# The Hunt is On: New Physics at Jefferson Lab

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

Outline

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


Oct 18, 2022

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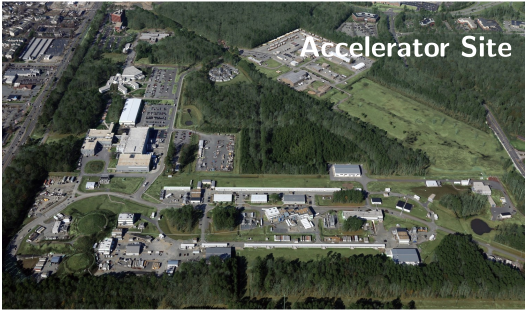
# What is the Mission of Jefferson Lab?

- 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.
- Test the theory of the strong or color force, Quantum Chromodynamics (QCD), in nucleons.
- One of the Millennium Prize Problems (Clay Mathematics Institute). Solving it gets you a cool million bucks.



# 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 |
| $\gamma$ 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 | | |
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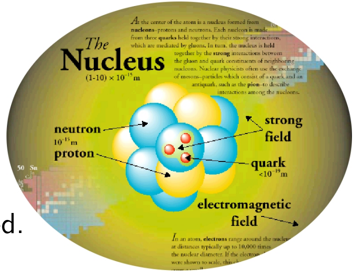
| $\tau$ tau | 1.777 | –1 | b bottom | 4.2 | –1/3 |

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



# 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 $\rightarrow$ 2 ups + 1 down.
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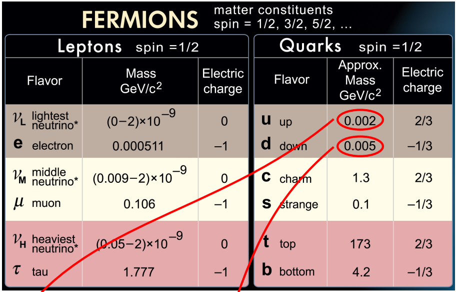

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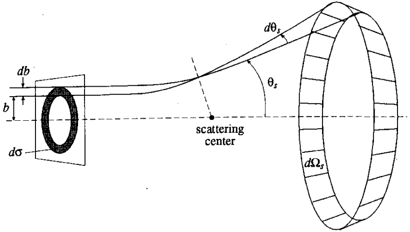
- $m_n - m_p = 1.29333205(48)\ MeV/c^2$ (exp) $= 1.51(16)(23)\ MeV/c^2$ (th)

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

# How Do We Learn What's Inside the Nucleon?

- Start with the cross section.

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered flux/solid angle}}{\text{incident flux/surface area}}$$



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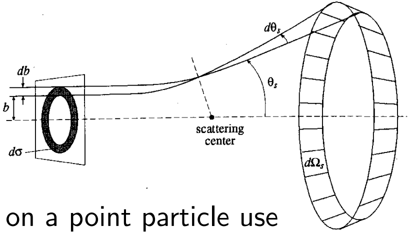


- For elastic scattering with electrons on a point particle use

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2(\hbar c)^2}{4E^2\sin^4(\theta/2)}\left(1 - \beta^2 \sin^2\frac{\theta}{2}\right)$$

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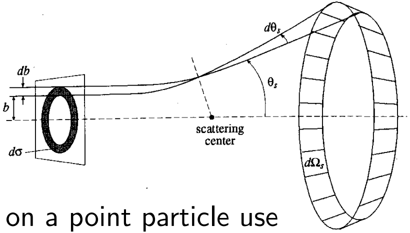


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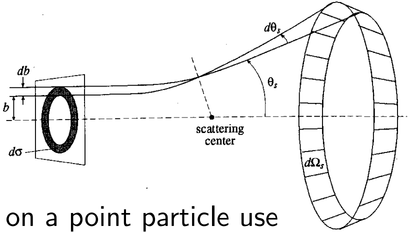


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THE FORM FACTOR!

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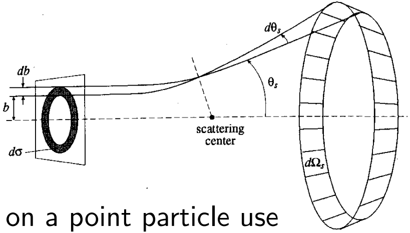


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THE FORM FACTOR!

- Where experiment and theory meet.

# 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.
- Rigorously test QCD in the non-perturbative/nuclear regime.
- Jargon: $G_E^p$, $G_M^p$, $G_E^n$, $G_M^n$.

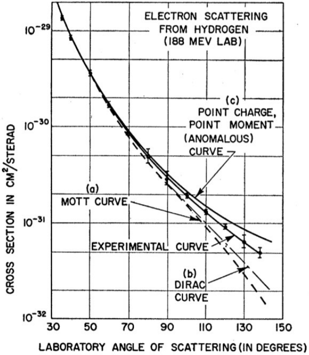


FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. 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 $0.70\times10^{-13}$ cm.

McAllister and Hofstadter, PR 102, 851 (1956)

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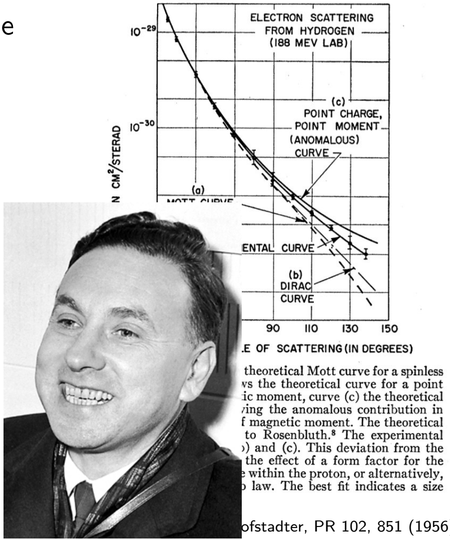


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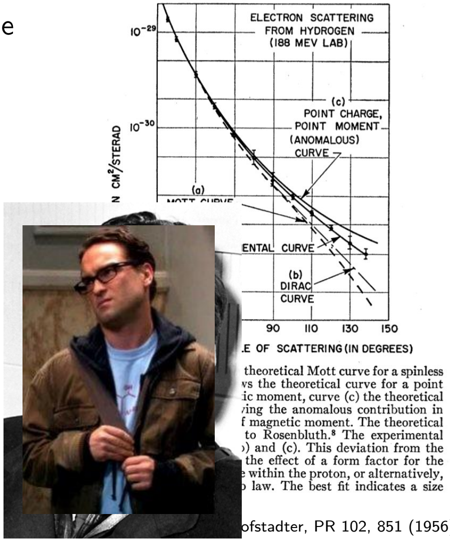


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# What We're Learning - The Campaign

**The JLab Lineup**

| Quantity | Method | Target | Hall | Status |
|---|---|---|---|---|
| $G_M^p$ * | Elastic scattering | $LH_2$ | A | published |
| $G_E^p/G_M^p$ | Polarization transfer | $LH_2$ | A | next year |
| $G_M^n$* | $E - p/e - n$ ratio | $LD_2, LH_2$ | B | analyzing |
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| $G_E^n/G_M^n$ | Double polarization asymmetry | polarized $^3\mathrm{He}$ | A | next week |
| $G_E^n/G_M^n$ | Polarization transfer | $LD_2$ | C | to be scheduled |
| $G_E^n/G_M^n$ | Polarization transfer | $LD_2$ | A | next year |

* At least some data is collected.

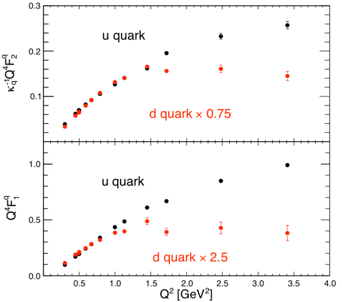
# What We're Learning - Flavor Decomposition

- With all four EEFFs we can unravel the contributions of the *u* and *d* quarks.
- With charge symmetry, no *s* quark, then

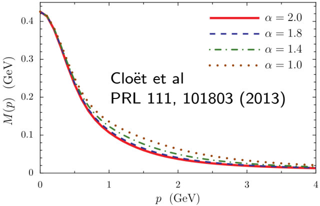
$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \qquad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

(Miller *et al.* Phys. Rep. **194**, 1 (1990))

- The *d*-quark $F_1$ is strongly suppressed.
- The Dyson-Schwinger Eqs are the 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!
  - Recall u,d masses are small.

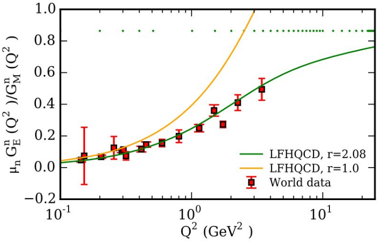



Cates et al. PRL **106**, 252003 (2011).



# 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 $|qqqq\bar{q}\rangle$. More recent work by Gutsche *et al.* (Phys. Rev. D97, 054011 (2018).)
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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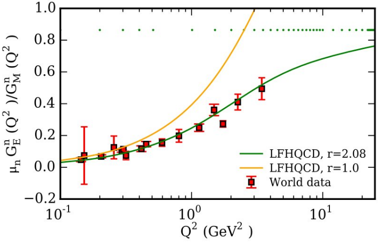
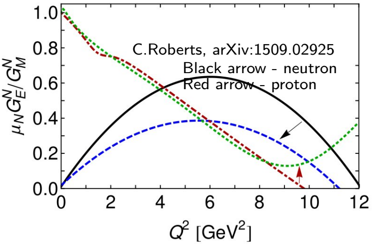
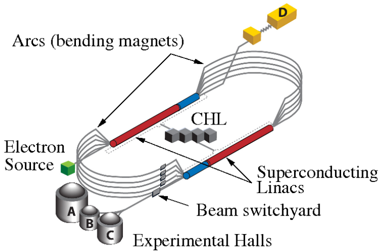



4. Model the nucleon dressed quark propagator as a quark-diquark.

# 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 three experimental halls.
- All four halls can run simultaneously.



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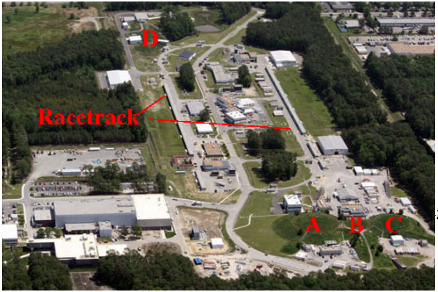

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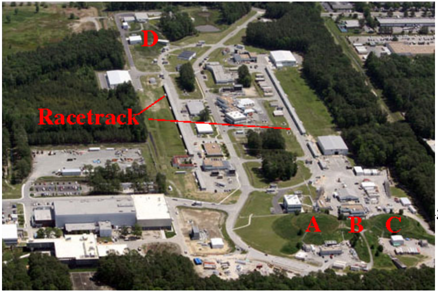


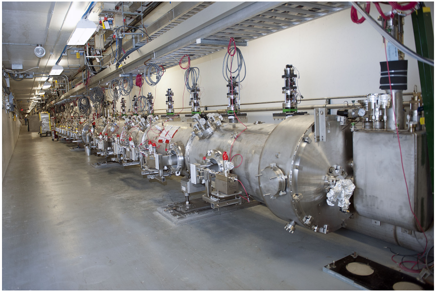

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- Start at your local mile-long, high-precision, 12-GeV electron accelerator.
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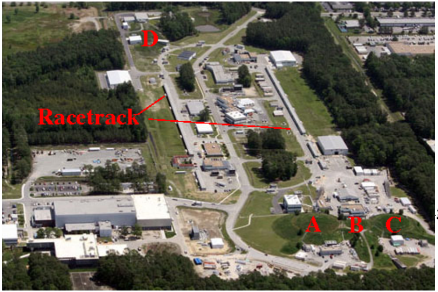
- Electrons do up to five laps, are extracted, and sent to one of three experimental halls.
- All four halls can run simultaneously.

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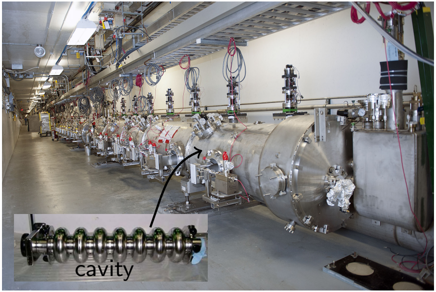
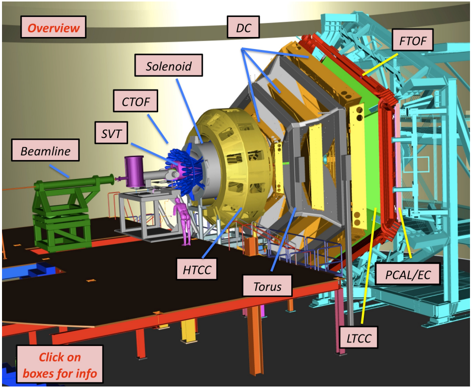


# How Do We Measure The Form Factors

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



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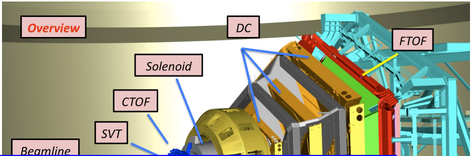


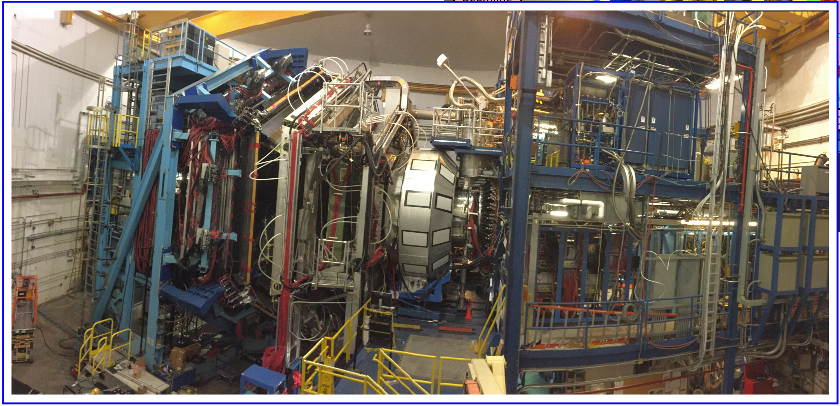

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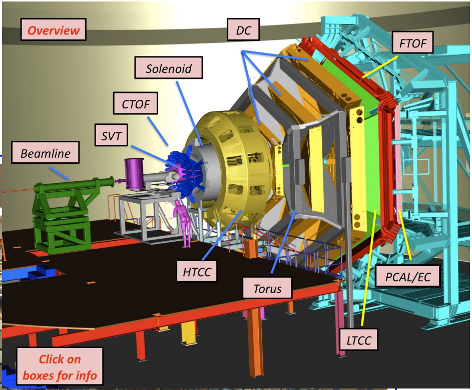
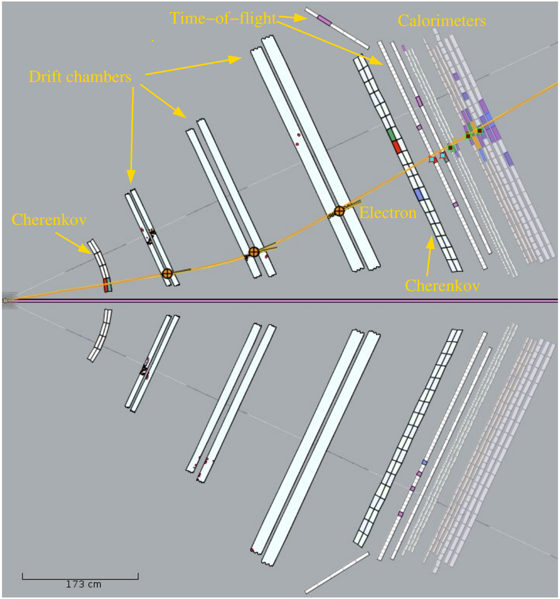


# A CLAS12 Event - Summary



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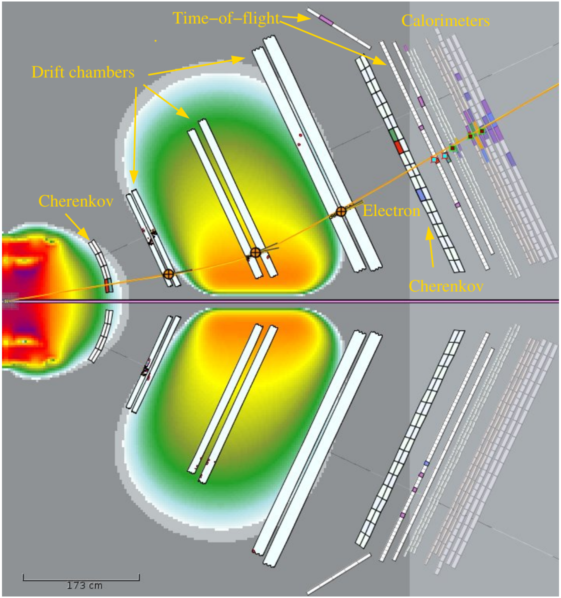


# How Do We Extract the Form Factors? - $G_M^n$

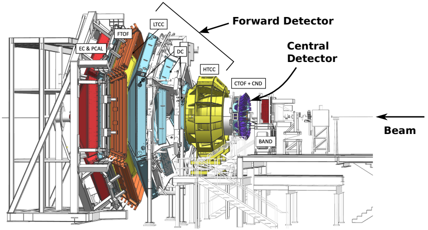
- Focus of my analysis group.
- Ratio Method on Deuterium:

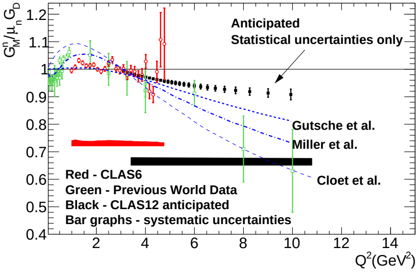
$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$

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

where $a$ is nuclear correction.

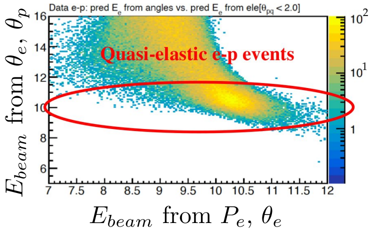
- Precise neutron detection efficiency needed to keep systematics low.
  - tagged neutrons from $^2\mathrm{H}(e,e'pn)$.
  - $LH_2$ target.
- Kinematics:$\mathrm{Q}^2 = 4.5 - 10.0\ (\mathrm{GeV/c})^2$.
- Data collected spring,2019 - spring, 2020, 43 billion triggers.
- Expected systematic uncertainties $< 3.0\%$ across full $\mathrm{Q}^2$ range.

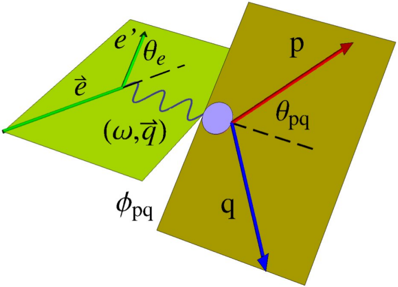


# Data Science - Getting the Physics Out

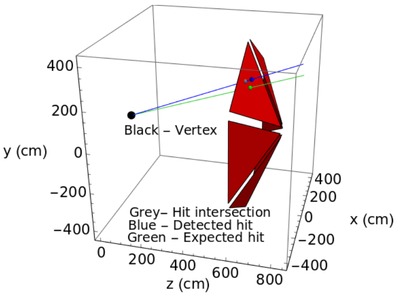
- The neutron magnetic form factor $G_M^n$ is extracted with the ratio $R_{observed} = e-n/e-p$ in quasielastic kinematics (QE).
  - Assume QE scattering.
  - Calculate the beam energy from the scattered electron and nucleon information. Apply cut.
  - Require $\theta_{pq}$ to be small.
  - Match $e-n$ and $e-p$ acceptances
- Correct $R_{observed}$ for neutron detection efficiency, Fermi motion, ...



# Data Science - Neutron Detection Efficiency

- Needed to correct $e - n$ yield in the ratio $R_{observed}$.
- Use the $^1\mathrm{H}(e, e'\pi^+ n)$ reaction and the CLAS12 Run Group A data set.
- Use only the $e'\pi^+$ information and identify the neutron events with the missing mass.
- Predict the location of the neutron (expected).
- Search for the neutron near that location (detected). NDE is ratio of detected/expected.



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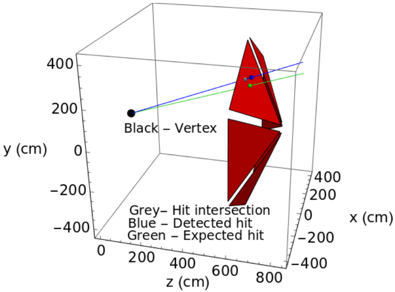


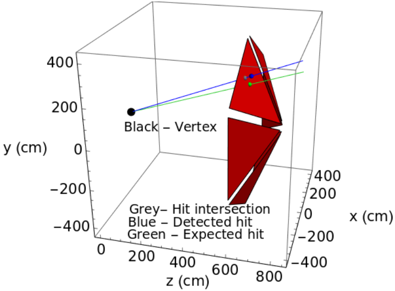

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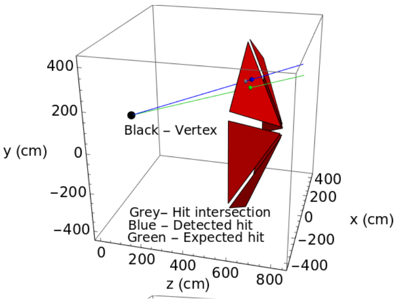
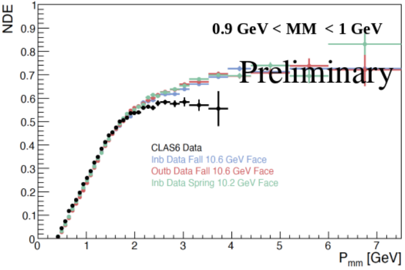


# Concluding Remarks

- 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.

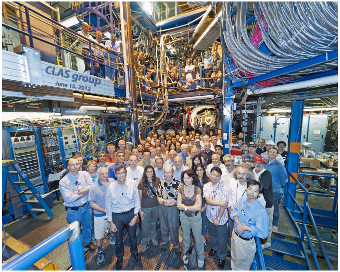
U. S. Department of Energy's Jefferson Lab

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

RICHMOND

# Some Facts of Life On The Frontier

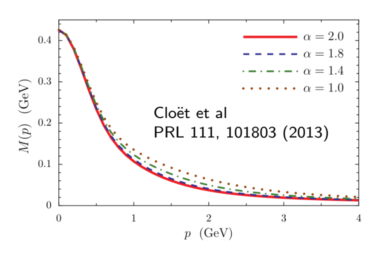
- Work at Jefferson Lab in Newport News.
  - 700 physicists, engineers, technicians, and staff.
  - Vibrant intellectual environment - talks, visitors, educational programs...
  - Lots going on.
- Richmond group part of CLAS Collaboration.
  - operates CLAS12.
  - $\sim$200 physicists, 43 institutions, 14 countries.
  - Part of Software Group - emphasis on software development.
  - Past Surrey masters students (and Richmond undergrads) have presented posters at meetings, appeared on JLab technical reports,....
- Run-Group B consists of seven experiments (including $G_M^n$) and about of the approved time has been used.

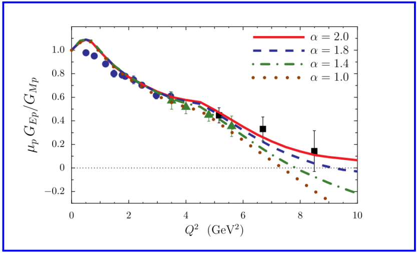
# Additional Slides

# 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!




- 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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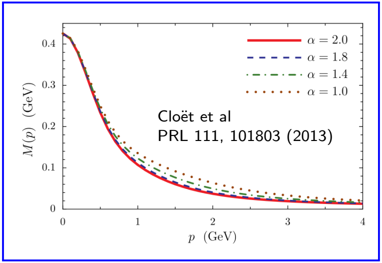


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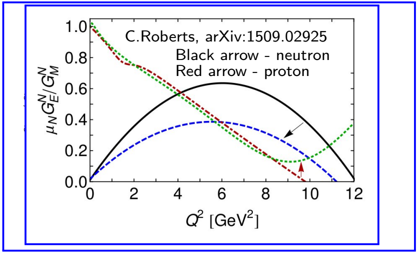

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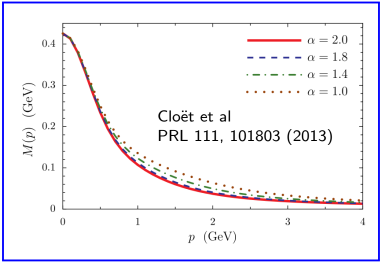
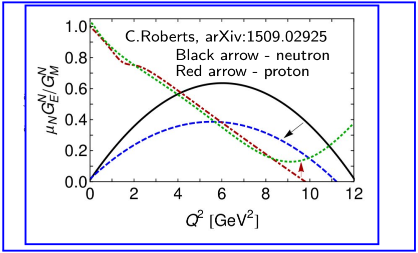



- Recent results (Cloët et al).
  - Model the nucleon dressed quark propagator as a quark-diquark.
  - Damp the shape of the mass function $M(p)$.

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 $M(p)$!



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

- For convenience use the Sachs form factors.

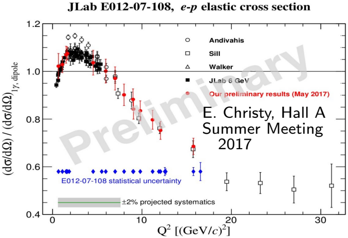
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2 + \tau G_M^2\right)$$

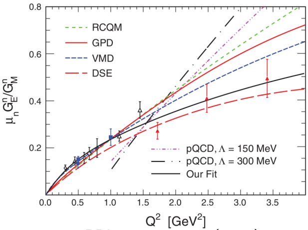
where

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

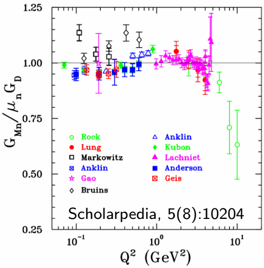
# Where We Are Now.

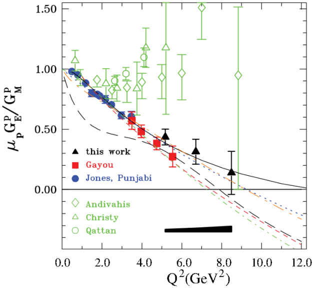
- $G_M^p$ well known over large $Q^2$ range.
- The ratio $G_E^p/G_M^p$ from polarization transfer measurements diverged from previous Rosenbluth separations.
  - Two-photon exchange (TPE).
  - Effect of radiative corrections.
- Neutron magnetic FF $G_M^n$ still follows dipole.
- High-$Q^2$ $G_E^n$ opens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



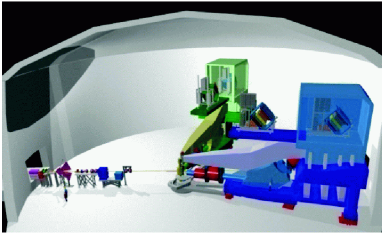

PRL 105, 262302 (2010)



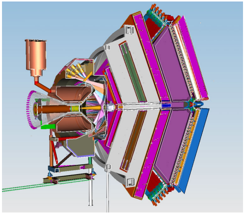




PRL **104**, 242301 (2010)

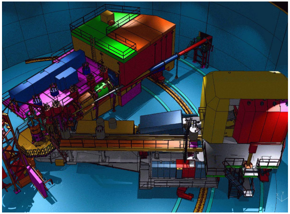
# The Experiments - New Detectors



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

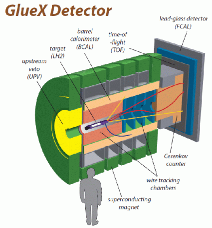


Hall B - CLAS12 large acceptance spectrometer operating at high luminosity with toroid (forward detector) and solenoid (central detector).



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.



# 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.

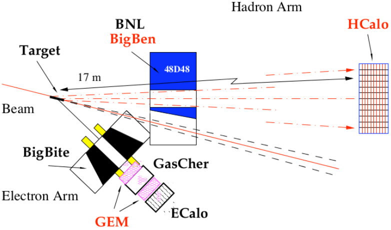
- Acceptance matching on $e-p$ and $e-n$ measurements.
  For each event swim both nucleons through CLAS12 and require both to strike the CLAS12 fiducial volume it to be accepted.
- Select quasi-elastic events by requiring the nucleon scattering angle to be within a narrow angular cone around the direction 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 $R$.

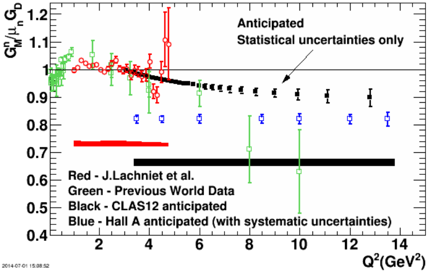
# Neutron Magnetic Form Factor $G_M^n$ - 2

- 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.



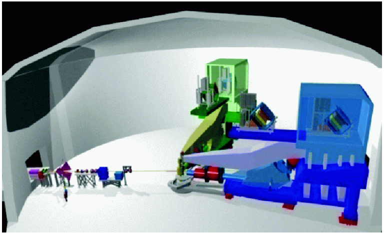



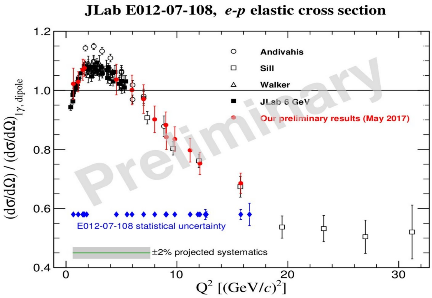
# Proton Magnetic Form Factor - $G_M^p$

- 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.
- $Q^2 = 7.0 - 15.5$ 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 → vary $\epsilon$ to constrain.
- Sets the scale of other EEFFs.
- Completed data collection in 2017.






E. Christy, Hall A Summer Meeting 2017