Nucleon Electromagnetic Form Factors

Gordon D. Cates
Spin 2014 - Beijing
October 21, 2014

I will focus mostly on three subjects:

- The proton charge-radius puzzle.
- G_E^p/G_M^p at high Q^2 and the proton spin.
- Flavor decomposition of the electromagnetic nucleon form factors.

University of Virginia

Definitions: the electromagnetic elastic nucleon FFs

The hadronic current:

$$\mathcal{J}^{\mu}_{\text{hadronic}} = e\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)\right]N(p)$$

Dirac FF (F_1) — Pauli FF (F_2)

The Sachs FFs:

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2$$

where

$$\tau = \mathrm{Q}^2/4\mathrm{M}^2_{\text{nucleon}}$$

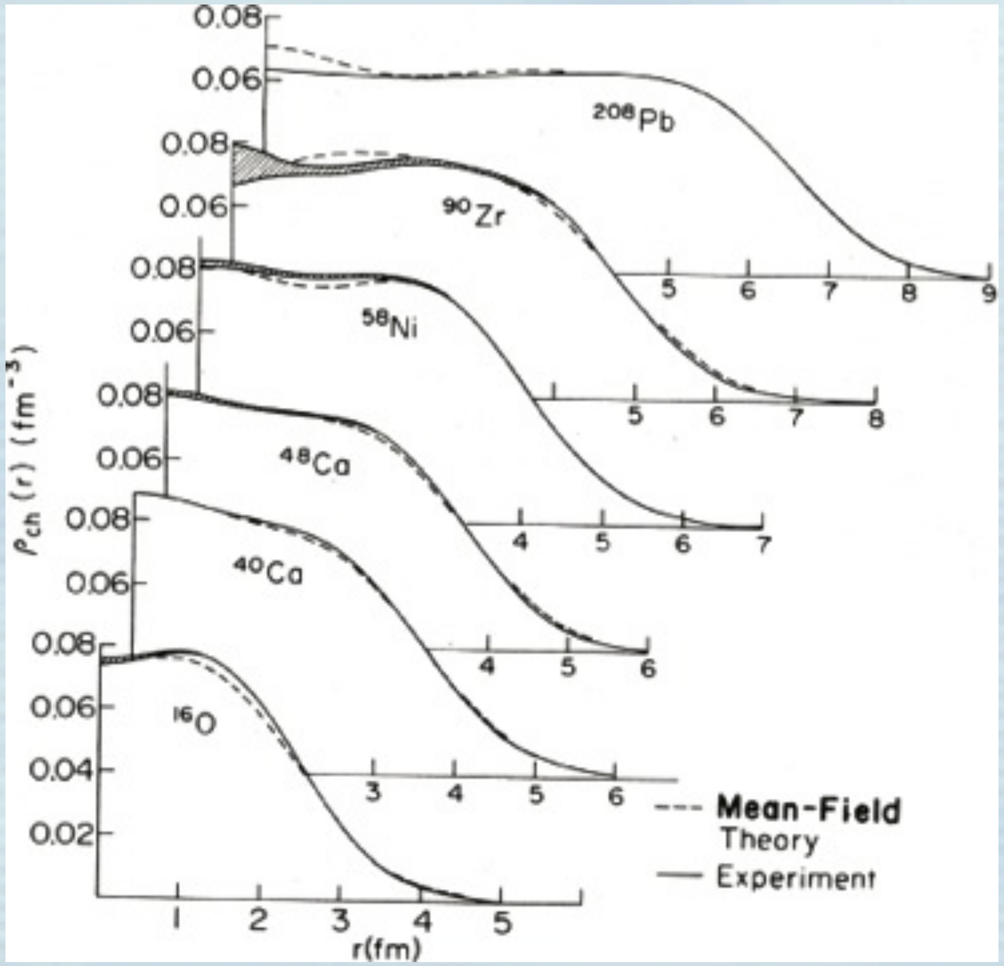
The elastic nucleon form factors are critical to understanding nucleon structure

It was noted in the 2007 Nuclear Science Advisory Committee (NSAC, convened by the DOE and the NSF) Long Range Plan that measurements of the ground-state form factors ...

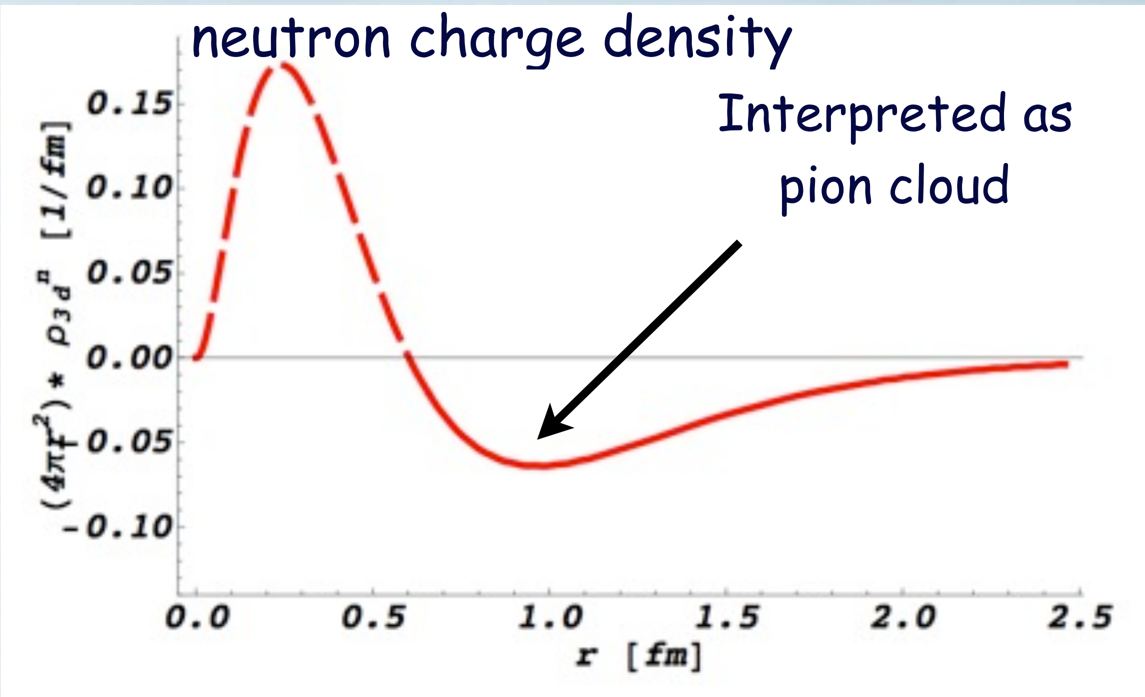
" ... remain the only source of information about quark distributions at small transverse distance scales."

The non-relativistic picture has long been used to determine both nuclear and nucleon structure

Both images below taken from review by Vanderhaeghen and Walcher



Fourier transforms of nuclear FFs have provided a detailed picture of the charge distribution of nuclei

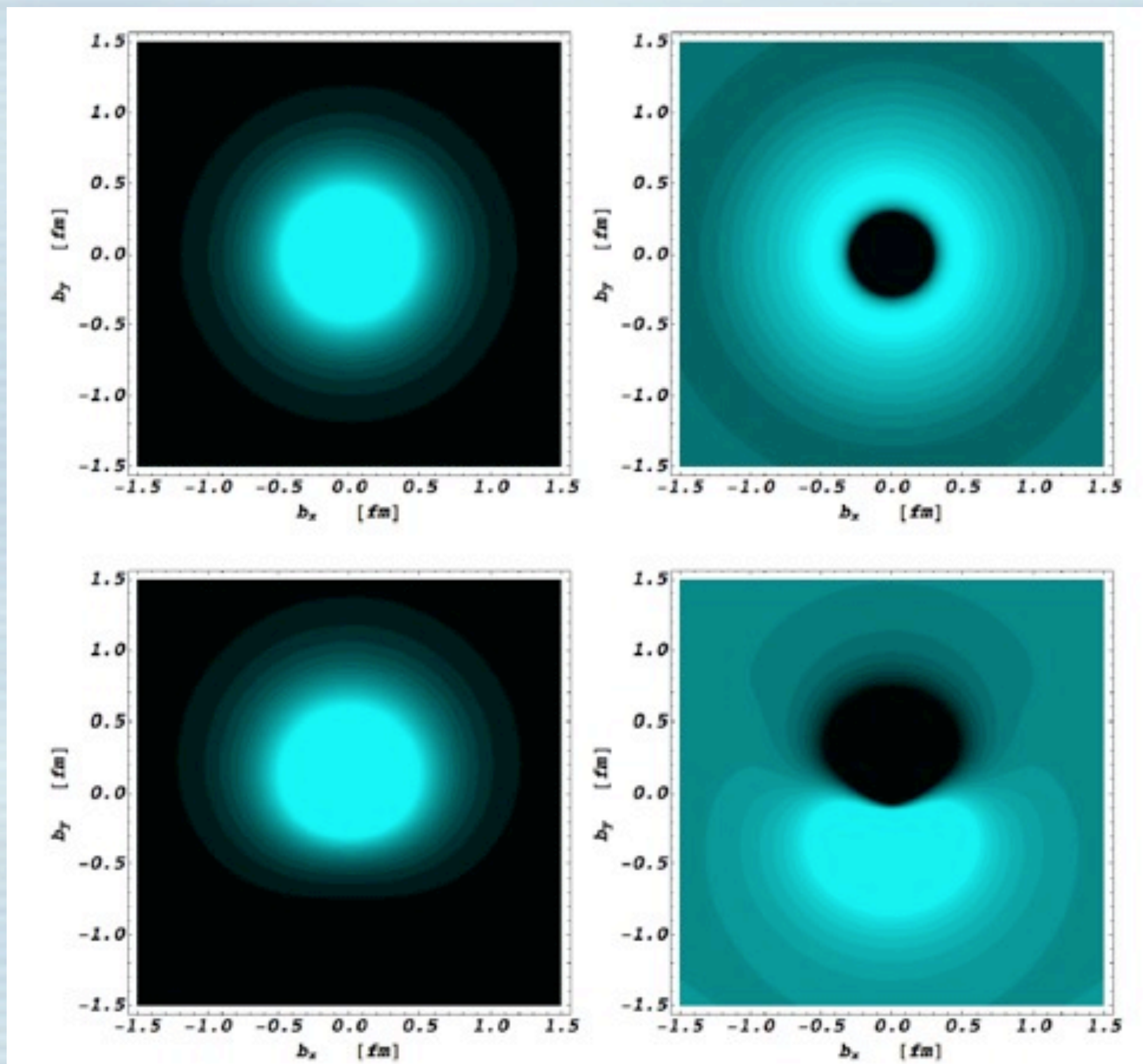


Fourier transforms of nucleon FFs (the neutron pictured above) have provided important insight, but suffer in that the momentum transfers are too large to ignore relativistic effects

The relativistic picture gives us the (not very intuitive) Light-front density distributions,

Longitudinally polarized proton

Longitudinally polarized neutron



Transversely polarized proton

Transversely polarized neutron

FFs provide important constraints for Generalized Parton Distributions

$$\int_{-1}^{+1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

Among other things, FFs thus play a role in determining the angular momentum of the quarks using Ji's Sum Rule:

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

FFs thus play a an important role in the entire GPD program, one of the signature goals of the 12 GeV upgrade

Measuring the form factors

Traditional Rosenbluth separation

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{\varepsilon\, G_E^2 + \tau\, G_M^2}{\varepsilon(1+\tau)}$$

where

$$\tau = Q^2/4\,M^2 \quad \text{and} \quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$$

- Becomes more difficult at high Q^2 where the scattering is dominated by G_M.
- Now recognized that two-photon and other effects cannot be neglected.

Measuring the form factors

Polarization techniques to access G_E/G_M

Polarization transfer

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan(\theta_e/2)}{2\,M}$$

Polarized beam/polarized target

$$A_\perp = \frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\,\tau(1+\tau)\tan^2(\theta/2)}$$

- Typically have fewer systematics from radiative effects and nuclear structure.
- Have proven very important at high Q^2

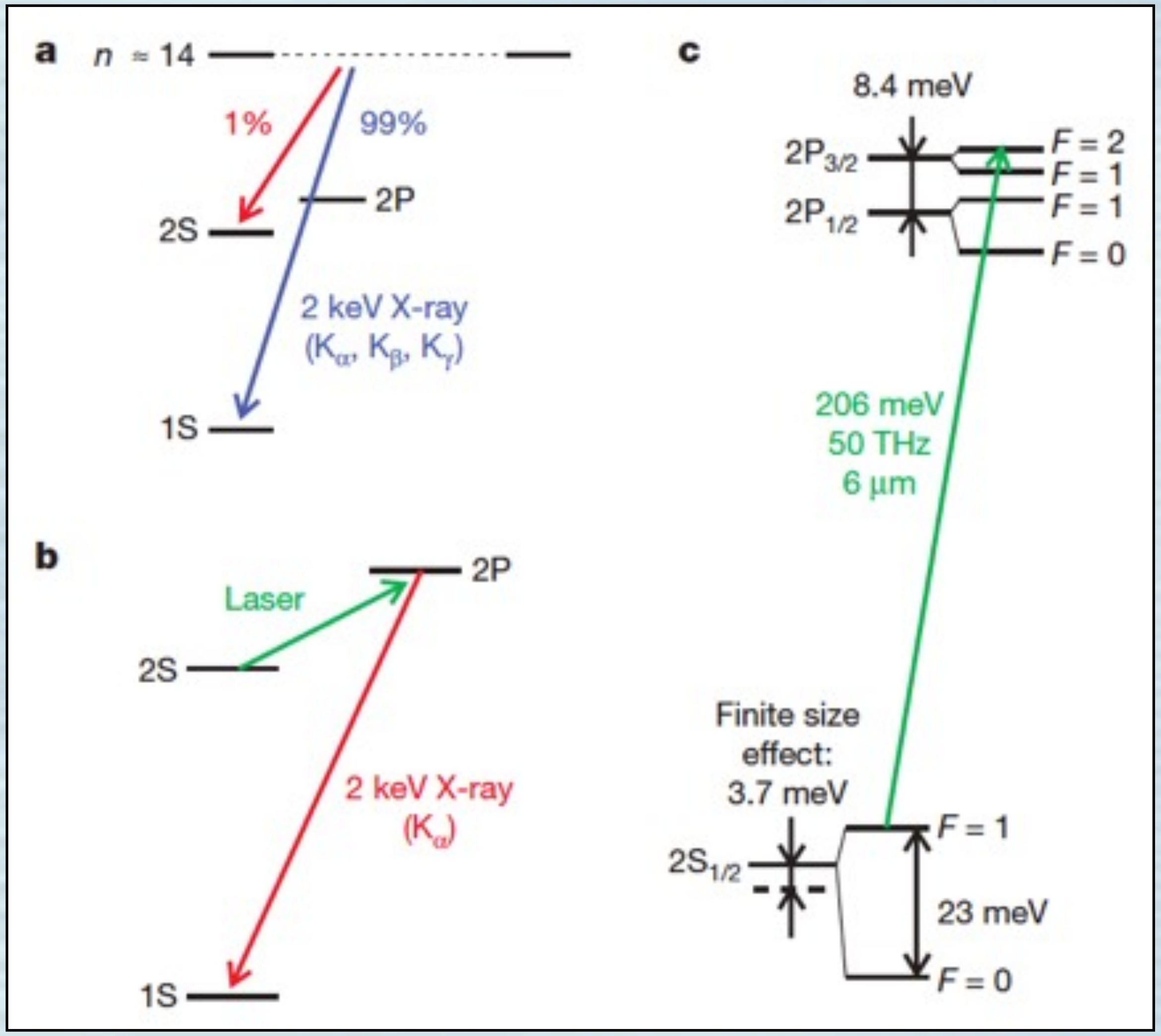
The charge radius of the proton

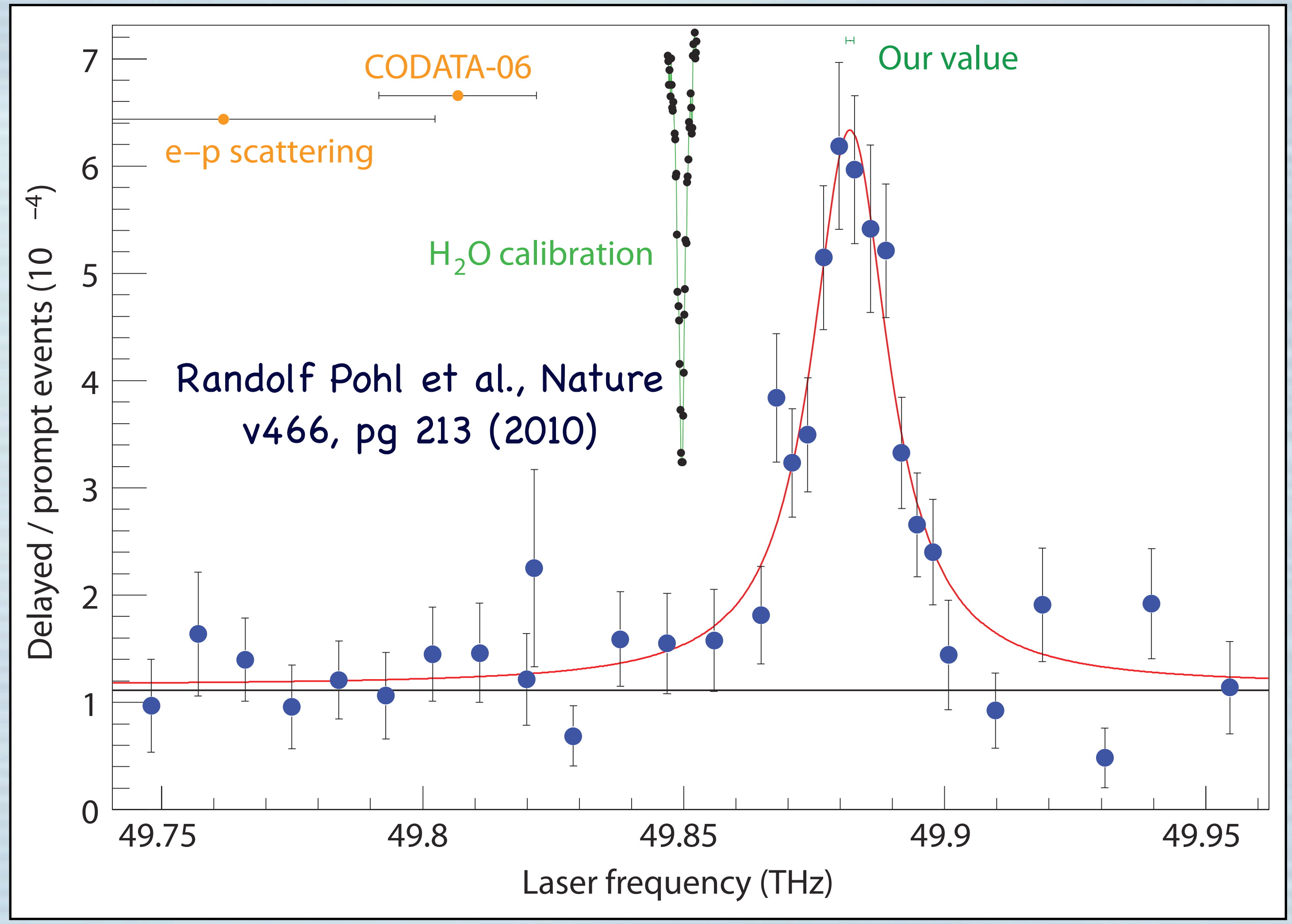
$$\langle r_E^2 \rangle = -\frac{6}{G_E(0)} \frac{dG_E}{dQ^2}\bigg|_{Q^2=0}$$

A long history beginning with Hofstadter. The problem is, a new measurement of the proton charge radius severely disagrees with this approach.

Proton charge-radius puzzle

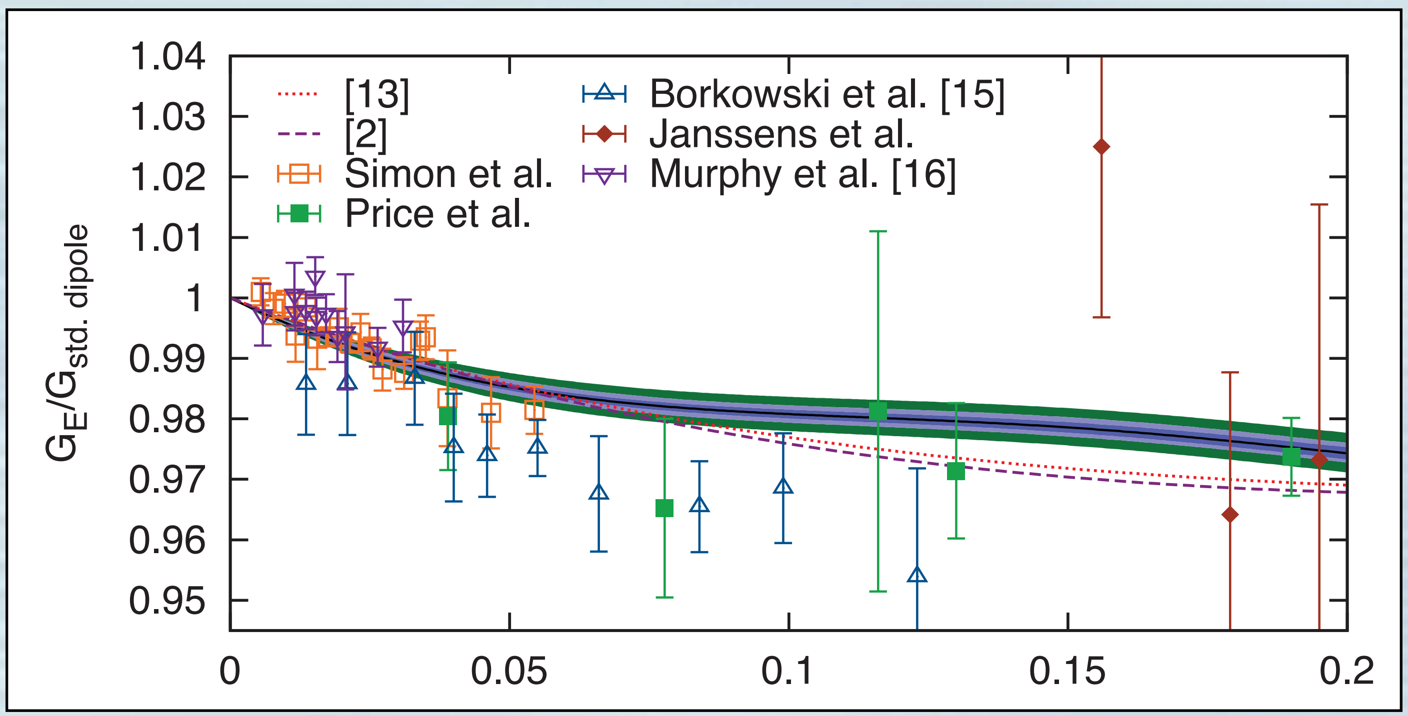
(See parallel session III - S4 - this afternoon)





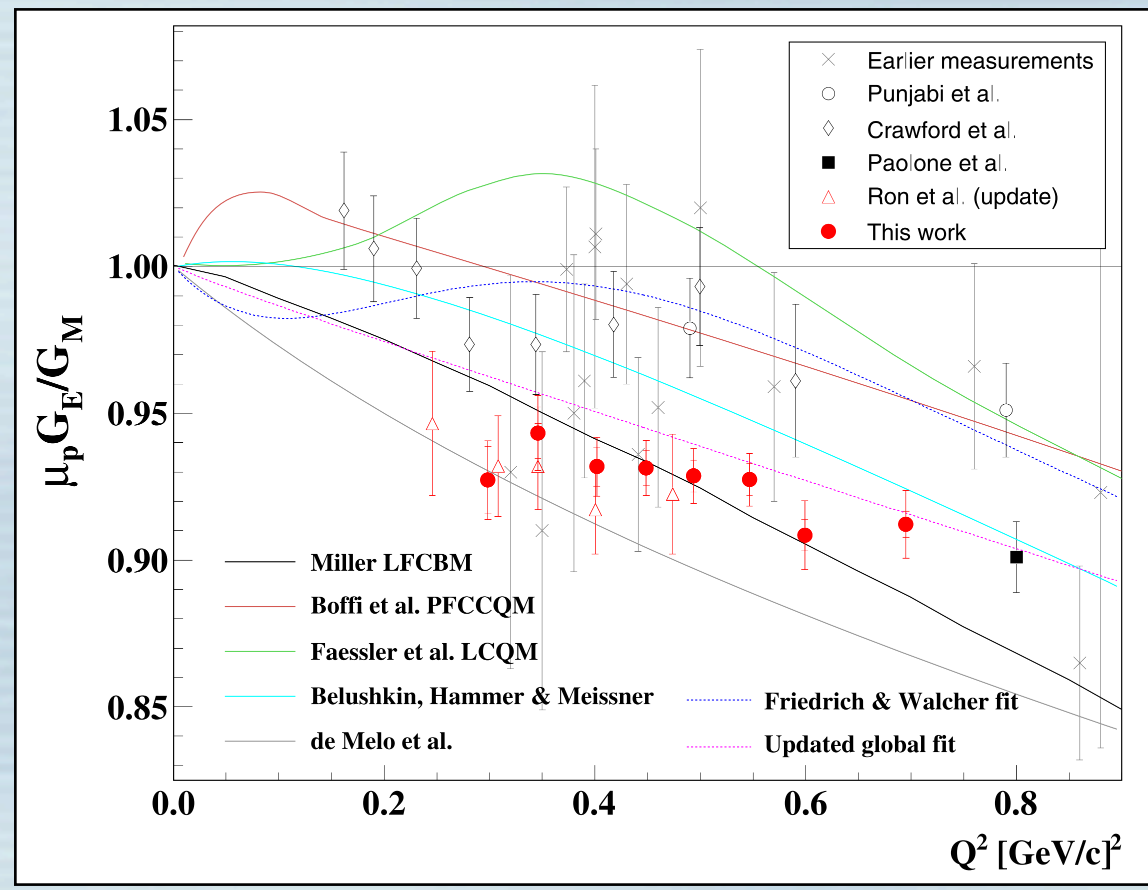
- The spectroscopic determination of the Lamb Shift in muonic hydrogen ($\mu^- H^+$), shown above, yields a proton charge radius r_p = 0.84184(69) fm MUCH smaller than other determinations. More recent measurement from 2013 measured 0.84087(39).
- The CODATA value was five (now seven) standard deviations away the new value.

The disagreement has persisted as new electron-scattering experiments of $\langle r_E^2 \rangle^{1/2}$ have increased precision



J.C. Bernauer, et al., PRL 105, 242001 (2010)

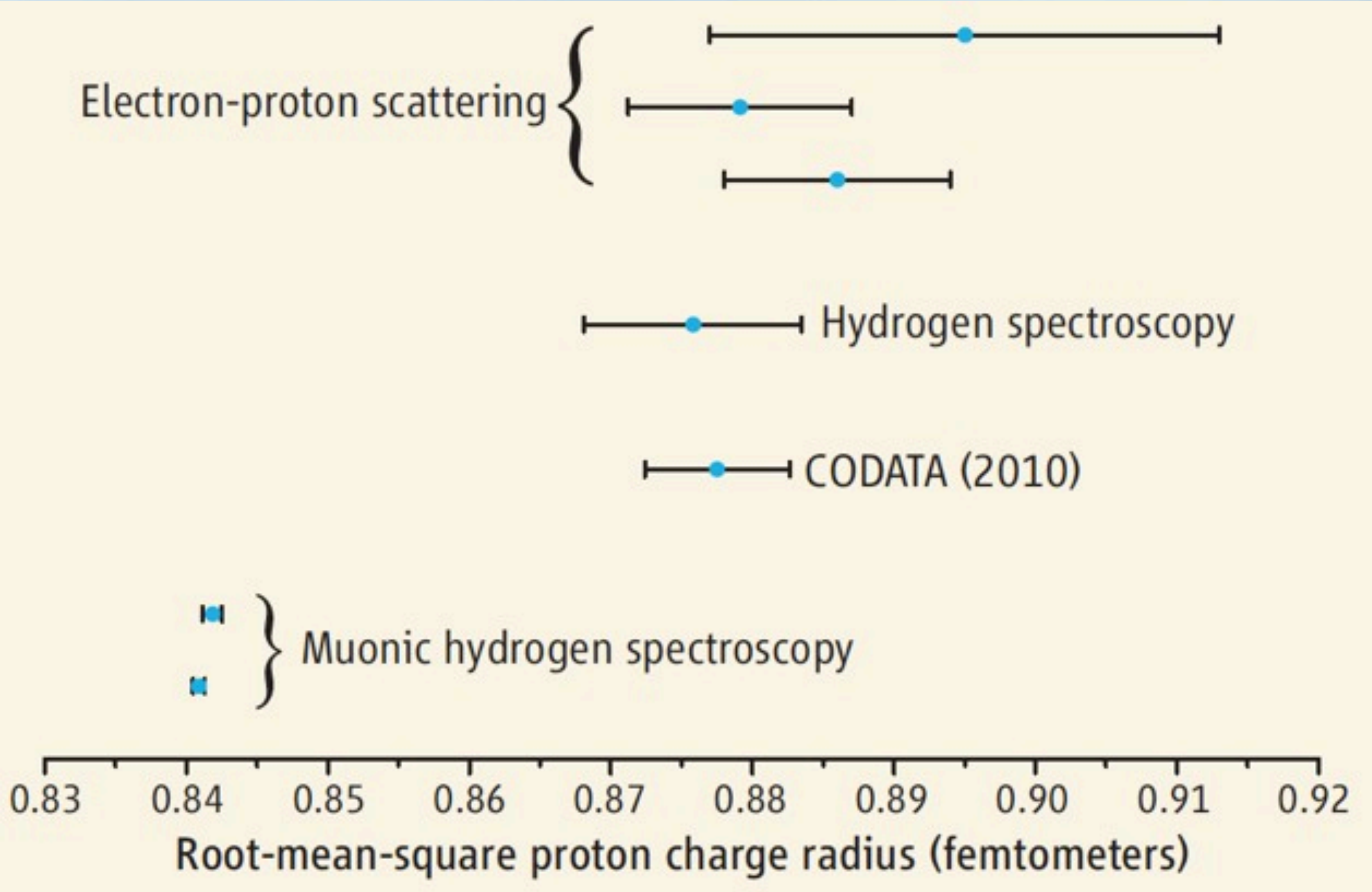
Extensive new electron-proton cross section measurements from Mainz (around 1400 in all) with statistical errors less than 0.2%.



X. Zhan et al., PLB 705, pg59 (2011)

Double polarization data from JLab.

Could the difference be due to probing with a μ^- instead of an e^-?



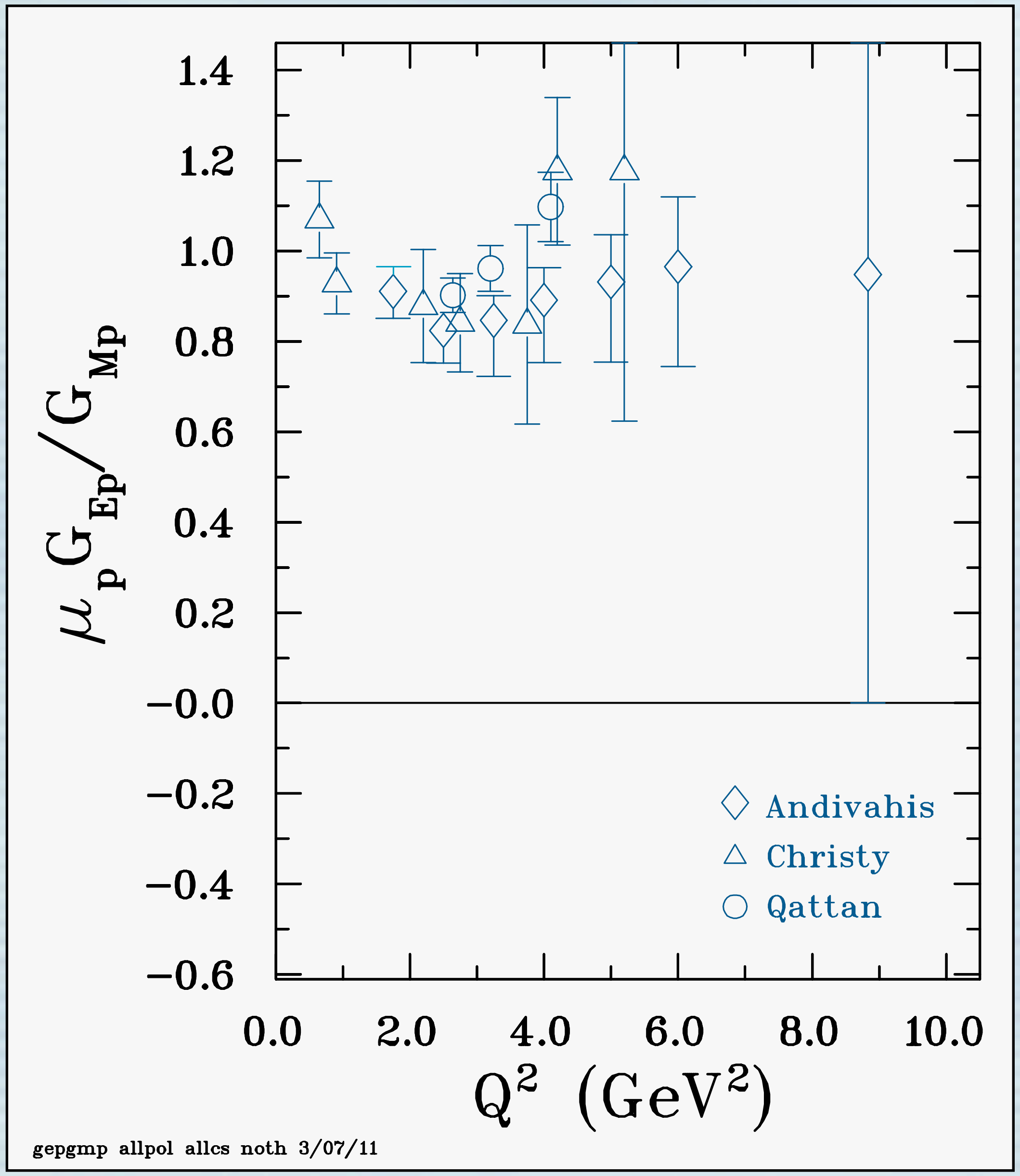
H.S. Margolis, Science 339, 405 (2013)

- If so, has some physics been left out? Are we seeing genuinely new physics?
- The MUSE experiment at PSI will measure r_p in muon-proton scattering.
- New more precise hydrogen lamb-shift spectroscopy results expected relatively soon.

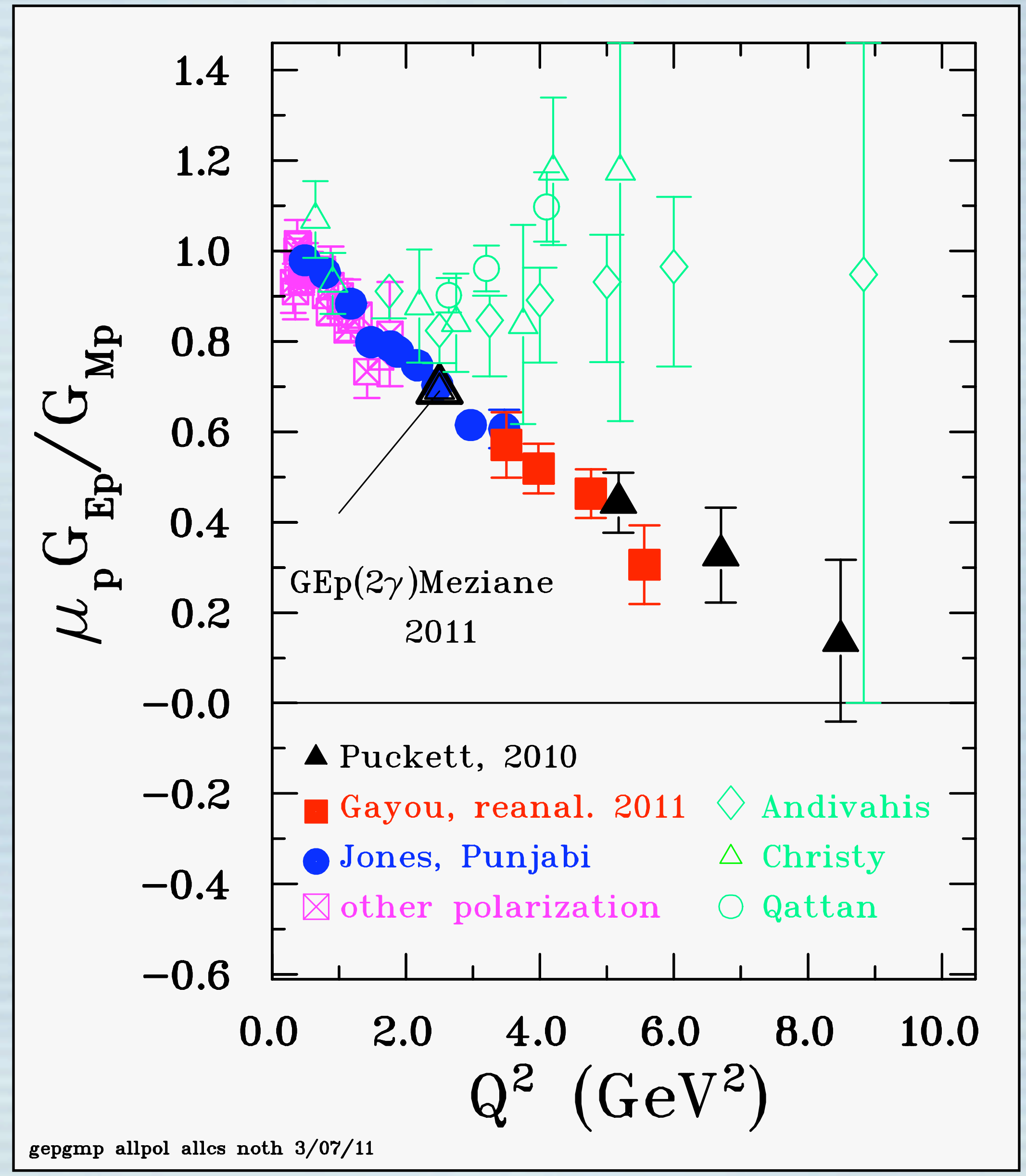
G_E^p/G_M^p at high Q^2

It was famously discovered at JLab that G_E^p/G_M^p decreases nearly linearly with Q^2

(when measured using double-polarization techniques)



Selected data showing G_E^p/G_M^p extracted using Rosenbluth separations.

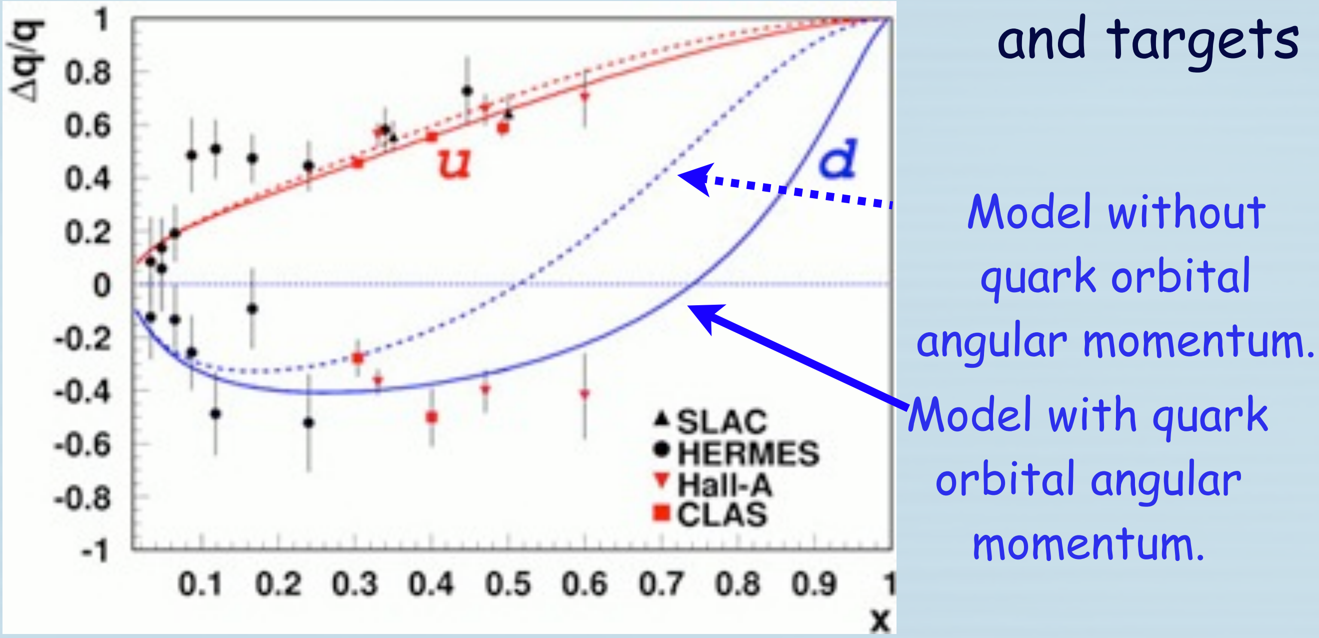


Data from both Rosenbluth separations and the double-polarization technique.

Most interpretations invoked the importance of quark orbital angular momentum (quark OAM)

Evidence for quark OAM soon began showing up in other experiments

Deep-inelastic scattering with polarized beam and targets



Flavor-separated spin contributions from up and down quarks

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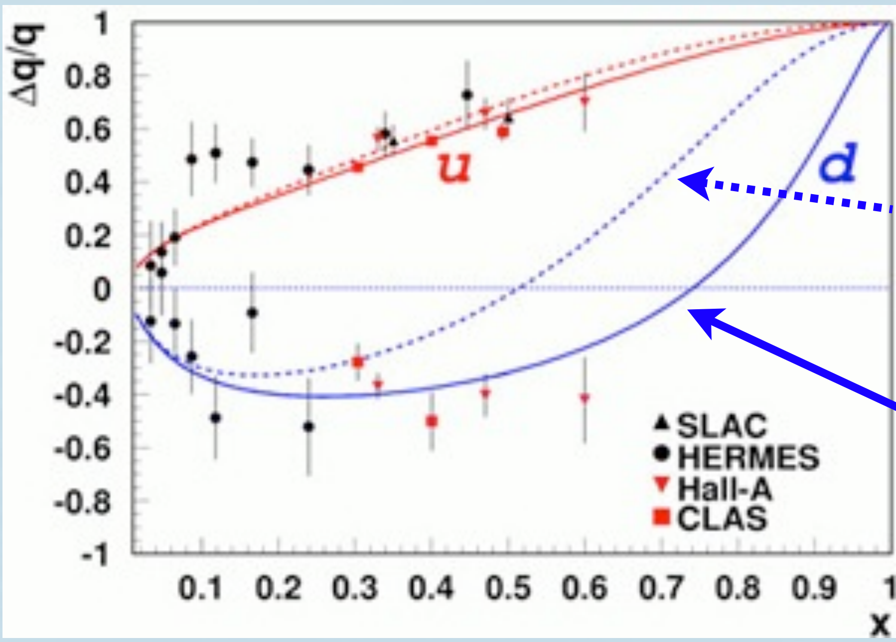
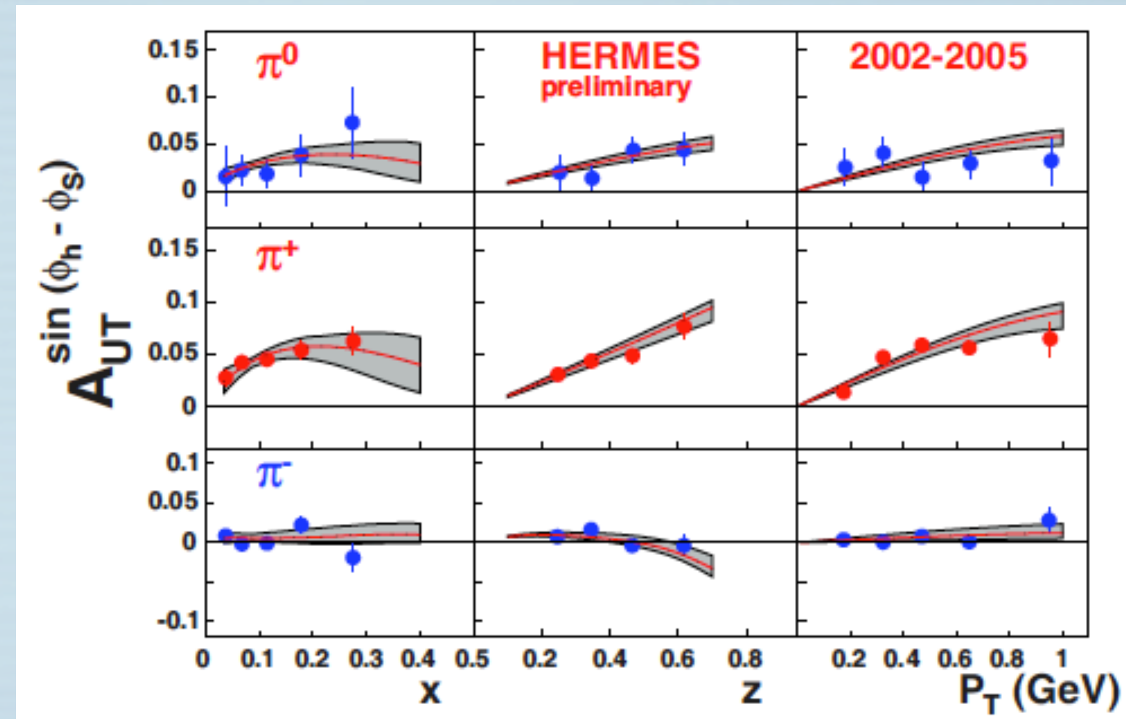


Model without quark orbital angular momentum.

Model with quark orbital angular momentum.

Flavor-separated spin contributions from up and down quarks

Non-zero Sivers effect in semi-inclusive DIS



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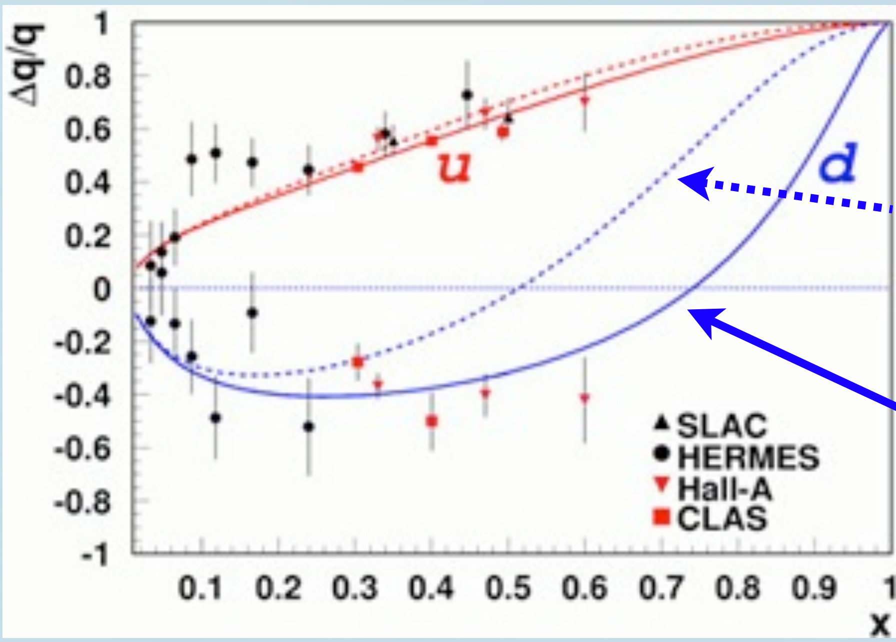

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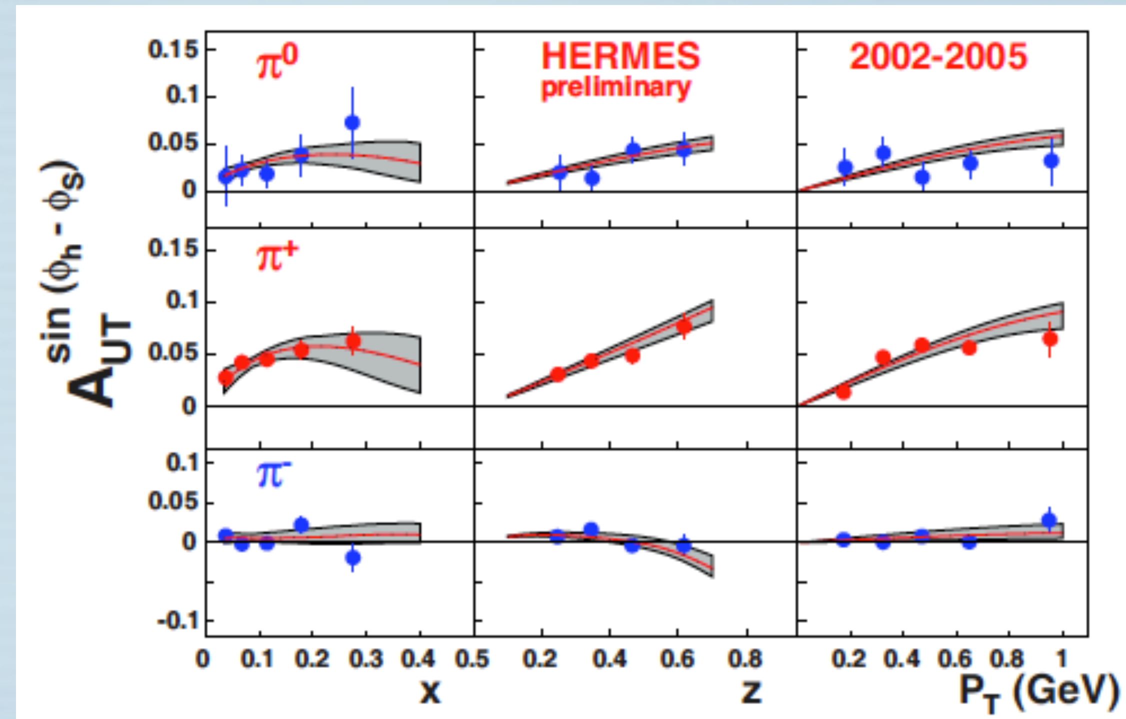
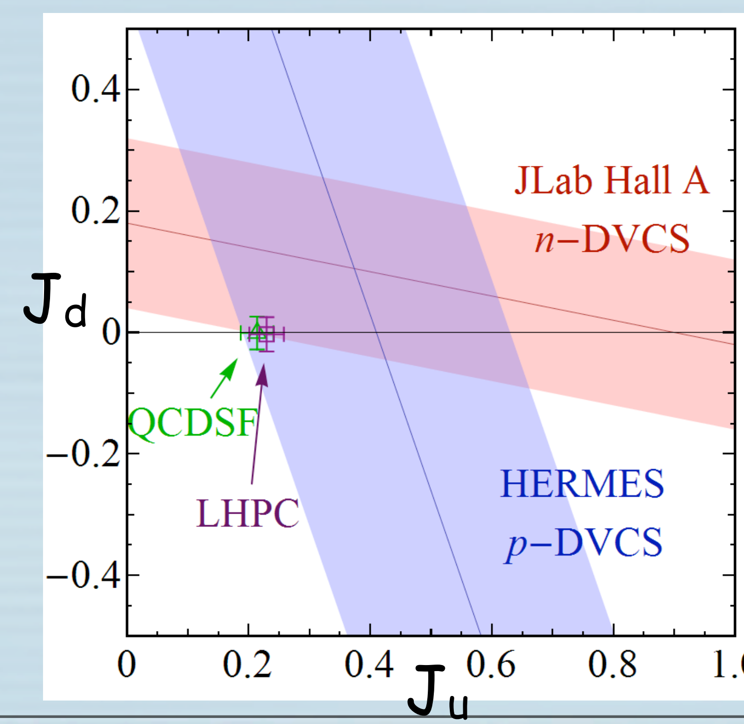
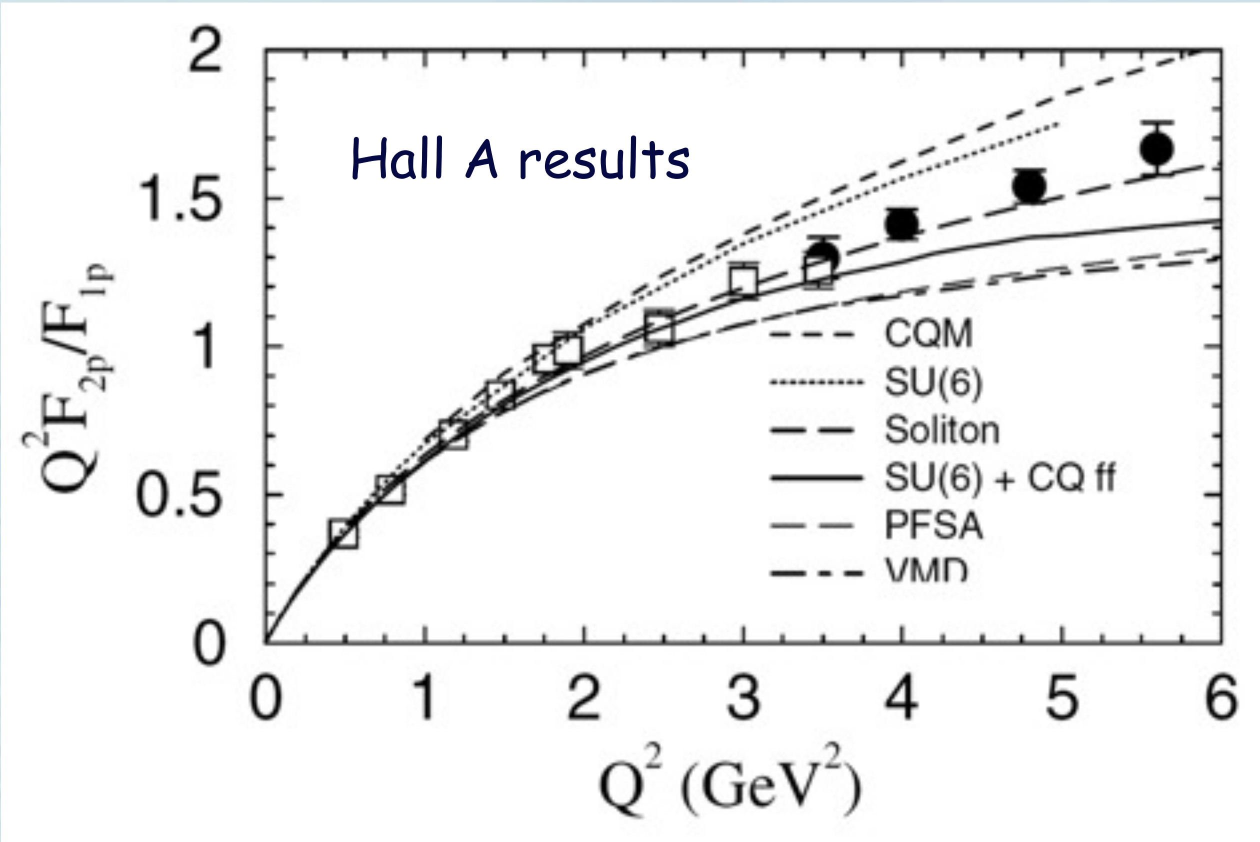


Data from deeply virtual Compton scattering, used to constrain GPD models and hence to evaluate the Ji Sum rule



One approach to understanding the Q^2 evolution of G_E^p/G_M^p relies on pQCD

Naive expectations from pQCD counting rules suggest $Q^2F_{2p}/F_{1p} \rightarrow$ constant.



As can be seen at left, the JLab data on Q^2F_{2p}/F_{1p} do not scale with the naive expectations.

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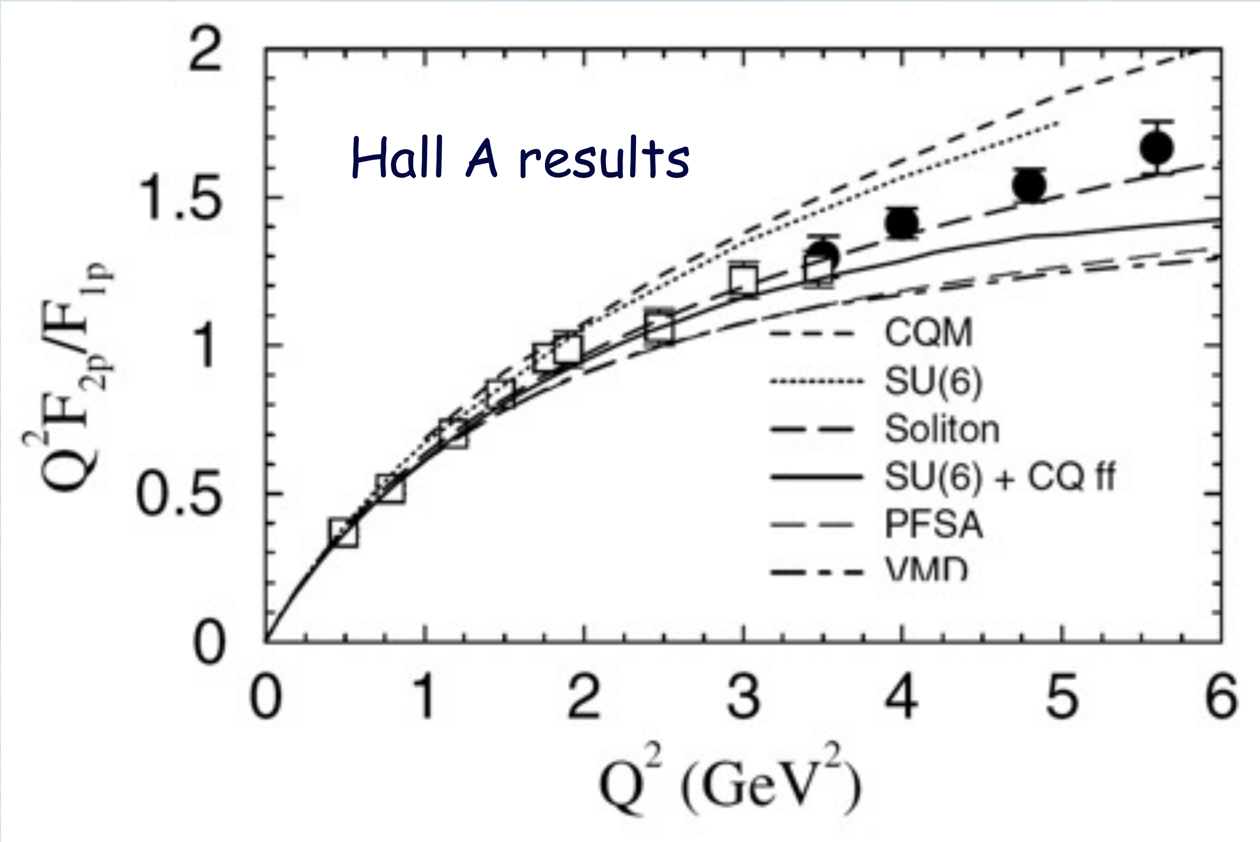
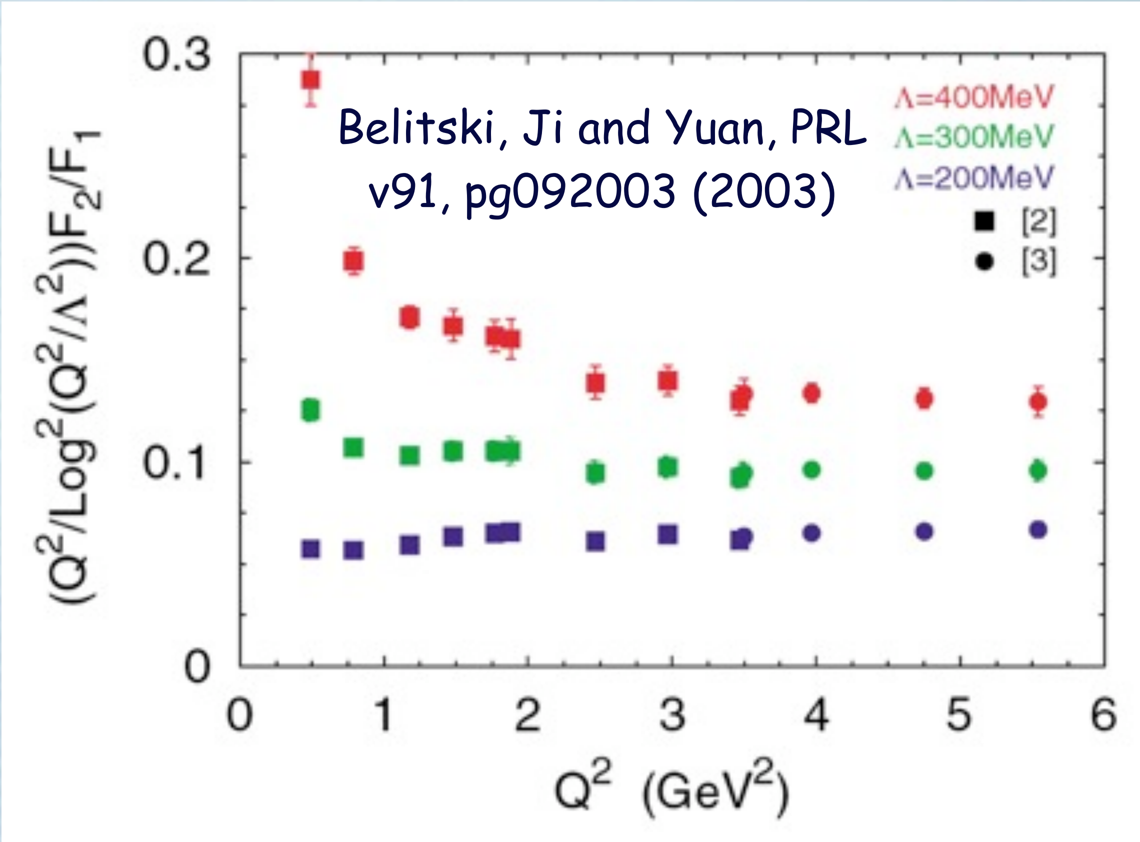


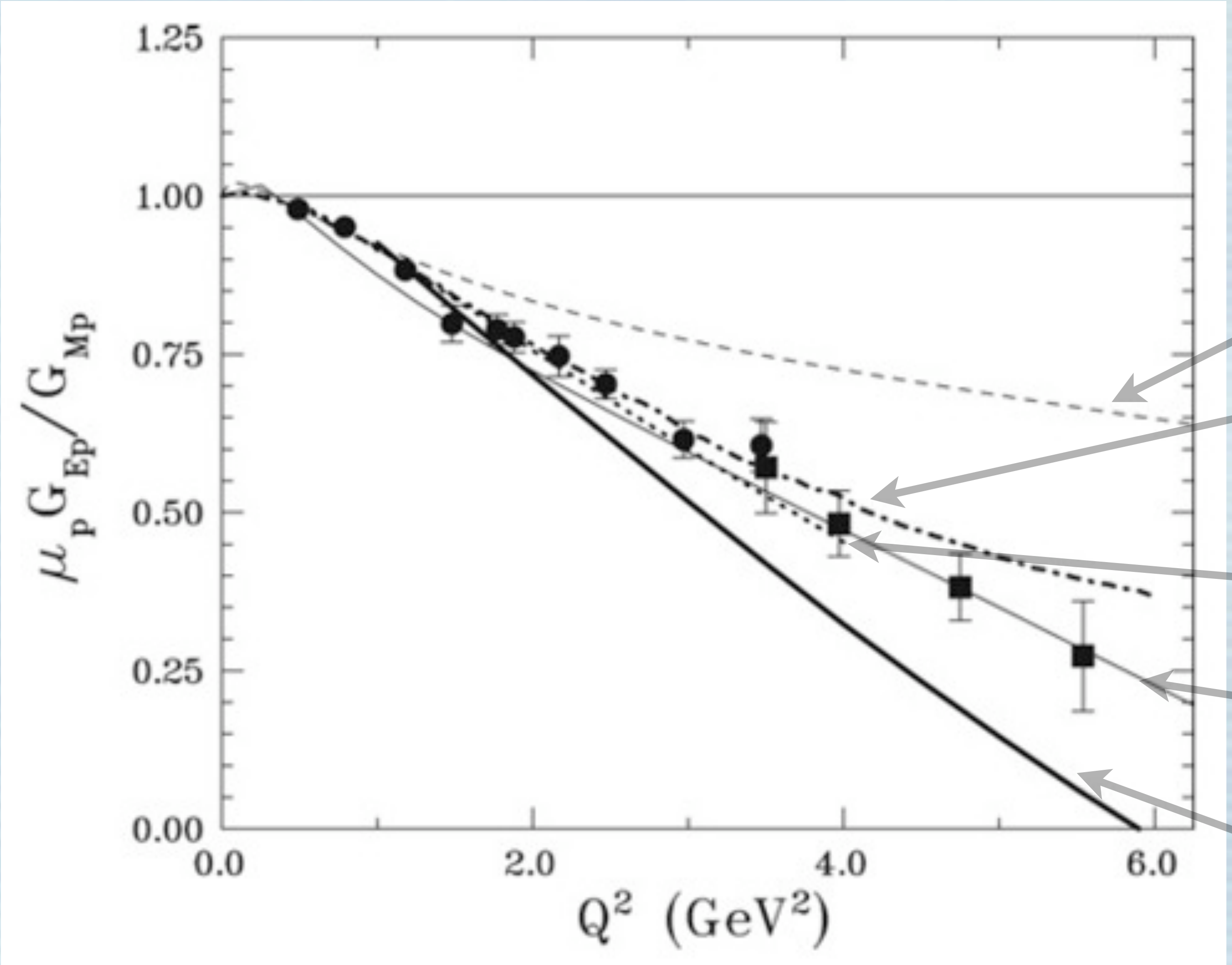


With logarithmic corrections, scaling appears to be restored. But is this just precocious scaling?

Either way, the logarithmic corrections result from including in the light-cone quark wave function components with L≠0, implying the importance of quark orbital angular momentum.

Relativistic constituent quark models all generally predict that G_E^p/G_M^p decreases Q^2

From Perdrisdat, Punjabi and Venderhaeghen, Progress in Part. and Nucl. Phys. v59, 694 (2007).



Boffi et al. (2002) (dashed line)

Cardarelli and coworkers (1995,2000) (dot-dash line)

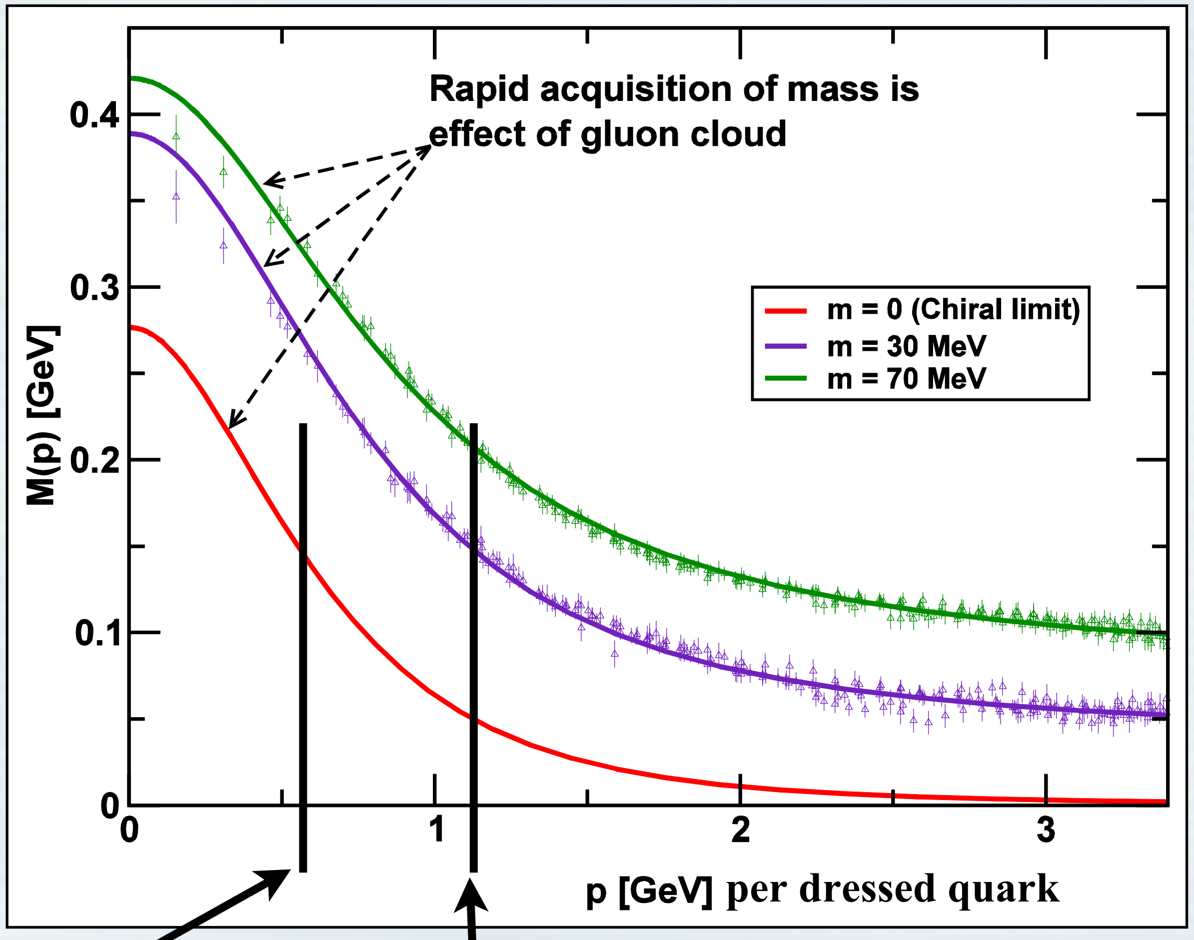
Chung and Coester (1991) (dotted line)

Gross and Agbakpe (2006) (thin solid line)

Miller and Frank (2002) (thick solid line)

This is related to the fact that these models, by imposing Poincaré invariance, lead to substantial violation of hadron helicity conservation, i.e., they include quark orbital angular momentum.

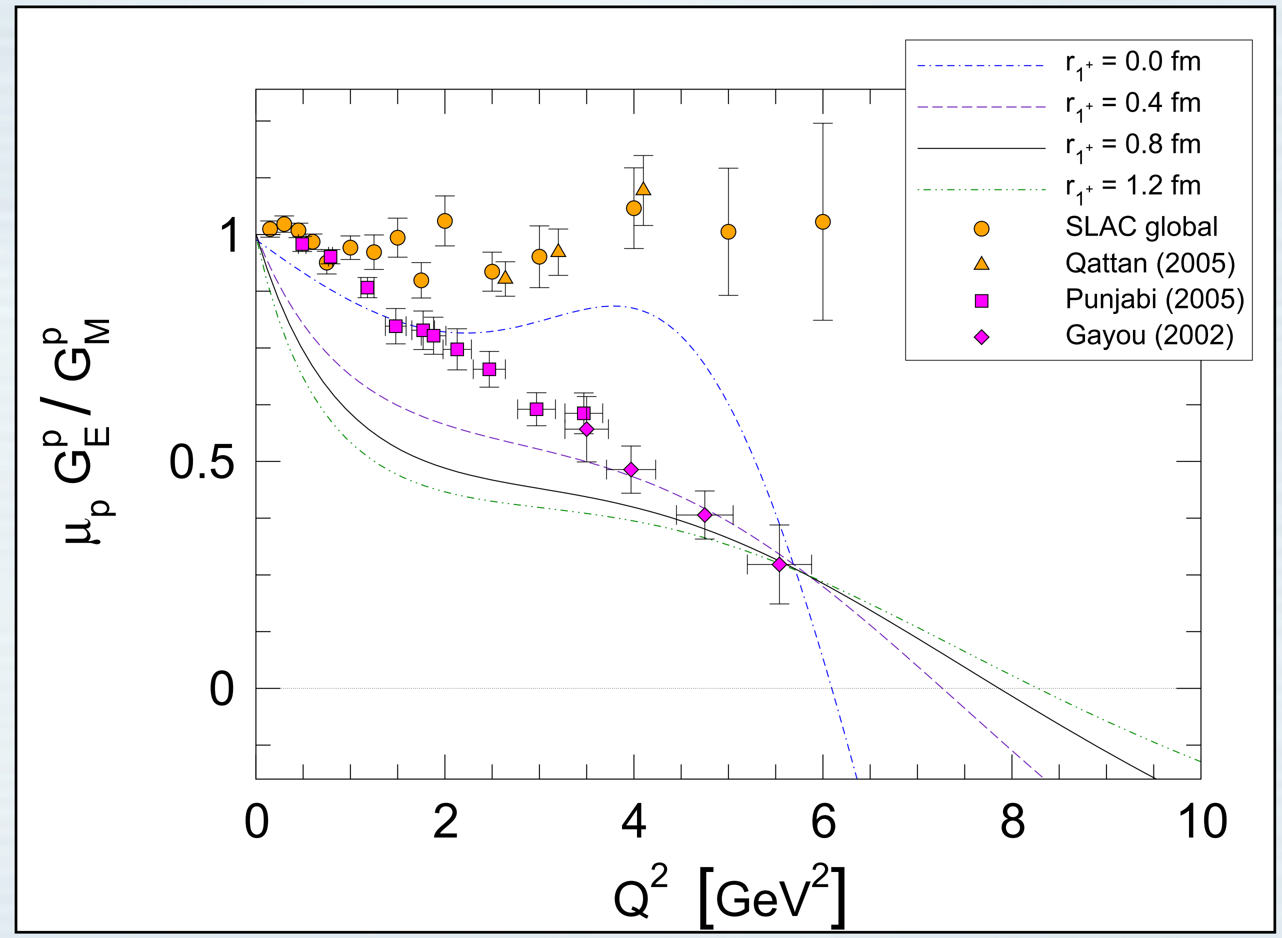
A DSE/Faddeev calculation from Argonne also predicts that G_E^p/G_M^p decreases with Q^2



Q^2 = 3.4 GeV^2 Q^2 = 10 GeV^2

Above is the dynamically generated mass function that appears in the dressed quark propagator:

$$S(p) = \frac{Z(p^2, \zeta^2)}{i\gamma \cdot p + M(p^2)}$$



The three constituent quarks then serve as the degrees of freedom for a calculation involving a Faddeev equation in which diquark-coupling is explicitly included.

Many things are interesting here, dynamically generated constituent quark mass, importance of quark orbital angular momentum, and the incorporation of diquark degrees of freedom.

Perhaps some light is being shed on one piece of the proton spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_g + L_q$$

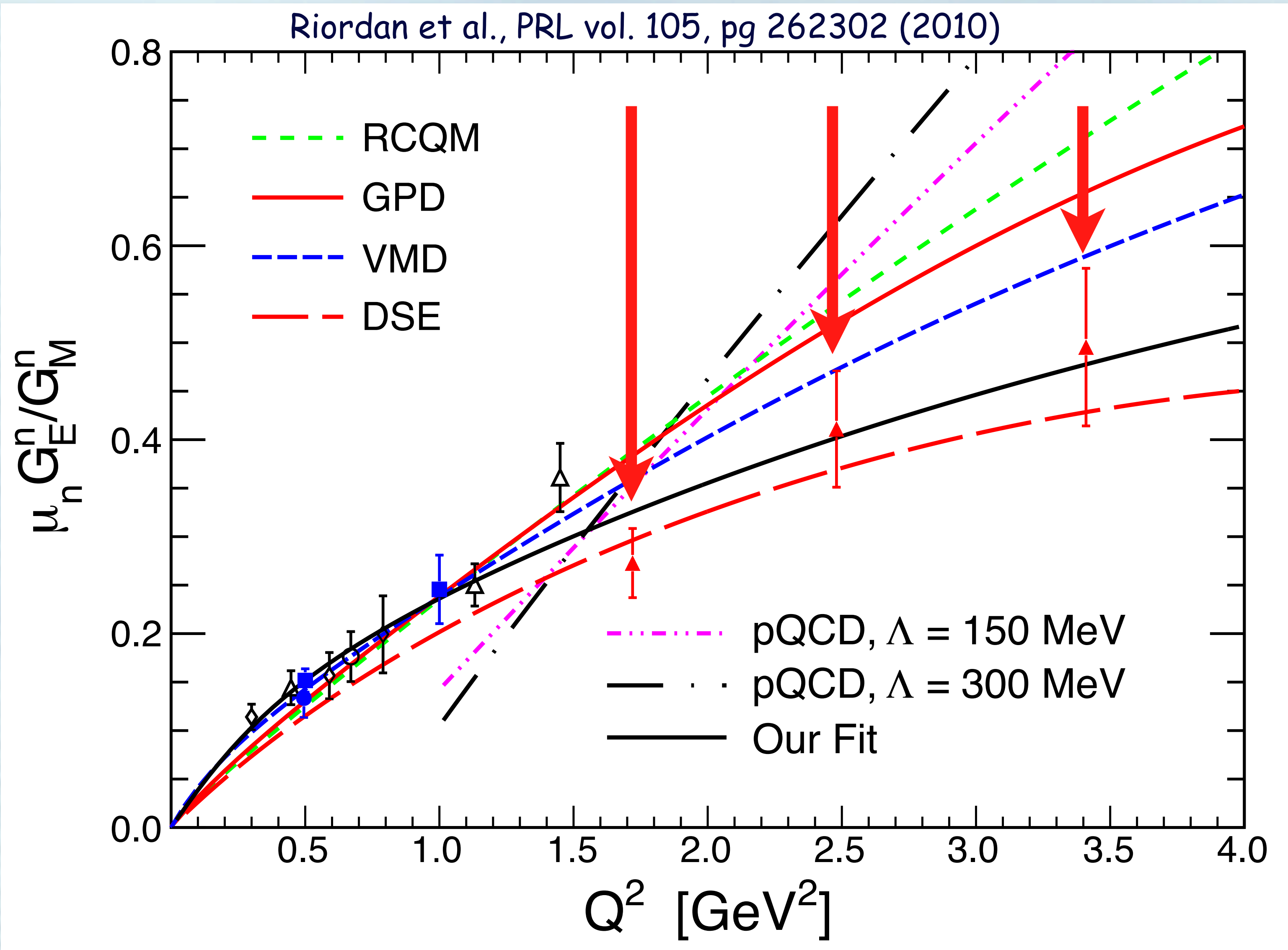
Quantifying L_q, however, will need to await more measurements, perhaps an evaluation of the Ji sum rule

It is ironic to note that when E93-027 (that discovered the effect) was proposed, it was only rated B+ by the PAC

Experiment	Spokesperson	Institutions	Title	Beam days	Rating
E-93-027	C. Perdrisat* V. Punjabi	W&M NSU	Electric Form Factor of the Proton by Recoil Polarization	16	B+

Flavor-decomposed form factors at high Q^2

High Q^2 Data for the neutron became available from JLab E02-013: polarized beam, polarized ^3He target

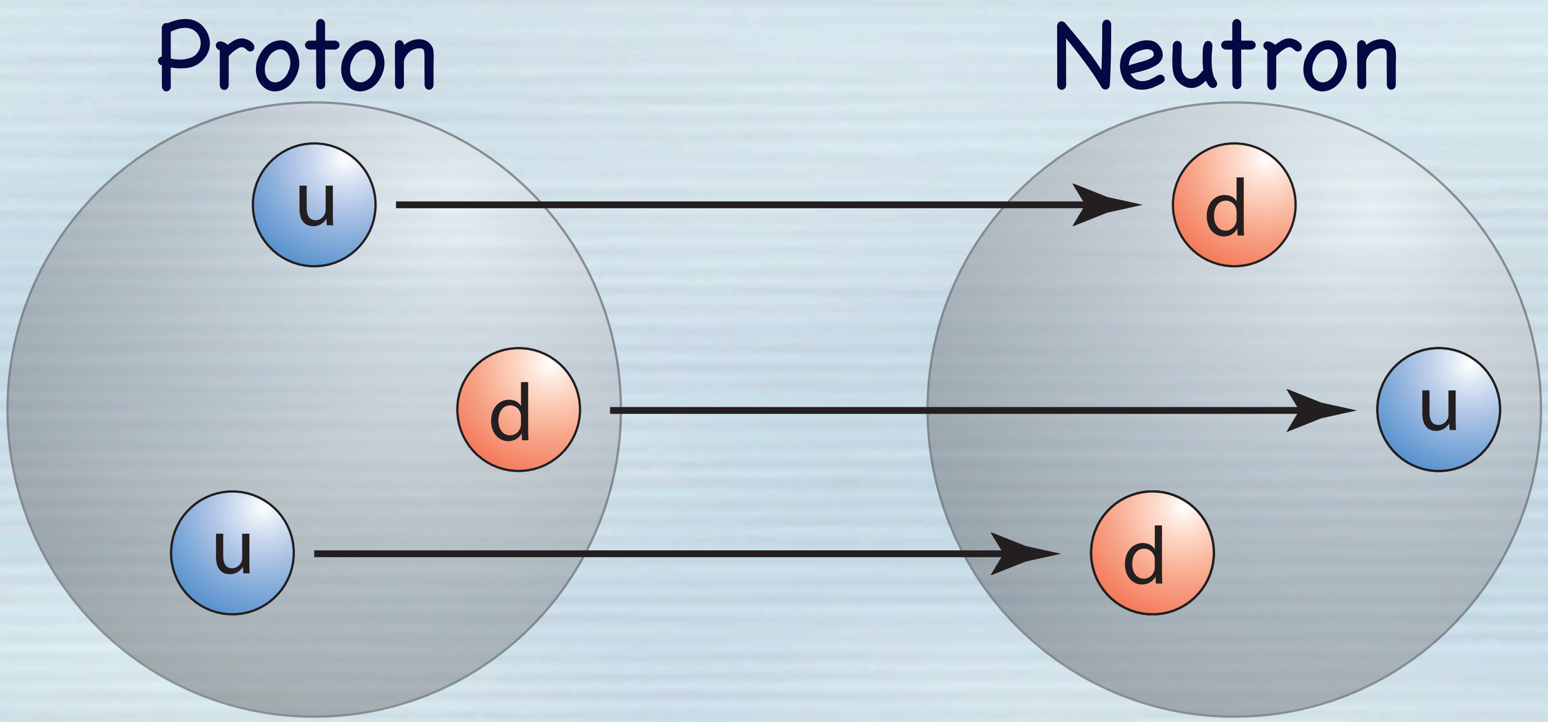


- More than doubled the Q^2 range over which G_E^n was known.
- Provided the first G_E^n results for the Q^2 range where the surprising proton results had been seen.
- The experiment relied critically on on high luminosity and the large solid angle provided by the BigBite spectrometer (first developed at NIKEF)

The BigBite G_E^n experiment provided the first test of theories developed to explain the surprising proton results, although clearly, higher Q^2 would be desirable

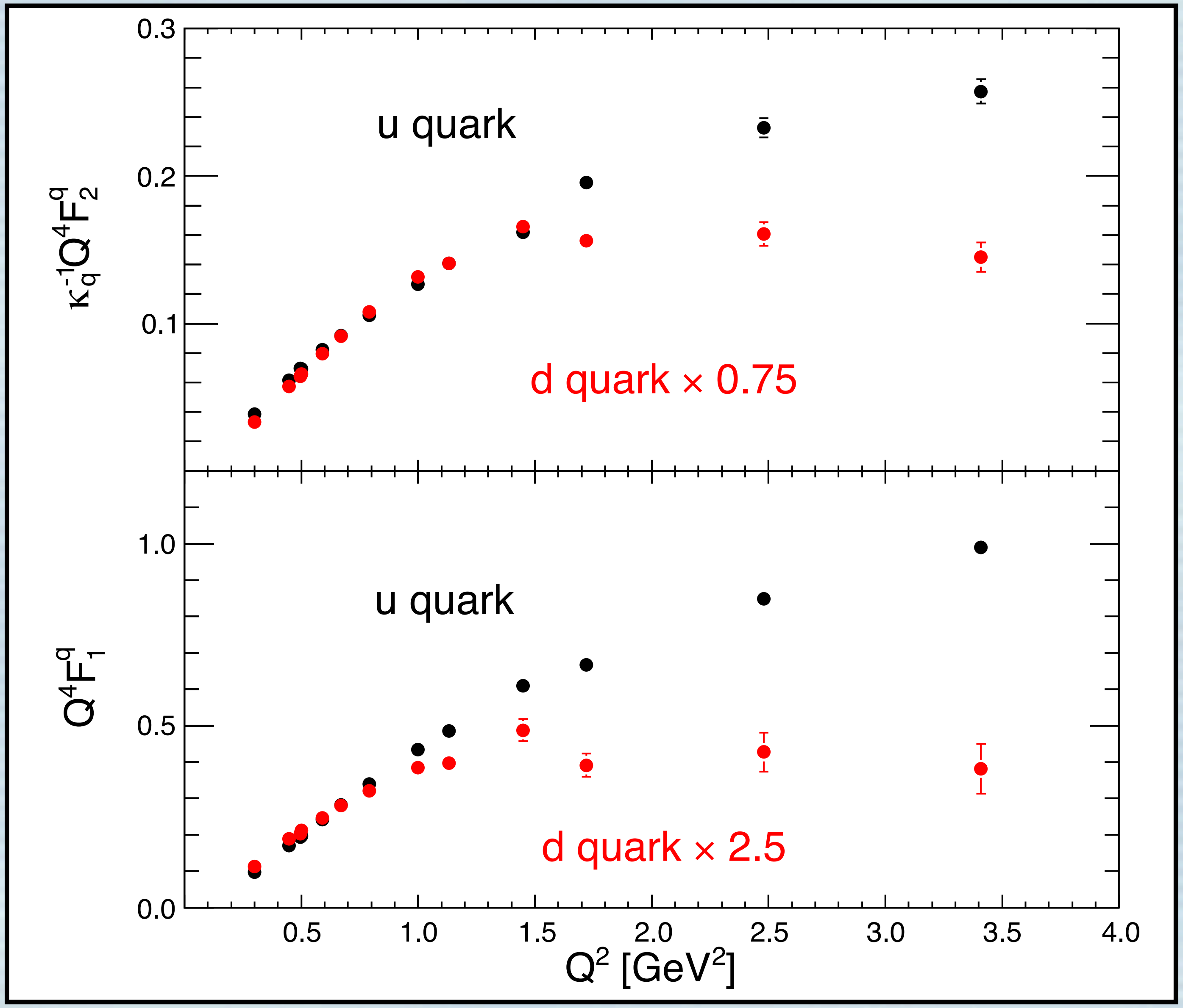
Seeing the quark flavors individually

With high Q^2 results for both G_E^p and G_E^n, and by assuming charge symmetry, we can extract the individual quark-flavor contributions to the elastic form factors.



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

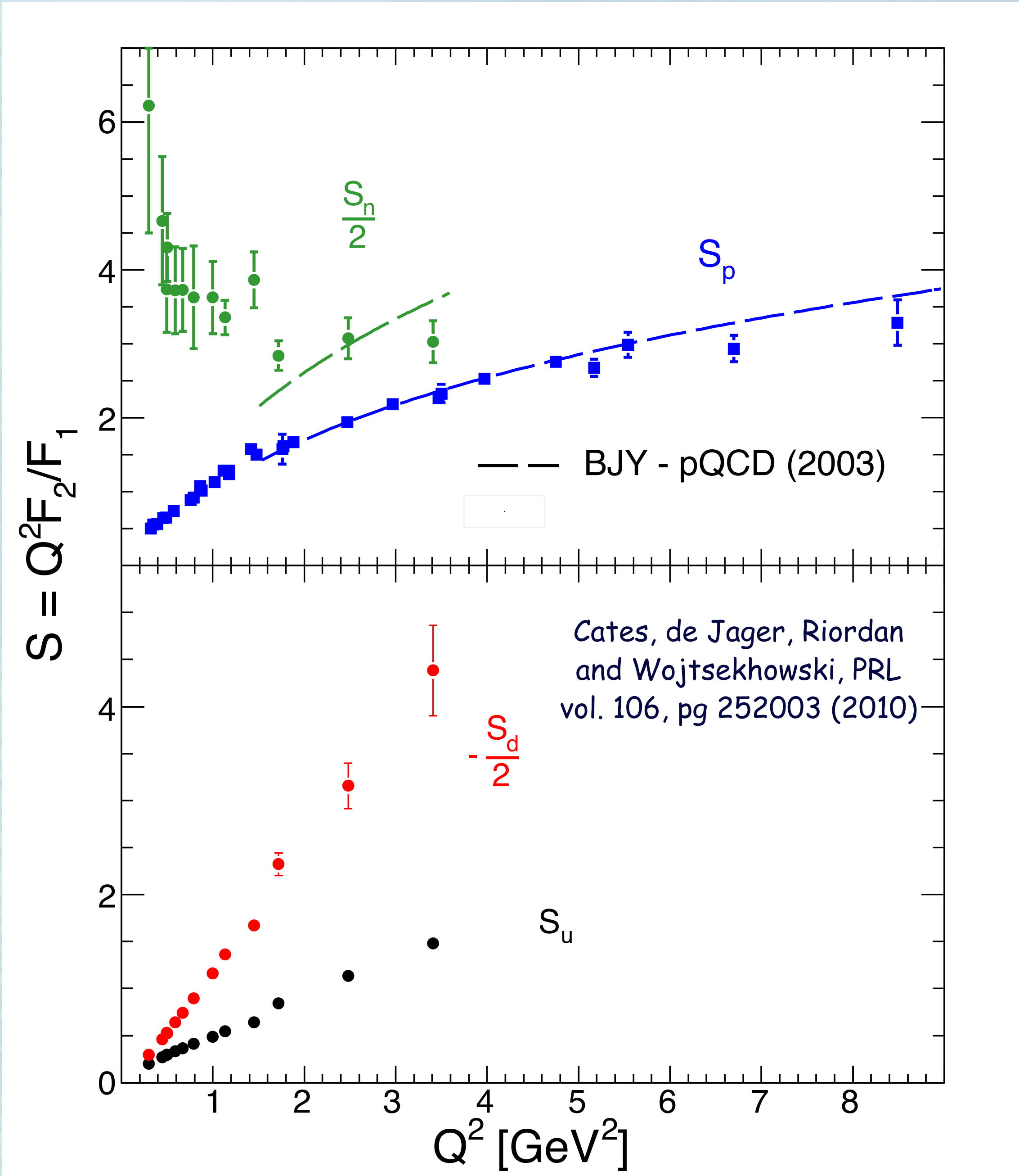
The extraction reveals very different scaling for the up and down quarks.



Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2010)

F_d seems to scale like $1/Q^4$ whereas
F_u seems to scale more like $1/Q^2$ (if at all).

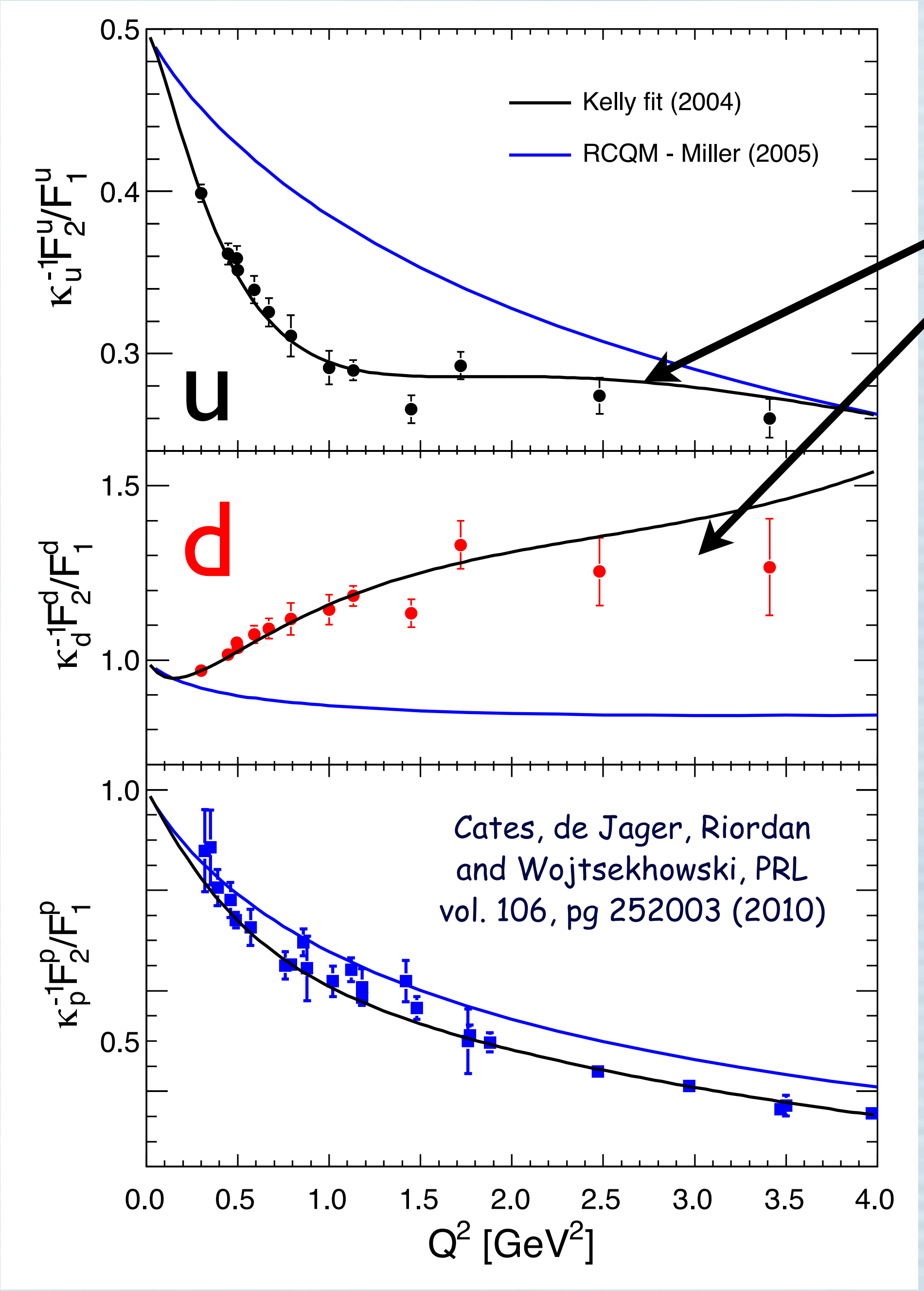
The extraction also shows that $Q^2F_2^q/F_1^q$ for individual flavors has very different behavior than the proton



At left: Q^2F_2/F_1 for the proton and neutron.

At left: $Q^2F_2^q/F_1^q$ for the u and d-quarks contributions to the FFs. They appear to be straight lines!

The ratios F_2^u/F_1^u and F_2^d/F_1^d become roughly constant for Q^2 > ~1 GeV^2



The ratios F_2^q/F_1^q become constant for Q^2 > ~1 GeV^2 !

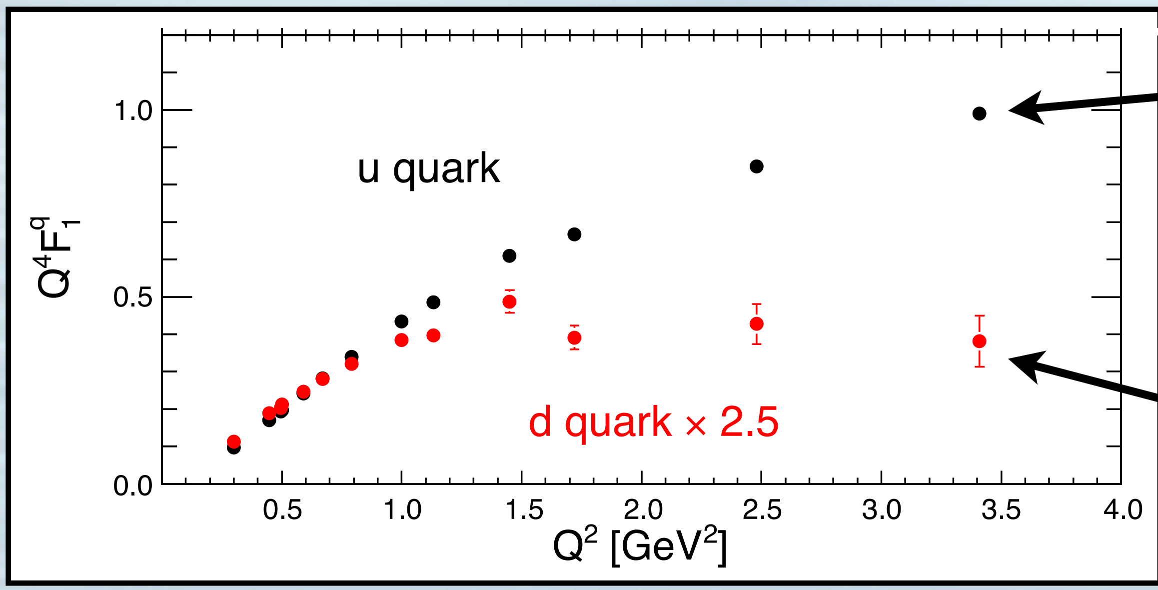
This disagrees with a generally accepted expectation that dates to Schwinger in the 1950's that:

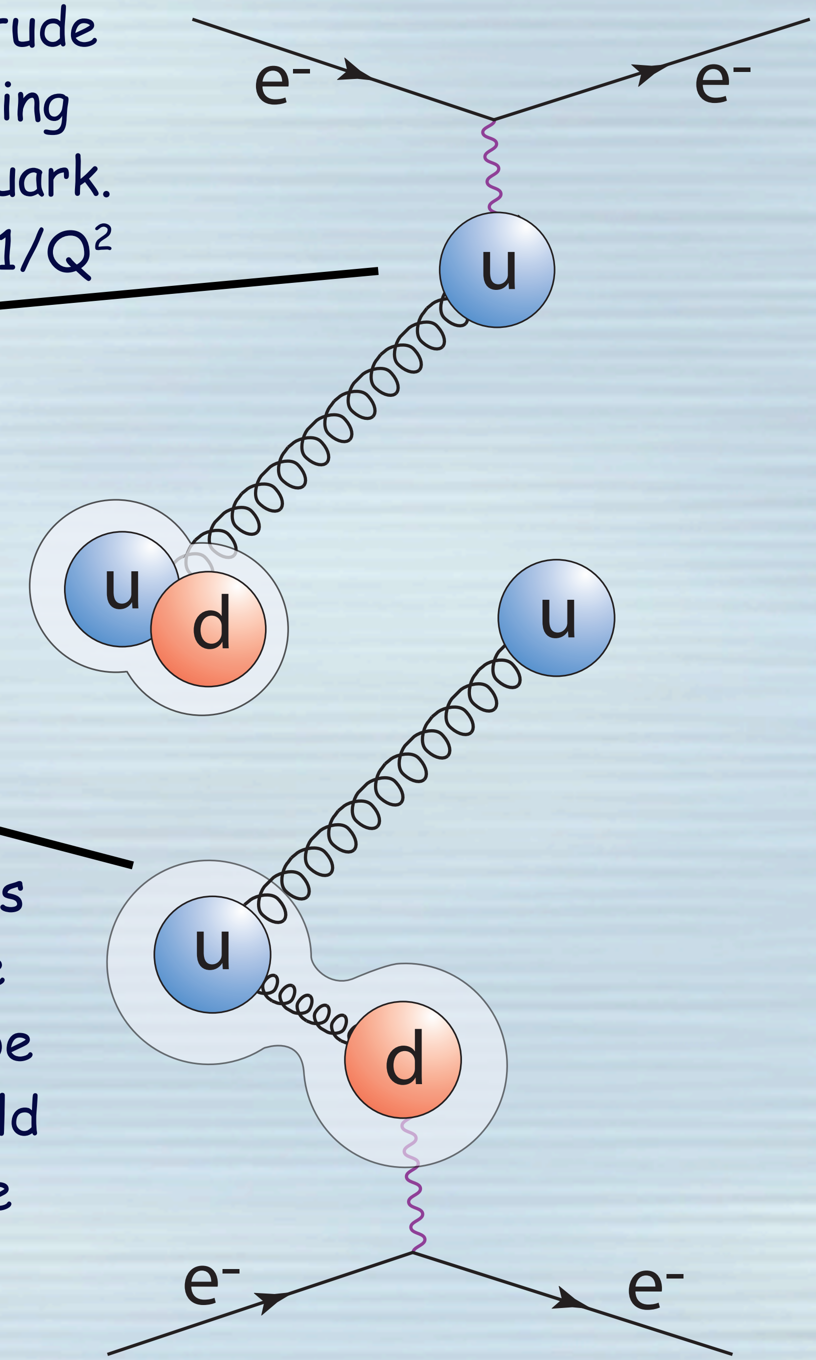
$$F_2/F_1 \propto 1/Q^2$$

Note that the corresponding ratio F_2^p/F_1^p shows no particular change in behavior for Q^2 > ~1 GeV^2

A naive scaling argument suggested by Jerry Miller invokes diquarks

u-quark scattering amplitude is dominated by scattering from the lone "outside" quark. Two constituents implies $1/Q^2$





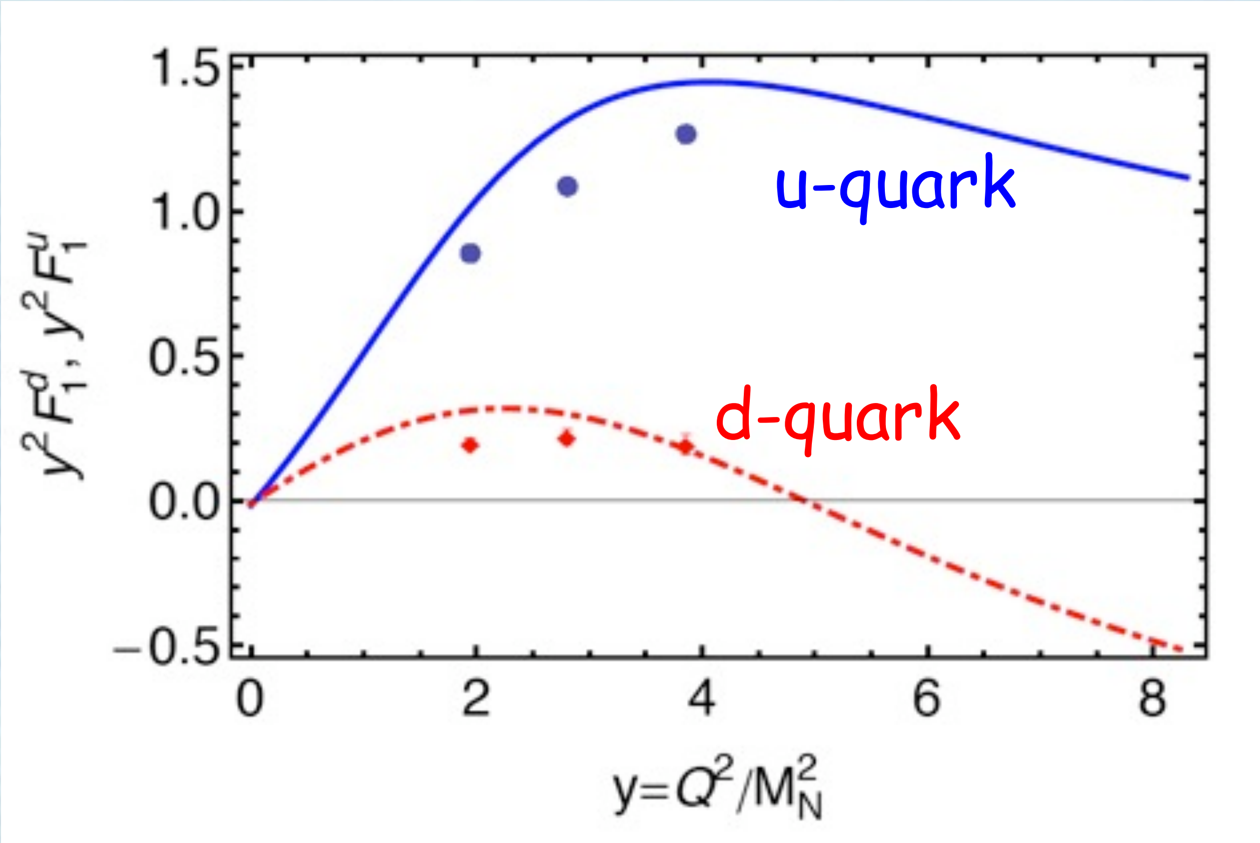
d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

While at present this idea is at the conceptual stage, it is an intriguingly simple interpretation for the very different behaviors, and dovetails nicely into the outstanding question of missing states in the N* spectrum.

DSE/Fadeev model from Argonne

Cloët, Roberts and Wilson, using the QCD DSE approach, have made:

" ... a prediction for the Q^2-dependence of u- and d-quark Dirac and Pauli form factors in the proton, which exposes the critical role played by diquark correlations within the nucleon."

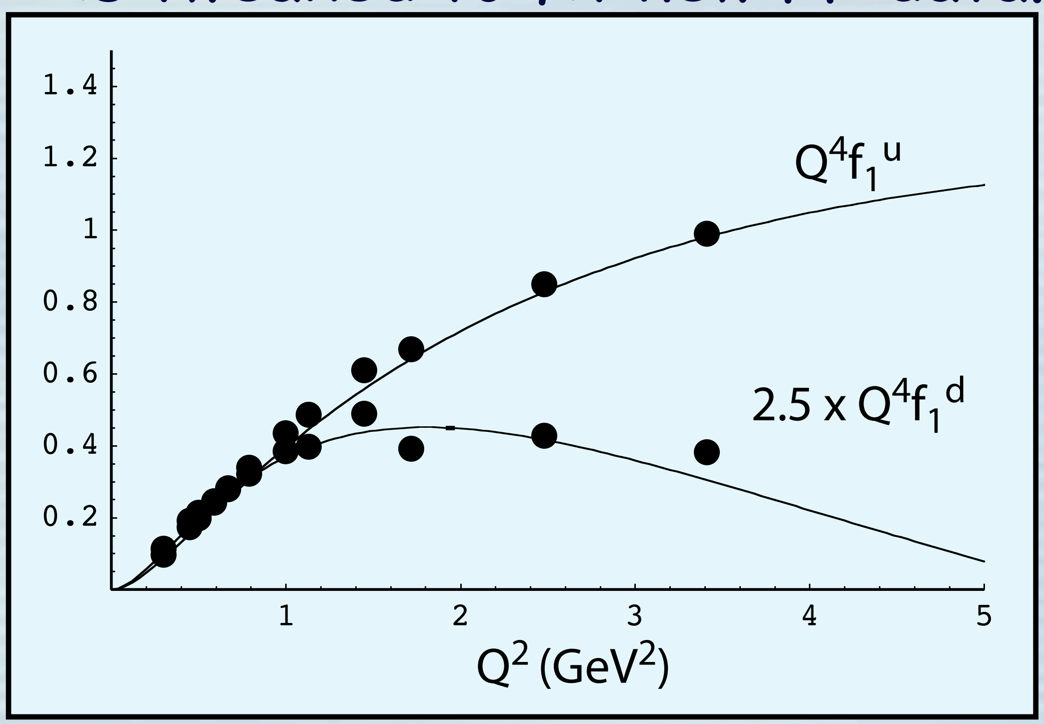


arXiv:1103.2432v1

Within their model, the different behaviors of the u- and d-quark FFs are a direct consequence of diquark degrees of freedom.

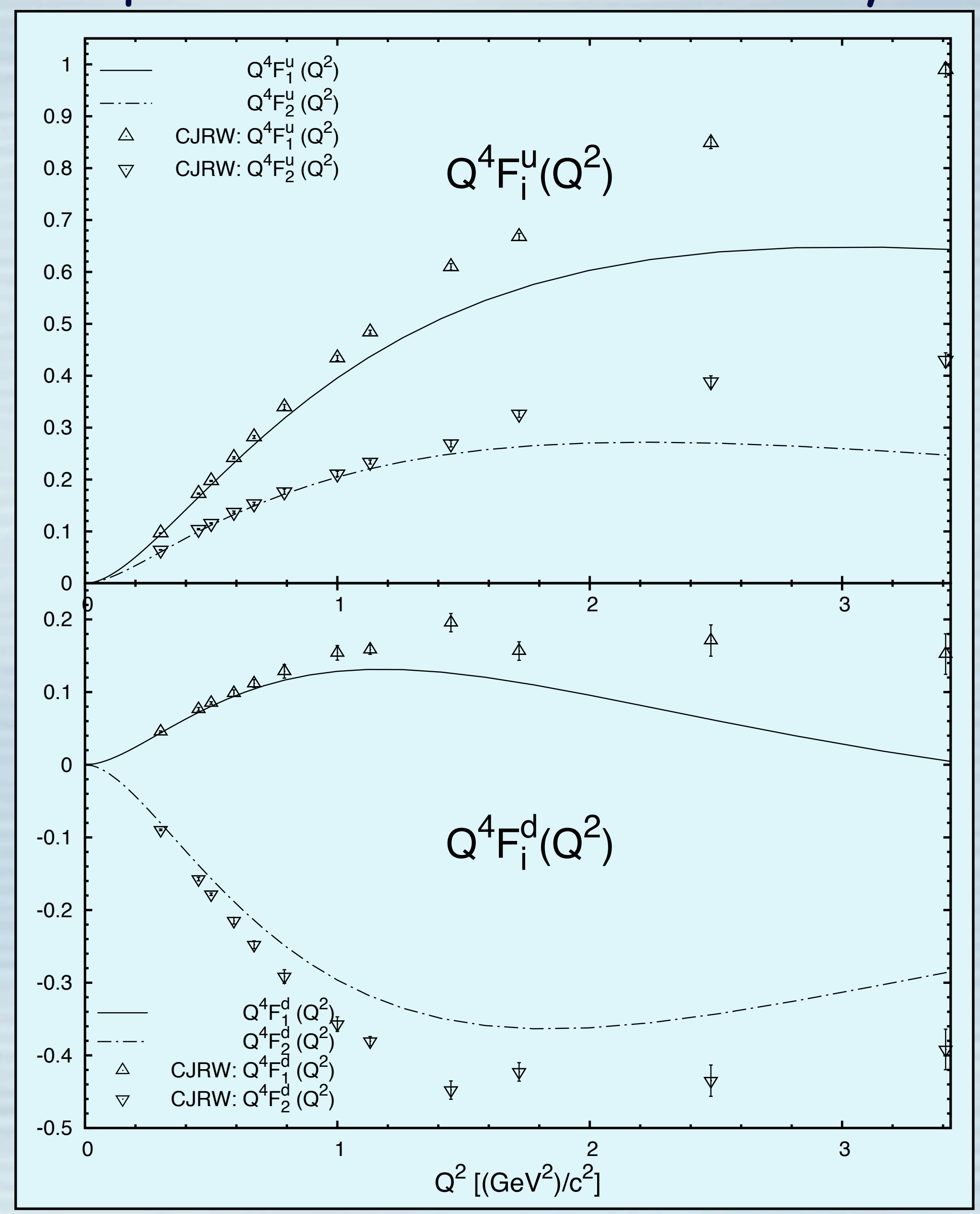
Relativistic Constituent Quark Models

Updated version of Jerry Miller's Light-Front Cloudy Bag Model, done in collaboration with Ian Cloët, that includes diquarks and is tweaked to fit new FF data.



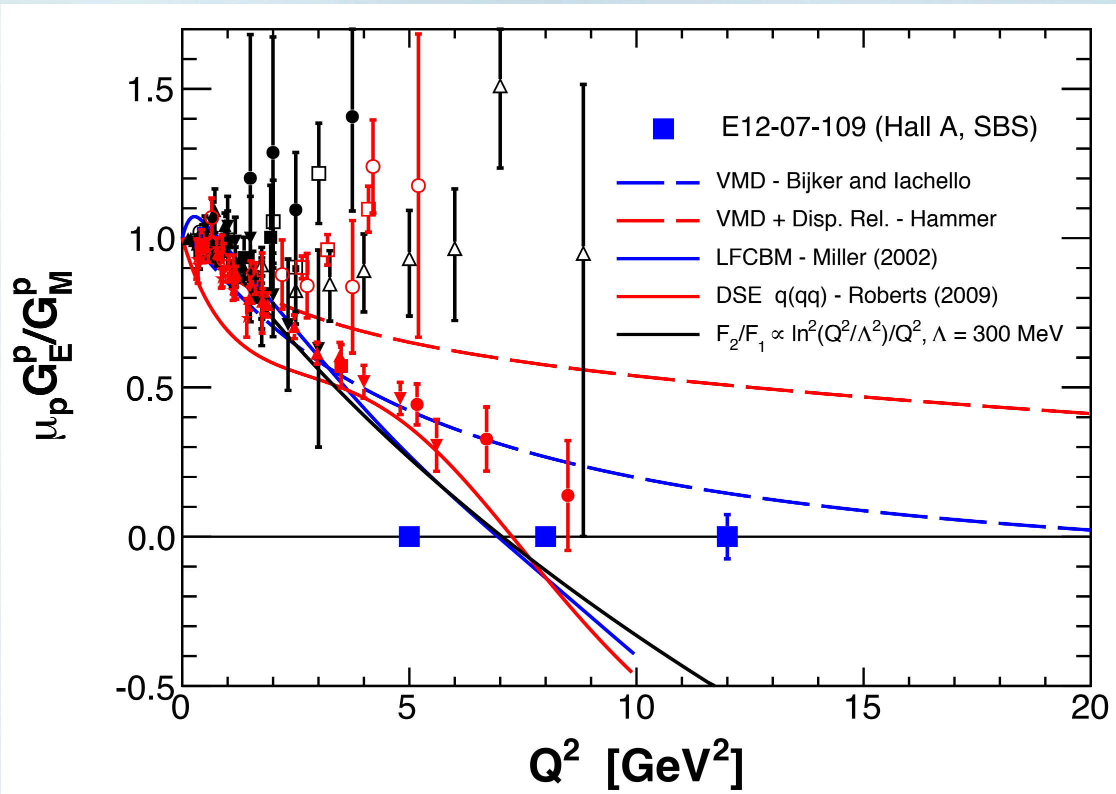
Using model from Phys. Rev. C 86, 015208 (2012)

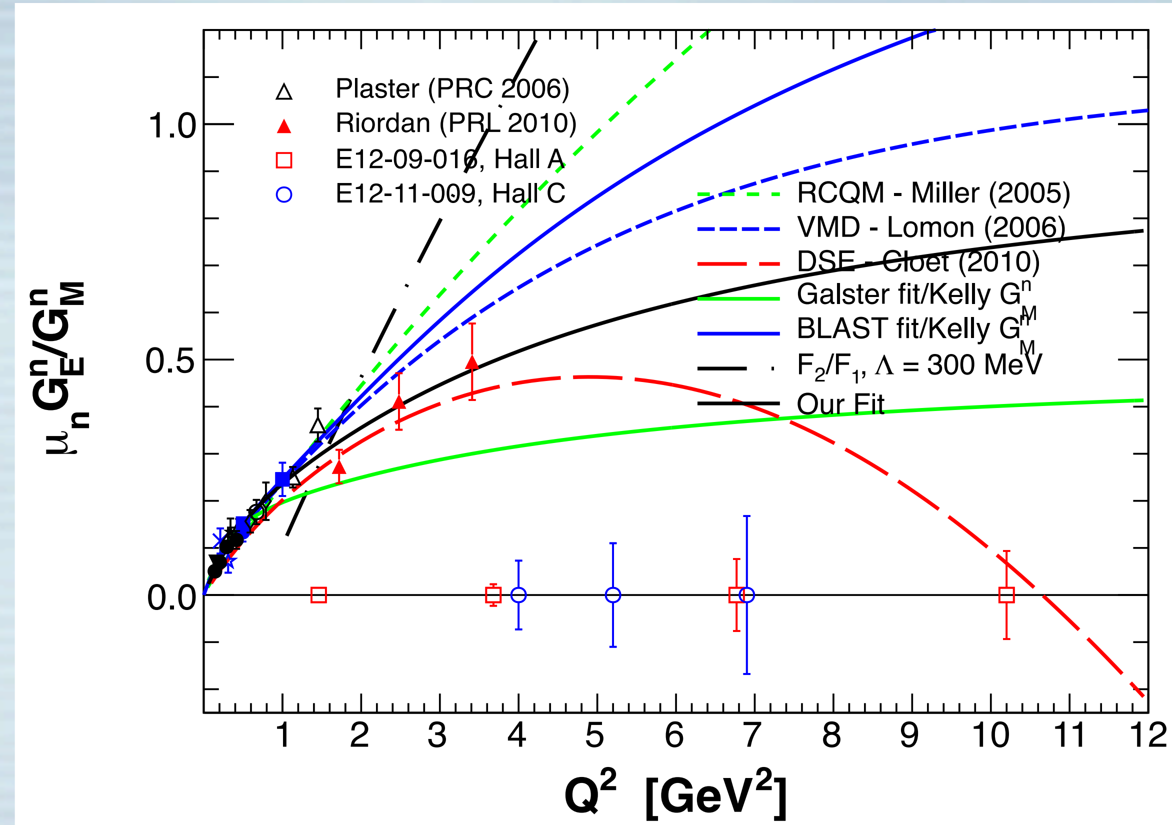
However, another RCQM with NO diquarks does not do too badly

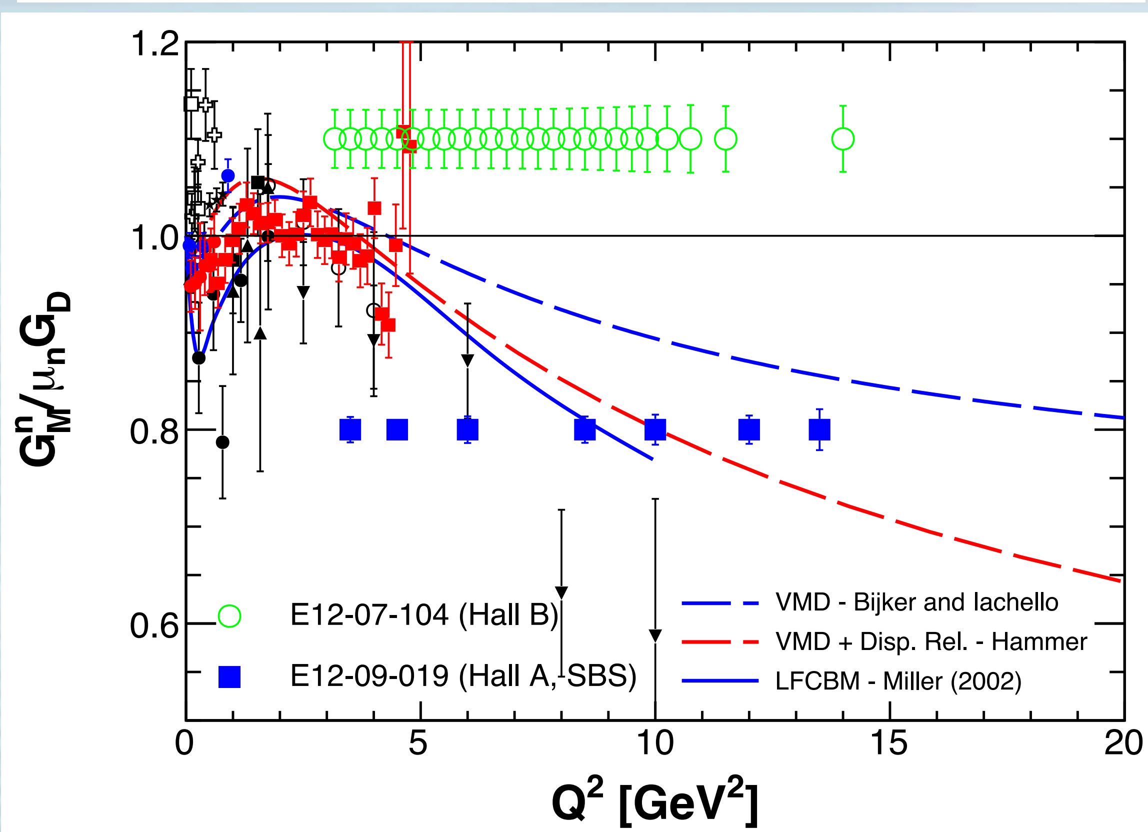


Rohrmoser, Choi and Plessas, arXiv:1110.3665

Super Bigbite will make it possible to measure G_E^p/G_M^p, G_E^n/G_M^n and G_M^n/G_M^p in a new Q^2 regime

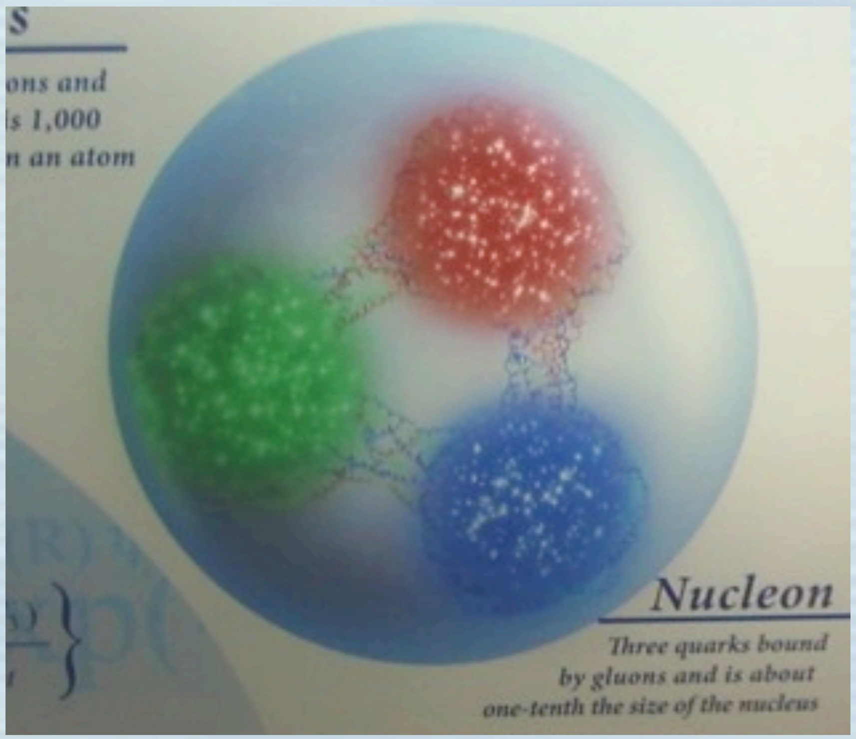




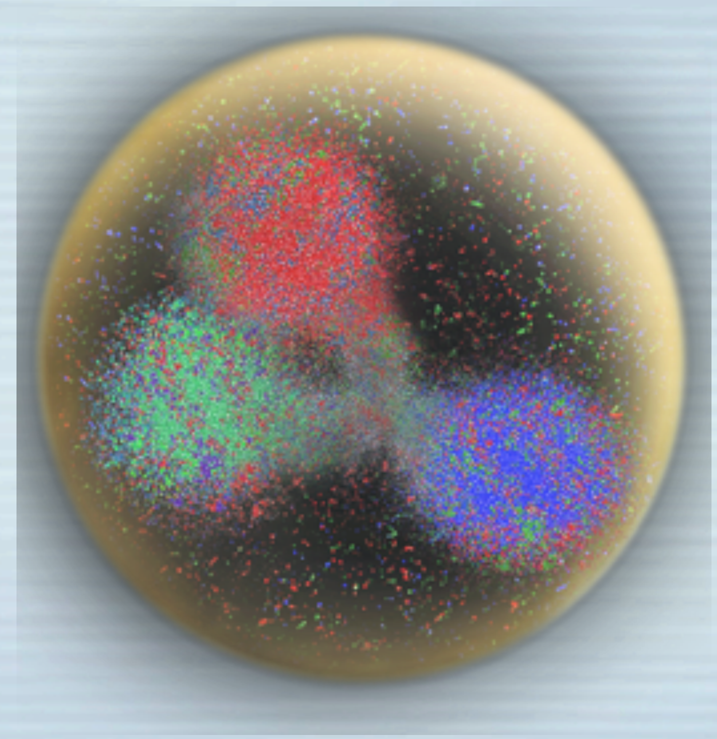


The three Super Bigbite experiments will meet the requirements to achieve the best physics by providing precise measurements at high Q^2.

Could flavor-decomposed form factors change our basic notions of nucleon struture?



A cartoon of the nucleon
from the lobby of JLab



From the DOE Pulse Newsletter:
A not-very-scientifically guided depiction of a nucleon with a diquark-like structure

Maybe .... but it is certainly useful to study the nucleon's constituent parts as much as possible

Summary

- Every major experimental step forward in the study of the elastic nucleon form factors has brought with it new discoveries.
- Our current knowledge of the FFs has contributed to a far more sophisticated view of nucleon structure than has ever previously existed.
- The behavior of the flavor-decomposed form factors is surprising, and may be pointing to new elements of nucleon structure.
- There is a rich future in further study:
  - The MUSE experiment will measure $< r_E^2 >^{(1/2)}$ using muons, and hydrogen Lamb shift measurements are also expected to improve.
  - At high-Q2, the JLab Super Bigbite Spectrometer (SBS) program will greatly improve the high Q^2 data
  - Time-like form factor studies at both BIS and PANDA