University of New Hampshire
Nuclear & Particle Physics Group

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

David Ruth

Hall A Collaboration Meeting

July 9, 2021

Essential Quantities in *ep* Scattering

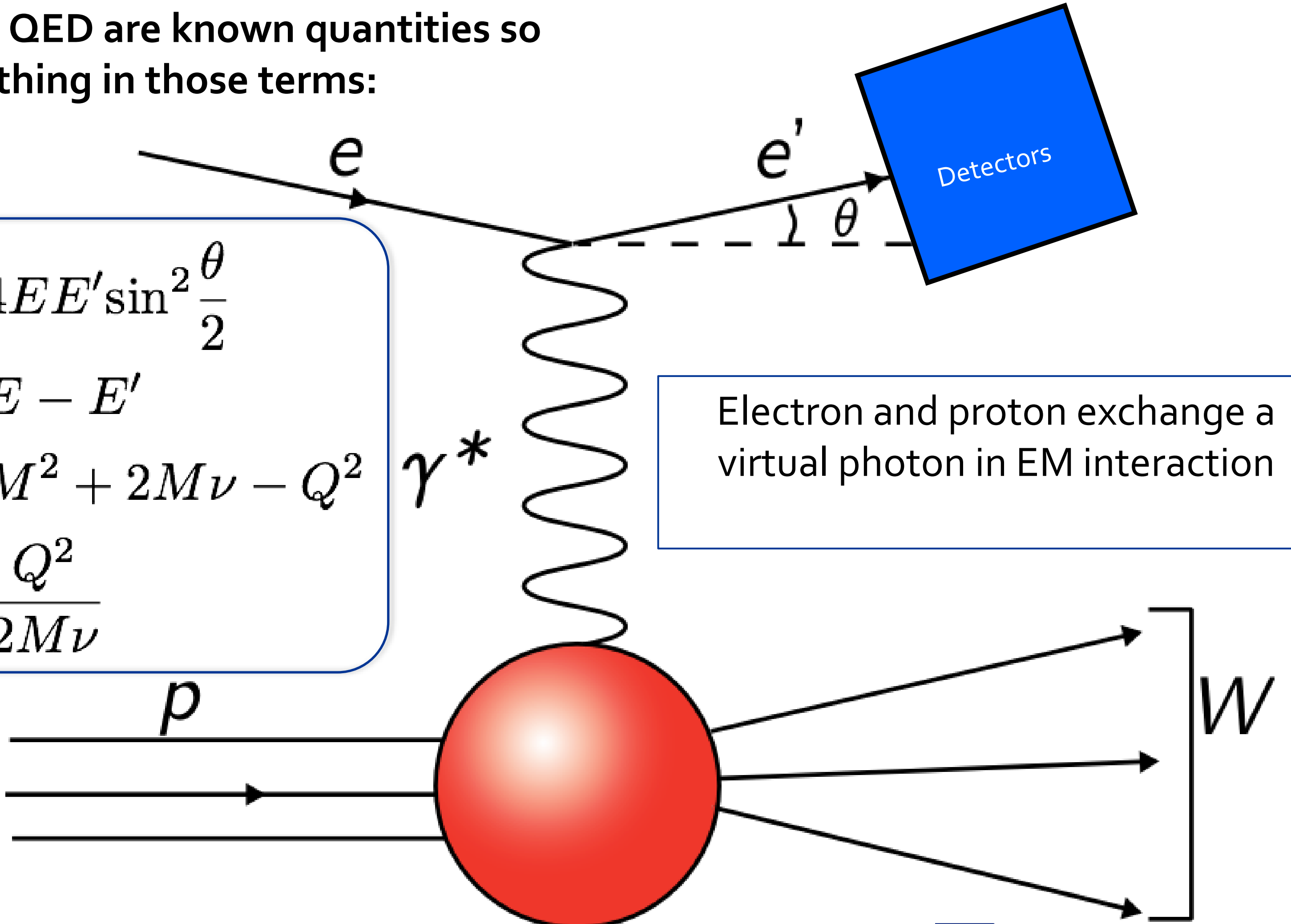
Electron and QED are known quantities so define everything in those terms:

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

$$\nu = E - E'$$

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

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



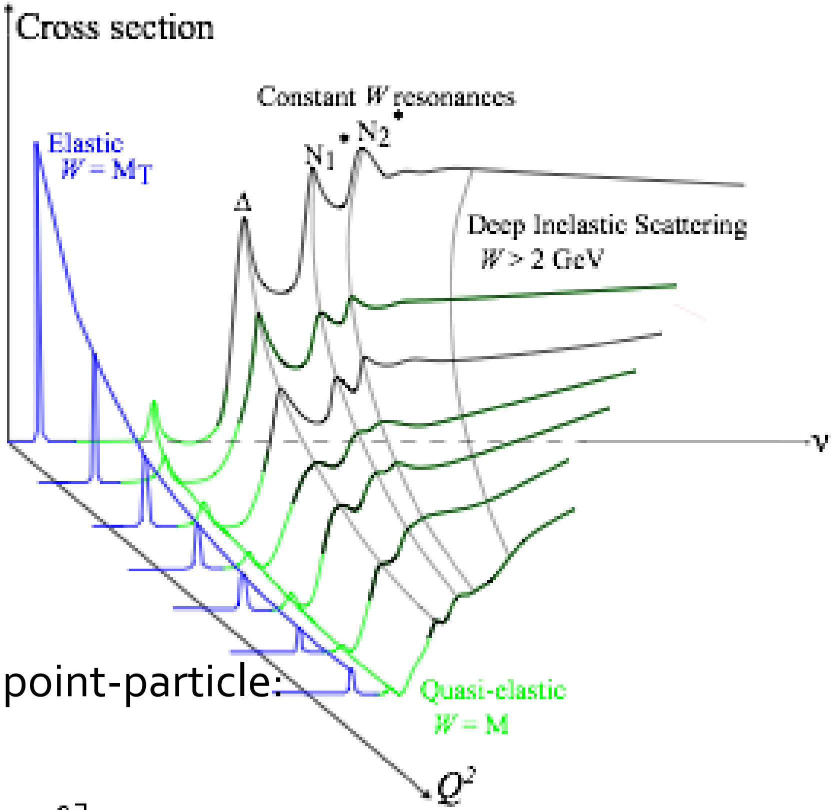
Inclusive *ep* Scattering Cross Sections describe normalized interaction rate

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

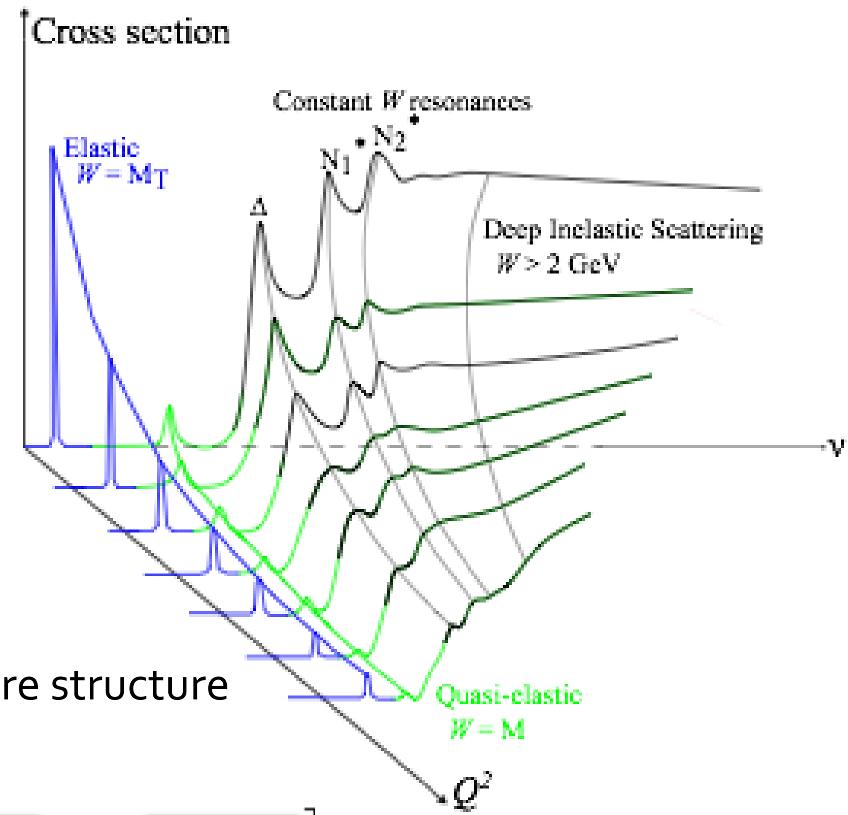
Inelastic scattering: Target is in excited state after interaction

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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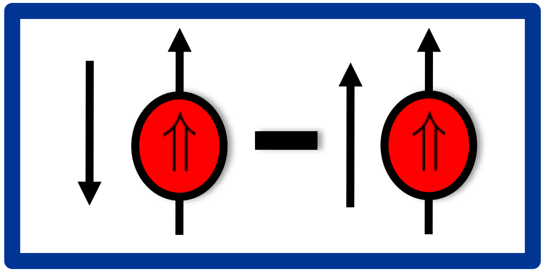
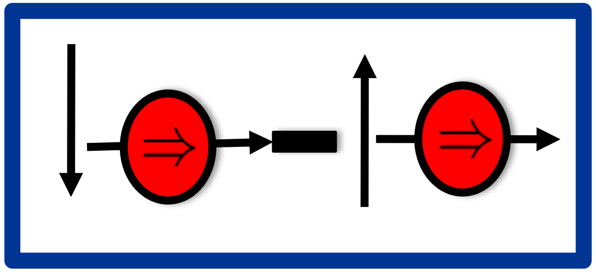
Extracting Spin Structure by Looking at Cross Section Differences



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



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

Perpendicular

Two equations, two unknowns…

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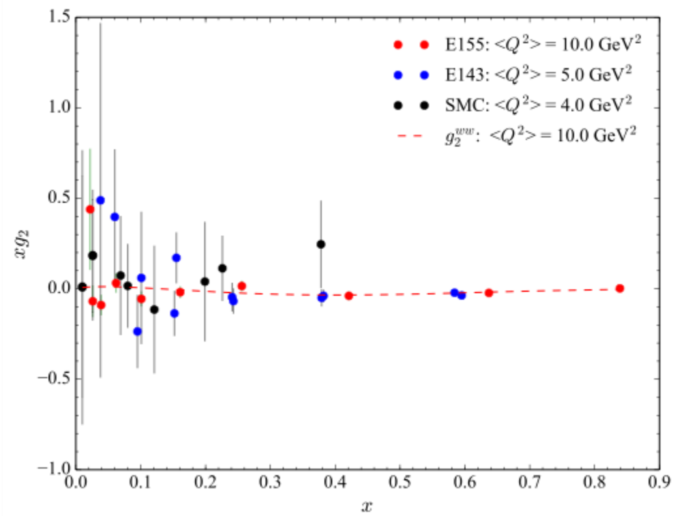
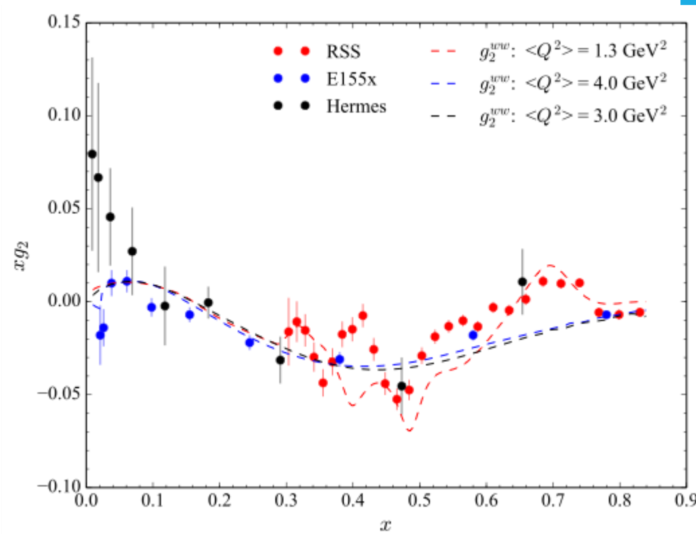
Motivation: Measure a fundamental spin observable (g_2) in the region $0.02 < Q^2 < 0.20$ GeV^2 for the first time

- 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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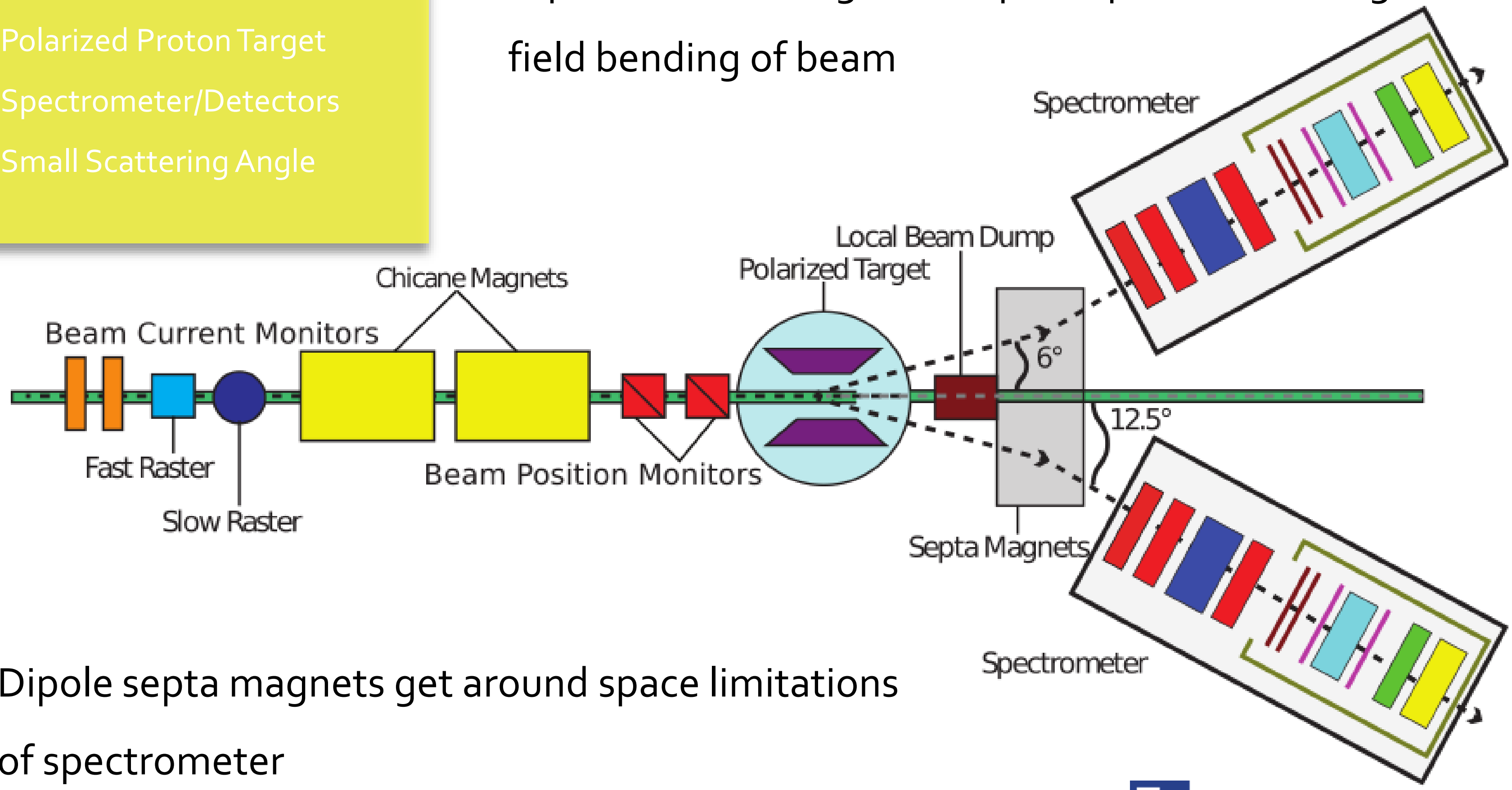
Hall A Experimental Setup:

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

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Polarized Protons Created with Dynamic Nuclear Polarization (DNP)

Creating initial polarization:

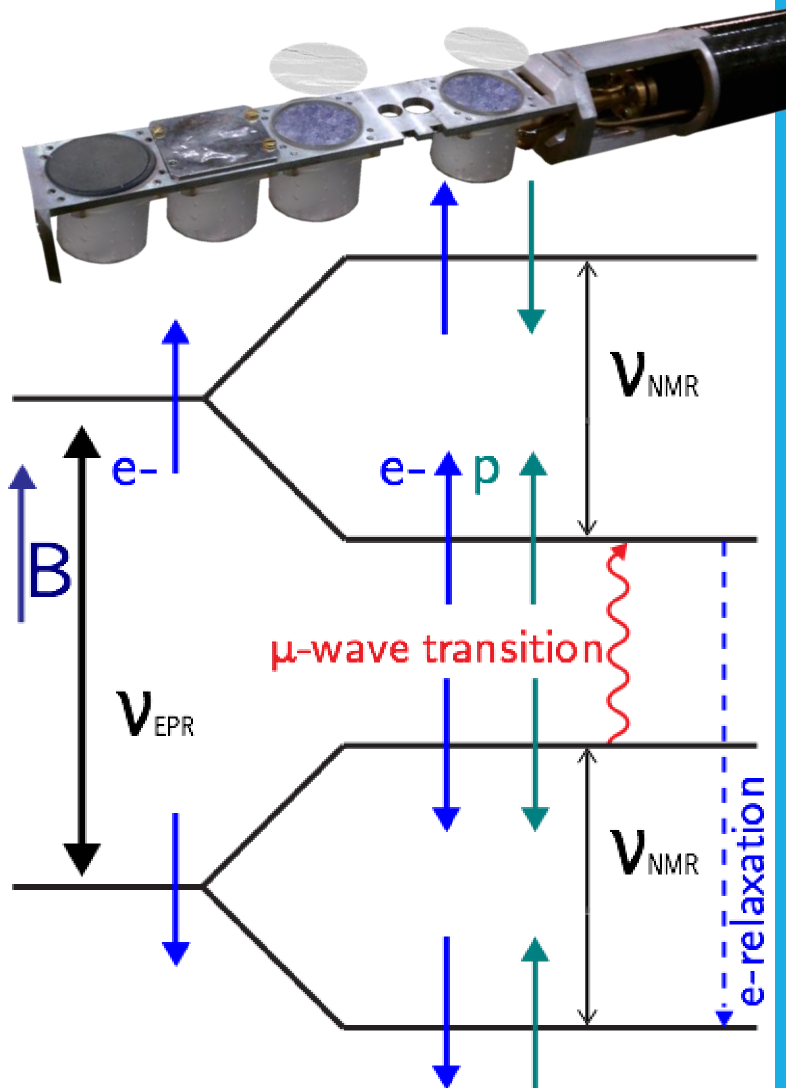
- Align spins in large B and low T
  - 5.0 T/ 2.5 T @ 1 K

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

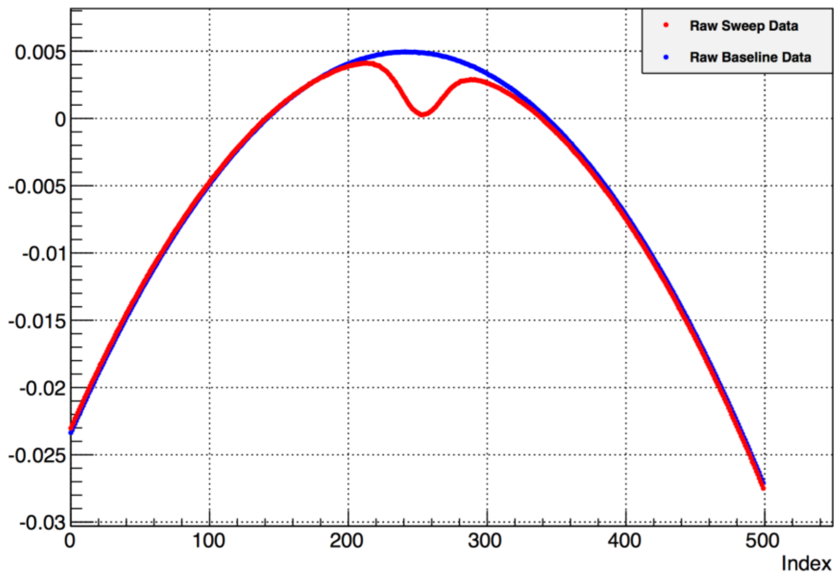
- Large μ_e (~660μ_p) creates large electron polarization (~99% at 5T/1K)

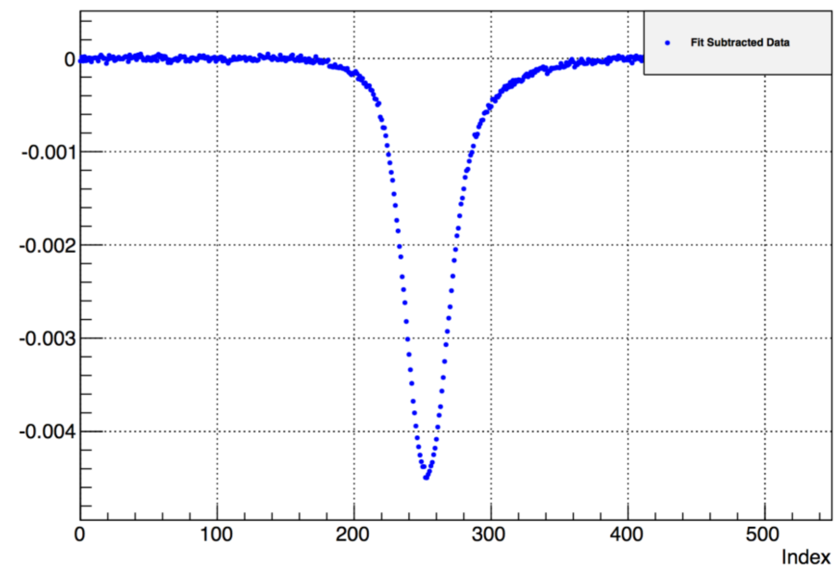
Enhancing initial polarization:

- 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

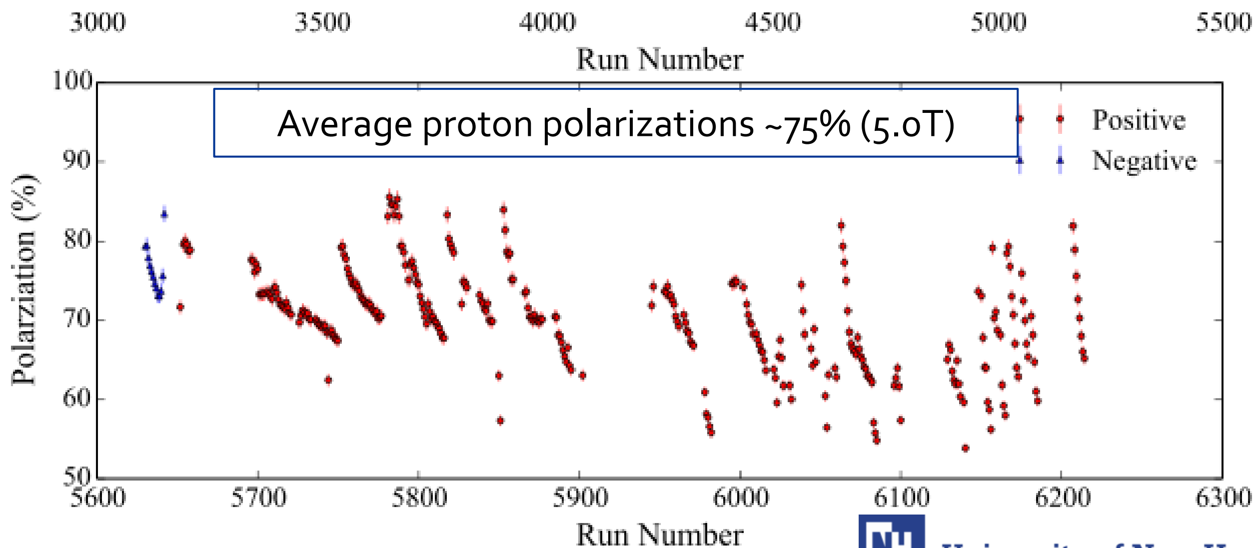


Proton Polarization Measured with Q-Meter





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



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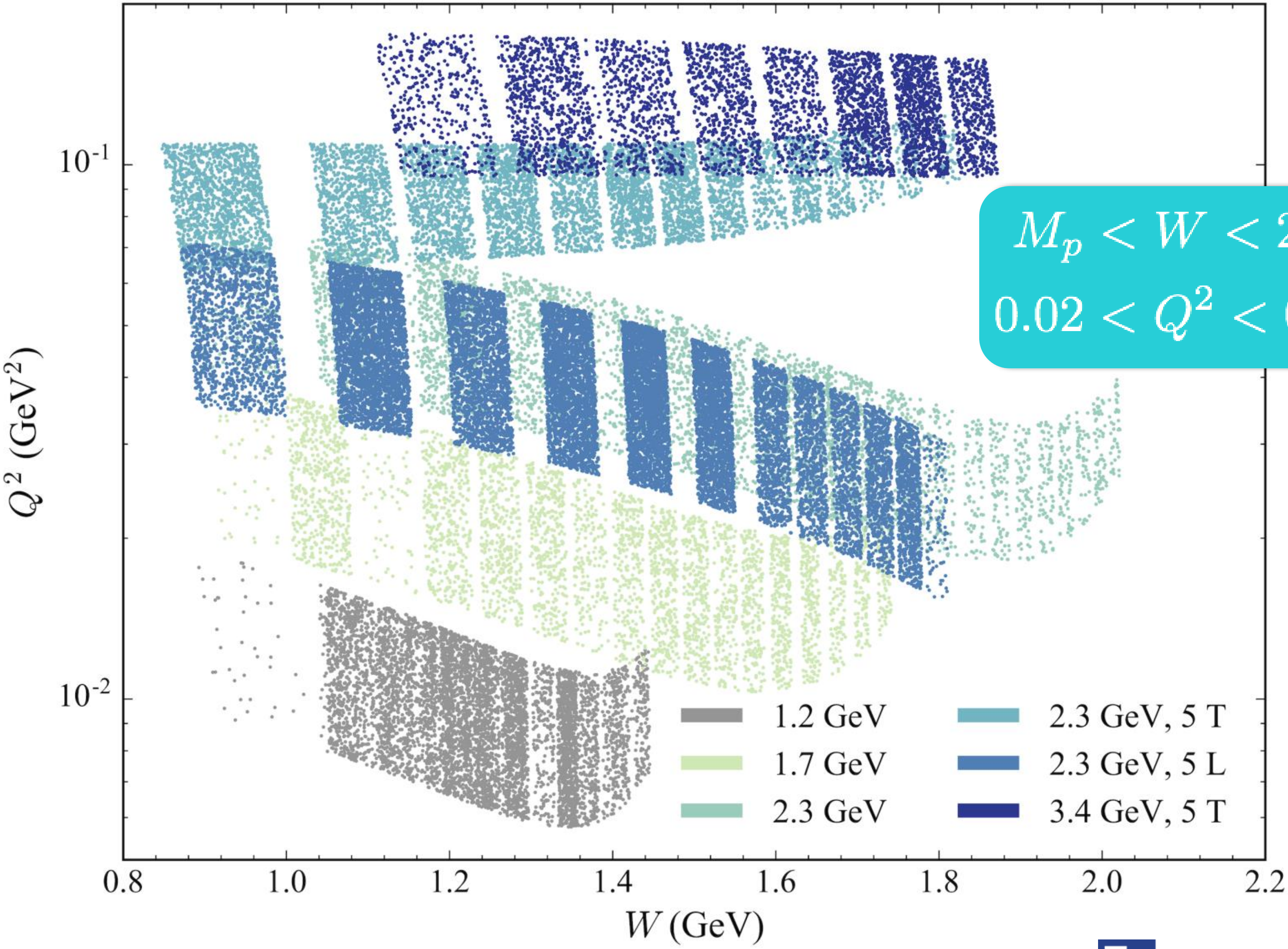
T. Badman (2013) TN #08: http://hallaweb.jlab.org/experiment/g2p/collaborators/toby/technotes/target.pdf

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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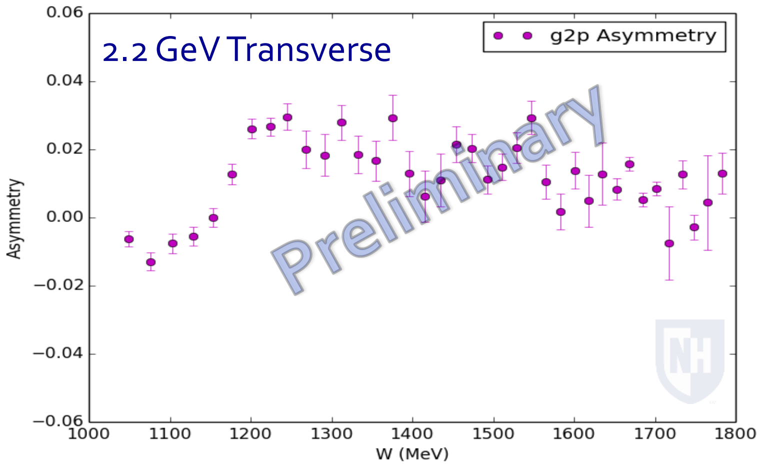
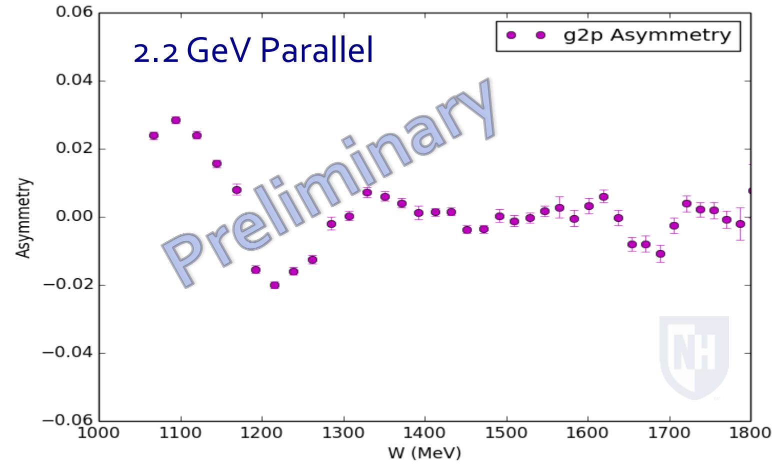
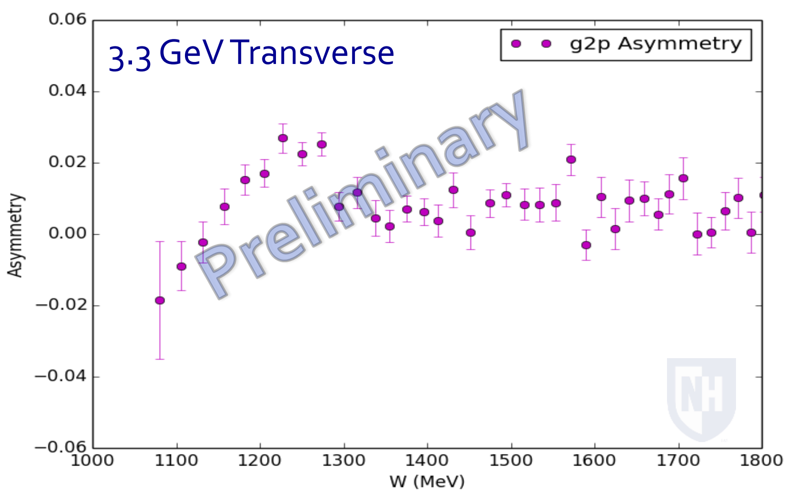
5T Proton Asymmetries







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

beam/target pol

Combine both HRS for best statistics!

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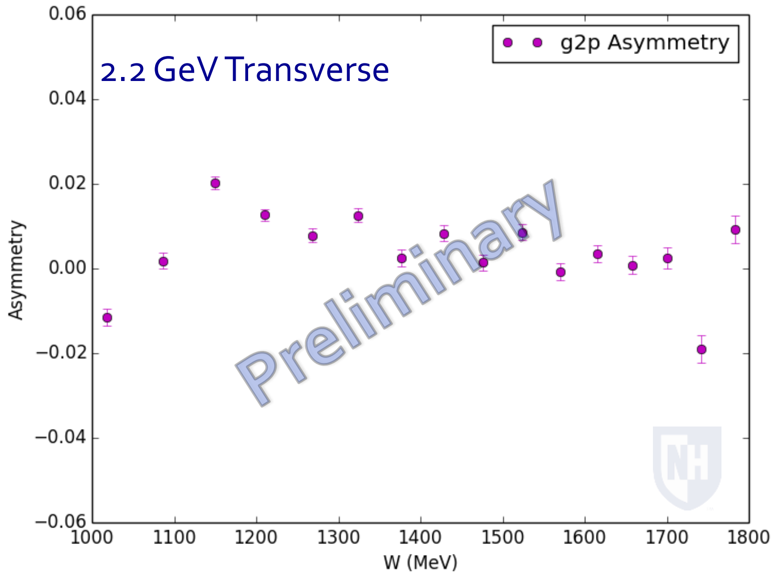
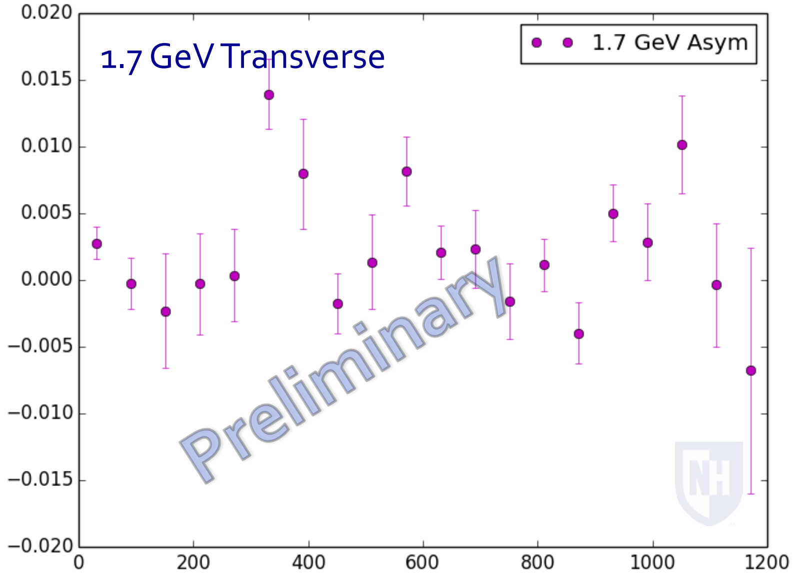
2.5T Proton Asymmetries





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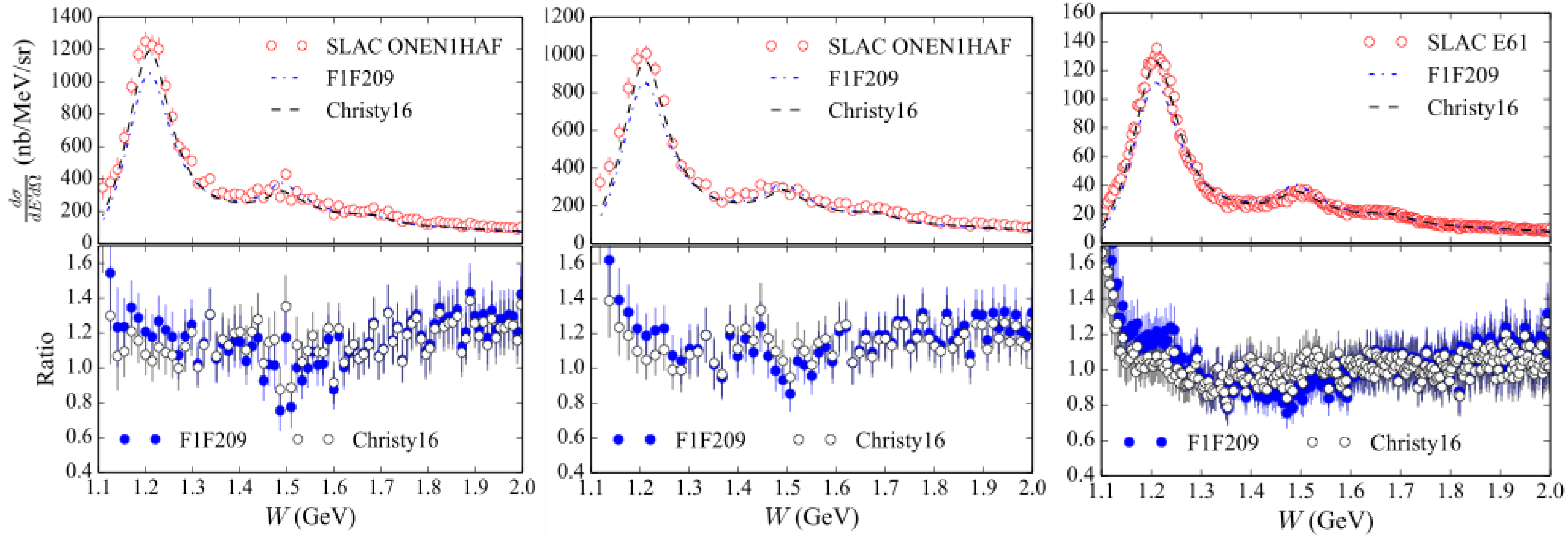
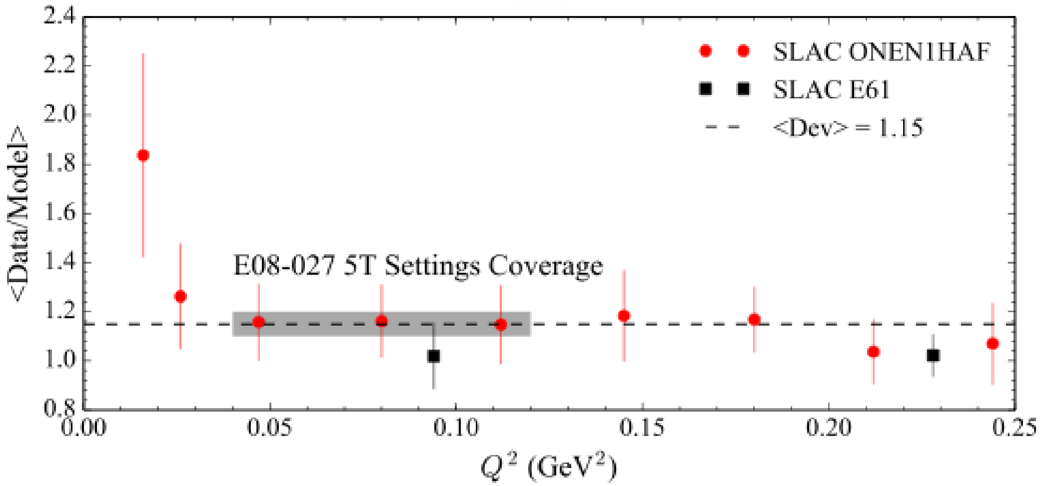
Model Cross Section





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

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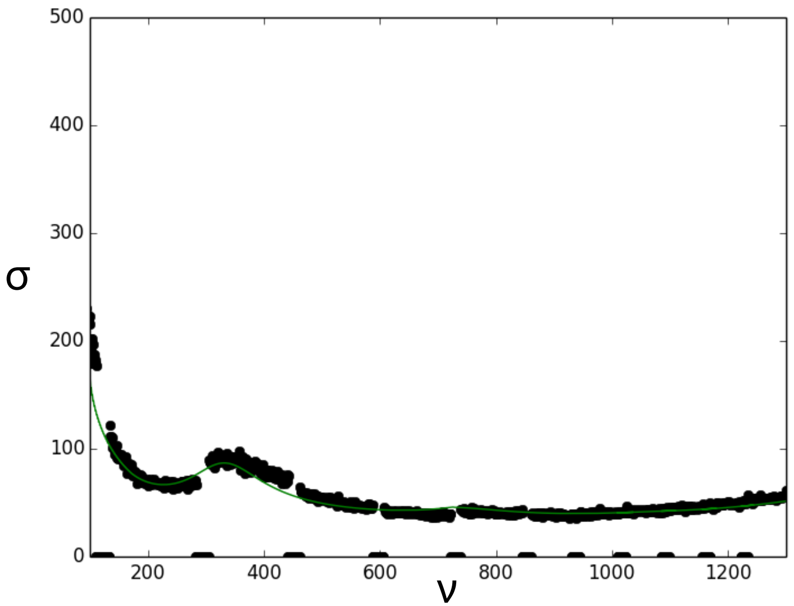
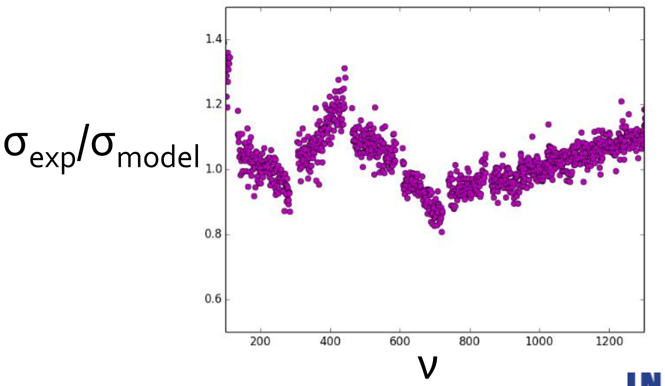
Model Cross Section

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

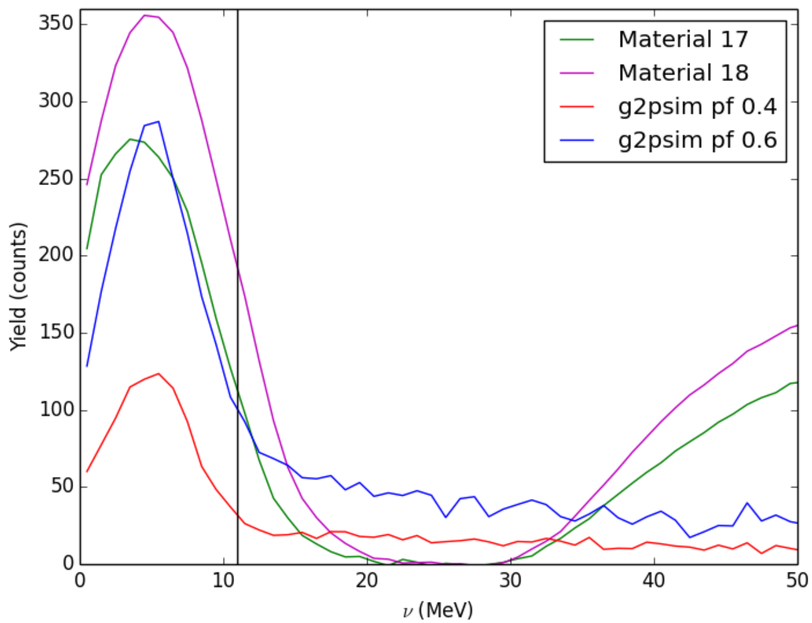


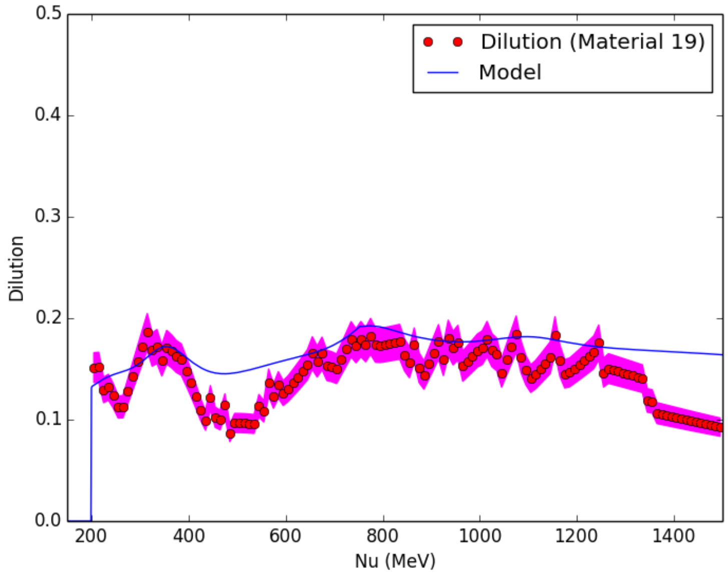


Packing Fraction & Dilution Analysis

- 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





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Extracting the Spin Structure Functions

Model driven procedure for unmeasured part

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

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

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

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

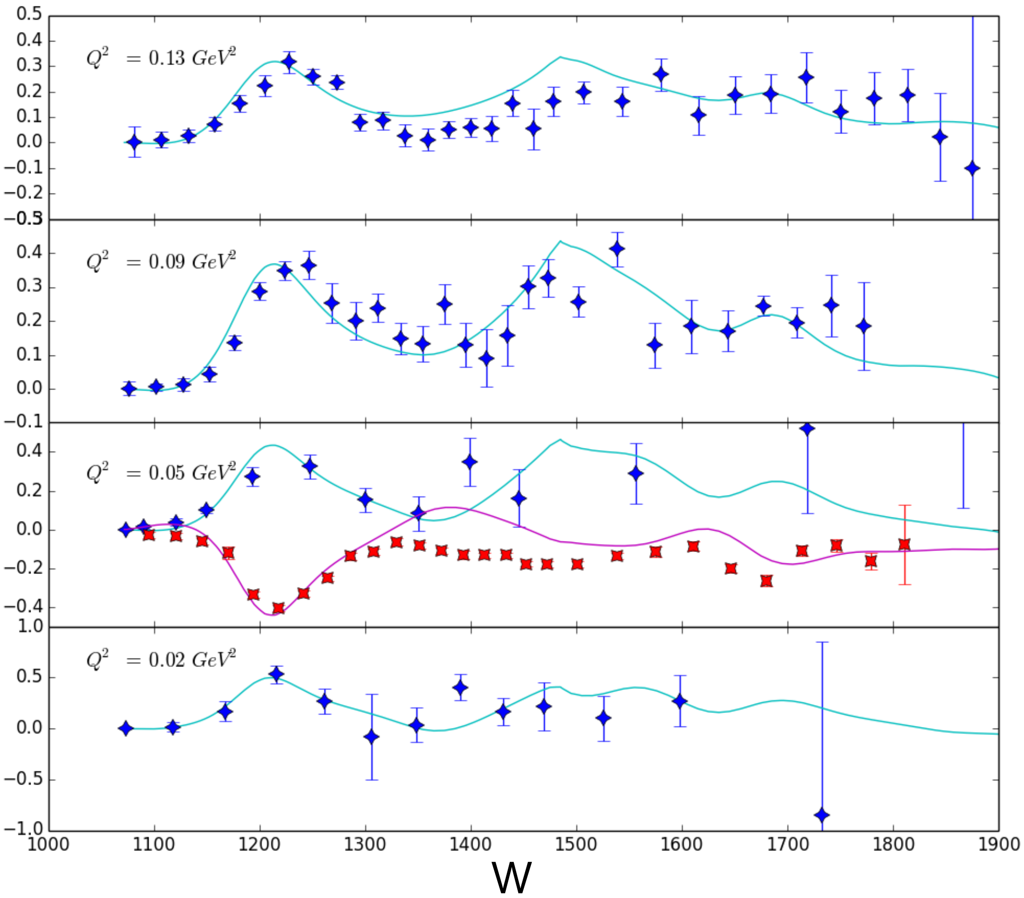
$$g_1(x,Q^2) = K_1\left[\Delta\sigma_{\|}\left(1 + \frac{1}{K_2}\tan\frac{\theta}{2}\right)\right] + \frac{2g_2(x,Q^2)}{K_2 y}\tan\frac{\theta}{2}$$

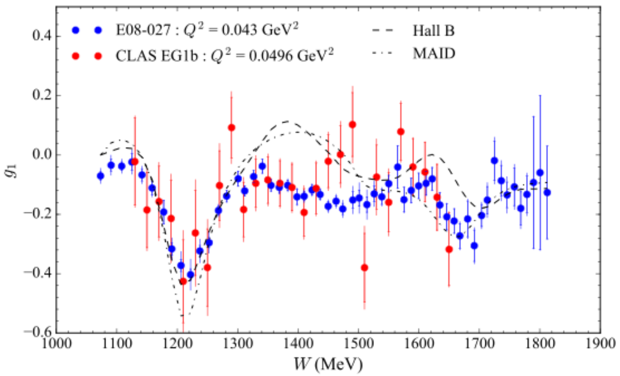
$$K_1 = \frac{MQ^2}{4\alpha}\frac{y}{(1-y)(2-y)}$$

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

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!!

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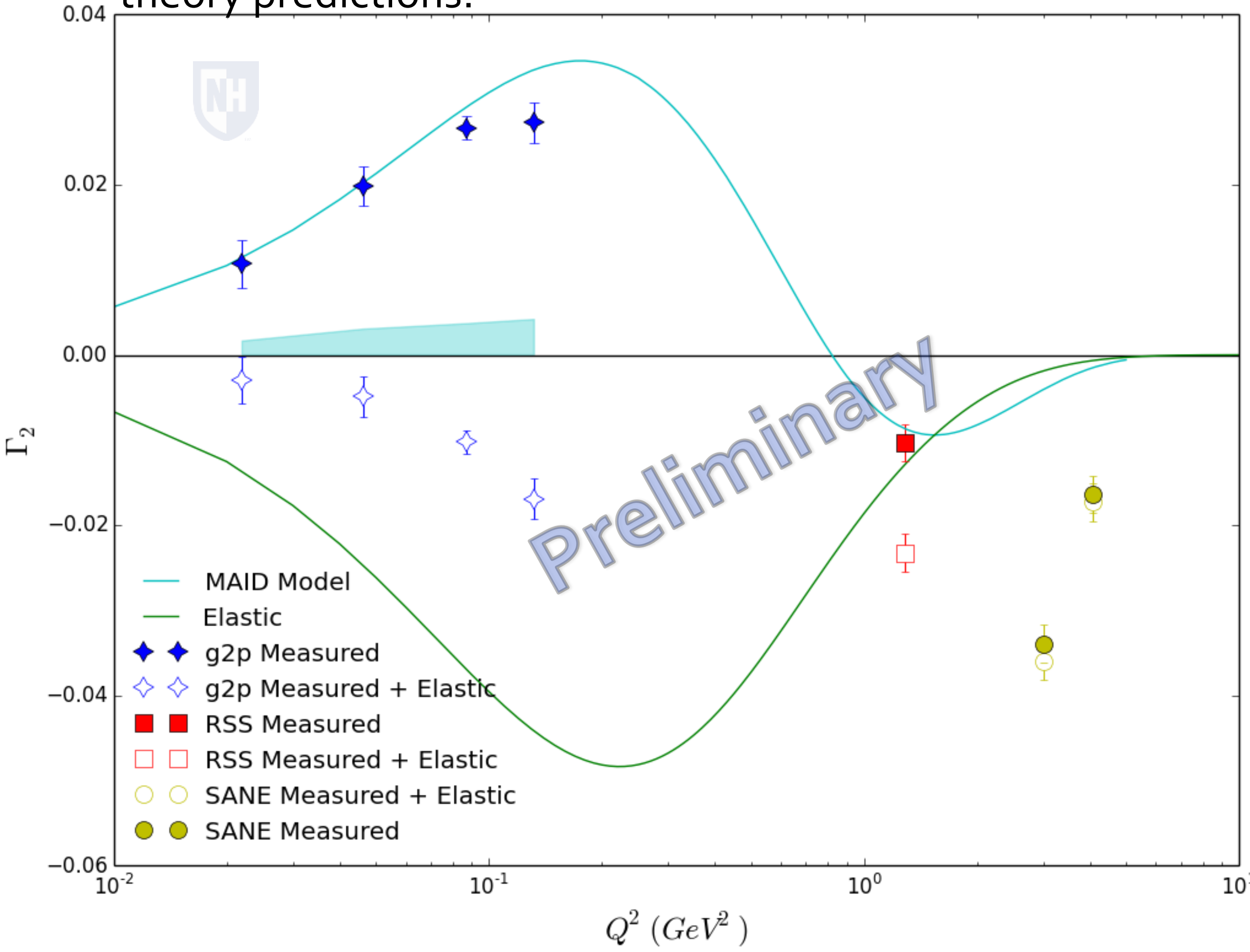
First Moment of $g_2(x,Q^2)$

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

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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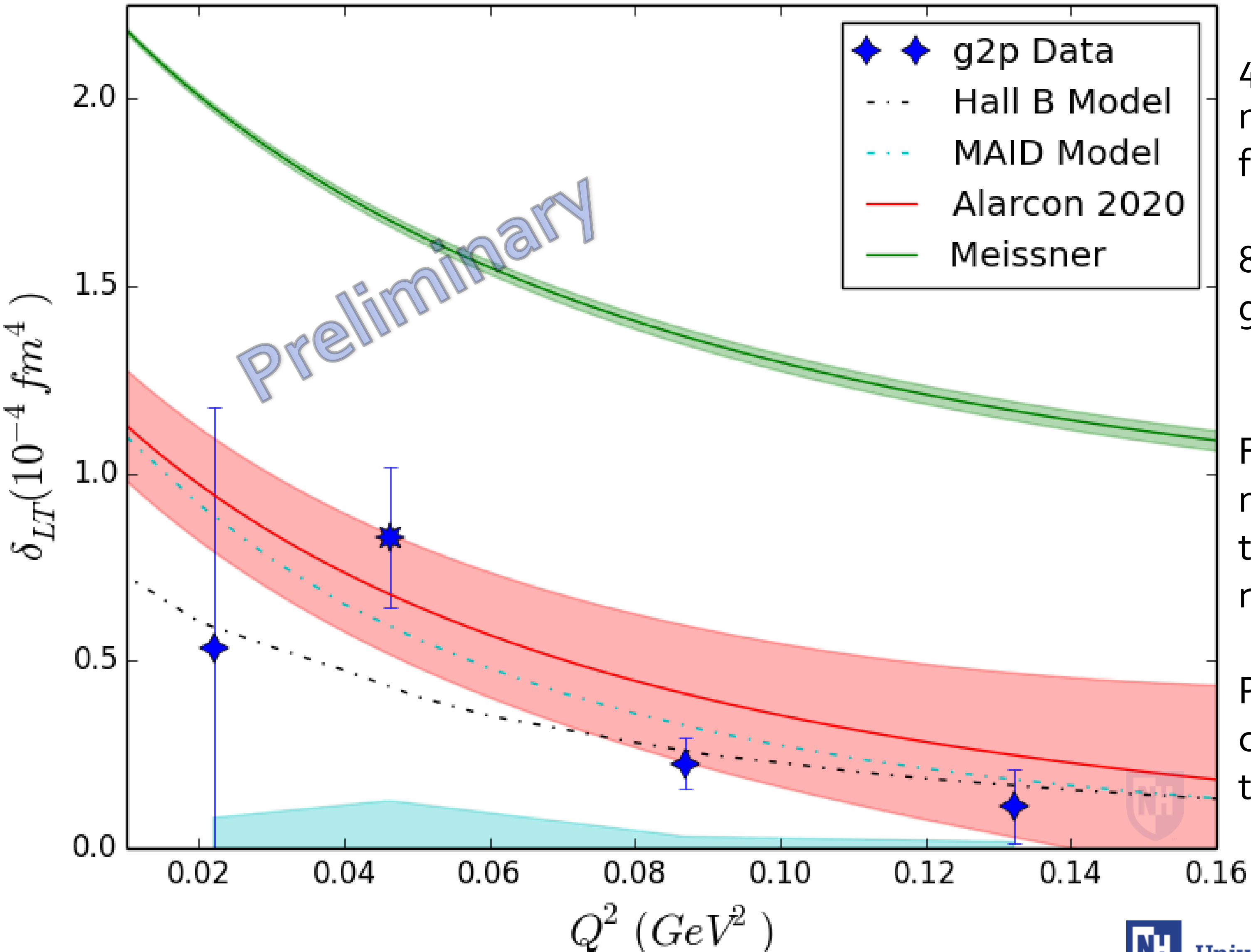
Transverse-Longitudinal Spin Polarizability

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



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

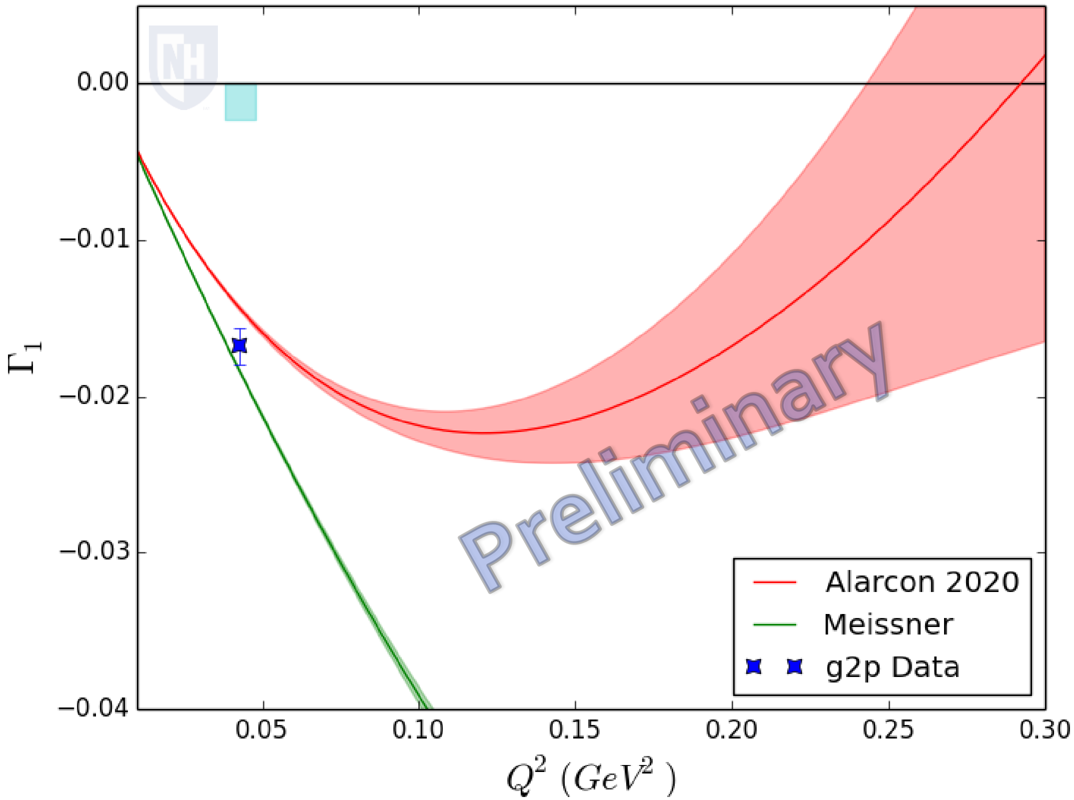
8 pt star – g1 and g2 both measured

First ever measurement of this quantity in this region!

Possible test of chiral perturbation theory

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

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



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

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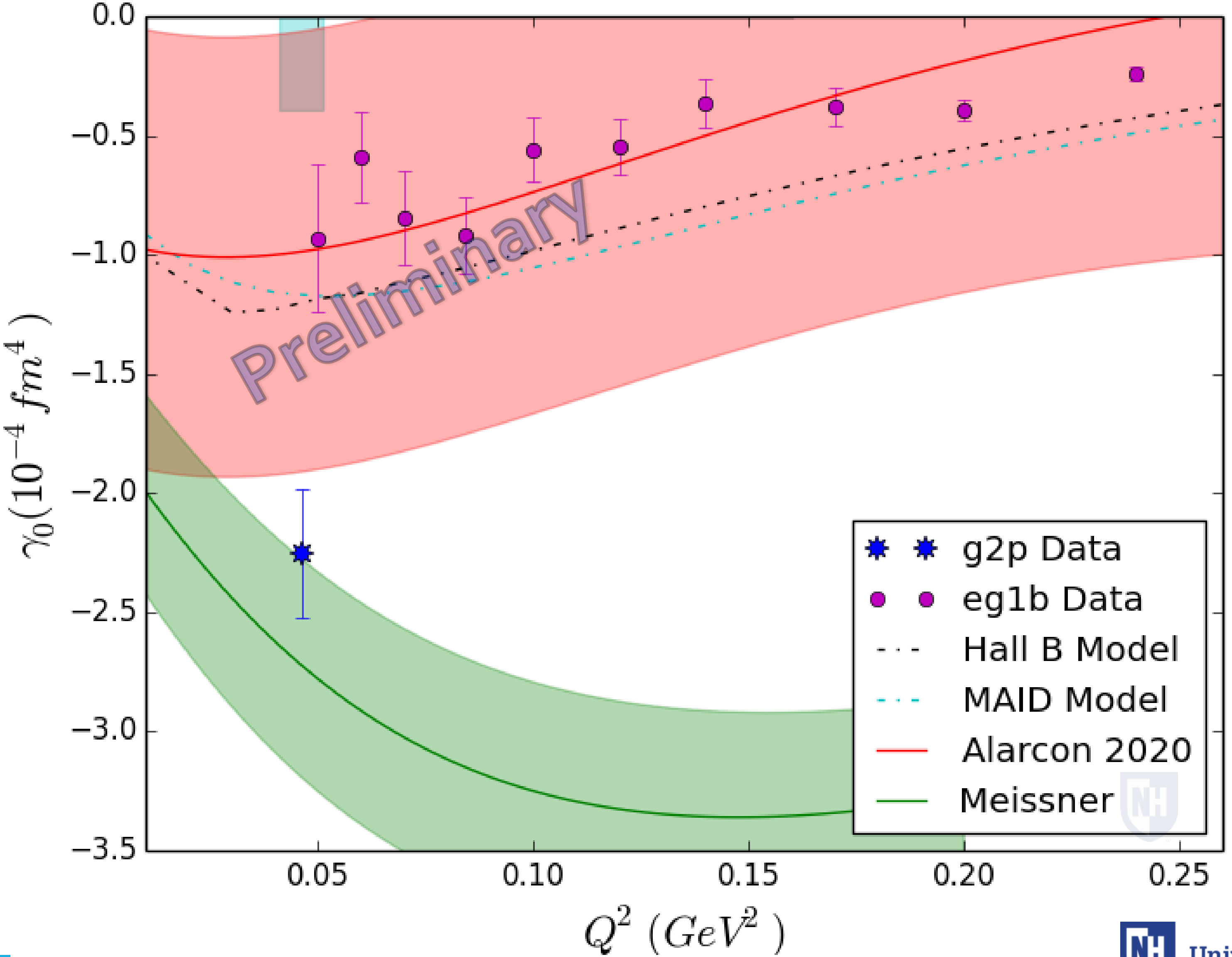
Generalized Forward Spin Polarizability

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



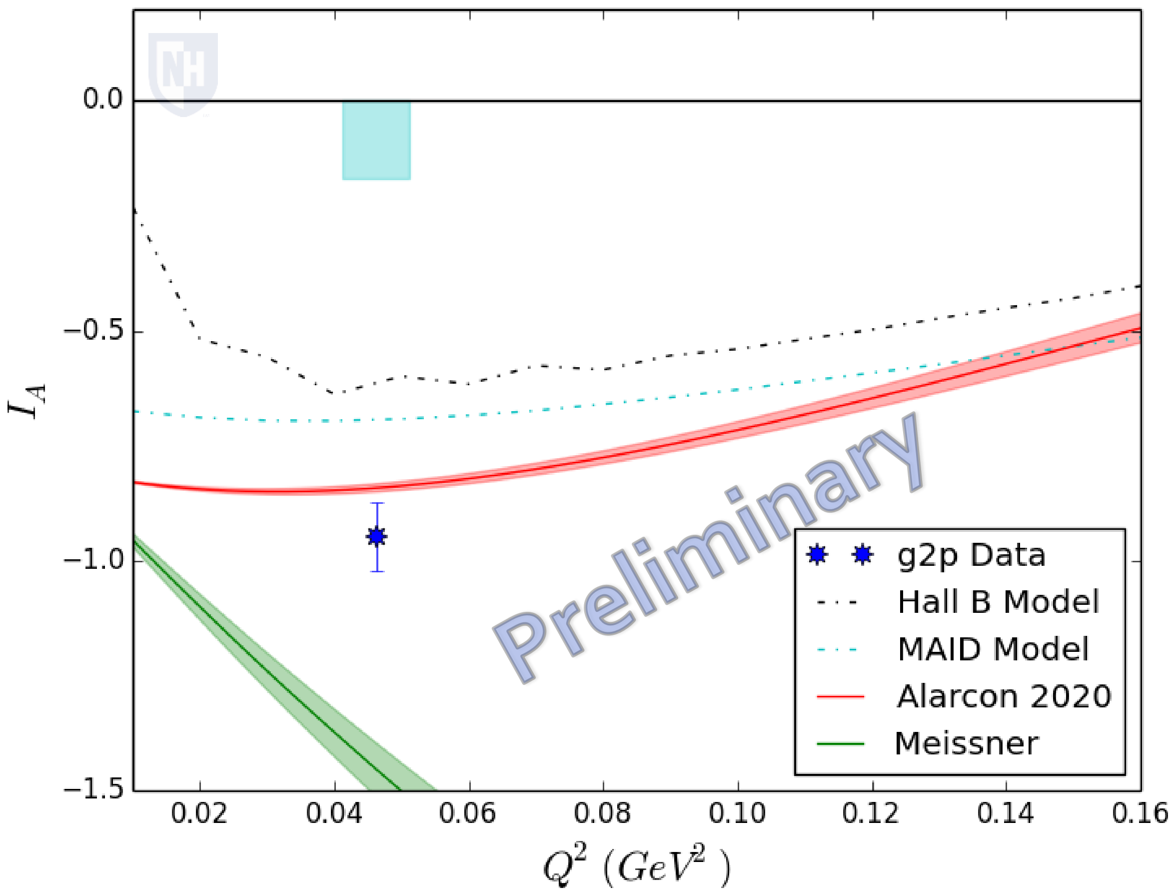
Strong disagreement with eg1b data

g_2^p data includes measured data for g_2…

And goes closer to threshold

Gerasimov-Drell-Hearn Sum Rule

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



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

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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!

Acknowledgements

g2p Analysis Team

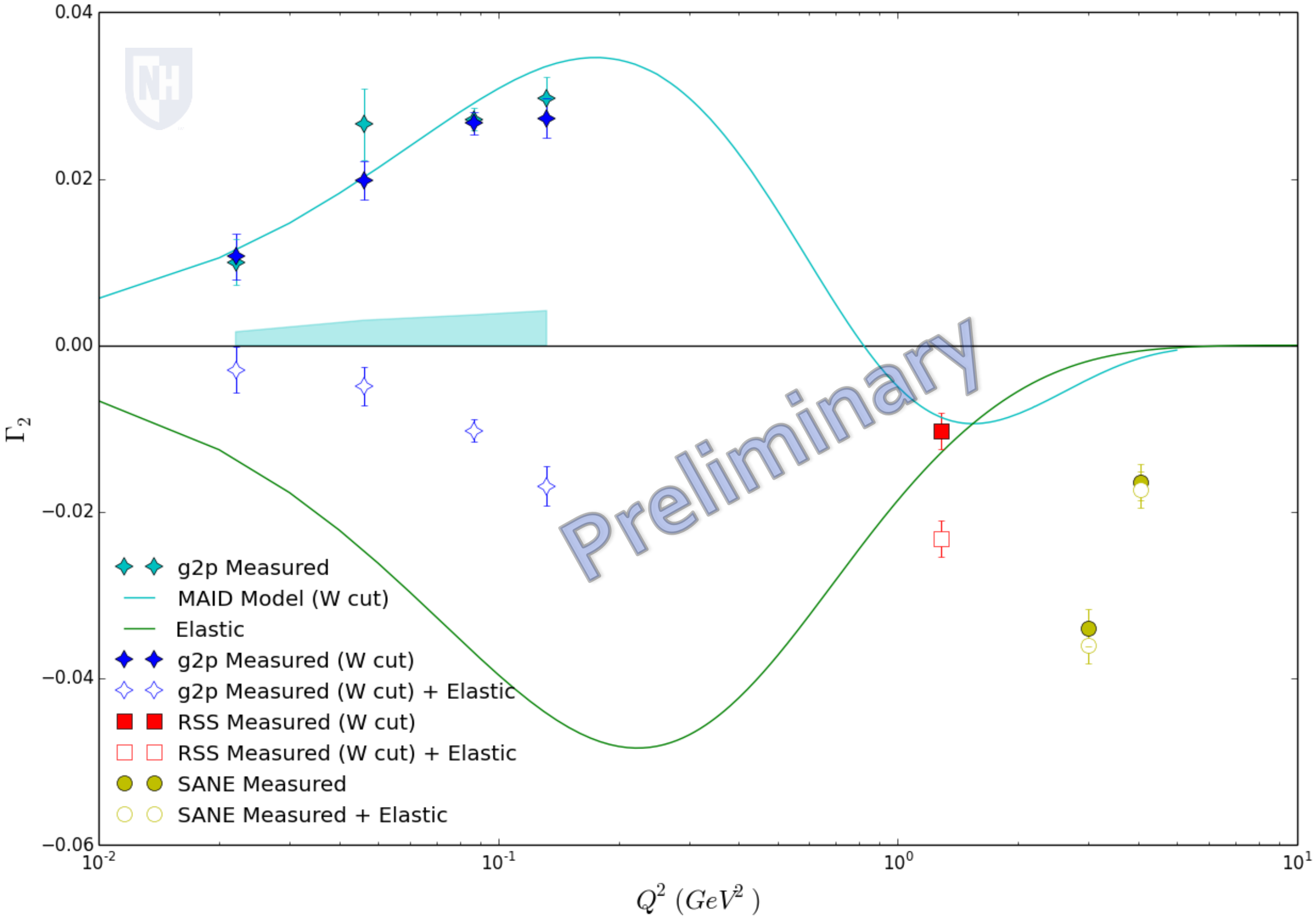
Spokespeople:
Alexandre Camsonne
JP Chen
Don Crabb
Karl Slifer

Post-Docs:
Kalyan Allada
James Maxwell
Vince Sulkosky
Jixie Zhang

Graduate Students:
Toby Badman
Melissa Cummings
Chao Gu
Min Huang
Jie Liu
Pengjia Zhu
Ryan Zielinski

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

Extra Slides: Gamma 2 Full Values



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