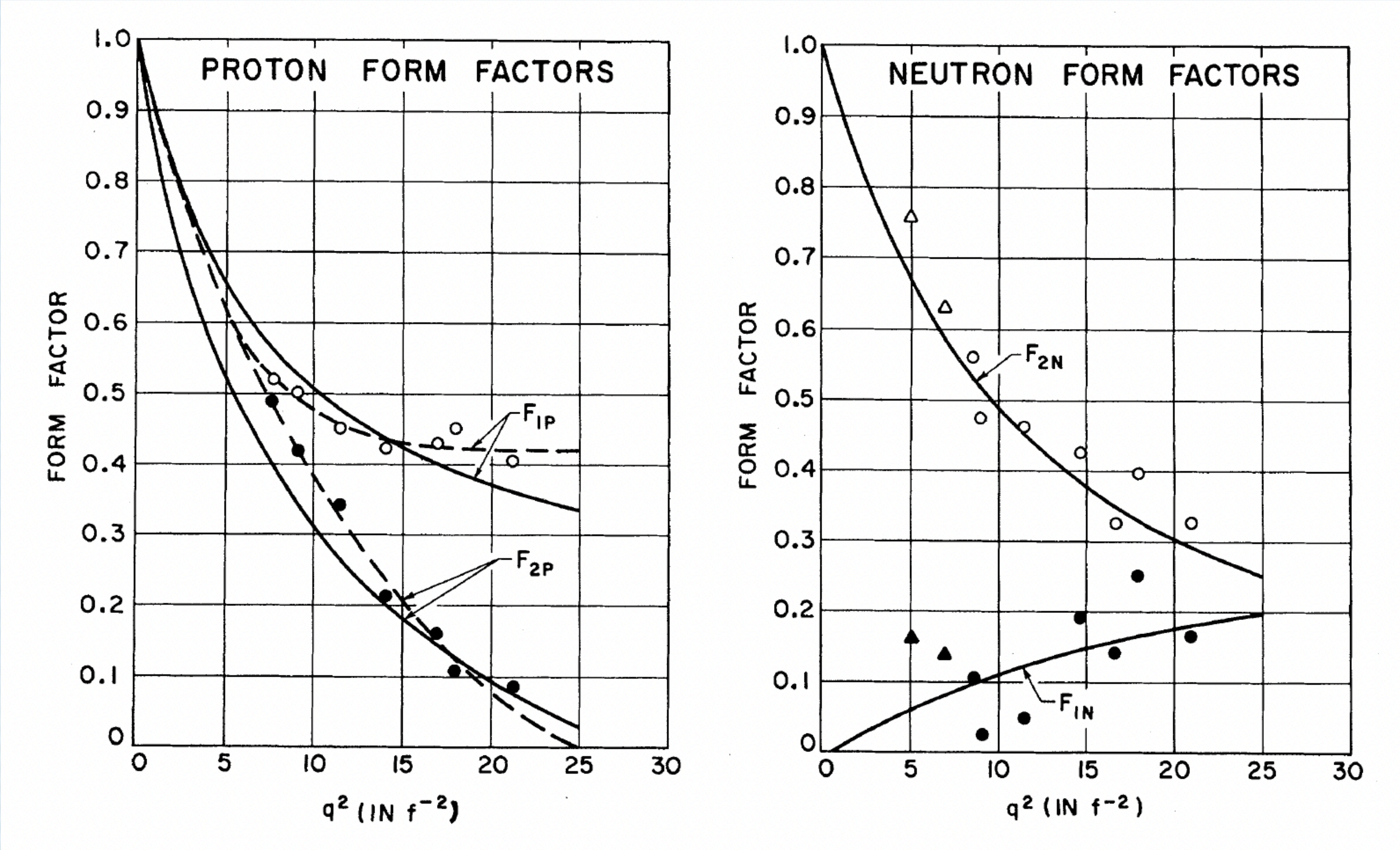
Nucleon form factors

- The long history of how the study of elastic nucleon form factors have contributed to discovery, both directly and indirectly.
- Increasingly precise measurements at Jlab of form factors at high Q^2 have dramatically influenced our view of the structure of the nucleon.
- The "Super Bigbite Spectrometer" (SBS) program (ongoing!) that is greatly expanding the frontier of high-Q^2 high-precision form factor measurements.

Gordon D. Cates
MENU 2023: October 16, 2023

Hofstadter directly measured of the size of the proton and neutron

1961



"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

The very first experiment at SLAC: Looking for the "nucleon core" in elastic scattering

One expectation was that at sufficiently high Q^2, a rapid drop off would occur in the elastic form factor indicating some kind of core to the nucleon

As Dick Taylor said in his Nobel Prize address, quoting Richard Wilson of Harvard, they found that

"The peach has no pit."

PROPOSALS FOR INITIAL ELECTRON SCATTERING EXPERIMENTS
USING THE SLAC SPECTROMETER FACILITIES

Submitted
By
SLAC-MIT-CIT Collaboration

January 1966

4a. Electron-Proton Elastic Scattering

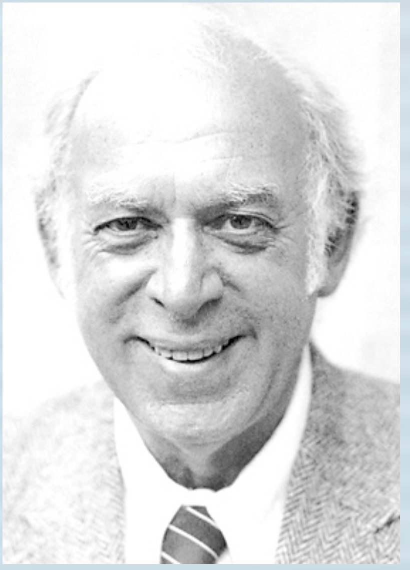
Summary

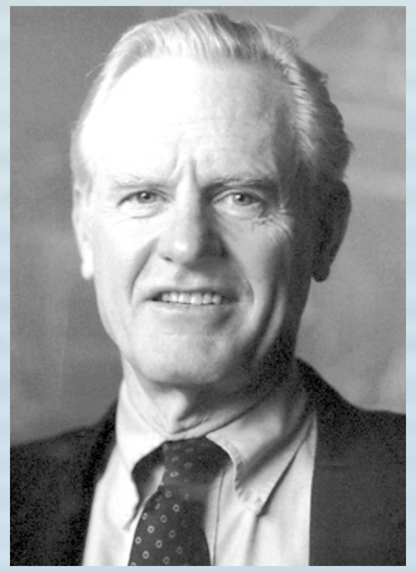
form factors. It is useful to list some of the questions of interest that can be investigated by extending the measurements to higher q^2:

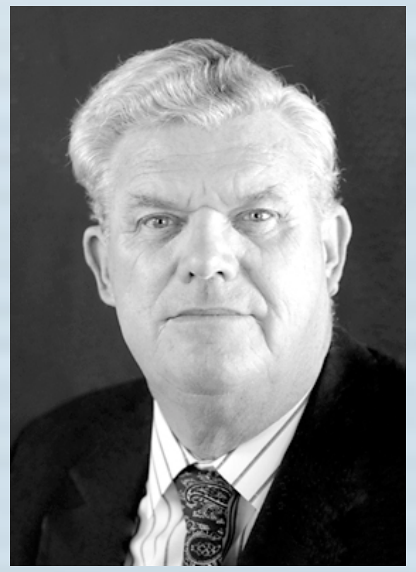
(1) Existence of a nucleon core.

(2) Validity of the pole description of nucleon form factors.

This finding set the stage for the inelastic scattering measurements that led to the discovery of quarks







In part, nucleon form factors are so important because they provide an exceptionally clean probe:

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

Pauli FF

The Sachs FFs:

$$G_{_E} = F_1 - \tau F_2 \quad \text{and} \quad G_{_M} = F_1 + F_2$$

where

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

Two ways for measuring elastic form factors

Rosenbluth separation: measure the cross section with various different kinematics (different ϵ but same Q^2) to extract G_E and G_M separately.

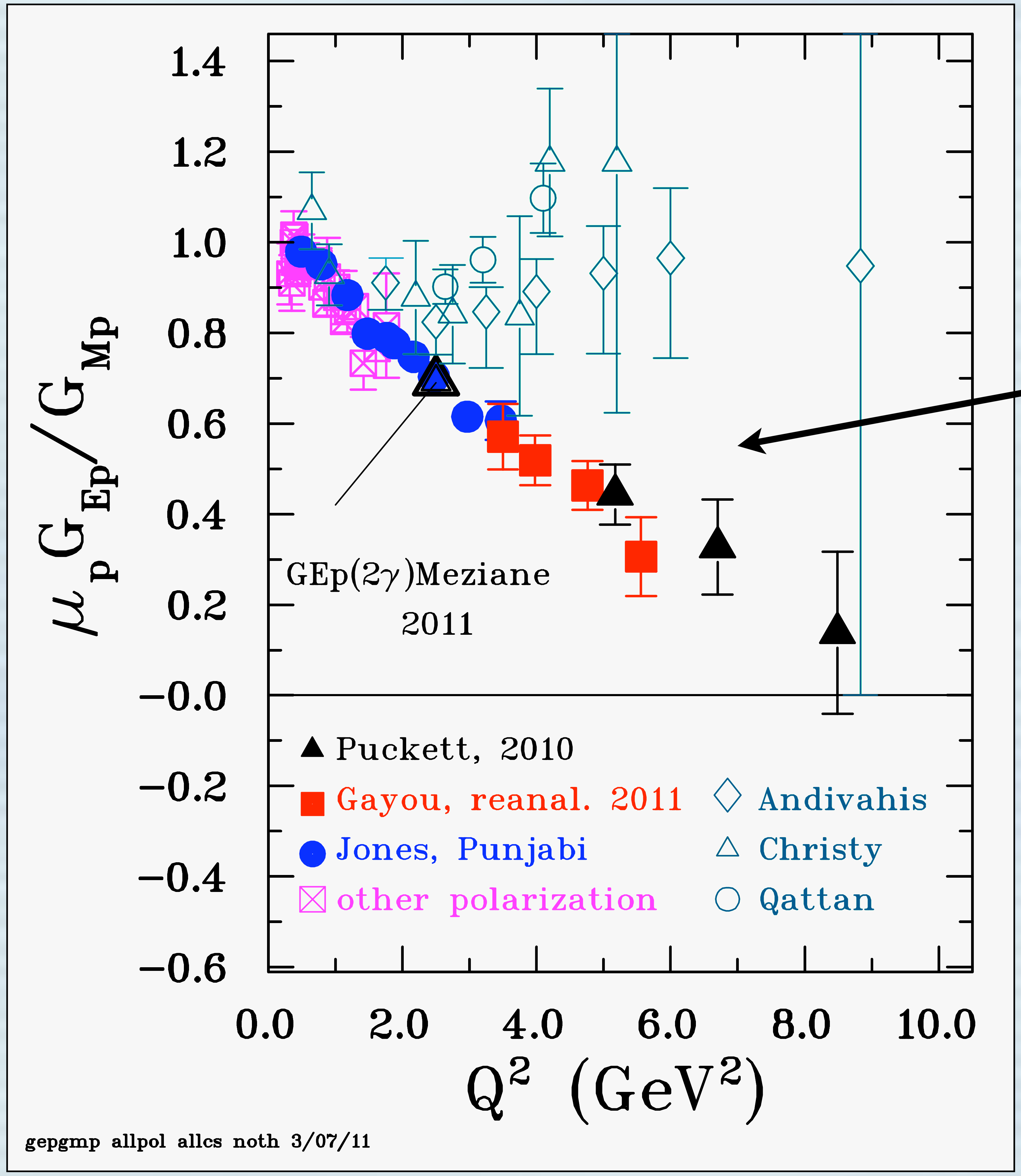
$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{\text{Mott}} \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon(1+\tau)} \qquad \tau = Q^2/4M^2 \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

The problem is that at high Q^2, the relative contribution from G_E becomes quite small

Double-polarization techniques that allow you to measure the ratio G_E/G_M and provides greatly improved accuracy at high Q^2. Below is the spin asymmetry when using polarized electrons and a polarized target (as in GEn-II).

$$A = \frac{-2\sqrt{\tau(\tau+1)}\tan(\theta_e/2)(G_E^n/G_M^n)}{(G_E^n/G_M^n)^2 + \tau[1 + 2(1+\tau)\tan^2(\theta_e/2)]}$$

Double polarization techniques enabled the discovery that the ratio $\mu_p G_E^p/G_M^p$ decreases nearly linearly with increasing Q^2



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

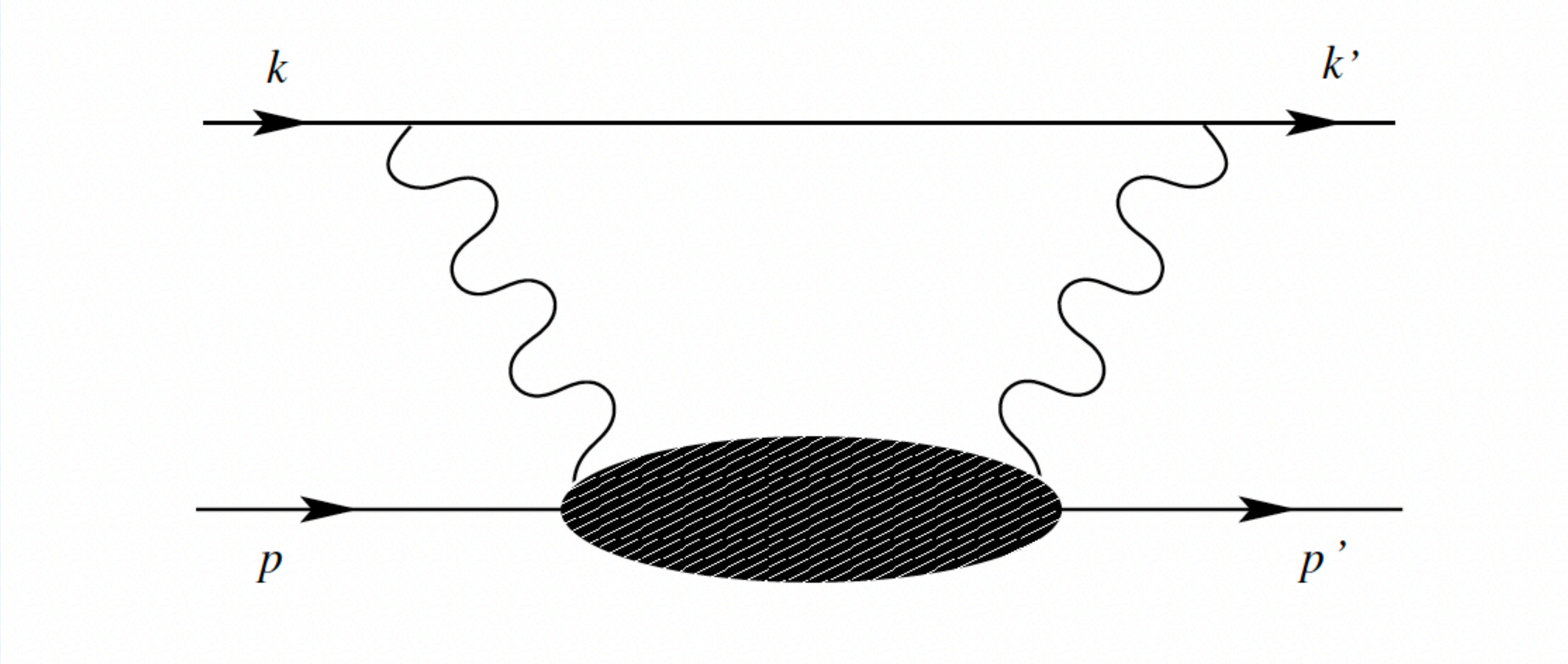
Resulted in the 2017 Bonner Prize in Nuclear Physics being awarded to to Charles Perdrisat of William and Mary

Explanations for the Q^2 behavior of G_E^p/G_M^p have typically relied upon the role of <u>quark orbital angular momentum</u>.

The Born approximation is not always good enough

Guichon and Vanderhaeghen, PRL
Vol. 91, pg. 142303 (2003)

$$T = \frac{e^2}{Q^2}\bar{u}(k')\gamma_\mu u(k) \times \bar{u}(p')\left(\tilde{G}_M\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma\cdot K P^\mu}{M^2}\right)u(p),$$

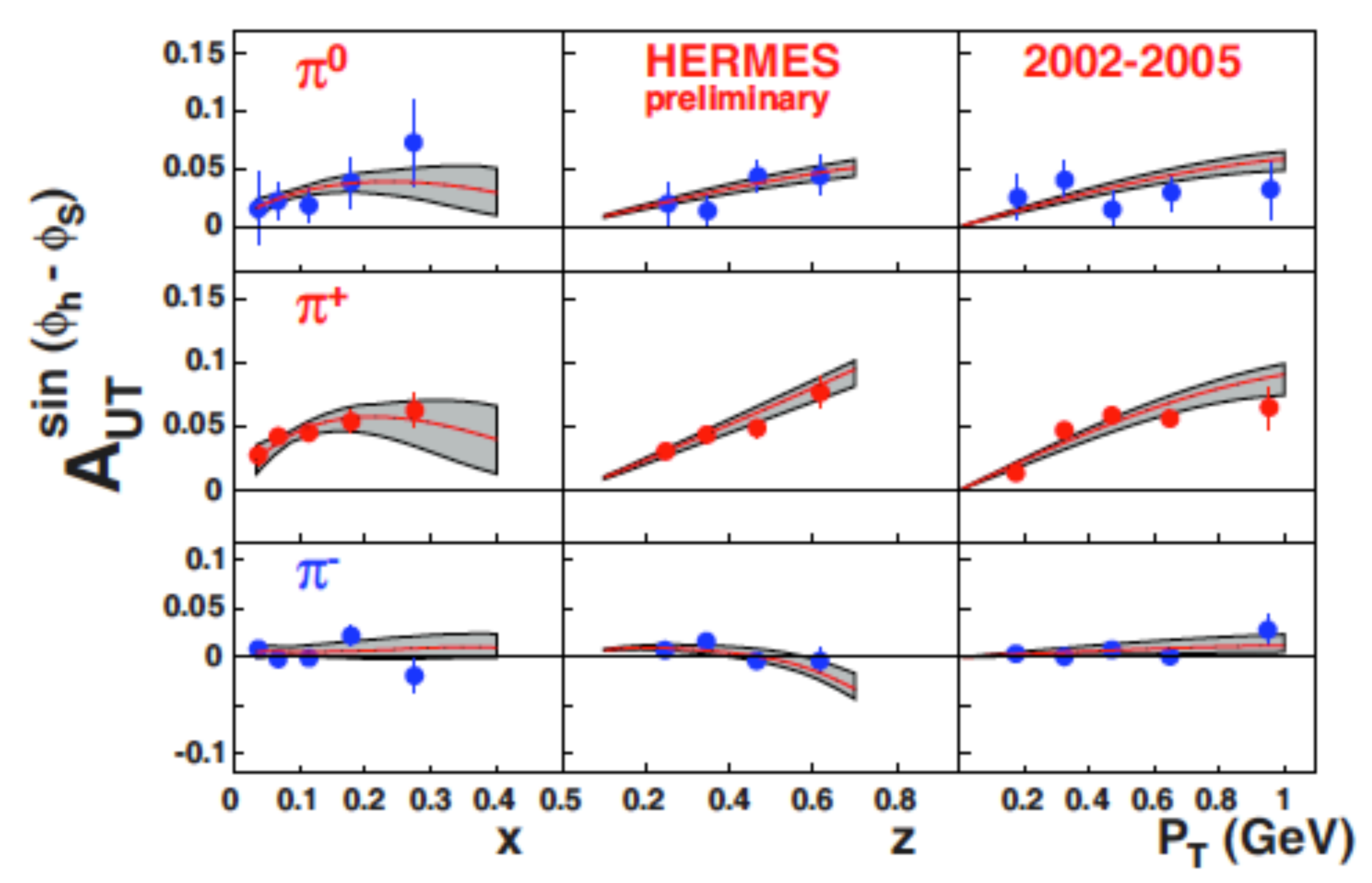


Including two-photon effects ...

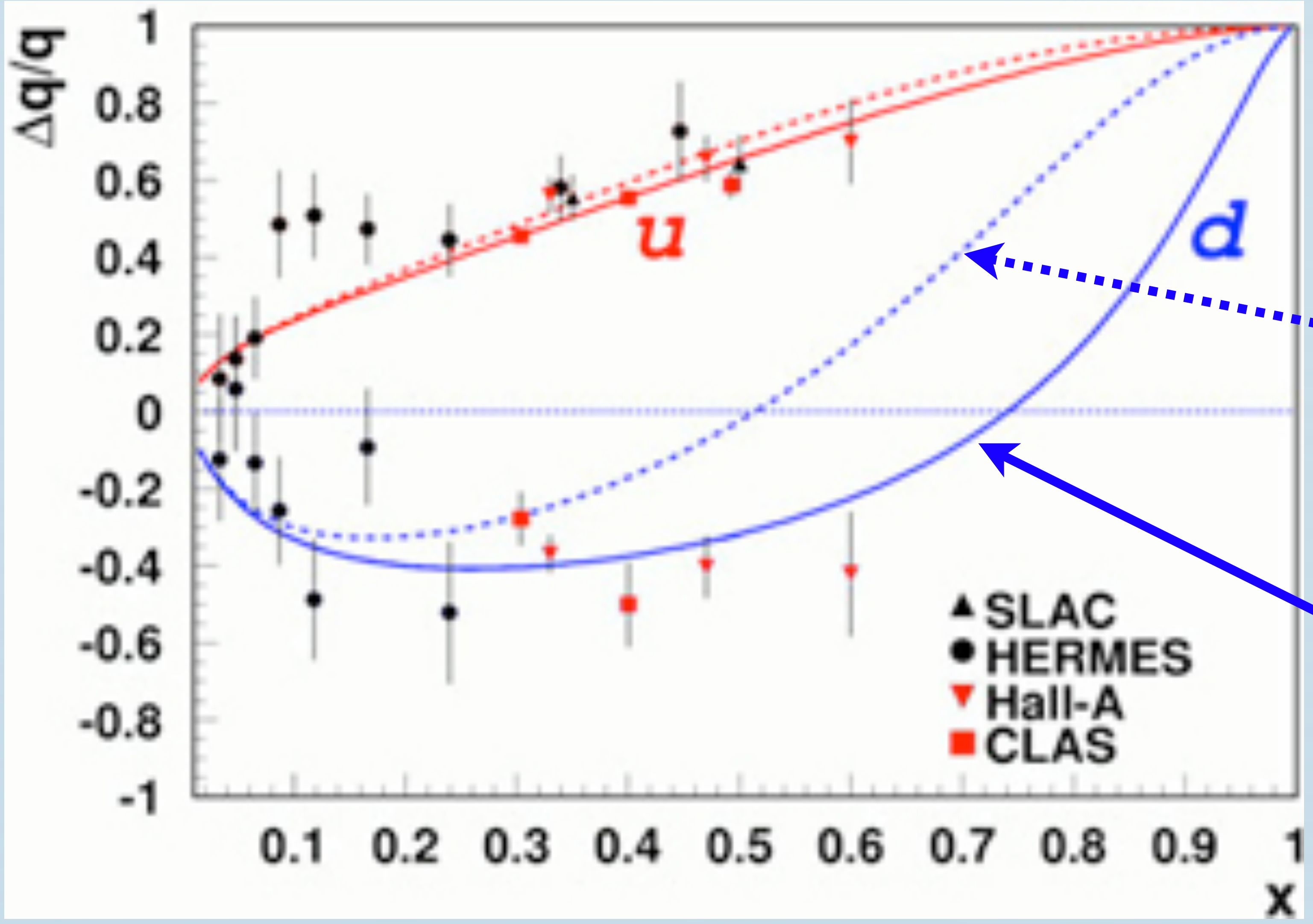
- The effects are typically only a few percent
- But extracting GE and GM using the Rosenbluth separation essentially involves subtracting two large number

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

Non-zero Sivers effect in semi-inclusive DIS



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

The form factors still provide one of the most important constraints for GPDs

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

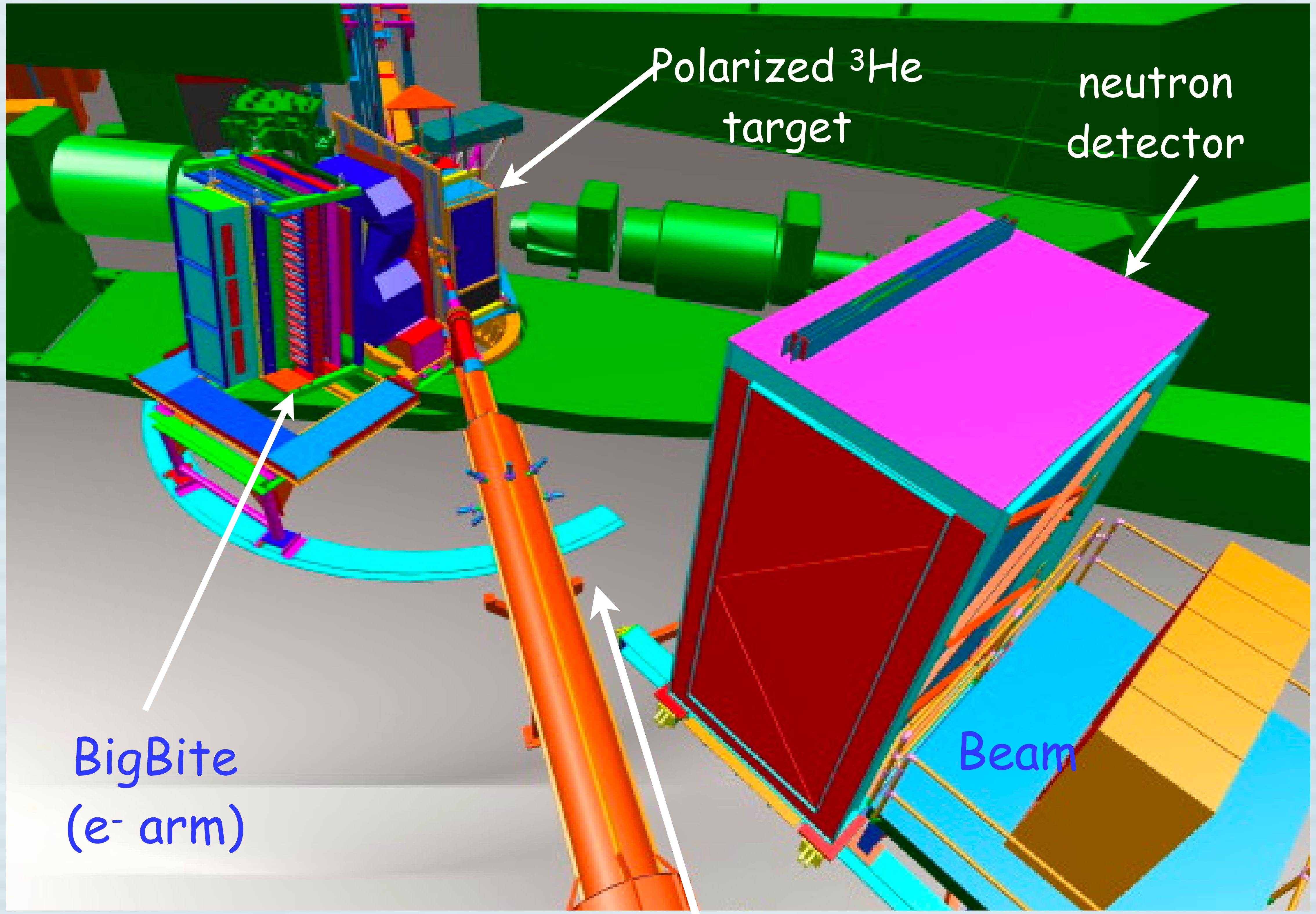
Among other things, FFs thus play a role in determining the angular momentum of the quarks using Ji's Sum Rule:

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

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

Proton results for G_E/G_M led to keen interest in gaining corresponding results for the **neutron**

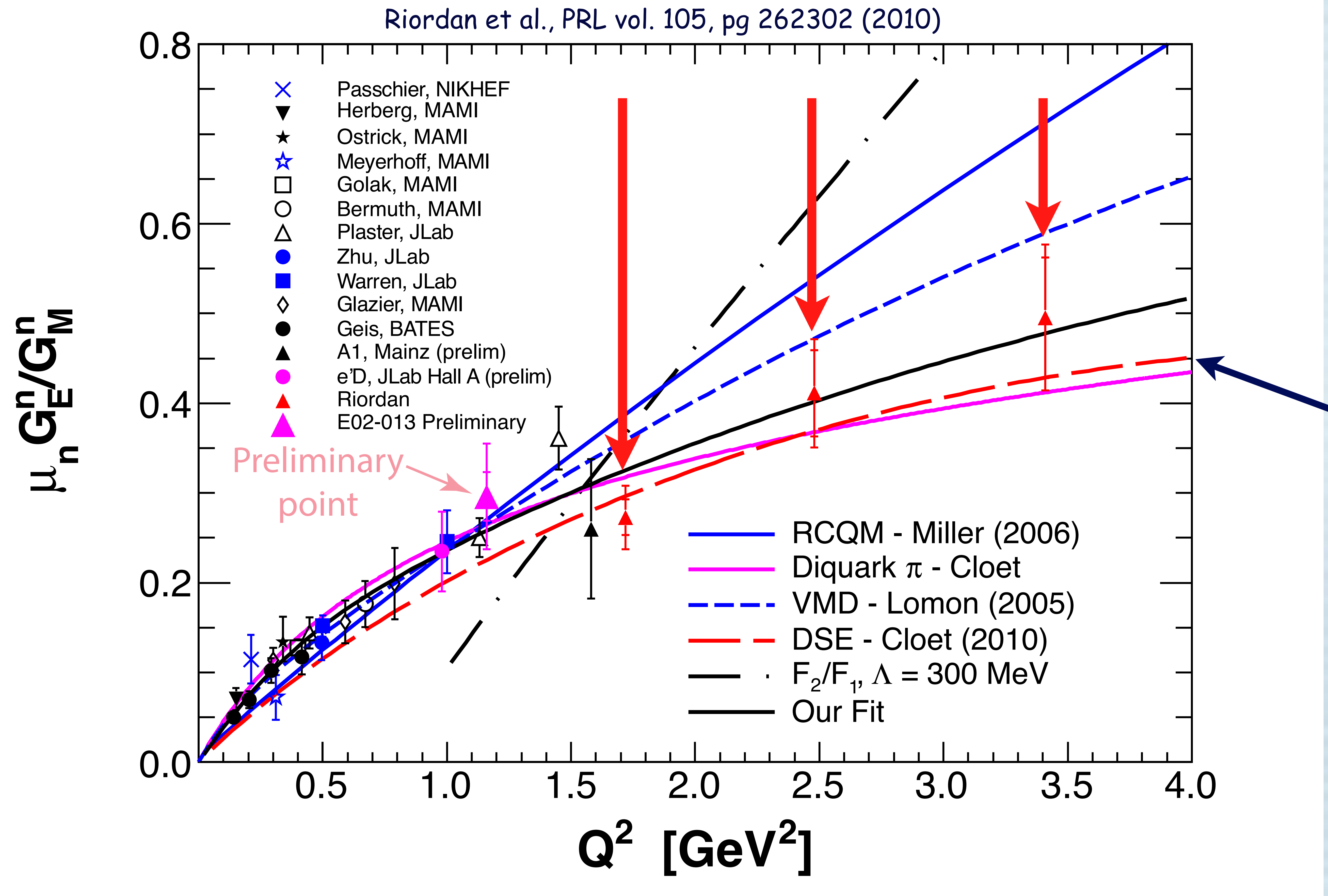
But elastic cross sections at high Q^2 are tiny! To get to a Q^2 comparable with the proton, considerable innovation was needed.



The JLab Hall A GEn-I experiment

- The experiment measured double-polarization asymmetries in $^3\mathrm{He}(\vec{e},\vec{e}'n)pp$
- The electron arm used Big Bite, an open geometry spectrometer using a single dipole, with a detector package that looked directly at the target.
- It also used a high luminosity polarized ^{3}He target, with a figure of merit more than 10x higher than E142 that measured the neutron spin structure.
- The neutron detector was, I believe the world's largest at that time.

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



Belitsky, Ji and Yuan, logrithmic corrections - 2003

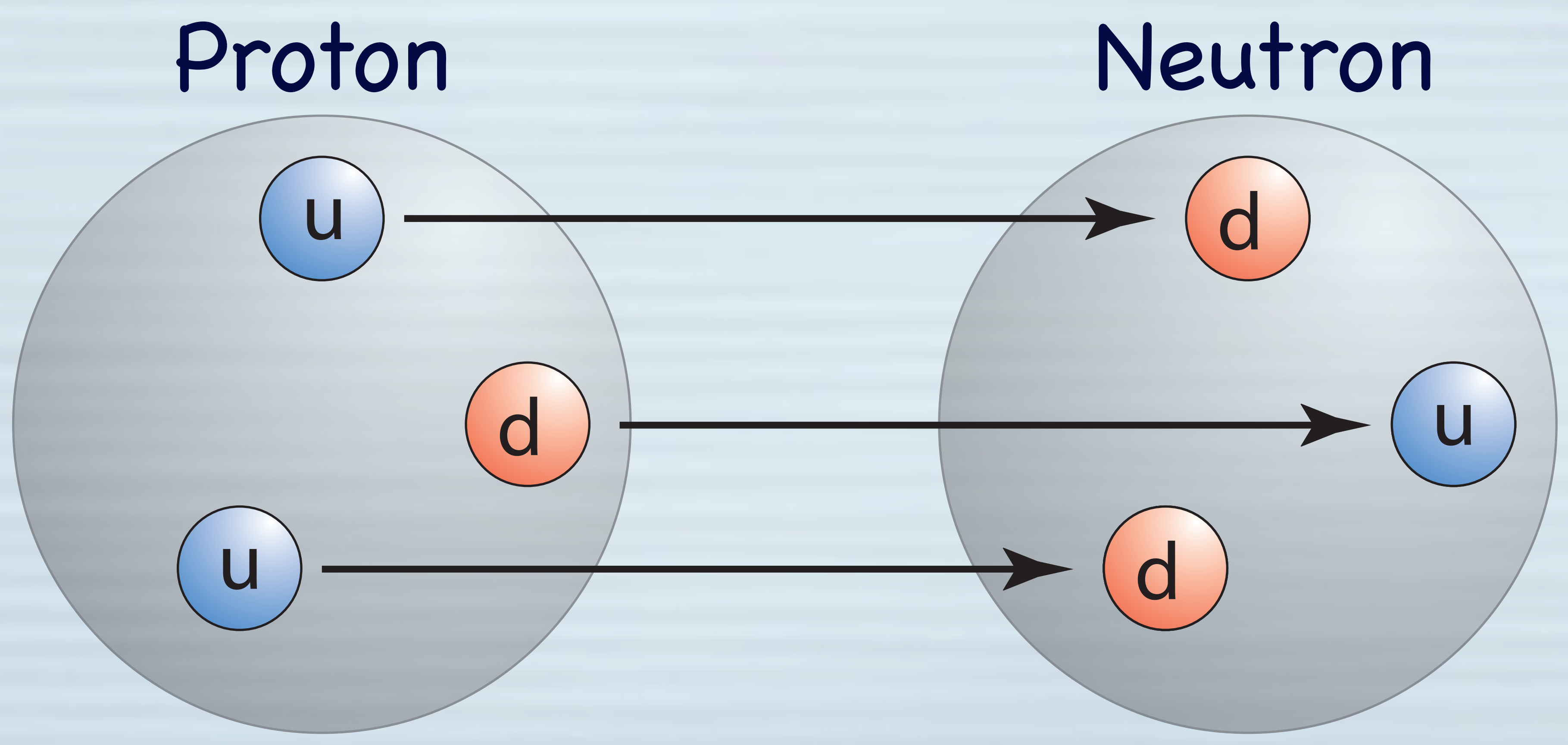
Miller's RCQM - 2002

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

Extracting flavor-separated form factors

By assuming charge symmetry and combining data from both proton and the neutron, the individual contributions from the up- and down-quarks can be extracted.

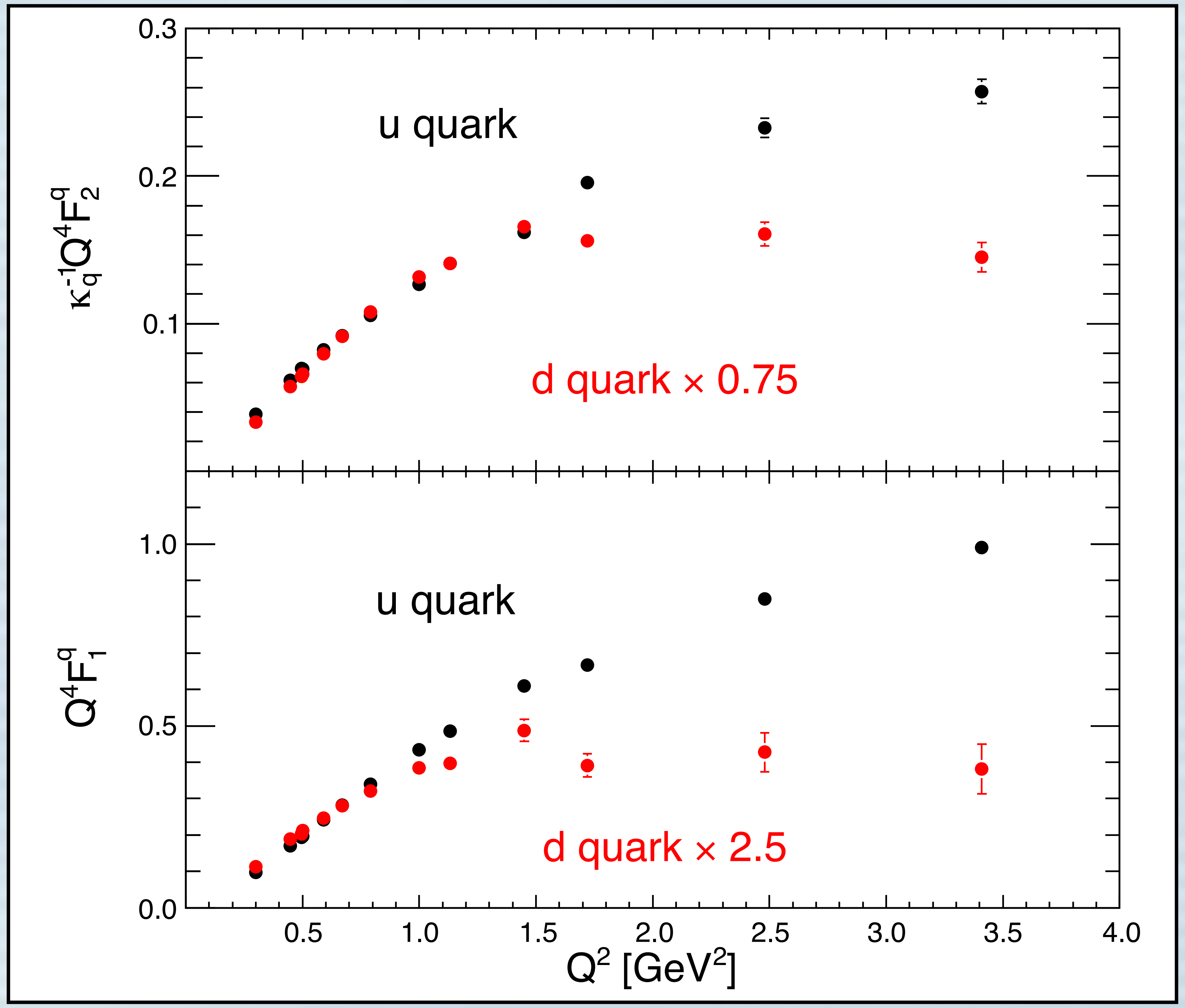


For the Dirac form factors (and similarly for the Pauli form factors):

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

The behavior of the u- and d-quark form factors are quite distinct from on another

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

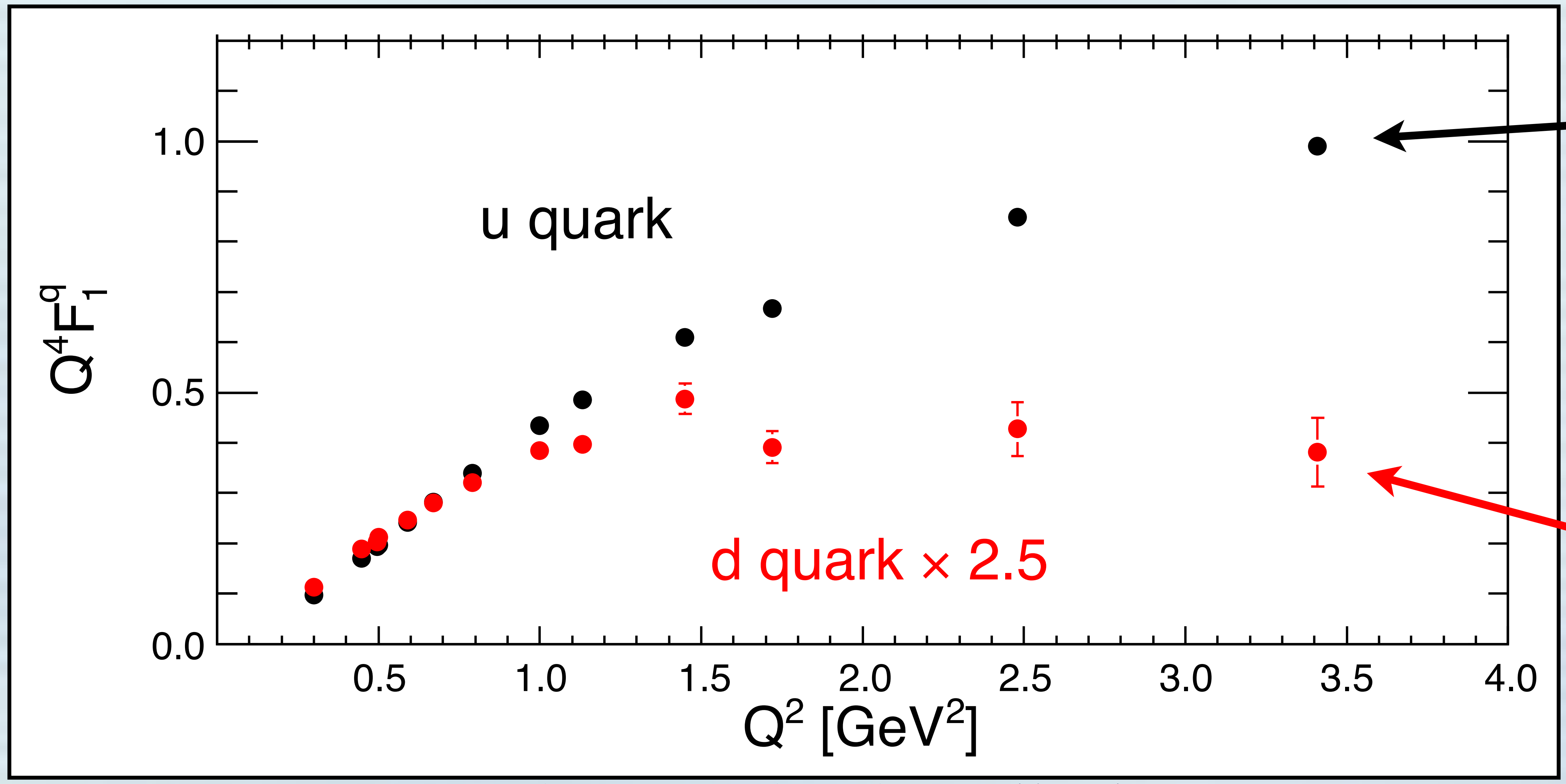


$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

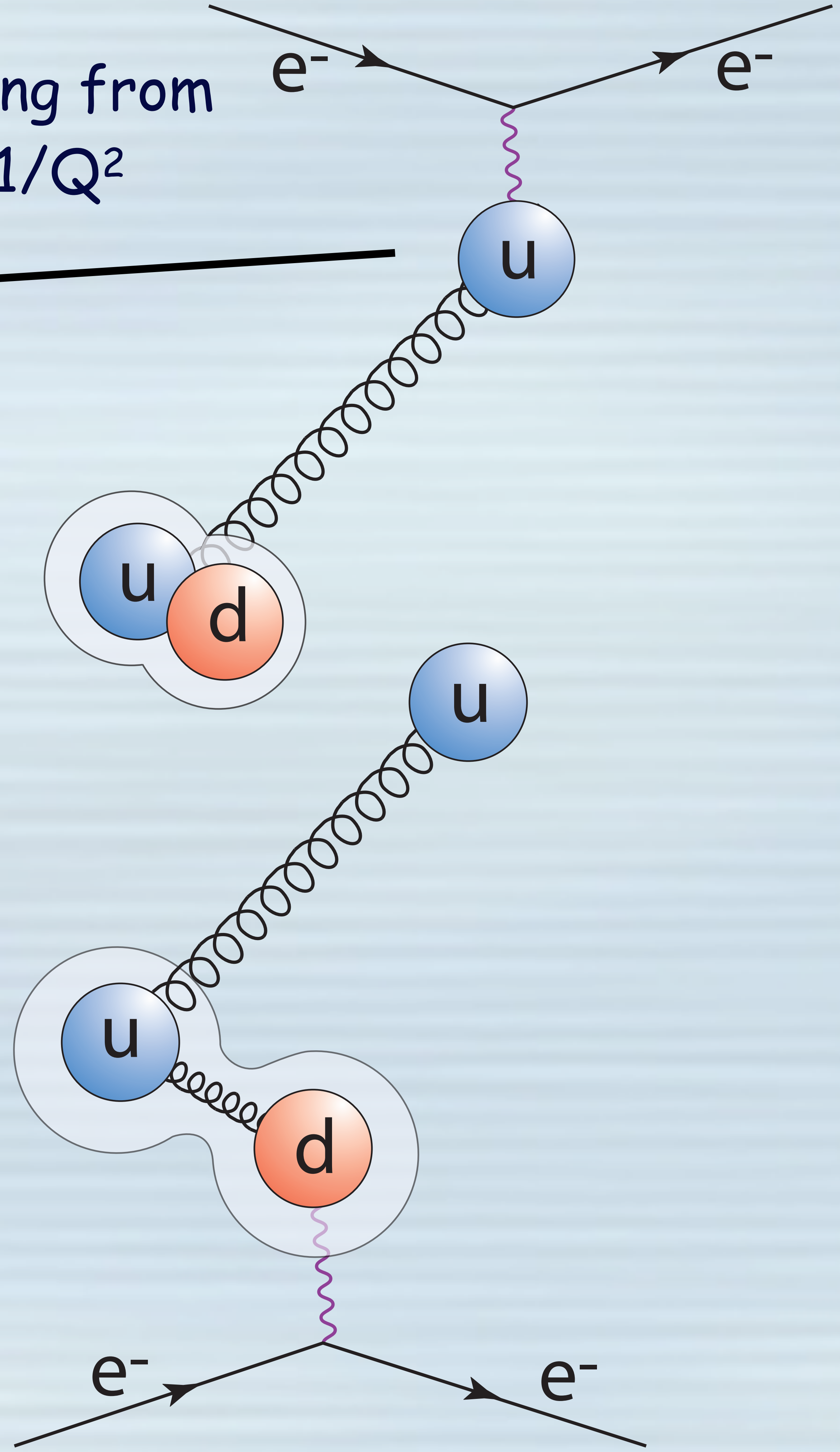
Many of the theoretical models that reproduce the above trends indicate the importance of diquark correlations.

Quark counting rules provide a potential naive explanation for how diquarks might cause different Q^2 behavior of the u- and d-quark form factors

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

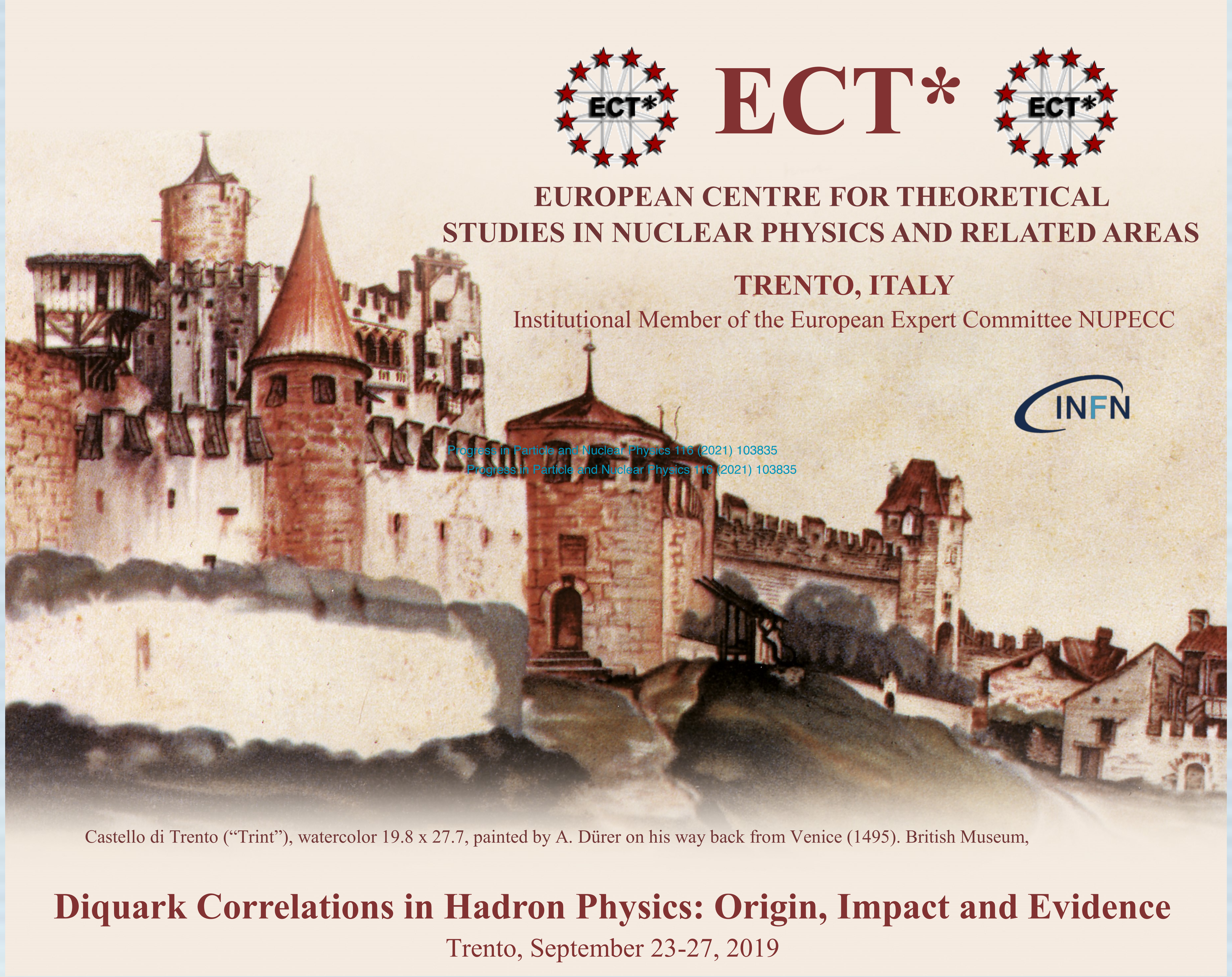


Cates, de Jager, Riordan and Wojtsekhowski,
PRL vol. 106, pg 252003 (2011)



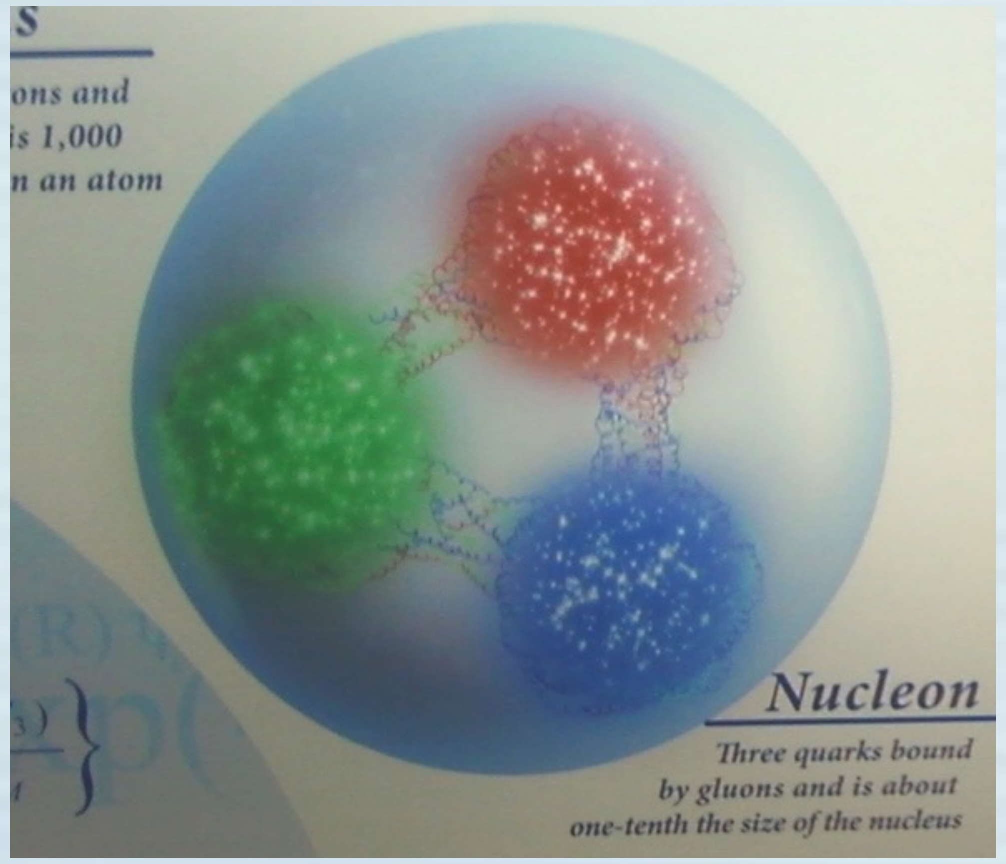
d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

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

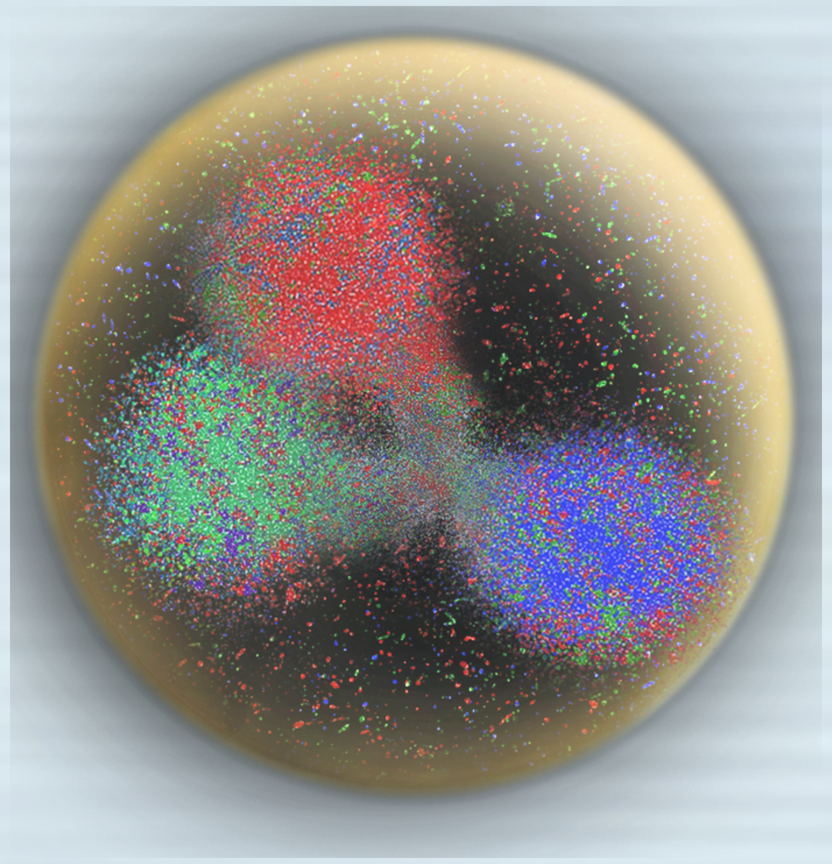


Review article grew out of the workshop: "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence", Progress in Particle and Nuclear Physics 116 (2021) 103835".

A fun question: could flavor-separated form factors <u>qualitatively</u> change our picture of the nucleon?



A cartoon of the nucleon
from the lobby of JLab

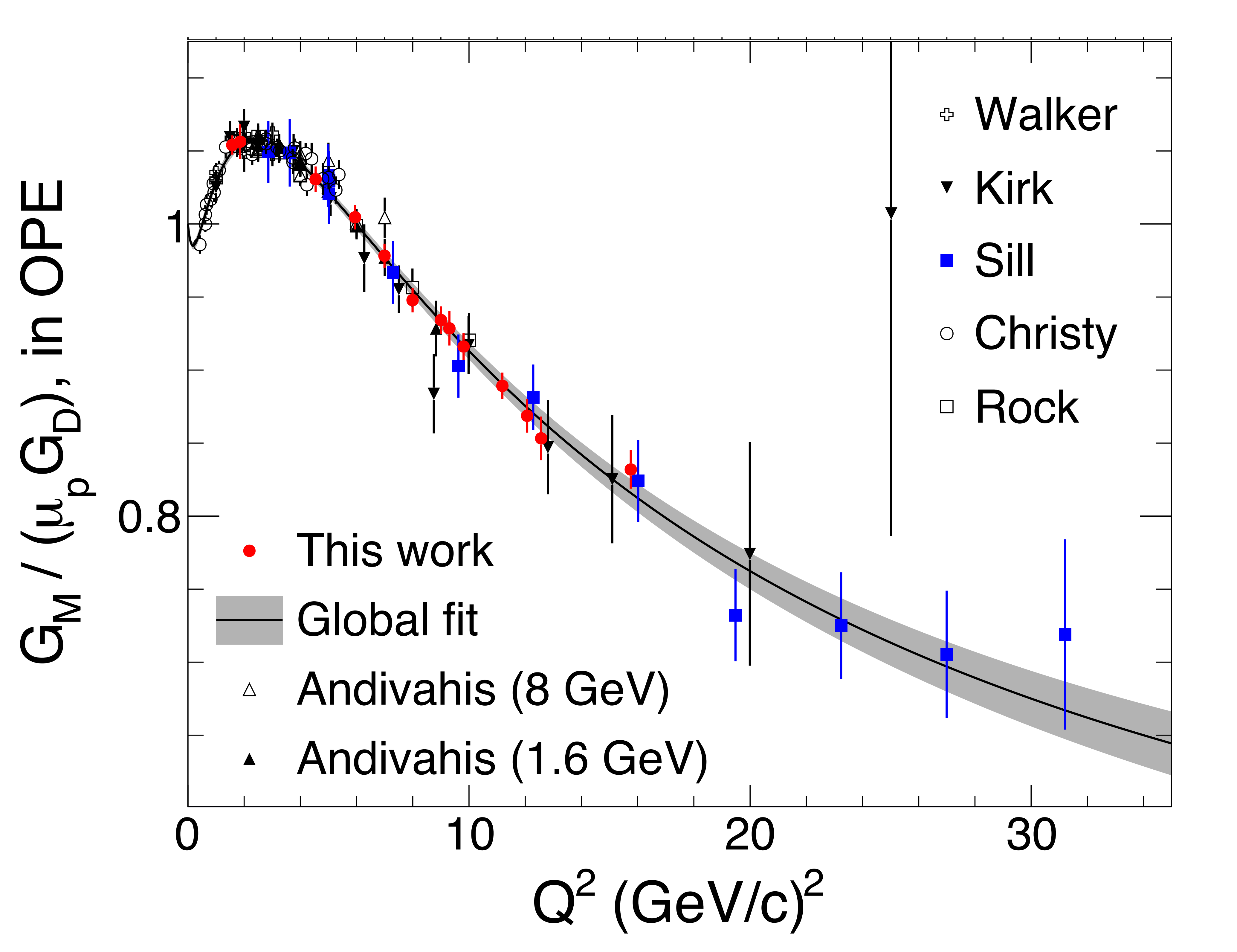


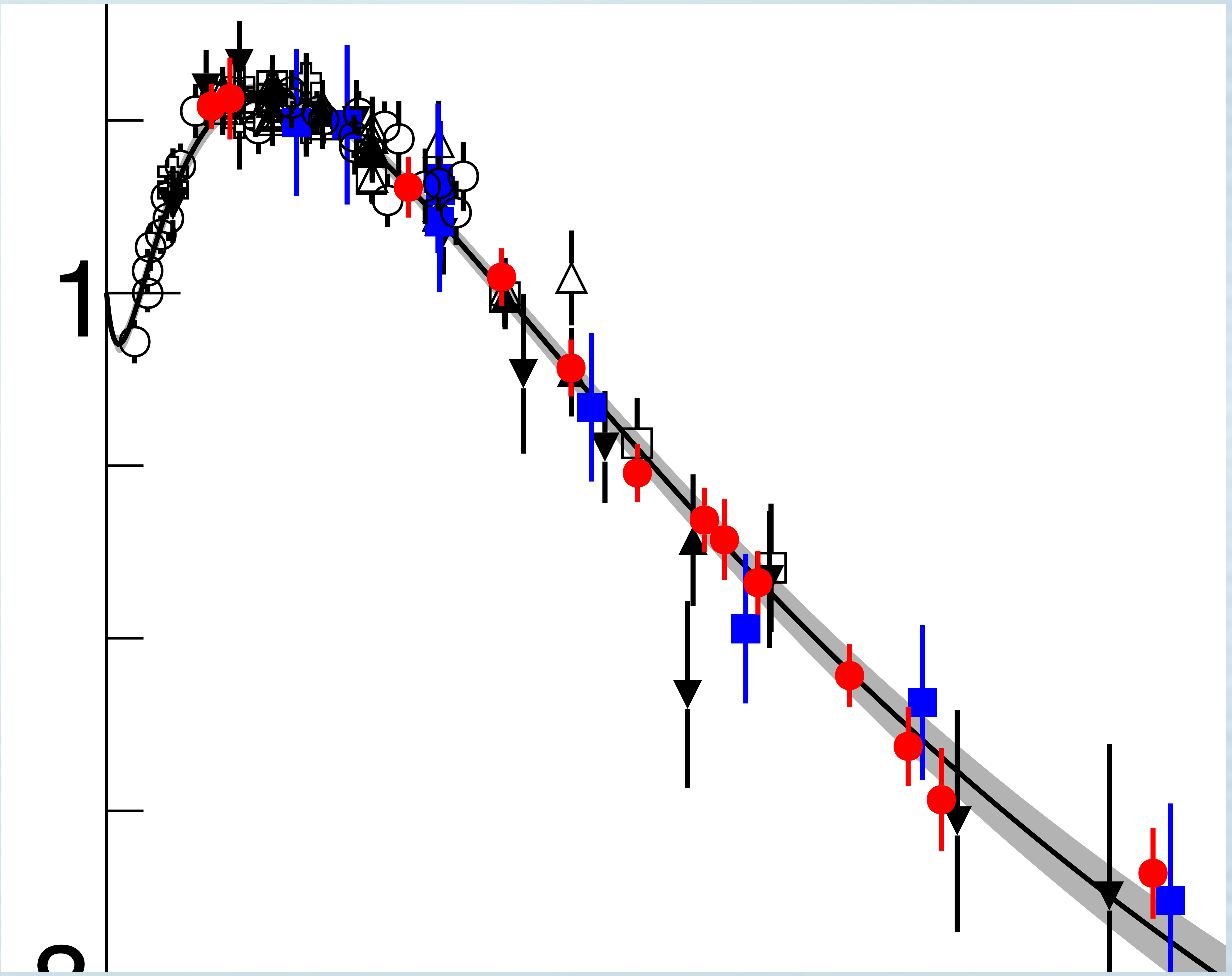
From the DOE Pulse Newsletter:
A not-very-scientifically guided depiction of a nucleon with a diquark-like structure

While this cartoon is WAY too simple, it illustrates how the flavor-separated form factors might influence fundamental concepts of hadronic structure

Nucleon form factors in the JLab 12 GeV era

Precise new extraction of the proton's magnetic form factor up to $Q^2 = 15.75\ GeV^2$

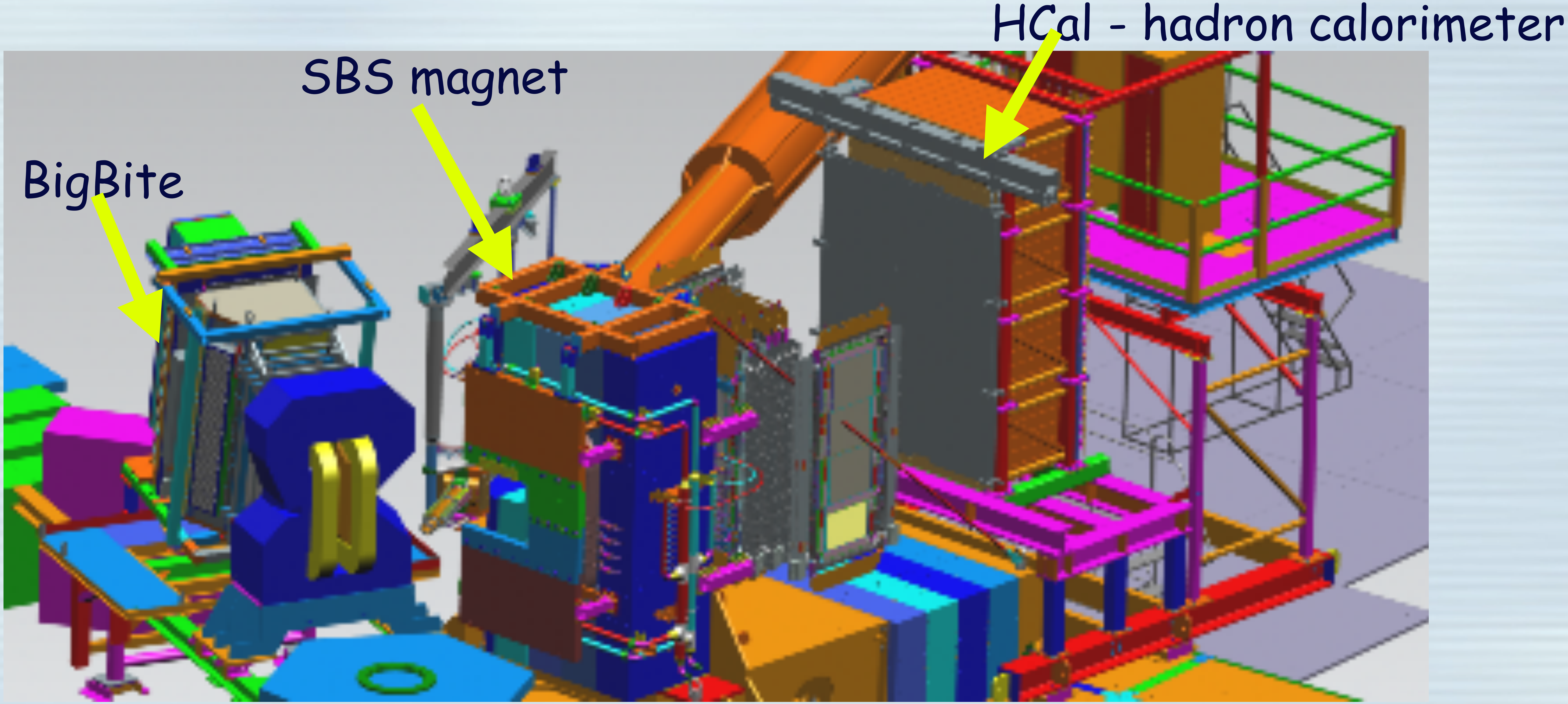




Shown at left is the extraction of G_M^p resulting from JLab E12-07-108 (PRL v128, 102002 (2022)).
At right is a blown up version of the of the figure at left to better visualize the new points.

The Super Bigbite Spectrometer (SBS) program

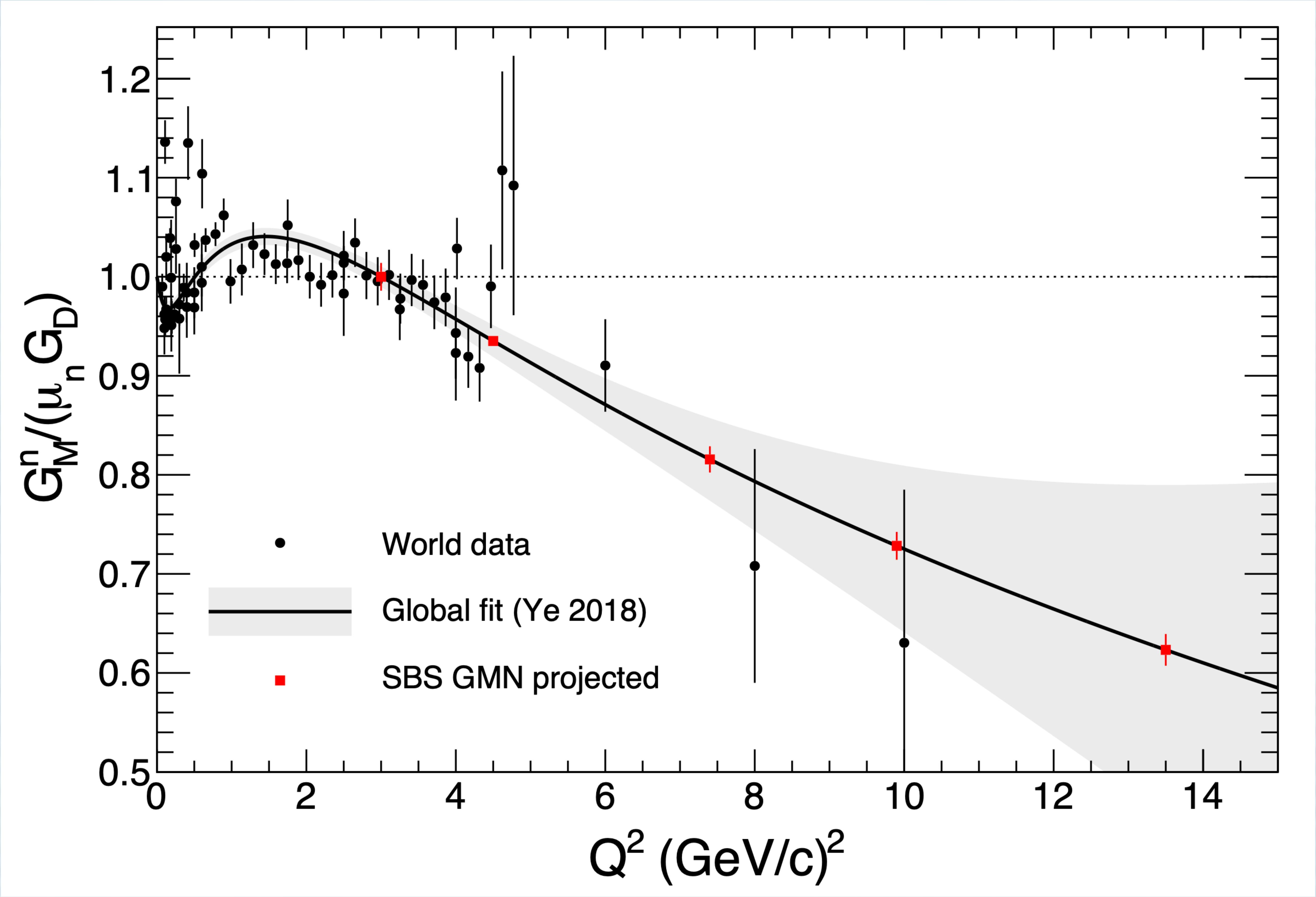
(apparatus shown in roughly the configuration used for GMn and GEn measurements)



The ongoing Super Bigbite Spectrometer (SBS) nucleon form factor program

- G_M^n/G_M^p (E12-09-019) - Q^2 up to 13.5 GeV^2. COMPLETE!!! – Oct. 2021 – Feb. 2022
- G_E^n/G_M^n (E12-09-016) - Q^2 up to ~ 9.7 GeV^2. ONGOING!!! – Oct. 2022 – present
- G_En-RP (E12-17-004) - Q^2 ~ 4.5 GeV^2 Beginning roughly January of 2024
- G_E^p/G_M^p (E12-07-109) - Q^2 up to ~12 GeV^2. Beginning roughly fall of 2024

The Projected error bars from the SBS GMn experiment based on the actual acquired data

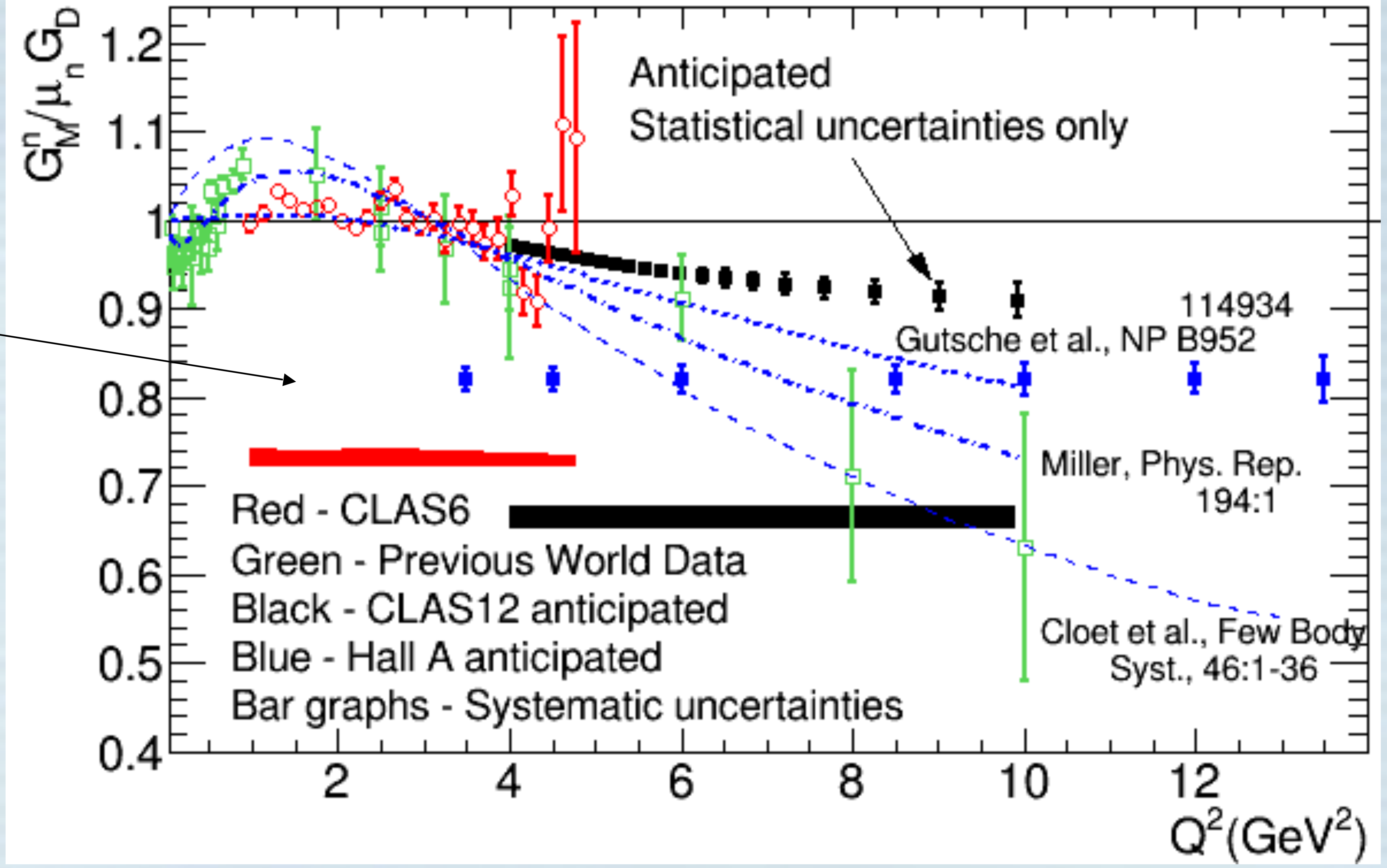


The SBS GMn experiment could establish a zero crossing in F1d/F1u, an observation that would be challenging to interpret within the GPD framework.

Neutron Magnetic Form Factor in CLAS12

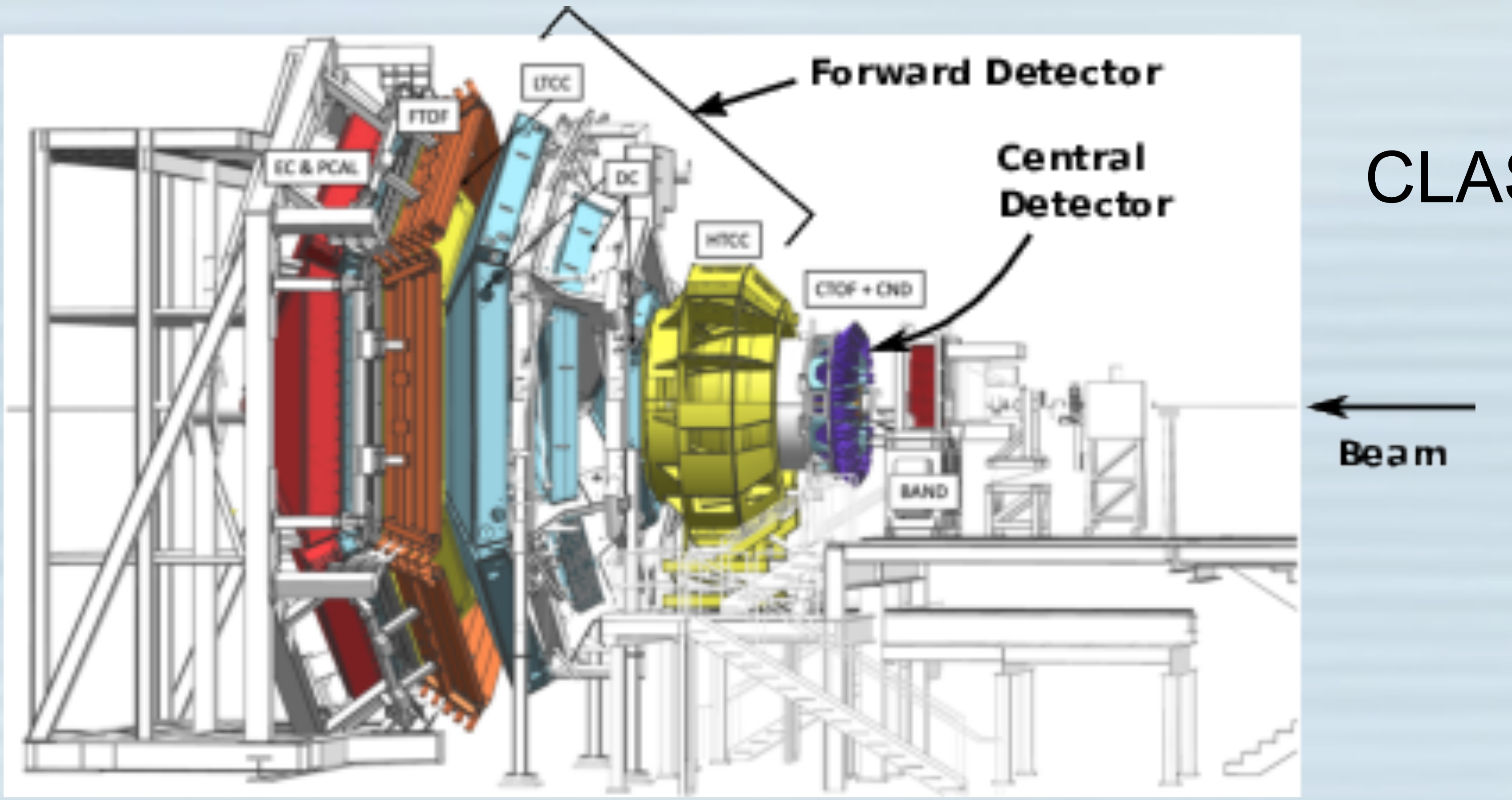
G_M^n Measurement with CLAS12 in Hall B

- Complementary to Hall A measurement – different systematic uncertainties.
- Uses the same *R=e-n/e-p* ratio method.
- Different Q^2 coverage than Hall A – higher angular density, smaller range.
- Run Group B, Lamya Baashen (FIU) thesis.



The CLAS12 Detector

- Covers most of 4π.
- Forward Detector covers ϴ = 5 - 40 deg.
- Over 100,000 readouts in 40 layers.



CLAS12

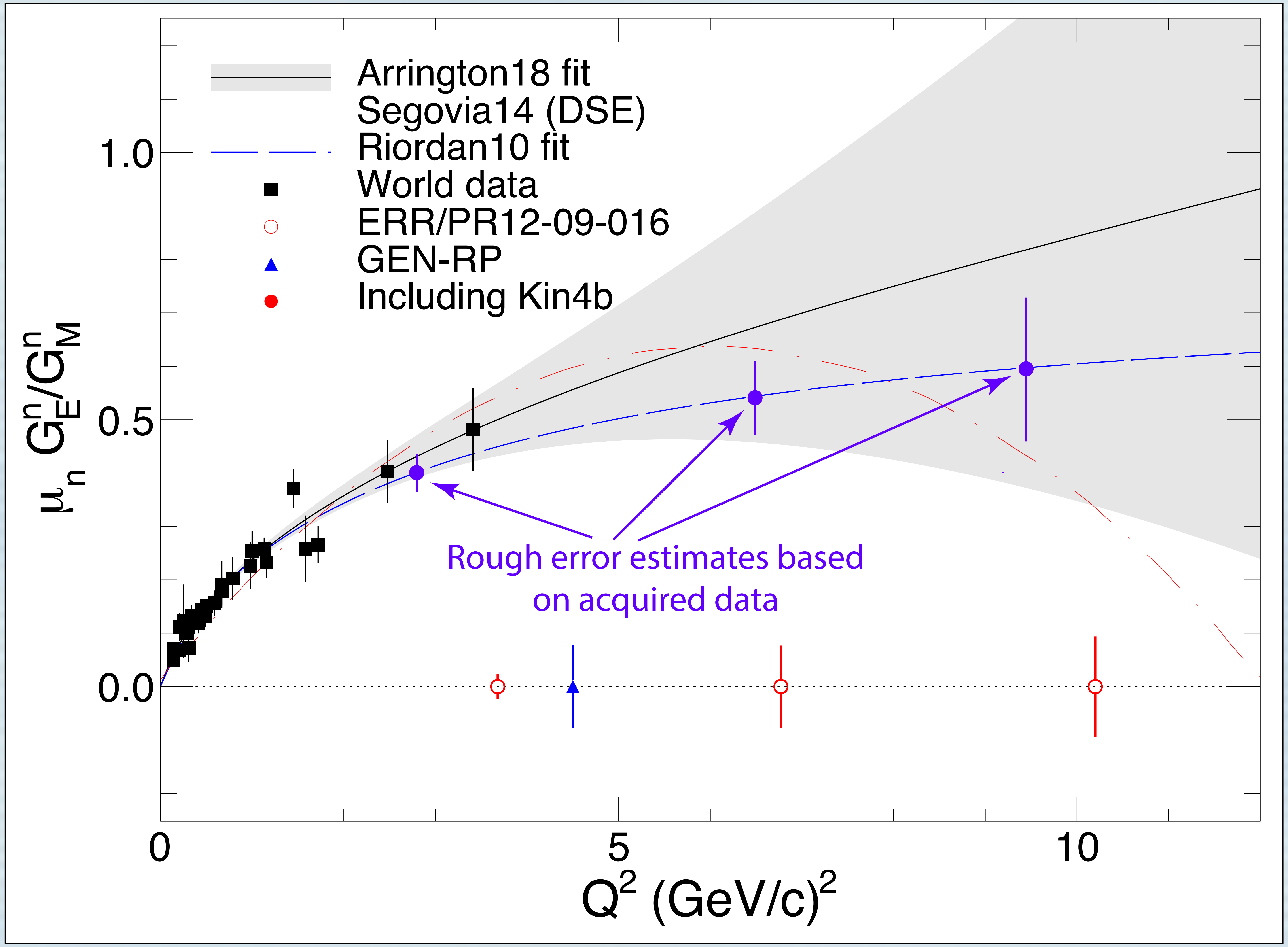
The Data Set – CLAS12 Run Group B

- 43 Billion triggers at 10.2, 10.4, and 10.6 GeV.
- Average beam polarization ~86%.
- 43% of approved beamtime used.
- All runs have completed cooking/pass 1.

courtesy of J. Gilfoyle

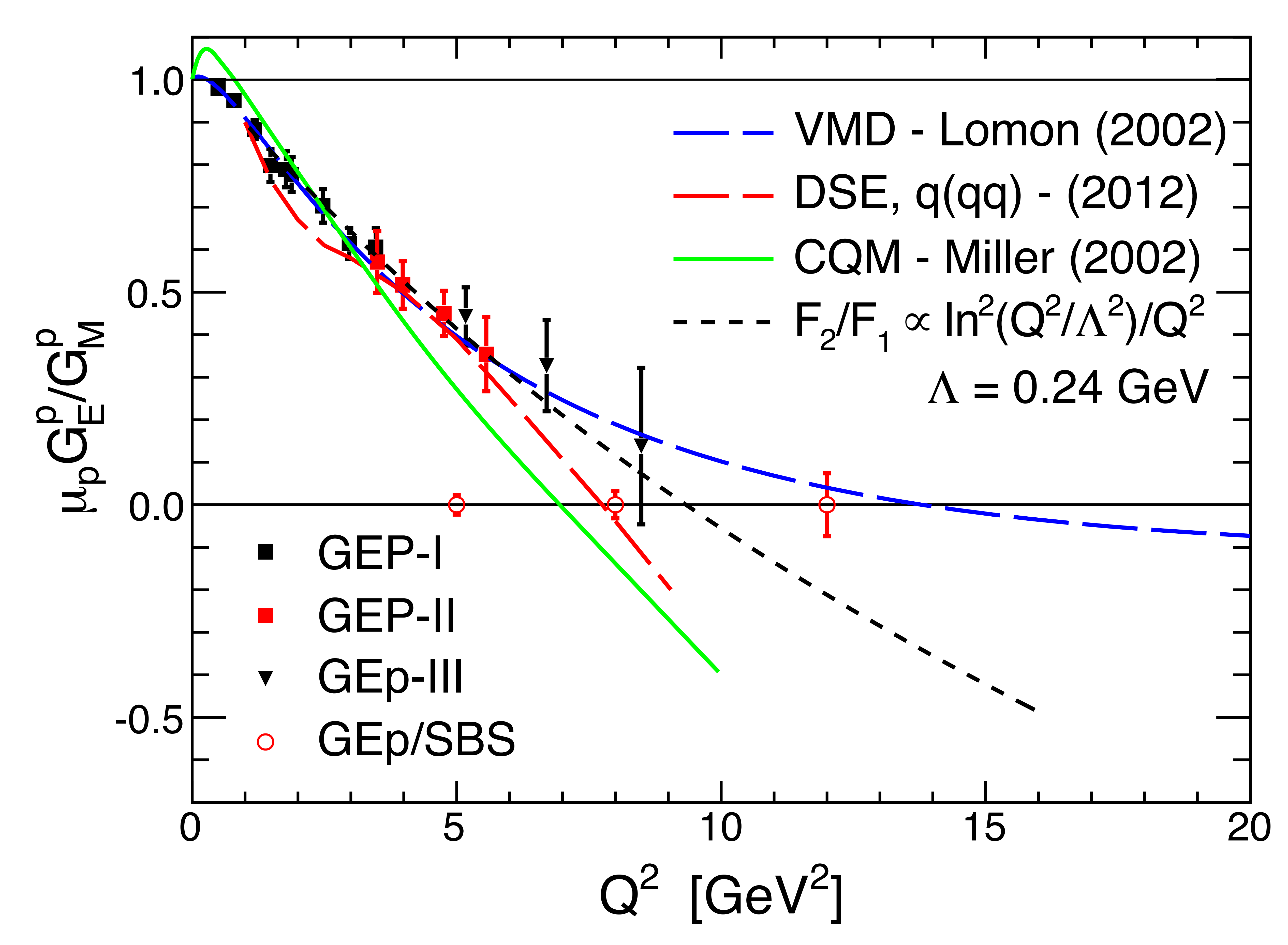
Projected errors for SBS GEn-II

October 2022 - present (running as we speak!)



- Data have been acquired for two out of three kinematic settings.
- Additional data taking is ongoing for our highest Q^2 point.
- The experiment will nearly triple the Q^2 range over which GEn is known.

The Projected error bars from the SBS GEp experiment



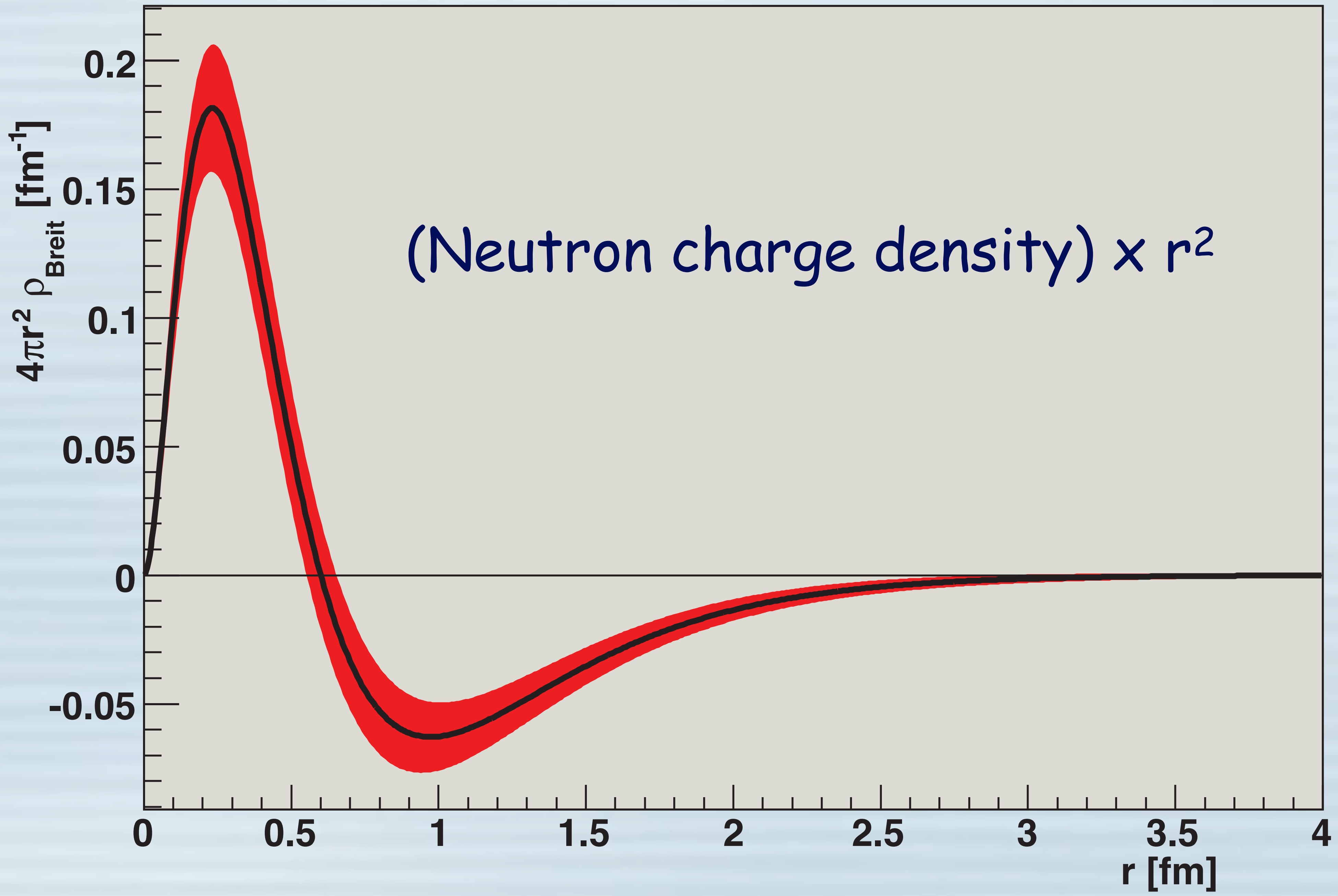
Summary

- The elastic nucleon form factors seem to be the gift that just keeps on giving!
- The form-factor program at JLab will provide the definitive measurements of these important quantities for a very long time come.
- The precision and the Q^2 reach of the JLab form factor program at JLab will provide valuable insights with real discovery potential.

Backup slides

A non-relativistic "snapshot" of the neutron

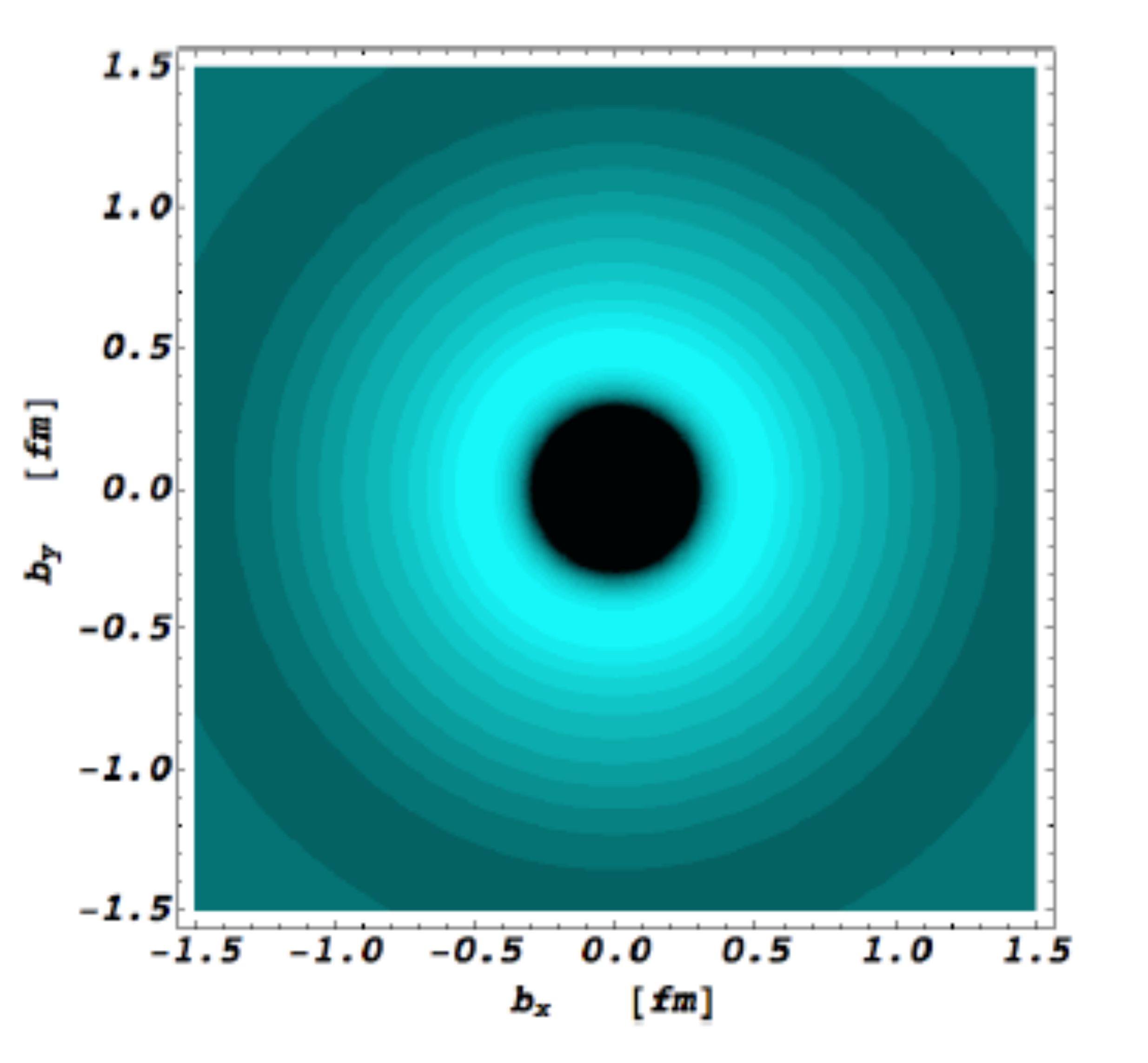
(in roughly the lab frame essentially taking the Fourier transform of G_E^n)



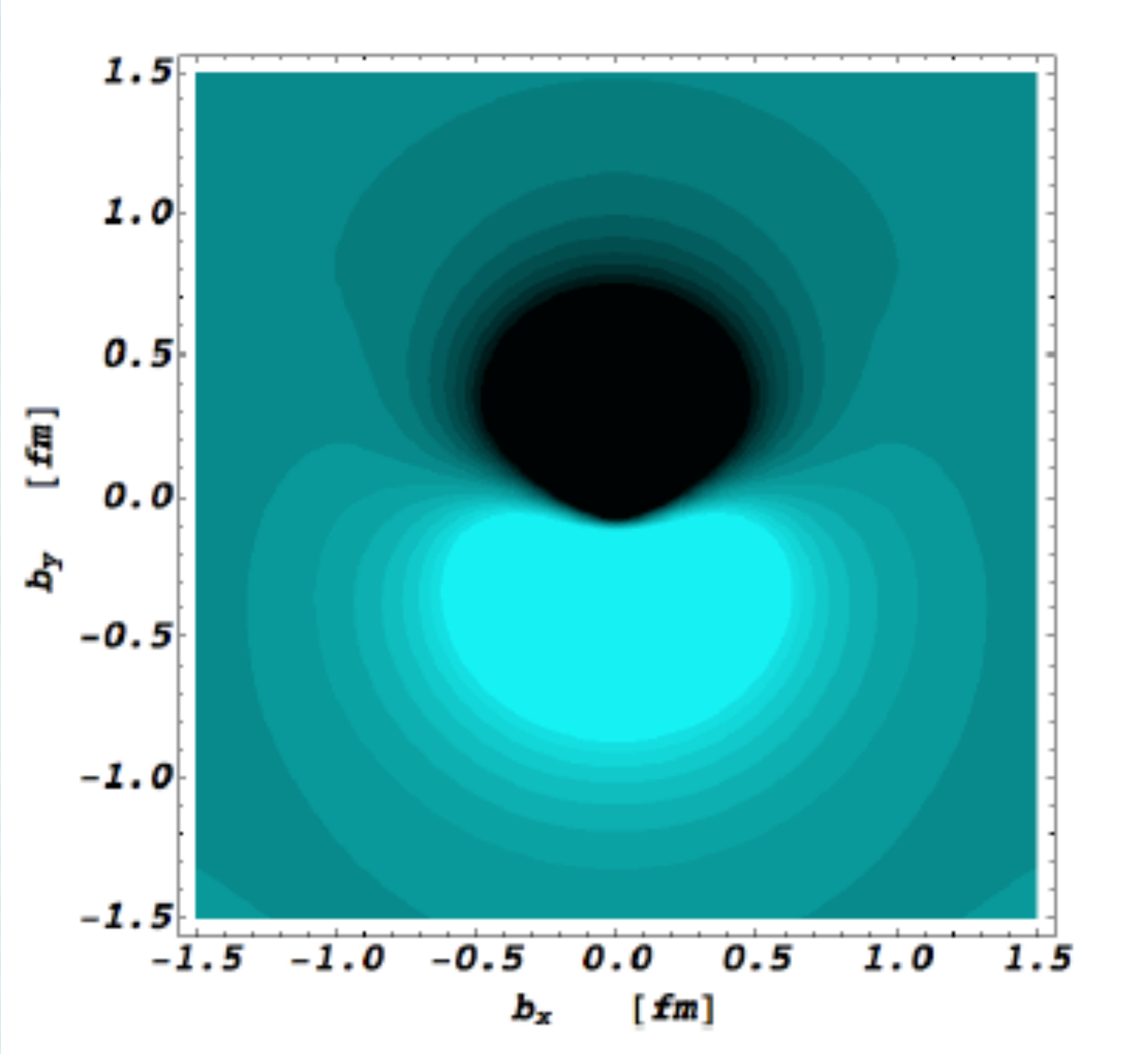
From the 2007 Long Range Plan

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



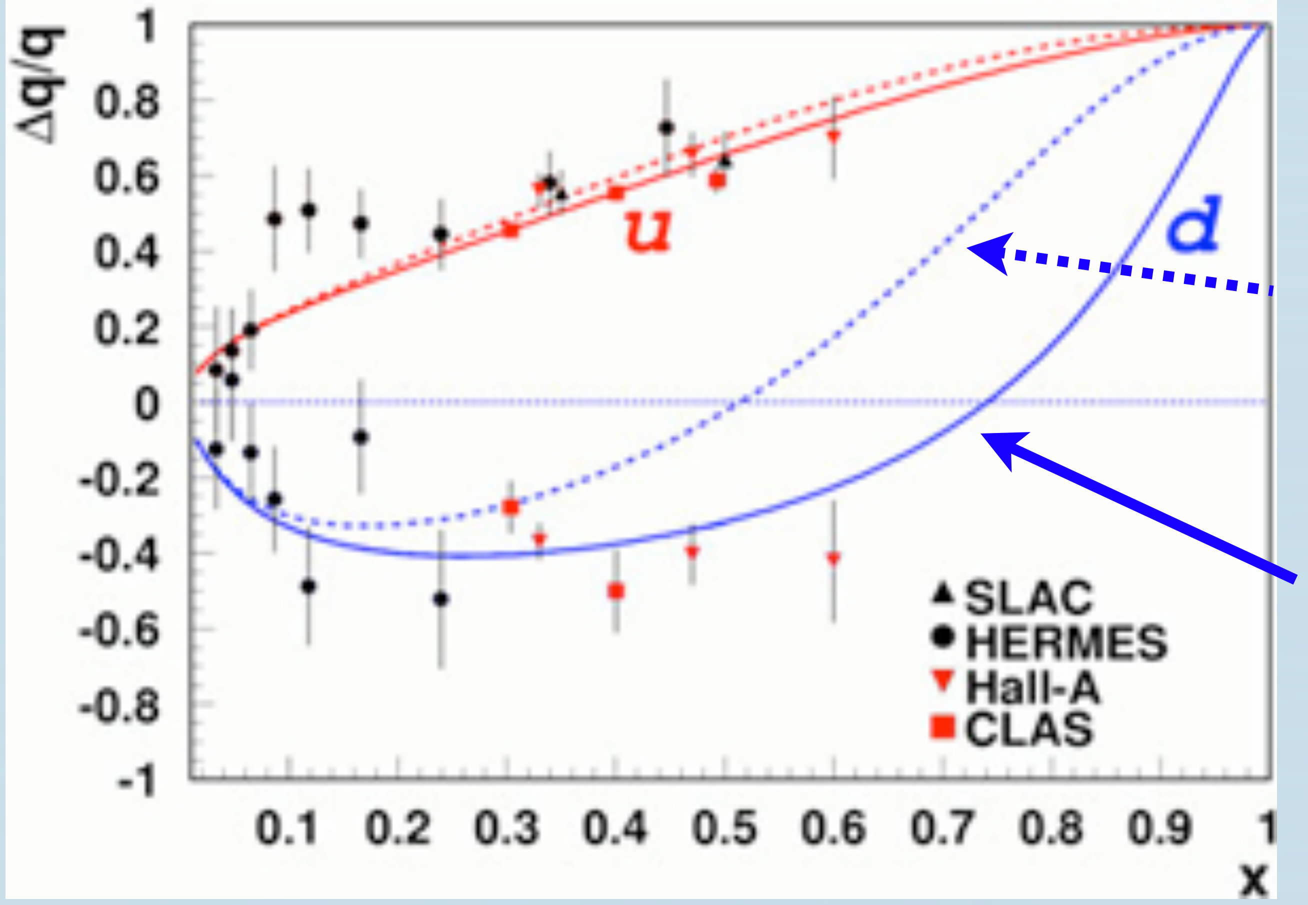
Transversely polarized neutron

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

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

Deep-inelastic scattering with polarized beam and targets

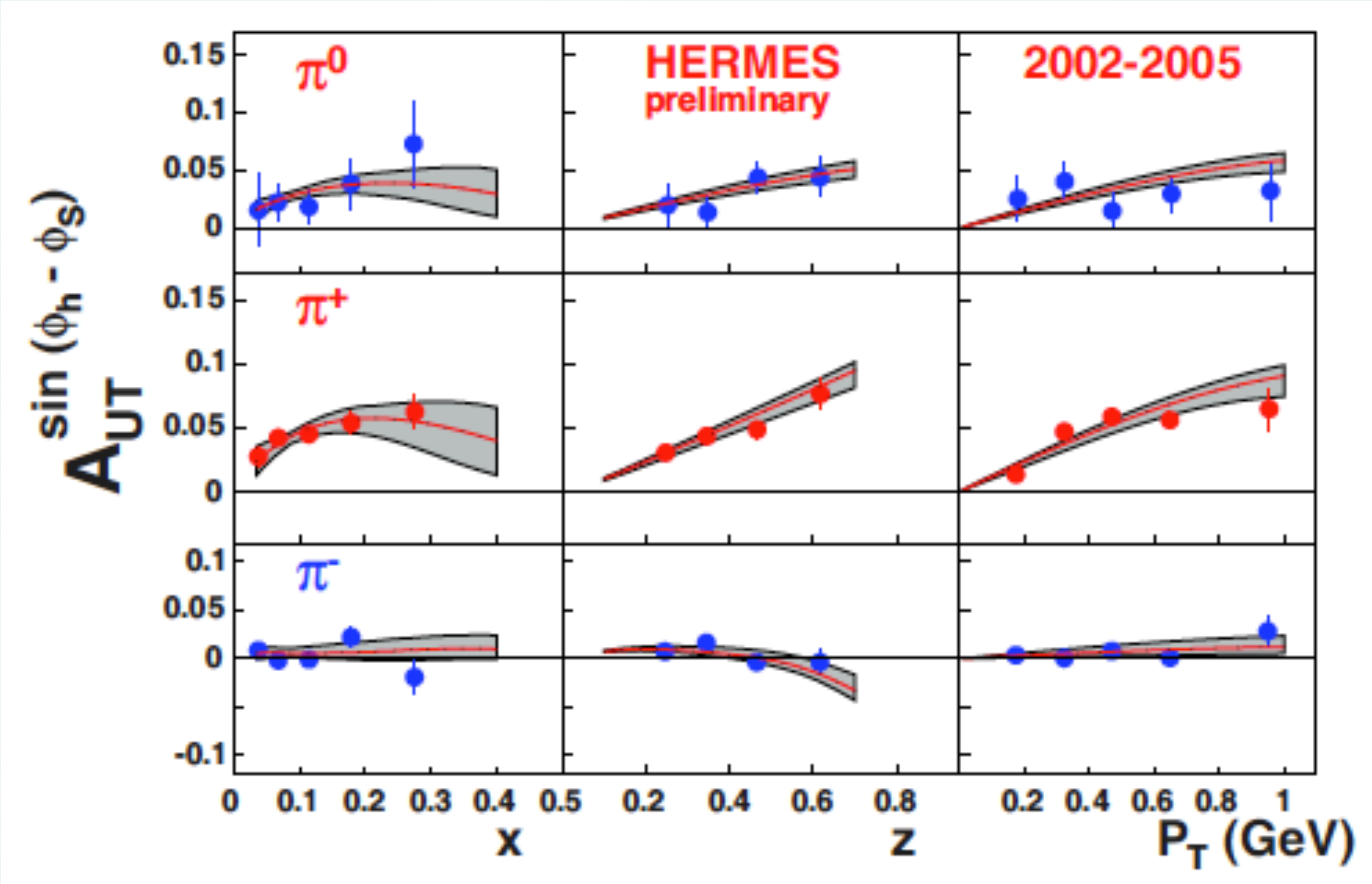


Model without quark orbital angular momentum.

Model with quark orbital angular momentum.

Flavor-separated spin contributions from up and down quarks

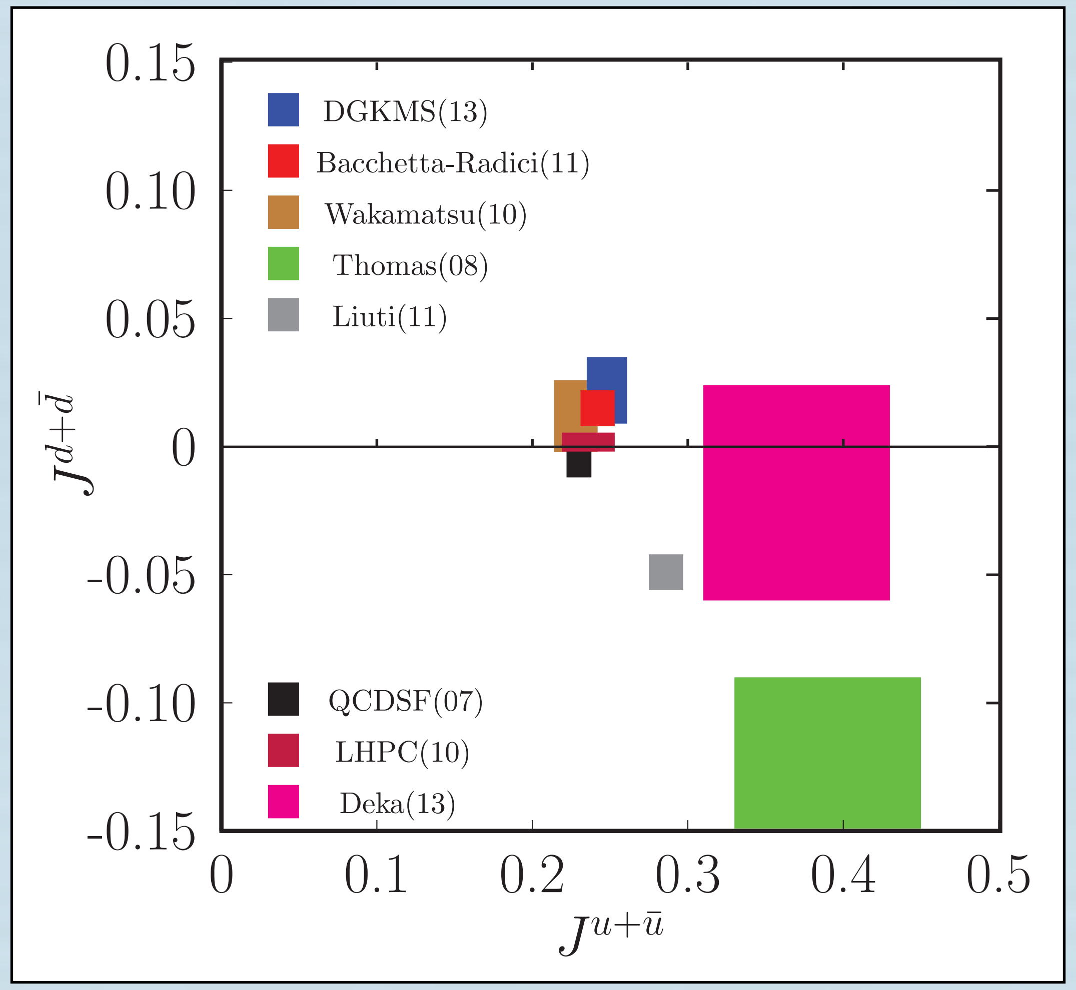
Non-zero Sivers effect in semi-inclusive DIS



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

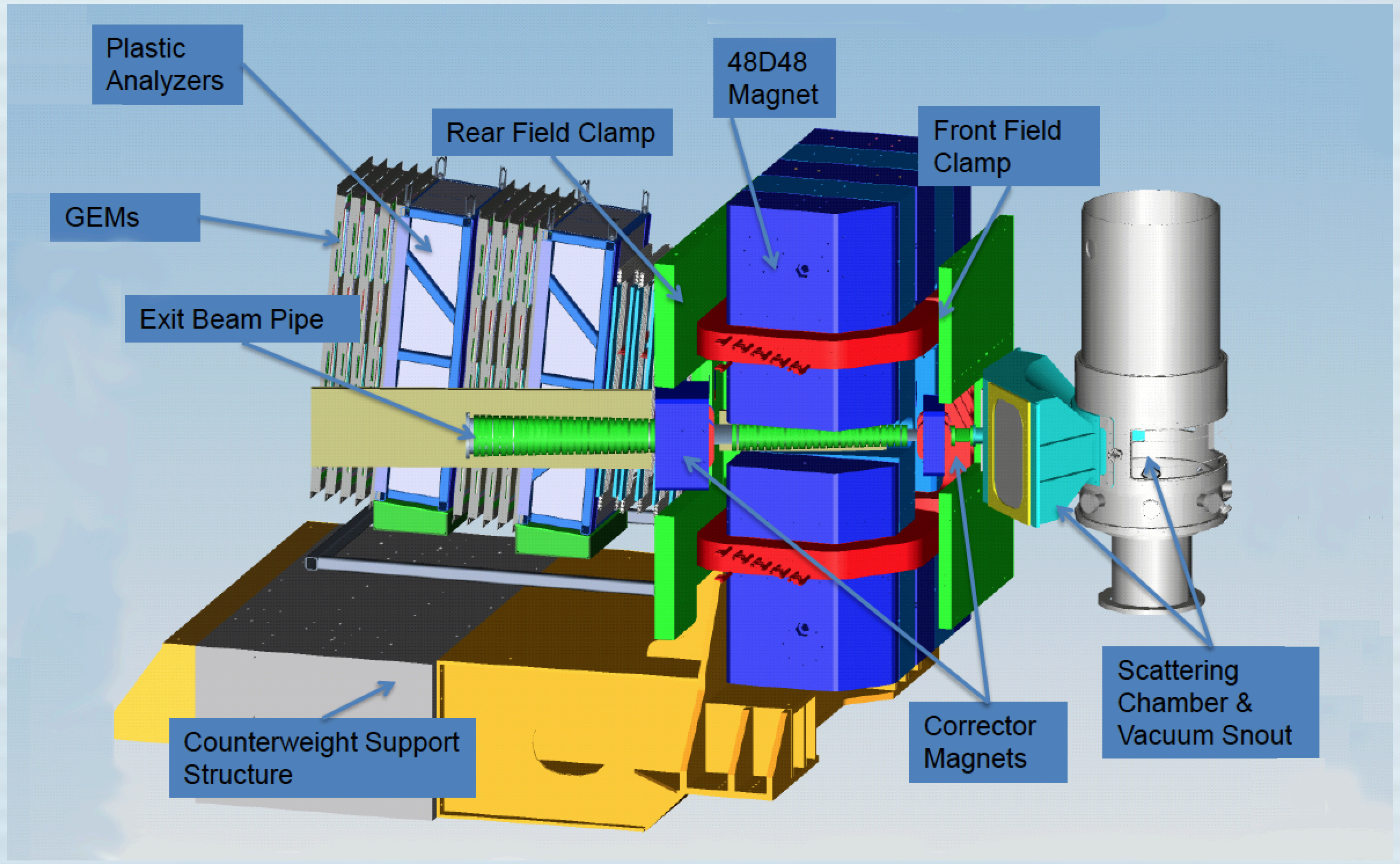
$$L^{u+\bar{u}} = -0.146 \ldots -0.172$$

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



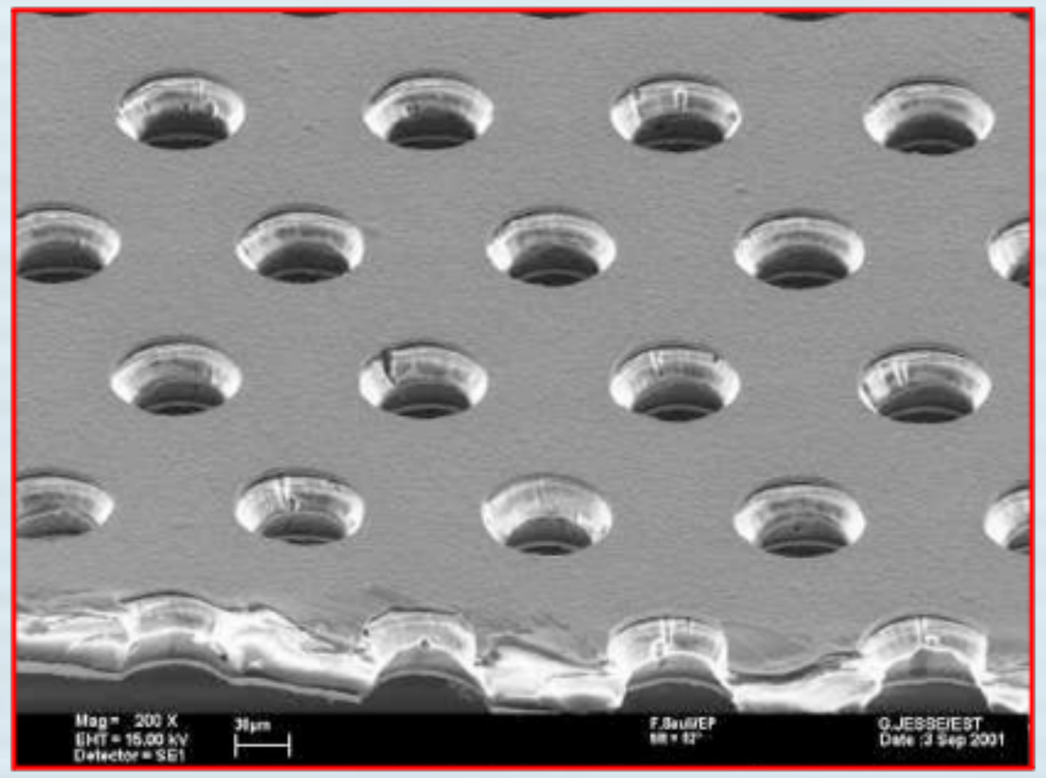
P. Kroll, EPJ Web of Conferences **85**, 01005 (2015)

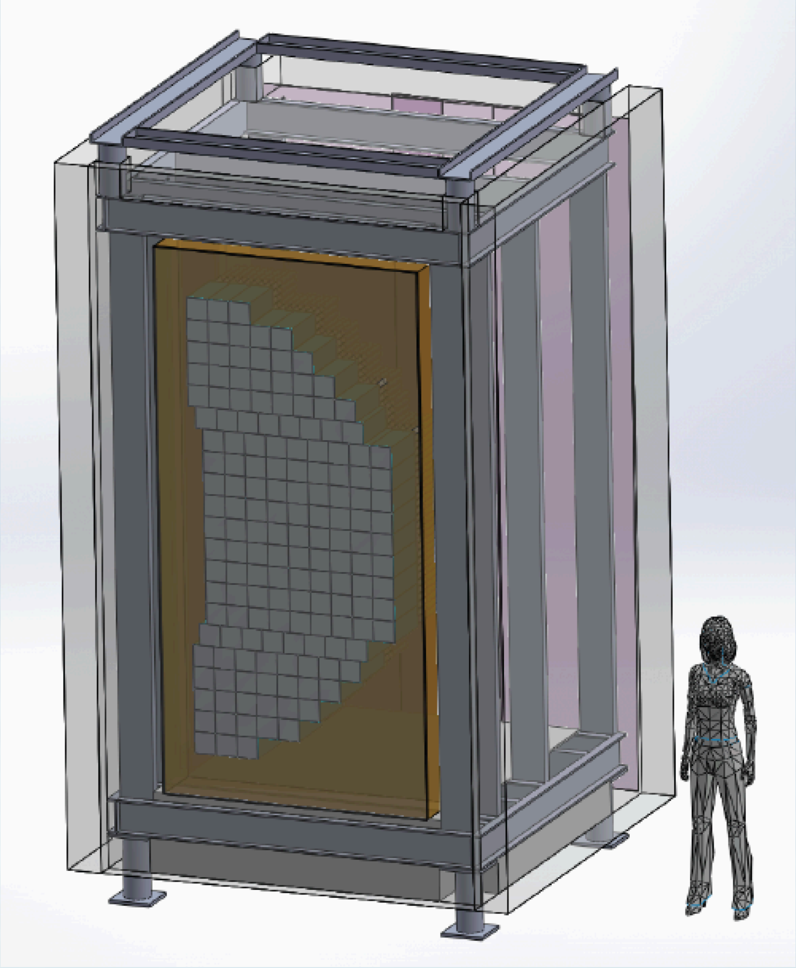
What is SBS ?



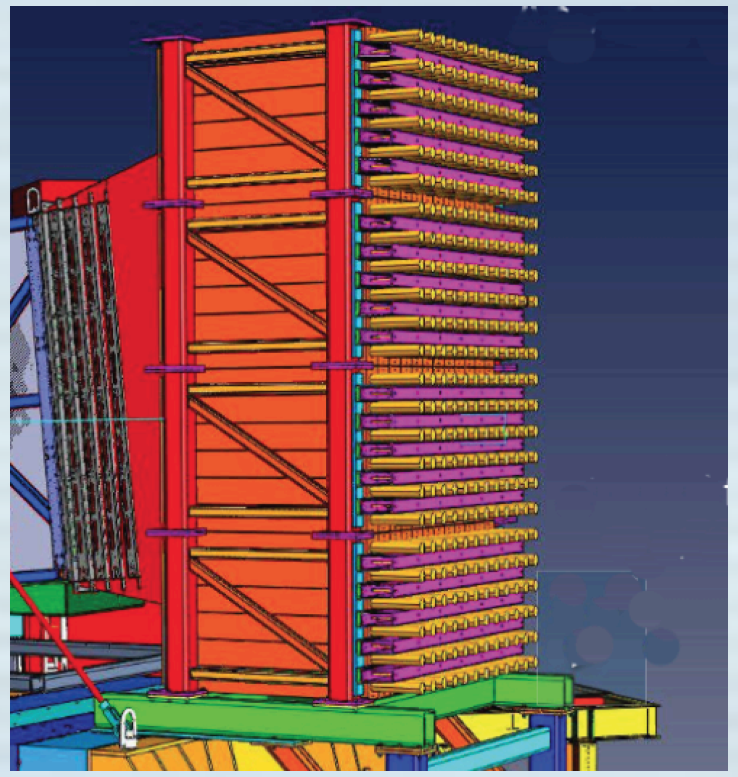
SBS configured for the G_{Ep} experiment

GEM foil: 50 μm Kapton + few μm copper on both sides with 70 μm holes, 140 μm pitch

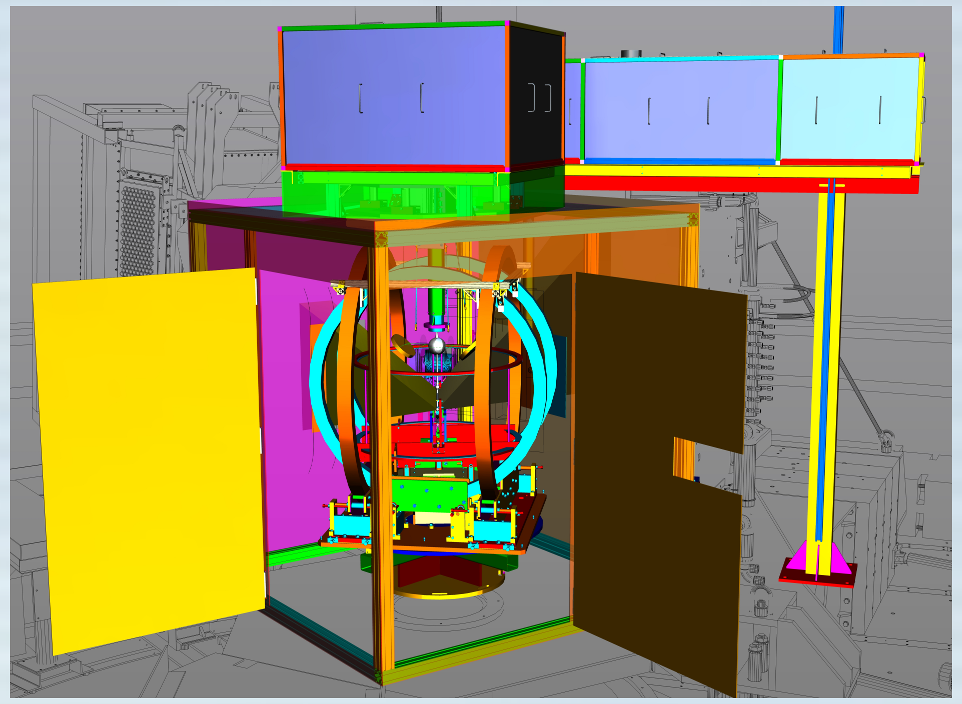




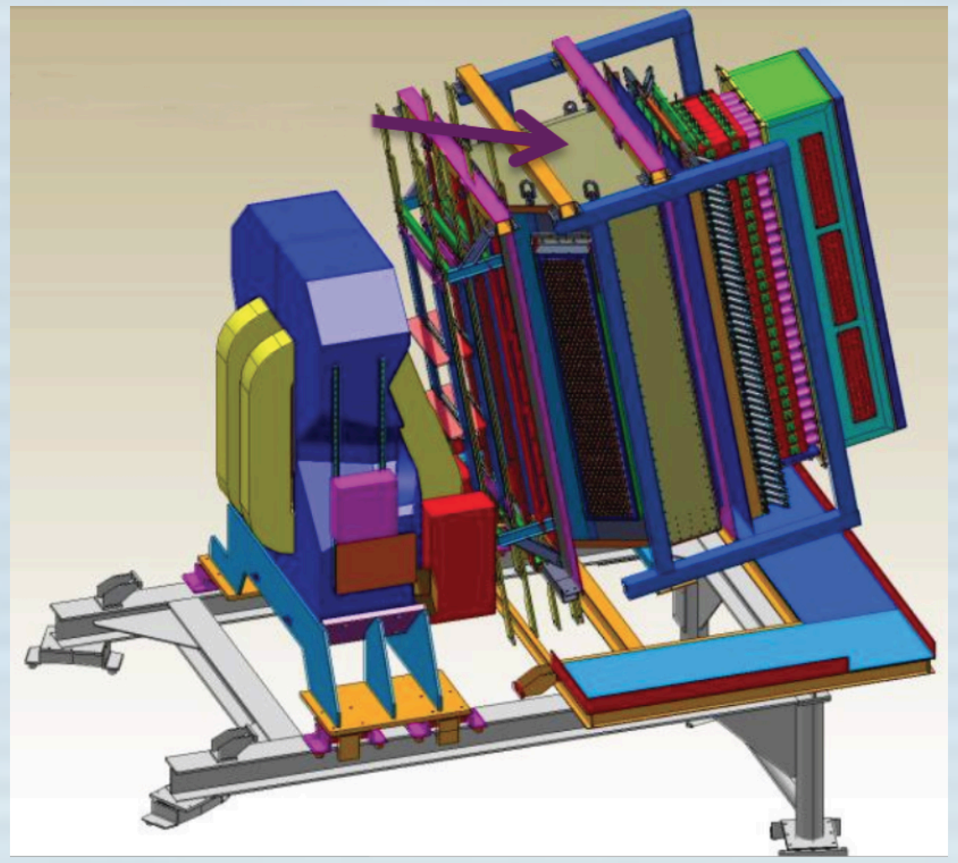
ECal - electron calorimeter



HCal - hadron calorimeter



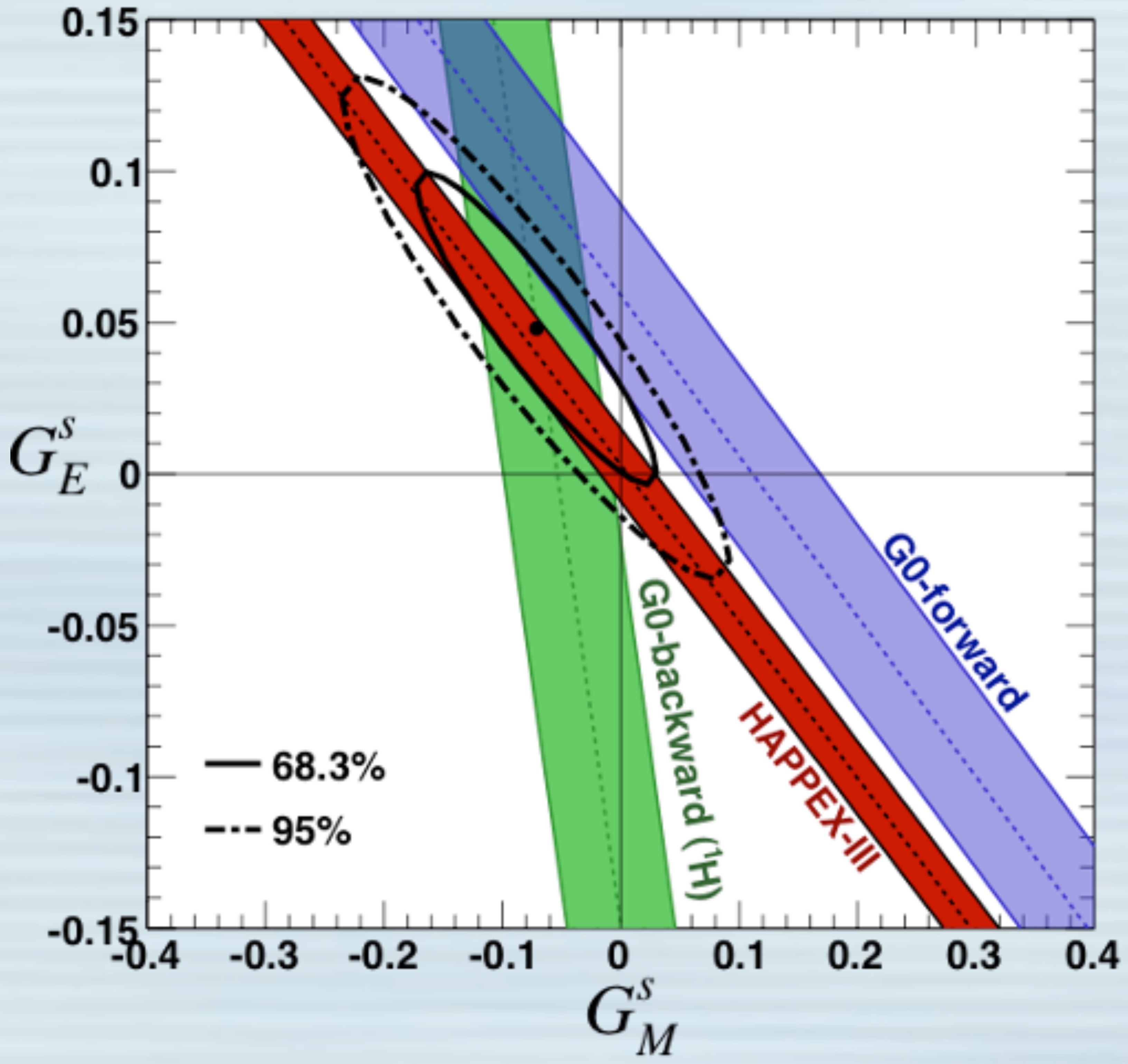
Polarized ^{3}He target

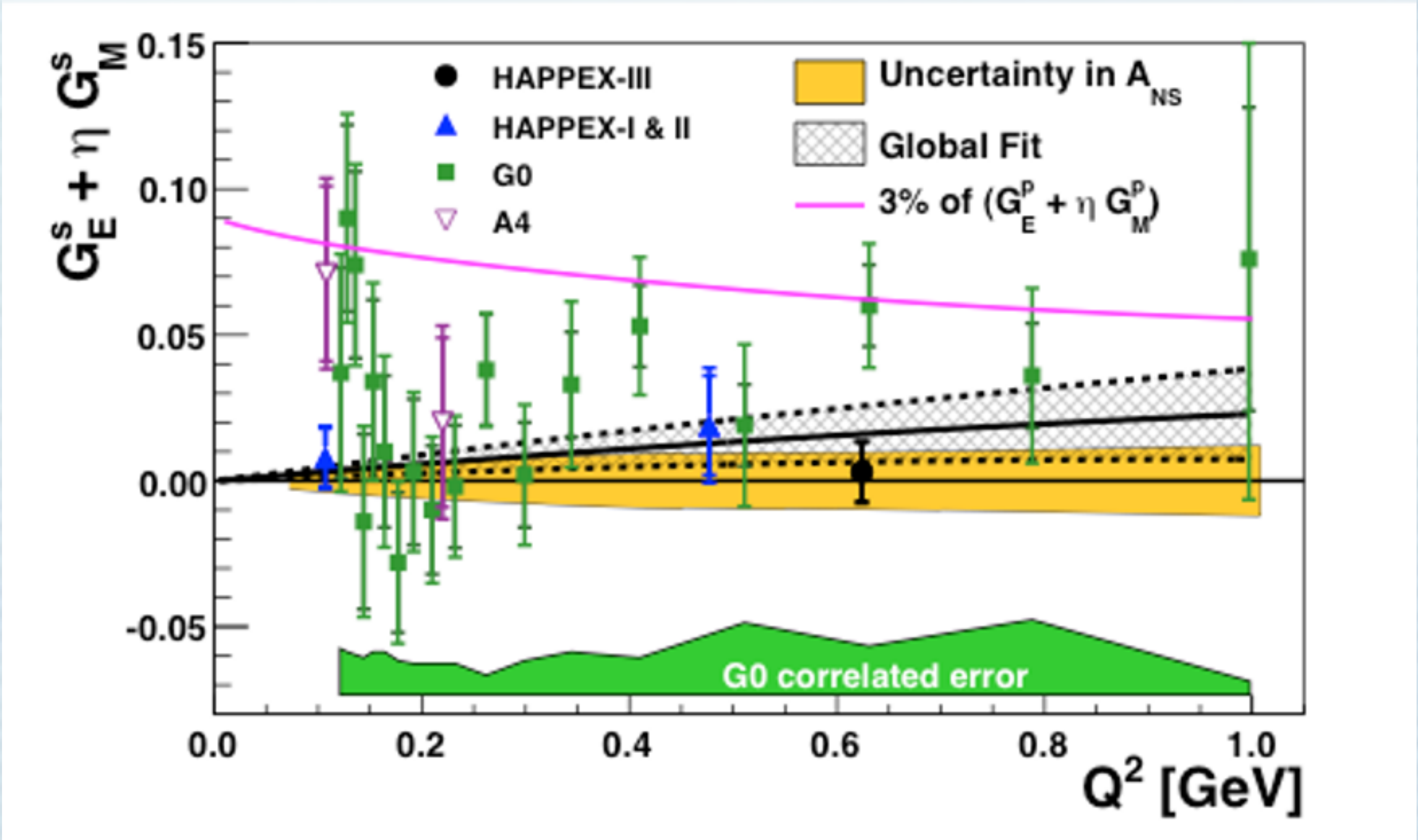


BigBite

Well …. with the primary construction and all its dependencies, it has lots of pieces.

Flavor separation depends on more than just charge symmetry



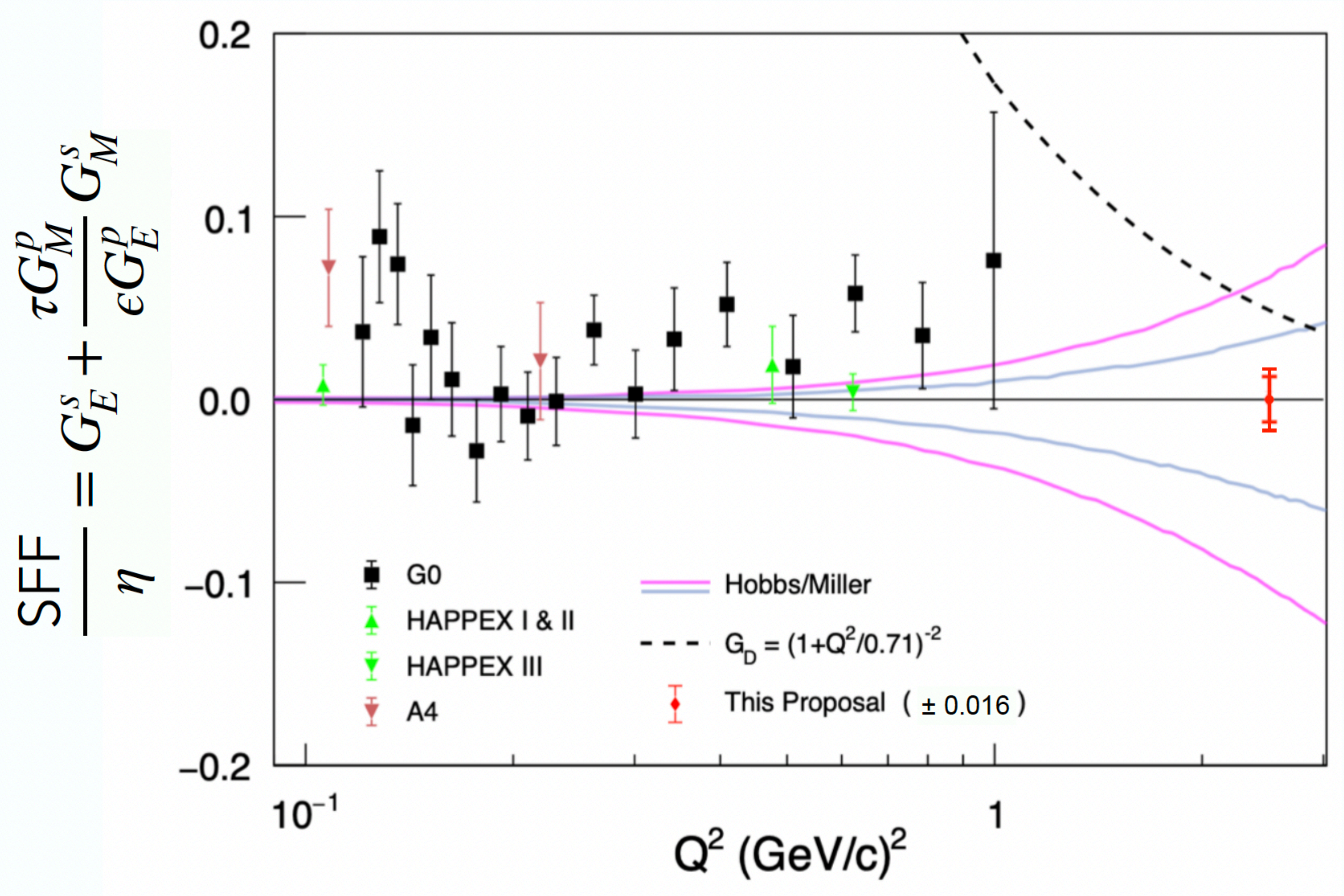


Shown above, determinations of the proton strange form factors using parity violation.

Projected result

δ A_{PV} = ± 6.2 (stat) ± 3.3 (syst)

$$\delta\left(G_E^s + 3.1 G_M^s\right) = \pm\ 0.013\ (\text{stat})\ \pm\ 0.007\ (\text{syst}) = 0.015\ (\text{total})$$



If $G_M^s = 0$, $\delta G_E^s \sim 0.015$, (about 34% of G_D)

If $G_E^s = 0$, $\delta G_M^s \sim 0.005$, (about 11% of G_D)

The proposed measurement is especially sensitive to G_M^s

The proposed error bar reaches the range of lattice predictions, and the empirically unknown range is much larger.

Courtesy of Kent Paschke