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

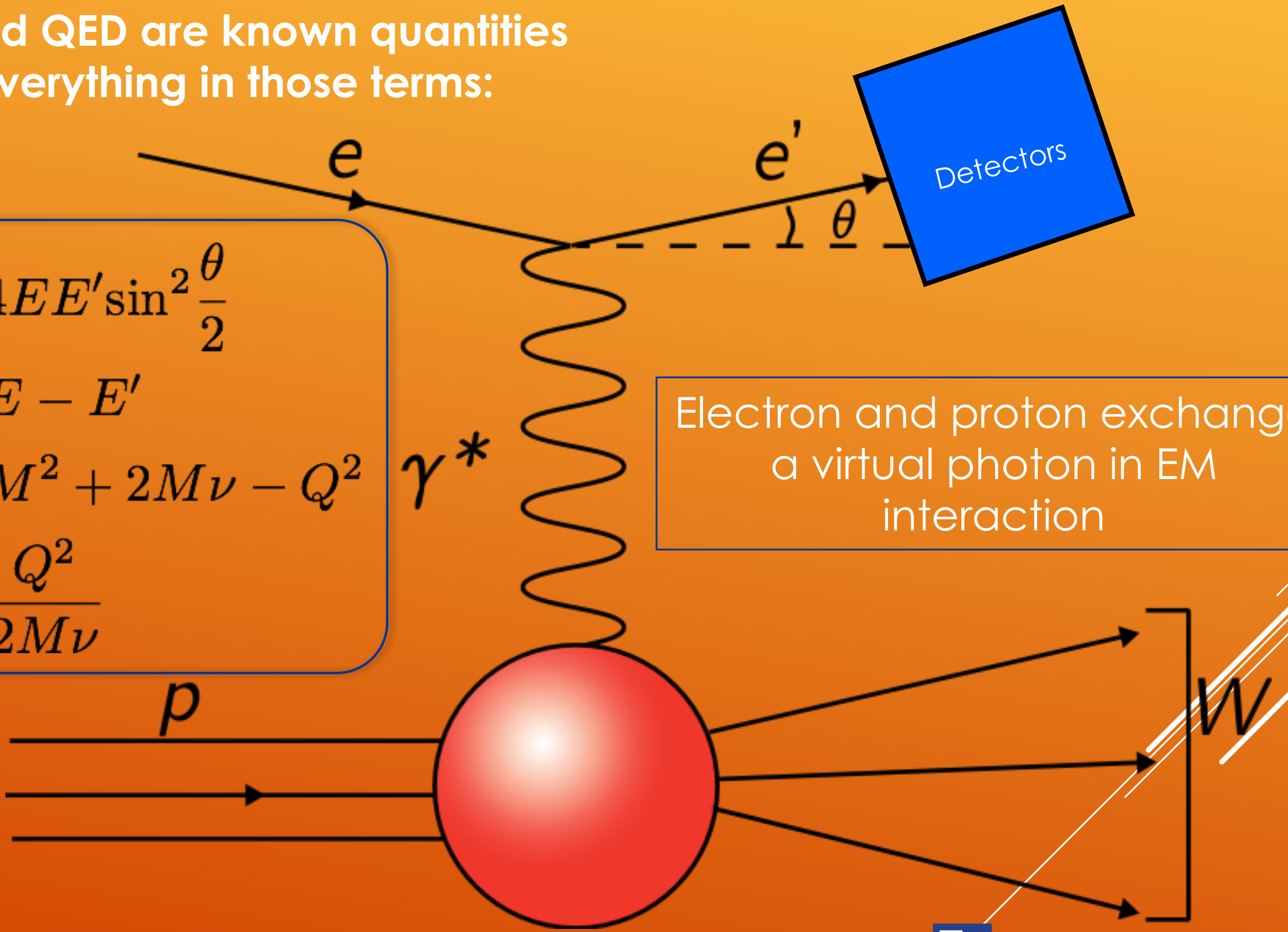
Electron and QED are known quantities so define everything in those terms:

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

$$\nu = E - E'$$

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

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



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

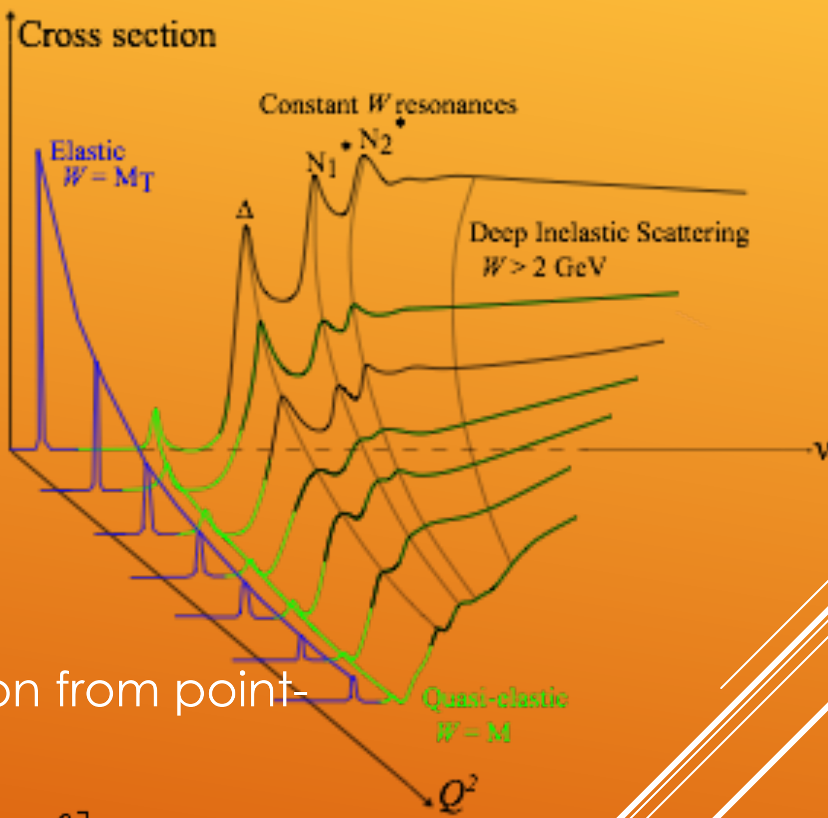
$$E'_{\text{elas}} = \frac{E}{1 + \frac{2E}{M}\sin^2\frac{\theta}{2}}$$

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

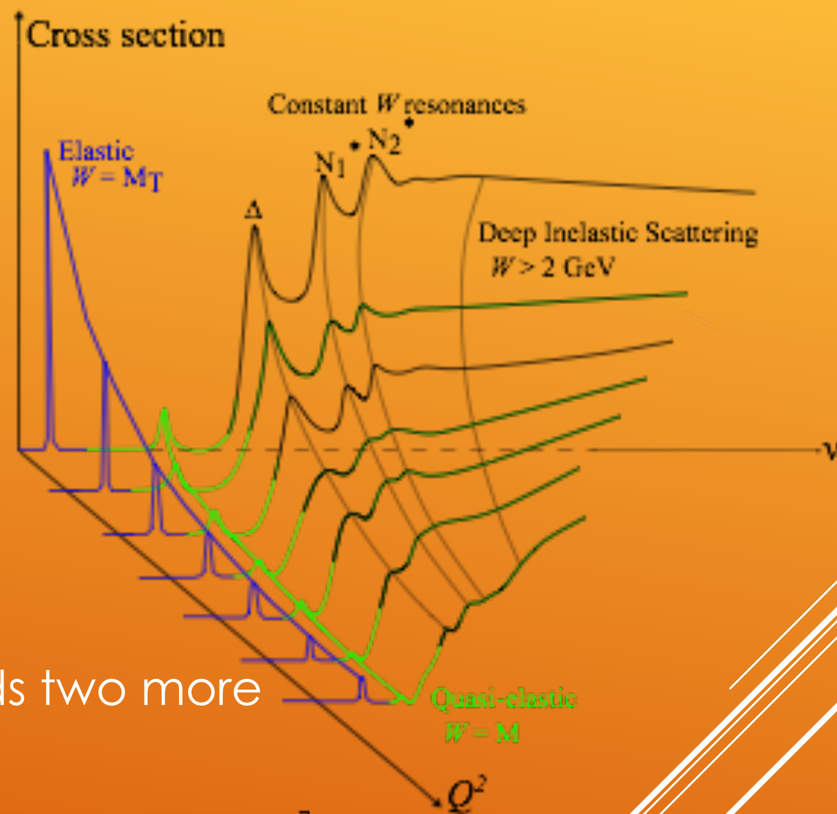
Inelastic scattering: Target is in excited state after interaction

Structure Functions:

Inclusive *unpolarized* cross sections

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

F_1 and F_2 related to quark/gluon distribution



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

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

g_1 and g_2 related to spin distribution

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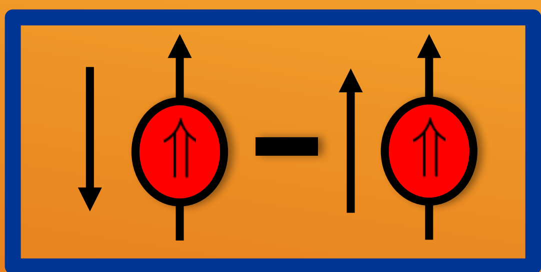
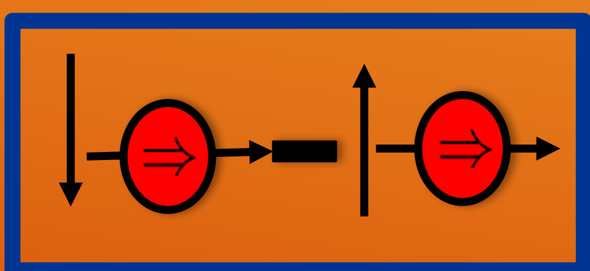
EXTRACTING SPIN STRUCTURE BY LOOKING AT CROSS SECTION DIFFERENCES

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…

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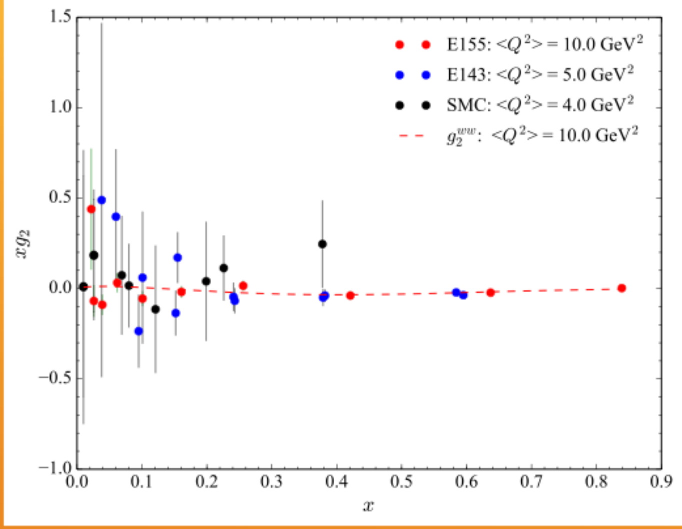
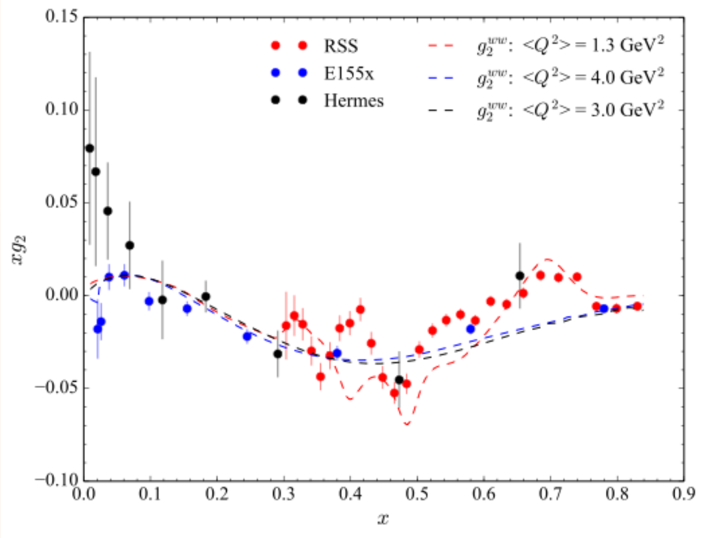
MOTIVATION: Measure a fundamental spin observable (g_2) in the region $0.02 < Q^2 < 0.20$ GeV^2 for the first time

- 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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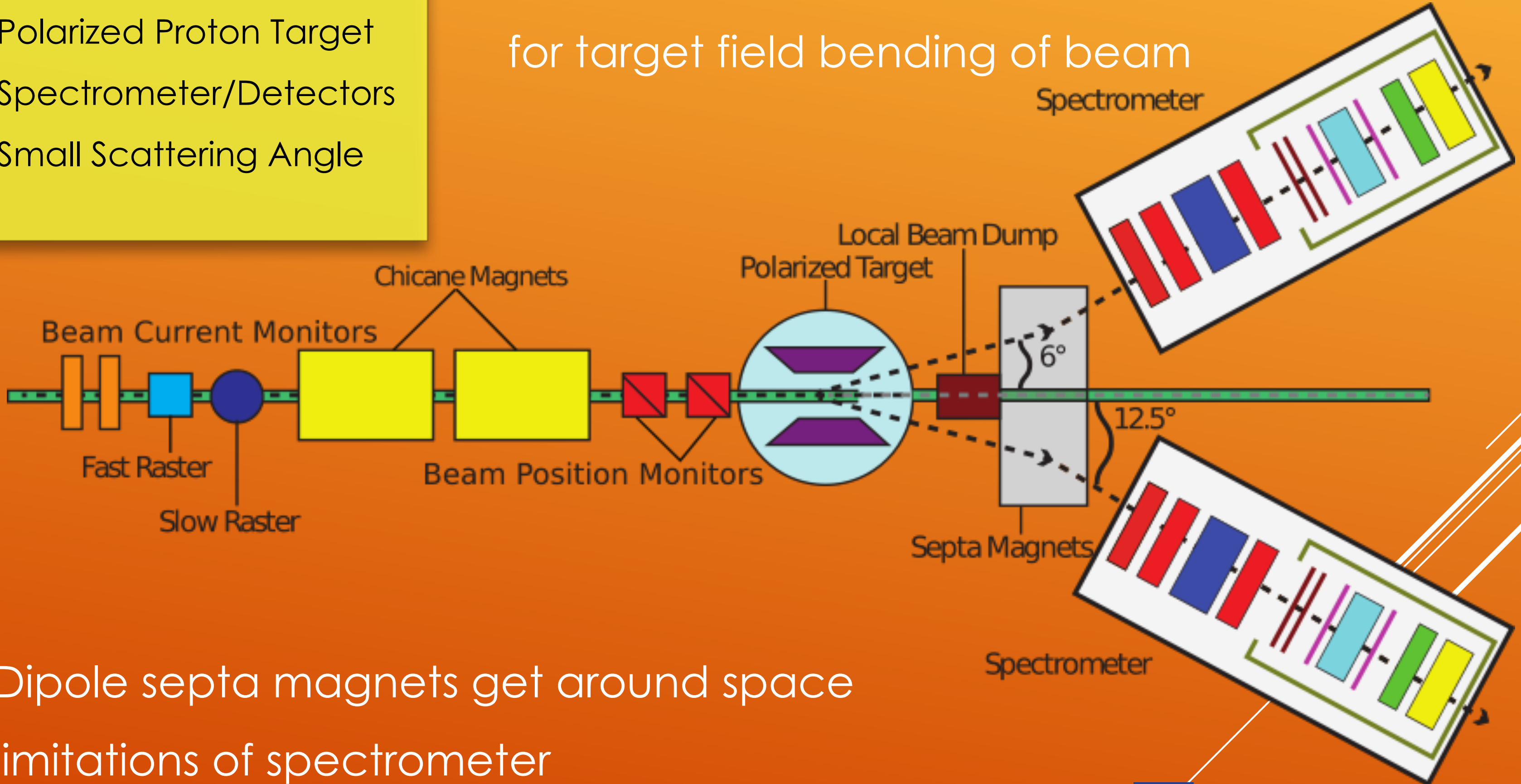
HALL A EXPERIMENTAL SETUP:

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:

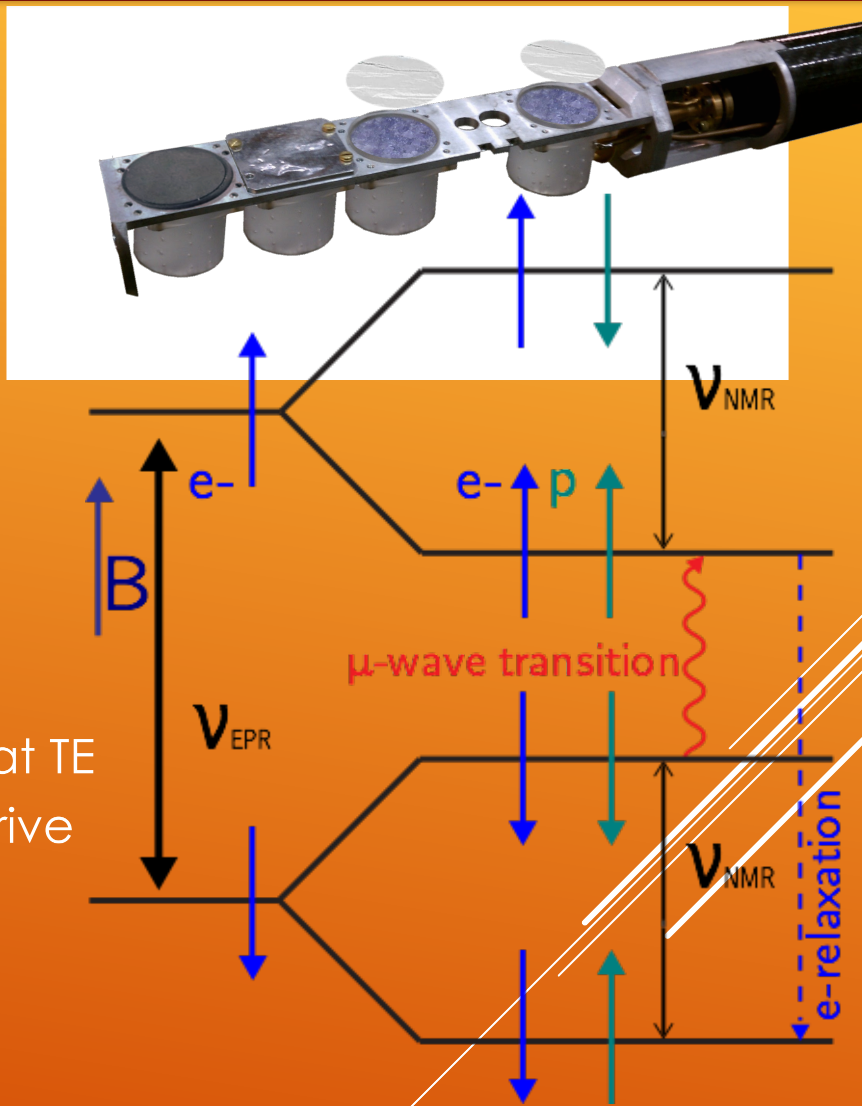
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

- 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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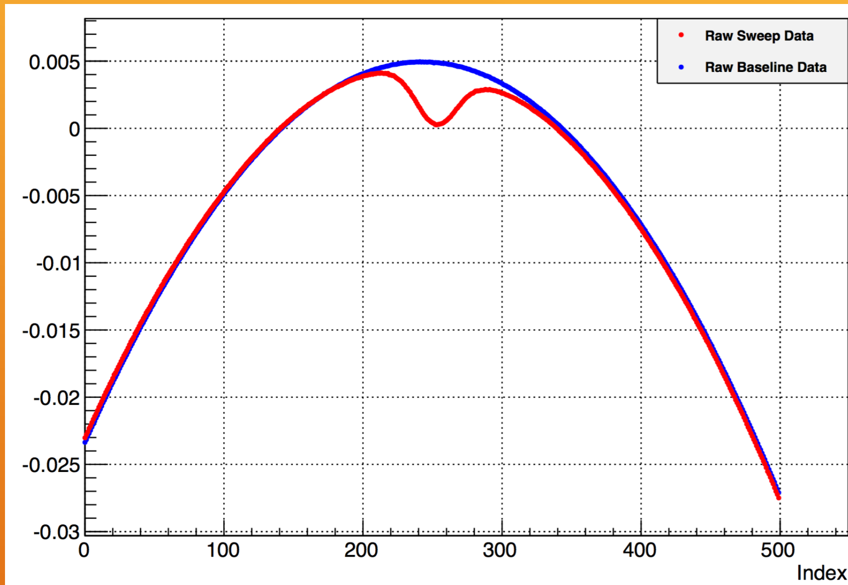
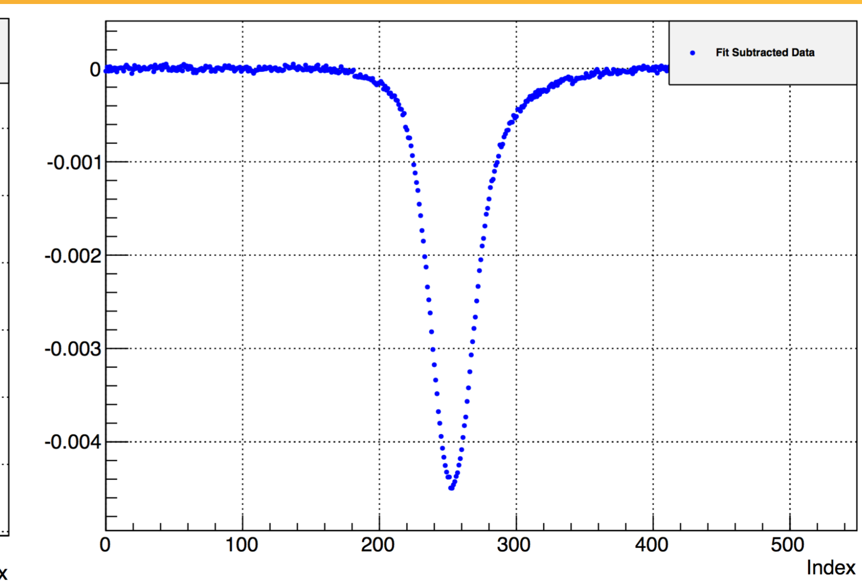
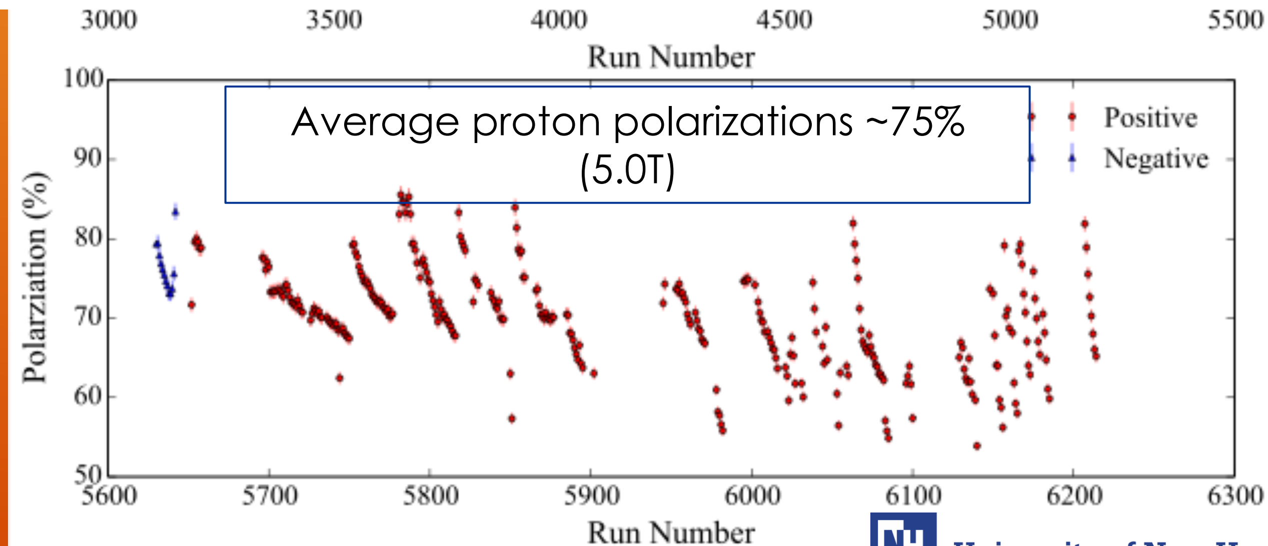
PROTON POLARIZATION MEASURED WITH Q-METER





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



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

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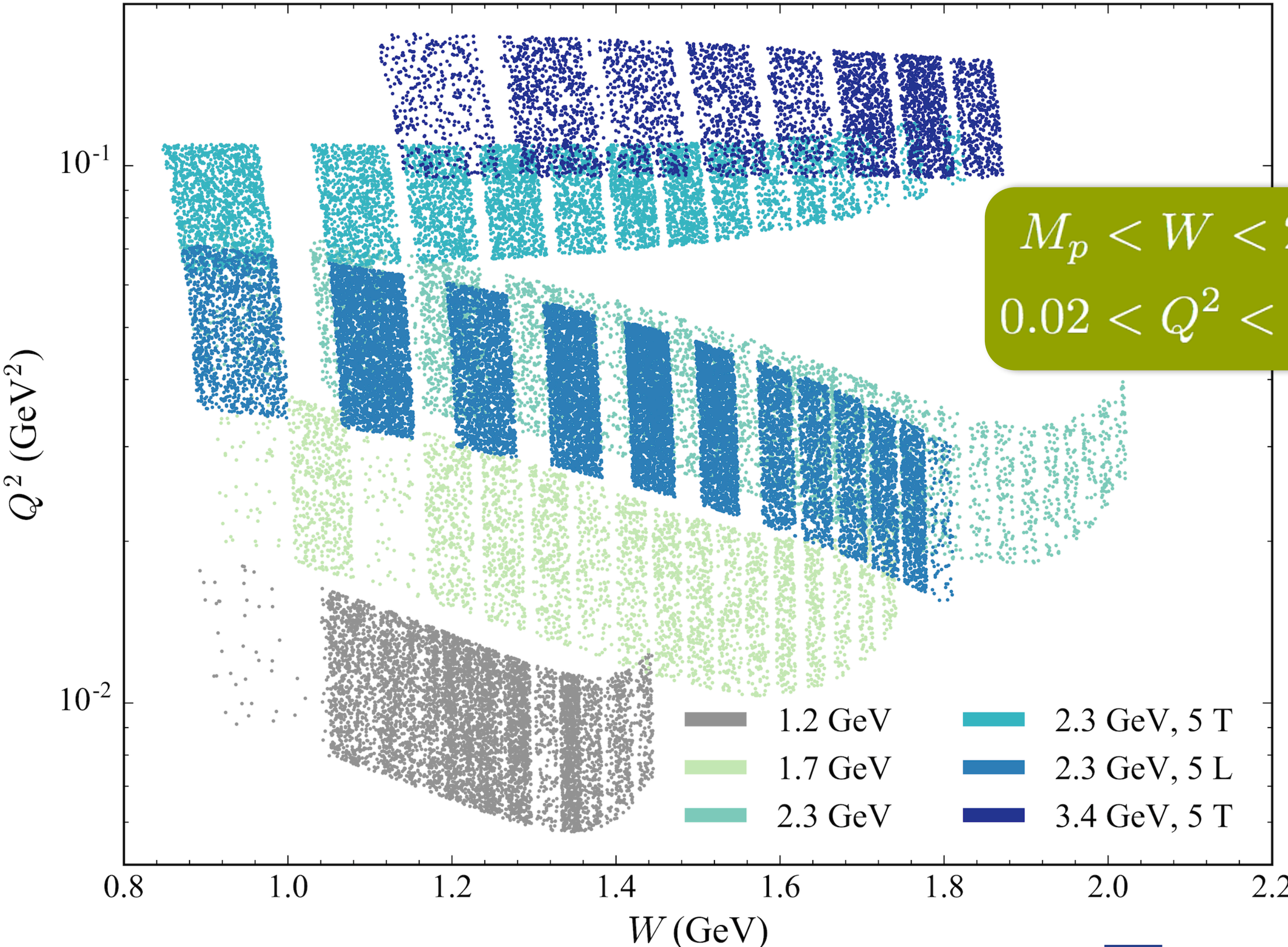
G₂P KINEMATIC COVERAGE



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

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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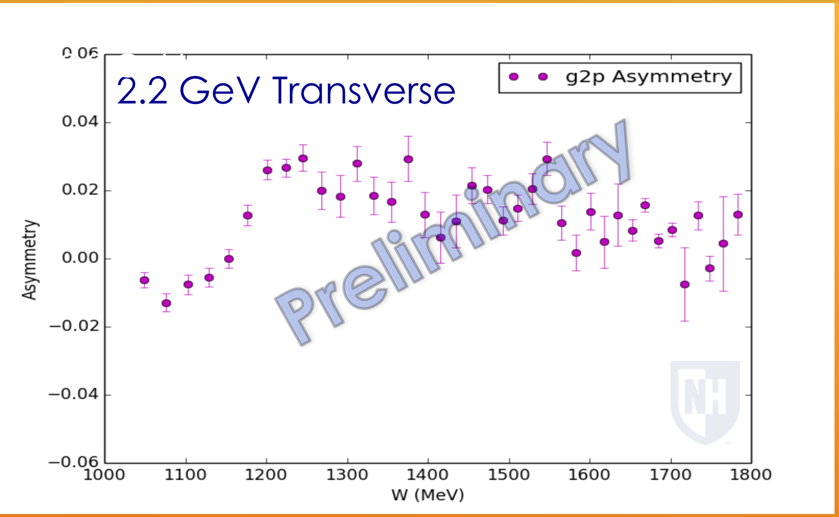
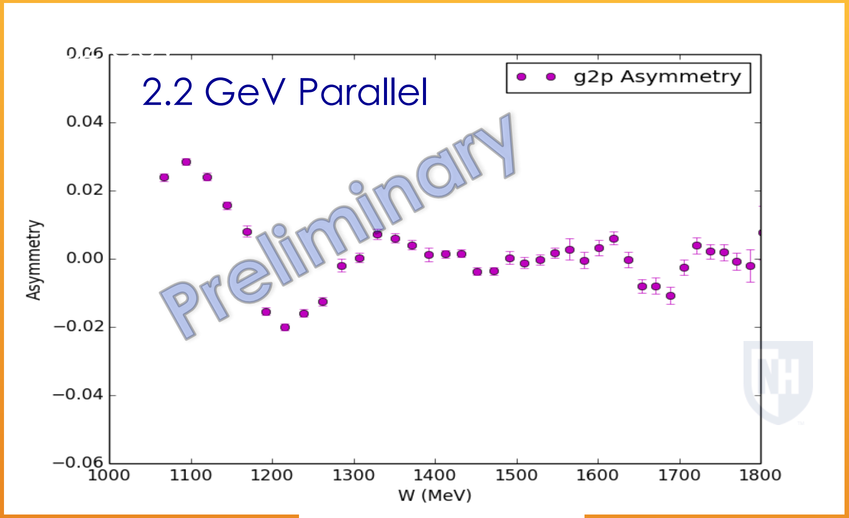
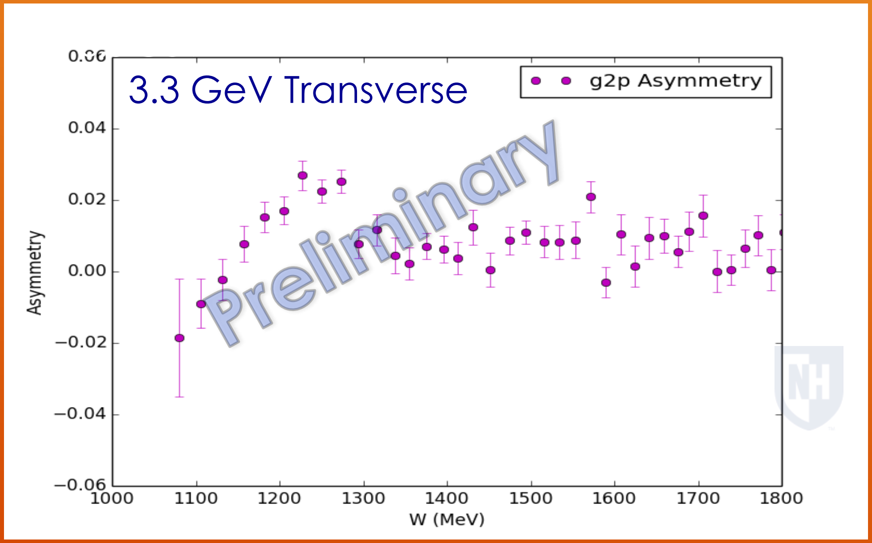
5T PROTON ASYMMETRIES







Raw Counts:

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

Measured Asymmetries:

$$A = \frac{Y_+ - Y_-}{Y_+ + Y_-},$$

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

dilution factor

beam/target pol

Combine both HRS for best statistics!

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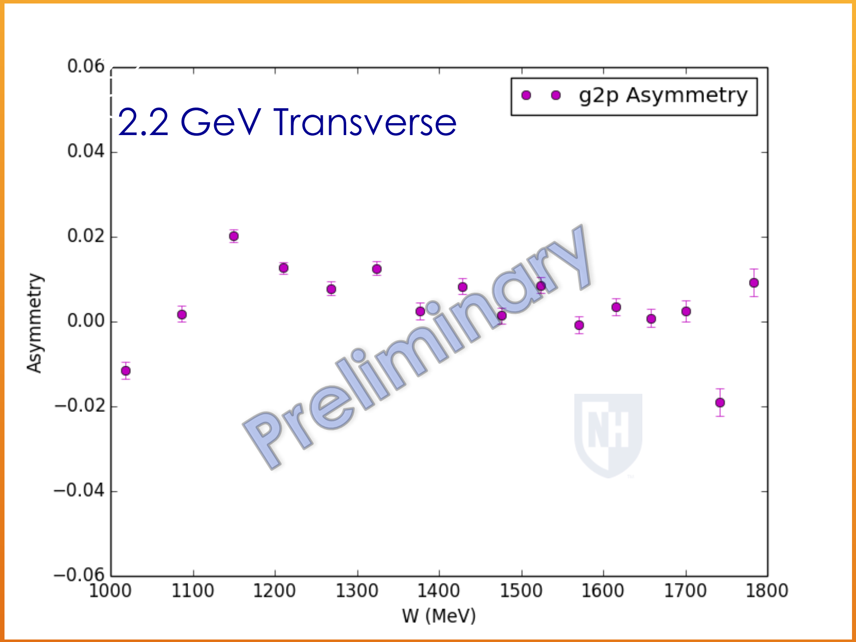
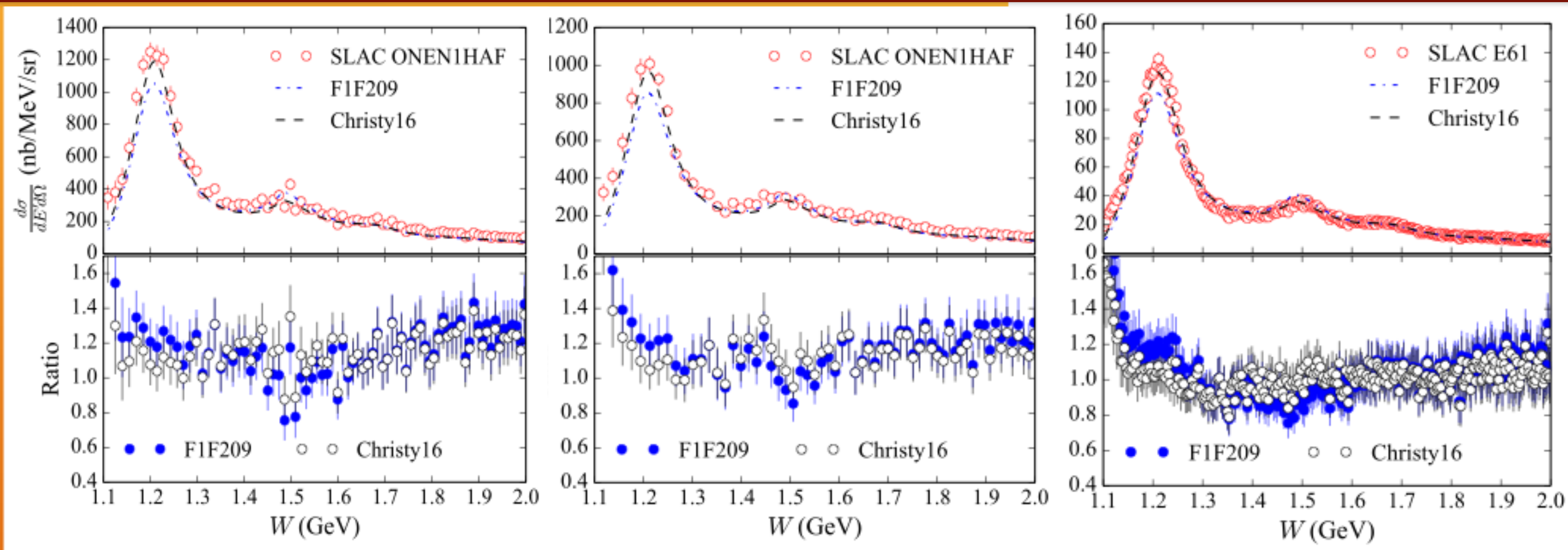
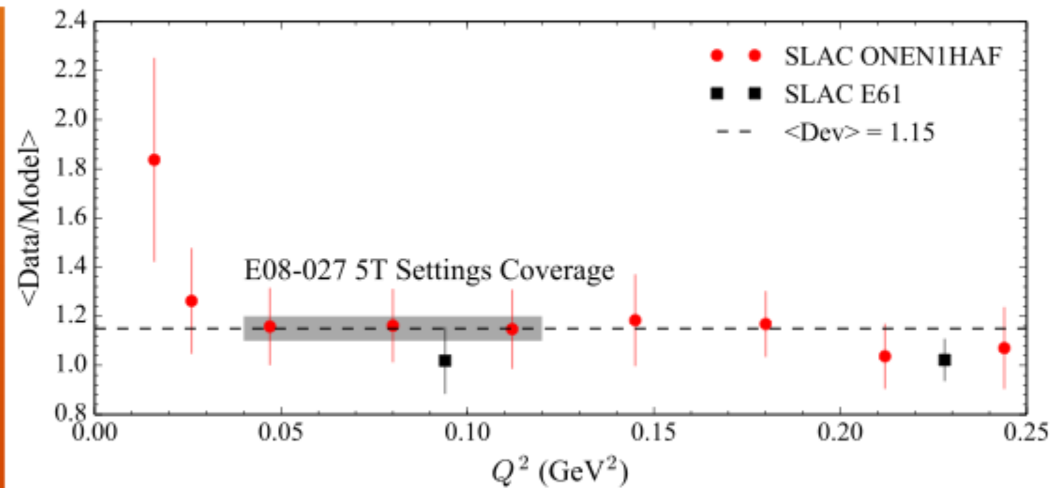
2.5T PROTON ASYMMETRIES



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

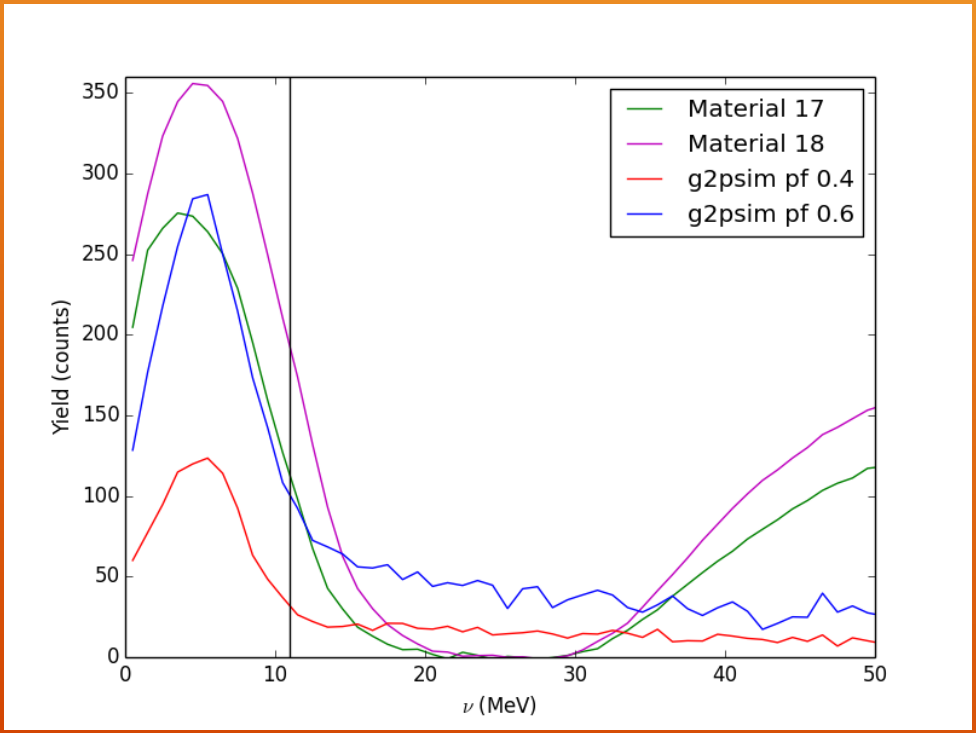


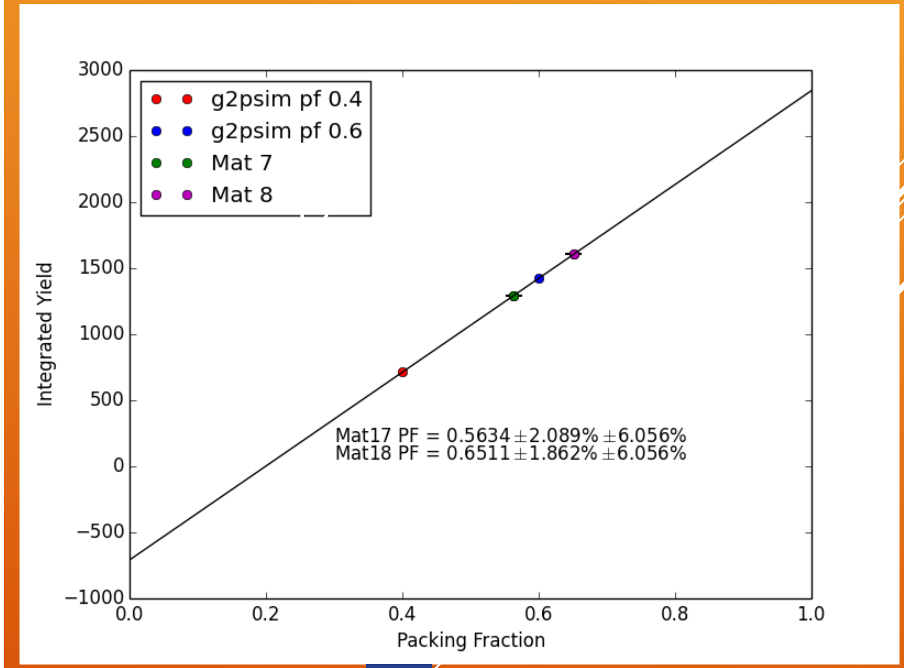


- Use proton model for unpolarized cross section
- Does a good job of reproducing data at E08-027 kinematics

NEW PACKING FRACTION ANALYSIS

- Packing fraction describes how much material is in the target cell, important for calculating dilution factor
- Previous packing fraction analysis yielded unrealistic results
- Analysis re-done with Oscar Rondon's method from RSS
- Because the Yield and Packing Fraction have a linear relationship, we can determine Packing Fraction by comparing integrated yield to simulated yields at known packing fractions





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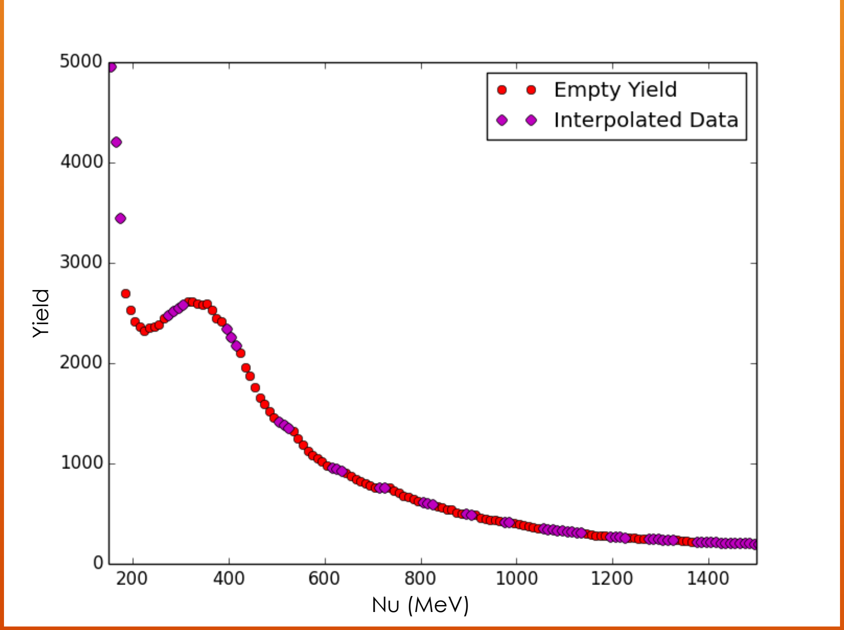
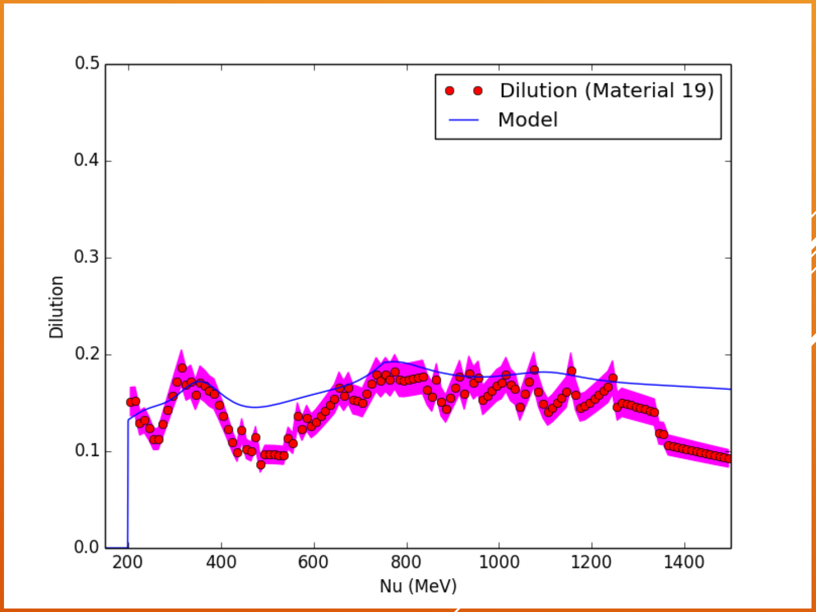
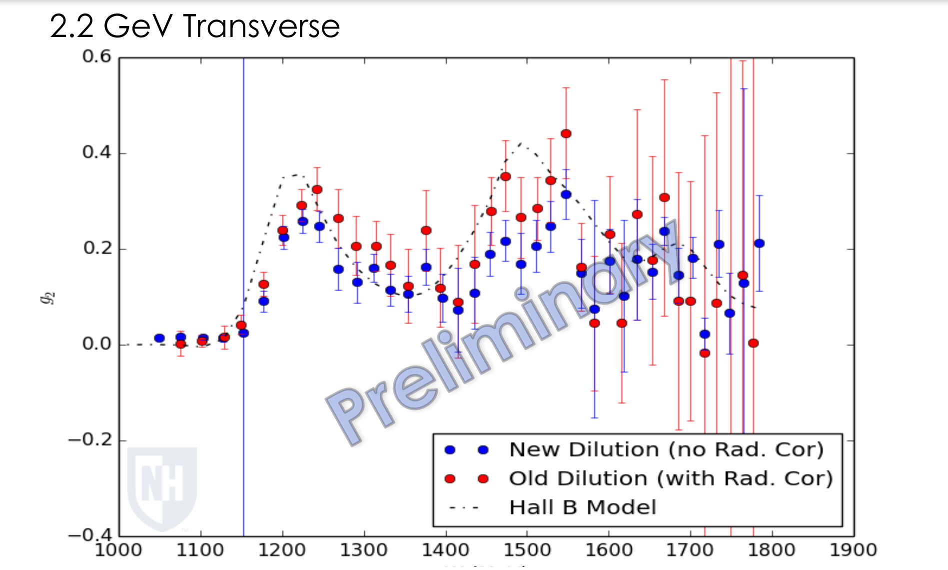
NEW DILUTION ANALYSIS

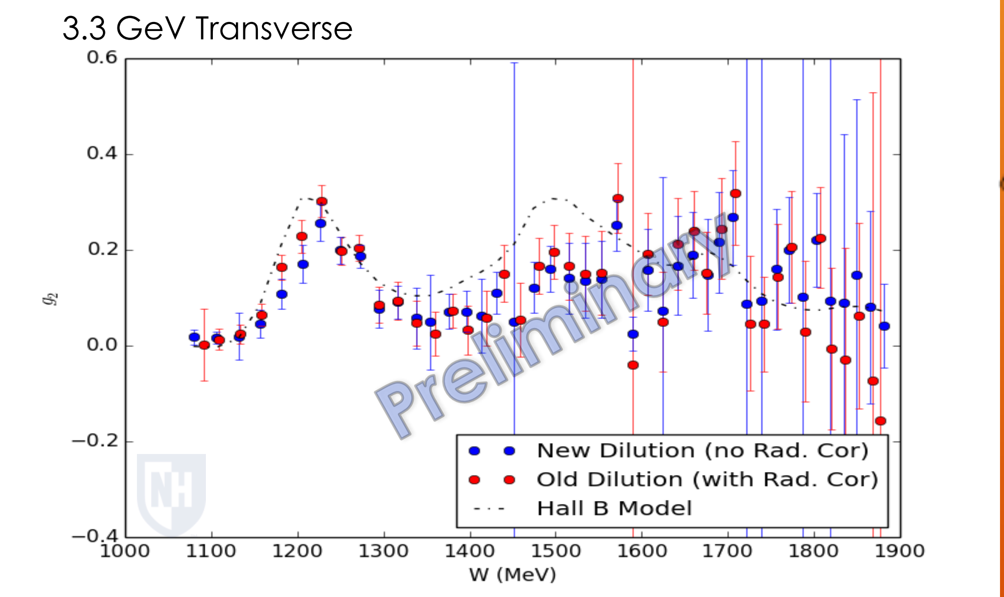
- Dilution approximates how much of data comes from other materials
- $f = \frac{\sigma_{Proton}}{\sigma_{Prod}} = 1 - \frac{Y_N + Y_{He} + Y_{Al}}{Y_{Prod}}$
- Acceptance effects on edge of momentum settings and BPM calibration issues complicated this analysis
- Sections missing above yields or including problematic data were replaced with the Bosted-Christy model, scaled to the data around it





EXTRACTING THE SPIN STRUCTURE FUNCTIONS : G_2





Model driven procedure for unmeasured part

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

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

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

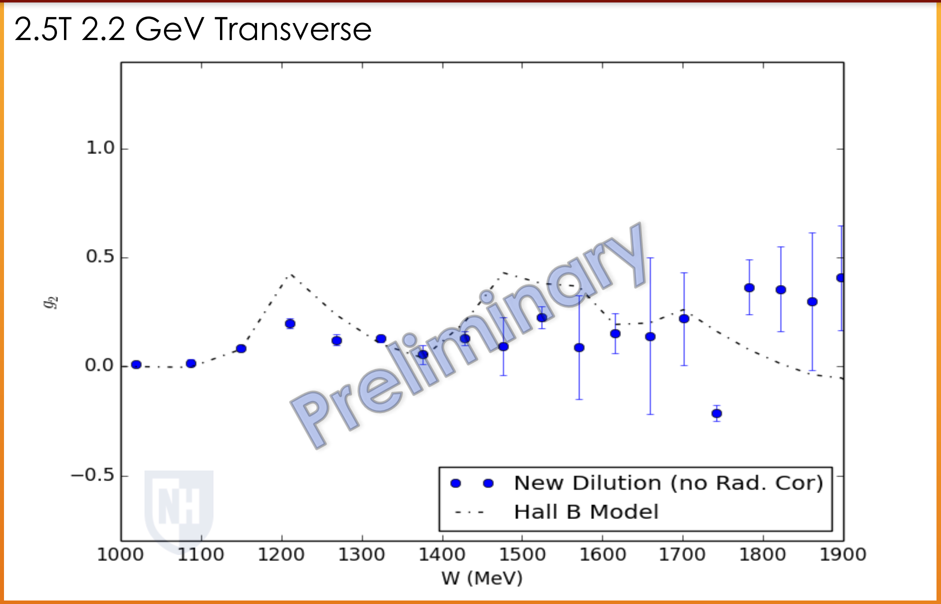
Adjusting to a constant Q^2

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

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

Small effect at the transverse settings

2.5T G2, RADIATIVE CORRECTIONS INCOMPLETE



- Structure functions with new dilution and packing fraction still need inelastic radiative corrections
- Our radiative corrections expert, Ryan Zielinski, is helping with this
- We expect R.C. to be done in the coming weeks

- Lack of R.C. is the likely reason for discrepancy from model

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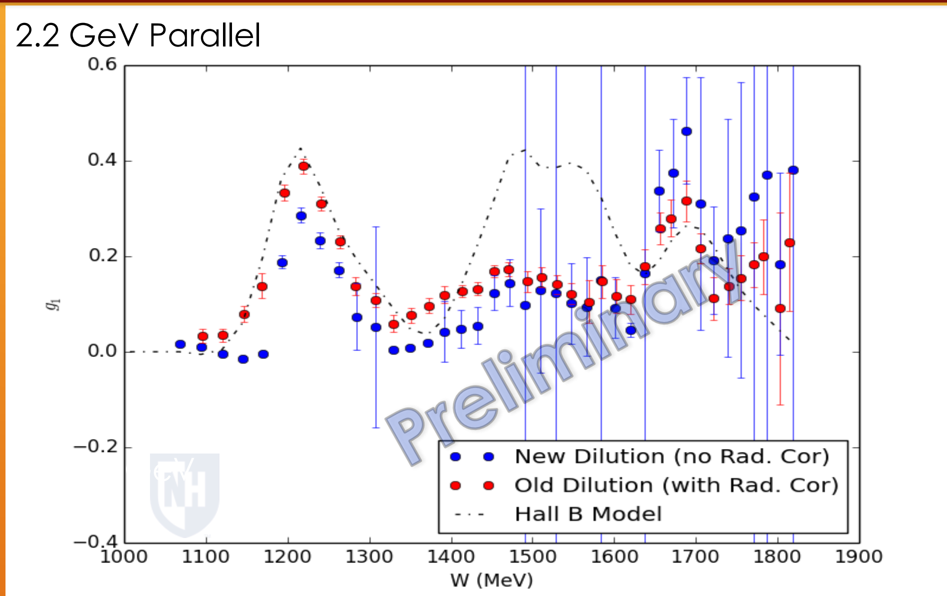
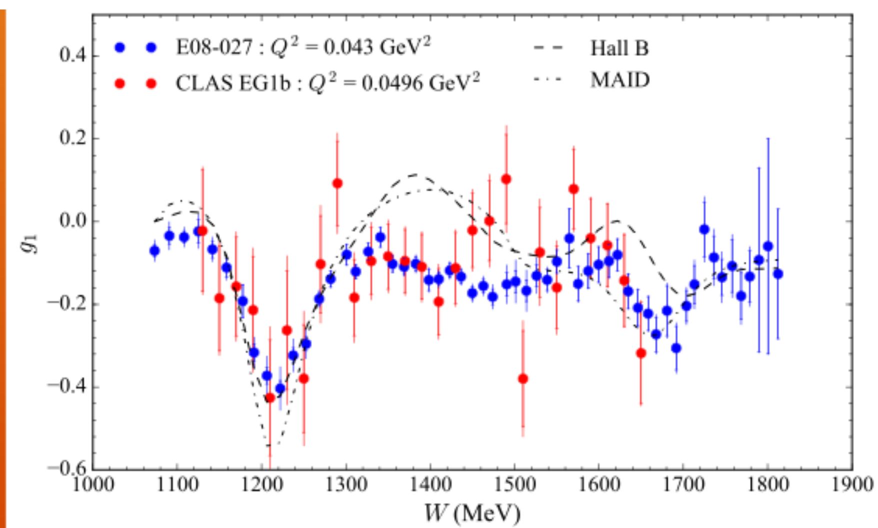
EXTRACTING THE SPIN STRUCTURE FUNCTIONS: G_1





Model driven procedure for unmeasured part

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

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

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

- 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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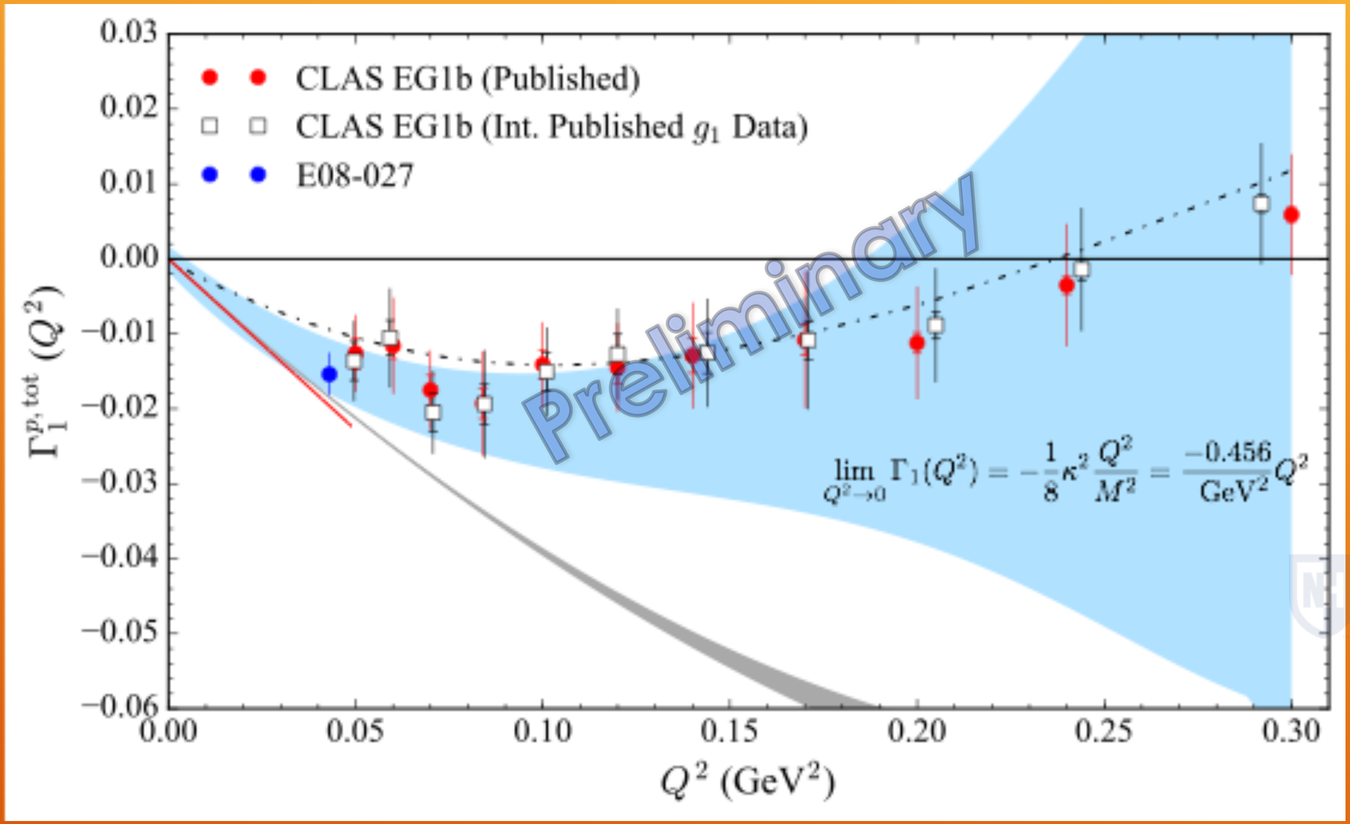
FIRST MOMENT OF g_1 (x,Q^2)

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

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



Setting	$\Gamma_1^{\rm meas.}$	$\Gamma_1^{\rm low\ x}$	$\Gamma_1^{\rm tot.}$	$\delta^{\rm tot.}_{\rm stat}$	$\delta^{\rm tot.}_{\rm sys}$
2254 5T Long.	−0.01541	0.0003	−0.01541	0.0006	0.0028

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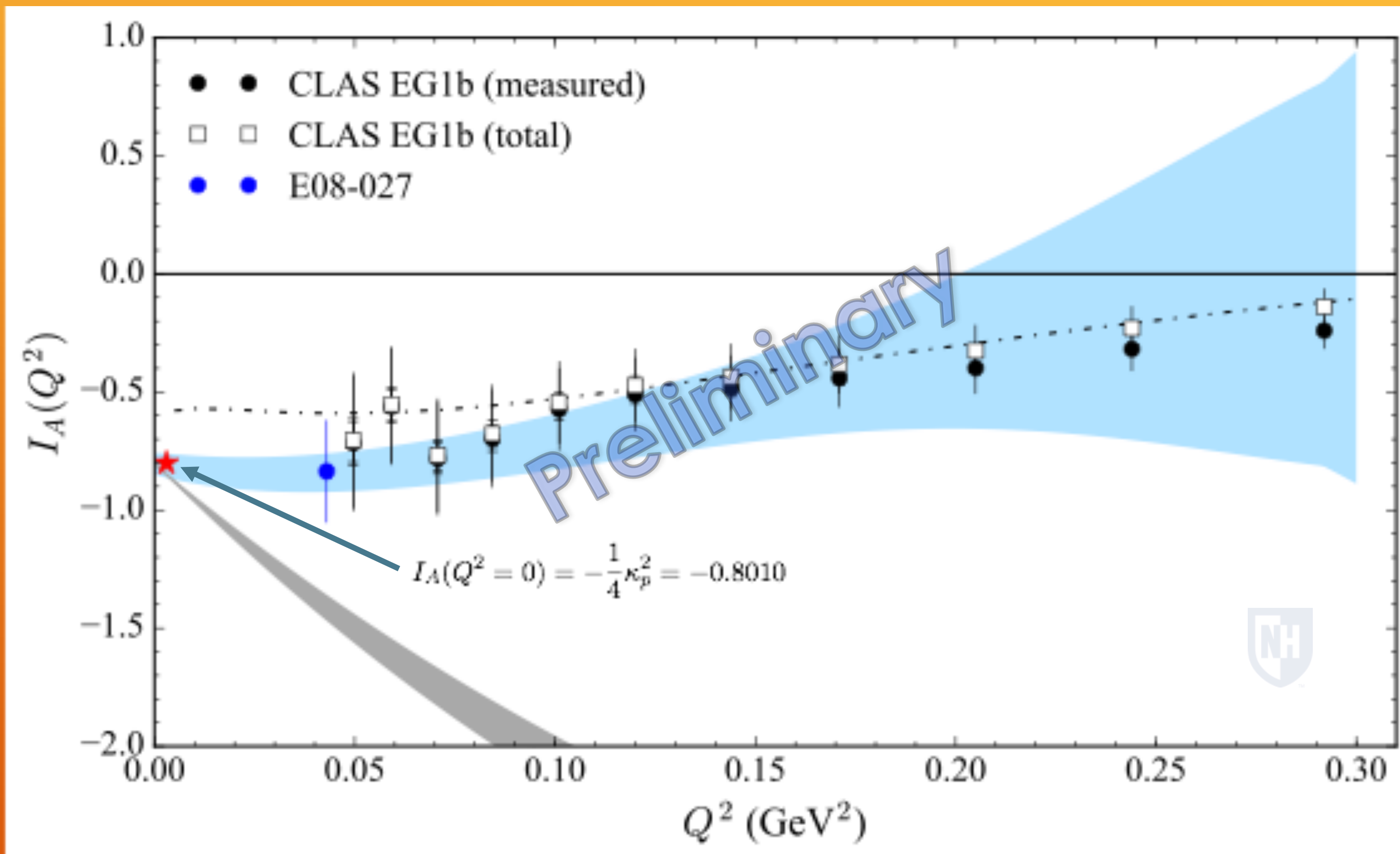
K.V. Dharmawardane (2006) *et al* https://doi.org/10.1016/j.physletb.2006.08.011

EXTENDED GDH SUM

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



Setting	$I_A^{meas.}$	$I_A^{low\ x}$	$I_A^{tot.}$	$\delta_{stat}^{tot.}$	$\delta_{sys}^{tot.}$
2254 5T Long.	−0.83669	0.0119	−0.83669	0.0240	0.2155

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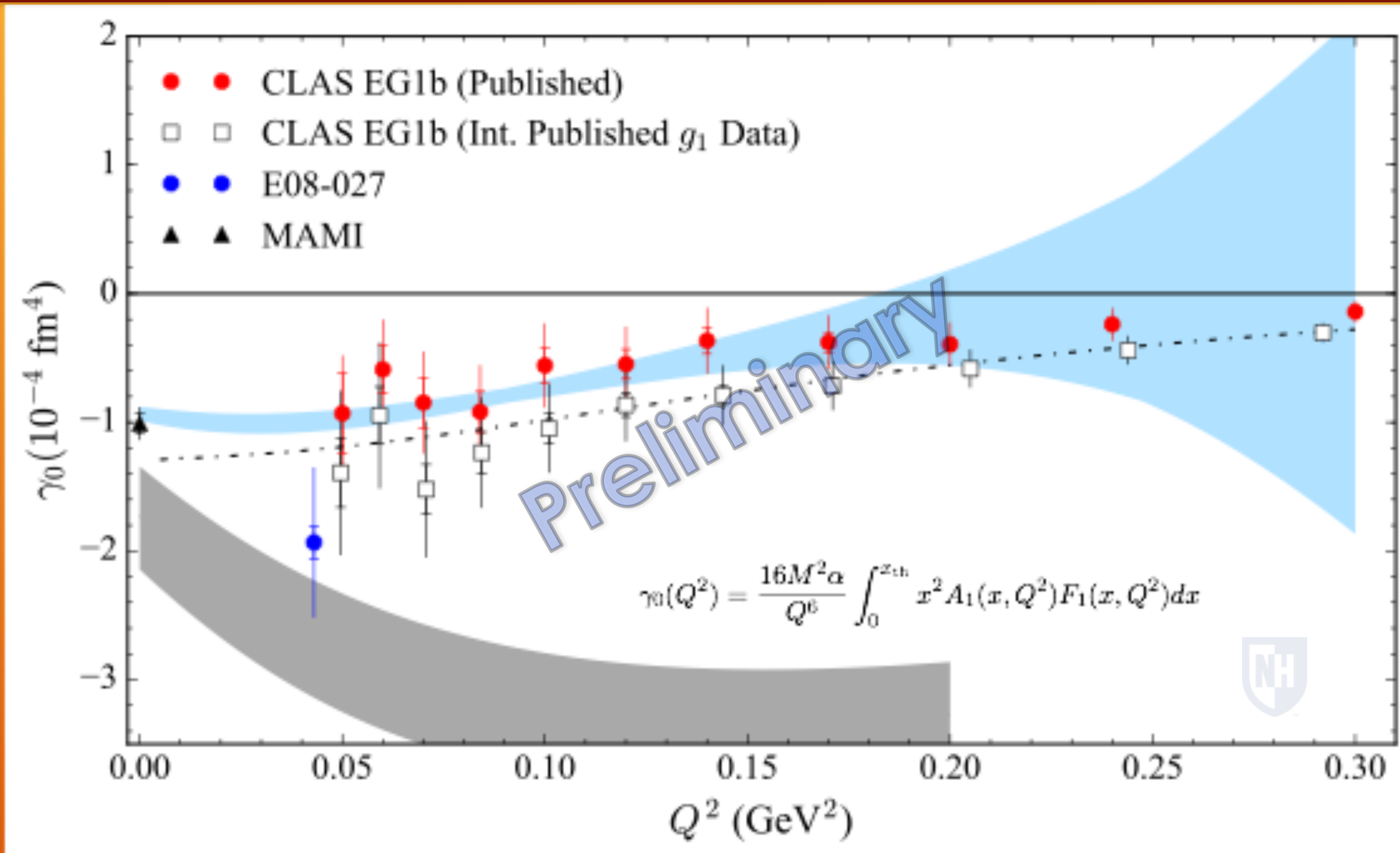
http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

FORWARD SPIN POLARIZABILITY

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



Setting	$\gamma_0^{meas.}$	$\gamma_0^{low\ x}$	$\gamma_0^{tot.}$	$\delta_{stat}^{tot.}$	$\delta_{sys}^{tot.}$
2254 5T Long.	−1.9352	−0.0007	−1.9352	0.1202	0.5663

$$\gamma_0(Q^2=0) = [-1.01 \pm 0.08\,(\mathrm{stat}) \pm 0.10\,(\mathrm{sys})]\cdot 10^{-4}\ \mathrm{fm}^4$$

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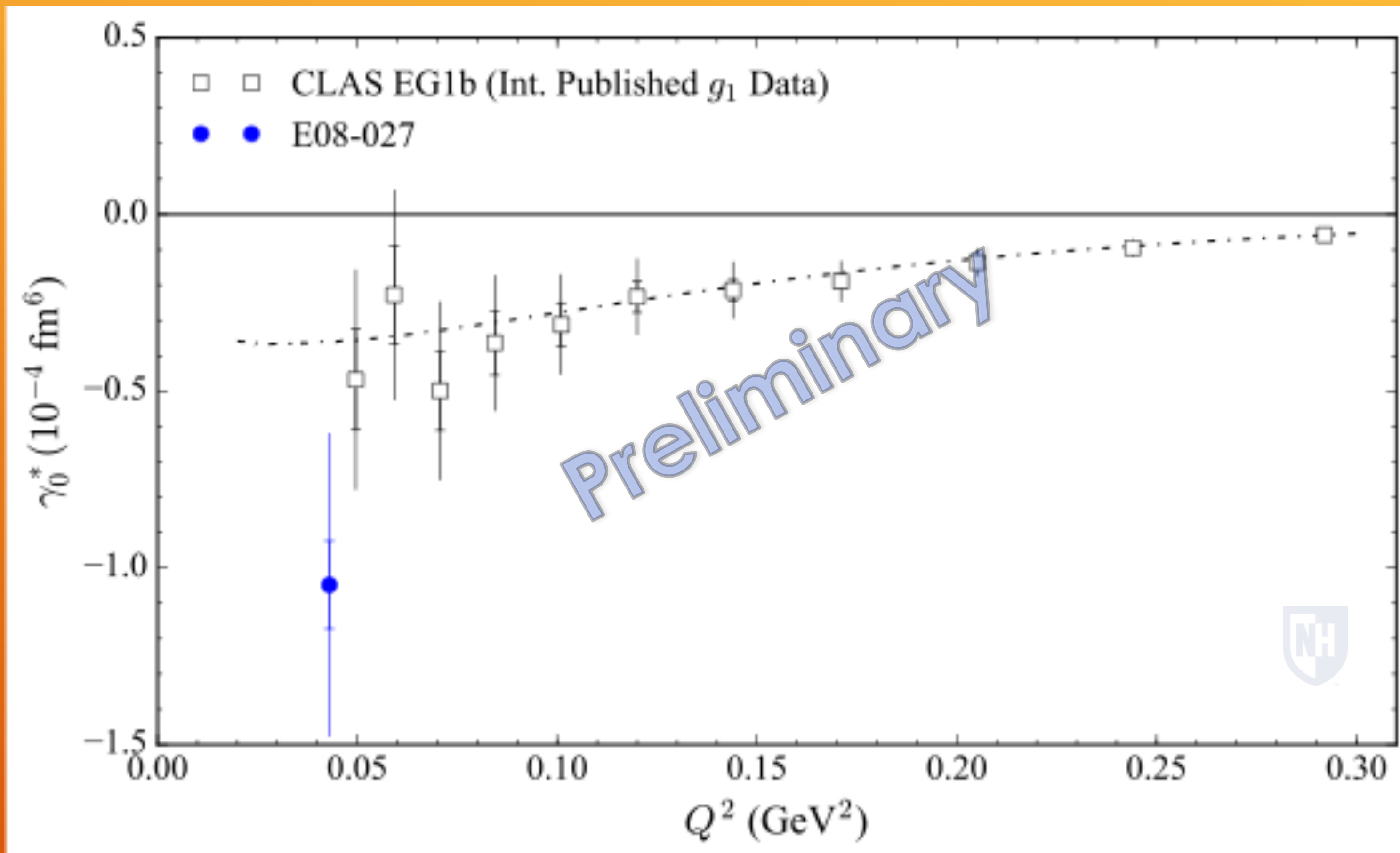
Y. Prok (2008) *et al* 10.1016/j.physletb.2008.12.063 H. Dutz (2003) *et al.* doi.org/10.1103/PhysRevLett.91.192001

HIGHER ORDER POLARIZABILITY

$$\gamma_0 * (Q^2) = \frac{64\alpha M^4}{Q^{10}} \int_0^{x_{\text{th}}} x^4 \left(g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right) dx$$



Setting	$\gamma_0^{*\,\text{meas.}}$	$\gamma_0^{*\,\text{low}\,x}$	$\gamma_0^{*\,\text{tot.}}$	$\delta_{\text{stat}}^{\text{tot.}}$	$\delta_{\text{sys}}^{\text{tot.}}$
2254 5T Long.	−1.0501	-2×10^{-5}	−1.0501	0.1203	0.4072

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!**
- Longitudinal data agrees with previous measurements.
- Dilution and packing fraction issues have consumed the analysis for some time but are now resolved
- Still need R.C. for revised Structure Functions – once this is complete, final results will be calculated for four energy settings
- We hope to wrap up the analysis of these settings in the coming months.

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ACKNOWLEDGEMENTS

g2p Analysis Team

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Jixie Zhang

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Min Huang
Jie Liu
Pengjia Zhu
Ryan Zielinski

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

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