University of New Hampshire
Nuclear & Particle Physics Group

The g_2p Experiment: A Measurement of the Proton's Spin Structure Functions 2018 Status Update

David Ruth

Hall A Collaboration Meeting

January 24, 2018

Most Slides & Figures by Ryan Zielinski

Essential Quantities in *ep* Scattering

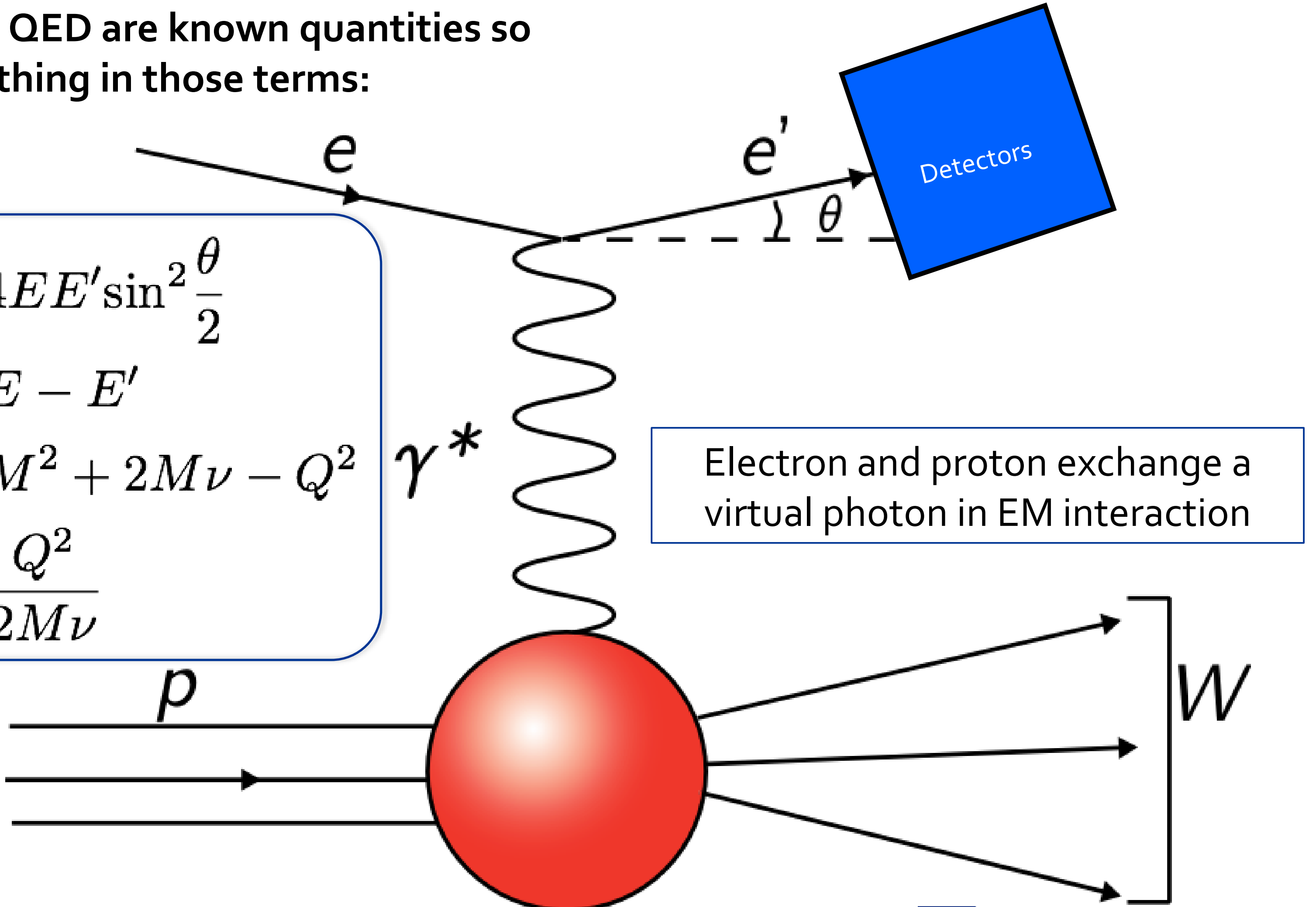
Electron and QED are known quantities so define everything in those terms:

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

$$\nu = E - E'$$

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

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



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

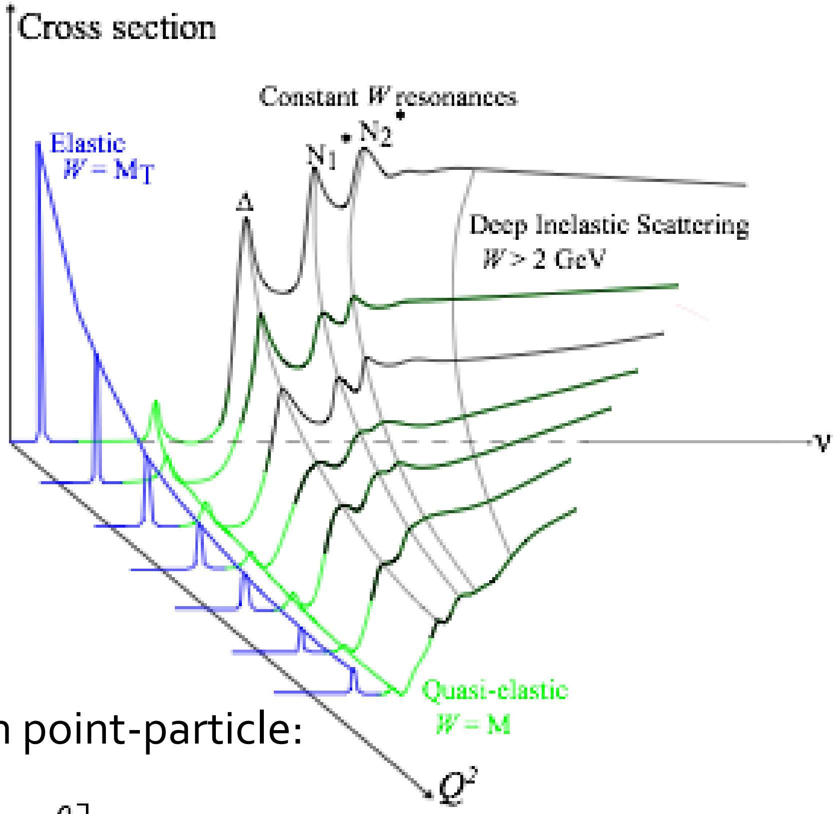
$$E'_{\text{elas}} = \frac{E}{1 + \frac{2E}{M}\sin^2\frac{\theta}{2}}$$

Mott cross section describes scattering from point-particle:

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

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

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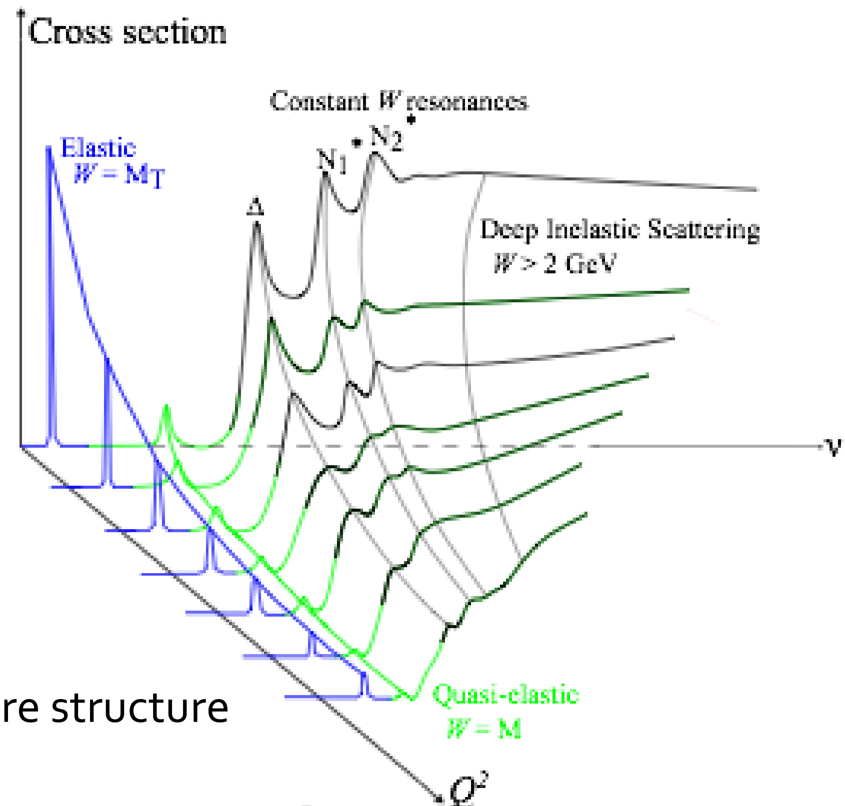
Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

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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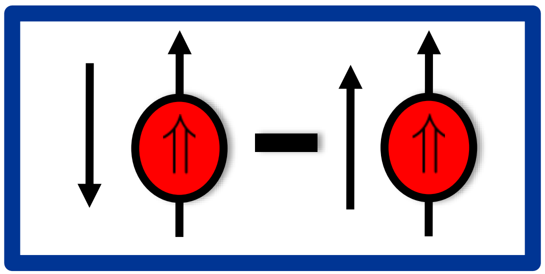
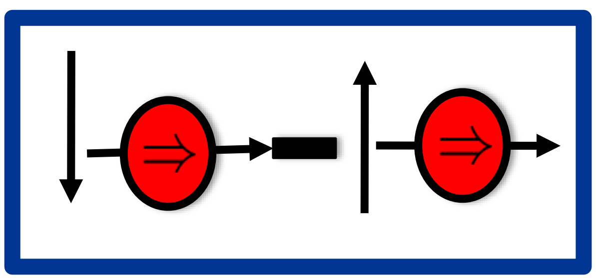
Extracting Spin Structure by Looking at Cross Section Differences

Inclusive *polarized* cross sections



Parallel

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



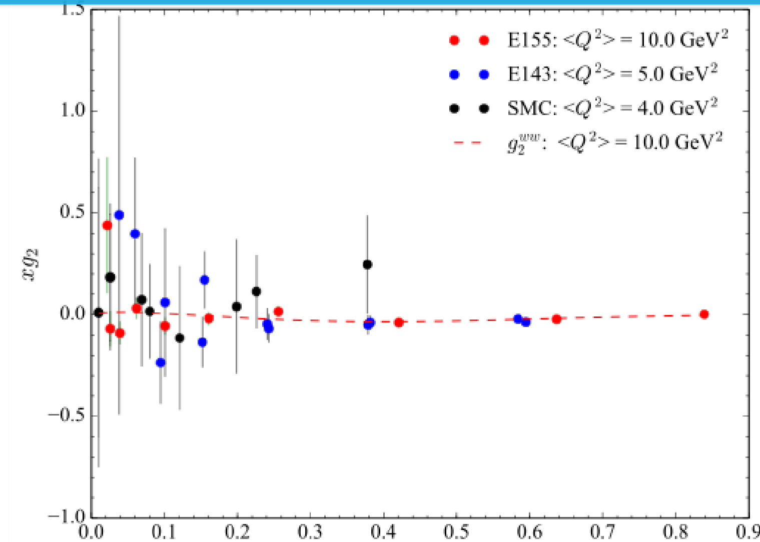
Perpendicular

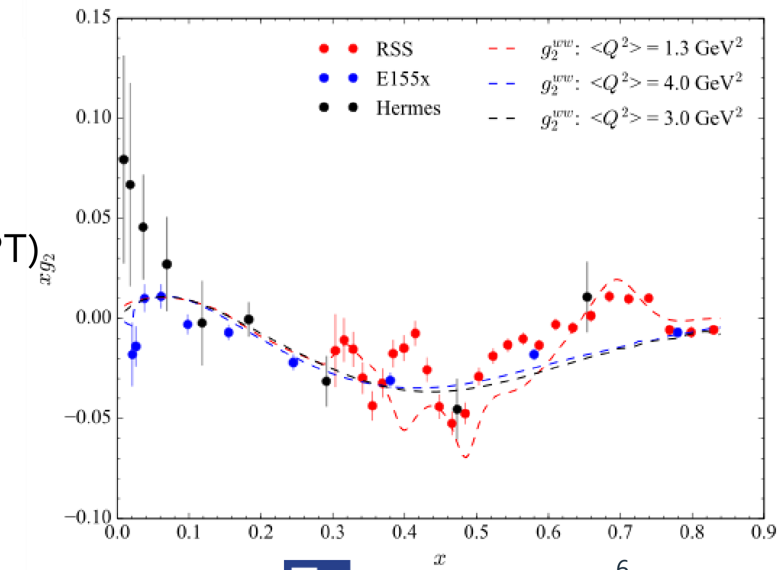
$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} = \frac{4\alpha^2}{M\nu Q^2}\frac{E'^2}{E}\sin\theta\left[\nu g_1(x,Q^2) + 2Eg_2(\nu,Q^2)\right]$$

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



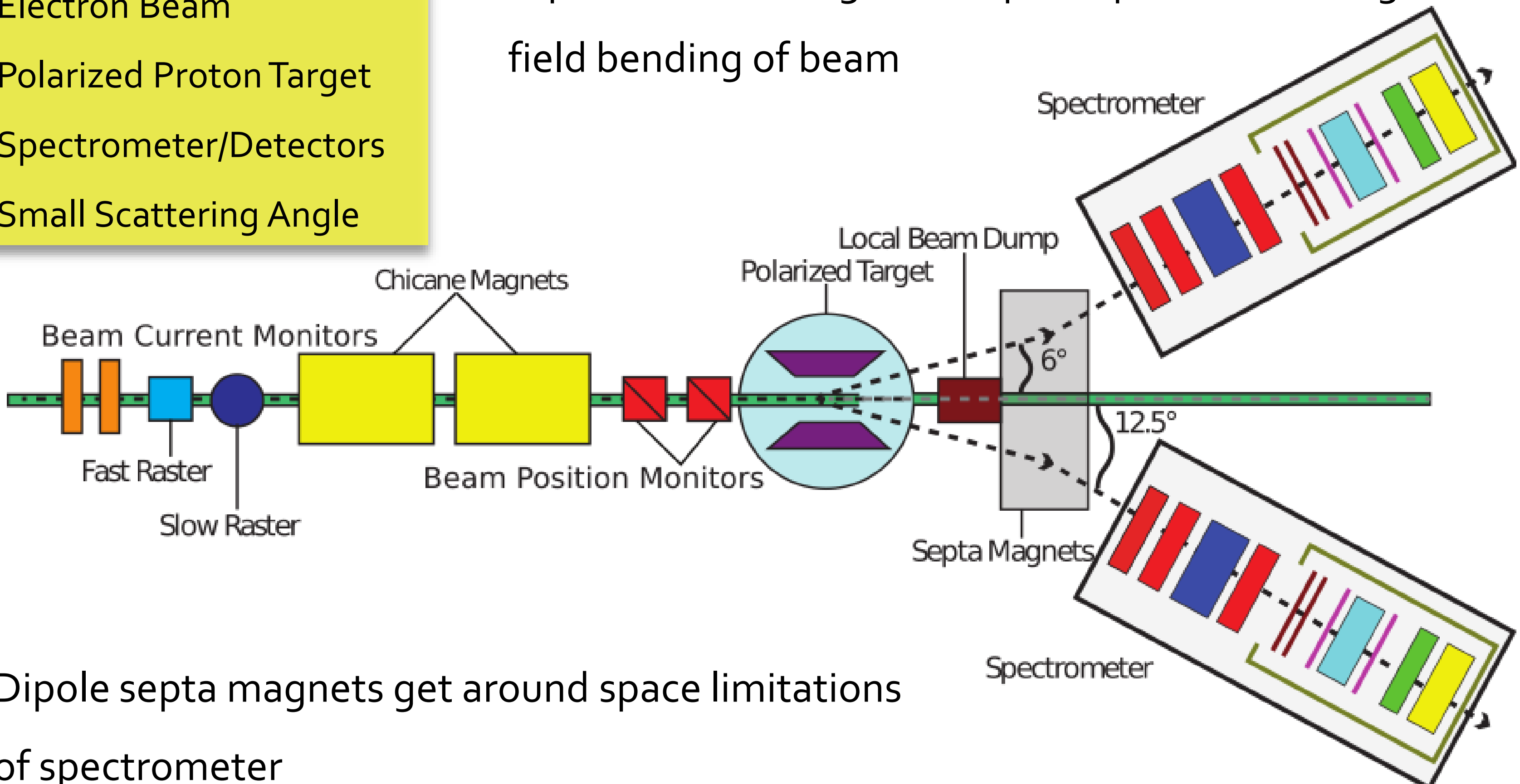


- **g_2p experiment ran spring 2012 in Hall A**

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:

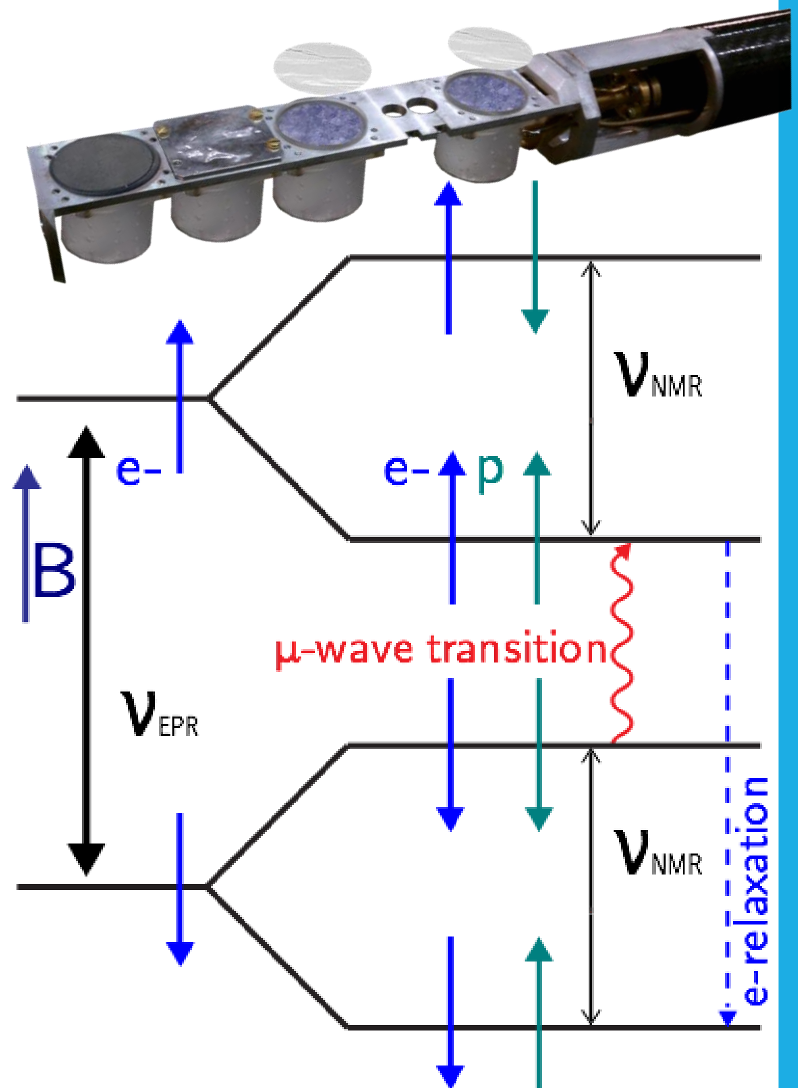
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

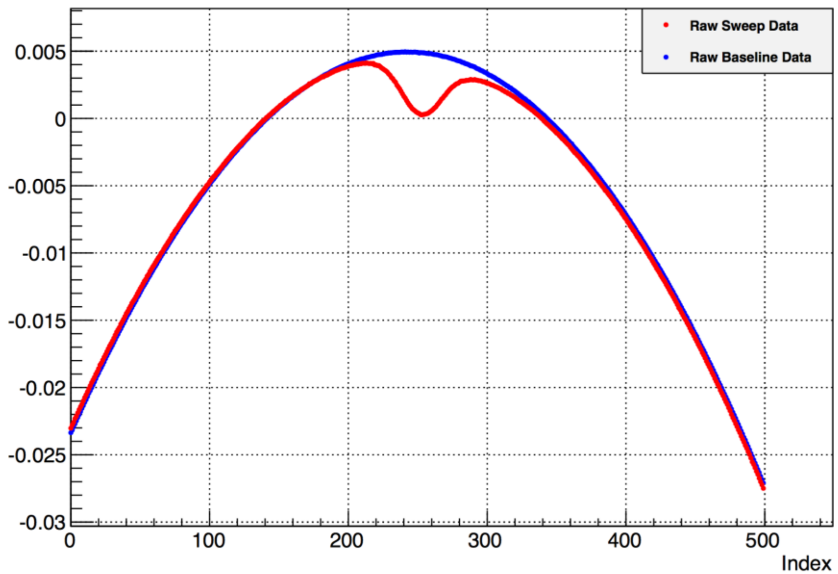
  - Large μ_e (~660μ_p) creates large electron polarization (~99% at 5T/1K)

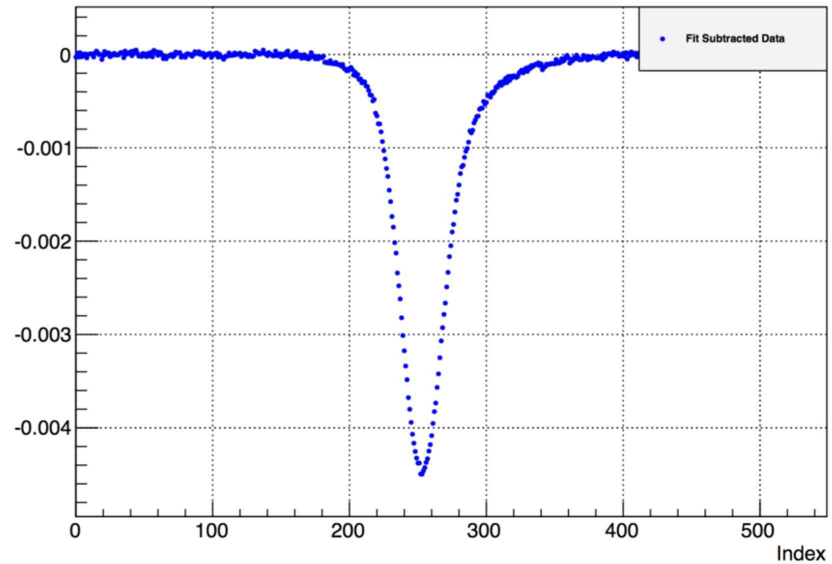
Enhancing initial polarization:

- 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

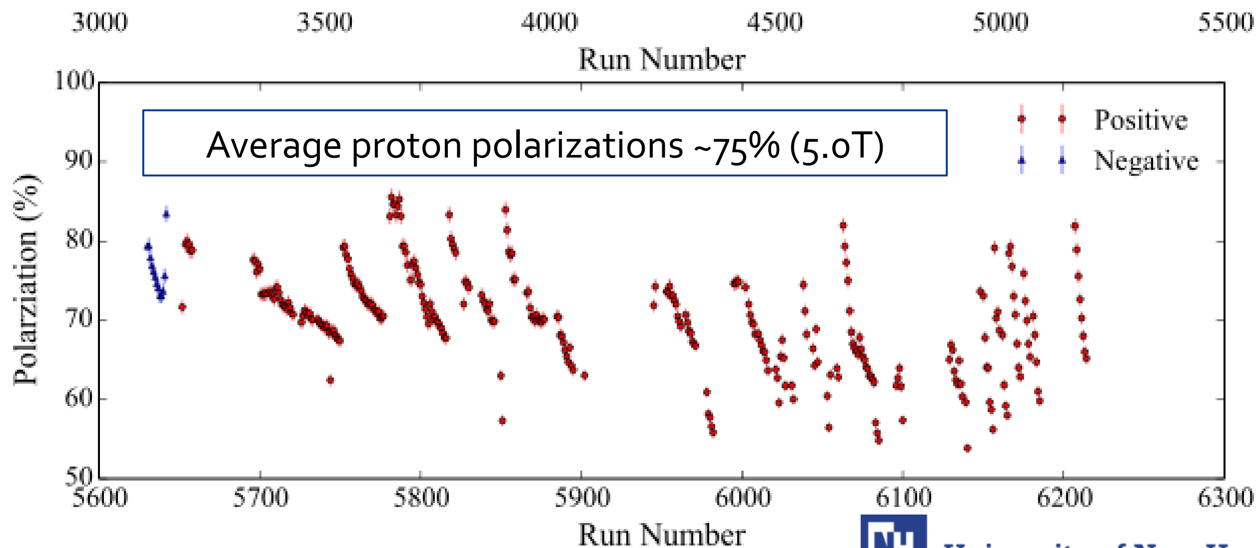


Proton Polarization Measured with Q-Meter





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



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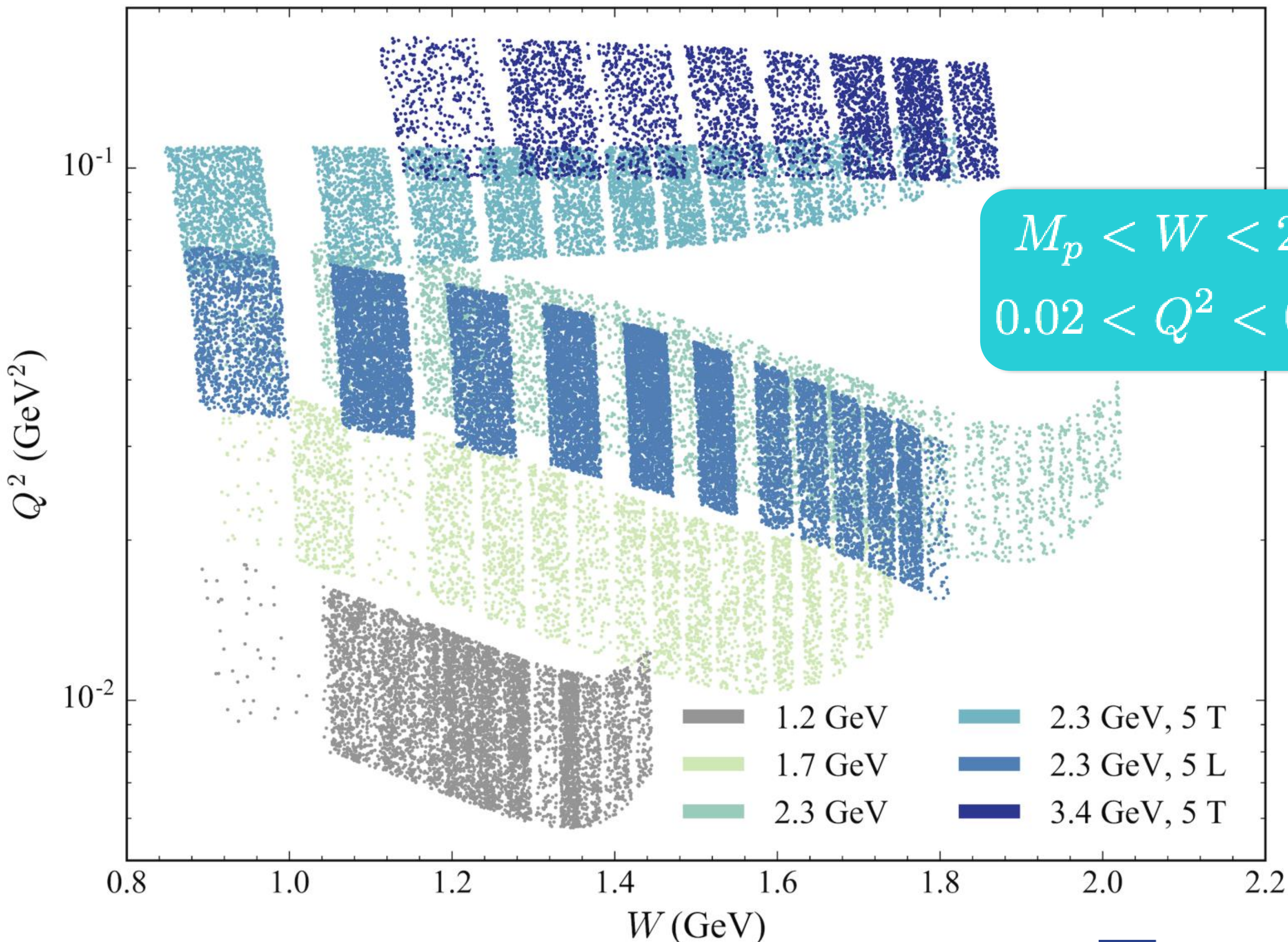
T. Badman (2013) TN #08: http://hallaweb.jlab.org/experiment/g2p/collaborators/toby/technotes/target.pdf

g_2p Kinematic Coverage



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

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

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.

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

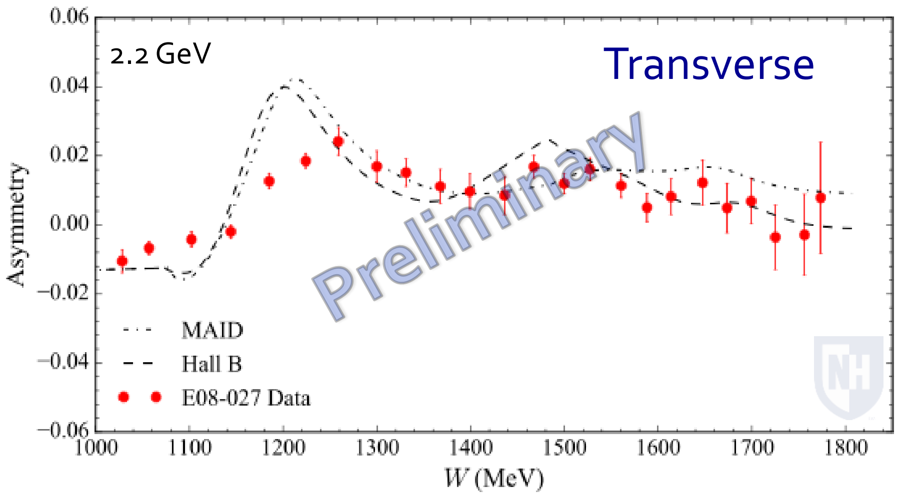
Similar equation for parallel polarized cross section

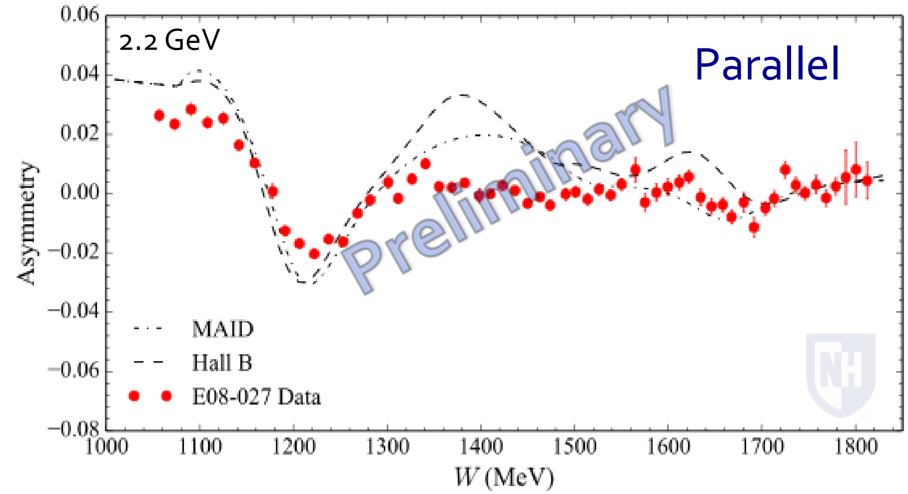
Why do it this way?

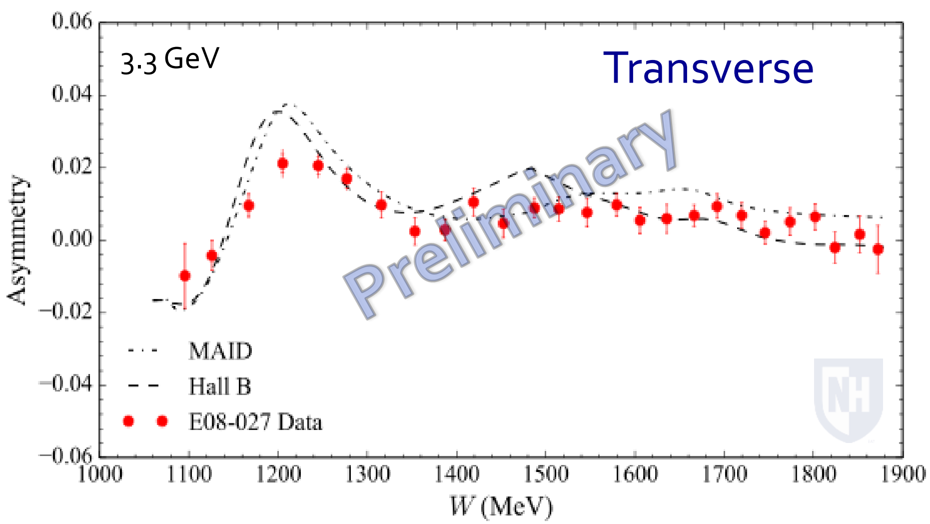
- Asymmetries are easy to measure
- Lots of data on unpolarized cross sections so models are a possibility

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

5T Proton Asymmetries







Raw Counts:

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

Measured Asymmetries:

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

Combine both HRS for best statistics!

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

dilution factor

beam/target pol

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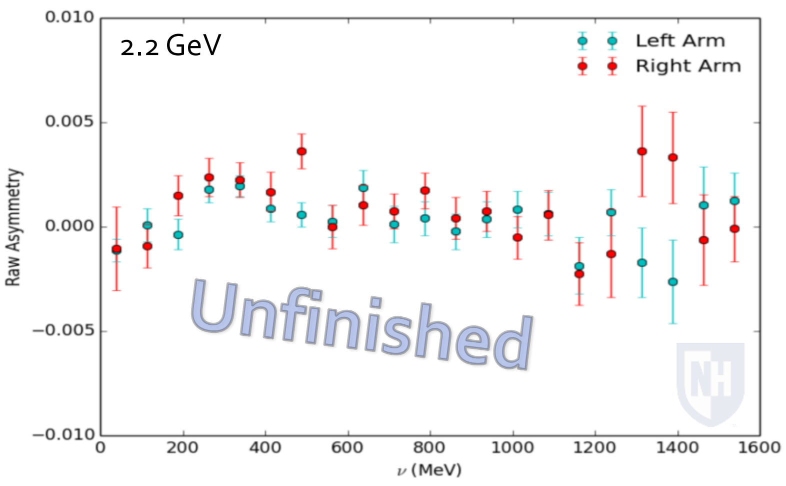
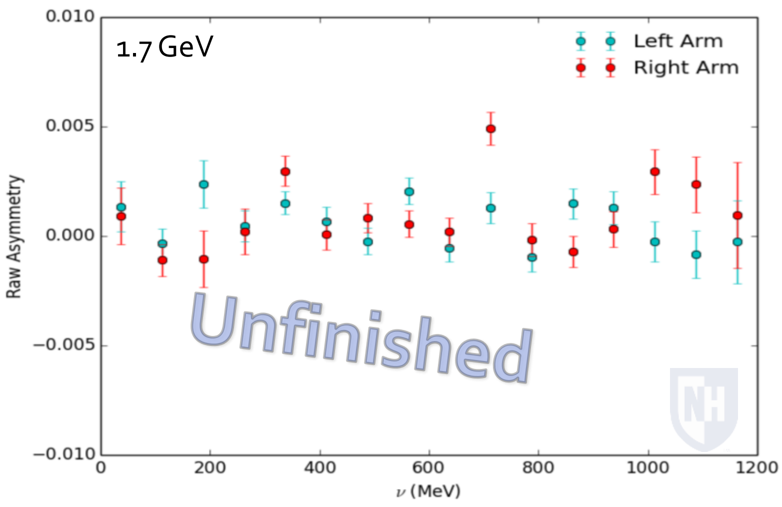
2.5T Proton Asymmetries

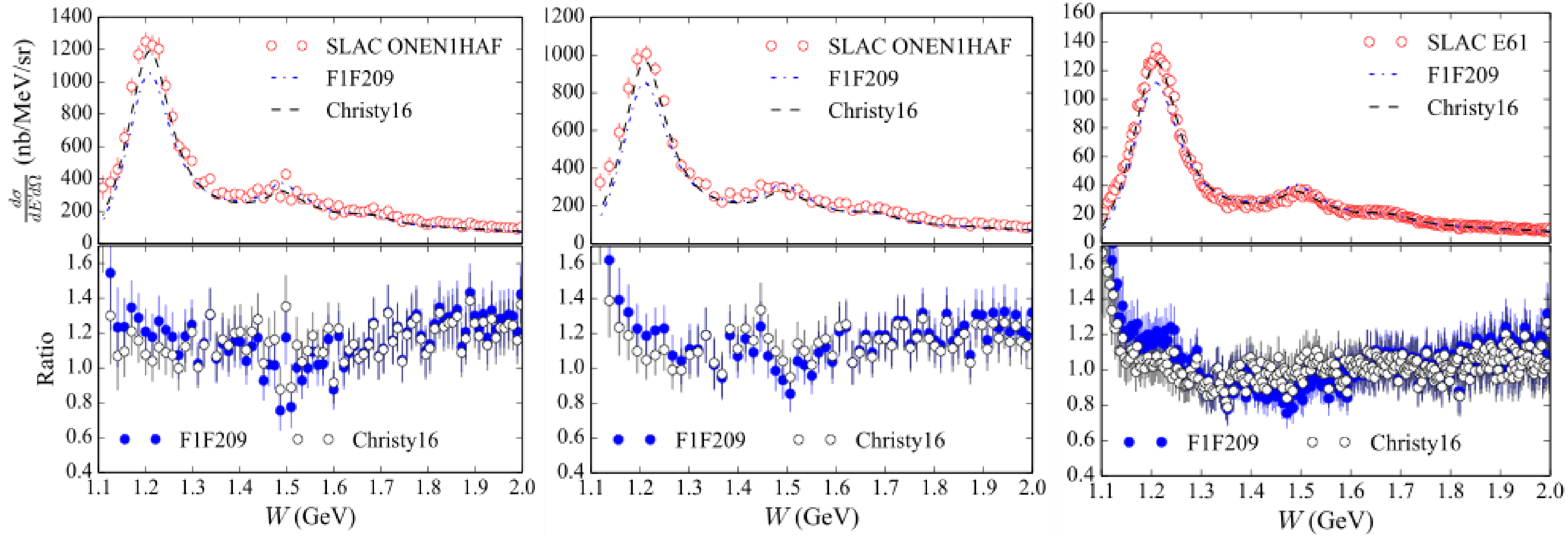


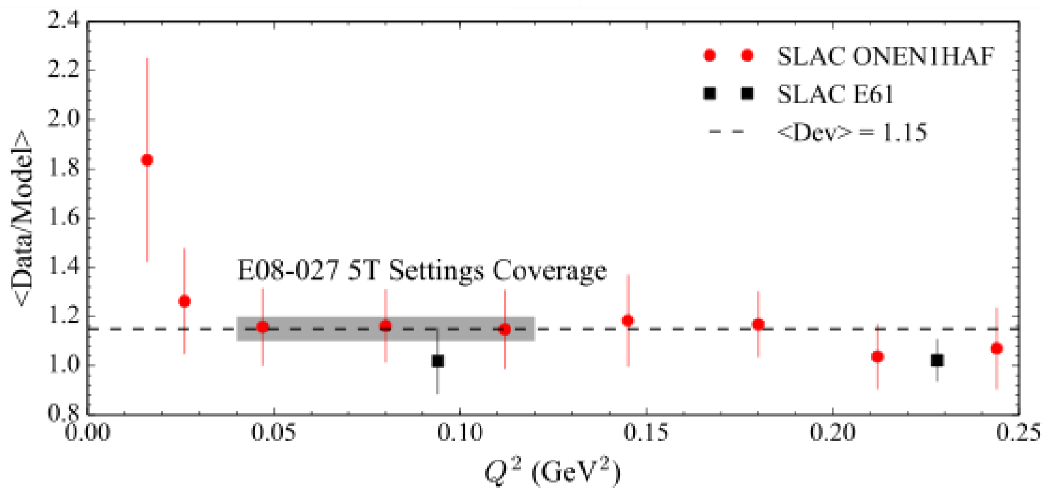


1.1 GeV data has large systematics that make it hard to work with.

2.5T Asymmetries show systematic shift in many places, working on resolving before data is usable

Model Cross Section





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

Acceptance Study

Acceptance study is on-going, we hope to be able to use data instead of model cross sections soon

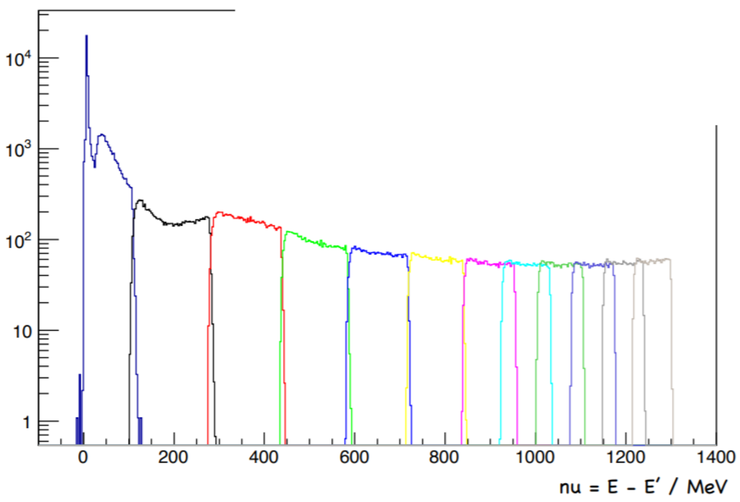
$$\sigma_0 = \frac{P_S N}{\frac{Q}{e}(\rho \Delta Z) T_L \epsilon_{\text{det}}} \frac{1}{\Delta\Omega \Delta E' A}$$

initial angle and momentum coverage in simulation ($\Delta\Omega \Delta E'$)

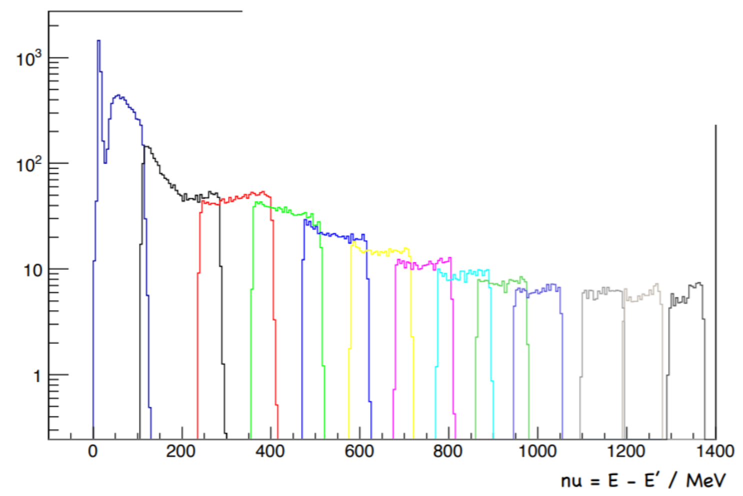
ratio of accepted events and total events (A)

Continuity on longitudinal spectrum for most recent acceptance is good, not as much on transverse

Longitudinal



Transverse



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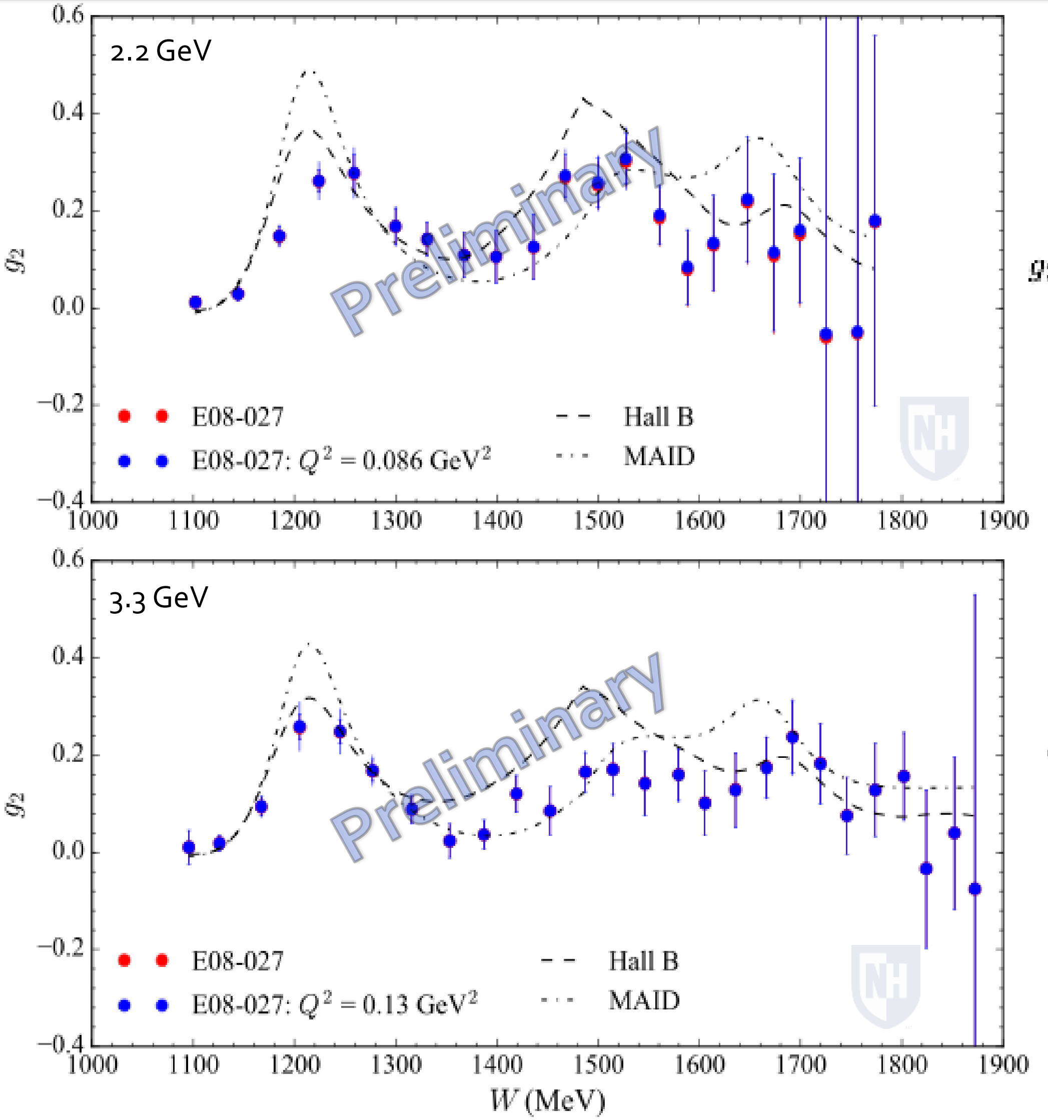
Extracting the Spin Structure Functions : g_2



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 *Q²*

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

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

Small effect at the transverse settings

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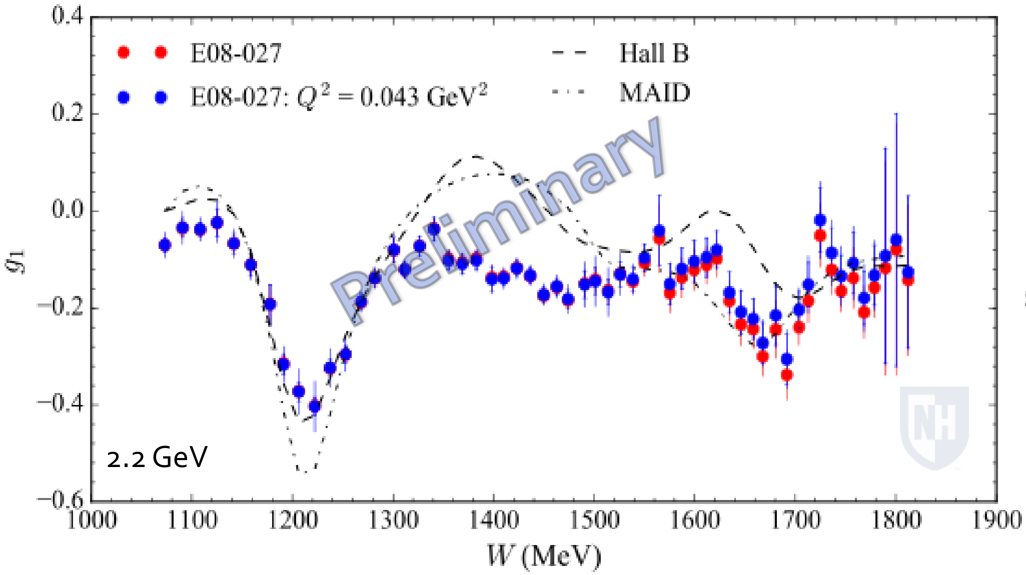
Extracting the Spin Structure Functions: g_1

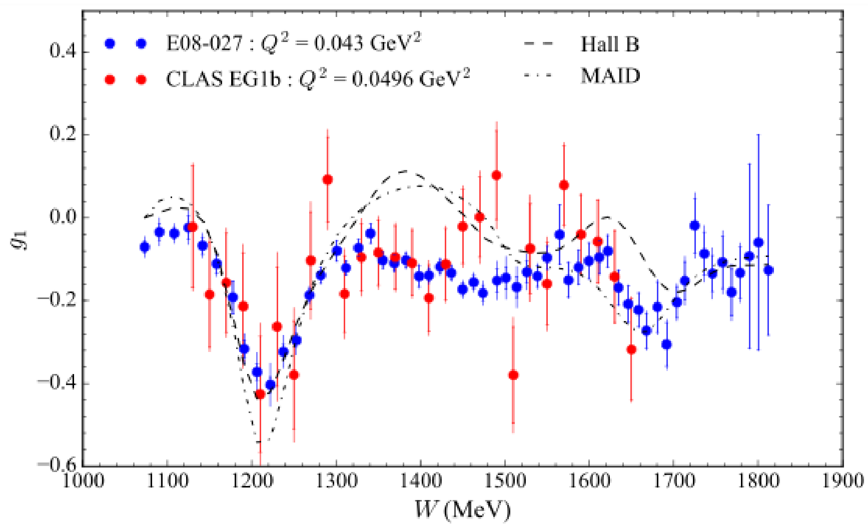


Model driven procedure for unmeasured part

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

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

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



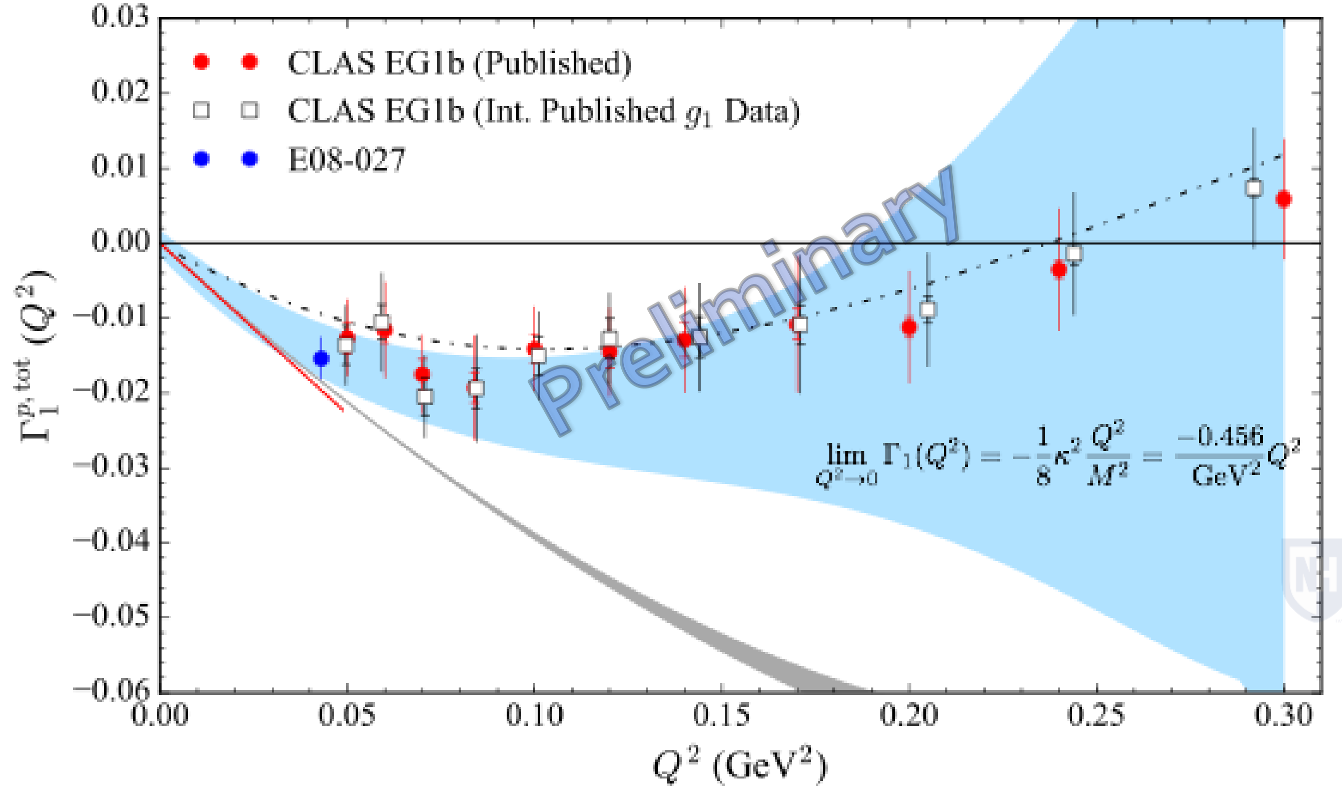
- E08-027 data is consistent with previously published data from CLAS
- But with much better statistics!!

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

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

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

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



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

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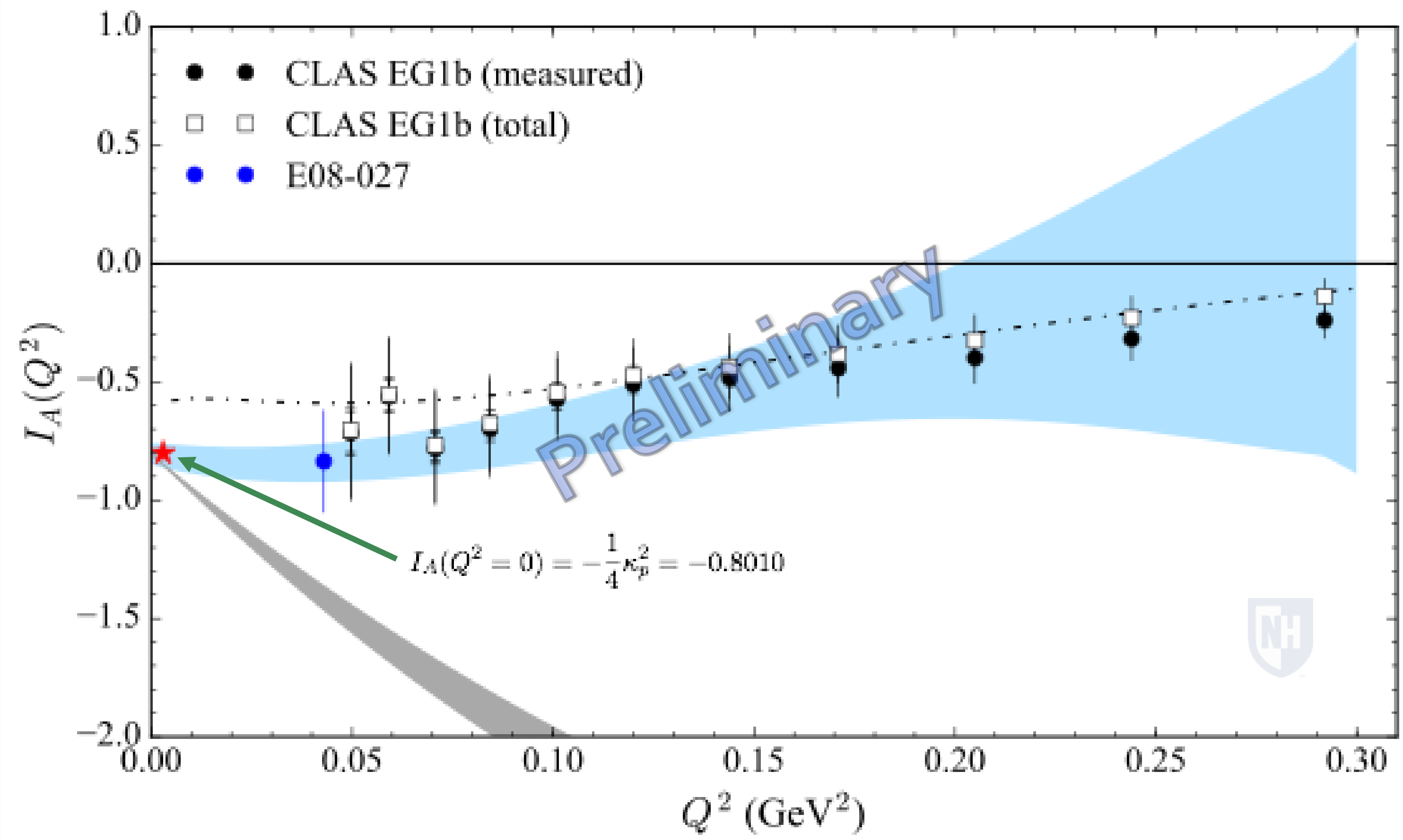
K.V. Dharmawardane (2006) *et al.* https://doi.org/10.1016/j.physletb.2006.08.011

Extended GDH Sum

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



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

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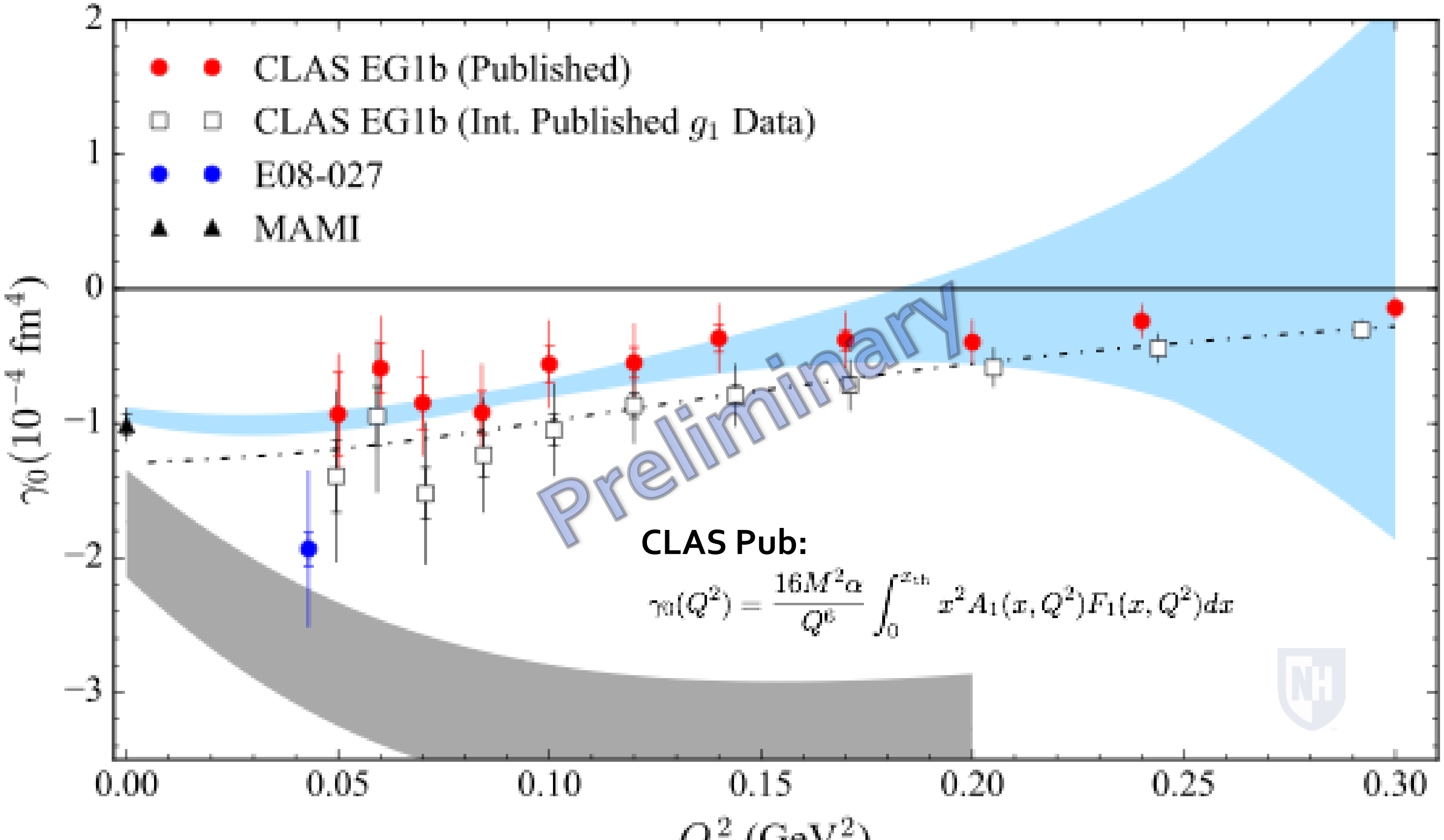
http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

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	$\gamma_0^{\mathrm{meas.}}$	$\gamma_0^{\mathrm{low}\ x}$	$\gamma_0^{\mathrm{tot.}}$	$\delta_{\mathrm{stat}}^{\mathrm{tot.}}$	$\delta_{\mathrm{sys}}^{\mathrm{tot.}}$
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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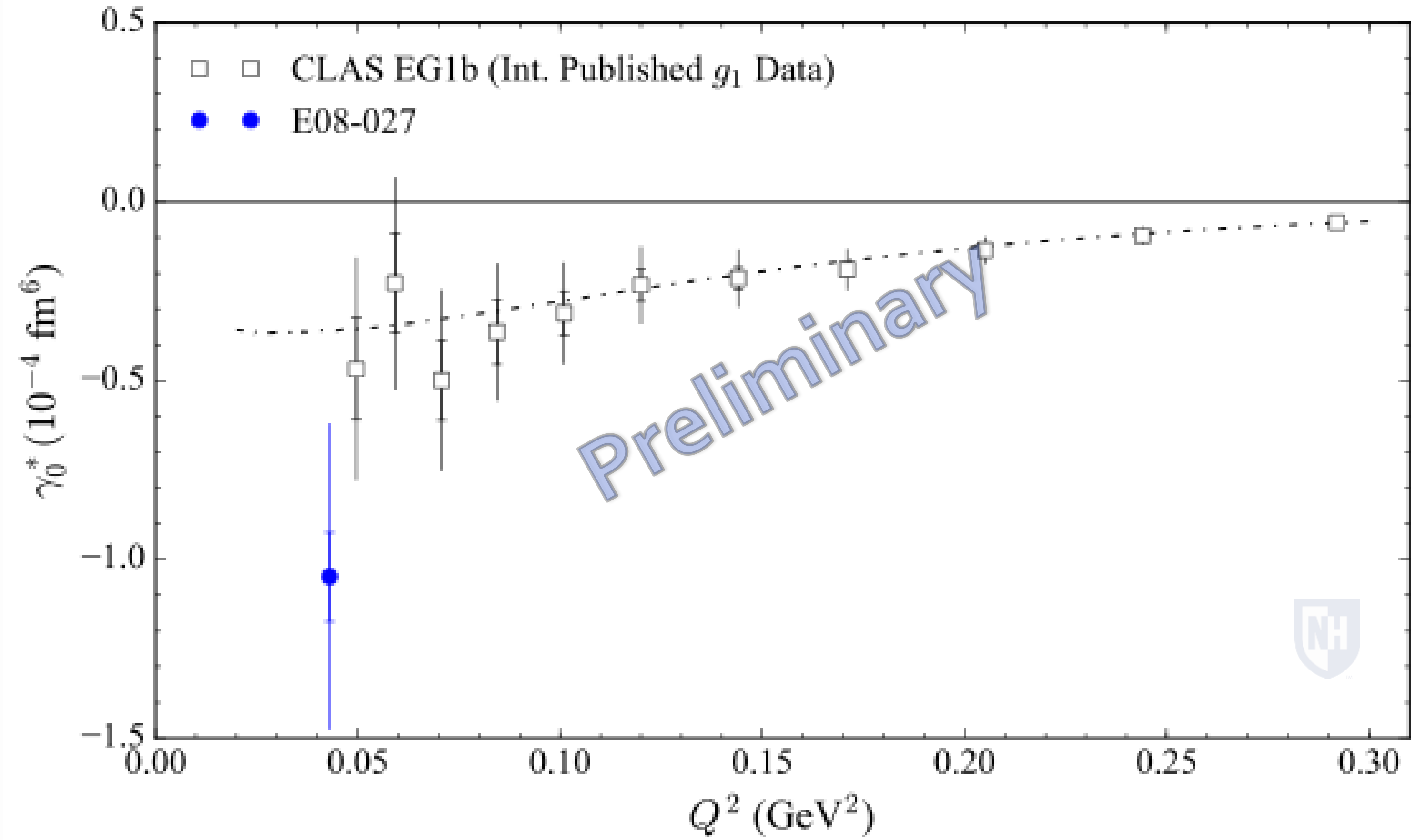
Y. Prok (2008) *et al.* 10.1016/j.physletb.2008.12.063 H. Dutz (2003) *et al.* doi.org/10.1103/PhysRevLett.91.192001

Higher Order Polarizability

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



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

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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.
- 5T Data Analysis is complete, 2.5T Analysis is ongoing. We hope to have publishable data at both the 2.2 GeV and 1.7 GeV energy levels at this target field.
- Acceptance study is on-going, to allow us to use experimental unpolarized cross sections.
- Packing fraction/dilution analysis also complete for 5T data, but may need more investigation for 2.5T data.

Acknowledgements

g2p Analysis Team

Spokespeople:
Alexandre Camsonne
JP Chen
Don Crabb
Karl Slifer

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Chao Gu
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Pengjia Zhu
Ryan Zielinski

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