Measuring Form Factors and Structure Functions With CLAS

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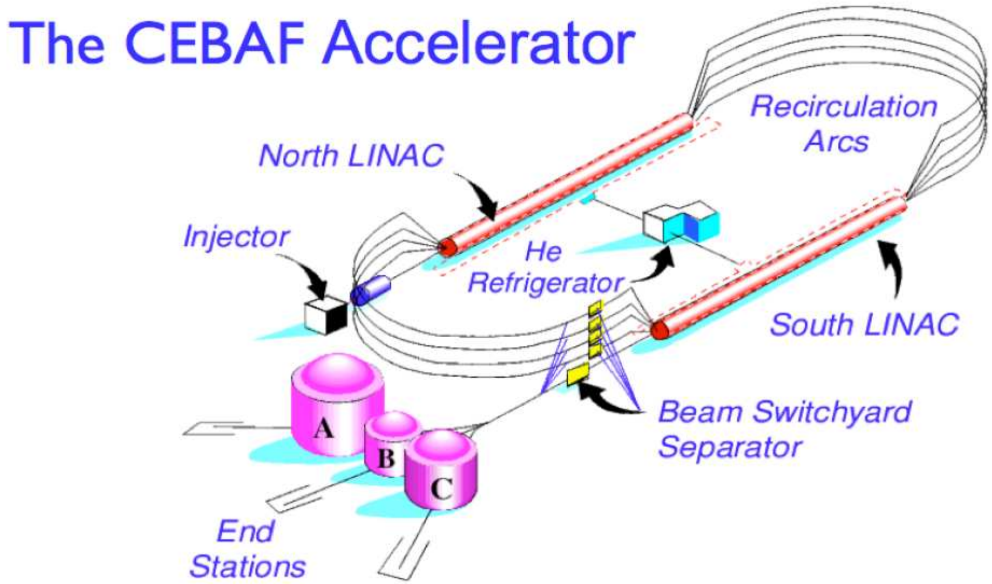
Outline:

1. Jefferson Lab and the CLAS Detector.
2. The Neutron Magnetic Form Factor G_M^n.
3. The Proton Virtual Photon Asymmetry A_1^p.
4. Conclusions and the Future.

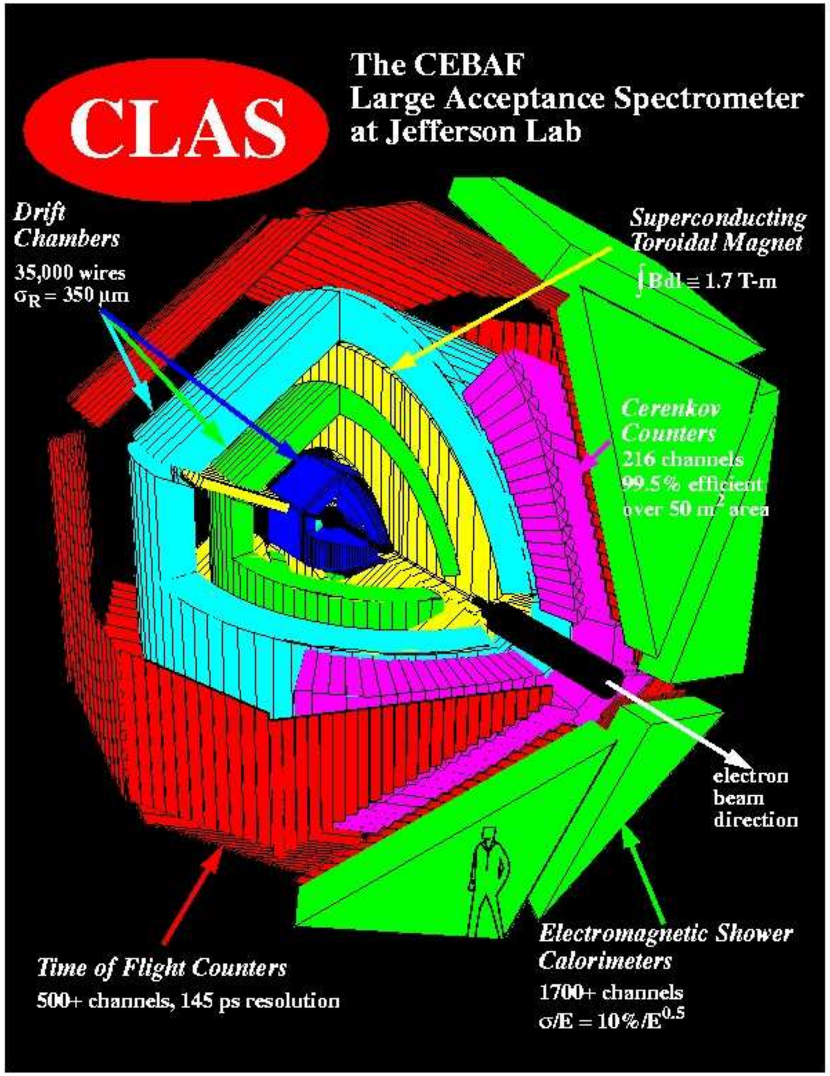
Jefferson Lab

- The Thomas Jefferson National Accelerator Facility (Jefferson Lab) is the newest US national lab and is located in Newport News, Virginia.
- The Continuous Electron Beam Accelerator Facility (CEBAF) is a 1.4-km-long, superconducting, machine that produces continuous beams.
- Beam energies up to energies of 5.7 GeV with 80% polarization and currents in the range 1-50 nA.



The CEBAF Large Acceptance Spectrometer (CLAS)

- The CLAS is a large solid angle device built around six, superconducting coils that produce a largely toroidal magnetic field.
- Layers of drift chambers for measuring charged particle tracks.
- Fast scintillators to measure time of flight.
- Cerenkov counters to separate negative pions from electrons.
- Electromagnetic calorimeters for energy measurements.



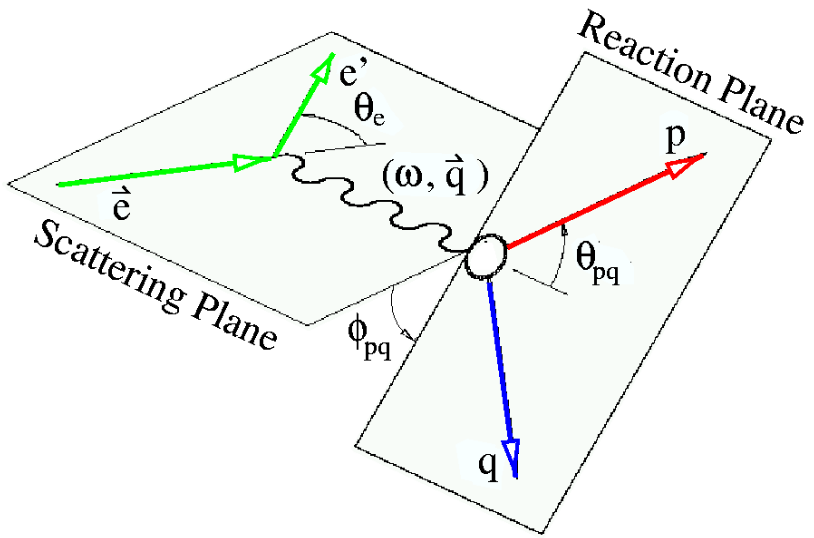
The Magnetic Form Factor of the Neutron (G_M^n)

- The elastic form factors are fundamental quantities related to the distribution of charge and magnetization in the nucleon.

$$\frac{d^2\sigma}{dE'\Omega} = \sigma_{Mott}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)\left(\frac{1}{1+\tau}\right)$$

$$\tau = \frac{Q^2}{4M^2} \qquad \epsilon = \frac{1}{1+2(1+\tau)\tan^2(\frac{\theta}{2})} \quad \sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})} \quad .$$

- Kinematic definitions - The angle θ_{pq} is between the virtual photon direction and the direction of the ejected nucleon.

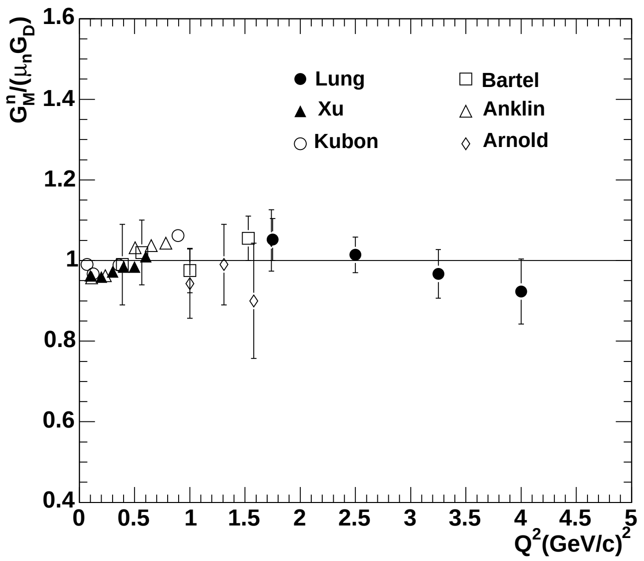


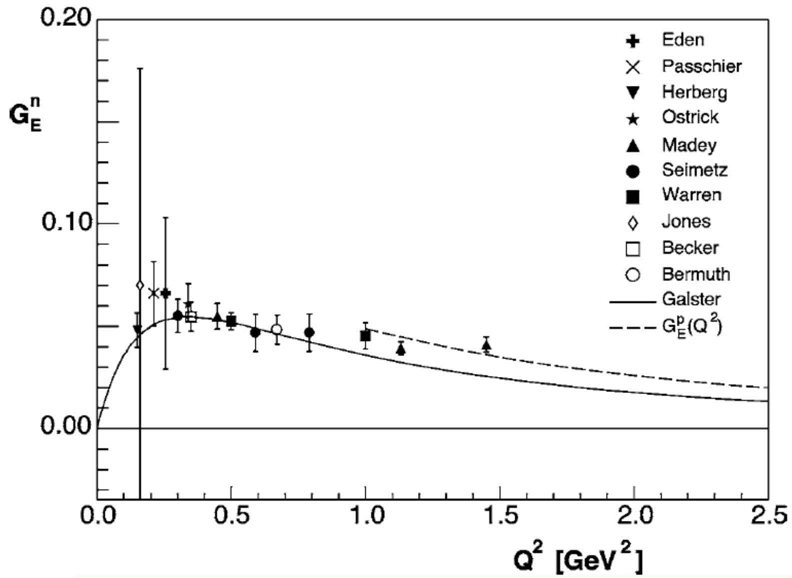
Scientific Motivation

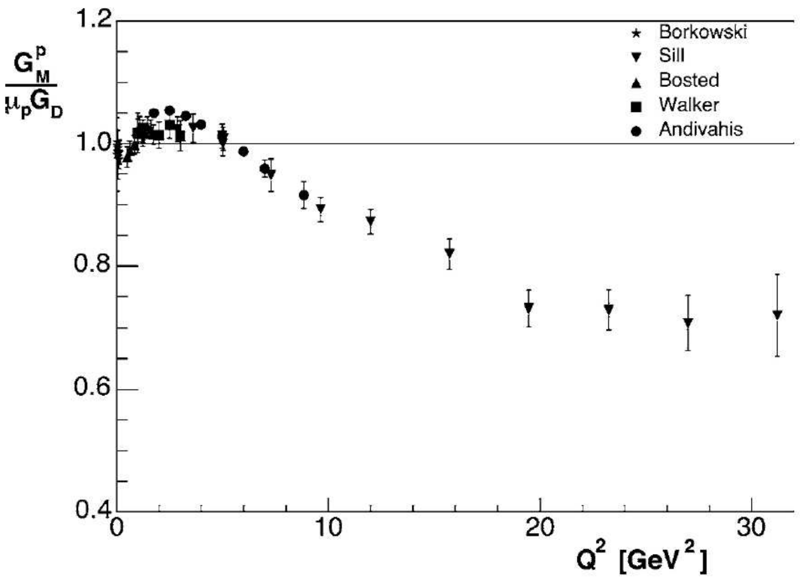
- To explore the ground state structure of the proton and neutron.
- $G_M^n(Q^2)$ is a fundamental observable related to the spatial distribution of the magnetization in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on generalized parton distributions (GPDs) which promise to give us a three-dimensional picture of hadrons.
- Elastic hadronic form factors are a fundamental challenge for lattice QCD.
- Required for extracting the strange quark distributions in the proton.
- Part of a broad effort to understand how nucleons are ‘constructed from the quarks and gluons of QCD’. *

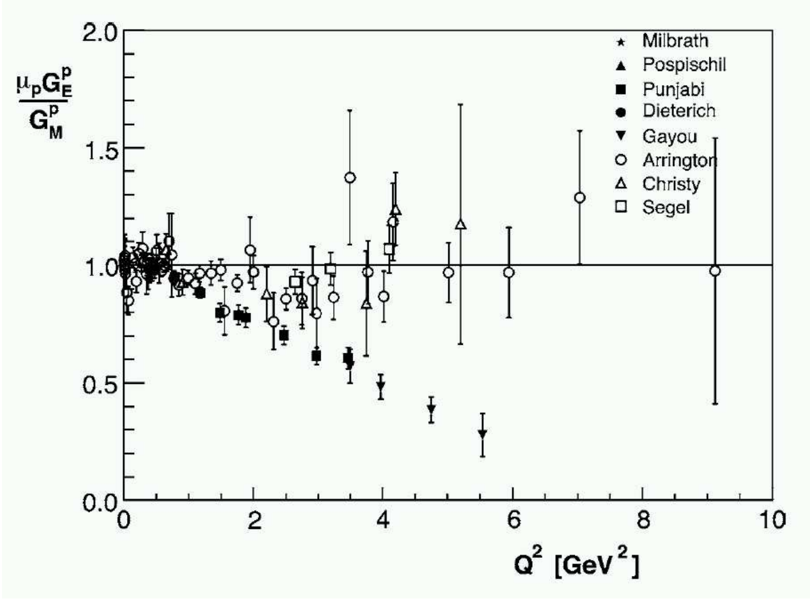
* ‘Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade’, NSF/DOE Nuclear Science Advisory Committee, April, 2002.

Current Status of the Elastic Form Factors









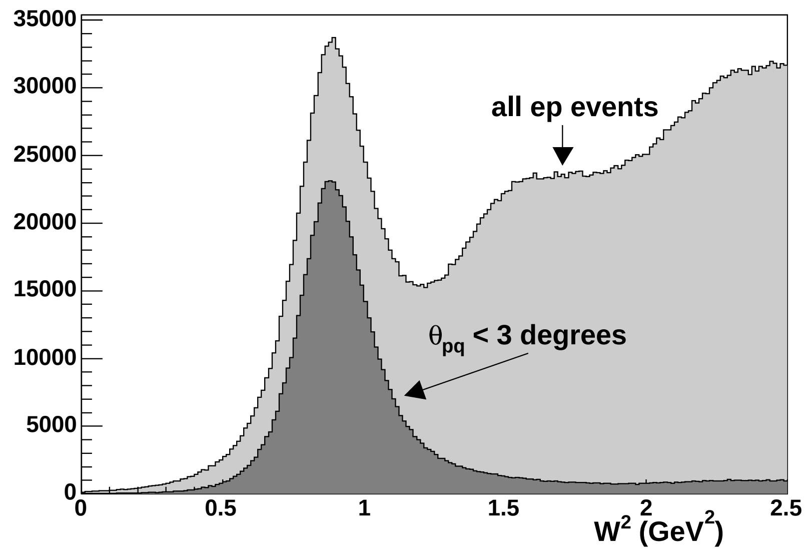
C.E. Hyde-Wright and K.deJager, Ann. Rev. Nucl. Part. Sci. **54** (2004) 54 and references therein.

The G_M^n Measurement - 1

- Use a deuterium target and take the ratio of the $e-p$ and $e-n$ cross sections (the ratio method).

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2\tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2\tan^2(\frac{\theta}{2})}$$

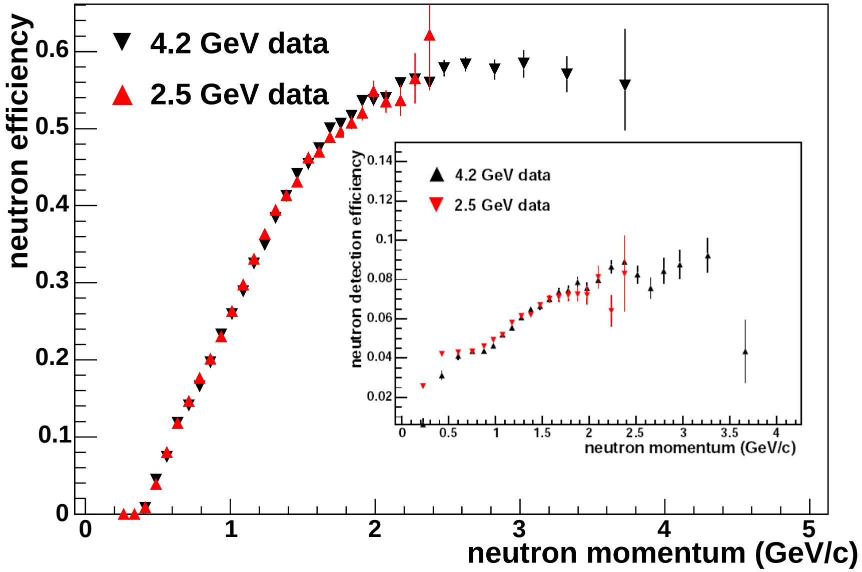
- Quasi-elastic event selection: Apply a maximum θ_{pq} cut to eliminate inelastic events plus a cut on W^2.



The G_M^n Measurement - 2

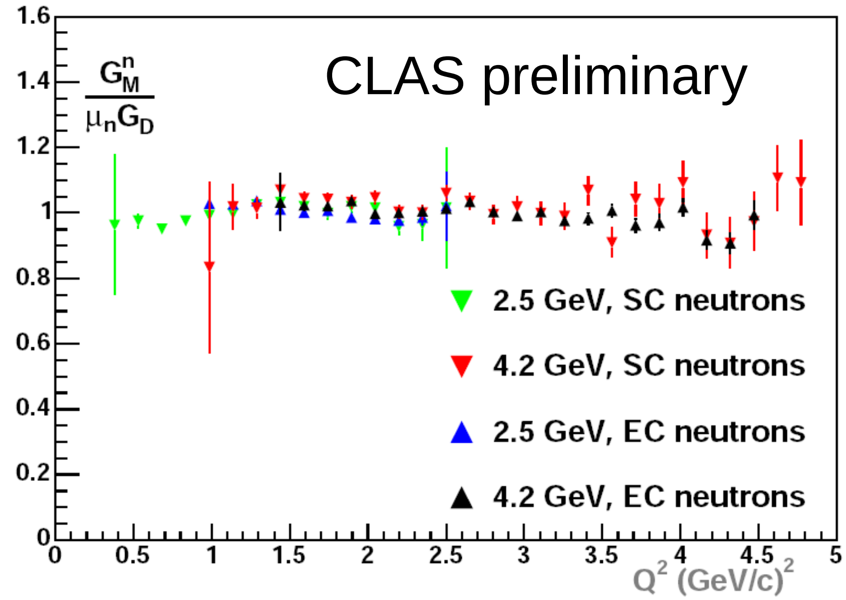
- Dual target cell with liquid hydrogen and deuterium. The hydrogen cell was downstream and separated from the deuterium target by 4.7-cm gap. Enables us to perform *in situ* calibrations during data collection.

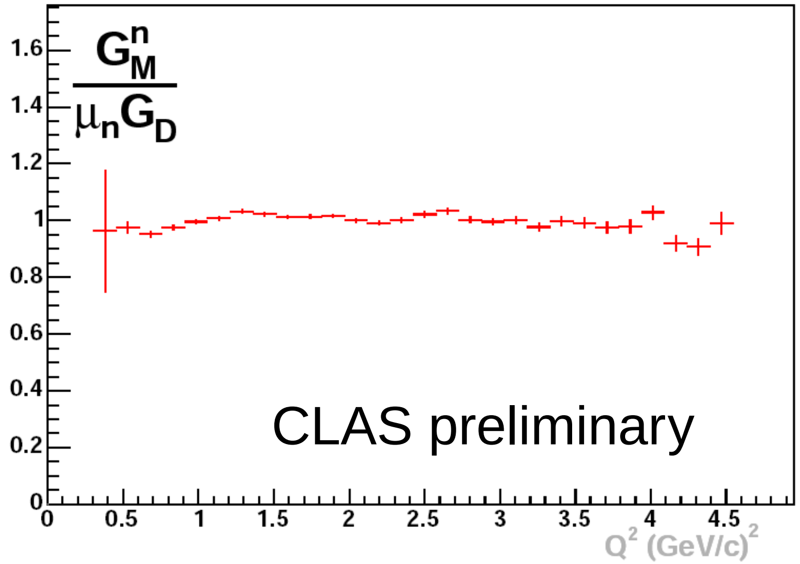
- Use the $ep \to e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.

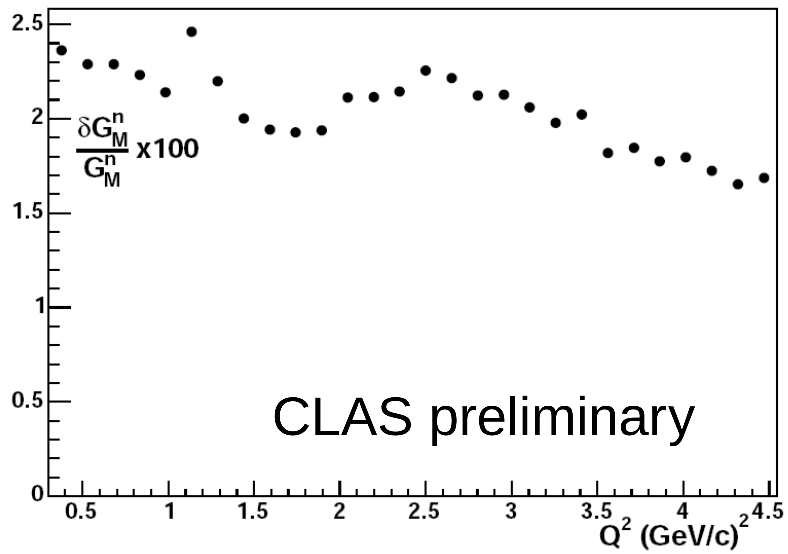


Results - Overlaps and Final Averages

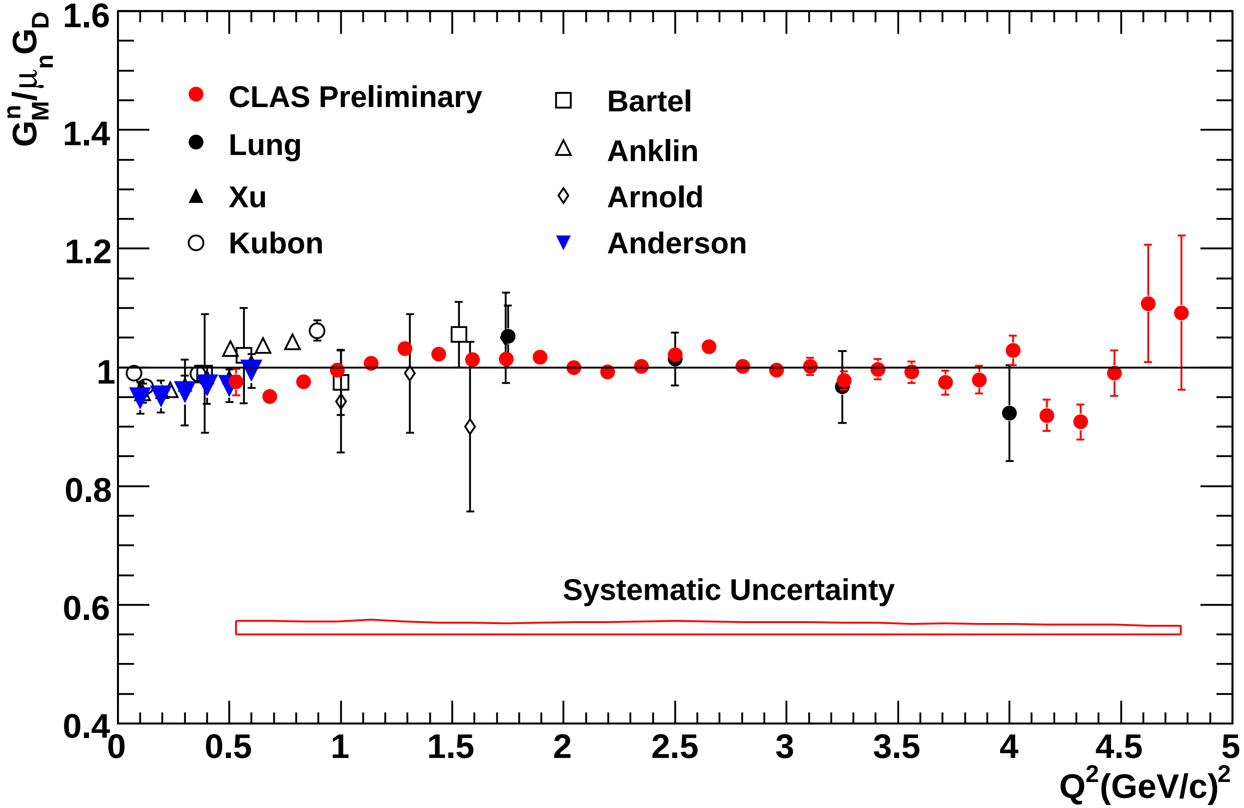
- Overlapping measurements of G_M^n scaled by the dipole are consistent.
- Weighted-average $G_M^n/\mu_n G_D$ and systematic uncertainty $\frac{\delta G_M^n}{G_M^n} \times 100$ ($< 2.5\%$).







Results - Comparison with Existing Data and Theory



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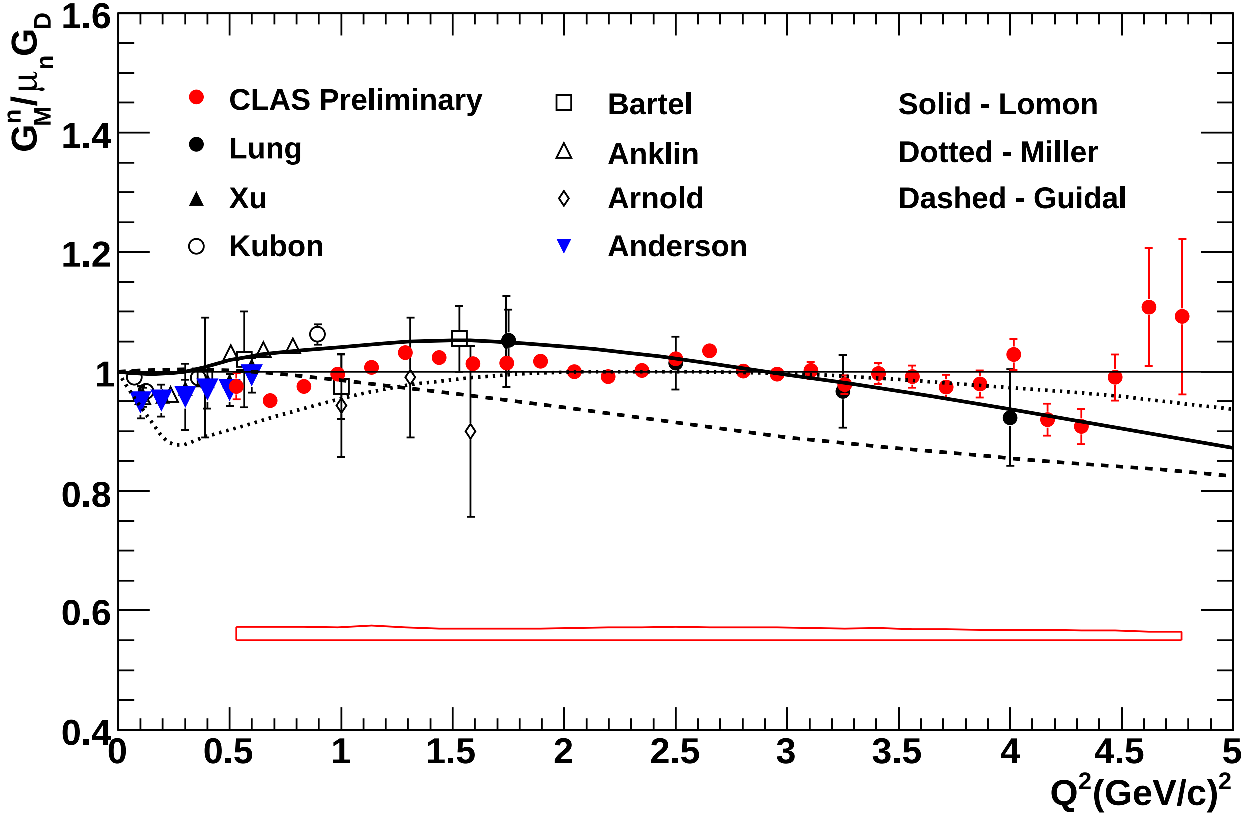


The Proton Virtual Photon Asymmetry (A_1^p)

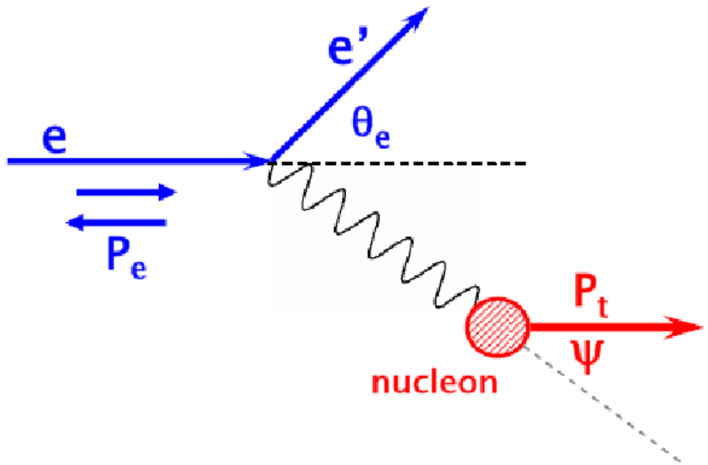
- The photon asymmetry is related to the spin forces between quarks and the spin composition of the nucleon

$$\frac{d^2\sigma}{dE'\Omega} = \Gamma_v[\sigma_T + \epsilon_L + P_e P_t(\sqrt{1-\epsilon^2}A_1\sigma_T \cos\Psi + \sqrt{2\epsilon(1-\epsilon)}A_2\sigma_T \sin\Psi)]$$

$$\epsilon = \frac{1}{1+2(1+\tau)\tan^2(\frac{\theta}{2})} \qquad A_1 = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)} \qquad x = \frac{Q^2}{2M(E-E')}$$

where q_i and Δq_i are the sum and differences of quark distributions with their spins aligned and anti-aligned with the nucleon spin.

- Requires polarized beam and targets.
- Kinematic definition - The angle Ψ is between the proton direction and the target polarization.

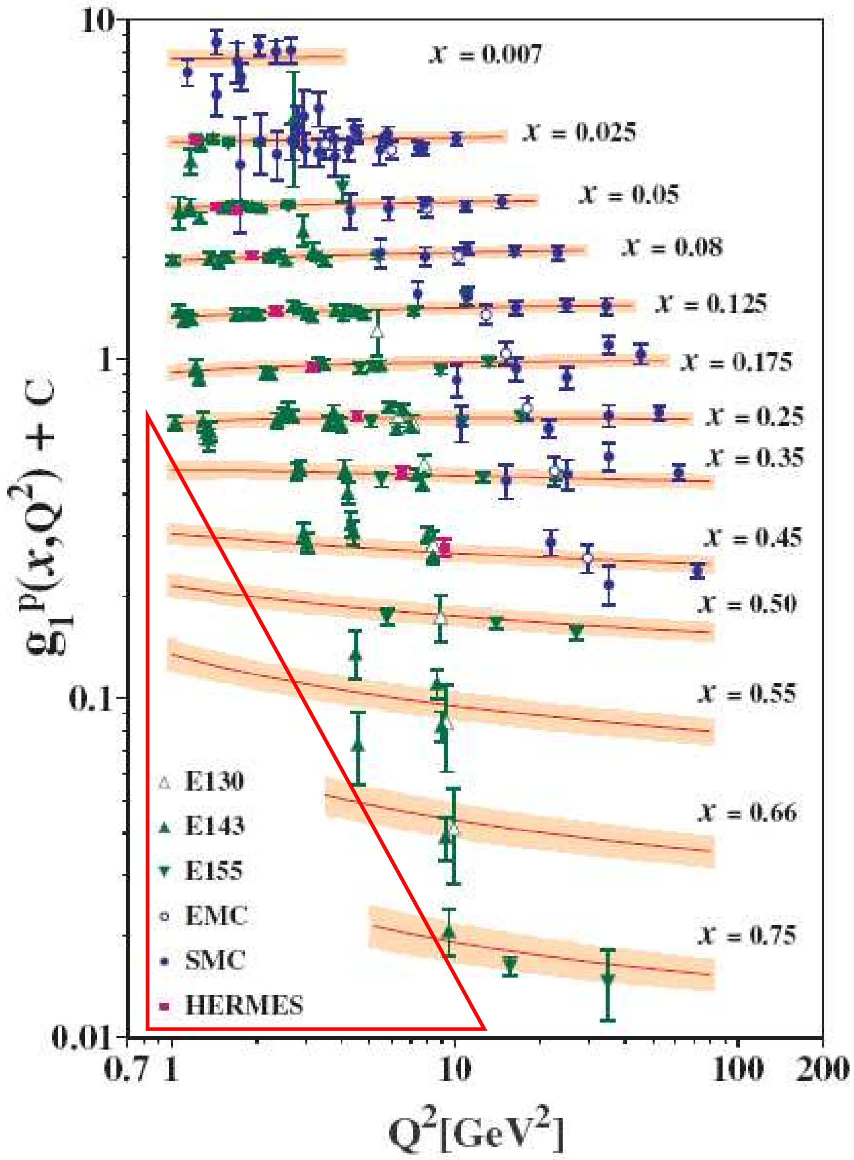


Scientific Motivation

- Spin structure functions measured in deep inelastic scattering in the 1970's at CERN and SLAC revealed the 'spin crisis'; only 25%-30% of the nucleon spin is carried by the quarks.
- The remaining portion of the spin is from contributions by gluons, sea quarks, and orbital angular momentum of the valence quarks.
- Probe the spin structure of nucleons, *i.e.* measure the forces arising from the spins of the quarks.
- Improve parton distribution function measurements.
- Test higher twist calculations.
- Test chiral Perturbation Theory at low Q^2.
- Probe quark-hadron duality over a wide Q^2.

Current Status

- Plot shows the proton structure function g_1 which is a linear combination of A_1 and A_2.
- Data are a sample of proton measurements from laboratories besides Jefferson Lab.
- Red triangle shows Jefferson Lab measurements will contribute.



The A_1 Measurement - 1

- Create a new asymmetry with inclusive electron events to extract A_1.

$$A^{||} = \frac{N^-/Q_c^- - N^+/Q_c^+}{N^-/Q_c^- + N^+/Q_c^+} = D(A_1 + \eta A_2)$$

$$D = \frac{1 - \frac{E'\epsilon}{E}}{1 + \epsilon R} \quad R = \frac{\sigma_L}{\sigma_T} \quad \eta = \frac{\eta\sqrt{Q^2}}{E - E'\epsilon} \quad \epsilon = \frac{1}{1 + 2(1+\tau)\tan^2(\frac{\theta}{2})}$$

  Superscripts refer to the nucleon-beam spins being aligned (+) or anti-aligned (-).

- Use parameterization of existing data and calculations to show that the contribution of A_2 and R are small.

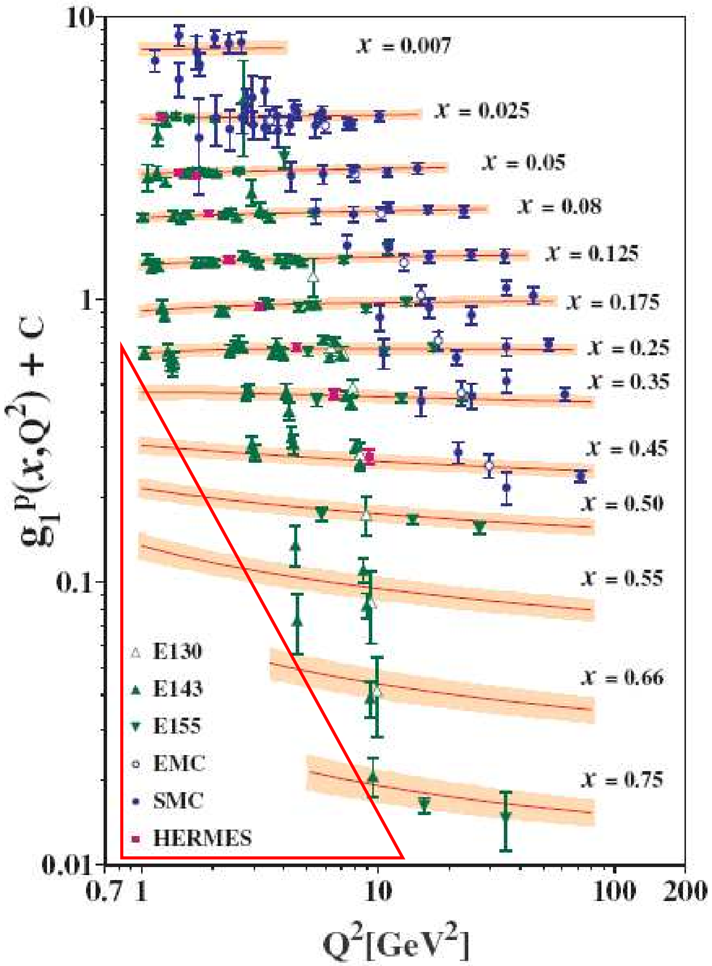
- Subtract backgrounds events, correct for non-proton events in target, radiation and finite beam and target polarizations.

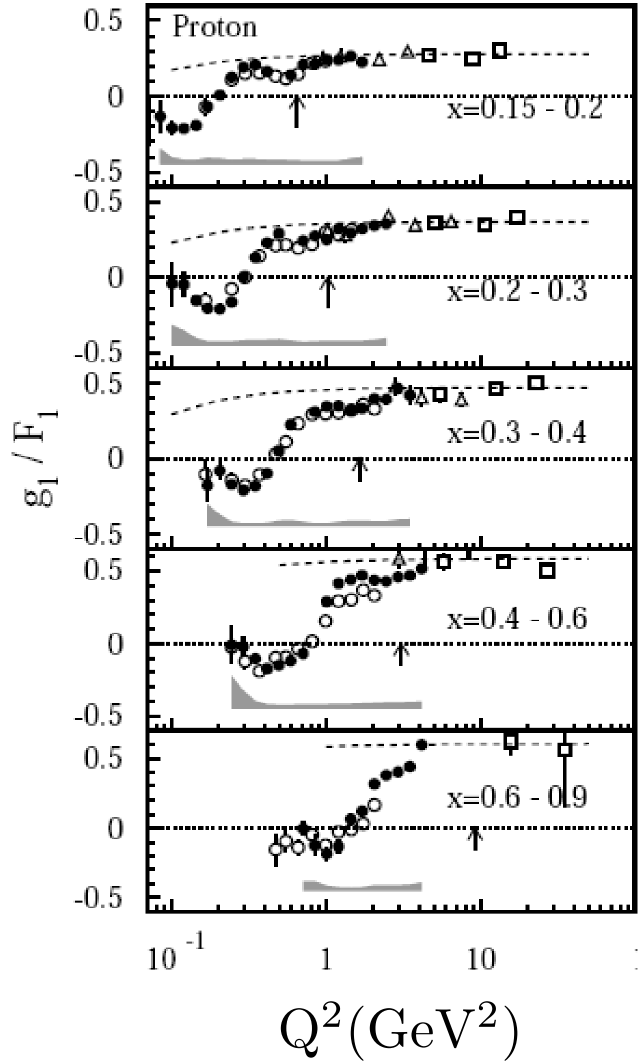
The A_1 Measurement - 2

- Polarized target uses dynamic nuclear polarization of $\mathrm{NH_3}$ and $\mathrm{ND_3}$.
- Polarizations of 70-80% for protons and 20-30% for deuterons.
- Luminosity $\approx 10^{35}\ cm^{-2}s^{-1}$.
- Movable ladder holds carbon, $\mathrm{NH_3}$, $\mathrm{ND_3}$, and empty cylindrical targets.
- Liquid helium bath at 1 K.
- Superconducting Helmholtz coils at 5 T.
- Microwaves at 140 GHz.

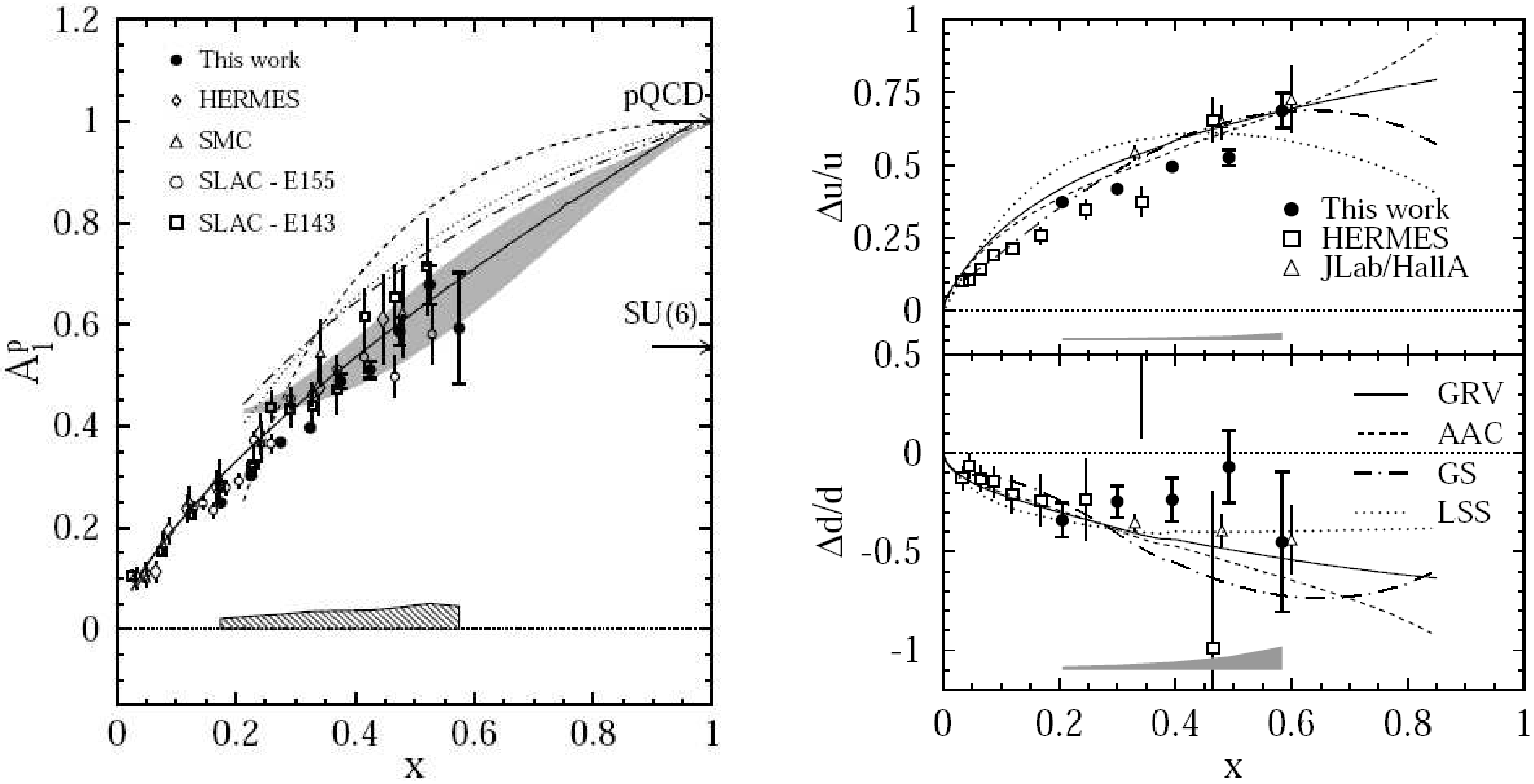
Results for g_1 and g_1/F_1.

Comparison with previous data. Data in right-hand panel are from K.A. Dharmawardane, *et al.* (the CLAS Collaboration), to be published in Phys. Rev. Lett. Boxes and triangles in right-hand plot are from SLAC experiments E155 and E143.





Results for A_1 on the Proton.



Filled points in left-hand panel are from a recent CLAS measurement (K.A. Dharmawardane, *et al.* (the CLAS Collaboration), to be published in Phys. Rev. Lett.) in the deep inelastic region ($W > 2.0$ GeV and $Q^2 > 1.0\ \mathrm{GeV}^2$). Gray band is from a model including color magnetism by Isgur, *et al.*, Phys. Rev. D 59, 034013 (2003). Extraction of polarizations in right-hand panel done with a naive quark model with no strange quarks.

Conclusions and the Future.

For G_M^n

- We have measured the neutron magnetic form factor G_M^n over the range $\mathrm{Q}^2 = 0.5 - 4.5\ (\mathrm{GeV/c})^2$ to a precision better than 2.5%.
- Results are consistent with the dipole approximation within 5% across almost the full range.

For A_1^p

- We have measured the proton virtual photon asymmetry at high precision over a wide range in x and Q^2.
- The polarization increases with x and confirms a prediction from pQCD. The Isgur, color-magnetism model has the best agreement with the data.

The Future.

- Analysis continues on the spin structure functions, *e.g.* new exit channels.
- Proposals to measure G_M^n and A_1^p have recently been approved for the upgraded CEBAF and CLAS. The 12-GeV Upgrade at Jefferson Lab is the highest US priority in nuclear physics.