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

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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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EEFFs have played an essential role in nuclear and nucleon structure for more than a half century.

Some Necessary Background

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

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

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.

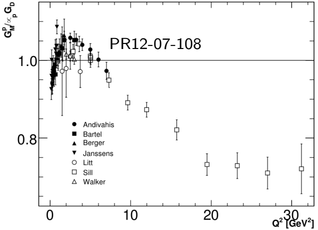
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2 + \tau G_M^2\right)$$

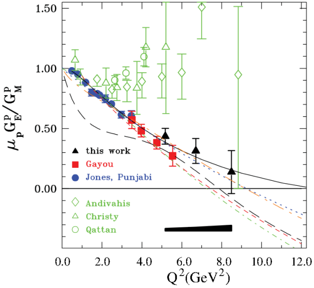
where

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

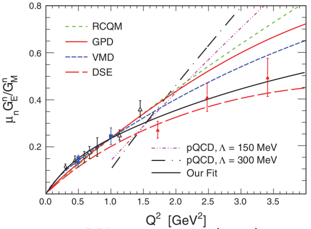
Where We Are Now.

- G_M^p reasonably well known over large Q^2 range.
- The ratio G_E^p/G_M^p from recoil polarization 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.





PRL **104**, 242301 (2010)



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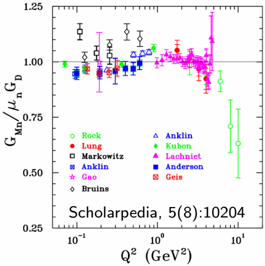

Scholarpedia, 5(8):10204

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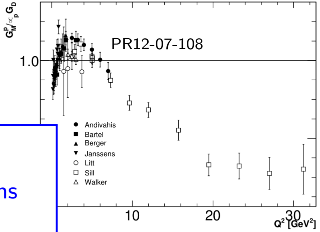
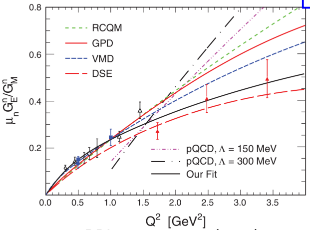
Advances driven by:

- high luminosity beams
- large acceptance detectors
- polarized beams, targets, detectors





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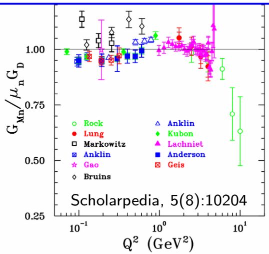

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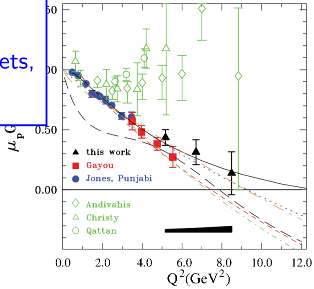

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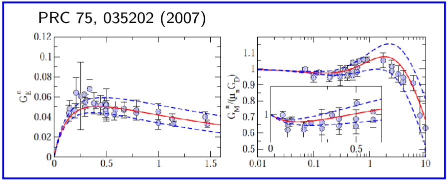
Where We Are Now.

- Vector Meson Dominance and dispersion analyses fit all four EEFFs, but use many parameters.
- Constituent Quark Models highlight relativity, but don't capture all of QCD.
- EEFFs are the first moments of the GPDs.
- EEFFs are an early test of lattice QCD because isovector form does not have disconnected diagrams.



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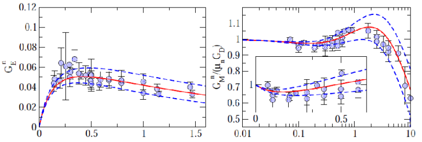

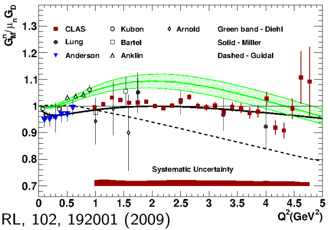

PRL, 102, 192001 (2009)

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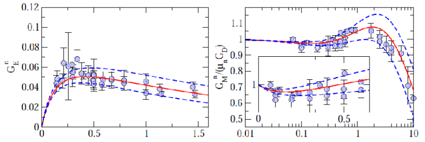

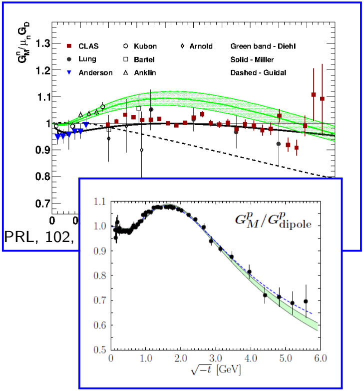

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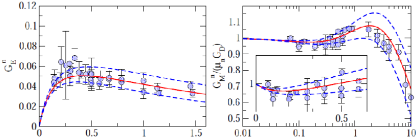

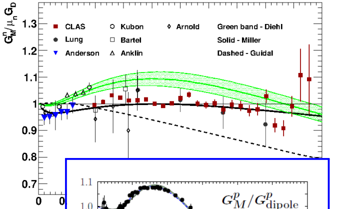

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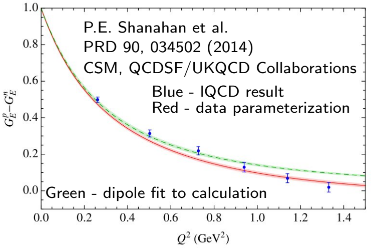

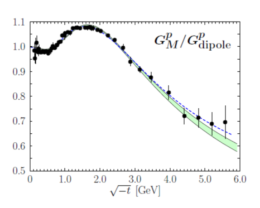

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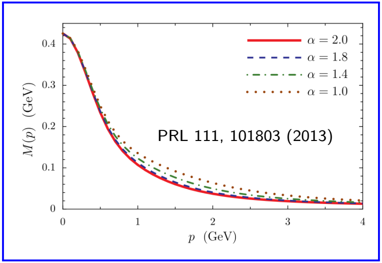
Where We Are Going - Dyson-Schwinger Eqs

- 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!



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

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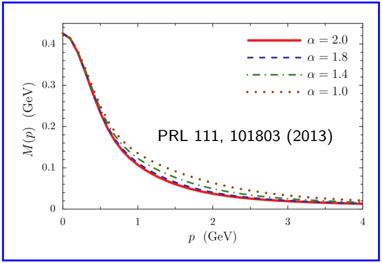

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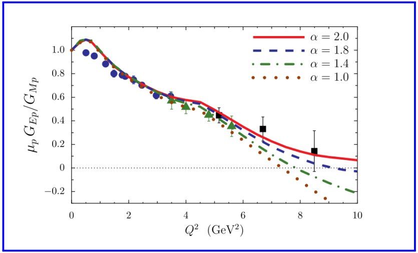

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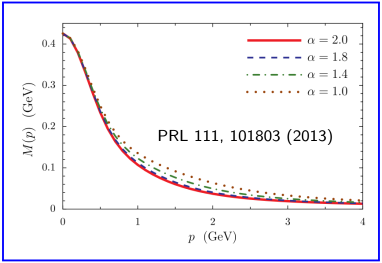

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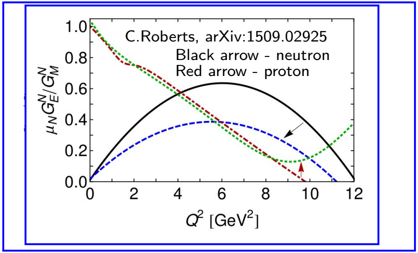

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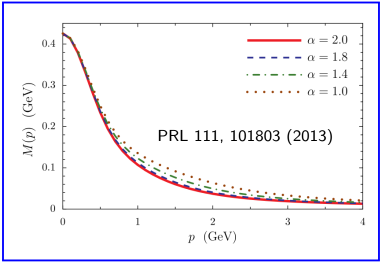

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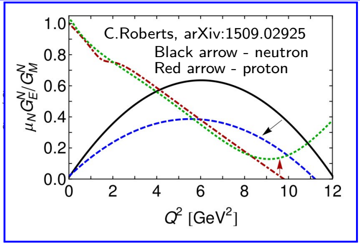
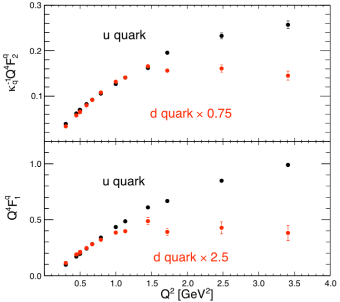
Position of zero in $\mu_p G_E^p / G_M^p$ and $\mu_n G_E^n / G_M^n$ sensitive to shape of $M(p)$!



Where We Are Going - Flavor Decomposition

- With all four EEFFs 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))

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \qquad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$



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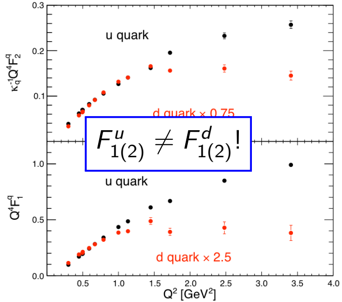

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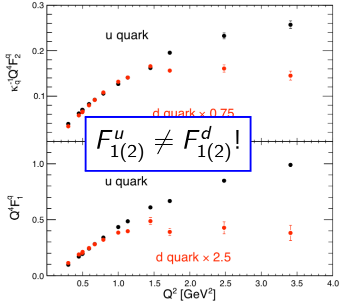

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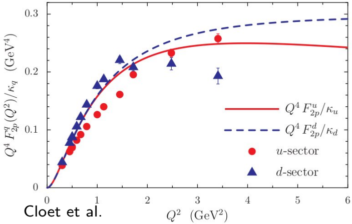

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PRC, 90 045202 (2014)

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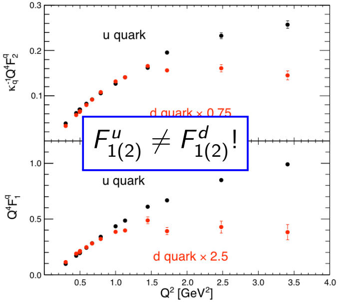

$$\boxed{F^{u}_{1(2)} \neq F^{d}_{1(2)}!}$$

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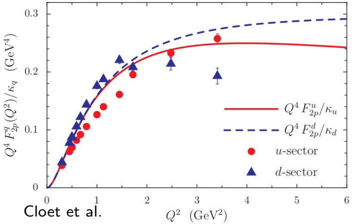

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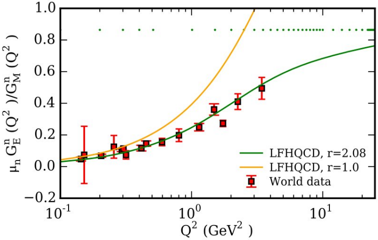
The JLab program will double our reach in Q^2 to $\approx 8\ GeV^2$.

Where We Are Going - Light Front Holographic QCD

1. Based on connections between light-front dynamic, 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 $|qqqq\overline{q}\rangle$.
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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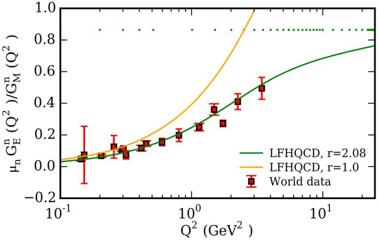
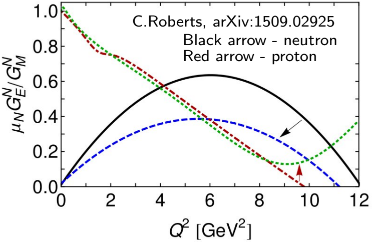




4. Major difference with DSE approach!

Where We Are Going - New Experiments

The JLab Lineup

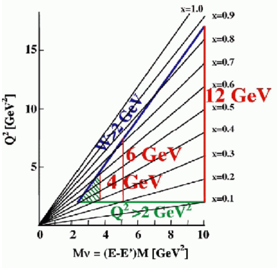
Quantity	Method	Target	$Q^2(GeV^2)$	Hall	Beam Days
G_M^p *	Elastic scattering	LH_2	$7-15.5$	A	24
G_E^p/G_M^p	Polarization transfer	LH_2	$5-12$	A	45
G_M^n	$E-p/e-n$ ratio	LD_2-LH_2	$3.5-13.0$	B	30
G_M^n	$E-p/e-n$ ratio	LD_2, LH_2	$3.5-13.5$	A	25
G_E^n/G_M^n	Double polarization asymmetry	polarized ^{3}He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

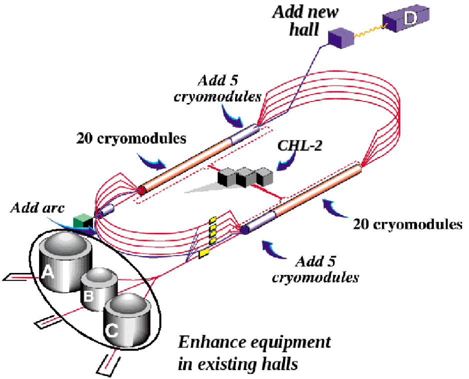
* Data collection is complete.

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

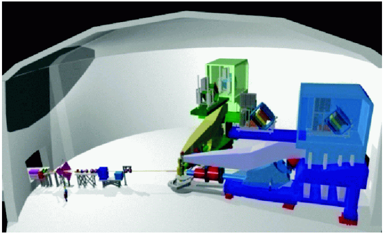




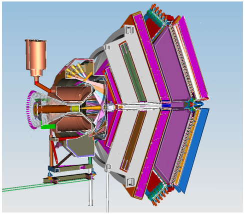
Continuous Electron Beam Accelerator Facility (CEBAF)

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

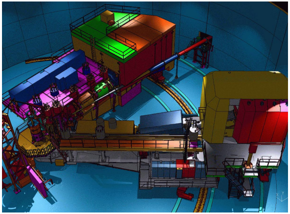
The Experiments - New Detectors



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

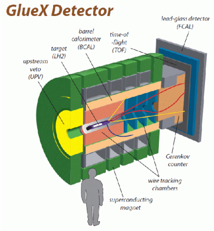


Hall B - CLAS12 large acceptance spectrometer operating at high luminosity with toroid (forward detector) and solenoid (central detector).



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

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

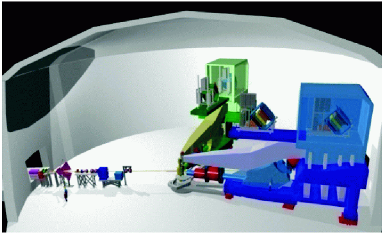


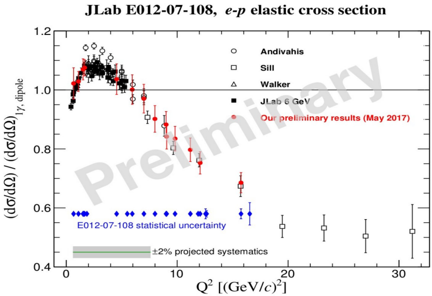
Proton Magnetic Form Factor - G_M^p

- 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 EEFFs.
- Completed data collection this year.





E. Christy, Hall A Summer Meeting 2017

Proton Form Factor Ratio G_E^p/G_M^p

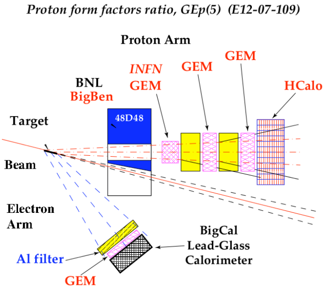
- E12-07-109 (GEp(5)) in Hall A (Brash, Jones, Perdrisat, Pentchev, Cisbani, Punjabi, Khandaker, Wojtsekhowski).
- Polarization transfer using $\mathrm{H}(\vec{e}, e'\vec{p})$:

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

- 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

- Combined with GEp(4).
- Rated high impact by JLab PAC.
- Running expected in 3-4 years.



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 $\mathrm{H}(\vec{e}, e'\vec{p})$:

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

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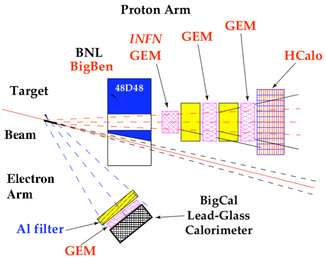
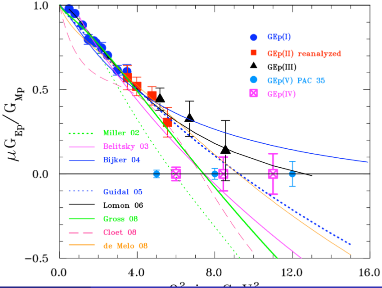
Proton form factors ratio, GEp(5) (E12-07-109)





Neutron Magnetic Form Factor G_M^n - 1

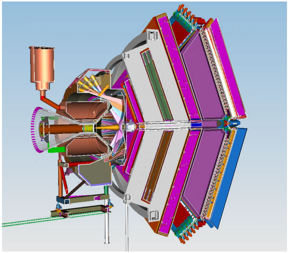
- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium:

$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$

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

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: $\mathrm{Q}^2 = 3.5 - 13.0\ (\mathrm{GeV/c})^2$.
- Beamtime: 30 days.
- Systematic uncertainties $<$ 2.5% across full Q^2 range.
- Running expected in 2019.



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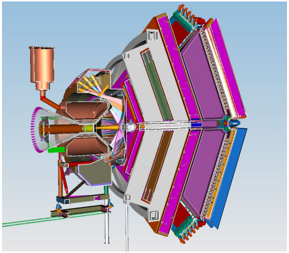

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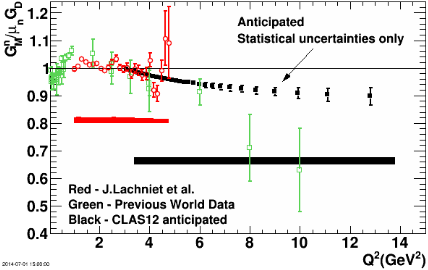
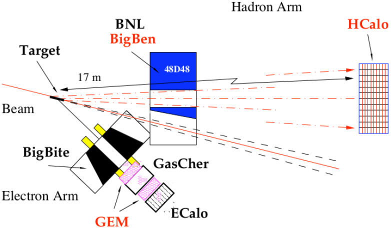


Neutron Magnetic Form Factor G_M^n - 2

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

  $R = \frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}] / \frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]$
- Electron arm: SuperBigBite spectrometer.
- Hadron arm: hadron calorimeter (HCal).
- Neutron detection efficiency:
  - Use $p(\gamma,\pi^+)n$ for tagged neutrons.
  - End-point method.
- Kinematics: $\mathrm{Q}^2 = 3.5 - 13.5\ (\mathrm{GeV/c})^2$.
- 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.



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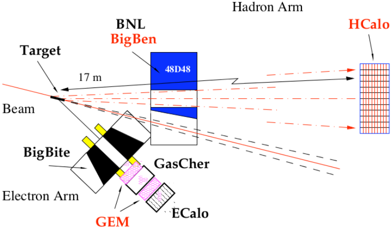

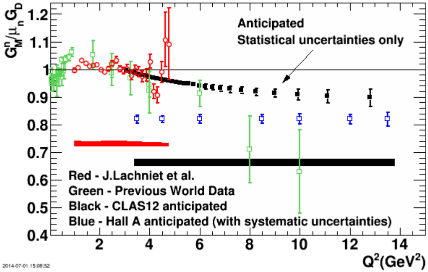

Neutron Form Factor Ratio G_E^n/G_M^n - 1

- E12-09-016 in Hall A (Cates, Wojtsekhowski, Riordan).
- Double Polarization Asymmetry: Get A_{en}^V from $^3\vec{\mathrm{He}}(\vec{e}, e'n)pp$.
- Longitudinally polarized electron beam.
- $^3\mathrm{He}$ 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.

$$A_{en}^V = \frac{-2\sqrt{\tau(\tau+1)}\tan(\theta_e/2)\cos\phi^*\sin\theta^* G_E^n/G_M^n}{(G_E^n/G_M^n)^2+\tau/\epsilon} + \frac{-2\tau\sqrt{1+\tau+(\tau+1)^2\tan^2(\theta_e/2)}\tan(\theta_e/2)\cos\theta^*}{(G_E^n/G_M^n)^2+\tau/\epsilon}$$

where $\epsilon = 1/\left(1+2(1+\tau)\tan^2(\frac{\theta_e}{2})\right)$

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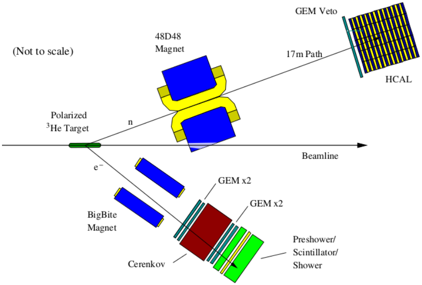

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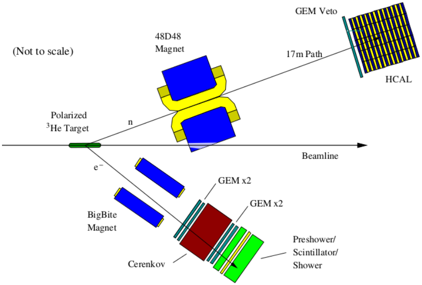
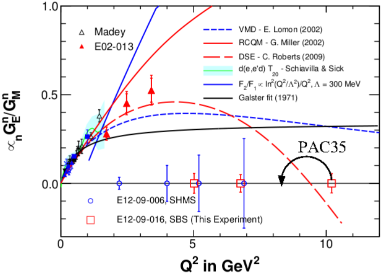


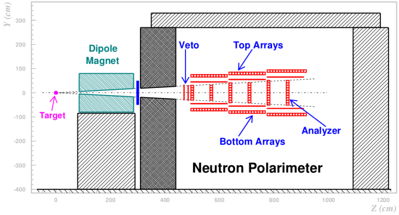


Neutron Form Factor Ratio G_E^n/G_M^n - 2

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

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

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



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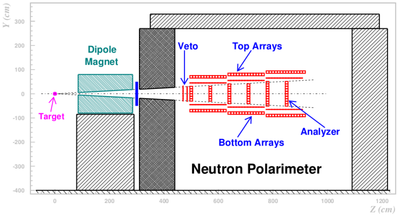
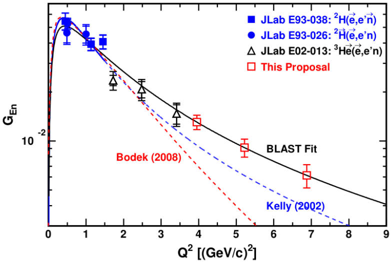


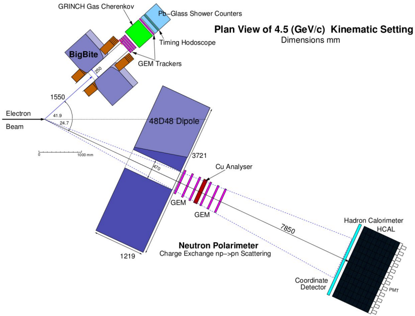


Neutron Form Factor Ratio G_E^n/G_M^n - 3

- E12-17-004 in Hall C (Annand, Bellini, Kohl, Psikunov, Sawatzky, Wojtsekhowski).
- Polarization transfer using $^2\mathrm{H}(\vec{e}, e'\vec{n})p$:

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

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



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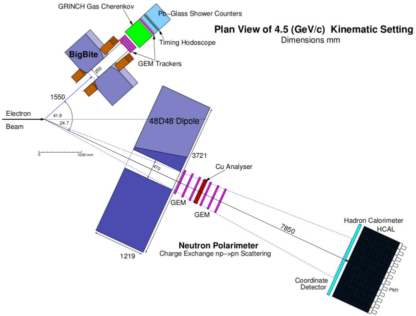
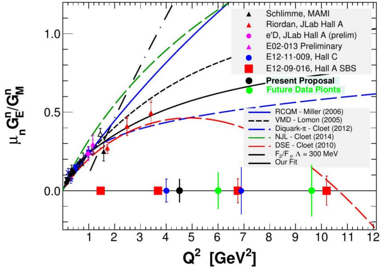




Summary and Conclusions

- 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

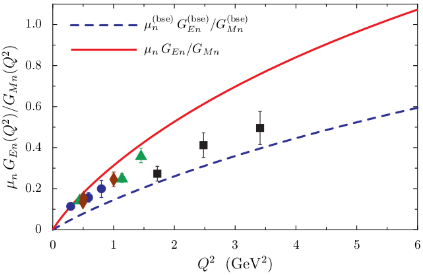
PAC41 "High Impact" Selection

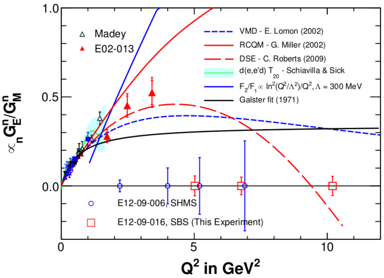
Row Color
Yellow = High Impact
Green = backup expt

Exp#	Exp name	Hall	Run Group/ Days	PAC Days	PAC grade	Comments
	TOPIC 1 : SPECTROSCOPY					
E12-06-102	**GlueX** : Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons	**D**		(120) 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** to High Q2	**C**		**52**	A	Requires fully commissioned SHMS
E12-07-109	**GEp/GMp** : Large Acceptance Proton Form Factor Ratio Meas's at 13 and 15 (GeV/c)2 Using Recoil Polarization Method	**A**		**45**	A-	Requires SBS and high power cryo target
E12-11-106	High Precision Measurement of the **Proton Charge Radius**	**B**		**15**	A	Non-CLAS12 experiment, Prad
	TOPIC 3 : PDFs					
E12-06-113	**BONuS** : The Structure of the Free Neutron at Large x-Bjorken	**B**	F/40	(40) approved **★21** ↓	A	Requires BONuS Radial TPC upgrade **★42 days High Impact for the experiment**
E12-10-103	**MARATHON** : Measurement of the F2n/F2p, d/u Ratios and A=3 EMC Effect in DIS off the Tritium and Helium Mirror Nuclei	**A**	Tritium target group/61	↑ **★21** (42) approved	A	**that runs first; experiments are equally important & both are essential**
E12-06-110	**A1n HallC–3He** : Meas of Neutron Spin Asymmetry A1n in the Valence 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					
C12-11-111	**TMD CLAS–HDIce** : SIDIS on Transverse polarized target	**B**	G/110	**110** concurrent	A	Requires transversely polarized HDIce with electron beam
C12-12-009	**Dihadron CLAS-HDIce** : Measurement of transversity with dihadron production in SIDIS with transversely polarized target	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-06-112	**TMD CLAS-H(Unpol)** : Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV	**B**	A/139	(60) 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 & GMp/62	(100) approved **★70**	A	Hall A commissioning
C12-12-010	**DVCS CLAS–HDIce** : DVCS at 11 GeV with transversely polarized target using the CLAS12 Detector	**B**	G/110	(**110**) concurrent	A	Requires transversely polarized HDIce with electron beam C1 Proposal
E12-11-003	**DVCS CLAS–D(UU,LU)** : DVCS on the Neutron with CLAS12 at 11 GeV	B	B/90	(90) approved	A	Requires D target; central neutron detector ready in 2016 **★Backup GPD-E meas if HDIce delayed**
	TOPIC 5 : NUCLEAR					
E12-13-005	**Bubble Chamber** : Measurement of 16O(³,±)12C with a bubblechamber and a bremsstrahlung beam	**INJ**		**14**	A-	Our guess: 2017
E12-11-101	**PREx-II** : Precision Parity-Violating Measurement of the Neutron Skin of Lead	**A**		**35**	A	Requires septum, Pb target, 1% Moller polarimetry
E12-06-105	**SRC–hiX** : Inclusive Scattering from Nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes	**C**		**32**	A-	
E12-11-112	**SRC–Tritium** : Precision measurement of the isospin dependence in the 2N and 3N short range correlation region	**A**	Tritium target group/61	**19**	A-	
	TOPIC 6 : FUNDAMENTAL SYMMETRIES					
E12-11-006	**HPS** : Status of the Heavy Photon Search Experiment at Jefferson Laboratory (Update on PR12_11_006)	**B**	H/180	(155) approved **★39**	A	non-CLAS12 experiment, HPS **★25 pre-CLAS engr + 14 physics @ 4.4 GeV**
E12-10-009	**APEX** : Search for new Vector Boson A1 Decaying to e+e-	**A**		**34**	A	Requires new septum and target system

Additional Theory Results

- Cloët, Bentz, and Thomas calculate the EEFFs using a covariant and confining Nambu-Jona-Lasinio model (arXiv:1405.5542v1 [nucl-th]).
- Bound state amplitude from solution of relativistic Faddeev equation.
- Get diquark degrees of freedom.
- Pion cloud added as a perturbation of the quark core.
- No model parameters.





Where We Are Now - Lattice QCD

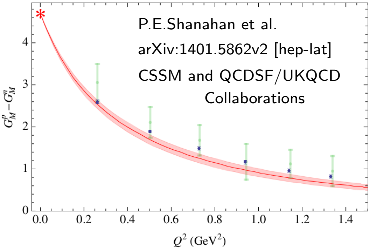
- Lattice gauge theory is the only means of *ab initio* QCD calculations in the non-perturbative regime.
- Computationally challenging.
- EEFFs are an early test of lQCD.
  - The isovector form of the EEFFs is

$$F^V_{1,2} = \frac{F^p_{1,2} - F^n_{1,2}}{2} \qquad \text{where}$$

$$F_1 = \frac{\tau G_M + G_E}{1+\tau} \qquad F_2 = \frac{G_M - G_E}{1+\tau}$$

and $\tau = Q^2/4M^2$.

  - This form does not have computationally demanding disconnected diagrams.



- Expect EEFF calculation in the next decade.

Other EEFF Measurements - Electron-Positron Colliders

- BEPC II/BES III - Continued running for next 7-9 years at higher energies to extend the reach of spectroscopic studies, search for exotics, ... See talks by Xiaobin Ji, Rong-Gang Ping, and Yinghui Guan.
- SuperKEKB/Belle II - Will also probe the precision frontier, flavor physics, CP violation, exotics, 4 and 7 GeV. Commissioning starts in early 2015.
- Novosibirsk - Super Charm/Tau Factory is planned to probe the precision frontier, exotics, 3-5 GeV, now in CDR phase.