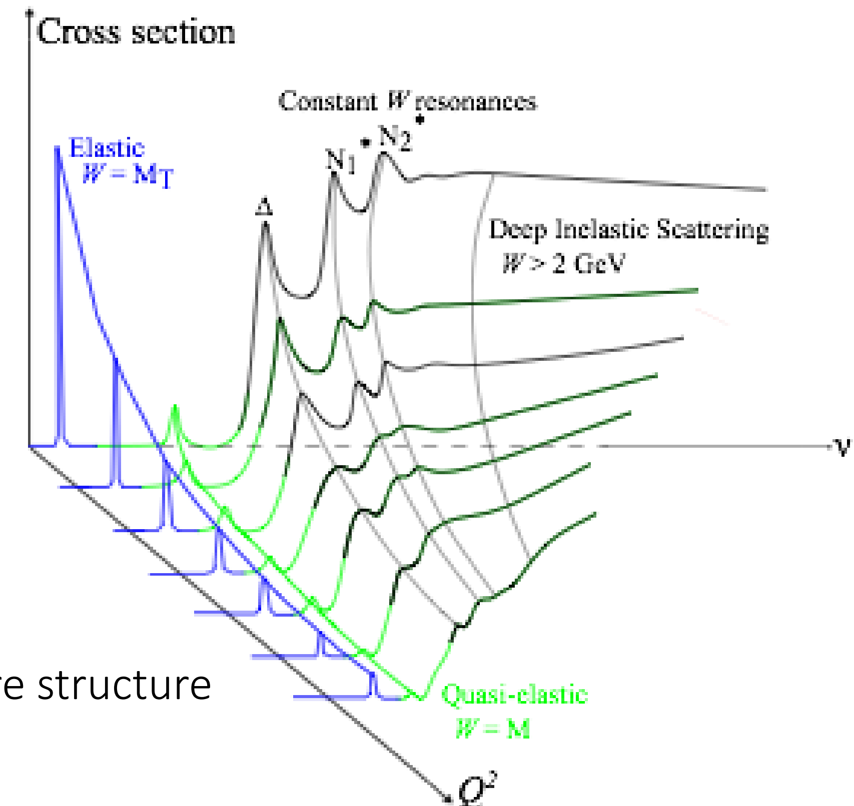
Inelastic scattering: Target is in excited state after interaction

Structure Functions:

Inclusive *unpolarized* cross sections

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

F_1 and F_2 related to quark/gluon distribution



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

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

g_1 and g_2 related to spin distribution

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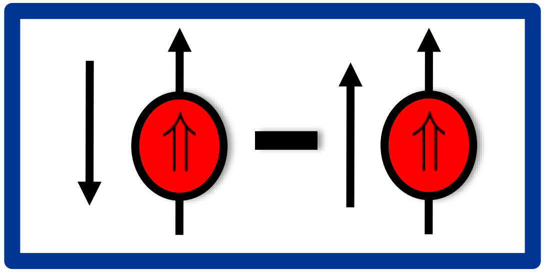
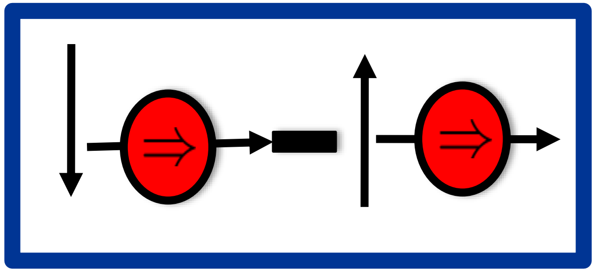
Extracting Spin Structure by Looking at Cross Section Differences



Parallel

Inclusive *polarized* cross sections

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



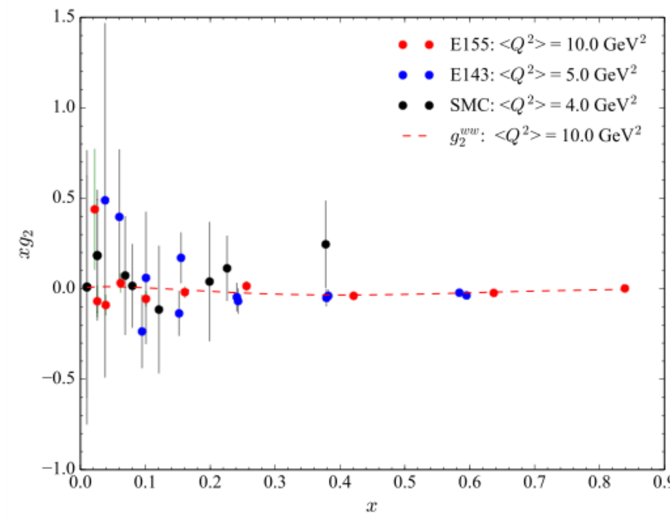
Perpendicular

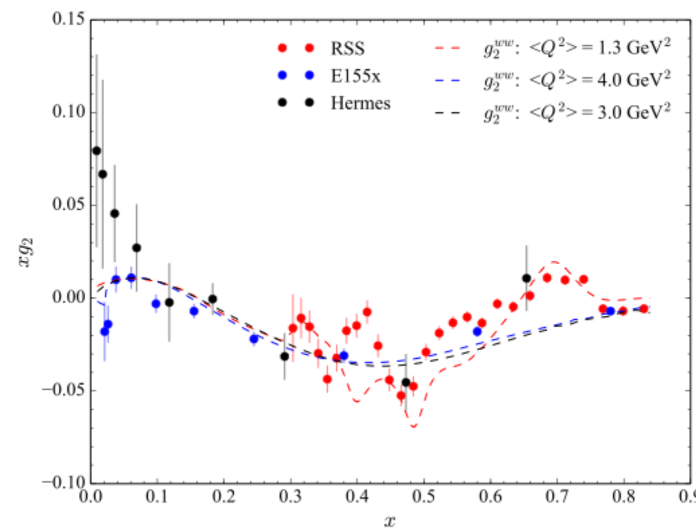
$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\left[\nu g_1(x,Q^2) + 2Eg_2(\nu,Q^2)\right]$$

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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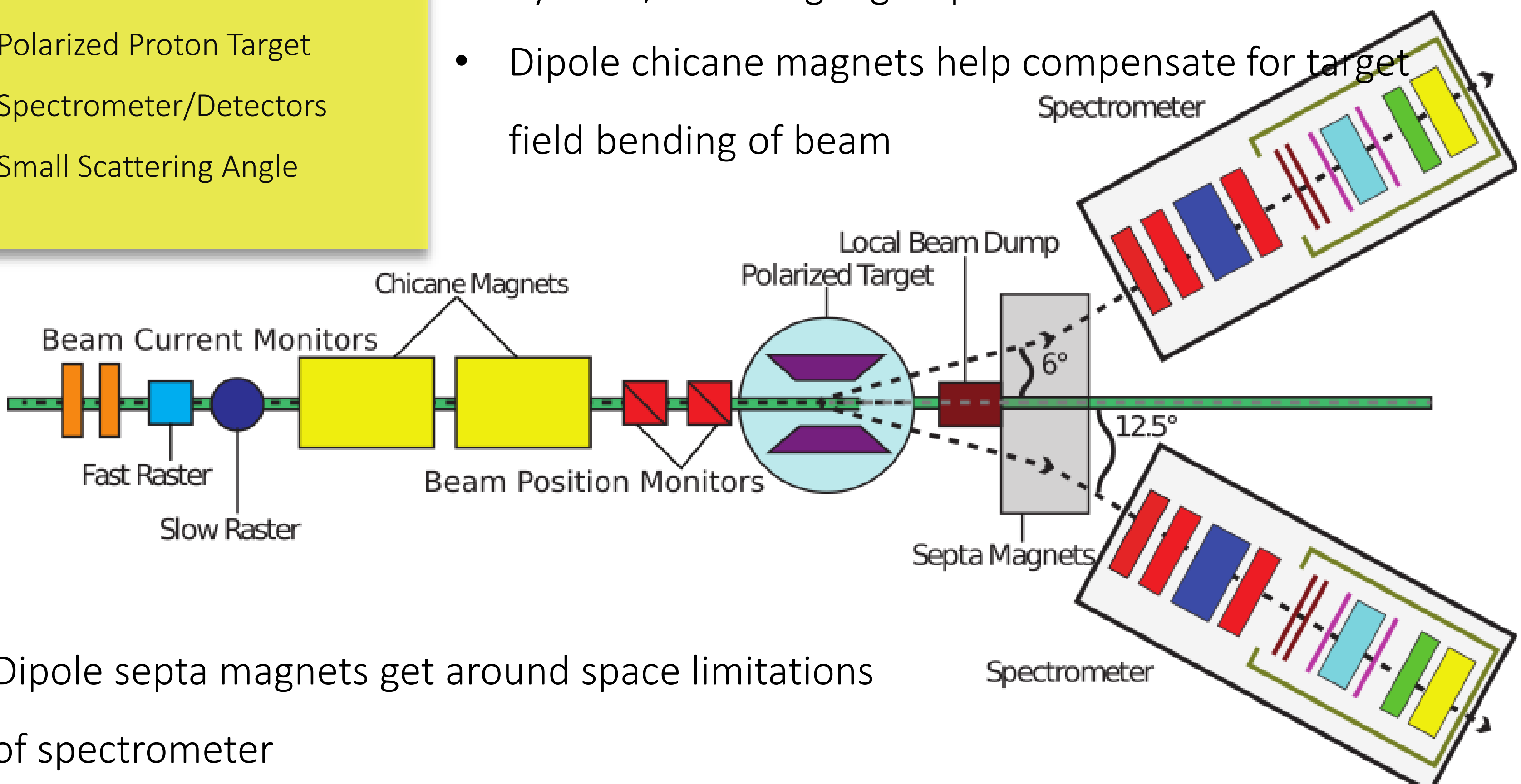
Hall A Experimental Setup:

Measuring g_2^p

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

- Transverse polarized NH_3 target (2.5/5.0T) provided by UVA / JLab target groups
- Dipole chicane magnets help compensate for target field bending of beam



- Dipole septa magnets get around space limitations of spectrometer

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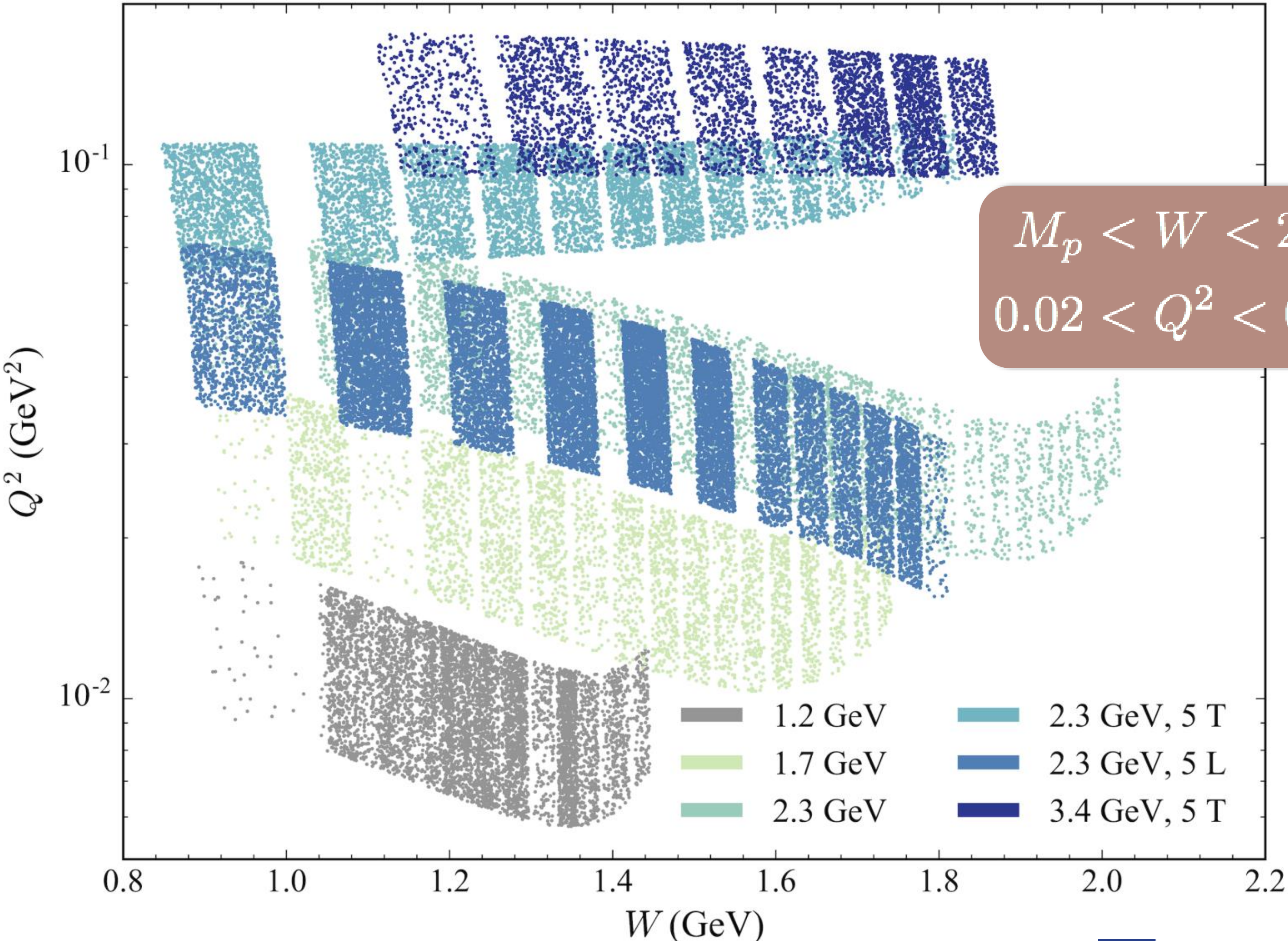
g_2p Kinematic Coverage



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

1.2 GeV setting for Rad. Cor.

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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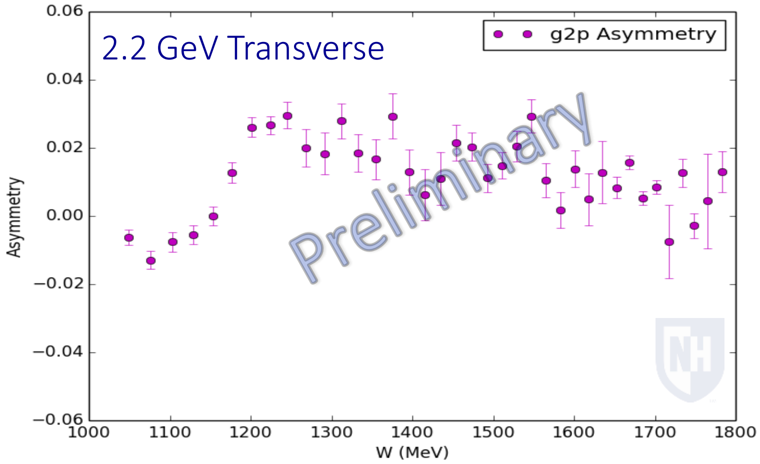
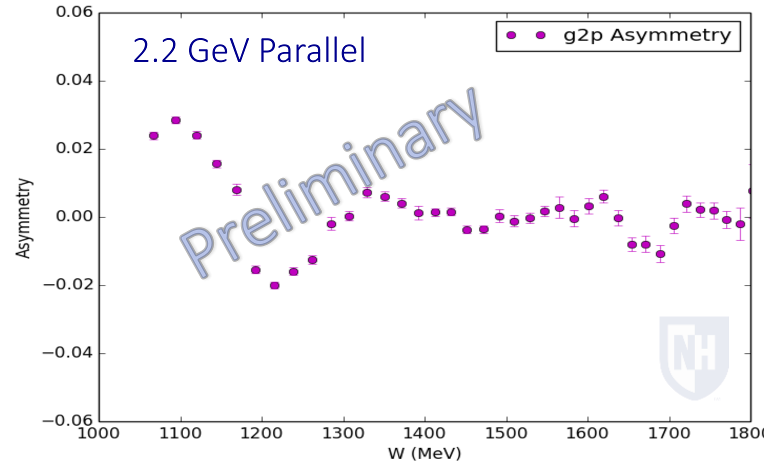
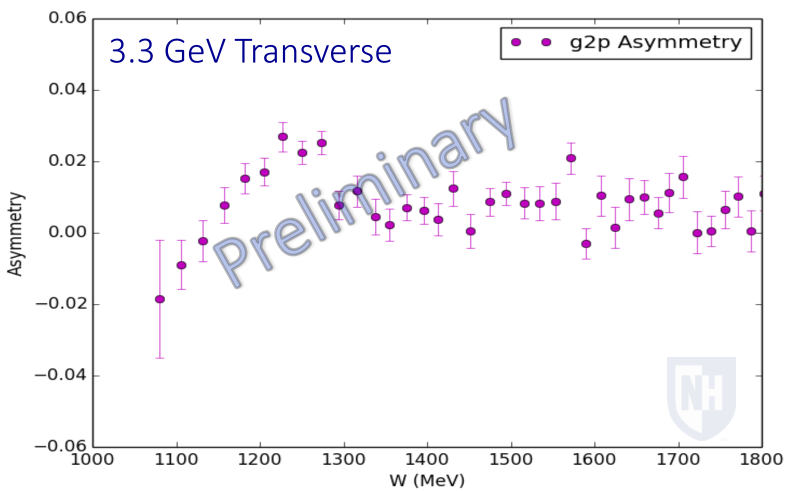
5T Proton Asymmetries







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

beam/target pol

Combine both HRS for best statistics!

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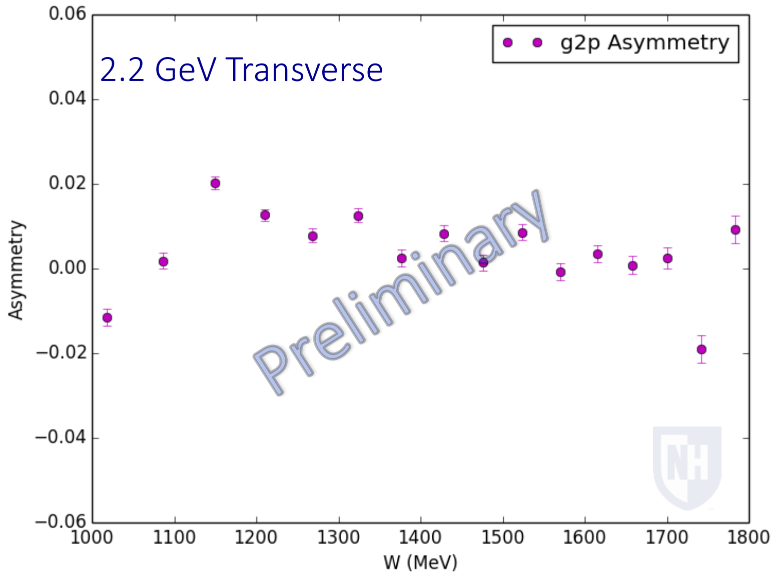
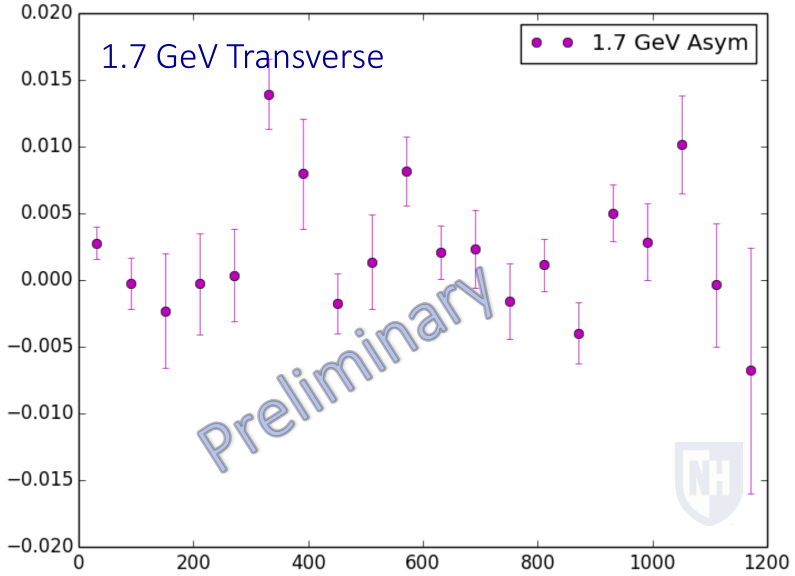
2.5T Proton Asymmetries





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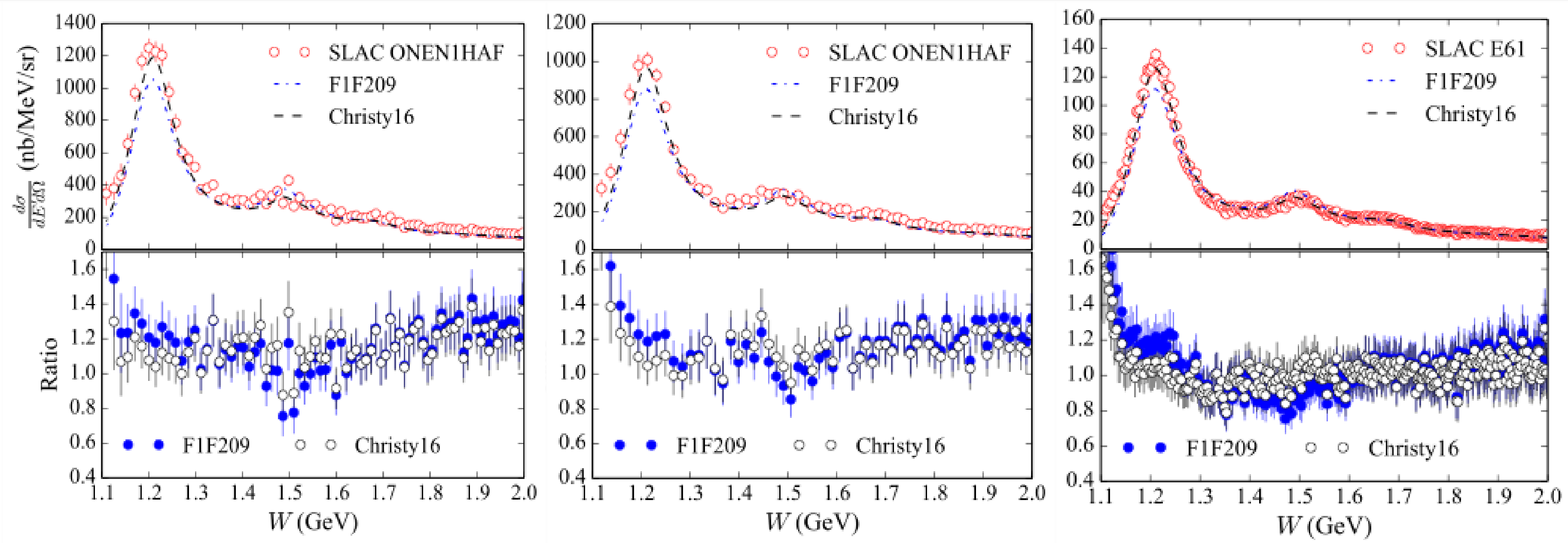
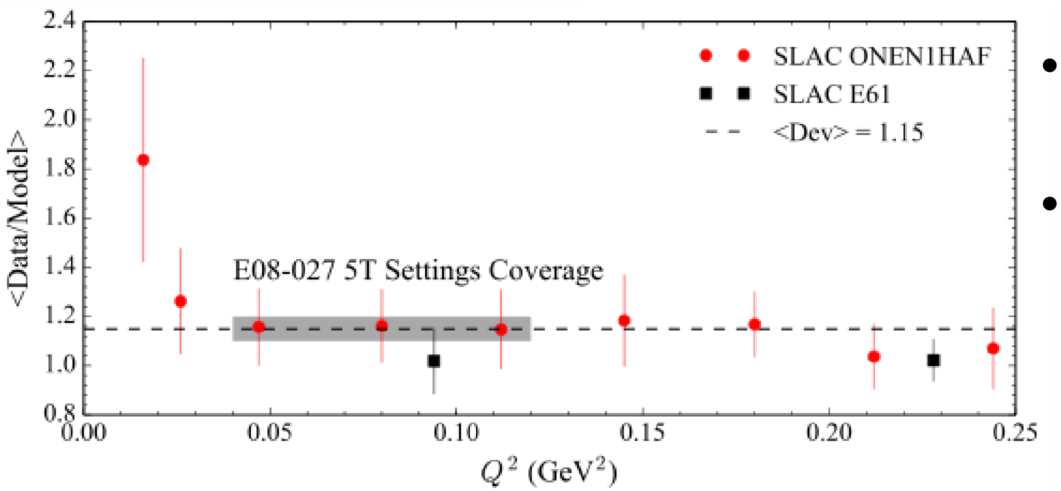
Model Cross Section





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

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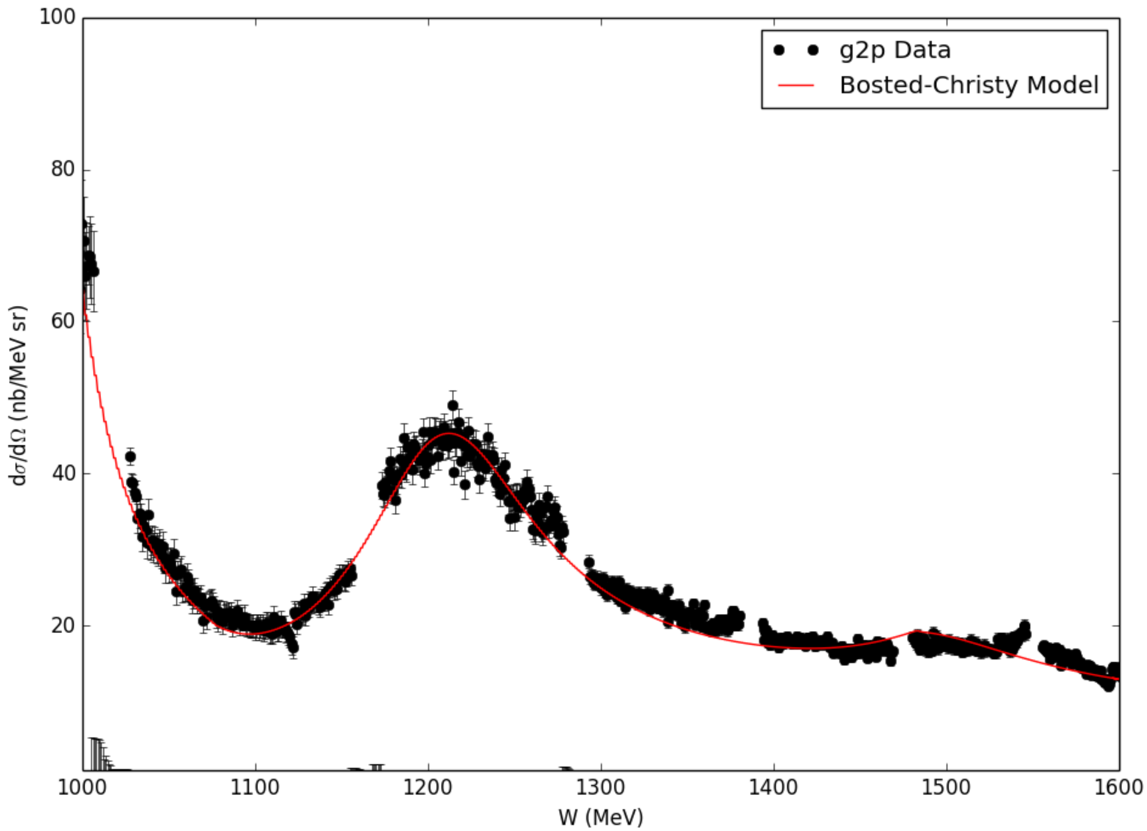
Model Cross Section



- Direct comparison to g2p Longitudinal cross section yields very similar comparison results
- Necessary to scale model by 1.15 to obtain good agreement for both SLAC and g2p
- Systematic impact on the moments is very small

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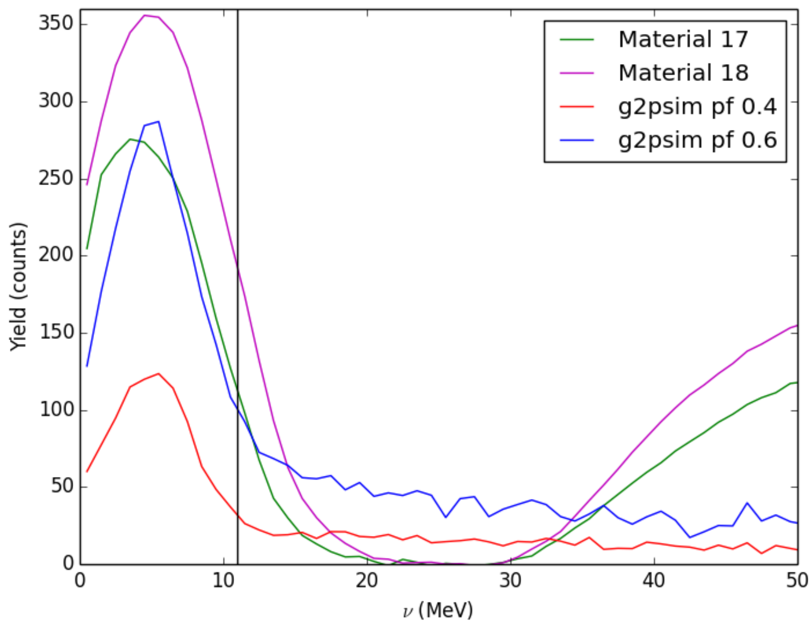
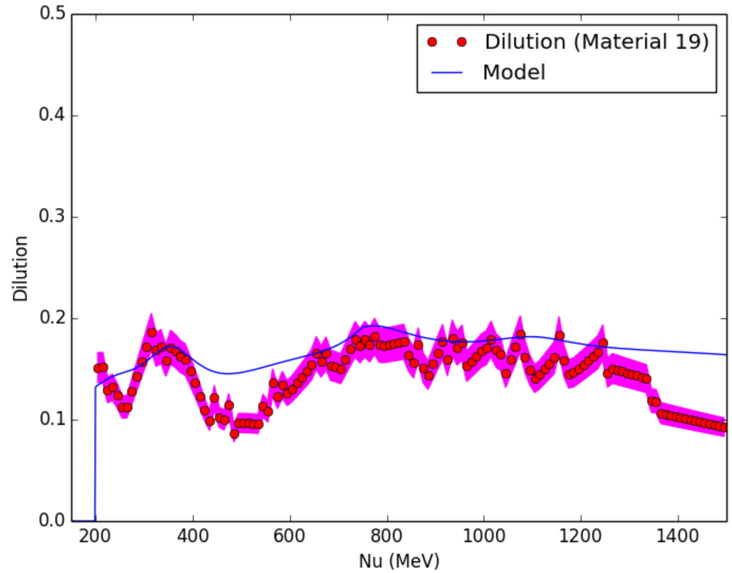
Packing Fraction & Dilution Analysis

- 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

Model driven procedure for unmeasured part

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

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

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

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

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

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

Adjusting to a constant Q^2

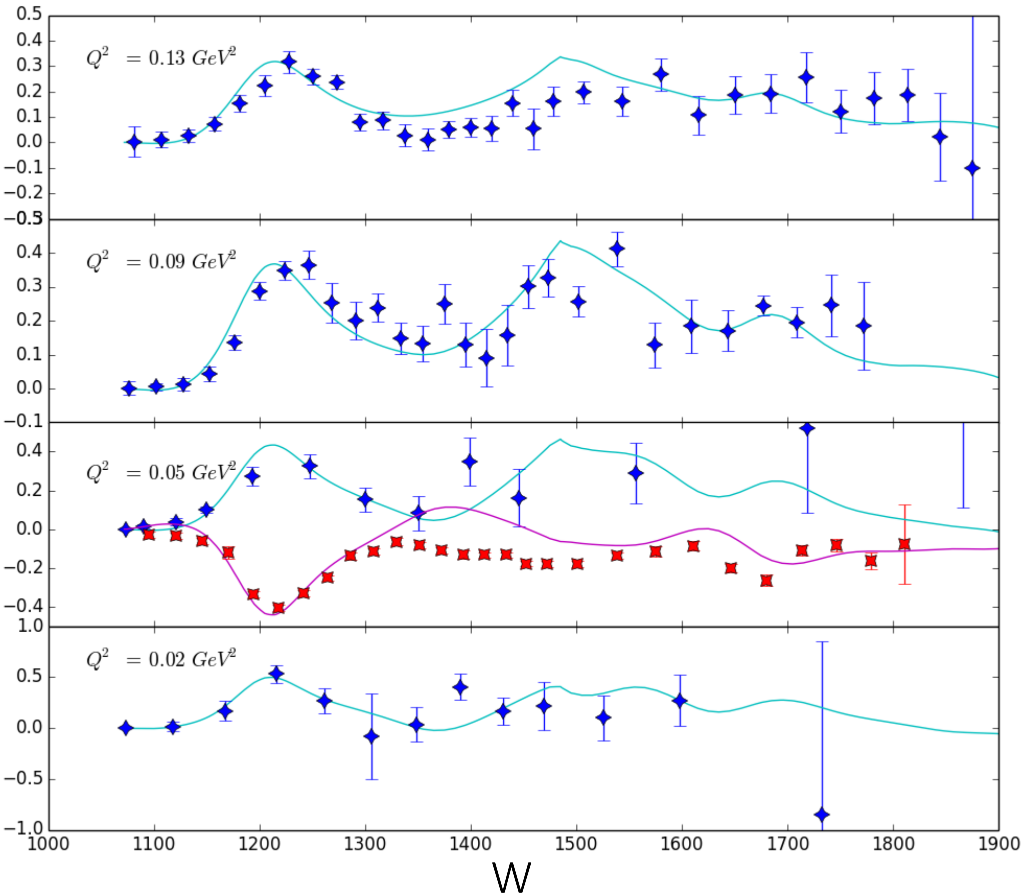
$$\delta_{\text{evolve}} = g_{1,2}^{\text{mod}}(x_{\text{data}}, Q^2_{\text{data}}) - g_{1,2}^{\text{mod}}(x_{\text{const}}, Q^2_{\text{const}}),$$

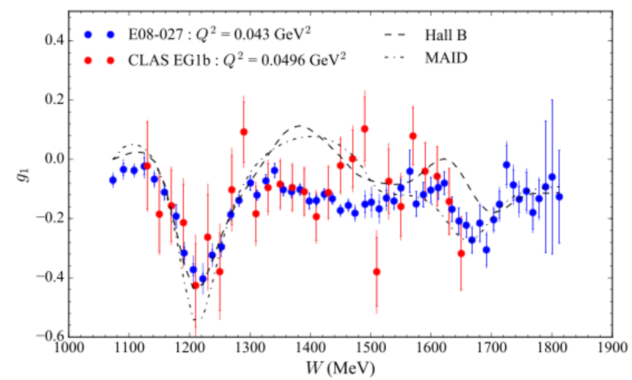
$$x_{\text{const}} = Q^2_{\text{const}}/(W^2 - M^2 + Q^2_{\text{const}});$$

Small effect at the transverse settings

Structure Function Results

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



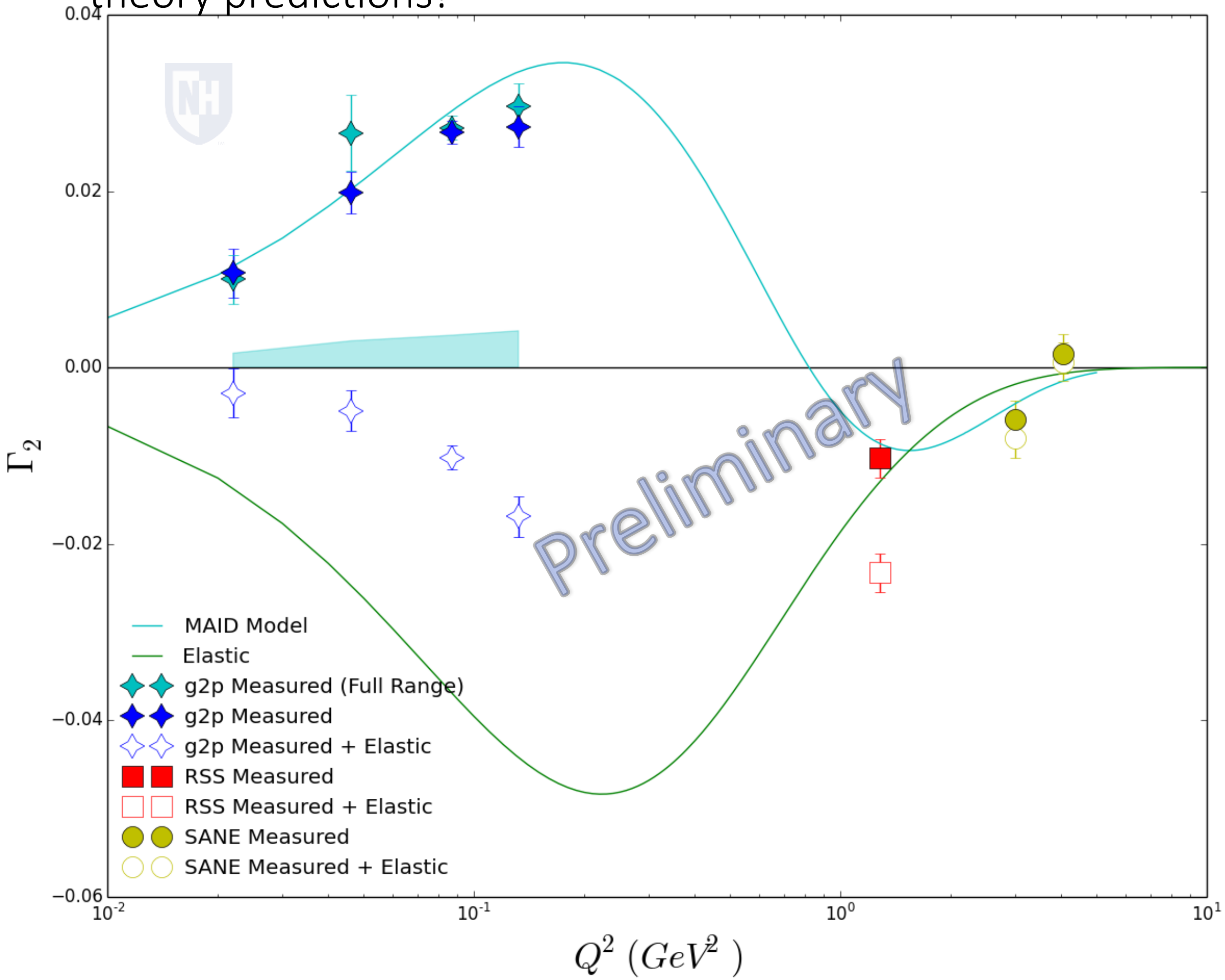


- E08-027 data is consistent with previously published data from CLAS
- But with much better statistics!

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!



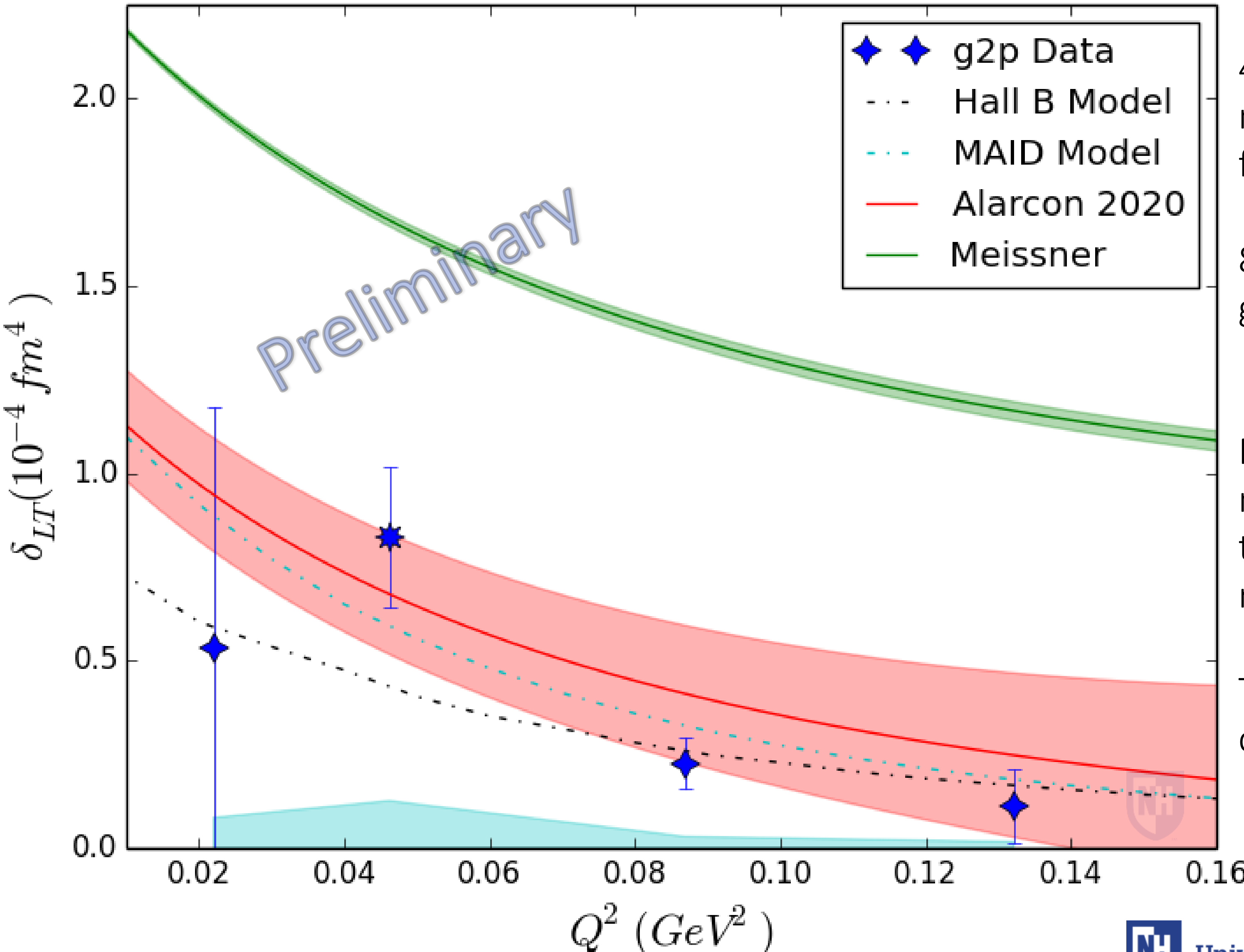
Burkhardt-Cottingham Sum rule says this moment should be zero everywhere…

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

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

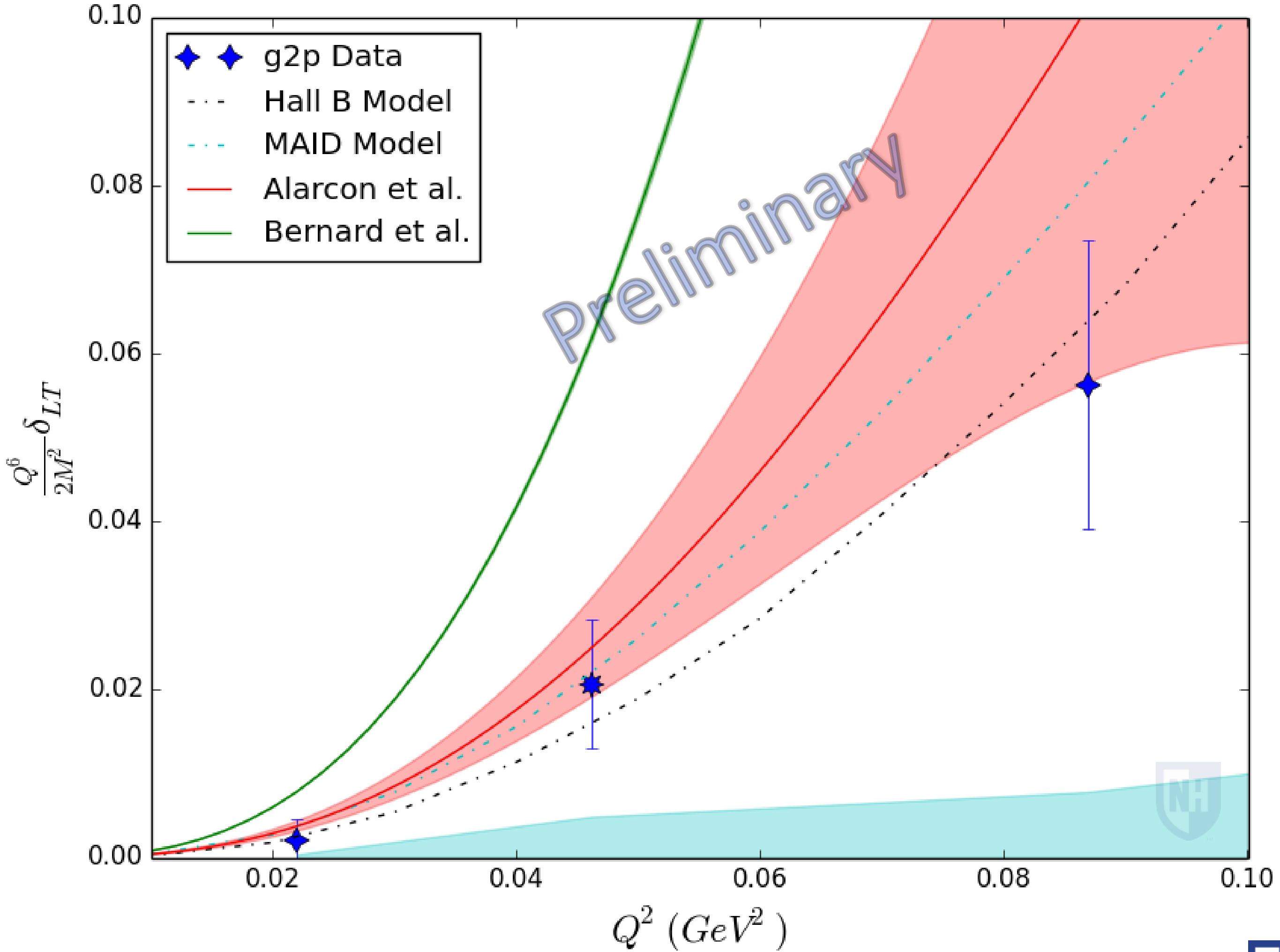
8 pt star – g1 and g2 both measured

First ever measurement of this quantity in this region

Test of χPT calculations

Transverse-Longitudinal Spin Polarizability

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



Known difference between calculations – δ-Power-Counting vs. ε-Power-Counting

Low Q^2 data is heavily weighted so many look at a unitless Q^6 scaling of the moment

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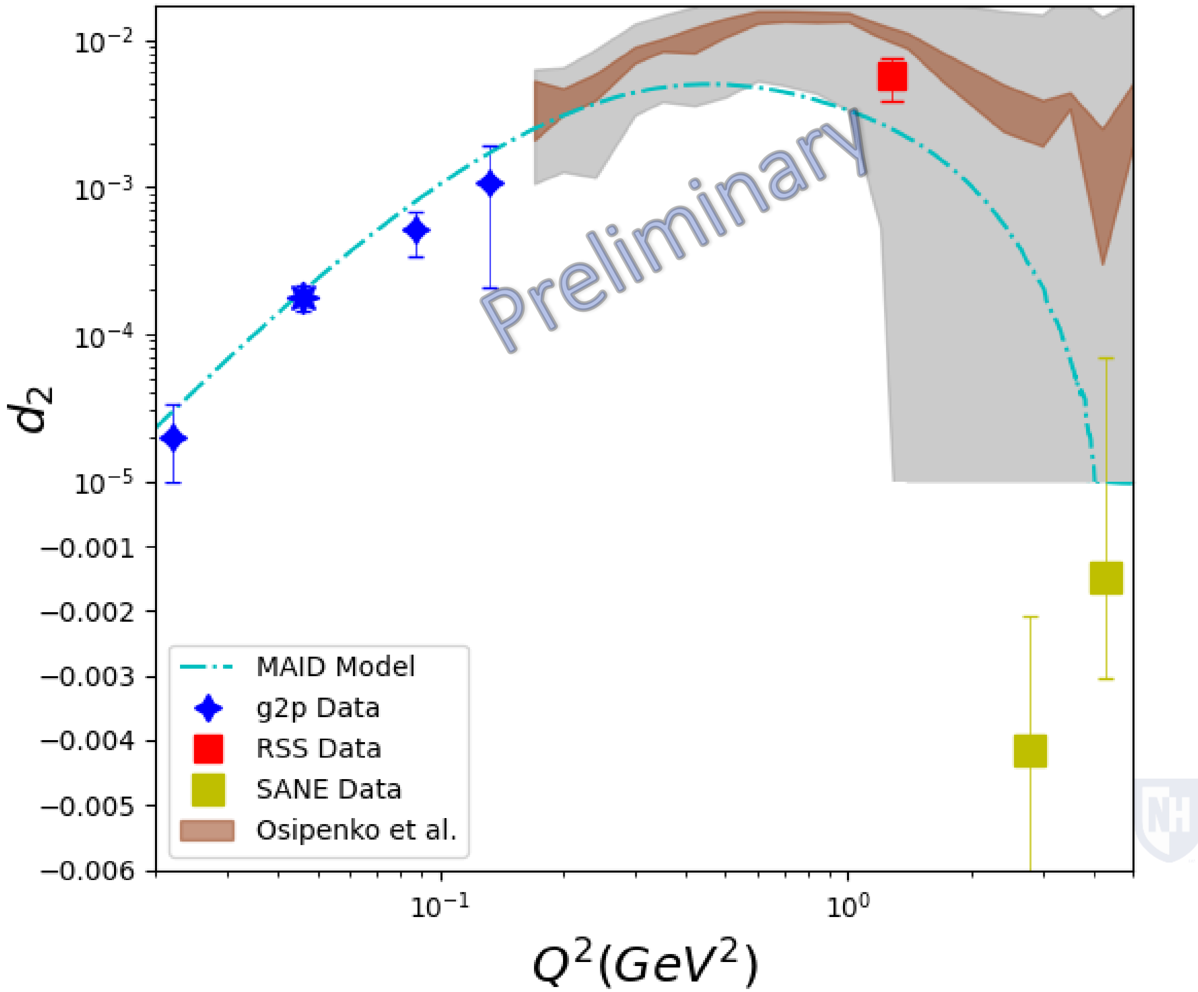
Higher Moment d_2

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



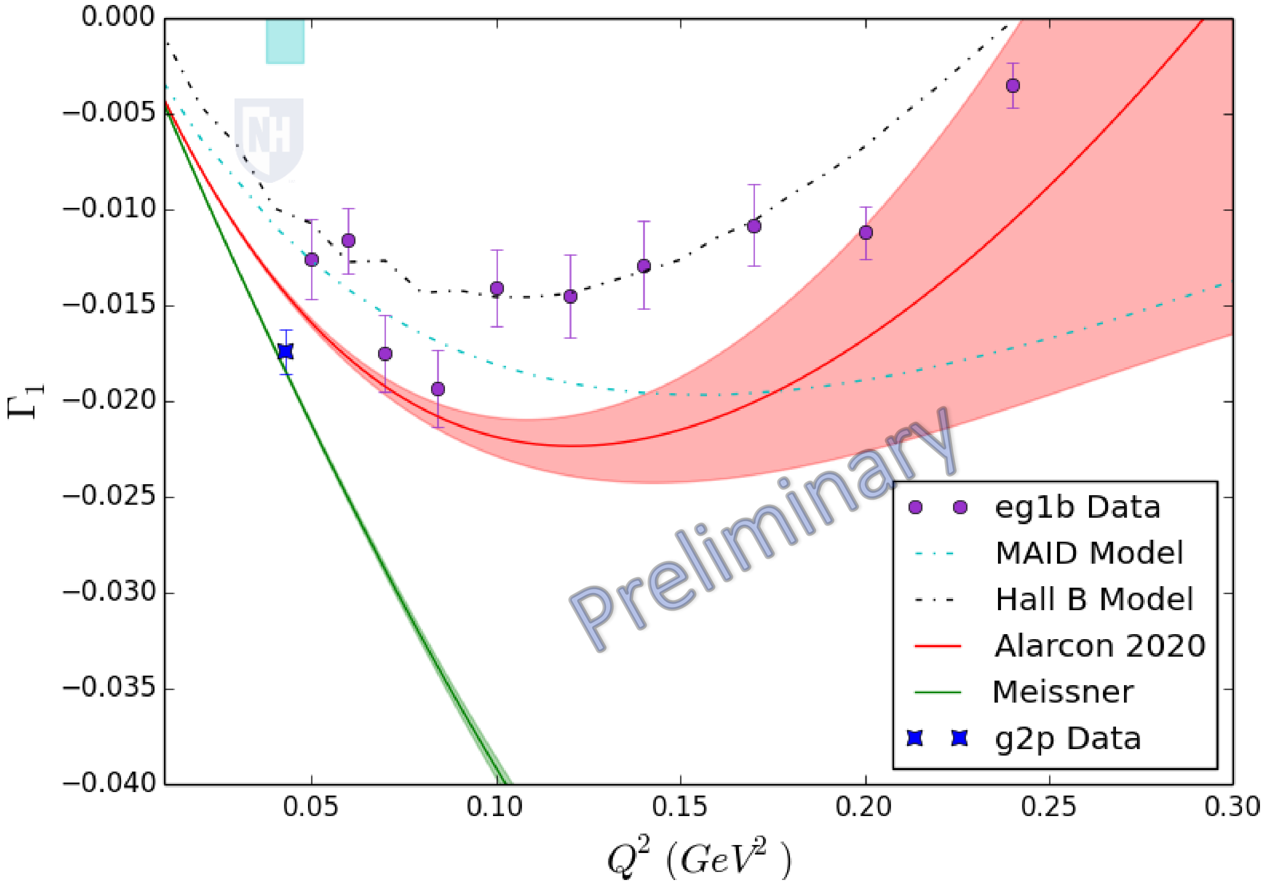
g2p agrees well with phenomenological MAID model

SANE measured anomalously negative moment at high Q^2

W. Armstrong et al. 10.1103/PhysRevLett.122.022002

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

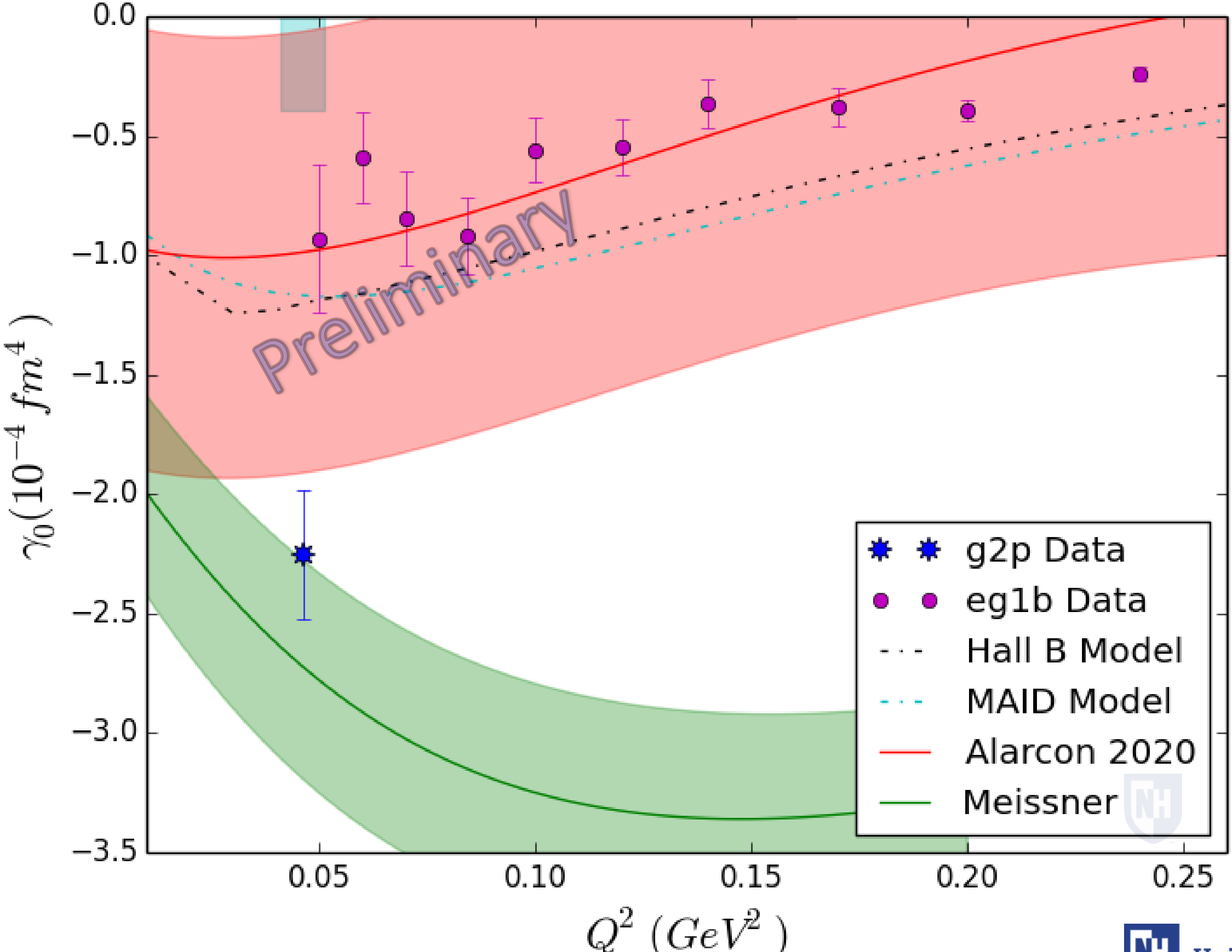
$$\Gamma_1(Q^2) = \int_0^{x_{th}} g_1(x,Q^2)dx$$



Another recently published experiment obtained lower Q^2 data for this moment (EG4, X. Zheng et al., Nature Physics 17-6)

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

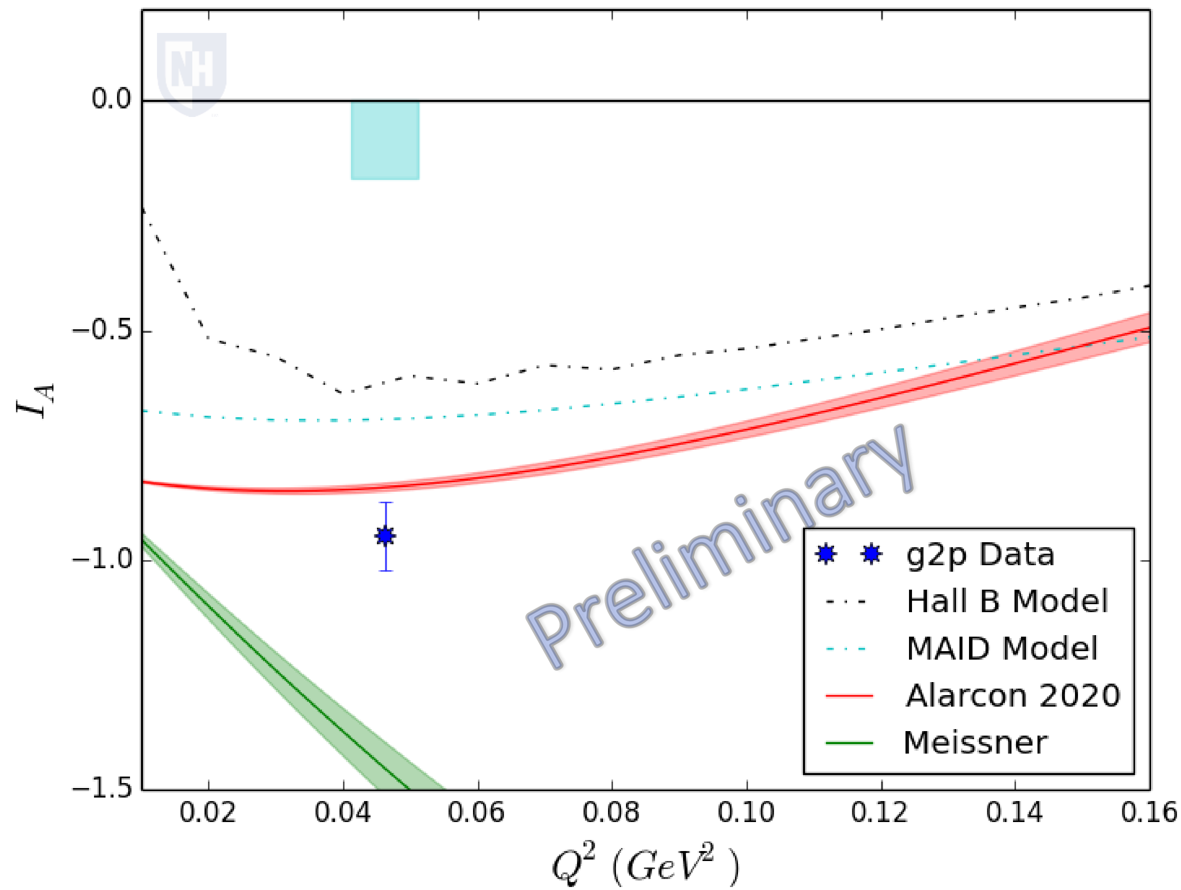
g_2^p data includes measured data for g_2…

And goes closer to threshold

Another recently published experiment obtained lower Q^2 data for this moment (EG4, X. Zheng et al., Nature Physics 17-6)

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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First publication nearly finished

- Results split into two intended publications: a paper focused on the transverse results which we intend to submit to Nature Physics, following the successful publications in that journal of EG4 and Small-Angle GDH, and a shorter paper focused on the longitudinal results to be submitted as a Physical Review C Rapid Publication.
- The transverse-focused paper is almost finished, we intend to circulate it to all our collaborators for comments after several more rounds of revisions!

Transverse Proton Spin Structure for $0.021 < Q^2 < 0.13$ GeV^2

Author Name[1]
(The E08-027 Collaboration)

[1] *Author's Institution*

(Dated: July 6, 2021)

We have extracted the polarized spin structure functions of the proton, g_1 and g_2, in the nucleon resonance region at four momentum transfer of $Q^2 = 0.021$, 0.045, 0.086 and 0.13 GeV^2. This paper will discuss the g_2 results obtained by measuring transversely polarized yields and using them to form asymmetries and polarized cross section differences $\Delta\sigma_{\parallel}(\nu, Q^2)$ and $\Delta\sigma_{\perp}(\nu, Q^2)$. These asymmetries were formed using measurements from the Jefferson Lab polarized electron beam, a solid polarized target and the Hall A high resolution spectrometers. The structure functions were used to calculate the $\overline{\Gamma}_2(Q^2)$, $\delta_{LT}(Q^2)$ and $d_2(Q^2)$ moments of the proton with high precision. Current chiral perturbation theory calculations disagree in the measured region, and our data seems to show a strong preference for one of these calculations over the other. This data represents the first determination of $\delta_{LT}(Q^2)$ for the proton, which had previously been subject to the "$\delta_{LT}(Q^2)$ puzzle" in the neutron.

PACS numbers: 11.55.Hx,25.30.Bf,29.25.Pj,29.27.Hj

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!**
- Analysis is **complete**!
- Two publications in progress: Transverse-focused paper almost finished!

Extra Slides

Polarized Protons Created with Dynamic Nuclear Polarization (DNP)

Creating initial polarization:

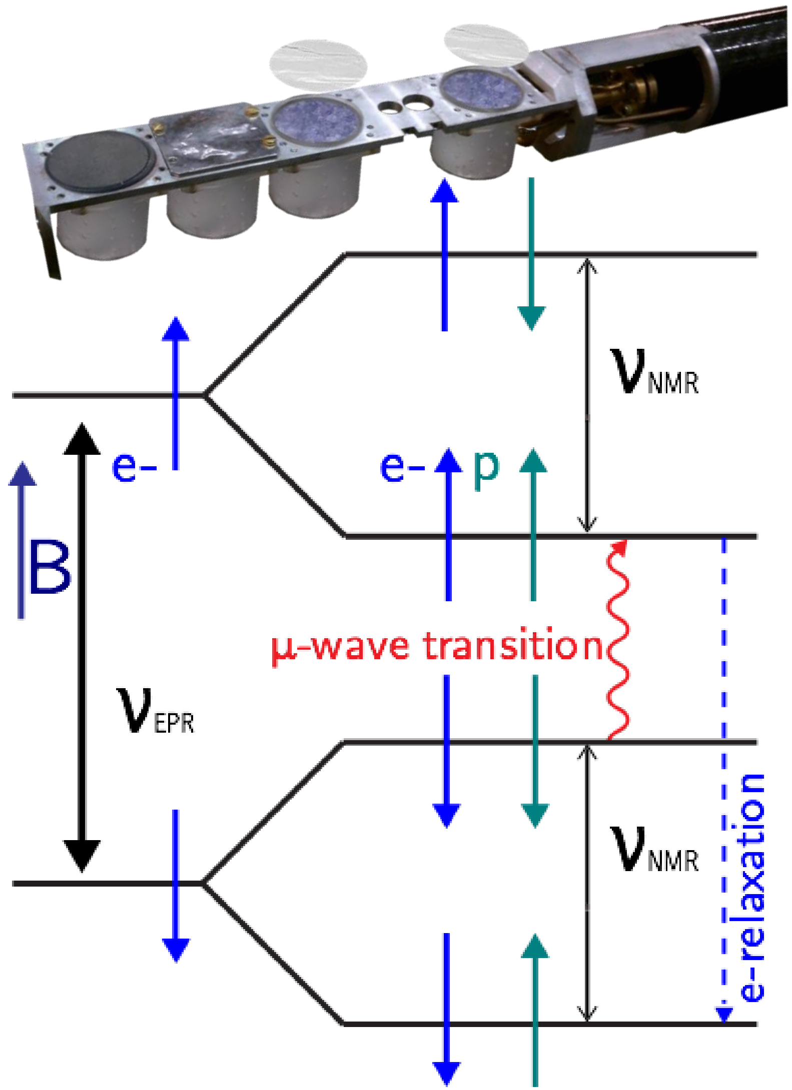
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

- 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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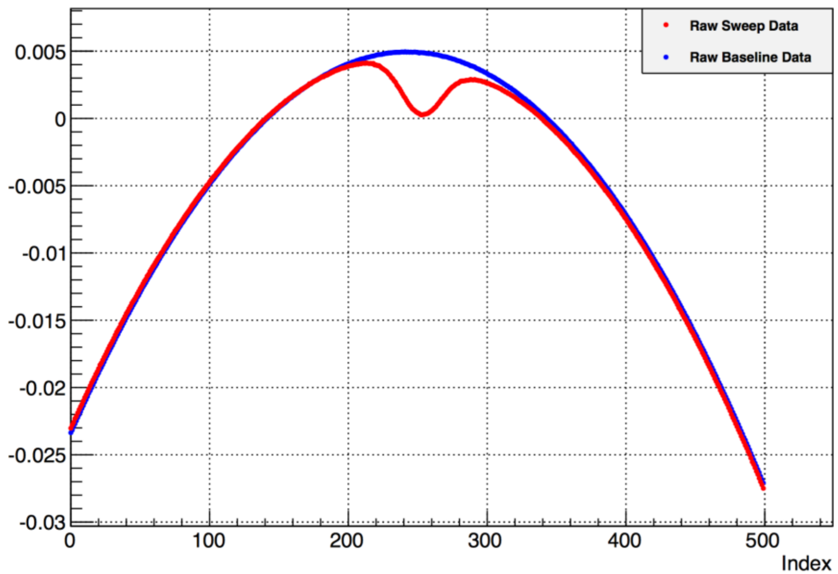
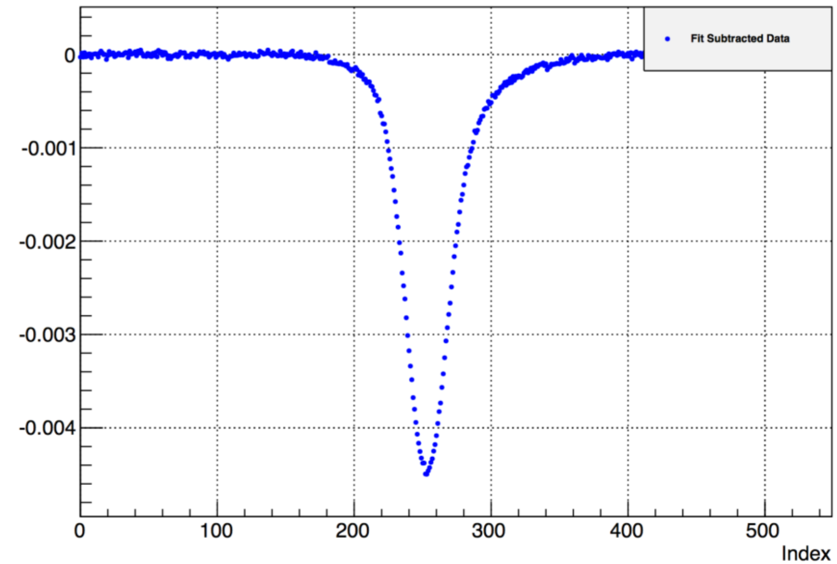
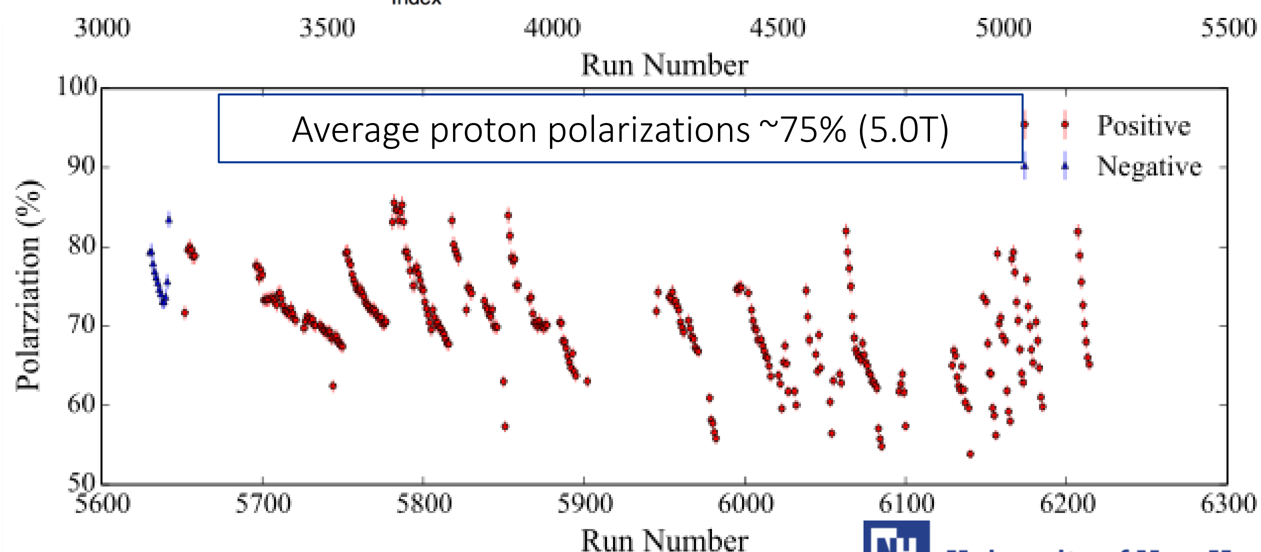
Proton Polarization Measured with Q-Meter





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



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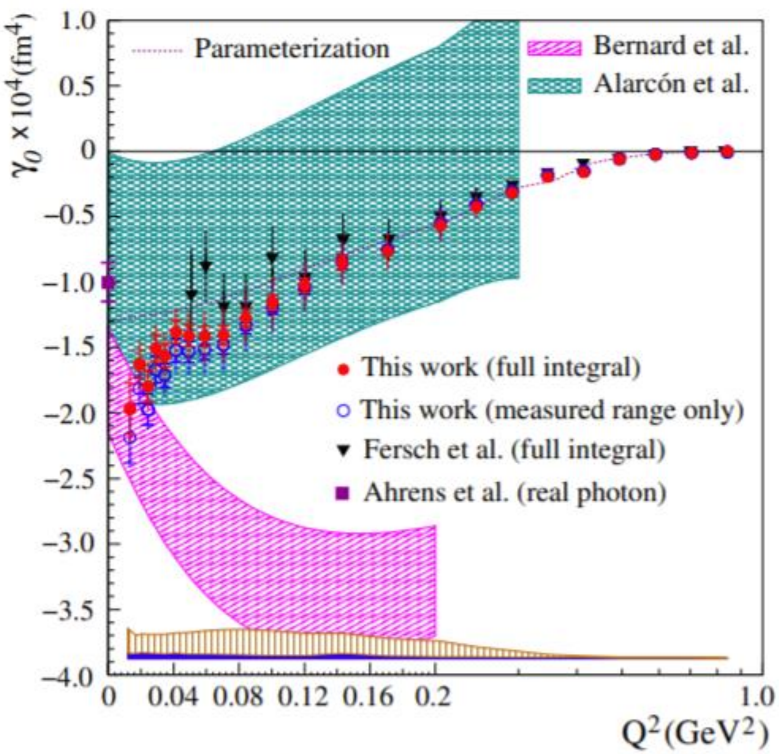
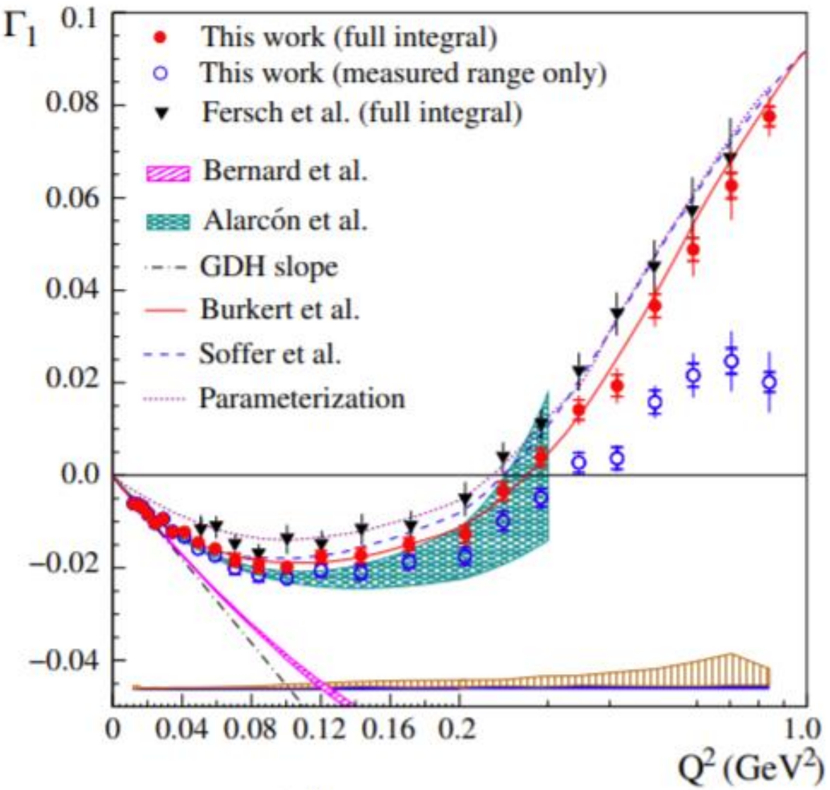
T. Badman (2013) TN #08: http://hallaweb.jlab.org/experiment/g2p/collaborators/toby/technotes/target.pdf

EG4 Moment Results





X. Zheng et al., “Measurement of the Proton Spin Structure at Long Distances”, Nature Physics Volume 17-6

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