

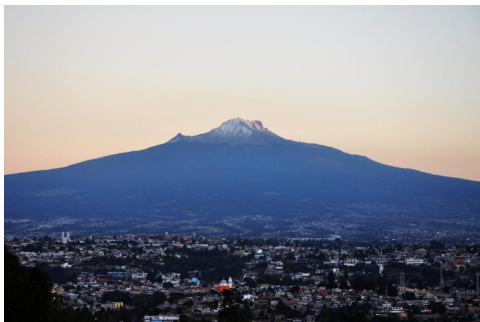
Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab

G.P. Gilfoyle

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Outline

1. Scientific Motivation
2. Necessary Background
3. What We Hope to Learn.
4. The Measurements
5. Summary and Conclusions



Tlaxcala City

Scientific Motivation - What We Hope to Learn.

- Nucleon elastic electromagnetic form factors (EEFFs) describe the distribution of charge and magnetization in the nucleon.
- Reveal the internal landscape of the nucleon and nuclei.
- Rigorously test QCD in the non-perturbative regime.
 - Nuclear models, constituent quarks,...
 - lattice QCD.
- Map the transition from the hadronic picture to QCD.

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Jefferson Lab has completed the 12 GeV Upgrade which doubled the CEBAF accelerator energy.

Some Necessary Background

- EEFs cross section described with Dirac (F_1) and Pauli (F_2) form factors

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \left[(F_1^2 + \kappa^2 \tau F_2^2) + 2\tau (F_1 + \kappa F_2)^2 \tan^2 \left(\frac{\theta_e}{2} \right) \right]$$

where

$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}$$

and κ is the anomalous magnetic moment, E (E') is the incoming (outgoing) electron energy, θ is the scattered electron angle and $\tau = Q^2/4M^2$.

- For convenience use the Sachs form factors.

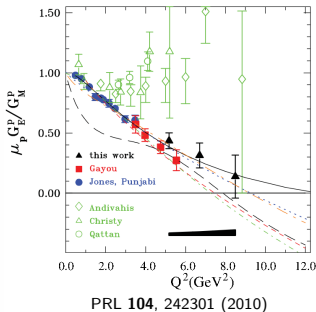
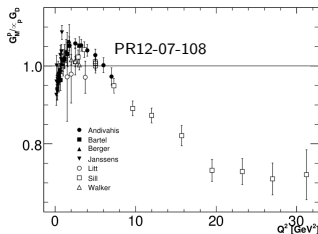
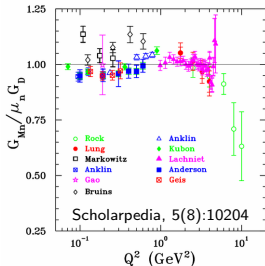
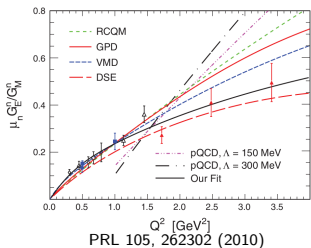
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)} (\epsilon G_E^2 + \tau G_M^2)$$

where

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2 \quad \text{and} \quad \epsilon = \left[1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2} \right]^{-1}$$

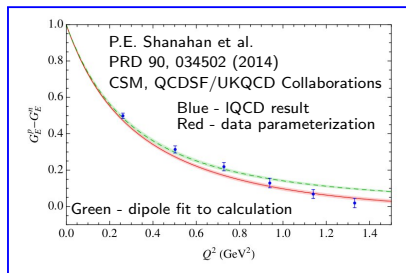
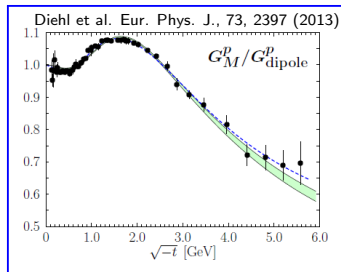
Where We Are Now.

- G_M^P reasonably well known over large Q^2 range.
- The ratio G_E^P/G_M^P from polarization transfer measurements diverged from previous Rosenbluth separations.
 - Two-photon exchange (TPE).
 - Effect of radiative corrections.
- Neutron magnetic FF G_M^n still follows dipole.
- High- Q^2 G_E^n opens up flavor decomposition.



Where We Are Now.

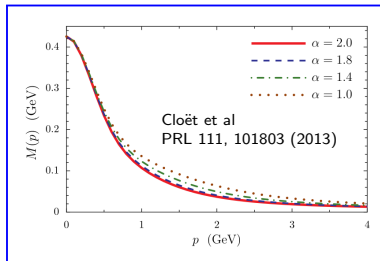
- Many years of model building - Vector Meson Dominance, Constituent Quarks capture much of the four EEFs, but use many parameters.
- Generalized Parton Distributions (GPDs) have also been used. The EEFs are the first moments of the GPDs.
- EEFs are an early test of lattice QCD because isovector form does not have disconnected diagrams.



Where We Are Going - Dyson-Schwinger Eqs

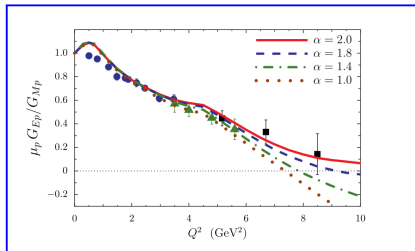
- Equations of motion of quantum field theory.

- Infinite set of coupled integral equations.
- Inherently relativistic, non-perturbative, connected to QCD.
- Deep connection to confinement, dynamical chiral symmetry breaking.
- Infinitely many equations, gauge dependent \rightarrow Choose well!



- Recent results (Cloët et al).

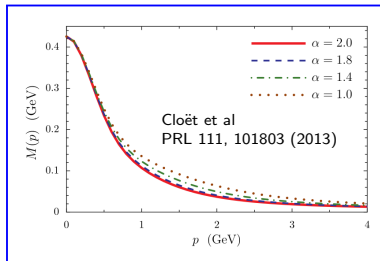
- Model the nucleon dressed quark propagator as a quark-diquark.
- Damp the shape of the mass function $M(p)$.



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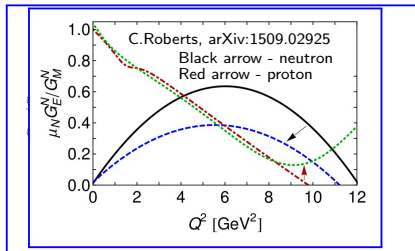
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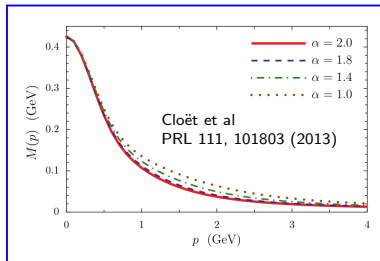
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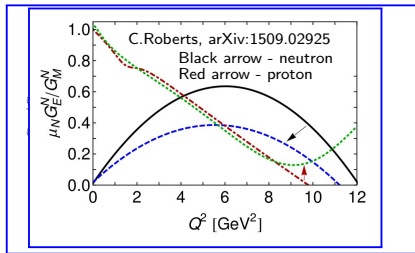
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- Model the nucleon dressed quark propagator as a quark-diquark.
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Position of zero in $\mu_p G_E^p / G_M^p$ and $\mu_n G_E^n / G_M^n$ sensitive to shape of $M(p)$!

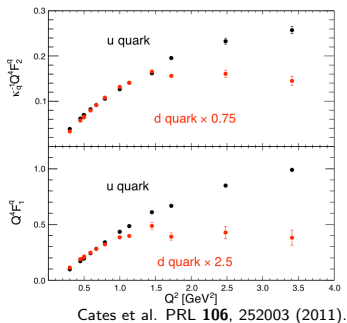


Where We Are Going - Flavor Decomposition

- With all four EEFs we can unravel the contributions of the u and d quarks.
- Assume charge symmetry, no s quarks and use (Miller *et al.* Phys. Rep. **194**, 1 (1990))

$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n \quad F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p$$

- Evidence of di-quarks? d -quark scattering probes the diquark.

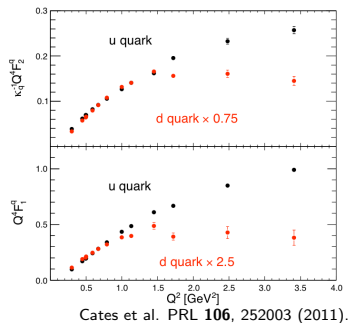
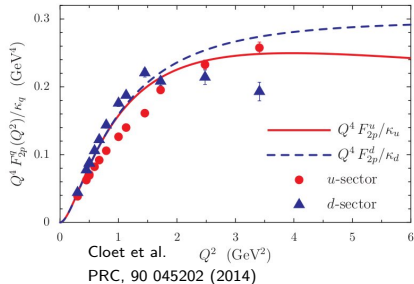


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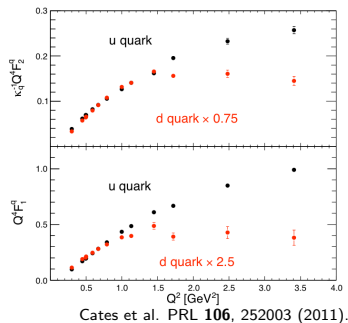
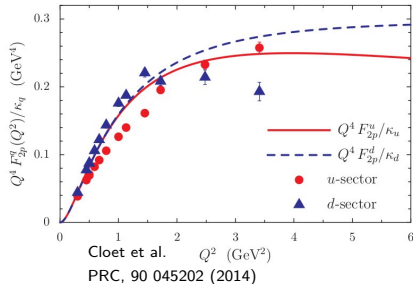
- Agreement with Nambu-Jona-Lasinio model encouraging - no parameter fits to the EEEFs.

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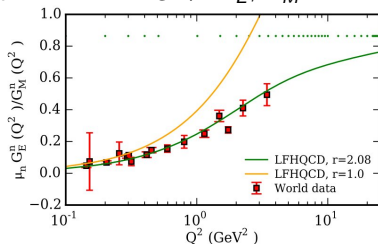


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The JLab program will double our reach in Q^2 to $\approx 8 \text{ GeV}^2$.

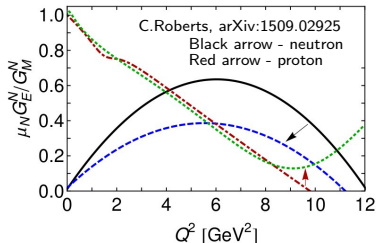
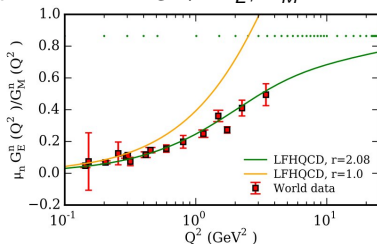
Where We Are Going - Light Front Holographic QCD

- 1 Based on connections between light-front dynamics, it's holographic mapping to anti-de Sitter space, and conformal quantum mechanics.
- 2 Recent paper by Sufian *et al.* (Phys. Rev. D95, 01411 (2017)) included calculations of the electromagnetic form factors that include higher order Fock components $|qqq\bar{q}\bar{q}\rangle$.
- 3 Obtain good agreement with all the form factor data with only three parameters, e.g. $\mu_n G_E^n / G_M^n$.



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- 4 Major difference with DSE approach!

Where We Are Going - New Experiments

The JLab Lineup

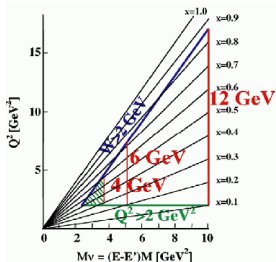
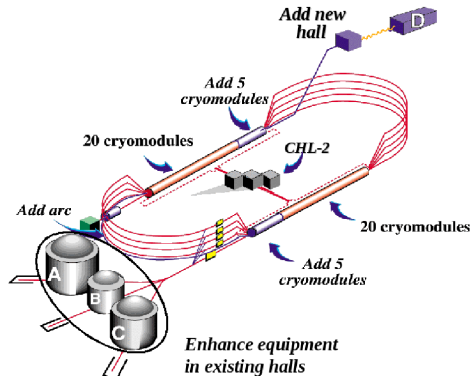
Quantity	Method	Target	$Q^2(\text{GeV}^2)$	Hall	Beam Days
G_M^p *	Elastic scattering	LH_2	7 – 15.5	A	24
G_E^p/G_M^p	Polarization transfer	LH_2	5 – 12	A	45
G_M^n	$E - p/e - n$ ratio	$LD_2 - LH_2$	3.5 – 13.0	B	30
G_M^n	$E - p/e - n$ ratio	LD_2, LH_2	3.5 – 13.5	A	25
G_E^n/G_M^n	Double polarization asymmetry	polarized ^3He	5 – 8	A	50
G_E^n/G_M^n	Polarization transfer	LD_2	4 – 7	C	50
G_E^n/G_M^n	Polarization transfer	LD_2	4.5	A	5

* Data collection is complete.

PAC approval for 229 days of running in the first five years.

All experiments build on successful ones from the 6-GeV era.

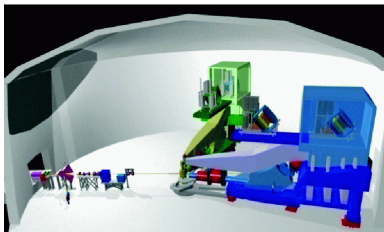
How We Will Get There: Jefferson Lab



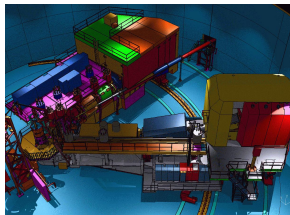
Continuous Electron Beam Accelerator Facility (CEBAF)

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

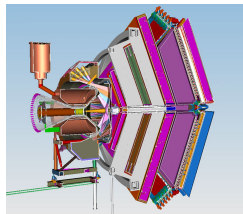
The Experiments - New Detectors



Hall A - High Resolution Spectrometer (HRS) pair, SuperBigBite (SBS), neutron detector, and specialized installation experiments.



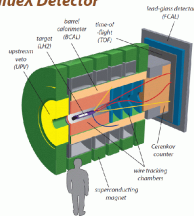
Hall C - New Super High Momentum Spectrometer to paired with the existing High Momentum Spectrometer.



Hall B - CLAS12 large acceptance spectrometer operating at high luminosity with toroid (forward detector) and solenoid (central detector).

Hall D - A new large acceptance detector based on a solenoid magnet for photon beams is under construction.

GlueX Detector

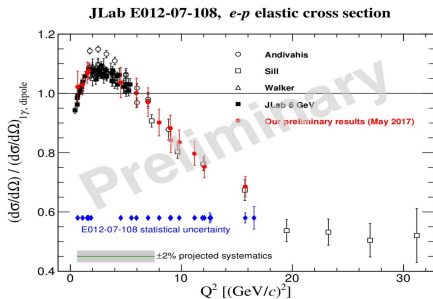
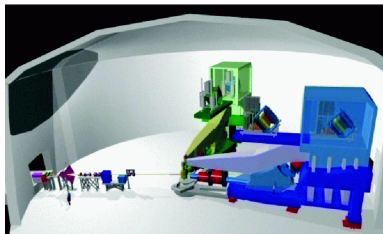


Proton Magnetic Form Factor - G_M^p

- 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.
- $Q^2 = 7.0 - 15.5 \text{ GeV}^2$ (1.0, 1.5 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 \rightarrow vary ϵ to constrain.
- Sets the scale of other EEEFs.
- Completed data collection this year.



E. Christy, Hall A Summer Meeting 2017

Proton Form Factor Ratio G_E^p/G_M^p

- E12-07-109 (Gep(5)) in Hall A (Brash, Jones, Perdrisat, Pentchev, Cisbani, Punjabi, Khandaker, Wojtsekhowski).
- Polarization transfer using $H(\vec{e}, e'\vec{p})$:

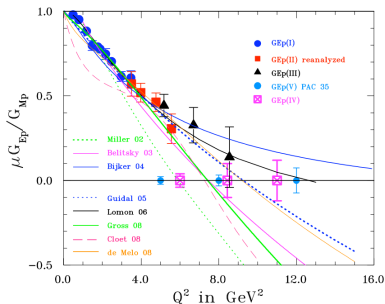
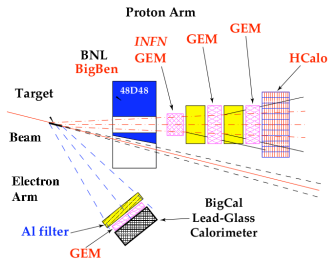
$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l} \frac{E + E'}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

- Electron arm: EM calorimeter (BigCal).
- Proton arm: new, large-acceptance magnetic spectrometer (SBS) with double polarimeter, and hadron calorimeter.
- Beamtime: 45 days.
- Kinematics and Uncertainties:

Q^2 (GeV ²)	5.0	8.0	12.0
$\Delta[\mu G_E/G_M]$	0.025	0.031	0.069

- Rated high impact by JLab PAC.
- Running expected in 3-4 years.

Proton form factors ratio, GEp(5) (E12-07-109)



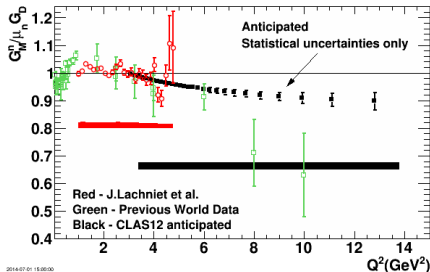
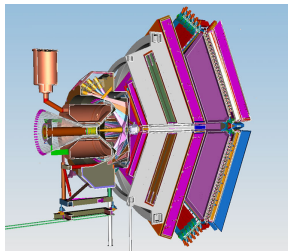
Neutron Magnetic Form Factor G_M^n - 1

- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium:

$$R = \frac{\frac{d\sigma}{d\Omega} [{}^2\text{H}(e, e'n)_{QE}]}{\frac{d\sigma}{d\Omega} [{}^2\text{H}(e, e'p)_{QE}]}$$
$$= a \times \frac{\sigma_{Mott} \left(\frac{(G_E^n)^2 + \tau(G_M^n)^2}{1+\tau} + 2\tau \tan^2 \frac{\theta_e}{2} (G_M^n)^2 \right)}{\frac{d\sigma}{d\Omega} [{}^1\text{H}(e, e')p]}$$

where a is nuclear correction.

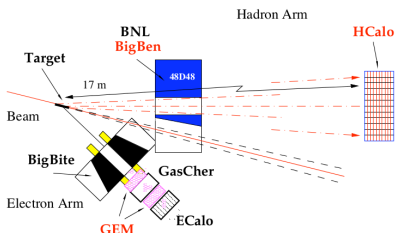
- Precise neutron detection efficiency needed to keep systematics low.
 - tagged neutrons from $p(e, e'\pi^+n)$.
 - Dual $LD_2 - LH_2$ target.
- Kinematics: $Q^2 = 3.5 - 13.0 \text{ (GeV/c)}^2$.
- Beamtime: 30 days.
- Systematic uncertainties $< 2.5\%$ across full Q^2 range.
- Running expected in 2019.



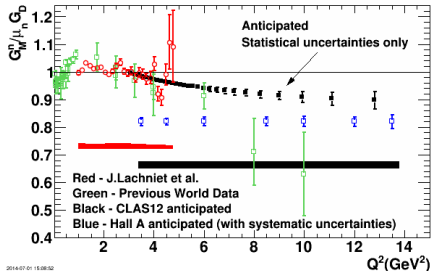
Neutron Magnetic Form Factor G_M^n - 2

- E12-09-019 in Hall A (Quinn, Wojtsekhowski, Gilman).
- Ratio Method on Deuterium as in Hall B:

$$R = \frac{d\sigma}{d\Omega} [{}^2\text{H}(e, e' n)_{QE}] / \frac{d\sigma}{d\Omega} [{}^2\text{H}(e, e' p)_{QE}]$$
- Electron arm: SuperBigBite spectrometer.
- Hadron arm: hadron calorimeter (HCal).
- Neutron detection efficiency:
 - Use $p(\gamma, \pi^+)n$ for tagged neutrons.
 - End-point method.



- Kinematics: $Q^2 = 3.5 - 13.5 \text{ (GeV}/c)^2$.
- Beamtime: 25 days.
- Systematic uncertainties $< 2.1\%$.
- Two G_M^n measurements 'allow a better control for the systematic error' (PAC34).
- Expected in next 2-3 years.

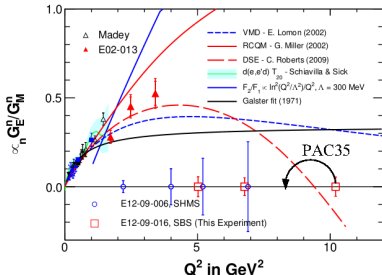
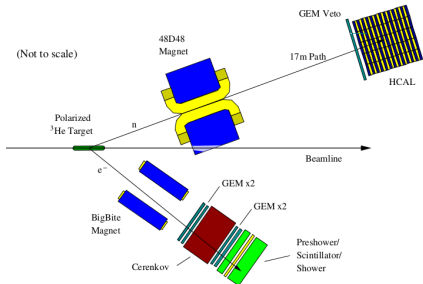


Neutron Form Factor Ratio $G_E^n/G_M^n - 1$

- E12-09-016 in Hall A (Cates, Wojtsekhowski, Riordan).
- Double Polarization Asymmetry: Get A_{en}^V from ${}^3\text{He}(\vec{e}, e'n)pp$.
- Longitudinally polarized electron beam.
- ${}^3\text{He}$ target polarized perpendicular to the momentum transfer.
- Electron arm: Super BigBite spectrometer.
- Neutron arm: hadron calorimeter HCAL (overlap with GEp(5) and Hall A G_M^n).
- Beamtime: 50 days.
- Kinematics and Uncertainties:

Q^2 (GeV ²)	5.0	6.8	8.0
$\Delta \left[\frac{\mu G_E}{G_M} \right]_{stat}$	0.027	0.022	0.032
$\Delta \left[\frac{\mu G_E}{G_M} \right]_{syst}$	0.018	0.021	0.013

- Expected in next 3-4 years.

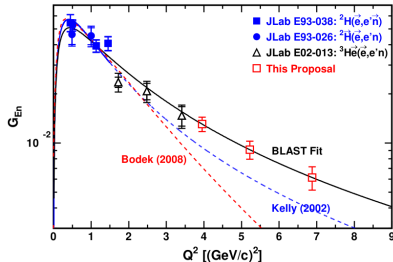
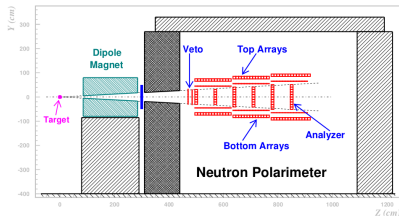


Neutron Form Factor Ratio $G_E^n/G_M^n - 2$

- E12-11-009 in Hall C (Sawatzky, Arrington, Kohl, Semenov).
- Polarization transfer using ${}^2\text{H}(\vec{e}, e'\vec{n})p$:

$$\frac{G_E^n}{G_M^n} = -\frac{P_t}{P_l} \frac{E + E'}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

- Electron arm: Super High Momentum Spectrometer (SHMS).
- Neutron arm: neutron polarimeter with tapered-gap neutron-spin-precession magnet and proton recoil detection.
- Kinematics: $Q^2 = 3.95, 6.88 \text{ (GeV}/c)^2$.
- Beamtime: 50 days.
- Systematic uncertainties about 2-3%.
- Statistical uncertainties about 10-16%.
- Complementary to the ${}^3\text{He}$ experiment.
- Expected after 2020.



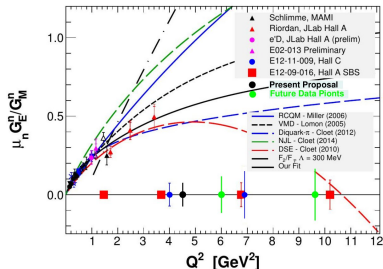
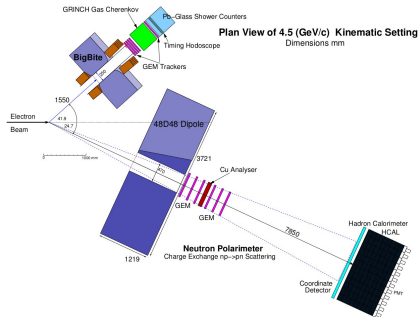
Neutron Form Factor Ratio $G_E^n/G_M^n - 3$

- E12-17-004 in Hall A (Annand, Bellini, Kohl, Psikunov, Sawatzky, Wojtsekhowski).

- Polarization transfer using $^2\text{H}(\vec{e}, e'\vec{n})p$:

$$\frac{G_E^n}{G_M^n} = -\frac{P_t}{P_l} \frac{E + E'}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

- Electron arm: Super Big Bite Spectrometer.
- Neutron arm: HCal, neutron polarimeter, CDet coordinate detector, scintillation counter.
- Kinematics: $Q^2 = 4.5 \text{ (GeV/c)}^2$.
- Beamtime: 5 days.
- Systematic uncertainties about 3%.
- Statistical uncertainties about 8%.
- Will test extension of neutron polarimetry to high Q^2 .
- Expected in the next 2-3 years.



Summary and Conclusions

- Large gains over the last decade in physics understanding of the EEFFs built on new technologies and capabilities.
- Major changes in our understanding of nucleon structure.
- At JLab we have begun a broad assault on the EEFFs and will significantly expand the physics reach of our understanding.
- Discovery potential in mapping out nucleon structure and understanding QCD.

Additional Slides

Beyond Elastic Form Factor Measurements

Additional form factor studies after the 12 GeV Upgrade.

Experiment	Spokesperson	Title	Hall	Beamtime
PR12-06-101	G. Huber	Measurement of the charged pion form factor to high Q^2	C	52 days
PR12-09-003	R. Gothe	Nucleon resonance studies with CLAS12	B	40 days

High-Impact Experiments from JLab PAC

PAC Days
 Boldface = days designated High Impact
 Parentheses = days not counting toward High Impact total

PAC41 "High Impact" Selection

Row Color
 Yellow = High Impact
 Green = backup exp

Exp#	Exp name	Hall	Run Group/ Days	PAC Days	PAC grade	Comments
TOPIC 1 : SPECTROSCOPY						
E11-06-102	GlueX Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	D		(125) approved +90	A	GlueX - assumed half commissioning/half physics +plus (30) commissioning days
TOPIC 2 : FORM FACTORS						
E12-06-101	Measurement of the Charged Pion Form Factor in High Q ²	C		52	A	Requires fully commissioned SHMS
E12-07-100	GEp-GMP Large-Acceptance Proton Form Factor Ratio Measurements at 13 and 15 GeV/c ² Using Recoil Polarization Method	A		45	A	Requires SRS and high power cryo target
E12-11-106	High Precision Measurement of the Proton Charge Radius	B		15	A	Non-CLAS12 experiment; Pilot
TOPIC 3 : PDFs						
E12-06-113	BONUS : The Structure of the Free Neutron at Large x-Bjorken	B	F40	(43) approved -	A	Requires BONUS Radial TPC upgrade +42 days High Impact for the experiment
E12-10-100	MARATHON Measurement of the F ₂ H ₂ , d ₂ Ratios and A-1 EMC Effect in DIS off the Tritium and Helium Mirror Nuclei	A	Tritium target group#1	(42) approved (42)	A	that runs first; experiments are equally important & both are essential
E12-06-114	AtN HallC-3He : Measurement of Neutron Spin Asymmetry A _{1n} in the Valencia Quark Region Using an 11 GeV Beam and a Polarized 3He target in Hall C	C		36	A	Requires high luminosity 3He
TOPIC 4T : TMDs						
E12-11-101	TMD CLAS-HDICE : SIDIS on Transversely polarized target	B	G110	110 concurrent	A	Requires transversely polarized HDice with electron beam
E12-12-009	Dihadron CLAS-HDICE : Measurement of transversity with dihadron production in SIDIS with transversely polarized target	B	G110	(110) concurrent	A	Requires transversely polarized HDice with electron beam C1 Proposed
E12-06-112	TMD CLAS-H(Umpol) : Probing the Proton's Quark Dynamics in Same-Inclusive Pion Production at 12 GeV	B	A139	(80) approved +10	A	Hall B commissioning + 10 days +plus (50) commissioning days
TOPIC 4G : GPDs						
E12-06-114	DVCS HallA-H(UU,LU) : Measurements of Electron-Helicity Dependent Cross Sections of DVCS with CEBAF at 12 GeV	A	Early DVCS & GPD/SD	(100) approved +70	A	Hall A commissioning
E12-12-110	DVCS CLAS-HDICE : DVCS at 11 GeV with transversely polarized target using the CLAS12 Detector	B	G110	(110) concurrent	A	Requires transversely polarized HDice with electron beam C1 Proposed
E12-11-004	DVCS CLAS-D(UU,LU) : DVCS on the Neutron with CLAS12 at 11 GeV	B	B-90	(80) approved	A	Requires D target; central neutron detector ready in 2016 +Backup GPD-E meas if HDICE delayed
TOPIC 5 : NUCLEAR						
E12-11-004	Bubble Chamber : Measurement of 90° ⁺ at12C with a bubblechamber and a transmutating beam	BNJ		14	A	Our guess: 2017
E12-11-101	PREx-II : Precision Parity-Violating Measurement of the Neutron Skin of Lead	A		35	A	Requires sputum, Pb target, 1% Moller polarimetry
E12-06-100	SRC-nix : Inclusive Scattering from Nuclei at $Q^2 \sim 15$ in the kinematic and density realistic regime.	C		32	A	
E12-11-102	SRC-Tritium : Precision measurement of the isospin dependence in the 2N and 3N short range correlation region.	A	Tritium target group#1	19	A	
TOPIC 6 : FUNDAMENTAL SYMMETRIES						
E12-11-006	HPS Status of the Heavy Pion Search Experiment at Jefferson Laboratory (Update on PR12_11_006)	B	H180	(150) approved +39	A	non-CLAS12 experiment; HPS +25 pre-CLAS engr + 14 physics @ 4.4 GeV
E12-10-000	APEX : Search for new Vector Boson A1 Decaying to e^+e^-	A		34	A	Requires new sputum and target system