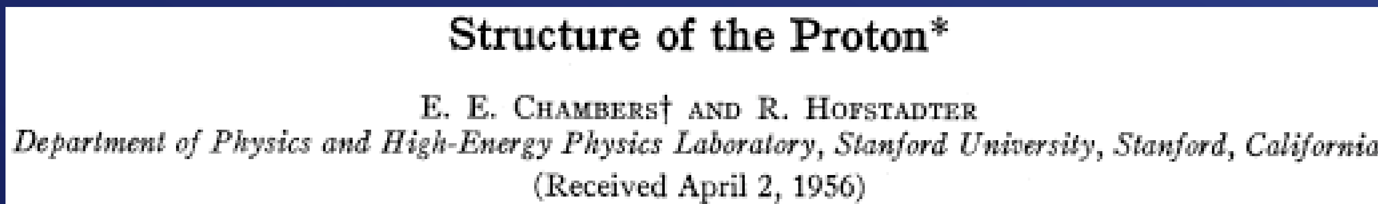
Nuclear matter and electromagnetic probes in the 21st century

Gordon D. Cates
University of Virginia

The 20th century was pretty good for electromagnetic probes


Structure of the Proton*

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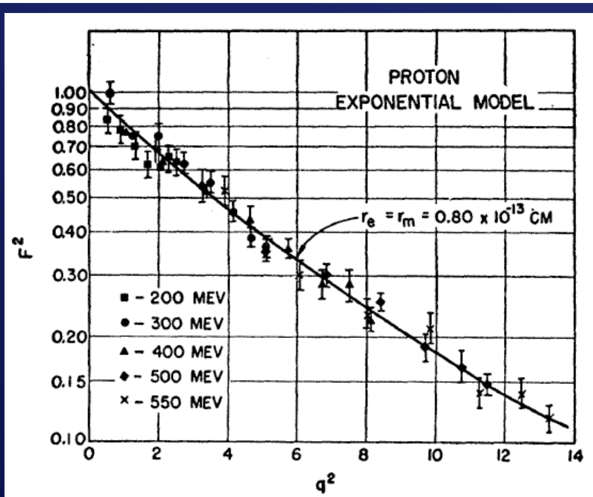
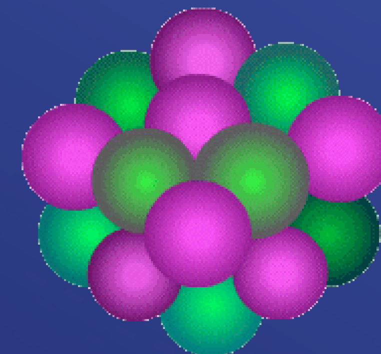
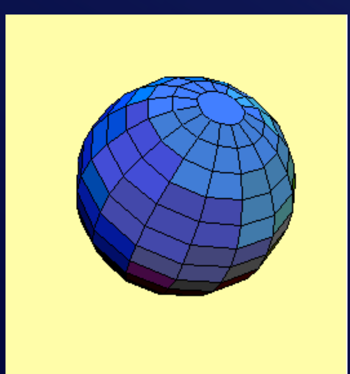
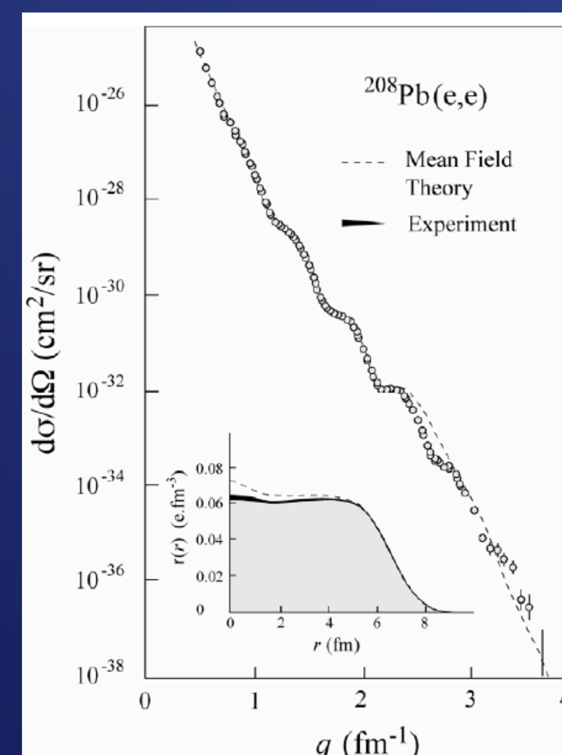
(Received April 2, 1956)





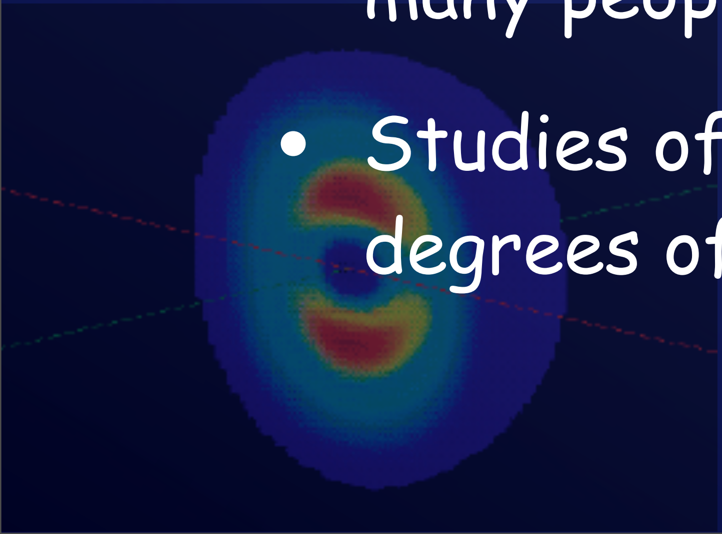
- Size of the proton
- Structure of nuclei
- Discovery of quarks
- Establishing the SM is correct (okay, I'm biased)
- Spin Structure
- Beginning to understand nuclear matter in terms of QCD.

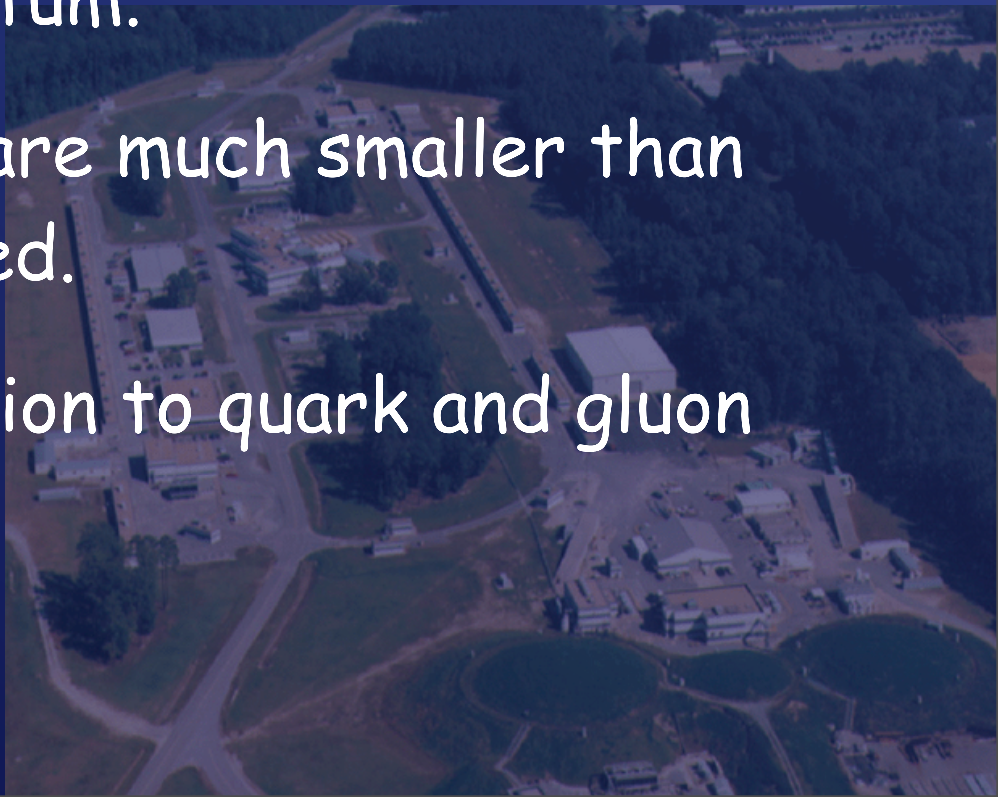




Important results (and some surprises) from JLab

- The hadronic picture works well to surprisingly high energy scales.
- A beginning to an understanding of quark orbital angular momentum.
- Higher twist effects are much smaller than many people anticipated.
- Studies of the transition to quark and gluon degrees of freedom.





Where are we in our understanding?

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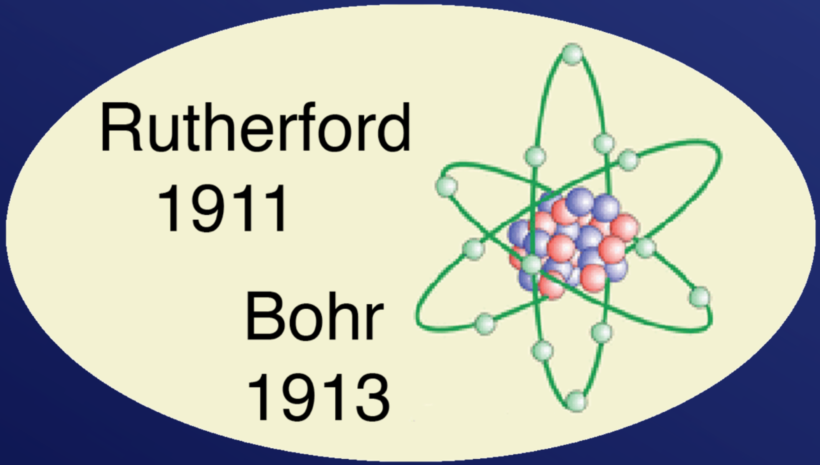

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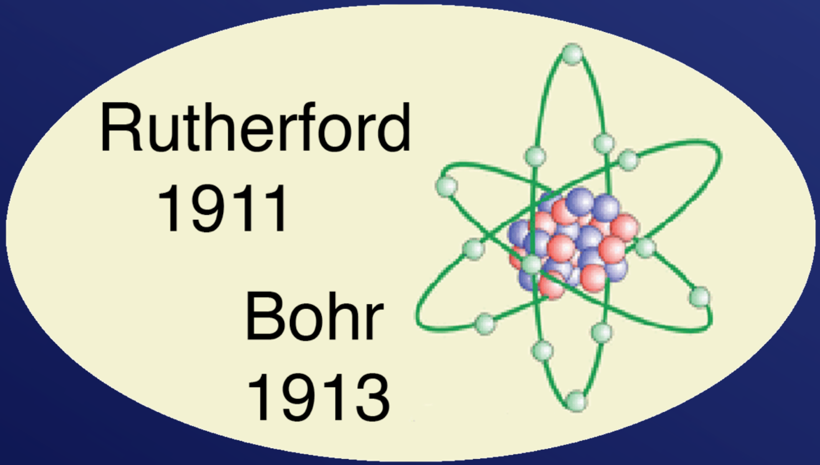

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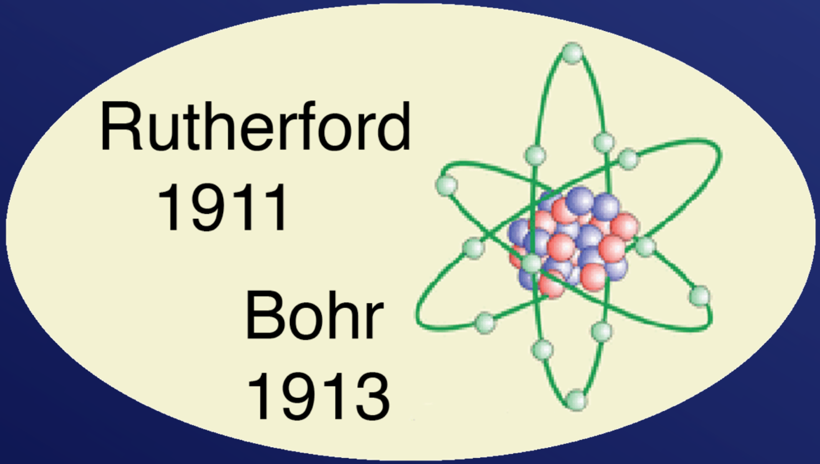

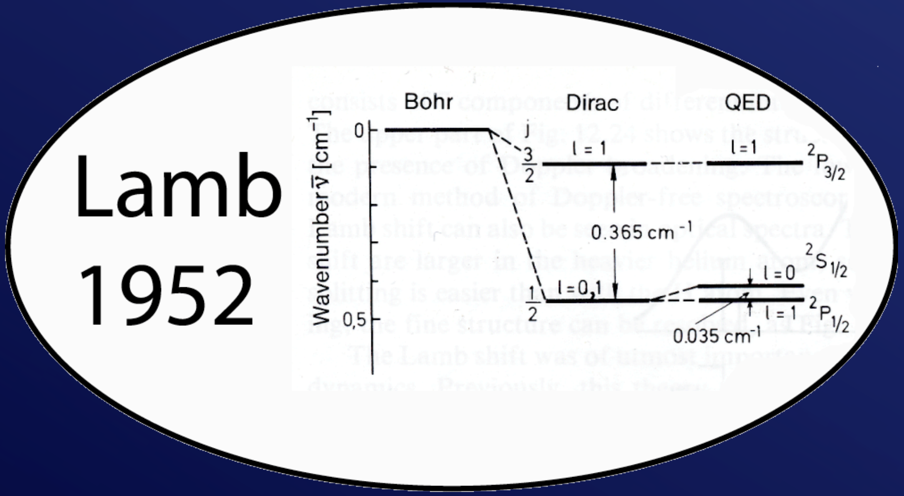

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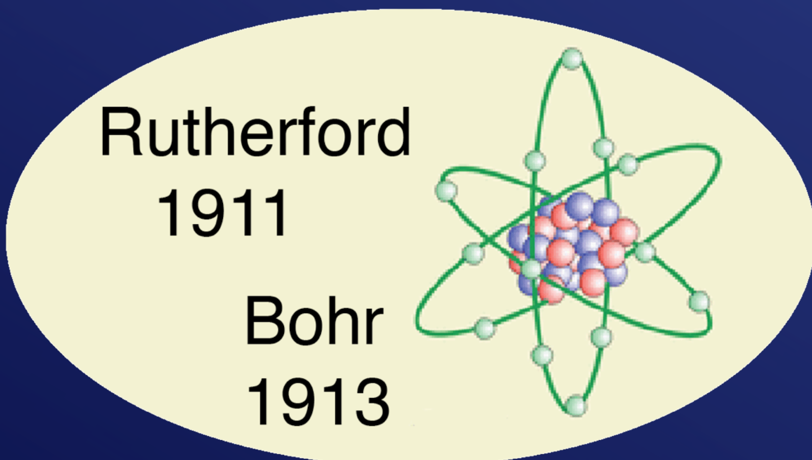

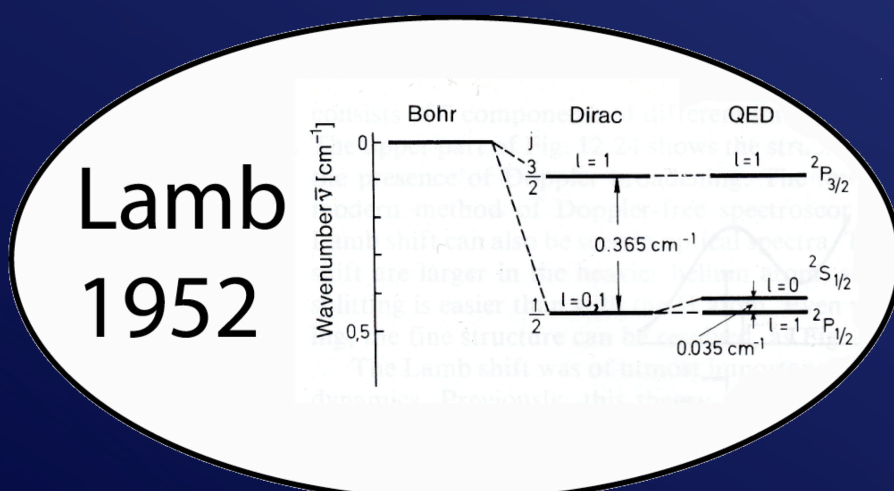

The problem is that
the proton is “all Lamb Shift” !!!

So ....

- We have more than half a century of highly successful nuclear physics
- We believe that QCD is correct

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To move forward we need to ask ourselves ...

- How should we adjust our understanding of nuclear matter change in light of QCD?
  - What are the important questions?

We know the proton has quantum numbers consistent with three valence quarks

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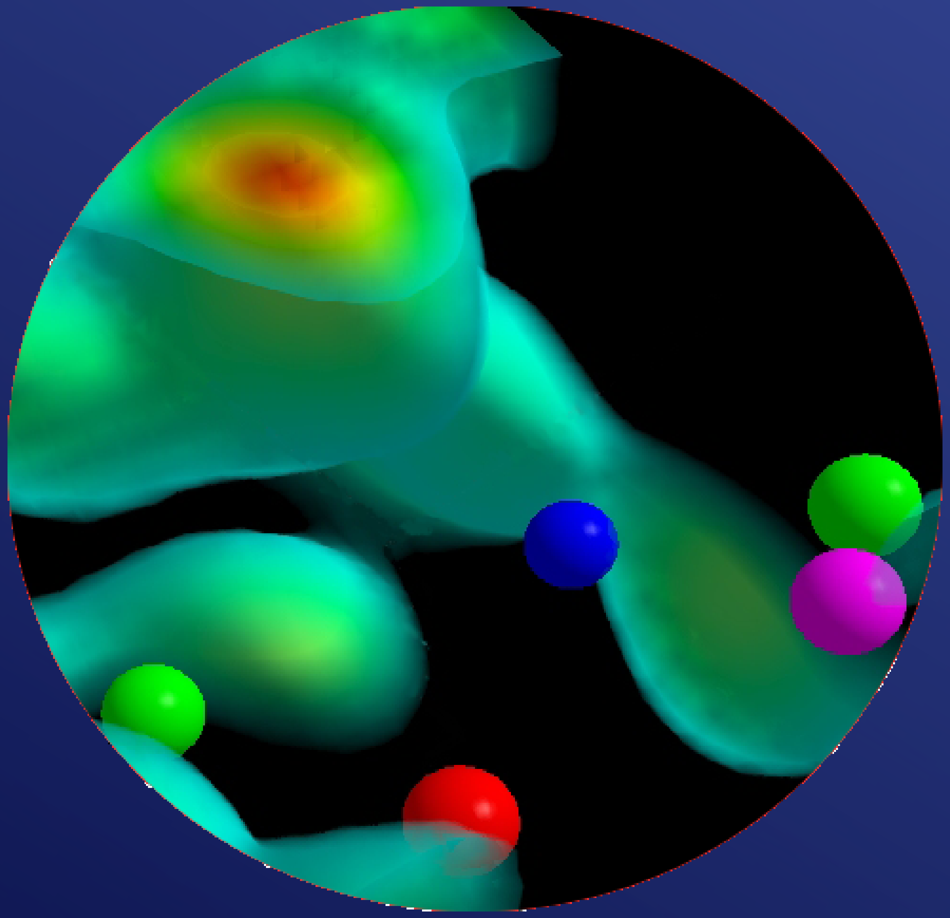

We also know that the gluonic field and quark/anti-quark pairs make up most of the mass.

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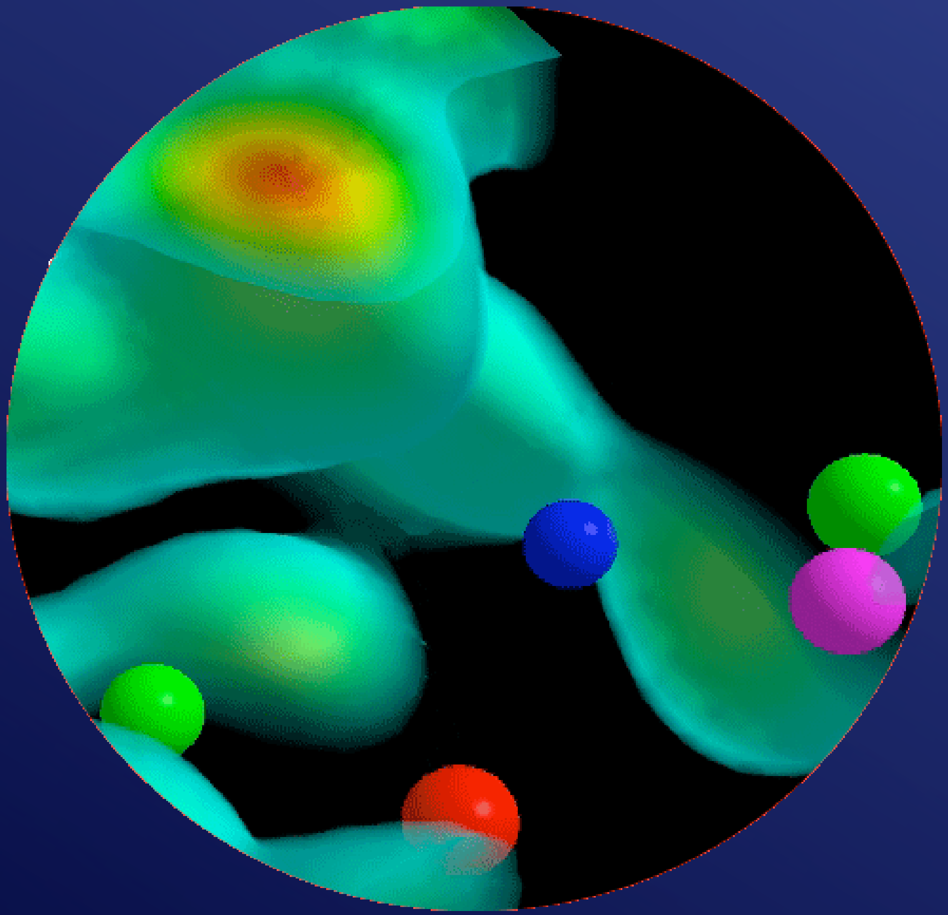

But we DO NOT have a detailed understanding of the internal structure

We also know that the gluonic field and quark/anti-quark pairs make up most of the mass.

We know about confinement and the process of hadronization

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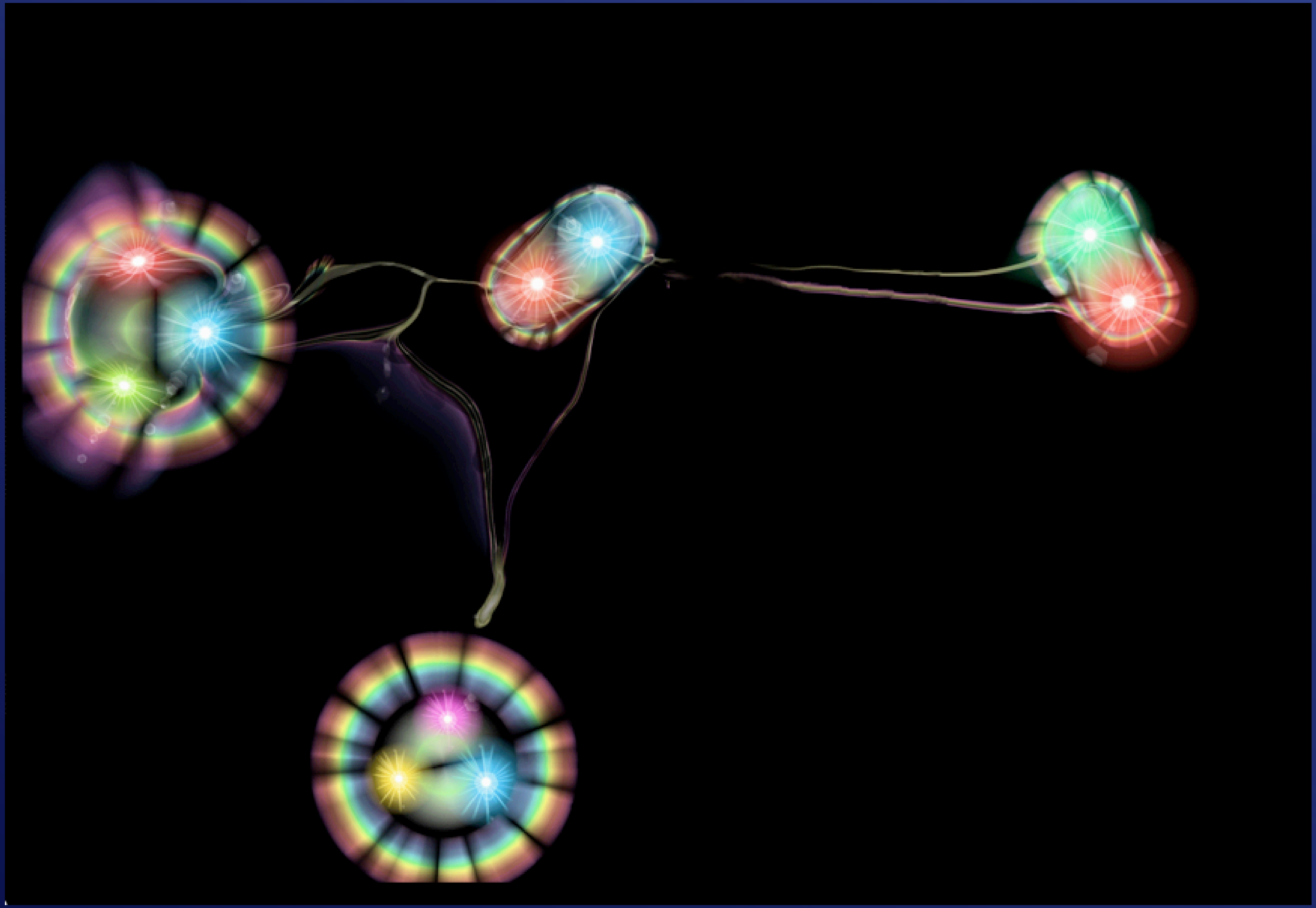

But we do not understand the underlying QCD dynamics

We know the QCD vacuum is dynamic

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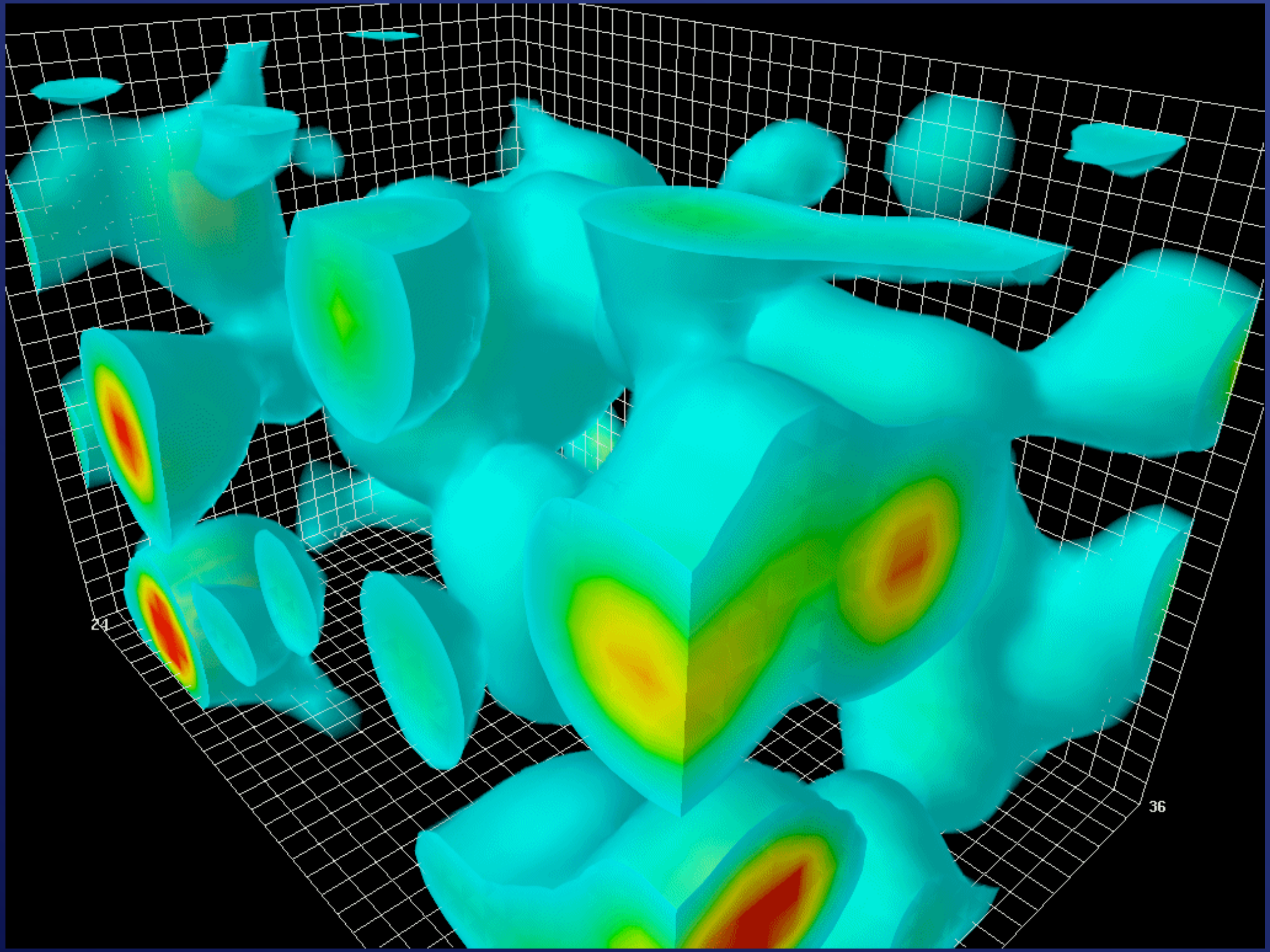
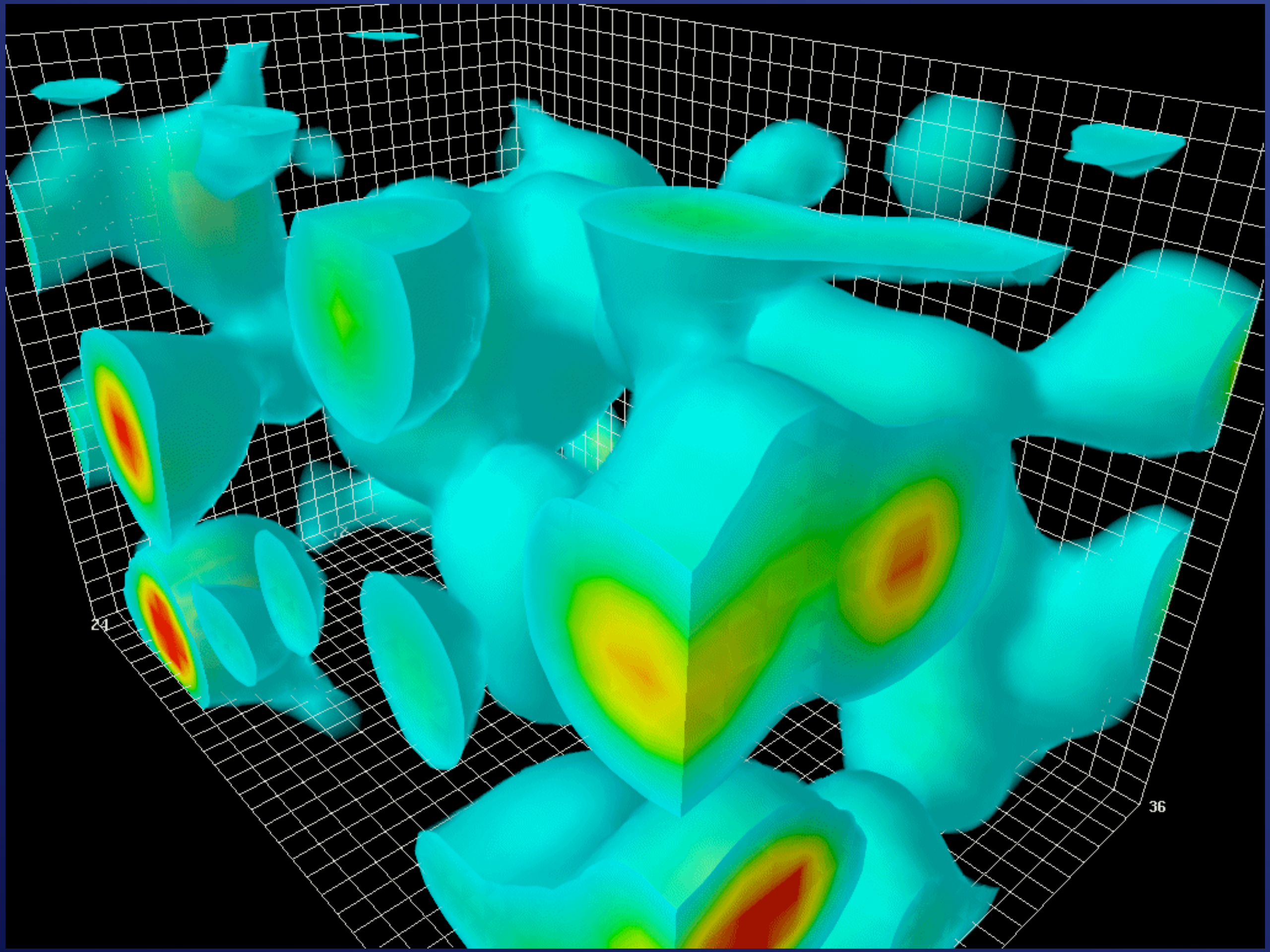


We know the QCD vacuum is dynamic



But our experimental signatures for the glue are very limited

We know the long range part of the NN force is (mostly) well described by pion exchange

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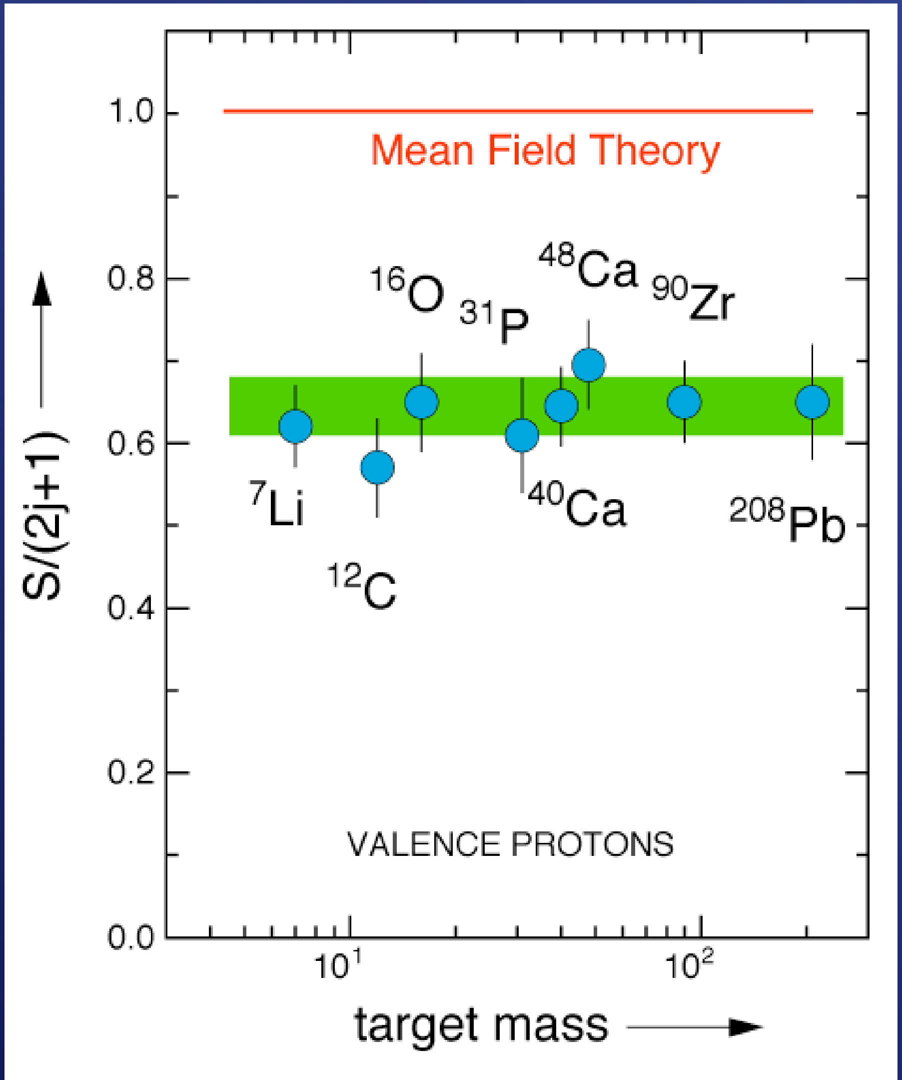
But our understanding of the short-range piece is limited.



Short-range correlations, for instance, are largely repsonsible for the missing strength of spectroscopic factors.

What should be our philosophy moving forward?

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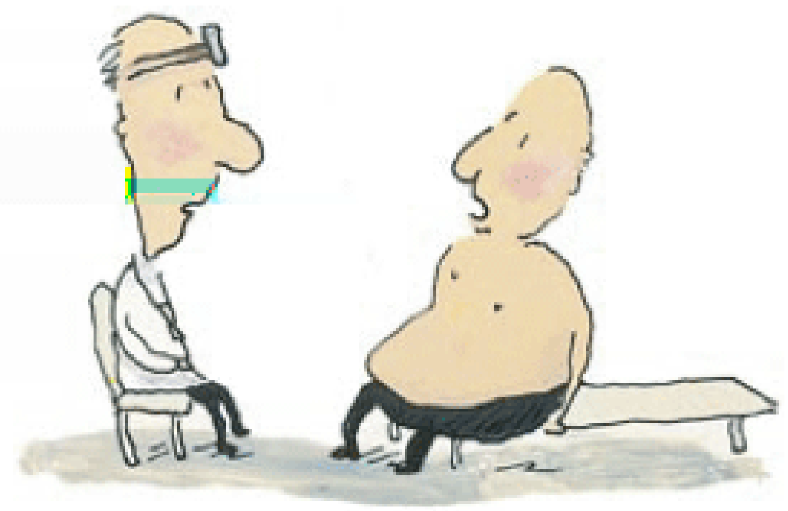
Weinberg's Third Law of Progress in Theoretical Physics: "You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry"



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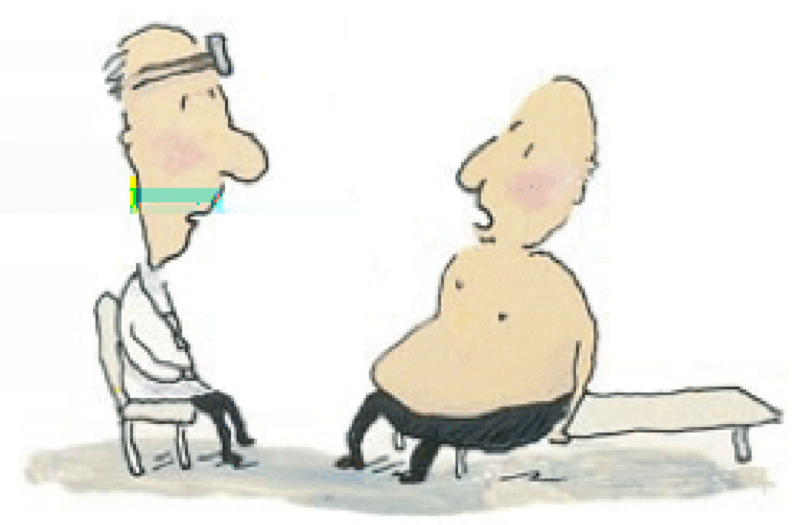

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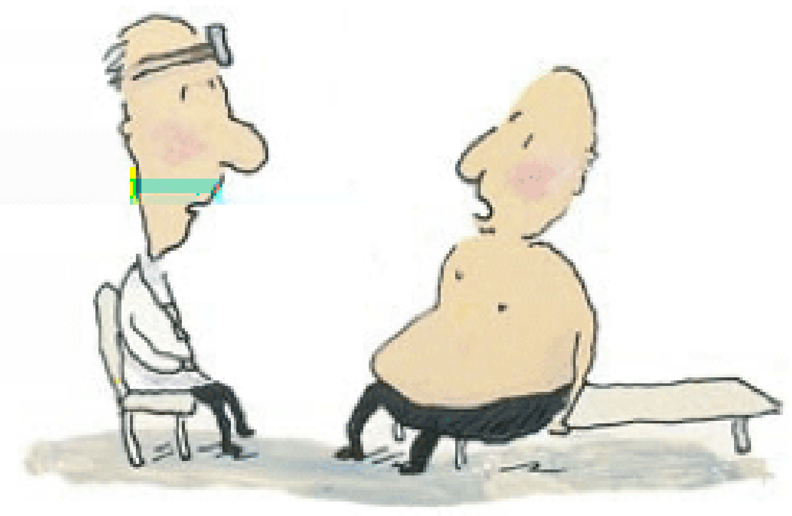

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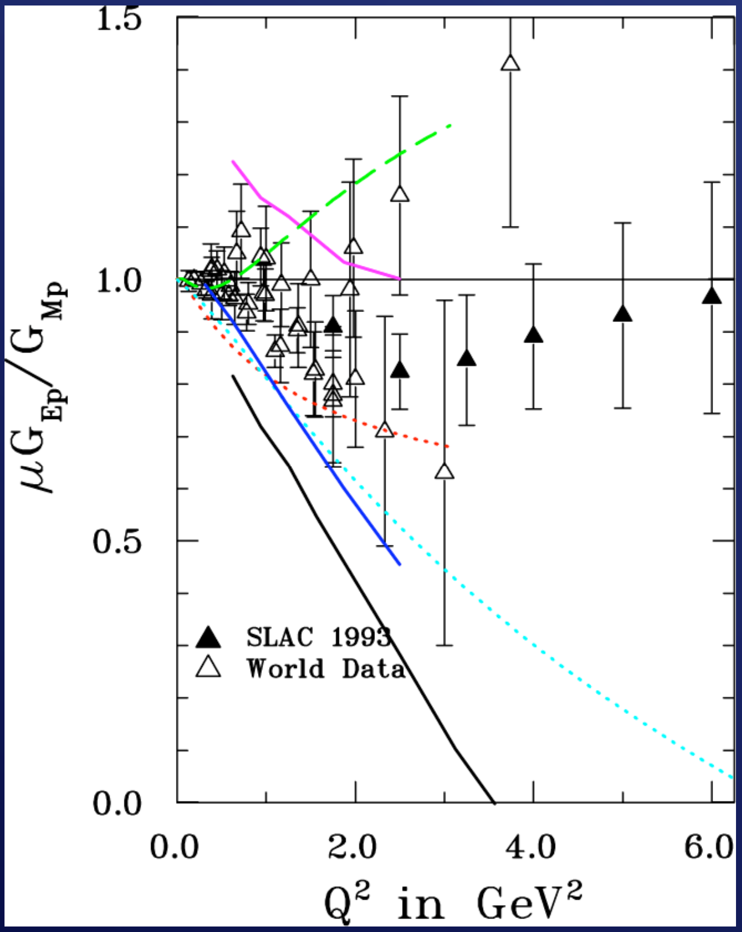
A judicious balance of these two ingredients will likely bring us real understanding.

Okay … what can we actually do?

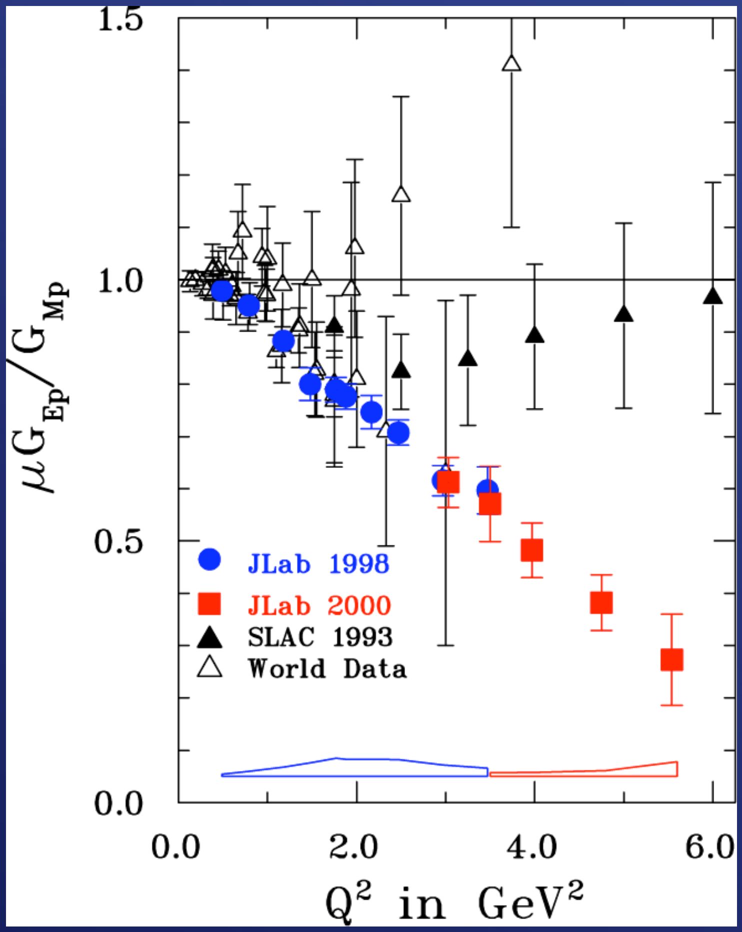
Nucleon structure: We have powerful new tools

- Elastic form factors at increasingly high Q^2
- Generalized Parton Distributions (GPD's)
- Inclusive spin structure studies
- Semi-inclusive spin structure studies
- Parity violation

Perhaps JLab's most important discovery to date: Q^2 dependence of G_{Ep}/G_{Mp}



Pre JLab



With JLab data

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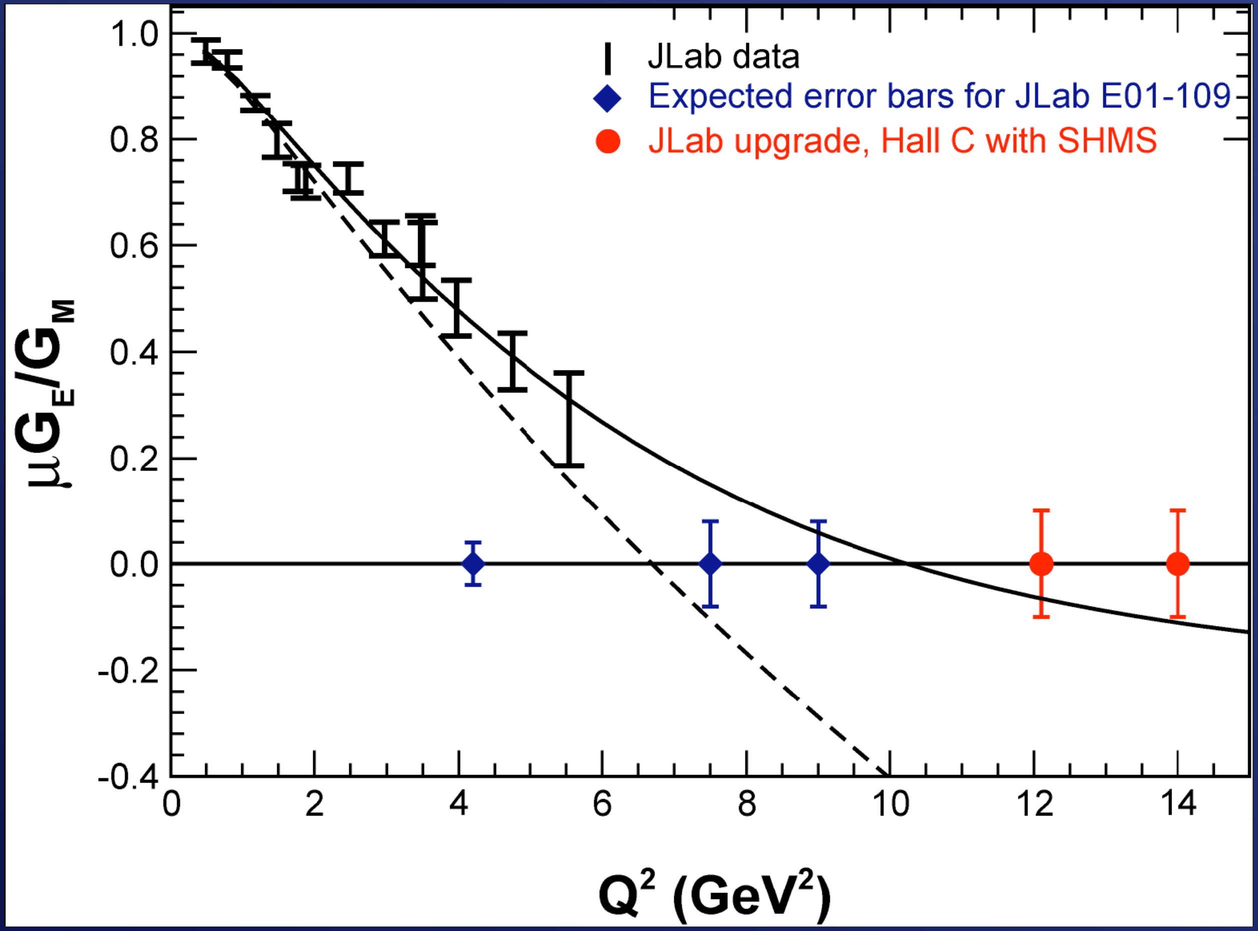
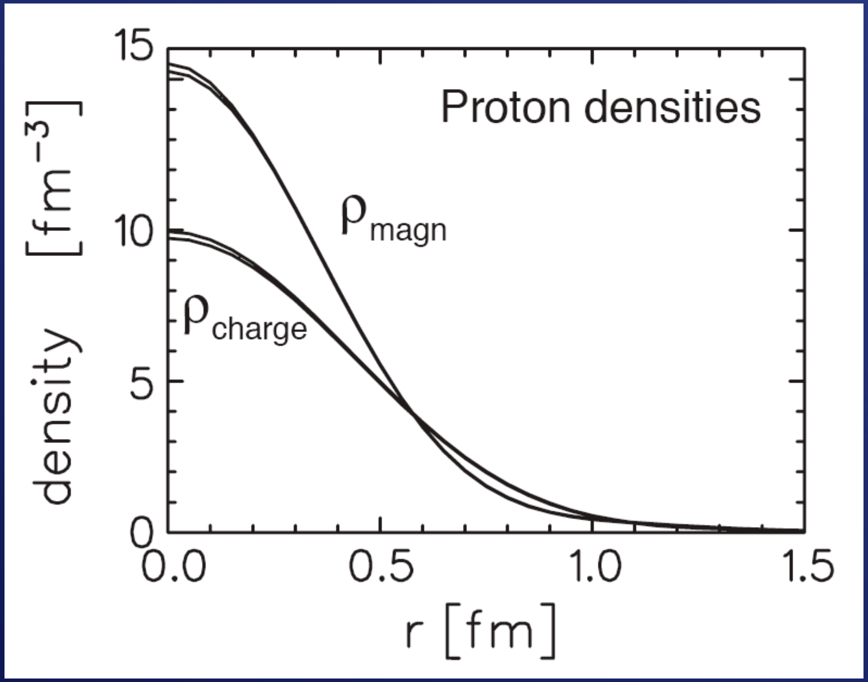


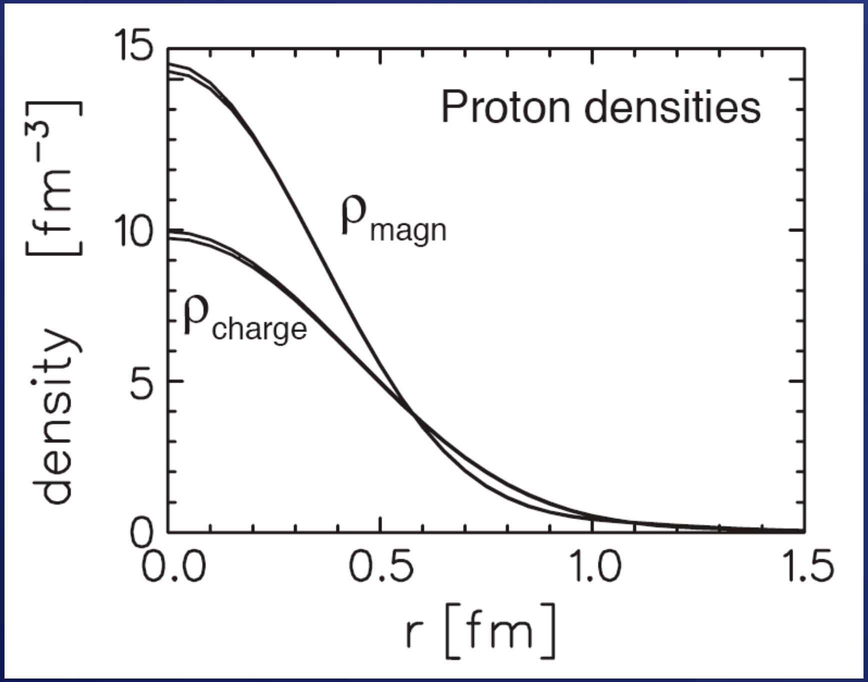
The reach in Q^2 will more than double with increasing energy

Stepping back for a pedestrian's view of form factors at higher Q^2

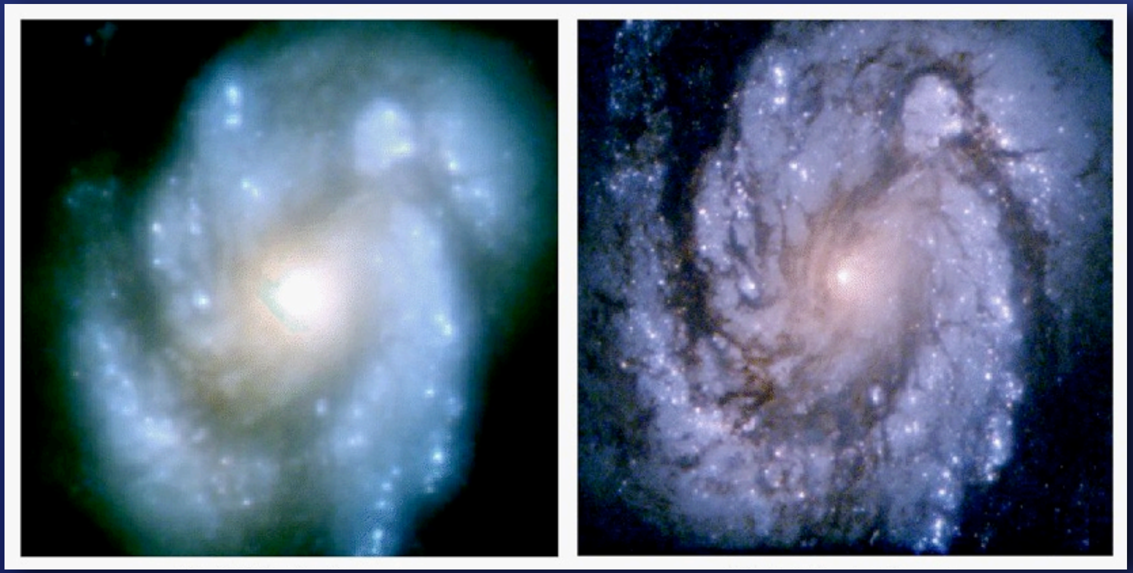


With appropriate caveats, the form factors tell us about the distribution of charge and currents. In a very real way, they are "snap shots" of the nucleon.

Stepping back for a pedestrian's view of form factors at higher Q^2



Just as the hubble improved the resolution with which we view the universe, JLab is improving the resolution with which we see the proton.



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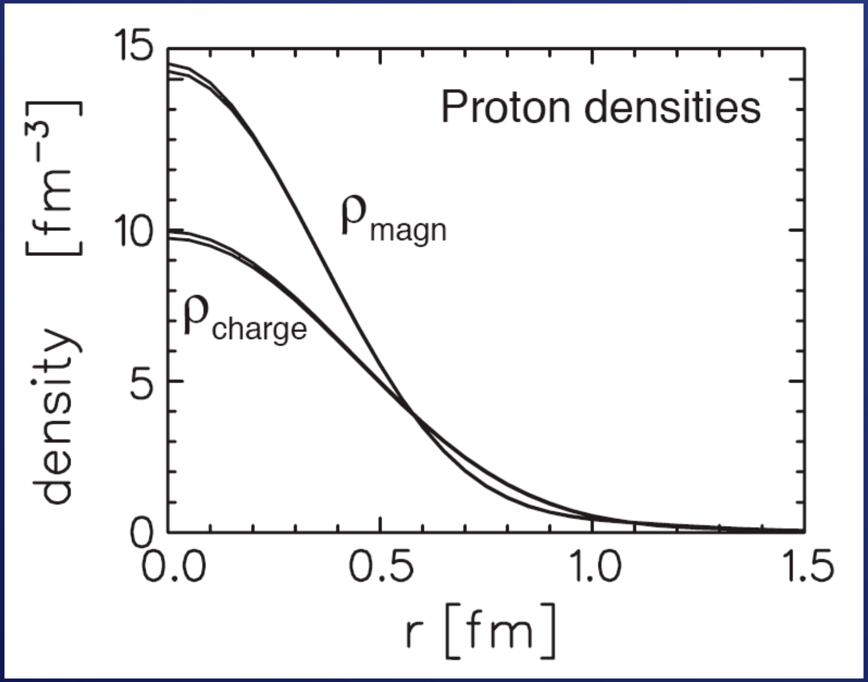

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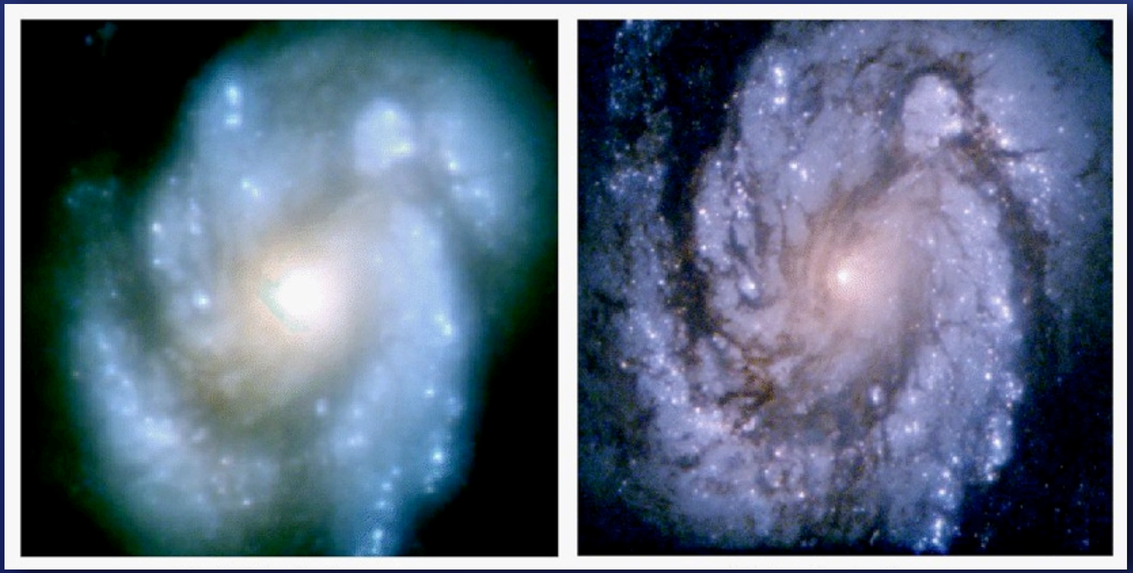

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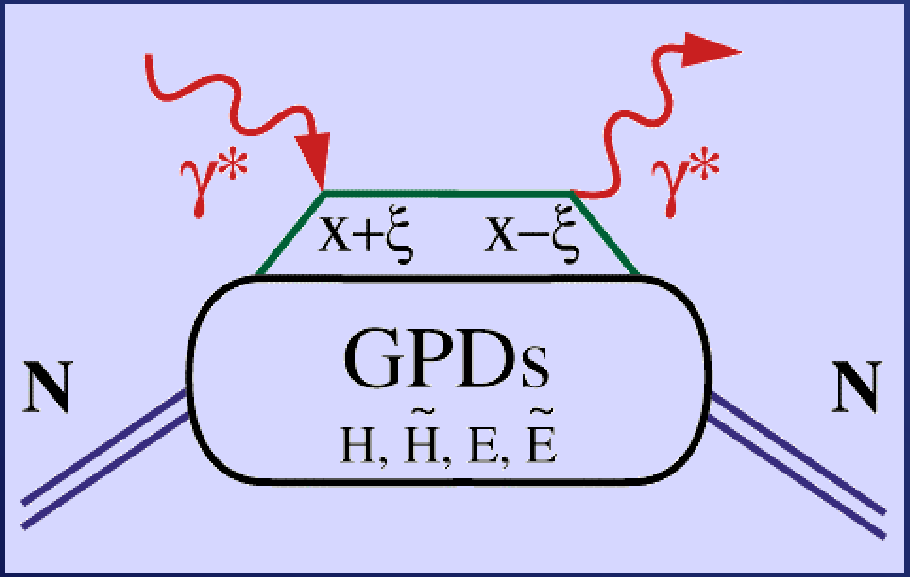
Among other things, the new results have profound implications regarding orbital angular momentum of quarks.

A huge step toward deeper understanding:

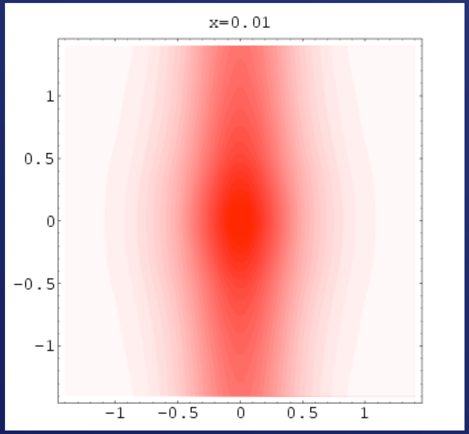
Generalized Parton Distributions (GPD's)



Transverse momentum distributions

Spin distributions

Tomography of the nucleon using Wigner Distributions



Ji's Sum Rule:

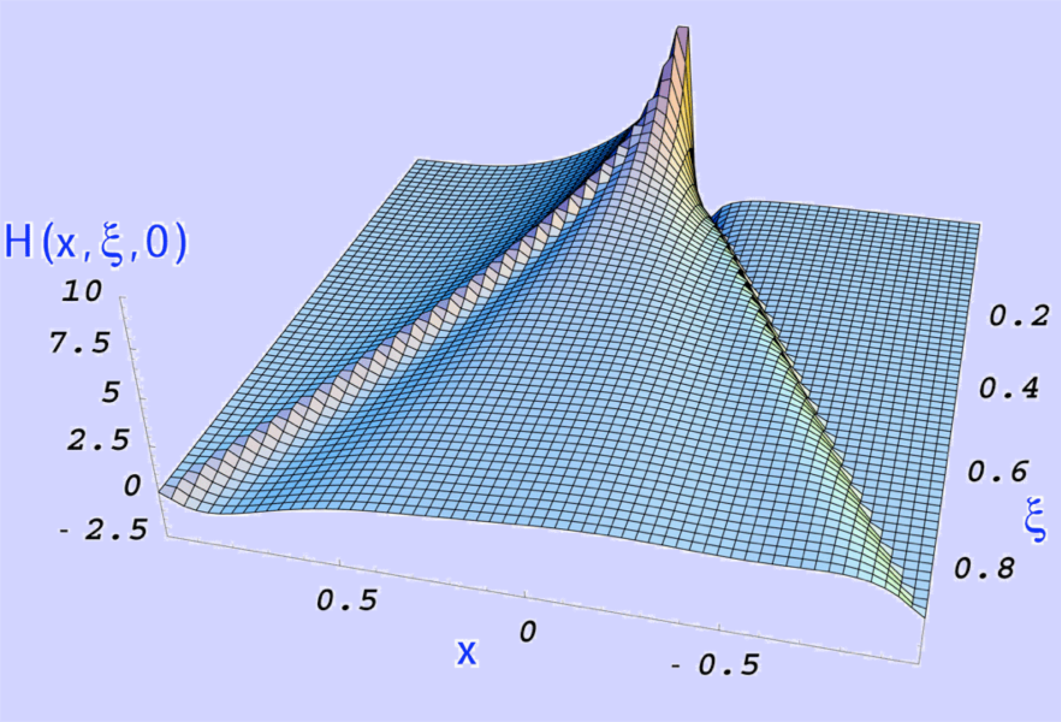
Yields angular momentum of the quarks

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,\left[\,H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

GPD's pick up where form factors and parton distribution functions leave off

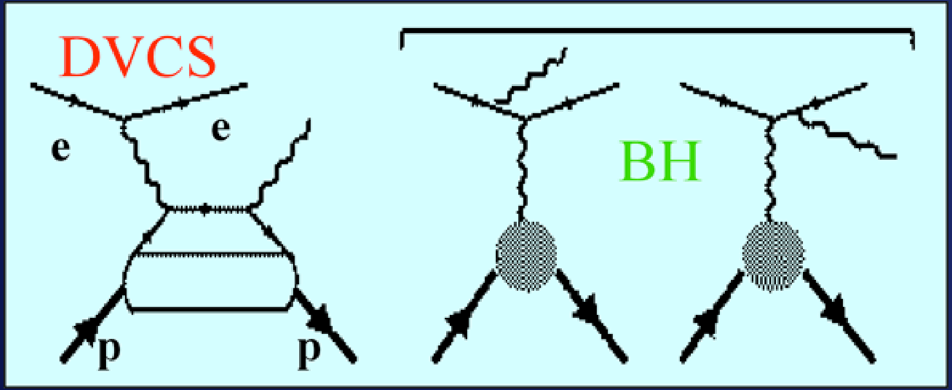
- GPD's contain within themselves PDF's and elastic form factors.
- Can be experimentally accessed by processes like Deeply Virtual Compton Scattering (DVCS)
- Can be parameterized and constrained much as PDF's are today.

Model GPD function

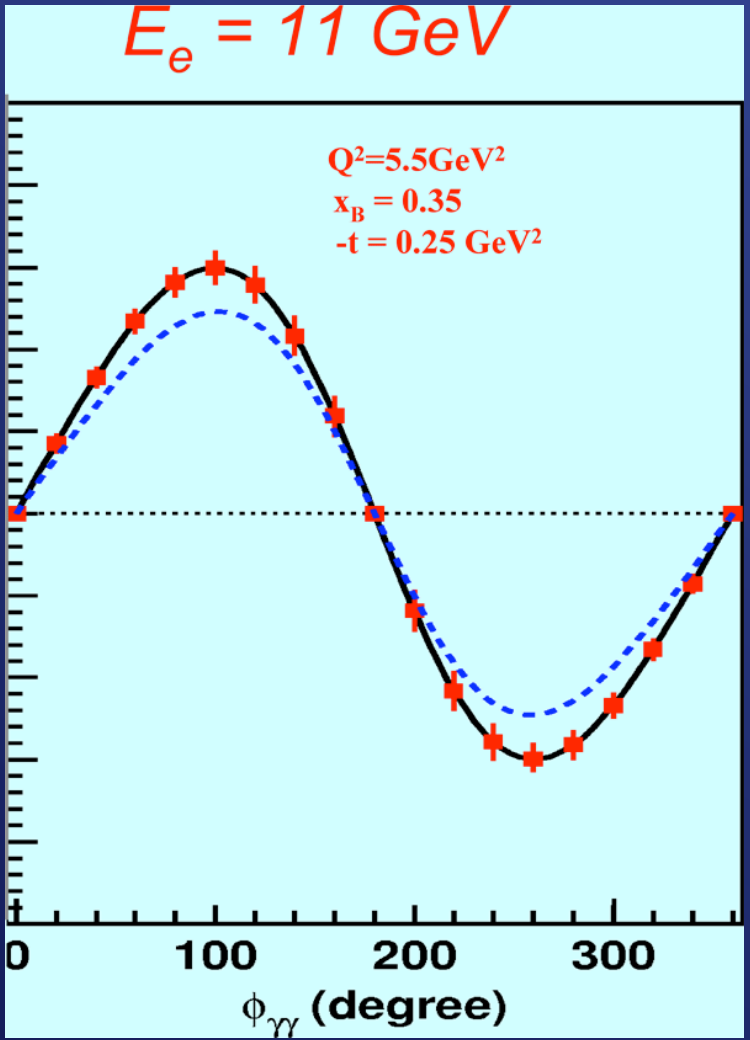


Deeply Virtual Compton Scattering (DVCS) at 11 GeV using CLAS 12

One way to access DVCS is by measuring single-spin asymmetries that result from the interference between DVCS and the Bethe-Heitler process

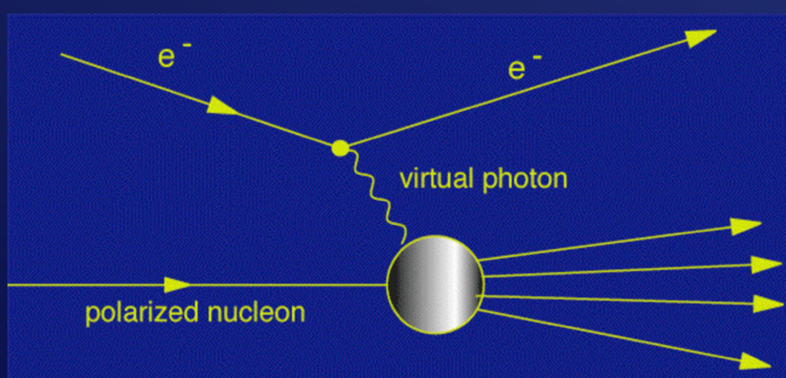


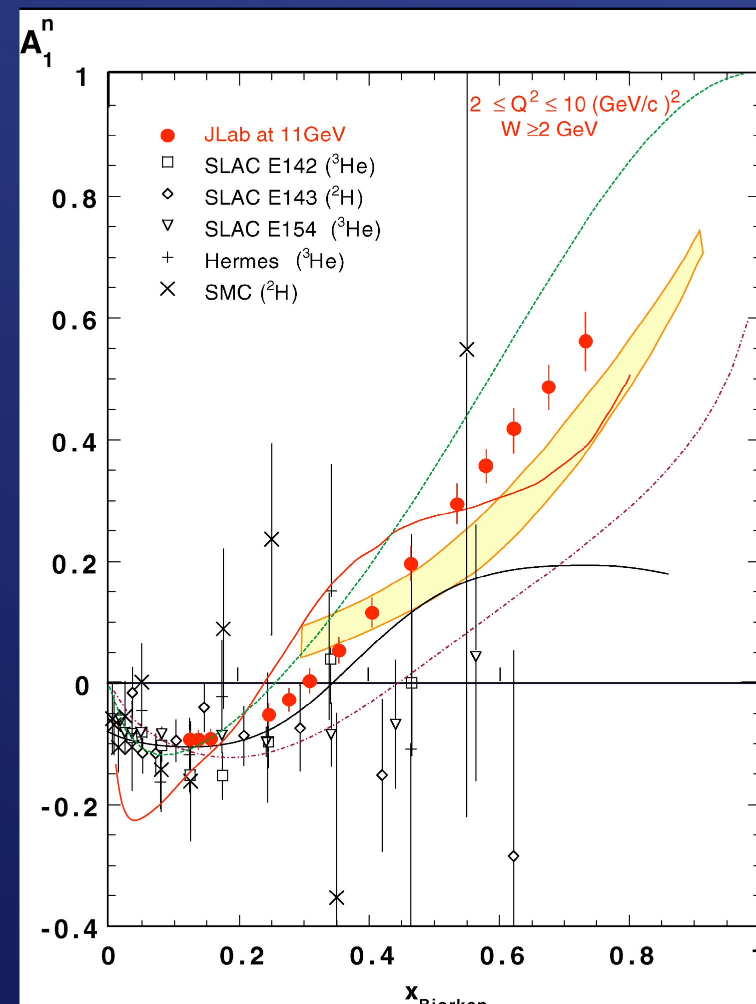
JLab at 12 GeV will be an excellent place for exploring GPD's. EIC may be even better.



Nucleon structure that is CALCULABLE: Valence-quark spin structure: $A_1^{n(p)}$ at high x

$$A_1^n = \frac{d\sigma_{1/2} - d\sigma_{3/2}}{d\sigma_{1/2} + d\sigma_{3/2}}$$





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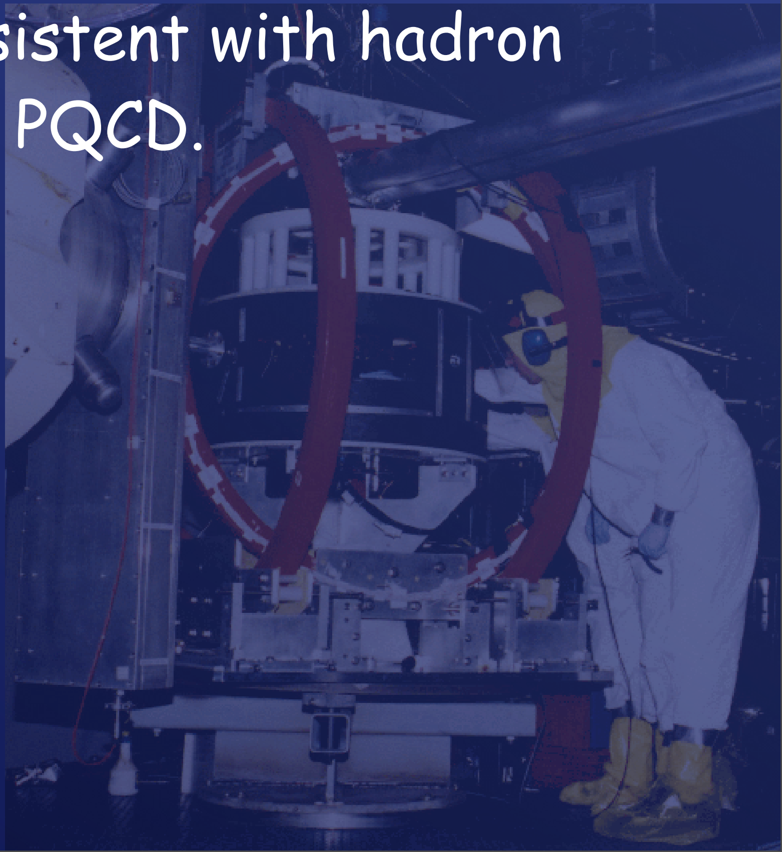

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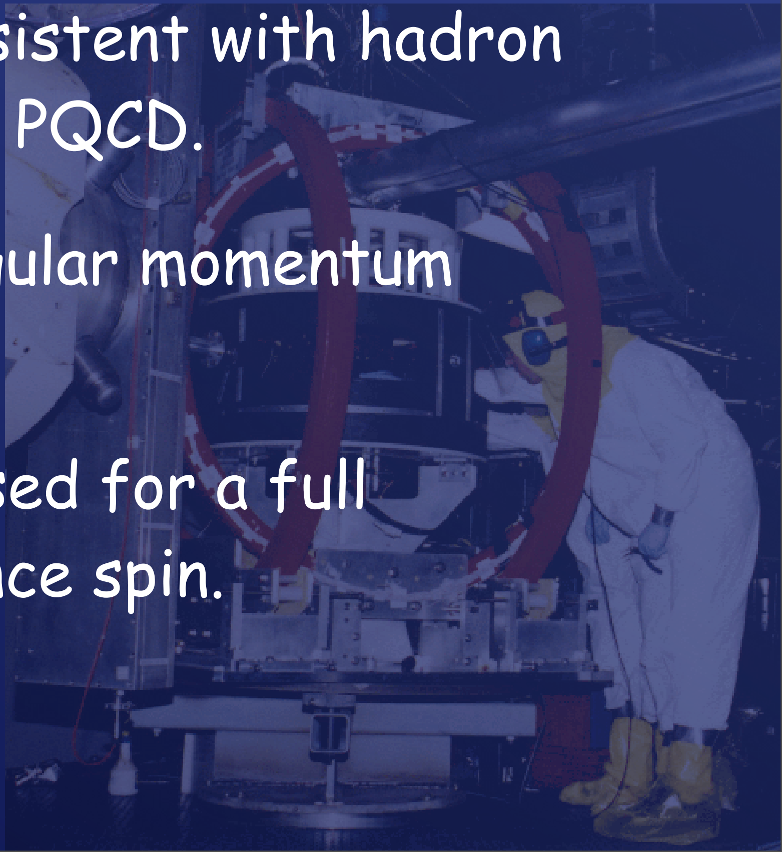
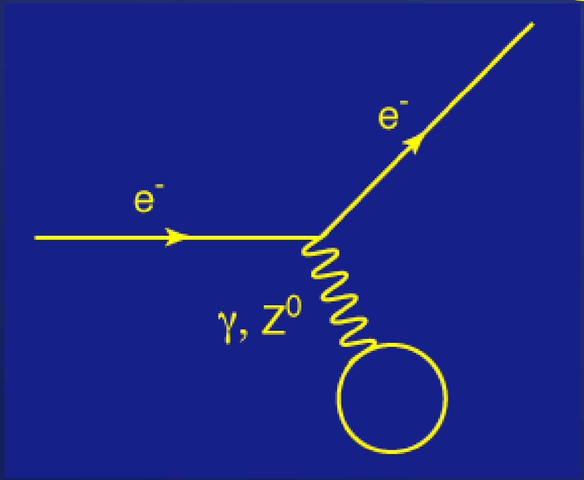
- The data (thus far) appear inconsistent with hadron helicity conservation constrained PQCD.
- The inclusion of quark orbital angular momentum looks promising to fit the data.
- A_1^n, together with A_1^p, can be used for a full flavor decomposition of the valence spin.



Probing the structure of the sea: Measuring strange-quark form factors



- Strange quarks are only present as part of the sea.
- Strange quark form factors can be probed using Parity violating asymmetries in elastic scattering

For hydrogen:

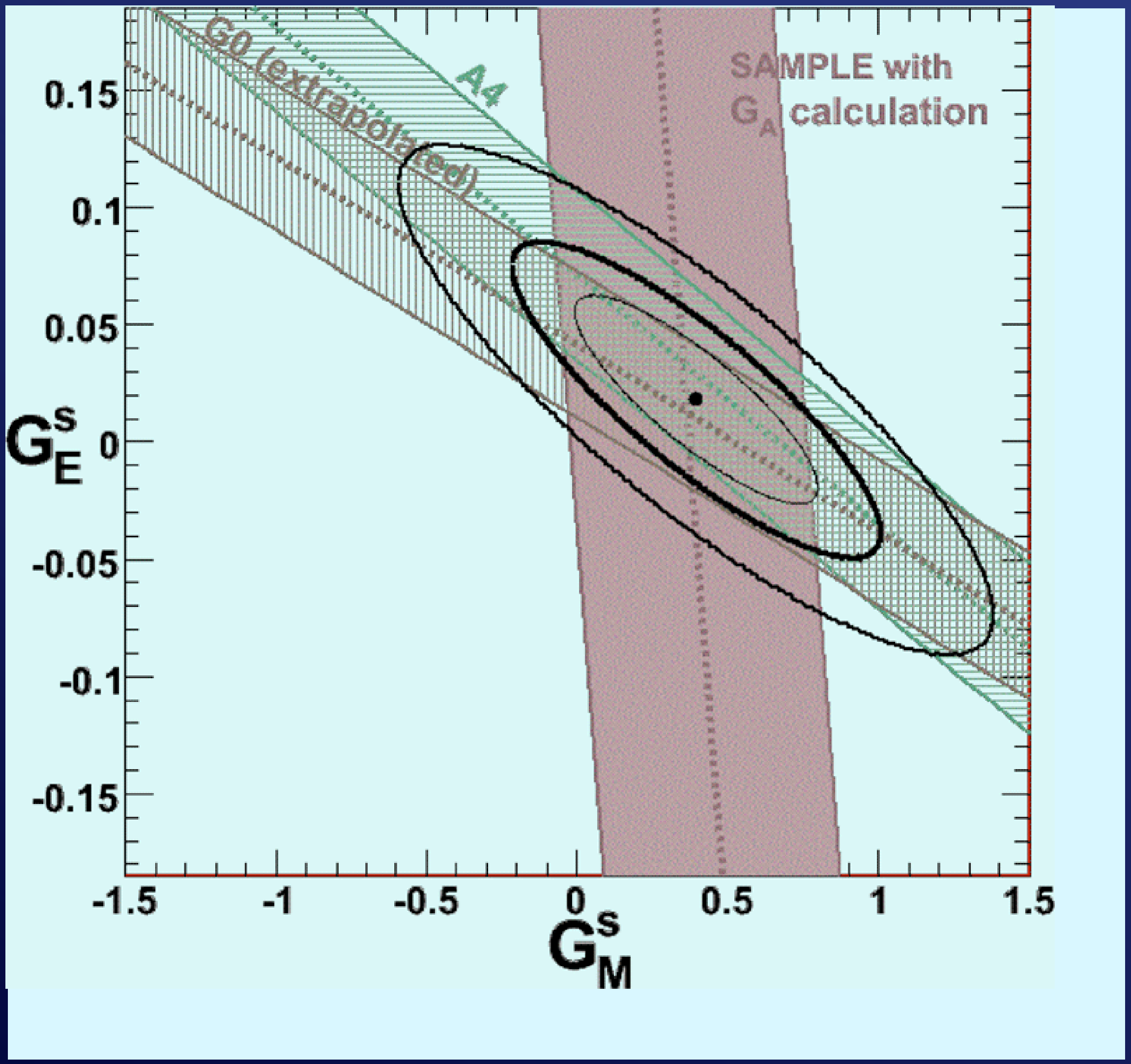
$$A^{PV} = \left[\frac{-G_F\, M_p^2\, \tau}{\pi\alpha\sqrt{2}}\right]\left[(1-4\sin^2\theta_W) - \frac{\epsilon\, G_E^{p\gamma}(G_E^{n\gamma}+G_E^s) + \tau\, G_M^{p\gamma}(G_M^{n\gamma}+G_M^s)}{\epsilon(G_E^{p\gamma})^2 + \tau(G_M^{p\gamma})^2}\right] - A_A$$

For helium:

$$A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma}+G_E^{n\gamma}}\right)$$

Experiments at Bates, Mainz, and JLab have shed considerable light on the role of strange quarks in nucleon structure.

Parity experiments have greatly constrained G_E^S and G_M^S



World data at Q^2 = 0.1 GeV^2 prior to Happex II.

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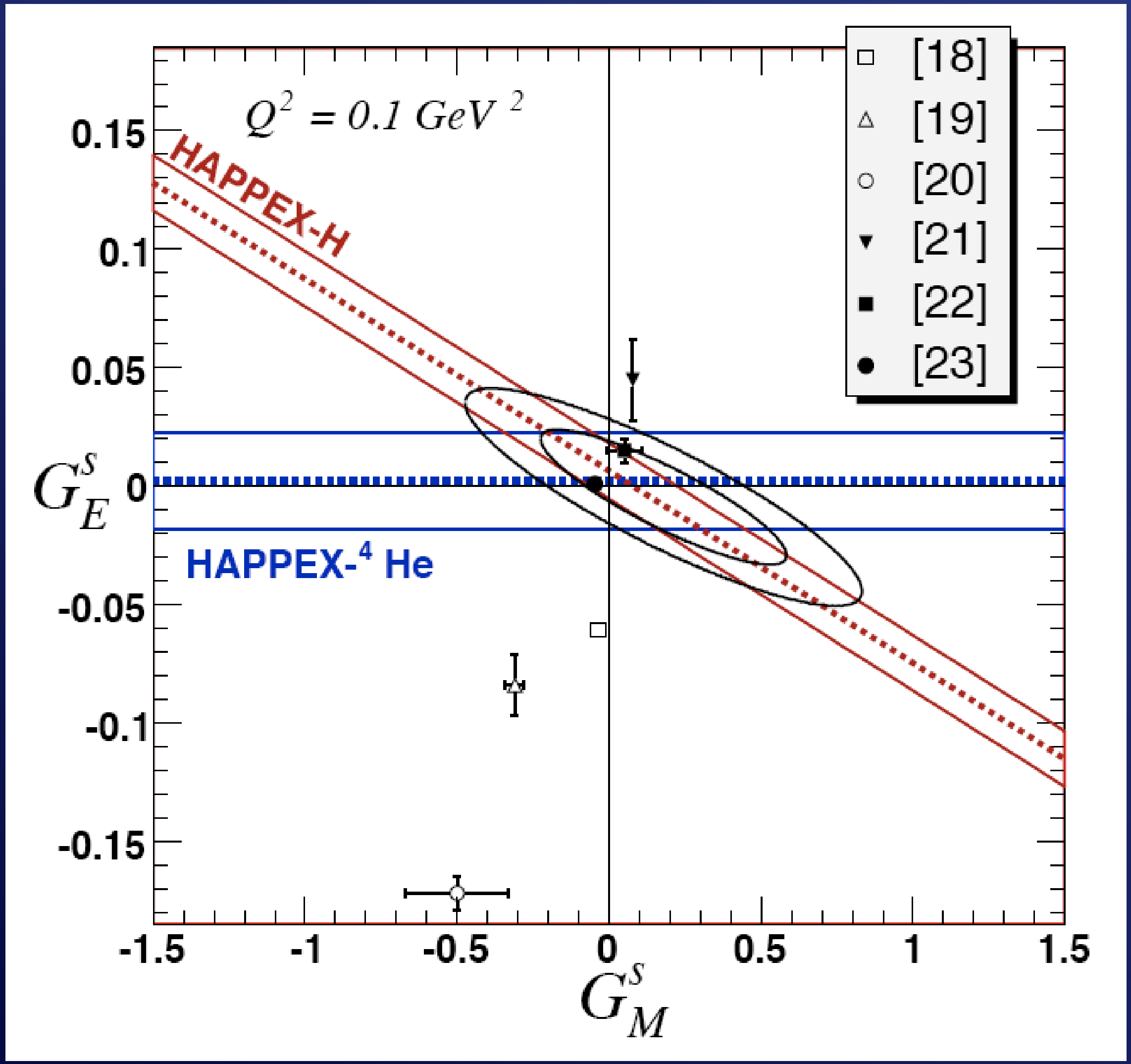


Happex II results

G_E^S = -0.005 +/- 0.019
G_M^S = 0.18 +/- 0.27

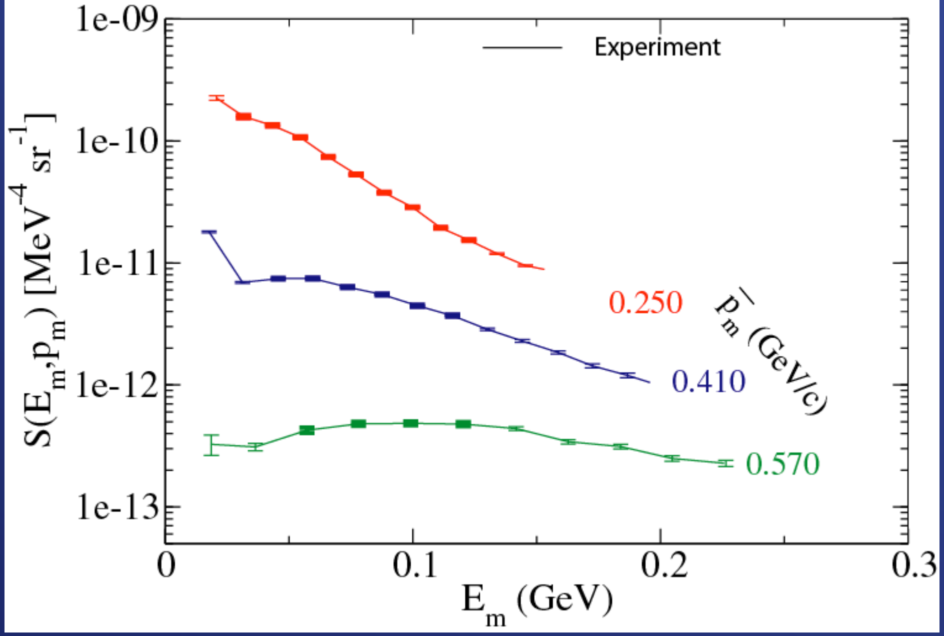
These values are quite consistent with recent Lattice calculations by Leinweber et al., shown on the plot as ref. [23].
PRL v94, 212001 (2005)
PRL v97, 022001 (2006)

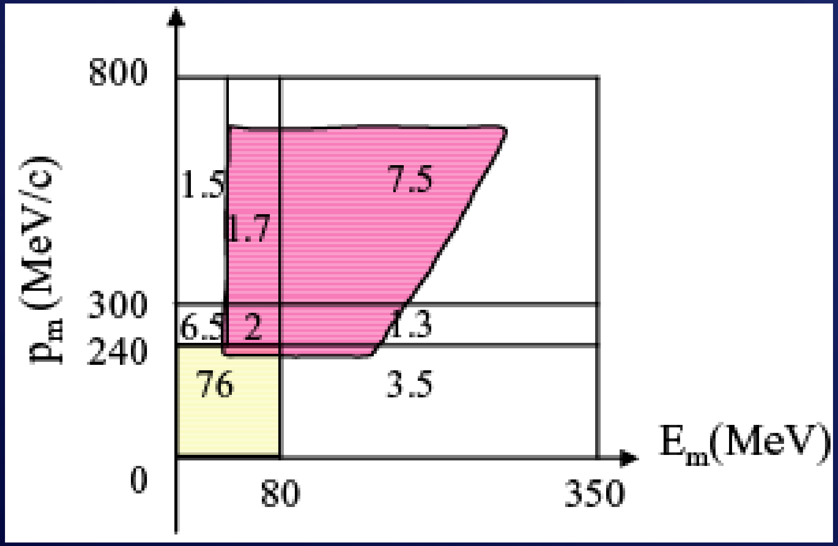
How can electromagnetic probes help our understanding of nuclear structure ?

- Short-range correlations and the NN force.
- Measuring neutron distributions using parity violation
- Hypernuclear spectroscopy

Direct measurement of correlated strength in the Nuclear Spectral Function

Experiment measured the nuclear spectral function S(k,E) in 12C(e,e'p) in quasi-parallel kinematics





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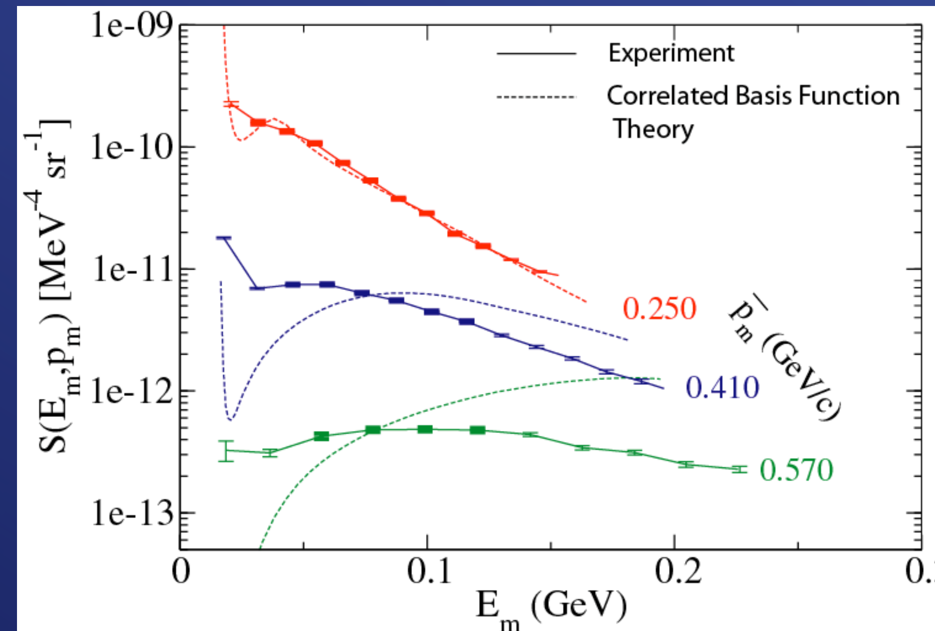
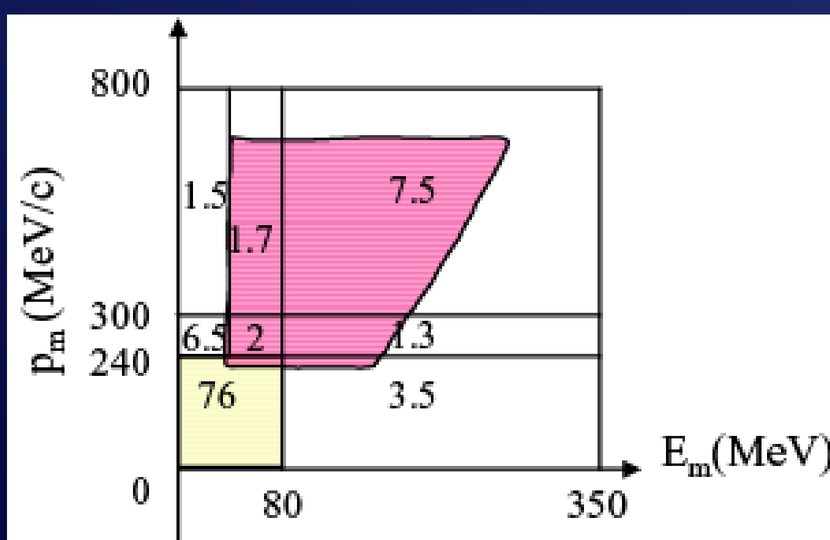




Correlated strength

(as fraction of total strength)

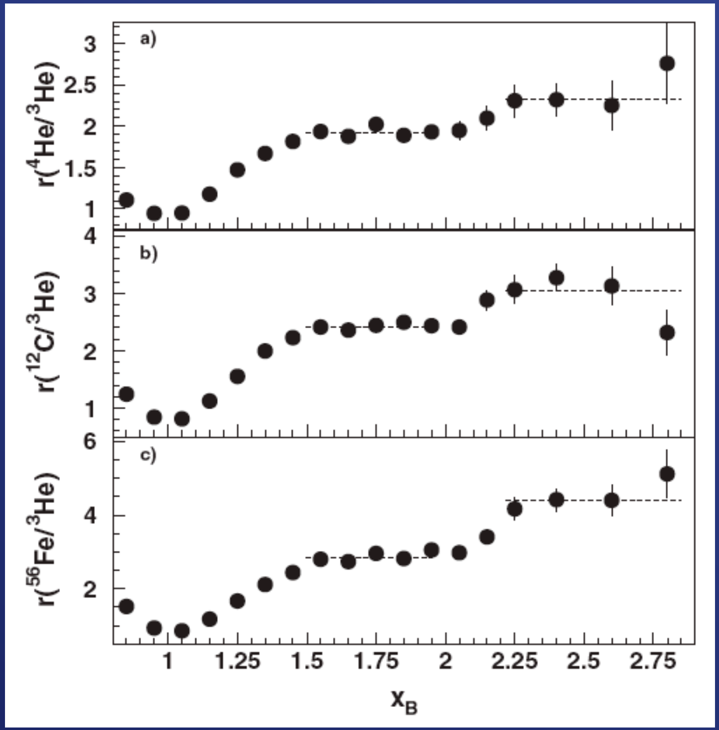
Integrated over measured kinematic range.

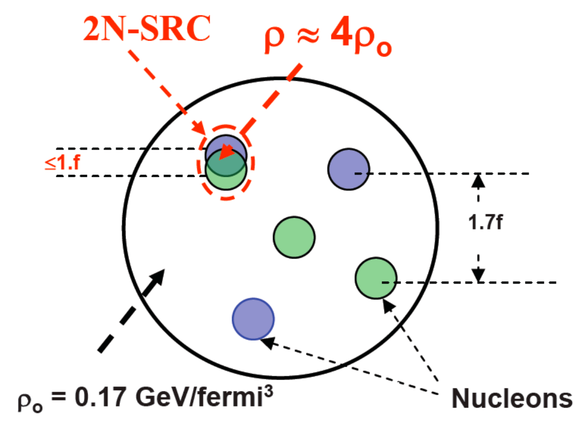
Experiment	10.2 +/- 1.0 %
Correlated Basis Function Theory	10.7%

Scaling and measurement of 2 and 3 nucleon short-range correlation probabilities

The ratio of cross sections R is expected to scale for certain values of x > 1 .

$$R(A, {}^3\mathrm{He}) = \frac{3\,\sigma_A(Q^2, x_B)}{A\,\sigma_{^3\mathrm{He}}(Q^2, x_B)}$$





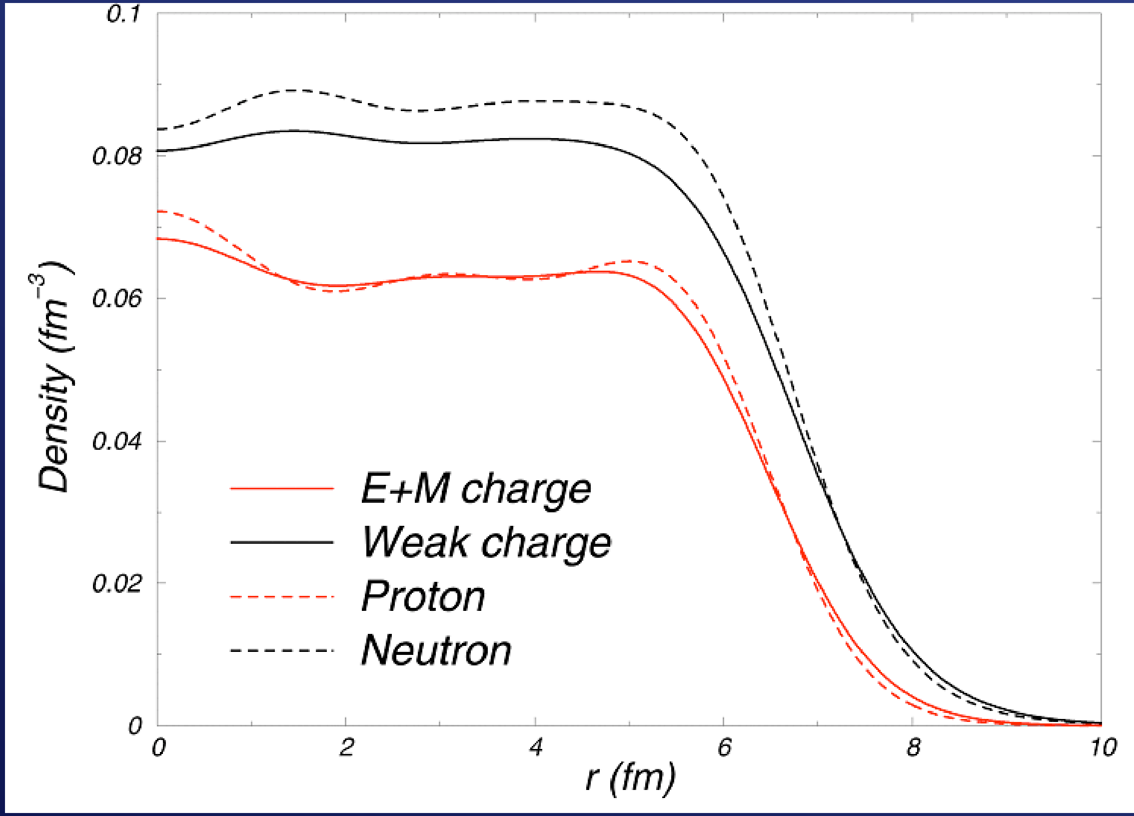
Nucleons are periodically much closer to one another than is the case on average.

Parity violation for probing neutron distributions: ^{208}Pb

$$A_{LR} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[4 \sin^2\theta_W - 1 + \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

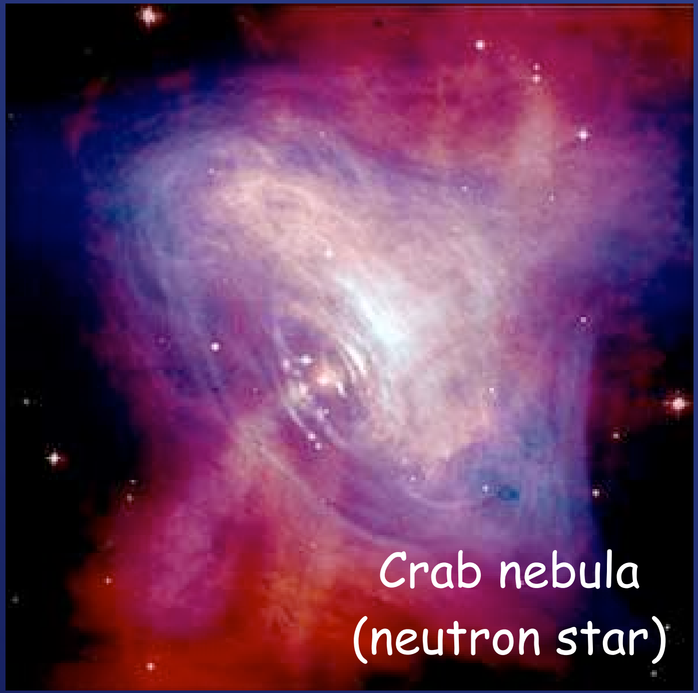
$$\frac{dA}{A} = 3\% \quad \rightarrow \quad \frac{dR_n}{R_n} = 1\%$$

- With minimal assumptions, extract neutron radius
- Single point will constrain mean field theories.



Implications of measuring R_n

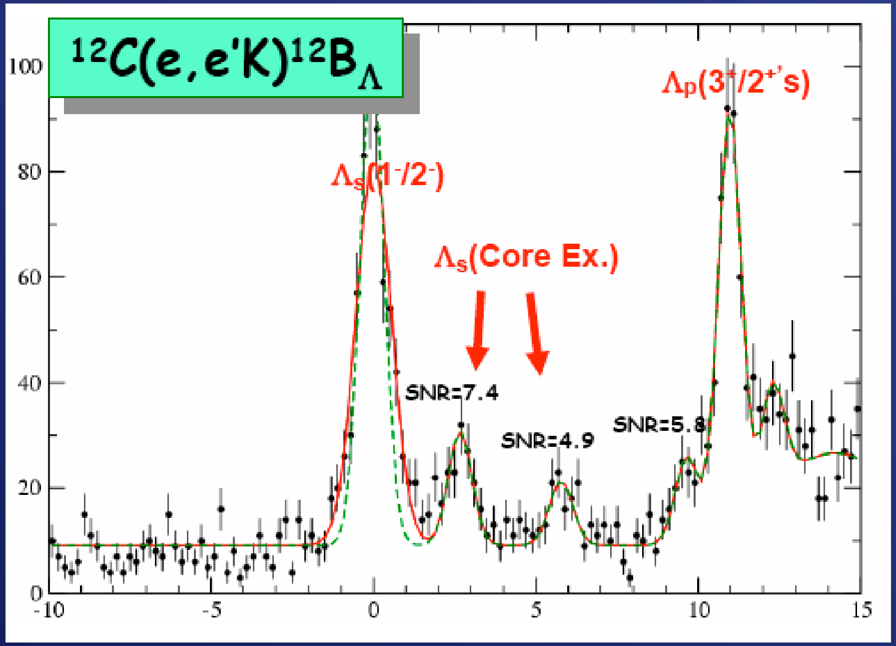
- Provides calibration for mean field theories.
- Constrains equation of state for neutron matter.
- Has implications for "star quakes" on neutron stars.
- Reduces systematic uncertainties due to neutron distributions from atomic parity experiments



Crab nebula (neutron star)

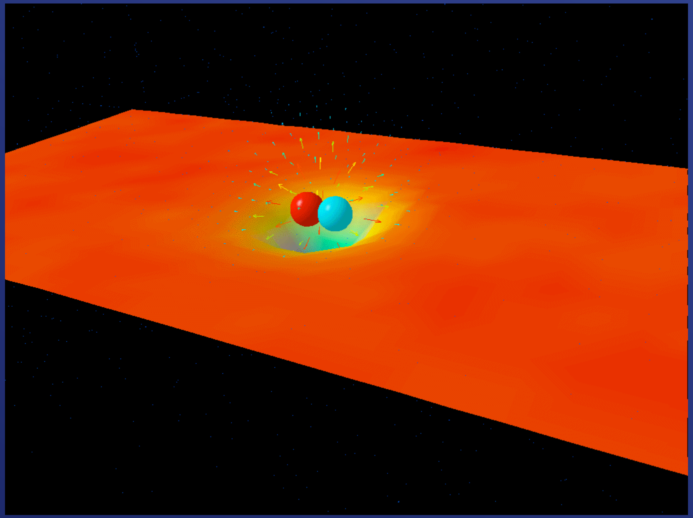
An exciting direction that is just getting started: hypernuclear spectrocopy

- Spectroscopy provides information on the strong interaction as felt by the Λ
- Non-identical particle avoids Pauli blocking, providing access to deeply bound (s & p wave) states
- Provides a unique opportunities for studying baryon structure inthe nuclear medium

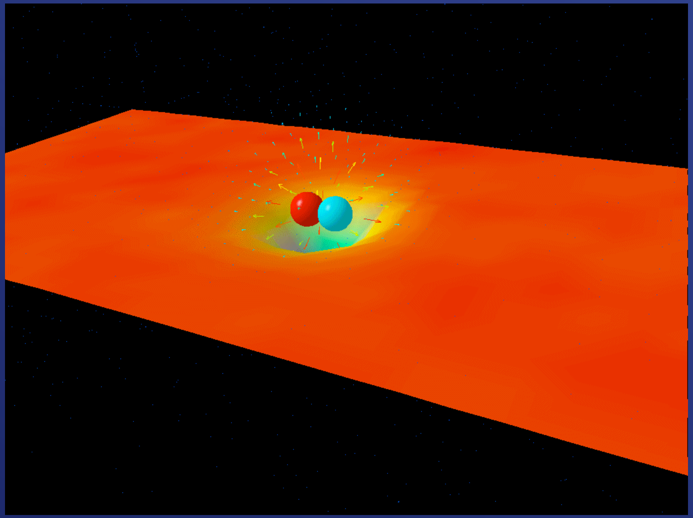


Probing the QCD vacuum and confinement: GlueX -- an experiment to discover hybrid mesons

- In QCD, a favored model of mesons is a $q\bar{q}$ pair connected by a gluonic flux tube.
- The flux tube can be excited, resulting in so-called "hybrid" mesons.
- Some hybrid mesons will have exotic quantum numbers, making their identification unambiguous.



Probing the QCD vacuum and confinement: GlueX -- an experiment to discover hybrid mesons



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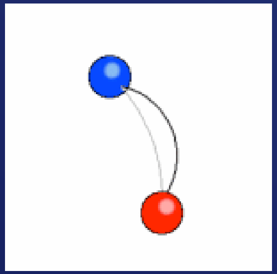
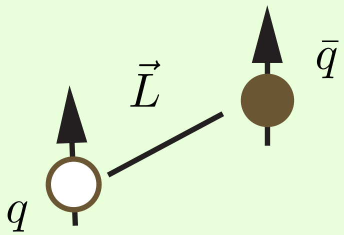


Conventional and hybrid mesons

Conventional mesons: no gluonic degrees of freedom



$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

these exotic combinations not allowed:

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$$

In flux-tube model,
expect 8 degenerate nonets

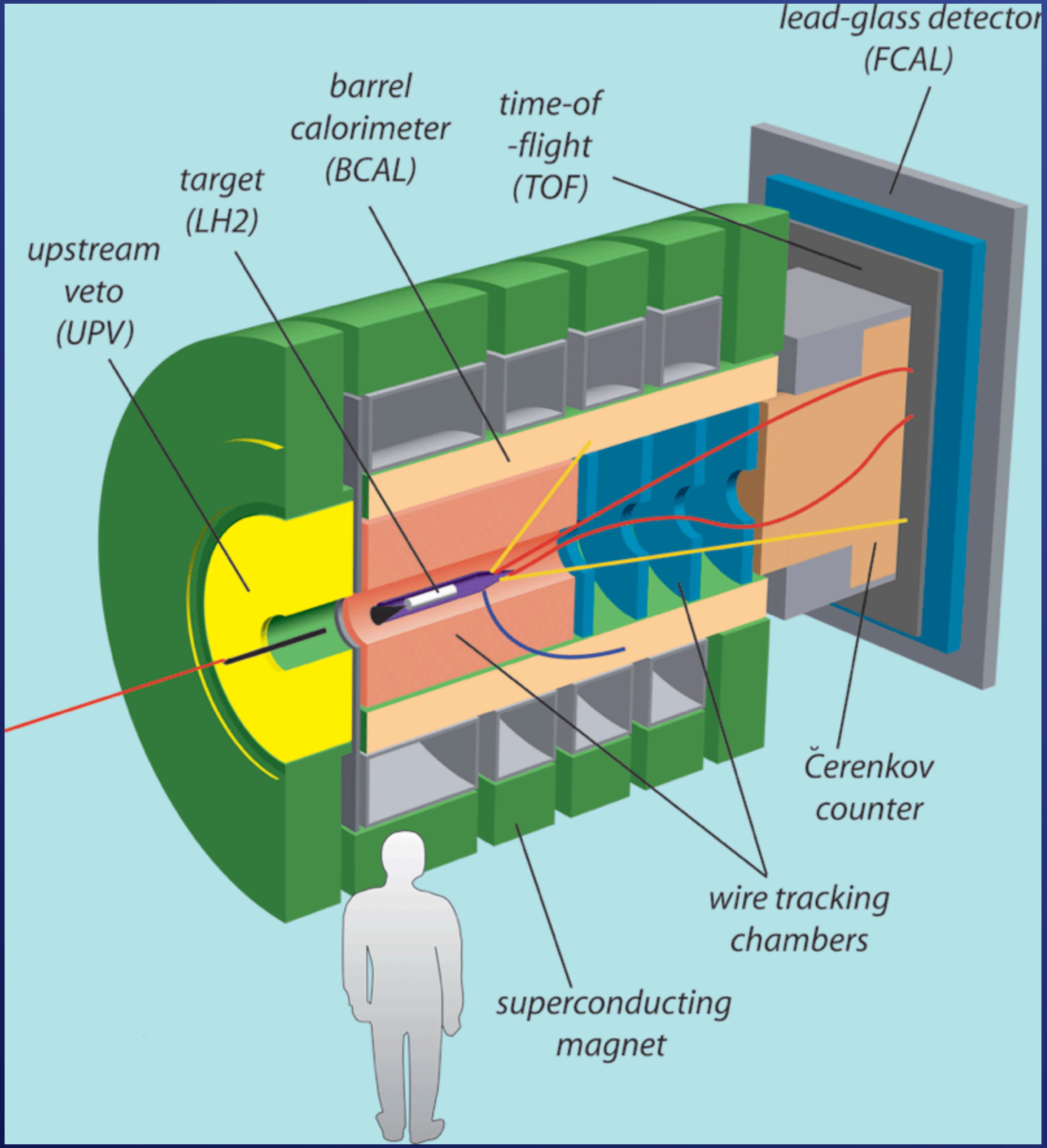
S=0	S=1
1^{++}, 1^{--}	0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}

Red indicates exotic quantum numbers

- Hybrid mesons with exotic quantum numbers can be unambiguously identified.
- Lattice calculations indicate a hybrid with $J^{PC} = 1^{-+}$ with mass of about 1.9 GeV

GlueX experimental setup in Hall D

- Hybrids produced by photoproduction.
- Hybrid decay products detected by hermetic solenoid detector.
- Optimal photon energy of 9 GeV sets the scale for the JLab upgrade.

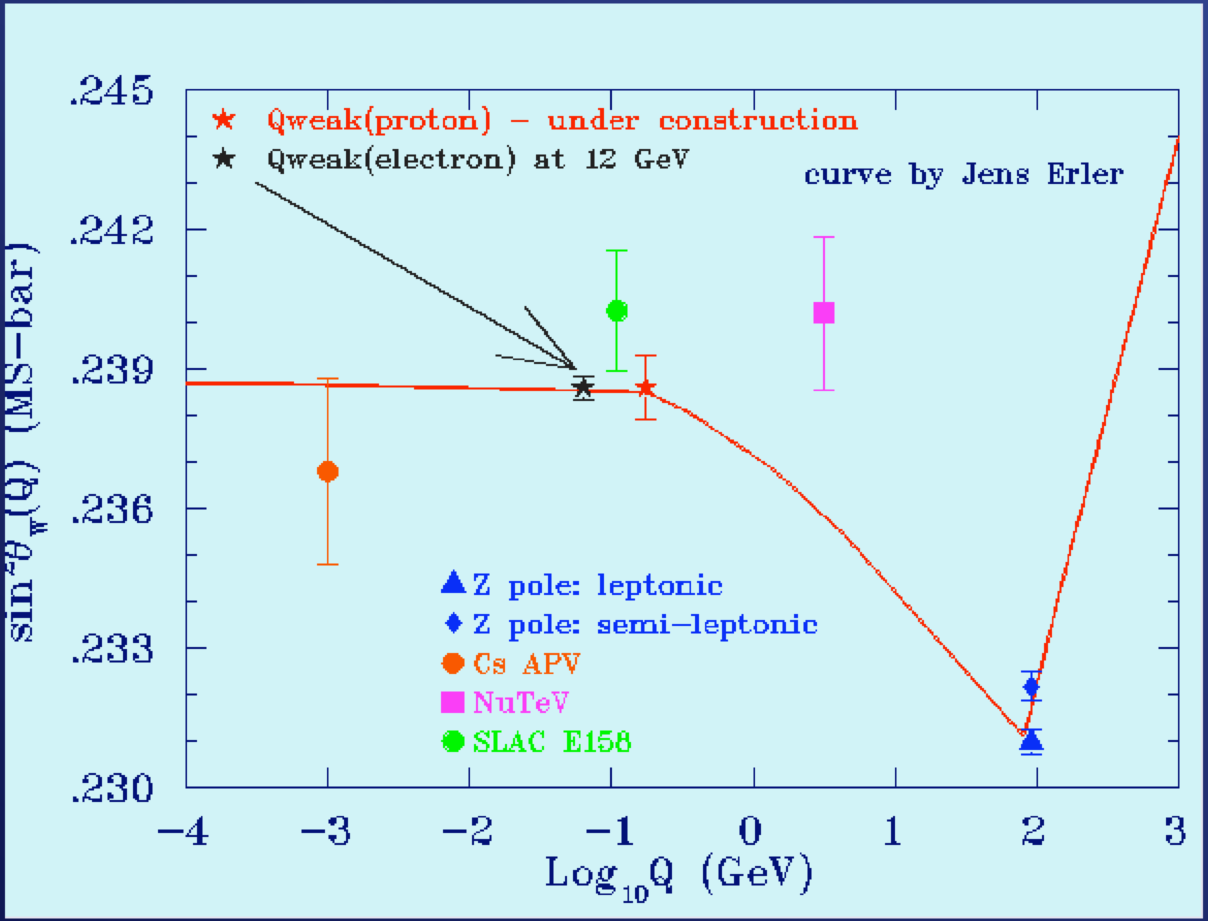


One final comment on electromagnetic probes:
Medium energy electroweak measurements

A PV Moller scattering measurement at 11 GeV at JLab has the potential for an energy reach comparable to LHC and a cleanliness that would compliment possible discoveries.

It is possible that a discovery at LHC could not be interpreted without a Moller measurment from JLab.

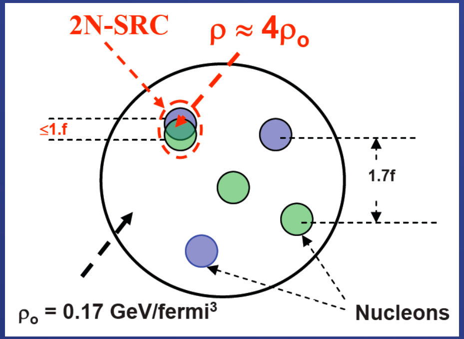
Parity violation in Moller scattering at JLab



Parting remarks

Parting remarks

- Nuclear Structure



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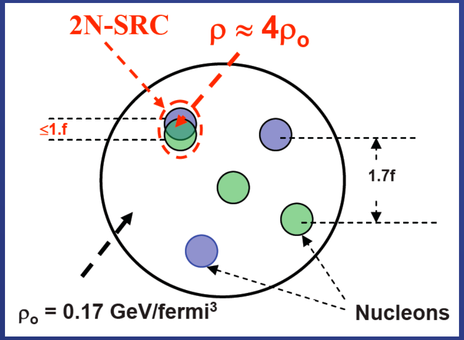
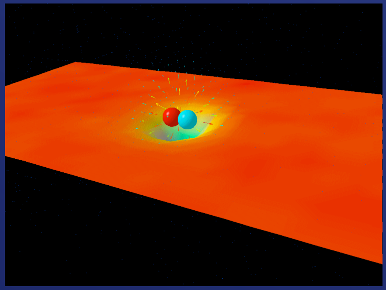


- Nuclear Structure
- The QCD vacuum and confinement



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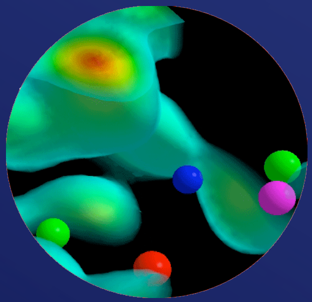
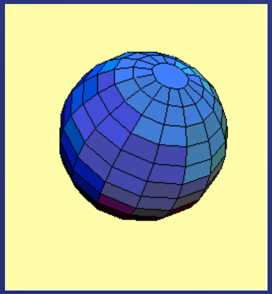
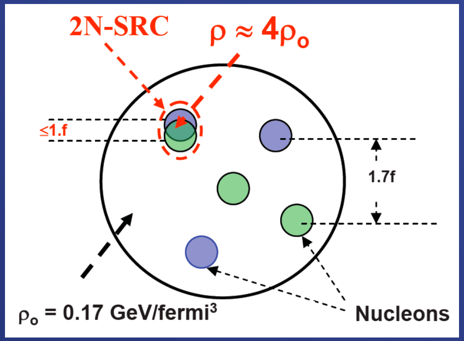
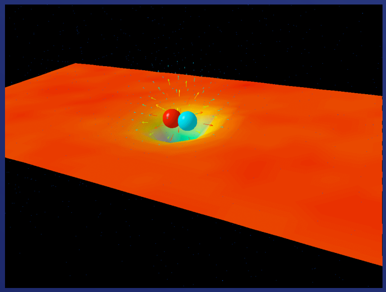






- Nuclear Structure
- The QCD vacuum and confinement
- The internal structure of the proton



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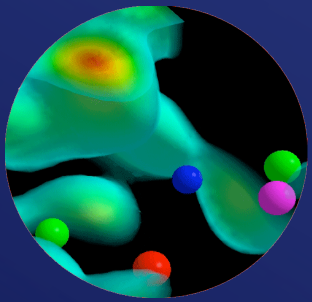
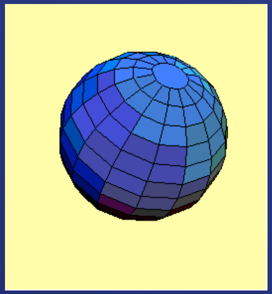
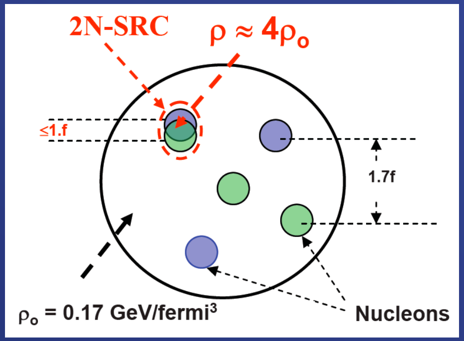
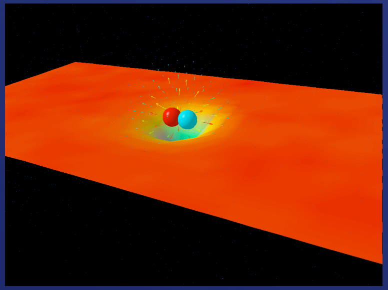






- Nuclear Structure
- The QCD vacuum and confinement
- The internal structure of the proton
- Electroweak meaurements



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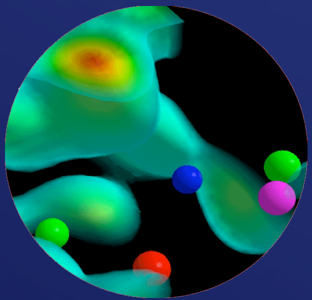
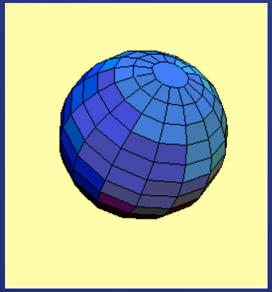
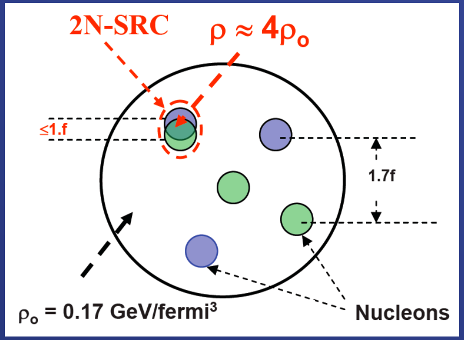
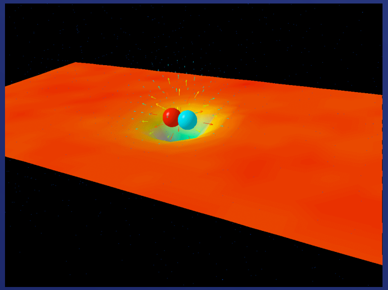
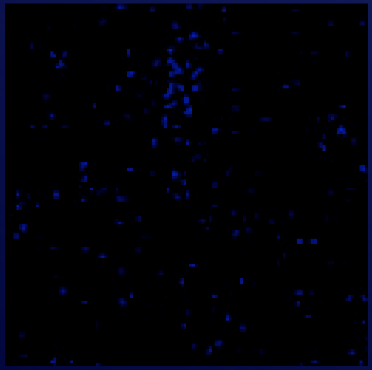






- Nuclear Structure
- The QCD vacuum and confinement
- The internal structure of the proton
- Electroweak meaurements
- Applications





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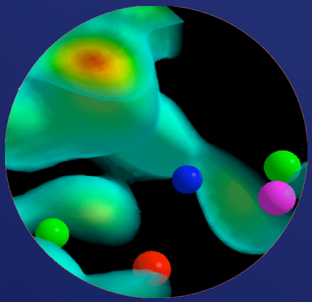

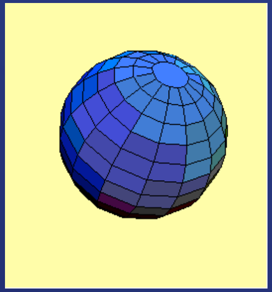

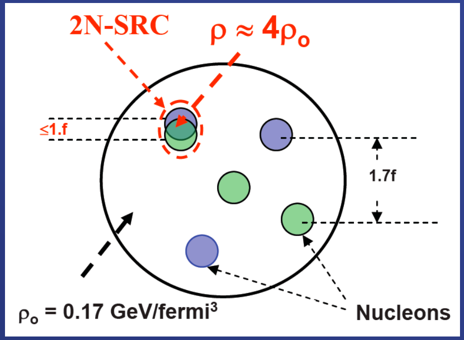

- Nuclear Structure
- The QCD vacuum and confinement
- The internal structure of the proton
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- Applications
- It's going to be a great century!