Electromagnetic Form Factors of Nucleons

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Rutgers University

Long Range Plan QCD Town Meeting

Temple University, Philadelphia, PA

Sep 13-15, 2014

Plan:

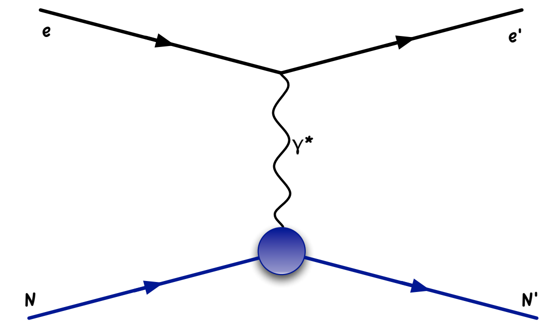
- Why
- 2007 LRP
- What has been learned since 2007 LRP
- The Future

Nucleon Form Factors - formalism & techniques assumed known

Not polarizibilities, nuclear form factors, non-EM nucleon form factors, ...

*Thanks to US NSF grant PHY 12-63280
the organizers (?)
Bogdan, Seamus, Jerry, Evie, Michael, Larry, ...

Why Form Factors?



- Fundamental properties of nucleons, so of general interest
  - Charge & magnetization distributions
  - Test theoretical models / QCD inspired calculations
  - Input to calculations and experiments in nuclear structure, atomic physics, nucleons in nuclei
- Dramatic improvements in our understanding from 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)
- A number of ongoing issues
  - High Q^2 behavior - the main thrust of the JLab 12 GeV FF program - and flavor separations
  - Radiative corrections
  - Low Q^2 behavior - the proton charge (and magnetic) radius
  - …

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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.

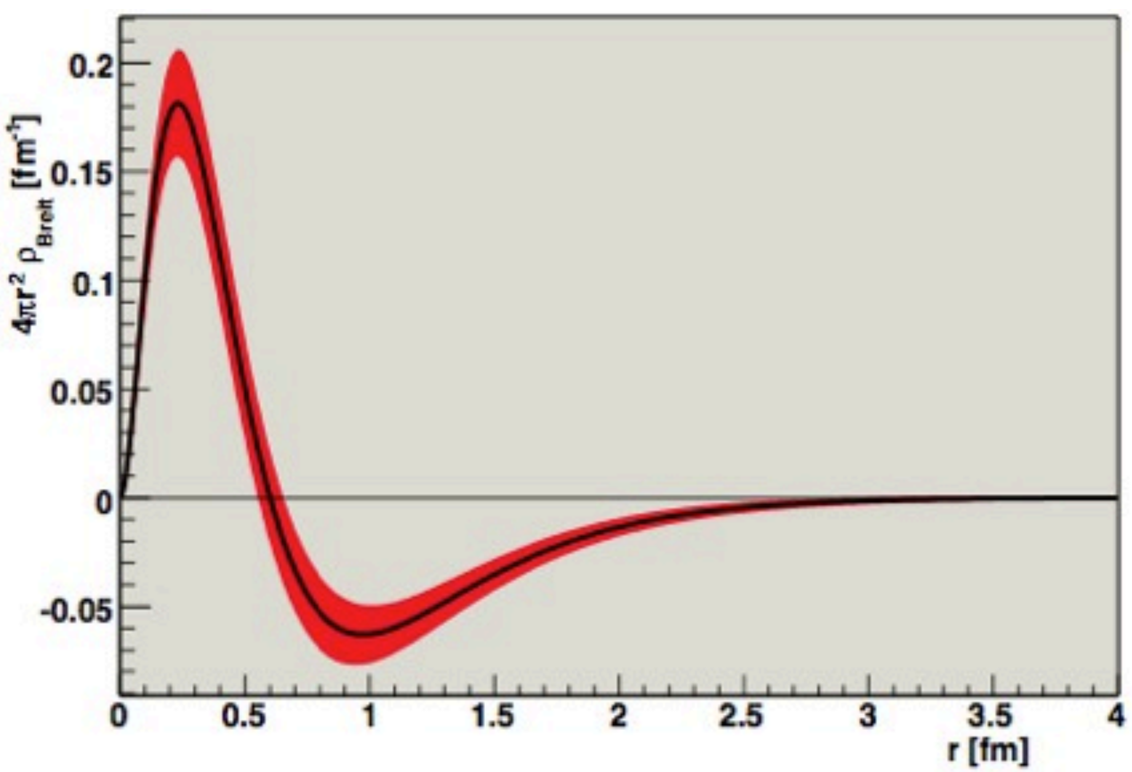
We all know how that worked out.

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, ...

From the 2007 LRP - 1 of 3

- Recent Achievements on page 16
  - "**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."



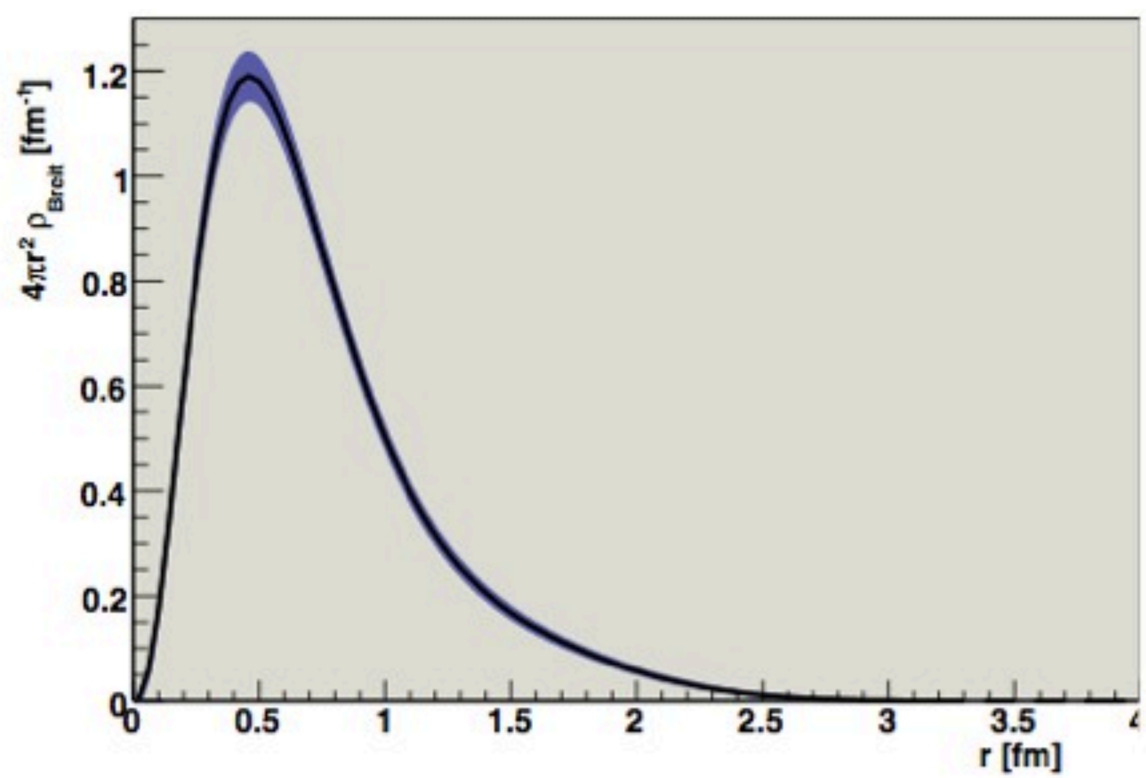


Figure from 2007 LRP, page 26

From the 2007 LRP - 2 of 3

- Recent Achievements on page 16
  - "**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 ..."

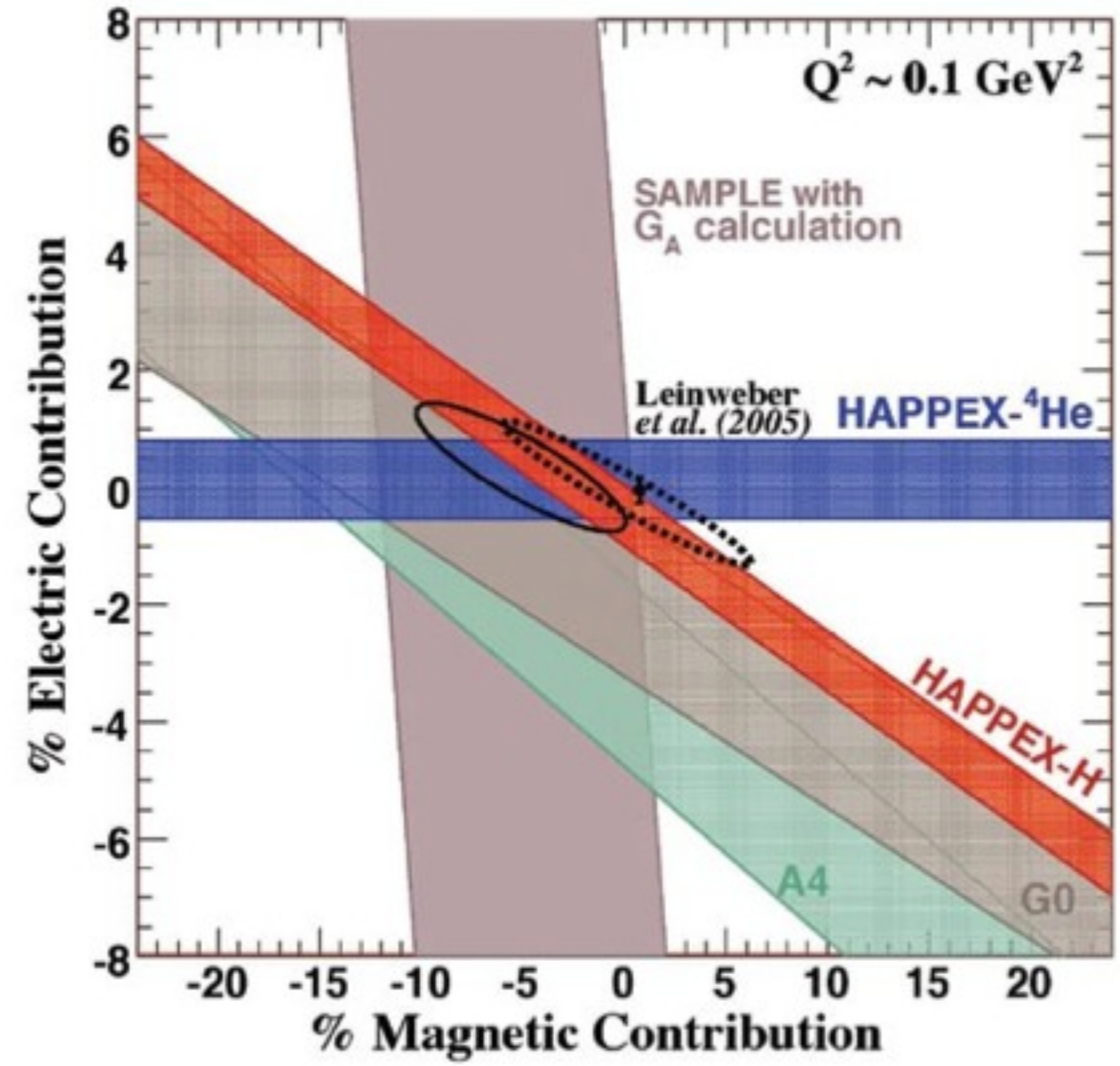


Figure from 2007 LRP, page 27

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From the 2007 LRP - 3 of 3
FF 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."

Now... what actually happened and was learned?

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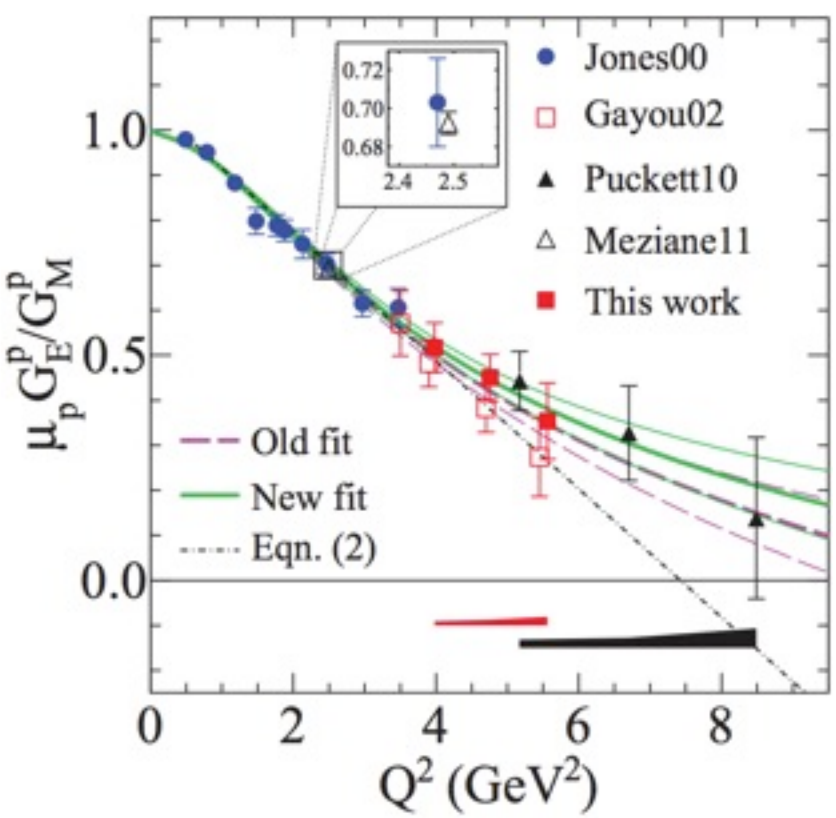
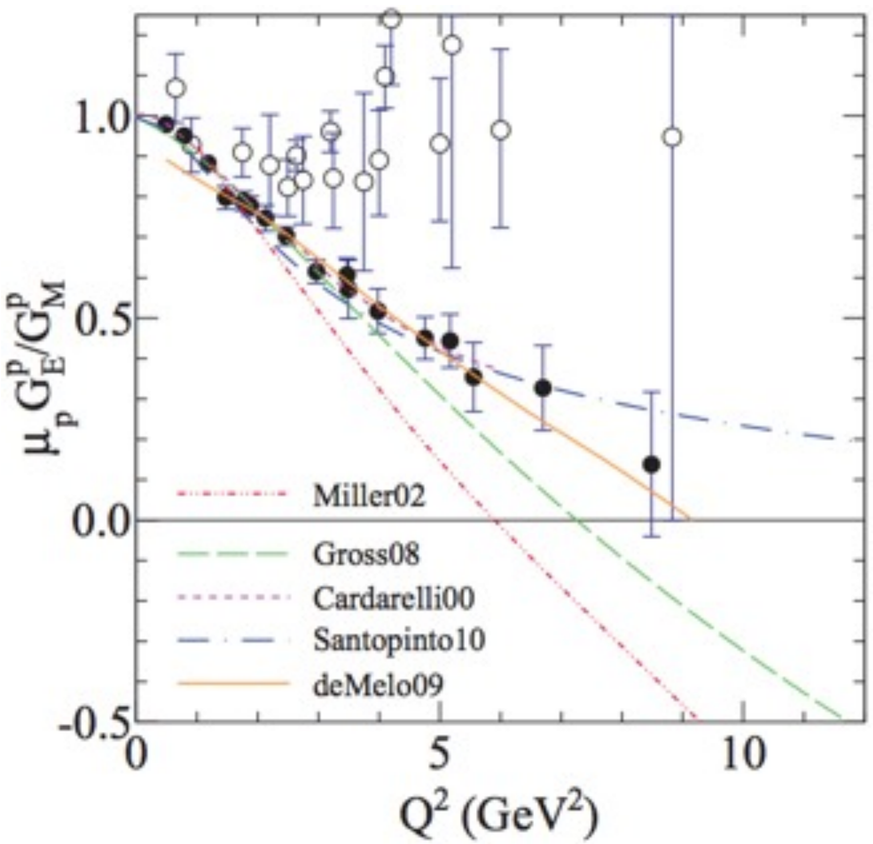
Since the 2007 LRP: What has been learned?

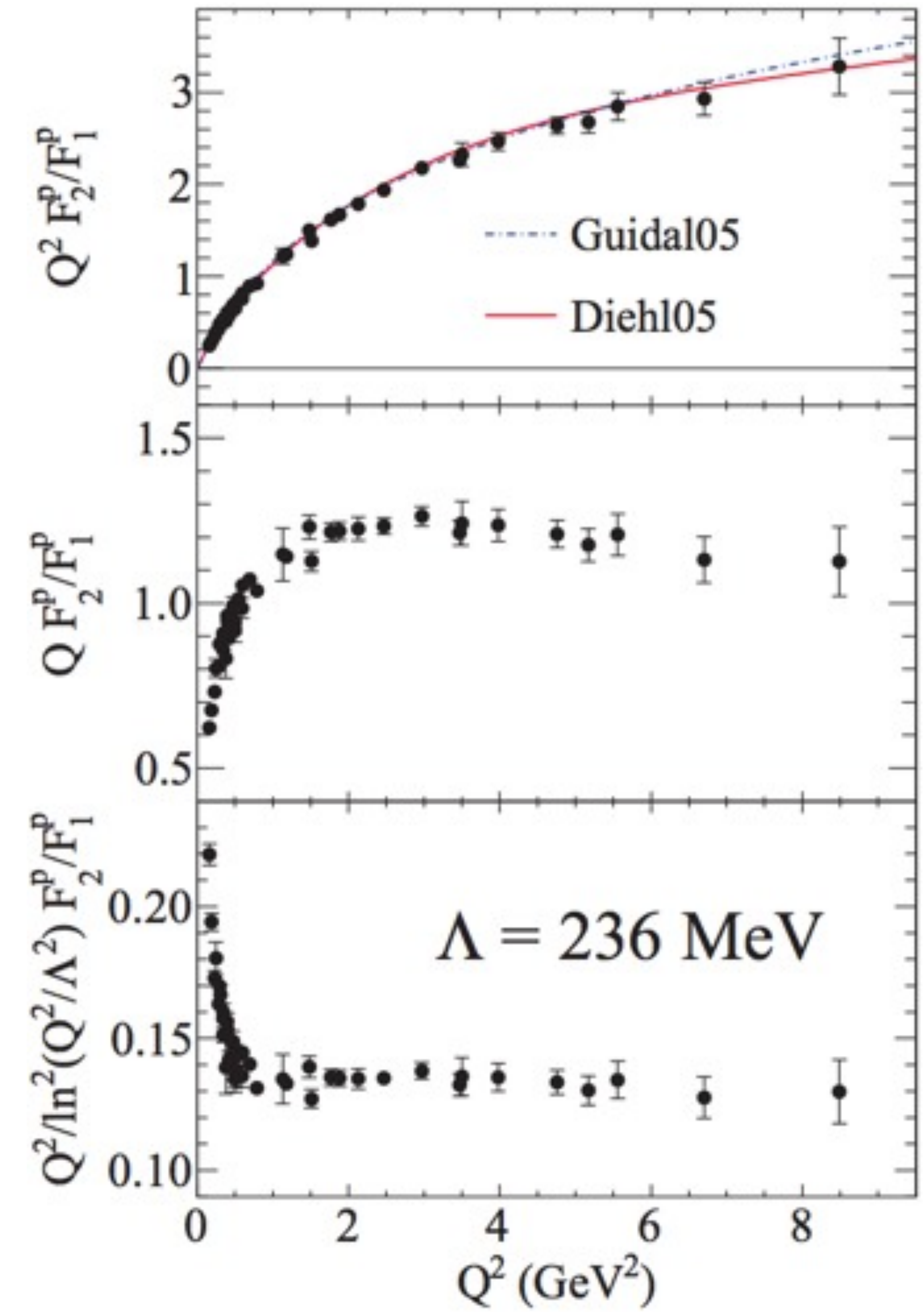
Proton at high Q^2

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







Form factor ratio data compared to relativistic CQM calculations

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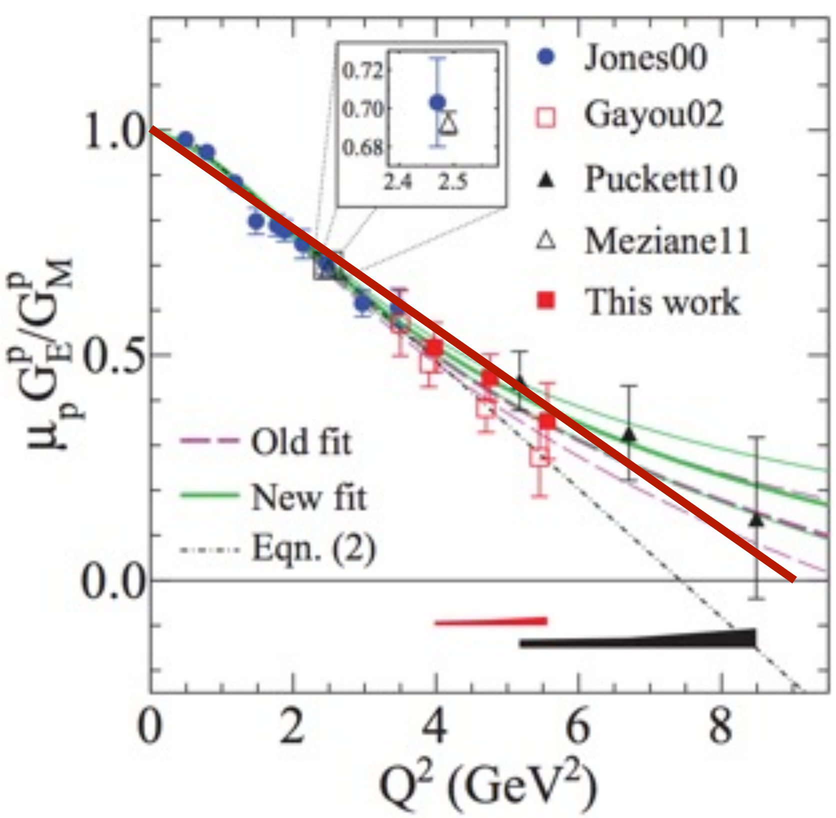
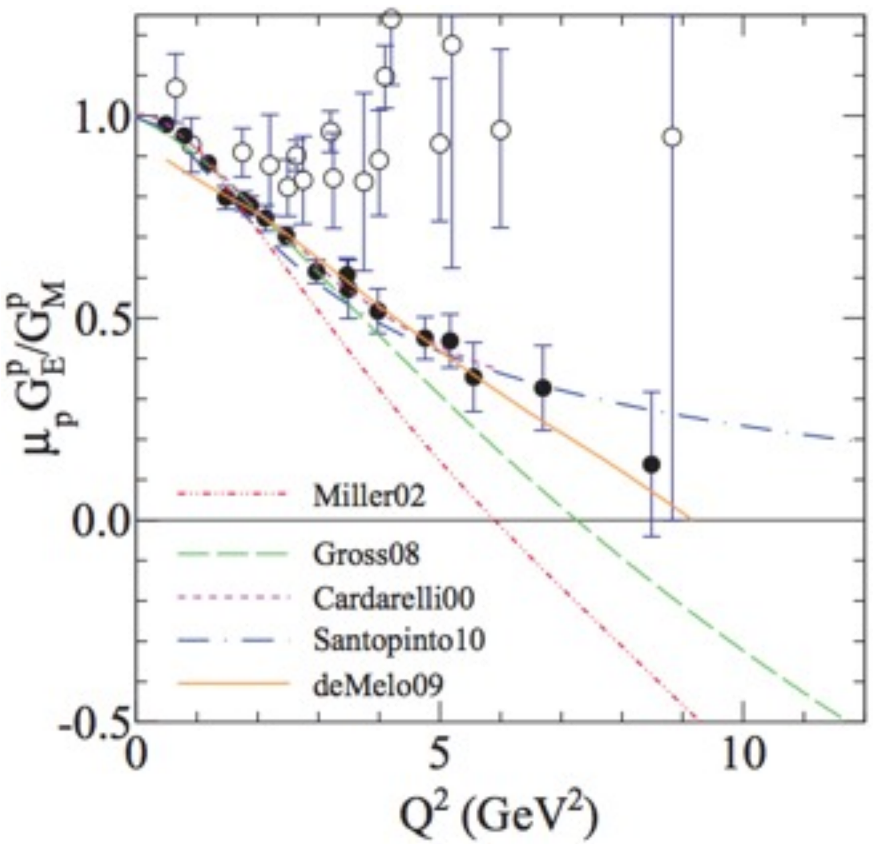


Linear fit remains not terrible



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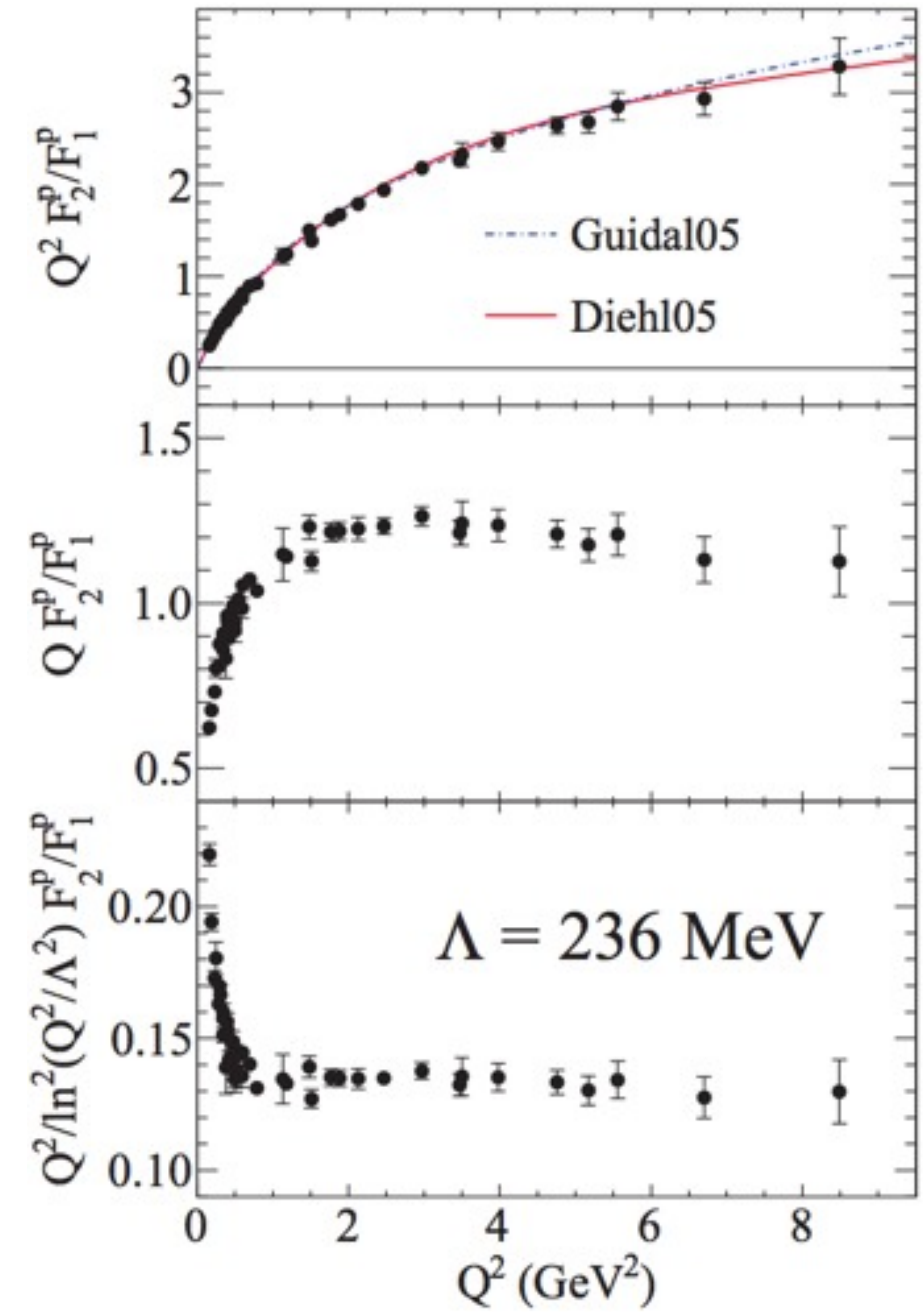

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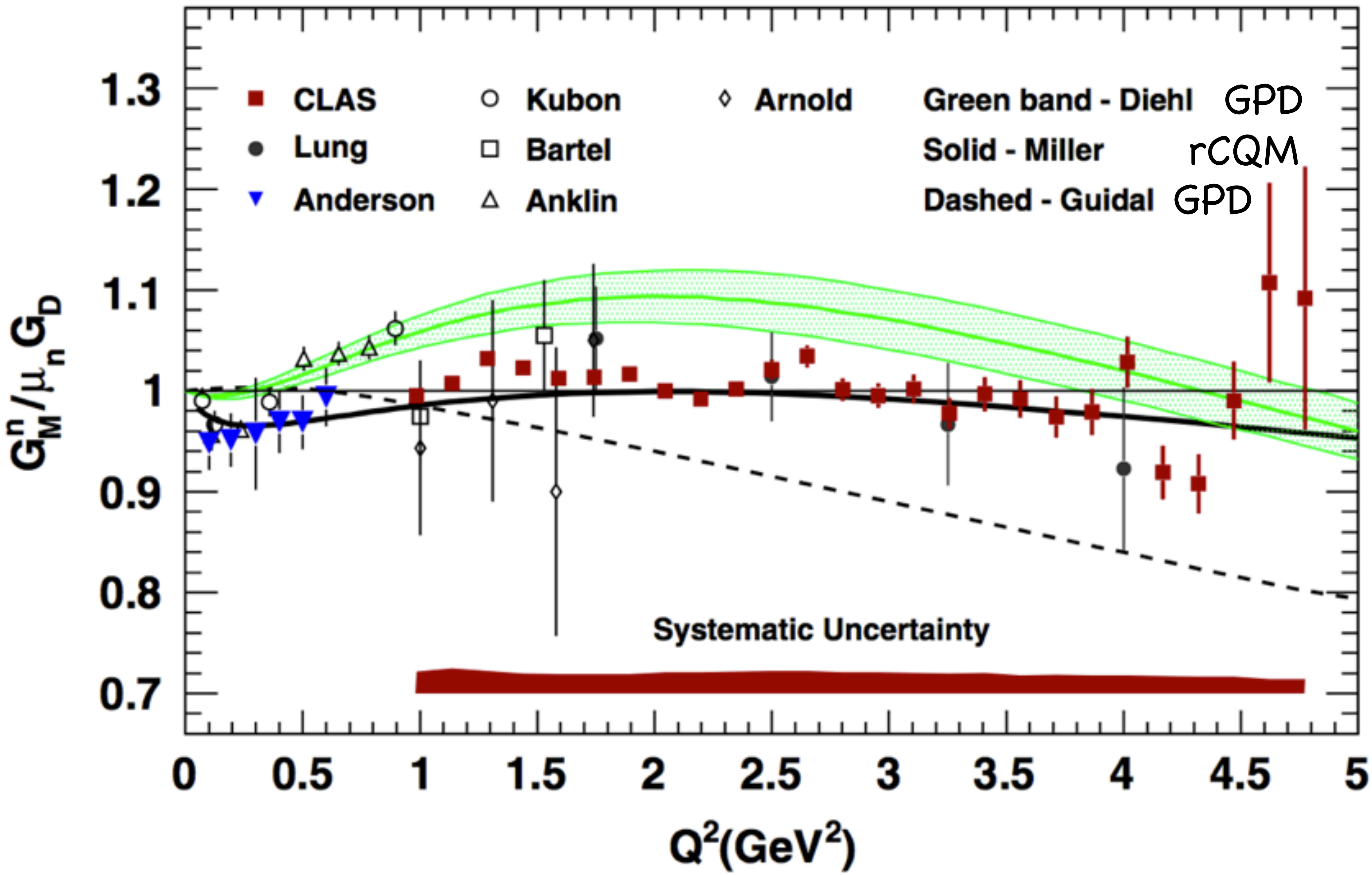
Since the 2007 LRP: What has been learned?

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

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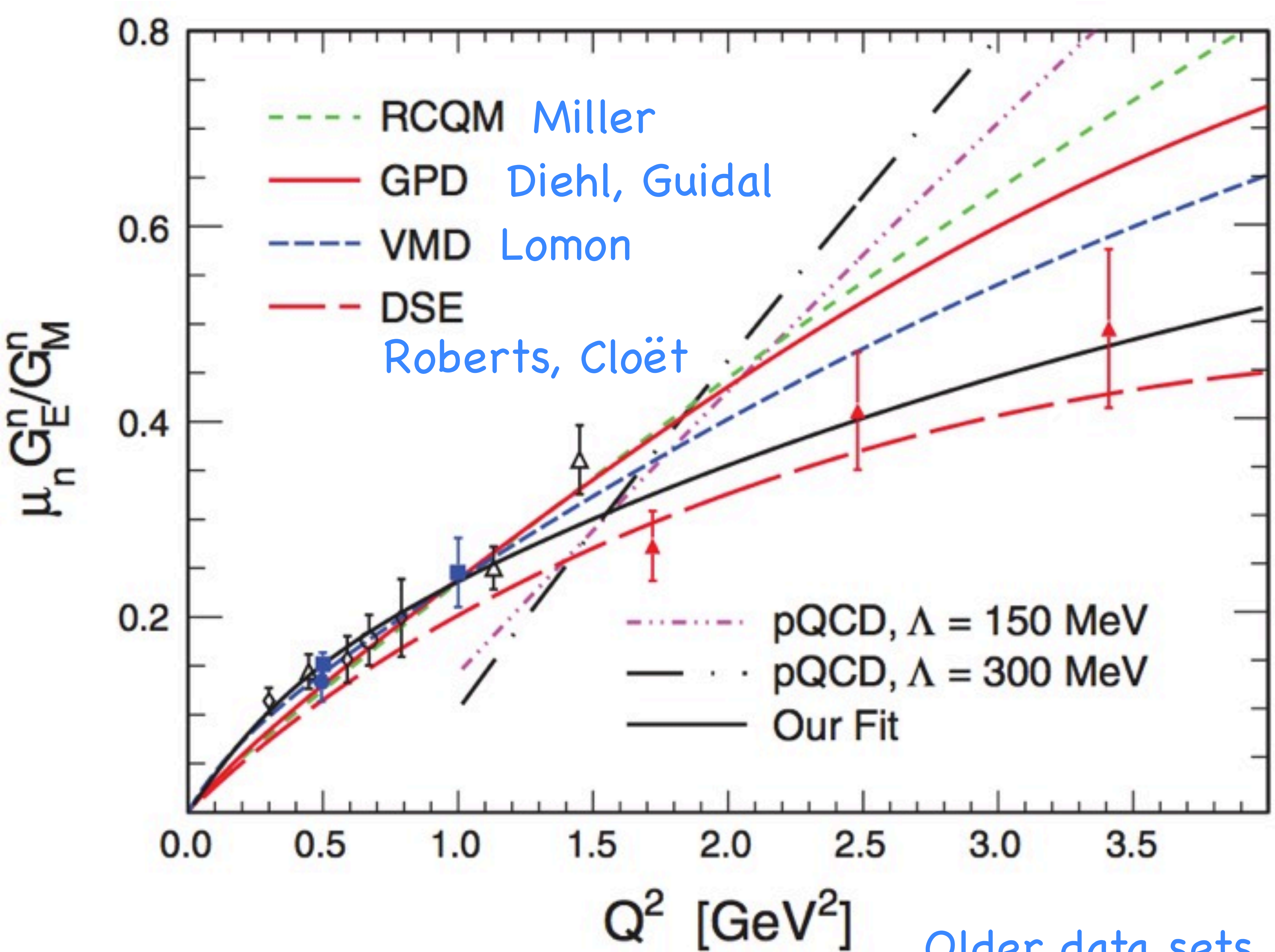
Since the 2007 LRP: What has been learned?

Neutron G_E



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

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

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Alternatives to $G_{E,M}^{P,N}$

Why? Different combinations might make physics clearer.

G_E^p, G_M^p, G_E^n, G_M^n

F_1^p, F_2^p, F_1^n, F_2^n

G_E^{IS}, G_M^{IS}, G_E^{IV}, G_M^{IV}

F_1^{IS}, F_2^{IS}, F_1^{IV}, F_2^{IV}

If only u and d quarks contribute, and $u^P = d^N$, $u^N = d^P$

G_E^u, G_M^u, G_E^d, G_M^d

F_1^u, F_2^u, F_1^d, F_2^d

With additional PV measurements...

G_E^u, G_M^u, G_E^d, G_M^d, G_E^s, G_M^s

F_1^u, F_2^u, F_1^d, F_2^d, F_1^s, F_2^s

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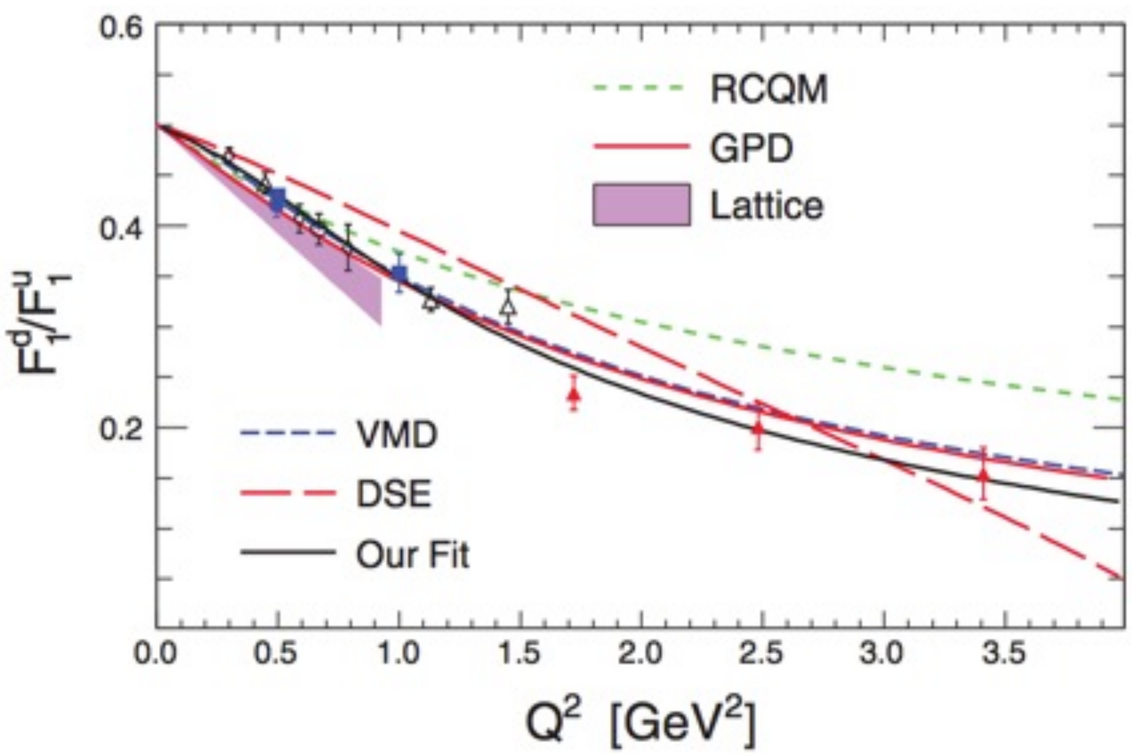
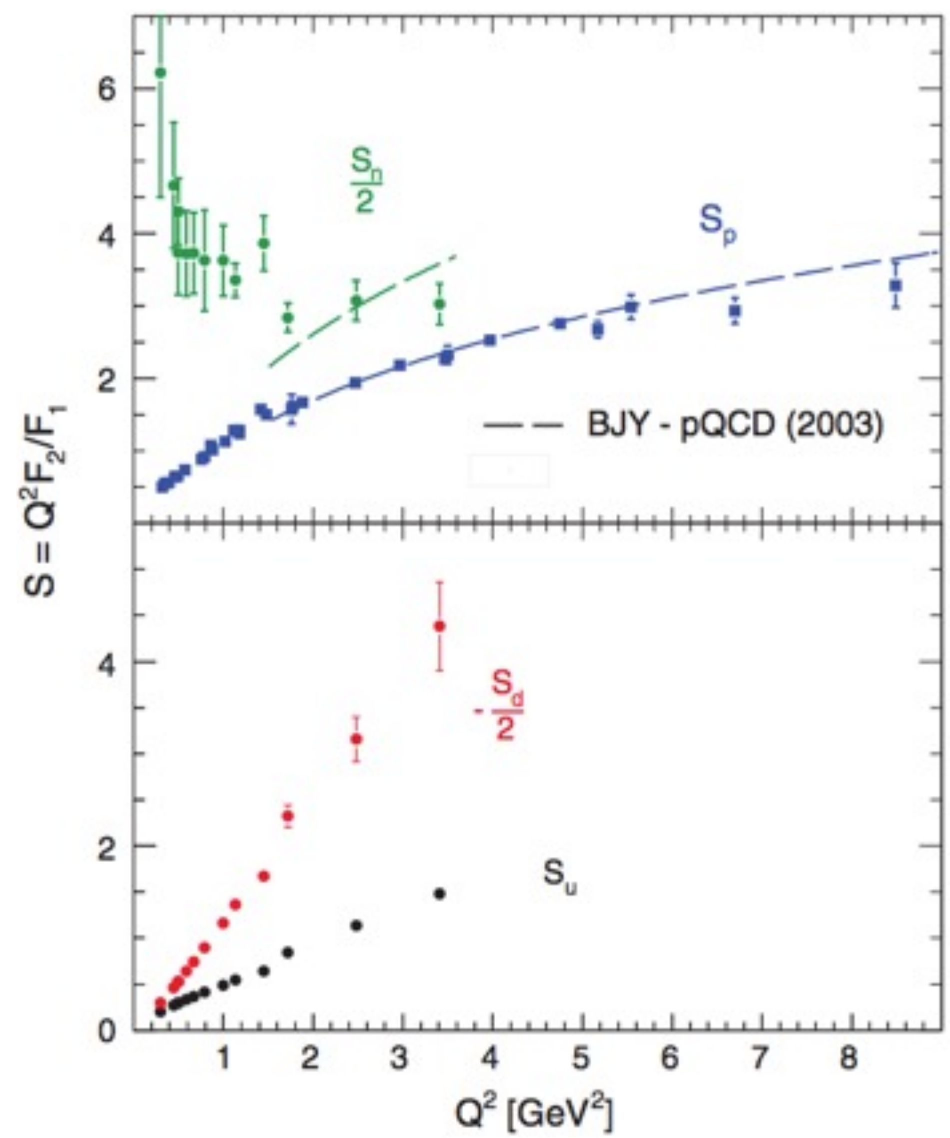
Since the 2007 LRP: What has been learned?

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 – ^{3}He

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

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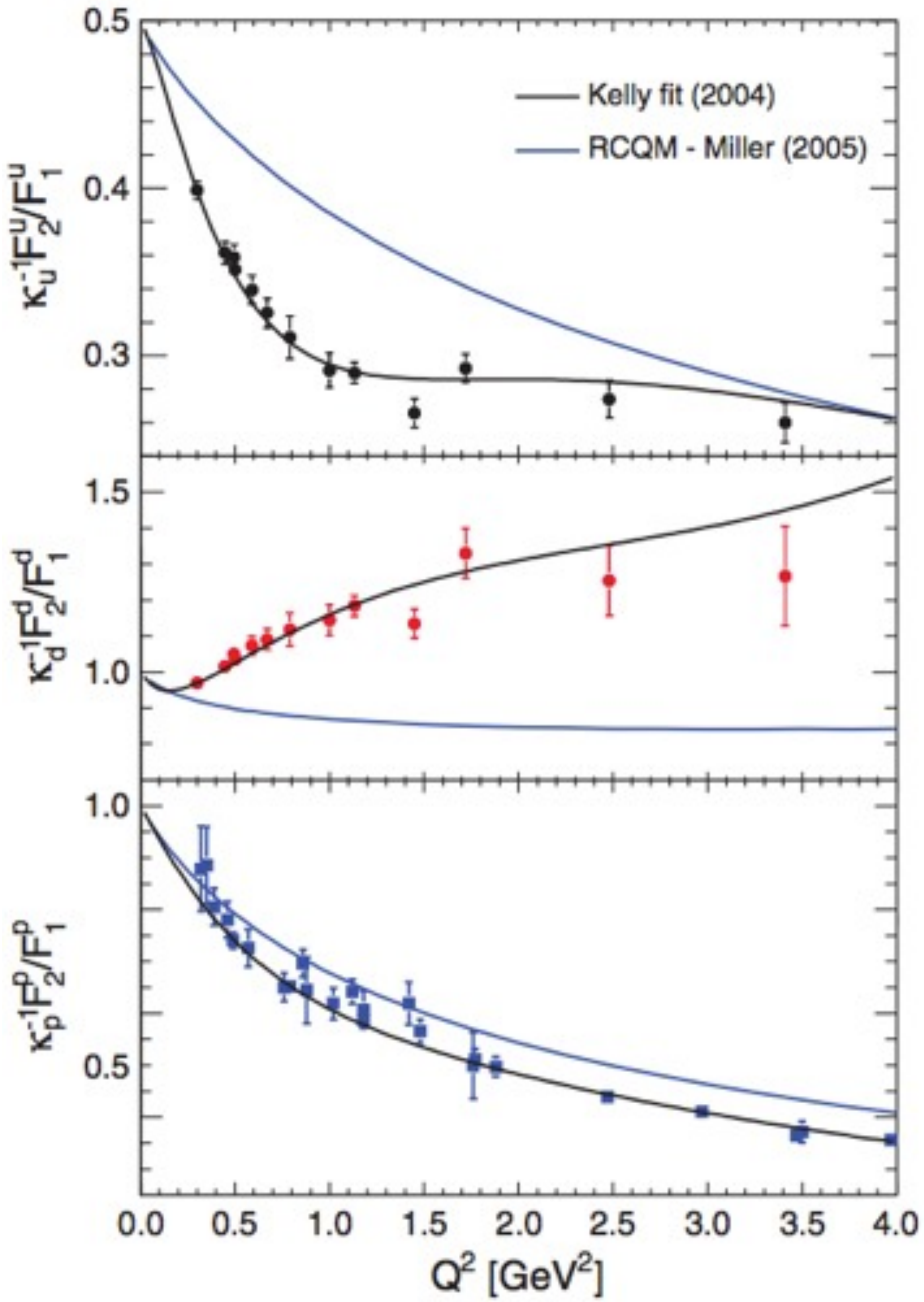

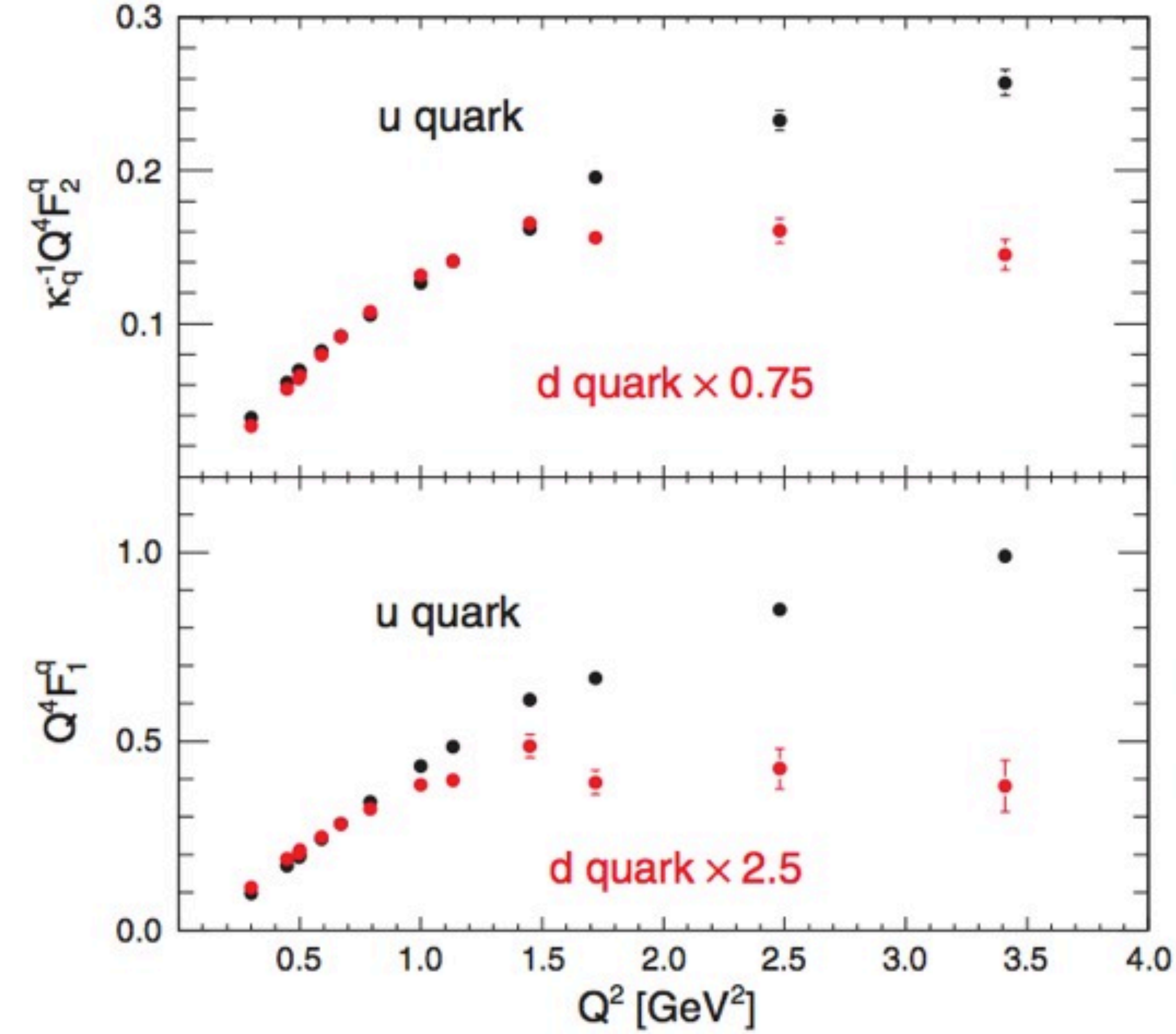

rCQM gets individual flavors wrong, but the ratio about right

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

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

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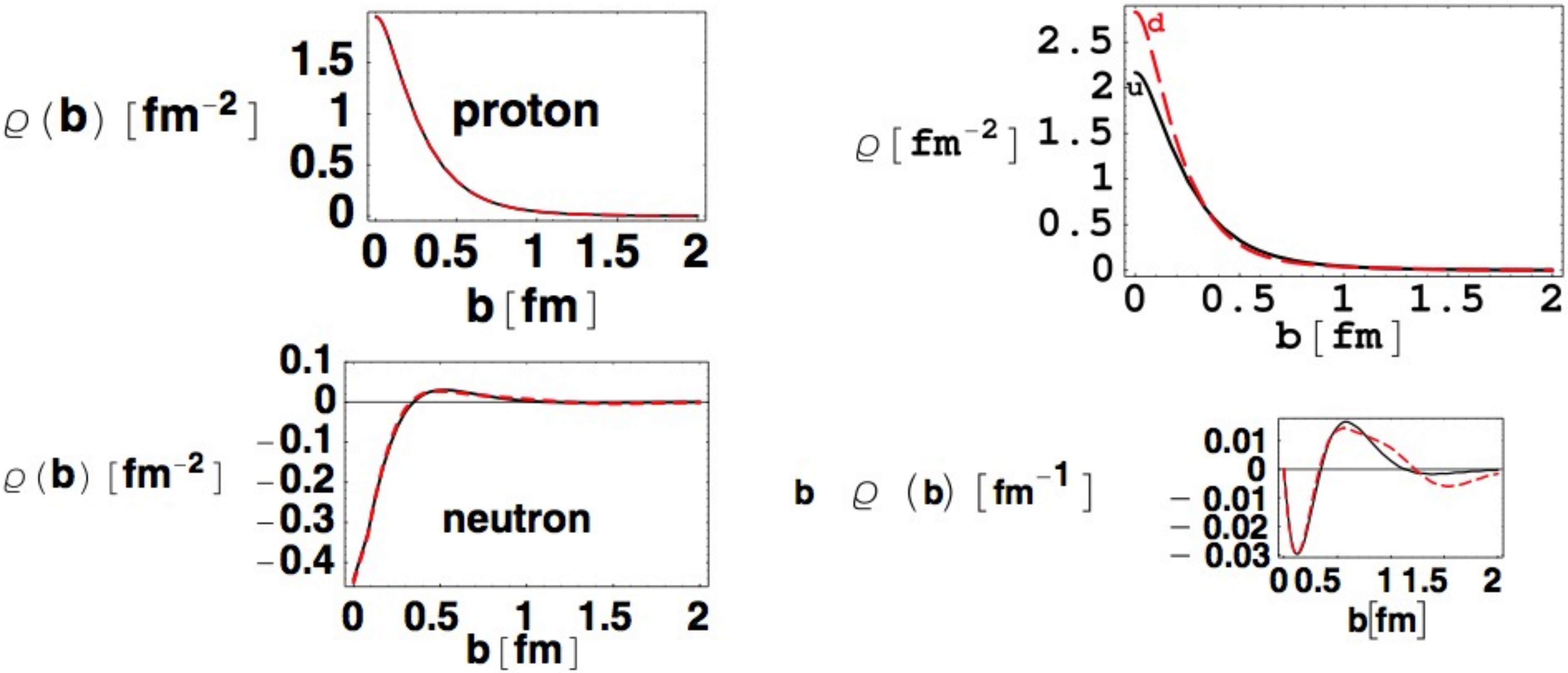
Since the 2007 LRP: What has been learned?

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).

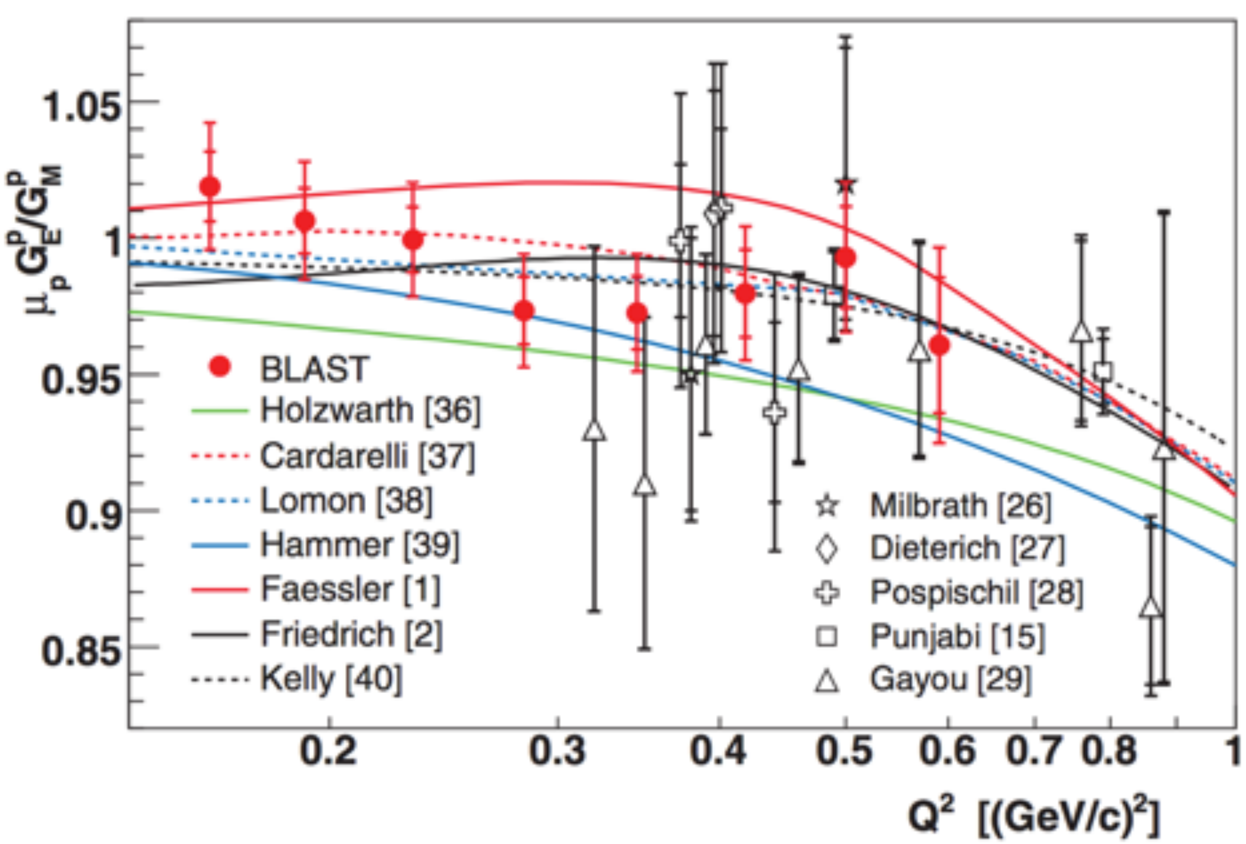
Should this bother us?

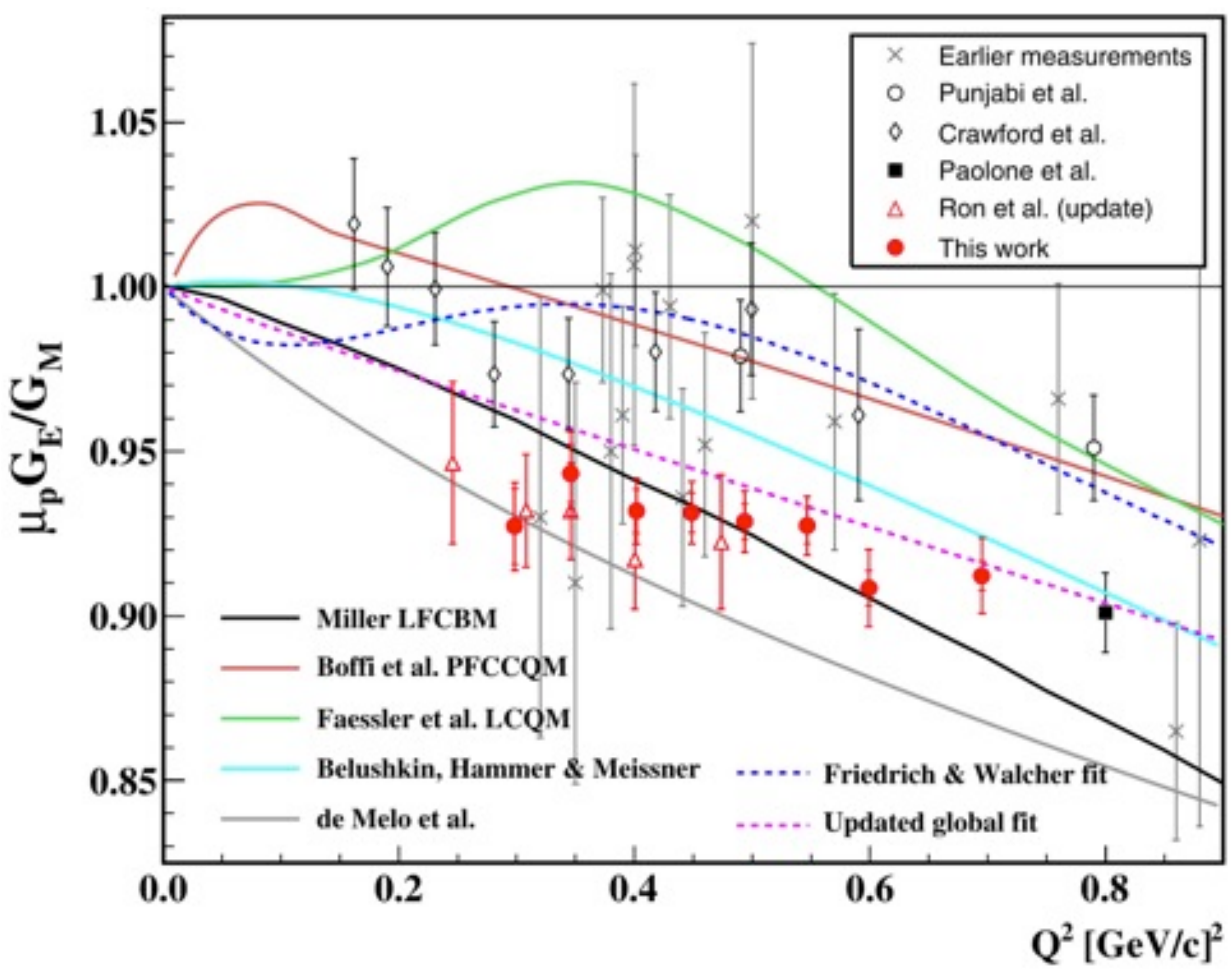
Probably not, but if G_E^N goes negative enough soon enough, the Breit frame distribution will go negative at the origin.

Miller PRL 99 (2007)

Since the 2007 LRP: What has been learned?

Proton at low Q^2



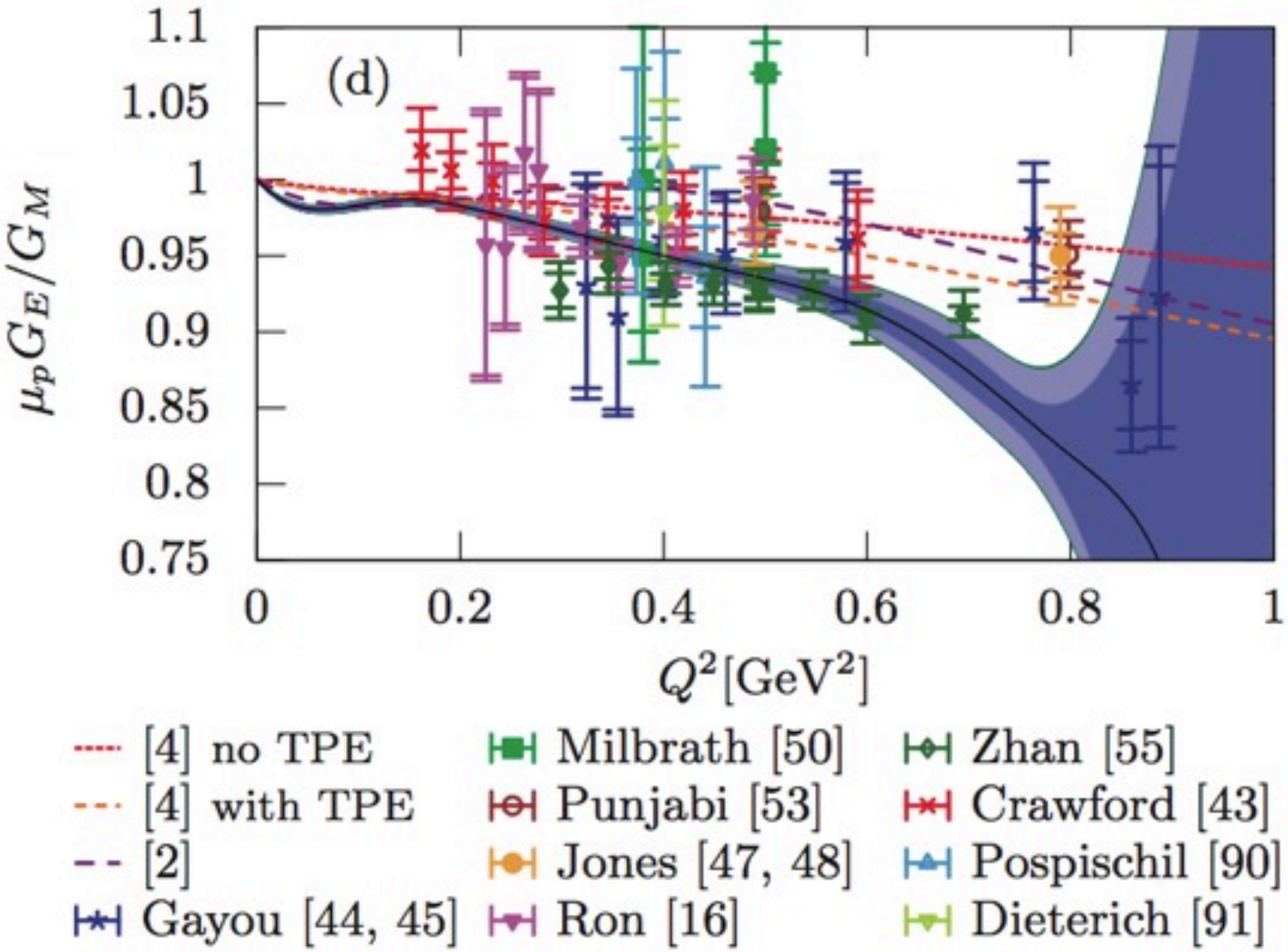


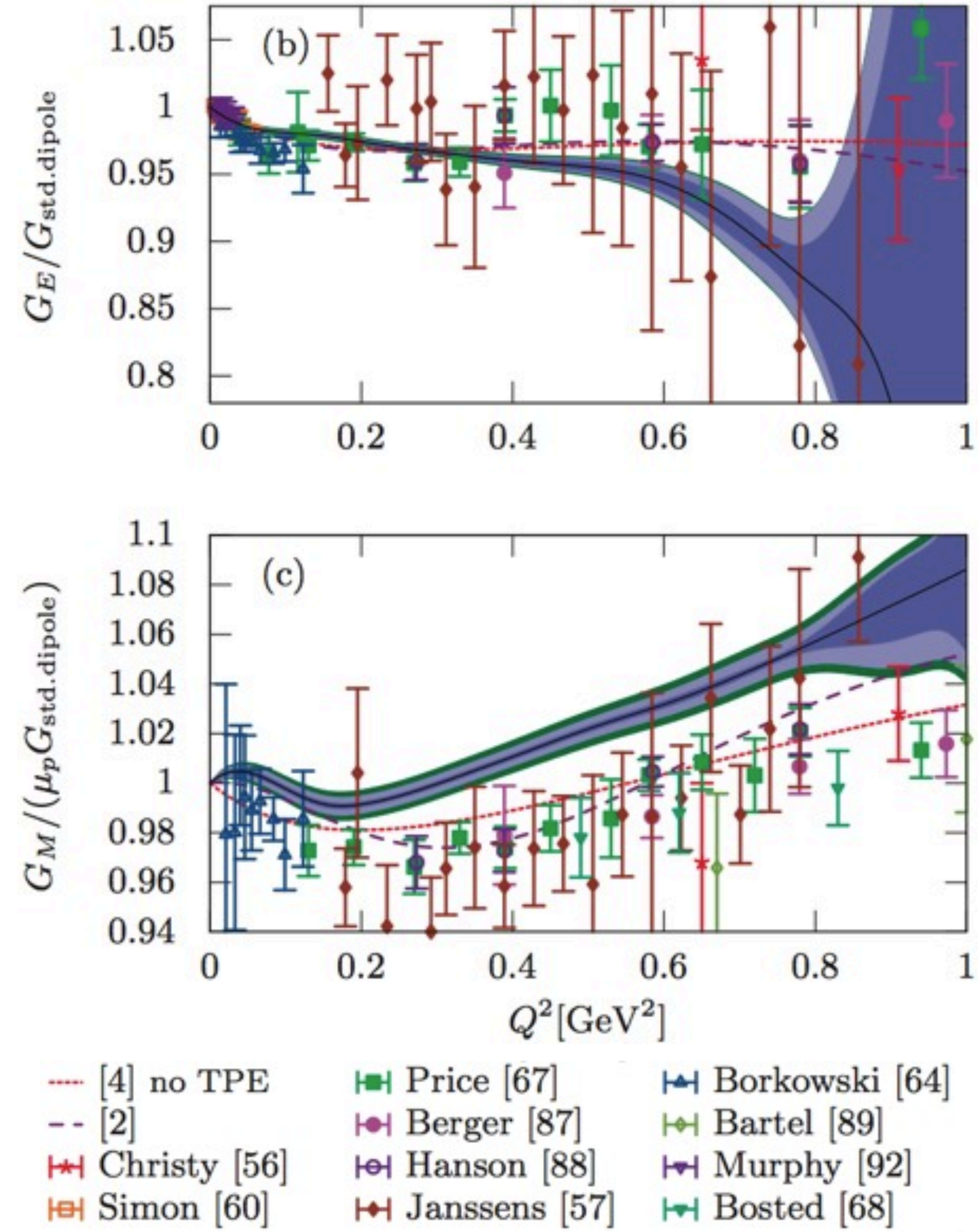
Crawford et al PRL 98, (2007)
Bates BLAST polarization data

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 the 2007 LRP:
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

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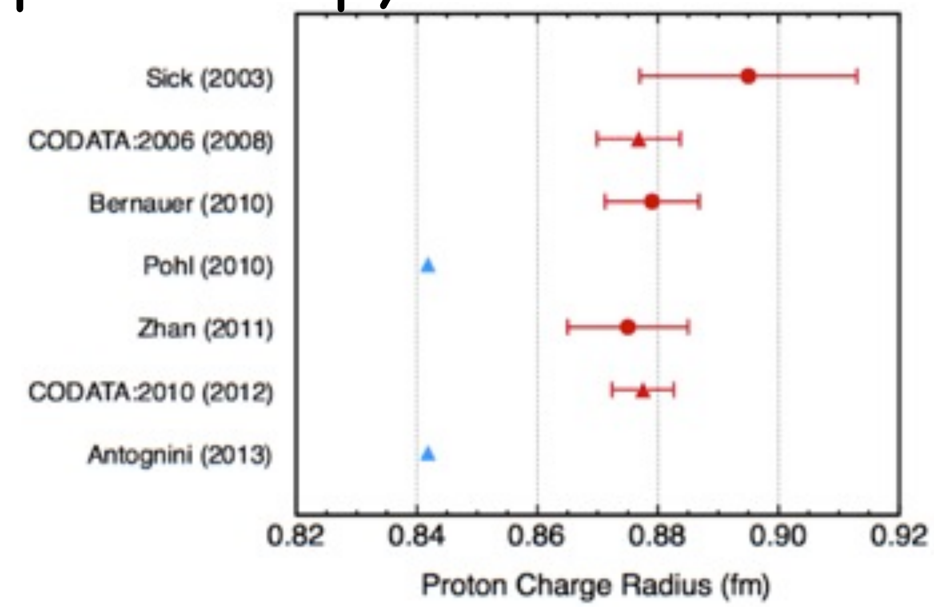
Proton Charge Radius Puzzle... another talk by itself

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) 0.875 ± 0.009 (JLab) 0.886 ± 0.008 (Sick) 0.871 ± 0.009 (Hill & Paz) 0.84 ± 0.01 (Lorenz, Hammer, Meissner)
muon	0.84087 ± 0.00039 (Antognini)	?

CODATA 2010: 0.8775 ± 0.0051 or 7.2σ difference

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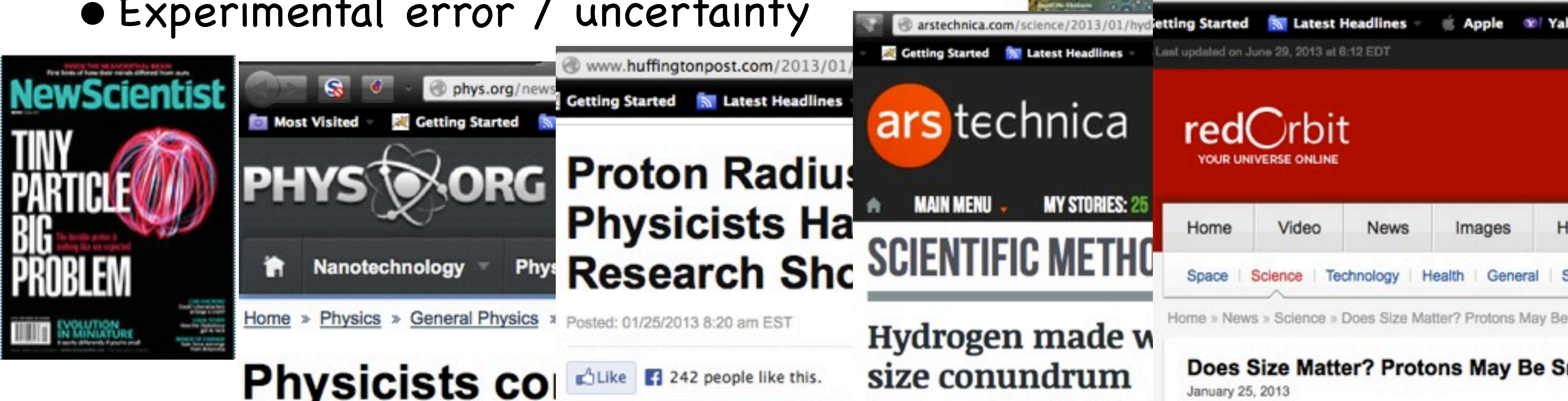
Proton Charge Radius Puzzle

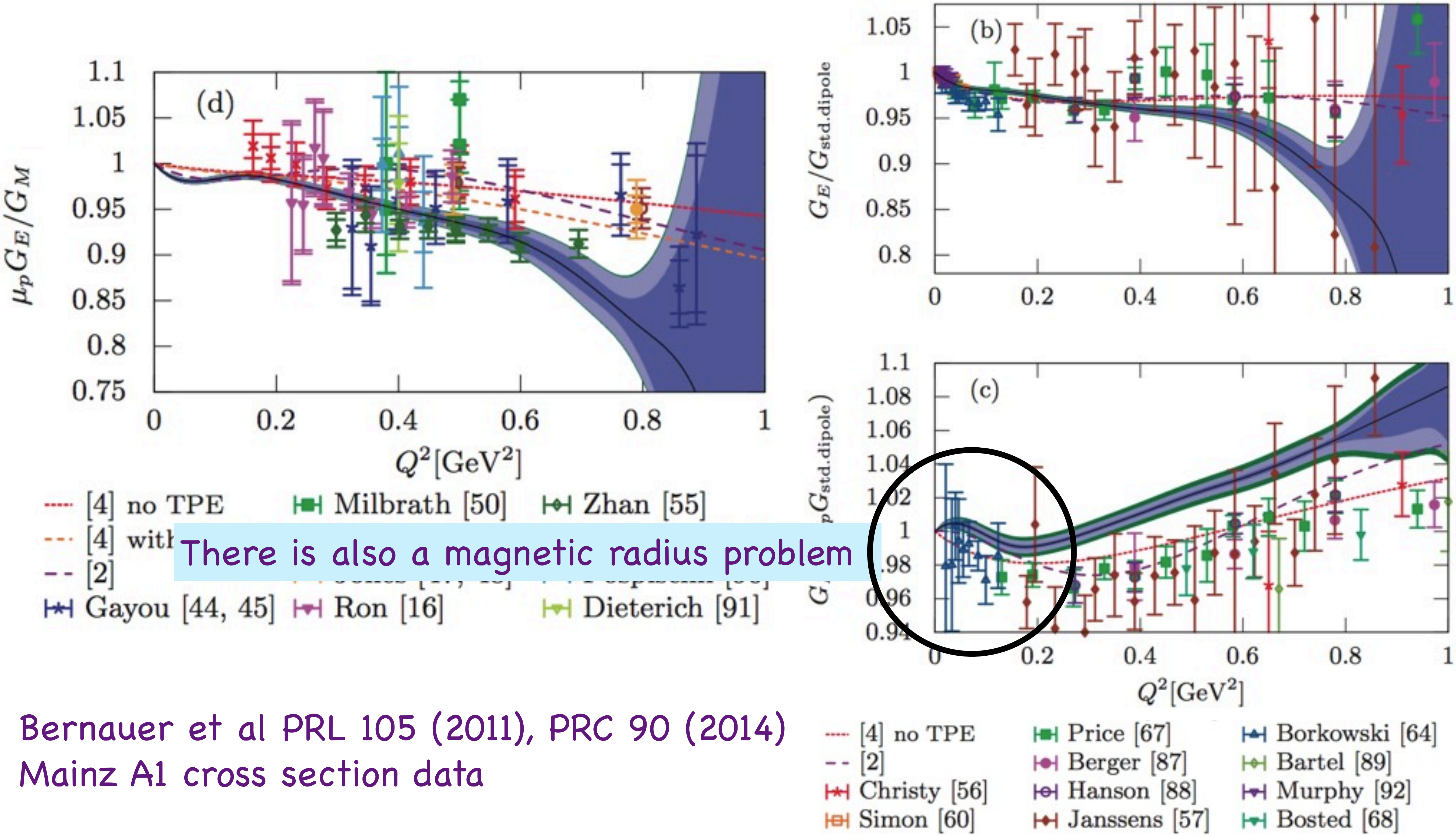
Proton radius puzzle has been high profile:

- Lots of news articles
- Lots of citations
- Workshops in Trento (2012) and Mainz (2014)
- New experiments inspired - muonic atoms, hydrogen spectroscopy, **ep scattering, muon scattering**
- All explanations to date arguably either ruled out or not likely:
  - Novel physics
  - Unanticipated conventional physics
  - Experimental error / uncertainty



Since the 2007 LRP: 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

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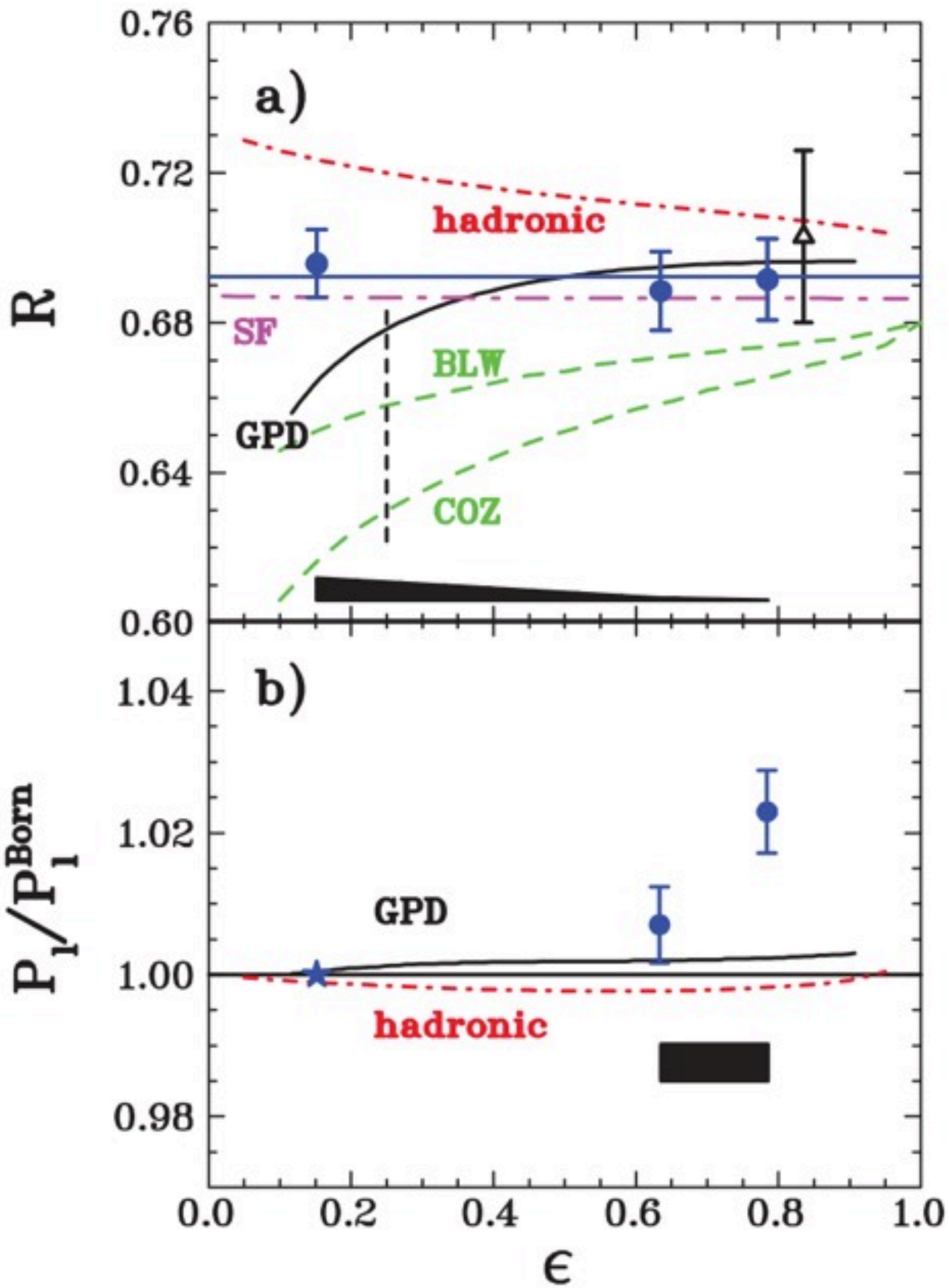
Since the 2007 LRP: What has been learned?

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

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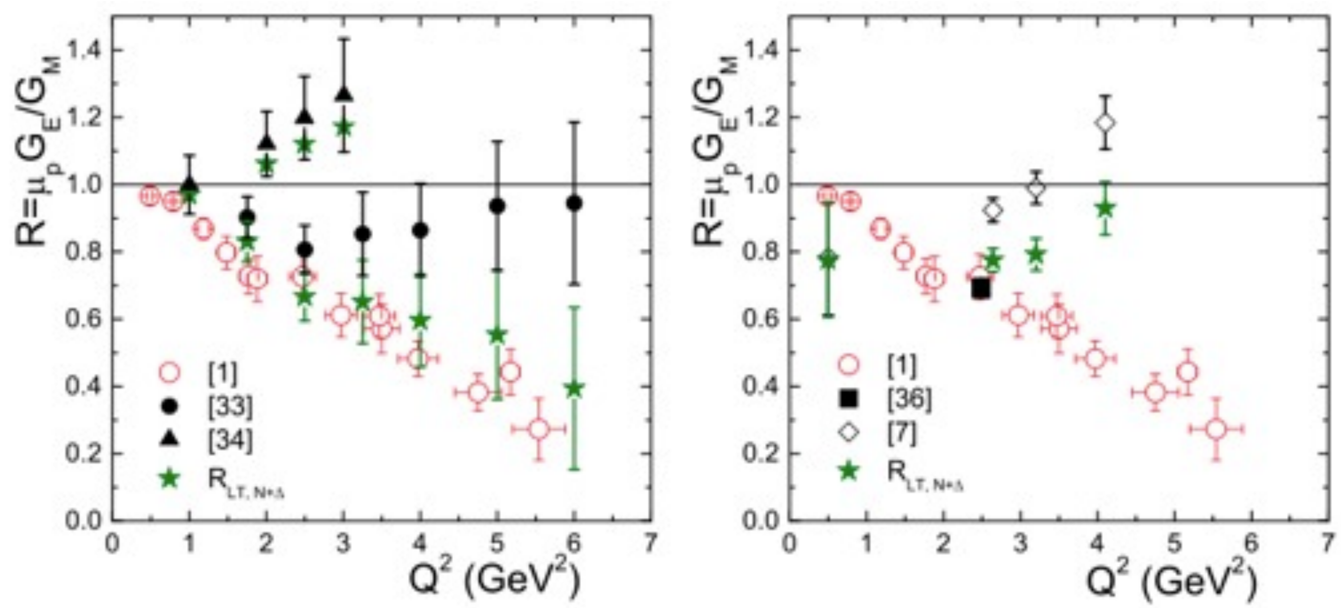
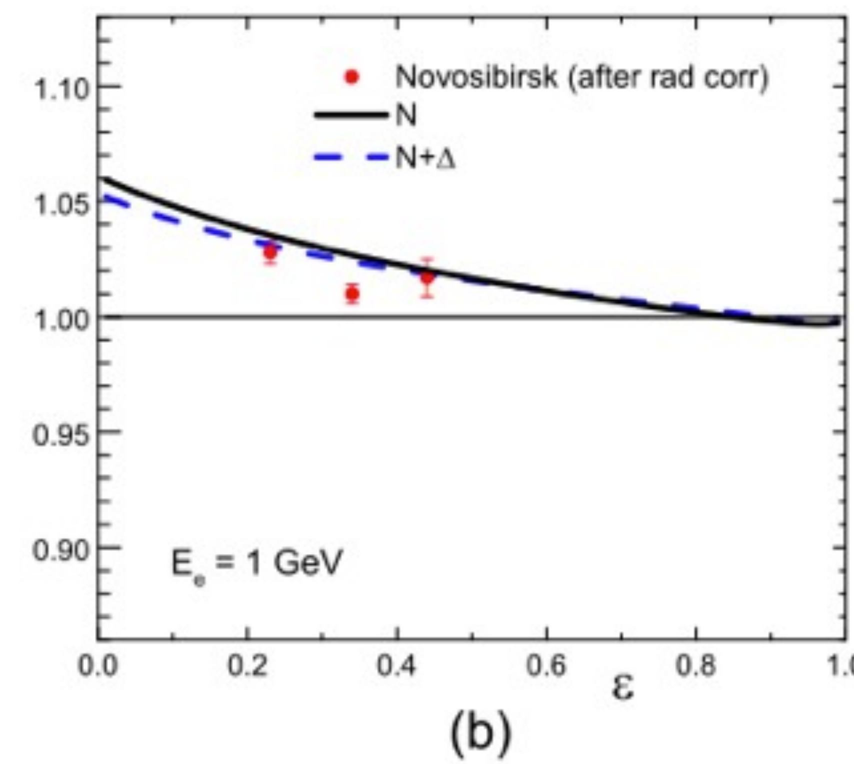
Since the 2007 LRP: What has been learned?

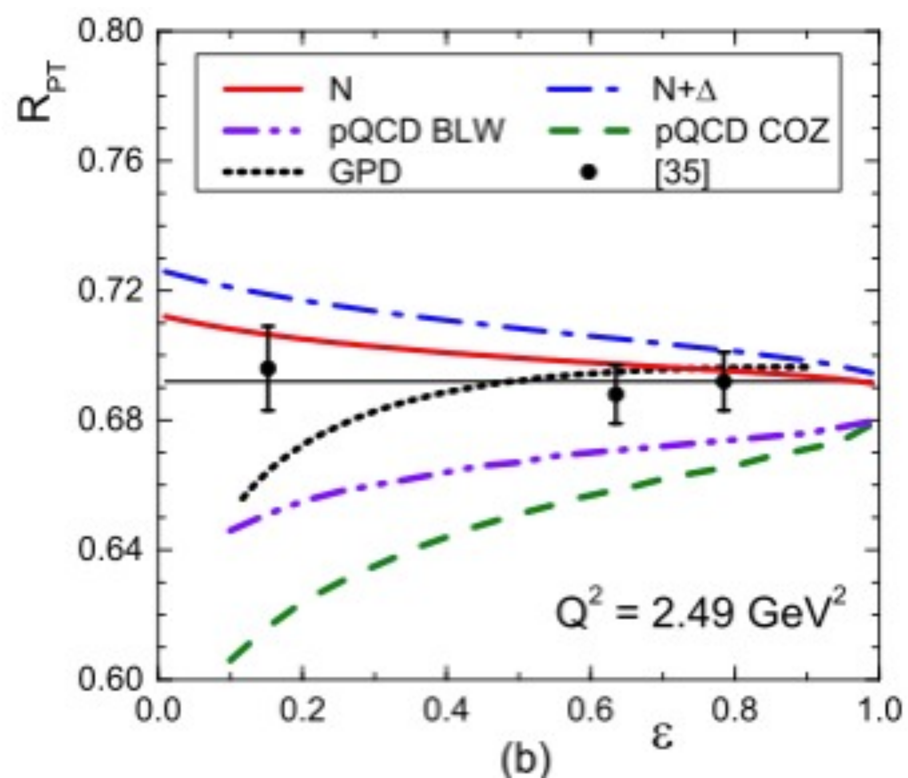
TPE Theory / Analysis



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



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



- Too large an effect compared to Meziane et al data

- Good sized asymmetries predicted for positron/ electron comparison

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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?
- 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?
- 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

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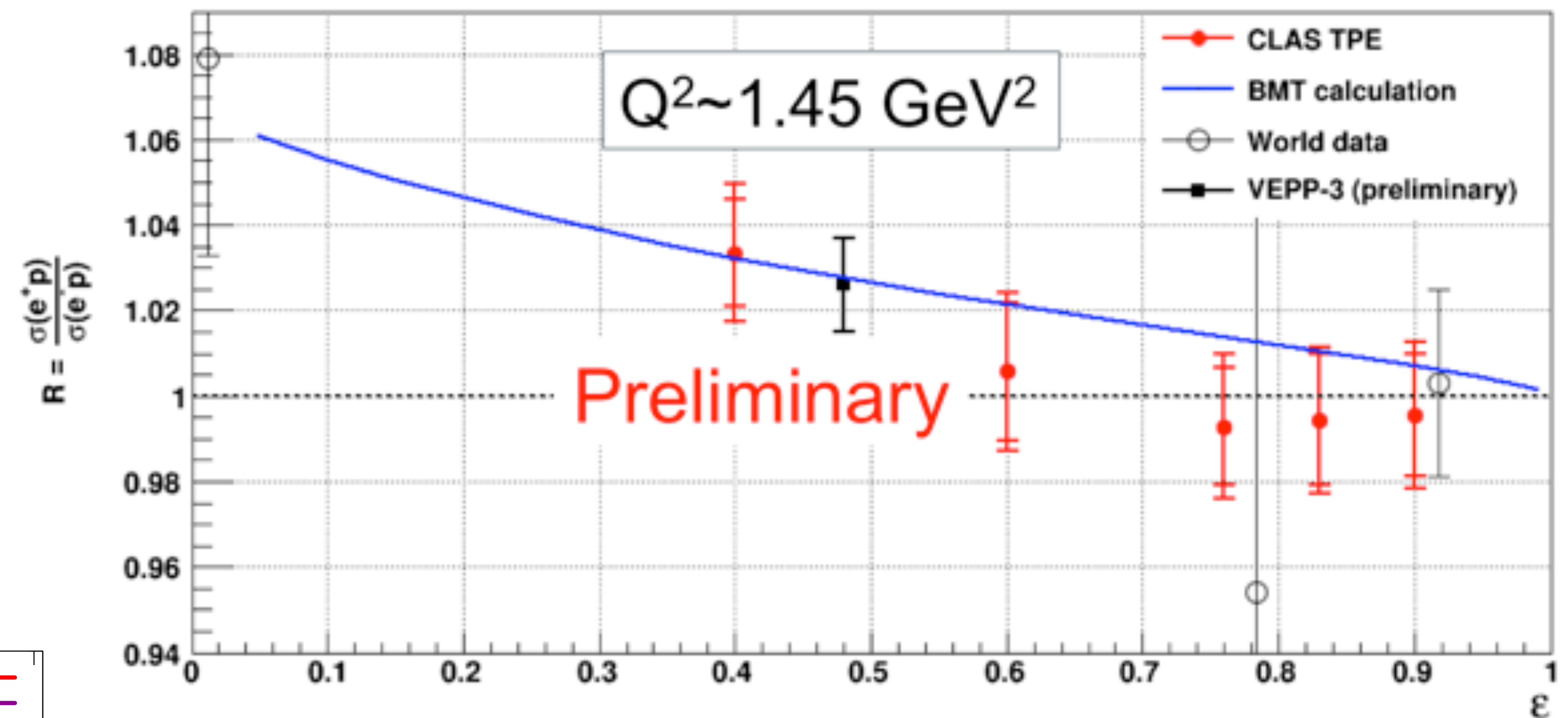
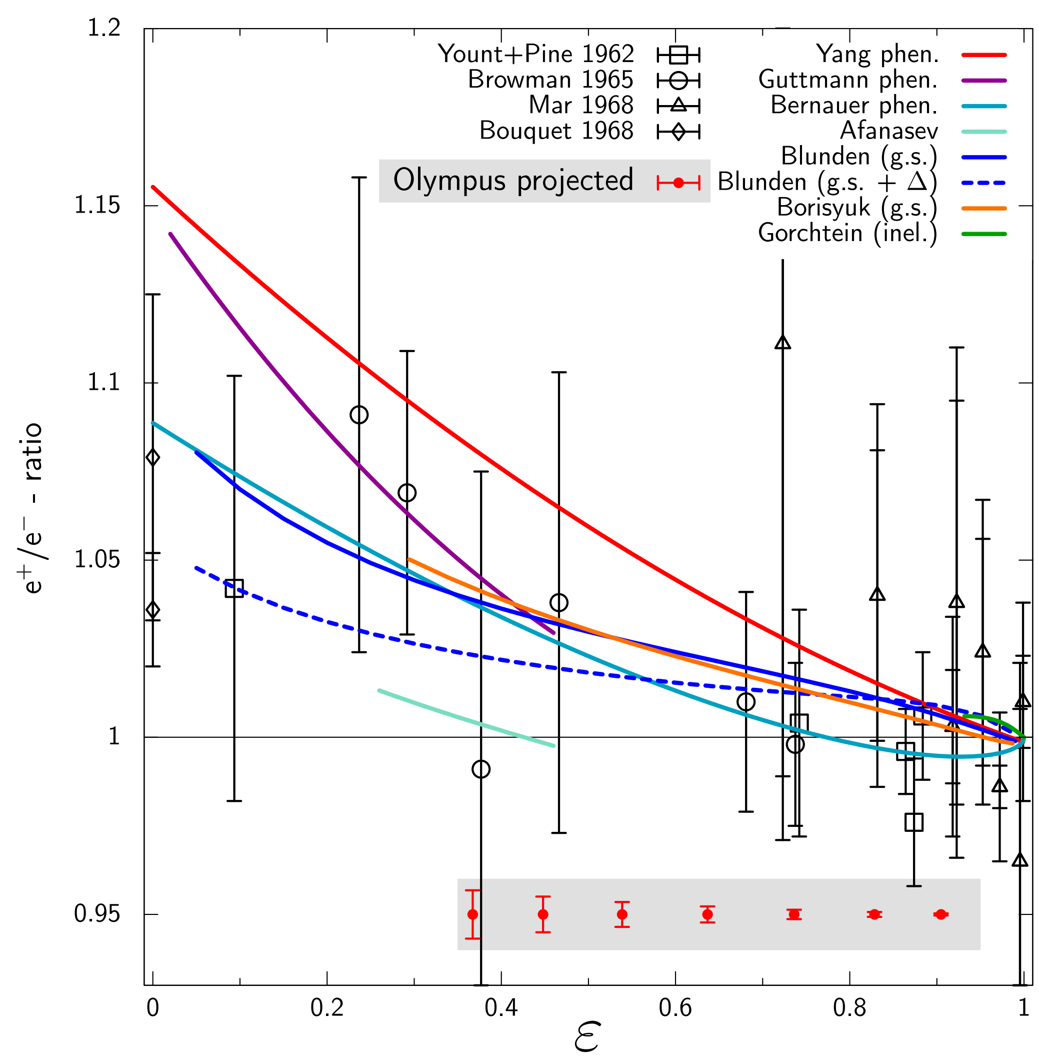
TPE

- 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, θ, ε

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

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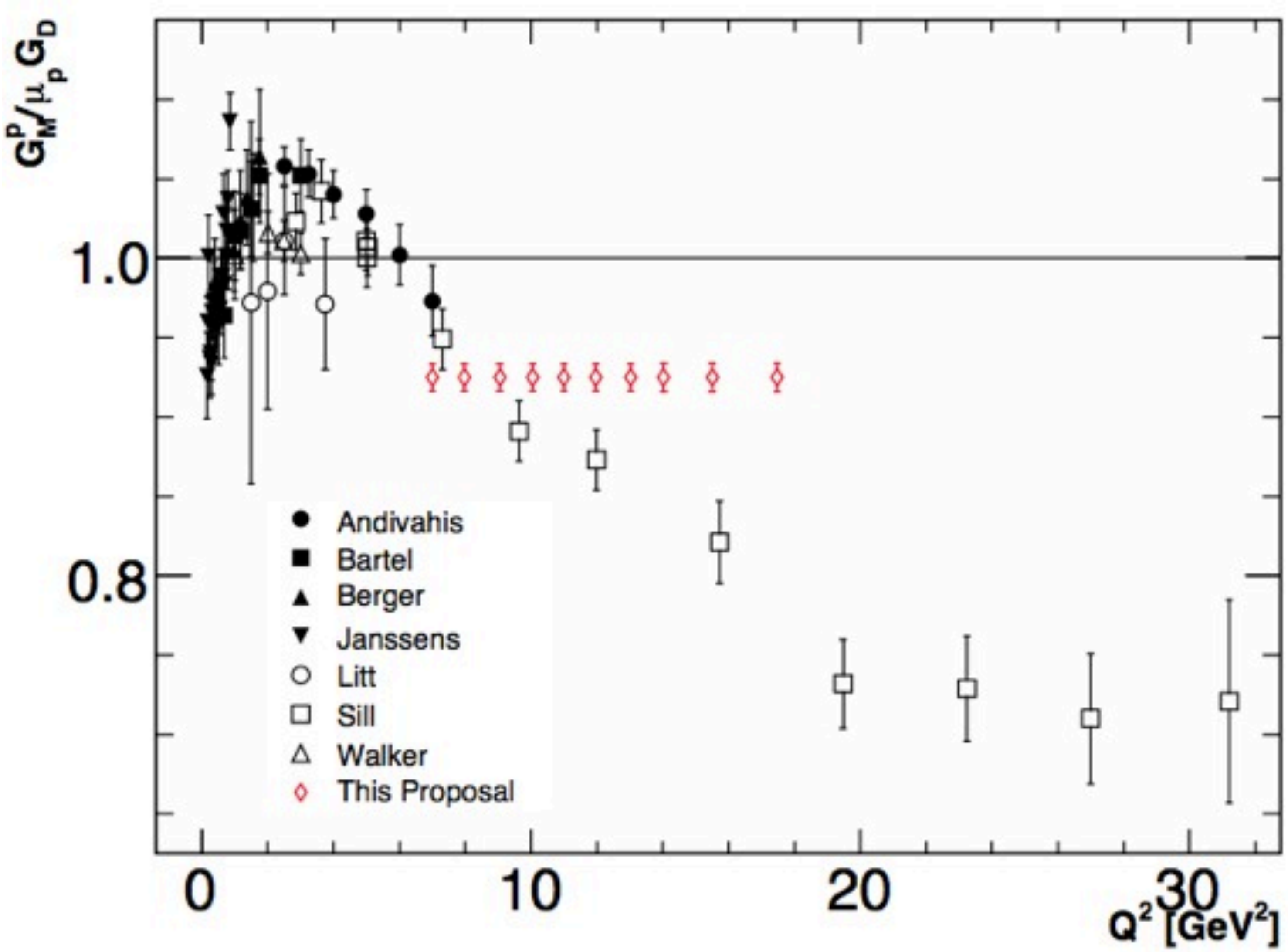
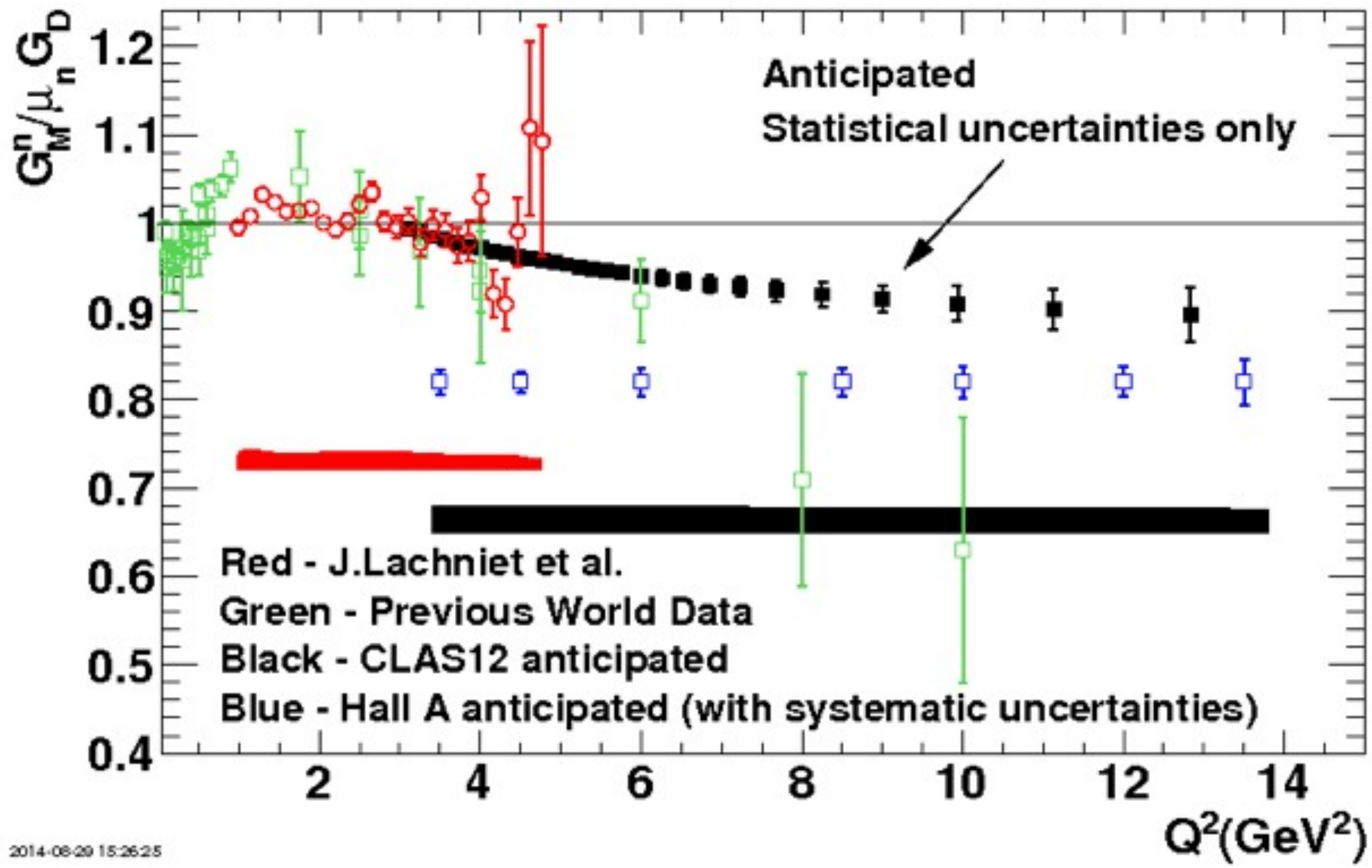
JLab Hall A Measurement of G_M^p



- Commissioning experiment that improves precision in the high Q^2 region

- Straightforward precise cross section measurement

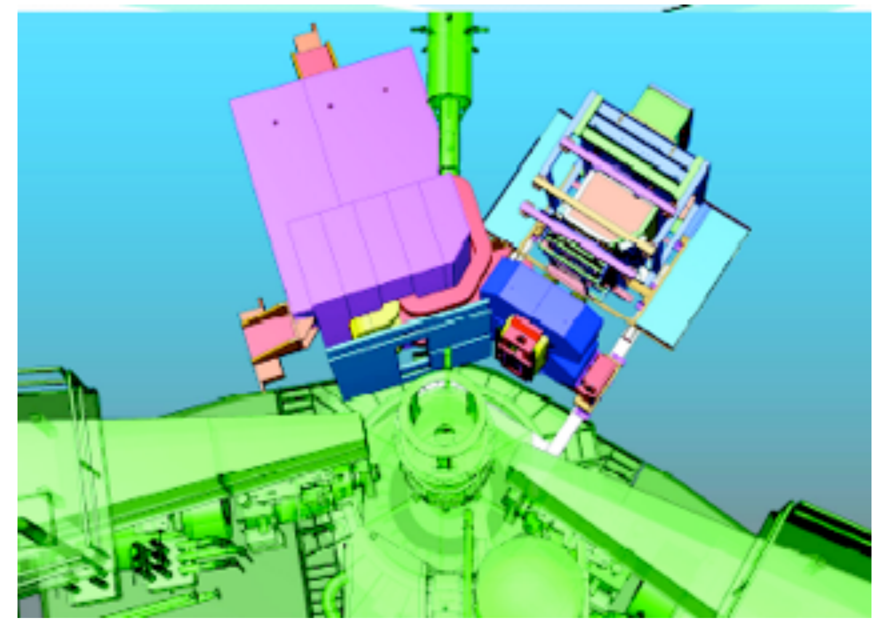
JLab Hall B CLAS Measurement of G_M^N

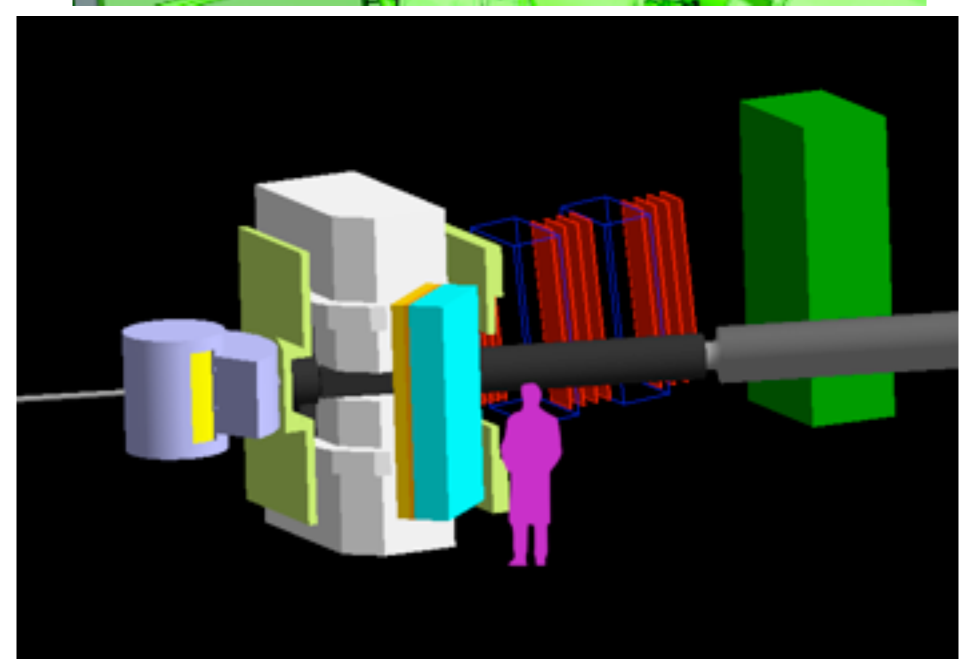


- High Q^2 reach for precision G_M^N nearly tripled
- Measurements use cross section ratio technique - d(e,e'n)/d(e,e'p)

SuperBigBite Program in JLab Hall A - 1 of 4

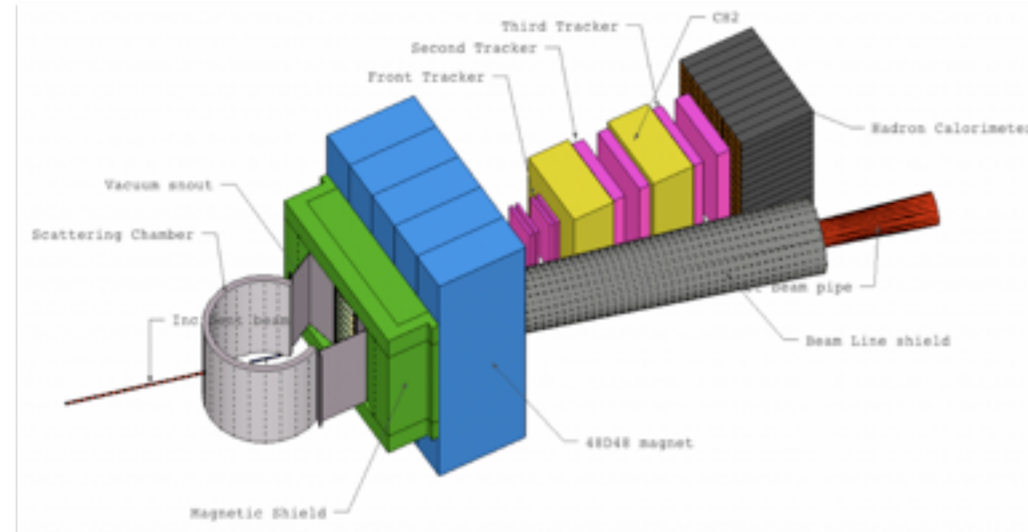
- A $5M DOE Project for Hall A at Jefferson Lab
- High Q^2 form factor measurements, for tests of QCD predictions, etc., are a major program for SBS.
- SBS will reach into new higher Q^2 territory with high precision
- Measurements could begin as early as 2017



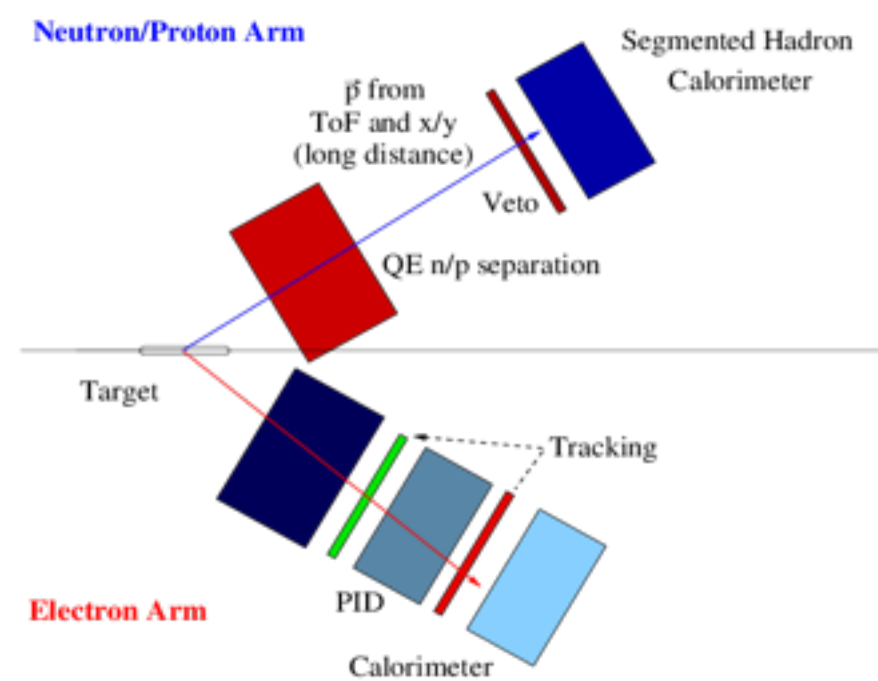


SuperBigBite Program in JLab Hall A – 2 of 4

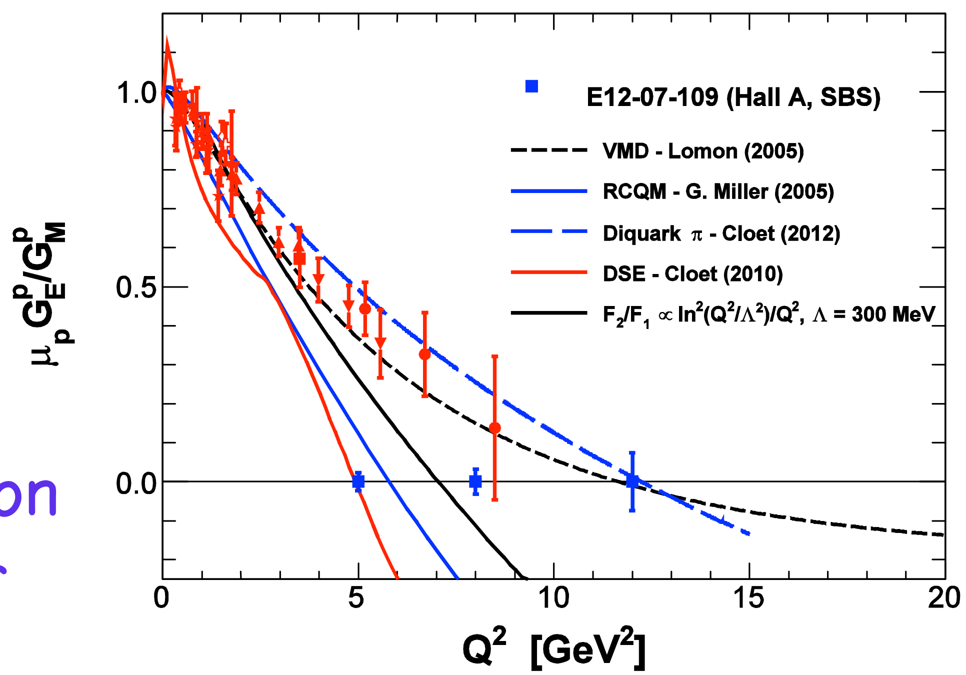
Development of a new unique hardware for coincident $e^{-}N$ scattering



- 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 ^3He target
- Large area GEM trackers for high rate, high precision tracking

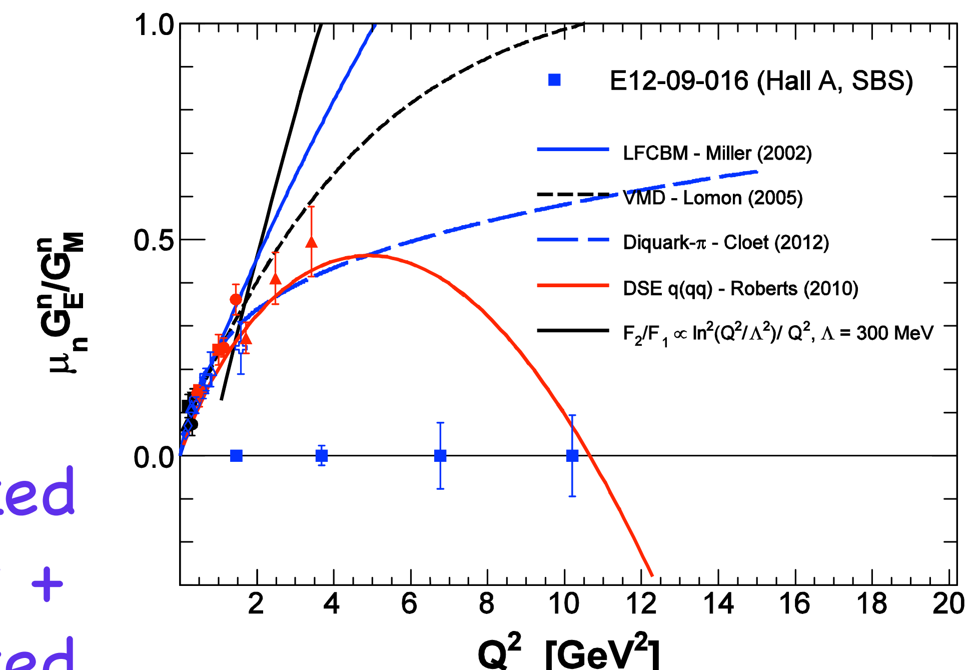


SuperBigBite Program in JLab Hall A – 3 of 4

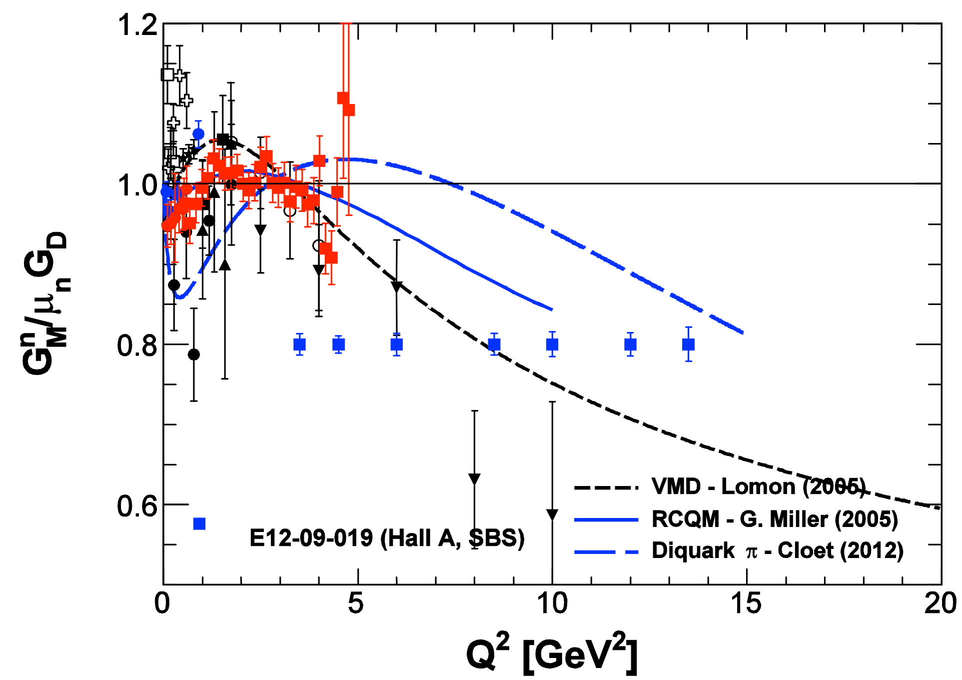


polarization transfer

- 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

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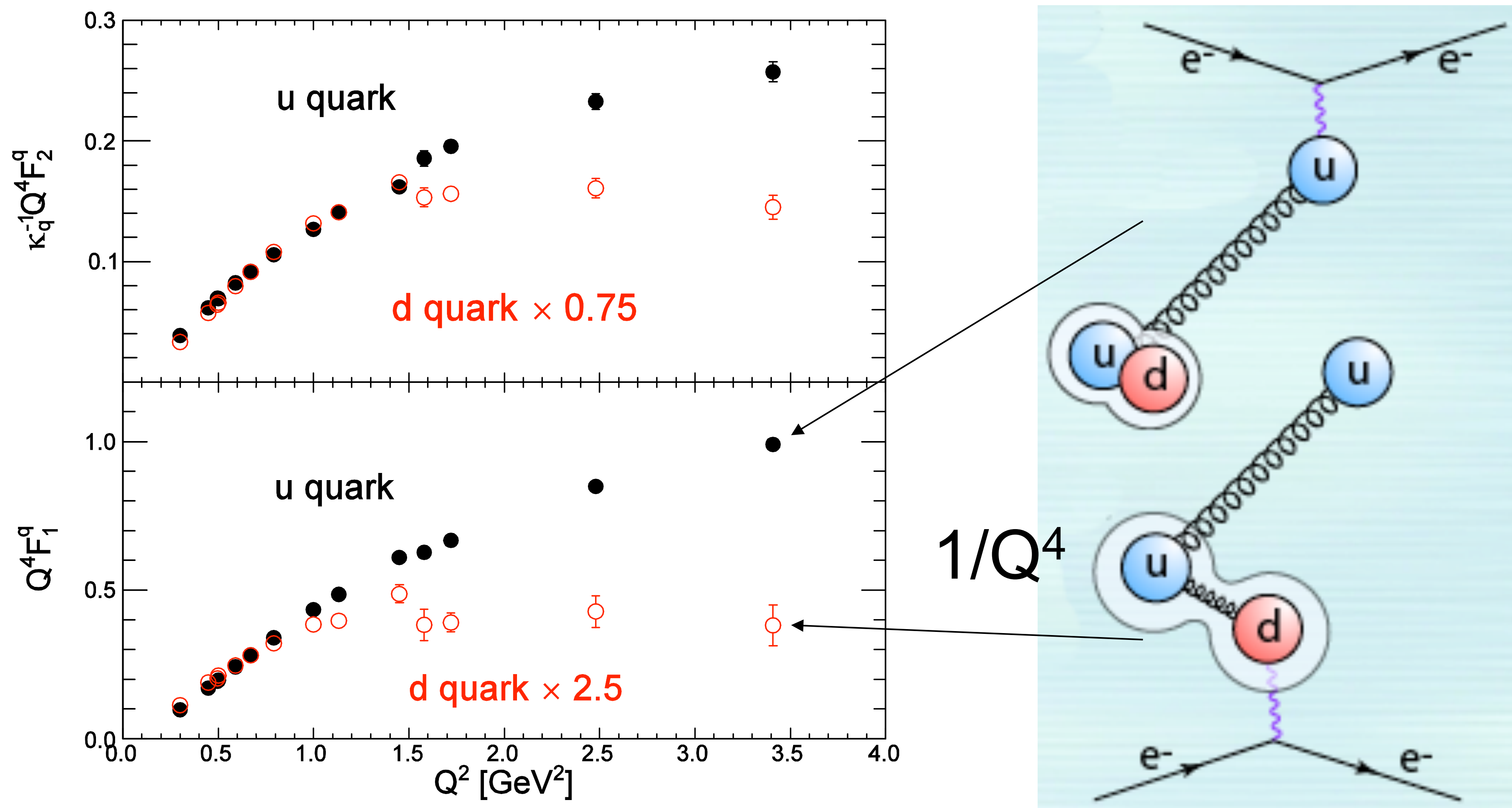
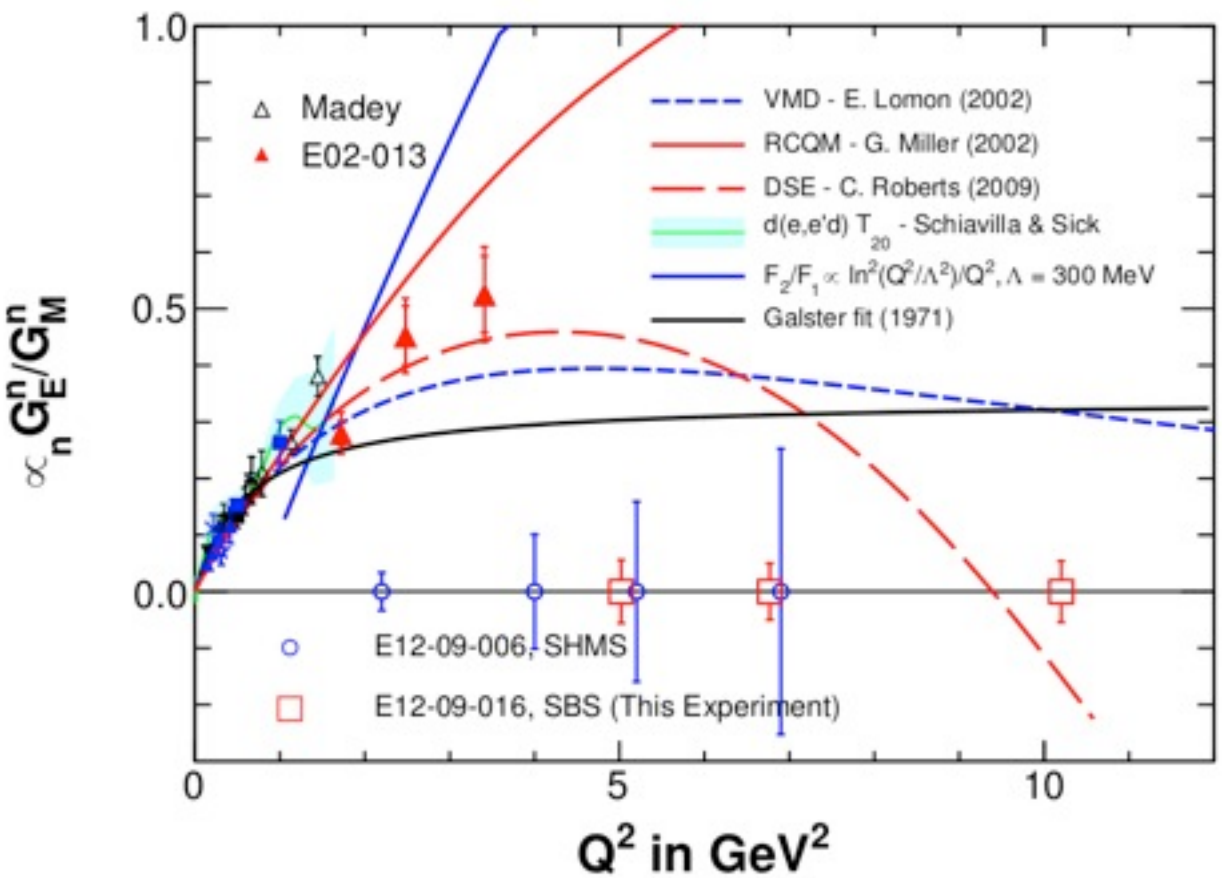
SuperBigBite Program in JLab Hall A - 4 of 4



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

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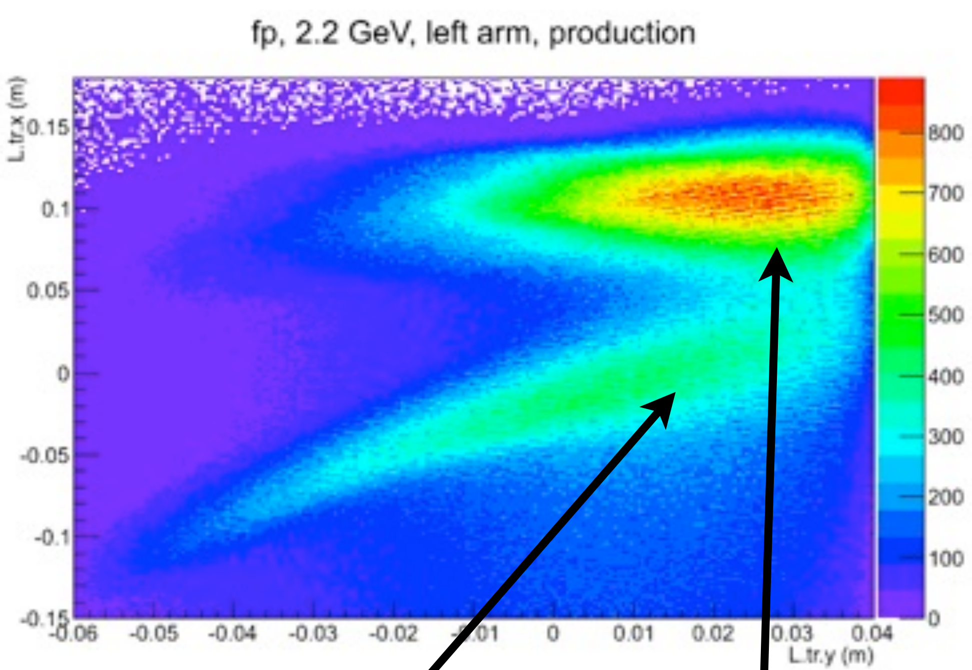
Low Q^2 and Proton Radius

JLab Hall A E08-007 Part II: Ron et al
Polarized target asymmetries for low Q^2
Ran winter/spring 2012

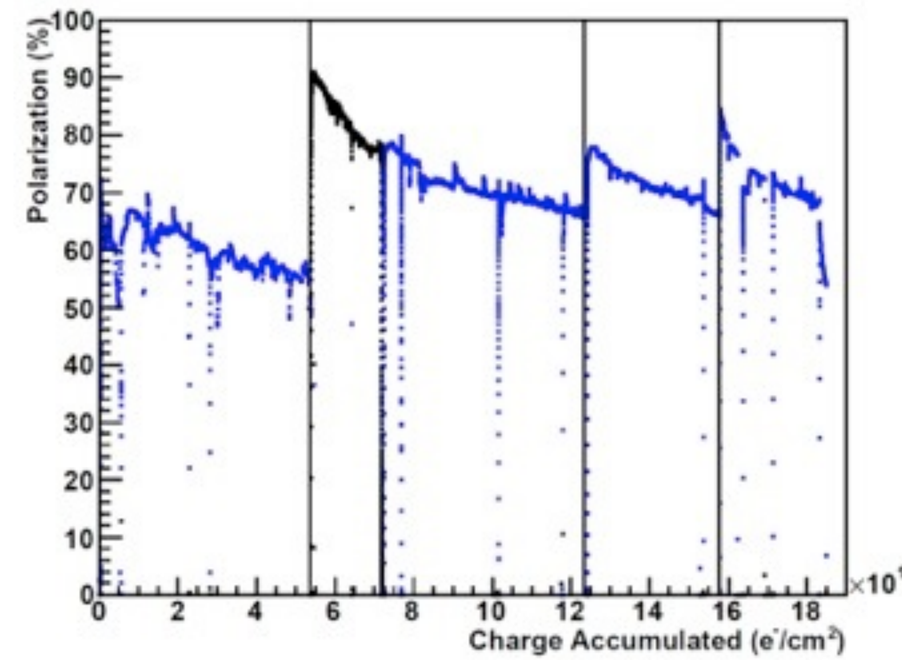
Spectrometer performance



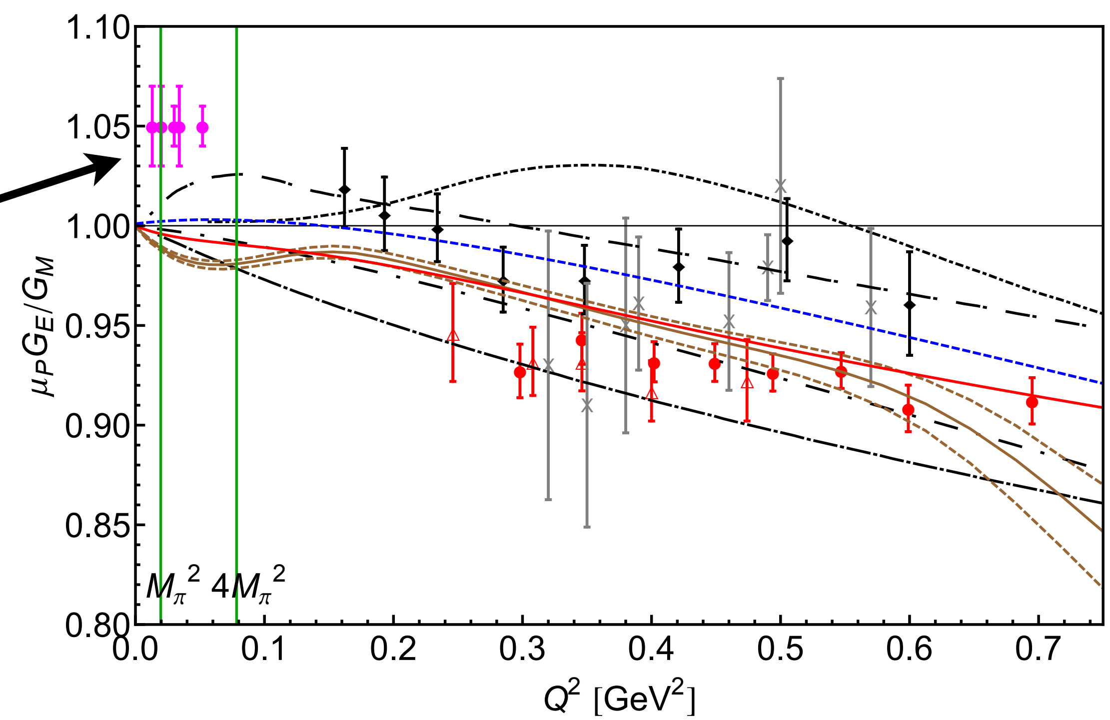
Hydrogen

Nitrogen

Target performance



Expected results – early 2015



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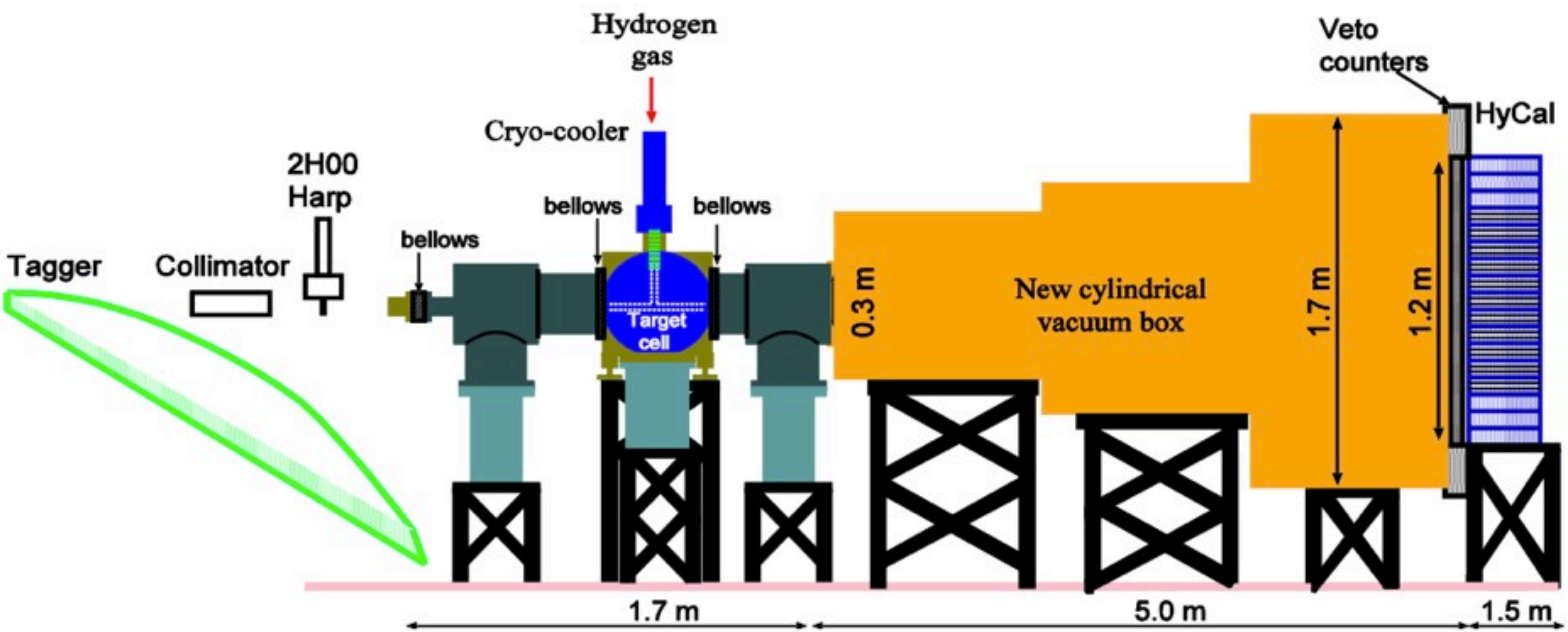
Low Q^2 and Proton Radius

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.



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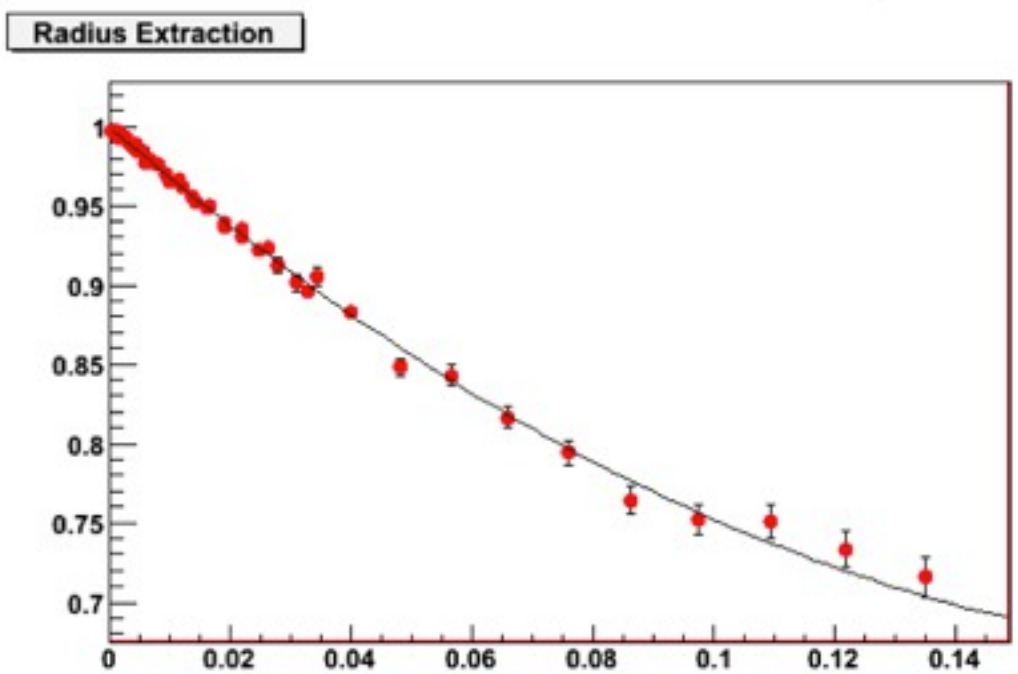
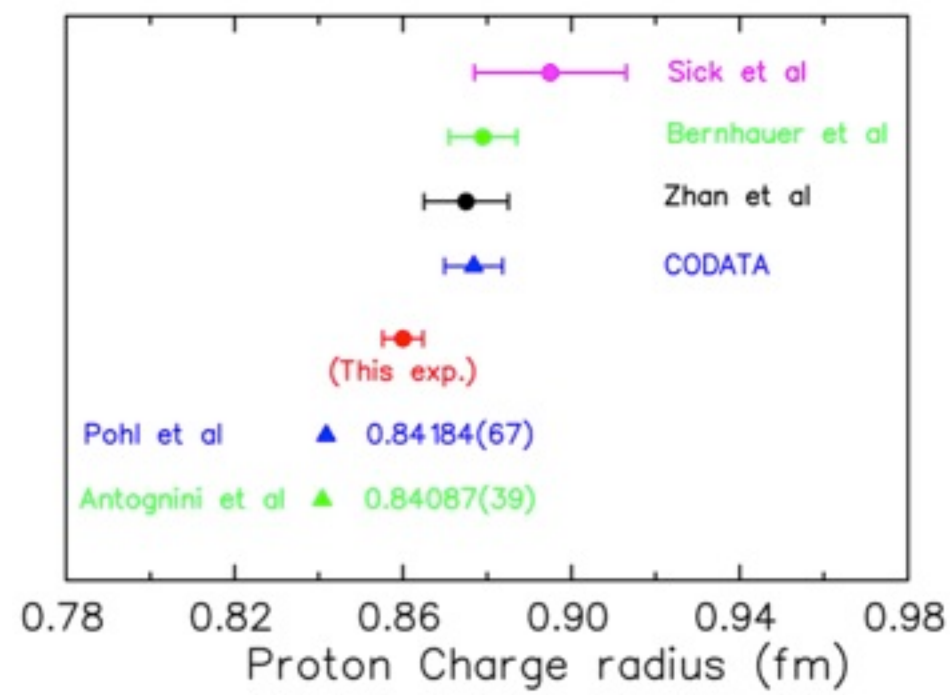


G_E vs Q^2 data simulated, to show radius out = radius in

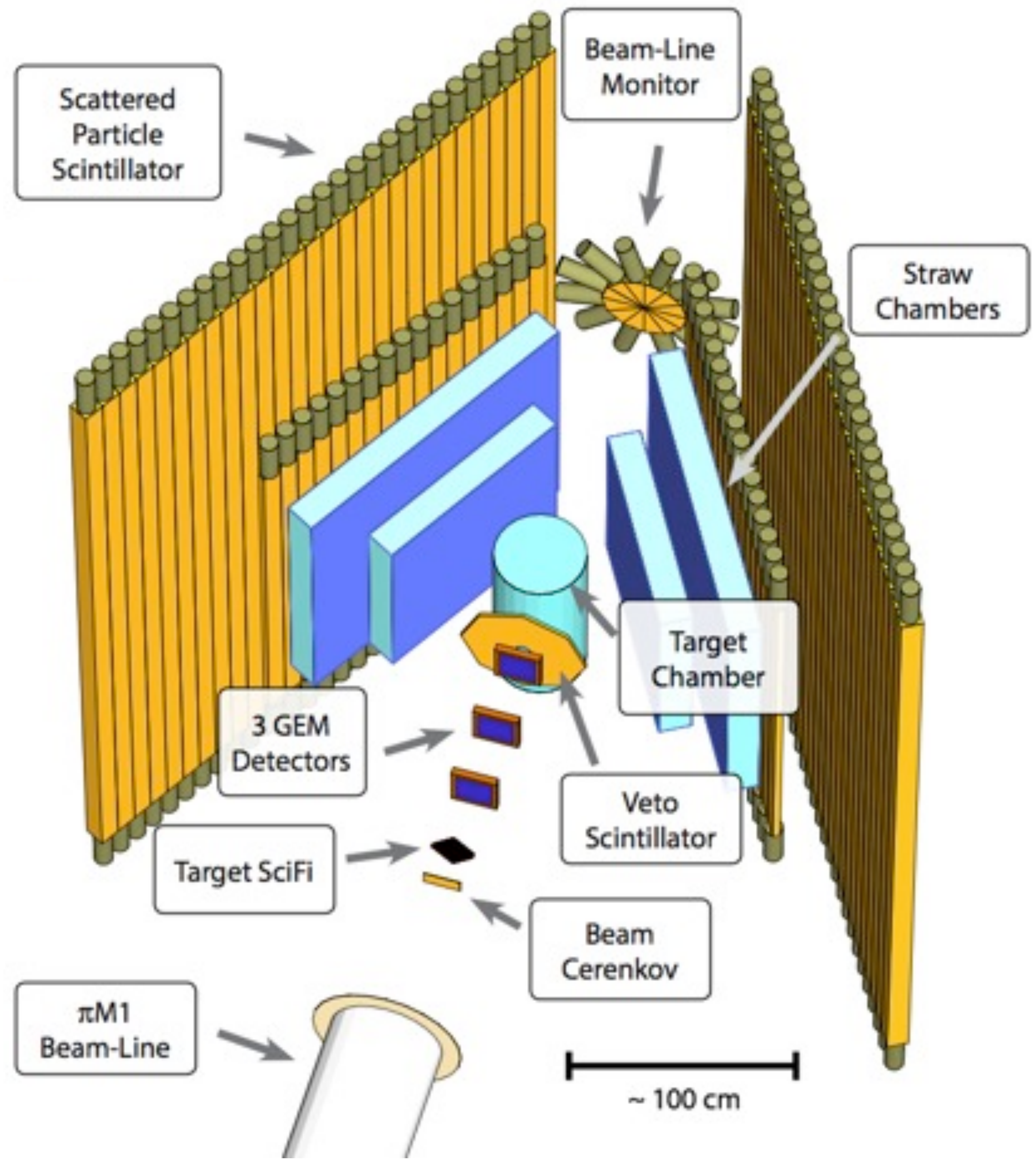


Projected result

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.



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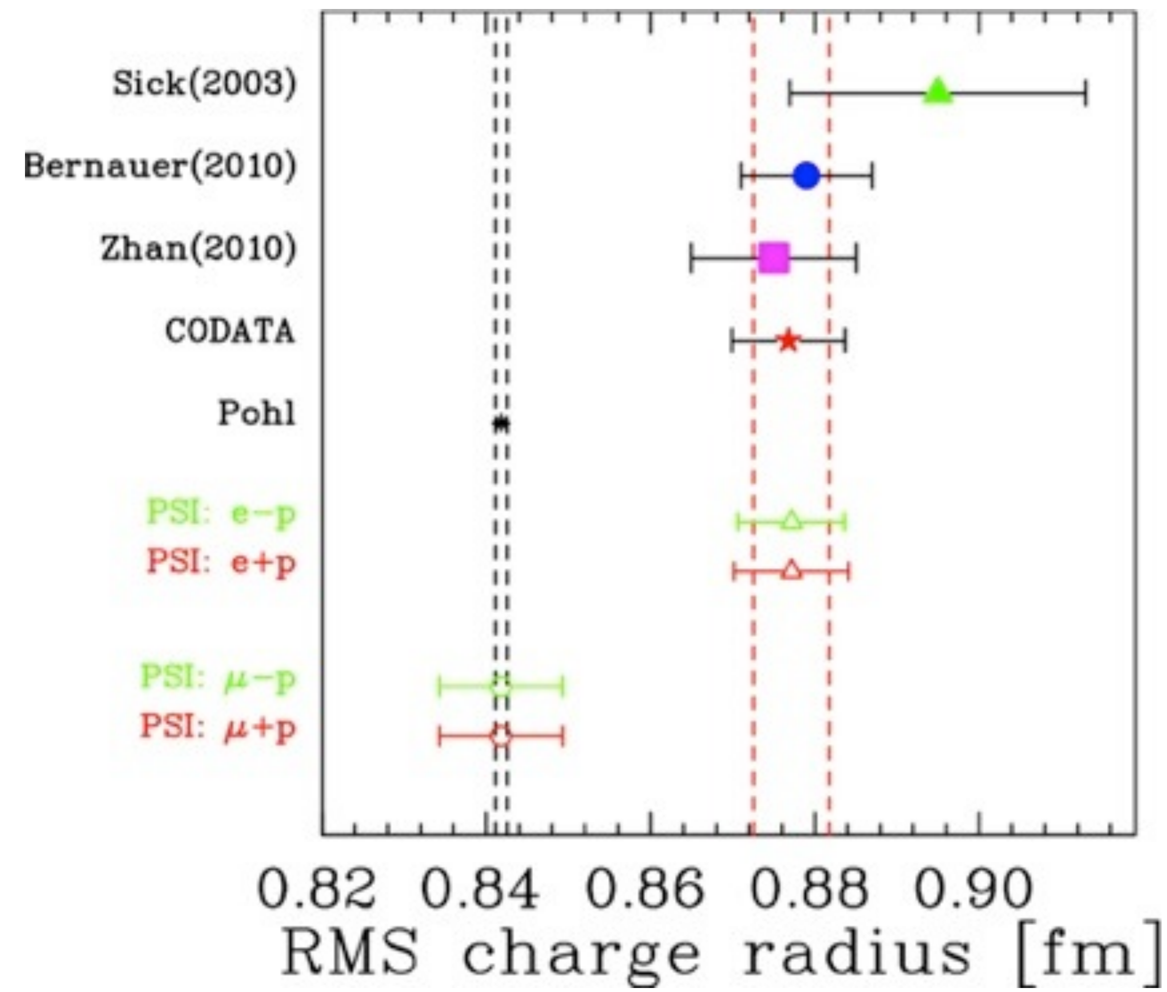

Projected result, using relative uncertainties for muons and electrons

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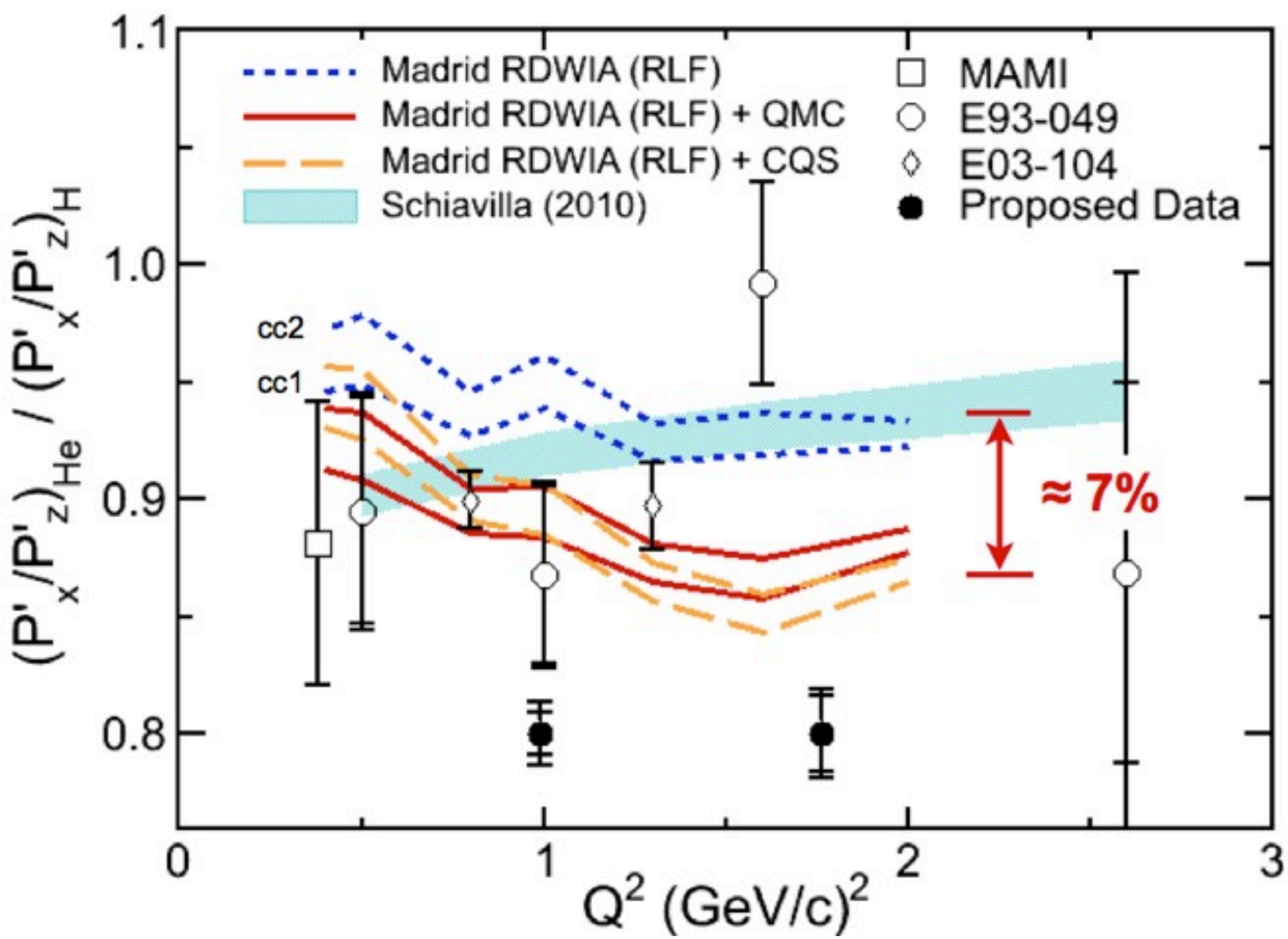
Do we understand nucleons in nuclei?

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 consistent with modified in-medium form factor or charge-exchange FSI
E11-002 tries to improve precision in the higher Q^2 region

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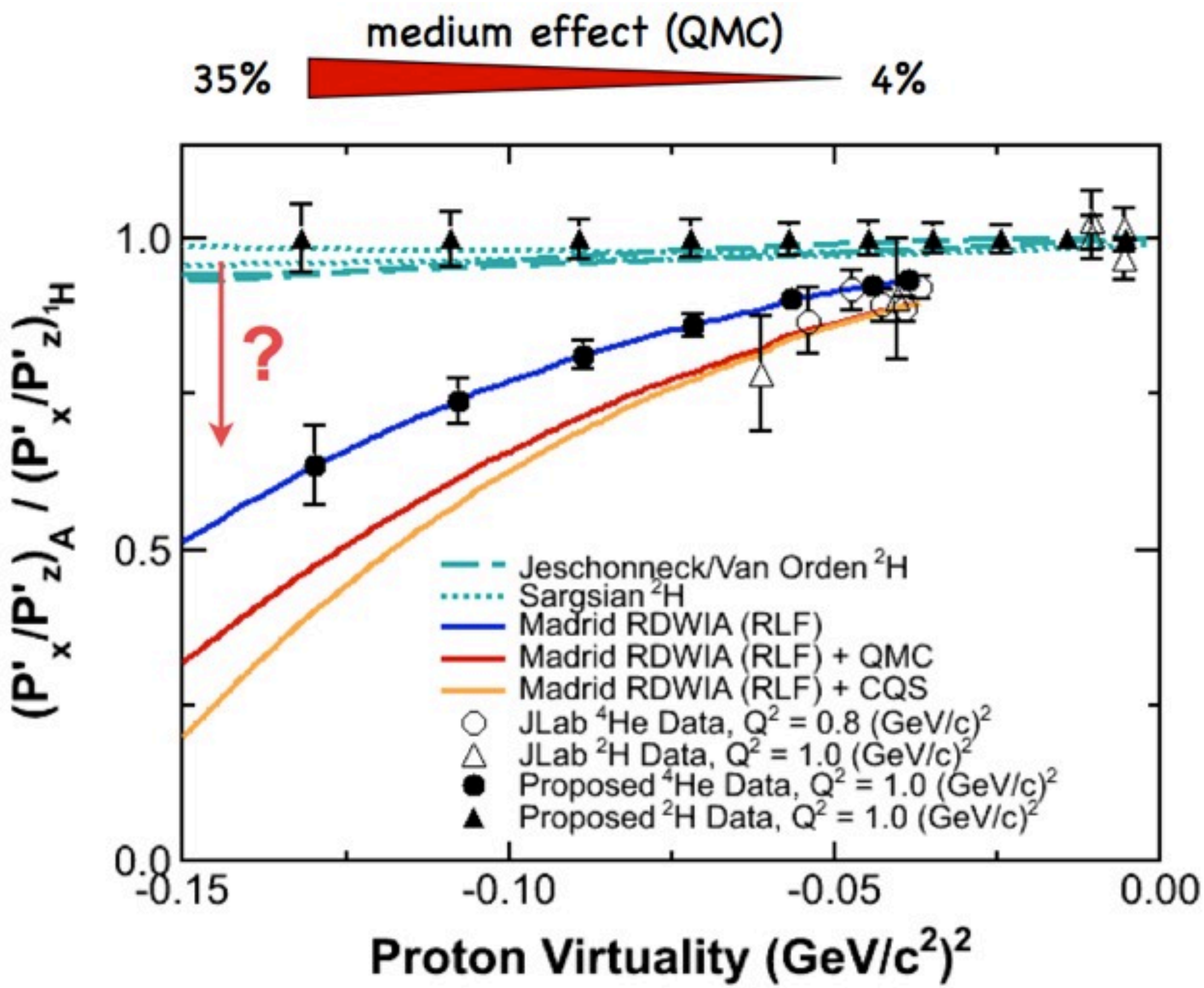

QCD inspired models suggest large effects and a simple dependence on virtuality absent from conventional nuclear calculations.
Previous d(e,e'p) data show large effect.
Study d and ^{4}He for dependence on virtuality.

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Form Factors at an EIC?

Some of us (GR, RG, ...) have looked at what can be done with form factor measurements at an EIC, for ep and eA.

A nice set up measurements is possible, but low luminosity prevents going to as high Q^2 as the fixed target program.

As it is not a focus of the EIC program...

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

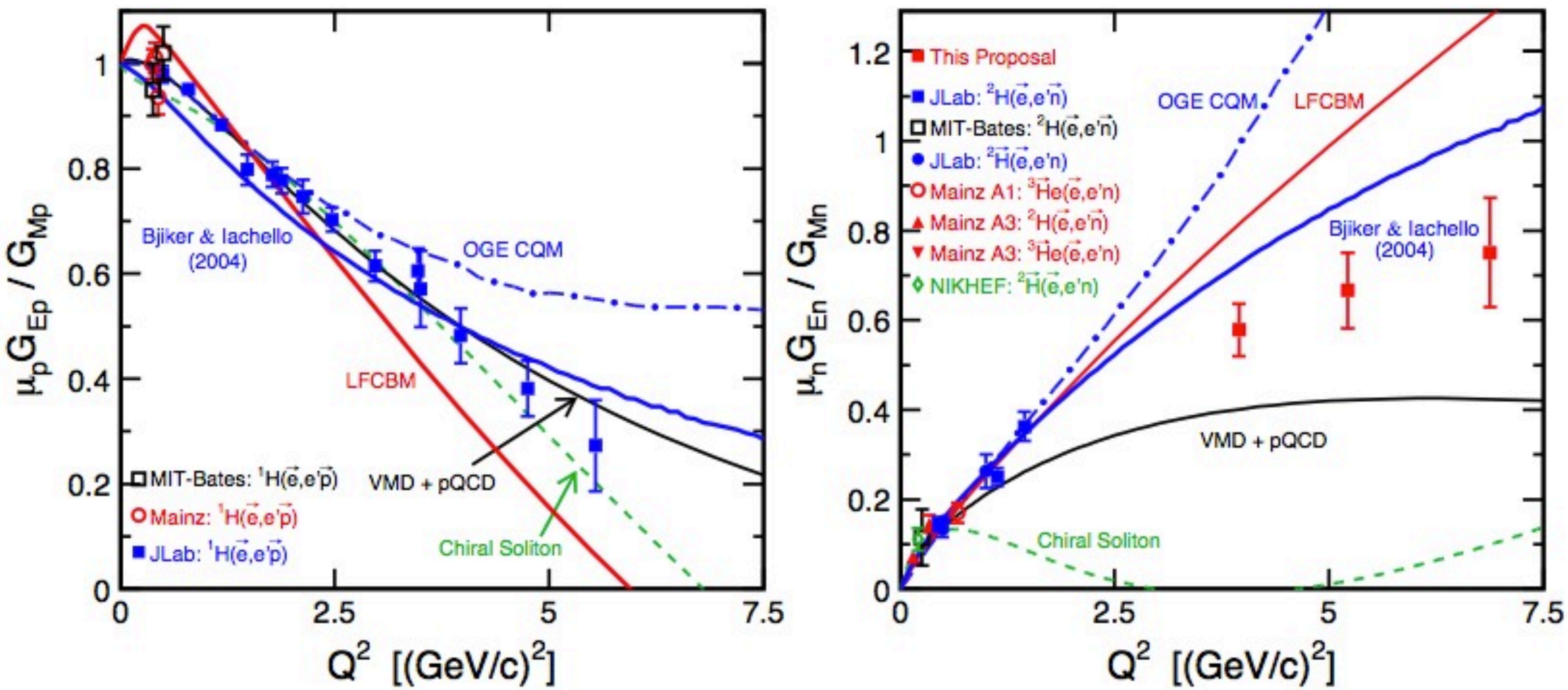
- Better understand TPE, but maybe not well enough
- Start to get new JLab high Q^2 data on various form factors, but maybe not enough for improved separations
  - Does G_E^P or G_E^N go negative?
  - Do $G_M^{P,N}$ continue to (approximately) follow the dipole?
  - Does Q^2F_2/F_1 scaling continue?
- 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

Backup Slides

It is hard to get both the proton and the neutron right



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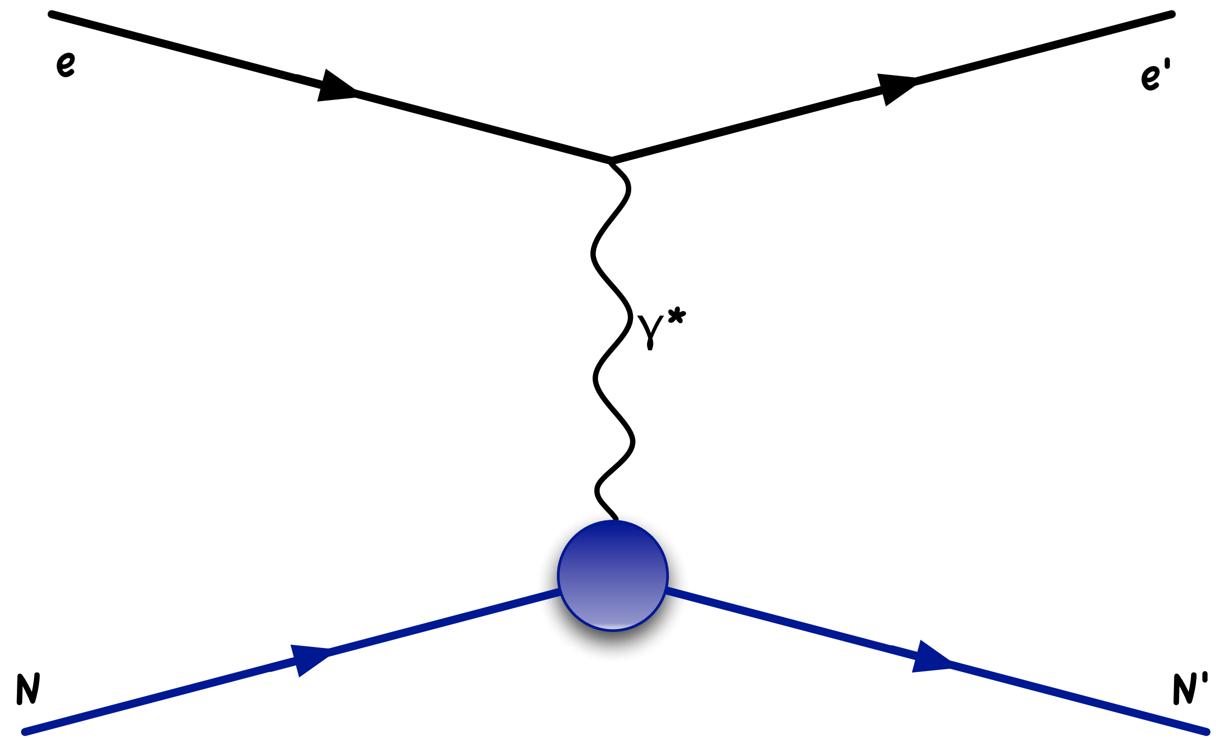
Stuff We Know: EM scattering from 1γ Exchange



Cross section formulas derived and put in modern form ≈ 60 years ago - Rosenbluth separation.

$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

$$\tau = \frac{Q^2}{4M^2}, \ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

Assumptions: one-photon exchange, electron mass small

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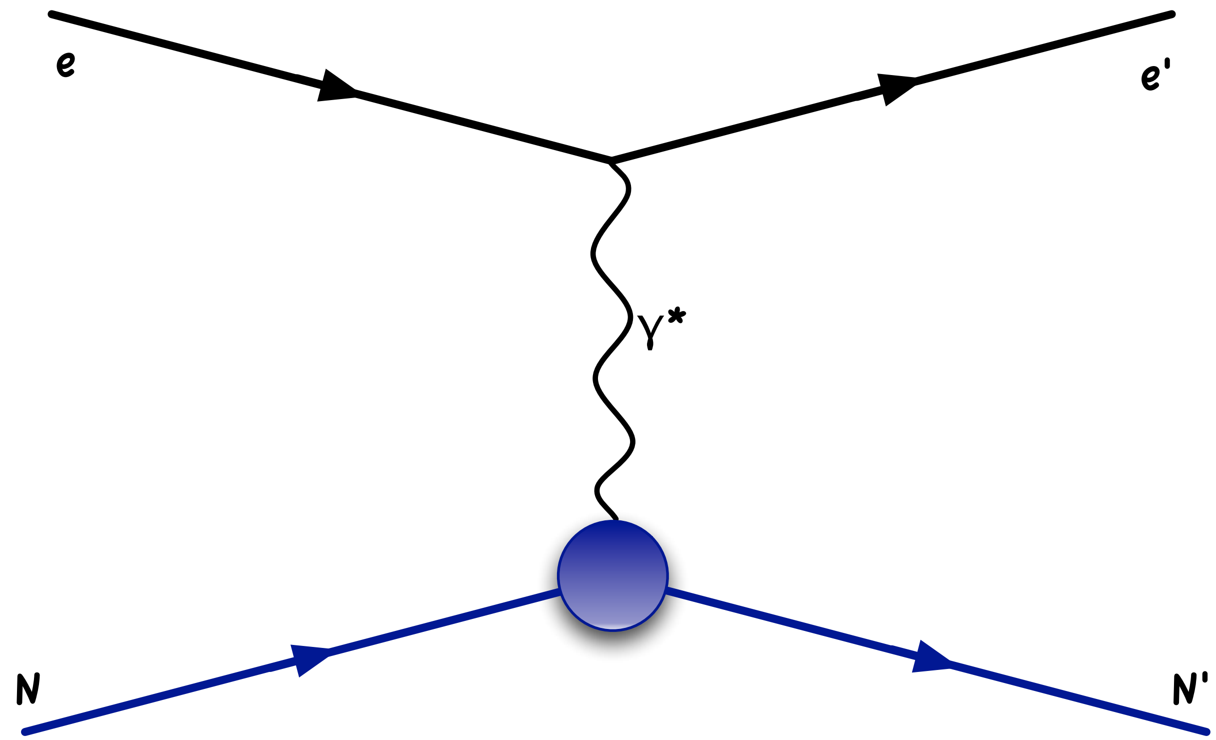
Stuff We Know: Form Factors



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Rosenbluth - Spin-1/2 with Structure

$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$

Two relativistic-invariant functions of four-momentum transfer Q^2

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

G_M's roughly follow the dipole form, $(1+Q^2/\Lambda^2)^{-2}$, which has no theoretical significance

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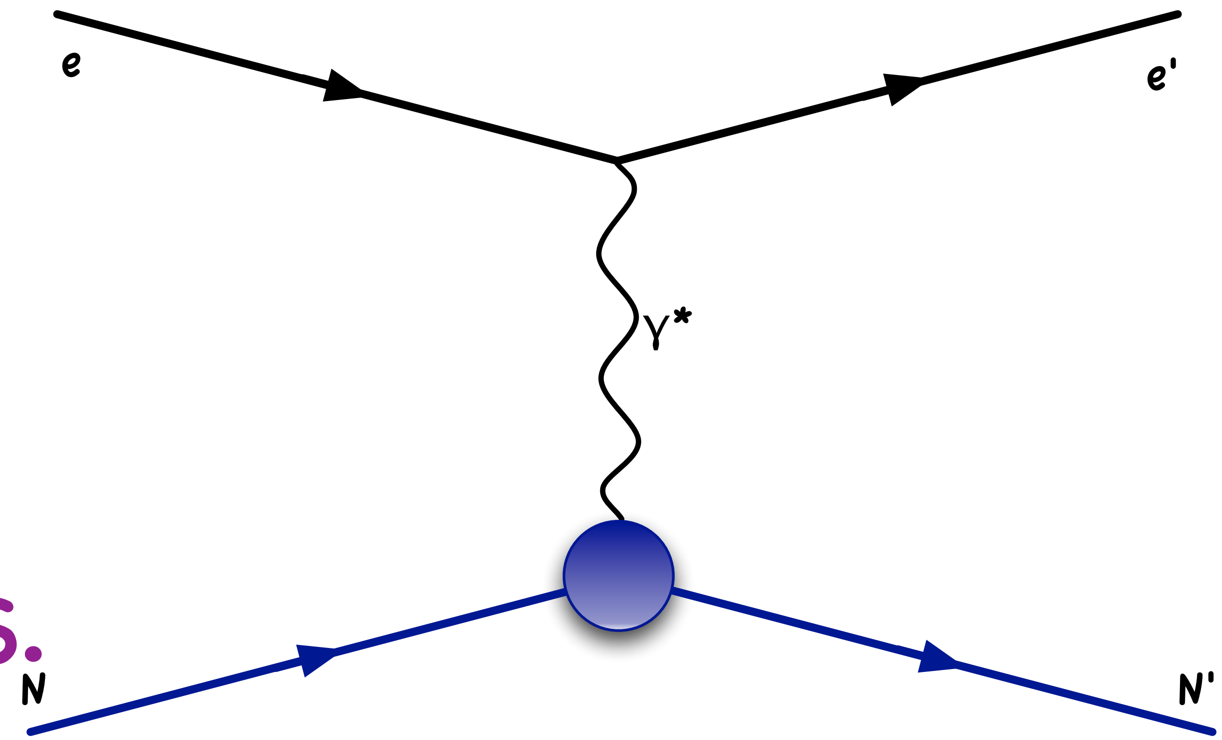
Stuff We Know: Radius means slope of FF at $Q^2 = 0$, it does not mean radius.



In NRQM, scattering theory, F.T. 3d spatial distributions, small-Q^2 expansion:

$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\langle r^2_{E,M}\rangle Q^2 + \frac{1}{120}\langle r^4_{E,M}\rangle Q^4 - \frac{1}{5040}\langle r^6_{E,M}\rangle Q^6 + \cdots$$

Sometimes you get the "right" answer despite the wrong approach

Overall factor of μ taken out of G_M

$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \langle r^2_{E,M}\rangle \equiv r^2_{E,M}$$

Slope of $G_{E,M}$ at $Q^2=0$ defines the radii. This is what FF experiments quote.

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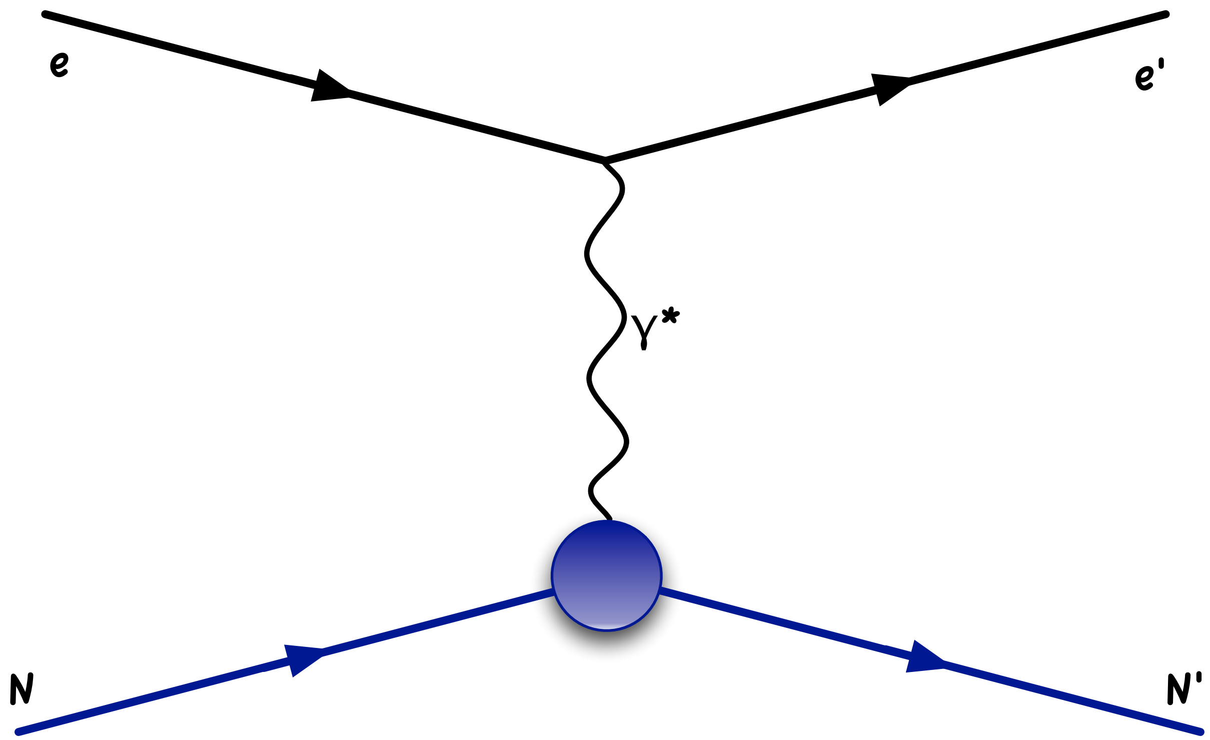
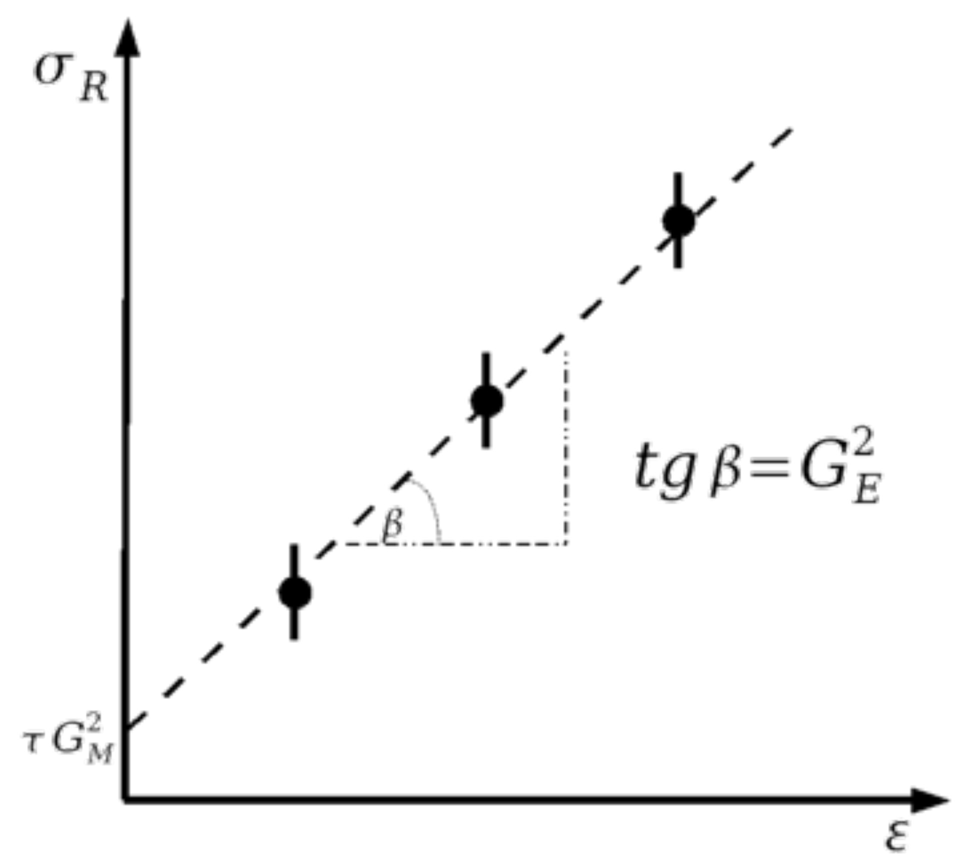
Stuff We Know: Rosenbluth separations do not determine FF with small contribution to cross section well



$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right]$$



For Rosenbluth, multiply RHS by ε/ε and use $\sigma_R = \varepsilon[\ldots]$

At high Q^2, τ is large and G_E is hard to determine

At low Q^2, τ is small and G_M is hard to determine (except for $\theta \approx 180^o$)

Solution already known by early 1960s ➪ polarization measurements

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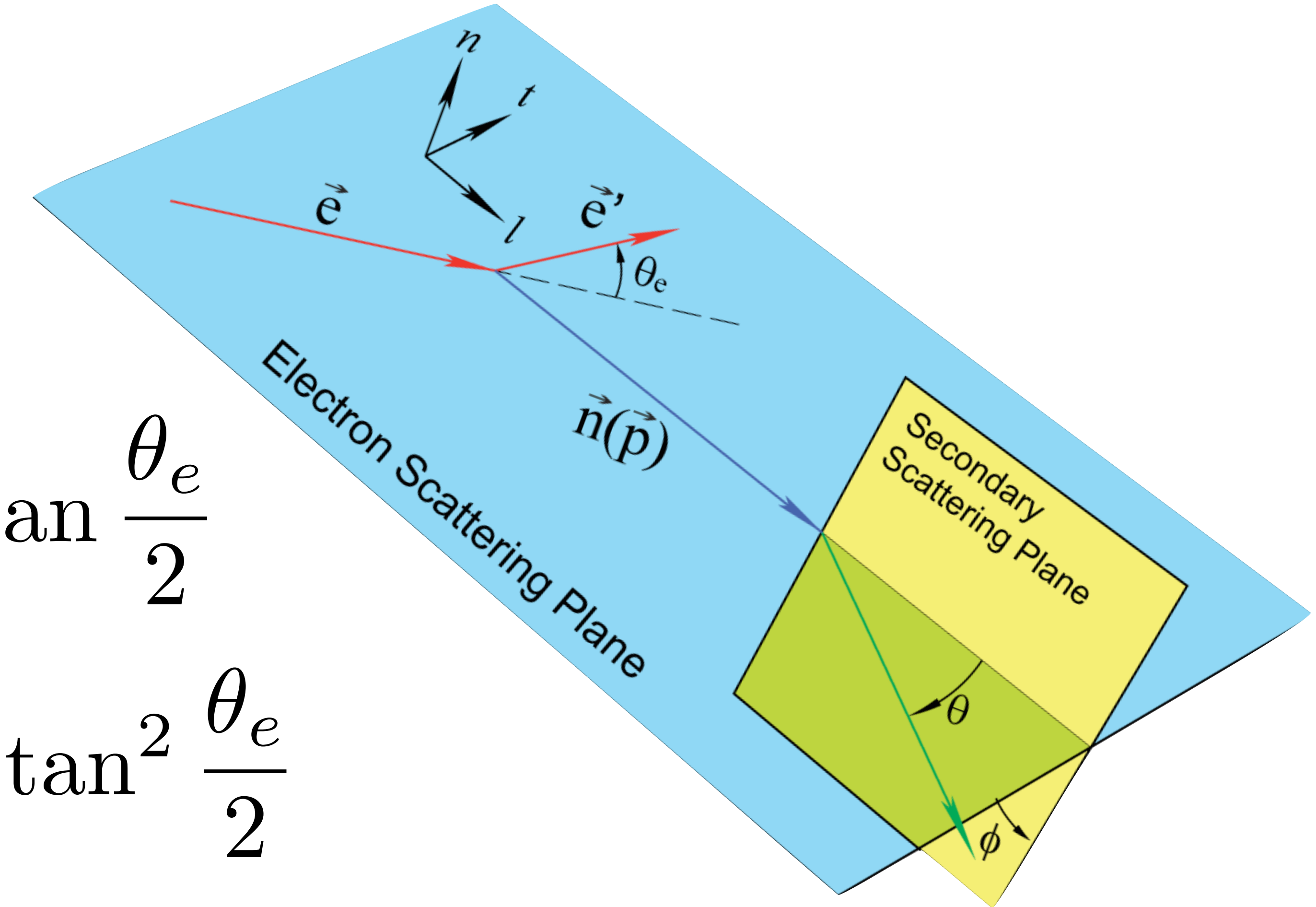
Stuff We Know: Polarization Transfer



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2\frac{\theta_e}{2}$$

$$P_n = 0 \ (1\gamma)$$

$$\boxed{\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}}$$

Polarizations worked on by many. Put in modern form first by Akhiezer & Rekalo (1973). "Popularized" in US by Arnold, Carlson & Gross (1981).

Polarizations measure the ratio G_E/G_M, not the individual form factors.

I_0 is the structure part of the cross section, the [...].

Done at Mainz, MIT Bates, and JLab.

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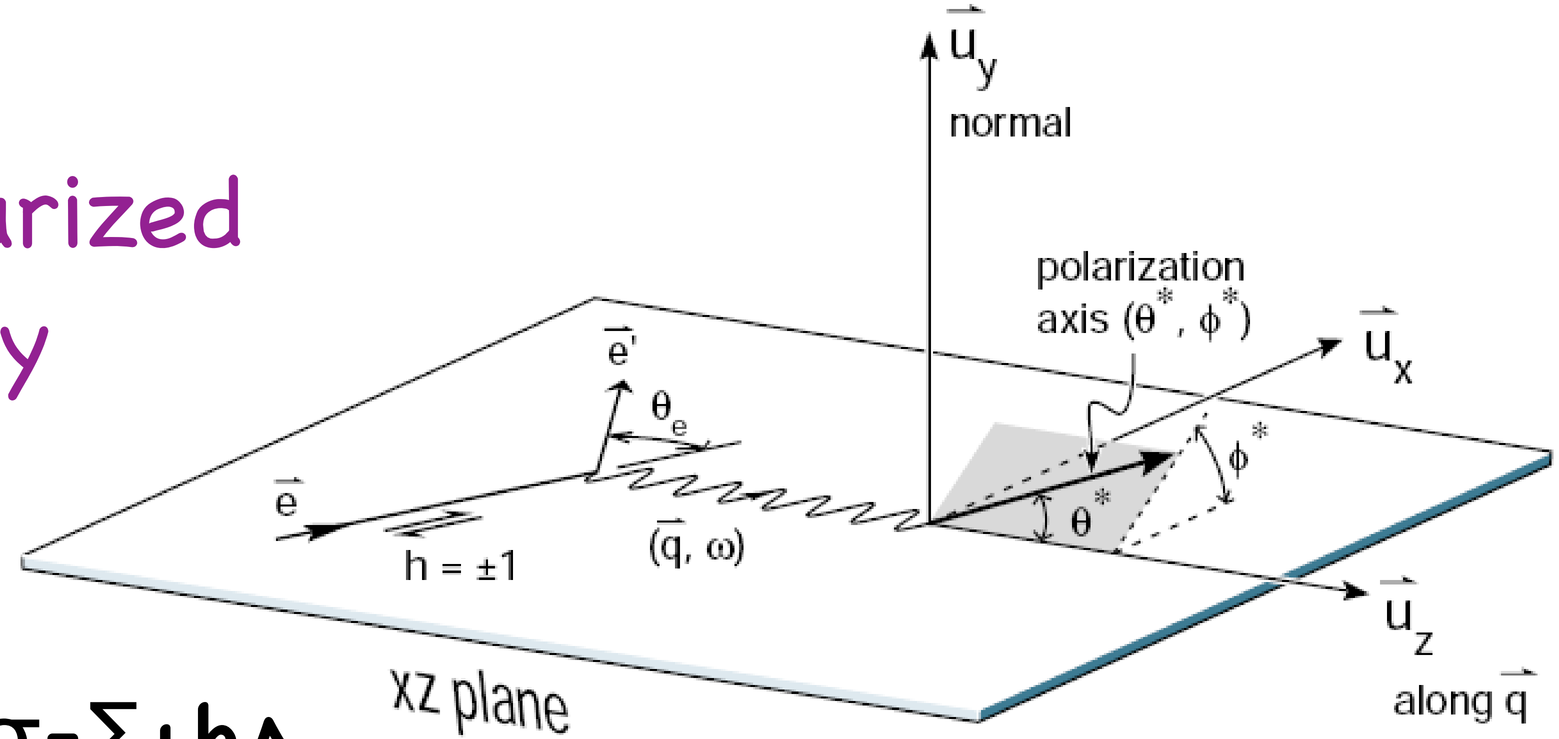
Stuff We Know: Polarized Beam - Polarized Target Asymmetry



Polarized Cross Section: σ=Σ+hΔ

$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\, cos\theta^* G_M^2}^{A_T} + \overbrace{b\, sin\theta^*\, cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

For a single polarization measurement, uncertainties can be limited by polarimetry, to a few percent.

For two simultaneous polarization measurements, these uncertainties can cancel in the ratio of the two.

Can swap between systematic & statistical uncertainties.

a, b, c, d are kinematic factors

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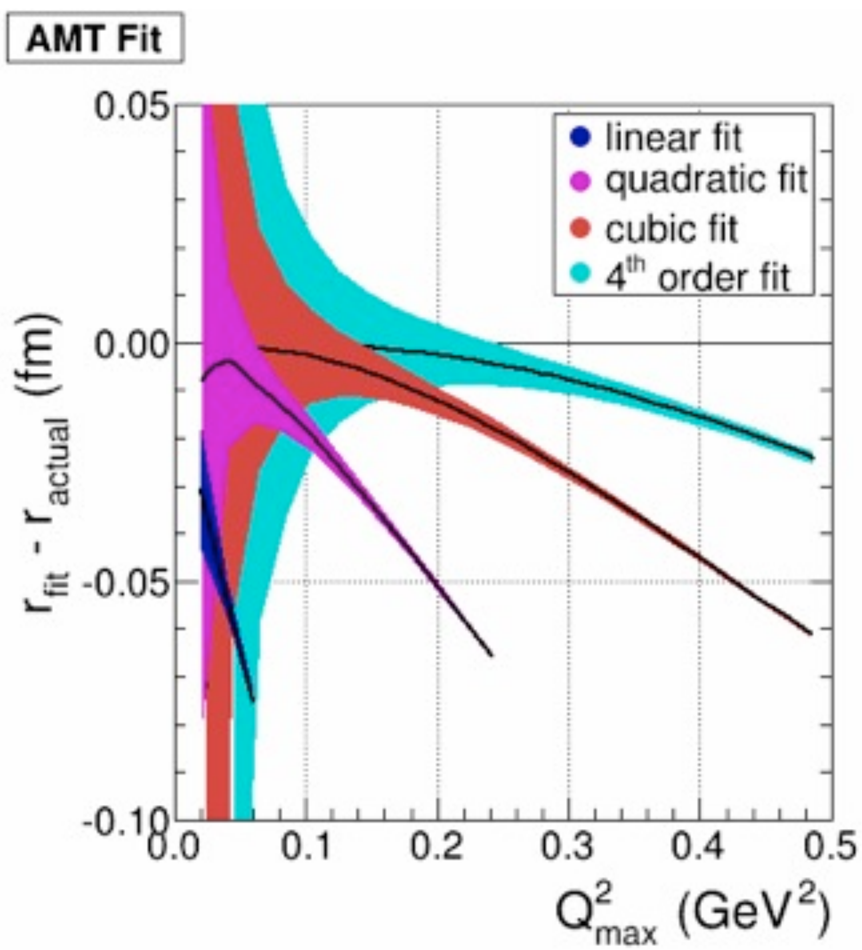
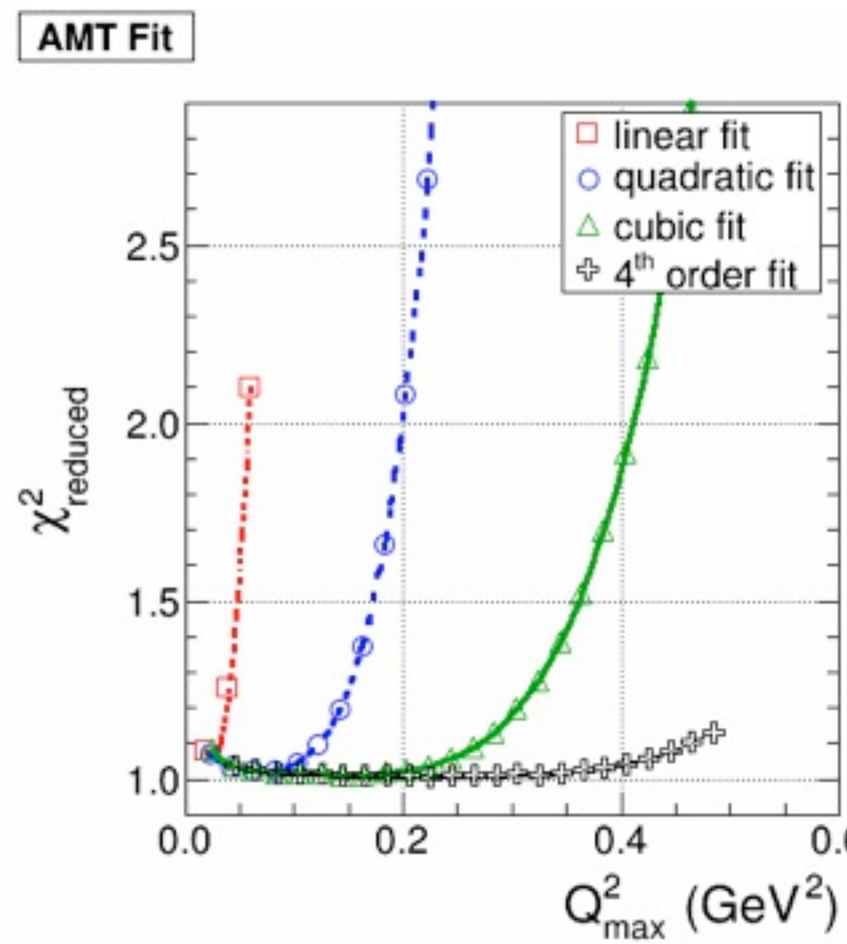
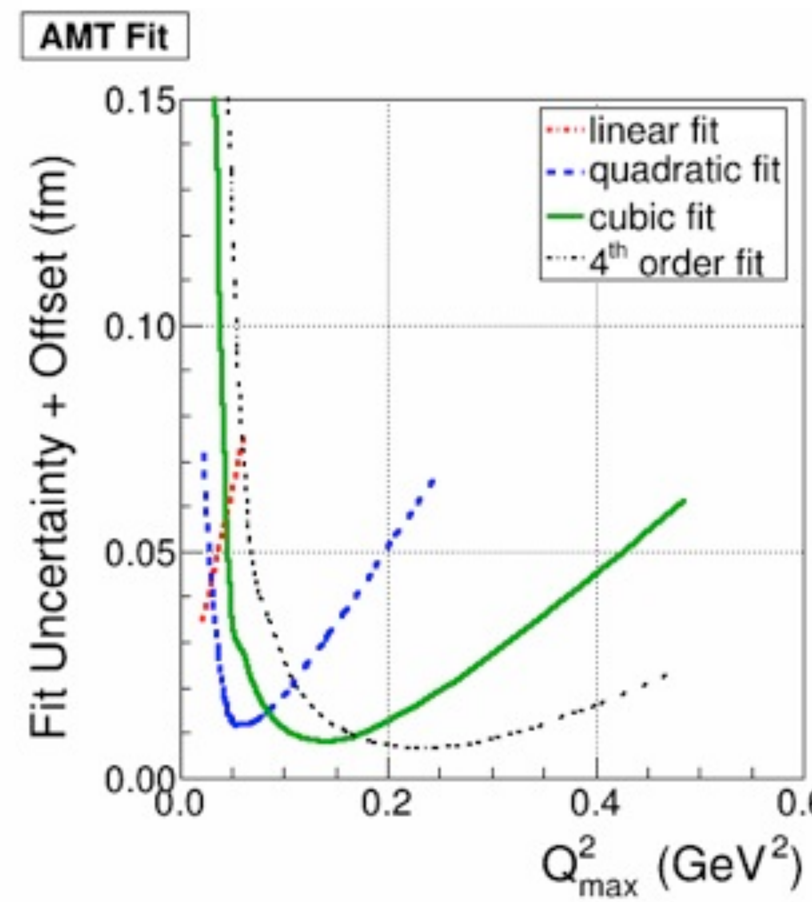
A quick slide on fits

arXiv:1405.4735







Bottom line: Ingo & Michael... have warned us not to do Taylor series fits. We agree.

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