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

G_M^n Co-conspirators:

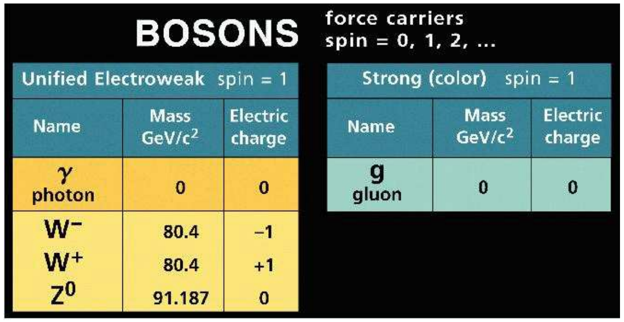
Jeff Lachniet	Will Brooks
Mike Vineyard	Brian Quinn
Kristen Greenholt (UG)	Rusty Burrell (UG)

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.



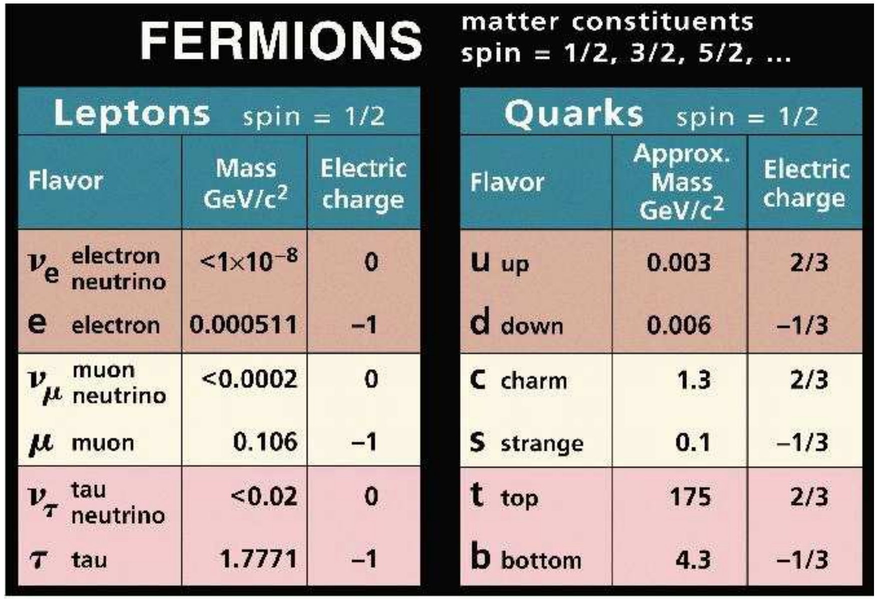
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0



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

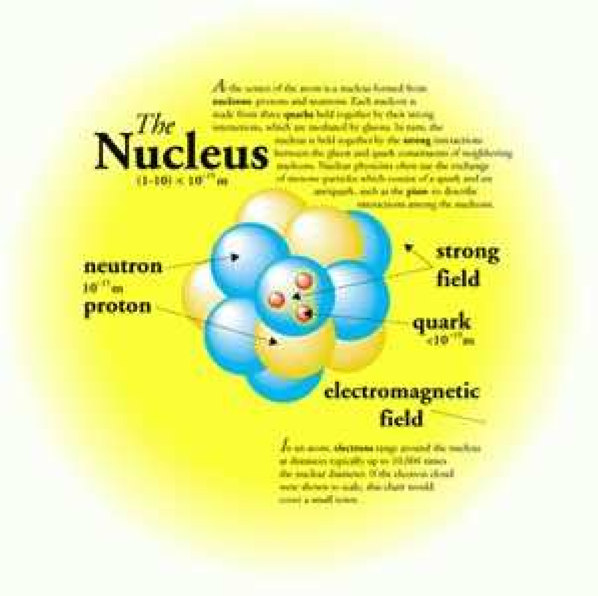
Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

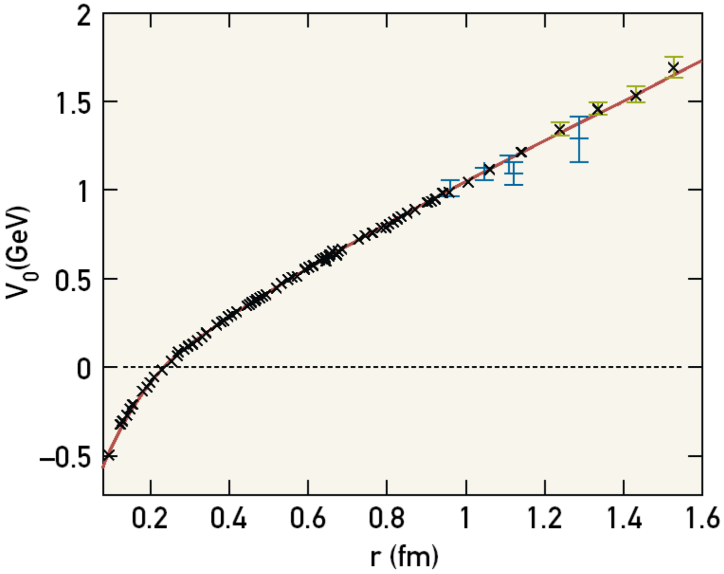
- The atomic nucleus is made of protons and neutrons bound by the strong force.



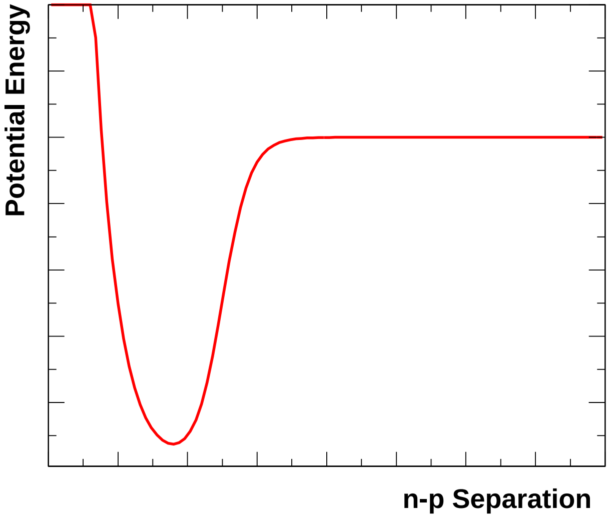
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.

What is the Force?

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



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



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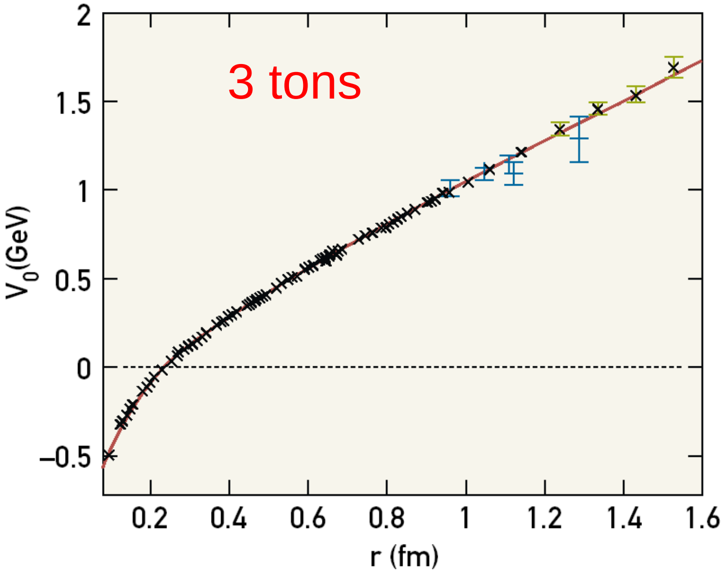

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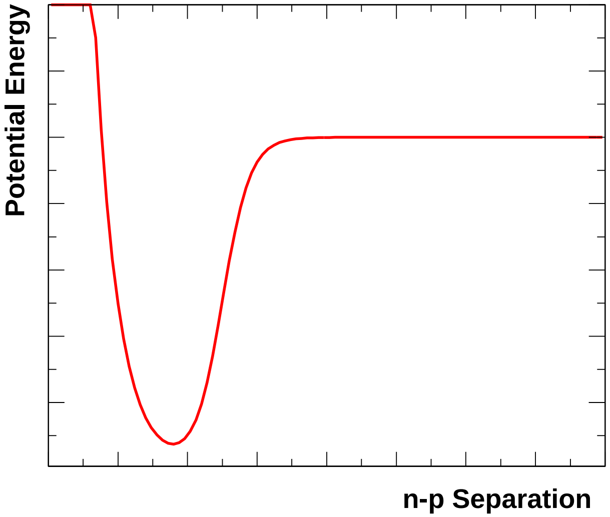
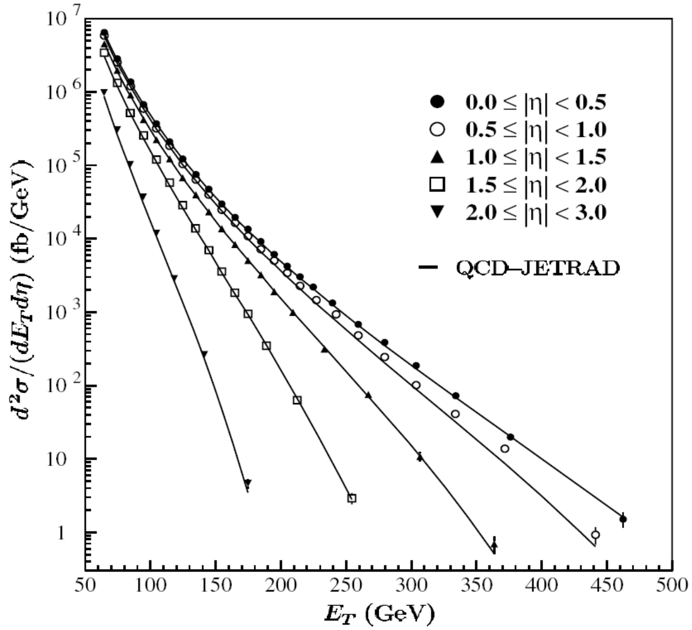
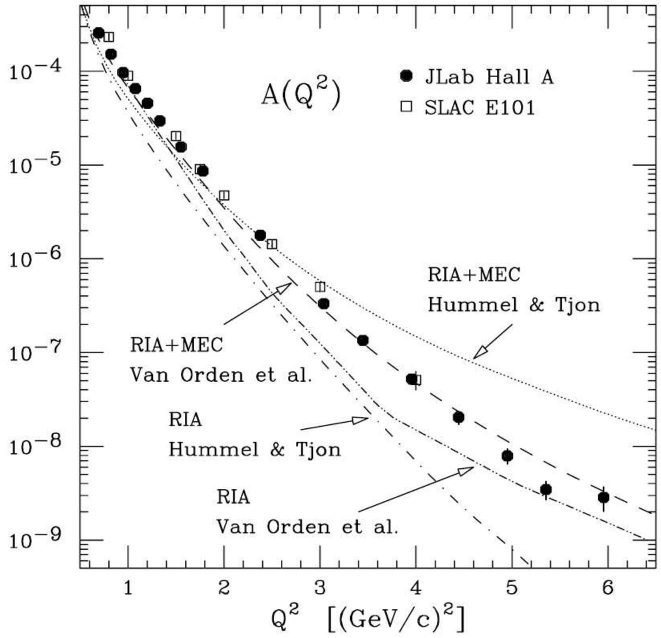


How Well Do We Know It?

- 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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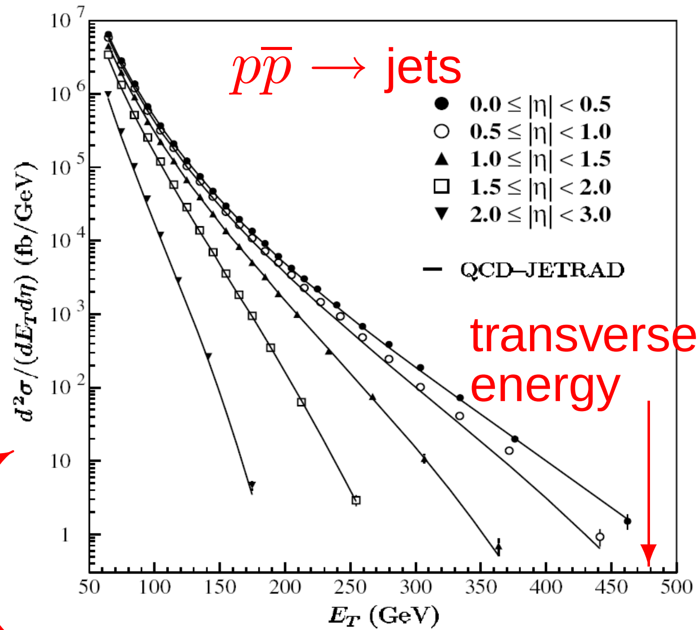

effective target area

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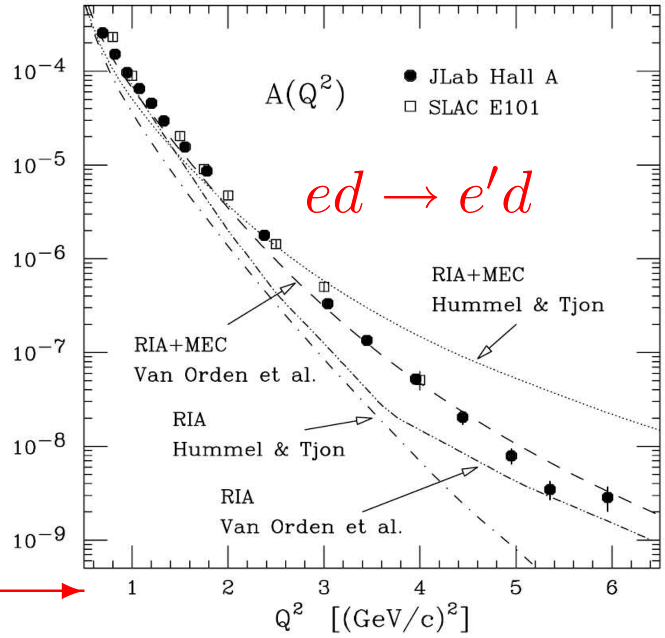
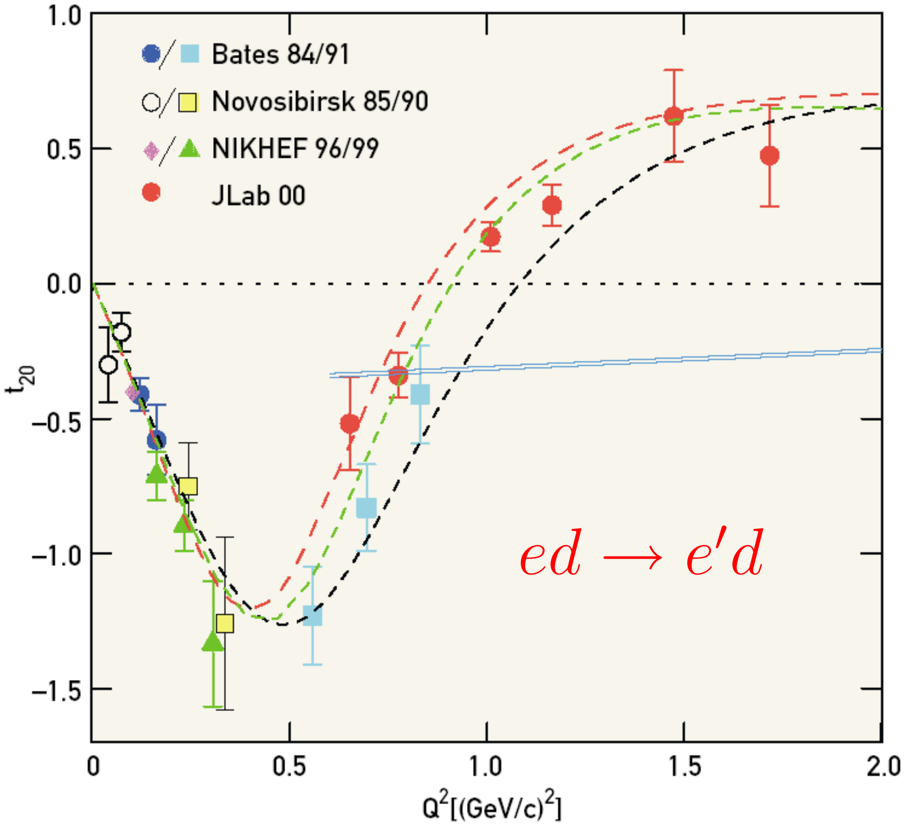


4-momentum transfer squared

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)

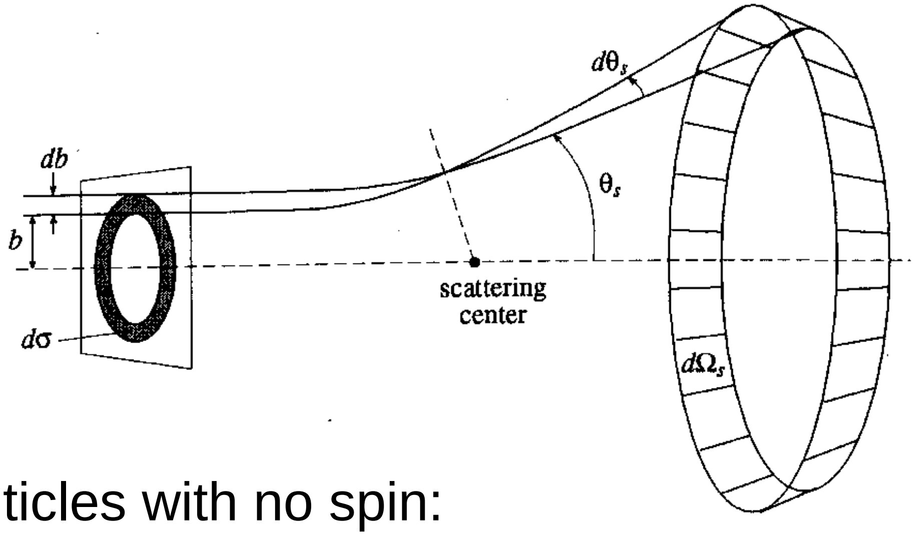
- Fundamental quantity related to the distribution of charge and magnetization/currents in the proton and neutron (the nucleons).
- Part of a broad effort to understand how nucleons are ‘constructed from the quarks and gluons of QCD’.*
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on generalized parton distributions (GPDs) which promise to give us a three-dimensional picture of hadrons.
- Fundamental challenge for lattice QCD.

* ‘Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade’, NSF/DOE Nuclear Science Advisory Committee, April, 2002.

What is a Form Factor?

- Start with the cross section.

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered rate/solid angle}}{\text{incident rate} \times \text{ targets/area}}$$



For elastic scattering by point particles with no spin:

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2(\hbar c)^2}{16E^2\sin^4(\theta/2)}$$

(Rutherford cross section, σ_{Ruth}).

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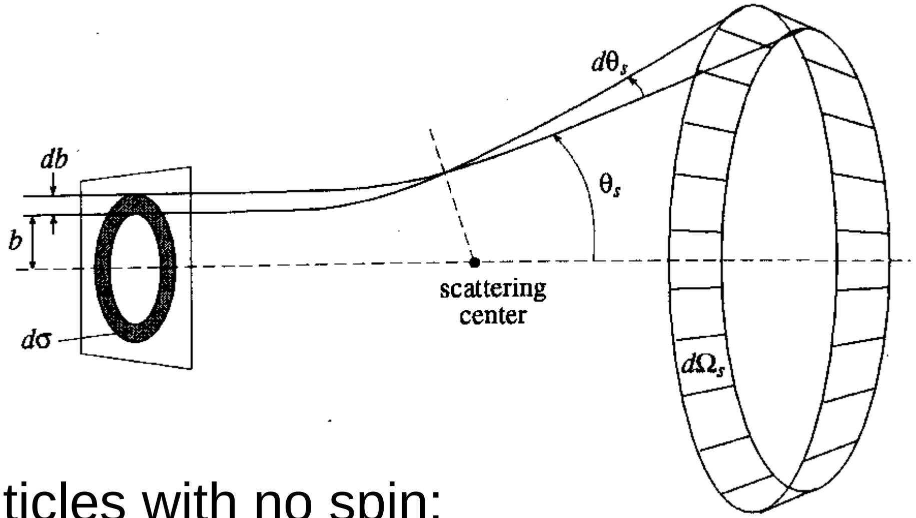

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- Get the cross section for elastic scattering by point particles with spin.

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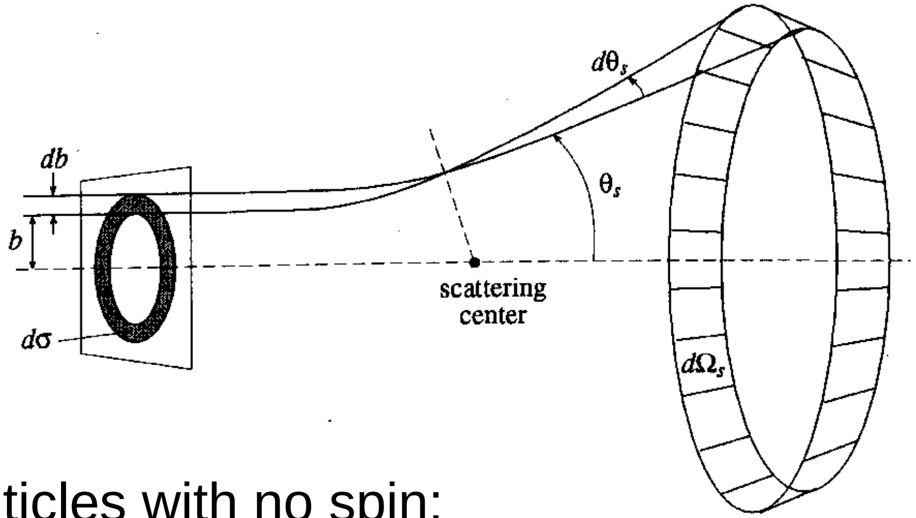

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- What happens when the beam is electrons and the target is not a point?

$$\frac{d\sigma}{d\Omega} = \sigma_{Ruth}\left(1-\beta^2\sin^2\frac{\theta}{2}\right)|F(Q^2)|^2$$

where Q^2 is the 4-momentum transfer.

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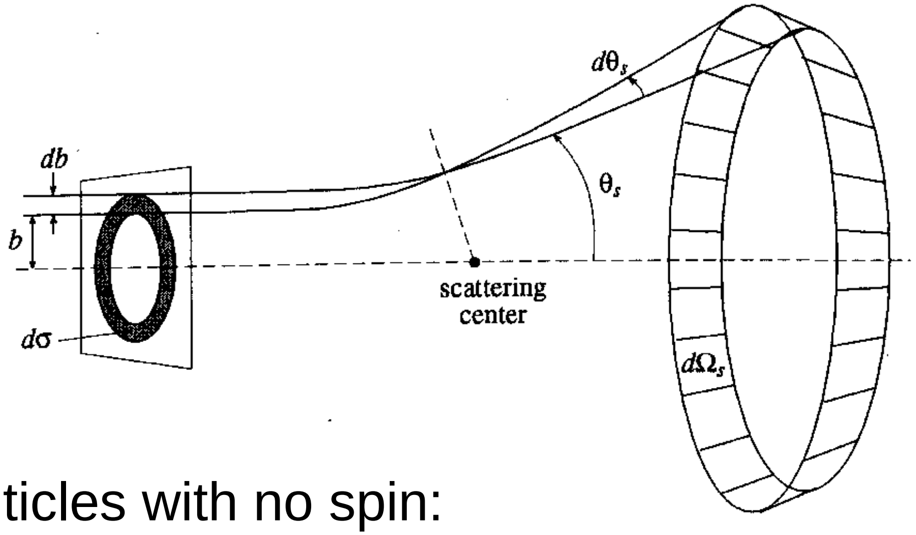

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THE FORM FACTOR!

Why Should You Care?

- The chain of reason.

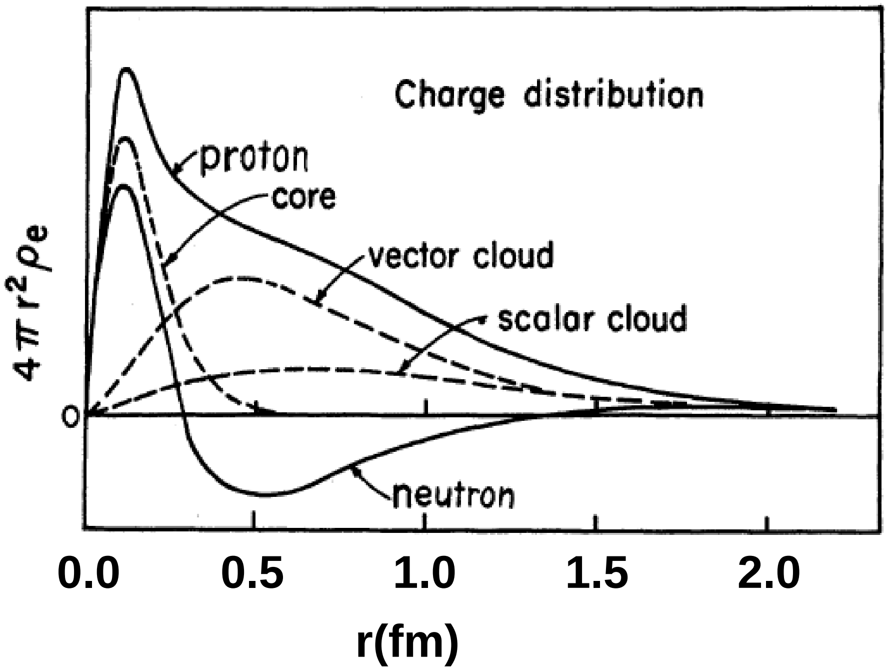
$$\frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow$$

QCD,
Constituent quarks

Experiment Comparison Theory

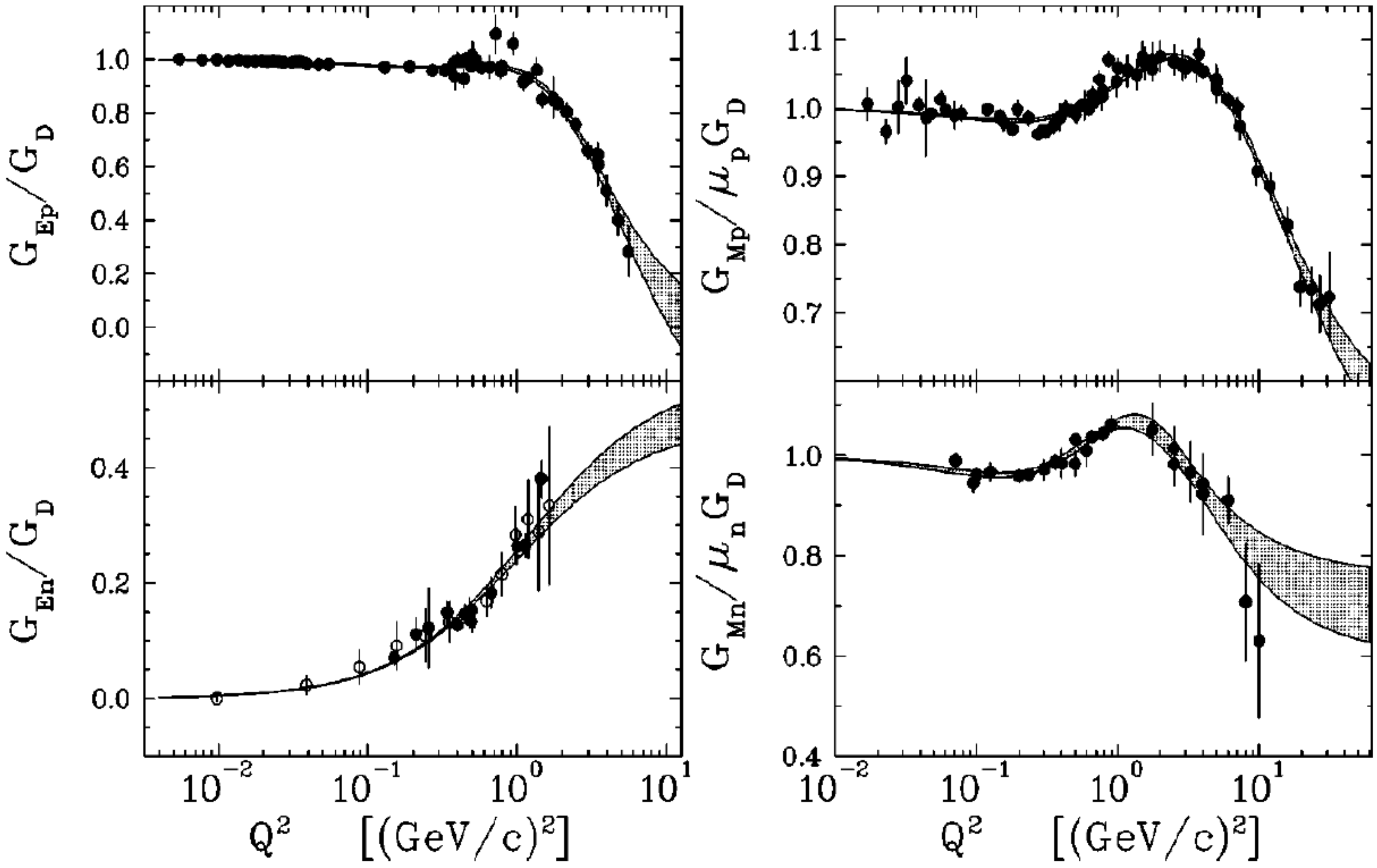
The form factors are the meeting ground between theory and experiment.

- The Fourier transform of the form factors are related to the charge and current distributions within the neutron. (R.M.Littauer, H.F.Schopper, R.R.Wilson, Phys. Rev. Lett., **7**, 144 (1961).)



The World’s Data.

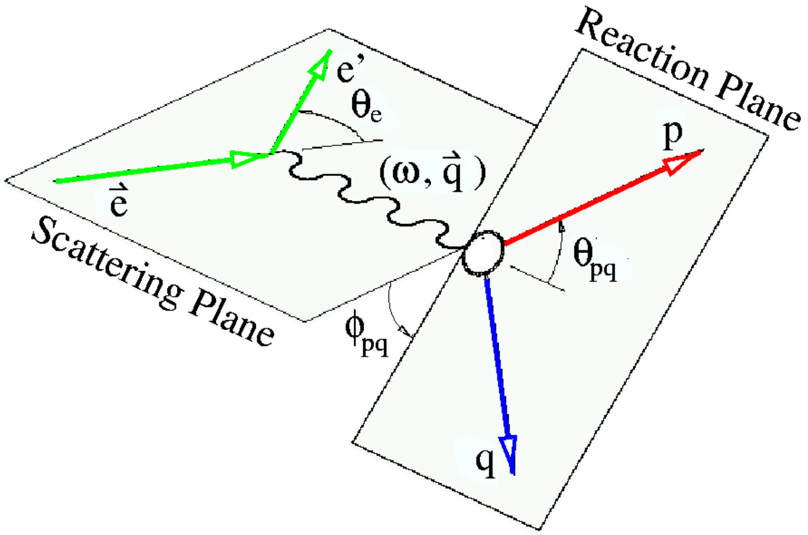
From J.Kelly, Phys. Rev. C **70**, 068202 (2004).



Why Should You Care Even More?

- Some kinematic definitions (θ_{pq}, ϕ_{pq}, b).

  The coordinate b is the transverse distance from the z axis defined by $\vec{q}$.



- Recent analysis of existing form factor data by G. Miller (Phys. Rev. Lett. **99**, 112001 (2007)).

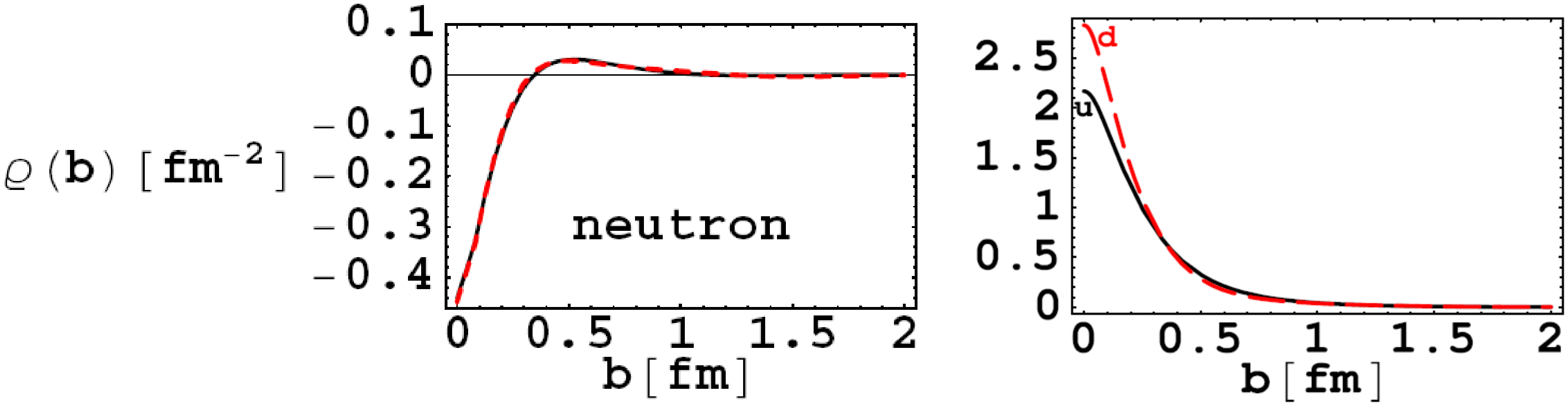
$$\rho(b) = \int_0^\infty dQ^2 \frac{1}{(2\pi)^2} \frac{G_E^n(Q^2) + \tau G_M^n(Q^2)}{1+\tau} e^{i\vec{q}\cdot\vec{b}} \qquad \tau = Q^2/4M_N^2$$

Why Should You Care Even More? - Part Deaux

- Final form of $\rho(b)$.

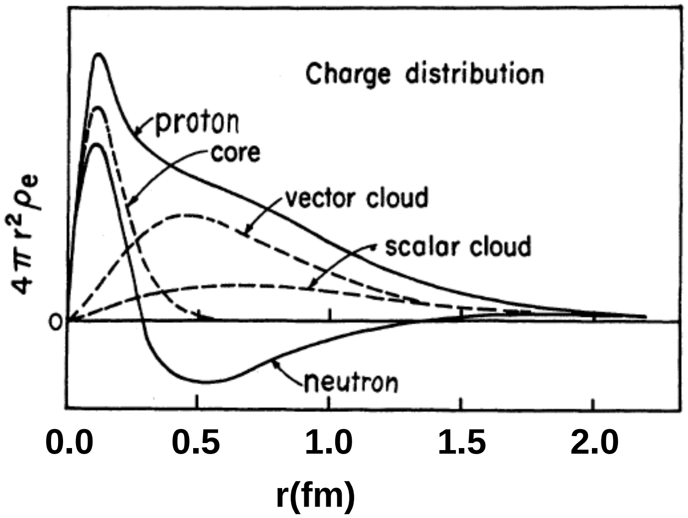
$$\rho(b) = \int_0^\infty dQ \frac{Q}{2\pi} J_0(Qb) \frac{G_E(Q^2) + \tau G_M Q^2}{1+\tau} \qquad \tau = Q^2/4M_N^2$$

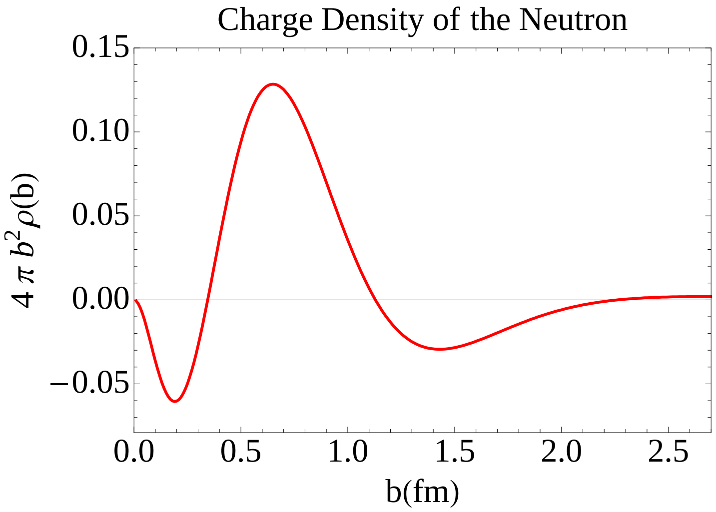
- Miller results



Why Should You Care Even More? - Part Three

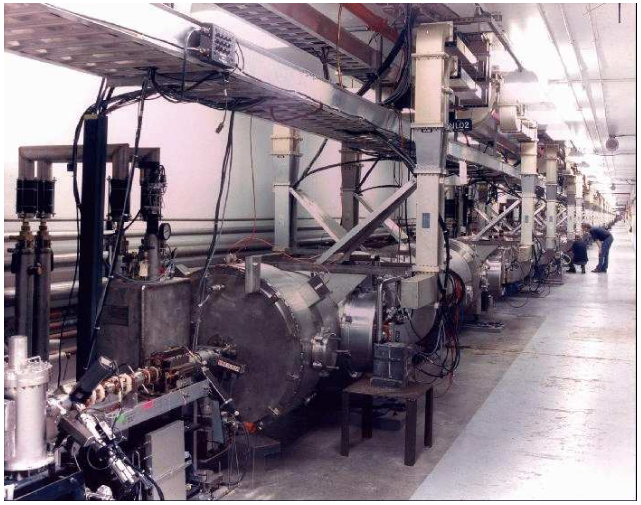
- Comparison with previous results. Note that b and r are conceptually different.





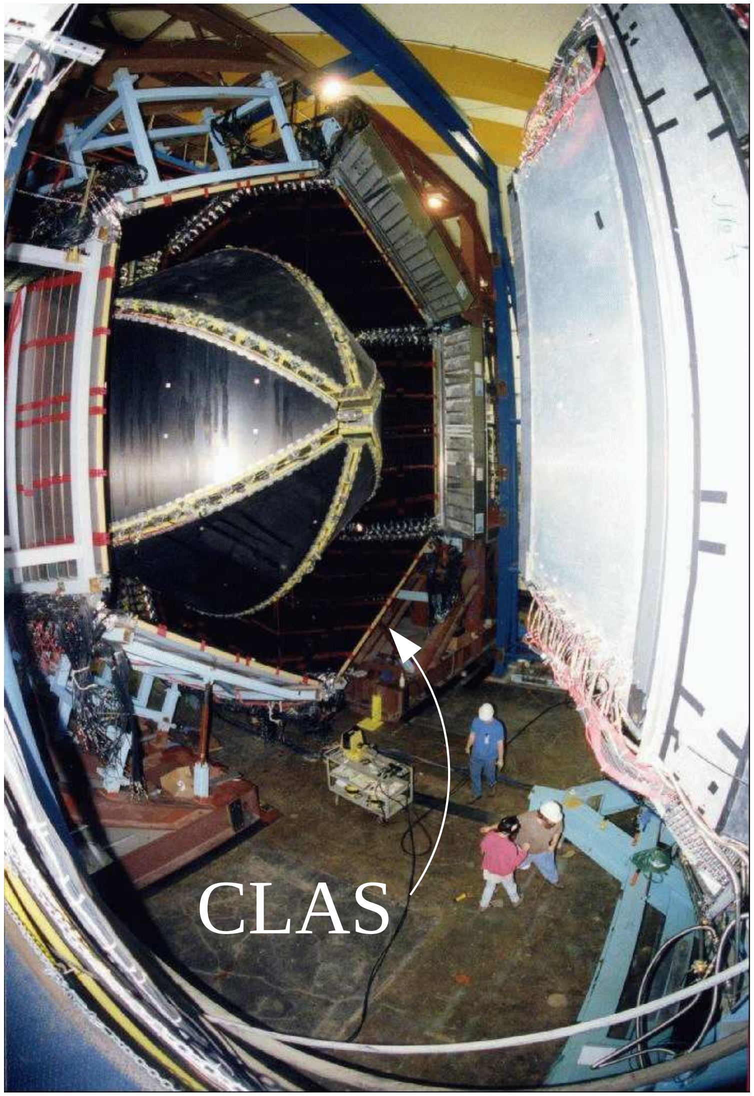
How Do We Measure G_M^n on a Neutron? (Step 1)

- 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.

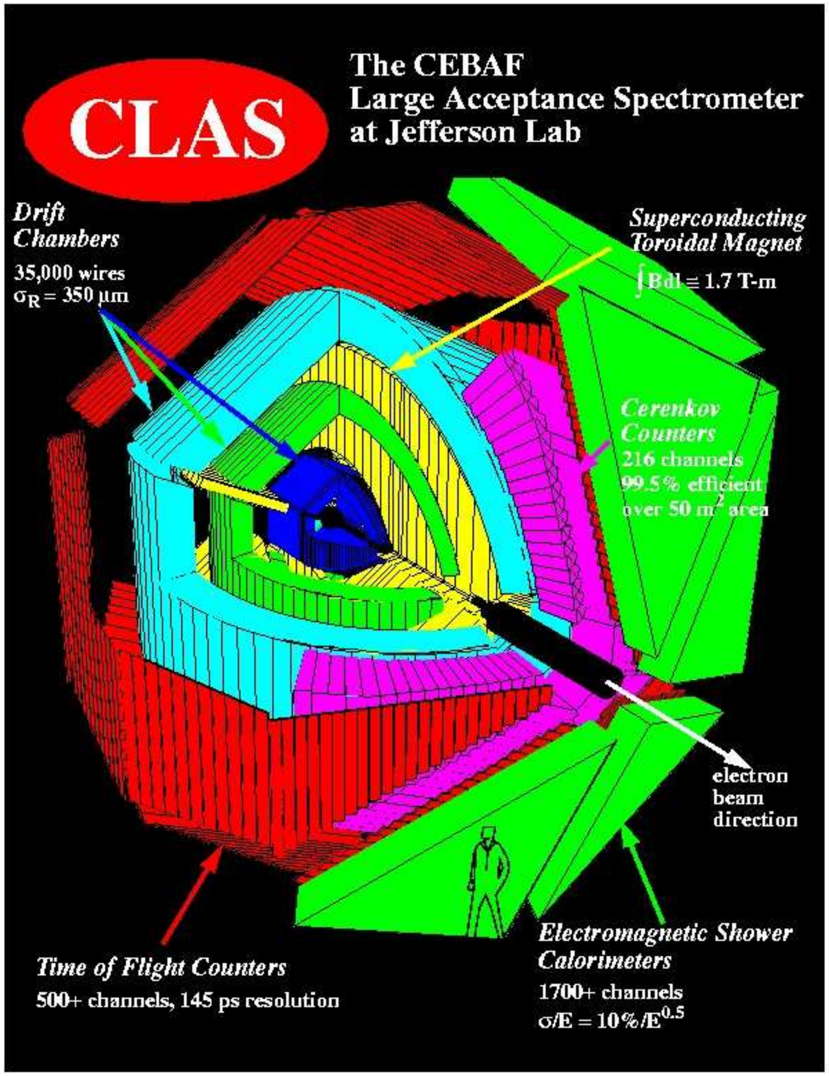


How Do We Measure G_M^n on a Neutron? (Step 2)

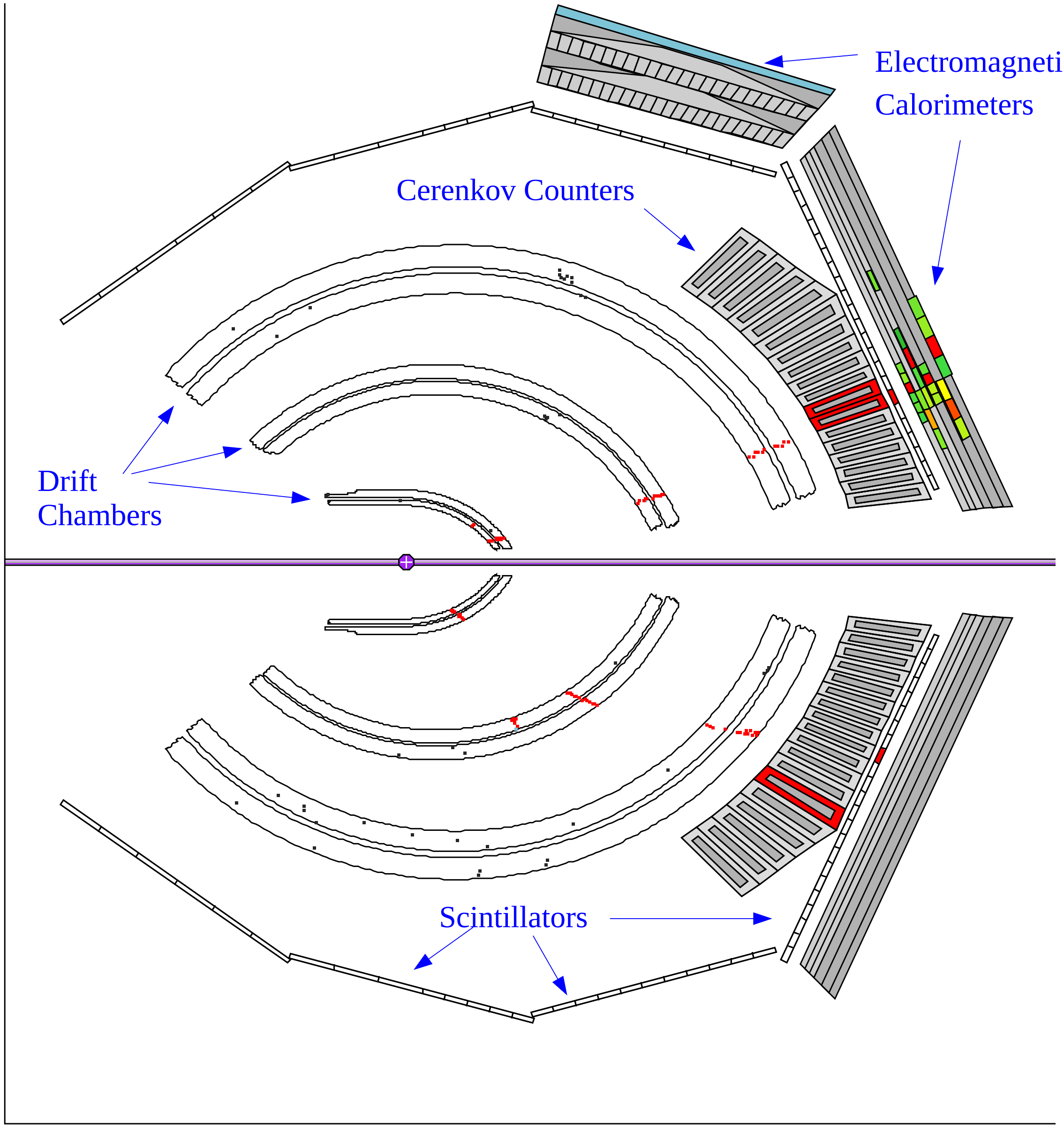
- Drift chambers map the trajectory of the collision. A toroidal magnetic field bends the trajectory to measure momentum.

- 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!

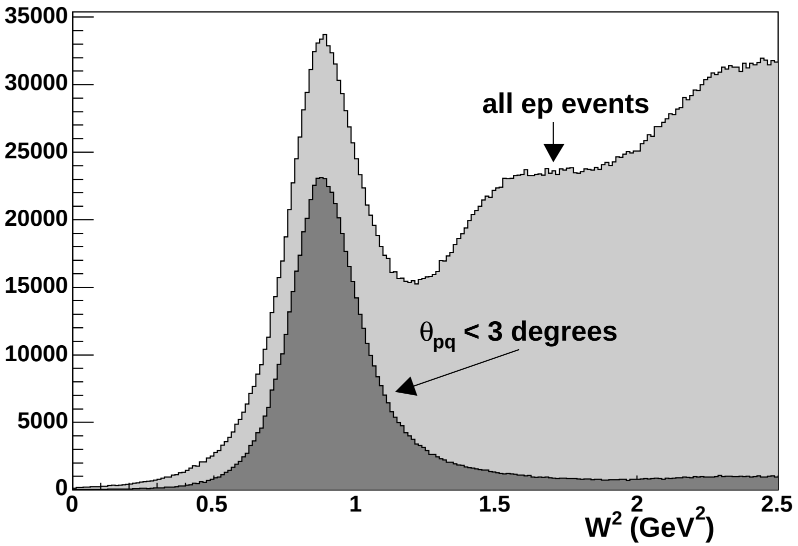
$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2 \tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2(\frac{\theta}{2})}$$

- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc*.

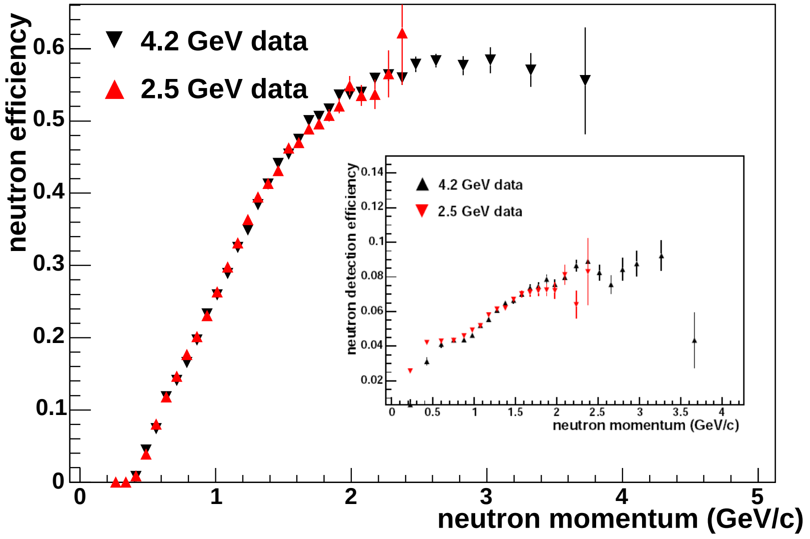
- The dual target enables us to perform *in situ* detection calibrations.

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).

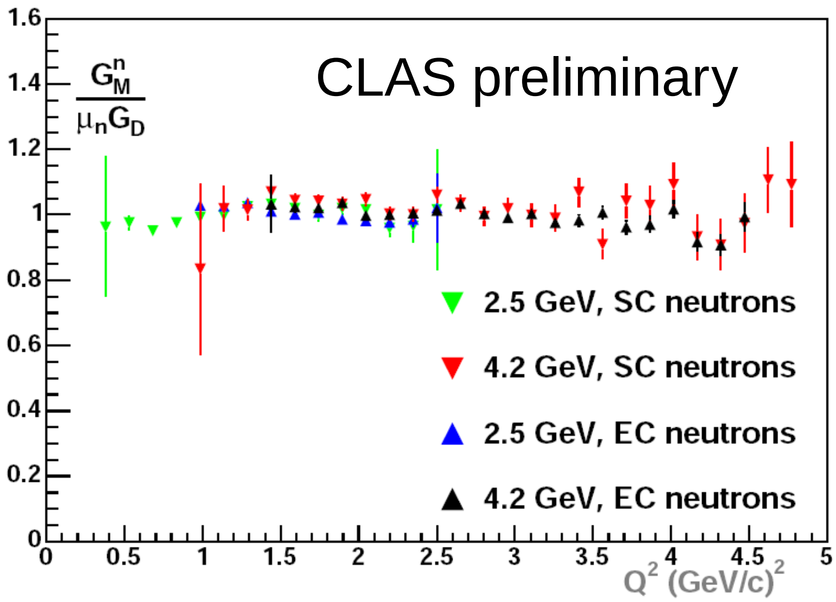


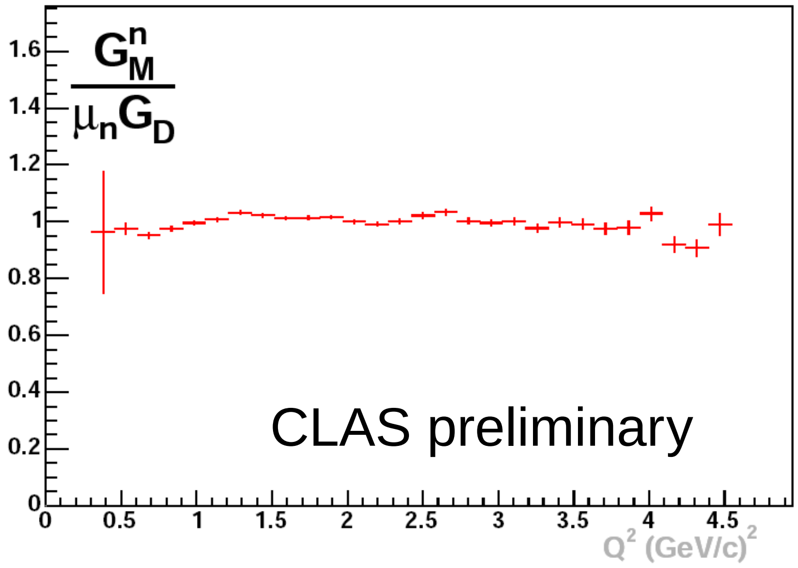
- Use the $ep \rightarrow e'\pi^+n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.

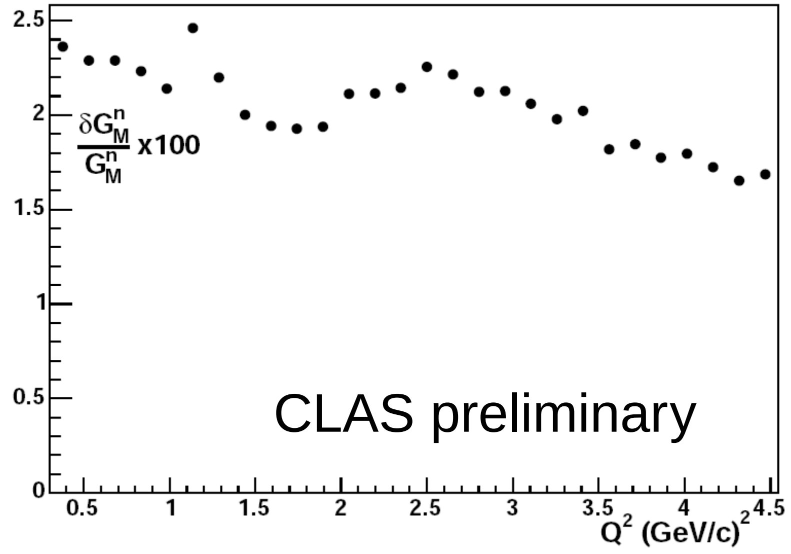


Results - Overlaps and Final Averages

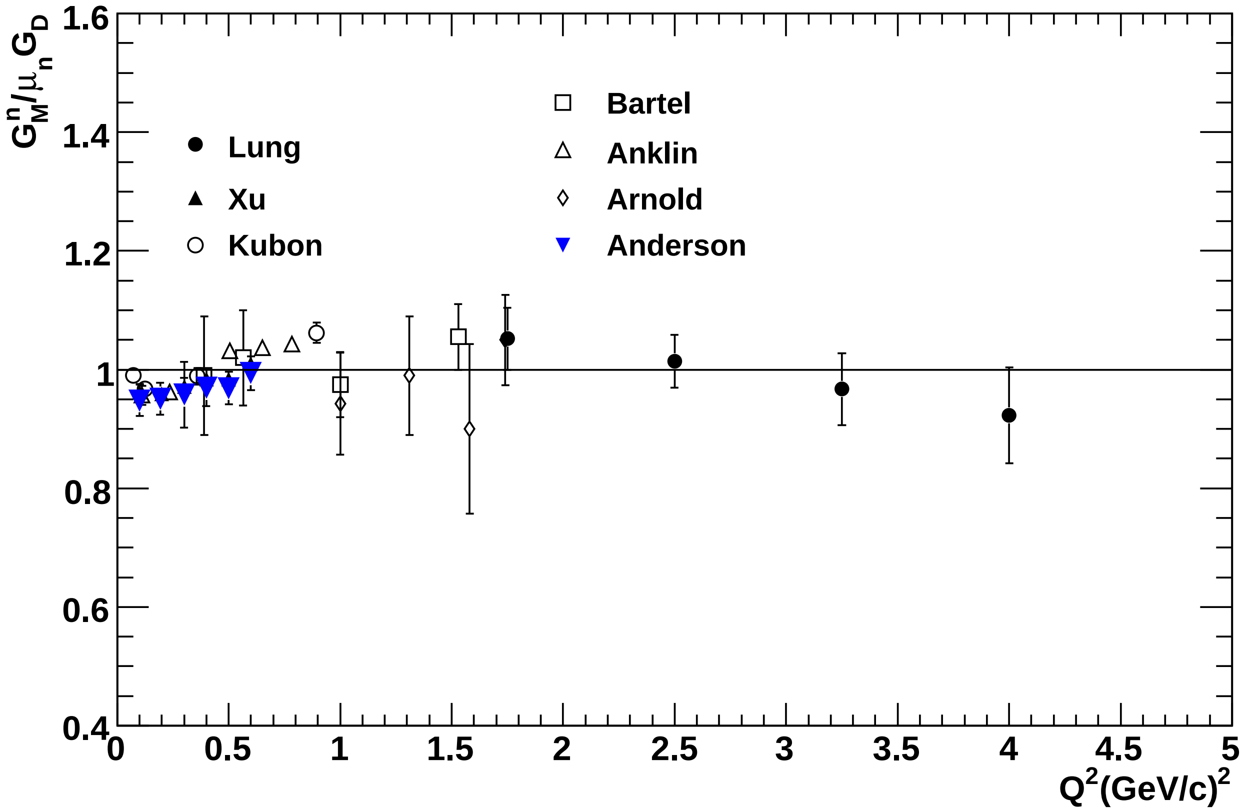
- Overlapping measurements of G_M^n scaled by the dipole are consistent.
- Weighted-average $G_M^n/\mu_n G_D$ and systematic uncertainty $\frac{\delta G_M^n}{G_M^n} \times 100\,(< 2.5\%)$.







Results - Comparison with Existing Data and Theory



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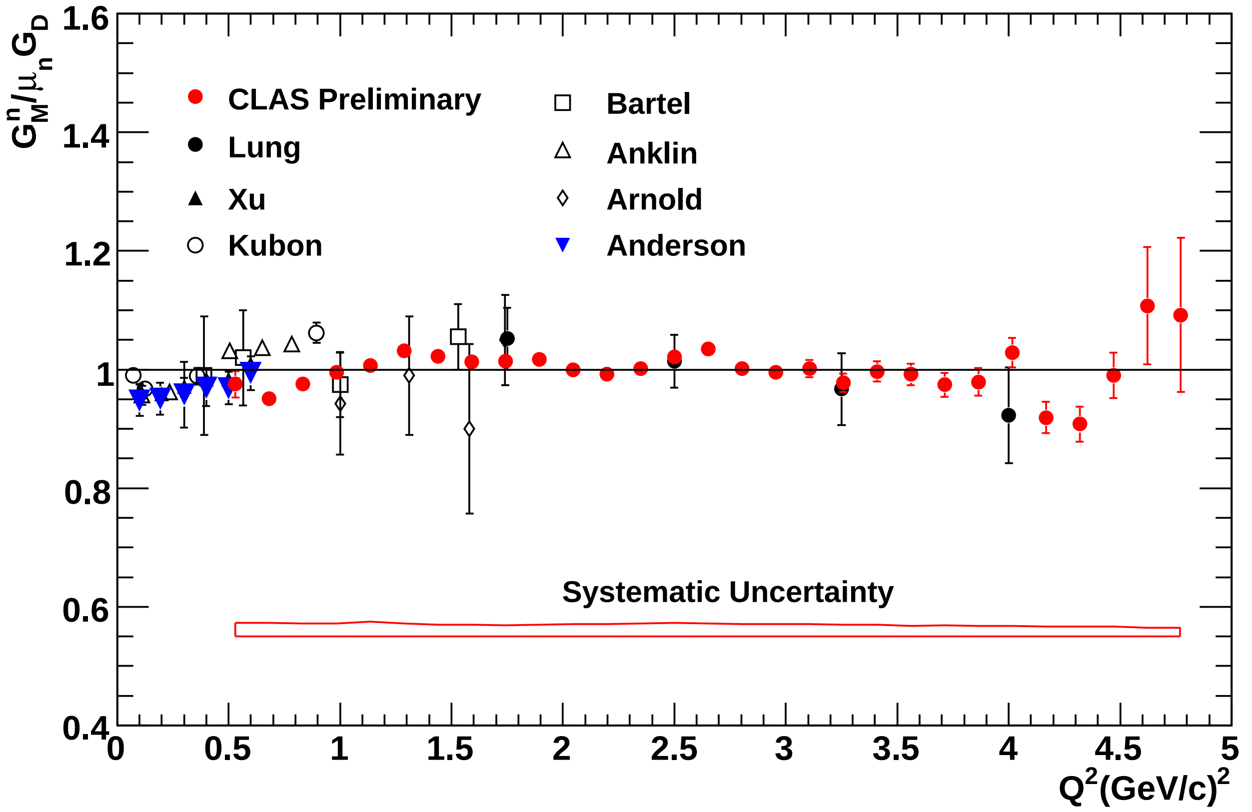

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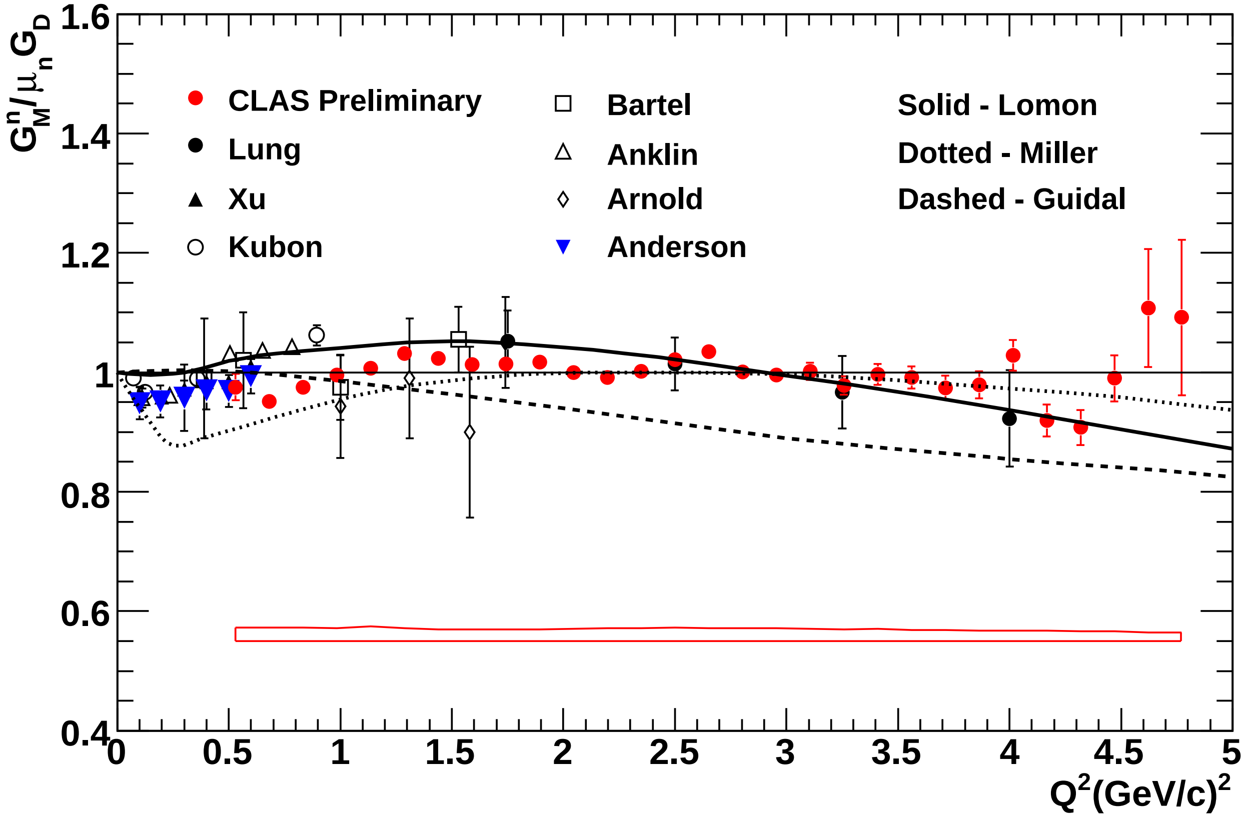
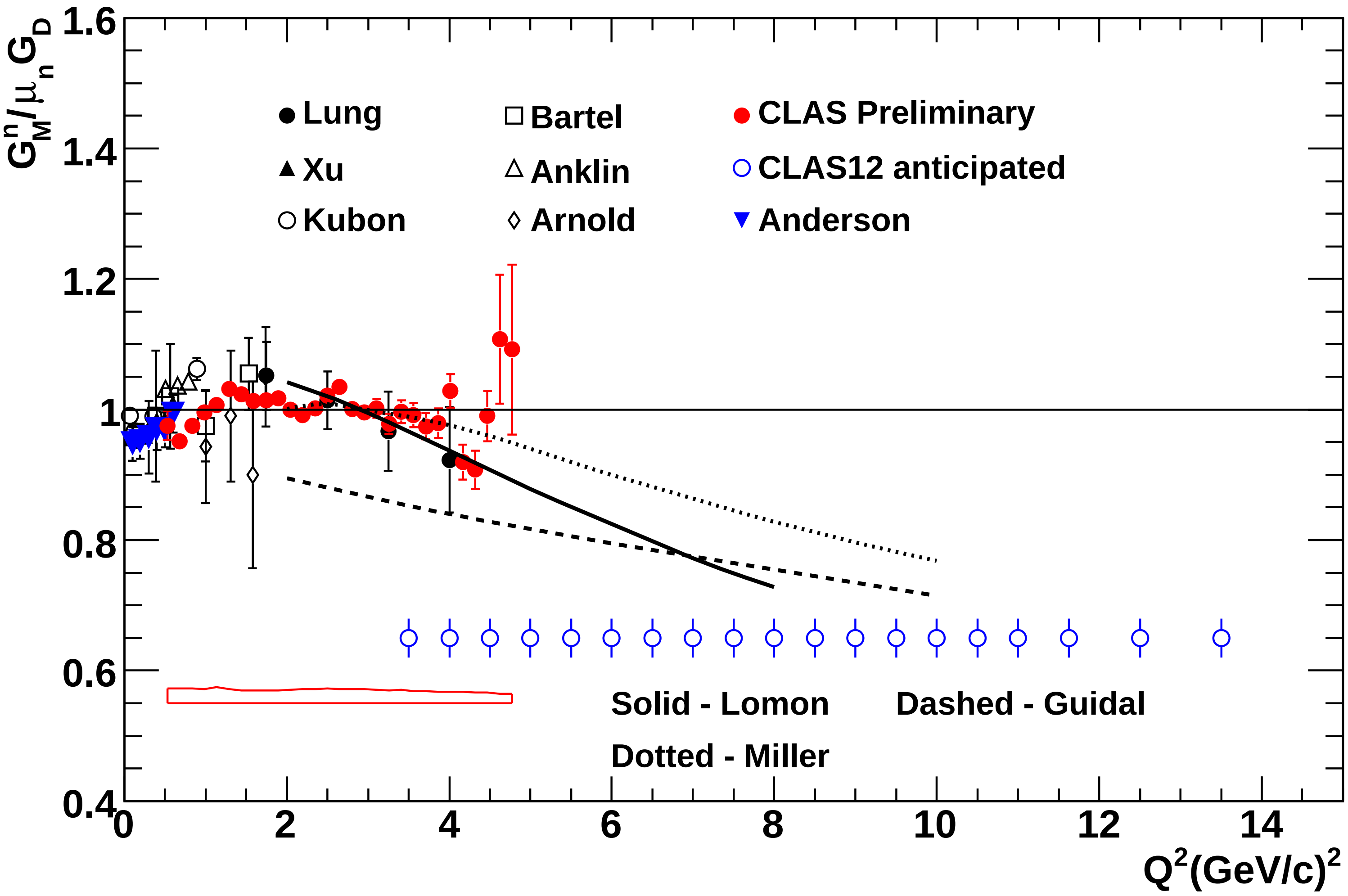


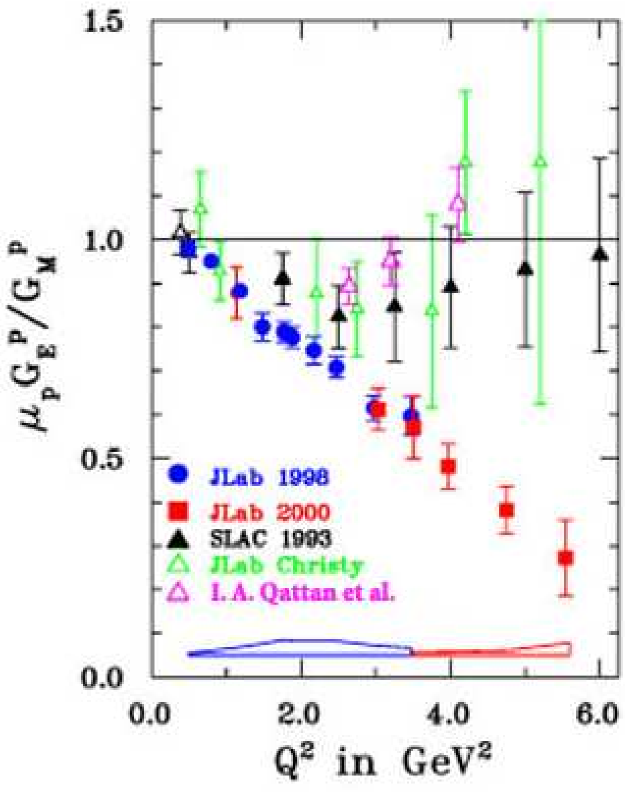
More To Come



Lomon, Phys.Rev.C **66** 045501 (2002); G. MIller, Phys. Rev. C **66**, 032201(R) (2002); M.Guidal, M.K. Polyakov, A.Radyushkin, and M. Vanderhaeghen, Phys. Rev. D **72**, 054013 (2005).

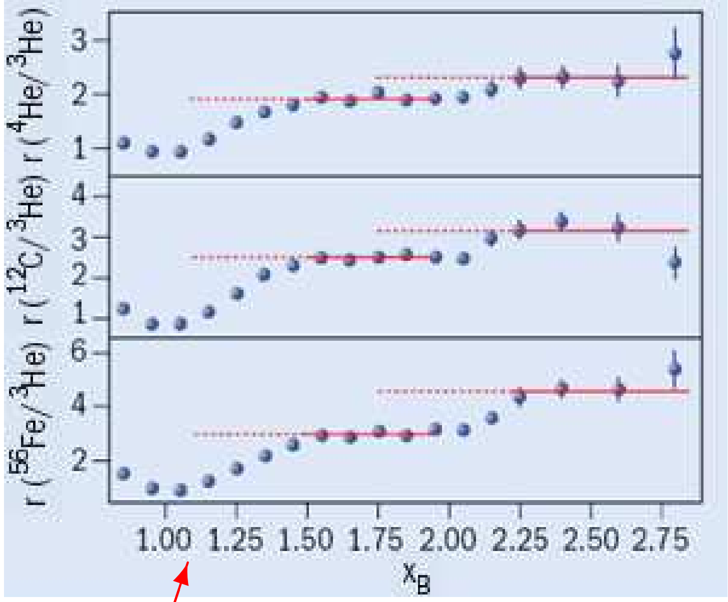
More Jefferson Lab Highlights

Ratio of charge and magnetization of the proton (G_E^p/G_M^p).



O. Gayou, *et al.*,Phys. Rev. Lett. **88**, 092301 (2002)

Short range correlations in nuclei.

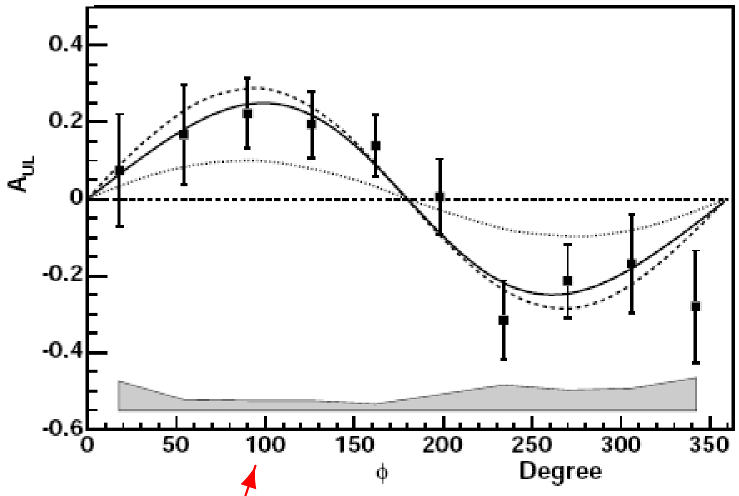


Fraction of nucleon momentum carried by struck quark.

K. S. Egiyan et al., Phys. Rev. Lett. **96** (2006) 082501

Even More Jefferson Lab Highlights

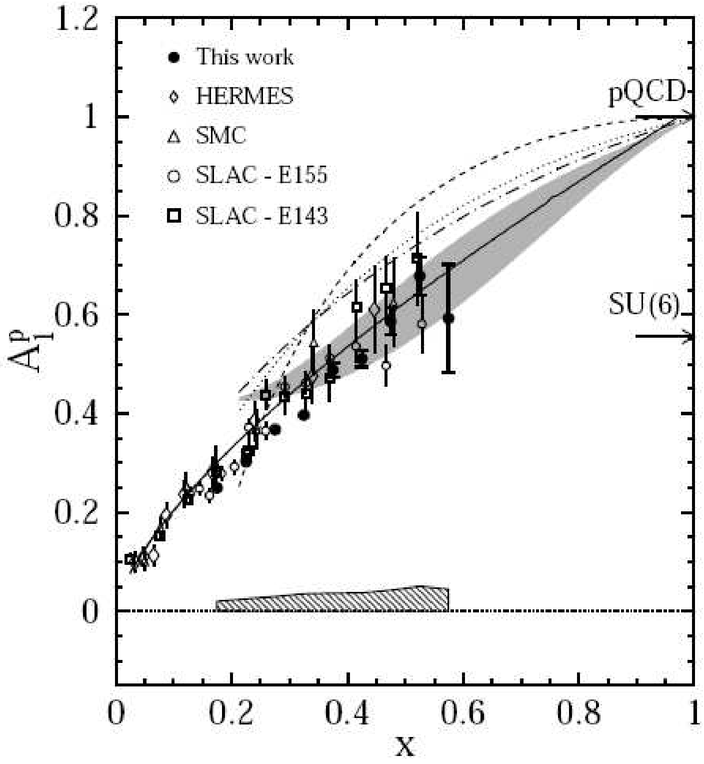
Towards a 3-dimensional picture of hadrons.



Azimuthal angle around the 3-momentum transfer $\vec{q}$.

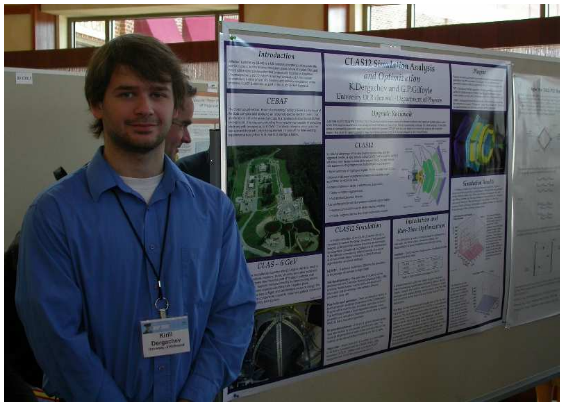
S. Stepanyan *et al.* (CLAS), Phys. Rev. Lett. **87** (2001) 182002

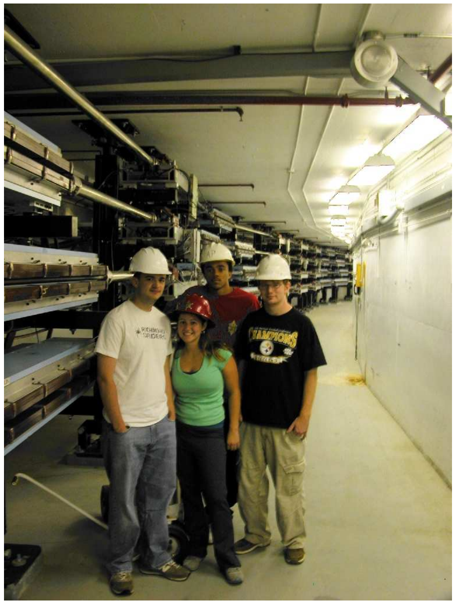
Where is the nucleon spin?.



K.V. Dharmawardane, *et al.* (CLAS),Phys. Lett. B **641**, 11 (2006)

Life on the Frontiers of Knowledge





Concluding Remarks

- 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.

Jefferson Lab
Exploring the Nature of Matter