Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration
University of Richmond

"The Periodic Table"

- Jefferson Lab's Mission
- What we know.
- What we don't know.
- What we measure.
- Experiments with CLAS12
- Concluding Remarks

What is the Mission of Jefferson Lab?

- Basic research into the quark nature of the atomic nucleus.
- Map the geography of the transition from proton-neutron picture of nuclei to one based on quarks and gluons.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
- Test the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.

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One of the seven Millenium Prize Problems from the Clay Mathematics Institute.

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		
Flavor	Mass GeV/c^2	Electric charge
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e electron	0.000511	–1
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μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
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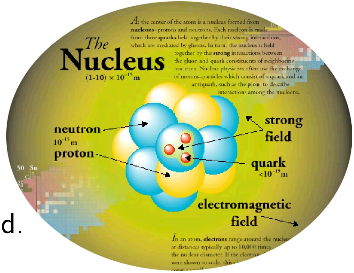
- The atomic nucleus is made of protons and neutrons bound by the strong force.
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.



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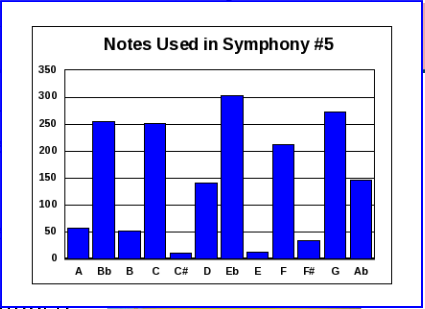

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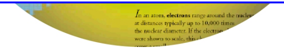
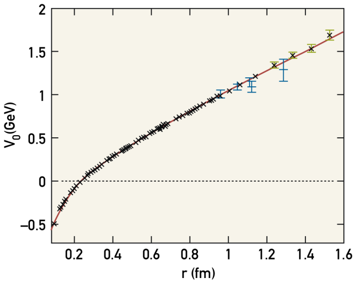


What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.



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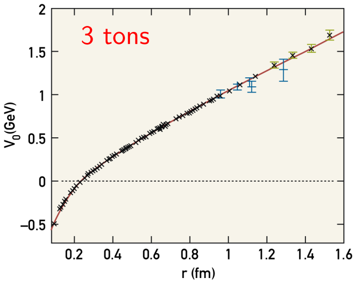

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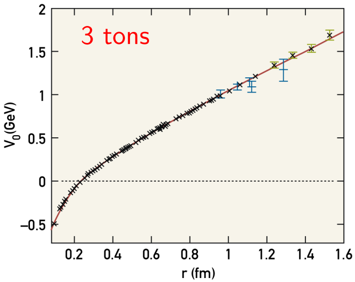
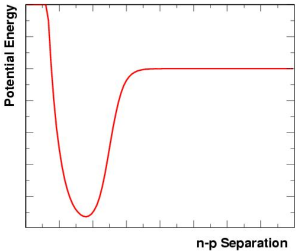
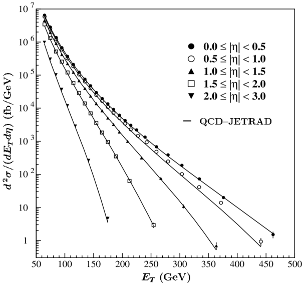


- The hadronic model uses a phenomenological force fitted to data at low energy. This 'strong' force is the residual force between quarks.



How Well Do We Know It?

- We have a working theory of strong interactions: quantum chromodynamics or QCD (B.Abbott, *et al.*, Phys. Rev. Lett., **86**, 1707 (2001)).



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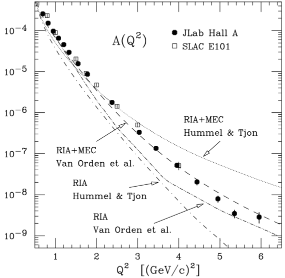

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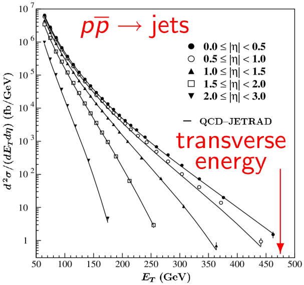
effective target area



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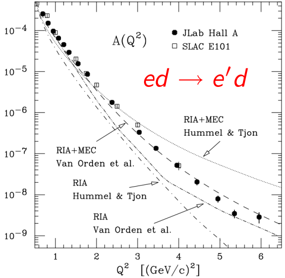

4-momentum transfer squared

What Don't We Know?

- Matter comes in pairs of quarks or triplets.
- We are made mostly of the triplets (protons and neutrons).
- More than 99% of our mass is in nucleons.
- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.

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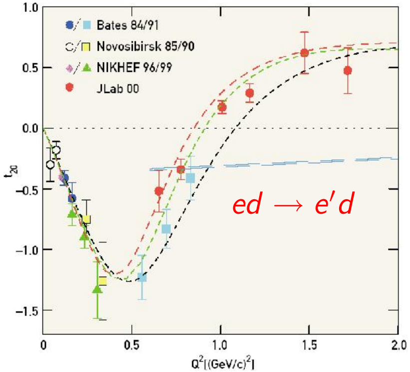
$$m_p = 2m_{up} + m_{down} = 2(0.002\ GeV/c^2) + 0.005\ GeV/c^2$$

$$= 0.939\ GeV/c^2 \quad \text{OOOPS!!!????}$$

1. We can't get QCD and the hadronic model to line up - D. Abbott, *et al.*, Phys. Rev Lett. **84**, 5053 (2000).

2. NEED TO FIGURE OUT QCD AT THE ENERGIES OF NUCLEI!!



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The Magnetic Form Factor of the Neutron (G_M^n)

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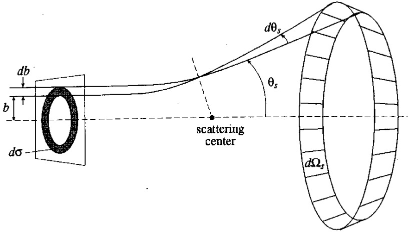
- Fundamental quantity related to the distribution of magnetization/currents in the neutron.
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on theory and the structure of hadrons.
- Part of a broad effort to understand how nucleons are 'constructed from the quarks and gluons of QCD'.*

* 'The Frontiers of Nuclear Science: A Long-Range Plan', NSF/DOE Nuclear Science Advisory Committee, April, 2007.

What is a Form Factor?

- 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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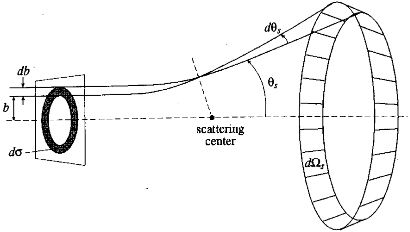

For elastic scattering use the Rutherford cross section.

- Get the cross section for elastic scattering by point particles with spin.

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

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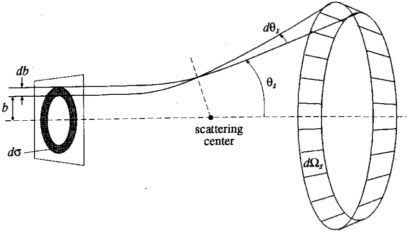

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where Q^2 is the 4-momentum transfer.

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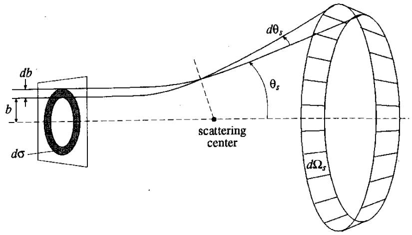

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THE FORM FACTOR!

Why Should You Care?

- The chain of reason.

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

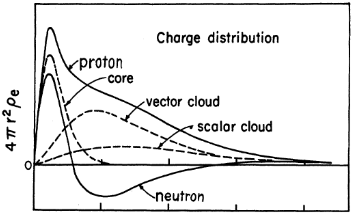
Experiment **Comparison** **Theory**

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.

Why Should You Care Even More?

- The old picture of the neutron (and proton).



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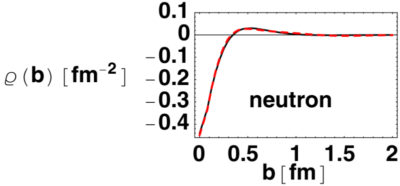

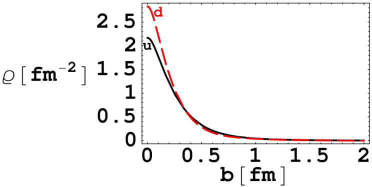

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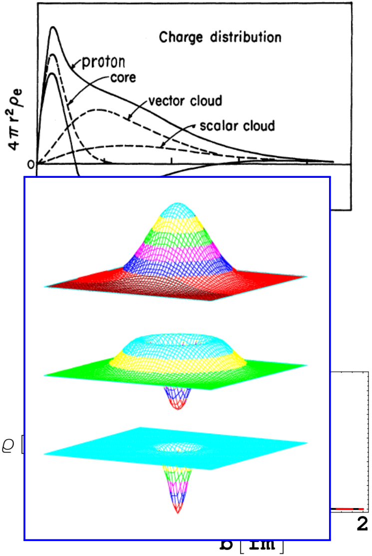
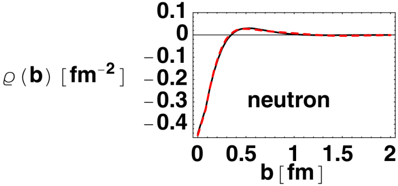
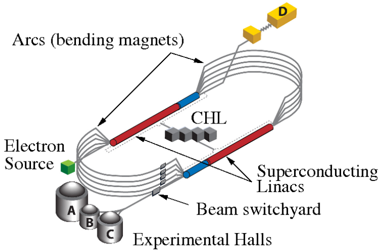




How Do We Measure G_M^n on a Neutron? (Step 1)

- 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.
- Three of four halls can run simultaneously.



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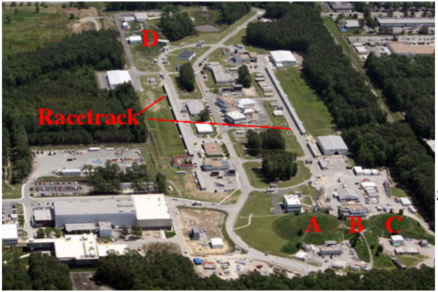

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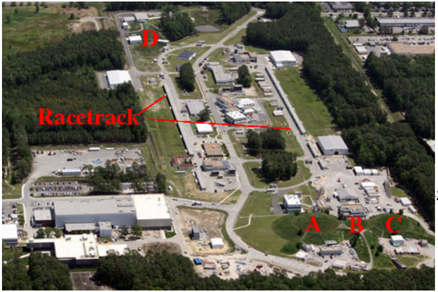
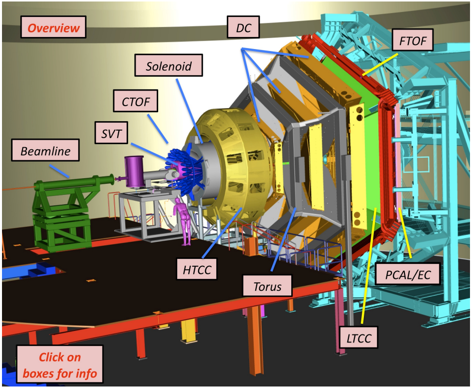


How Do We Measure G_M^n on a Neutron? (Step 2)

- Add one 45-ton, \$80-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
- CLAS covers a large fraction of the total solid angle at forward angles.
- Has about 62,000 detecting elements in about 40 layers.



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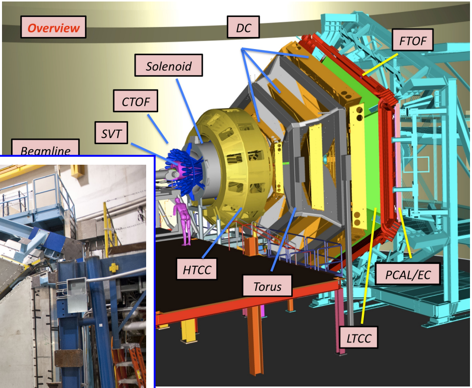
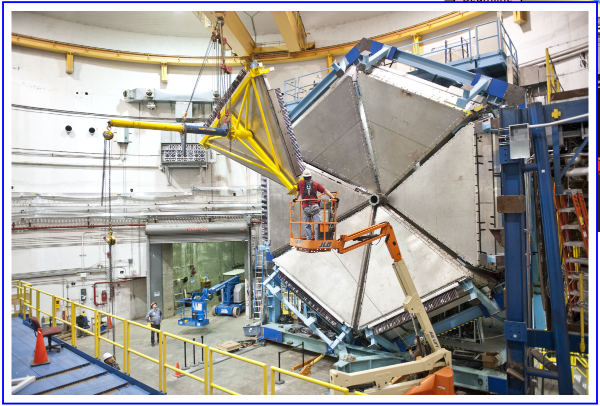
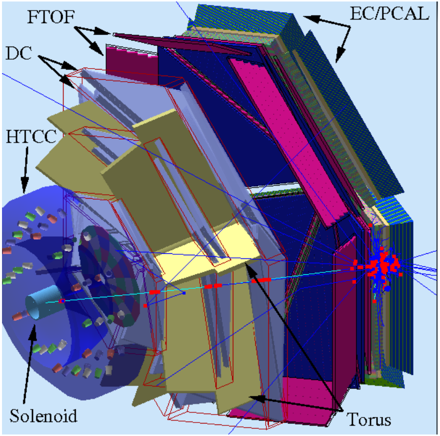


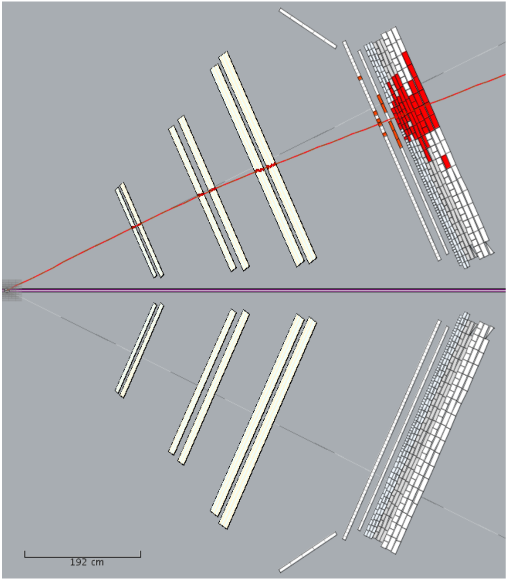


How Do We Measure G_M^n on a Neutron? (Step 2a)

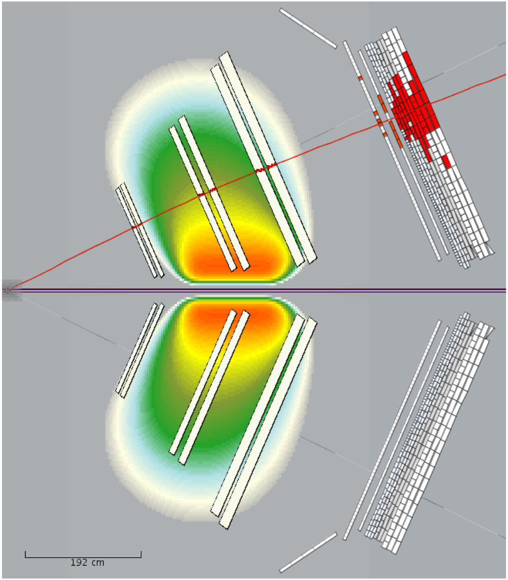
- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.
- Scatter electrons off protons and deuterons (proton+neutron).



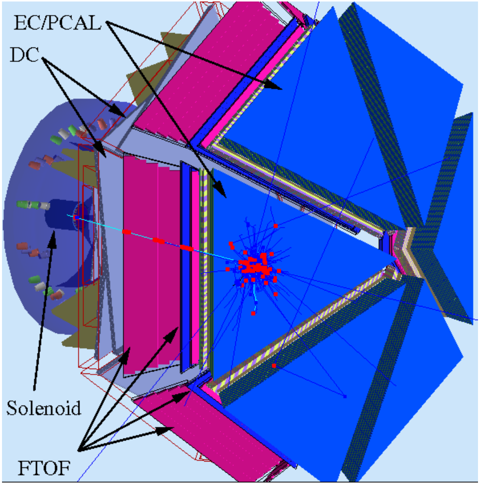
A Simulated CLAS12 Event



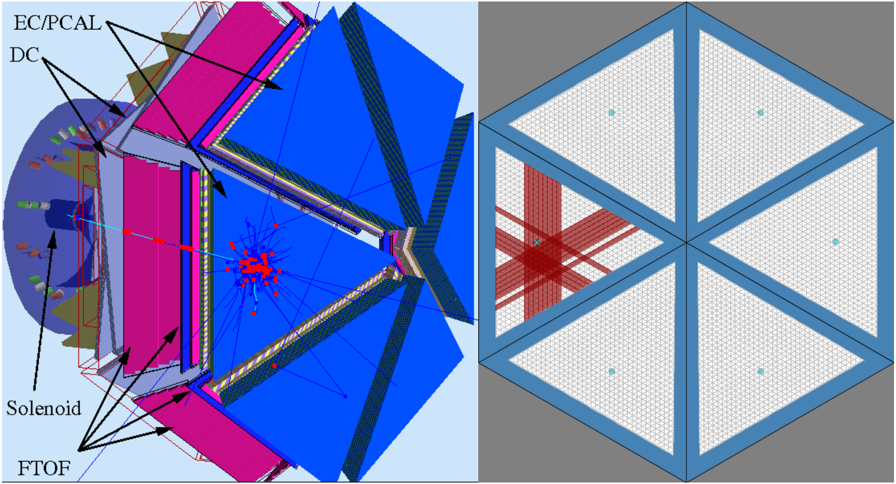
A Simulated CLAS12 Event



A Simulated CLAS12 Event



A Simulated CLAS12 Event

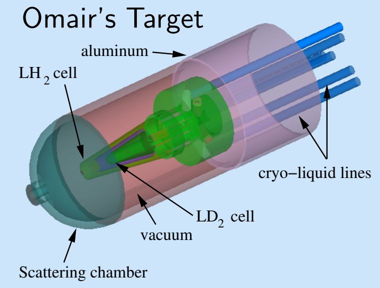


How Do We Measure G_M^n on a Neutron? (Step 3)

- Where's my target?

  Use a dual target cell with liquid hydrogen and deuterium.

- How bad do the protons mess things up? They help!

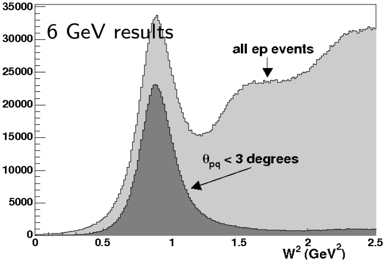


$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{G_E^{n2}+\tau G_M^{n\,2}}{1+\tau} + 2\tau G_M^{n\,2}\tan^2(\frac{\theta}{2})}{\frac{G_E^{p2}+\tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2}\tan^2(\frac{\theta}{2})}$$

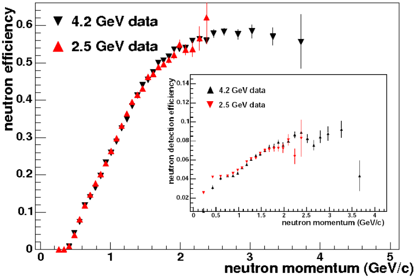
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc.*
- Use the dual target to perform *in situ* detector calibrations.

How Do We Measure G_M^n on a Neutron? (Step 4)

- Quasi-elastic event selection: Apply a maximum θ_{pq} cut to eliminate inelastic events plus a cut on W^2 (J.Lachniet thesis).



- Use the $ep \rightarrow e'\pi^+n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.



How Do We Measure G_M^n on a Neutron? (Step 5)

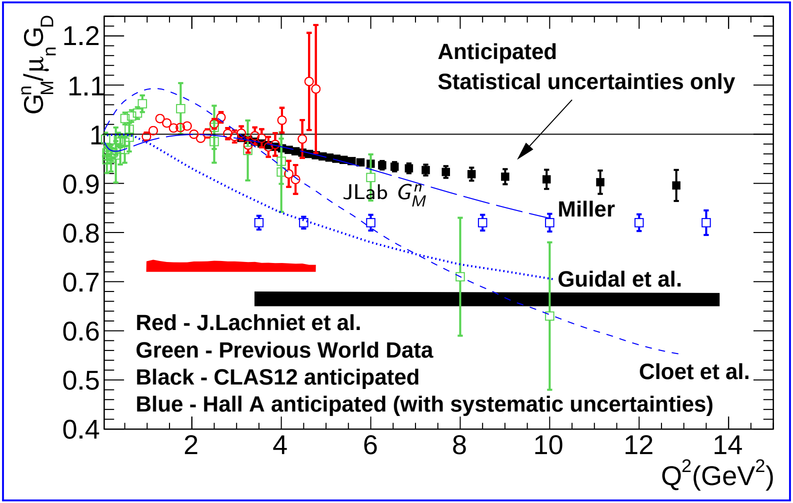
Analyzing the data - CLAS12 computing requirements.

	Cores	Disk(TBytes)	Tape (TByte/year)
DAQ			1,270
Calibration	173		
Reconstruction	1,387	508	5,080
Simulation	8,139	318	1,558
Reconstruction Studies	1,214	508	
Physics Analysis	607	889	
Sum	11,520	2,223	7,938

We'll collect 5-10 TByte/day!

Intel Many-Integrated CoProcessor computer

Anticipated Results



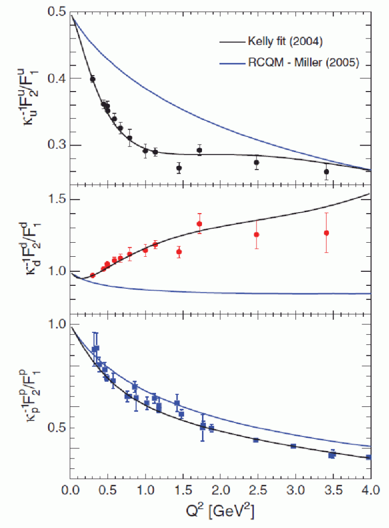
Nuclear Structure - Flavor Decomposition

- By measuring all four EEFFs we have an opportunity to 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))

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

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

- *u* and *d* are different.
- AND different from the proton and neutron form factors.
- Evidence of di-quarks, *s* quark influence, ...?



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

- JLab is a laboratory to test and expand our understanding of quark and nuclear matter, QCD, and the Standard Model.
- We continue the quest 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.

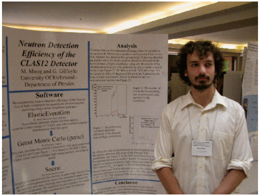
U. S. Department of Energy's

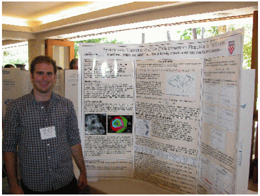
Jefferson Lab

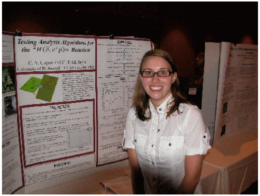
THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

Additional Slides

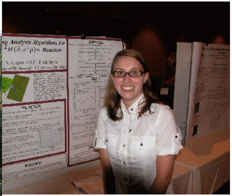
Life on the Frontiers of Knowledge

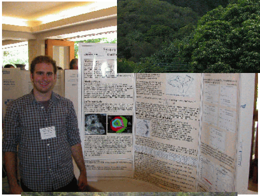


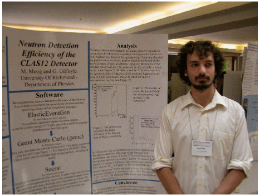


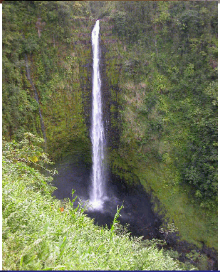


Life on the Frontiers of Knowledge



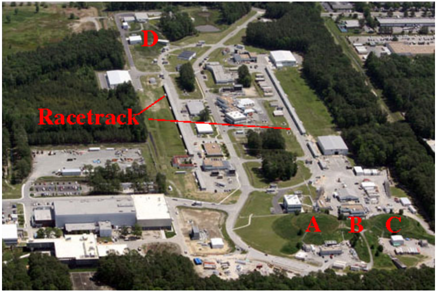






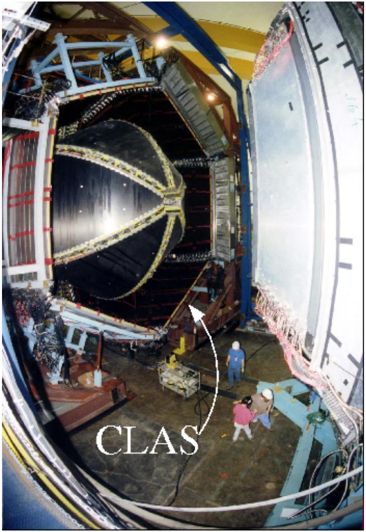
How Do We Measure G_M^n on a Neutron? (Step 1)

- 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 three halls can run simultaneously.



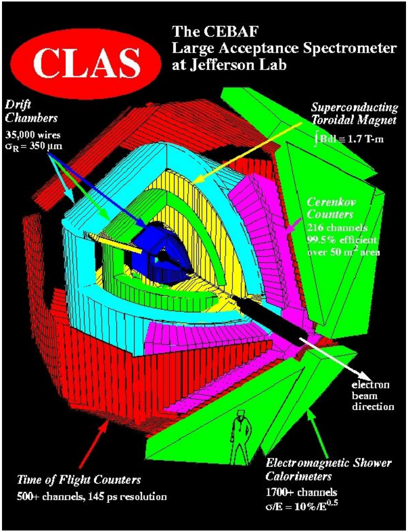
How Do We Measure G_M^n on a Neutron? (Step 2)

- Add one 45-ton, $50-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS).
- CLAS covers a large fraction of the total solid angle.
- Has about 35,000 detecting elements in about 40 layers.

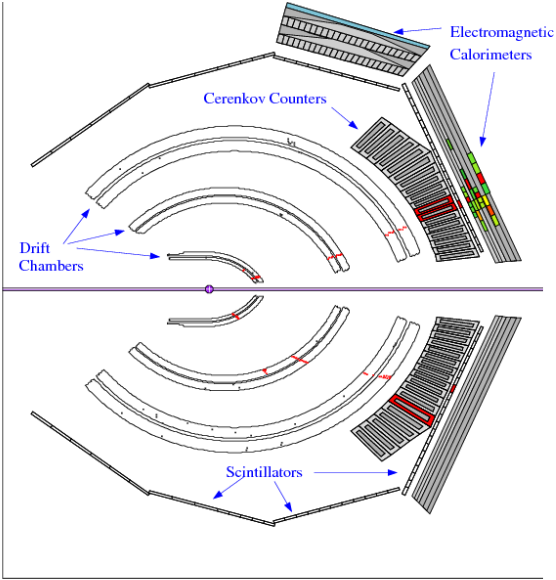


How Do We Measure G_M^n on a Neutron? (Step 2a)

- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.



A CLAS Event



Electromagnetic
Calorimeters
Cerenkov Counters
Drift
Chambers
Scintillators

How Do We Measure G_M^n on a Neutron? (Step 3)

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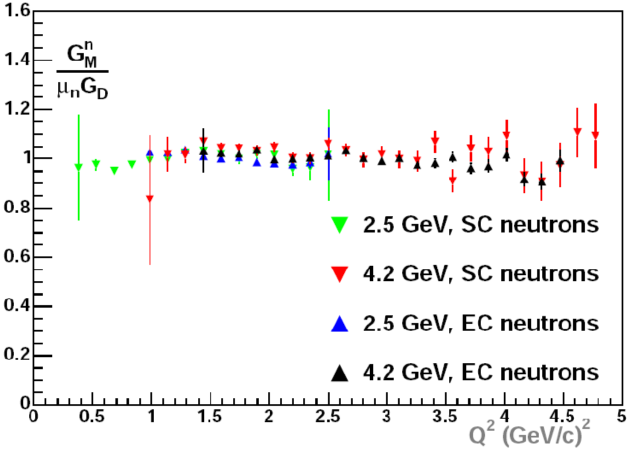
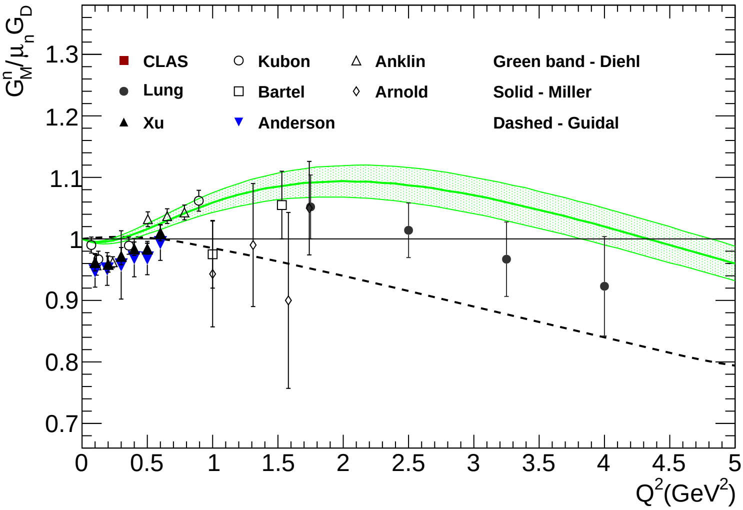
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc*.
- Use the dual target to perform *in situ* detector calibrations.

Results - Overlaps and Final Average

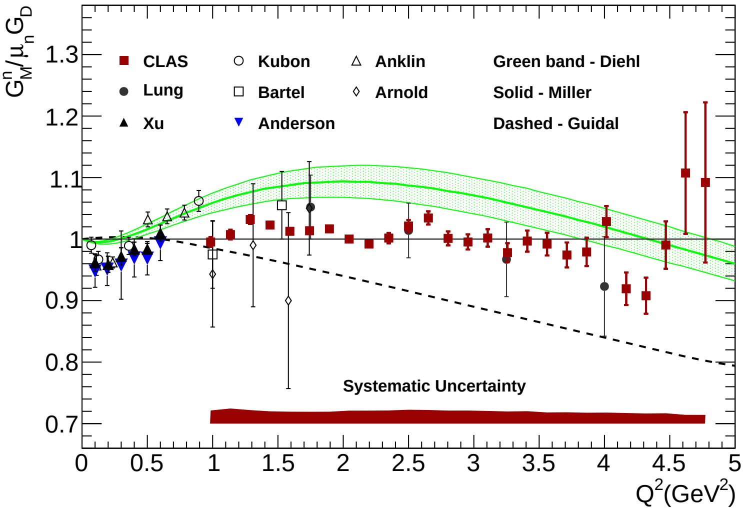
Overlapping measurements of G_M^n scaled by the dipole are consistent.



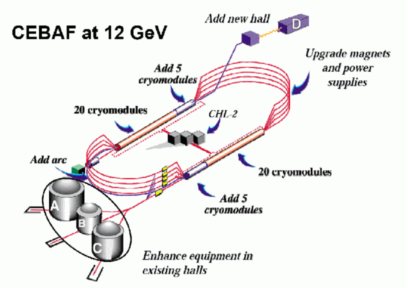
Results - Comparison with Existing Data

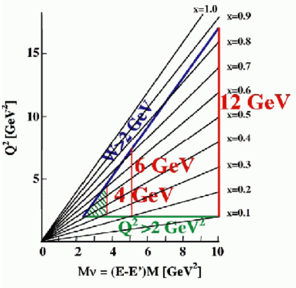


Results - Comparison with Existing Data



- The electron beam energy at JLab (CEBAF) has been doubled from 6 GeV to 12 GeV.
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.





JLab 12 GeV Upgrade - New Detectors