Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration
University of Richmond

"The Periodic Table"

- JLab Mission
- What we know and don't know.
- The Neutron Magnetic Form Factor
- Experiments with CLAS
- More JLab Highlights
- Concluding Remarks

What is the Mission of Jefferson Lab?

- Pursue 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.
- Provide a testing ground for the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.

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

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

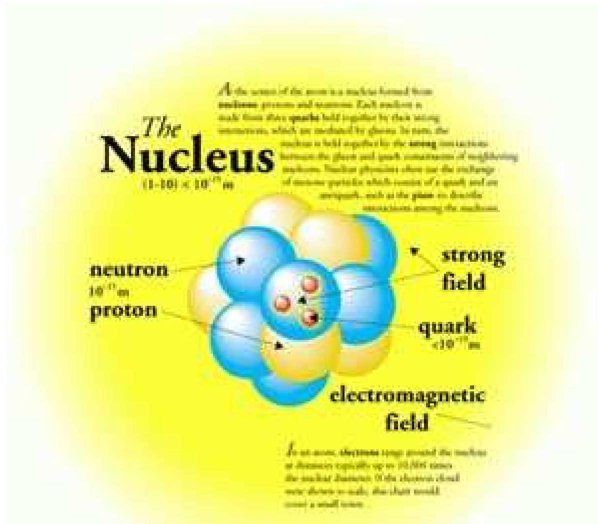
Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	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
s strange	0.1	–1/3
t top	173	2/3
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.

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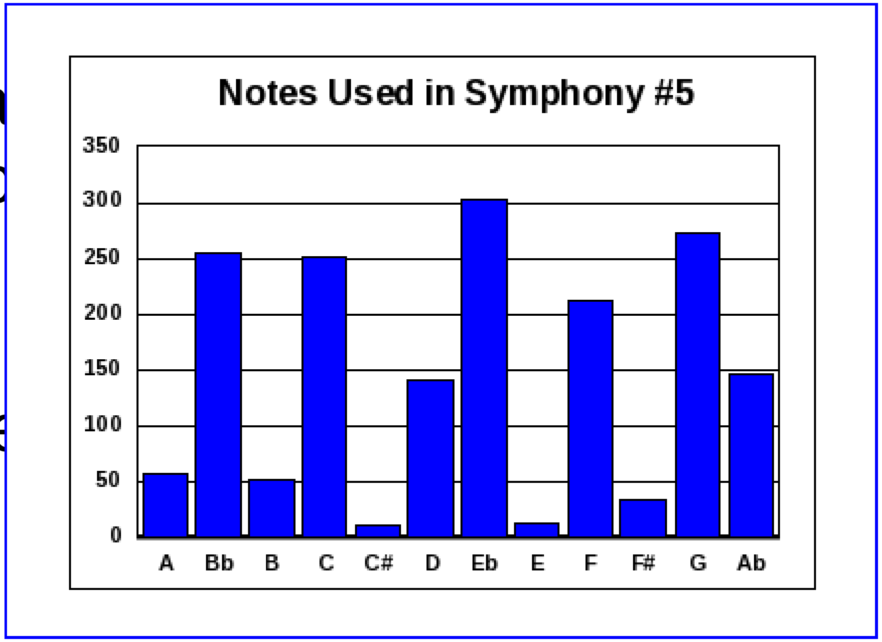
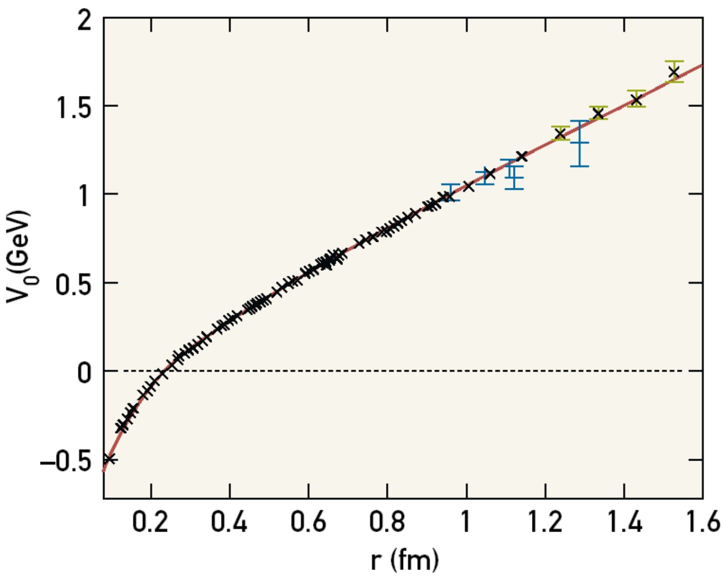


What is the Force?

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



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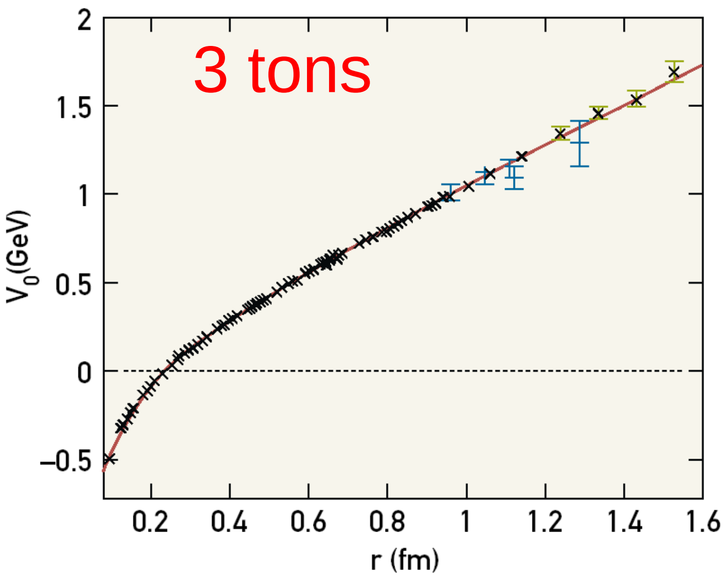

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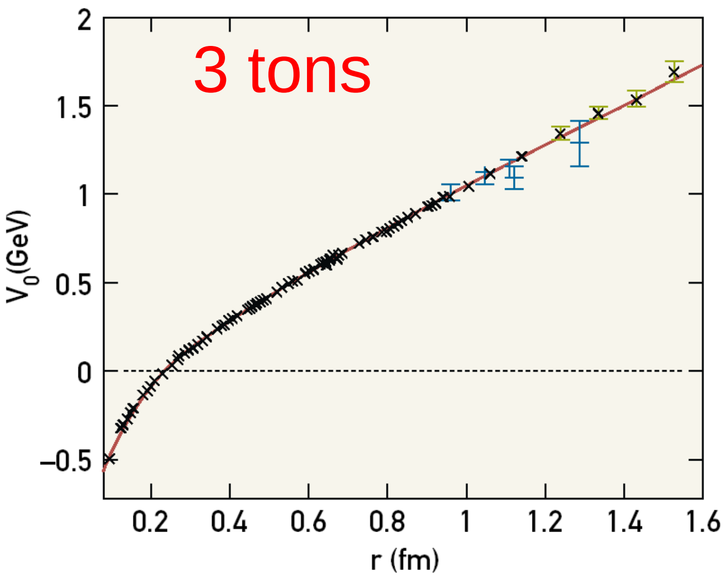
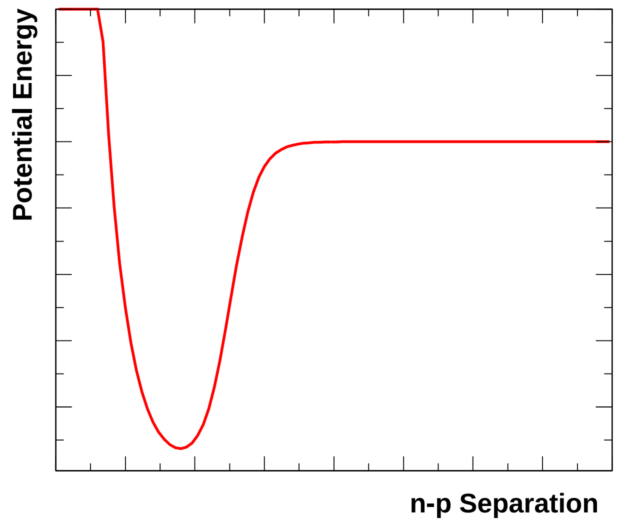
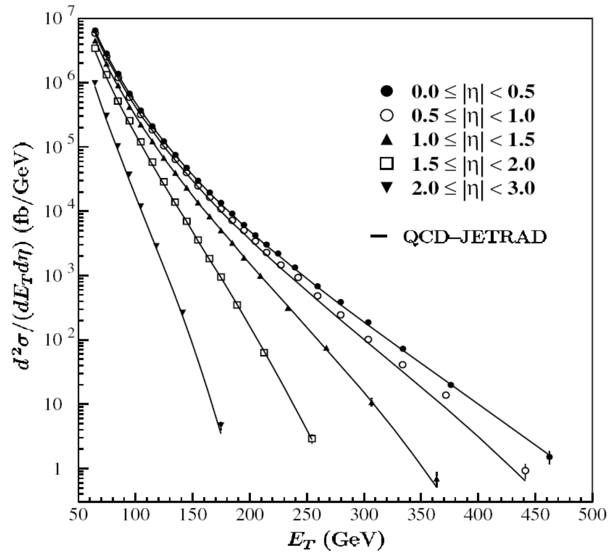
- The hadronic model uses a phenomenological force fitted to data at low energy. This 'strong' force is the residual force between quarks.



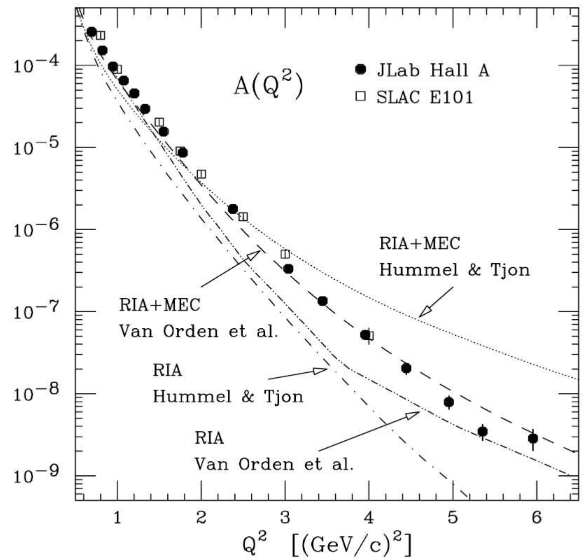


How Well Do We Know It?

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



- The coherent hadronic model (the standard model of nuclear physics) works too (L.C.Alexa, *et al.*, Phys. Rev. Lett., **82**, 1374 (1999)).



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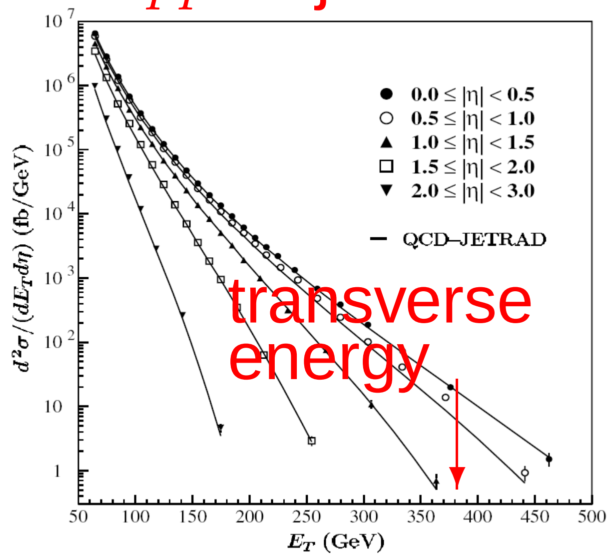
$p\bar{p} \longrightarrow$ jets



effective target area

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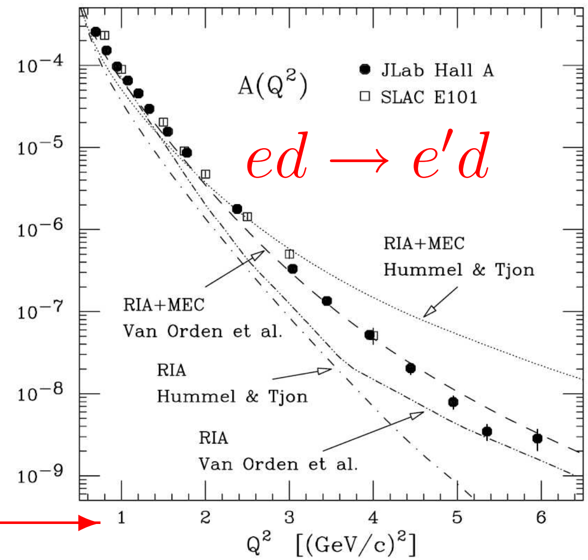

4-momentum transfer squared

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.

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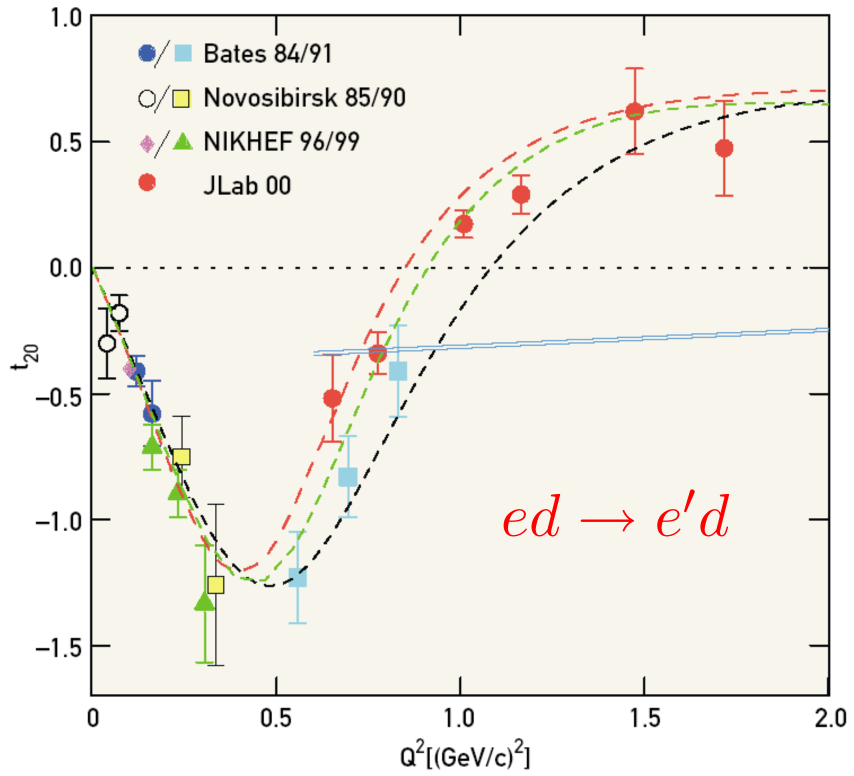
$$= 0.939\ GeV/c^2$$ OOOPS!!!????

What Don’t We Know?

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!!



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

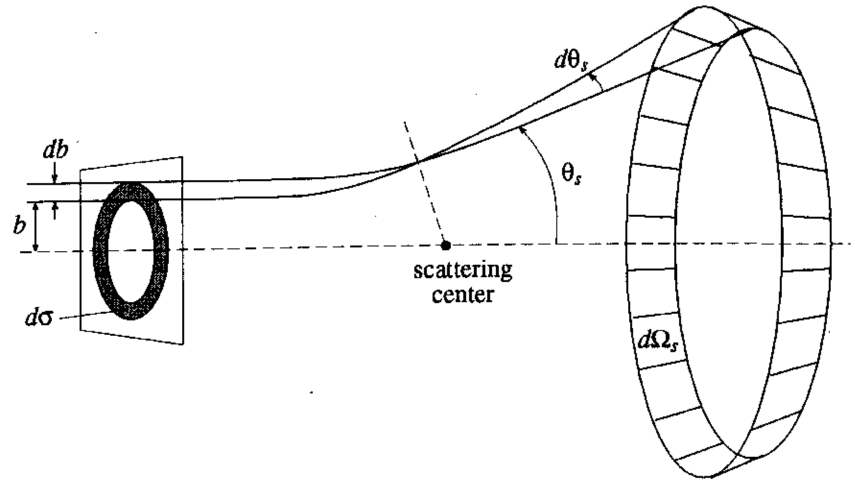
- Fundamental quantity related to the distribution of magnetization/currents in the neutron.
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on theory and the structure of hadrons.
- Part of a broad effort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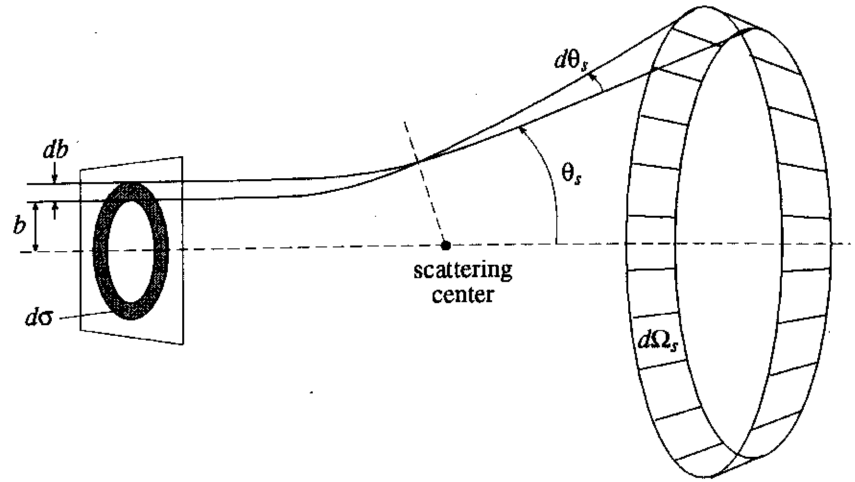

For elastic scattering use the Rutherford cross section.

- 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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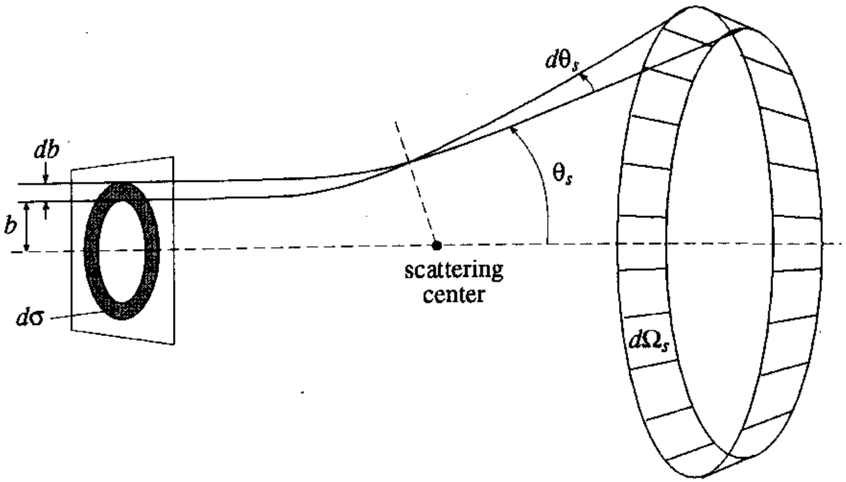

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- What happens when the beam is electrons and the target is not a point?

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where Q^2 is the 4-momentum transfer.

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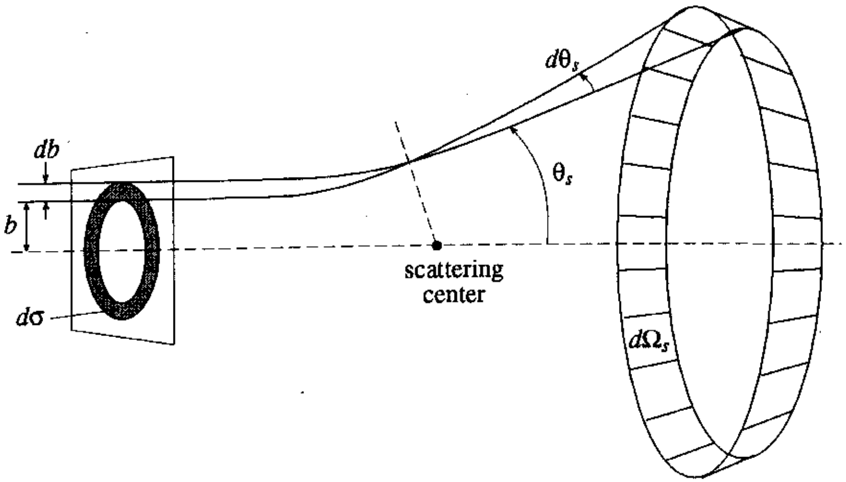

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THE FORM FACTOR!

Why Should You Care?

- The chain of reason.

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

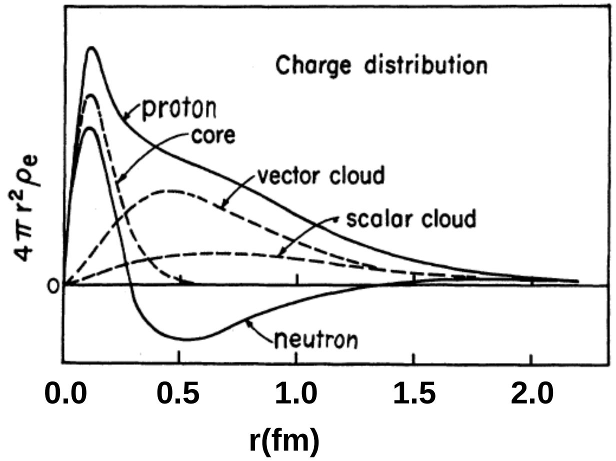
  Experiment **Comparison** **Theory**

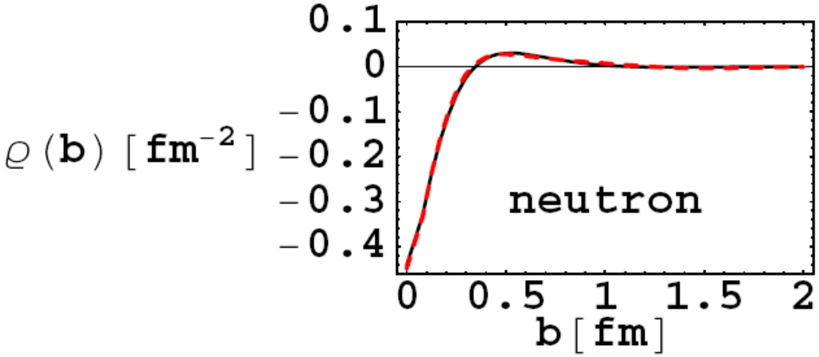
  The form factors are the meeting ground between theory and experiment.

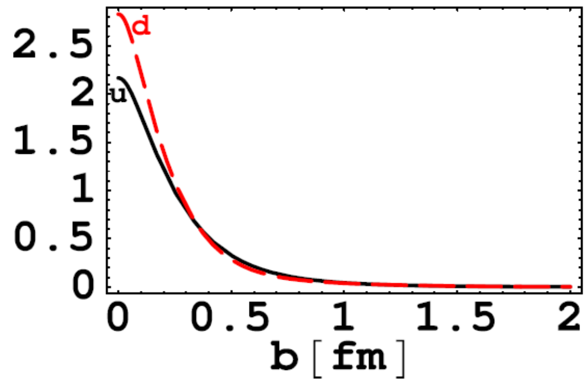
- The Fourier transform of the form factors are related to the charge and current distributions within the neutron.

Why Should You Care Even More?

- The old picture of the neutron (and proton).
- What we know now - analysis of form factor data by G. Miller(Phys. Rev. Lett. **99**, 112001 (2007)).







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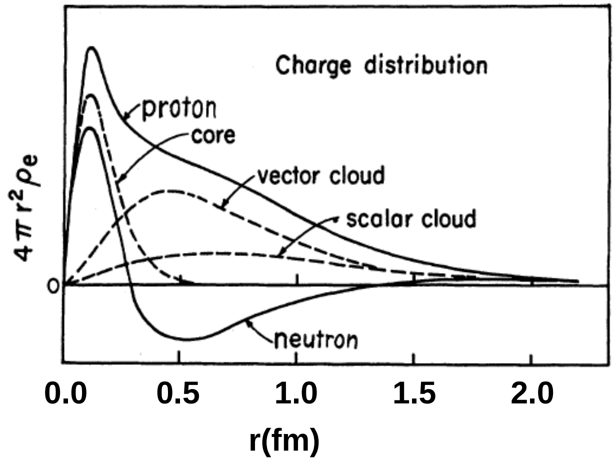

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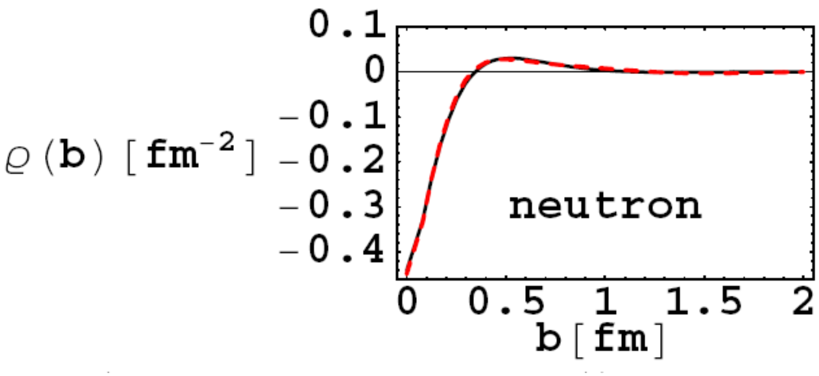
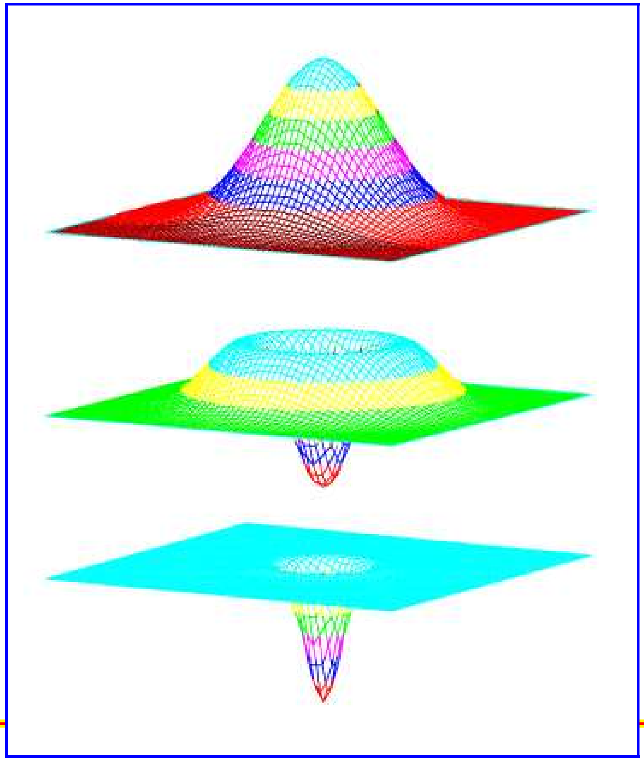
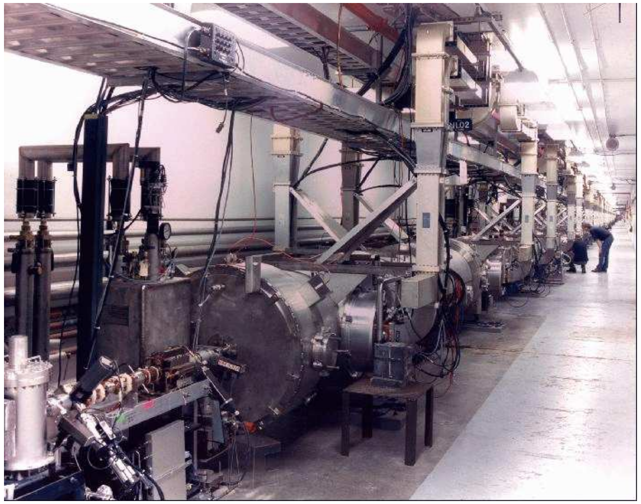




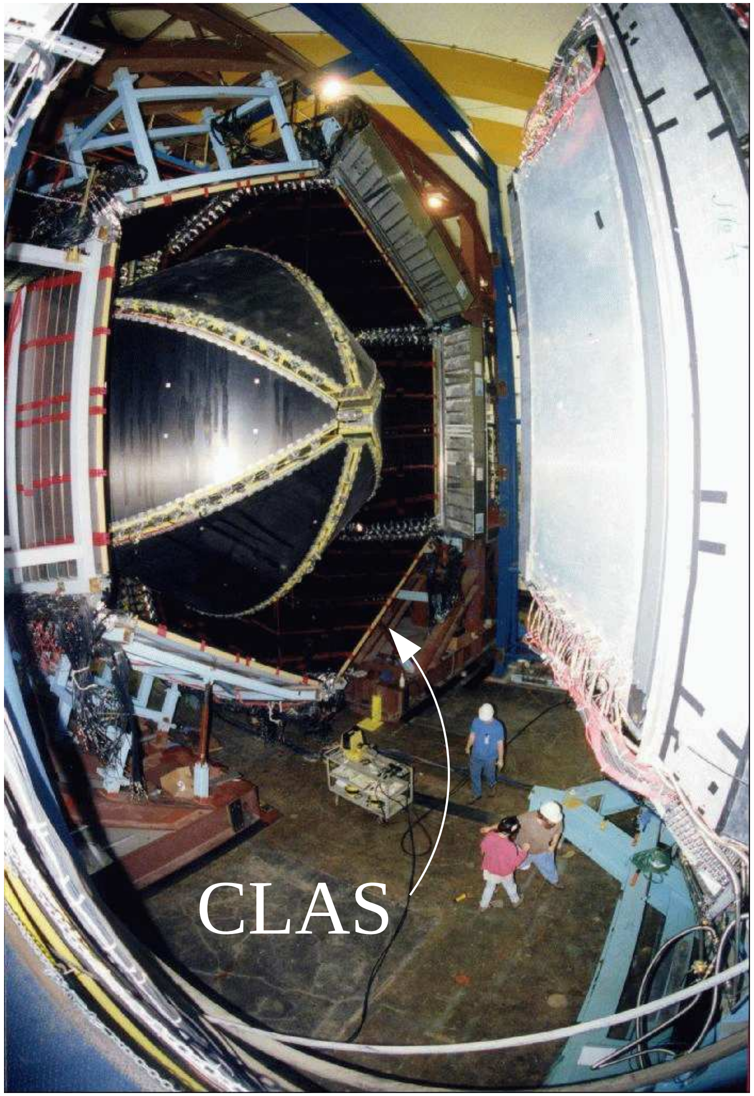
How Do We Measure G_M^n on a Neutron? (Step 1)

- Start at your local mile-long, high-precision, 6-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.



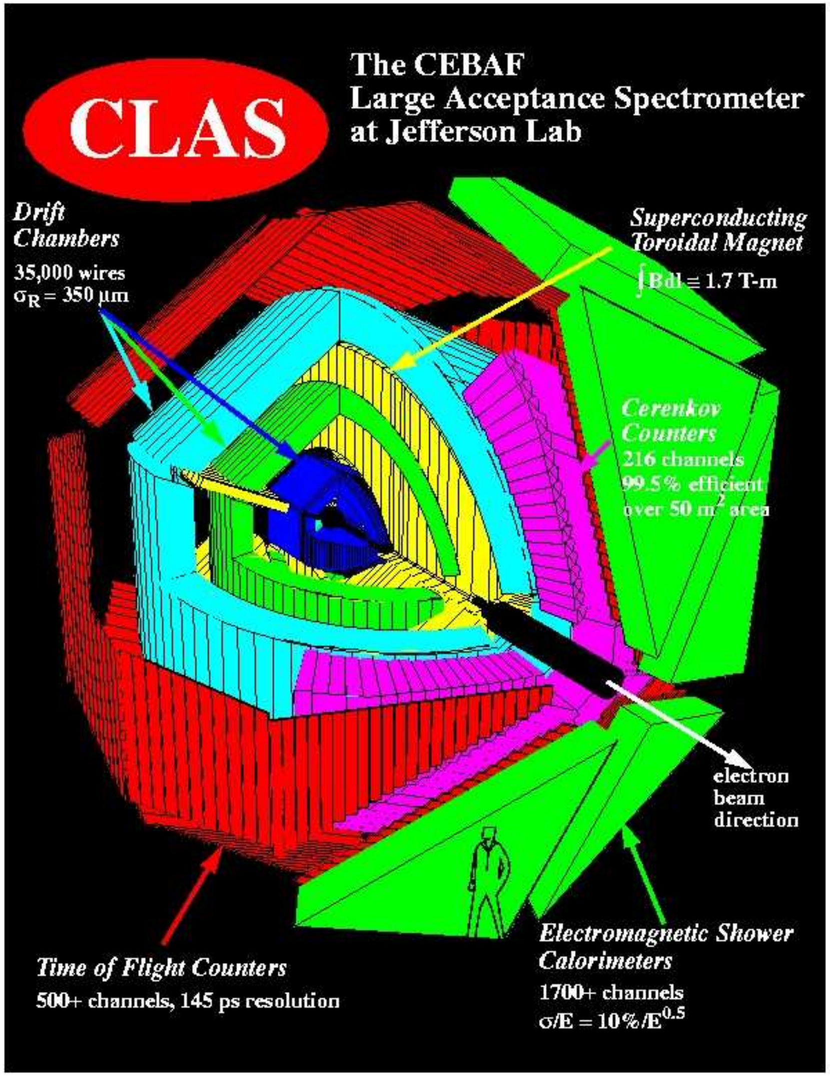
How Do We Measure G_M^n on a Neutron? (Step 2)

- 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.

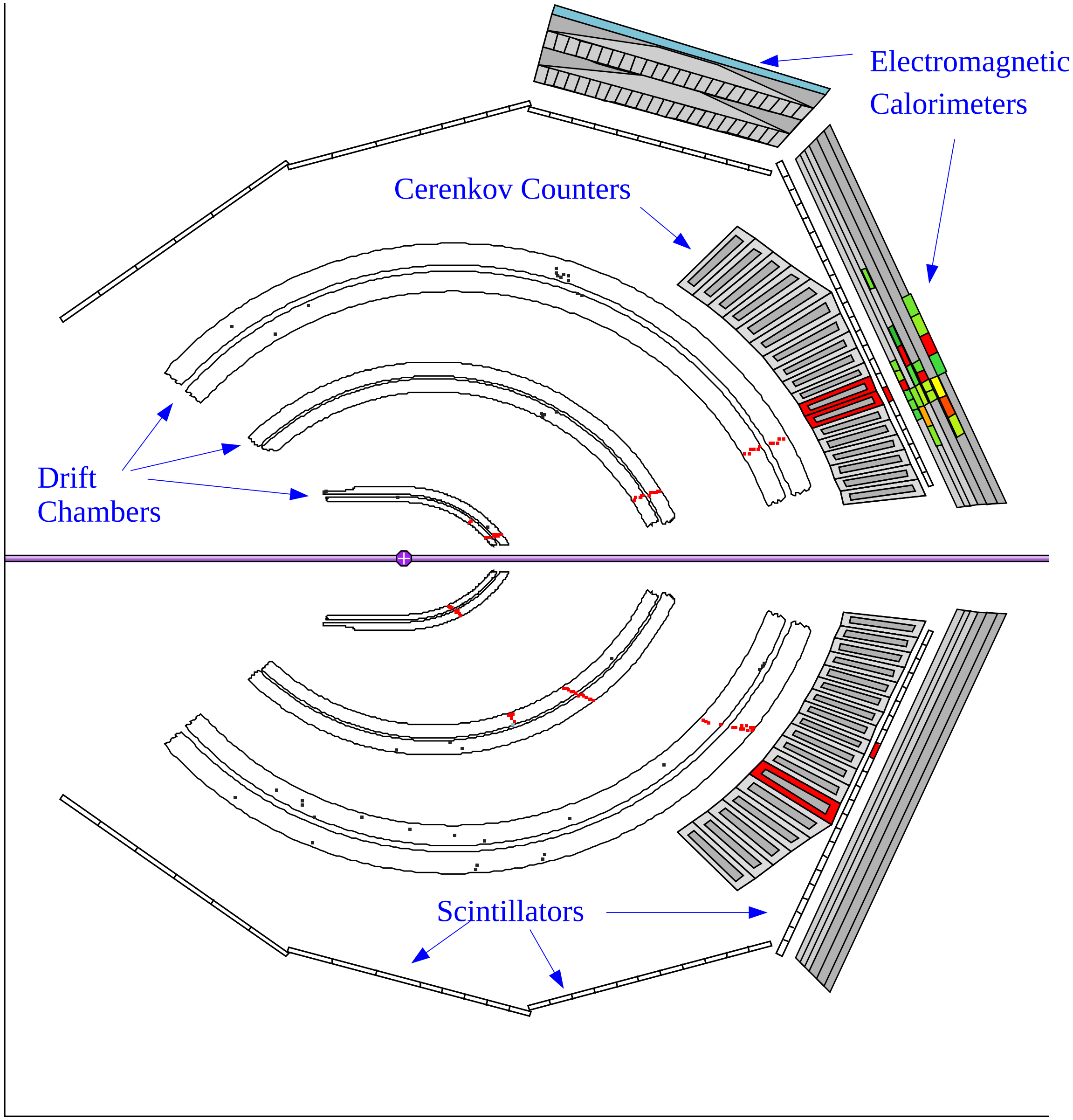


How Do We Measure G_M^n on a Neutron? (Step 2a)

- Drift chambers map the trajectories. A toroidal magnetic field bends the trajectory 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)

- Where's my target?

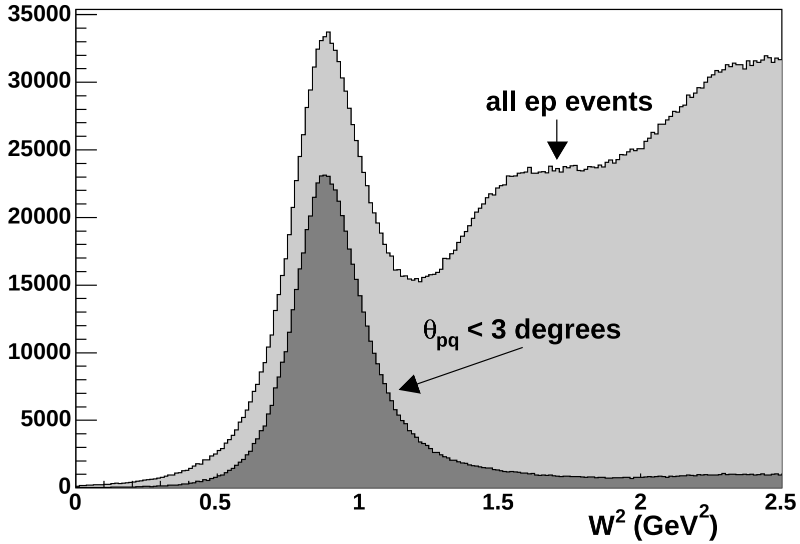
  Use a dual target cell with liquid hydrogen and deuterium.
- How bad do the protons mess things up? They help!

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

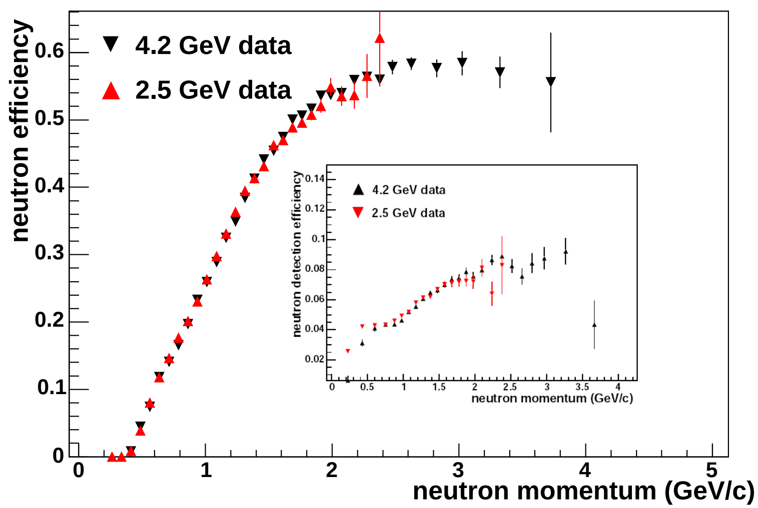
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc*.
- Use the dual target to perform *in situ* detection calibrations.

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).

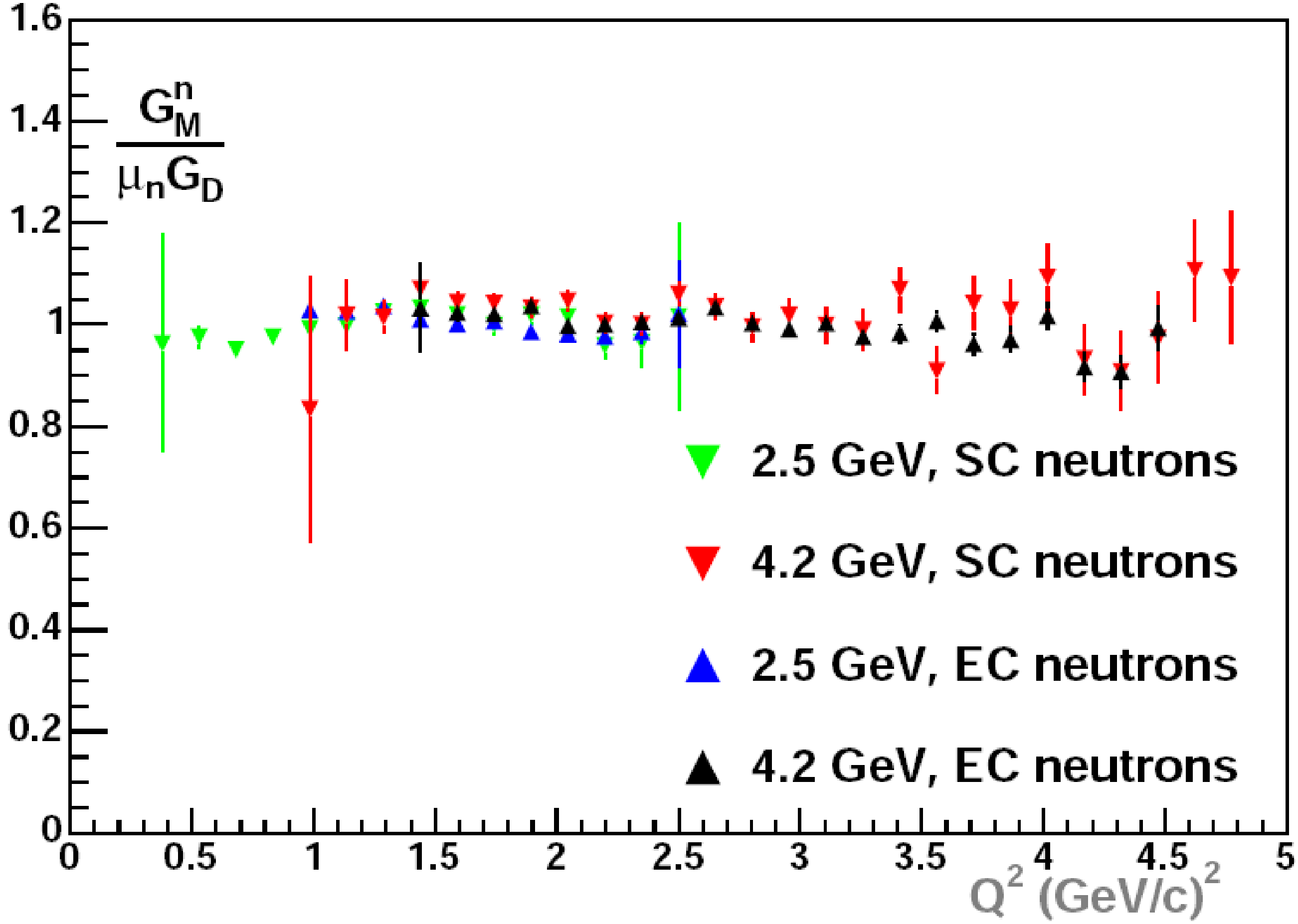


- Use the $ep \rightarrow e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.



Results - Overlaps and Final Average

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



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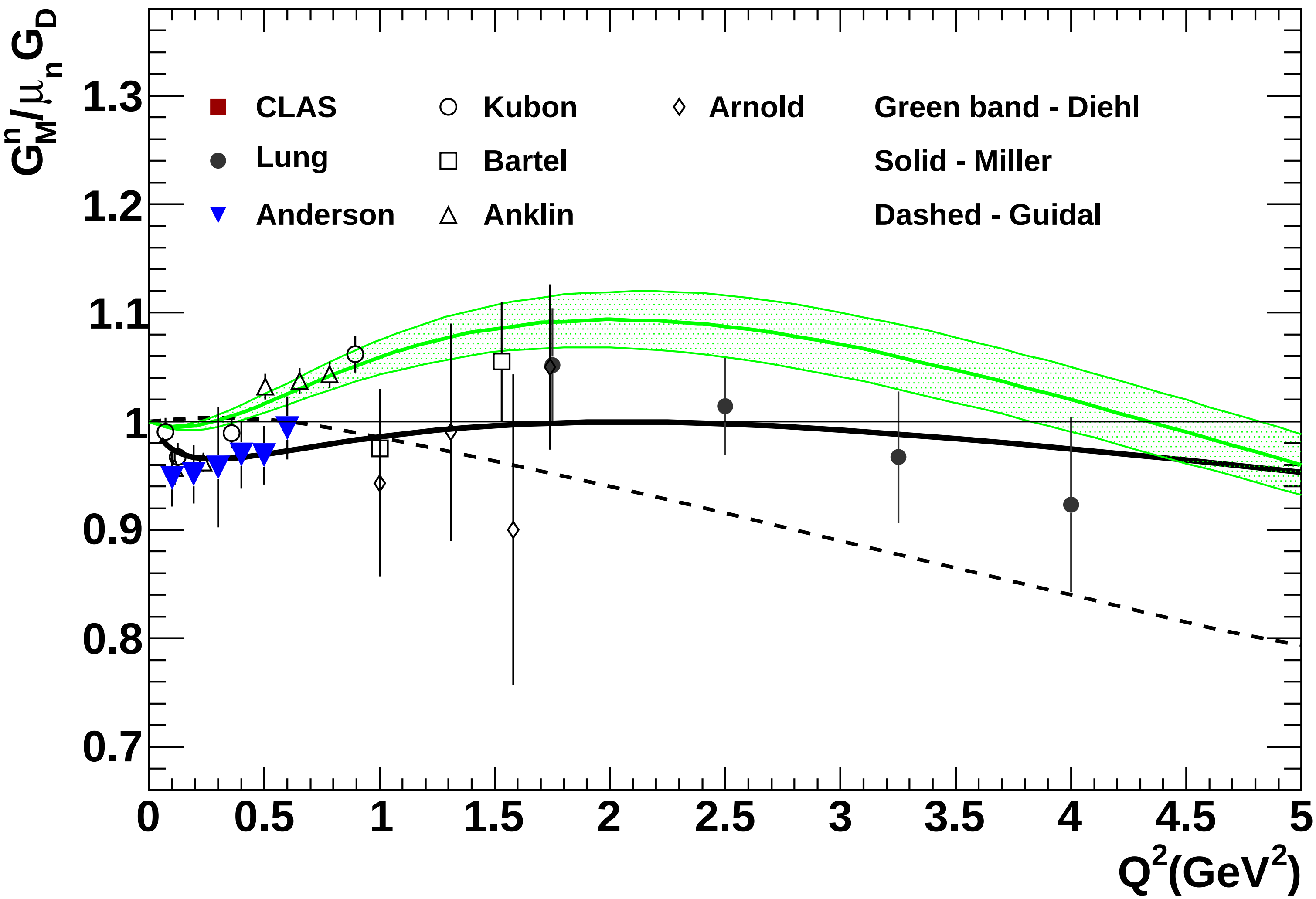

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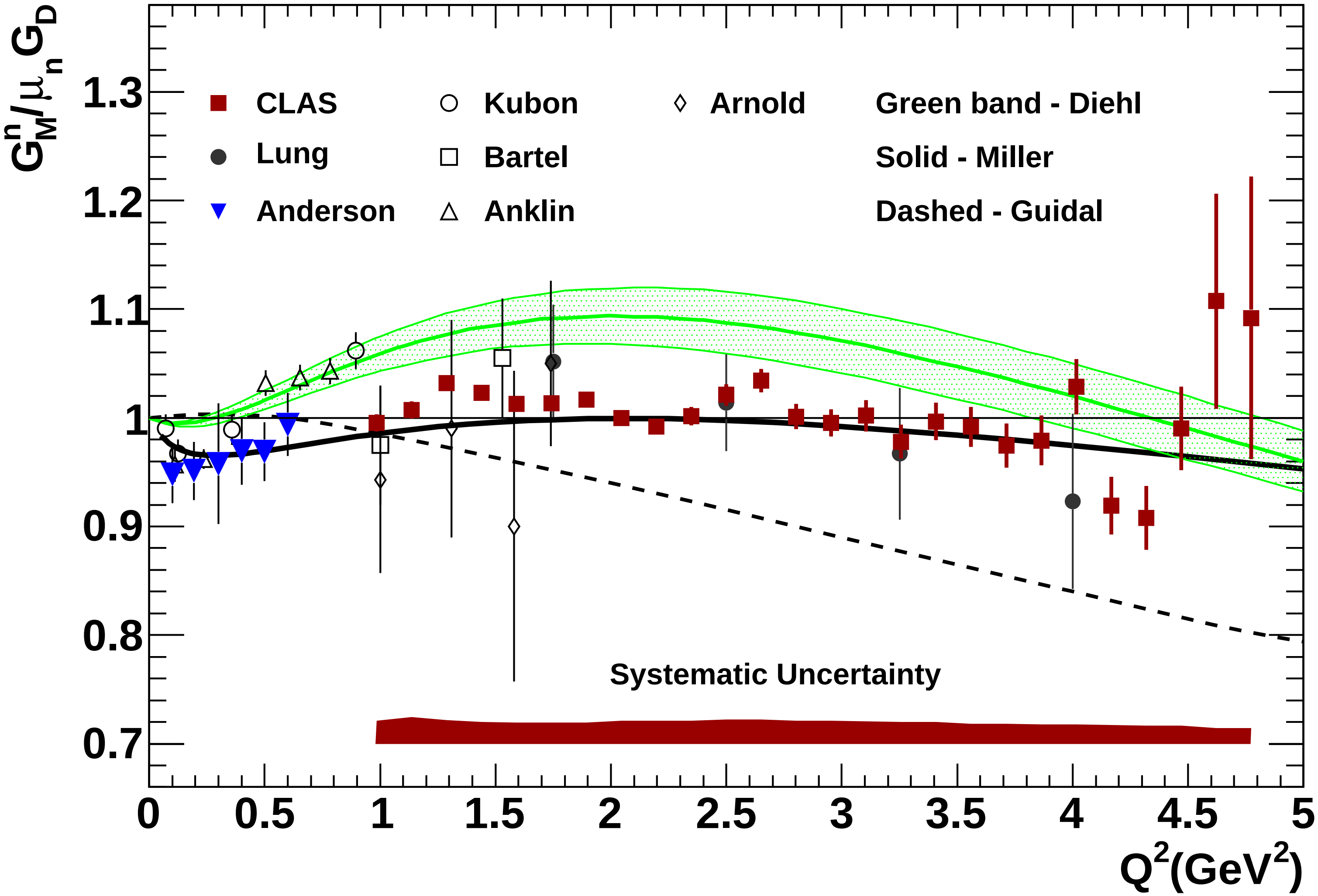


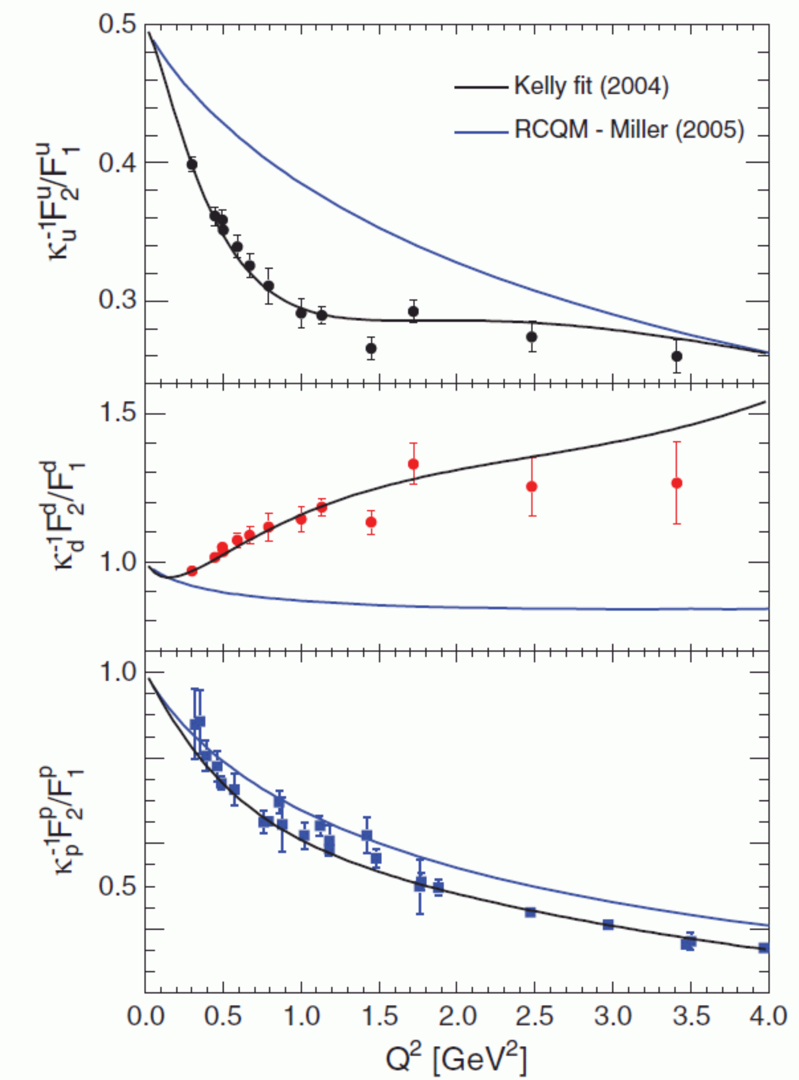
Nuclear Structure - Flavor Decomposition

- 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))

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

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

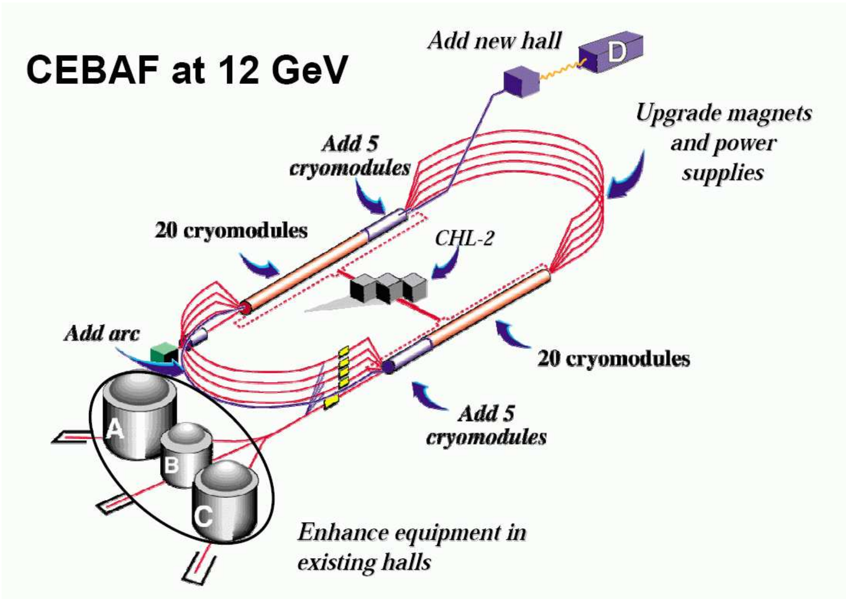
- u and d are different.
- AND different from the proton and neutron form factors.
- Evidence of di-quarks, s quark influence, ...?

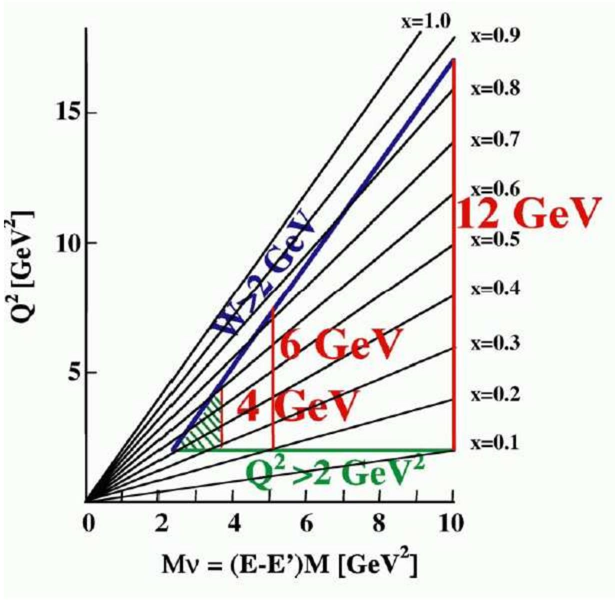


Gordon Cates, Sean Riordan *et al.*, PRL **106**, 252003 (2011).

JLab 12-GeV Upgrade

- The electron beam energy at JLab (CEBAF) will be 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.





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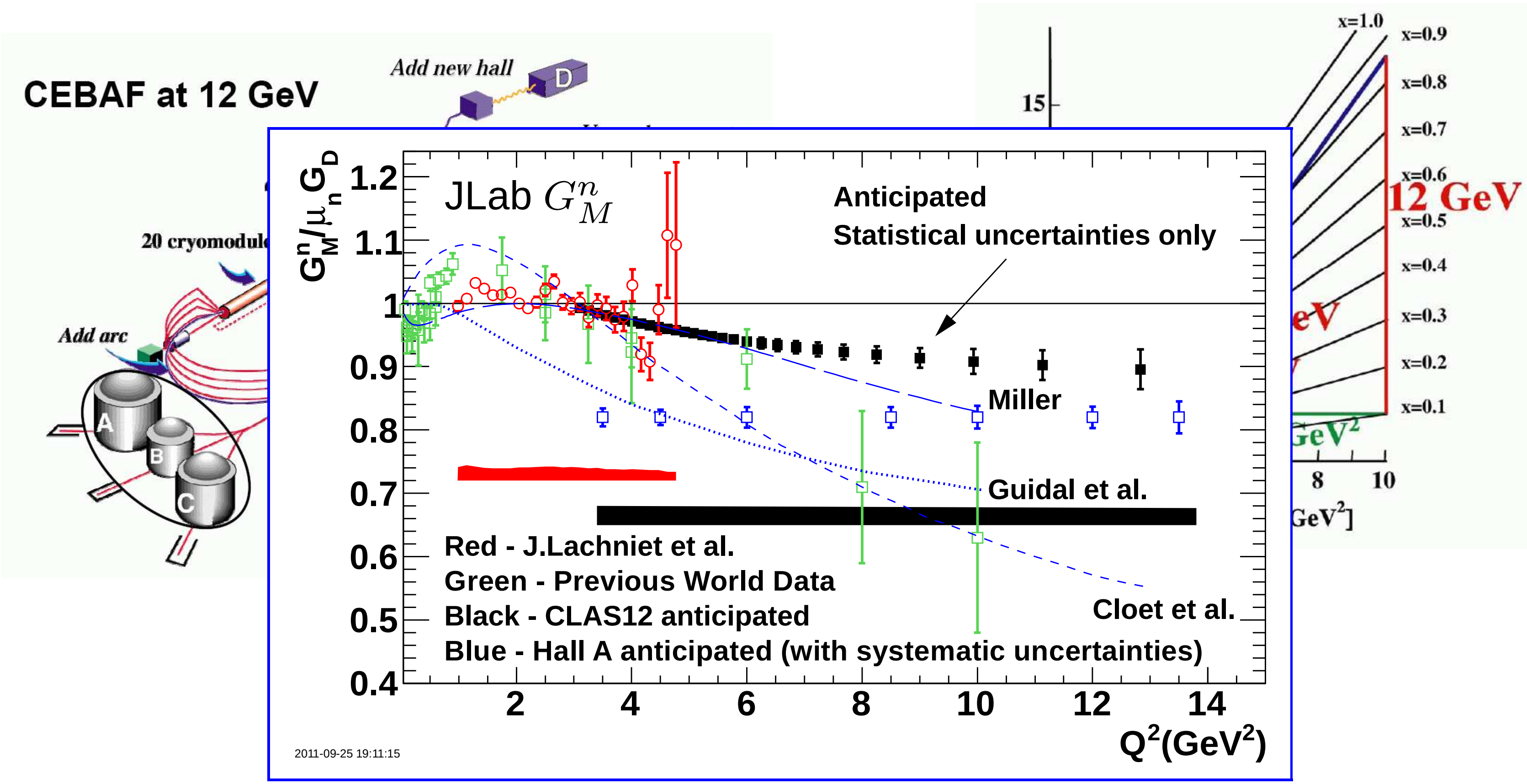
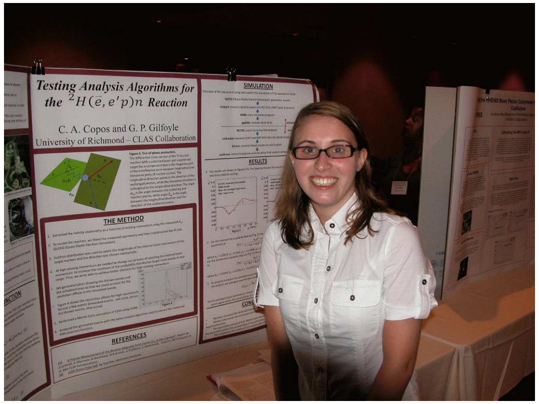
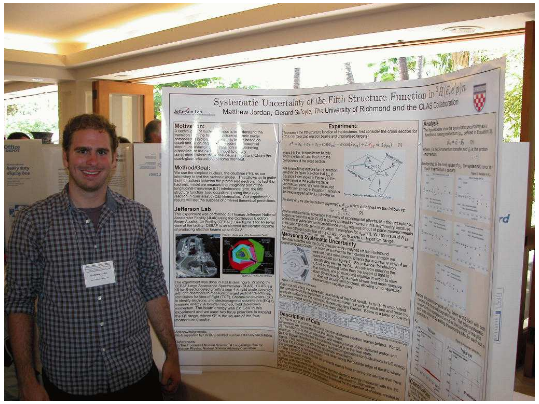
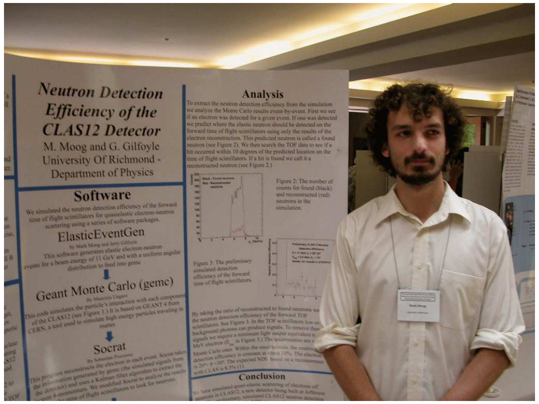
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.



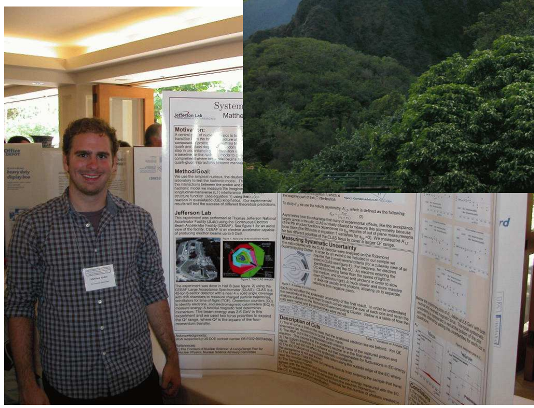
Life on the Frontiers of Knowledge

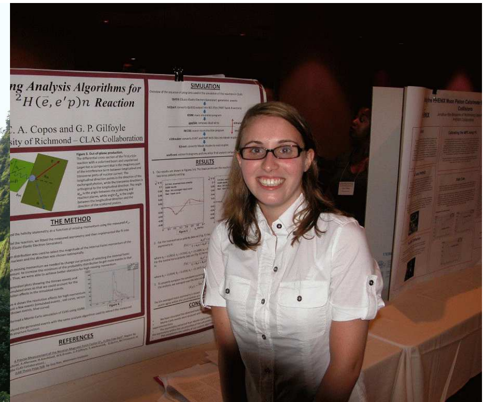


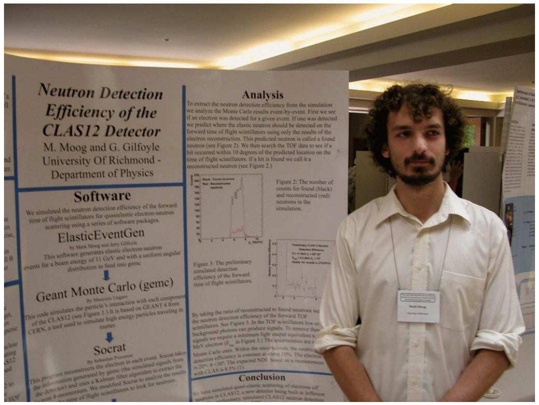


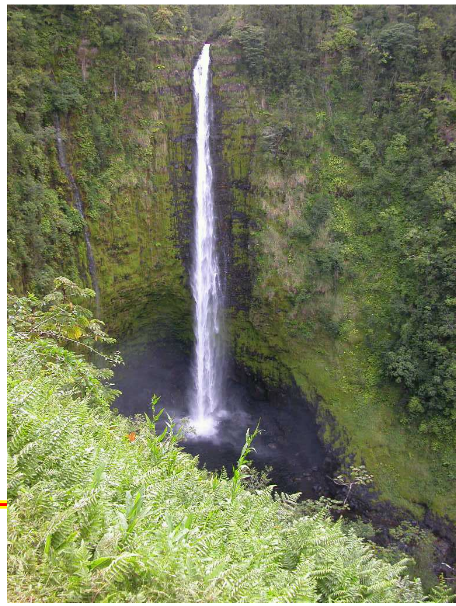


Life on the Frontiers of Knowledge









Concluding Remark

- 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 with the JLab 12-GeV Upgrade.