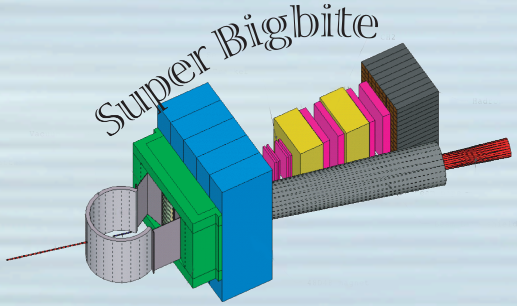
Nucleon Form Factors at high momentum transfer

- The rich physics encoded in the elastic nucleon form factors.
- Some of what we have already learned
- A brief look at the future

Gordon D. Cates

June 23, 2020



University of Virginia

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Elastic nucleon form factors: critical to our picture of the nucleon

It was noted in the 2007 NSAC 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."

To a great extent, this is still true.

The elastic nucleon form factors impact multiple aspects of hadronic physics

For example, they provide:

- The closest thing we have to a "snapshot" of the nucleon.
- Currently one of the strongest constraints on GPDs.
- Insight into high-Q^2 behavior expected from QCD.
- When considering flavor-separated form factors, the separate behavior of up and down quarks.

Elastic form factors, particularly at high Q^2, have fundamentally changed our QUALITATIVE picture of the nucleon.

Definitions: the electromagnetic elastic nucleon FFs

The hadronic current:

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

The Sachs FFs:

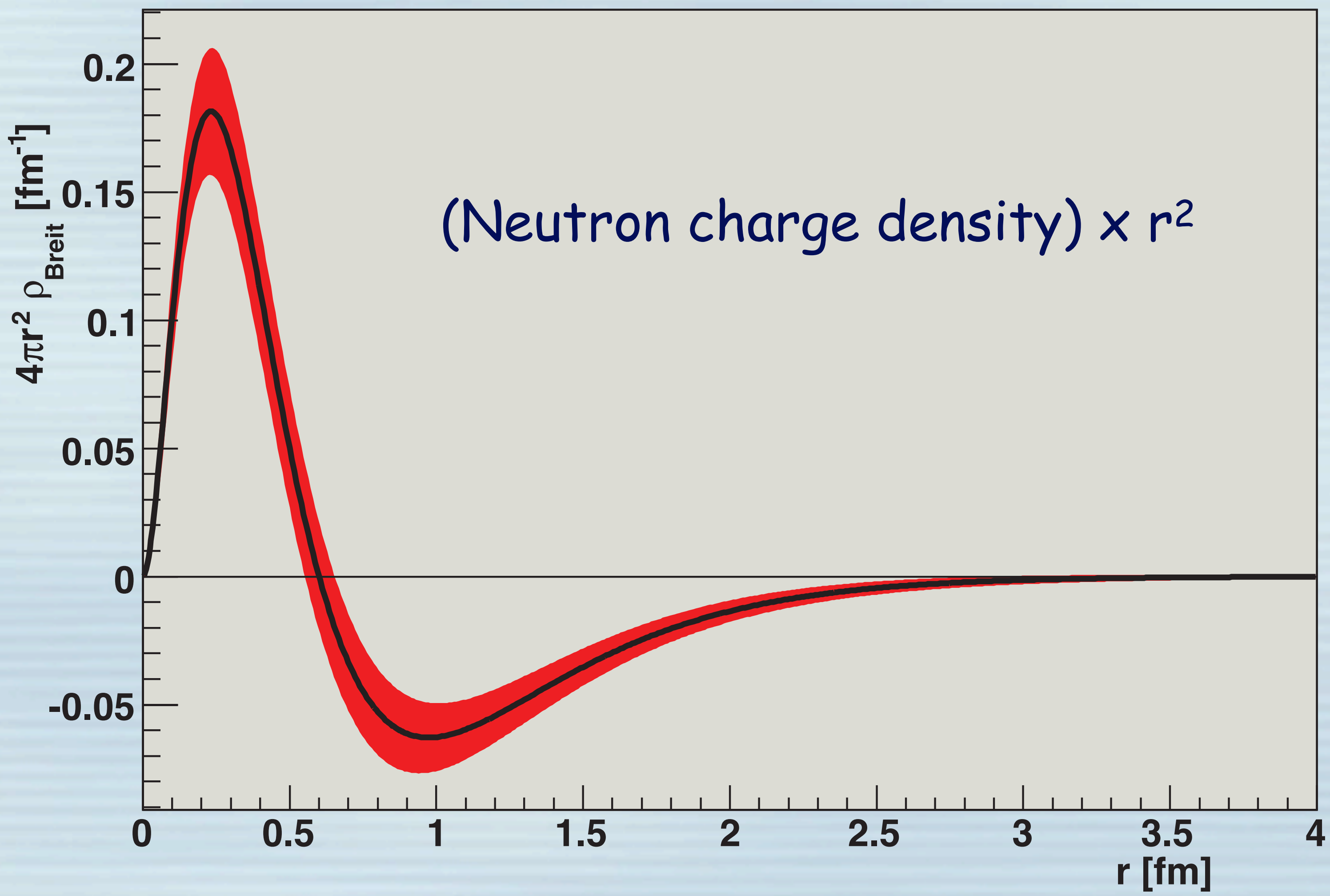
$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2$$

where

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

A non-relativistic "snapshot" of the neutron

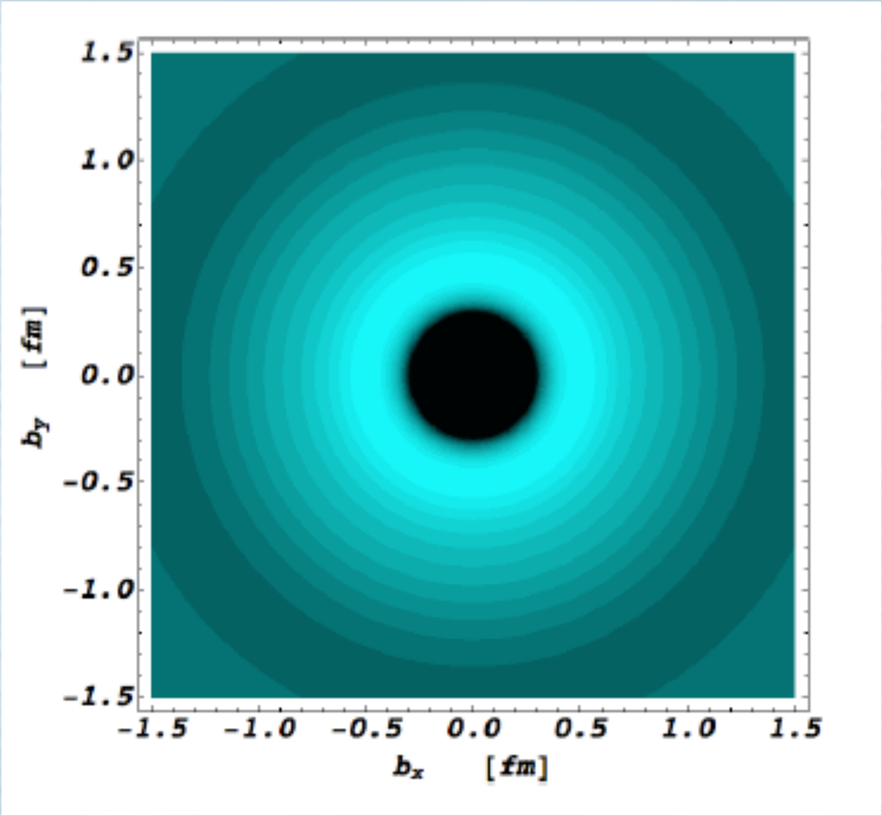
essentially taking the Fourier transform of G_E^n



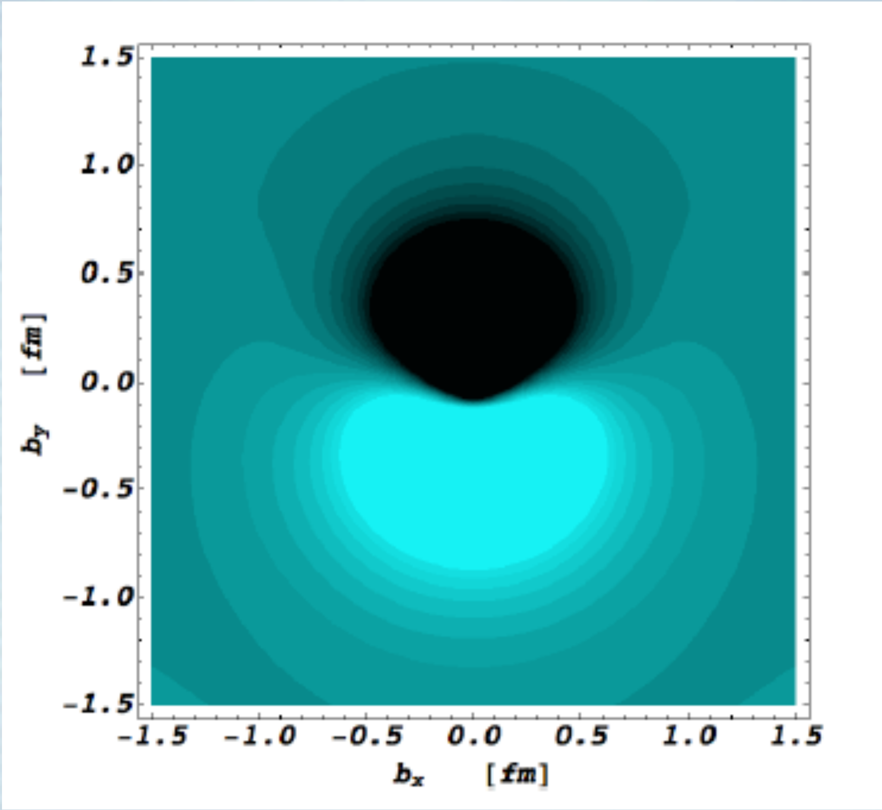
From the 2007 Long Range Plan

From the text of the Long Range Plan: "These results clearly identify the neutron's positively charged interior and negatively charged halo…" [from the pion cloud].

A relativistic "snapshot" of the neutron
(light-front density distribution)



Longitudinally polarized neutron



Transversely polarized neutron

Carlson and Vanderhaeghen, PRL v.100, pg.032004 (2008)

- Here we are seeing what we can think of as a charge density when viewed from a light front moving toward the neutron.
- Notice that the transversely polarized neutron appears to have an electric dipole moment - this is due to the magnetic dipole moment when viewed from a boosted reference frame

The FFs provide important constraints for GPDs

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

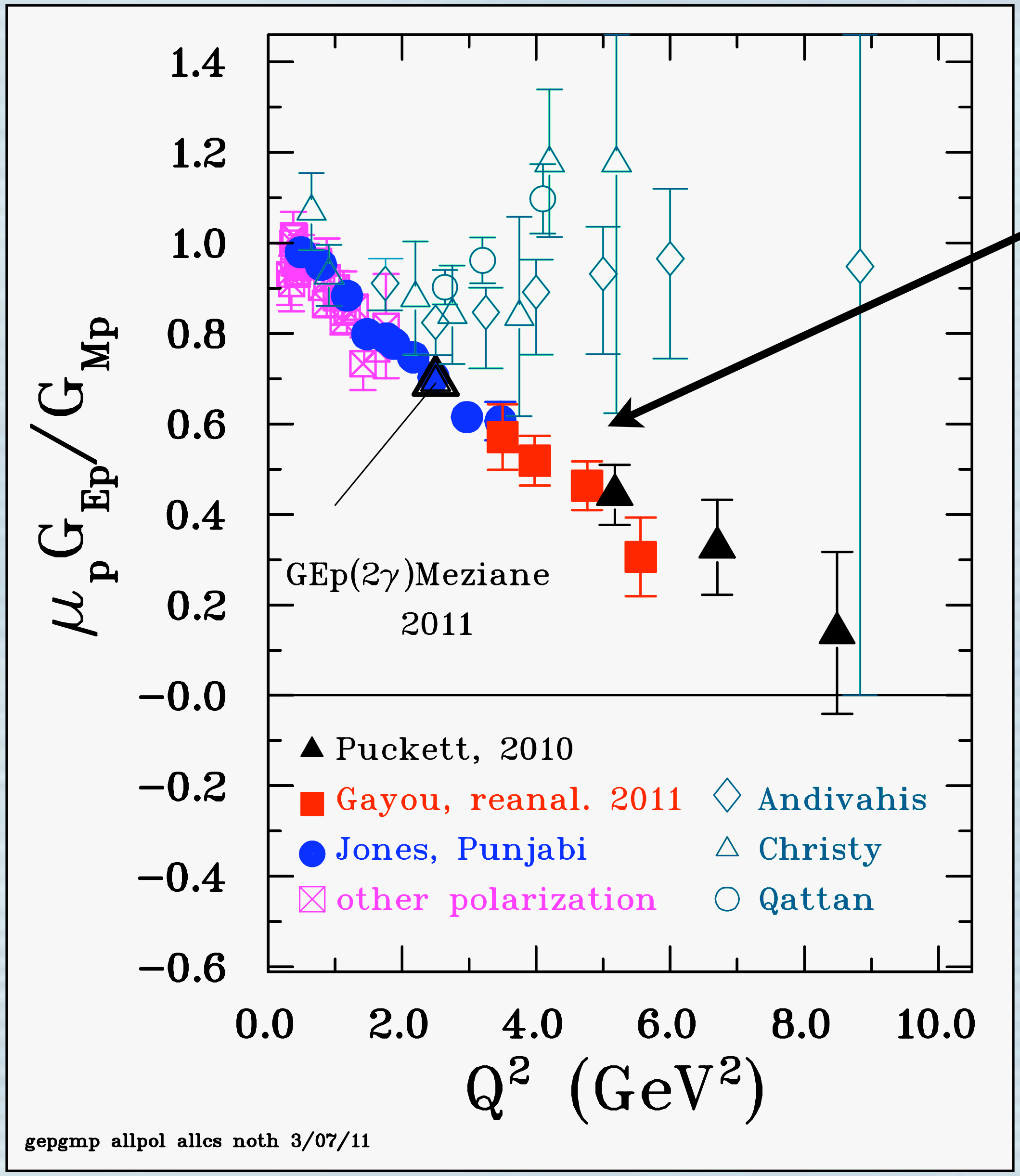
Among other things, FFs thus play a role in determining the angular momentum of the quarks using Ji's Sum Rule:

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

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

What elastic nucleon form factors at high Q^2 have taught us during the JLab era.

Measurement of $\mu_p G_E^p/G_M^p$ using the recoil polarization technique at JLab



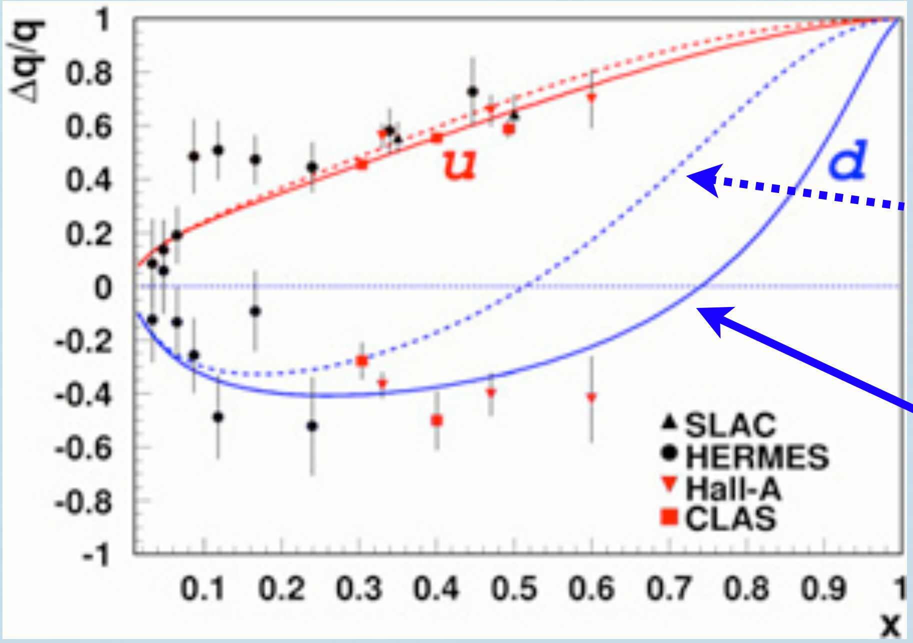
Data from both Rosenbluth separations and the double-polarization technique.

Resulted in the 2017 Bonner Prize in Nuclear Physics being awarded to to Charles Perdrisat of William and Mary

- Explanations for the Q^2 behavior of G_E^p/G_M^p have often been pointed to the role of <u>quark orbital angular momentum</u>.
- It should be noted, however, that diquark correlations could also be responsible (not necessarily to the exclusion quark OAM).

Evidence for quark orbital angular momentum has subsequently been seen in a variety of other experiments

Deep-inelastic scattering with polarized beam and targets



Model without quark orbital angular momentum.

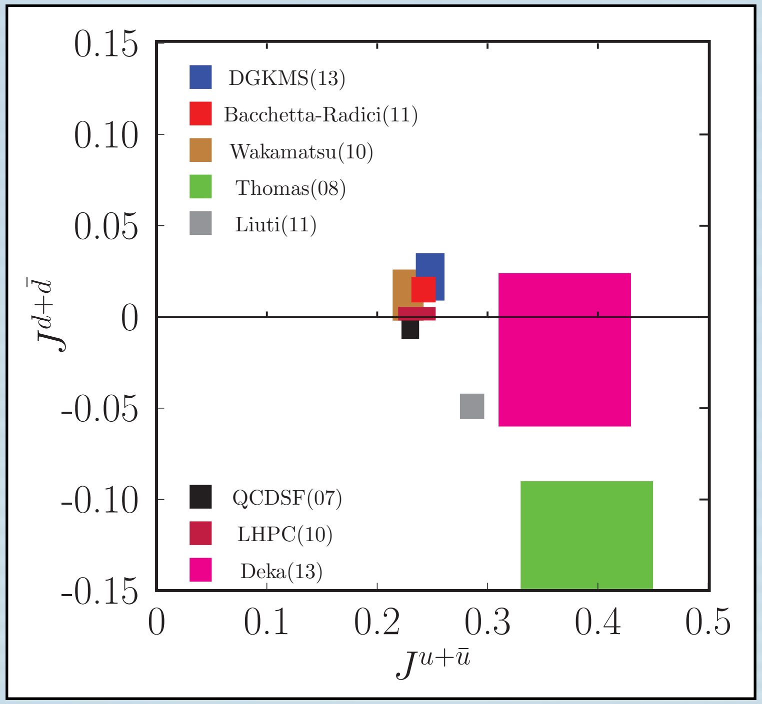
Model with quark orbital angular momentum.

Flavor-separated spin contributions from up and down quarks

GPD models constrained by data from DVCS, DVMP, FF's and more used with the Ji Sum Rule.

$$L^{u+\bar{u}} = -0.146 \ldots -0.172$$

$$L^{d+\bar{d}} = 0.263 \ldots 0.237$$



P. Kroll, EPJ Web of Conferences **85**, 01005 (2015)

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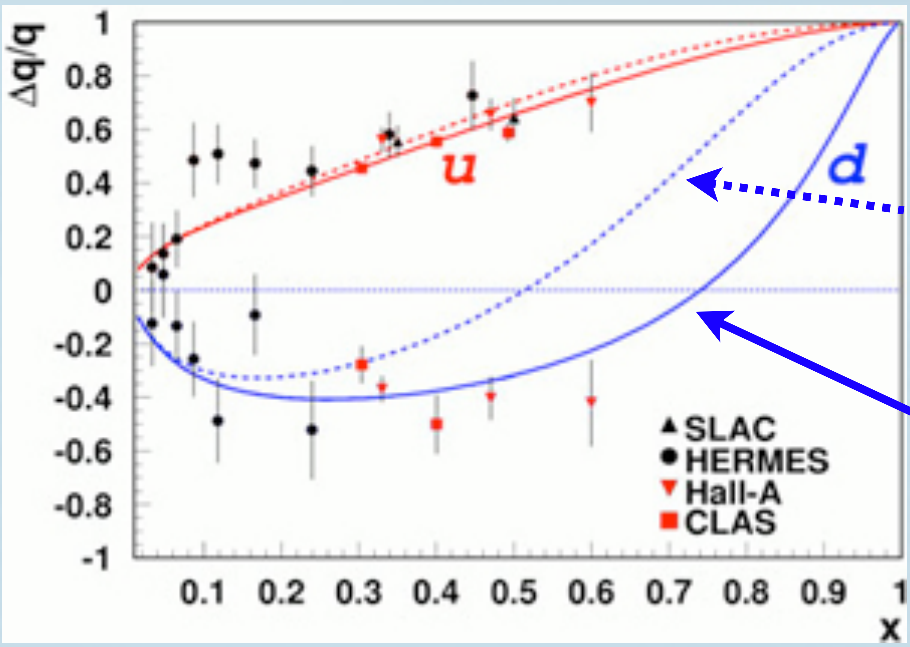

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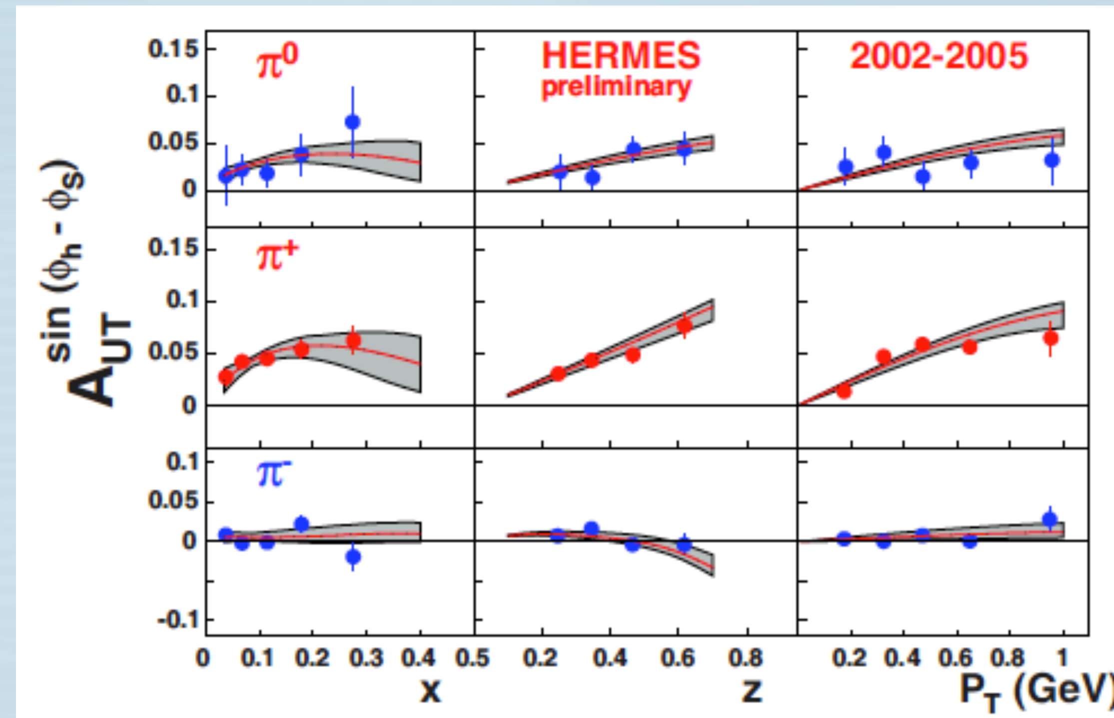
Flavor-separated spin contributions from up and down quarks

Non-zero Sivers effect in semi-inclusive DIS



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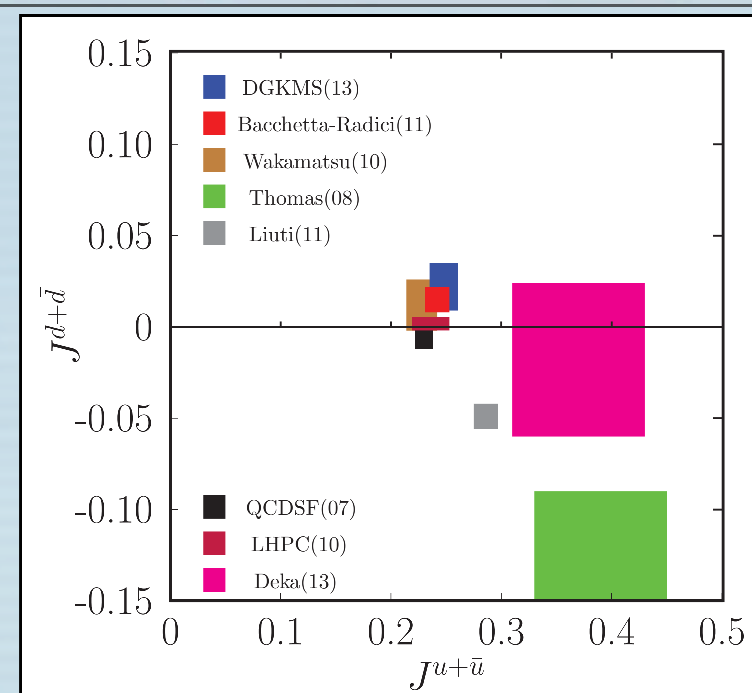

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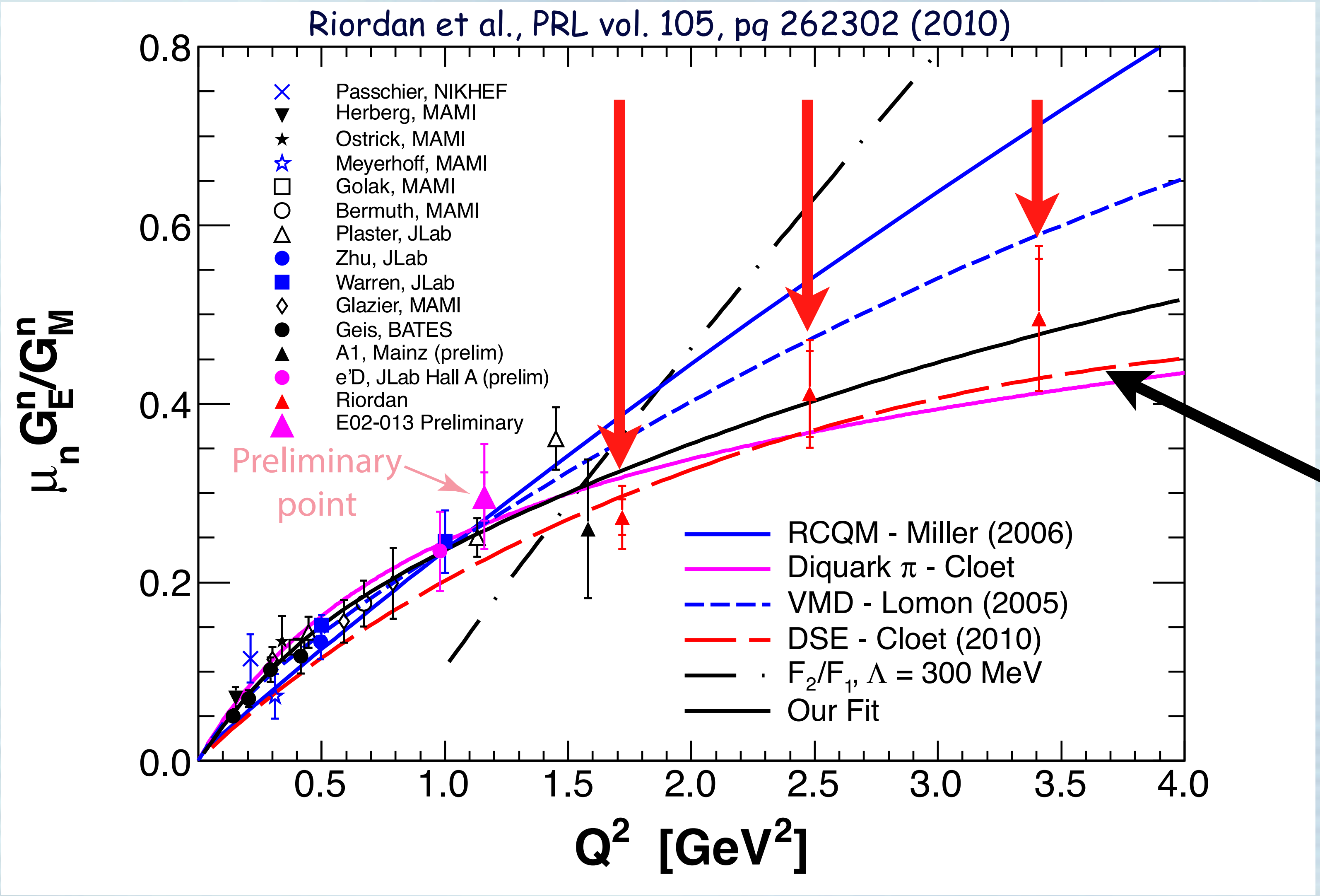
Data from the Hall A polarized ^{3}He experiment (E02-013) extended knowledge of G_E^n to high Q^2



Cloet, Eichmann, El-Bennich, Kahn and Roberts - DSE/Faddeev - 2009

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

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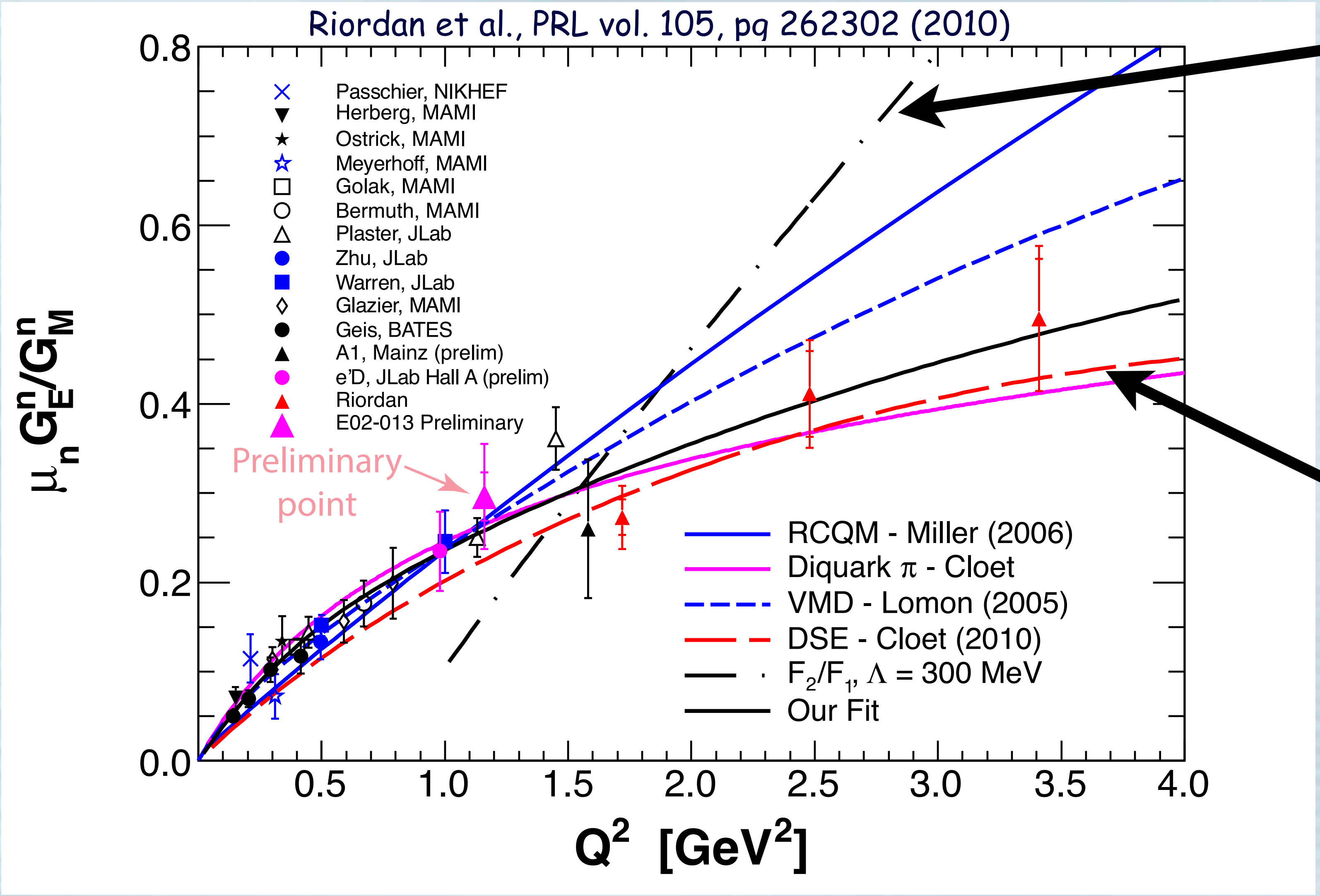

Belitsky, Ji and Yuan, logrithmic corrections - 2003

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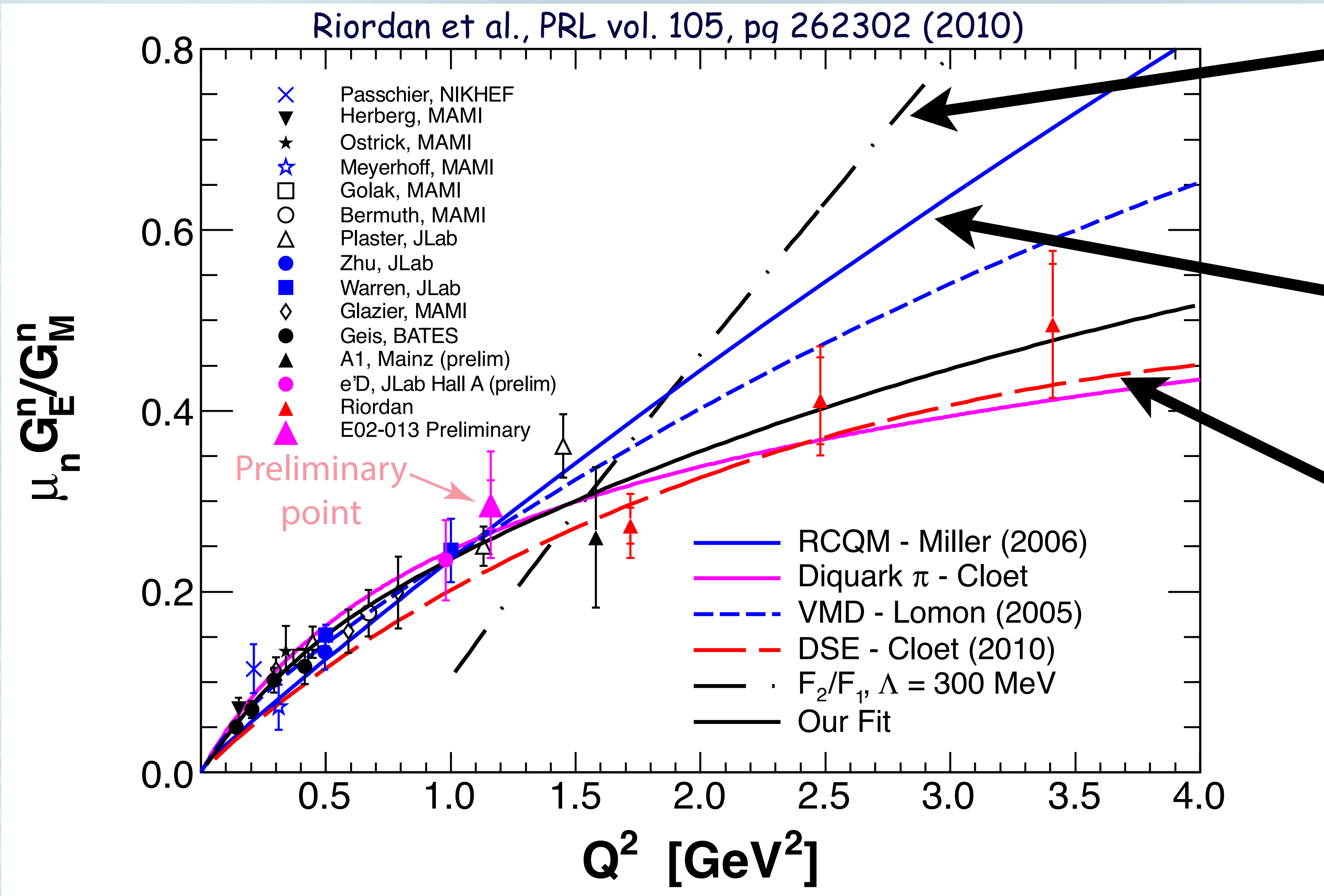

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Miller's RCQM - 2002

Cloet, Eichmann, El-Bennich, Kahn and Roberts - DSE/Faddeev - 2009

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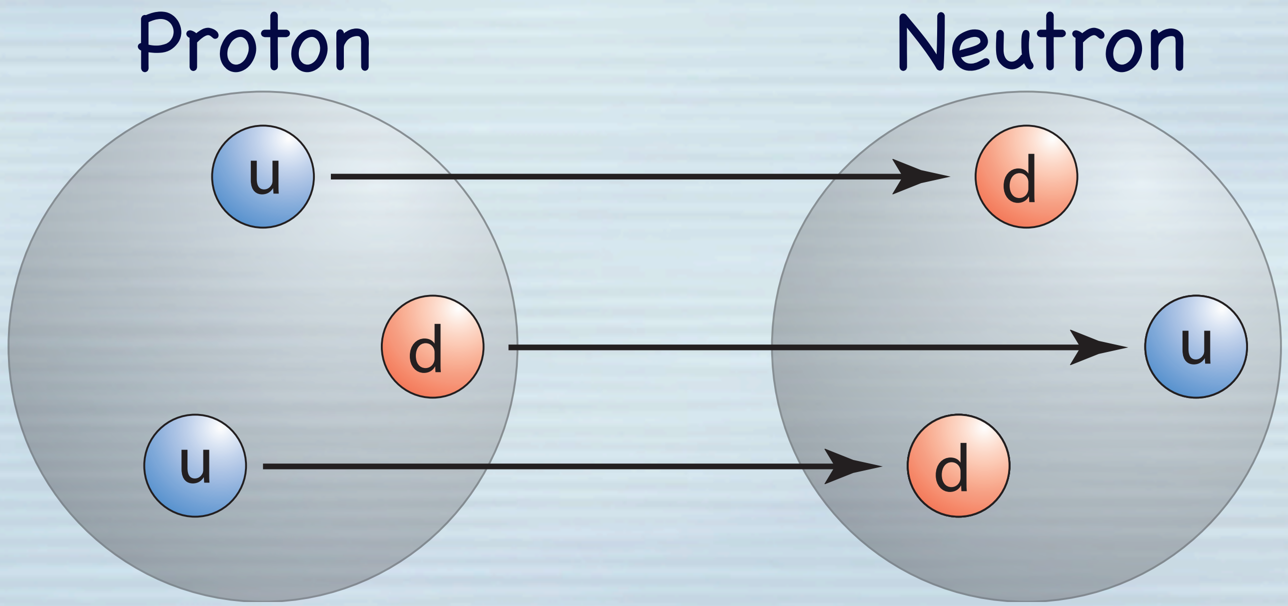
Flavor-separated form factors

Can be extracted by assuming charge symmetry and combining data from both proton and the neutron.

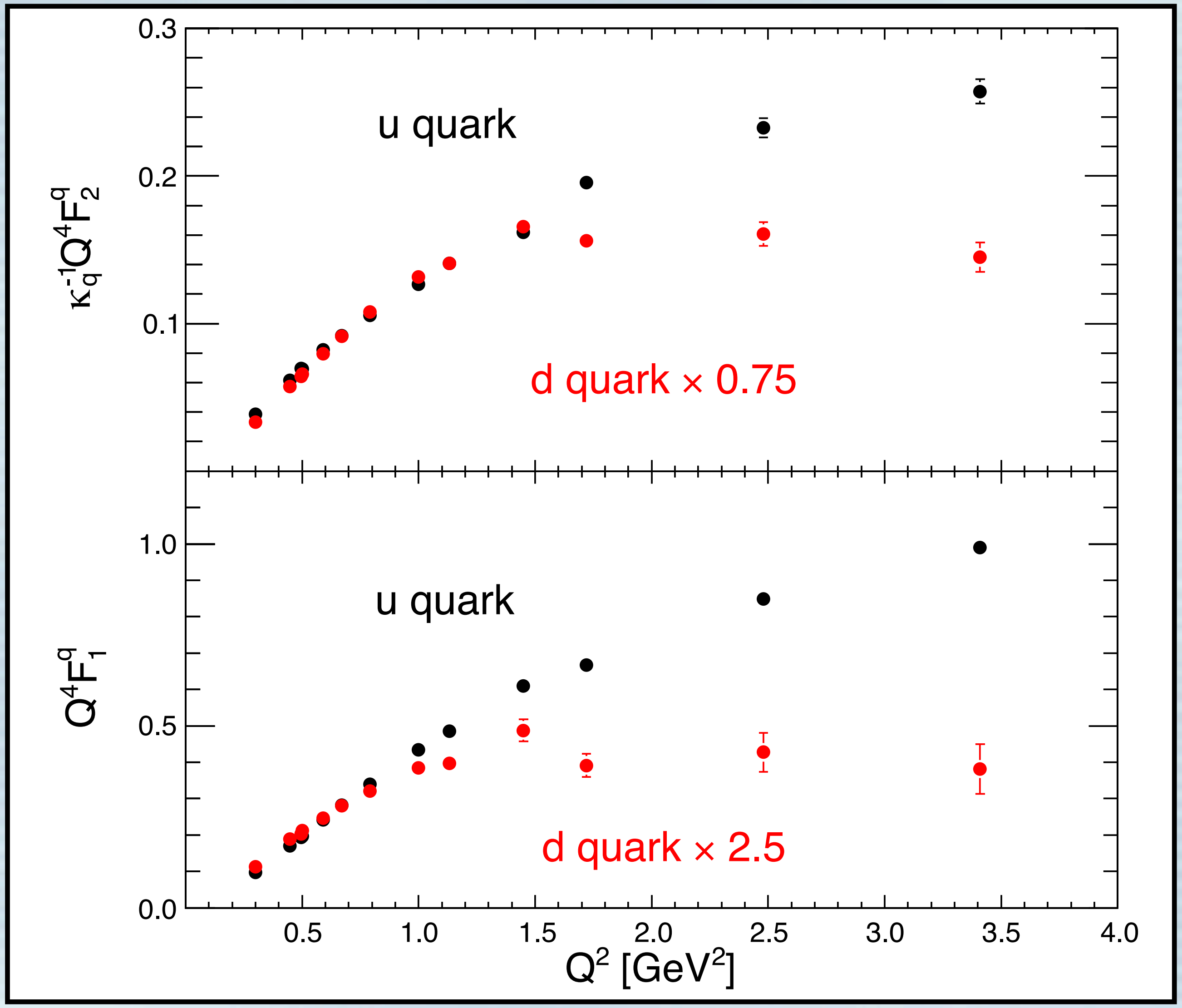


For the Dirac form factors (and similarly for the Pauli form factors):

up quark: $F_1^u = 2F_1^p + F_1^n$ down quark: $F_1^d = 2F_1^n + F_1^p$

With both proton and neutron FF data, one can extract the individual quark contributions

Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2011)



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

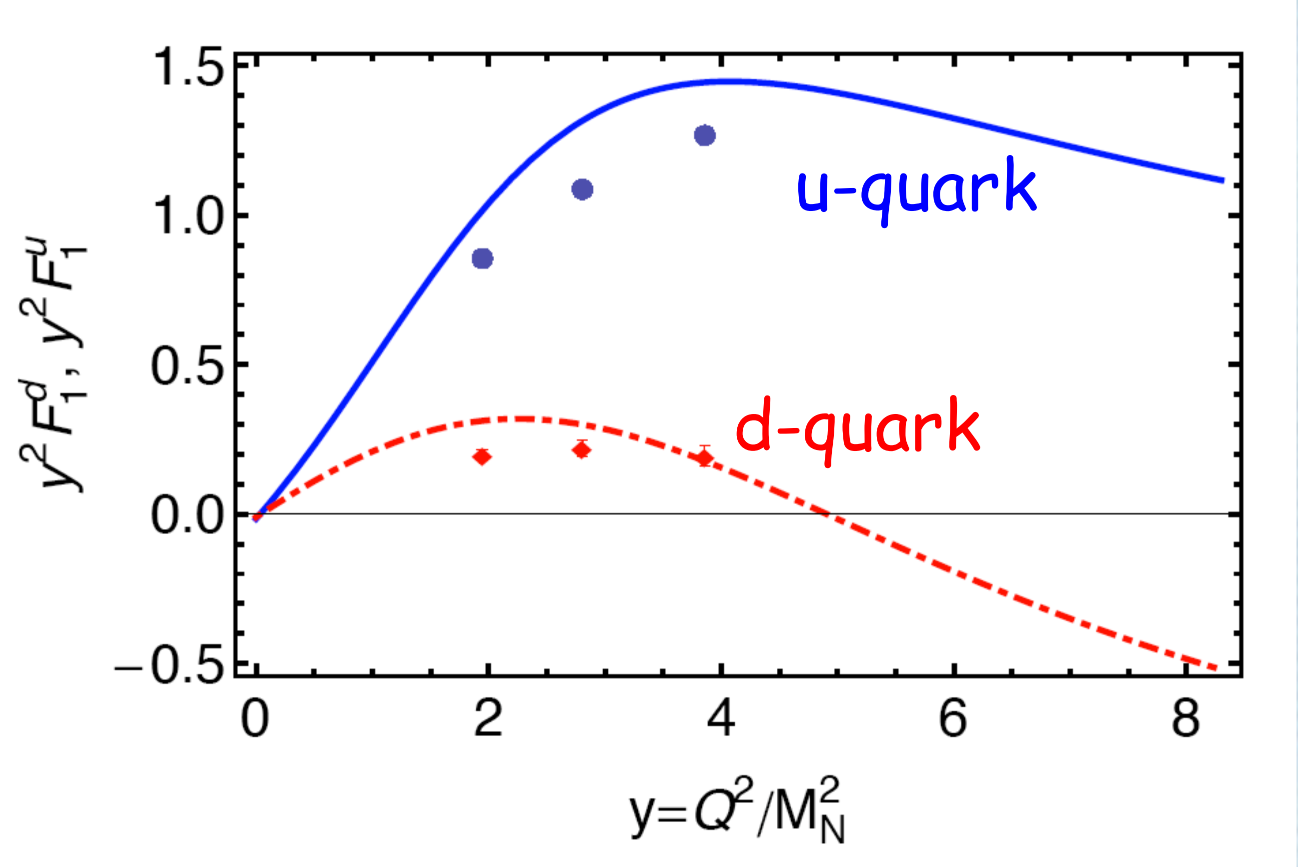
More details on this from Bogdan Wojtsekhowski tomorrow.

Many of the theoretical models that reproduce the above trends indicate the importance of diquark correlations.

DSE/Faddeev calculation of $Q^4F_1^u$ and $Q^4F_1^d$

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."

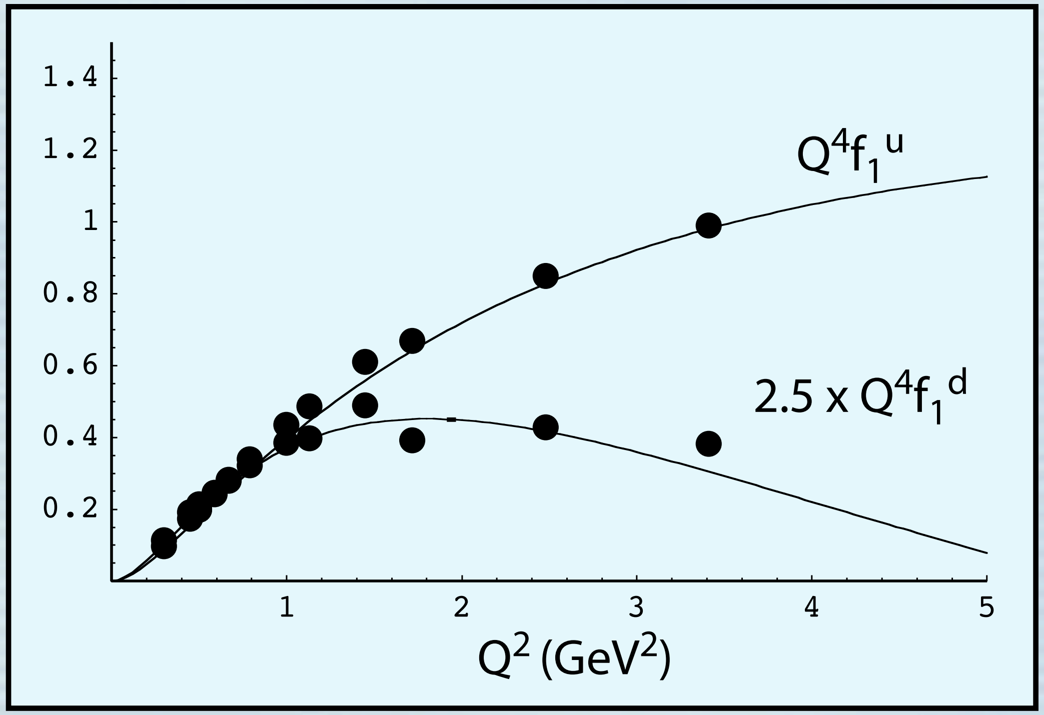


arXiv:1103.2432v1

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

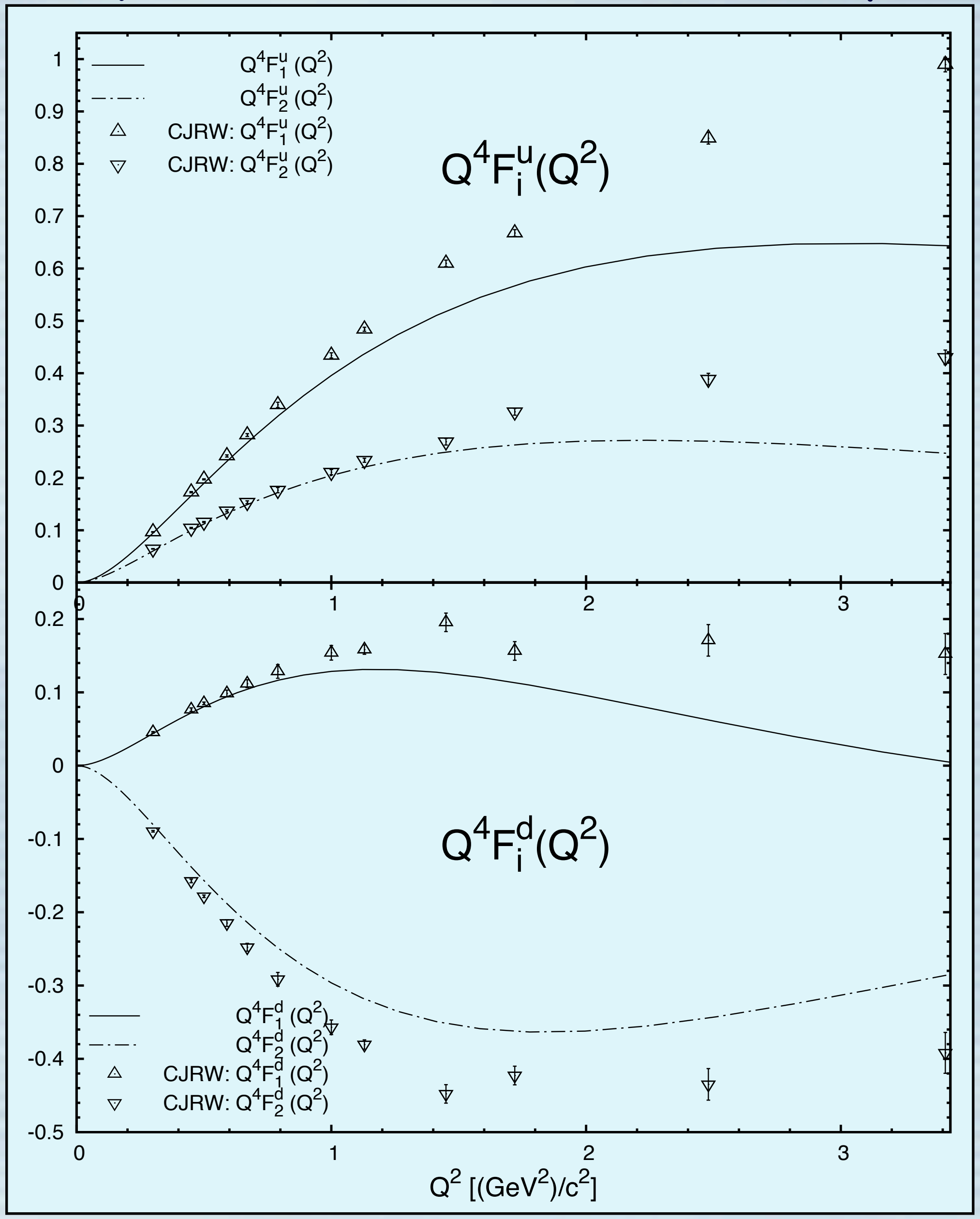
Relativistic Constituent Quark Models

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.



Not yet published (but soon). Shown with permission.

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



Rohrmoser, Choi and Plessas, arXiv:1110.3665

Workshop on diquarks at ECT* in Trento
(September 2019)

ECT*

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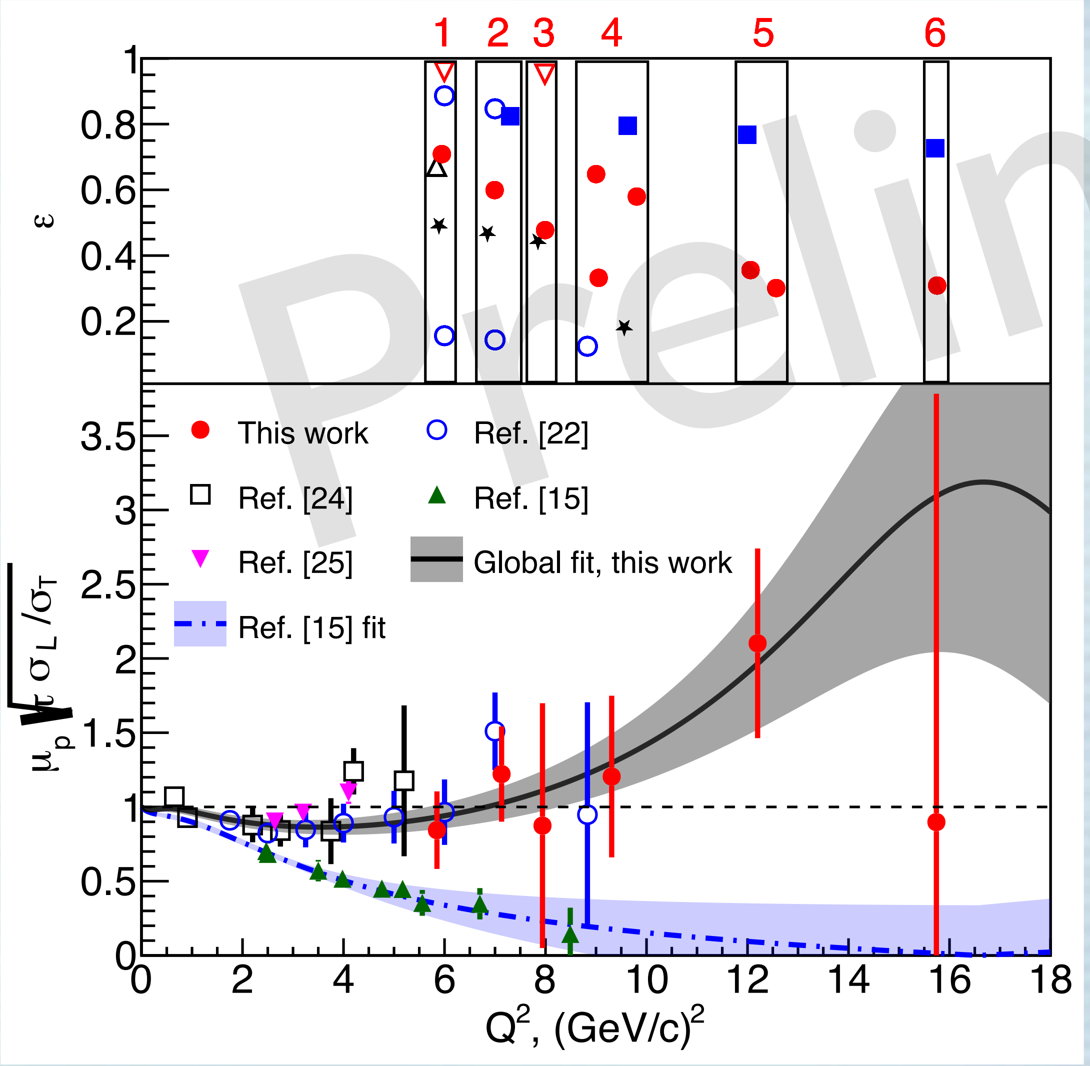
Castello di Trento (“Trint”), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

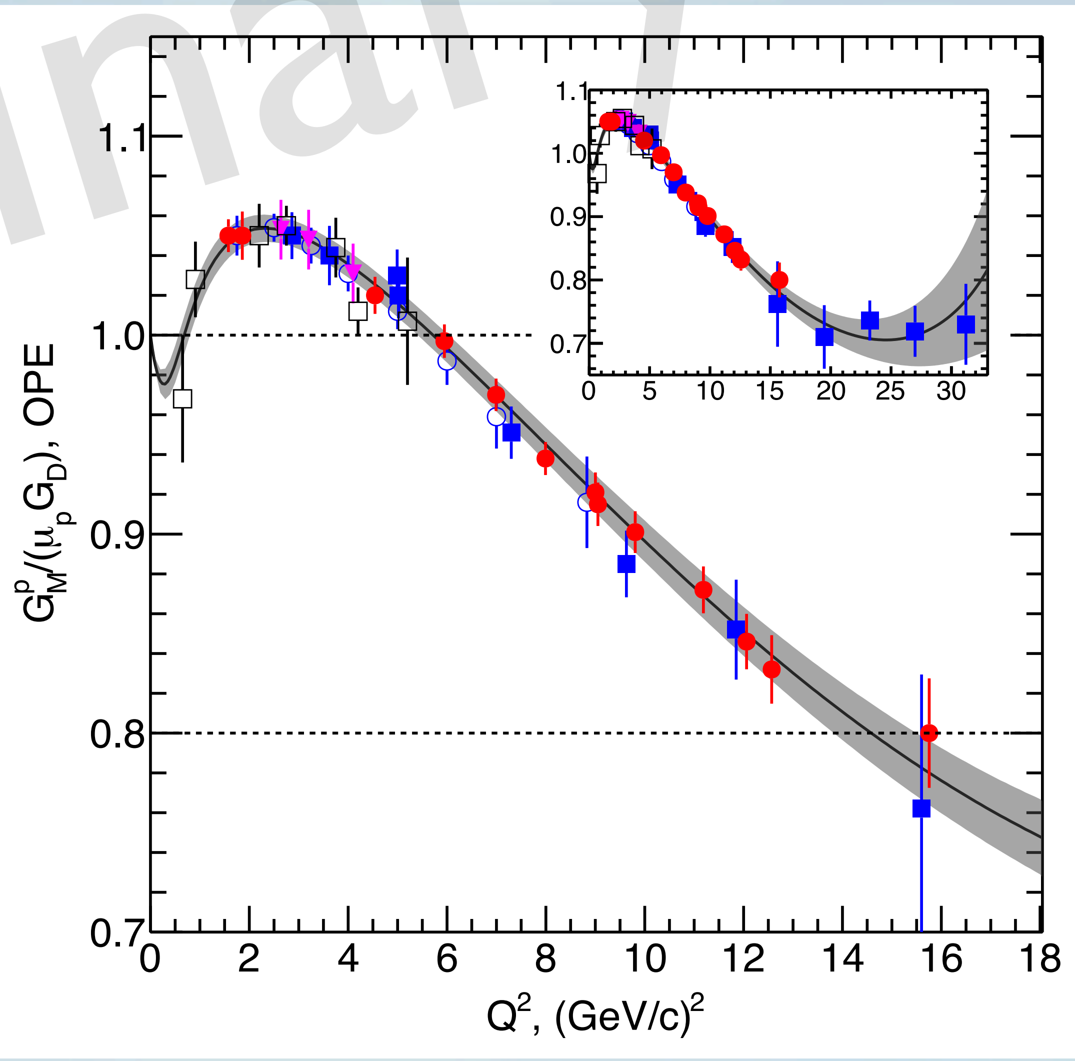
Diquark Correlations in Hadron Physics: Origin, Impact and Evidence

Trento, September 23-27, 2019

The Hall A results on precision measurements of e - p elastic scattering, the GMp12 expt.



In the absence of TPE effects, the grey curve would be proportional to G_E^p/G_M^p



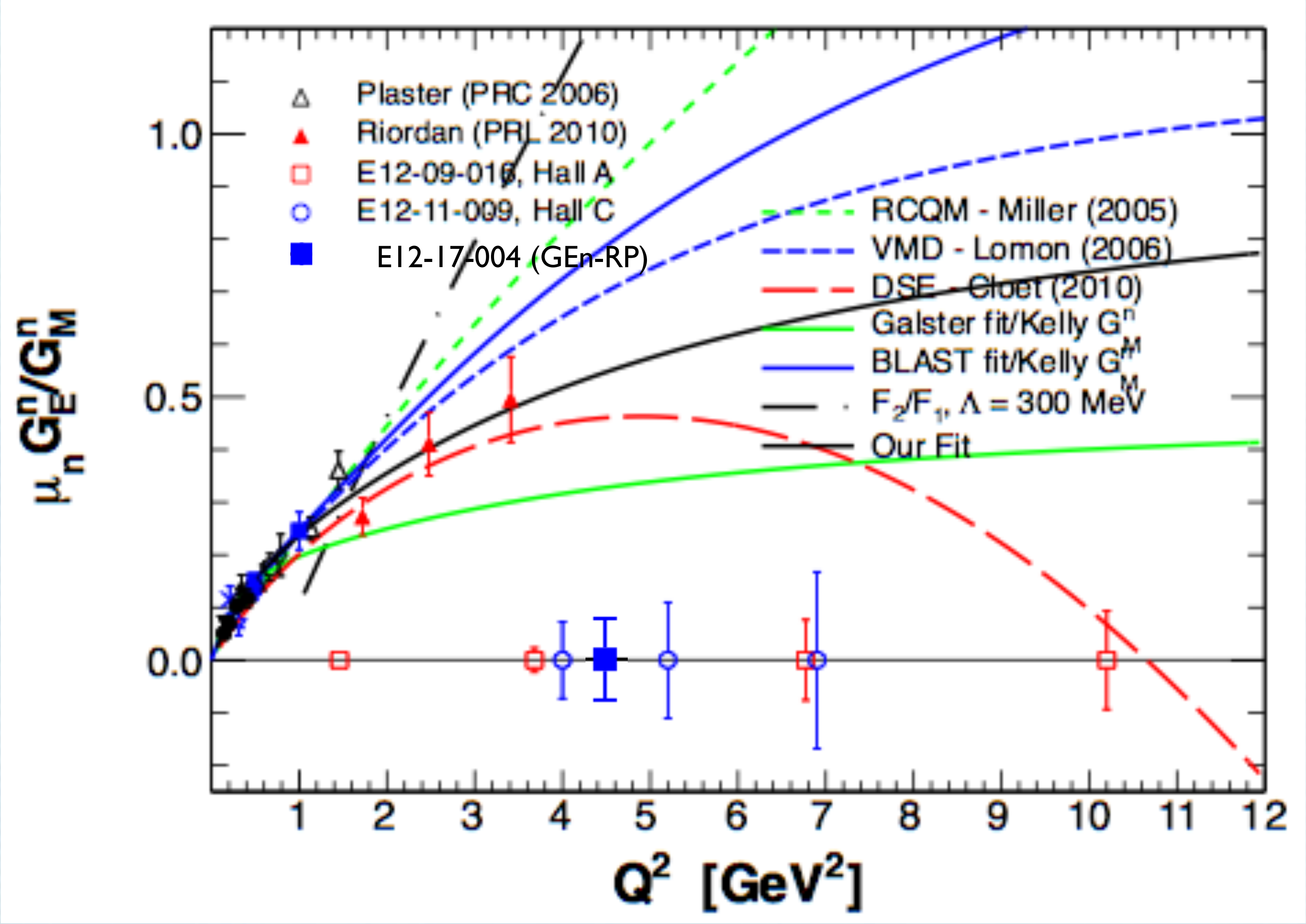
World fit to $G_M^p/(\mu_p G_D)$

What can we learn at even higher Q^2

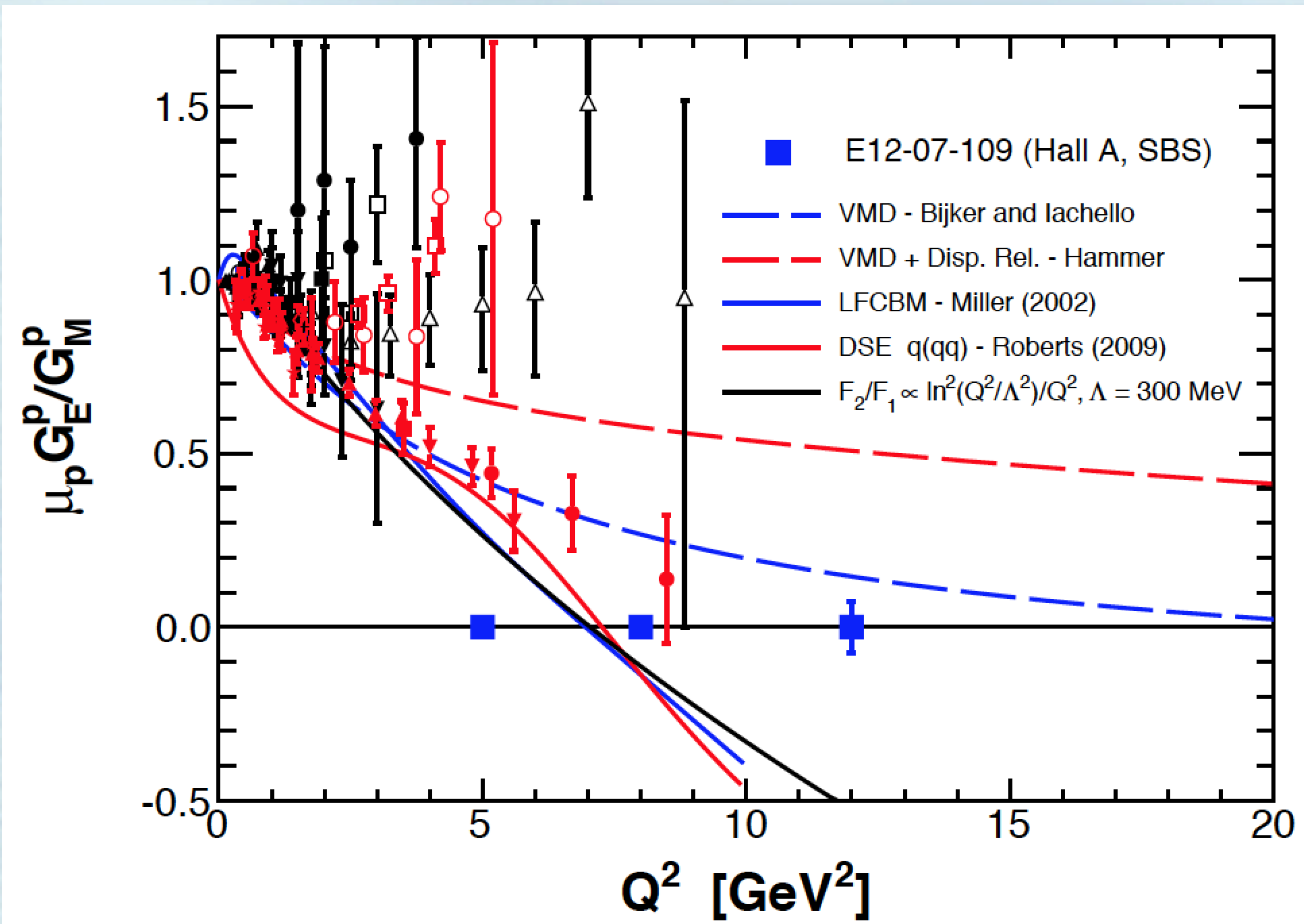
A great deal will be learned by the Super Bigbite Spectrometer (SBS) program

Two completely unauthorized ideas for SBS logos

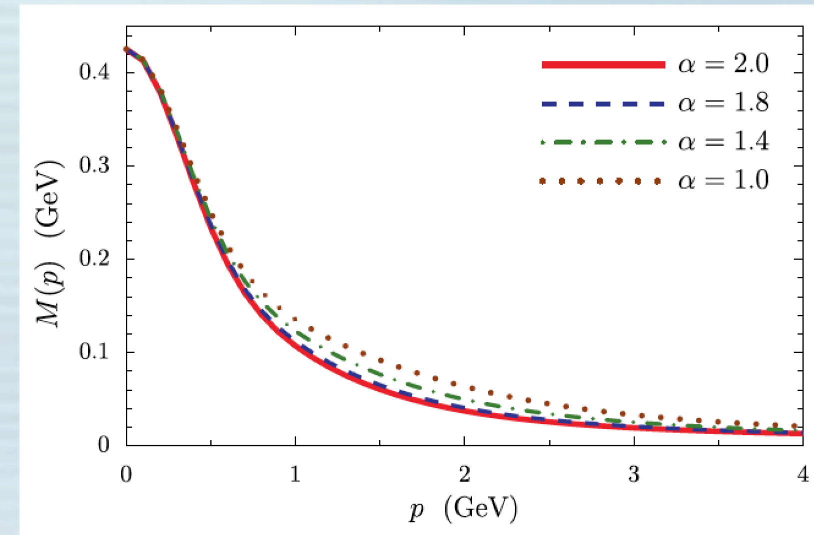
The SBS polarized-^{3}He G_E^n experiment: projected results

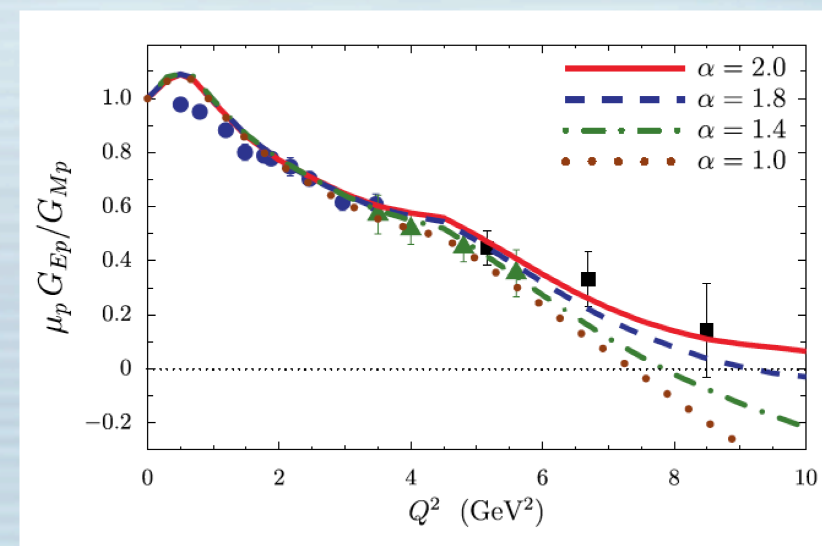


The SBS measurement of G_E^p/G_M^p: E12-09-019



G_E^p/G_M^p projected data



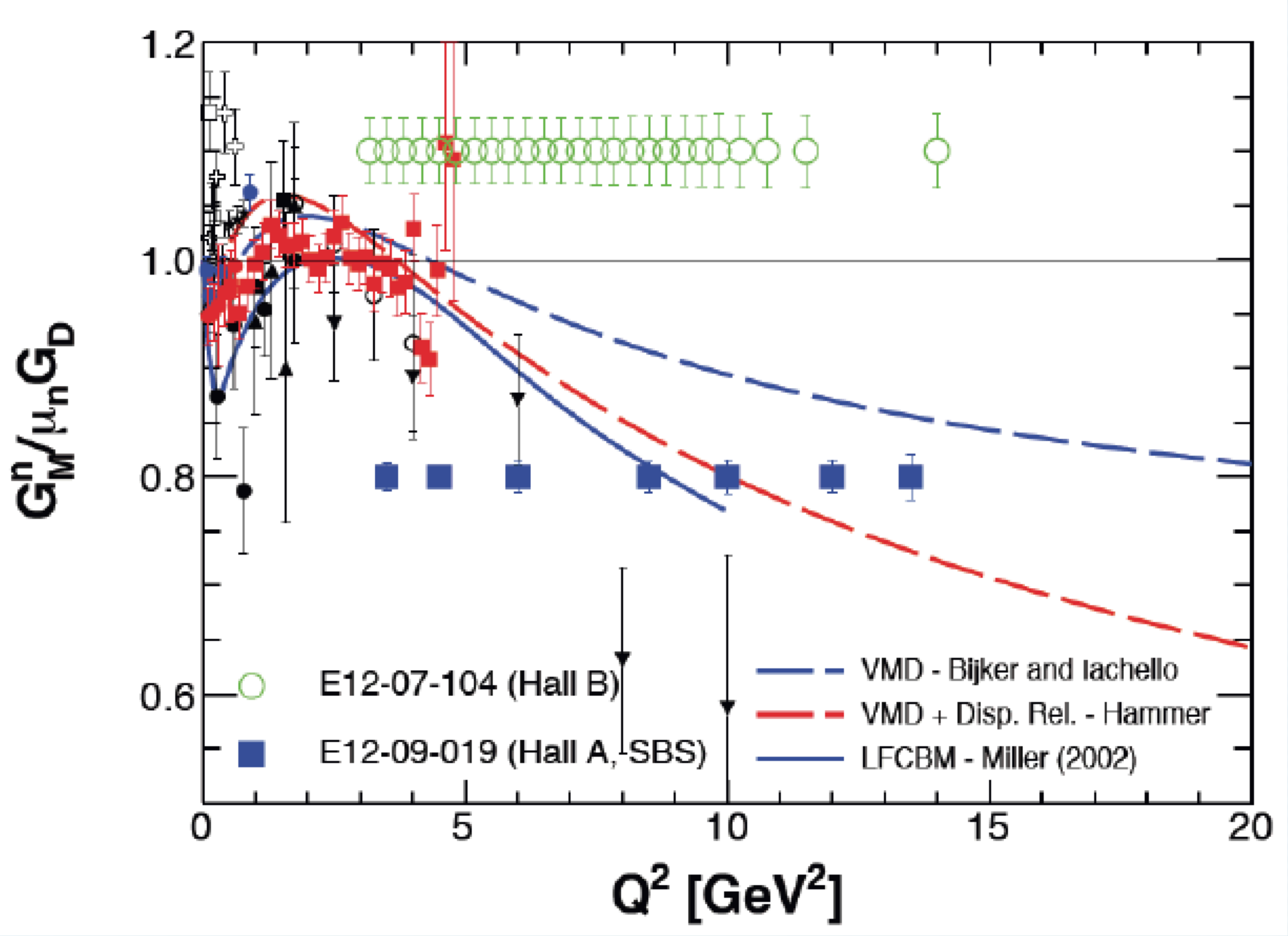


Cloet, Roberts, Thomas, PRL 111, 101803 (2013)

The zero crossing of G_E^p/G_M^p provides sensitivity to the mass function $M(p^2)$

The **first** SBS experiment: measurement of the ratio G_M^n/G_M^p:

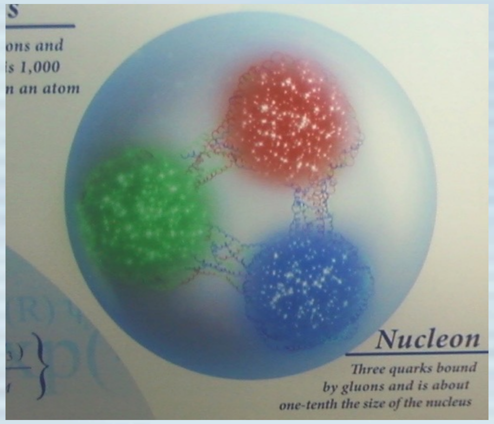
E12-09-019



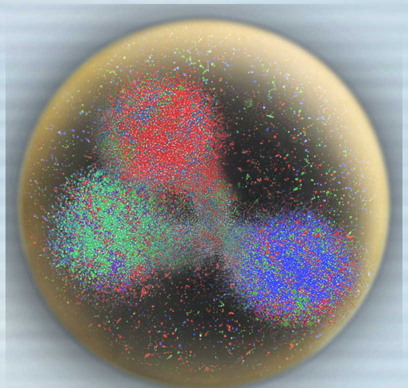
Summary

- The form factors of the nucleon have a long history of providing surprises.
- The existing data has already reshaped our understanding of the nucleon, and points in tantalizing directions.
- The SBS program will enable precise determinations of all of the elastic nucleon form factors up to 10 GeV^2 and higher.

One possible direction for our evolving understanding of nucleon structure:



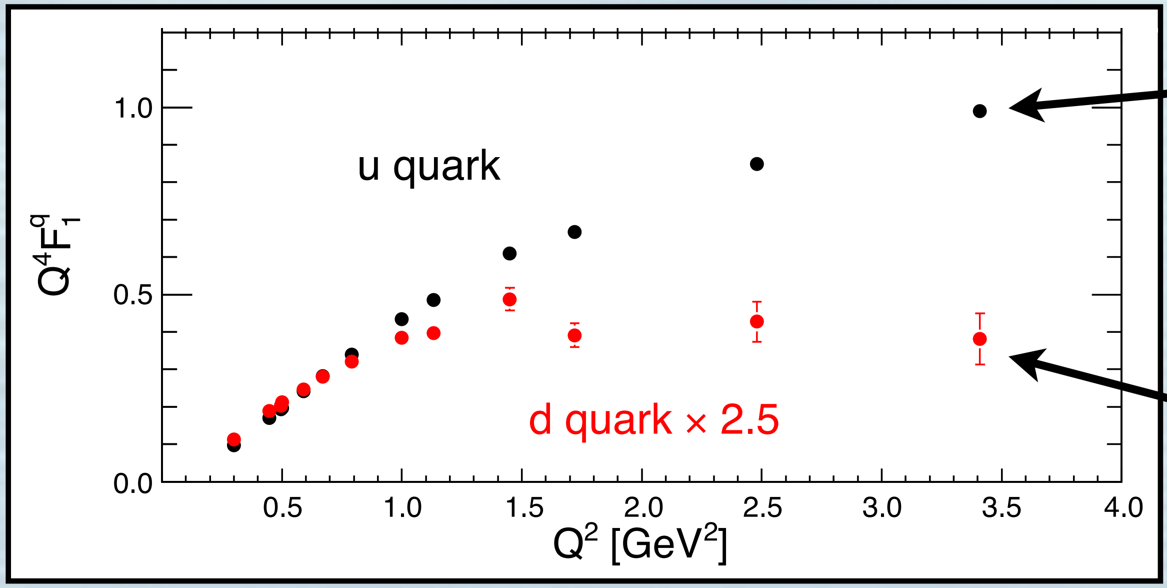
A cartoon of the nucleon from the lobby of JLab

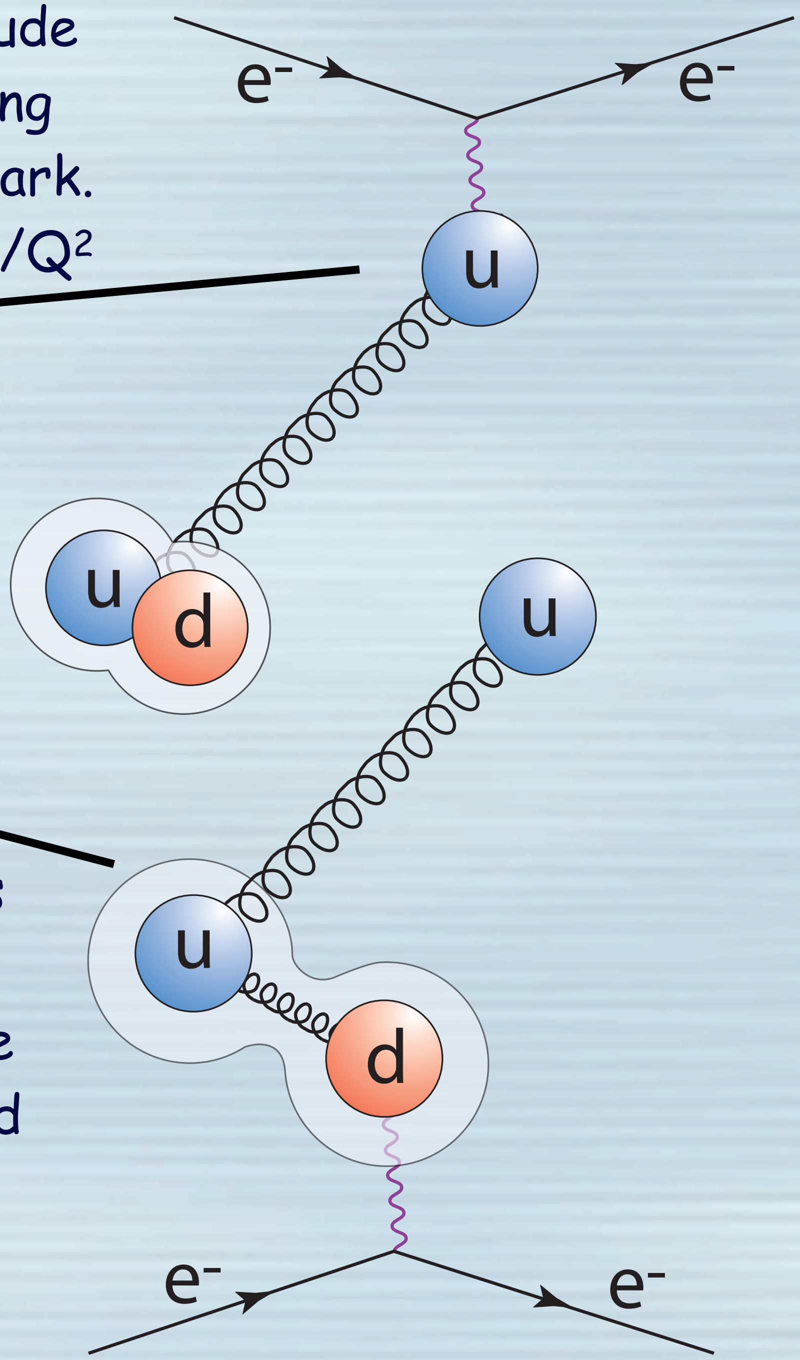


From the DOE Pulse Newsletter: An artist's conception of a nucleon with quark-diquark structure

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.