Searching for the Mass of the Nucleon

G.P. Gilfoyle
University of Richmond, Richmond, VA 23173

Outline

- Jefferson Lab's Mission
- What we know.
- What we don't know.
- What we'll learn.
- How we'll do it.
- Concluding Remarks

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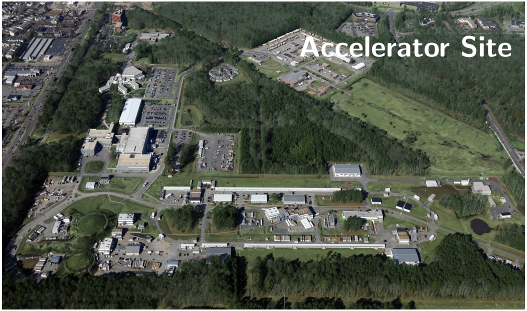
"The Periodic Table"

What is the Mission of Jefferson Lab?

- Basic research into the nature of the nucleus and the nucleon.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
- Map the geography of the transition from proton-neutron picture of nuclei to one based on quarks and gluons.
- Test Quantum Chromodynamics (QCD) and quark confinement.
- One of the Millennium Prize Problems (Clay Mathematics Institute).



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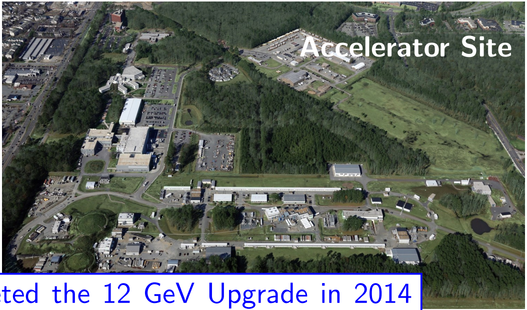
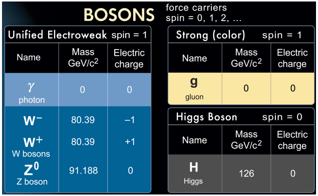


Jefferson Lab completed the 12 GeV Upgrade in 2014 doubling the CEBAF accelerator energy.

What Do We Know?

- The Universe is made of quarks and leptons and the force carriers.

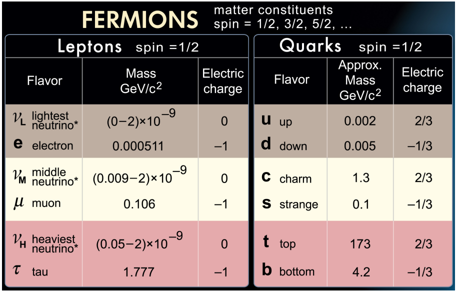


BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

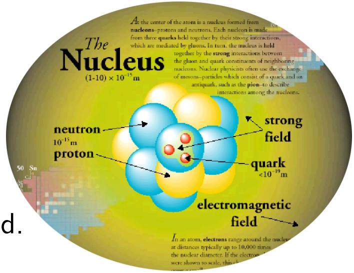
Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2			Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0	u up	0.002	2/3
e electron	0.000511	–1	d down	0.005	–1/3
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	c charm	1.3	2/3
μ muon	0.106	–1	s strange	0.1	–1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	t top	173	2/3
τ tau	1.777	–1	b bottom	4.2	–1/3

- The atomic nucleus is made of protons and neutrons (nucleons) bound by the strong force.
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.



At the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by **gluons**. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.

In an atom, **electrons** range around the nucle at distances typically up to 10,000 times the nuclear diameter. If the electron were shown to scale, this ch

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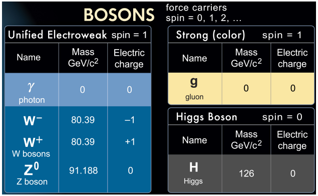

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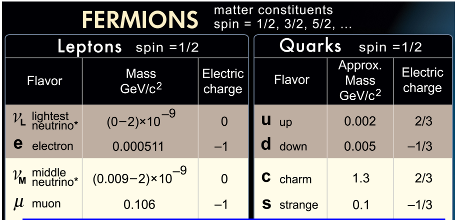

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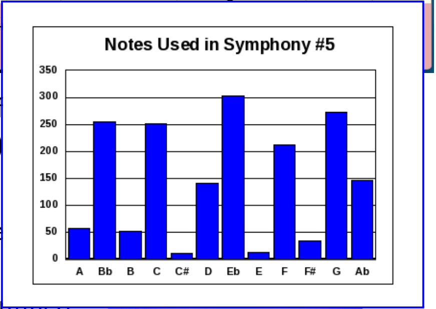

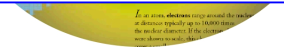

What Don't We Know?

- Matter comes in pairs of quarks or triplets.
- We are mostly triplets (protons and neutrons).
- More than 99% of our mass is in nucleons.
- Proton → 2 ups + 1 down.
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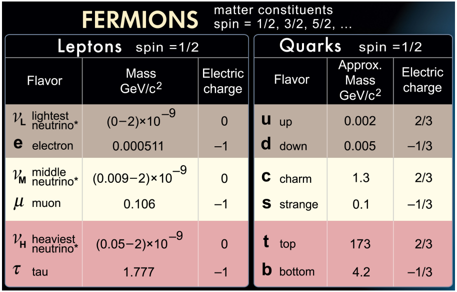

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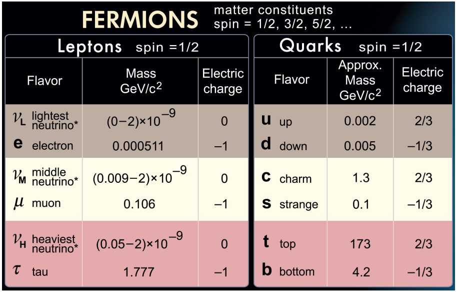

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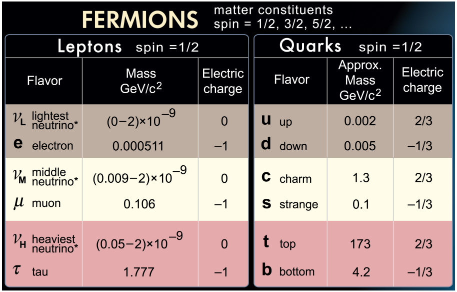

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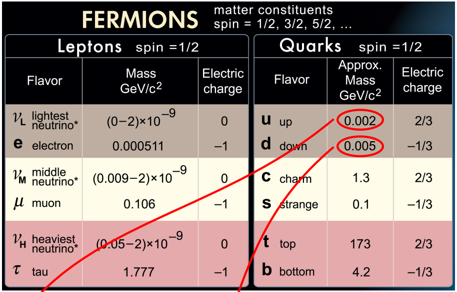

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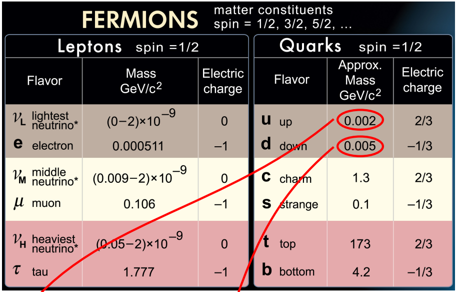

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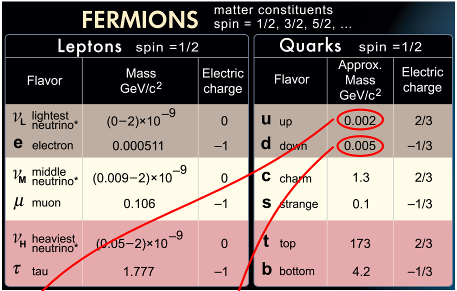

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- $m_n - m_p = 1.29333205(48)\ MeV/c^2$ (exp) $= 1.51(16)(23)\ MeV/c^2$ (th)

Sz. Borsanyi et al. *Science* 347, 1452 (2015).

How do we get out of this?

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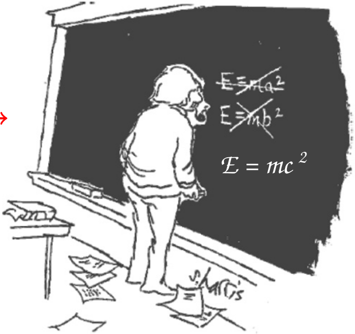

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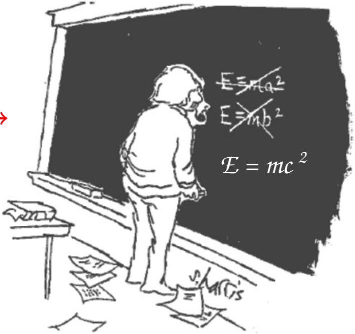
- Most of the mass we see comes from the quark color fields → gluon cloud!



How Do We Learn What's Inside the Nucleon?

- Nucleon elastic electromagnetic form factors (EEFFs) describe the distribution of charge and magnetization in the nucleon.
- They encode the deviations from point-particle behavior.
- Reveal the internal quark-gluon landscape of the nucleon and nuclei.
- We are in the region where the quarks get dressed.
- Rigorously test QCD in the non-perturbative regime.
- Jargon: G_E^p, G_M^p, G_E^n, G_M^n, F_1, F_2.

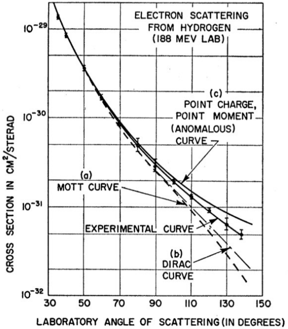


FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. The theoretical curves (b) and (c) are due to Rosenbluth.[8] The experimental curve falls between curves (b) and (c). This deviation from the theoretical curves represents the effect of a form factor for the proton and indicates structure within the proton, or alternatively, a breakdown of the Coulomb law. The best fit indicates a size of 0.70×10^{-13} cm.

McAllister and Hofstadter, PR 102, 851 (1956)

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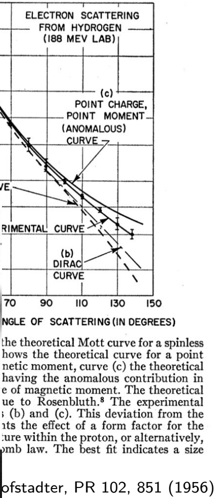

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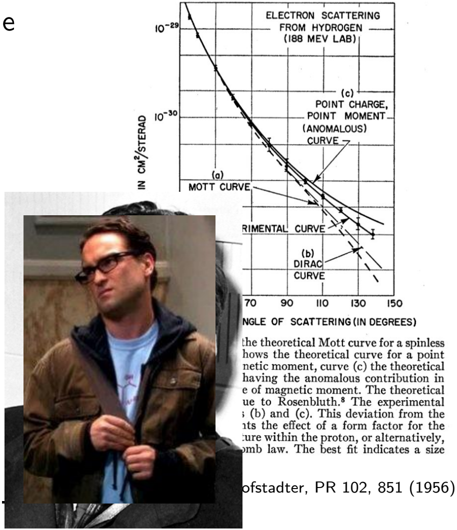

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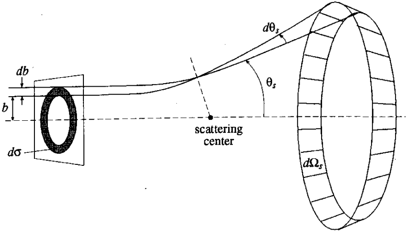

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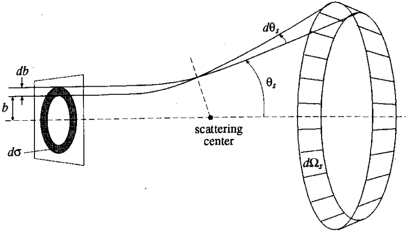

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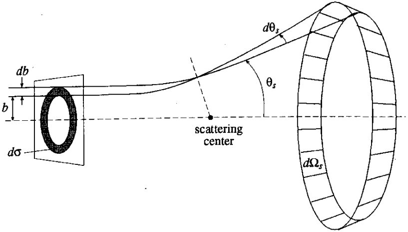

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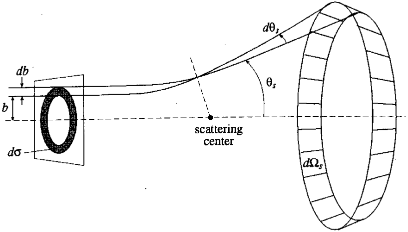

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THE FORM FACTOR!

What Is a Form Factor?

- The chain of reason.

$$\frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow_{\text{Constituent quarks}}^{\text{QCD,}}$$

Experiment **Comparison** **Theory**

  The form factors are the meeting ground between theory and experiment.

- The Fourier transform of the form factors are related to the charge and current distributions within the neutron.

What We'll Learn - The Campaign

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	$e-n/e-p$ ratio	LD_2, LH_2	$3.5-13.0$	B	30
G_M^n	$e-n/e-p$ 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.

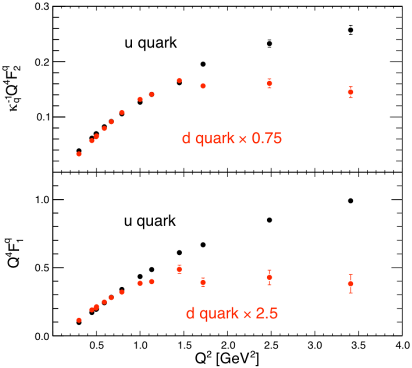
What We'll Learn - Flavor Decomposition

- 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))

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

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

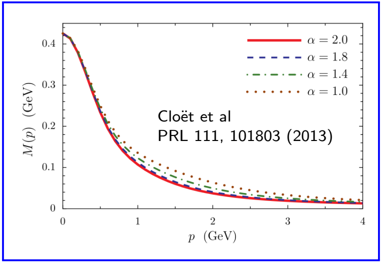
- Evidence of di-quarks?
  - the missing resonances mystery.
  - *d*-quark scattering probes the diquark.
  - correlated *d*-quark can lead to high momentum and interaction cross section.



Cates et al. PRL **106**, 252003 (2011).

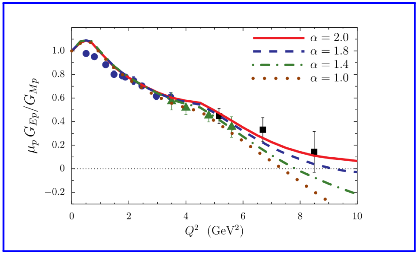
What We'll Learn - Dyson-Schwinger Eqs

- 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 → Choose well!



Cloët et al
PRL 111, 101803 (2013)

- 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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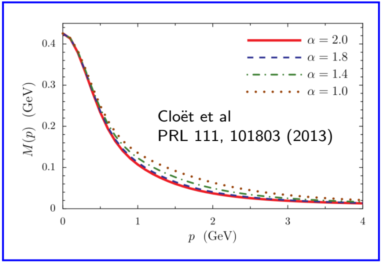

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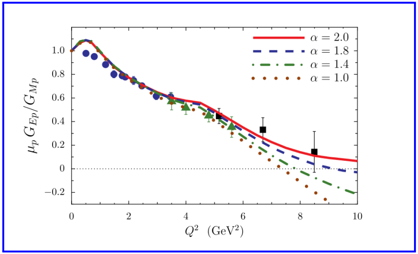

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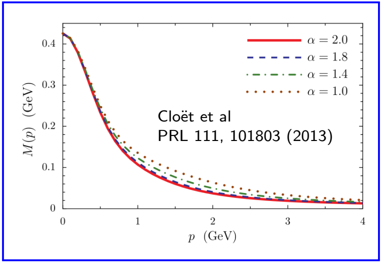

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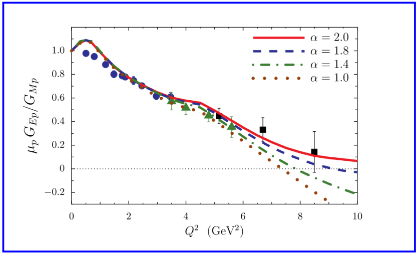
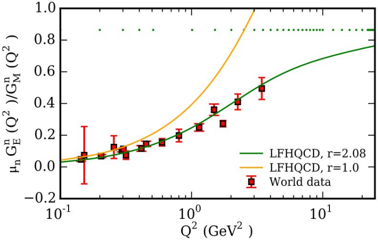


Position of zero in $\mu_p G_E^p/G_M^p$ and $\mu_n G_E^n/G_M^n$ sensitive to shape of $M(p)$!

What We'll Learn - 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. Paper by Sufian *et al.* (Phys. Rev. D95, 01411 (2017)) included calculations of the electromagnetic form factors that include higher order Fock components $|qqqq\bar{q}\rangle$.
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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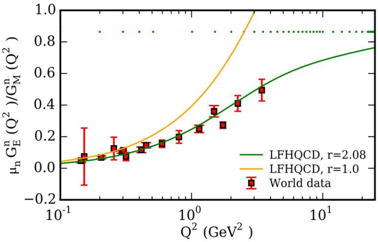
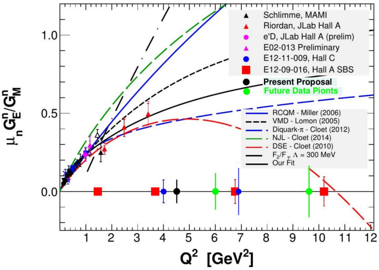
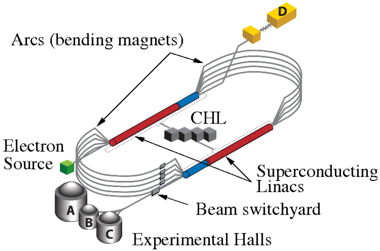




How Will We Get There - Jefferson Lab

- Start at your local mile-long, high-precision, 12-GeV electron accelerator.
- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.
- Electrons do up to five laps, are extracted, and sent to one of four experimental halls.
- All four halls can run simultaneously.



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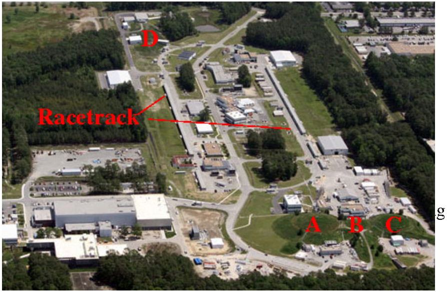

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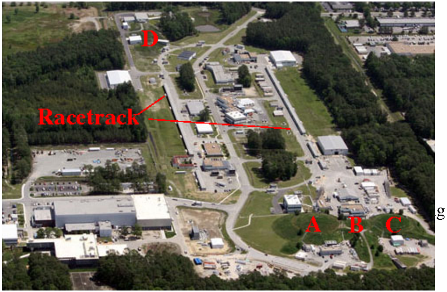

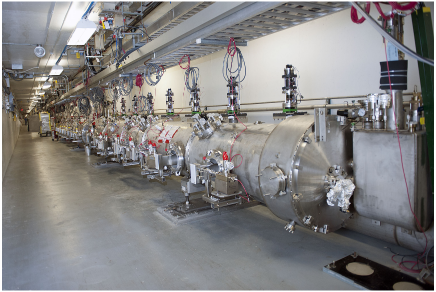

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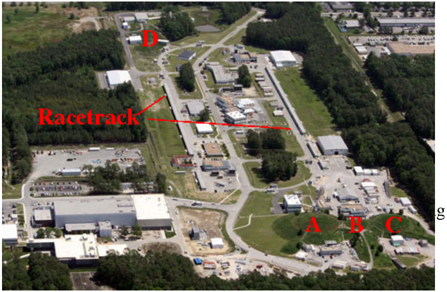
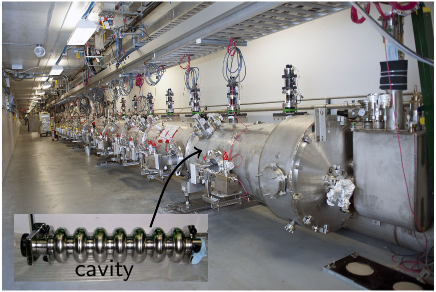
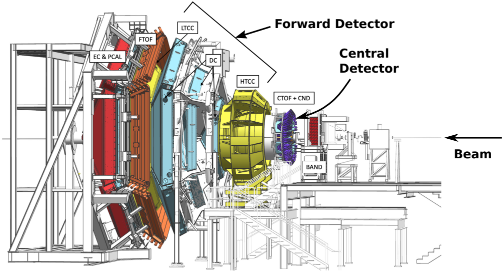




How Do We Measure The Form Factors

- Add one 45-ton, $80-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
- CLAS12 covers a large fraction of the total solid angle out to large angles.
- Has about 100,000 readouts in about 40 layers.



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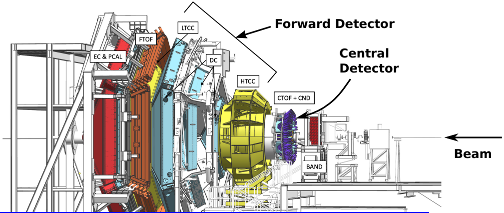

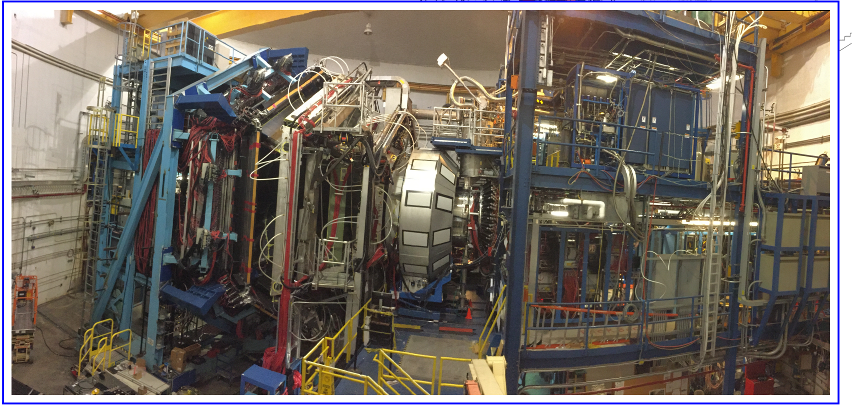

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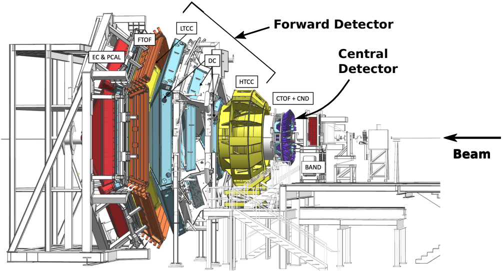
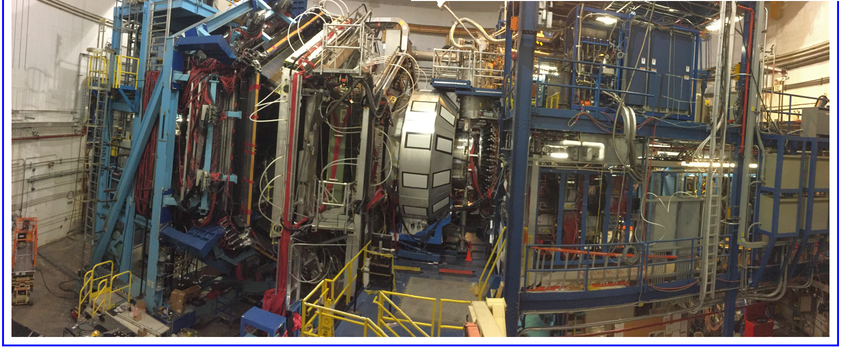
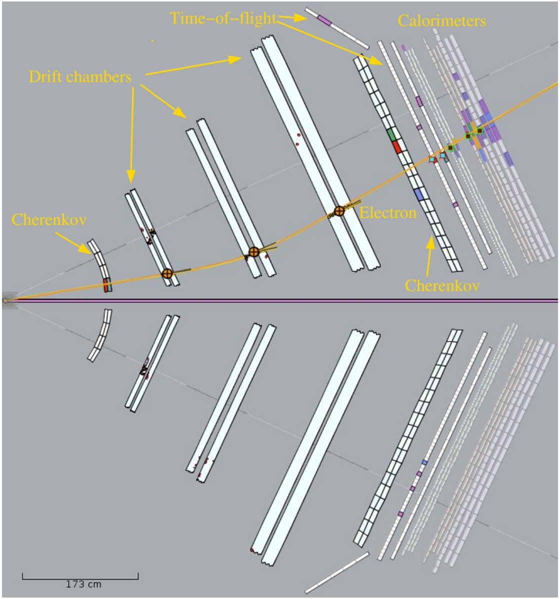




A CLAS12 Event - Summary



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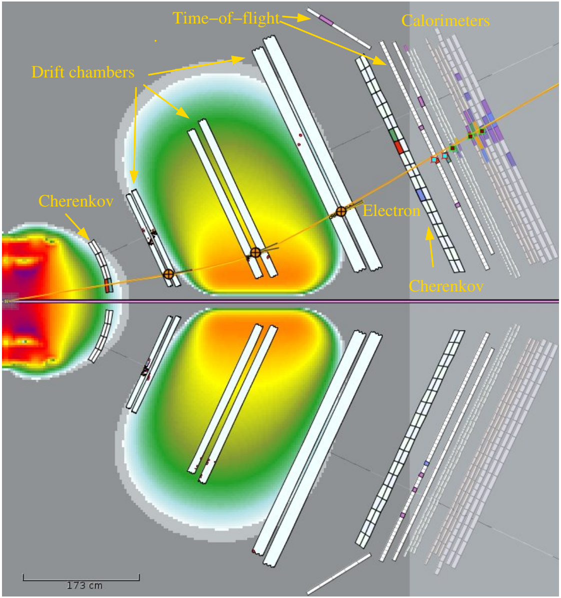


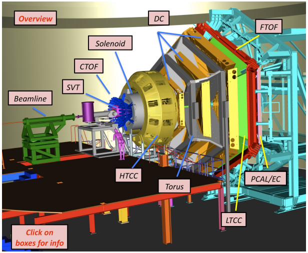
How Do We Extract the Form Factors? - G_M^n

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

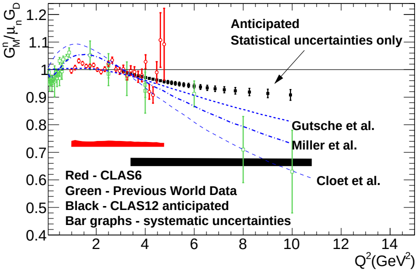
$$R = \frac{\frac{d\sigma}{d\Omega}[{}^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[{}^2\mathrm{H}(e,e'p)_{QE}]}$$

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

where a is nuclear correction.



- Precise neutron detection efficiency needed to keep systematics low.
  - tagged neutrons from ${}^2\mathrm{H}(e,e'pn)$.
  - LH_2 target.
- Kinematics: $\mathrm{Q}^2 = 3.5 - 13.0\ (\mathrm{GeV/c})^2$.
- Beamtime: 40 days.
- Systematic uncertainties $<$ 2.5% across full Q^2 range.
- Run Group B started January, 2019.



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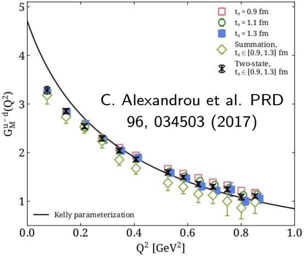
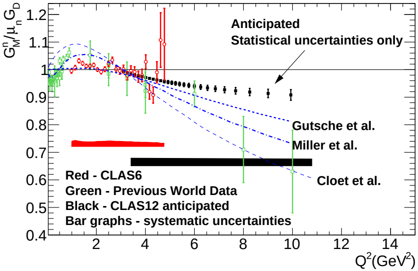


C. Alexandrou et al. PRD 96, 034503 (2017)



Concluding Remarks

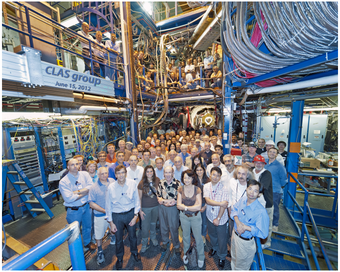
- JLab is a laboratory to test and expand our understanding of quarks, gluons, nuclear matter and QCD.
- We continue to unravel the nature of matter at greater and greater depths.
- Lots of new and exciting results are coming out.
- A bright future lies ahead in the 12 GeV Era.

U. S. Department of Energy's
Jefferson Lab
THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

RICHMOND

Some Facts of Life On The Frontier

- Work at Jefferson Lab in Newport News.
  - 700 physicists, engineers, technicians, and staff.
  - Vibrant intellectual environment - talks, visitors, educational programs...
  - Lots going on.
- Richmond group part of CLAS Collaboration.
  - operates CLAS12.
  - ∼190 physicists, 40 institutions, 13 countries.
  - Part of Software Group - emphasis on software development.
  - Past Surrey masters students (and Richmond undergrads) have presented posters at meetings, appeared on JLab publications,....
- Run-Group B consists of seven experiments (including G_M^n) and is expected to run in spring 2019.



Additional Slides

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.

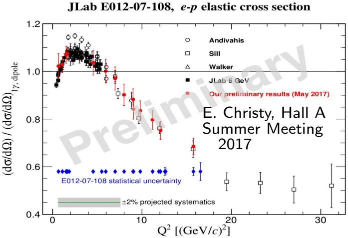
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2 + \tau G_M^2\right)$$

  where

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

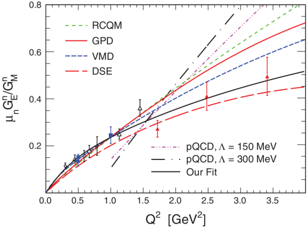
Where We Are Now.

- G_M^p 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.

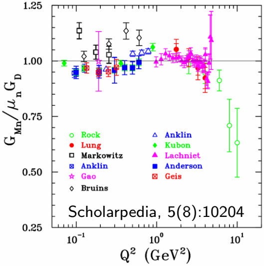


E. Christy, Hall A Summer Meeting 2017

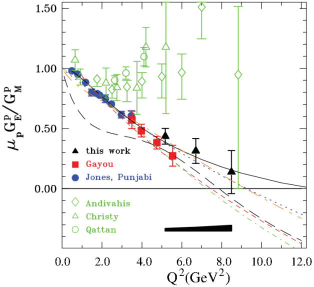
- Neutron magnetic FF G_M^n still follows dipole.
- High-Q^2 G_E^n opens up flavor decomposition.



PRL 105, 262302 (2010)



Scholarpedia, 5(8):10204



PRL **104**, 242301 (2010)

The Experiments - New Detectors

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.

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

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

Extracting G_M^n

- Use 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 a nuclear correction.

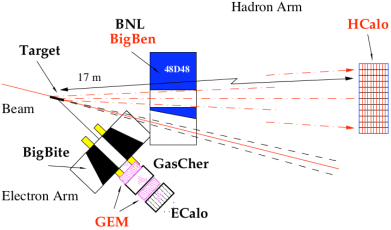
- Acceptance matching on $e-p$ and $e-n$ measurements. For each event swim both nucleons through CLAS12 and require both to strike the CLAS12 fiducial volume it to be accepted.
- Select quasi-elastic events by requiring the nucleon scattering angle to be within a narrow angular cone around the direction predicted by elastic scattering (no Fermi motion).
- Require no other particles in the final state to reduce inelastic contributions.
- Apply neutron/proton detection efficiency, Fermi motion, nuclear corrections and others to R.

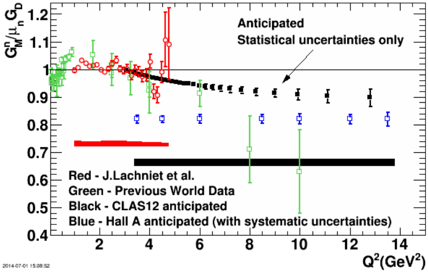
Neutron Magnetic Form Factor G_M^n - 2

- 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.





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.
- $\mathrm{Q}^2 = 7.0 - 15.5\ \mathrm{GeV}^2$ (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