Nucleon Form Factor Measurements with 12 GeV CEBAF at Jefferson Lab

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Outline

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Nucleon structure

Double Polarization Method to obtain form factor ratio

Results of Proton and Neutron form factors

12 GeV JLab upgrade

Nucleon Form Factor Experiments with 12 GeV CEBAF Beam

Conclusions

Introduction

Ground-state electromagnetic nucleon form factors are among the most fundamental quantities that describe the nucleon's non-perturbative structure

Spectacular experimental progress in measuring G_E/G_M followed after the opening of Jefferson Lab, for proton and neutron. Our understanding of the shape, charge and current distributions in the nucleon has increased considerably, and changed drastically

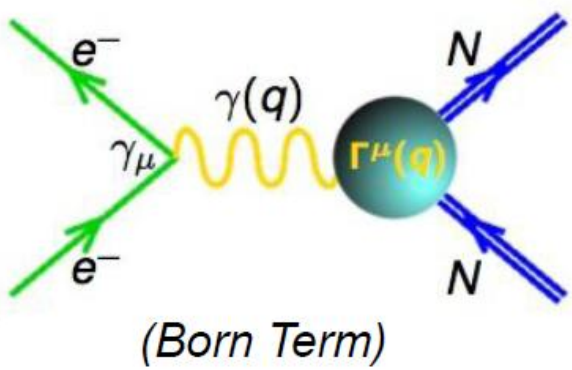
New information on hadron structure, such as role of quark orbital angular momentum, transverse charge density distribution, dressed quark form factor has followed in short order

Evident that only way to achieve clarity in discriminating between theoretical explanations of nucleon form factor is to measure it with considerable precision to highest possible values of Q^2. Also the quality of the experimental data is clearly important for the quantitative extraction of GPDs.

New experiments in preparation for the 12 GeV era, will provide answers to a number of open questions crucial to our understanding of fundamental nucleon properties and the nature of QCD in the confinement regime

Nucleon Structure and Elastic Form Factors

$j_\mu = \langle e' | \gamma_\mu | e \rangle$



$J_\mu = \langle p' | \Gamma | p \rangle$

using parity conservation and current conservation, the hadron current is parameterized by two form factors

$$\Gamma_\mu(p,p') = \gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}}{2M} q^\nu F_2(Q^2)$$

F_1 helicity conserving Dirac FF, F_2 helicity non-conserving Pauli FF.

Alternately, the Sachs form factors

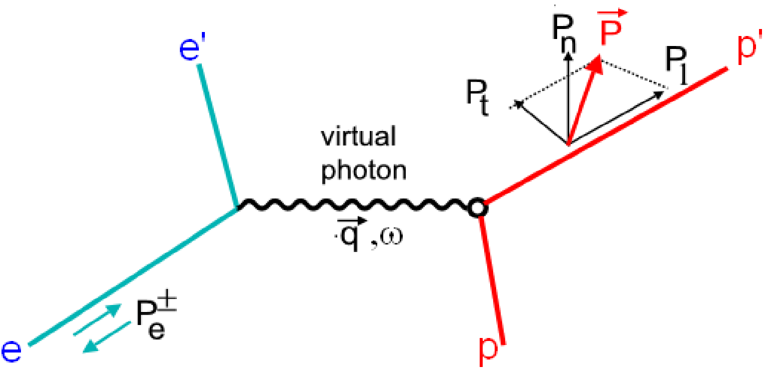
$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \qquad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

For $Q^2 \to 0$, G_E and G_M are Fourier transforms of charge and current distributions in the Breit frame.

Recoil Polarization Method

Polarization transfer in $\vec{e}N \rightarrow e\vec{N}$ or spin-target asymmetry $\vec{e}\vec{N} \rightarrow eN$, (N=p or n), two different techniques, but give same information.

For recoil polarization, the two polarization components are in the reaction plane, no normal component:(Akhiezer and Rekalo, Sov. J. Part. Nucl. 4, 277 (1974), Arnold, Carlson and Gross, Phys. Rev. C 23, 363 (1981))



$$hP_eP_t = -hP_e 2\sqrt{\tau(1+\tau)}G_{Ep}G_{Mp}\tan(\frac{\theta_e}{2})/I_0$$

$$hP_eP_\ell = hP_e\frac{(E_e+E_{e'})}{M}G_{Mp}^2\sqrt{\tau(1+\tau)}\tan^2(\frac{\theta_e}{2})/I_0$$

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e+E_{e'})}{2M}tan\frac{\theta_e}{2} \quad and \quad I_o = G_E^2 + \frac{\tau}{\varepsilon}G_M^2$$

Superior method: " much smaller systematics"

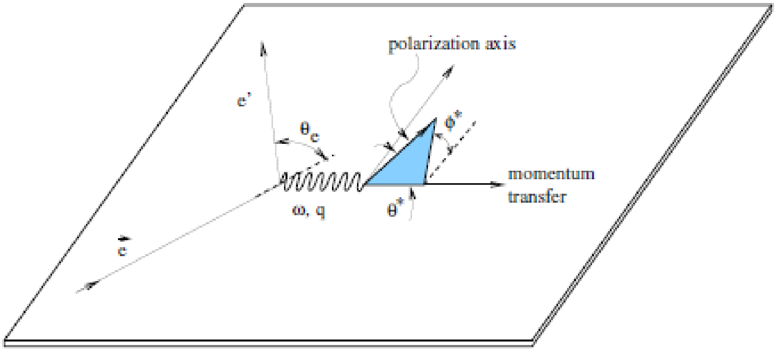
Form Factor ratio is independent of the electron polarization P_e and of the polarimeter analyzing power A_y (h is beam helicity ±1).

Statistical uncertainty depends directly on both P_e and A_y.

Remaining systematics mostly from spin precession.

Asymmetry with polarized targets

Long. polarized beam/polarized target transverse to $\vec{q}$ in scattering plane

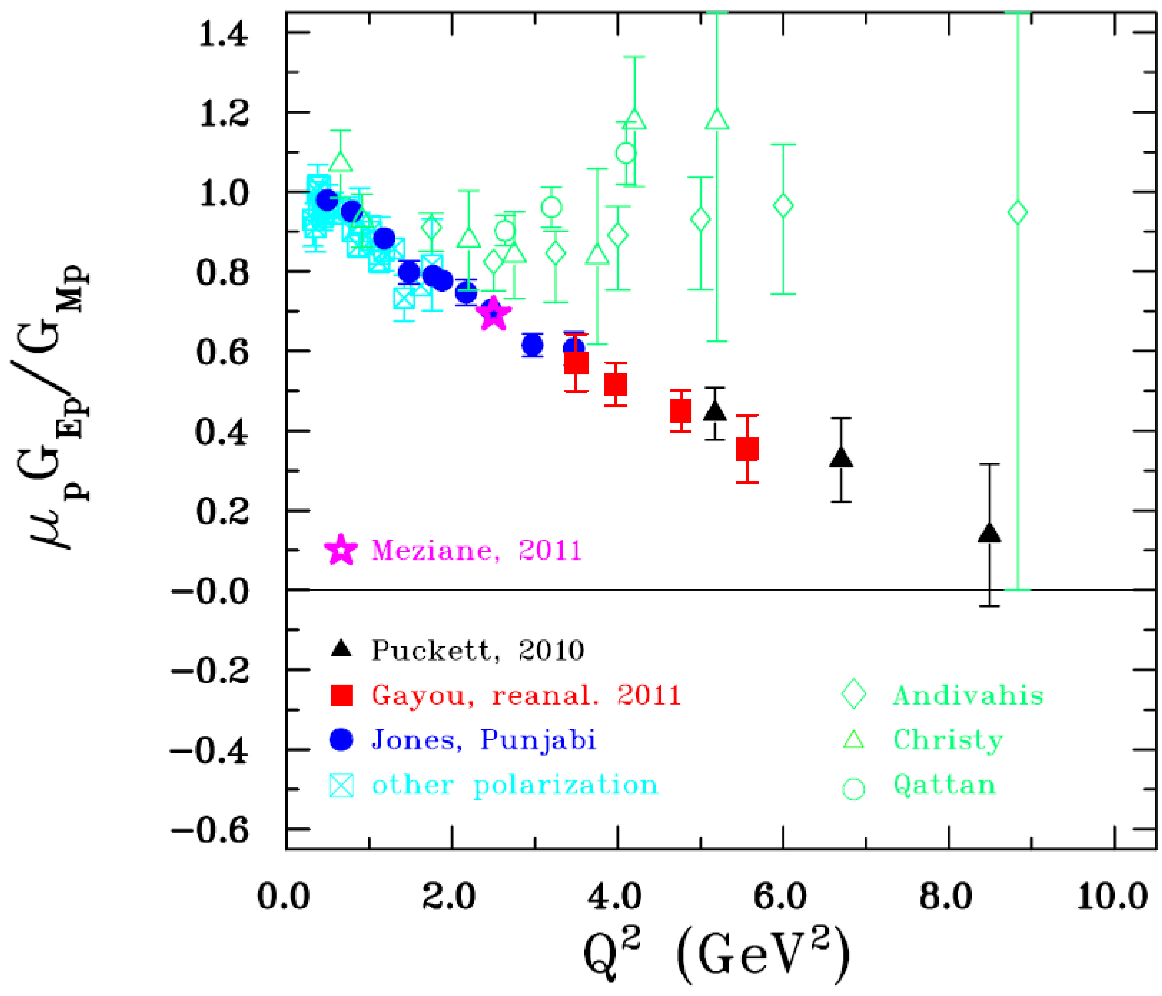


Helicity-dependent asymmetry roughly proportional to G_E/G_M

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

- Polarized D or $^3\mathrm{He}$
- Technique used by GEn(1) to $Q^2 = 3.4\ \mathrm{GeV}^2$

Proton Form Factor Ratios

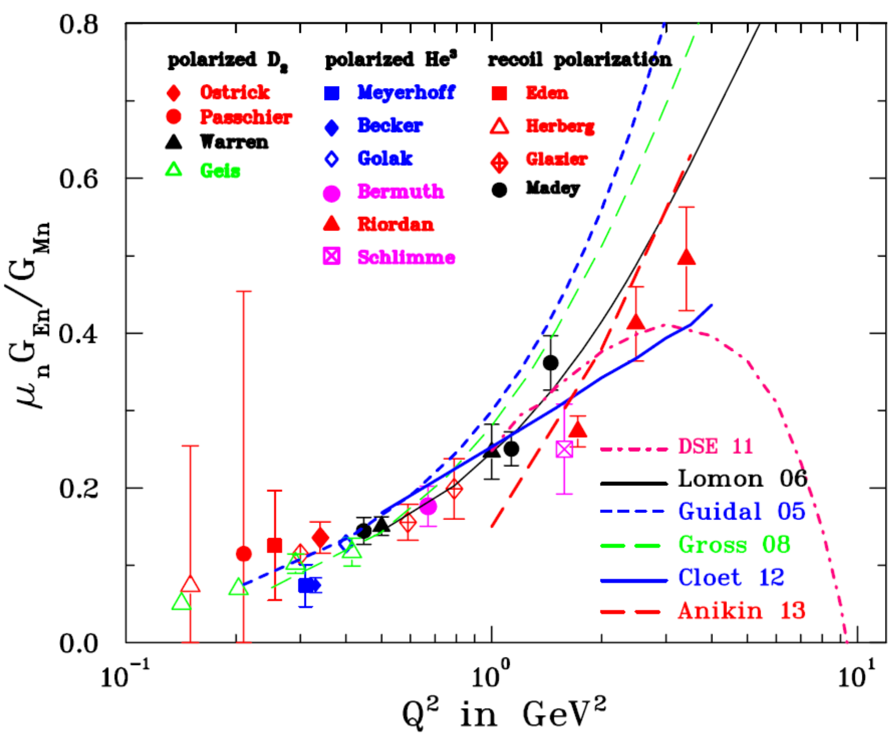


Linear decrease observed in first two GEp experiments seems to slow down in GEp(3) experiment

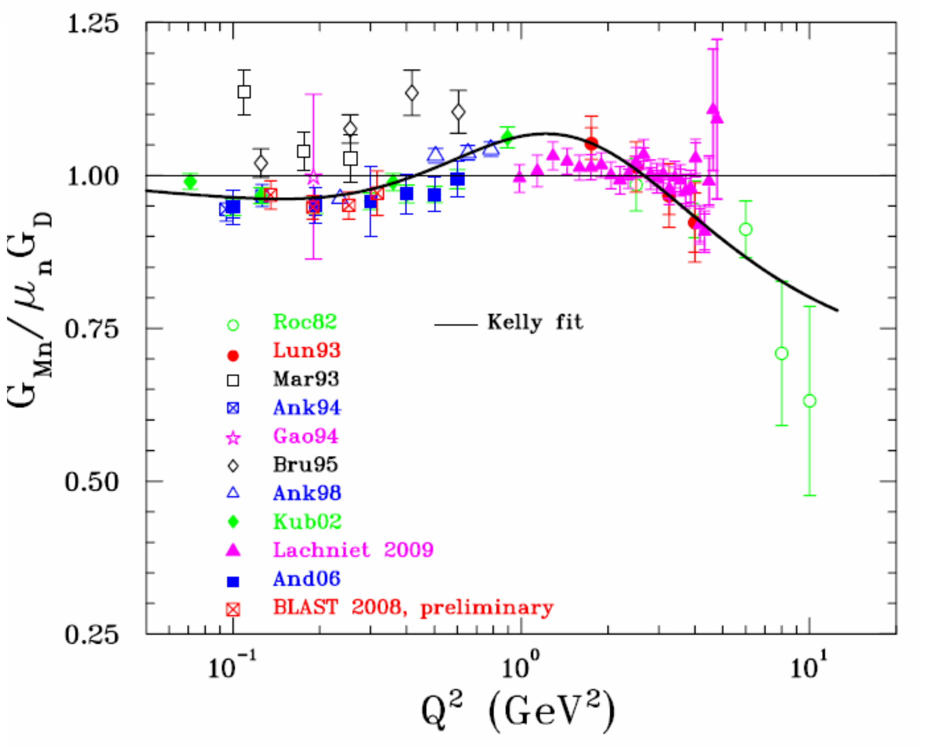
Puckett et al., PRL 104, 242301 (2010)

Neutron Form Factor Data

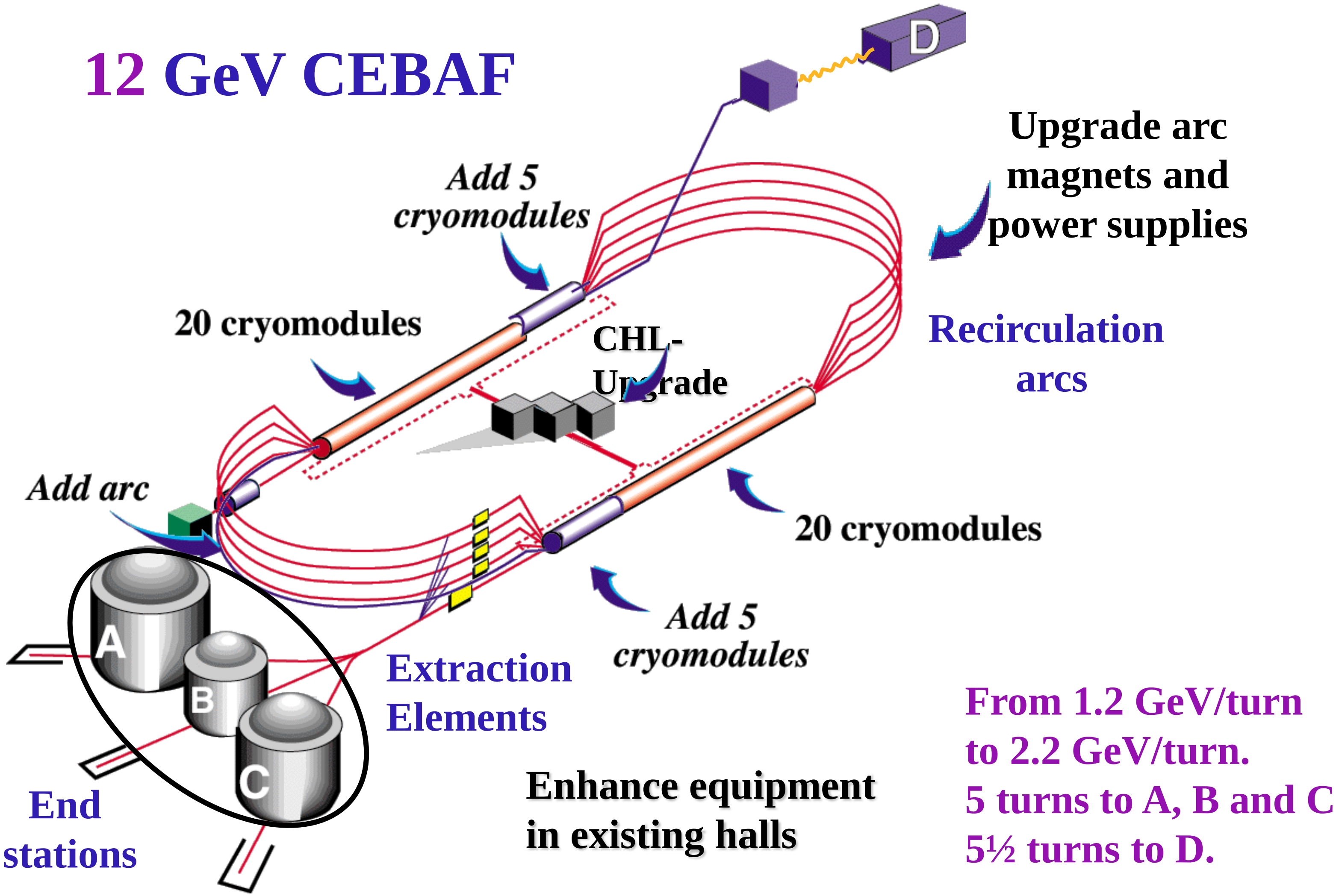
All polarization results, including JLab Hall A high Q^2 data



Polarization and cross section Data, including JLab Hall B data



12 GeV CEBAF



Continuous Electron Beam Accelerator Facility (CEBAF):

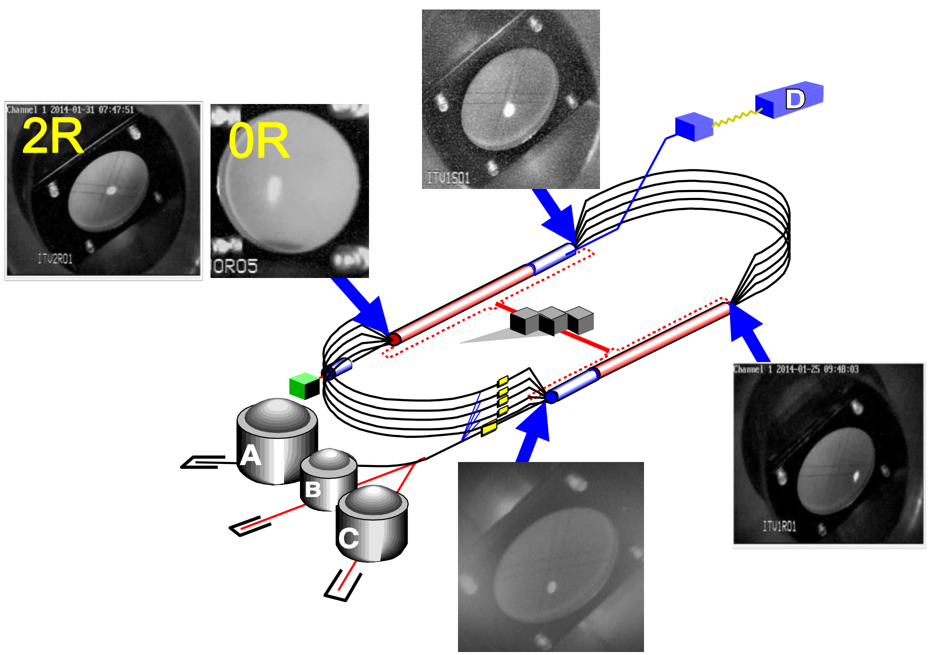
- **Superconducting Electron Accelerator (currently 338 cavities), 100% duty cycle**
- **E_{max} = 11 GeV (Halls A, B, and C) and 12 GeV (Hall D), $\Delta E/E \approx 2 \times 10^{-4}$, $I_{summed} \approx 90\ \mu A$, $P_e \geq 80\%$**

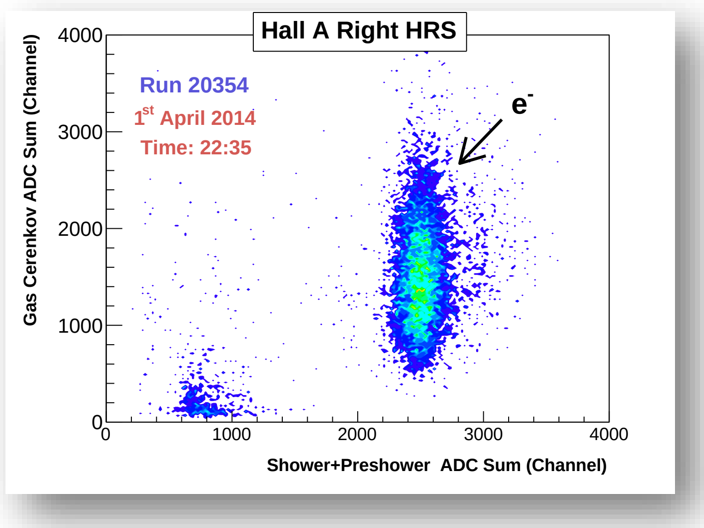
Beam Commissioning to Hall A

Jefferson Lab in Newport News hits major milestone in accelerator upgrade

April 30, 2014|By Tamara Dietrich, tdietrich@dailypress.com | Daily Press

Jefferson Lab in Newport News has reached a "major milestone" in its drive to double the energy of its electron accelerator and become the only facility in the world capable of answering key questions about quarks, the building blocks of matter.





Beam on carbon target in Hall A ; E_{beam} = 6.1 GeV

Approved Nucleon Form Factor Experiments at Jefferson Lab with 11 GeV CEBAF Beams

Hall	Exp#	Title	E_e	Q^2_{max}
A	E12-07-108	Precision Measurement of the **Proton Elastic Cross Section** at High Q^2	6.6 8.8 11	17,5 (14)
A	E12-07-109	Large Acceptance **Proton Form Factor Ratio Measurements** at 13 and 15 $(GeV/c)^2$ using **Recoil Polarization Method**	6.6 8.8 11	12(14)
A	E12-09-019	Precision Measurement of the **Neutron Magnetic Form Factor** up to Q^2 = 18.0 $(GeV/c)^2$ by the Ratio Method	4.4 6.6 8.8 11	13.5 (18)
A	E12-09-016	Measurement of the **Neutron Electromagnetic Form Factor Ratio** G^n_E / G^n_M at High Q^2	4.4 6.6 8.8	10.2
B	E12-07-104	Measurement of the **Neutron Magnetic Form Factor** at High Q^2 Using the Ratio Method on Deuterium	11	14
C	E12-11-009	The **Neutron Electric Form Factor** at Q^2 up to 7 $(GeV/c)^2$ from the Reaction 2H(e,e'n)1H via Recoil Polarimetry	4.4 6.6 11	7

PAC approval for 224 days of running in the first five years.

Slide from talk by P. Rossi, Jefferson Lab

Proton Form Factors with 11 GeV beam

The higher energy of 11 GeV CEBAF will give access to higher momentum transfers in all form factor measurements

The new facility being constructed in Hall A to measure G_{Ep}/G_{Mp}, G_{En}/G_{Mn} and G_{Mn} is the Super Bigbite Spectrometer (SBS)

SBS was developed for G_{Ep}/G_{Mp} measurements to 15 GeV^2; it will be first used in a simpler configuration to measure G_{En} and G_{Mn}

Problems facing higher Q^2 experiments to measure G_{Ep}/G_{Mp} are:

Extremely small elastic cross-section $\sigma \sim E^2/Q^{12}$

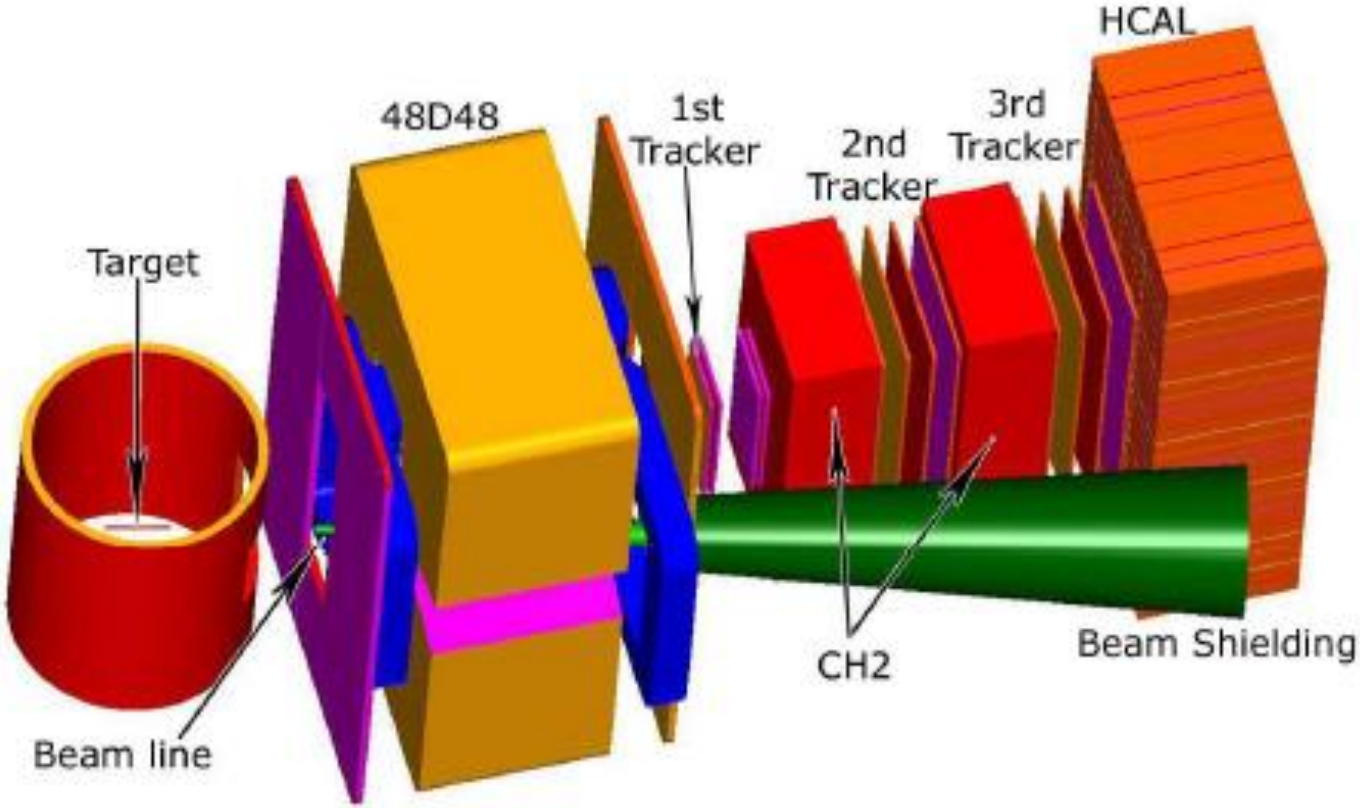
Low analyzing power $A_y \sim 1/p \sim 1/Q^2$ (for recoil polarization measurement)

Overall experimental FOM $\sim \sigma A_y^2 \sim E^2/Q^{16}$

Need large statistics ⟹ maximum luminosity and solid angle
Maximum luminosity ⟹ large background

Solution? Super Bigbite Spectrometer with modern tracking detector based on Gas Electron Multiplier (GEM).

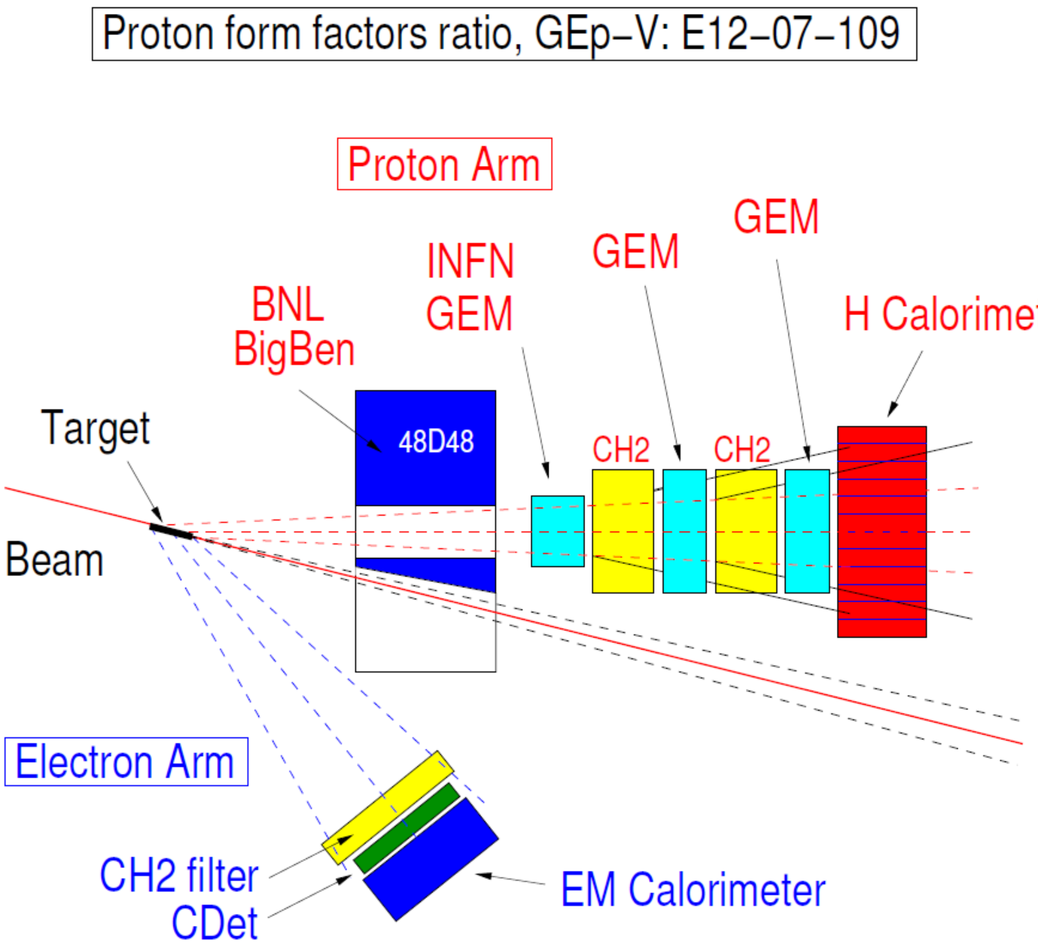
Super Bigbite Spectrometer



SBS capabilities derived from using a large open-geometry dipole magnet providing vertical bending, therefore precession of P_ℓ, together with a detector package with direct view of the target

GEM-based tracking system able to tolerate the very high rates.

Setup for GEp(5)

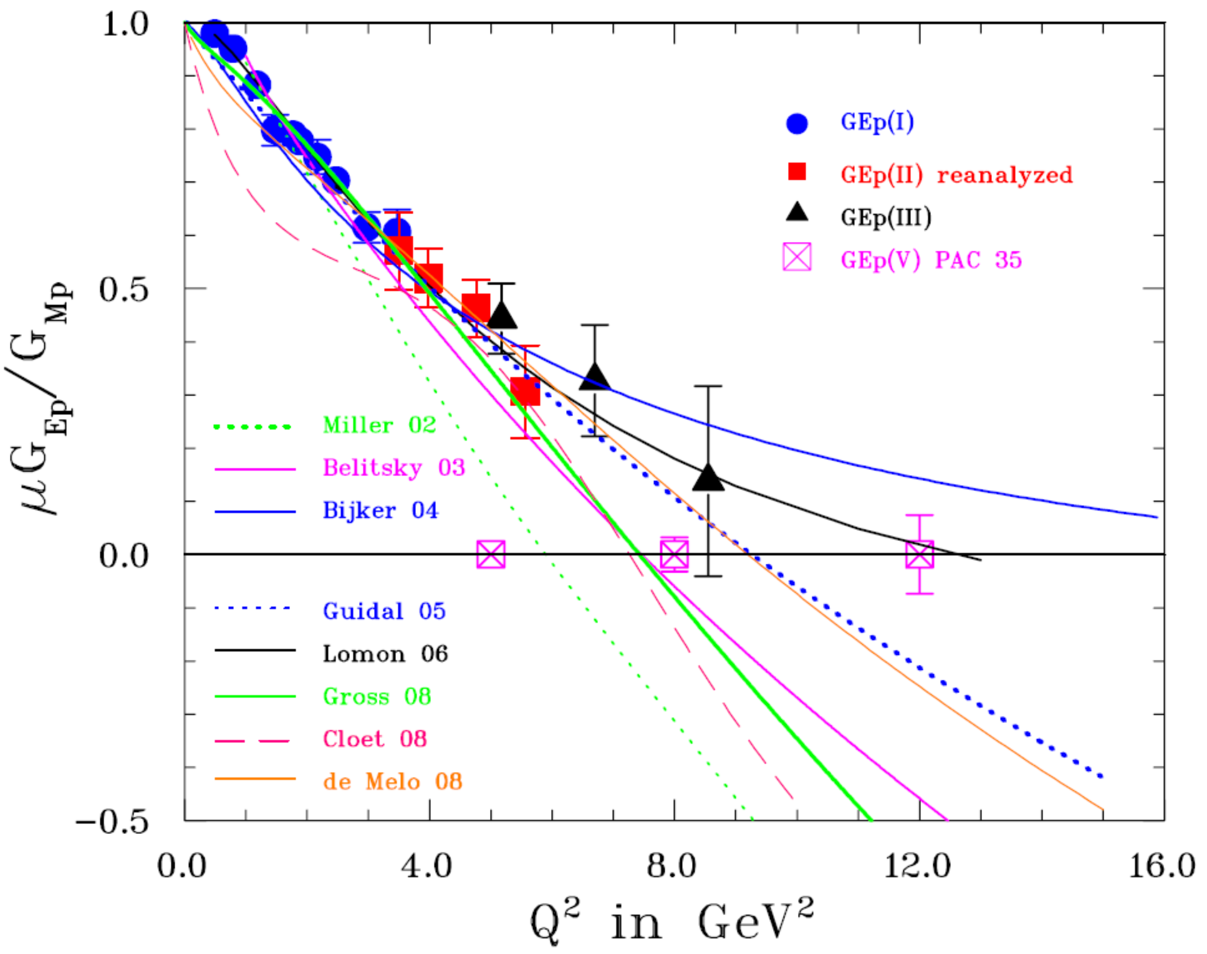


Recoil proton polarization measured using the large-acceptance SBS double polarimeter with large GEM trackers (50 × 200 cm2) together with a highly segmented hadron calorimeter.

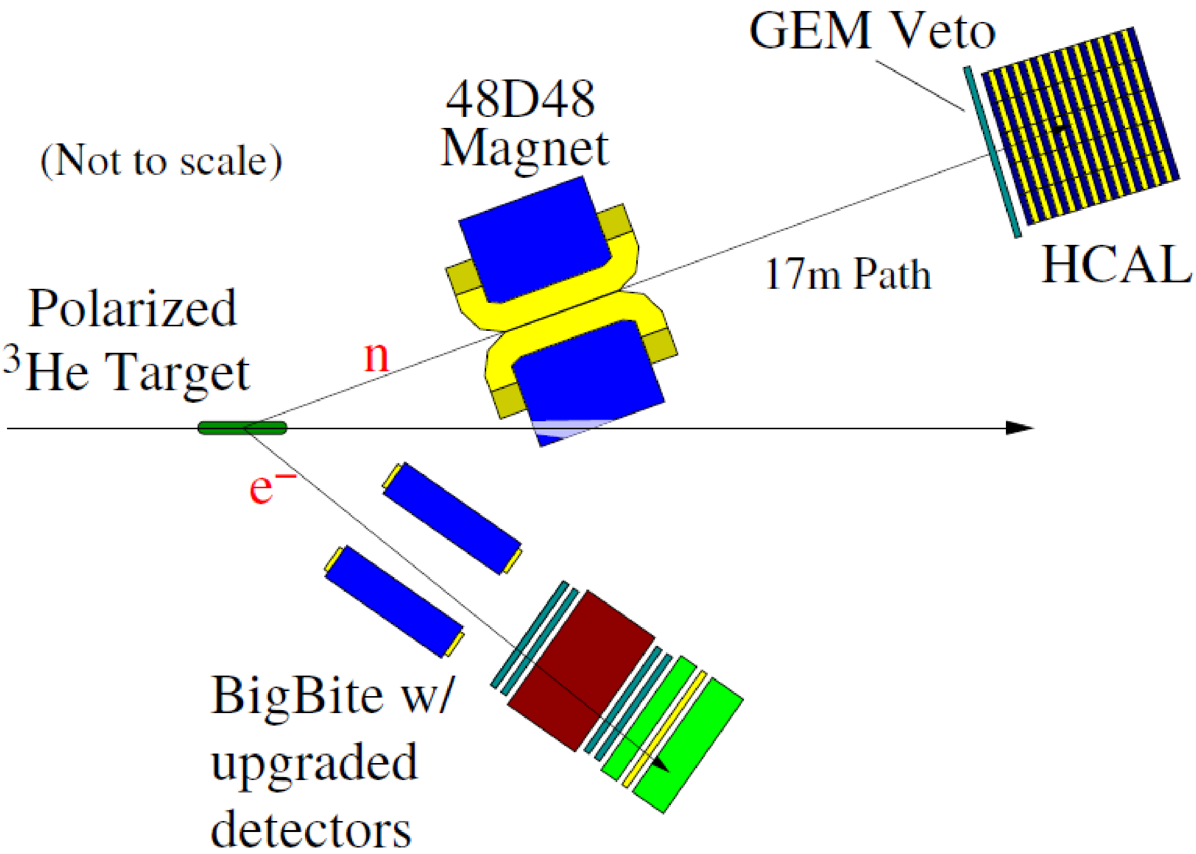
Electron detected in coincidence by a large EM calorimeter, reconfigured "BigCal".

GEp(5) Projected Errors with SBS

Anticipated statistical uncertainties for approved GEp(5) with 45 days of beam.



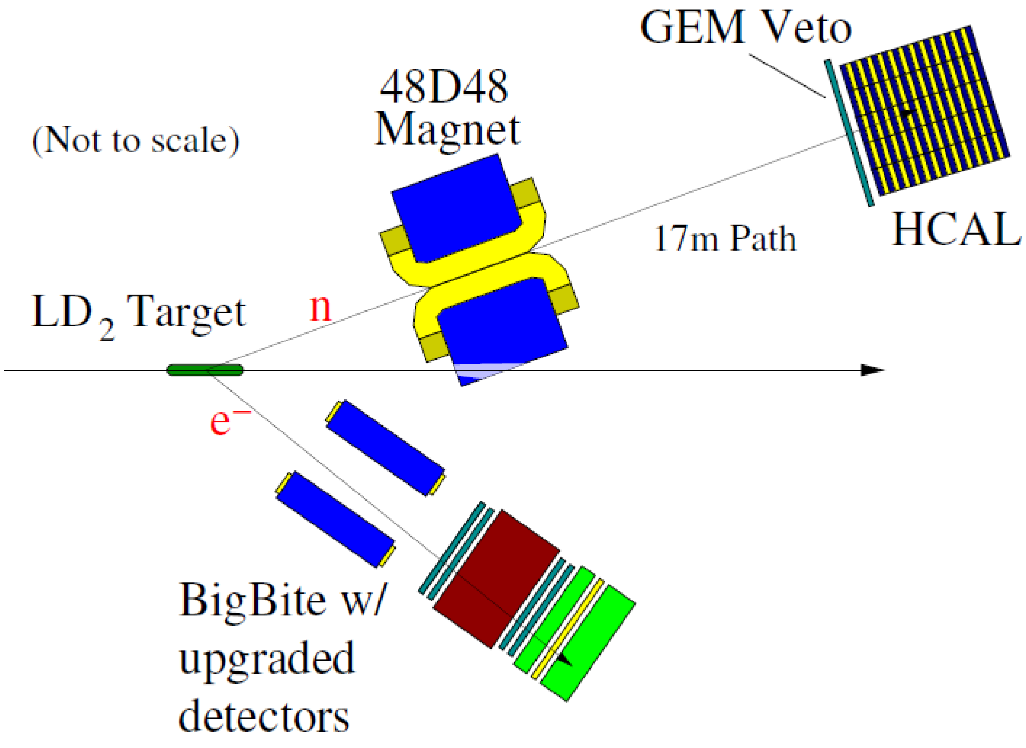
Setup for GEn(2) Experiment



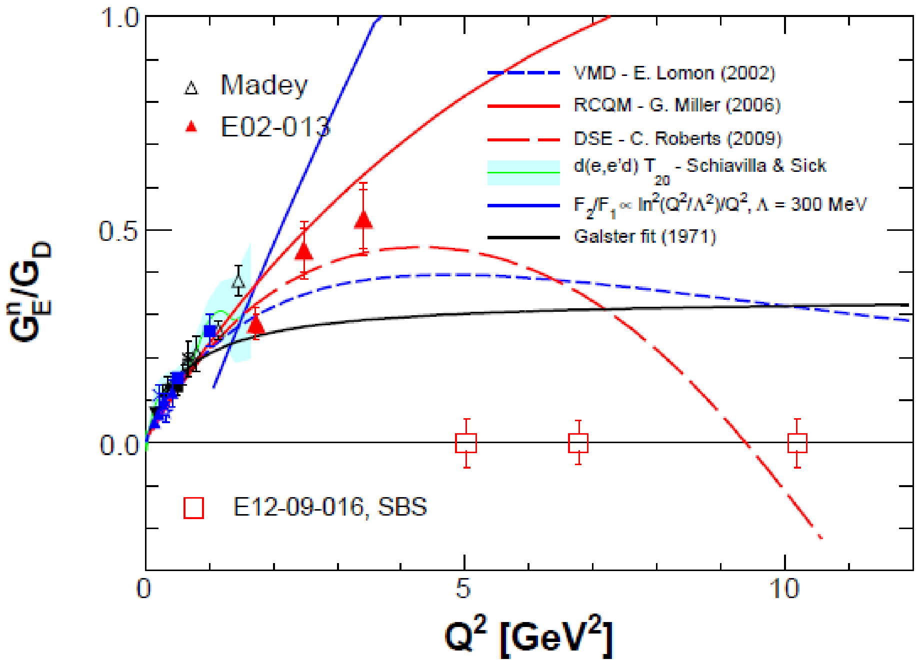
- **Upgraded Bigbite detector stack for higher rates, better resolution for PID**
- **Hadron calorimeter at 17 m, need 0.5 ns ToF resolution**
- **48D48 detects protons**
- **New addition of Cherenkov and GEMs for π^- rejection and high rate tracking**

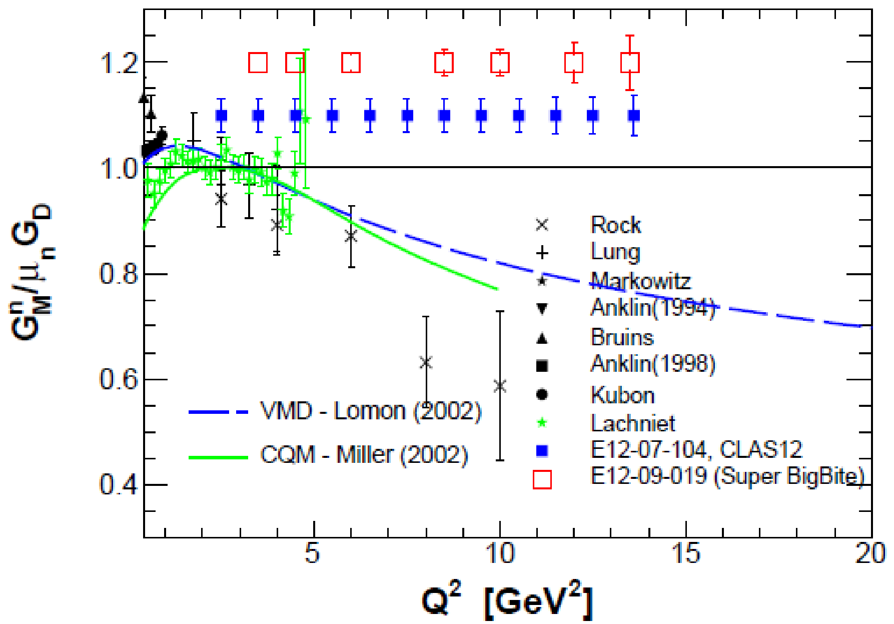
Setup for G_{Mn} Experiment in Hall A

- 7 Q^2 points ranging from 3.5 GeV^2 to 13.5 GeV^2
- Setup similar to G_E^n with LD_2 target



GEn(2) and GMn Projected Errors with SBS

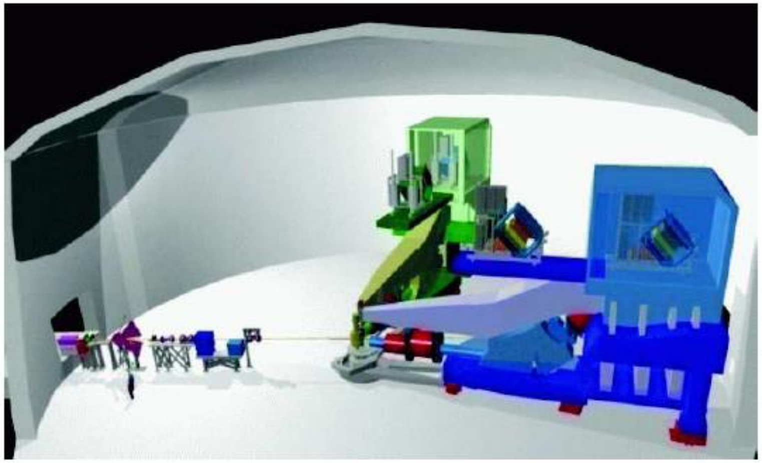




G_{En} in a Q^2 range similar to the other form factors

Red points - with SBS in Hall A
Blue points – with CLAS12 in Hall B

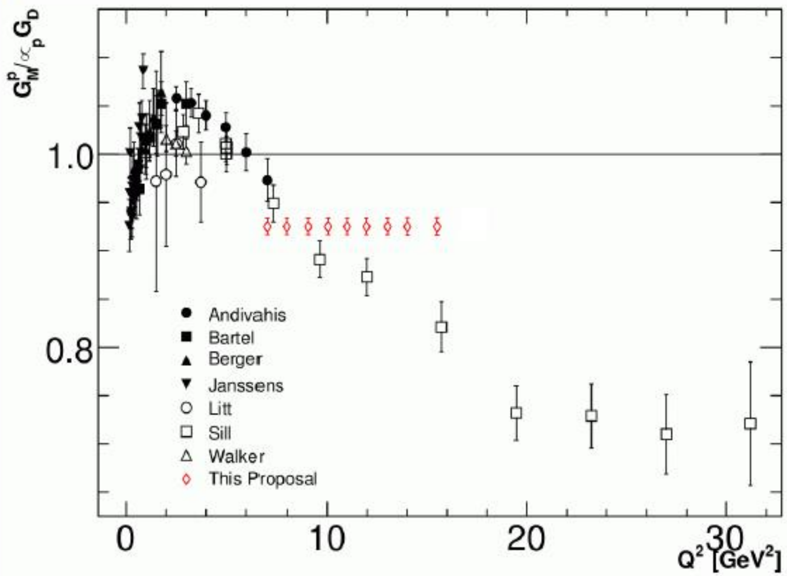
Precision Measurements of G_{Mp} at High Q^2



- E12-07-108 in Hall A (Gilad, Moffitt, Wojtsekhowski, Arrington).
- Precise measurement of ep elastic cross section and extract G_M^p.
- Both HRSs in electron mode.
- Beamtime: 24 days.
- $\mathrm{Q}^2 = 7.0 - 15.5\ \mathrm{GeV}^2$ $(1.0,\ 1.5\ \mathrm{GeV}^2$ steps).
- Significant reduction in uncertainties:

	$d\sigma/d\Omega$	G_M^p
Point-to-Point	1.0-1.3	0.5-0.6
Normalization	1.0-1.3	0.5-0.6
Theory	1.0-2.0	0.5-1.0

- Two-Photon Exchange is a major source of uncertainty → vary ϵ to constrain.
- Sets the scale of other EEFFs.



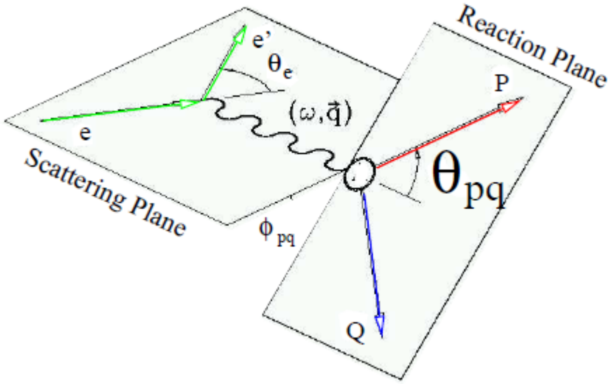
The Ratio Method to measure G_{Mn} in Hall B

- Express the cross section in terms of the Sachs form factors.

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

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

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

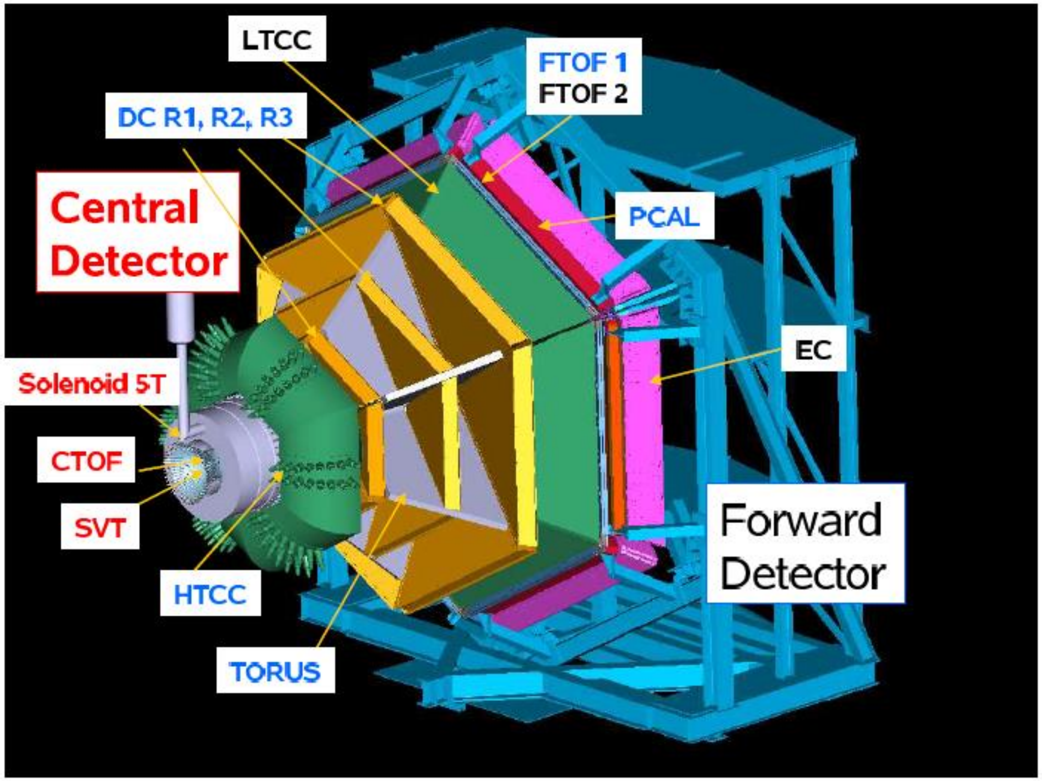


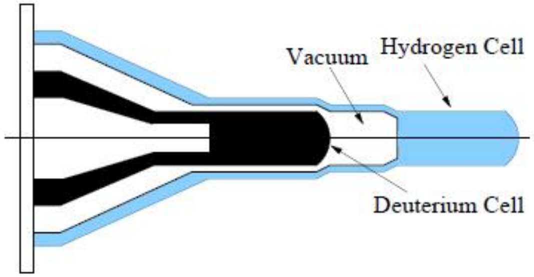
- We can now take the ratio of the $e-p$ and $e-n$ cross sections (the ratio method).

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

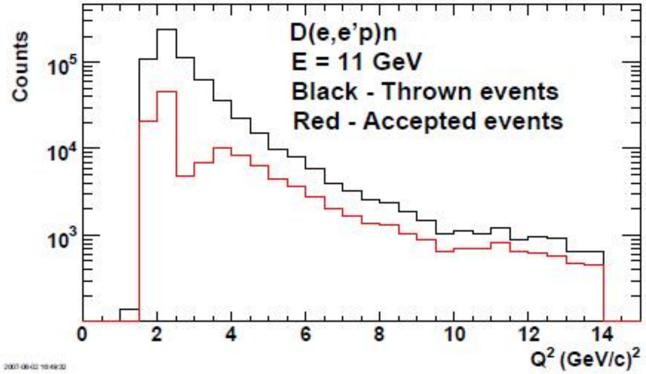
Slide taken from Talk by G.P. Gilfoyle, University of Richmond, Richmond, VA 23173

The CLAS12 Detector and Dual Target Cell





The dual target enables us to collect high-precision, consistent calibration data so systematic uncertainties $\leq 3\%$.



CLAS12 acceptance for quasi-elastic $e-p$ events calculated with FASTMC (CLAS12 parameterized simulation). Range is $Q^2 = 2 - 14(\mathrm{GeV/c})^2$.

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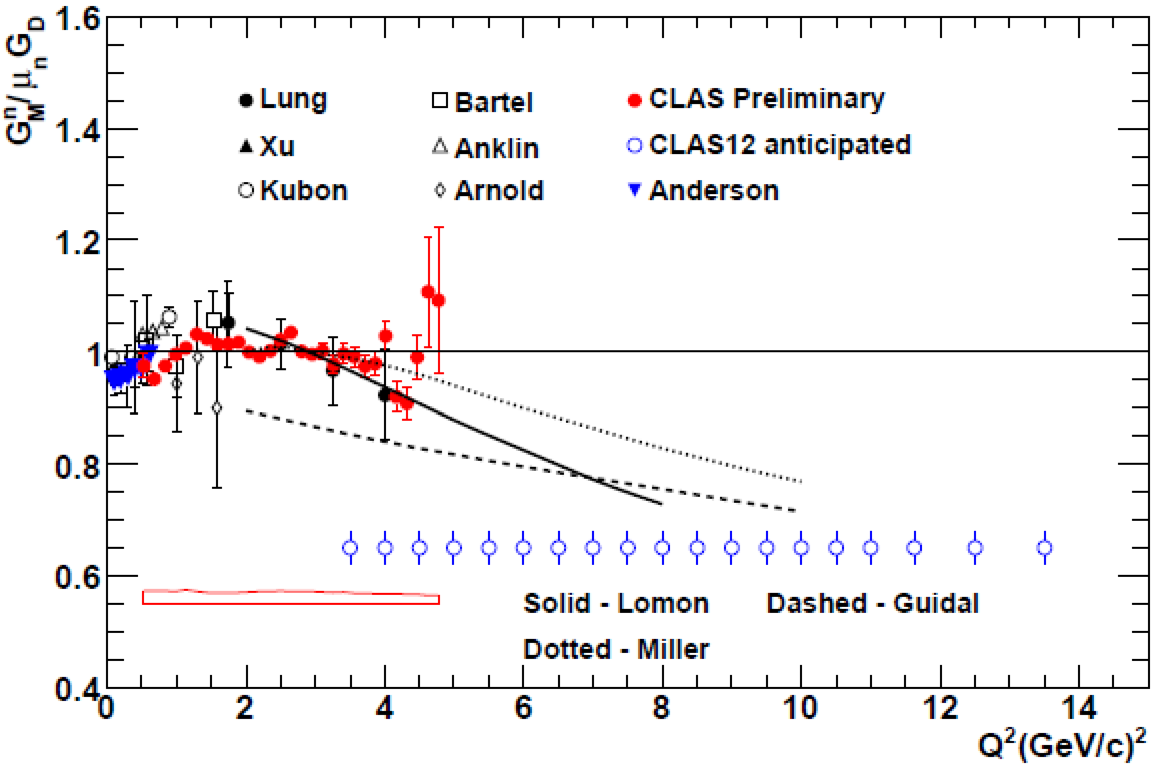
Anticipated Uncertainty for G_{Mn} Hall B Measurements

Expected Q^2 range, systematic uncertainty of 3 % and world data for G_{Mn}



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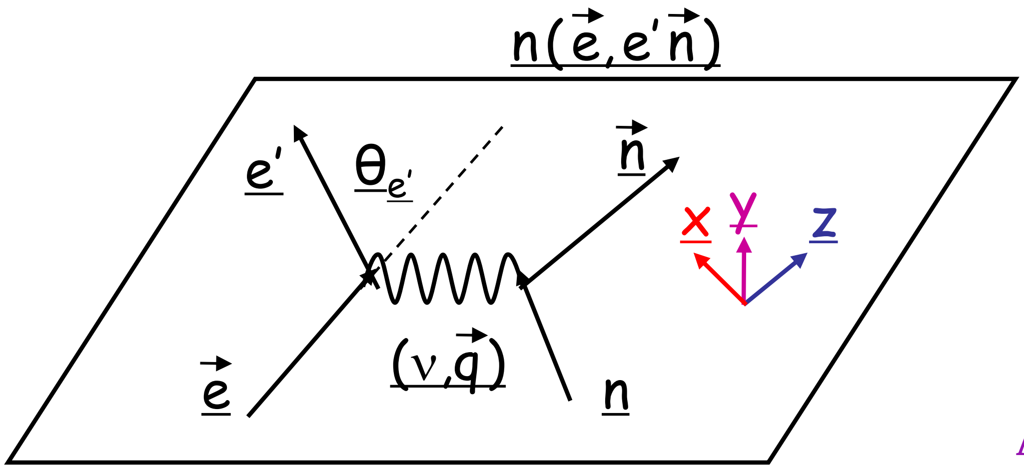
G_{En}/G_{Mn} by Recoil Polarimetry in Hall C



electron scattering plane

Recoil polarization

$$P_x = -P_e K_t G_{En} G_{Mn}$$

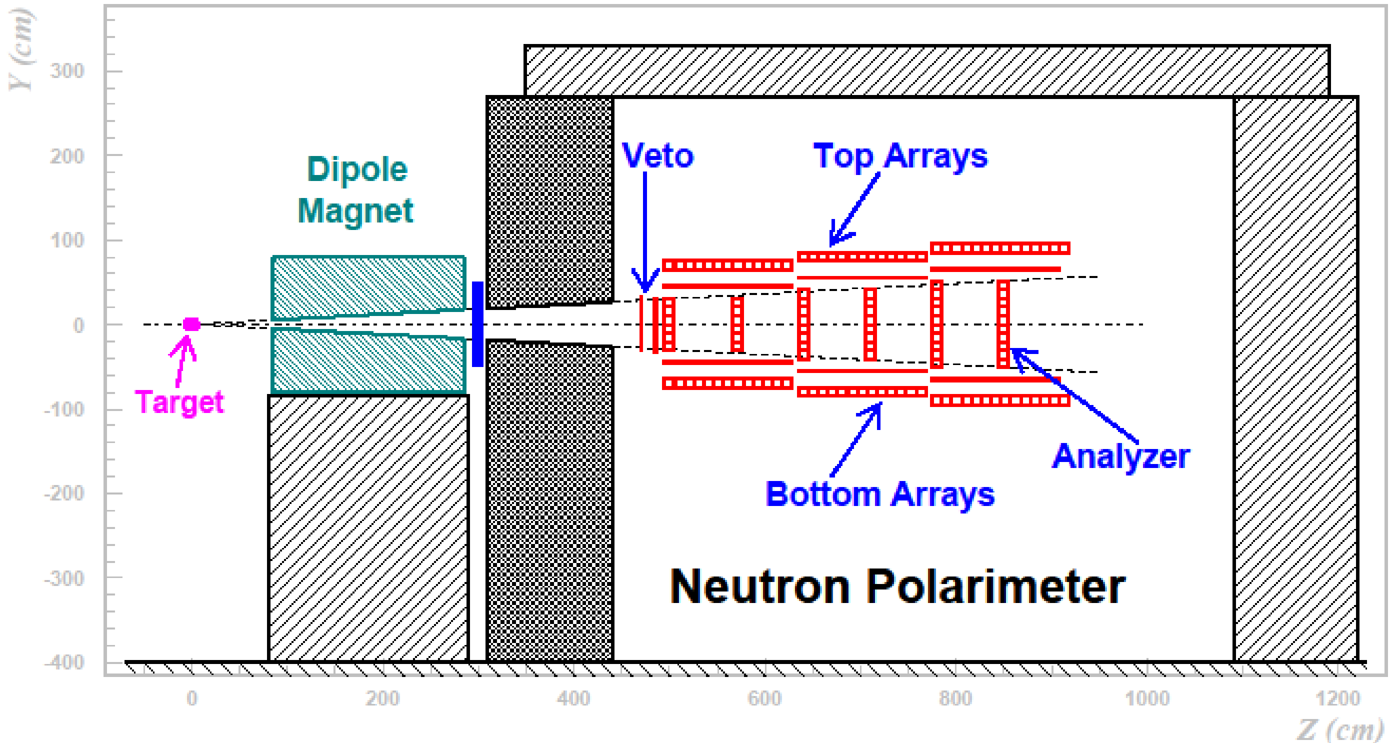
$$P_z = P_e K_\ell G_{Mn}^2$$

Analyzed by second scattering in polarimeter with analyzing power A_Y

Ratio Technique: Measure P_x and P_z → $$\frac{P_x}{P_z} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}}$$ → **small systematics $A_Y(q)$ and P_e cancel**

- **Electrons detected in SHMS**
- **Neutron spin precessing in dipole magnet**
- **Neutron detected, polarization analyzed in neutron polarimeter**
- **Two linear combinations of P_x and P_z (two precession angles)**

Setup for G_{En}/G_{Mn} Experiment in Hall C



New design:Segmented analyzing scintillator
Detection of struck proton rather than scattered neutron
Reconstruct recoil proton direction to 5-6° corresponds to 1.5-2° in neutron angle
Access small neutron angles (large cross section and analyzing power)
Thin analyzer layers reduces multiple interactions (which reduce A_y)
Segmentation of analyzer (plus proton PID and reconstruction) eliminate losses due to random analyzer hits blocking good e-n quasi-elastic events

Projected Errors for G_{En}/G_{Mn} in Hall C

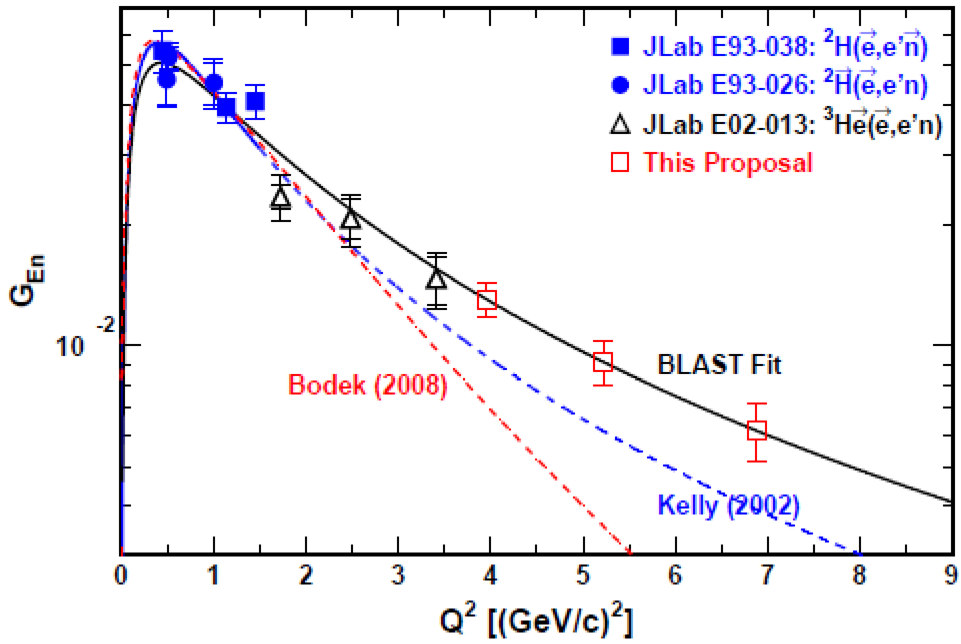


Figure 2: G_E^n versus Q^2. Data from JLab and projections from this proposal. The red line reflects the Bodek (2008) fit, the blue line is our modified Galster fit [Kelly (2002)], and solid black line reflects BLAST fit [Geis (2008)].

Conclusions

- High-Q^2 surprise in G_{Ep}/G_{Mp}, has led to a fundamental change in picture of the internal structure of the proton
- strong impact on theoretical progress, Relativistic dynamics
- no evidence for two-photon exchange effects in ratio obtained from polarization observables
- Form Factors are used to determine the Generalized Parton Distributions for Valence quarks and it allows one to estimate the orbital angular momentum carried by valence quarks, using Ji’s sum rule
- A series of new experiments planned for the era of 12 GeV CEBAF will provide answers to a number of open questions crucial to our understanding of fundamental proton properties, and the nature of QCD in the confinement regime

Thank you for your attention