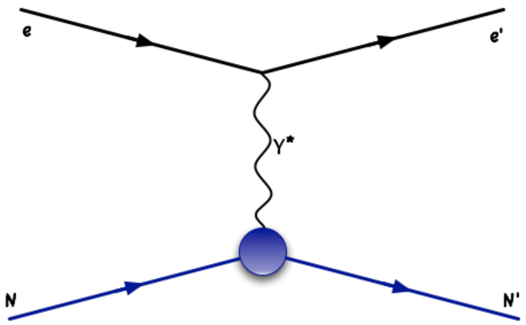
# Electromagnetic Form Factors of Nucleons at JLAB

Bill Briscoe*

*In collaboration with Ron Gilman

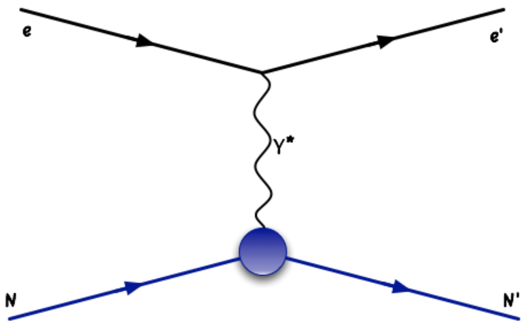
Funded in part by US-DOE (BB) and US-NSF (RG)

# Why Form Factors?



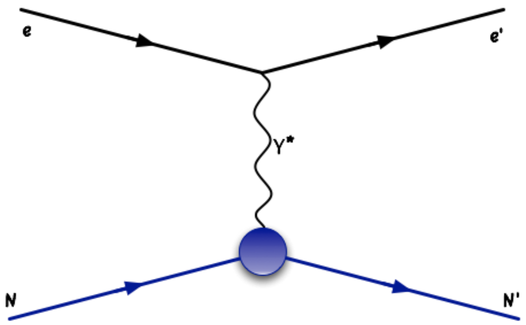
- Probe the fundamental properties of the nucleon, so they are of general interest;
- Measures charge & magnetization distributions;
- Test theoretical models and QCD inspired calculations;
- Provide input to calculations and experiments in nuclear structure, atomic physics, nucleons in nuclei

# Why Form Factors?




- There have been dramatic improvements in our understanding owing to JLab 6 GeV era:
  - Near linear fall off of $G_E^P/G_M^P(Q^2)$ (Perdrisat et al.);
  - Much improved data for $G_E^N$, $G_M^N$;
  - Interpretation of FF as the 2D Fourier transform of a transverse density, or as moments of generalized parton distributions (GPDs).

# Why Form Factors?




- A number of ongoing issues:
  - High $Q^2$ behavior - the main thrust of the JLab 12 GeV form factor program;
  - Flavor separations;
  - Radiative corrections;
  - Low $Q^2$ behavior - the proton charge (and magnetic) radius.

# Pre - JLab

- $G_E^N$ was the most compelling form factor factor program. It was the form factor we knew the least about.

- $G_E^P$ was "B+" physics, expected to improve uncertainties but not show much of anything new.

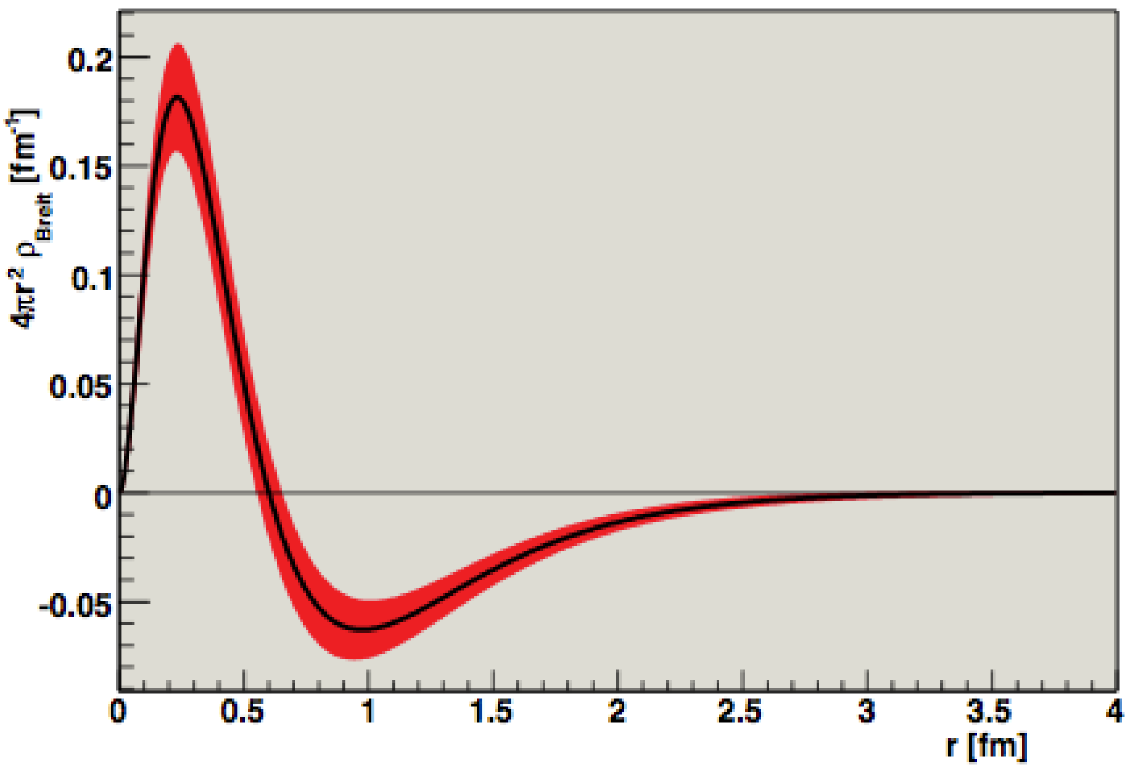
We all know how that worked out.

- $G_E^P$ arguably among most important JLab results.

- Helped crystalize understanding of role of relativity, OAM in form factors, transverse (not 3d) Fourier transforms, nonspherical aspects of nucleon structure, ...

# Situation in 2007
# Last US Long-Range Plan

- "**The charge distribution of the neutron was mapped precisely and with high resolution.** The measurements confirmed that the neutron has a positively charged core and a negatively charged pion cloud."



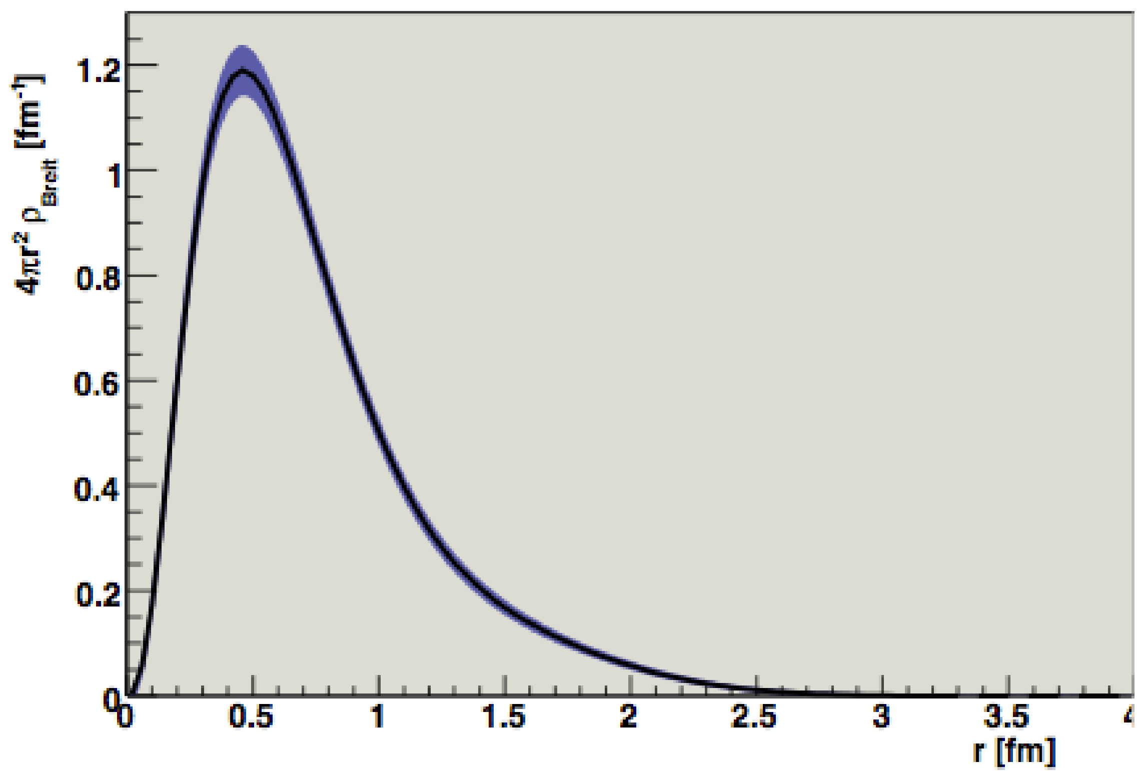




Figure from 2007 LRP, page 26

# Situation in 2007
# Last US Long-Range Plan

- “**Precision measurements of mirror symmetry (parity) violation in electron scattering set tight upper constraints on the contributions of strange quarks to the electric and magnetic properties of the proton.**

- These results provide one of the most precise comparisons of experiment with lattice QCD ...”

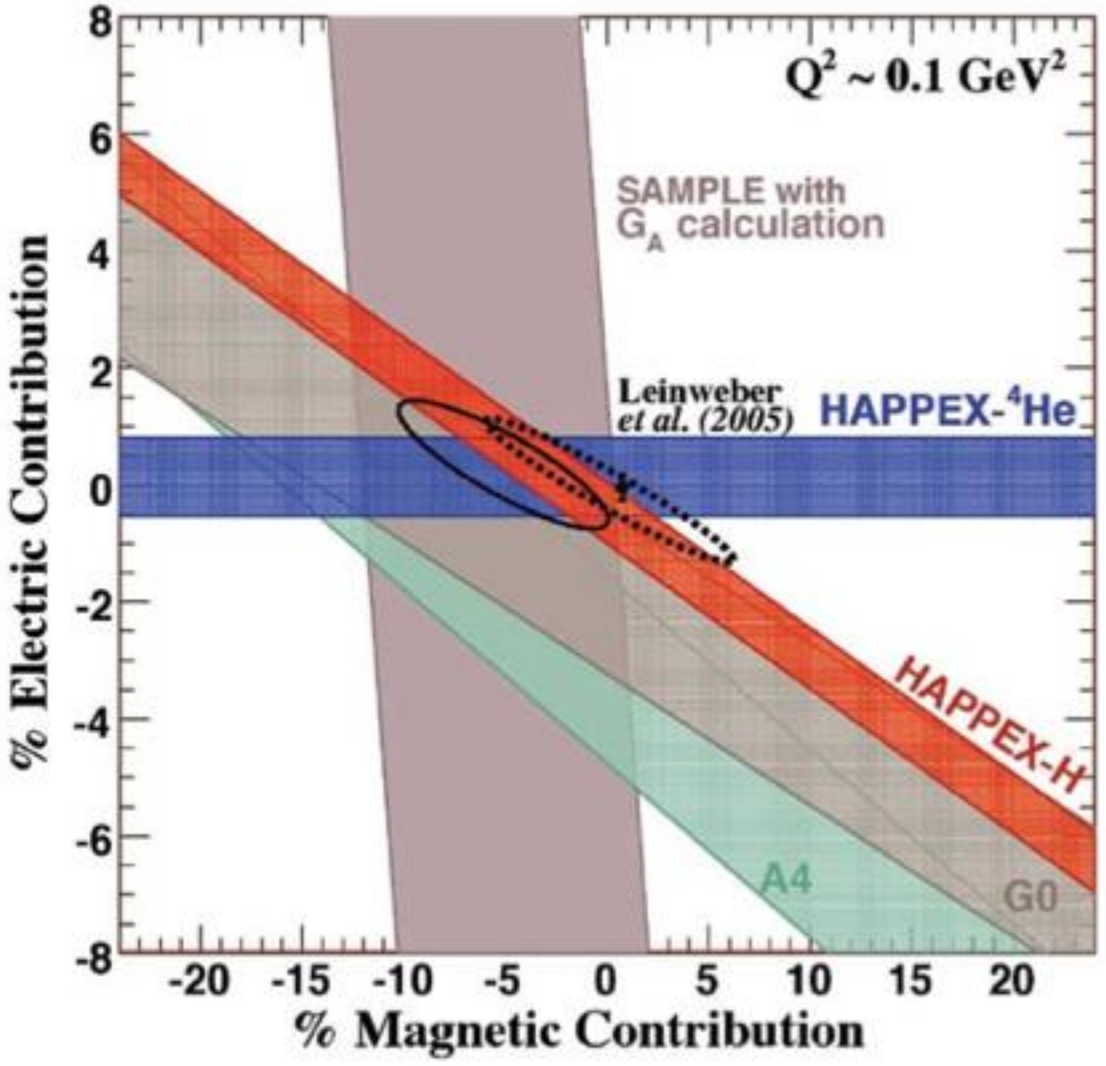



Figure from 2007 LRP, page 27

# Situation in 2007
# Last US Long-Range Plan

- Form Factors  Physics highlighted for future advances

- Two-photon exchange (TPE) experiments: “Future experiments comparing the scattering of electrons and positrons with the aim to directly determine the two-photon contributions are planned at JLAB, at the VEPP-3 facility in Novosibirsk, Russia, and at DESY.”

- Form factors: “As we look toward the next decade, experiments will probe ever shorter distance scales, going into a regime where the details of, for example, the quark orbital motion will play a more significant role. Such measurements remain the only source of information about quark distributions at small transverse distance scales. The differences between proton and neutron form factors represent an important benchmark for lattice QCD calculations.”

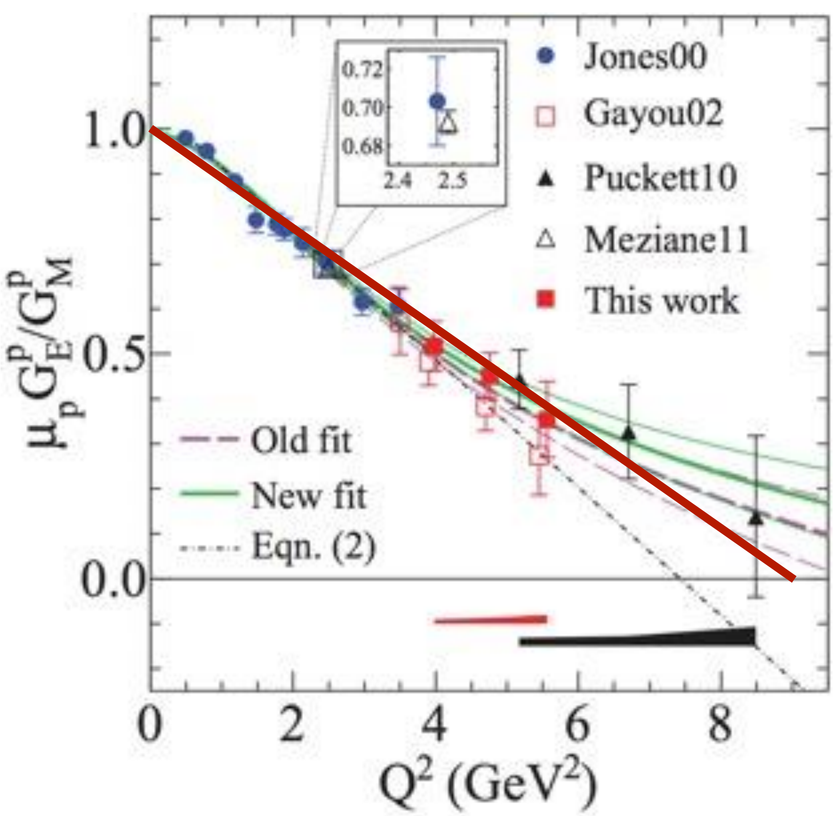
*Refer to opening talks

# Since 2007
# What has been learned?

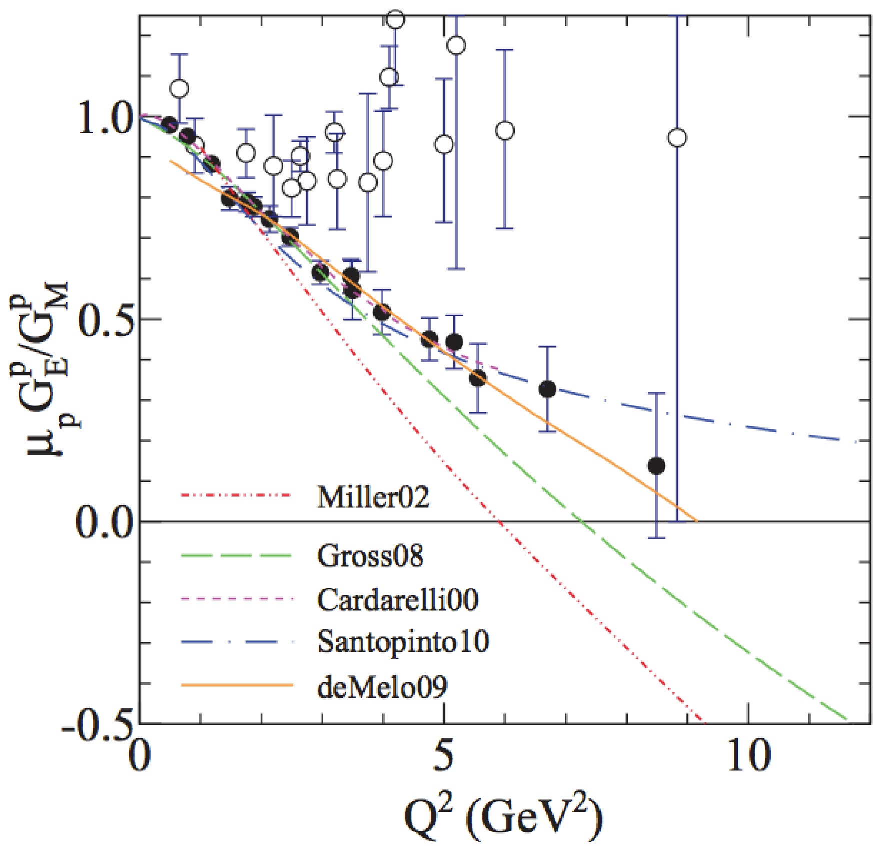
After original Gep-I and II in Hall A, Perdrisat, Punjabi, Brash, Jones et al shifted to Hall C for higher momentum transfer.

Puckett et al. PRL 104, (2010), PRC 85 (2012)
JLab Hall C polarization data & Hall A reanalysis

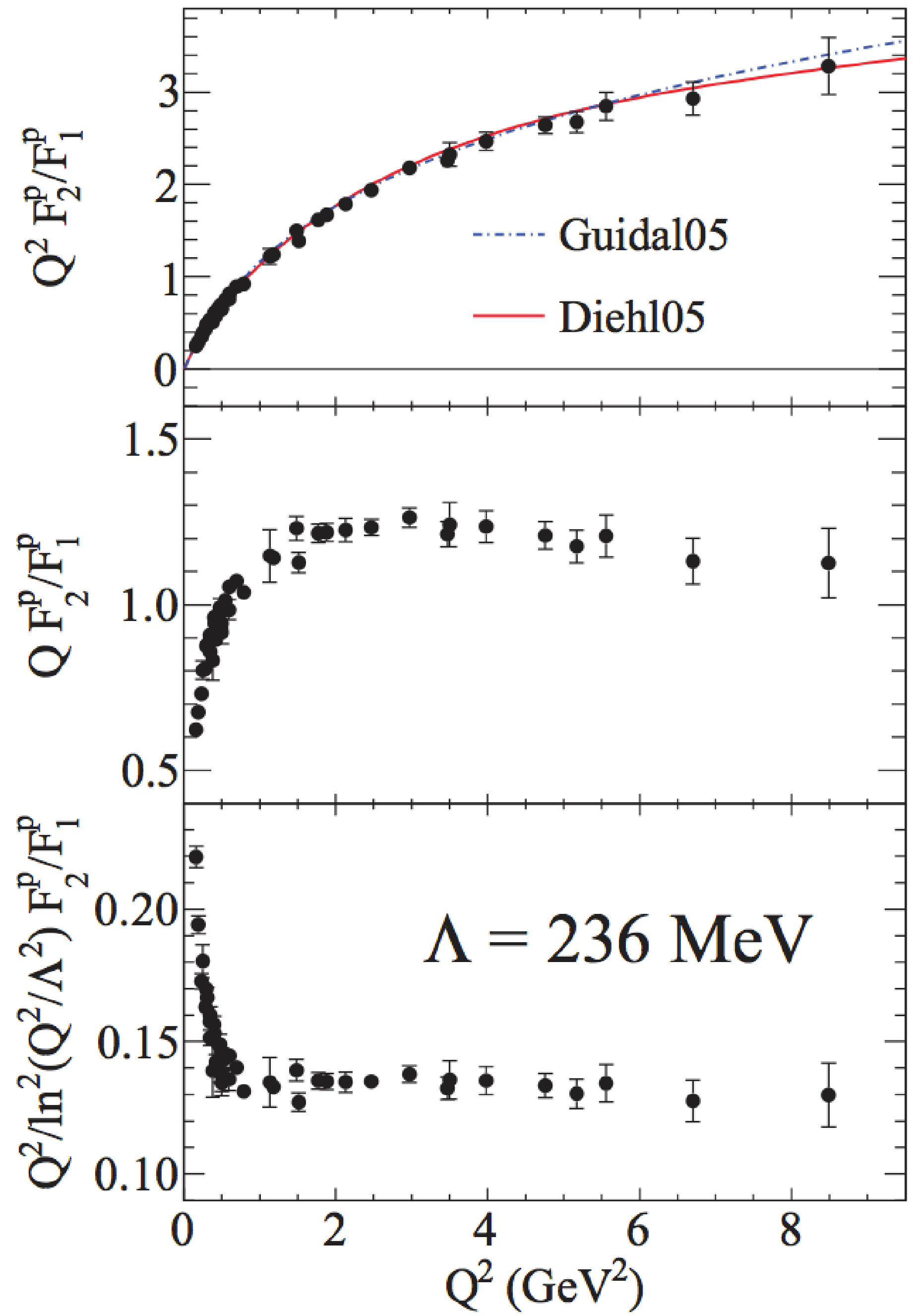
Proton at high $Q^2$




Linear fit remains not terrible

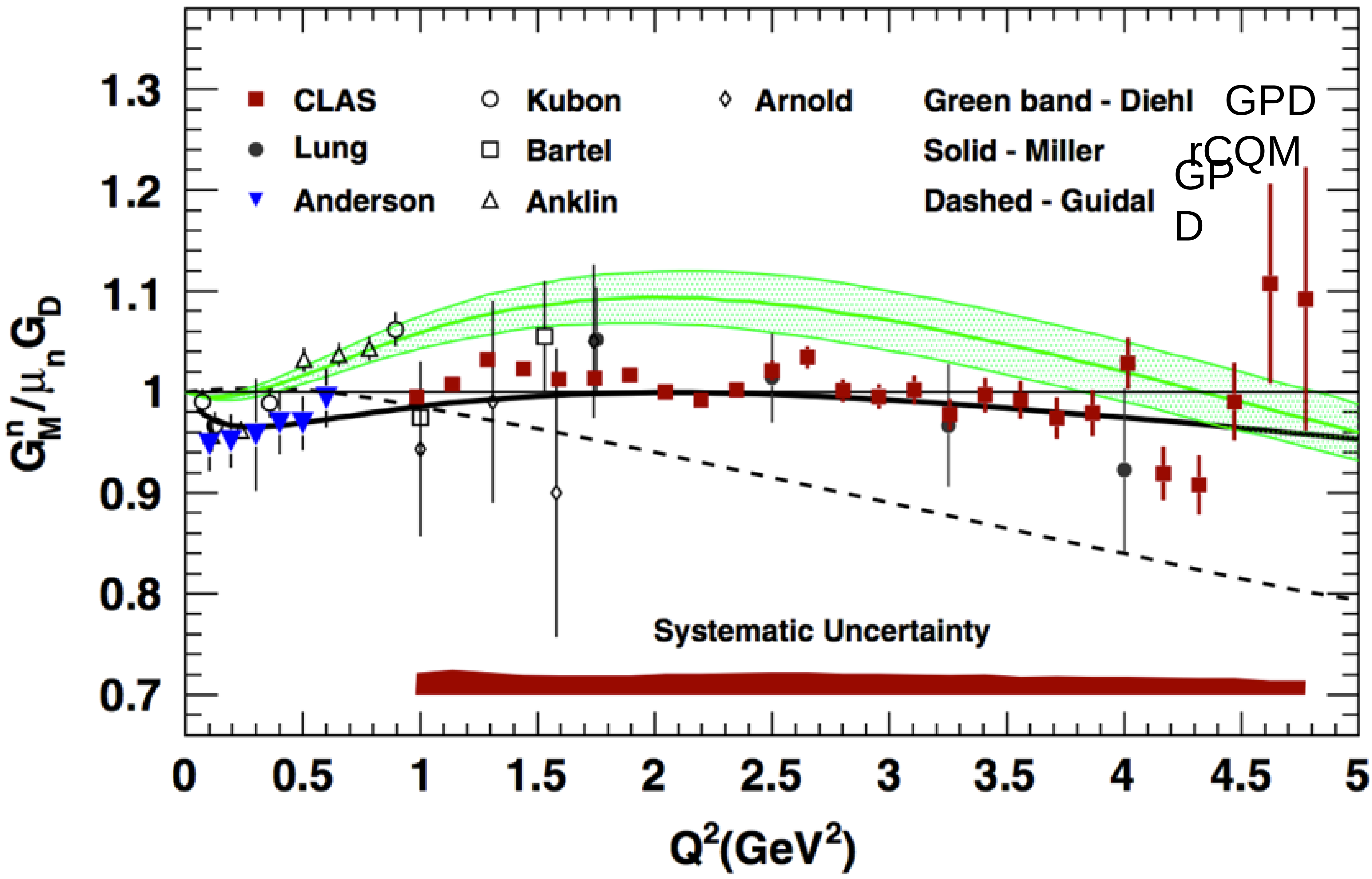



Form factor ratio data compared to relativistic CQM calculations



# Since 2007
# What has been learned?

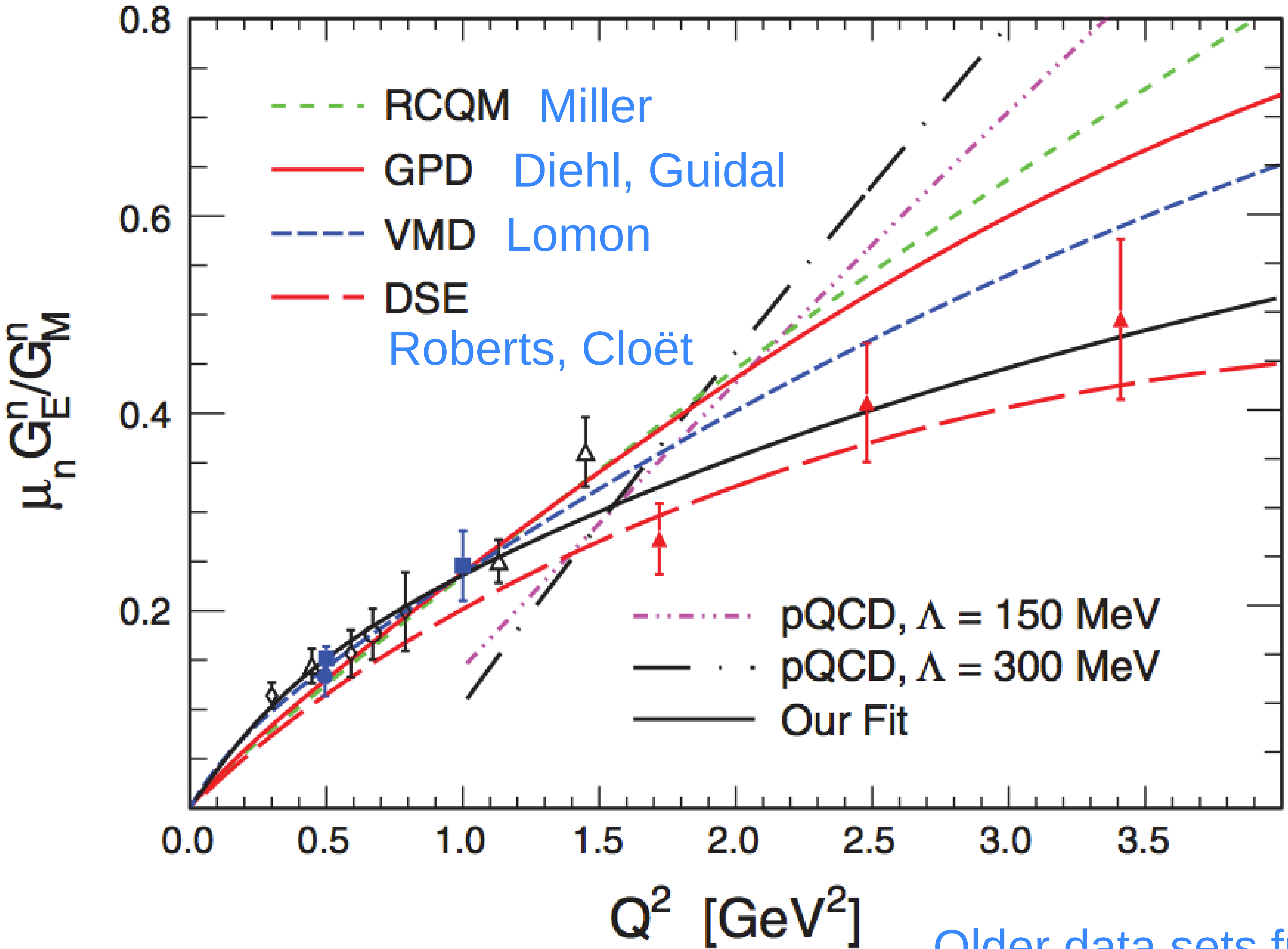
Neutron $G_M$




Lachniet et al PRL 102 (2009)
JLab Hall B cross section data - d(e,e'n)/d(e,e'p) ratio method

# Since 2007
# What has been learned?

Neutron $G_E$

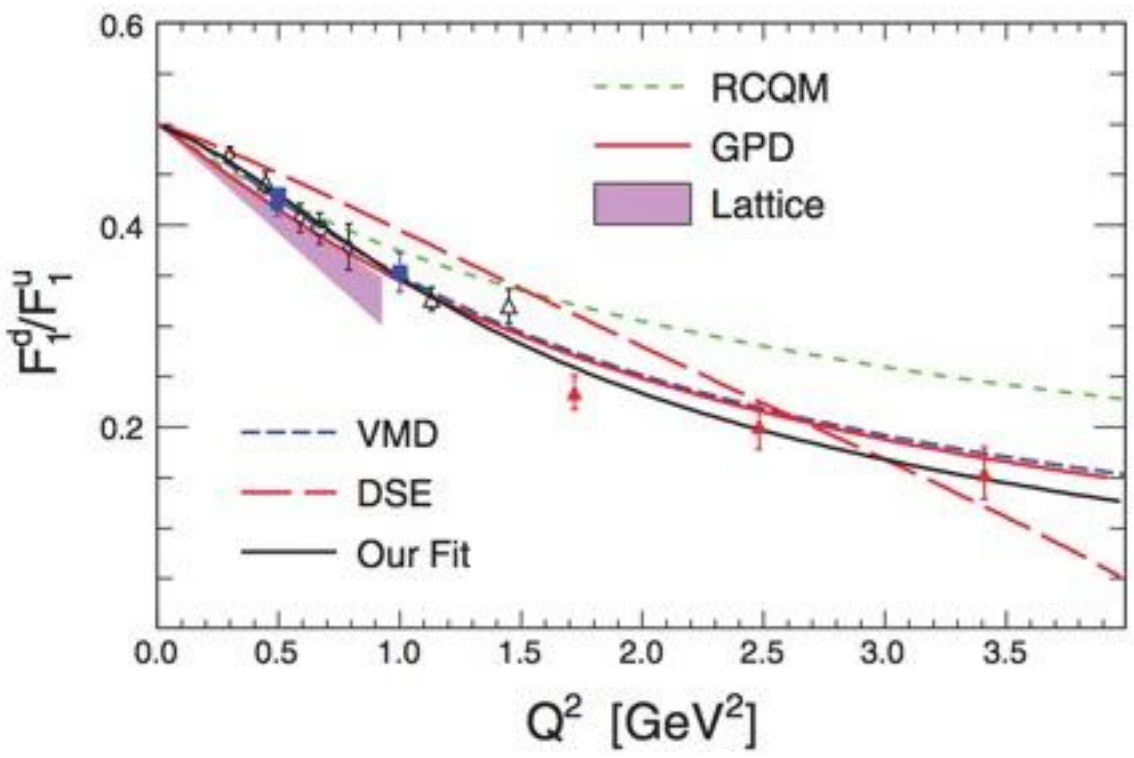


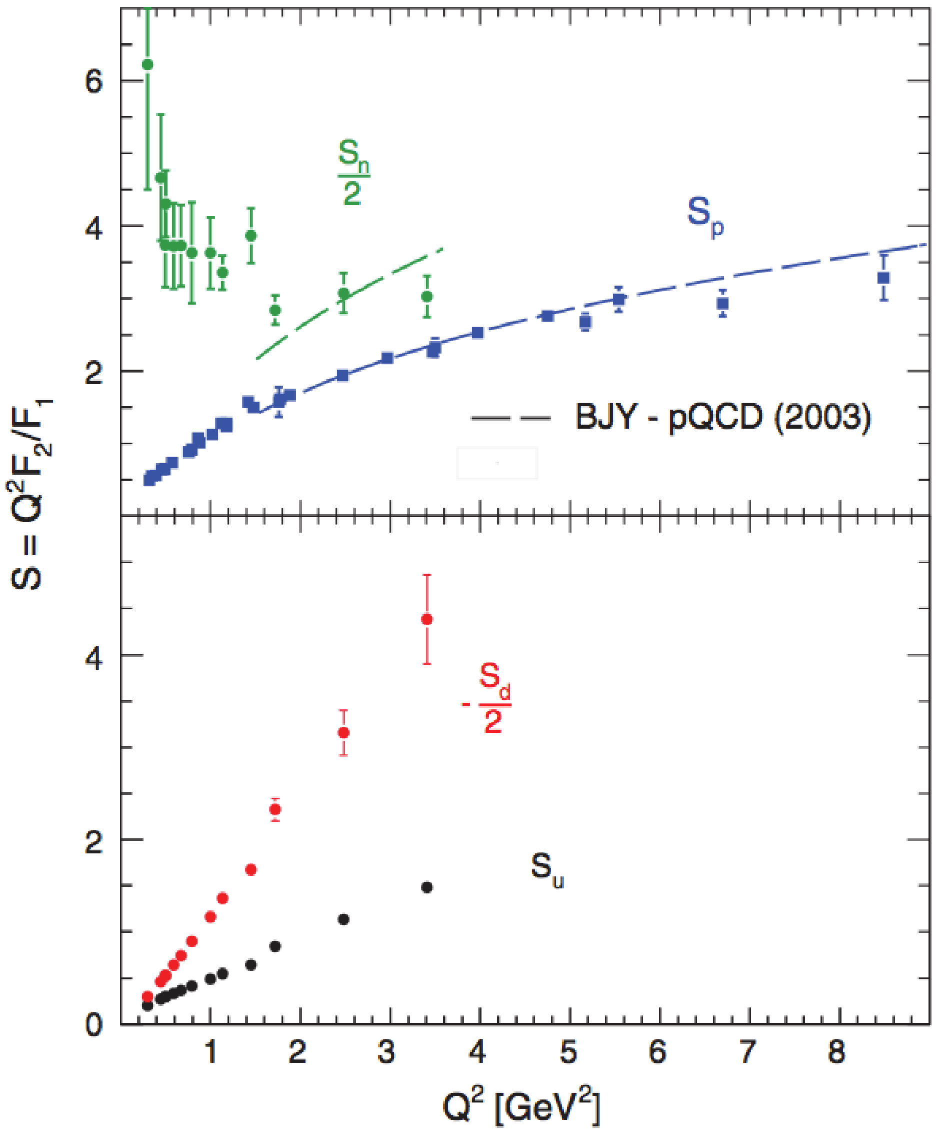

Older data sets from Glazier, Plaster, Zhu, Warren, Rohe, Bermuth

Riordan et al PRL 105 (2010)
JLab Hall A polarization data - $^3He$

# Since 2007
# What has been learned?

Flavor separations



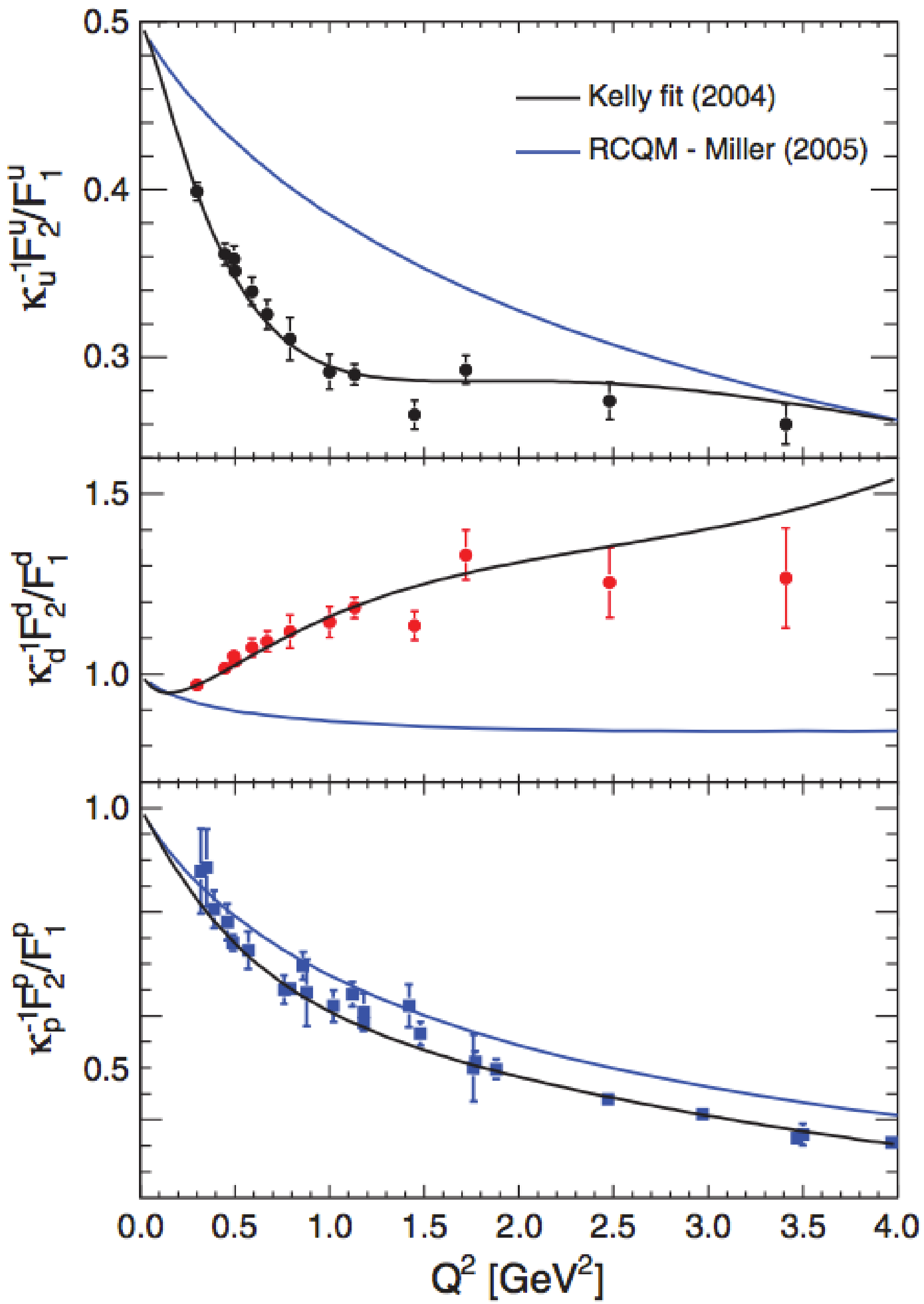

Different $Q^2$ dependence for $F_1^u$ and $F_1^d$
u (d) quarks more centered in proton (neutron)

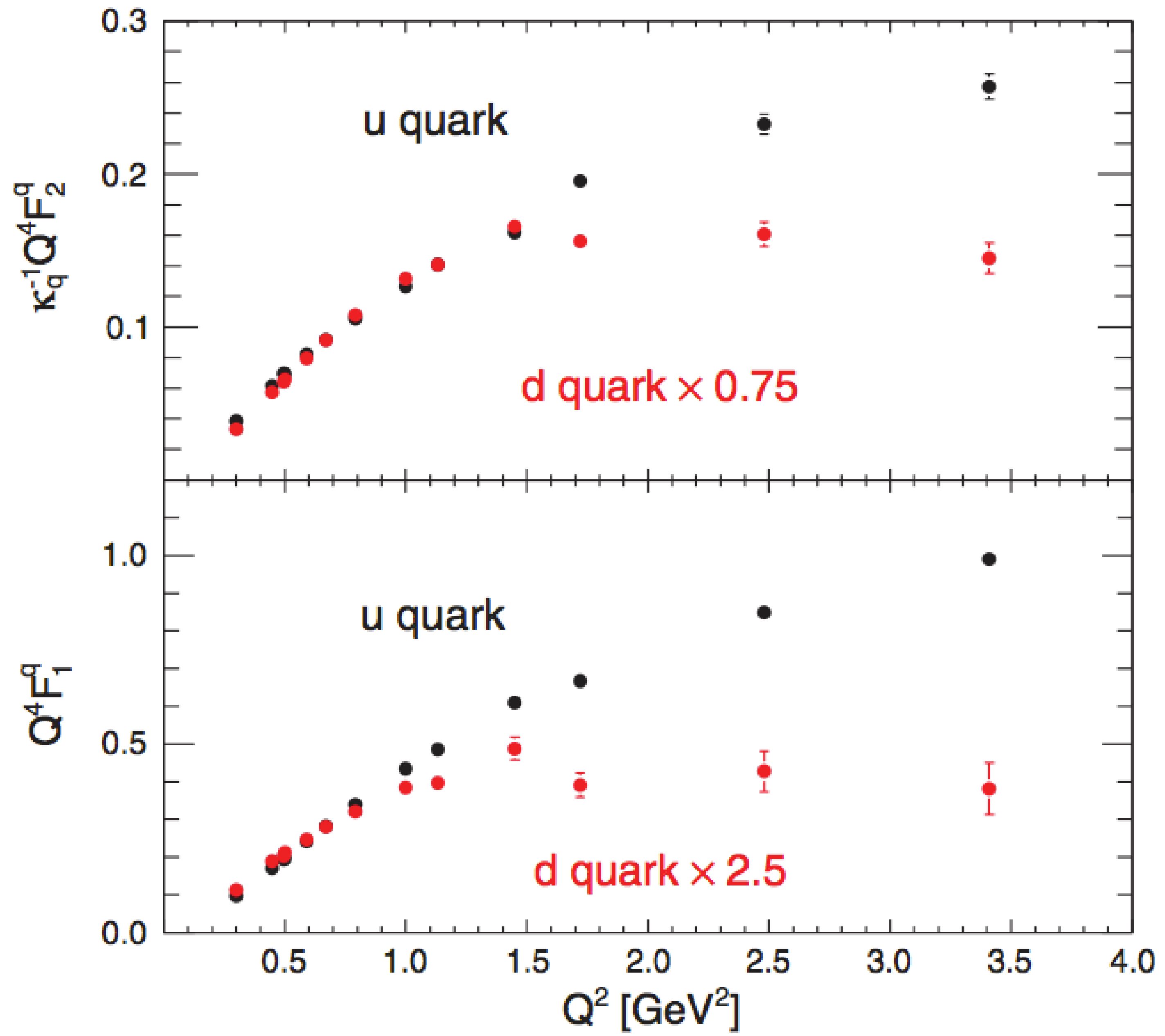
Riordan et al PRL 105 (2010)
JLab Hall A polarization data - $^3He$

Cates, de Jager Riordan, and Wojtsekhowski, PRL 106 (2011)

# Since 2007
# What has been learned?

Flavor separations



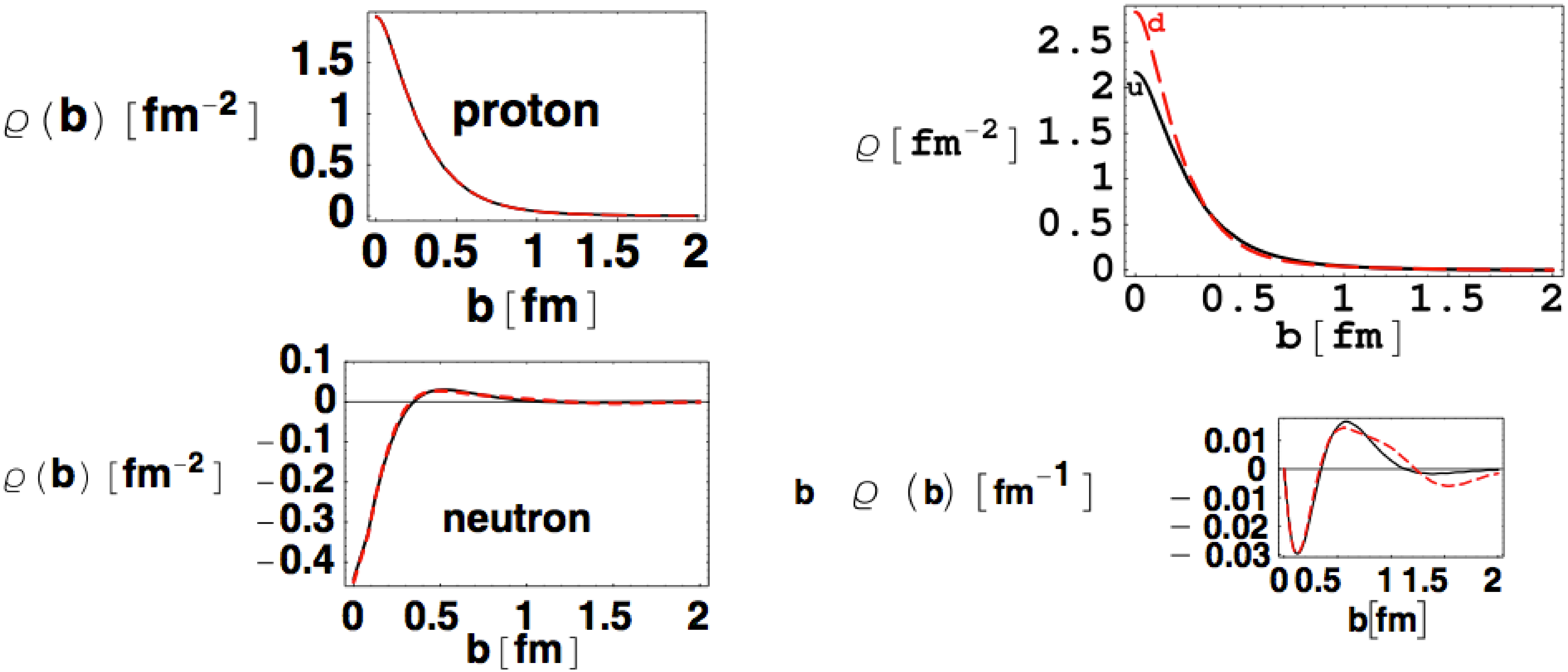

rCQM gets individual flavors wrong, but the ratio about right

Harder u quark distributions → smaller u quark size (anticipated by Miller)

Cates, de Jager Riordan, and Wojtsekhowski, PRL 106 (2011)

# Since 2007
# What has been learned?

Transverse densities




Neutron is positive at origin in Breit frame since $G_E$>0 (pion cloud) but negative at the origin in transverse frame since $F_1$<0 (central d quarks).

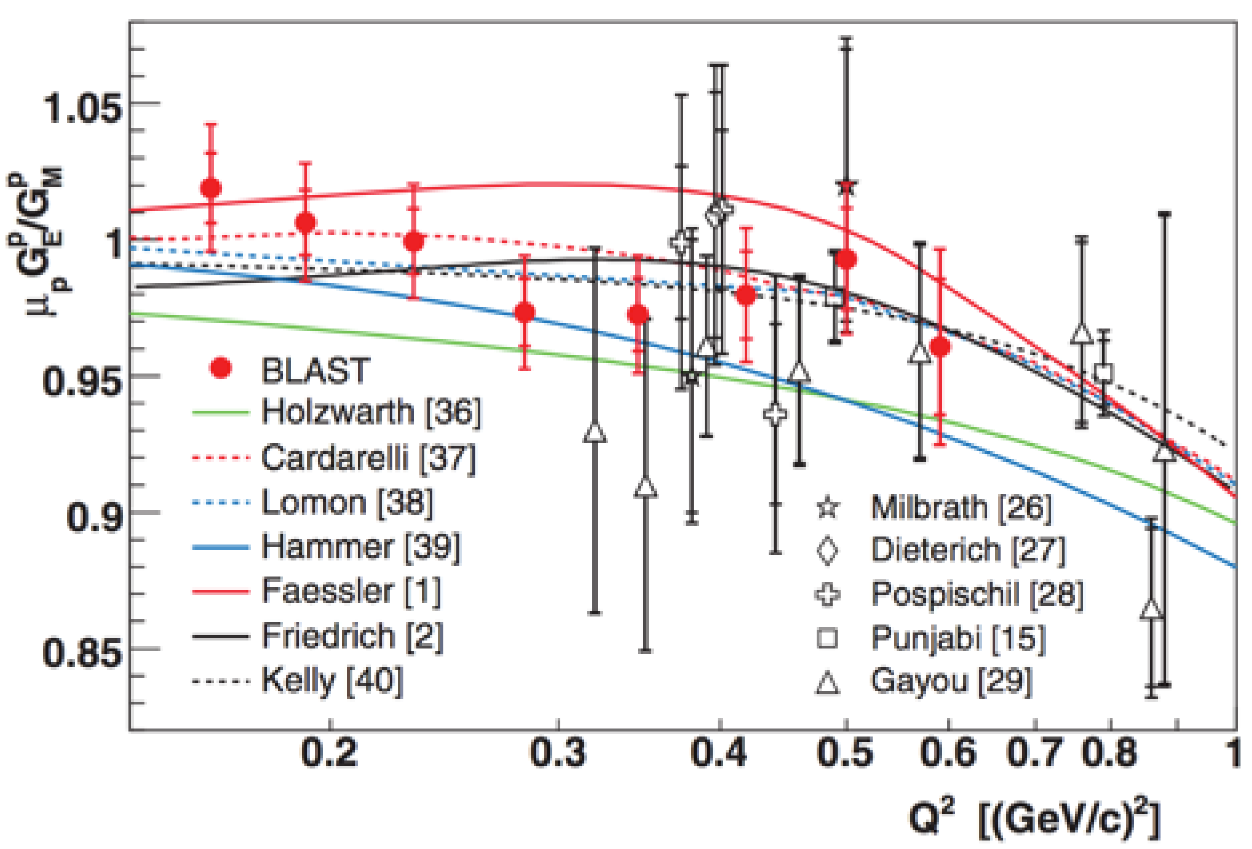
Should this bother us?

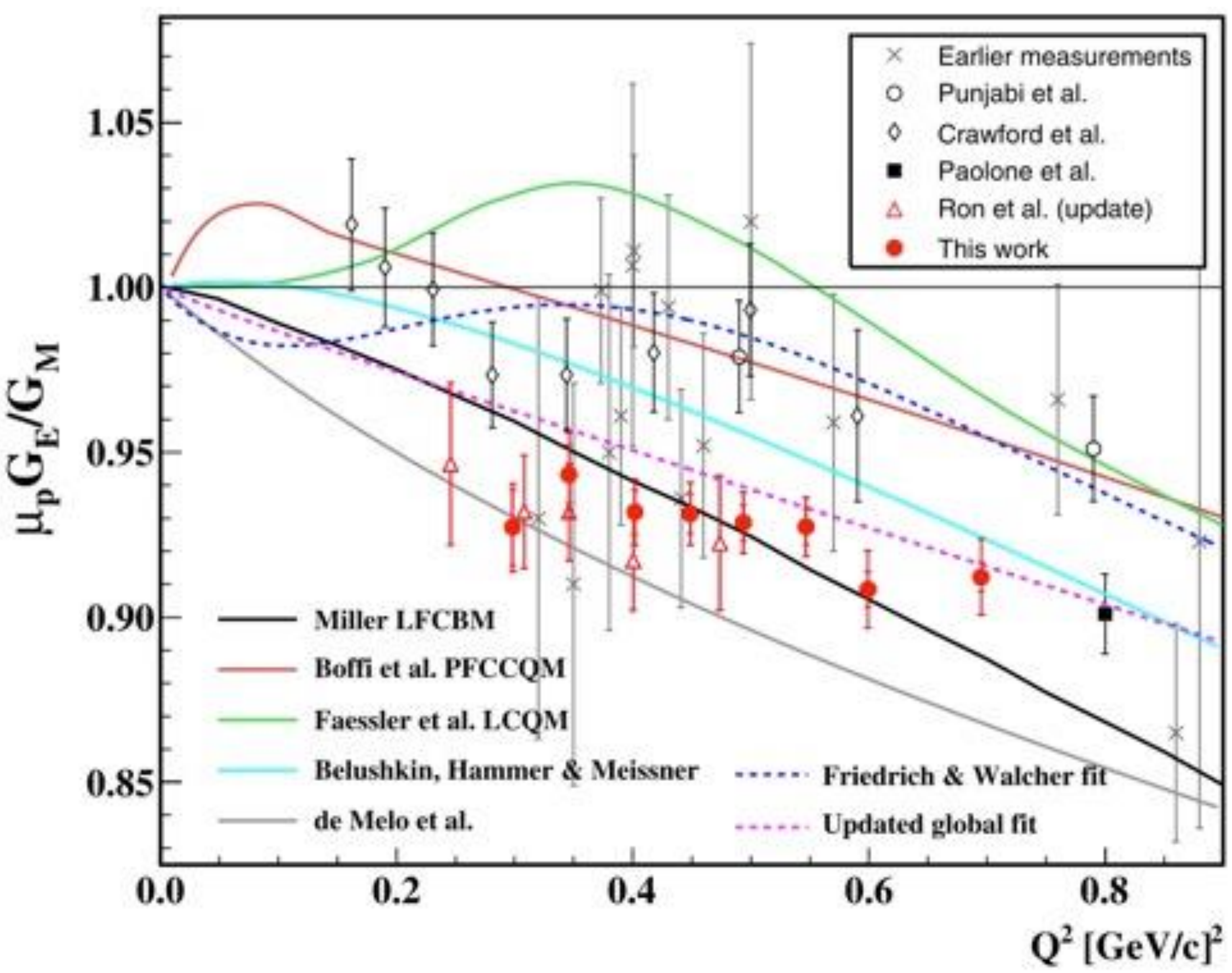
Probably not, but if $G_E^N$ goes negative enough soon enough, the Breit frame distribution will go negative at the origin.

Miller PRL 99 (2007)

# Since 2007
# What has been learned?

Proton at low $Q^2$



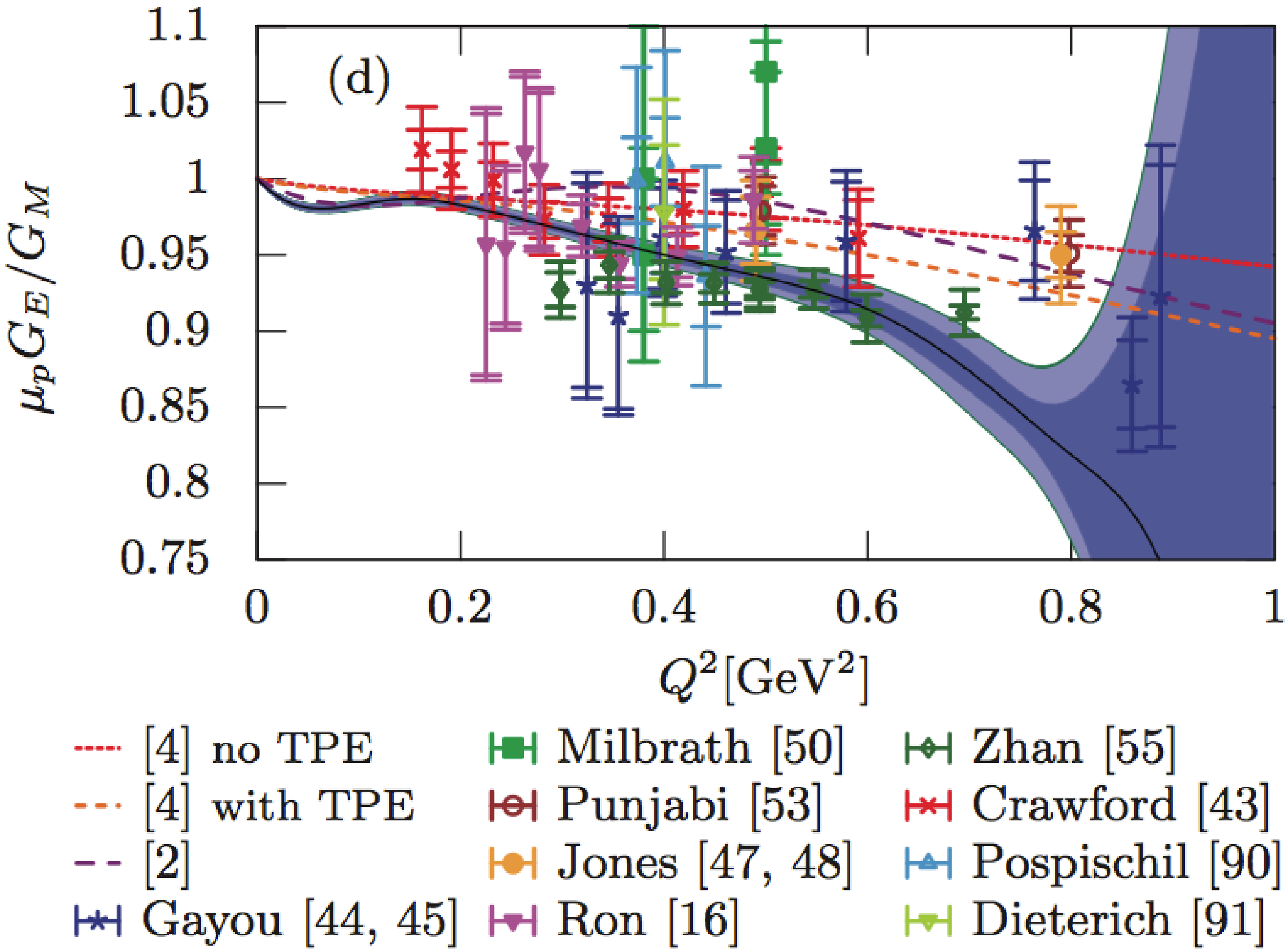



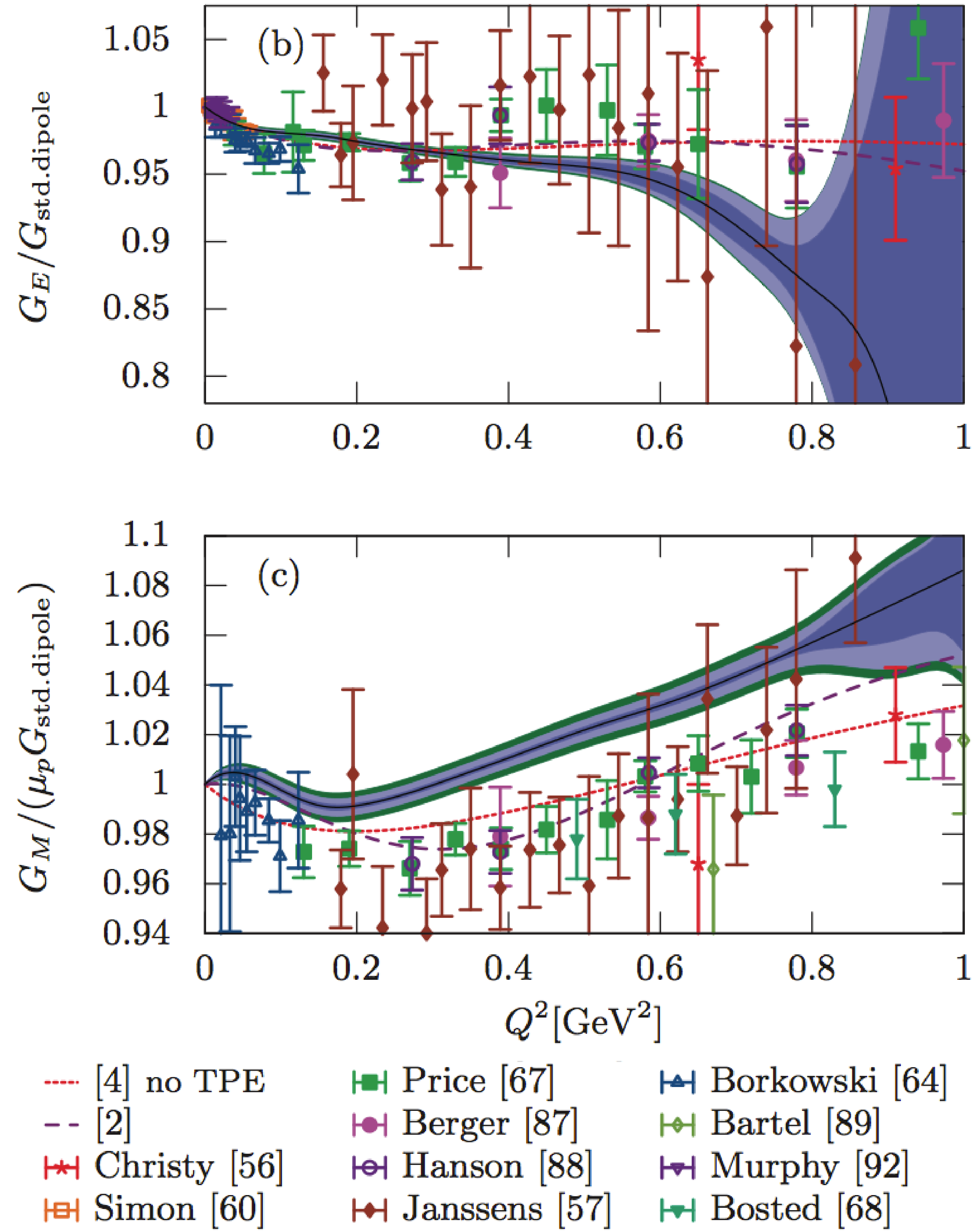

Crawford et al PRL 98, (2007)
Bates BLAST polarization data

Zhan et al PBL 705, (2011)
Paolone et al, PRL 105 (2010)
Ron et al, PRL 99 (2007), PRC 84 (2011)
JLab Hall A polarization data

# Since 2007
# What has been learned?

Proton at low $Q^2$




Bernauer et al PRL 105 (2011), PRC 90 (2014)

Mainz A1 cross section data

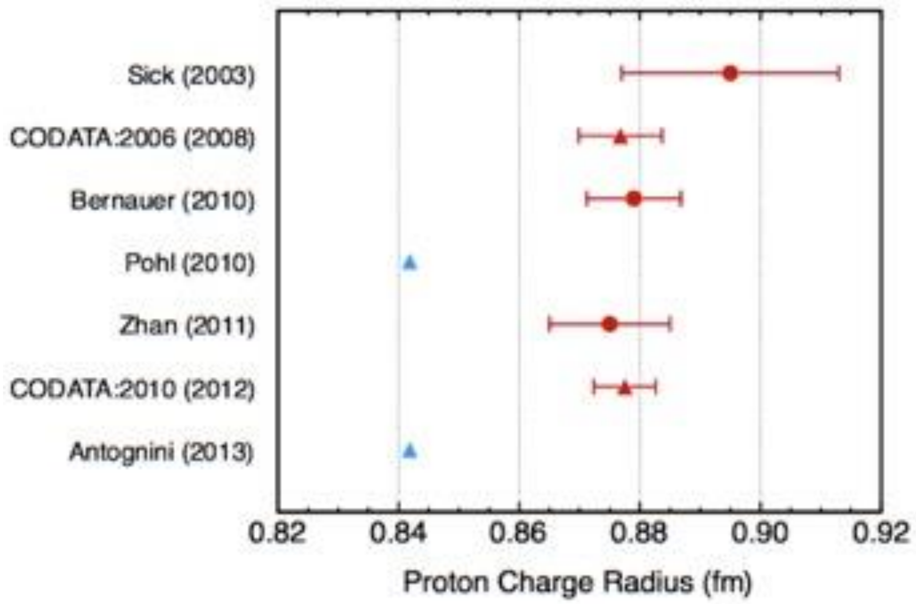
2: Friedrich & Walcher fit 4: AMT fit

# Proton Charge Radius Puzzle... Following talk

agreement between ep scattering & Hydrogen spectroscopy, disagreement with muonic Hydrogen spectroscopy

Randolf Pohl et al., Nature 466, 213 (2010):
0.84184 ± 0.00067 fm 5σ off 2006 CODATA

Aldo Antognini et al., Science 339, 417 (2013):
0.84087 ± 0.00039 fm 7σ off 2010 CODATA

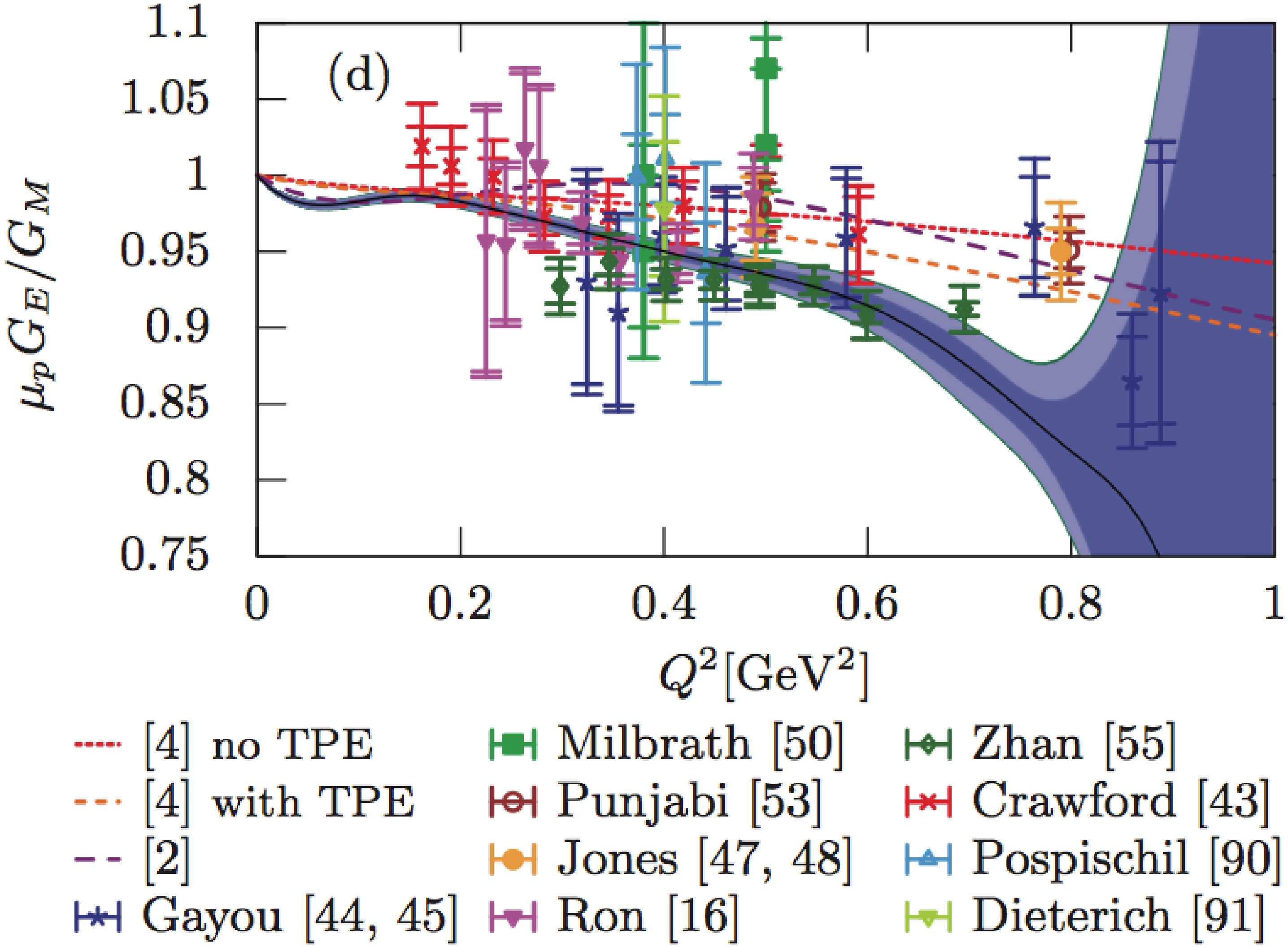


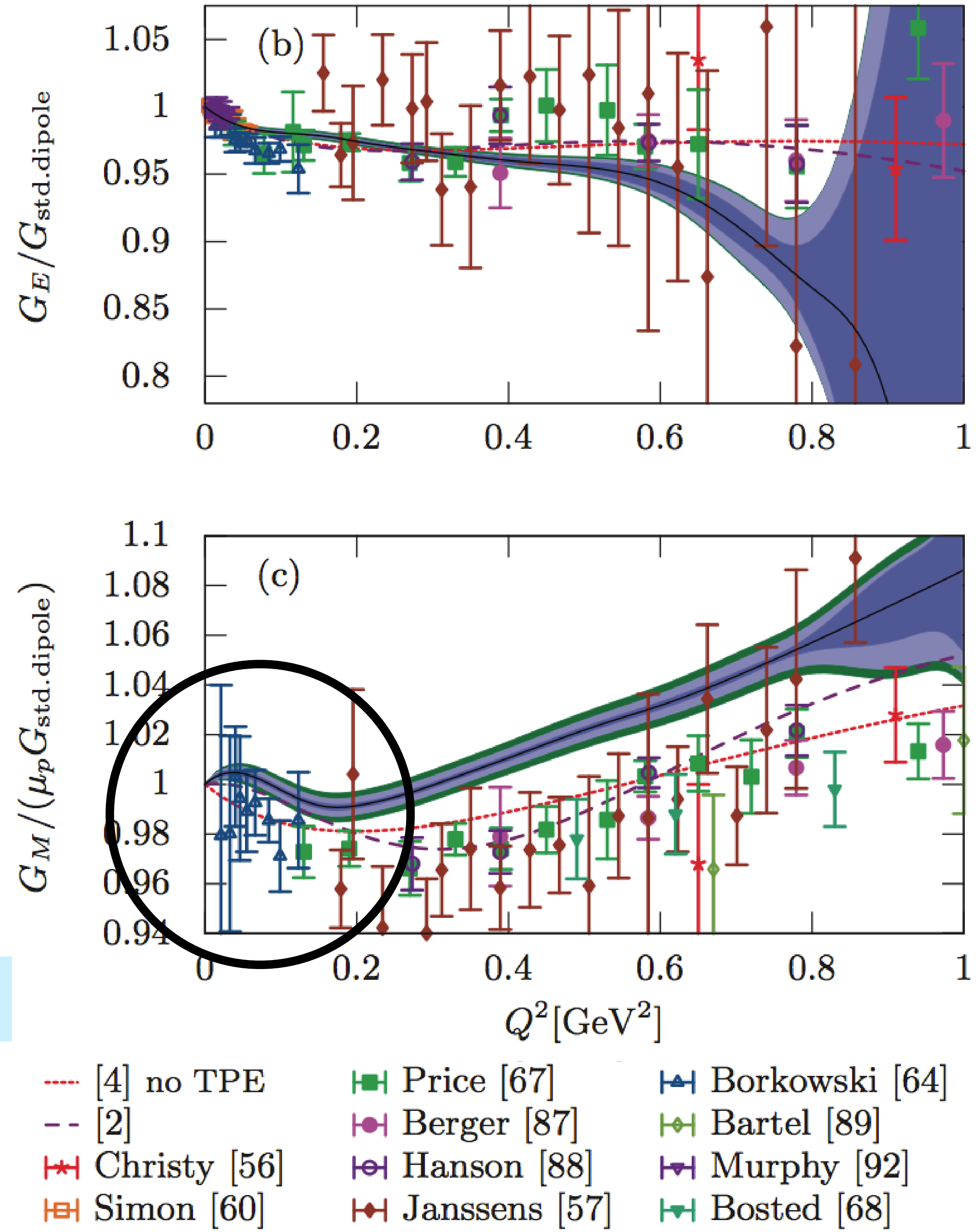

| $r_p$ (fm) | atom | scattering |
|---|---|---|
| electron | 0.8779 ± 0.0094 (Pohl averaging) | 0.879 ± 0.008 (Mainz)<br>0.875 ± 0.009 (JLab)<br>0.886 ± 0.008 (Sick)<br>0.871 ± 0.009 (Hill & Paz)<br>0.84 ± 0.01 (Lorenz, Hammer, Meissner) |
| muon | 0.84087 ± 0.00039 (Antognini) | ? |

CODATA 2010: 0.8775 ± 0.0051 or 7.2σ difference

# Since 2007
# What has been learned?

Proton at low $Q^2$




There is also a magnetic radius problem

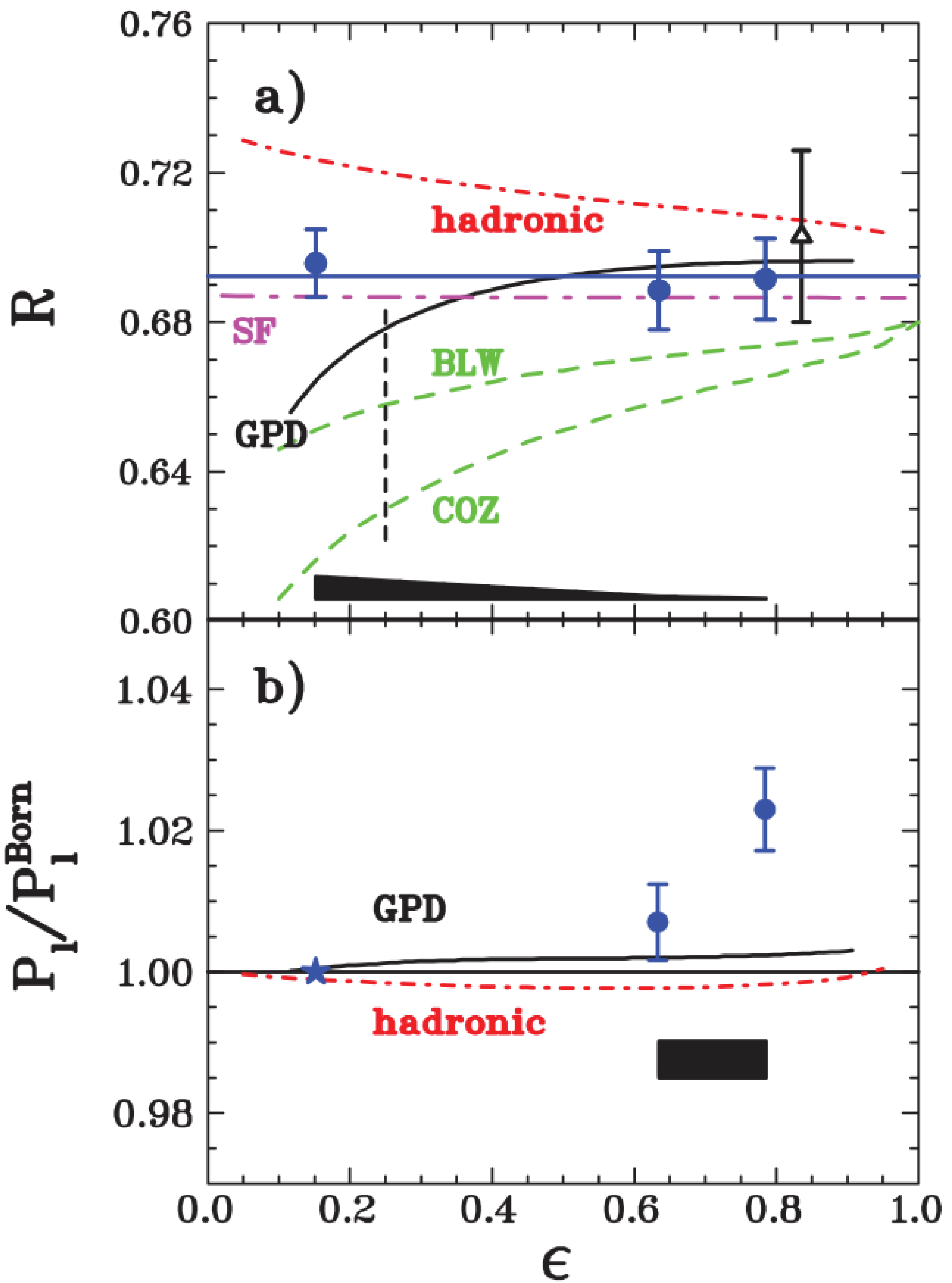
Bernauer et al PRL 105 (2011), PRC 90 (2014)

Mainz A1 cross section data

2: Friedrich & Walcher fit 4: AMT fit

# Since 2007
# What has been learned?

TPE

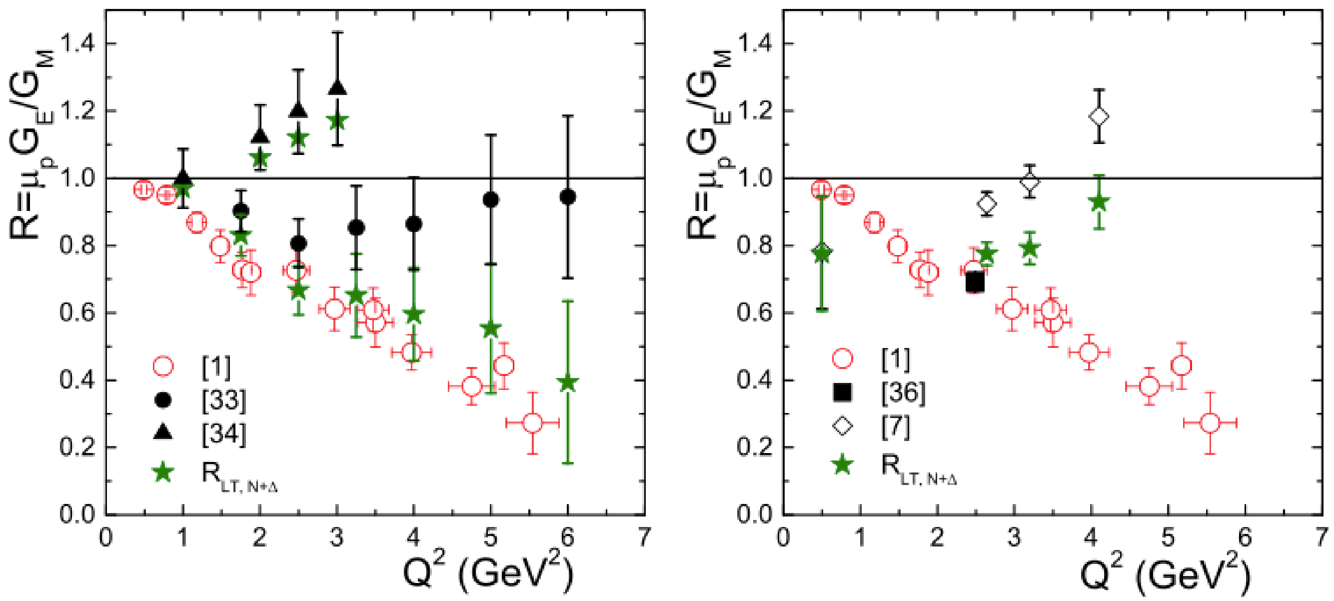



- $R \approx \mu G_E^P/G_M^P$ at 2.5 GeV$^2$ basically flat - flatter than anticipated from some models that can be used to understand the difference between polarization transfer and Rosenbluth separation measurements.
- $P_l$ has more variation than expected
- But... it is the $e^+p/e^-p$ cross section ratio that is most directly connected to the size of the TPE corrections to Rosenbluth

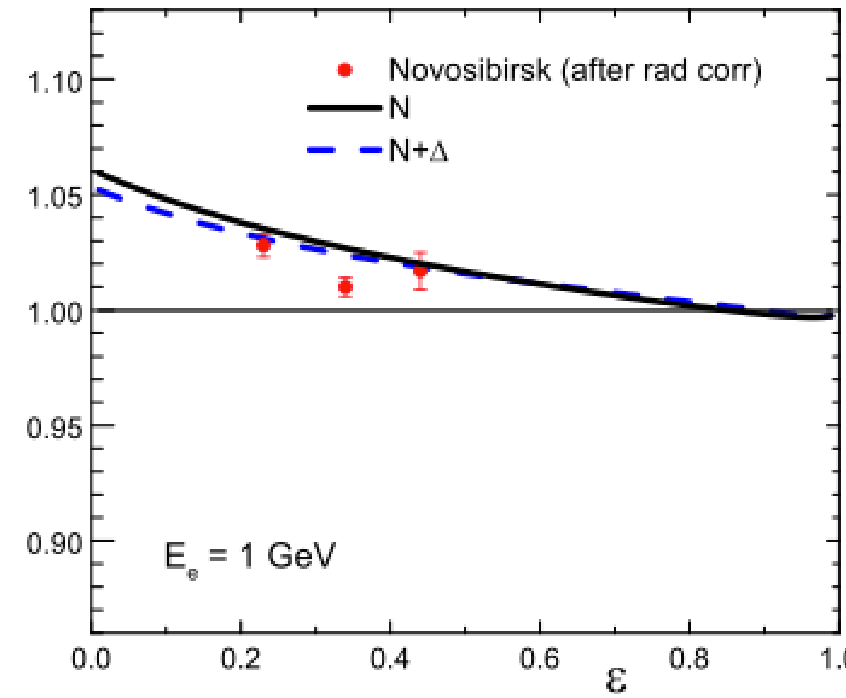
Meziane et al PRL 106 (2011)
Hall C polarization data

# Since 2007
# What has been learned?

TPE Theory / Analysis



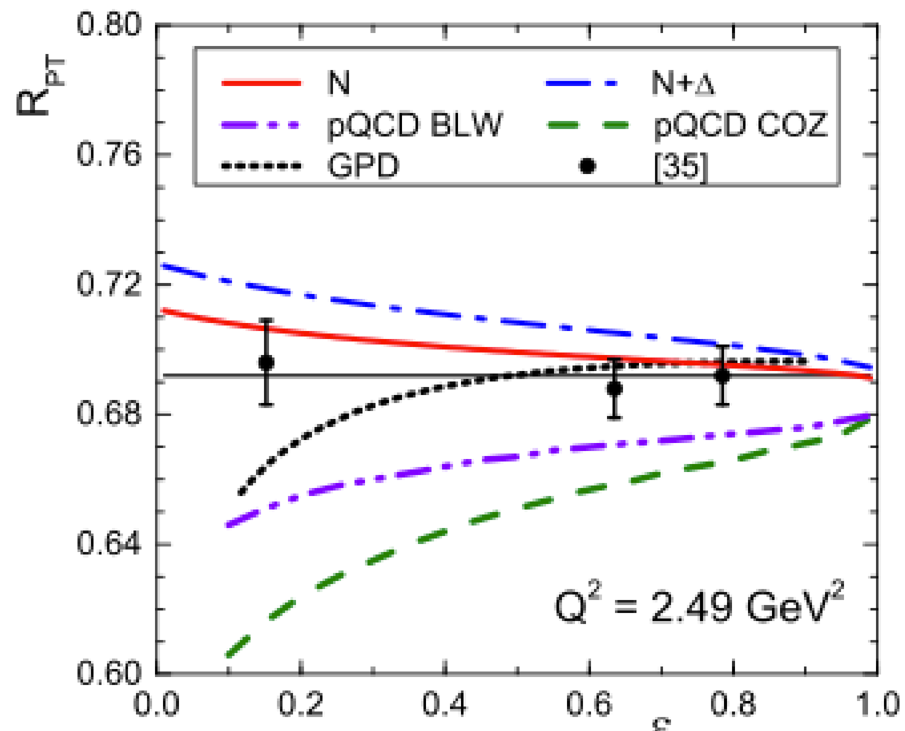

Hai-Qing Zhou and Shin Nan Yang, arXiv:1407.2711v2
Hadronic TPE calculation



(b)

- Calculated TPE correction moves Rosenbluth results towards the polarization data, but not entirely

- Too large an effect compared to Meziane et al data



(b)

- Good sized asymmetries predicted for positron/electron comparison

# Issues for the Future

We have encountered a lot of issues - some inter-related:

- Do we understand radiative corrections well enough?
- Conventional RC and the proton magnetic radius
- TPE: Where is the new data mentioned in the 2007 LRP?

# Issues for the Future

- High $Q^2$ behavior of form factors, including individual flavors
- Does $G_E^P$ go negative?
- Does $G_E^N$ go negative? (neutron central density)
- Do $G_M^{P,N}$ continue to (approximately) follow the dipole and $1/Q^4$ at high $Q^2$?

# Issues for the Future

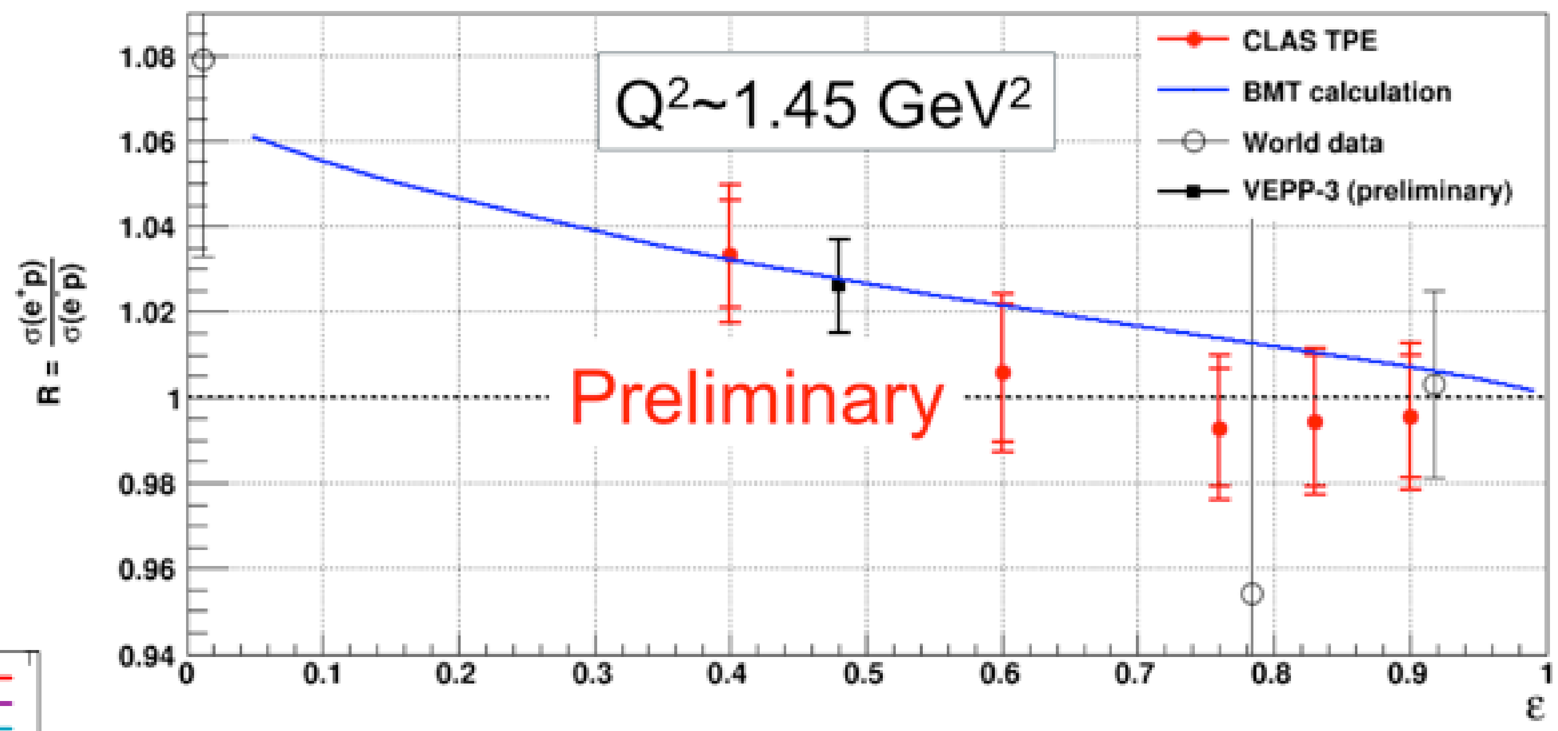
- Low $Q^2$:
  - Proton charge radius
  - Proton magnetic radius

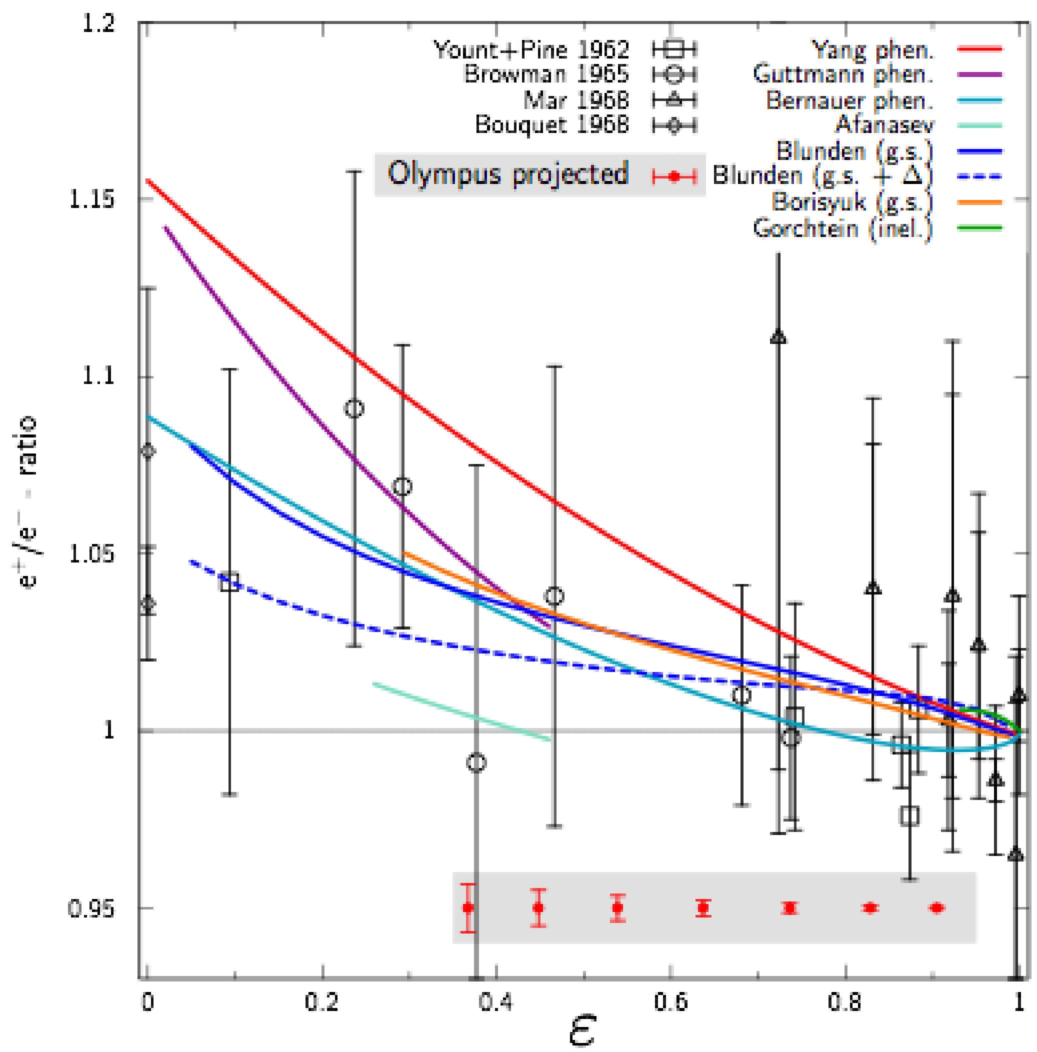
- Do we understand the neutron / nucleon in nuclei well enough to obtain good $G^N$ data?

- Data sets often have few percent overlap problems

# TPE

- Three experiments compare electron/positron scattering
  - VEPP-3
  - JLab CLAS
  - DESY OLYMPUS
- All have taken data
- None have final results



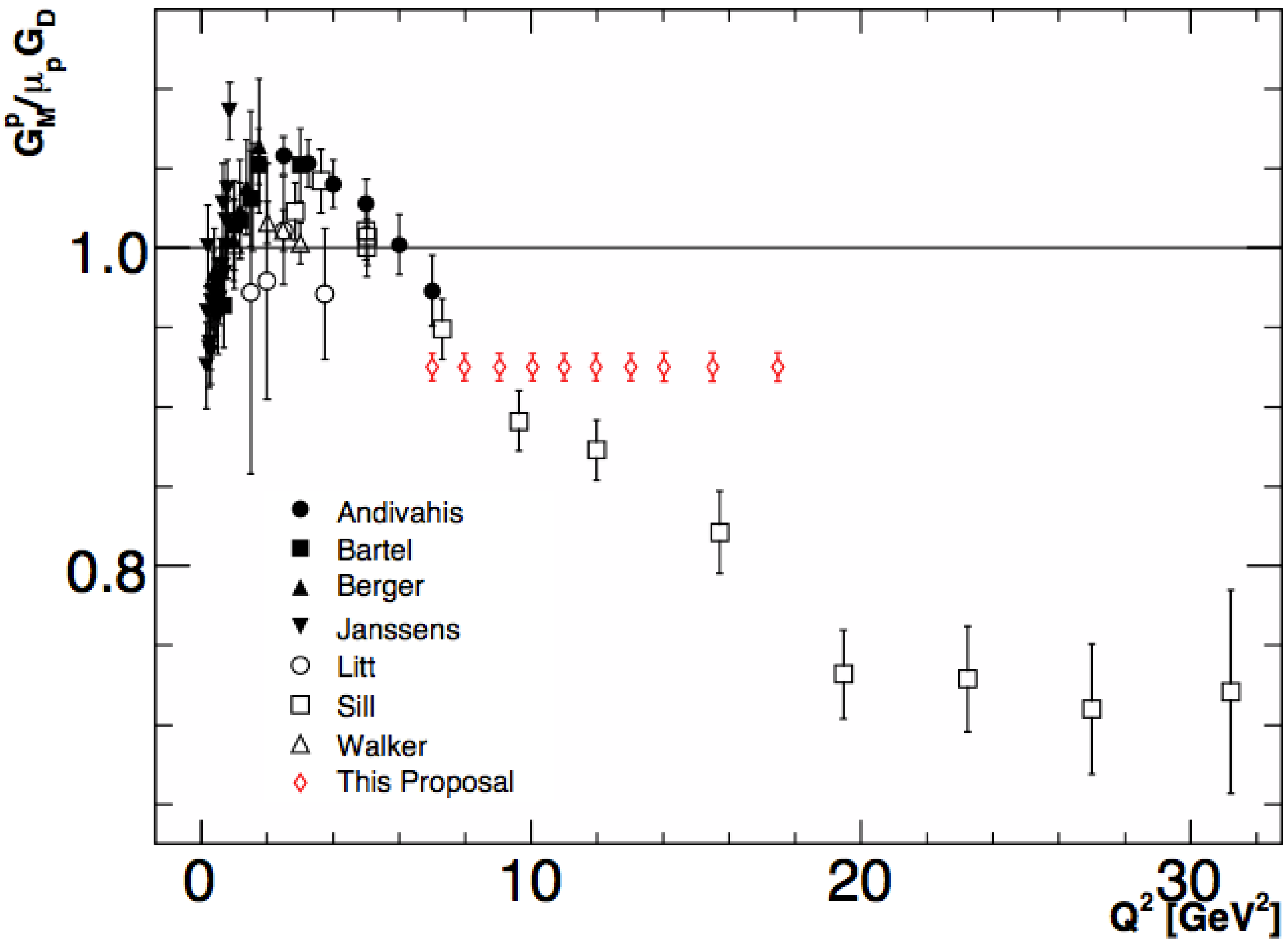




- JLab CLAS: $e^-$ beam creates photon beam creates mixed $e^+/e^-$ beam incident on CLAS target. Kinematics calculated from outgoing particles.
  - Some indication TPE too small to fully explain polarization / Rosenbluth differences
- DESY OLYMPUS: Fixed 2 GeV beam incident on internal target, correlations between $Q^2$, $\theta$, $\varepsilon$

# Future “Results”

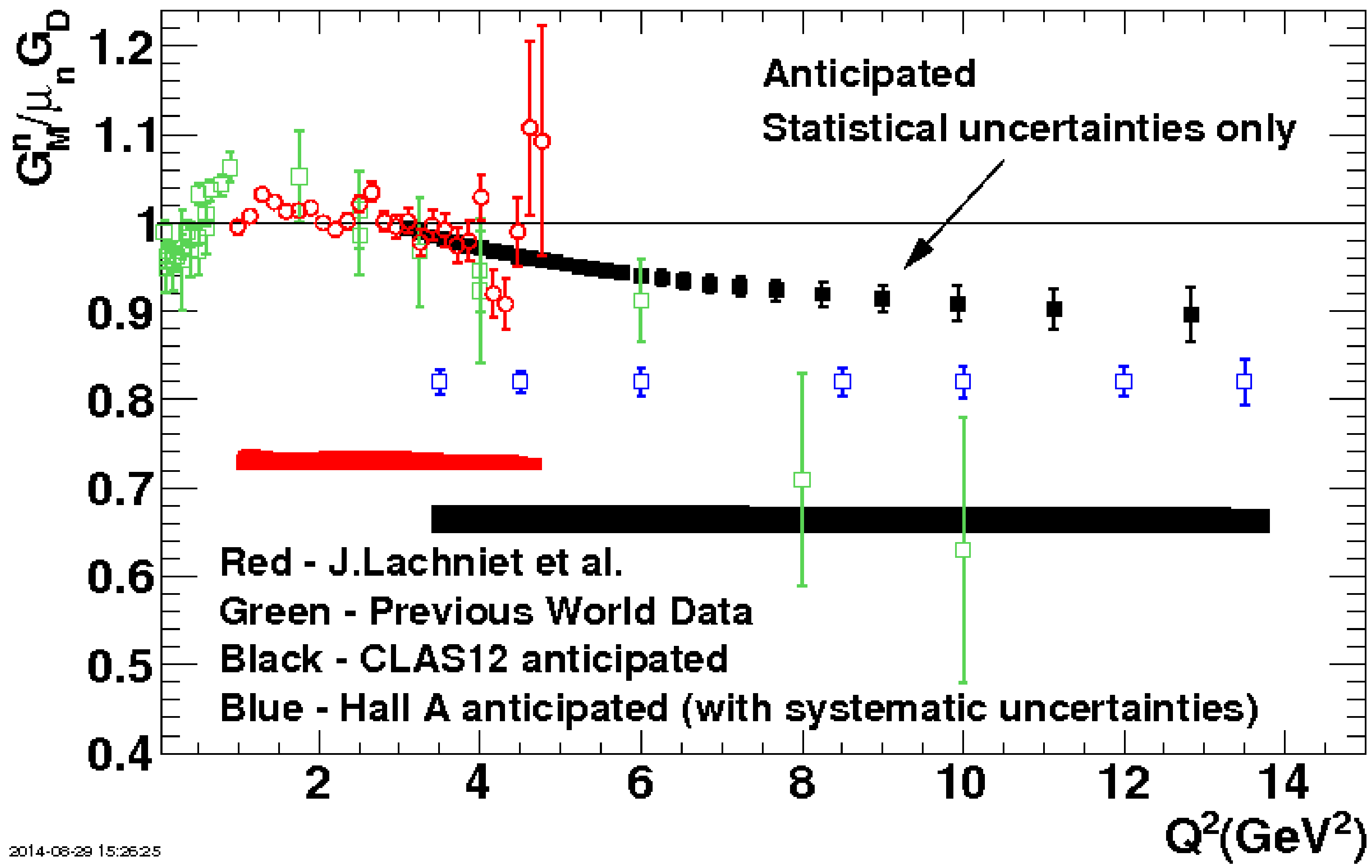
- JLab PAC41 High Impact experiments included 3 studying form factors
  - E12-05-101: Measurement of the Charged Pion Form Factor to High $Q^2$
  - E12-07-109: $G_E^P/G_M^P$: Large Acceptance Proton Form Factor Ratio Measurement at 13 and 15 (GeV/c)2 Using Recoil polarization Method
    - Neutron form factor ratio E12-09-016 given honorable mention
  - E12-11-106: High Precision Measurement of the Proton Charge Radius

# JLab Hall A Measurement of $G_M^P$




- Commissioning experiment that improves precision in the high $Q^2$ region
- Straightforward precise cross section measurement

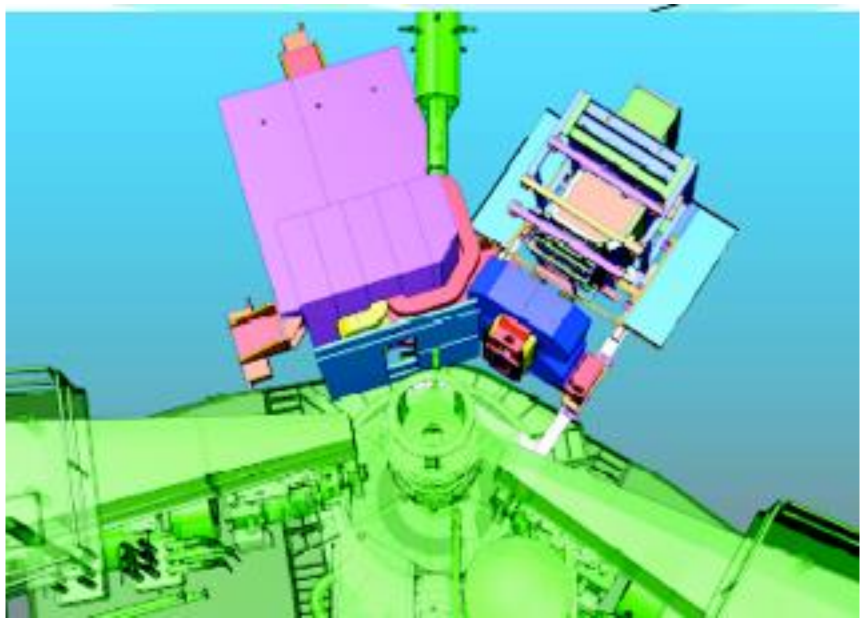
# JLab Hall B CLAS Measurement of $G_M^N$

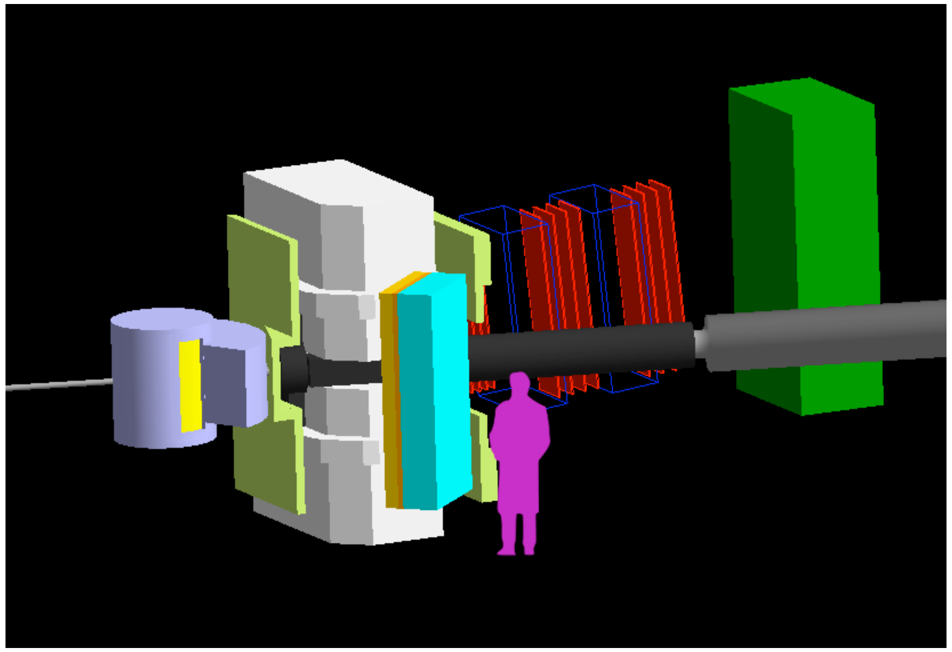



- High $Q^2$ reach for precision $G_M^N$ nearly tripled
- Measurements use cross section ratio technique - d(e,e'n)/d(e,e'p)

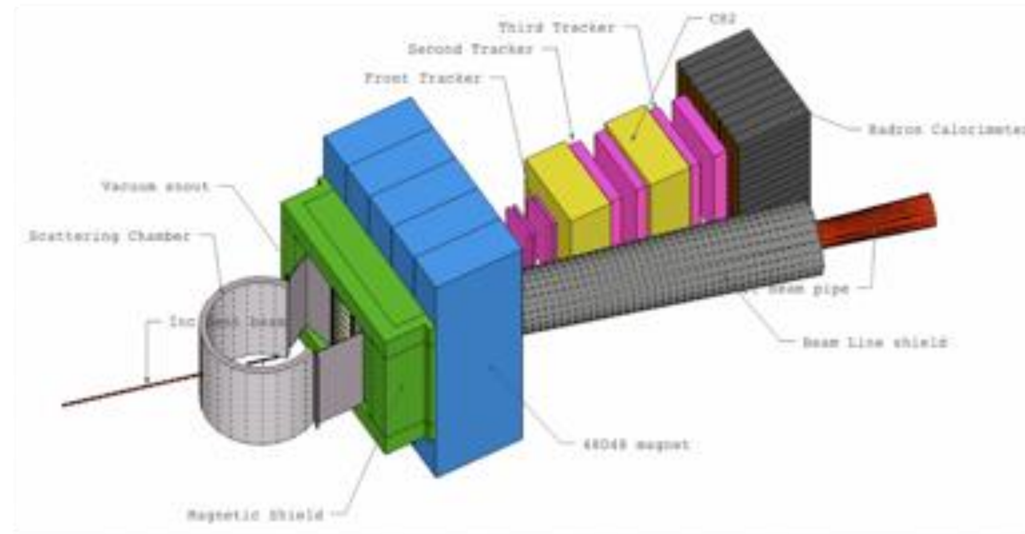
# SuperBigBite Program in JLab Hall A

- A $5M DOE Project for Hall A at Jefferson Lab
- High $Q^2$ form factor measurements, for tests of QCD predictions, etc., are a major program for SBS.
- SBS will reach into new higher $Q^2$ territory with high precision
- Measurements could begin as early as 2017



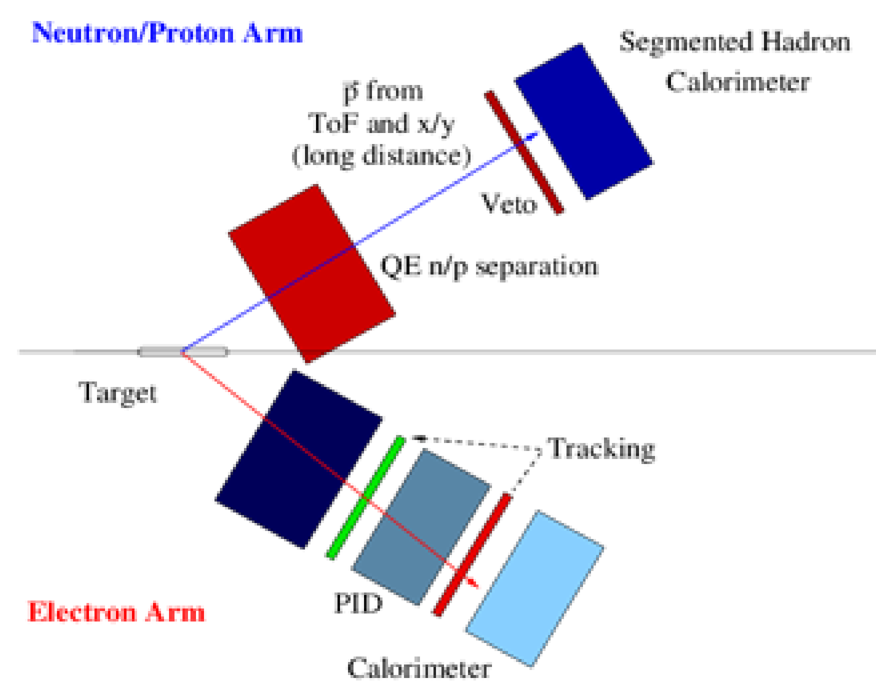


# SuperBigBite Program in JLab Hall A



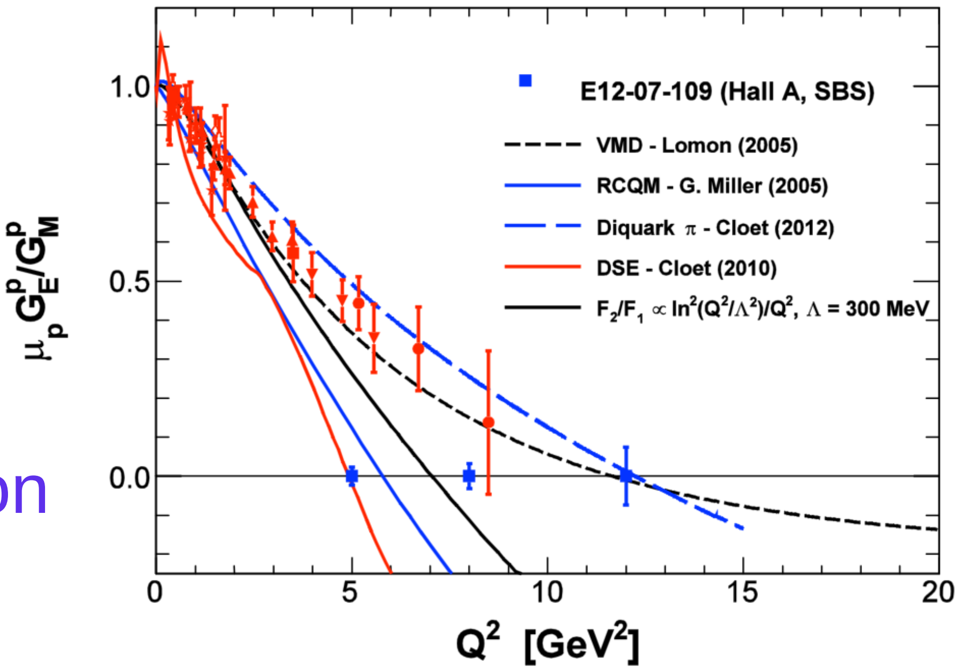

Development of a new unique hardware for coincident $e^-N$ scattering

- Spectrometer with large solid angle at small scattering angle and very high luminosity
- Double polarimeter for the recoil proton at high momentum of 8 GeV/c
- High luminosity polarized $^3$He target
- Large area GEM trackers for high rate, high precision tracking



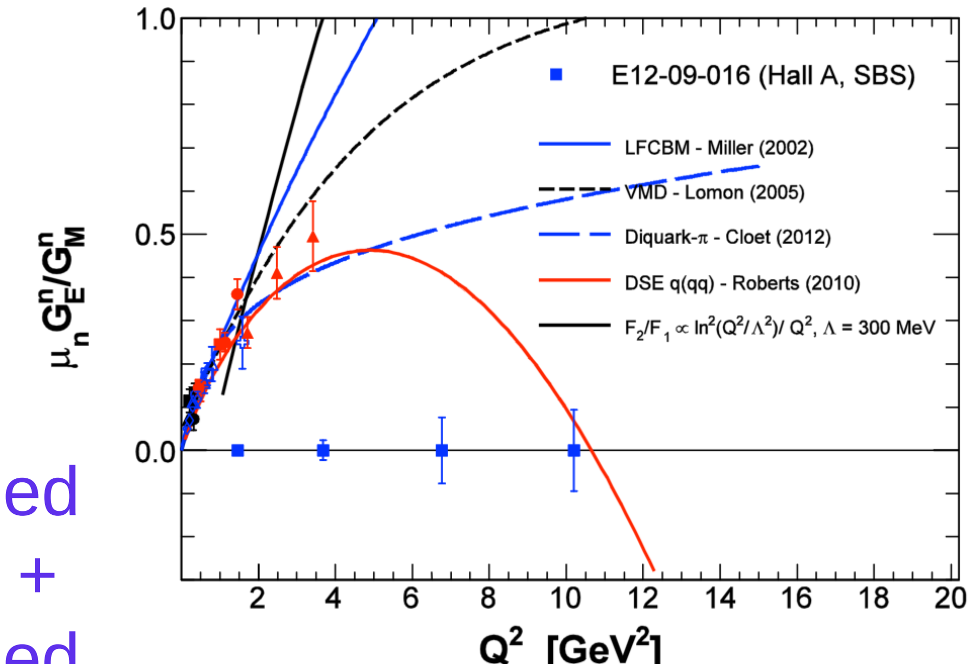
# SuperBigBite Program in JLab Hall A

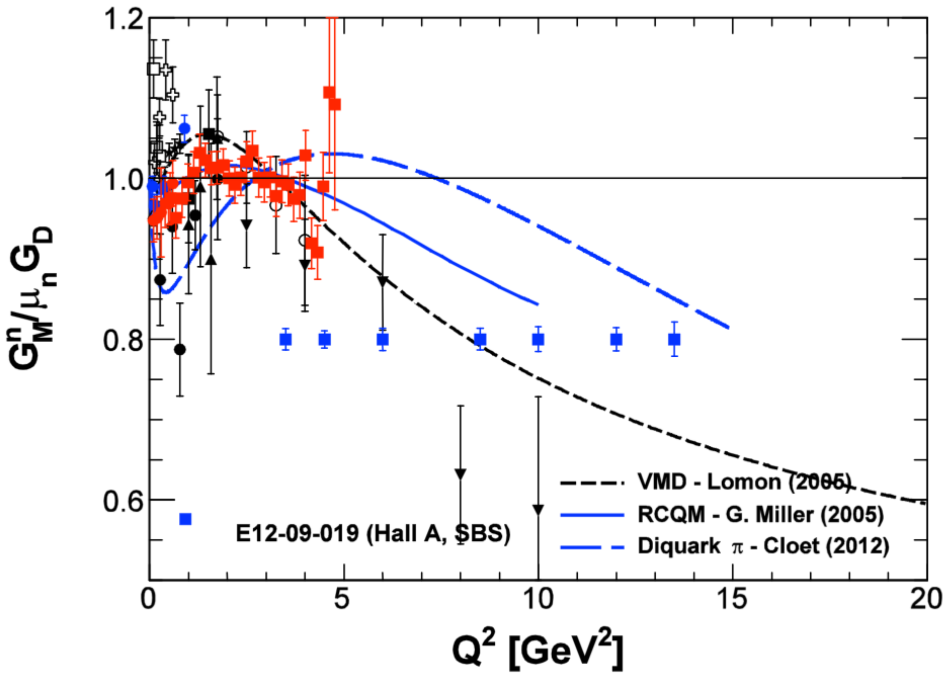
polarization transfer




- All form factors will be completed to $Q^2 = 10$ $GeV^2$ with high precision
- Allows for flavor decomposition and QCD model tests

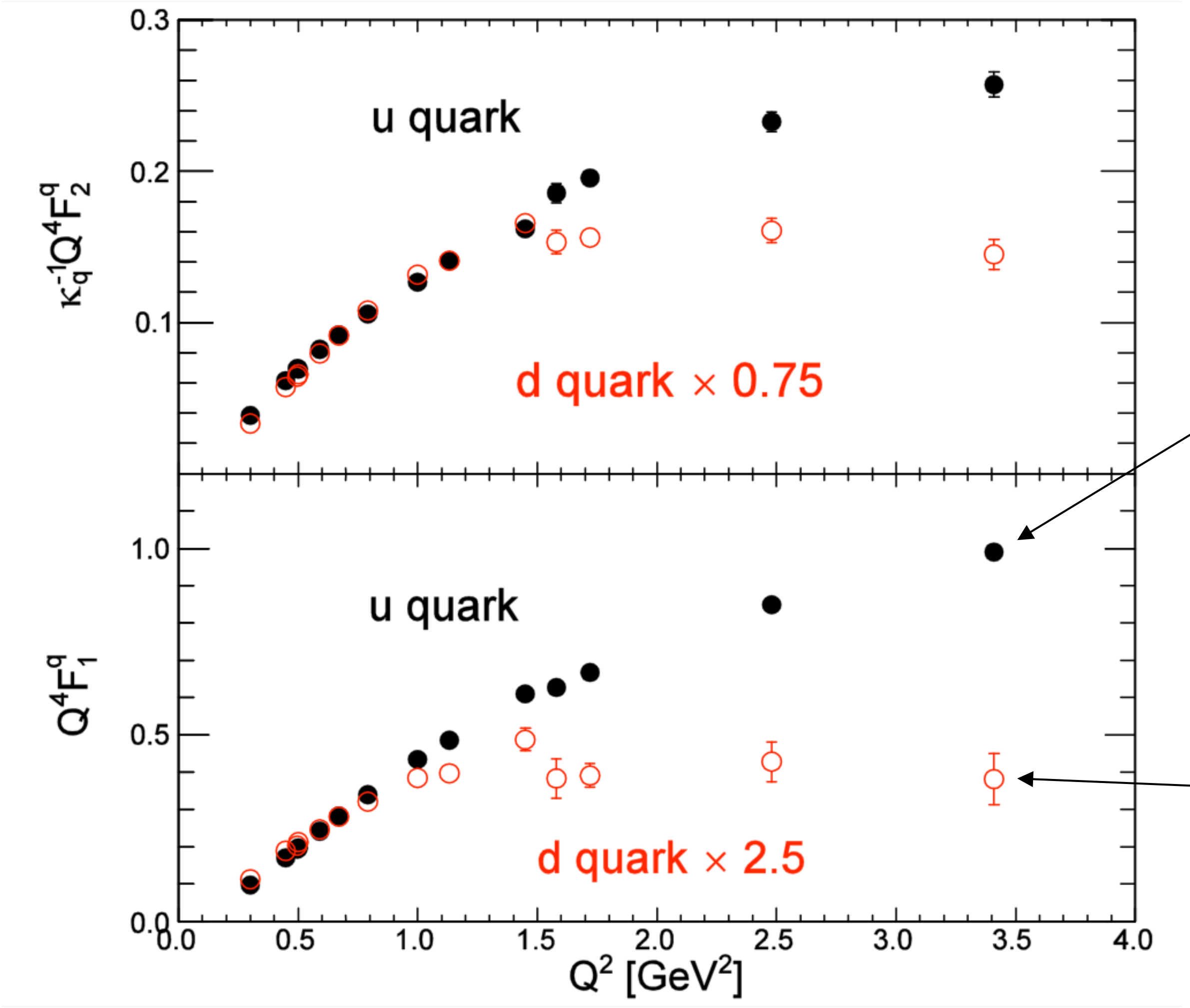
polarized target + polarized beam

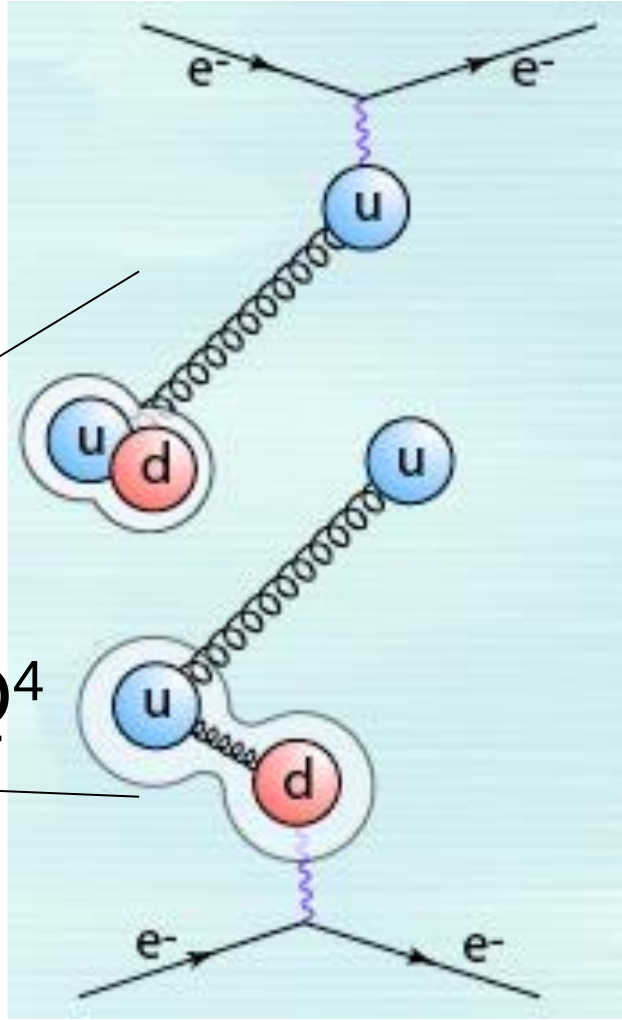



cross section ratio (e,e'n)/(e,e'p) technique

# SuperBigBite Program in JLab Hall A

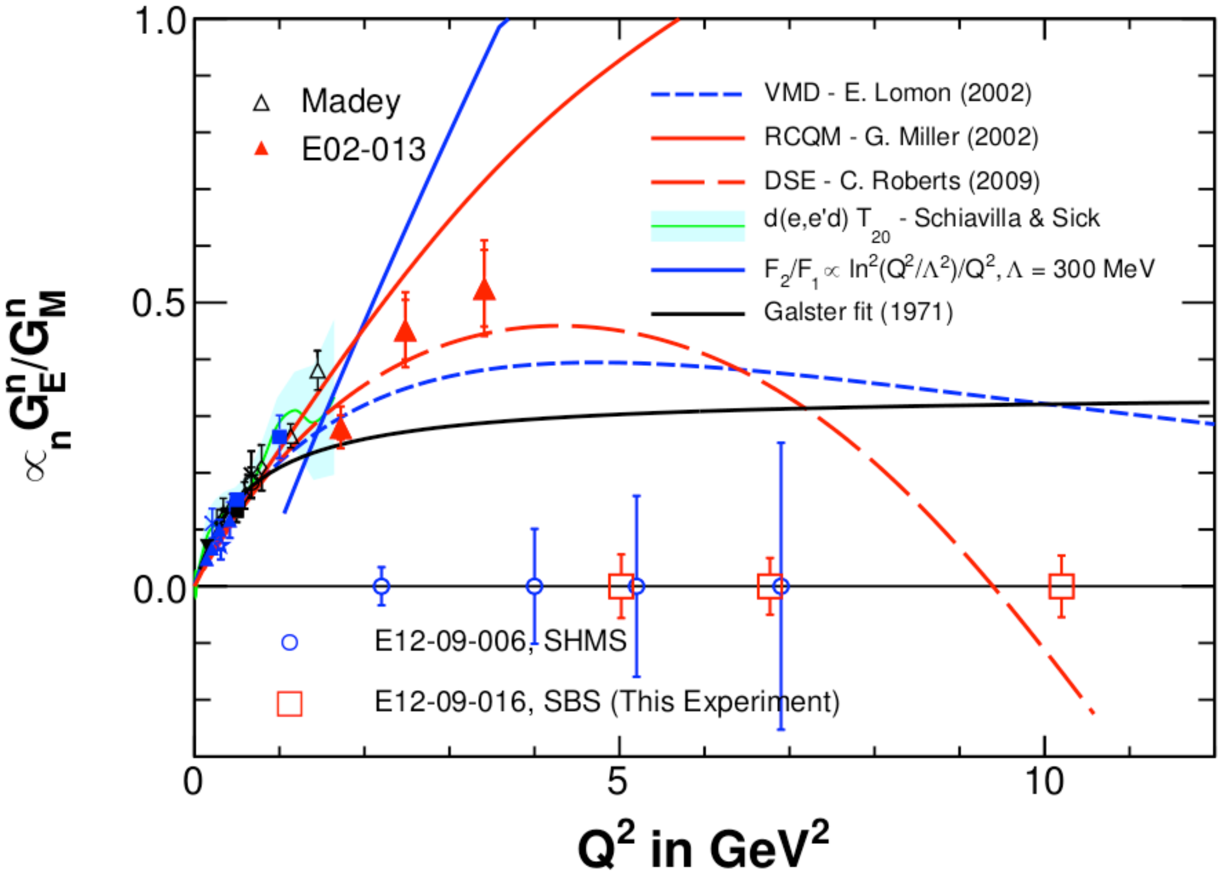



$1/Q^4$

Flavor decomposition of nucleon FFs revealed new features, maybe a high $Q^2$ scaling, a property previously obscured before in combinations

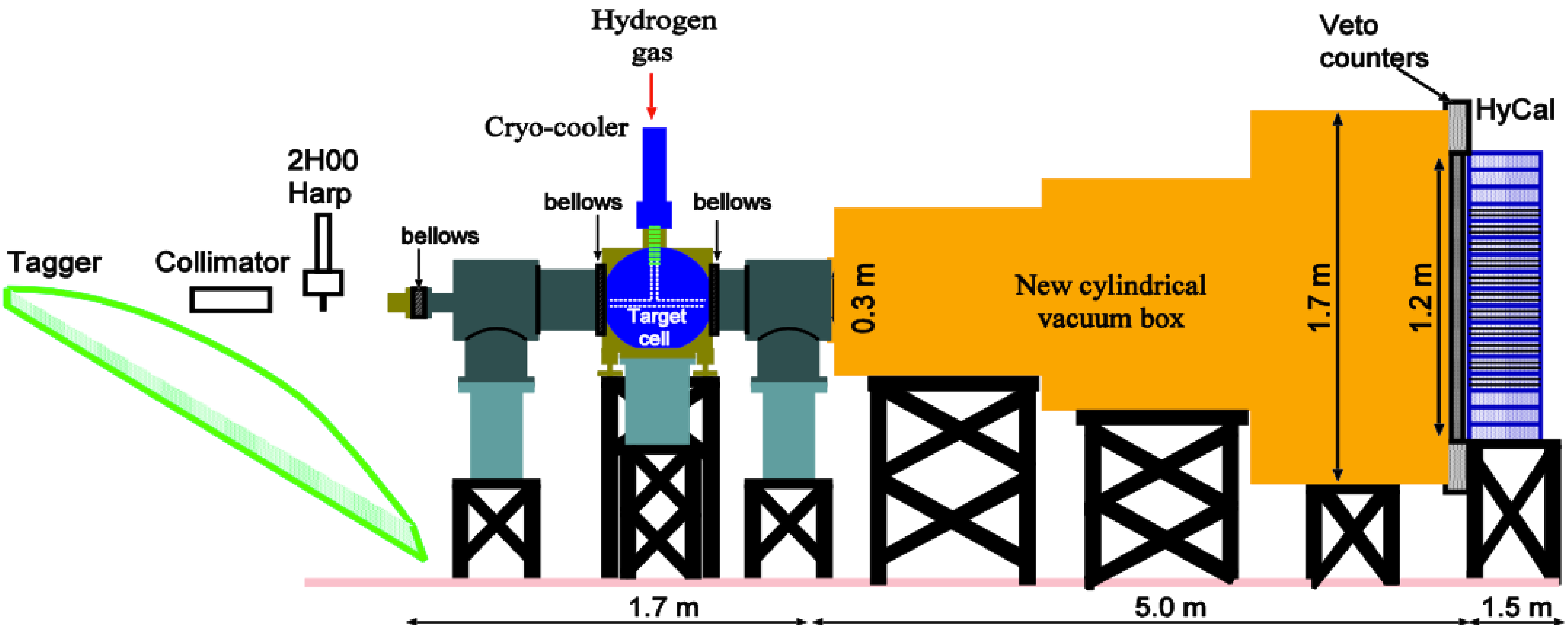
# Neutron Form Factor Ratio




- Wide disparities in predictions of various calculations / extrapolations of various fits
- Will we see $G_E^N$ go negative?
- Experiments use d(e,e'n) polarization transfer with Hall C SHMS and 3He(e,e'n) polarized beam + polarized target with Hall A SBS

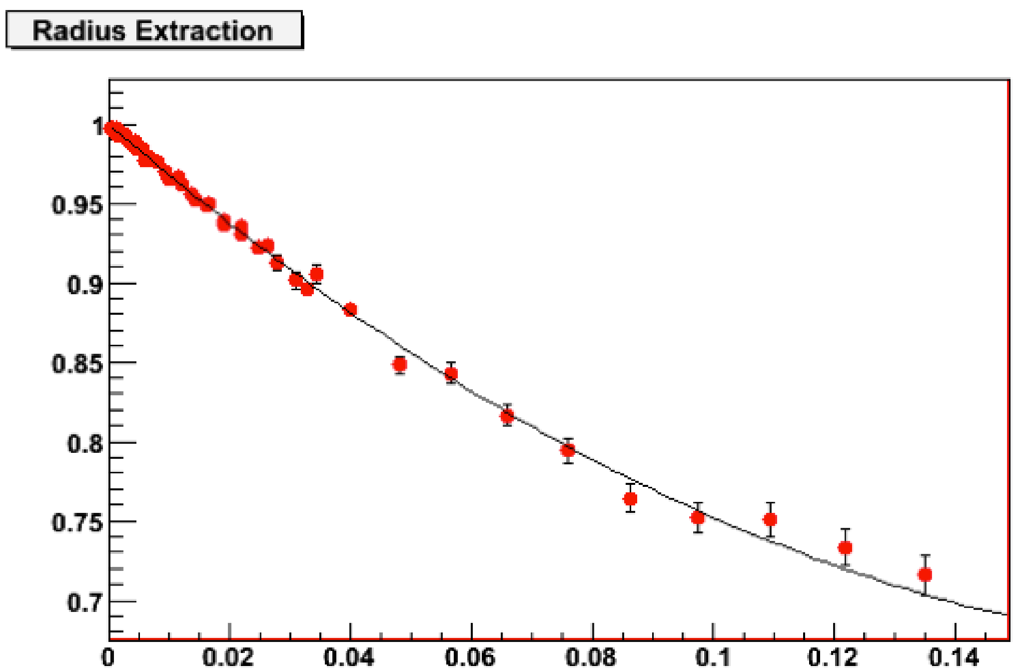
# Low $Q^2$ and Proton Radius

JLab Hall B PRAD:
Gasparian, Dutta, Gao, Khandaker, et al.
Small-angle low $Q^2$ scattering into the PRIMEX calorimeter, cross calibrating ep to Moller scattering.

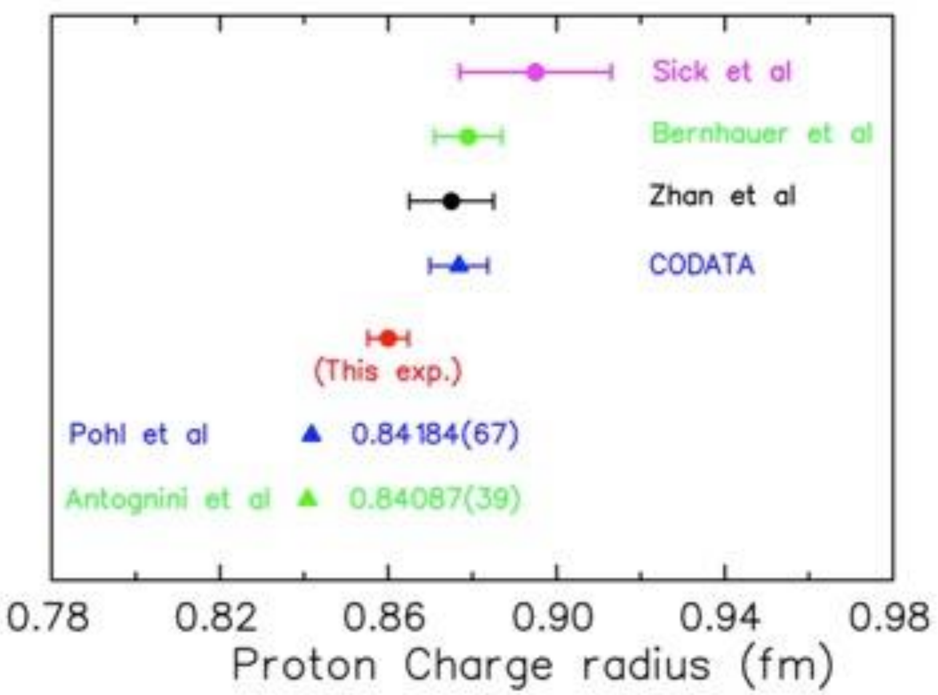


# Low $Q^2$ and Proton Radius

JLab Hall B PRAD:
Gasparian, Dutta, Gao, Khandaker, et al.
Small-angle low $Q^2$ scattering into the PRIMEX calorimeter, cross calibrating ep to Moller scattering.




$G_E$ vs $Q^2$ data simulated, to show radius out = radius in

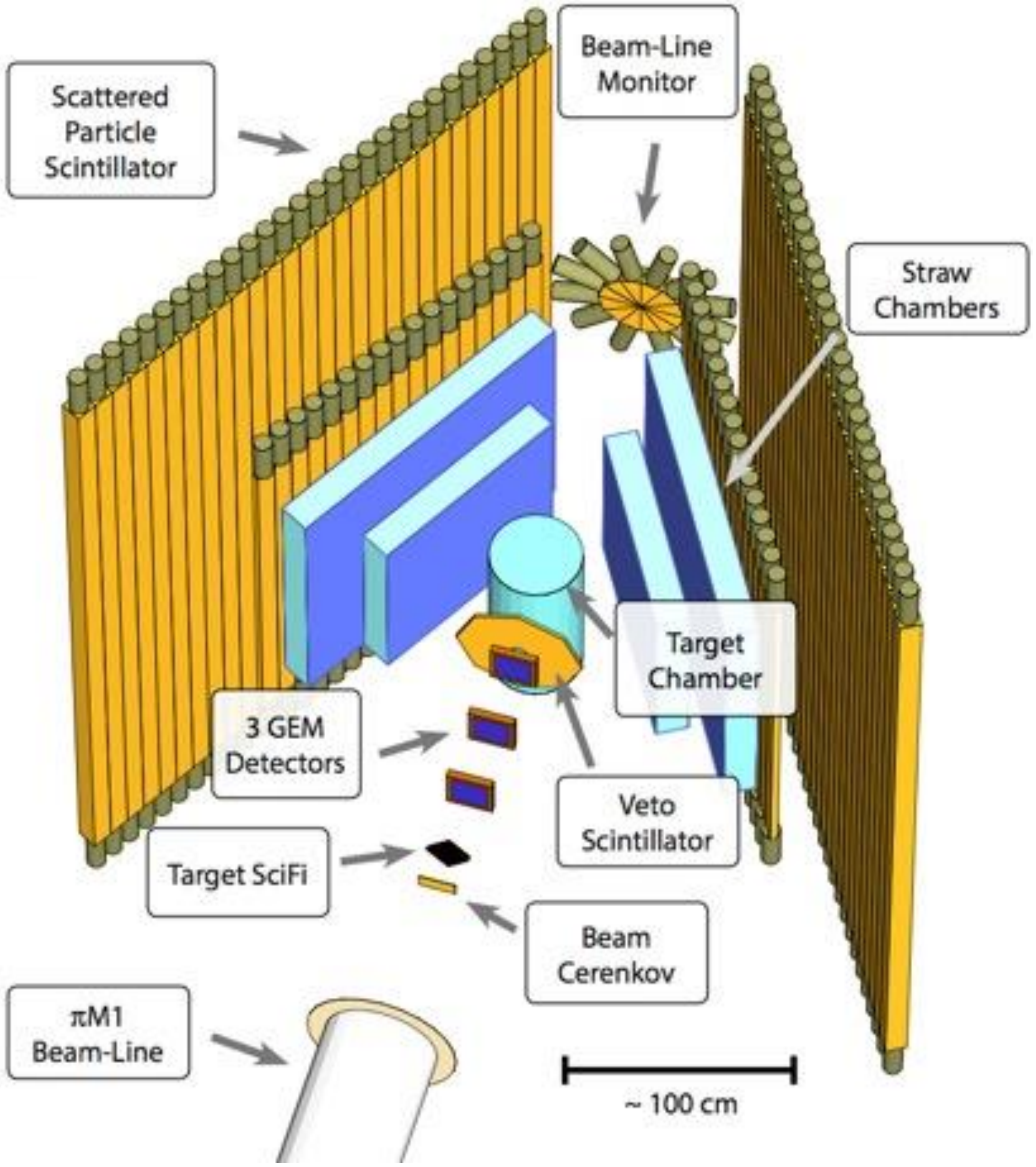



Projected result

# Low $Q^2$ and Proton Radius

PSI MUSE Experiment - at PSI, but largely an American effort:
Gilman, Downie, Ron, et al.

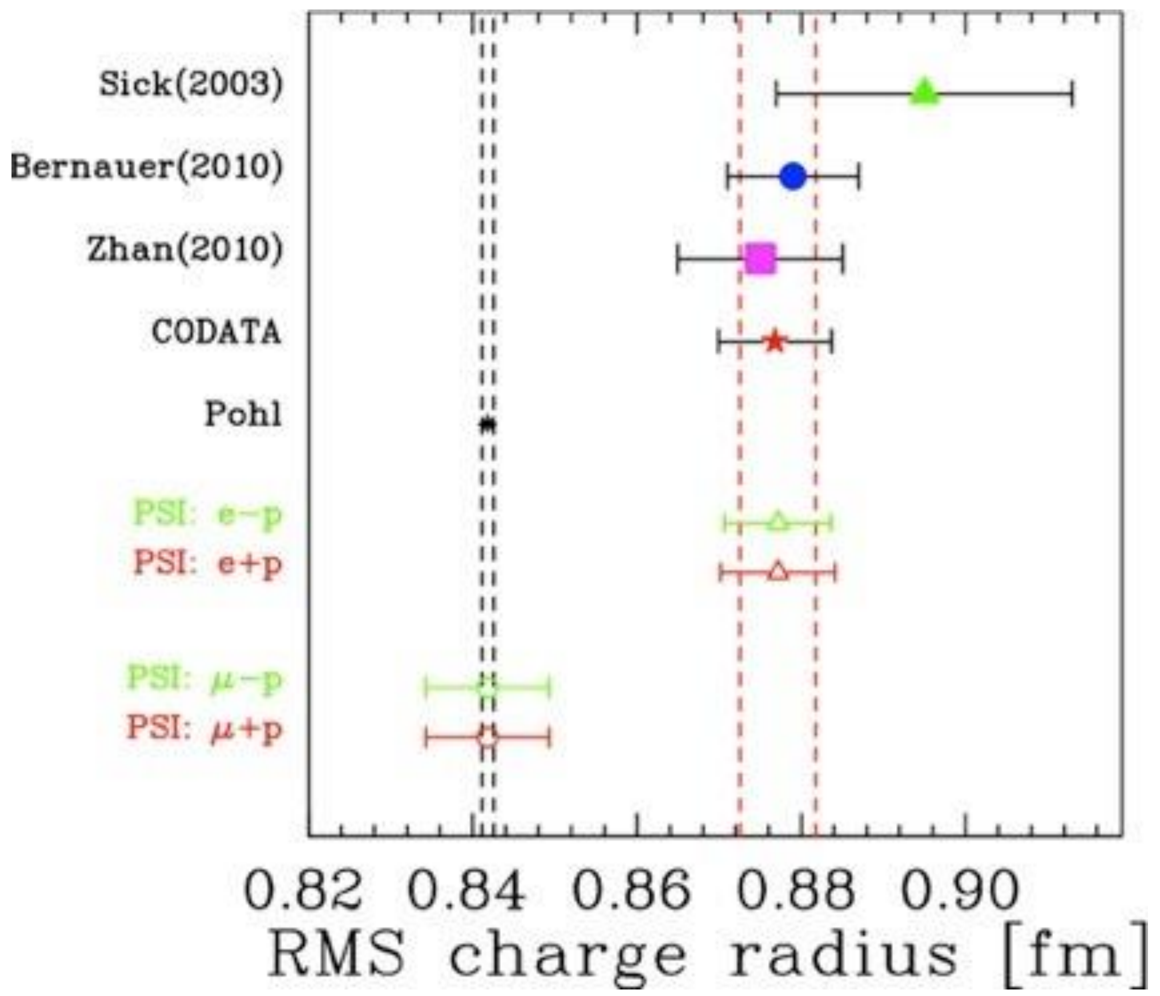
- Mixed low momentum muon+electron beam scattering into large solid angle non-magnetic spectrometer.
- Measure both beam polarities to measure TPE.
- Ongoing tests & simulations
- First dedicated funding by NSF & DOE recently received.



# Low $Q^2$ and Proton Radius

PSI MUSE Experiment - at PSI, but largely an American effort:
Gilman, Downie, Ron, et al.

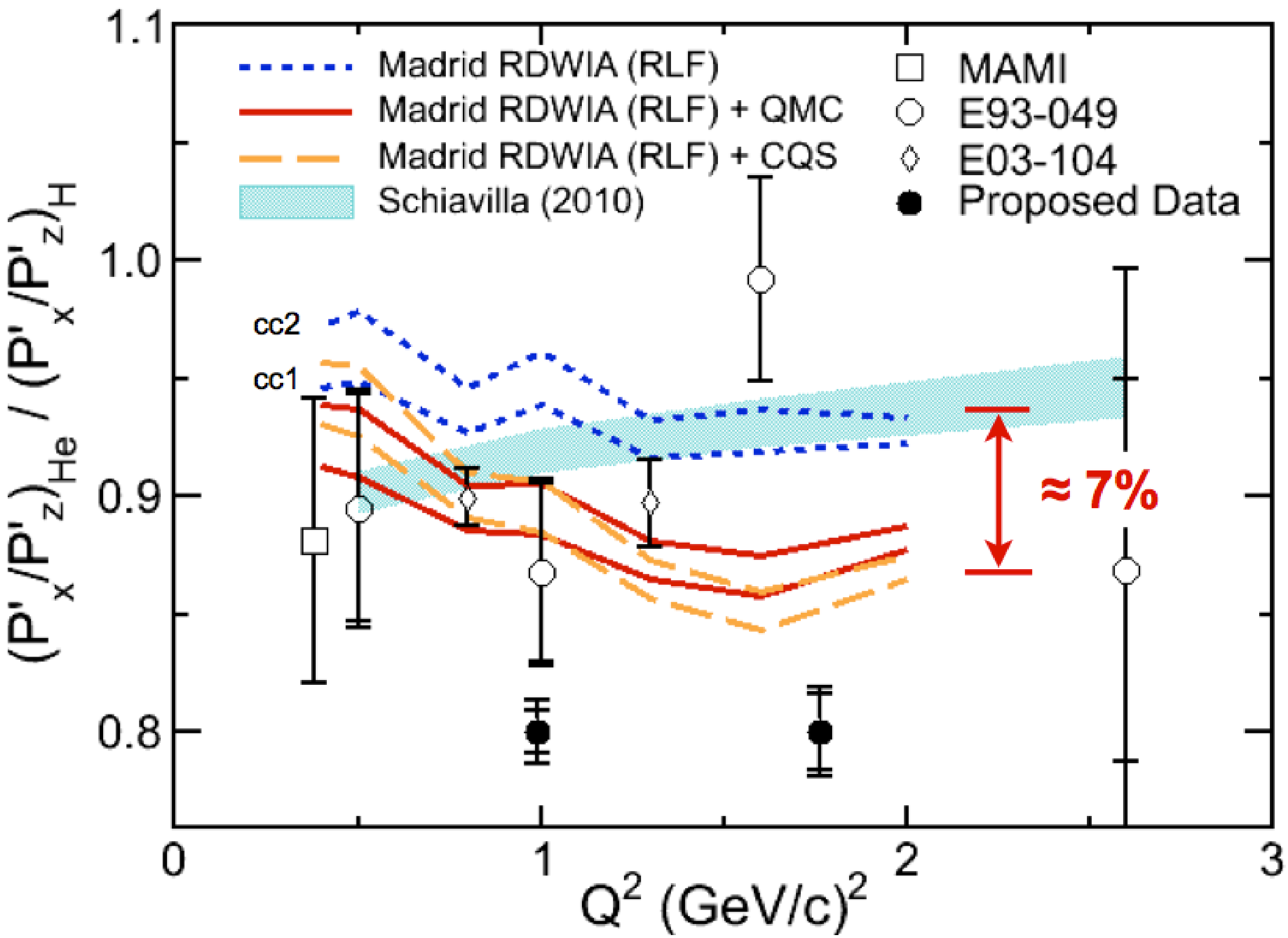
- Mixed low momentum muon+electron beam scattering into large solid angle non-magnetic spectrometer.
- Measure both beam polarities to measure TPE.
- Ongoing tests & simulations
- First dedicated funding by NSF & DOE recently received.




Projected result, using relative uncertainties for muons and electrons

# Do we understand nucleons in nuclei?

No. And at some point it will be a problem for extractions of neutron properties, if we get precise enough.
We can test how well we understand protons in nuclei.

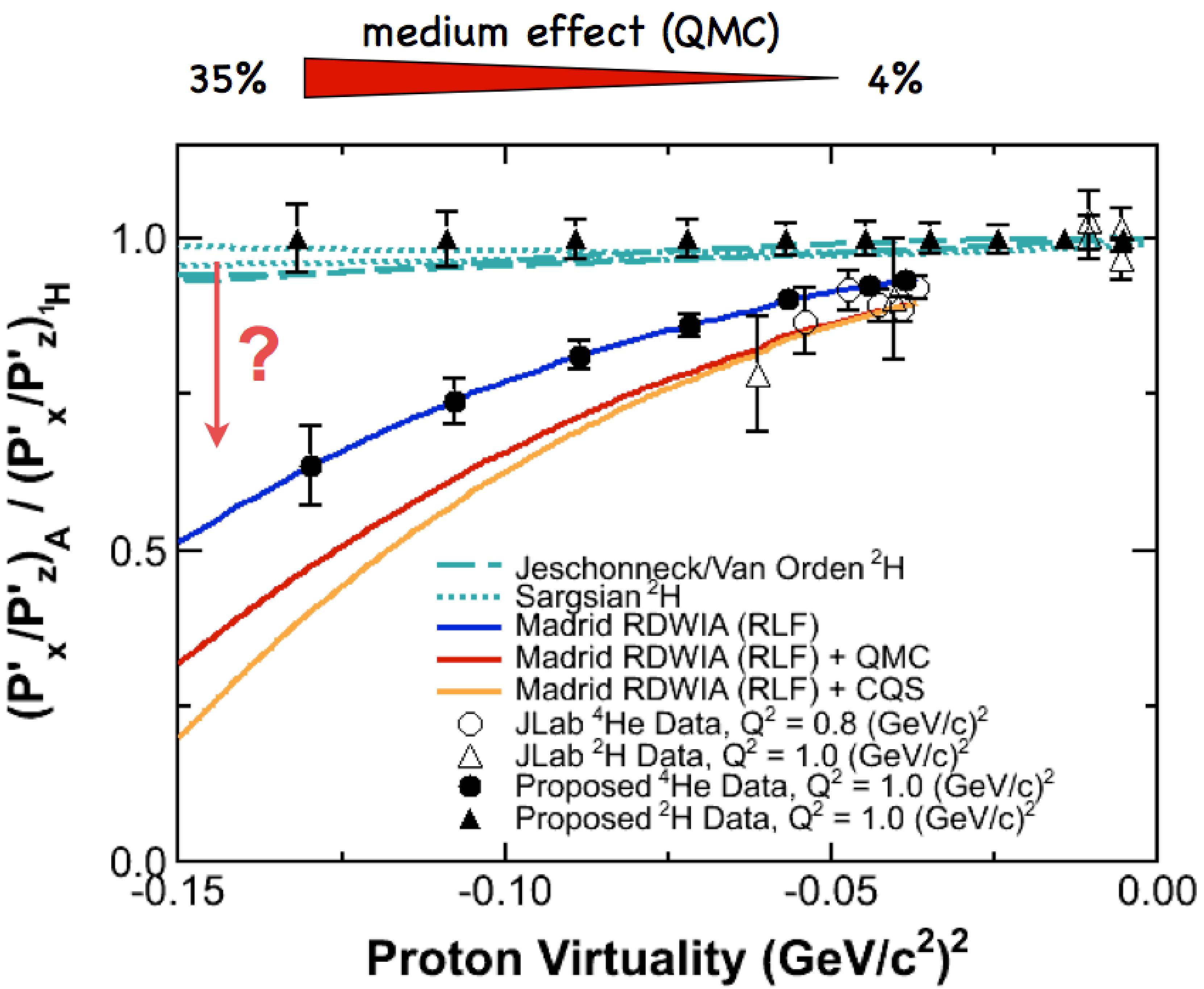



Existing data are consistent with modified in-medium form factor or charge-exchange FSI.

E11-002 tries to improve precision in the higher $Q^2$ region

# Do we understand nucleons in nuclei?

No. And at some point it will be a problem for extractions of neutron properties, if we get precise enough.
We can test how well we understand protons in nuclei.




QCD inspired models suggest large effects and a simple dependence on virtuality absent from conventional nuclear calculations.
Previous d(e,e'p) data show large effect.
Study d and $^4$He for dependence on virtuality.

# Summary

Highlights of past years:

- Radius puzzle?
- High $Q^2$ of $G_E^{P+N}$? Flavor separations?

Both programmatic reasons and compelling issues for form factors.

In the next 5 years we should

- Better understand TPE, but maybe not well enough
- Start to get new JLab high $Q^2$ data on various form factors, but maybe not enough for improved separations
  - Does $G_E^P$ or $G_E^N$ go negative?
  - Do $G_M^{P,N}$ continue to (approximately) follow the dipole?
  - Does $Q^2F_2/F_1$ scaling continue?
- Understand the muon/electron measured proton radii are really the same, or different - but if so we might still not understand why

There is a broad program in nearly all areas. What might be missing?

1) Follow up TPE, contingent on data coming out