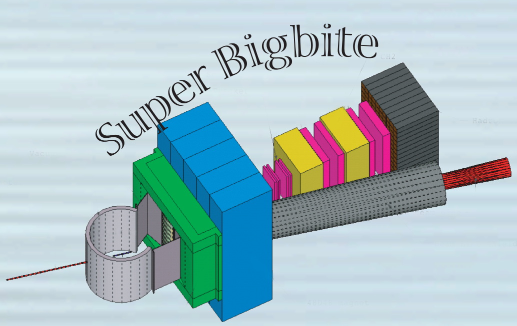
SBS Science Update and Overview

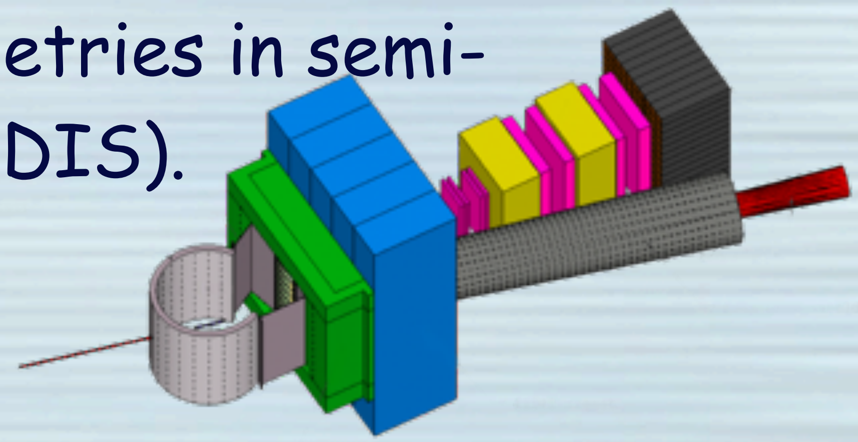
- Quick snapshot of the SBS Program
- A few words on the different subsystems you will hear about and where they fit into the larger picture.
- An update on the science motivation since the October 2011 review.



Gordon D. Cates

The Super Bigbite Spectrometer (SBS) Program

- The SBS Program is comprised of three work breakdown structures (WBSs):
  - WBS 1: The SBS Basic Project (magnet and infrastructure).
  - WBS 2: Neutron Form Factor Project
  - WBS 3: Proton Form Factor Project
- While the SBS Program should be viewed as an independent entity, the scope of the work performed under the three WBSs will make possible high-Q^2 measurements of three out of four of the nucleon elastic form factors (note that G_M^p will be measured using the existing Hall A equipment).
- The SBS program will also facilitate additional experiments, such as the measurement of single-spin asymmetries in semi-inclusive deep inelastic scattering (SSAs in SIDIS).



The Super Bigbite Program will enable the measurement of three out of four elastic nucleon FFs at high Q^2

(and G_M^p will be measured with existing Hall A equipment)

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

  Figure-of-merit > 30x better than previous experiments.

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

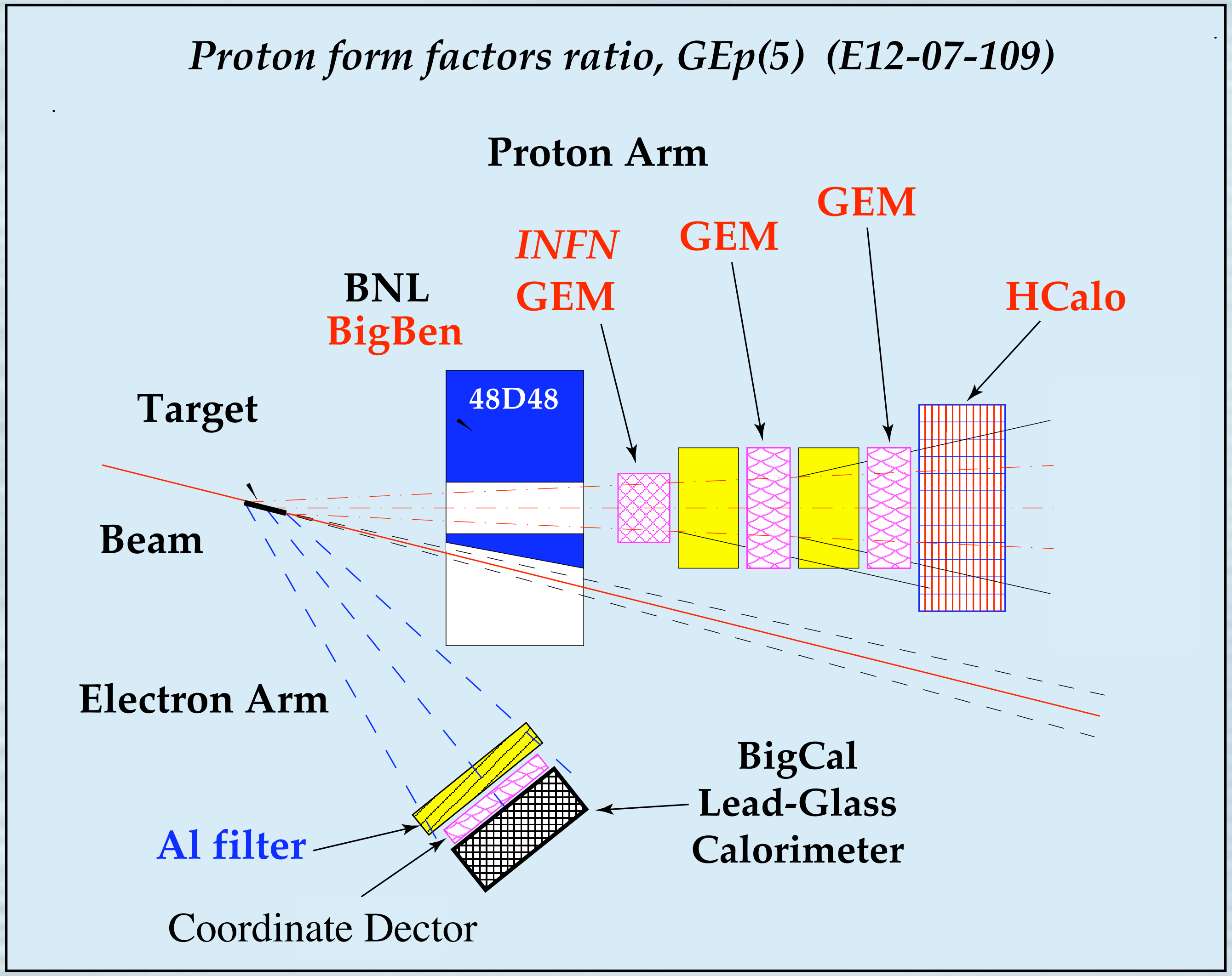
  Figure-of-merit >10x better than previous experiments.

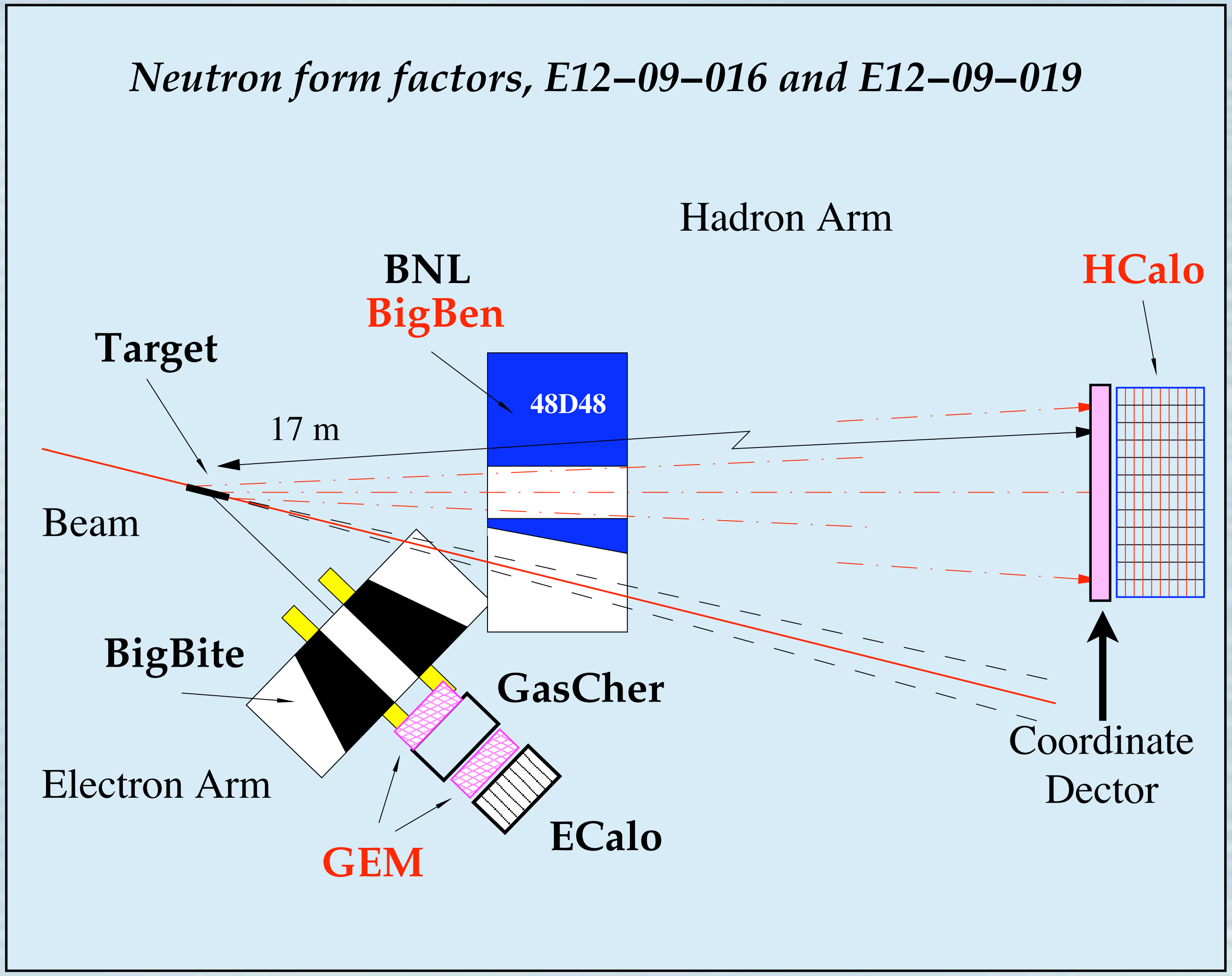
- E12-09-019: measurement of G_M^n/G_M^p to Q^2=13.5 GeV^2.

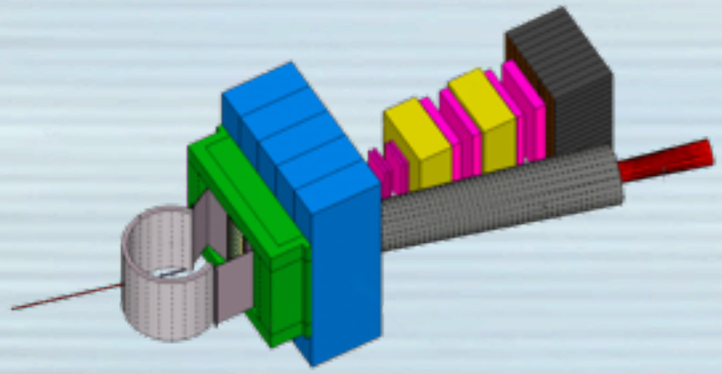
  Figure-of-merit > 20x better than previous experiments.

Super Bigbite will provide game-changing capability that meets the requirements for accessing the discovery potential of elastic form factors

The SBS equipment will be configured differently depending on the experiment



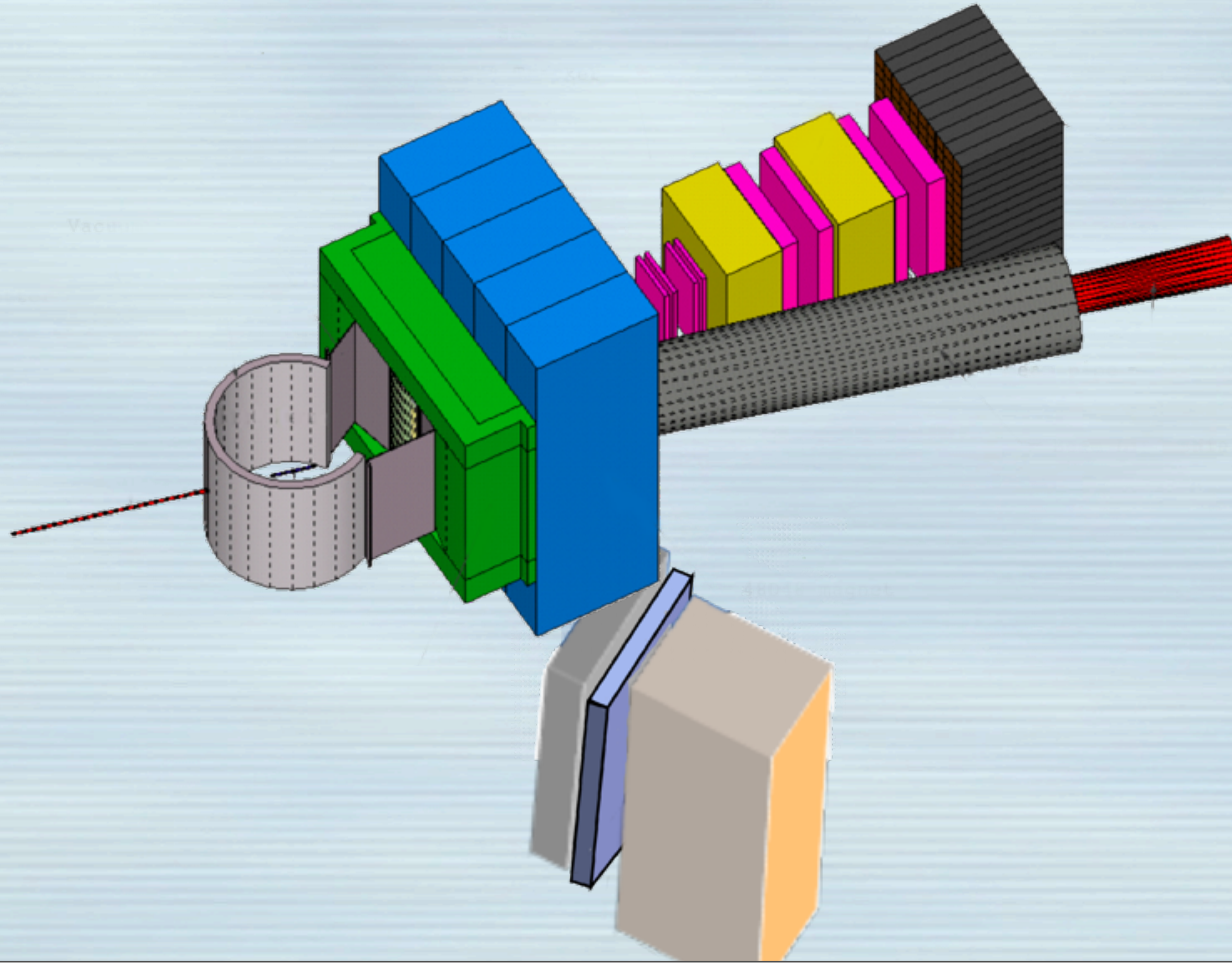




G_E^p/G_M^p

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

The SBS subsystems we will hear about today



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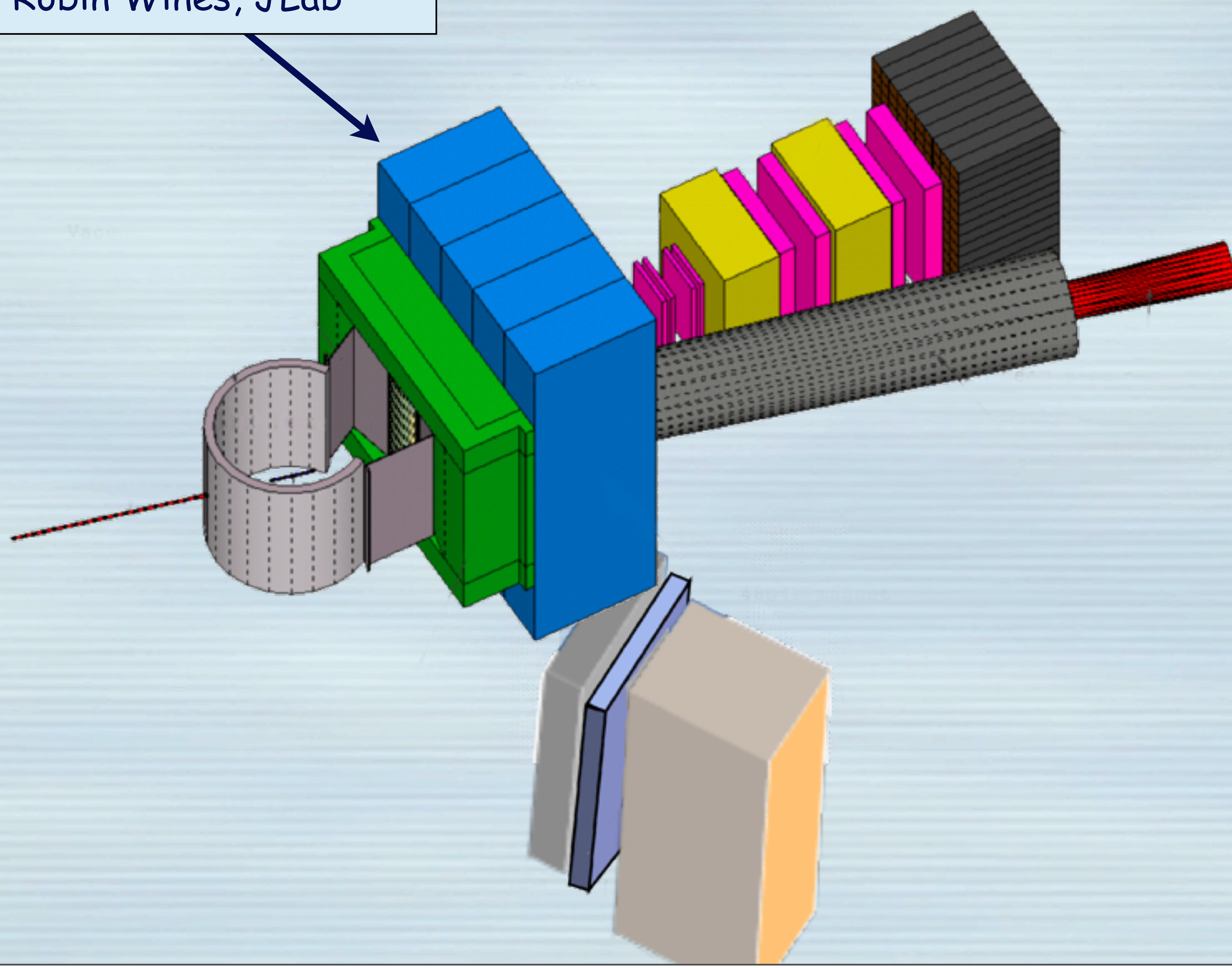
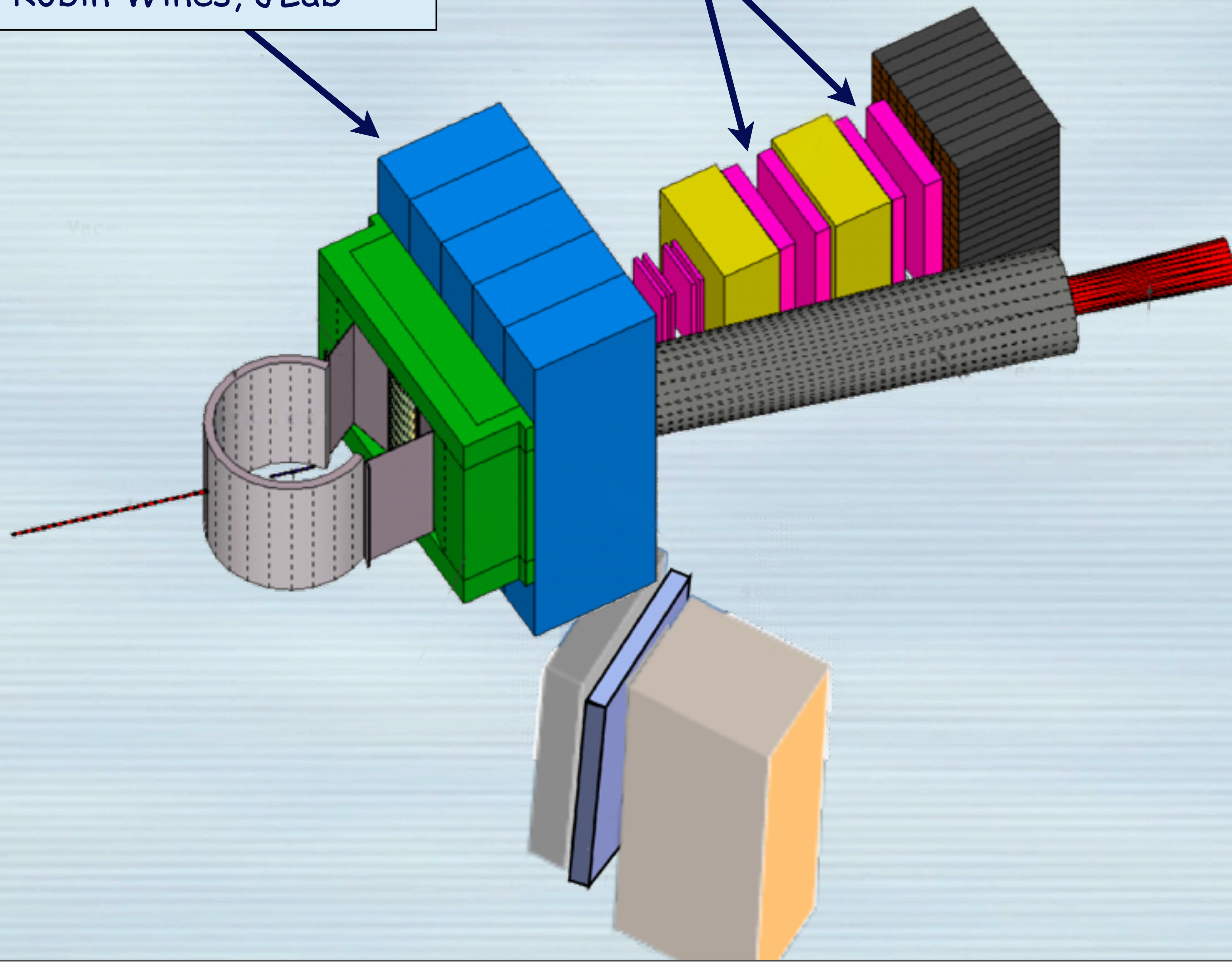
WBS1 - Magnet and Infrastructure,
Robin Wines, JLab



The SBS subsystems we will hear about today

WBS1 - Magnet and
Infrastructure,
Robin Wines, JLab

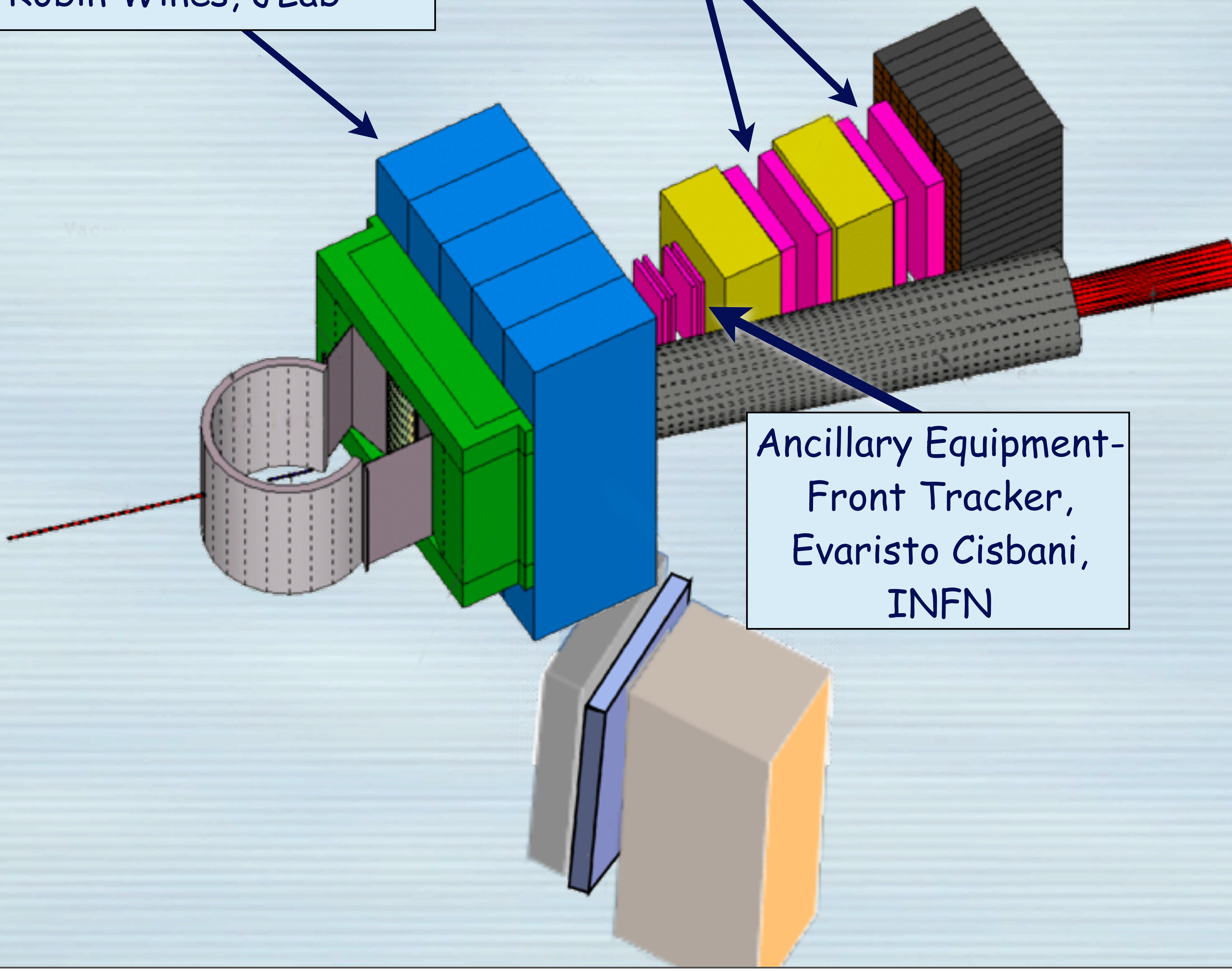
WBS2 - Neutron Form
Factor, GEM Detectors,
Nilanga Liyanage, UVa



The SBS subsystems we will hear about today

WBS1 - Magnet and Infrastructure, Robin Wines, JLab

WBS2 - Neutron Form Factor, GEM Detectors, Nilanga Liyanage, UVa

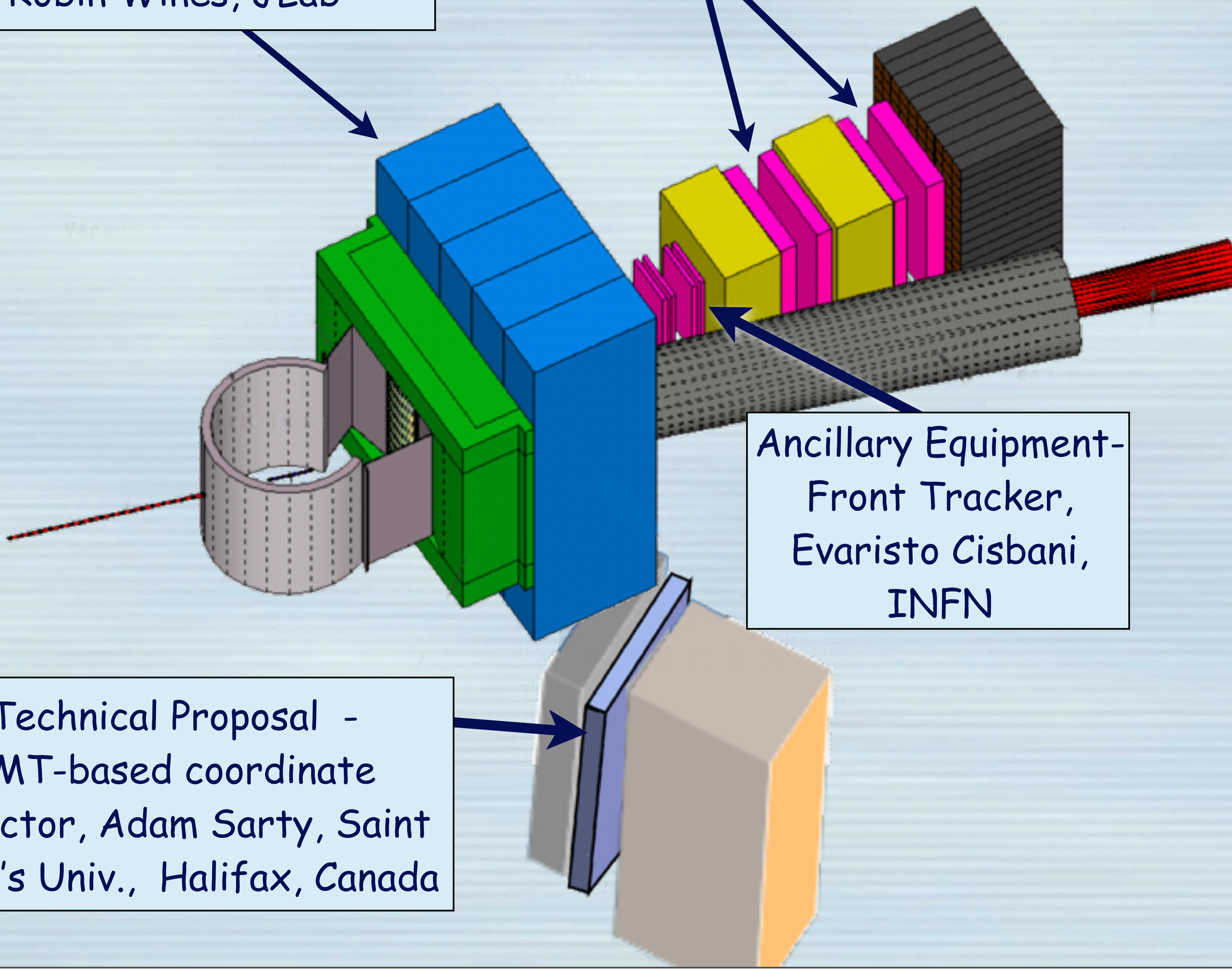


Ancillary Equipment- Front Tracker, Evaristo Cisbani, INFN

The SBS subsystems we will hear about today

WBS1 - Magnet and Infrastructure, Robin Wines, JLab

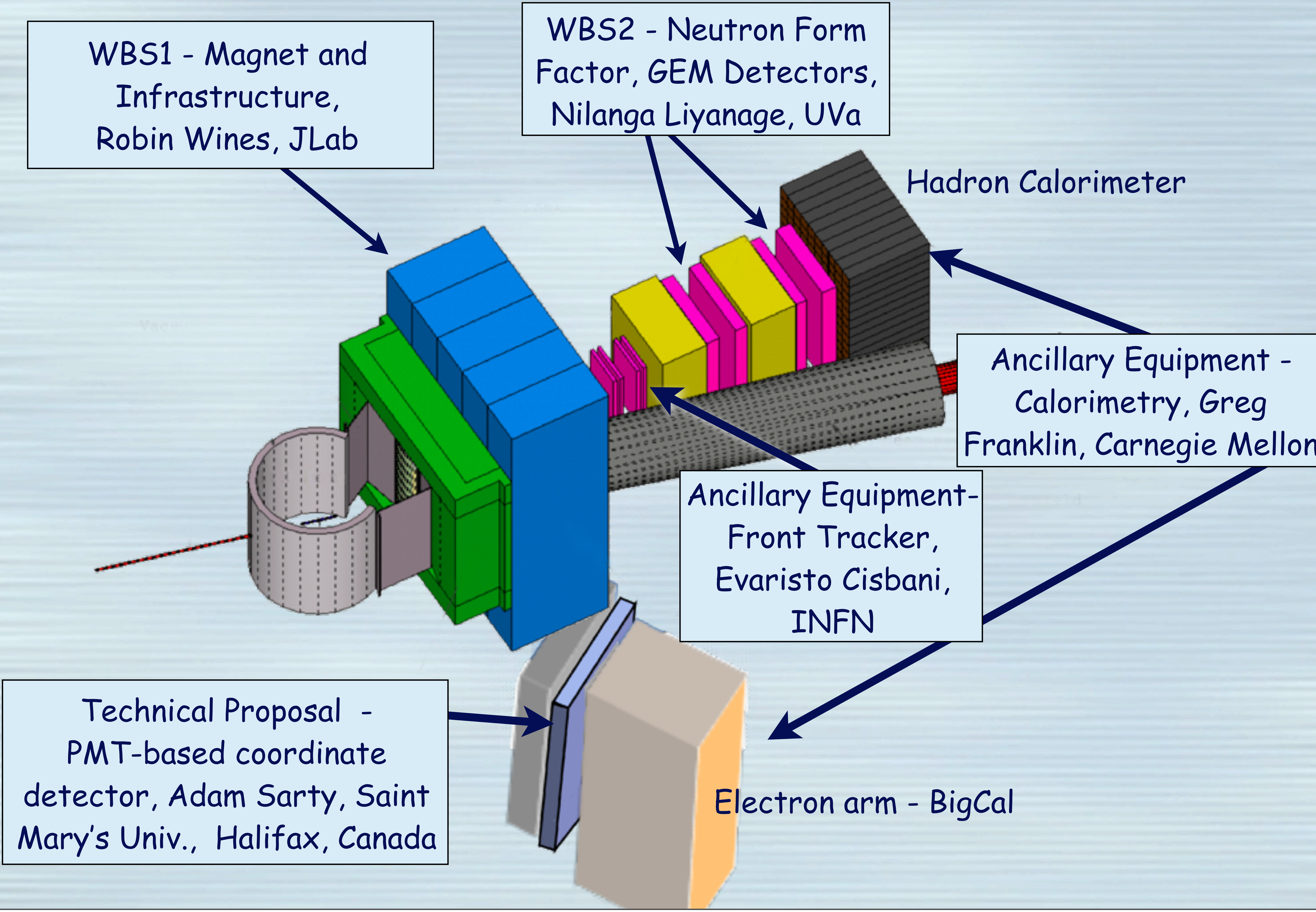
WBS2 - Neutron Form Factor, GEM Detectors, Nilanga Liyanage, UVa



Ancillary Equipment- Front Tracker, Evaristo Cisbani, INFN

Technical Proposal - PMT-based coordinate detector, Adam Sarty, Saint Mary's Univ., Halifax, Canada

The SBS subsystems we will hear about today



Science update since the October 2011 Review

Points we want to emphasize in our science update:

- The increasingly central role that the elastic nucleon form factors are playing in solving the QCD structure of the nucleon.
- The potentially profound impact that the upcoming SBS form-factor data will play in reshaping our ideas of nucleon structure
- Some high-points of the rich spectrum of physics made accesible by SBS going beyond the nucleon form factors.

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)

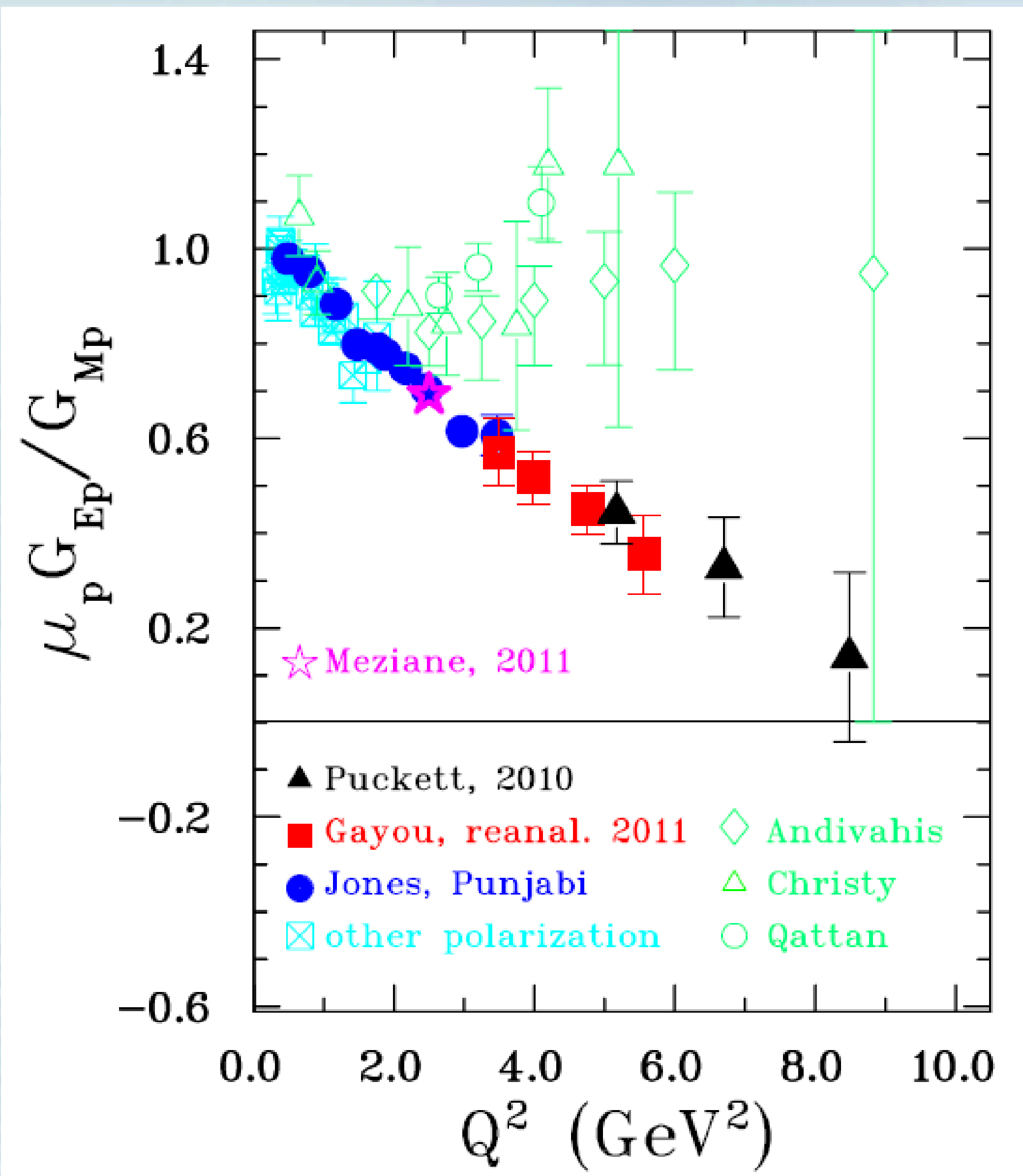
The Sachs FFs:

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

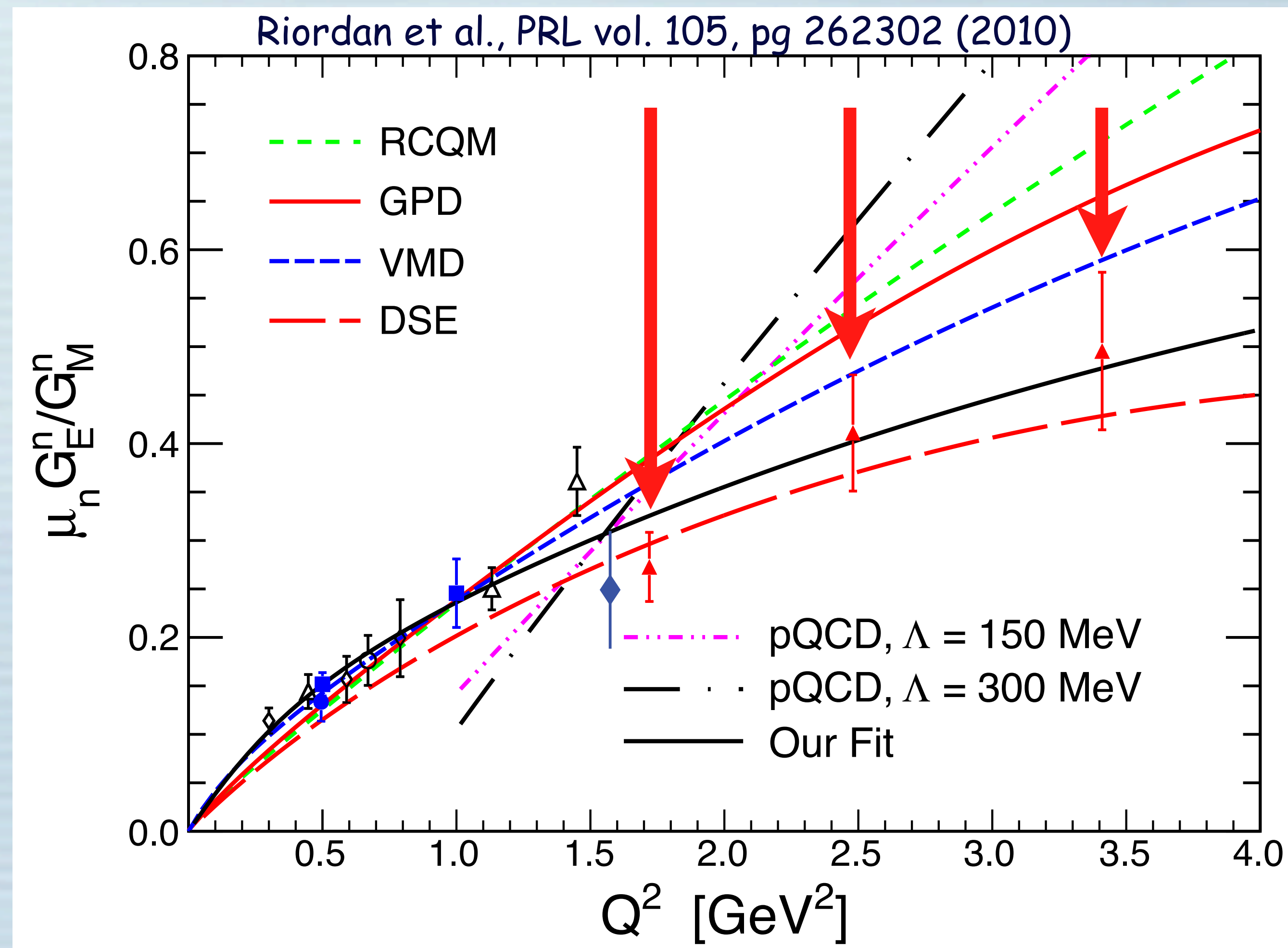
where

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

The current status of high Q^2 data on G_E^p/G_M^p and G_E^n/G_M^n from double polarization experiments



proton data



neutron data

BigBite data (red arrows) published for less than a year at the time of the Oct. 2011 review

Selected impacts of the existing high-Q^2 elastic form-factor data

- We have high-resolution "snapshots" of the nucleon.
- The Q^2 behavior of the proton (and neutron) indicate the importance of quark orbital angular momentum.
- Significant new constraints on GPDs, including new predictions for quark orbital angular momentum via the Ji Sum Rule.
- Mounting theoretical evidence that the high-Q^2 behavior of the FFs must be understood in terms of the importance of quark-diquark degrees of freedom.

It is increasingly clear that the form-factor data from the SBS has the potential to profoundly alter our understanding of nucleon structure

The FFs provide important constraints for GPDs

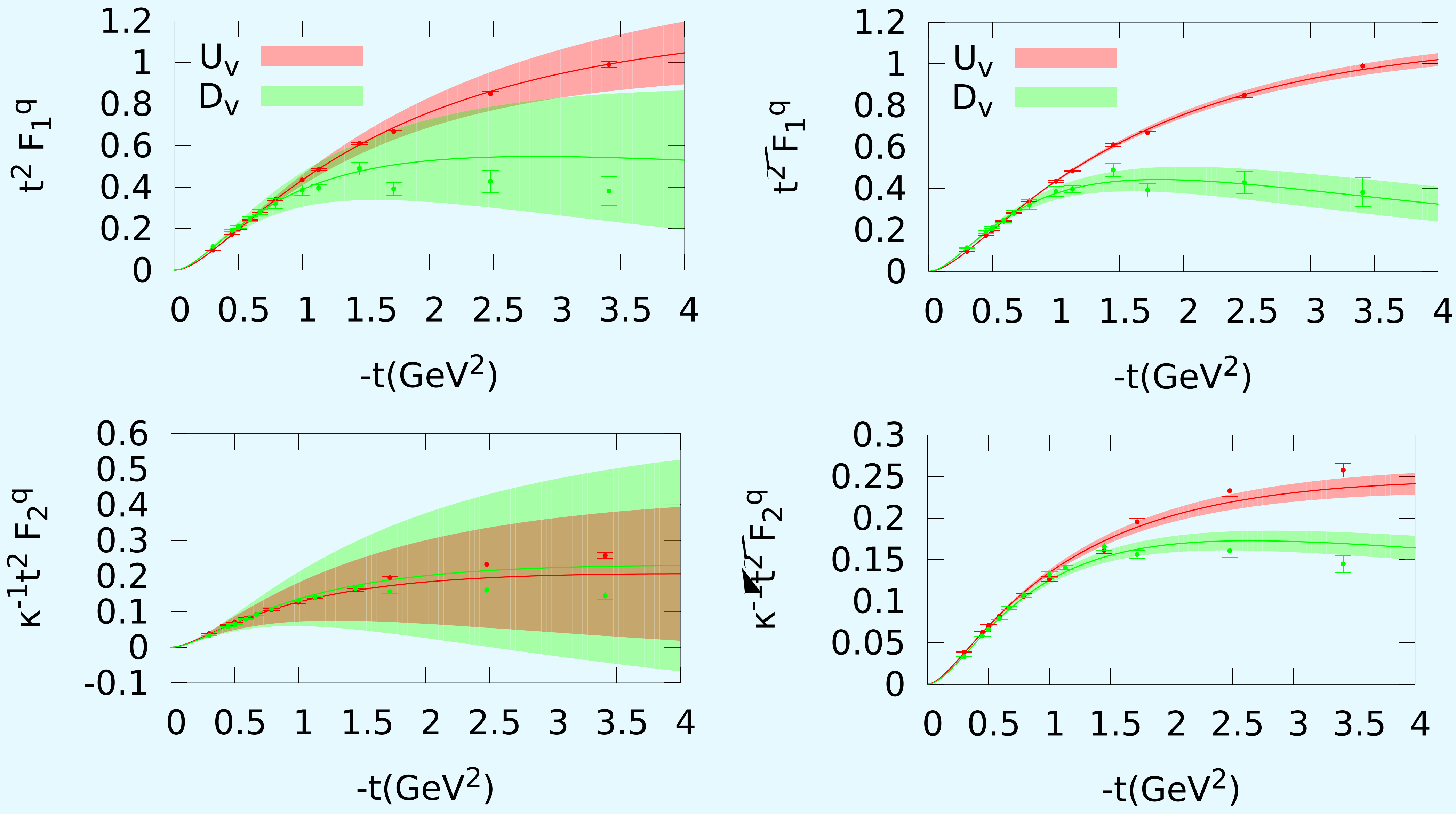
$$\int_{-1}^{+1} dx H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} dx E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

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

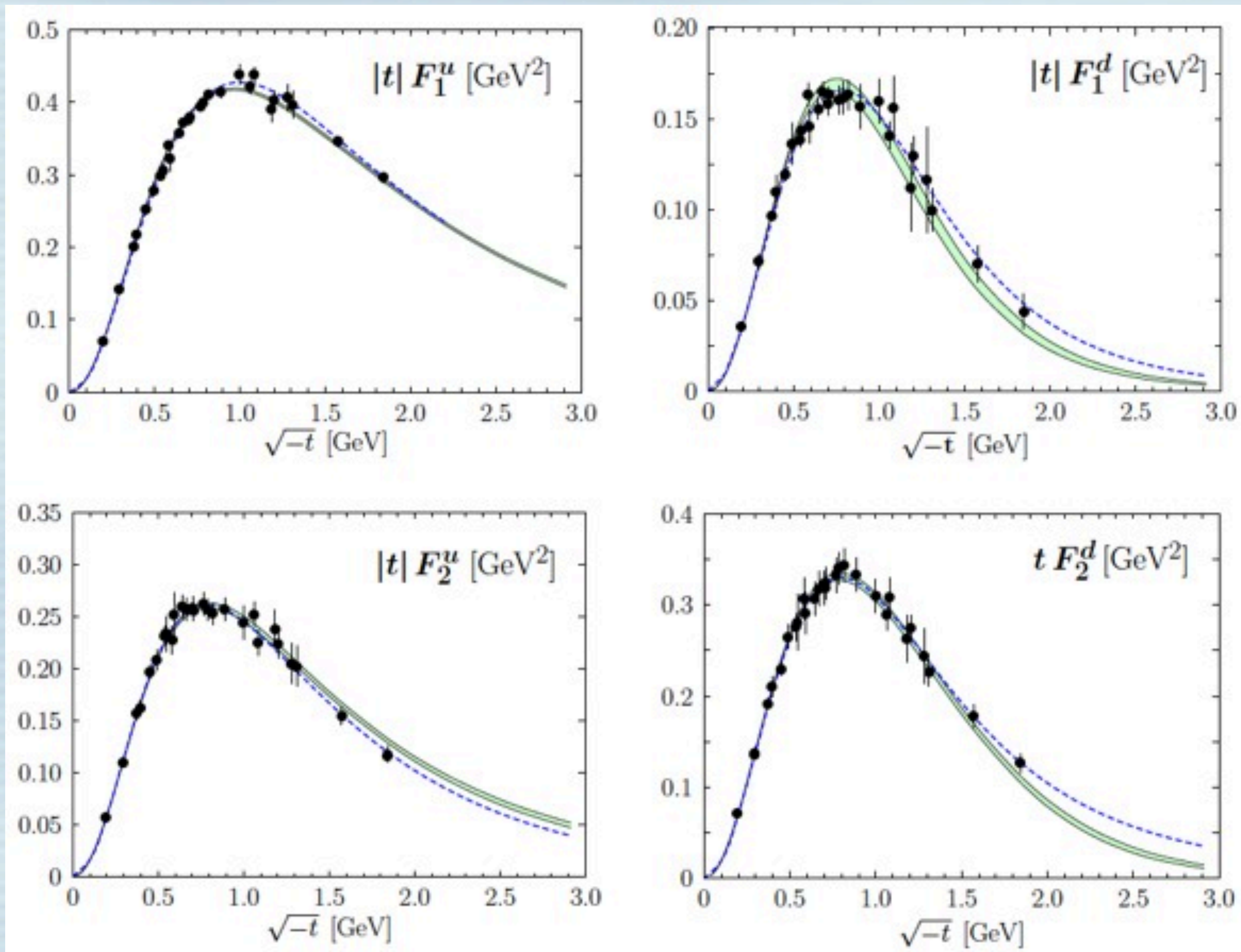
High Q^2 form-factor data constrain reggeized quark-diquark GPD Model



J. O. Gonzalez-Hernandez, S. Luiti, G. R. Goldstein and K. Kathuria arXiv:1206.1876v2 [hep-ph] (2012)

Here the parameters in a reggeized quark-diquark model are greatly constrained when fit to the flavor-separated form factors. The fit is excellent, but we should keep in mind the model has 16 parameters.

Constrained GPD Model and evaluation of the Ji Sum Rule

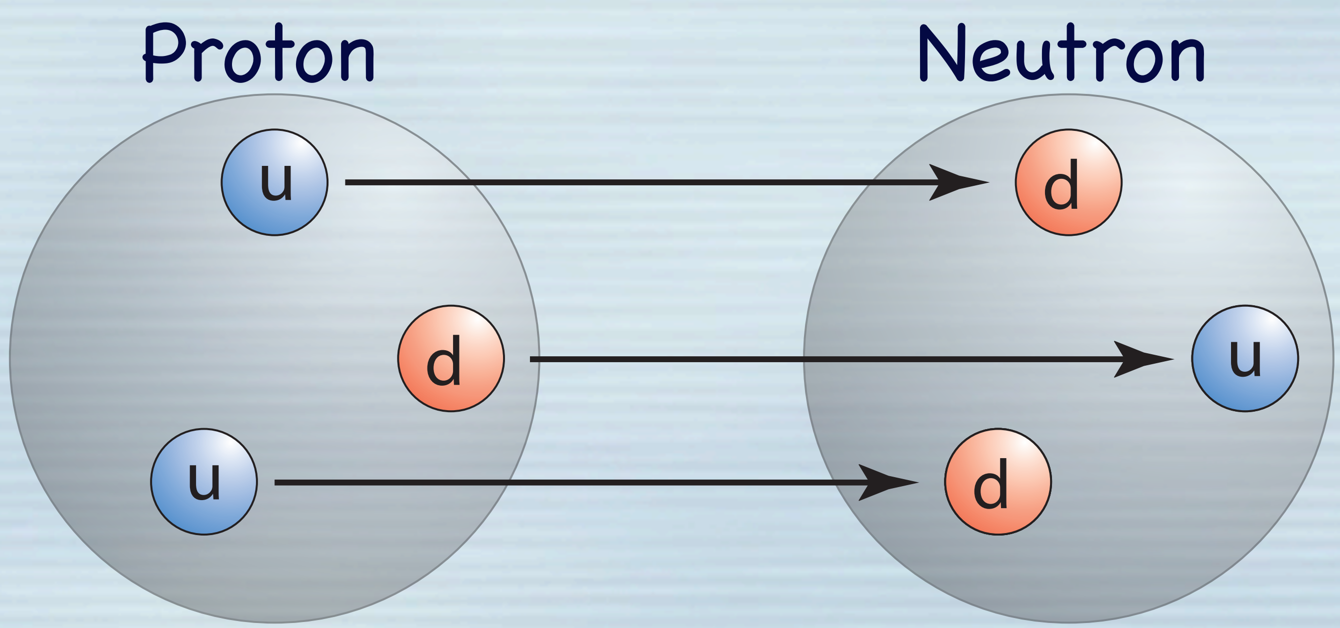


Marcus Diehl and Peter Kroll: Eur. Phys. J. C, v.73, pg.2397 (2013), also arXiv:1302.4604v1 [hep-ph] 19 Feb 2013

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

Extracting the individual quark-flavor contributions to the form factors

By assuming charge symmetry, we can combine form-factor data from protons and neutrons to gain insight into the tranverse structure of the nucleon's constituents.

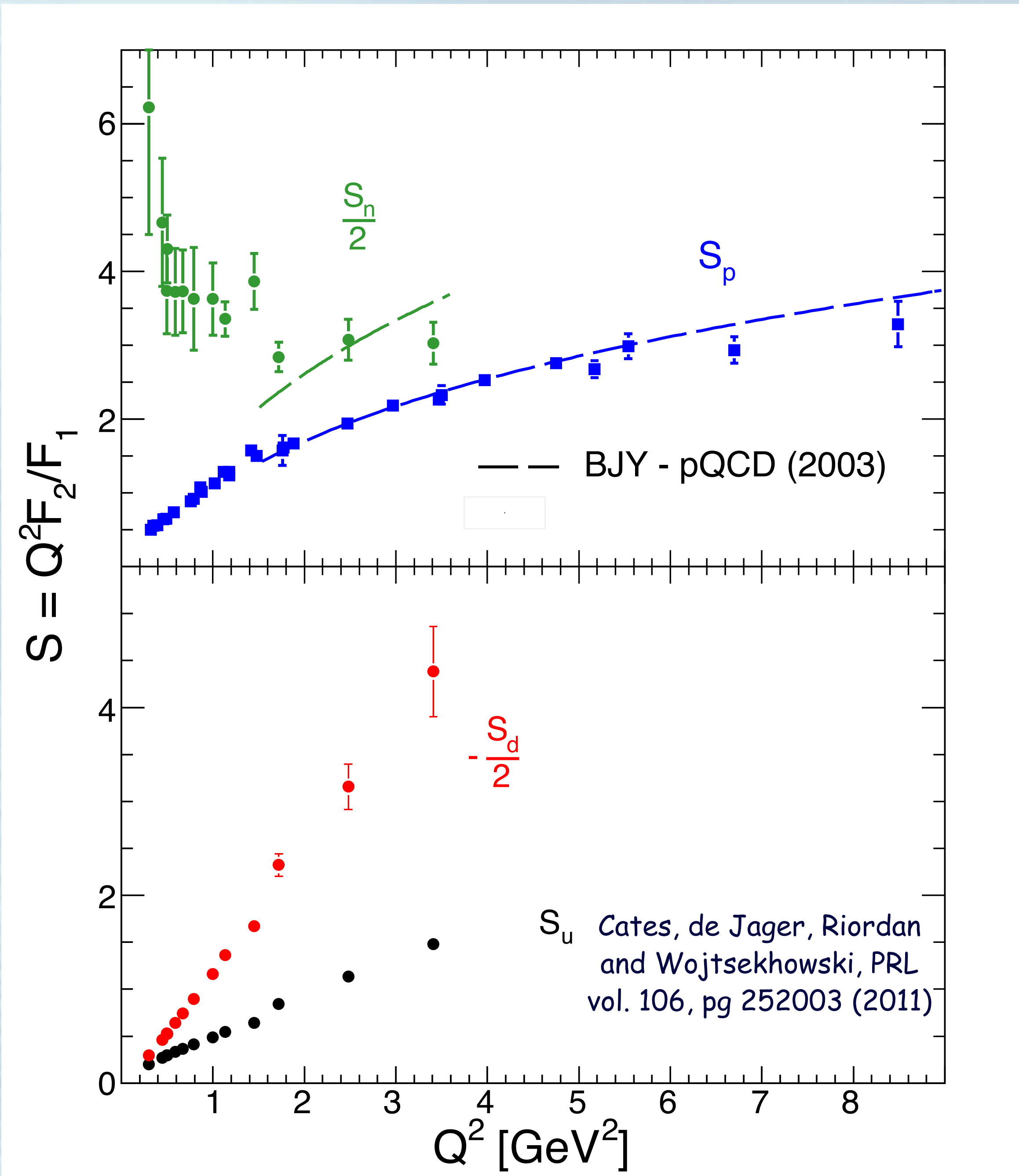


$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

The first such extraction was published shortly before the October 2011 review:

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

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

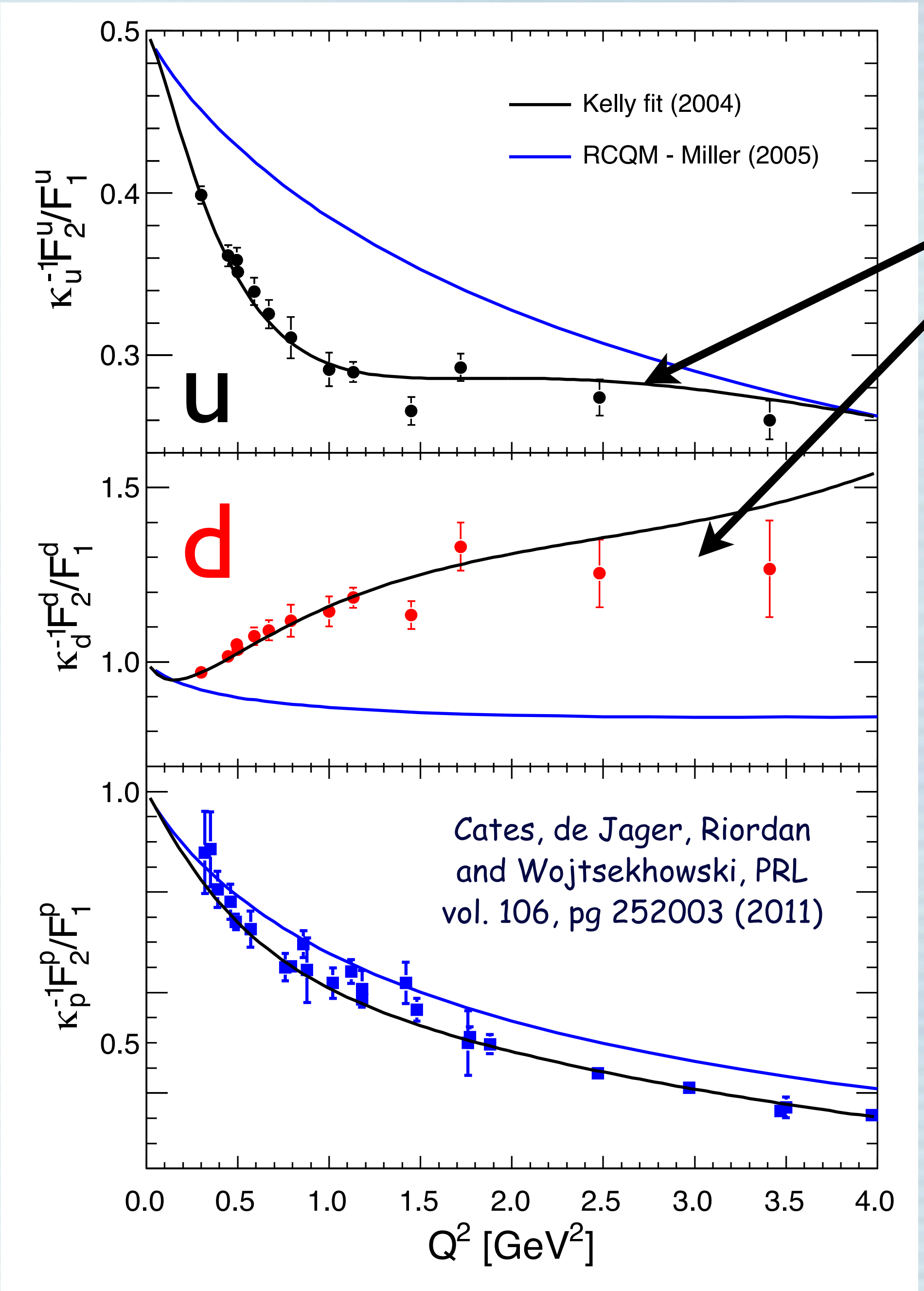


At left: Q^2F_2/F_1 for the proton and neutron.

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



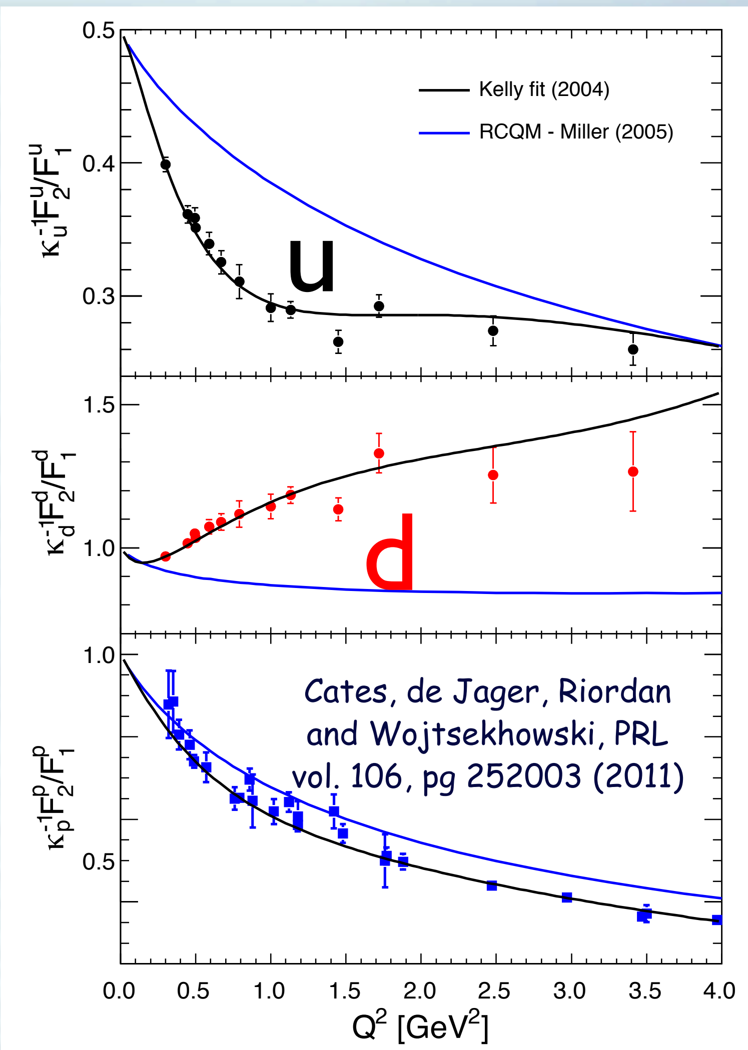
The ratios F_2^q/F_1^q become constant for Q^2 > ~1 GeV^2 !

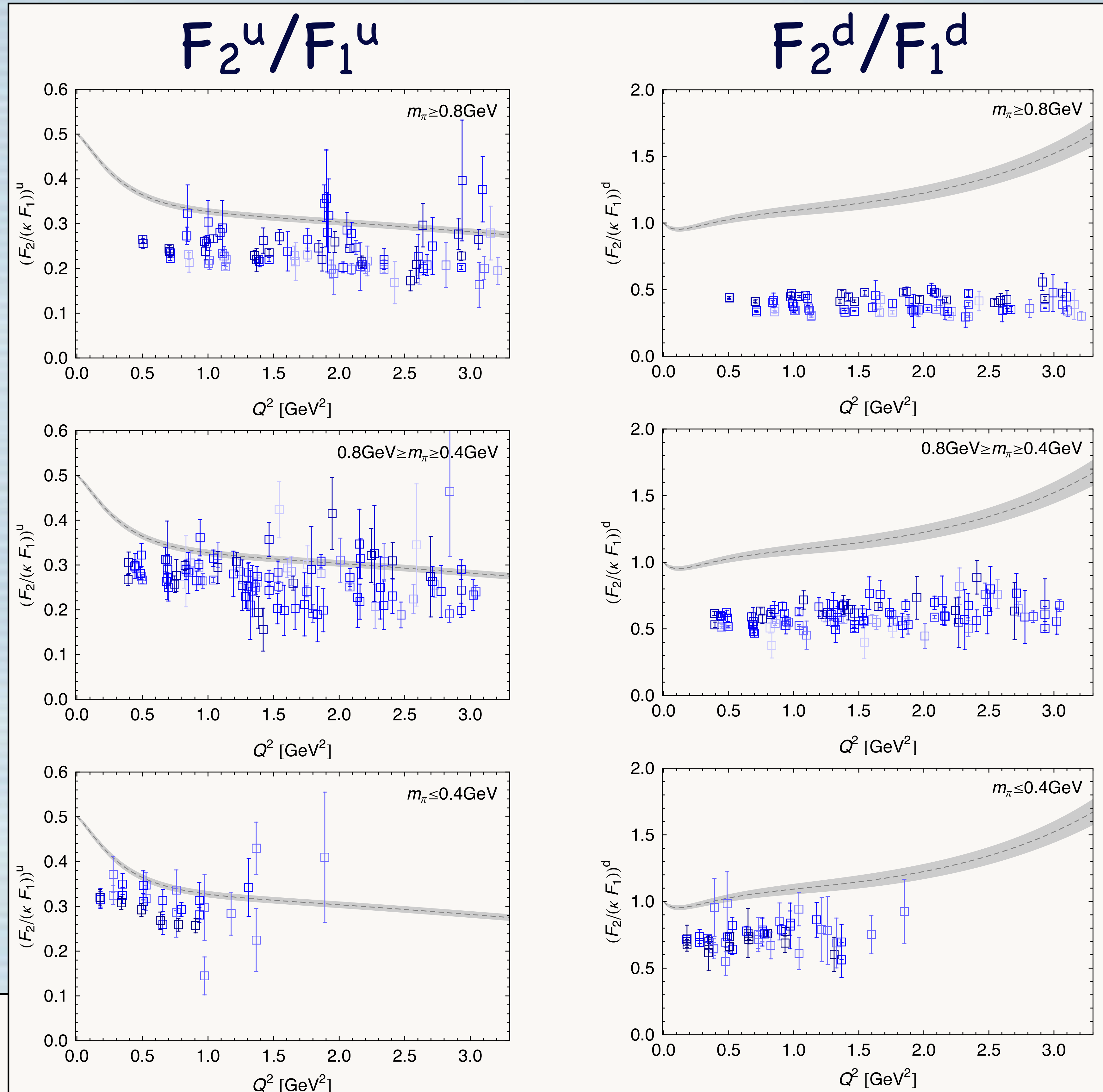
This disagrees with a generally accepted expectation that dates to Schwinger in the 1950's that:

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

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

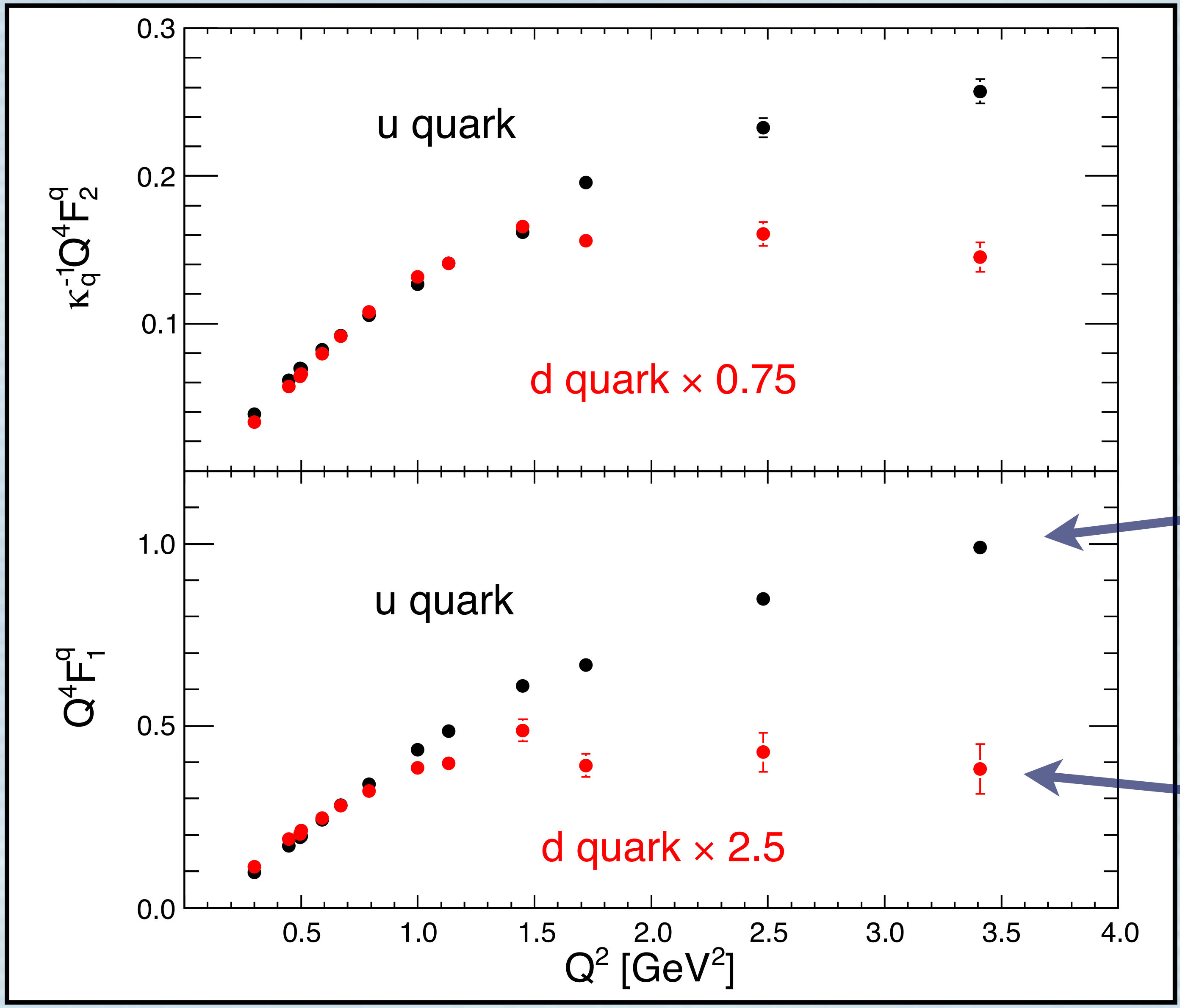




S. Collins et al. (QCDSF/UKQCD Collaboration), PRD v.84, 074507 (October, 2011)

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).

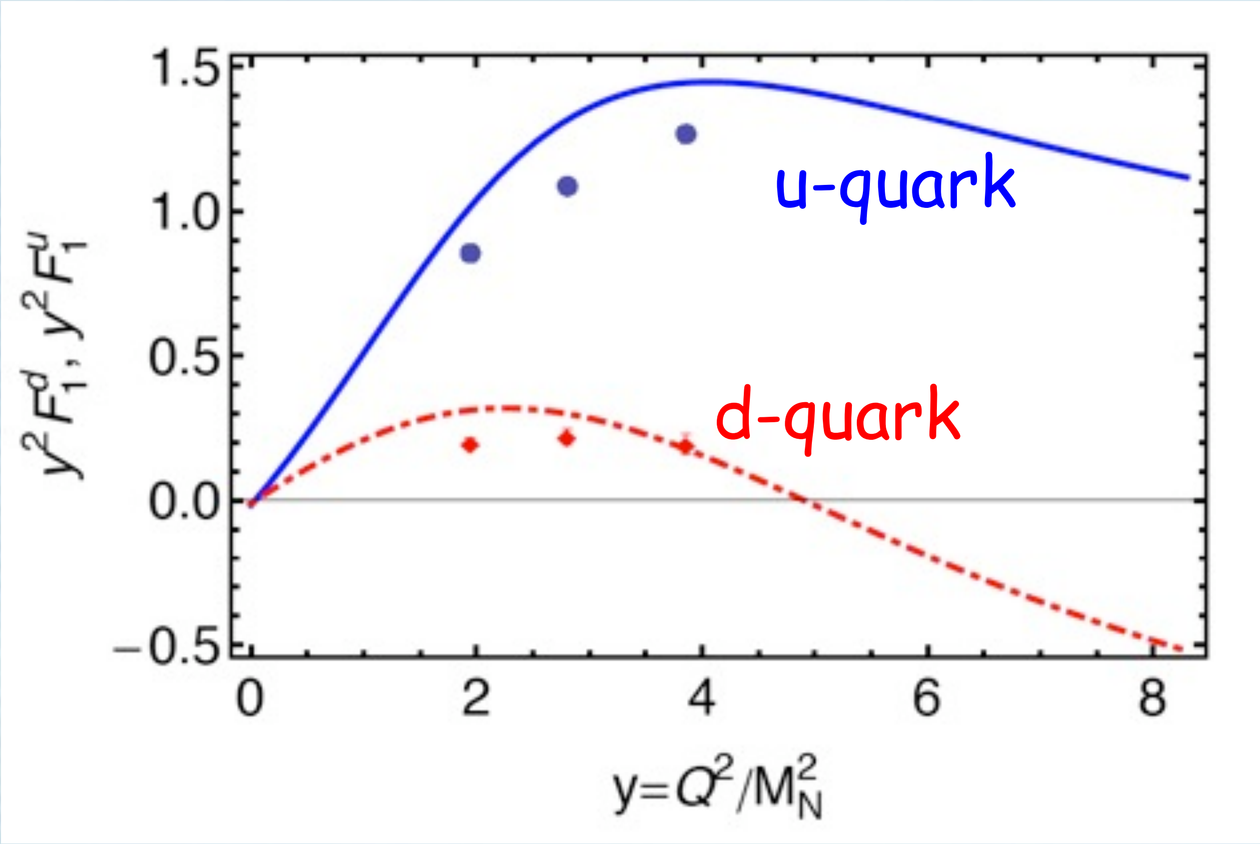
F^d seems to scale roughly like $1/Q^4$

What is the significance of these different behaviors?

Behavior was predicted by quark-diquark DSE/Fadeev model from Argonne

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

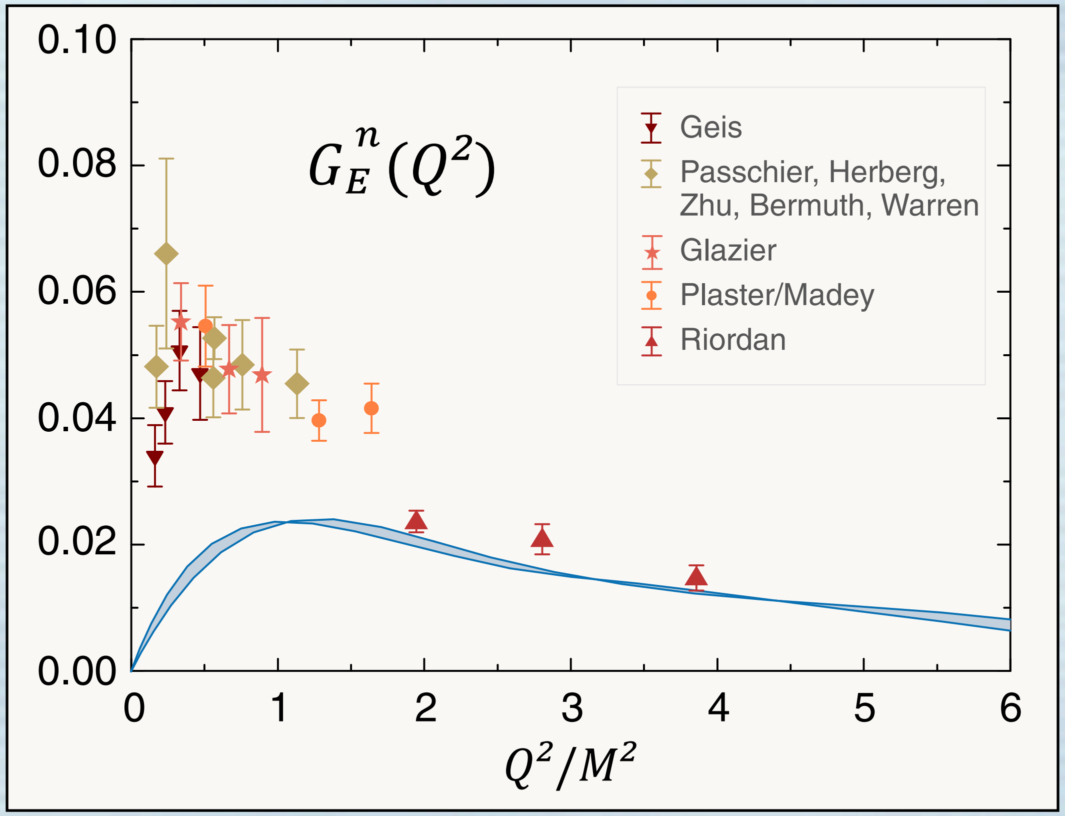
" ... a prediction for the Q^2-dependence of u- and d-quark Dirac and Pauli form factors in the proton, which exposes the critical role played by diquark correlations within the nucleon."

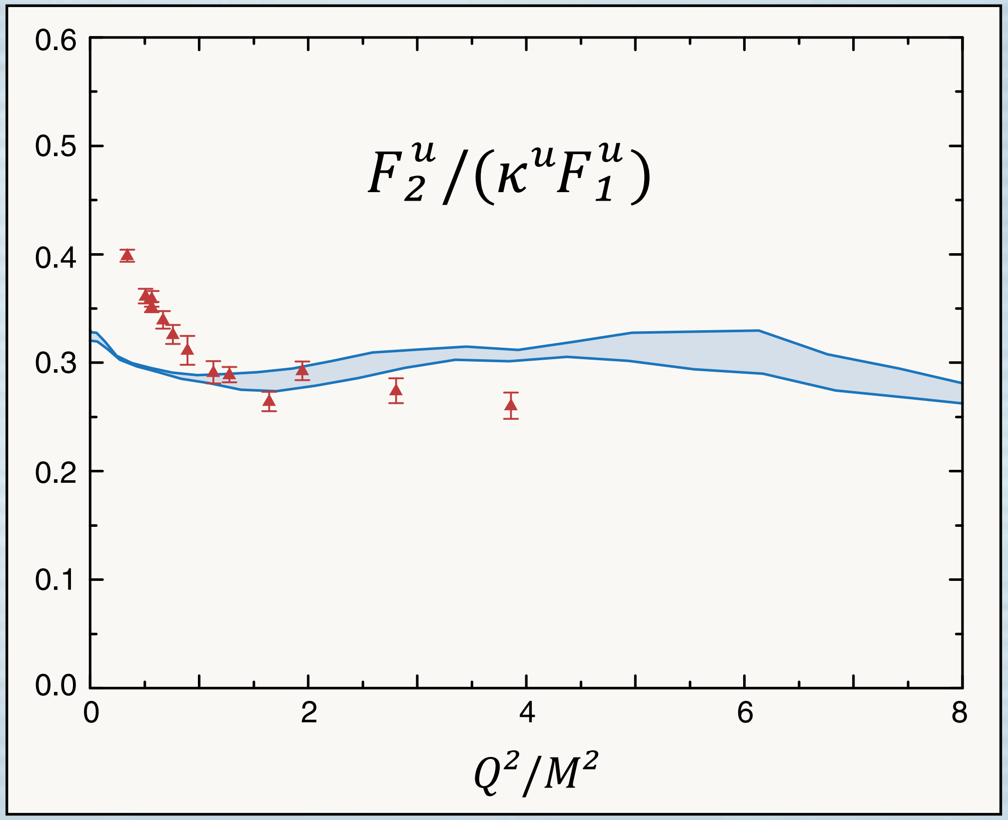


arXiv:1103.2432v1

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

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





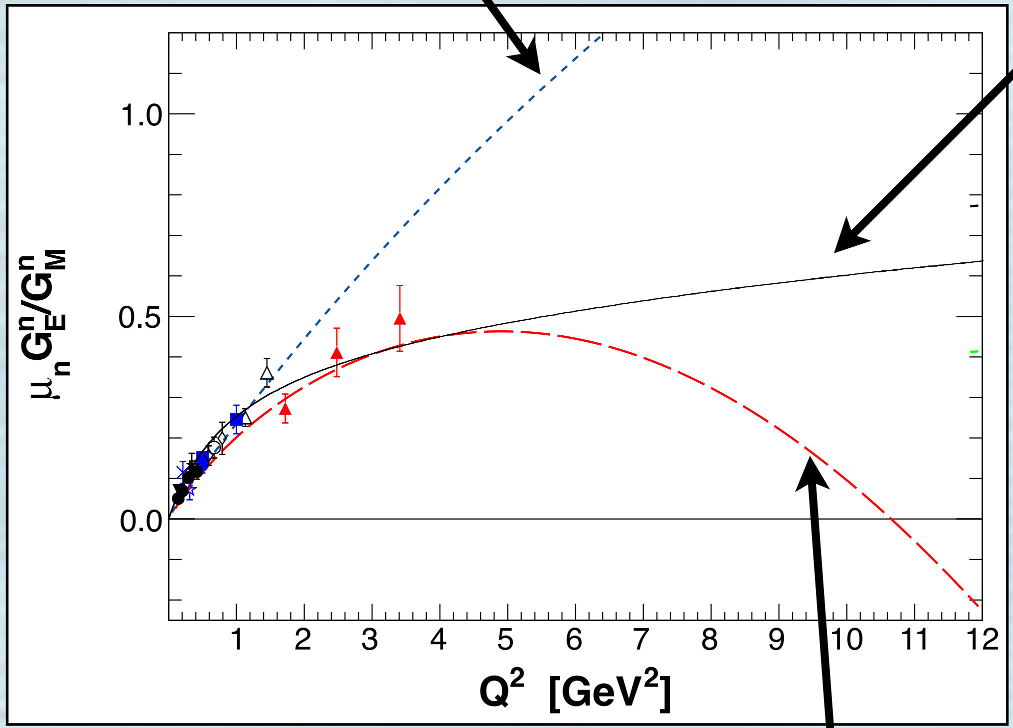
PRD Vol. 84, pg. 014014 (2011)

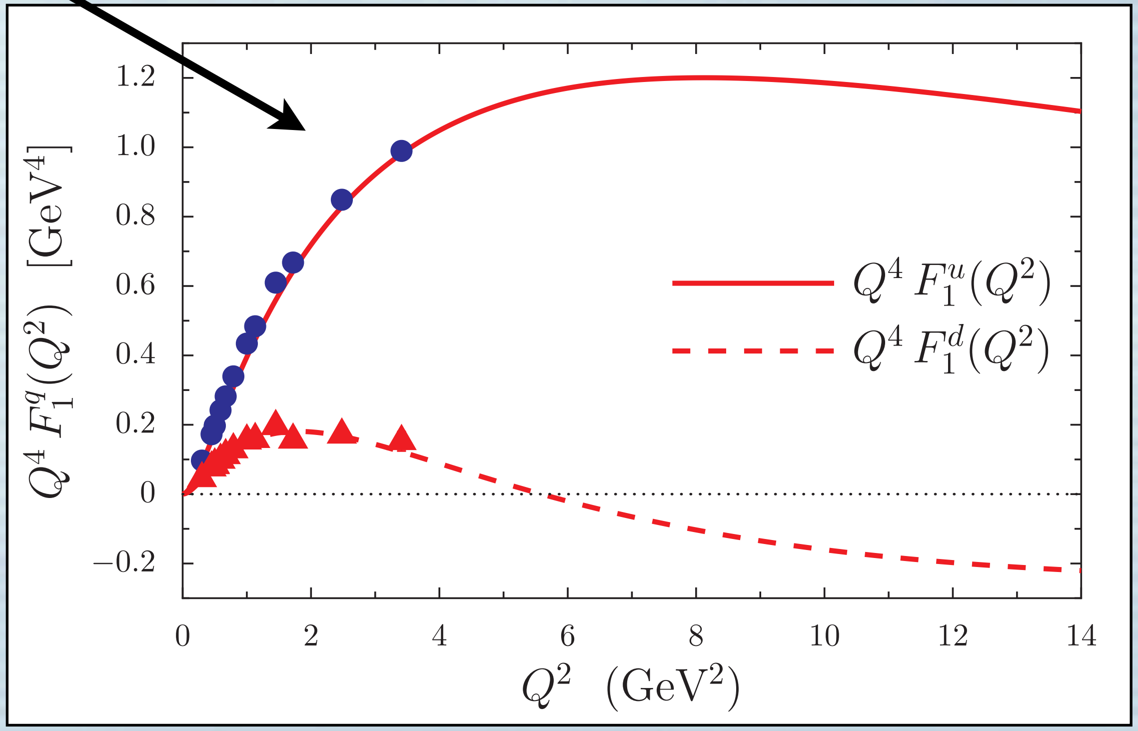
The overall agreement between our results and those obtained in the quark-diquark model <u>provides further evidence for the quark-diquark structure of the nucleon</u>, and it implies that scalar and axial-vector diquark degrees of freedom can account for most of its characteristic features.

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



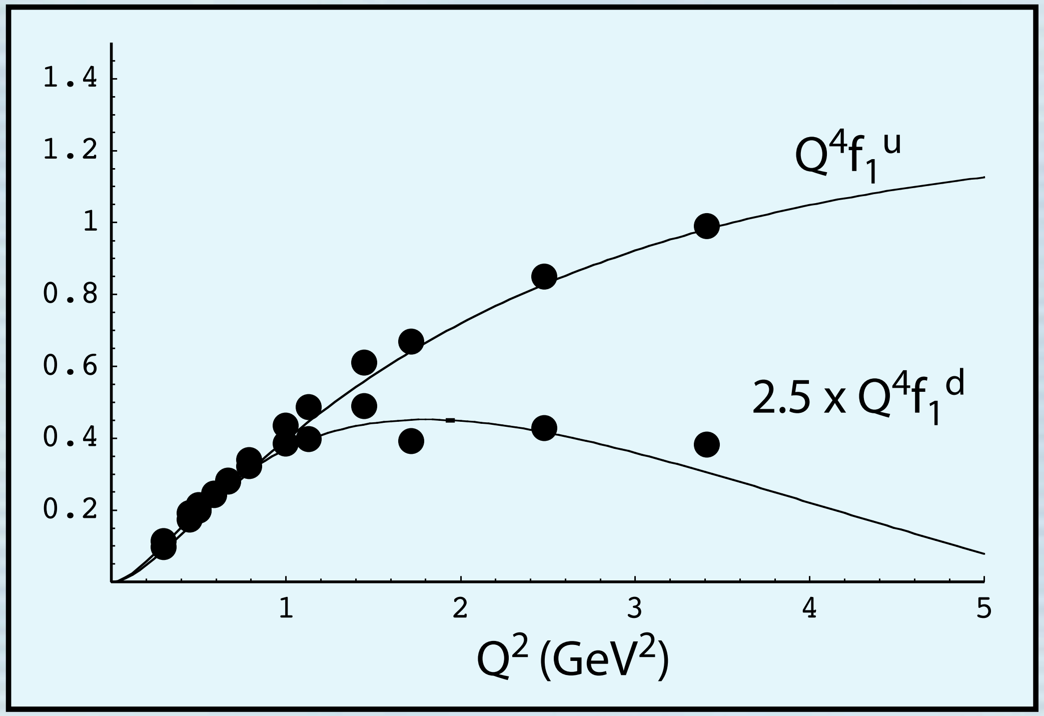


The QCD DSE model of Cloët, Roberts et al. in which the constituent quark mass is dynamically generated and diquark degrees of freedom are incorporated.
(Few Body Systems v46, pg1 2009)

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.

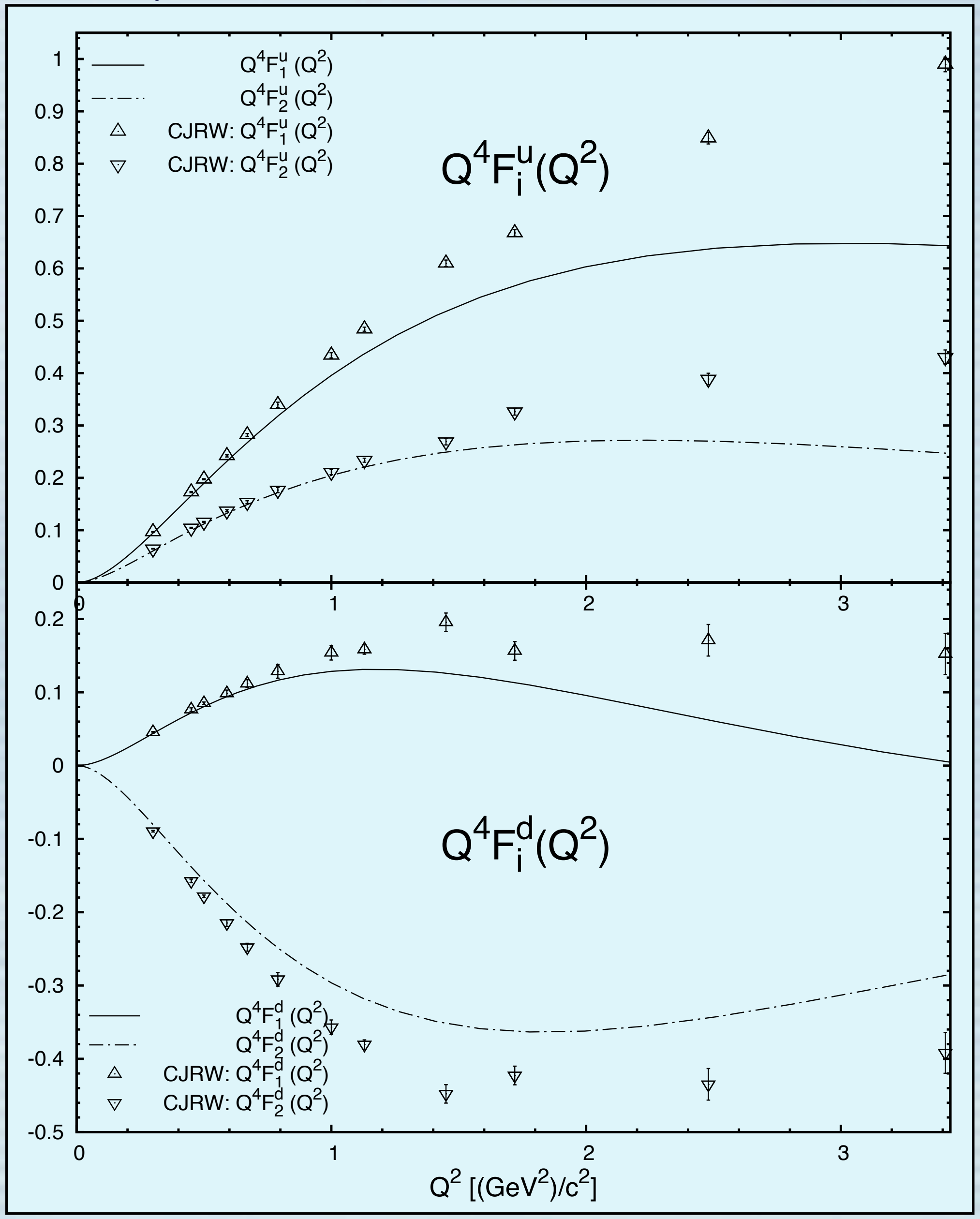
Comparing RCQMs with and without quark-diquark strucutre

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.



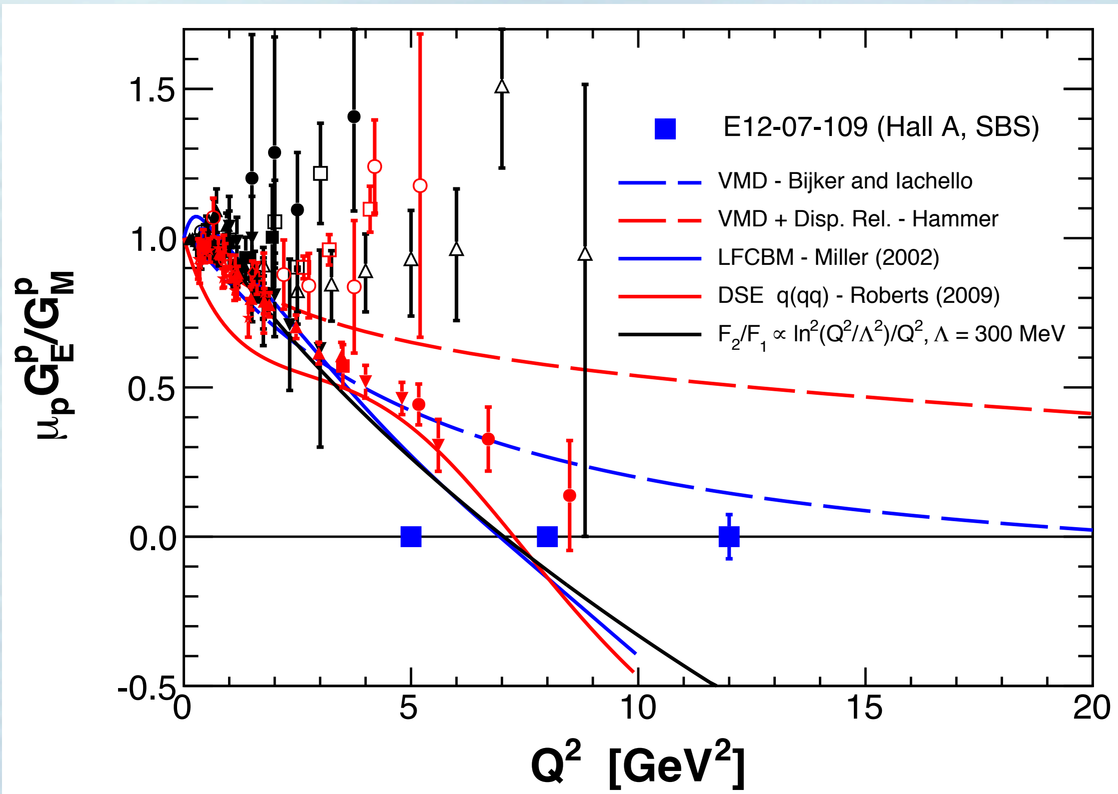
Same Miller/Cloet model as previous slide, plotted slightly differently

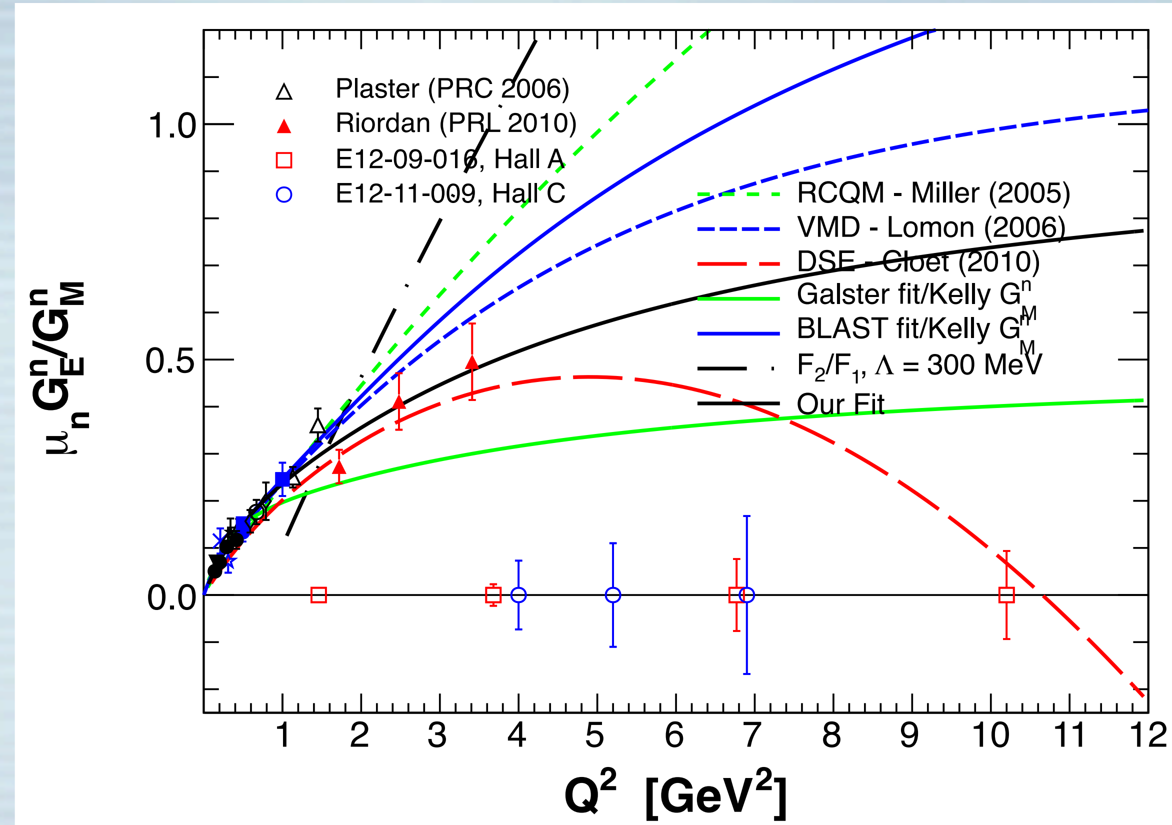
However, another RCQM with no diquarks does not do as well

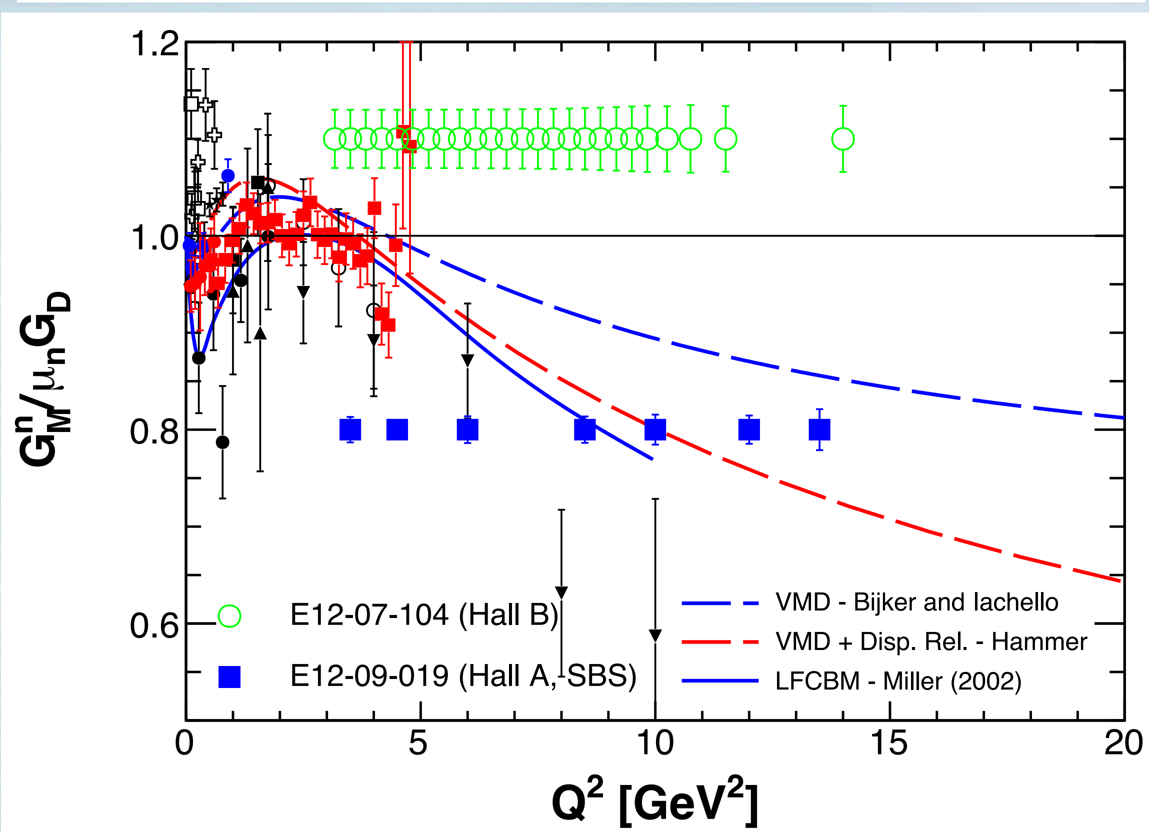


Rohrmoser, Choi and Plessas, arXiv:1110.3665

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

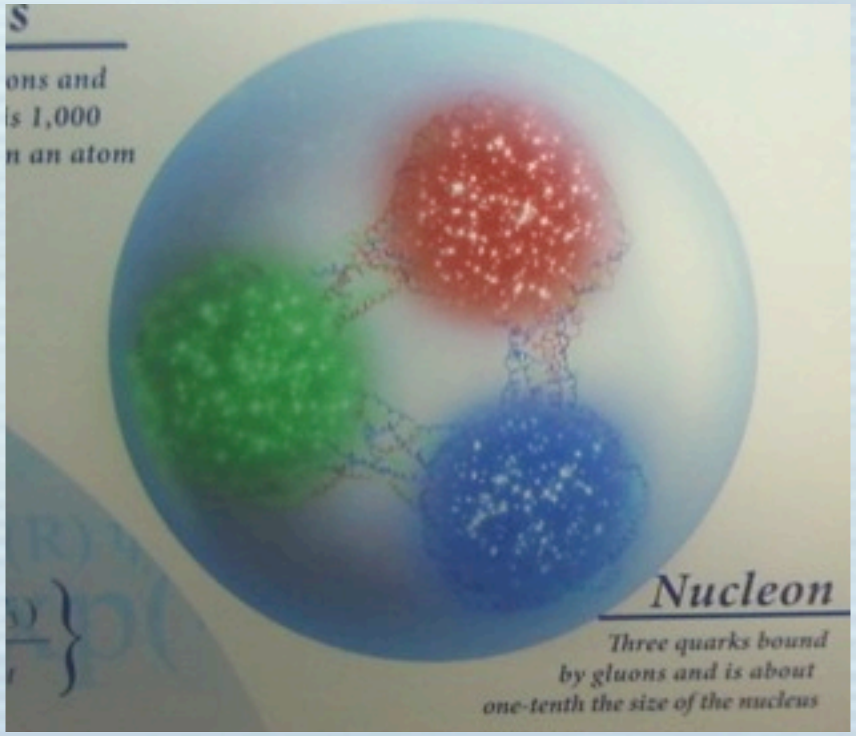




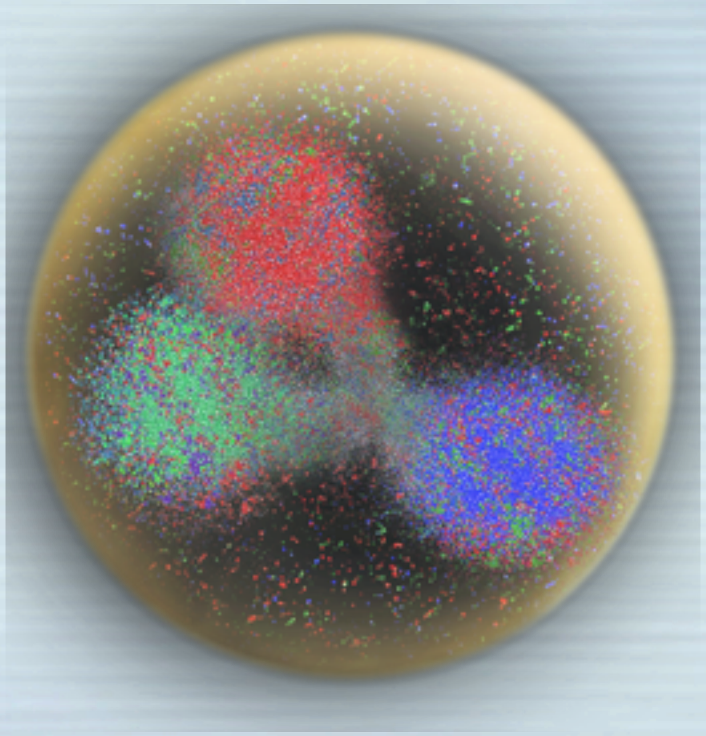


The three Super Bigbite experiments will meet the requirements to achieve the best physics by providing precise measurements at high Q^2.

Can high-Q^2 FF elastic nucleon FF data 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

To conclude with a quote from a recent paper by Cloet and Roberts:

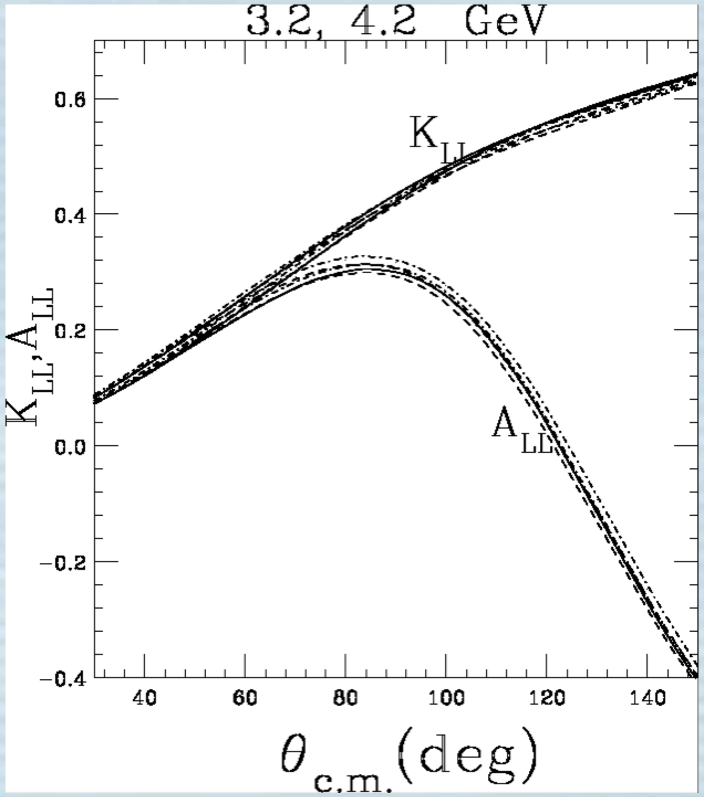
"Given the pace of expansion in experiment and improvement in theory, it appears possible that the next five years will bring profound growth in our store of knowledge about hadrons and nuclei."

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

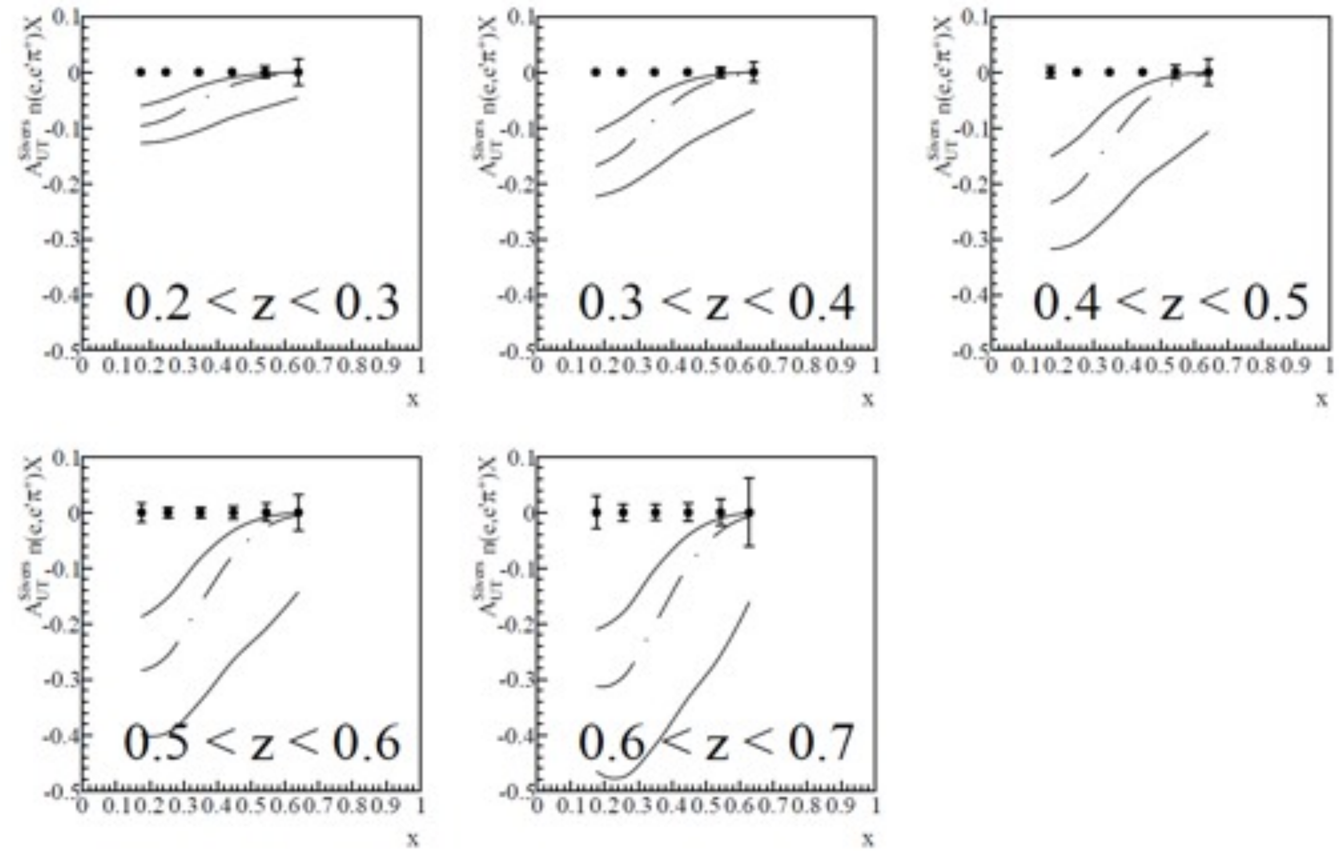
- Structure functions of the pion, studied using the Sullivan process in which one studies DIS scattering off the pion cloud. Upcoming workshop January 16-18, 2014.

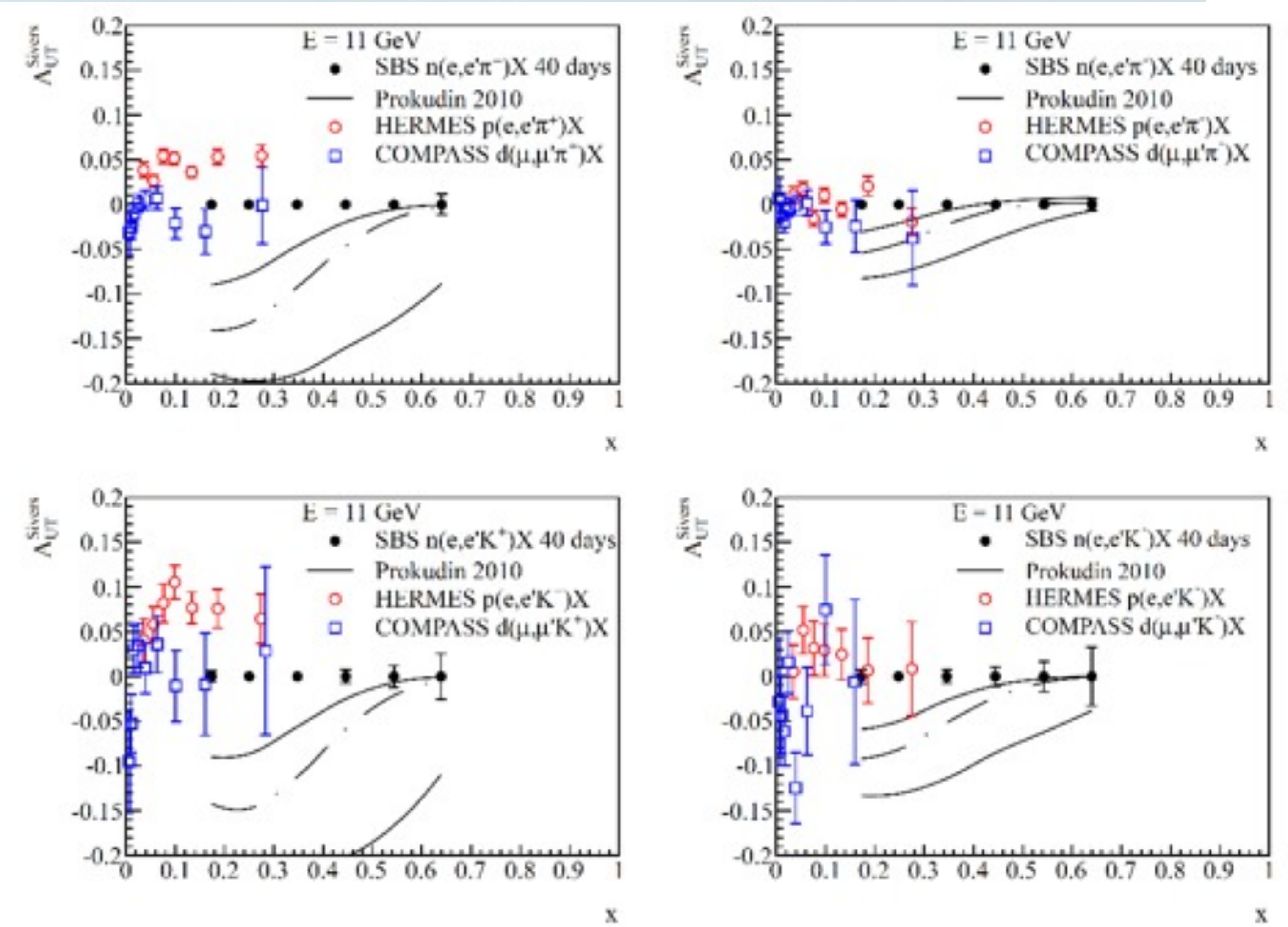
- Wide angle Compton scattering, with polarized beam and target, measure the asymmetry A_{LL}. Sensitive to mass of constituent quark.



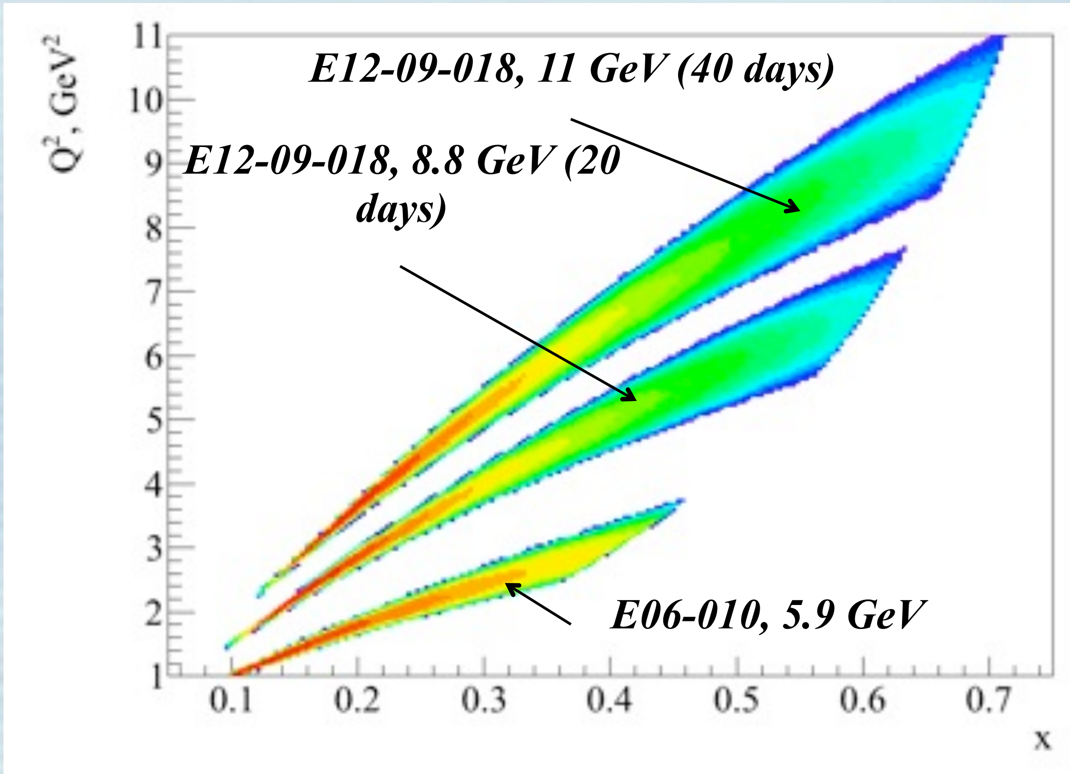
Neutron transversity in SIDIS

- 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



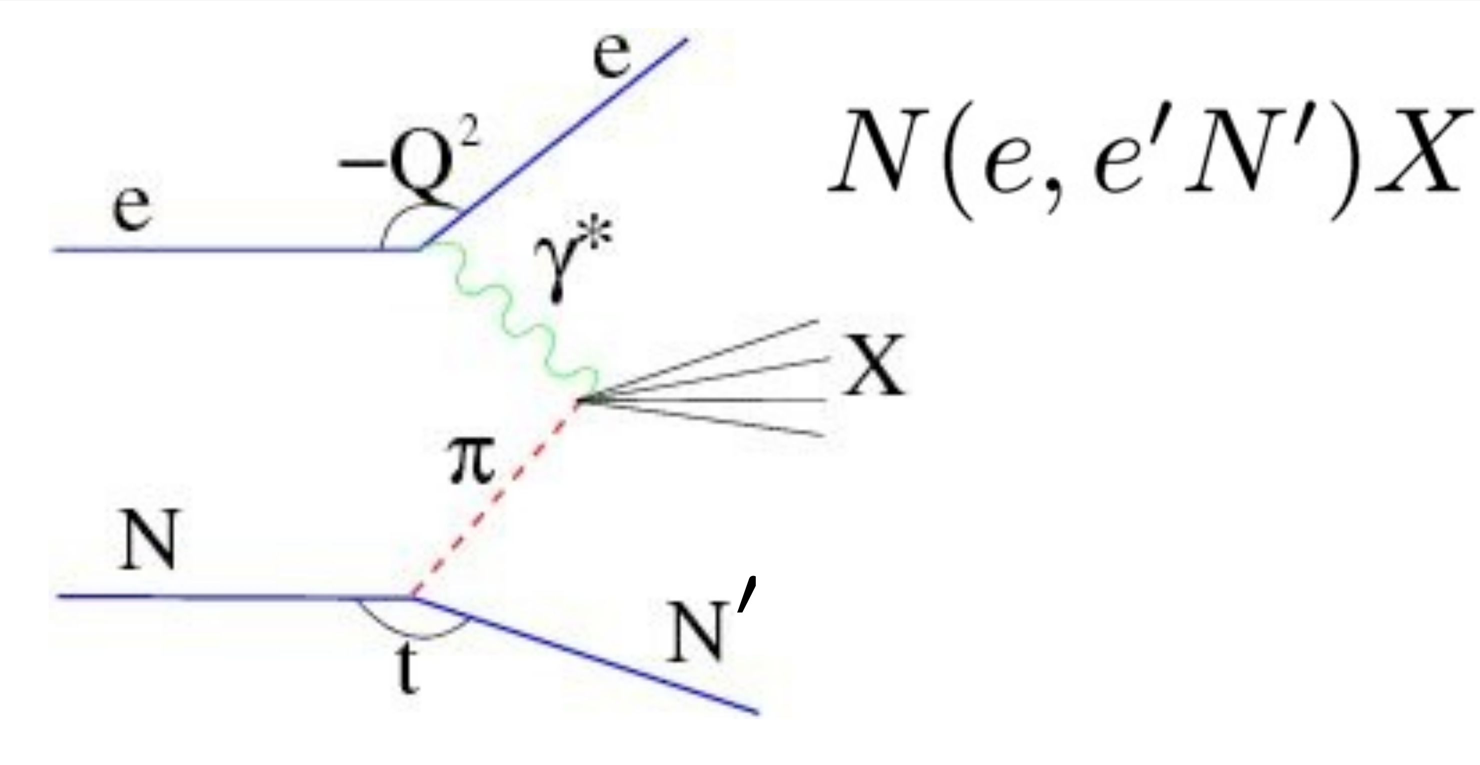


$\pi^{\pm}$, $K^{\pm}$ neutron Sivers asymmetries compared to HERMES, COMPASS, phenomenological fit

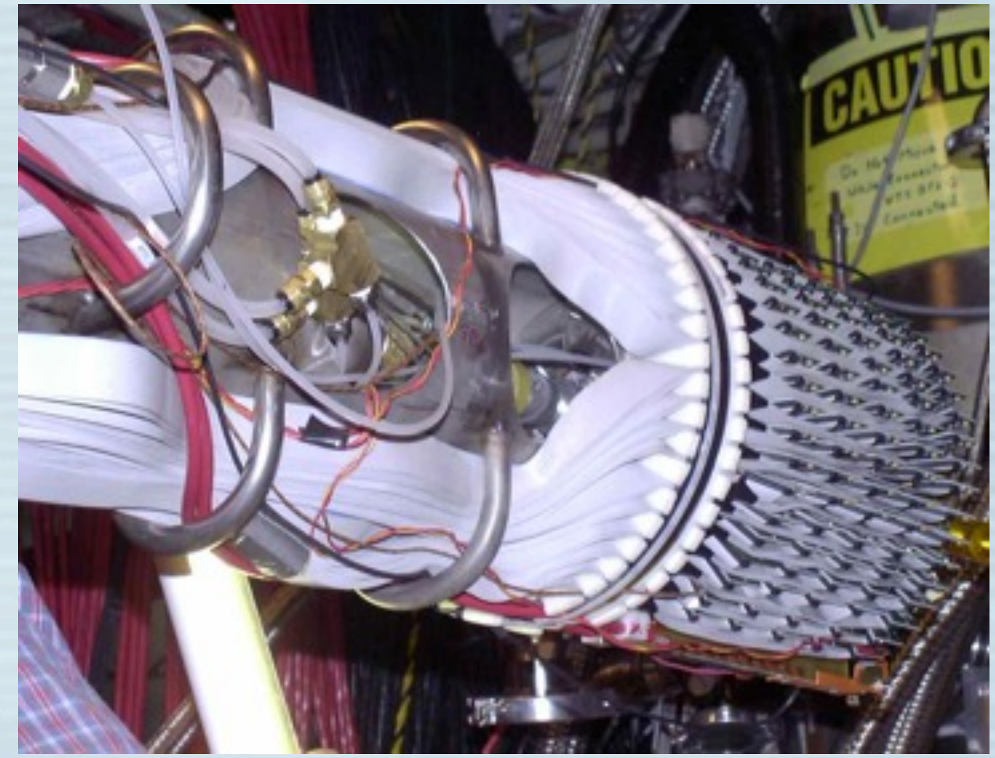


- Data at two beam energies provide a range of Q^2 at fixed x
- RICH preparation effort starting at UConn

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

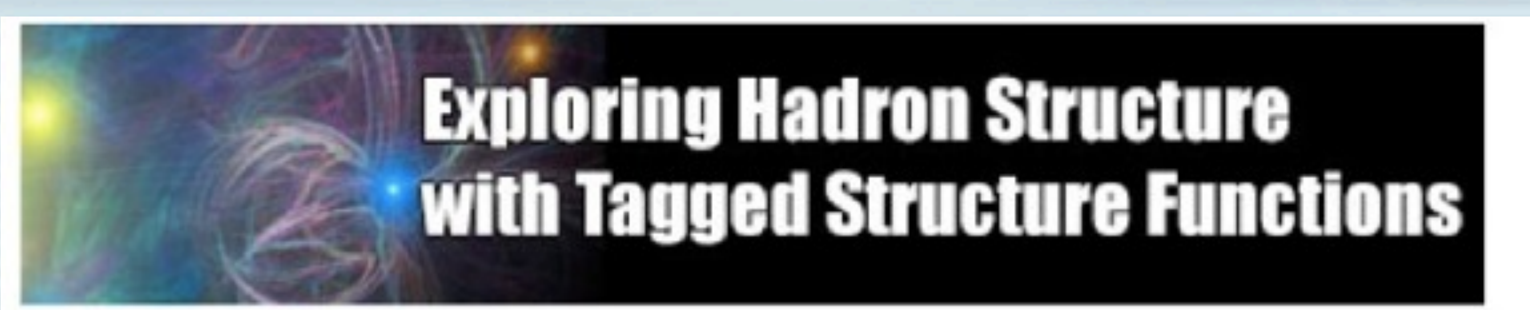


$$t = (p_{N'} - p_N)^2 = m_N^2 + m_{N'}^2 - 2m_N E_{N'}$$



- |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

Summary

- The two years since the last SBS review has allowed some time to digest the high-Q^2 FF data, and important ideas have emerged.
- SBS is poised to turn some of these important ideas into true discovery.
- The physics SBS will make possible beyond the form-factor measurements promises to be similarly ground breaking.