SBS:

A program with the initial goal of measuring the elastic nucleon form factors at high momentum

- A brief overview
- The physics (related to form factors)
- Scheduling and opportunities to get involved.

Gordon D. Cates
June 22, 2018

The first SBS experiments and their likely order:

- E12-09-019: measurement of G_M^n/G_M^p to Q^2=13.5 GeV^2.

  Unofficial estimate is that installation will begin in the summer of 2020

- E12-09-016: measurement of G_E^n/G_M^n to Q^2=10 GeV^2.

- E12-07-109: measurement of G_E^p/G_M^p to Q^2=12 GeV^2.

Super Bigbite will provide game-changing capability to study the elastic nucleon form factors at very high momentum transfer.

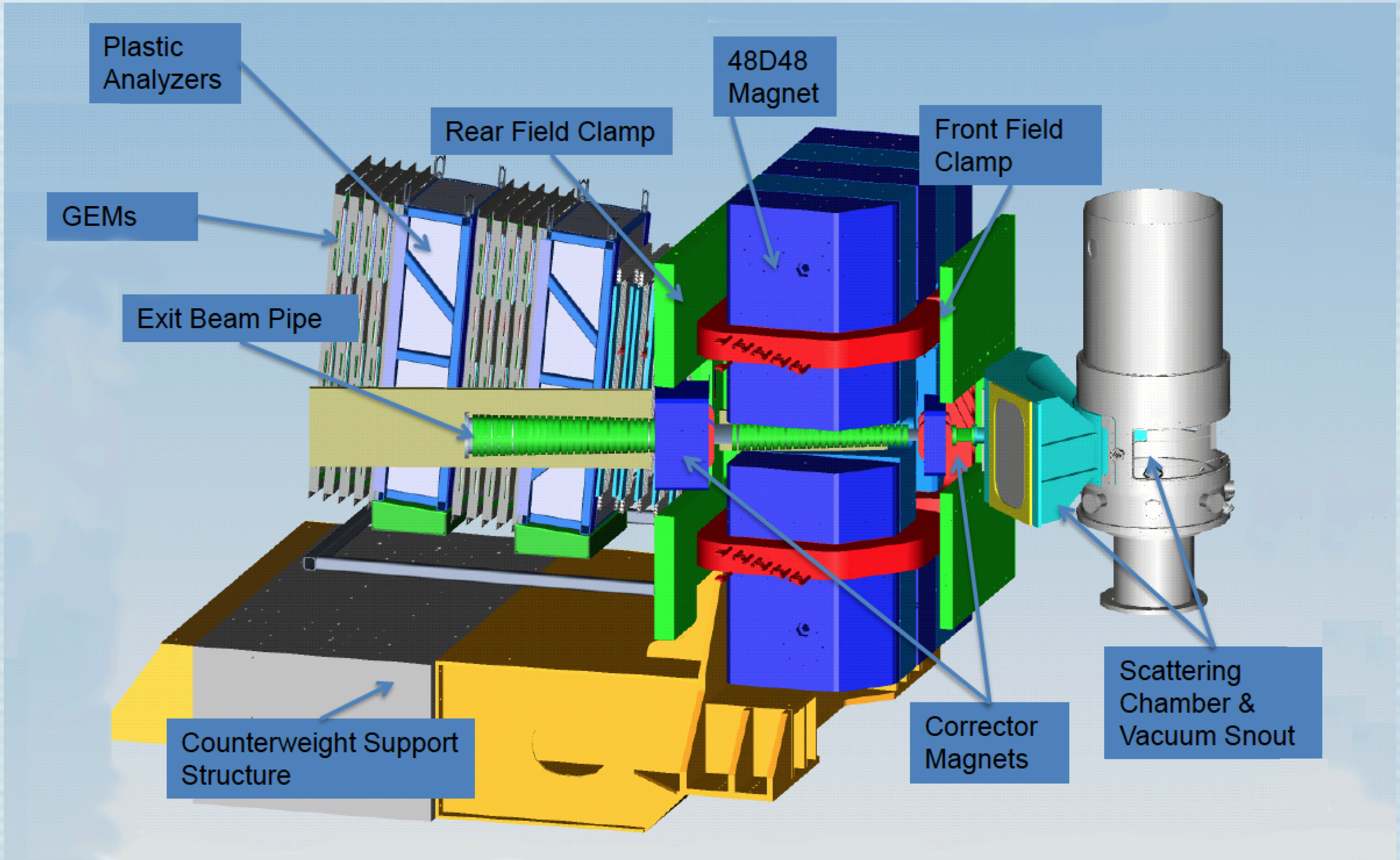
The SBS Physics Program

- **GEP** : 12 $(GeV/c)^2$
- GMN: 13.5 $(GeV/c)^2$
- GEN: 10 $(GeV/c)^2$
- SSA in nSIDIS: 30,000 gain vs HERMES

====================================

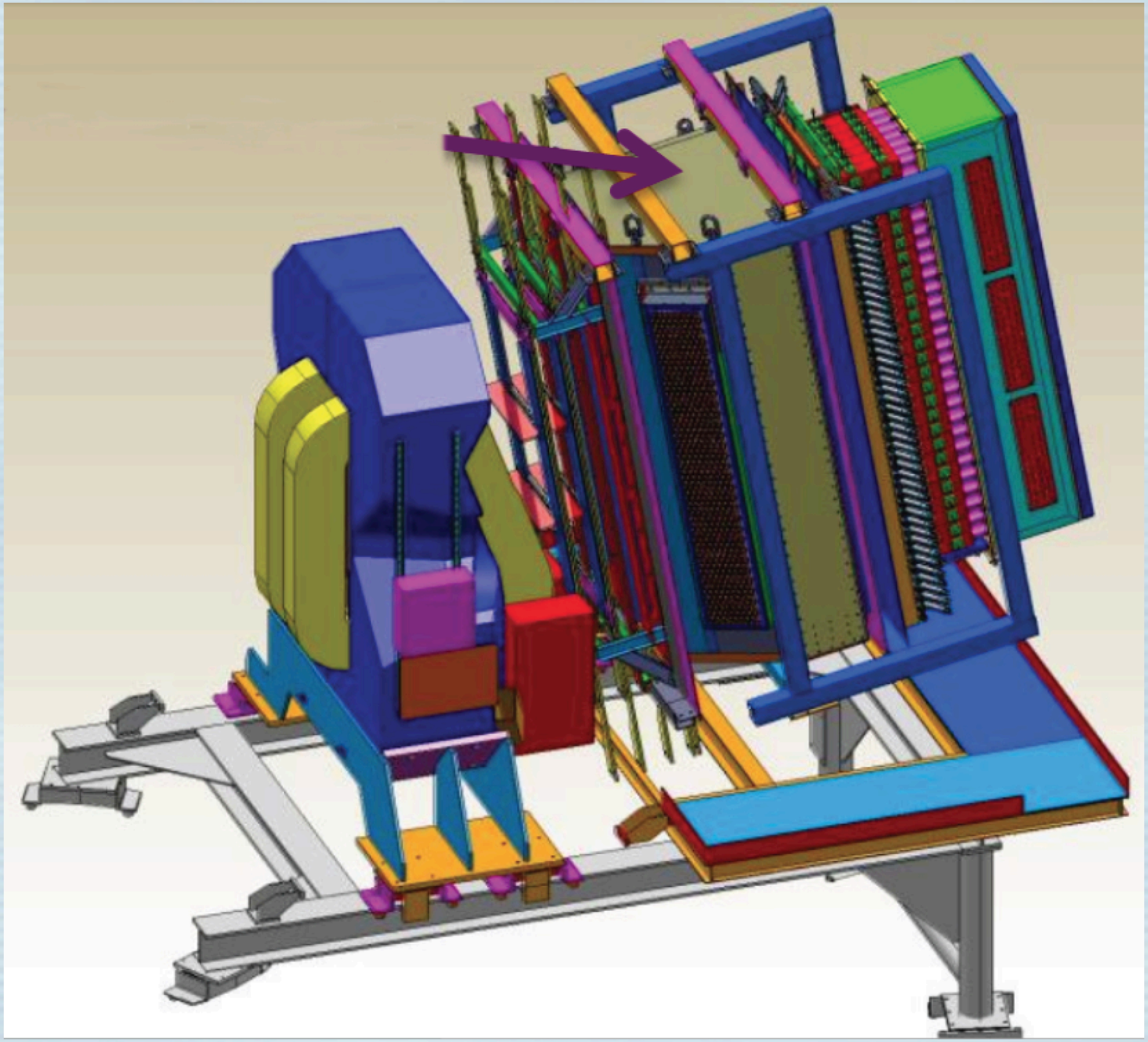
- **A1n**/d2n – gain ~ 20-30 compared with HMS/SHMS
- TDIS meson (π, K) DIS
- WACS-ALL, 100+ gain in productivity (Hall C/A)
- GEnRP with charge exchange
- J/Psi near threshold – hot physics
- g2p with a wide open magnet for the polarized target
- double polarized $H(\gamma,\varphi\ p)$, $H(\gamma,\pi^o\ p)$

The Super Bigbite Spectrometer (SBS) configured for the proton experiment



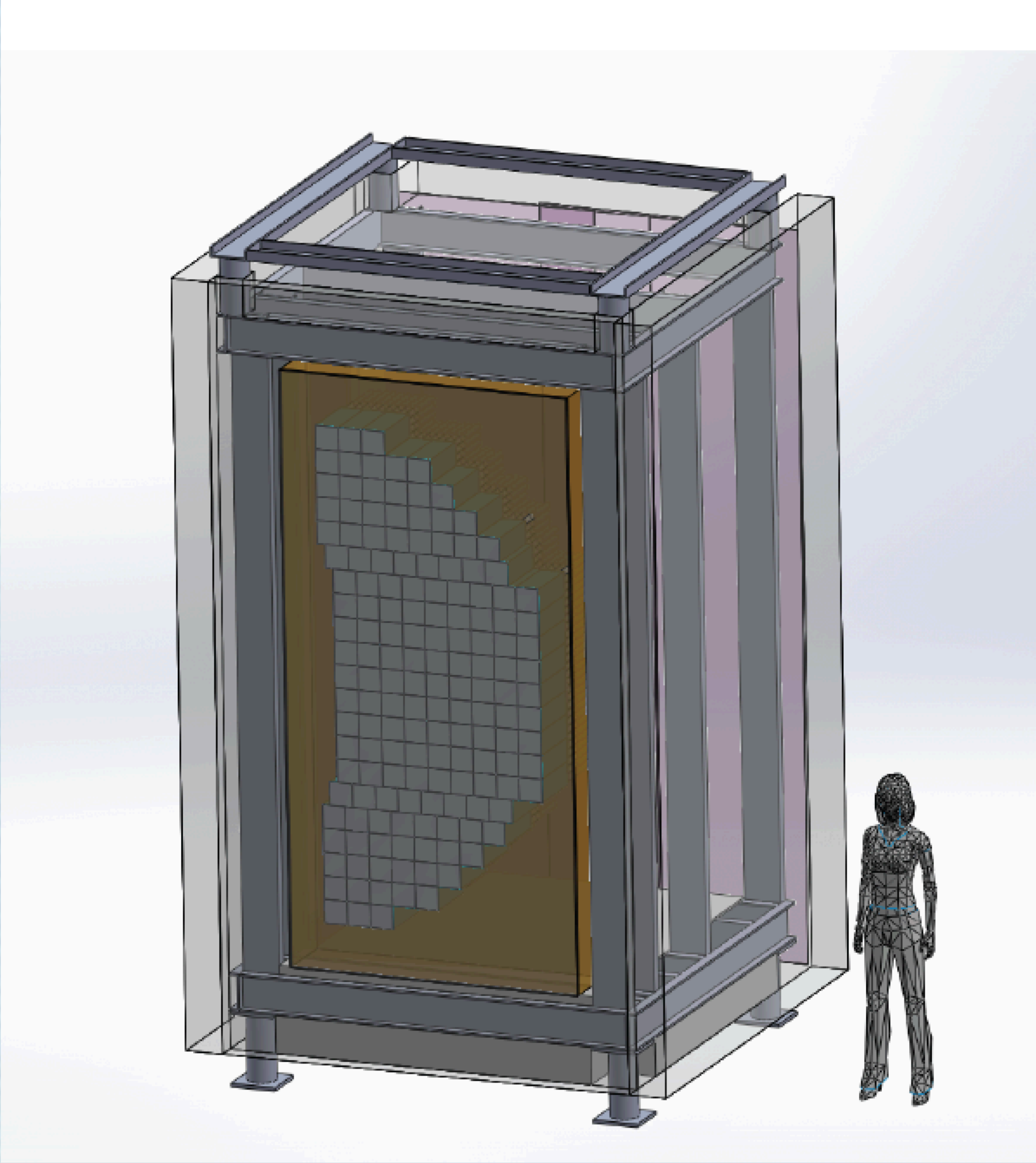
- Detector package views target through single wide aperture dipole with ~ 70 mSr acceptance
- Large area GEM detectors can tolerate huge singles rates (up to 150 kHz/cm^2)
- Luminosity of over 10^{38} Hz/cm^2

The BigBite Spectrometer upgraded with GEMs and a "GRINCH" Cerenkov



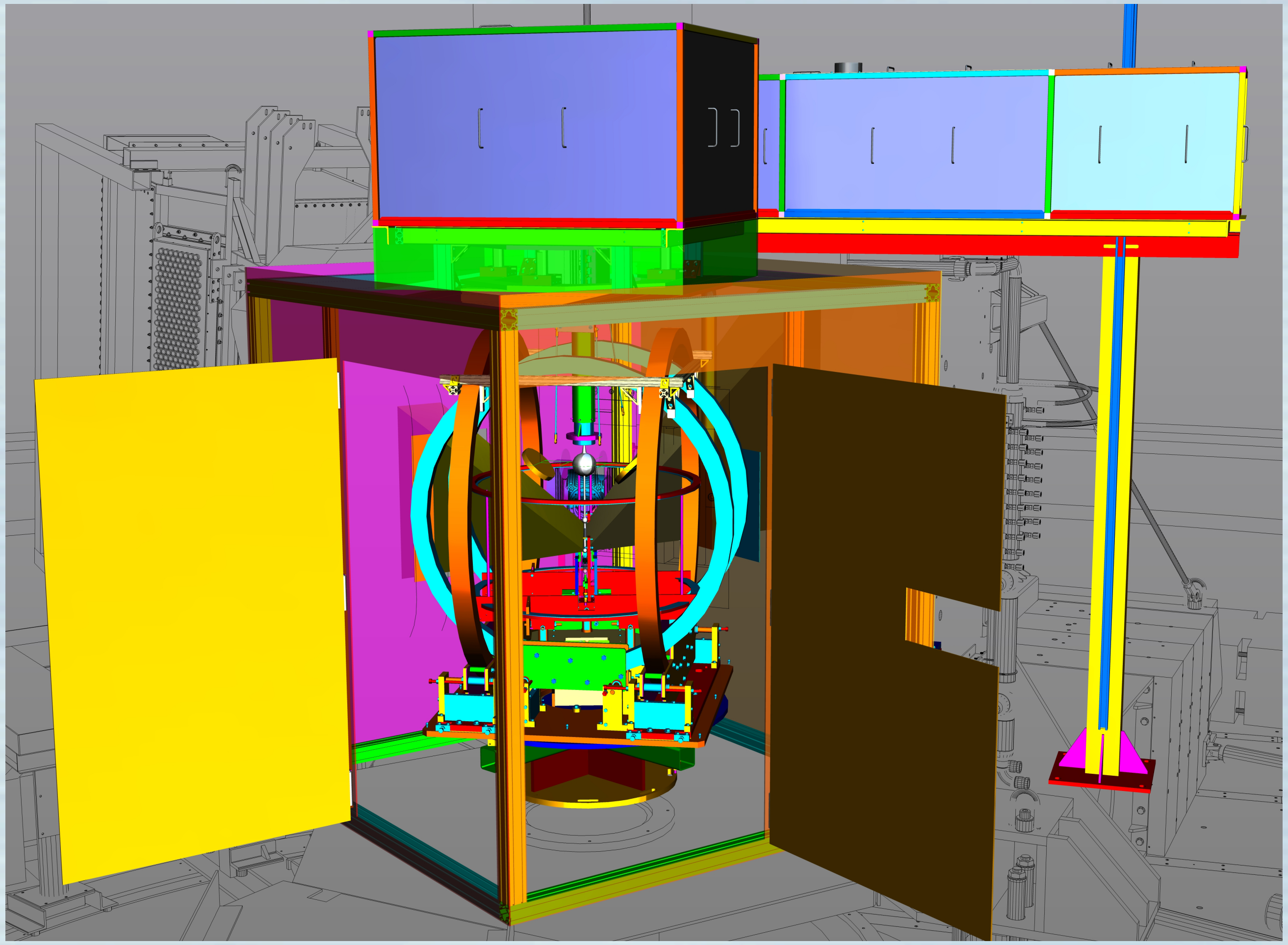
G_E^p lead-glass electron calorimeter (ECal)

- ECal will absorb 0.5 kRad/hour during the G_E^p experiment
- Based on lead glass blocks
- Thermal annealing at 250 C will provide optical transparency without interrupting running time.

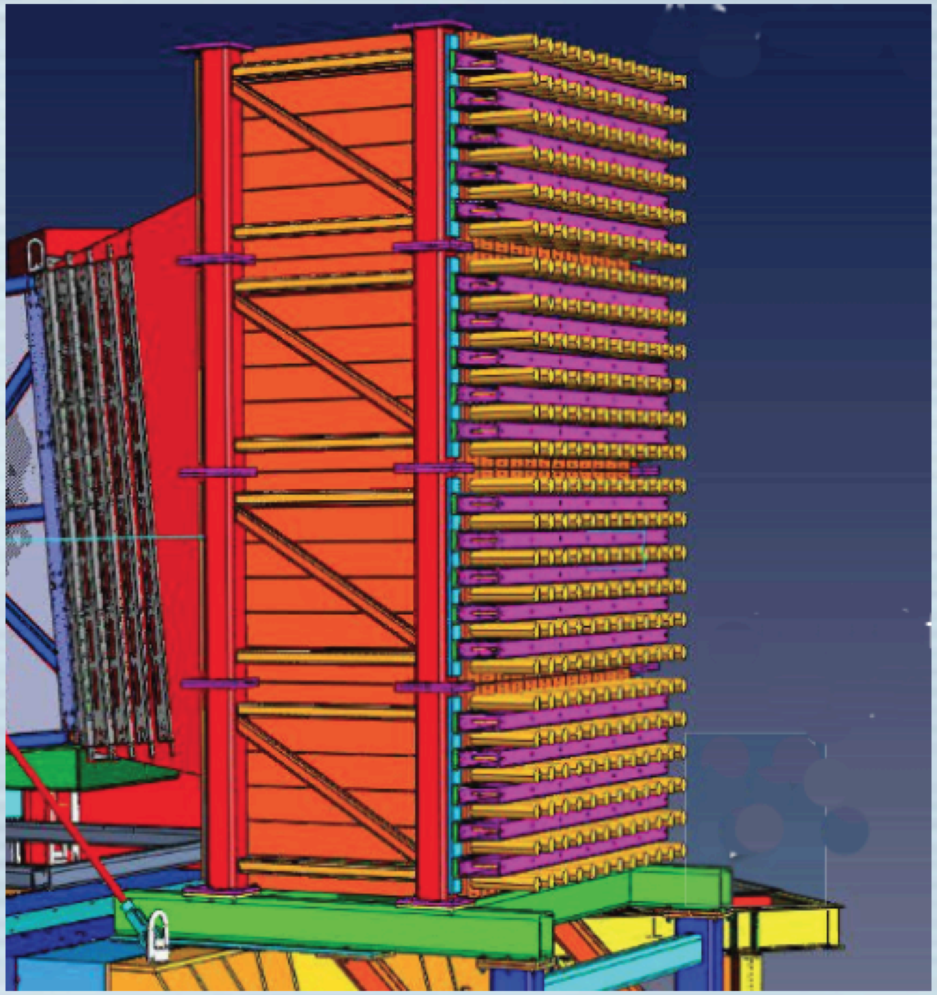


ECal

Additional "dependencies" for the SBS Program

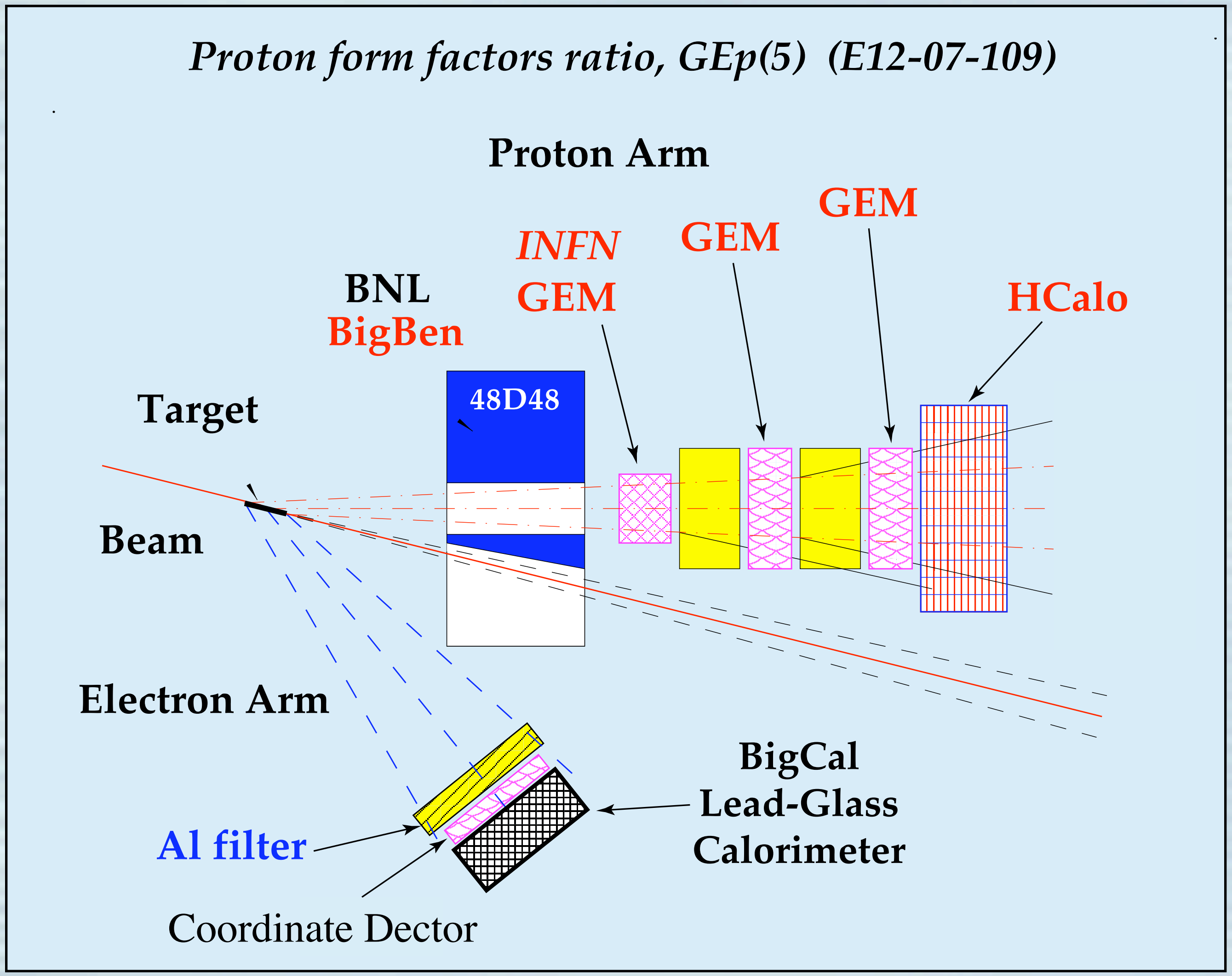


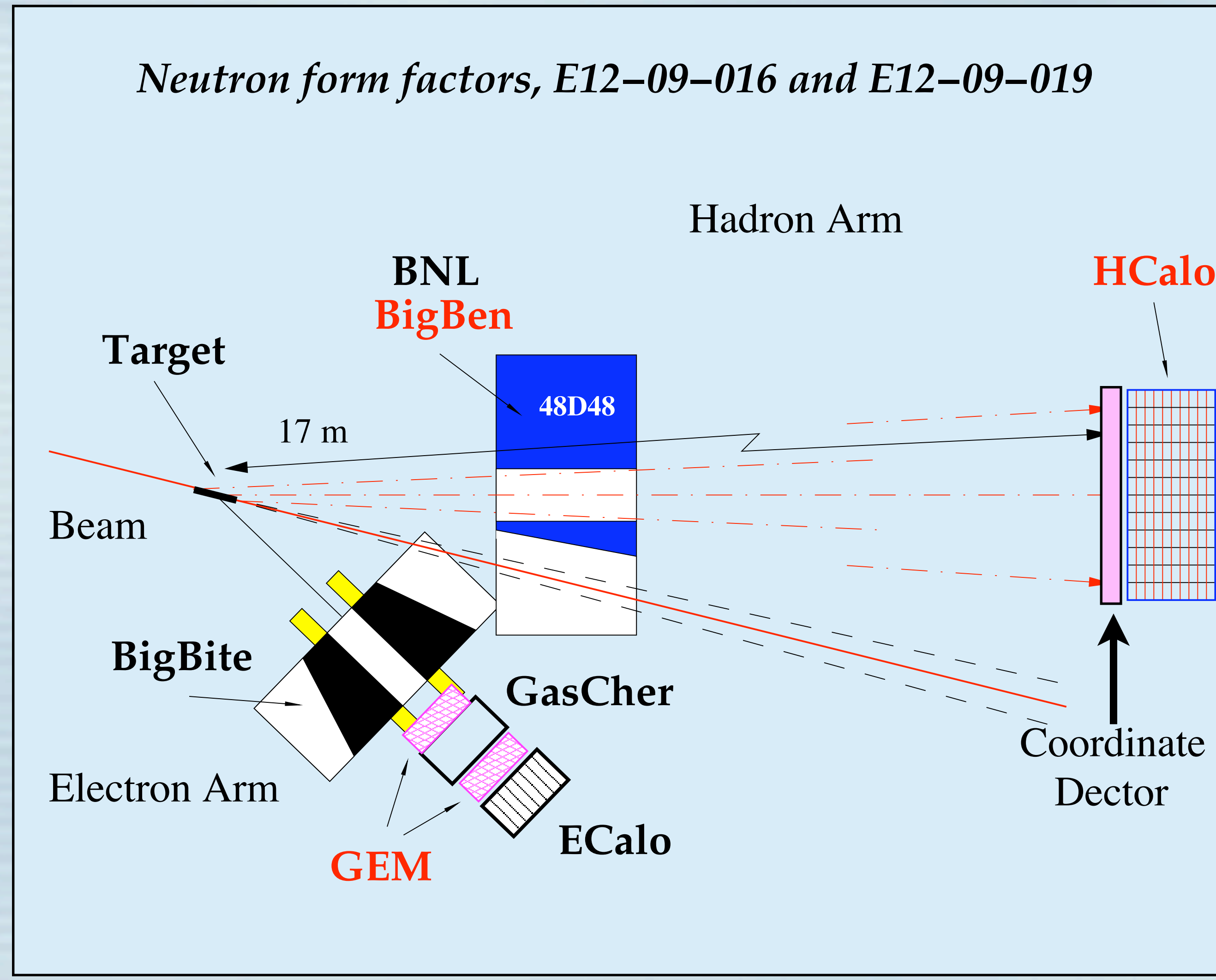
Upgraded polarized 3He target will operate at six times the figure of merit over previous experiments

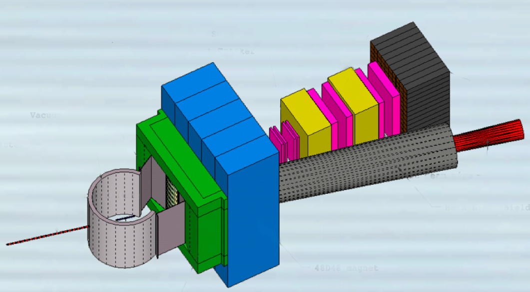


Hadron calorimeter with expected efficiency of 95% for p and n with excellent suppression of low-energy background.

The SBS equipment will be configured differently depending on the experiment







G_E^p/G_M^p

G_E^n/G_M^n and G_M^n/G_M^p

With large new systems just now ready to be assembled and commissioned, and a likely start date in 2020, these are wonderful opportunities for graduate students and post-docs!

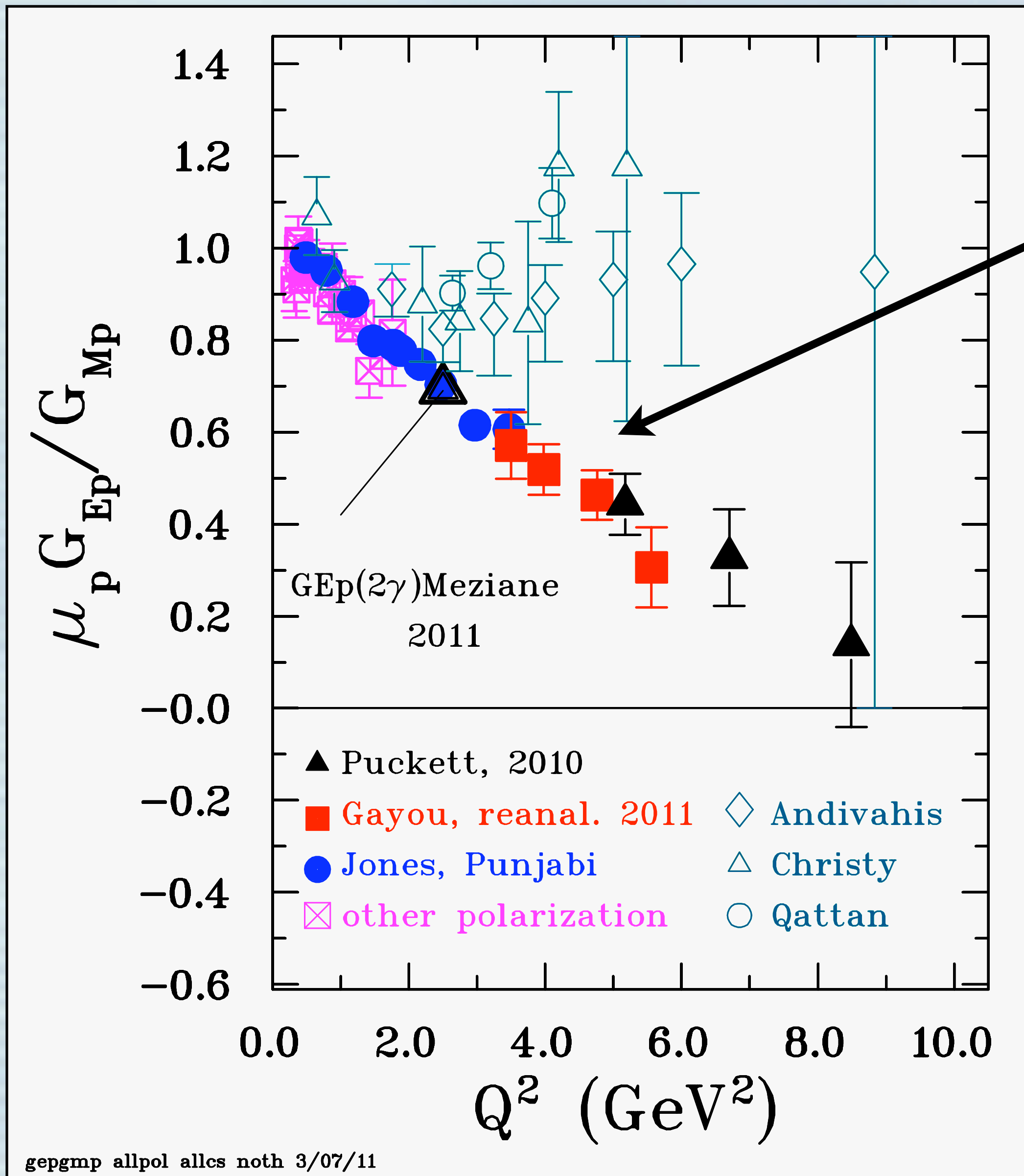
Examples of the some of the physics impacted by the SBS program

(focusing here on the form-factor program)

- The very way in which we visualize the nucleon.
- The origin of most of the mass in the Universe.
- Quark orbital angular momentum

This list is nowhere near complete, but I touch on each point. First some historical context…

One of the important discoveries at JLab: the Q^2 behavior of the ratio of G_E^p/G_M^p



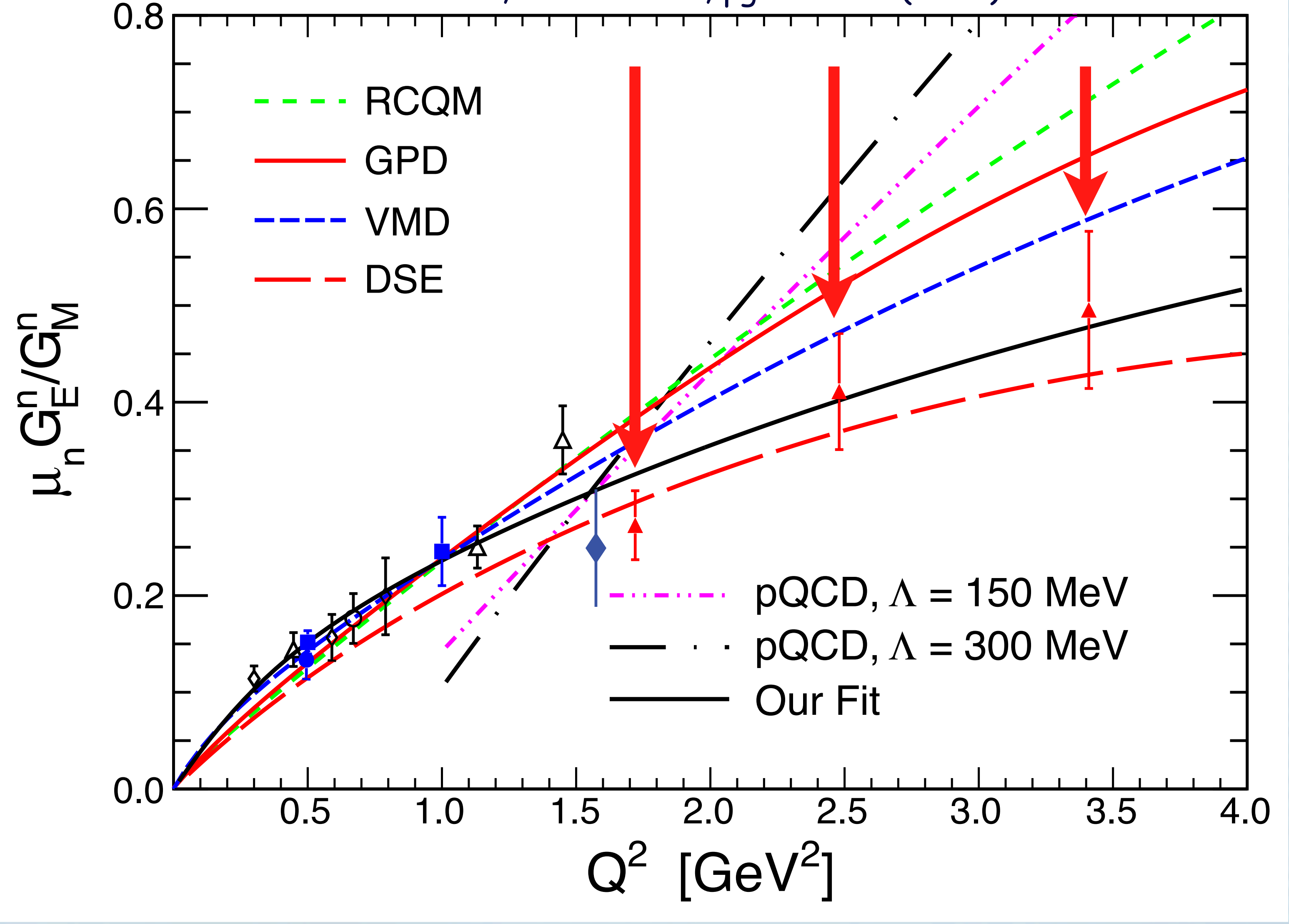
Data from both Rosenbluth separations and the double-polarization technique.

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

- The observation triggered greatly renewed interest in nucleon structure.
- Explanations for the Q^2 behavior of G_E^p/G_M^p have emphasized the role of <u>quark orbital angular momentum</u>.
- The observation made it imperative to study the neutron at similarly high Q^2.

The first measurement of G_E^n/G_M^n in Hall A using a polarized ^{3}He target, BigBite and a huge neutron detector

Riordan et al., PRL vol. 105, pg 262302 (2010)



neutron data

Data from the BigBite experiment shown with red arrows

The existing high Q^2 data on the proton and the neutron already have intriguing implications

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:

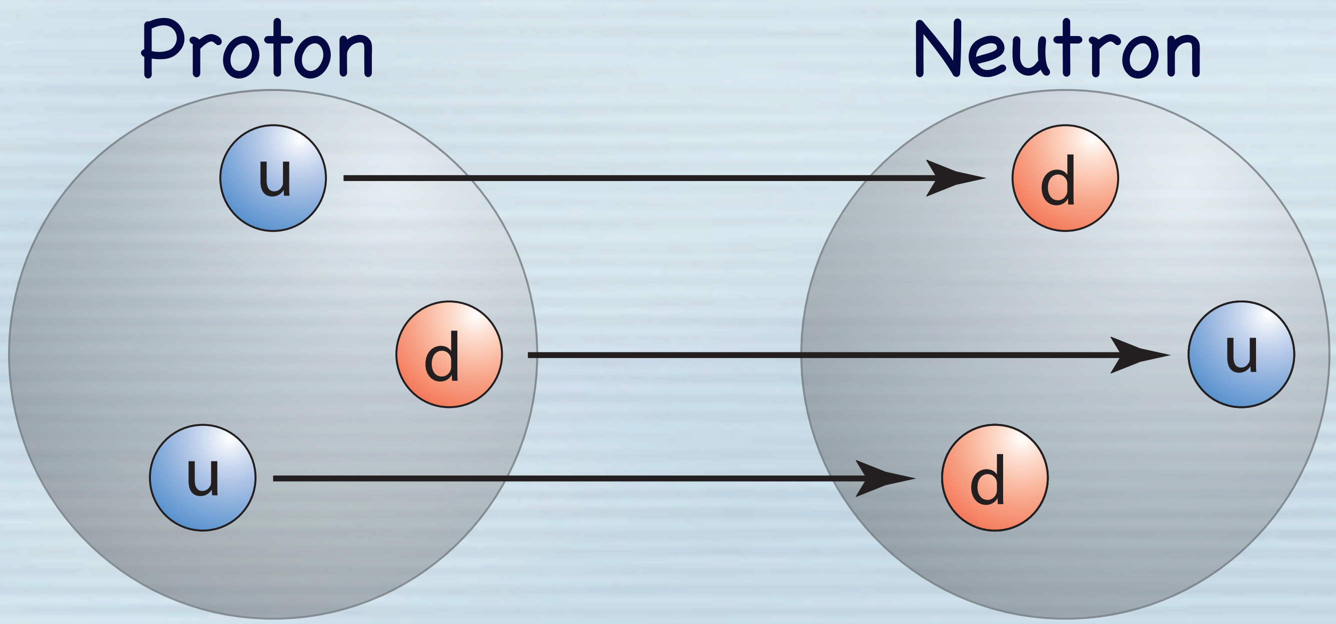
$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2$$

where

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

Proton and neutron data can be combined to extract the flavor-separated form factors

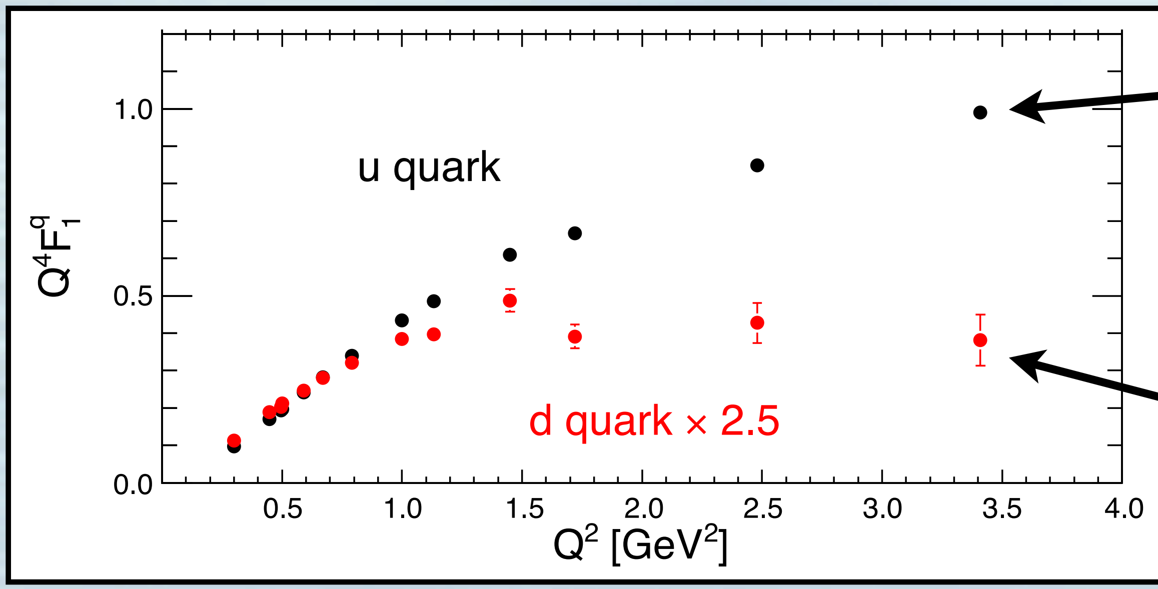
By assuming charge symmetry, we can combine form-factor data from protons and neutrons to extract F_1^q and F_2^q for the individual quark constituents of the nucleon.



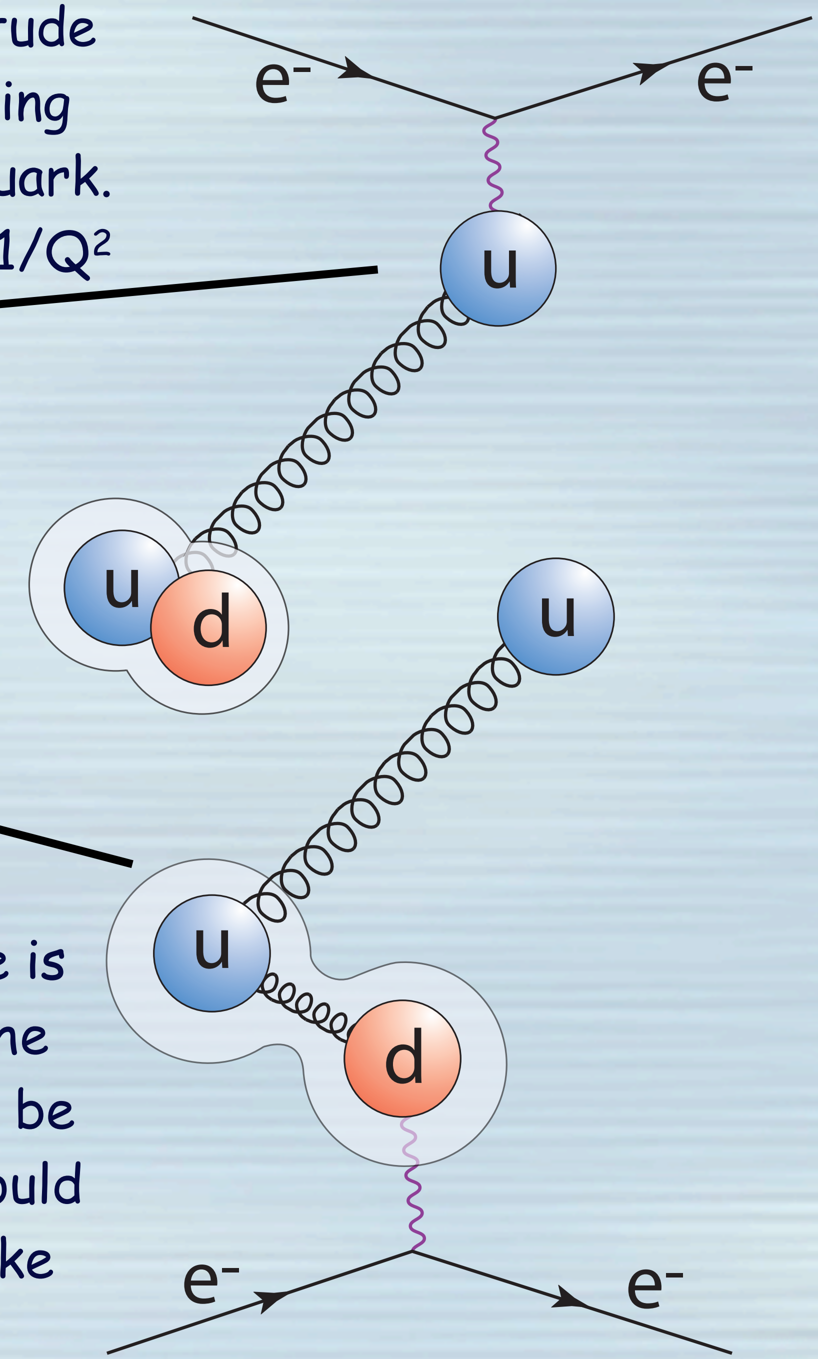
$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

The flavor separated form factors for the u- and d-quarks have dramatically different behavior

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)



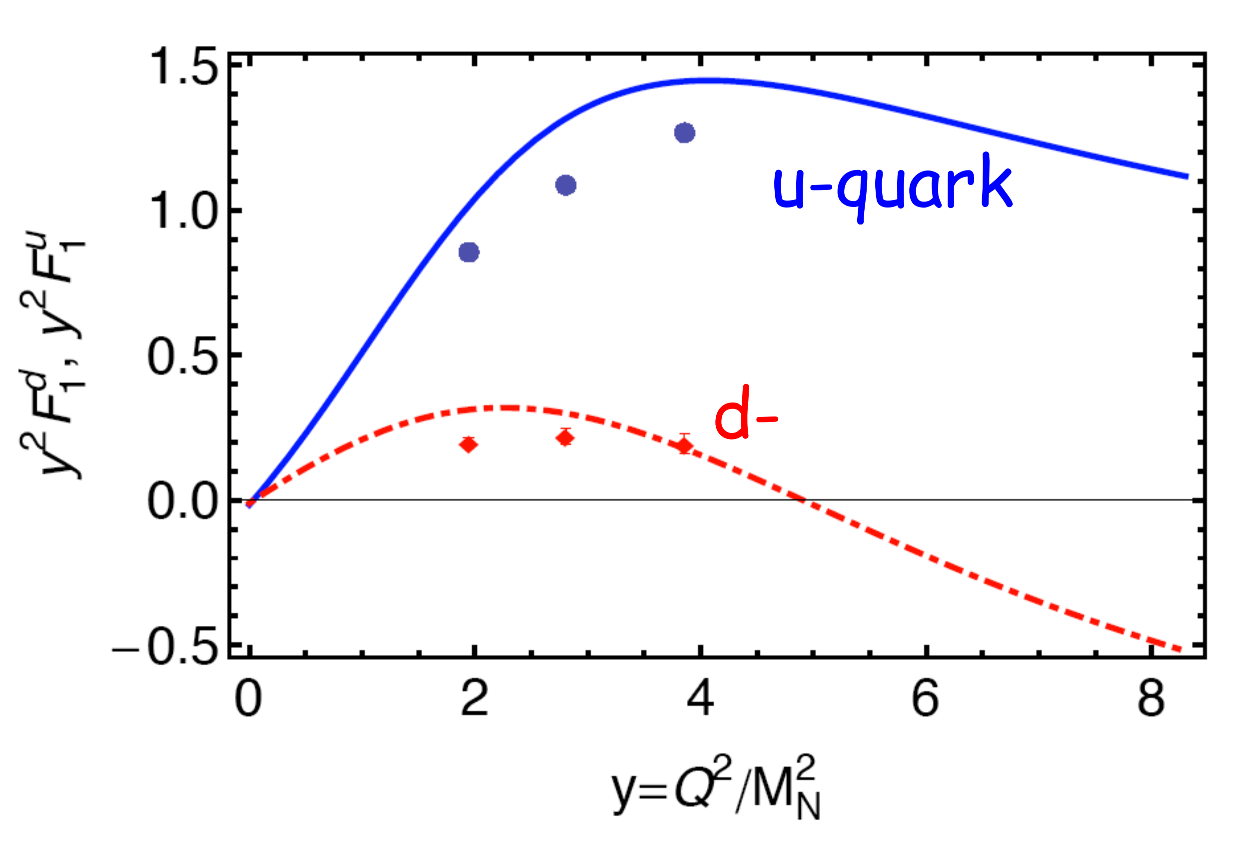
d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

The different behaviors can be interpreted as evidence of diquark correlations within the nucleon, as shown by the overly simplistic cartoon above.

Behavior was predicted by the Dyson-Schwinger Equation (DSE)/Fadeev calculations from Argonne

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

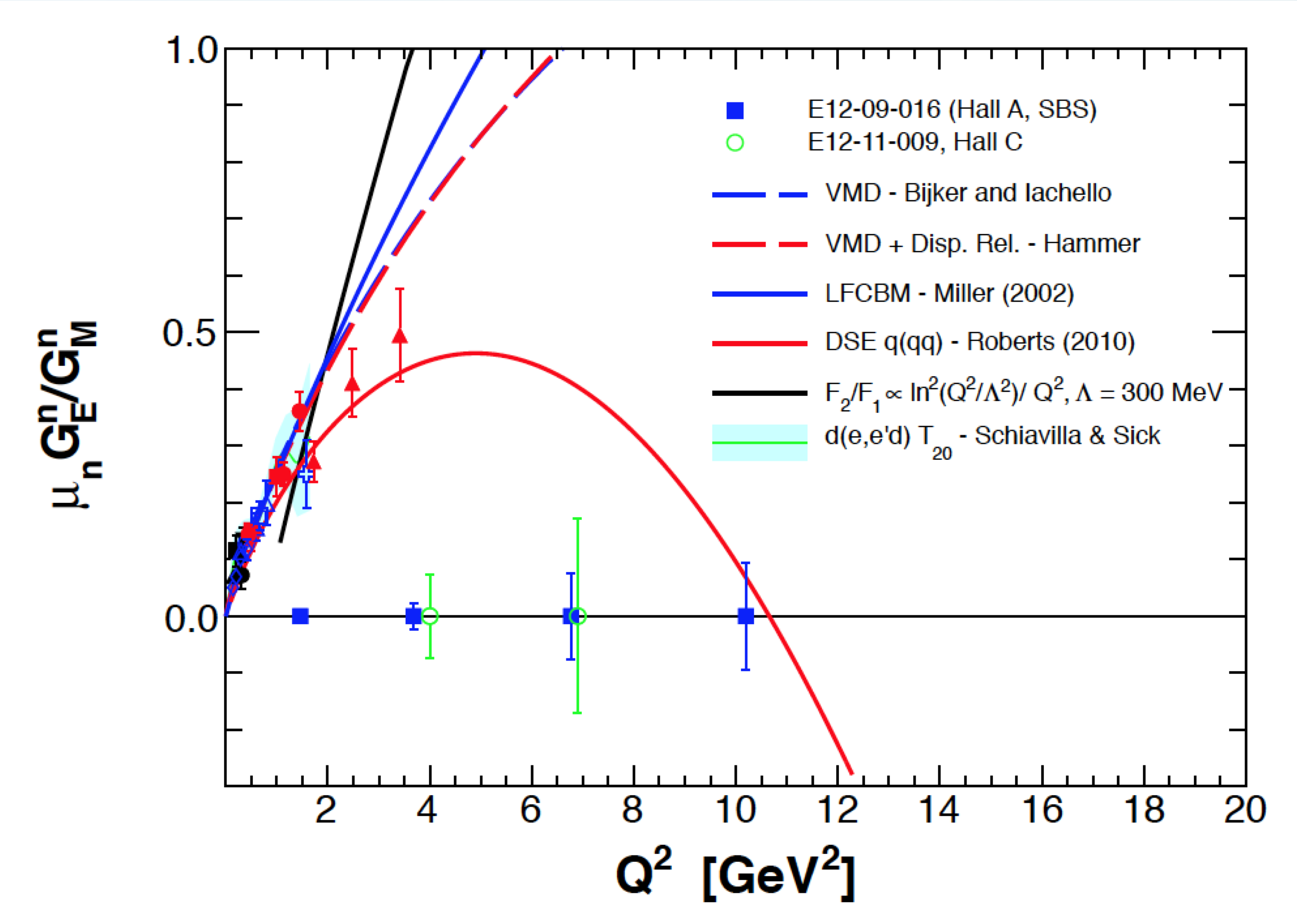
" ... a prediction for the Q^2-dependence of u- and d-quark Dirac and Pauli form factors in the proton, which exposes the critical role played by diquark correlations within the nucleon."



arXiv:1103.2432v1

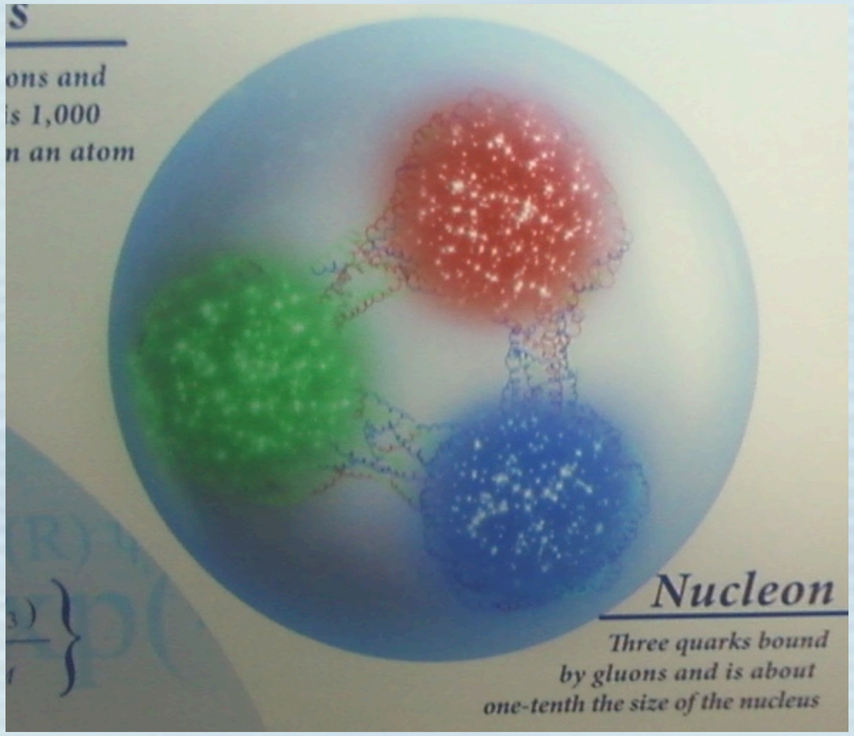
Within their model, the different behaviors of the u- and d-quark FFs are a direct consequence of diquark degrees of freedom.

For the high Q^2 SBS data on the neutron, the DSE/Fadeev model makes a dramatic prediction

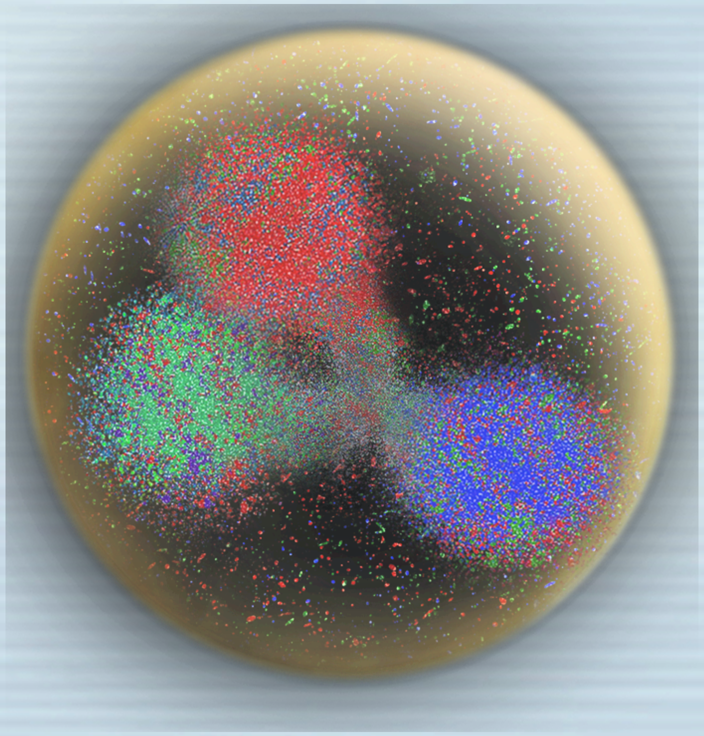


The observation of a zero crossing would provide strong evidence of the validity of the DSE approach

High-Q^2 elastic nucleon FF data change could change our basic notions of nucleon structure

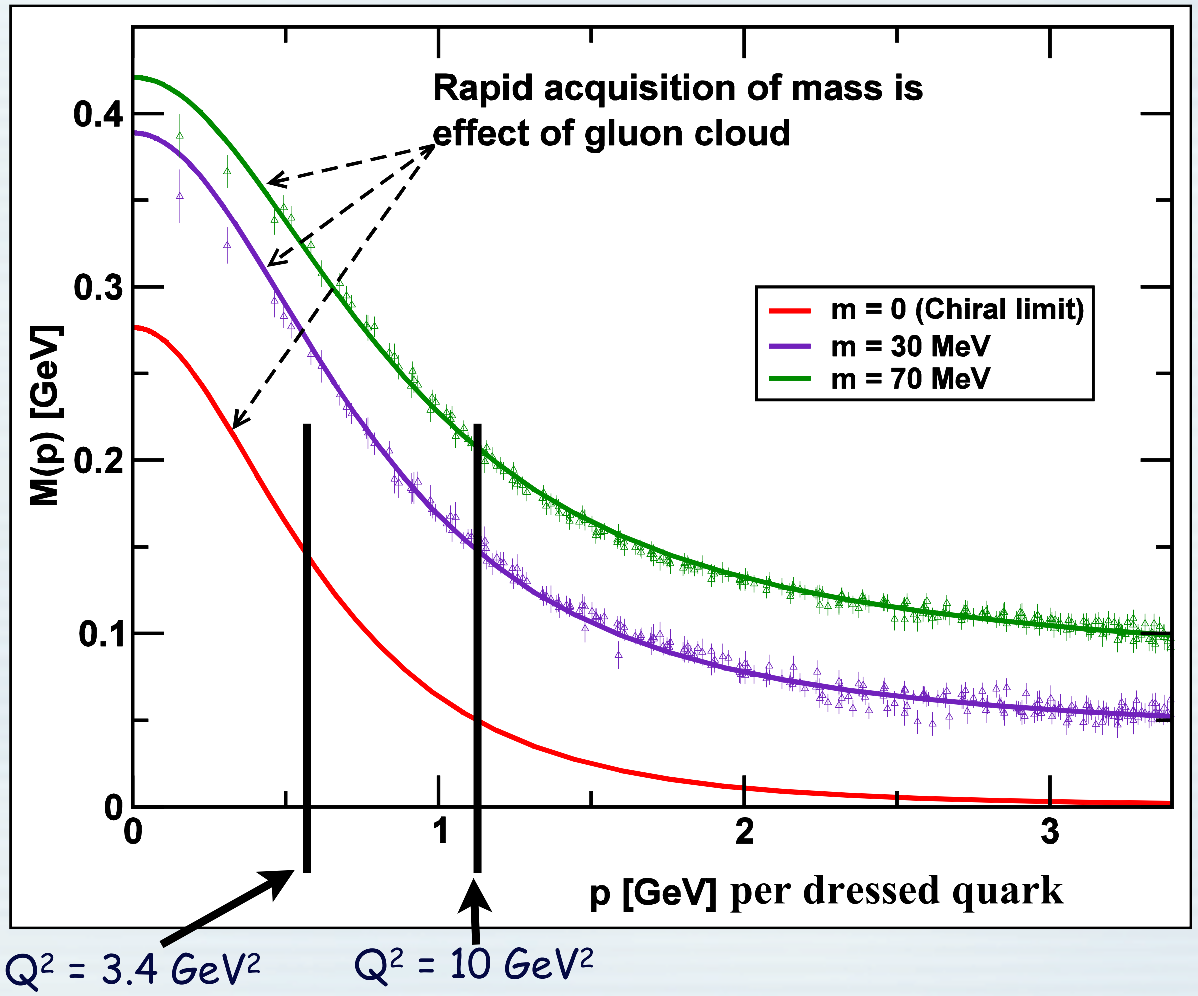


A cartoon of the nucleon
from the lobby of JLab



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

A key element of the DSE approach is the dynamic generation of mass

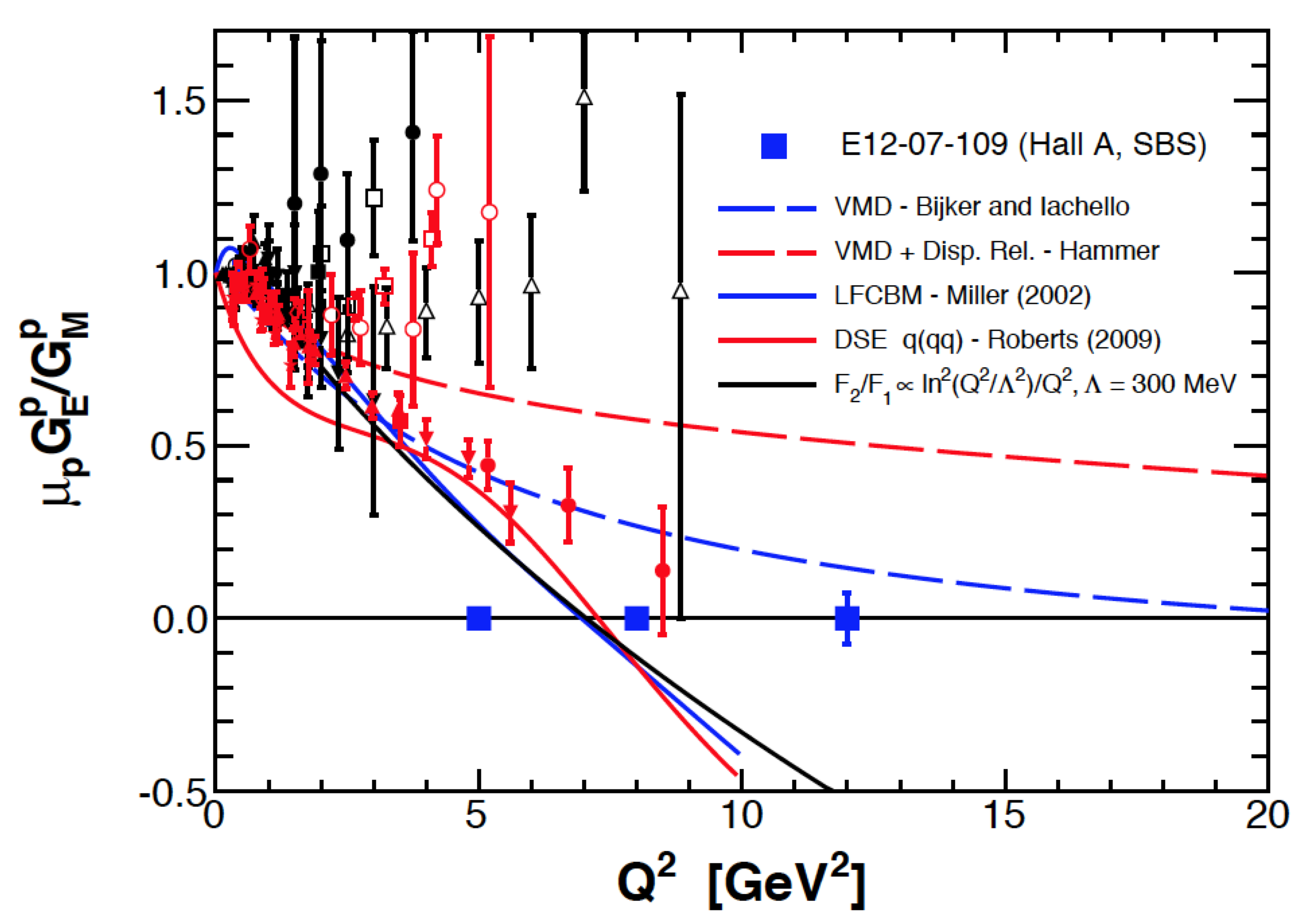


Above is the dynamically generated mass function that appears in the dressed quark propagator:

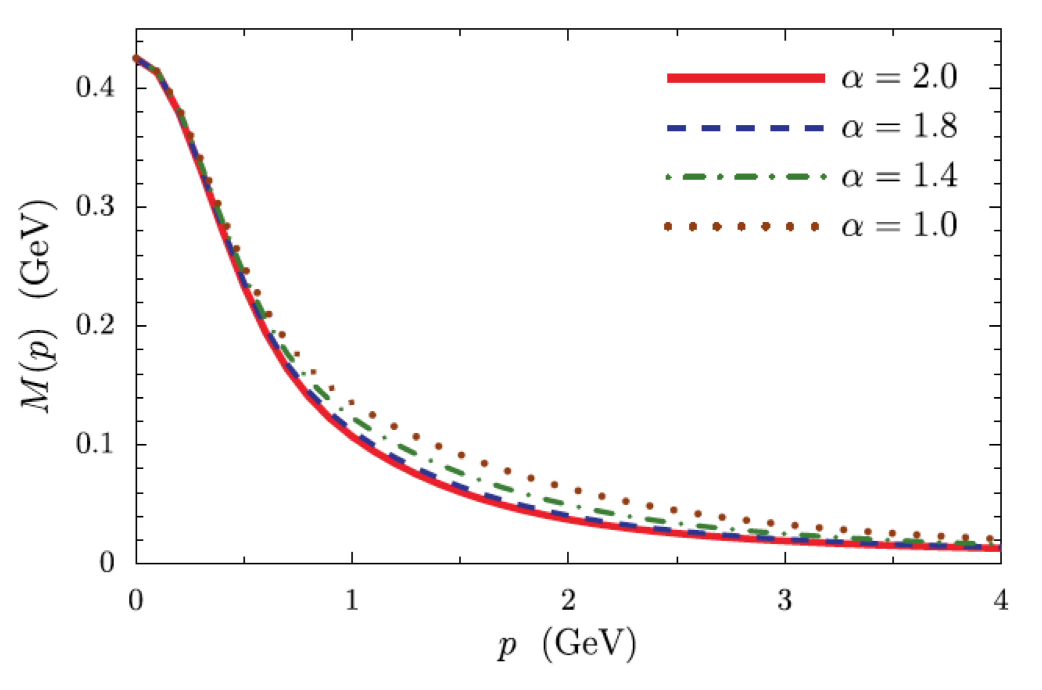
$$S(p) = \frac{Z(p^2, \zeta^2)}{i\gamma \cdot p + M(p^2)}$$

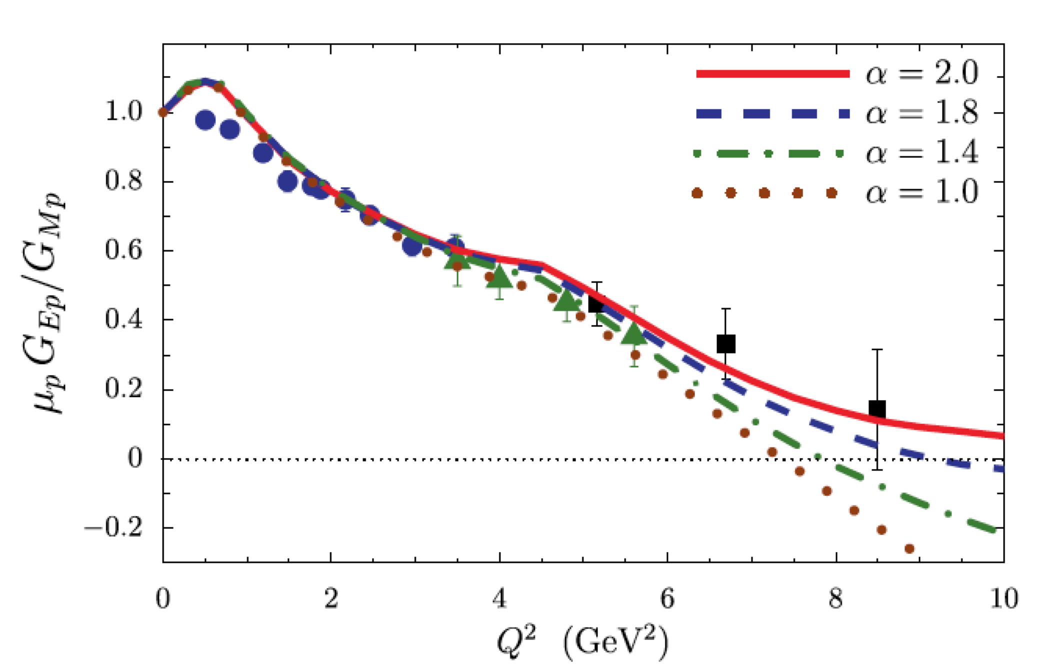
In the realm of non-physical pion mass, where lattice QCD can readily reproduce the mass of the dressed quarks, the DSE calculations are in excellent agreement.

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



G_E^p/G_M^p projected data





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

The FF data provide some of the most important constraints on certain GPDs

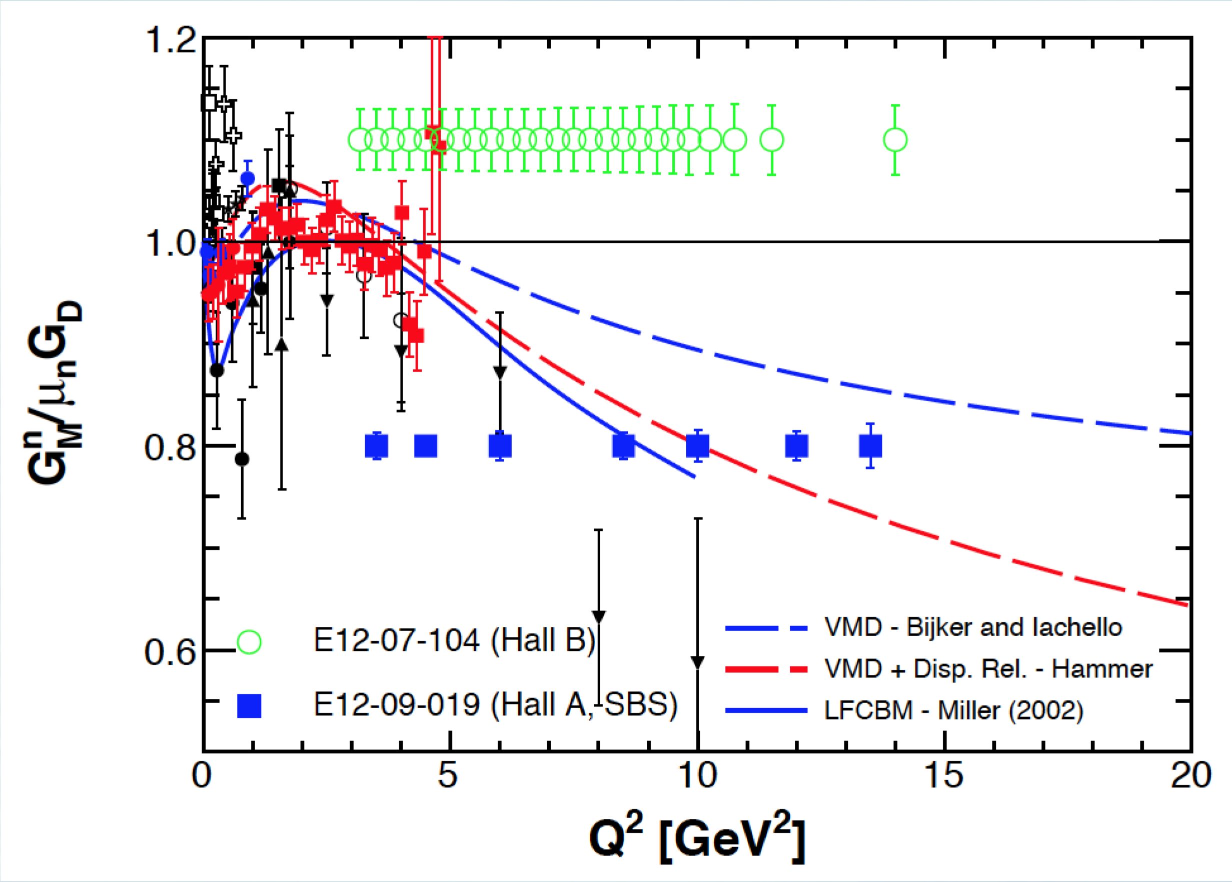
$$\int_{-1}^{+1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

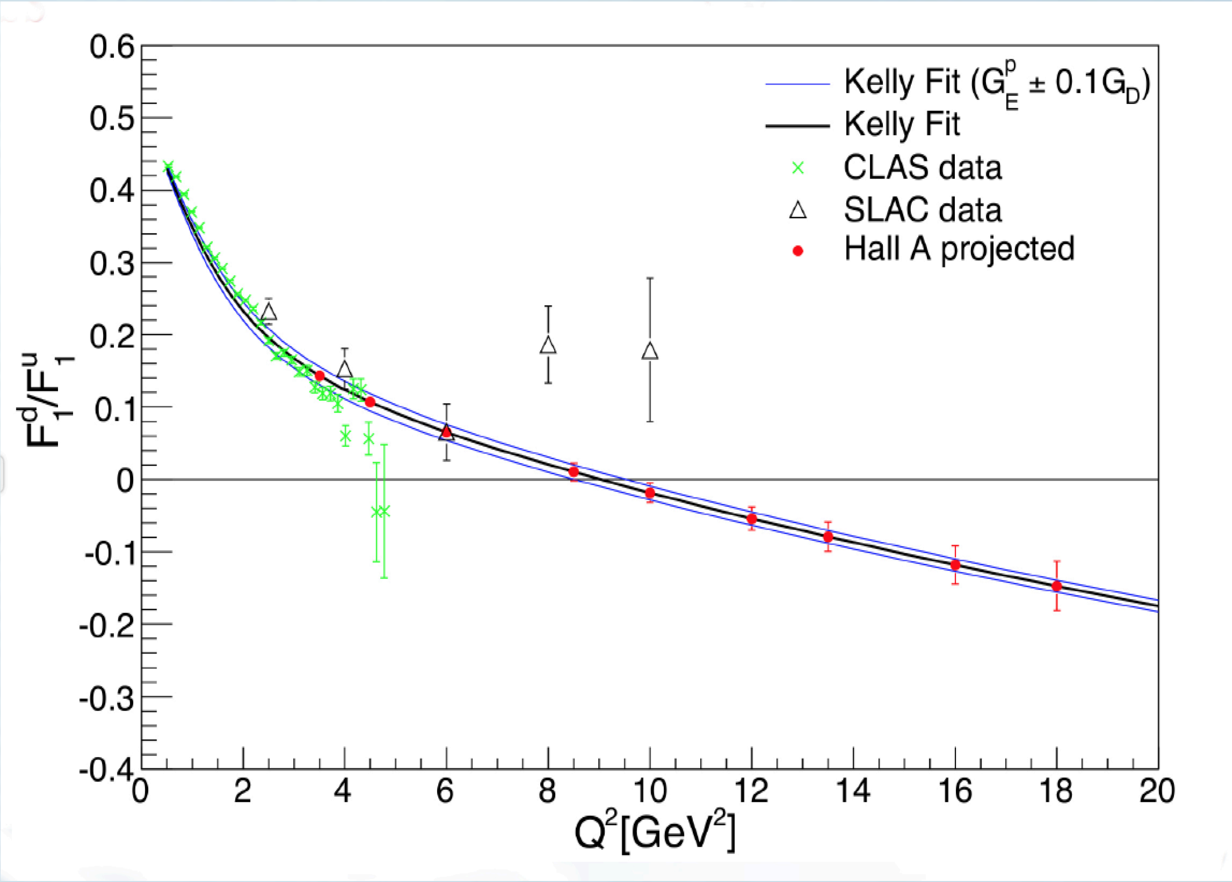
They can thus provide early insight into determining
the orbital angular momentum of the quarks using Ji's Sum Rule:

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

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

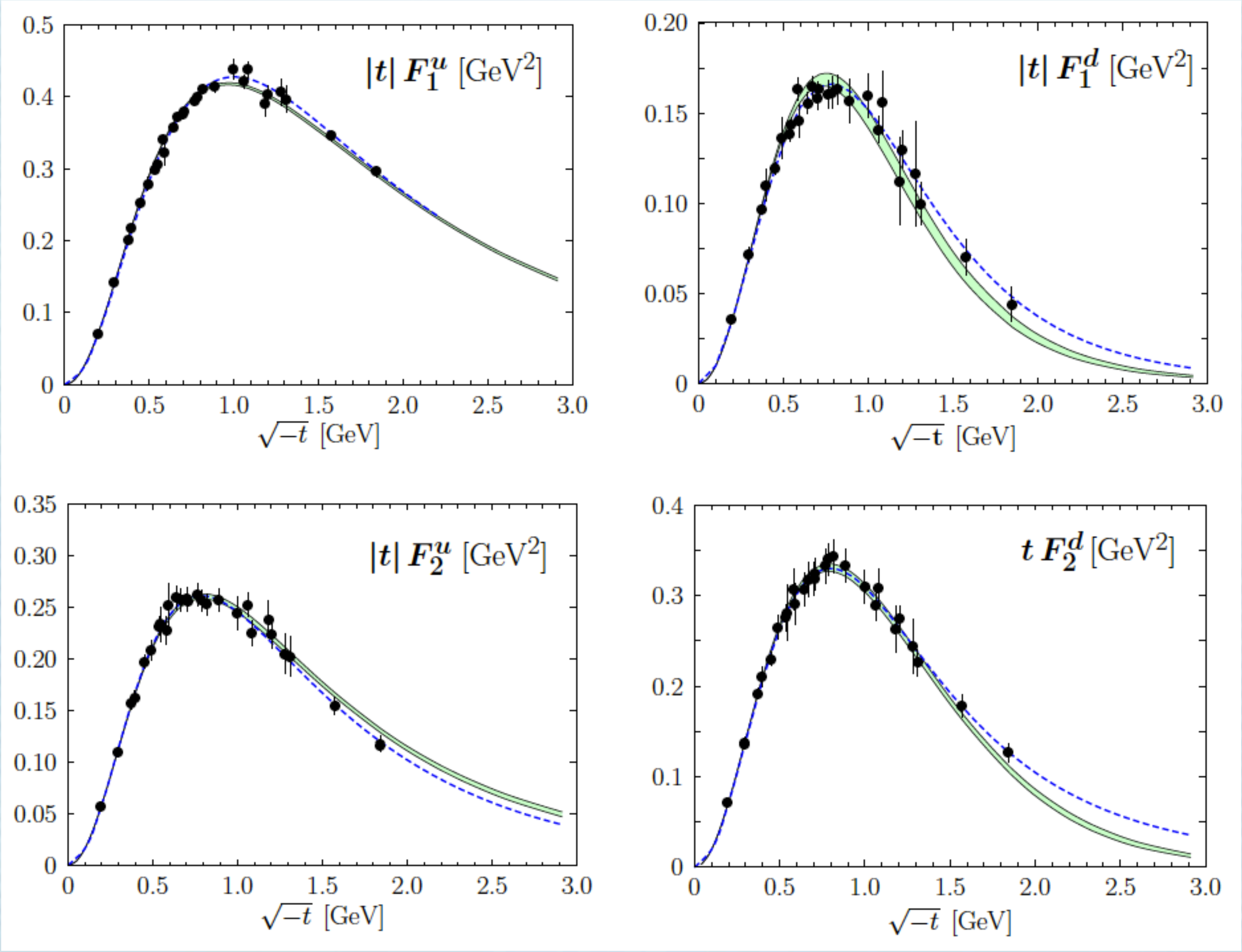
For example:
Projections from the first SBS experiment
G_M^n/G_M^p





Will provide strong constrains on the “H” GPD

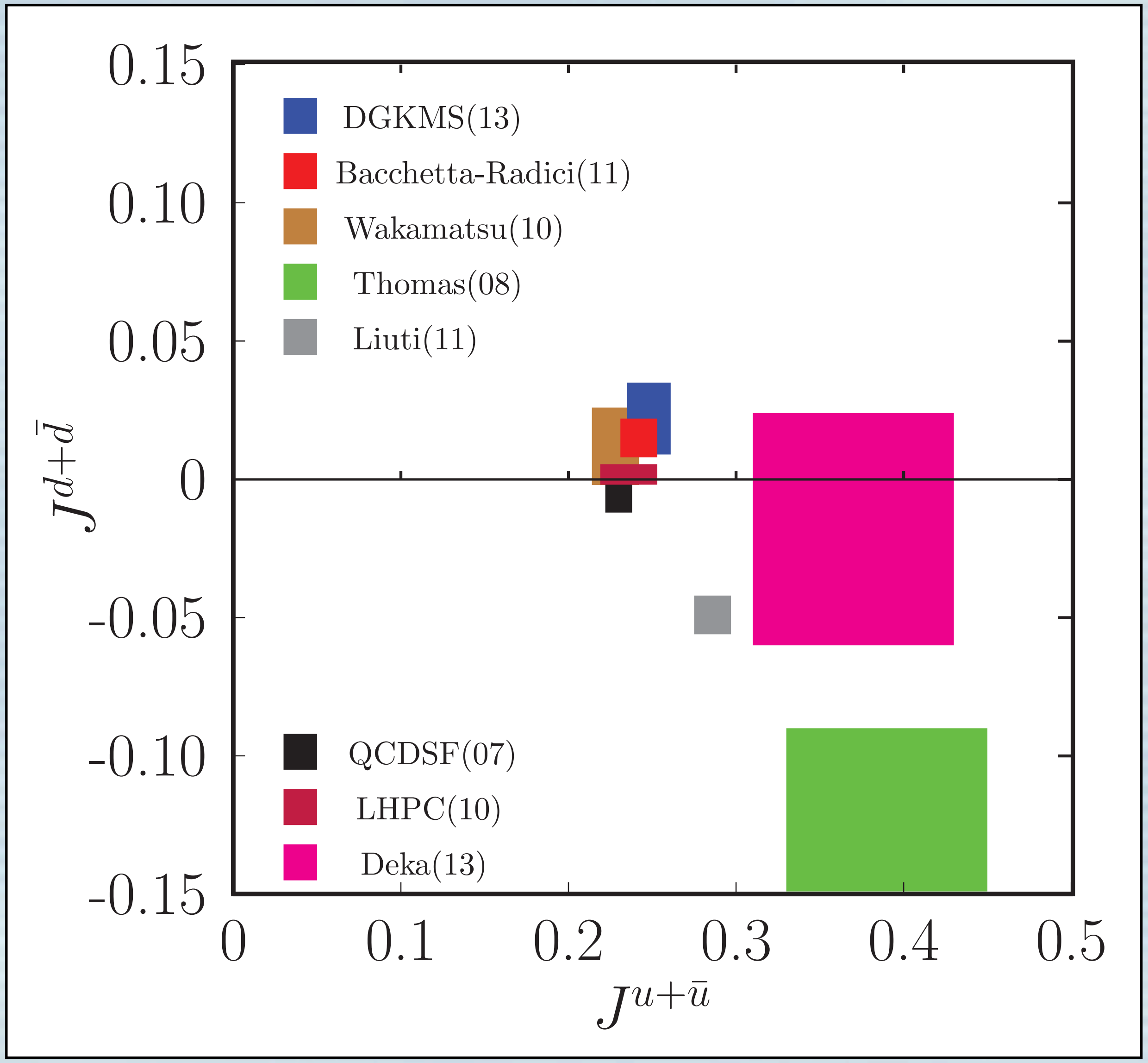
Constrained GPD Model and evaluation of the Ji Sum Rule



Marcus Diehl and Peter Kroll: Eur. Phys. J. C, v.73, pg.2397 (2013), also arXiv:1302.4604v1 [hep-ph] 19 Feb 2013

$$J_v^u = 0.230^{+0.009}_{-0.024} \text{ and } J_v^d = -0.004^{+0.010}_{-0.016}$$

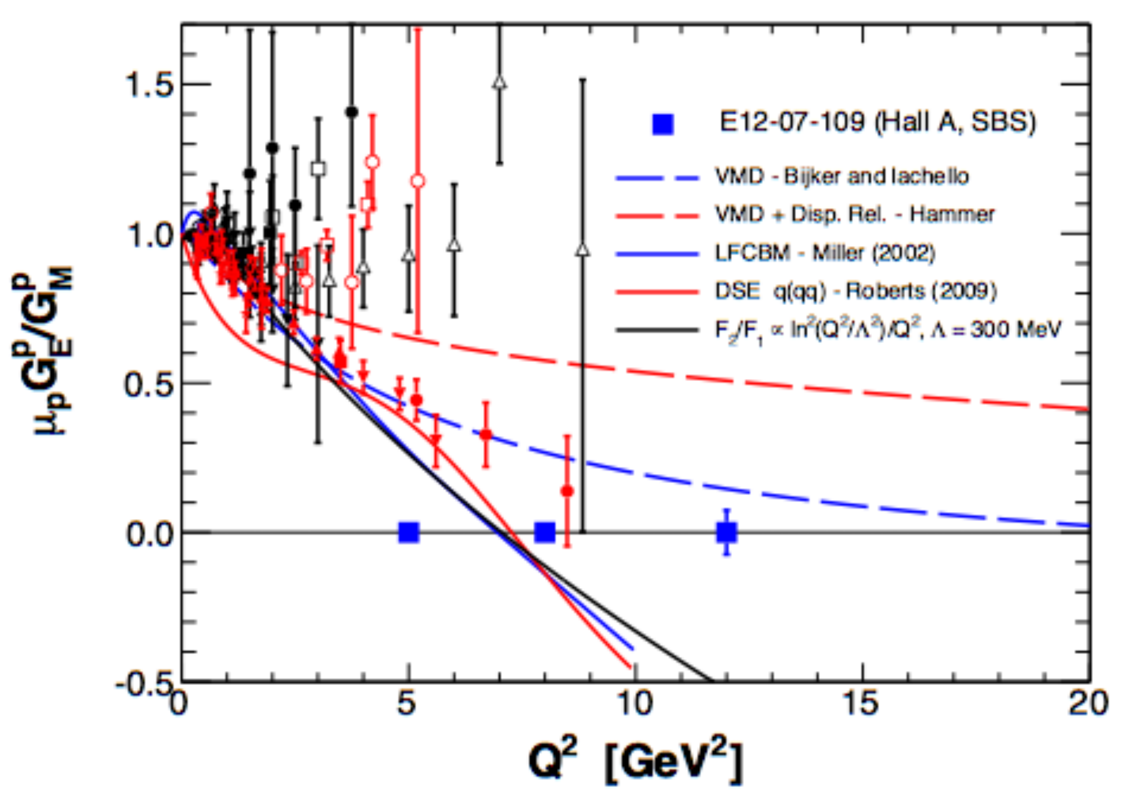
Combining elastic and DIS data to obtain total flavor-separated quark contribution to angular momentum

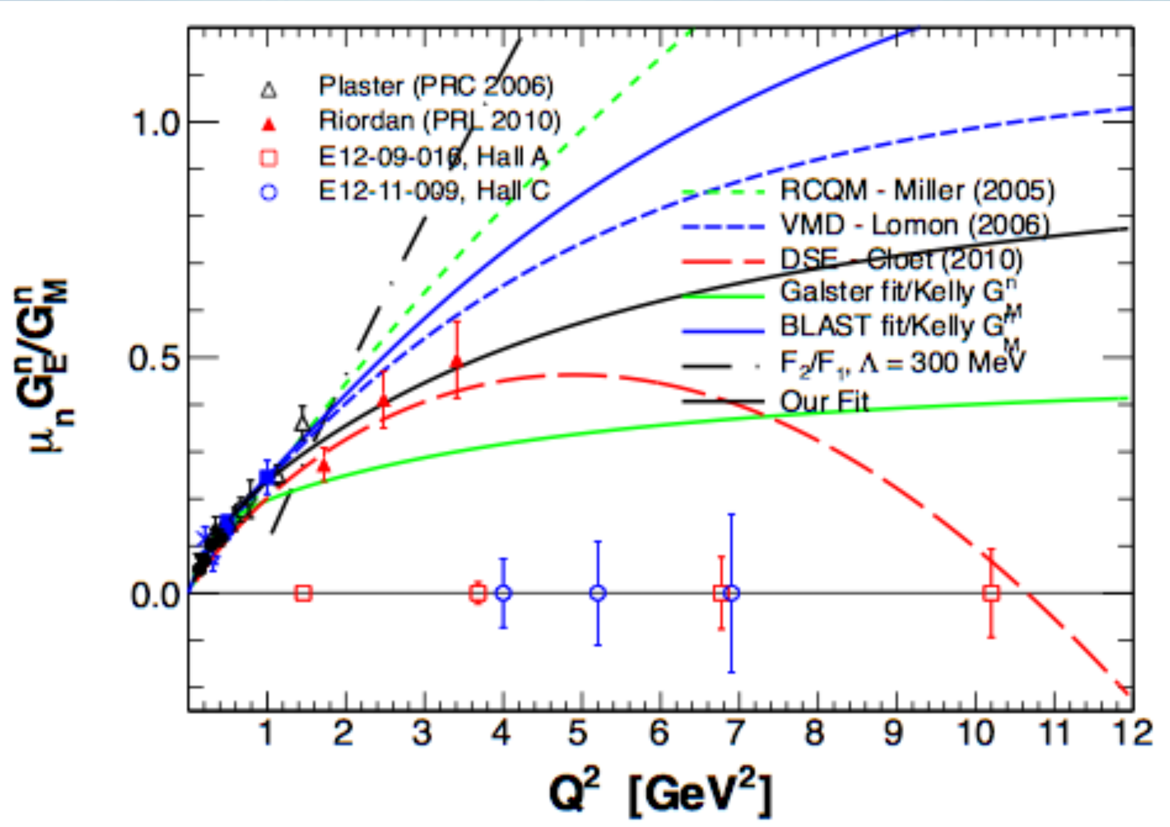


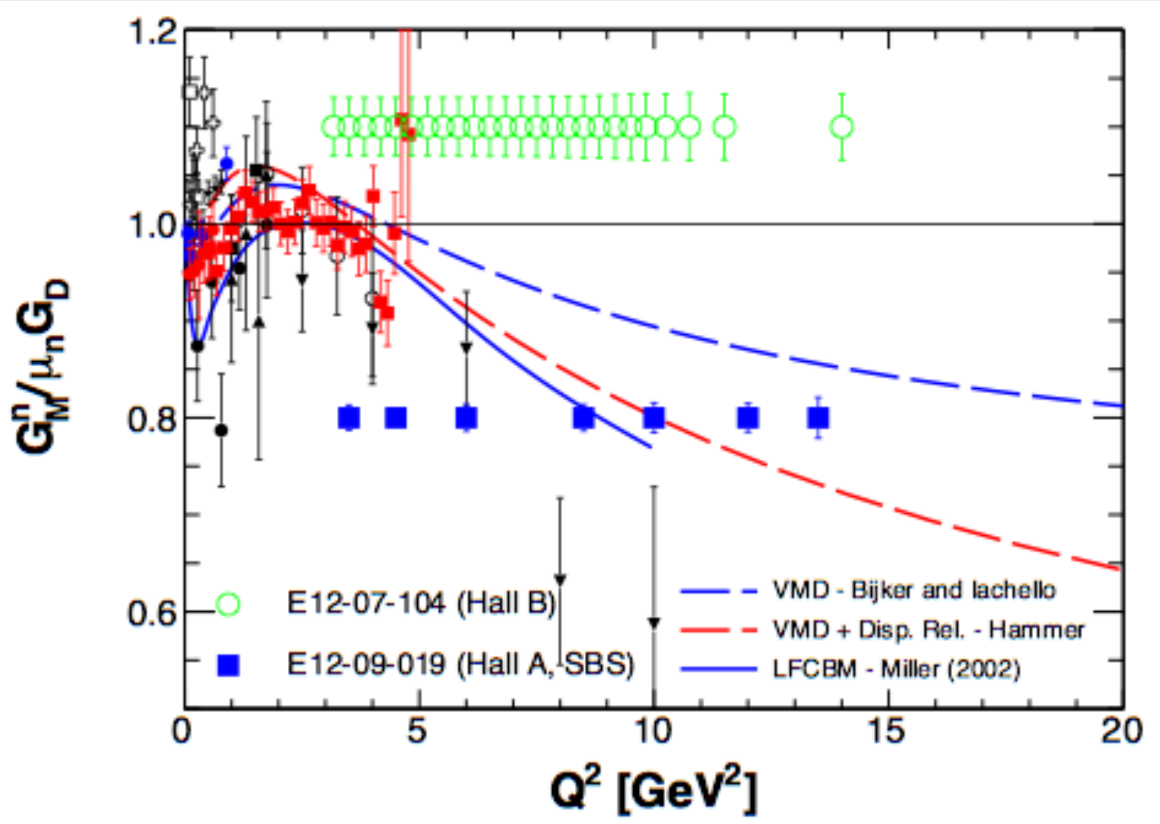
P. Kroll, EPJ Web of Conferences **85**, 01005 (2015)

While I don't want to suggest that the above analysis should be taken too seriously, it clearly shows the promising future of this approach.

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





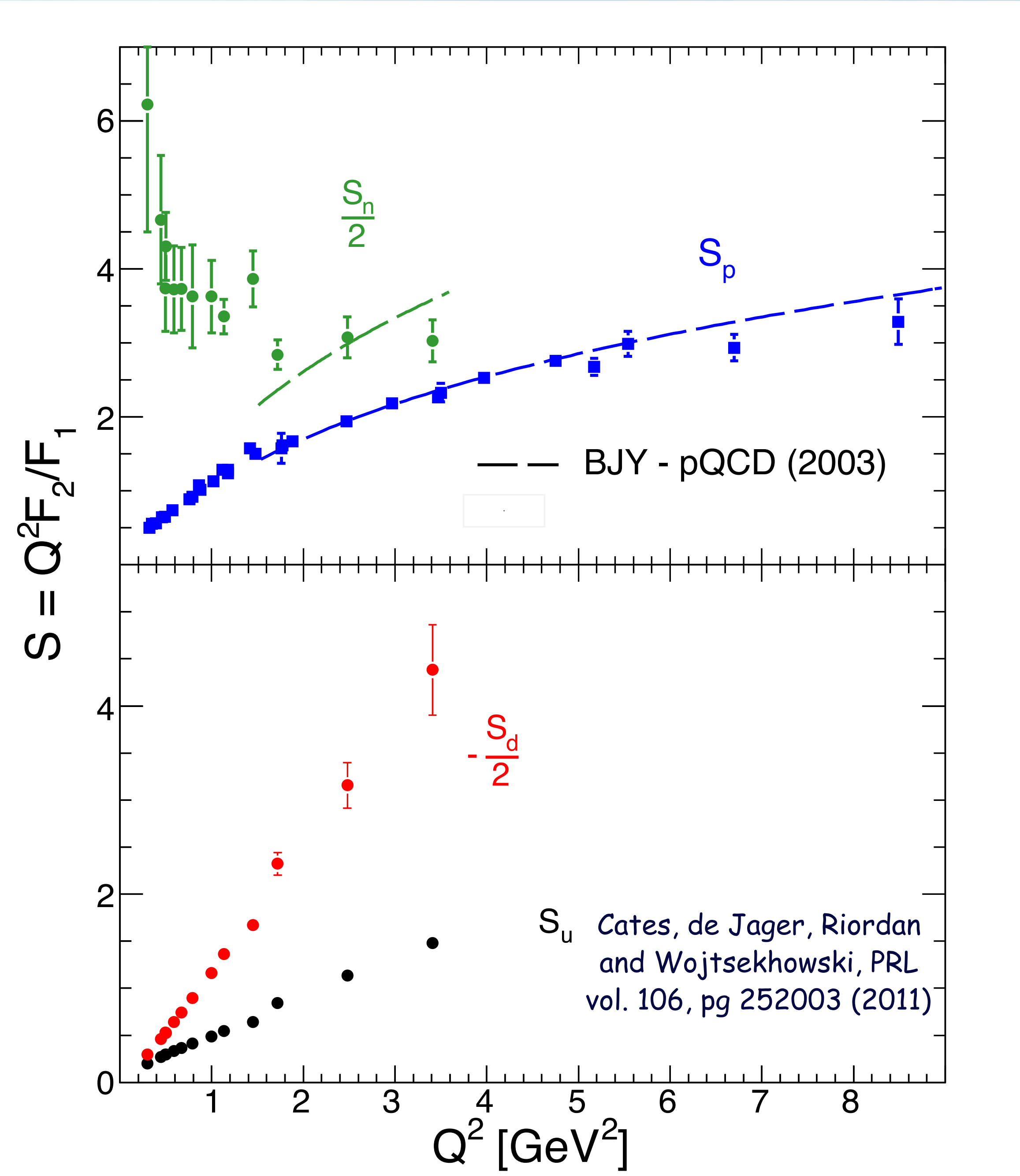


The three Super Bigbite experiments will meet the requirements to achieve the best physics by providing precise measurements at high Q^2.

Summary

- SBS is opening a new era for high Q^2 form factor studies and a broad new range of physics.
- The timing (installation beginning ~summer 2020) is perfect for starting graduate students.
- The richness of hardware, data-taking and analysis work offers tremendous opportunities.

The quantity $Q^2F_2^q/F_1^q$ has a very different behavior than is the case with the proton

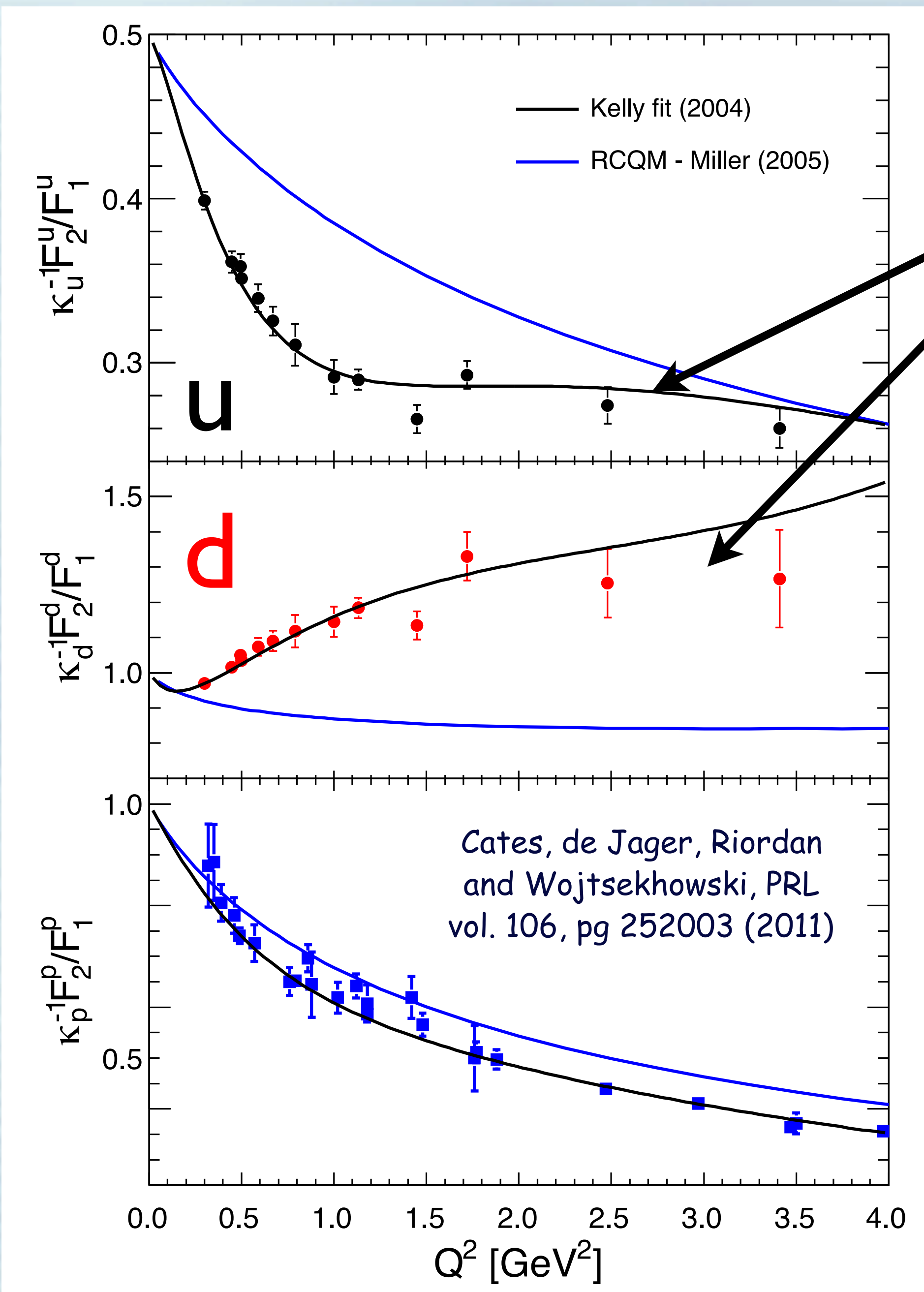


At left: Q^2F_2/F_1 for the proton and neutron.

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!

Why? F_2^u/F_1^u and F_2^d/F_1^d are relatively constant for $Q^2 > 1$ GeV^2

The ratios F_2^u/F_1^u and F_2^d/F_1^d

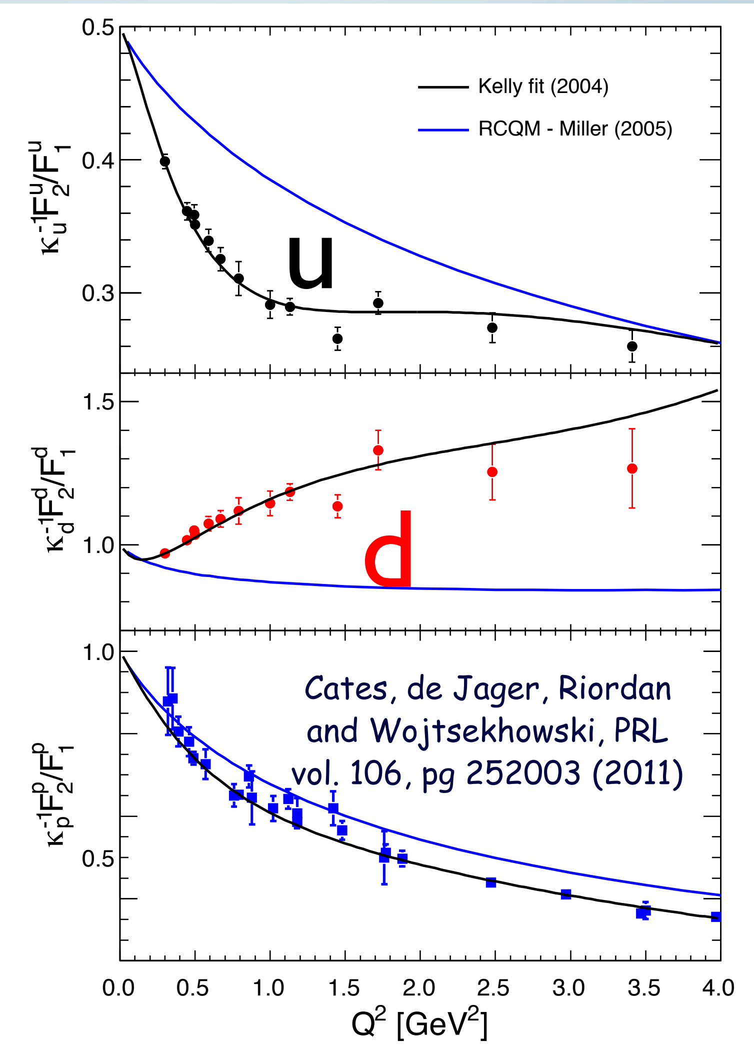


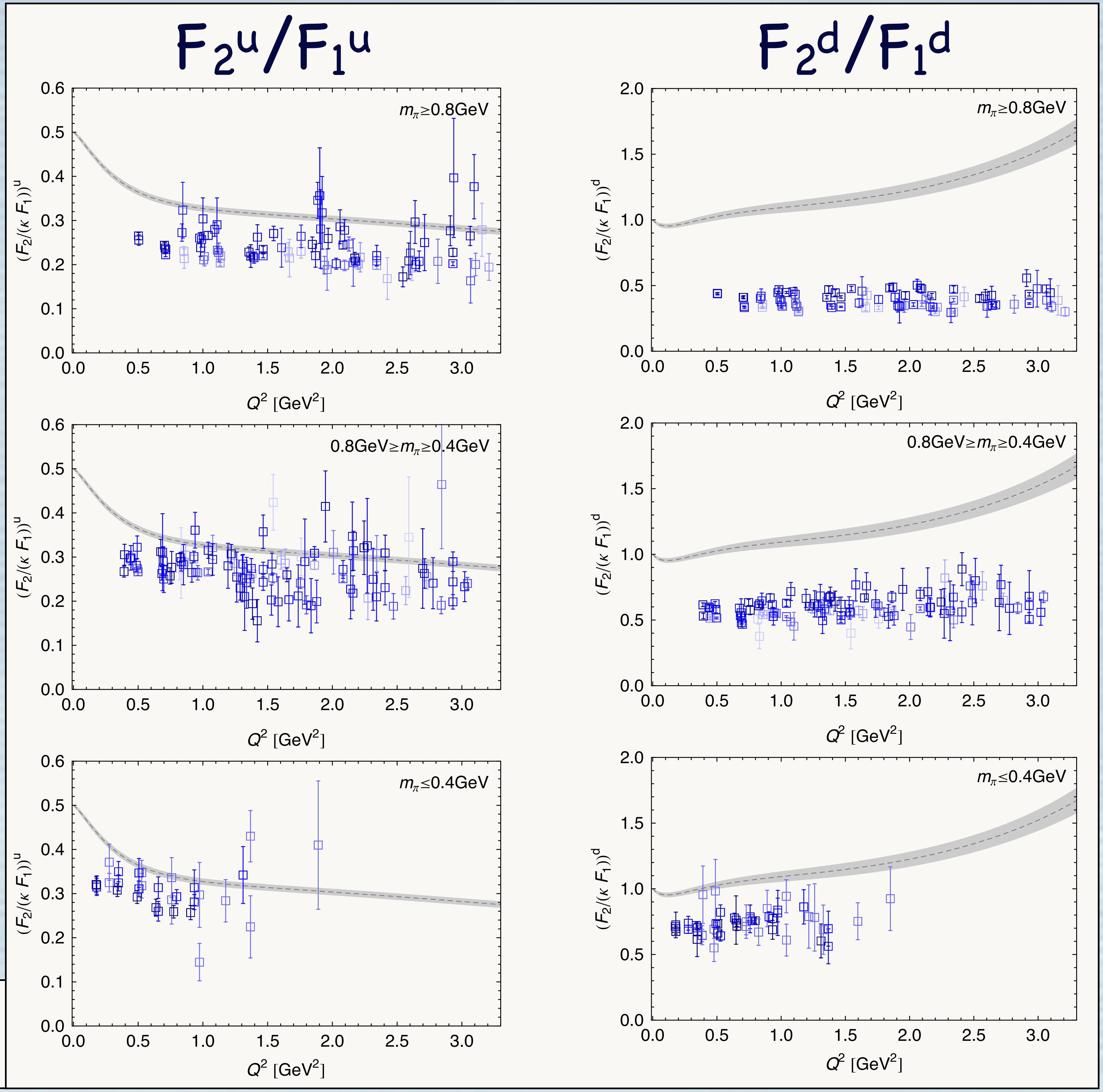
The ratios F_2^q/F_1^q become constant for Q^2 > ~1 GeV^2 !

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

LQCD calculations reproduce the behavior of F_2/F_1

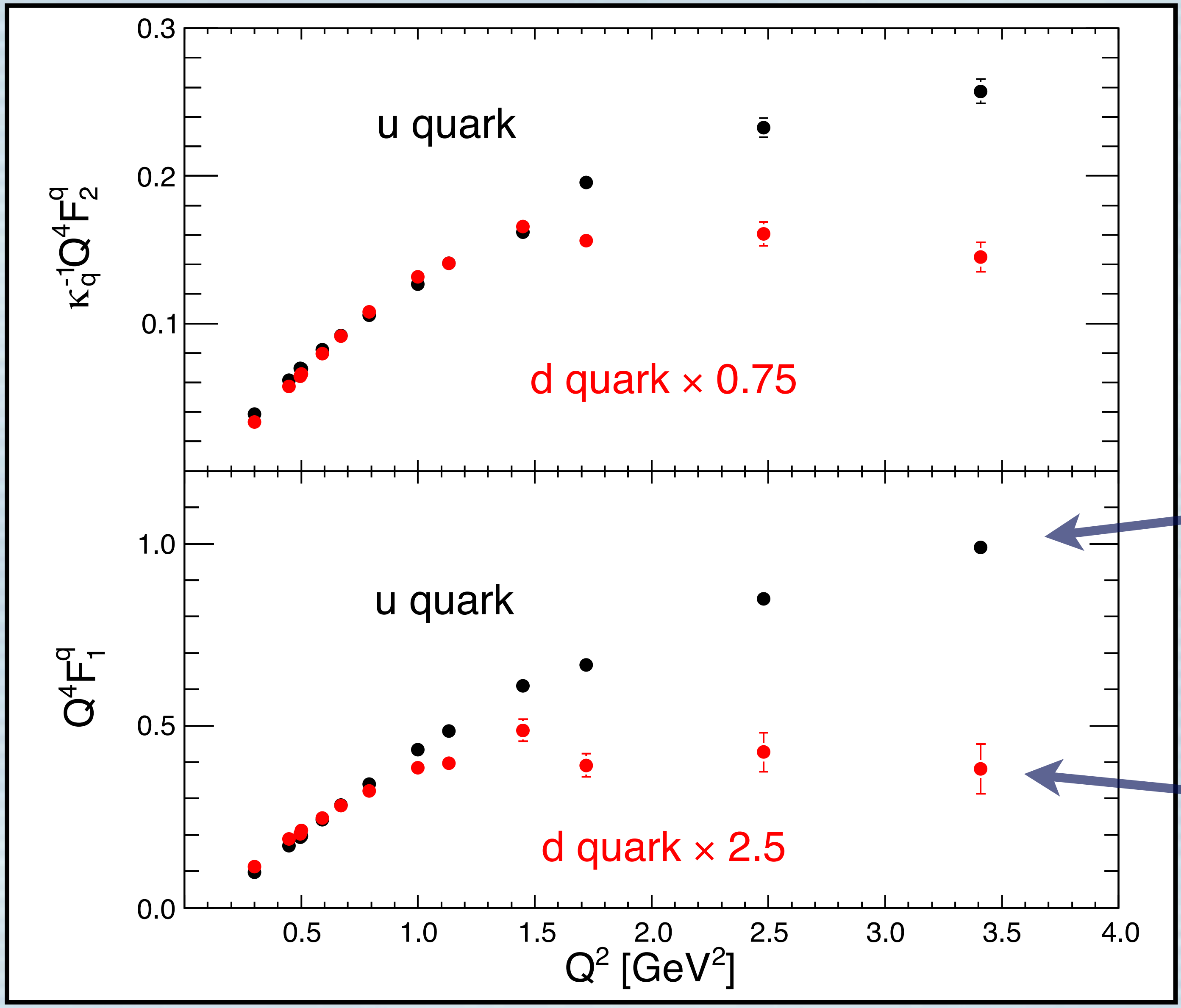




S. Collins et al. (QCDSF/UKQCD Collaboration), PRD v.84, 074507 (October, 2011)

The flavor separated form factors for the up and down quarks have very different Q^2 behavior above 1 GeV^2

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

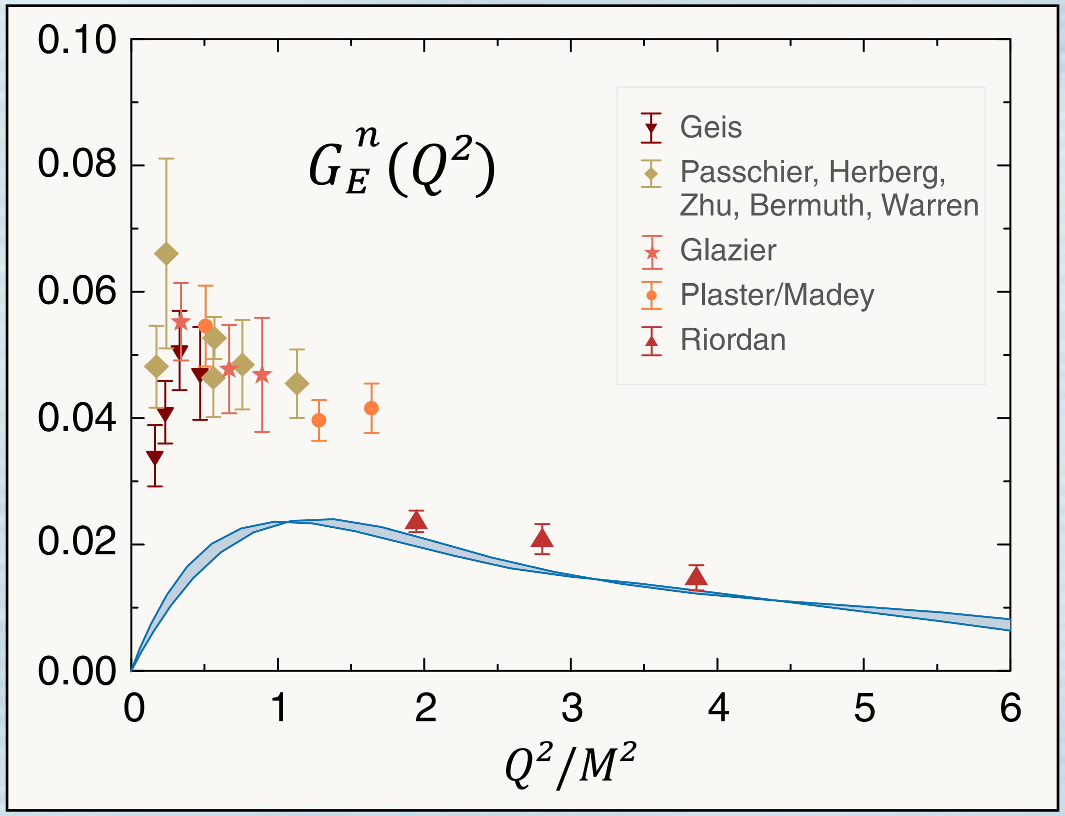


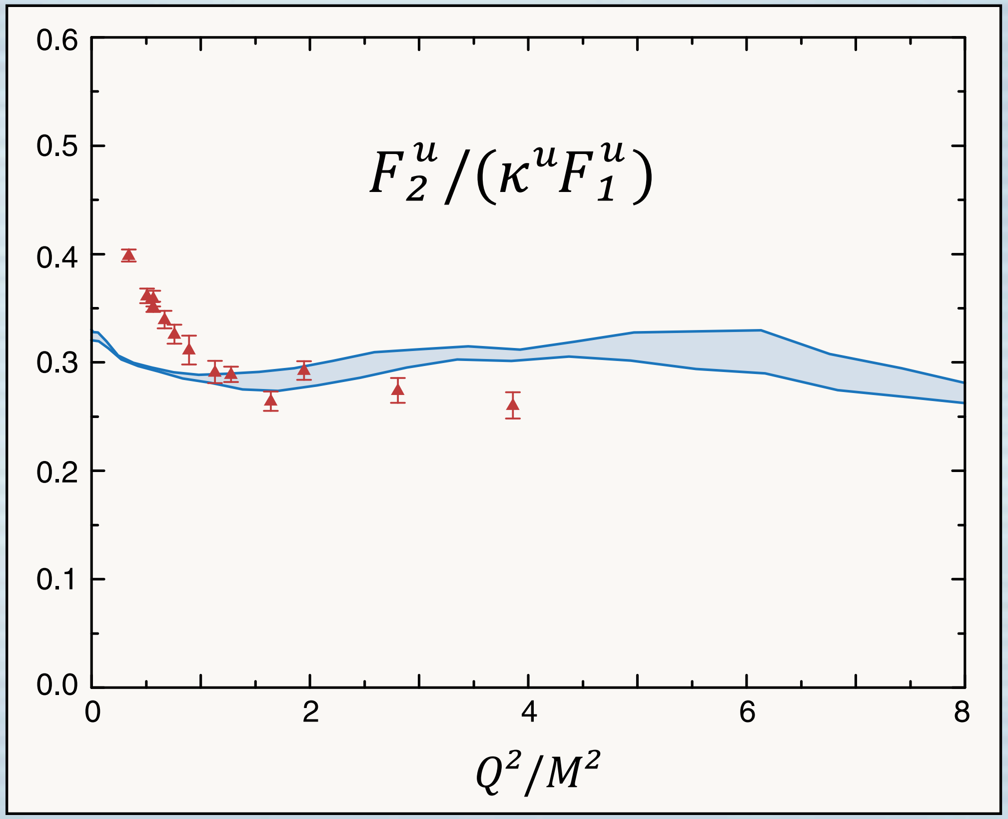
F^u seems to scale more like $1/Q^2$ (if at all).

F^d seems to scale roughly like $1/Q^4$

What is the significance of these different behaviors?

DSE/Fadeev calculation from G. Eichmann did not explicitly put in the quark-diquark structure "by hand", but arrived at similar results anyway





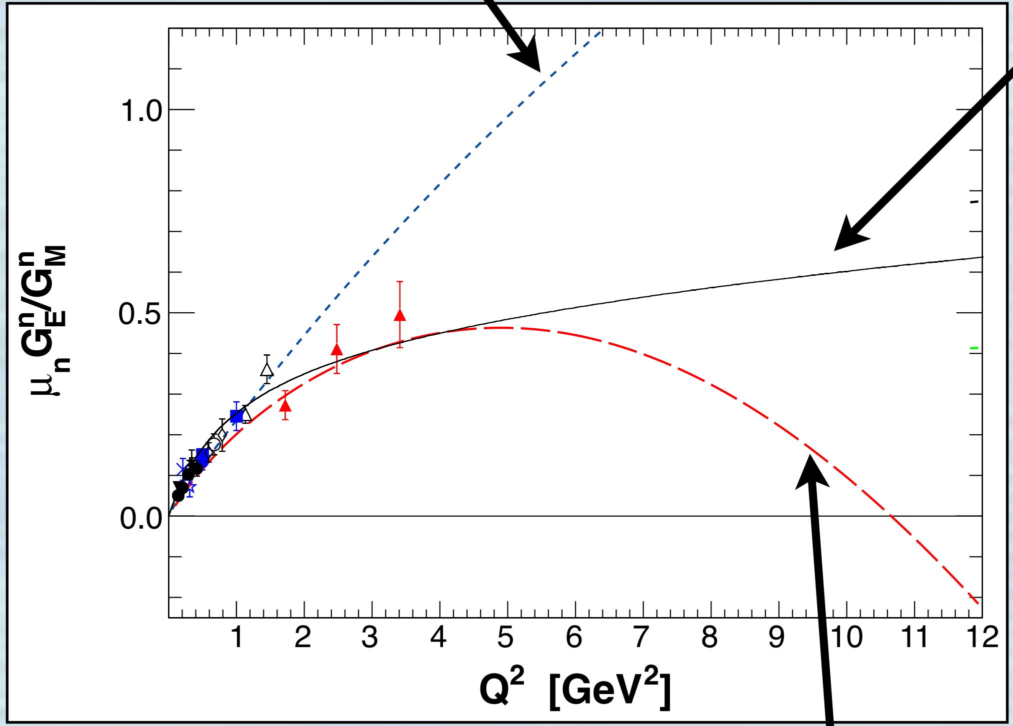
PRD Vol. 84, pg. 014014 (2011)

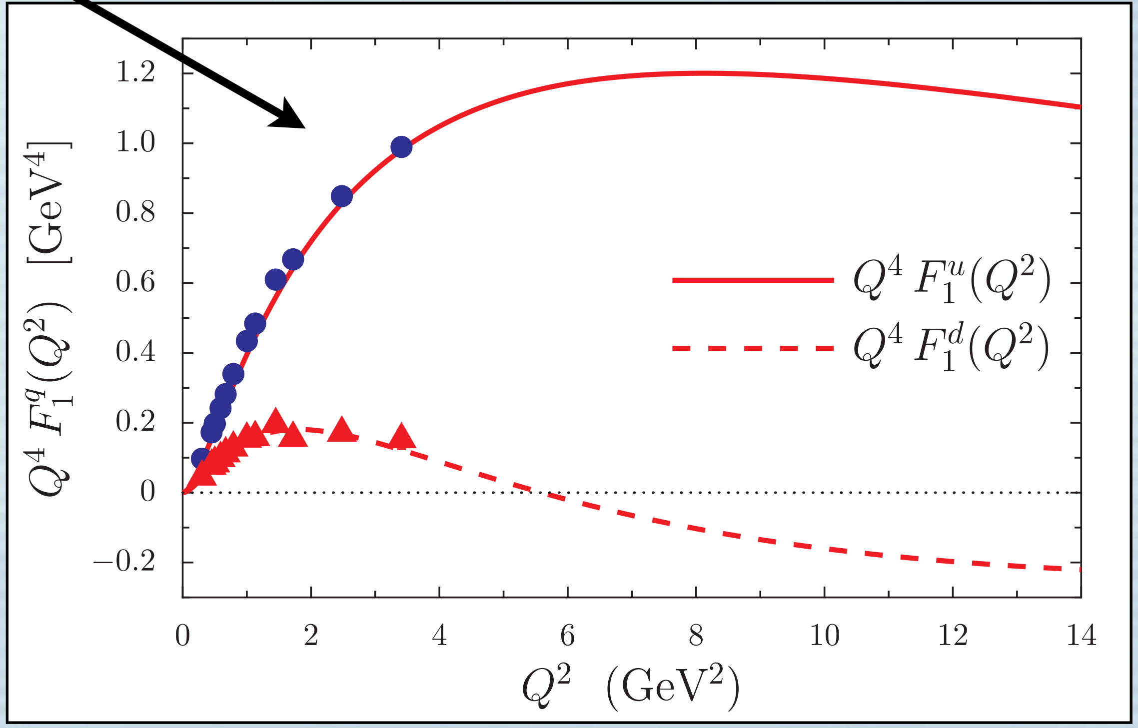
The overall agreement between our results and those obtained in the quark-diquark model provides further evidence for the quark-diquark structure of the nucleon, and it implies that scalar and axial-vector diquark degrees of freedom can account for most of its characteristic features.

Relativistic Constituent Quark Models (RCQMs) that emphasize diquark features fit the data well

Light-front cloudy bag model Jerry Miller (PRC v66, pg032201, 2002).

Updated RCQM model emphasizing quark-diquark structure: Ian Cloët and Jerry Miller



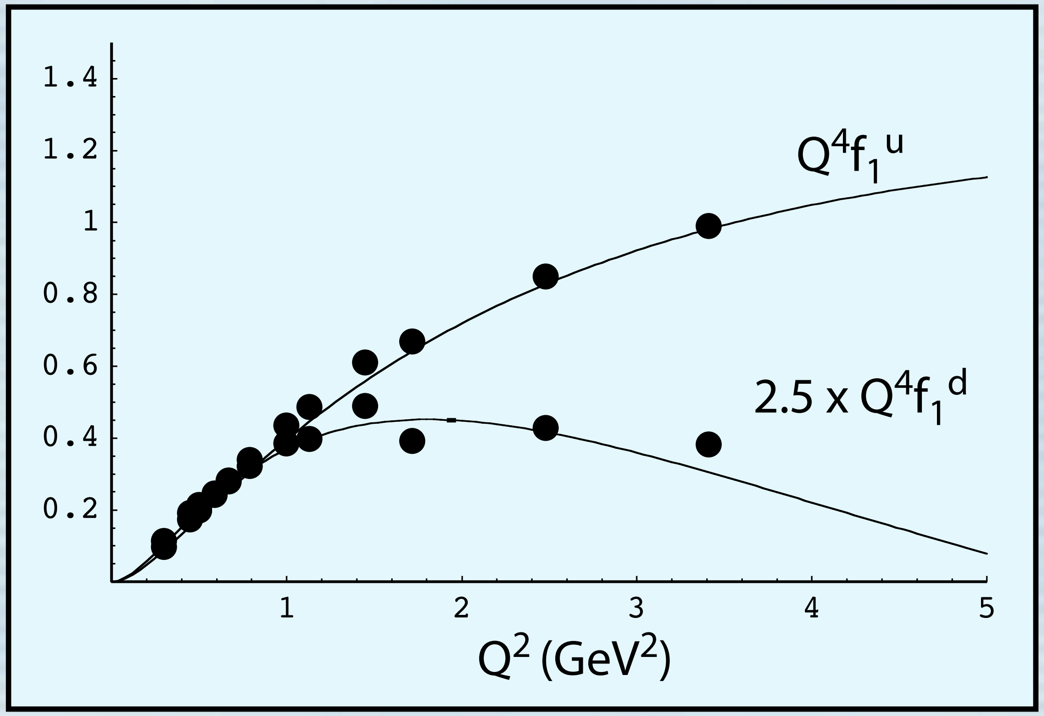


The QCD DSE model of Cloët, Roberts et al. in which the constituent quark mass is dynamically generated and diquark degrees of freedom are incorporated.
(Few Body Systems v46, pg1 2009)

It appears that it is important to include terms related to diquarks in RCQMs in order to fit the behavior of the flavor decomposed form factors.

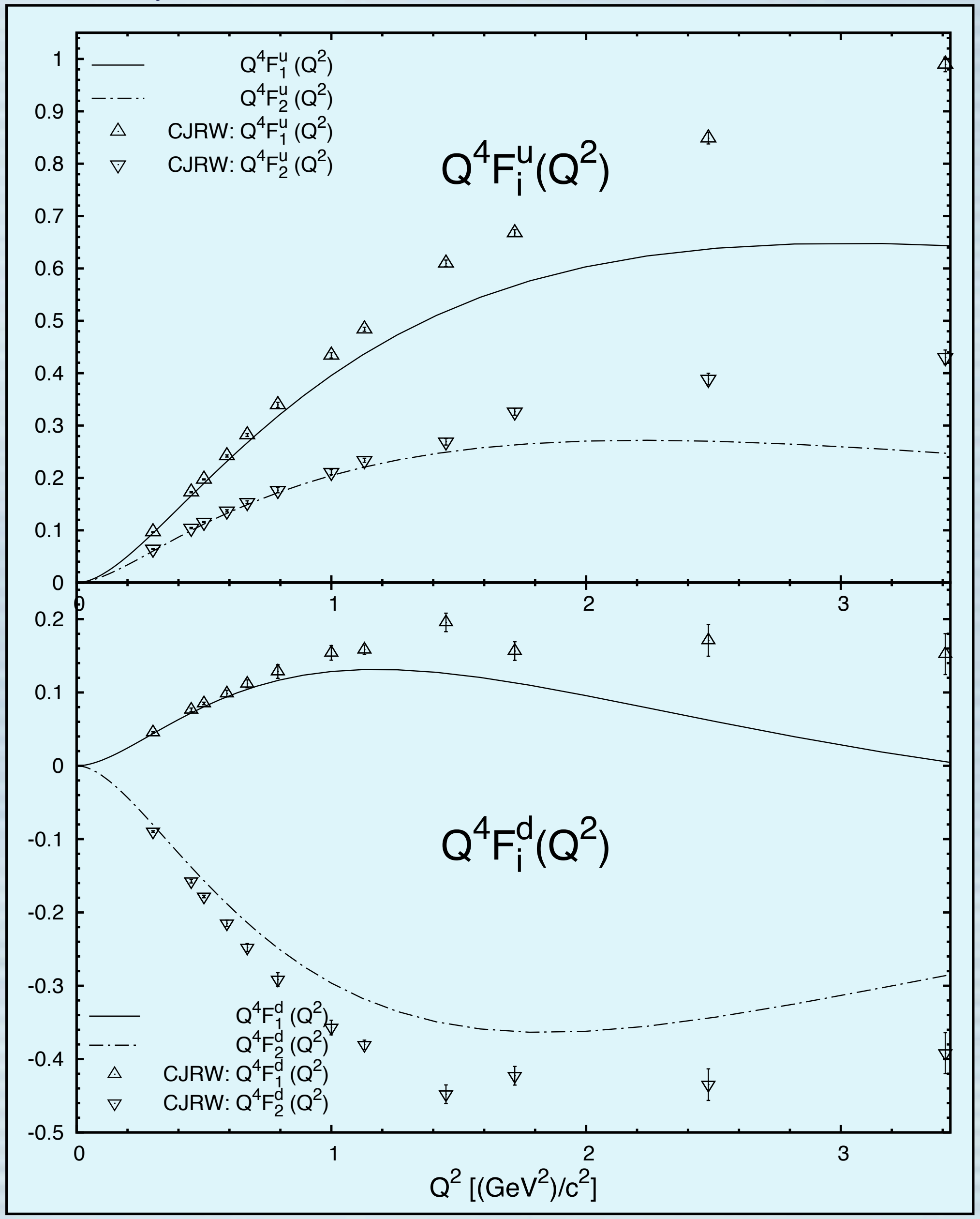
Comparing RCQMs with and without quark-diquark strucutre

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.



Same Miller/Cloet model as previous slide, plotted slightly differently

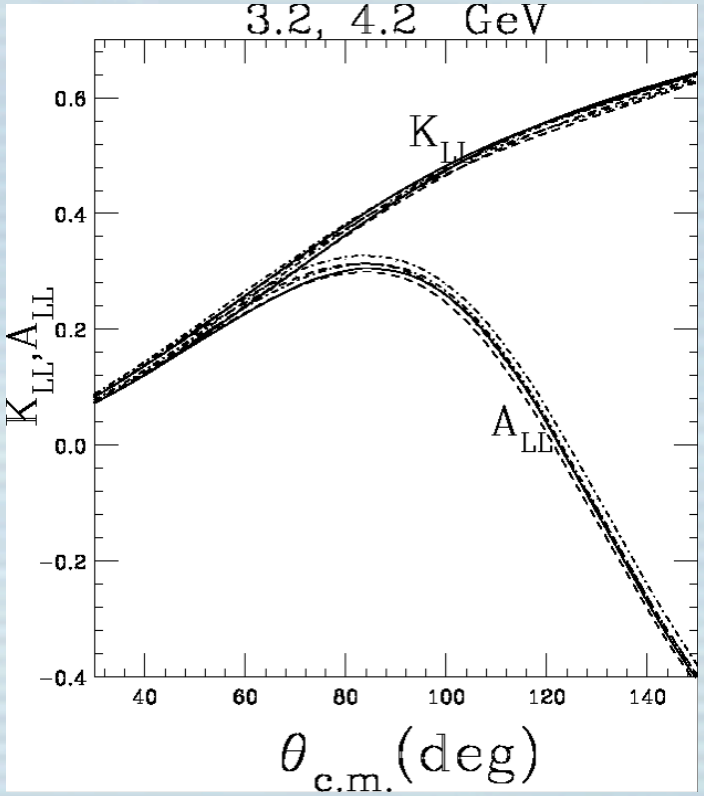
However, another RCQM with no diquarks does not do as well



Rohrmoser, Choi and Plessas, arXiv:1110.3665

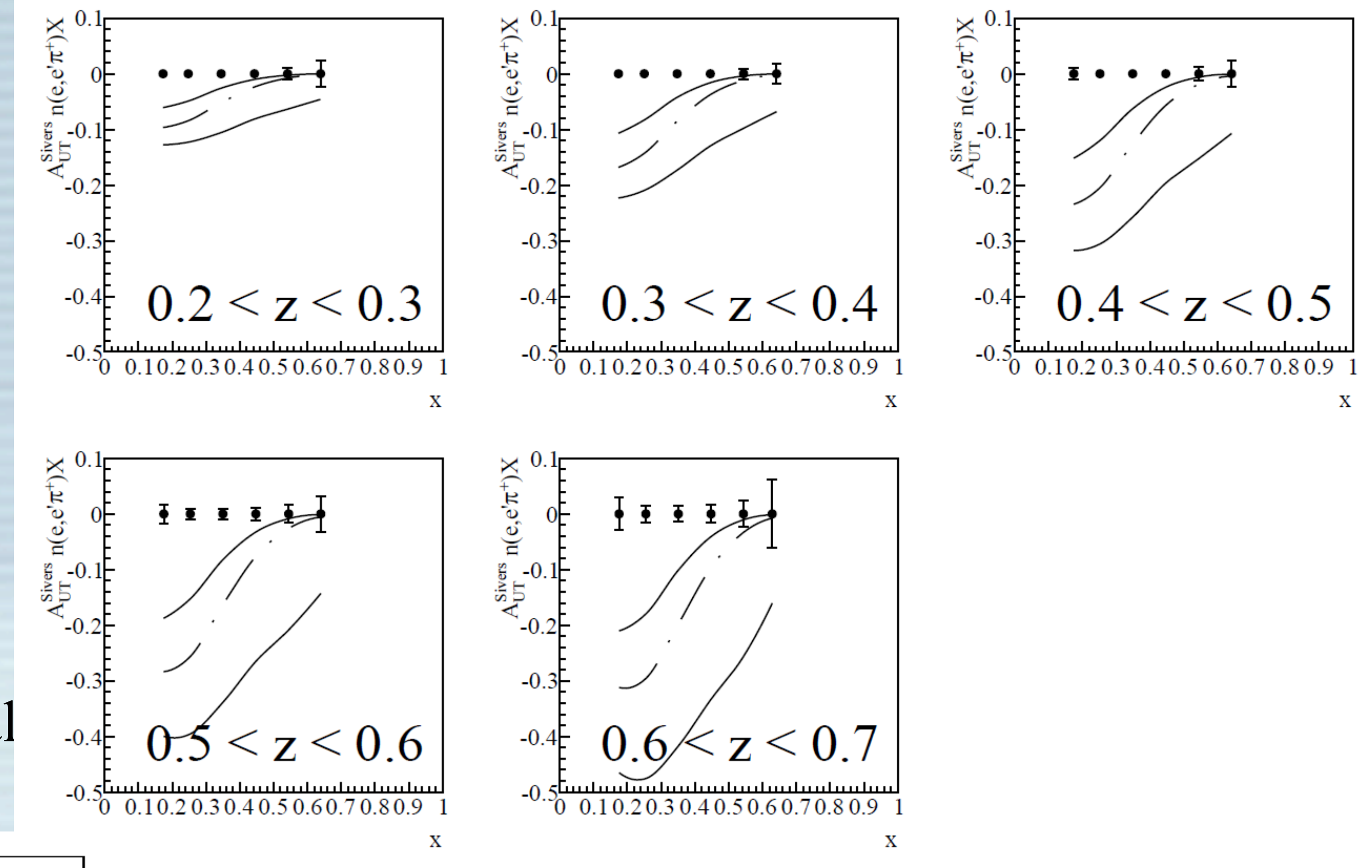
High profile physics with SBS beyond the elastic nucleon form factors

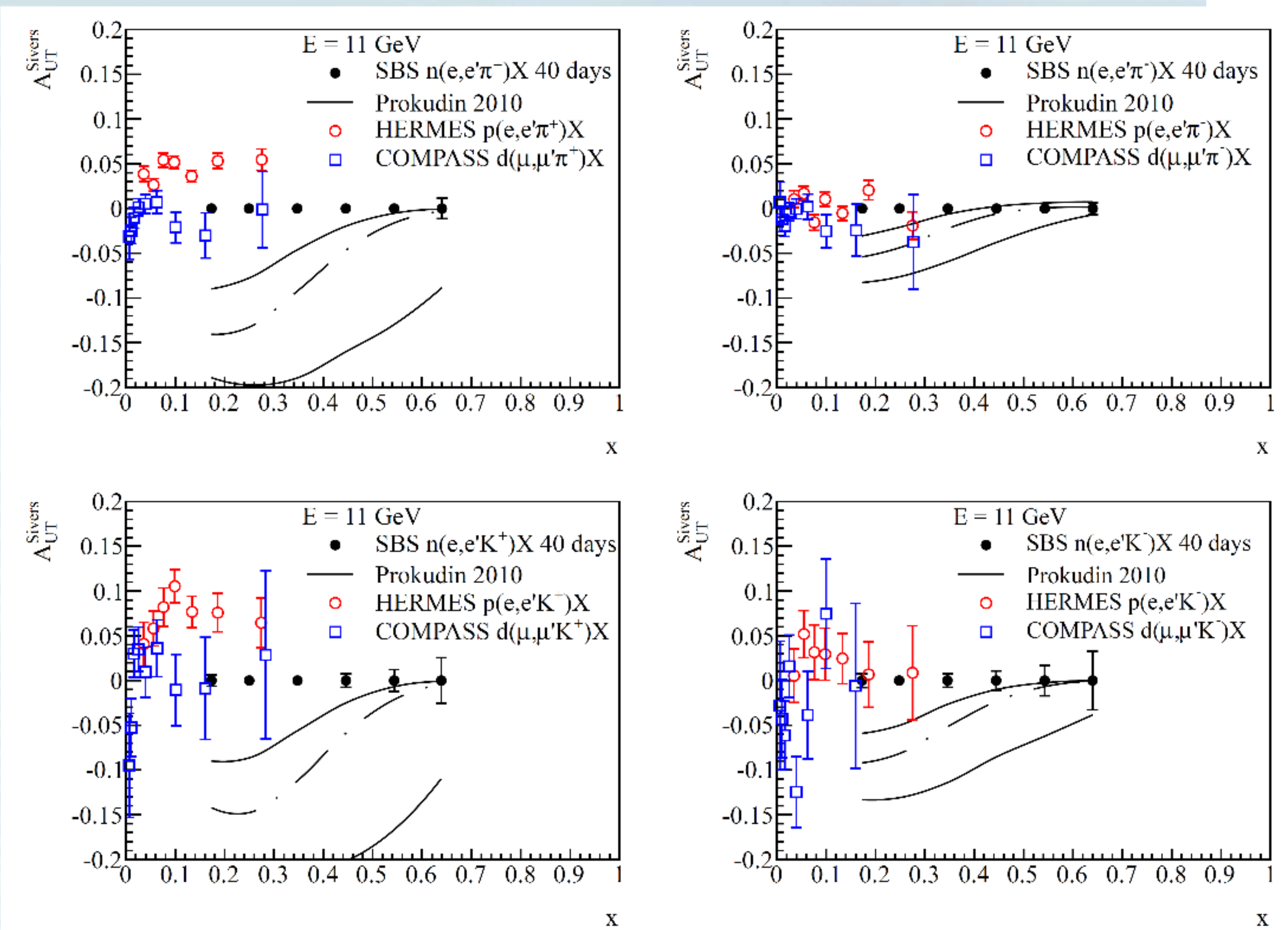
- E12-09-018: Neutron Transversity, studied using single-spin asymmetries (SSAs) in semi-inclusive deep inelastic scattering (SIDIS) - fully approved, 64 PAC days
- Structure functions of the pion, studied using the Sullivan process in which one studies DIS scattering off the pion cloud. Upcoming workshop January 16-18, 2014.
- Wide angle Compton scattering, with polarized beam and target, measure the asymmetry A_{LL}. Sensitive to mass of constituent quark.



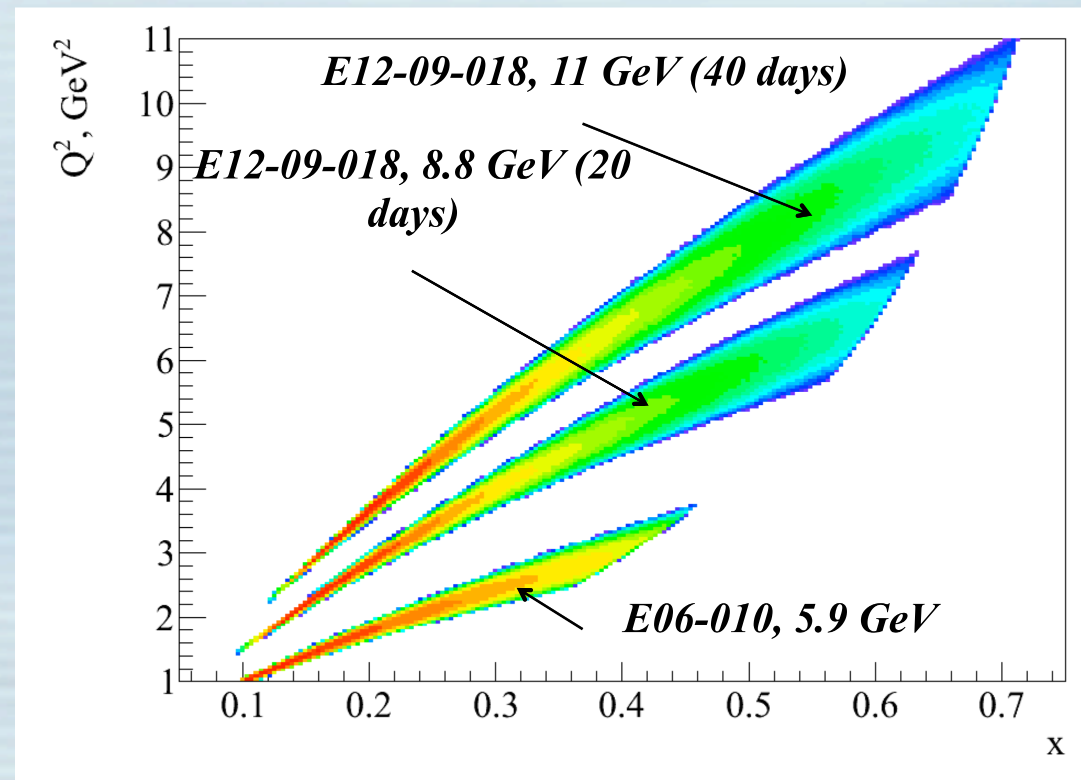
Neutron transversity in SIDIS

- JLab E12-09-018—approved for 64 beam-days by JLab PAC38, A- scientific rating
- Transverse target single-spin asymmetries in ^{3}**He**(e,e'h)X (h=$\pi^{\pm,0}$, $K^{\pm}$)
  - Collins and Sivers effects
  - Precision input to global TMD extraction
- ~100X higher statistical figure-of-merit for neutron than HERMES proton data
- First precision measurements in a multi-dimensional kinematic binning



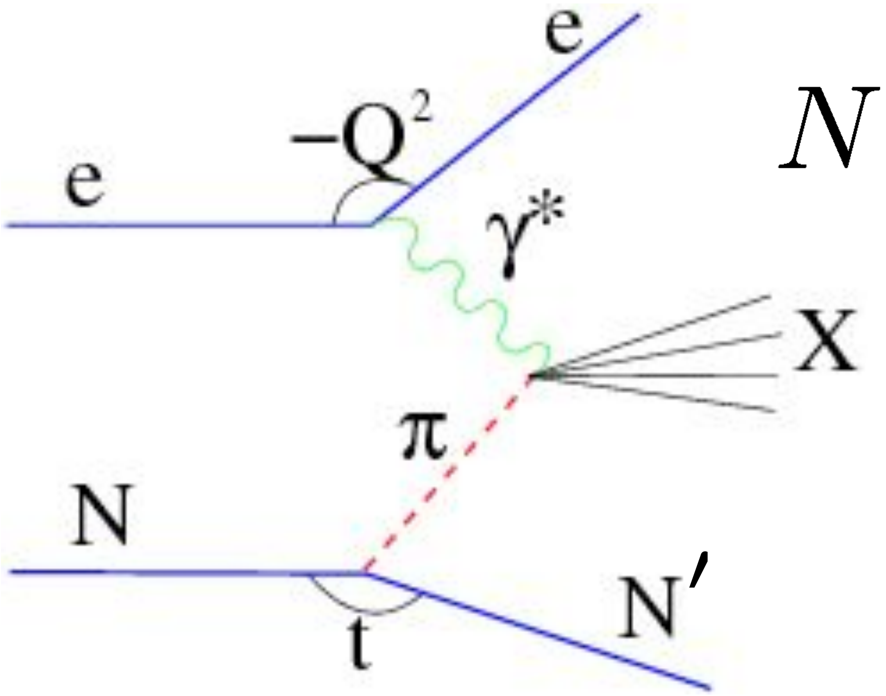


$\pi^{\pm}$, $K^{\pm}$ neutron Sivers asymmetries compared to HERMES, COMPASS, phenomenological fit



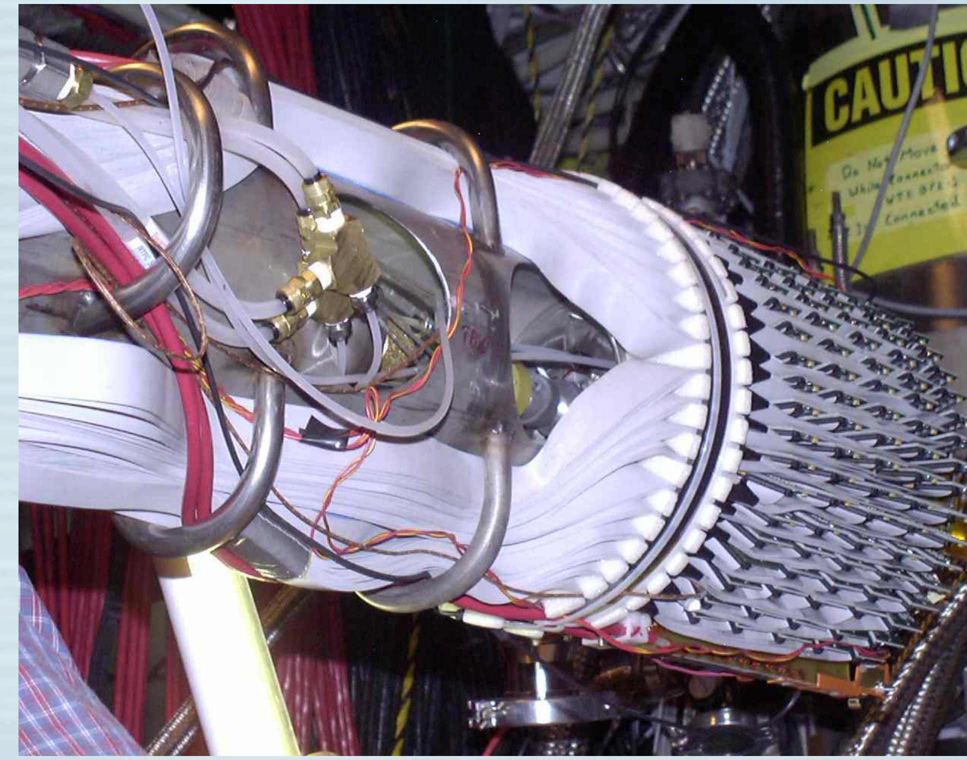
- Data at two beam energies provide a range of Q^2 at fixed x
- RICH preparation effort starting at

Pion Exchange (Sullivan) Process – DIS from the pion cloud of the nucleon



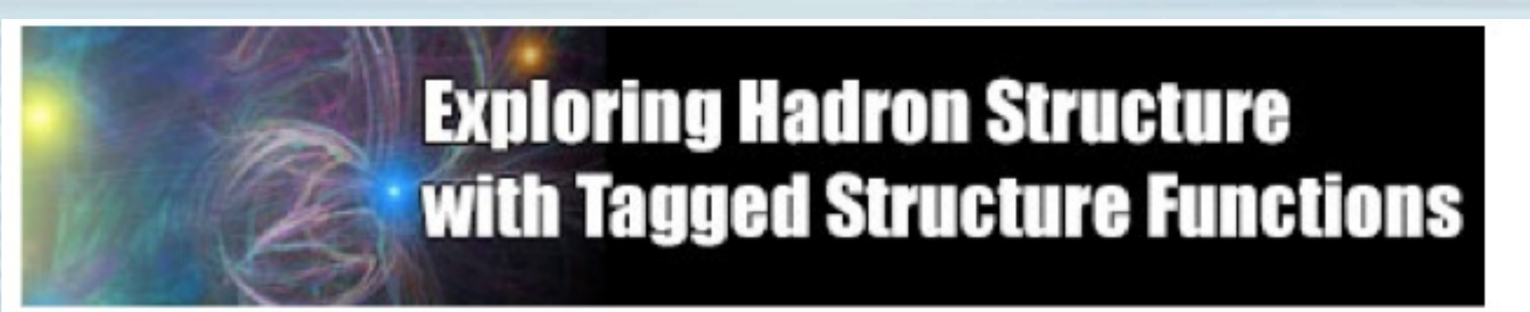
$$N(e, e'N')X$$

$$t = (p_{N'} - p_N)^2 = m_N^2 + m_{N'}^2 - 2m_N E_{N'}$$



- |t| has to be small to enhance contribution from Sullivan process -> use rTPC detection technique pioneered by JLab BONUS experiment with CLAS6
- BUT, small cross section means need luminosity – solution: use an optimized rTPC with Super BigBite, L ~ 10^{37}

Substantial theory interest



Upcoming workshop:
January 16-18, 2014 at JLab