Intense Electron Beams Workshop Cornell June 18, 2015

Polarization in Low Q^2 ep Scattering

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Why?

How?

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Why?

What is measured in ep elastic scattering?

Why?

What is measured in ep elastic scattering?

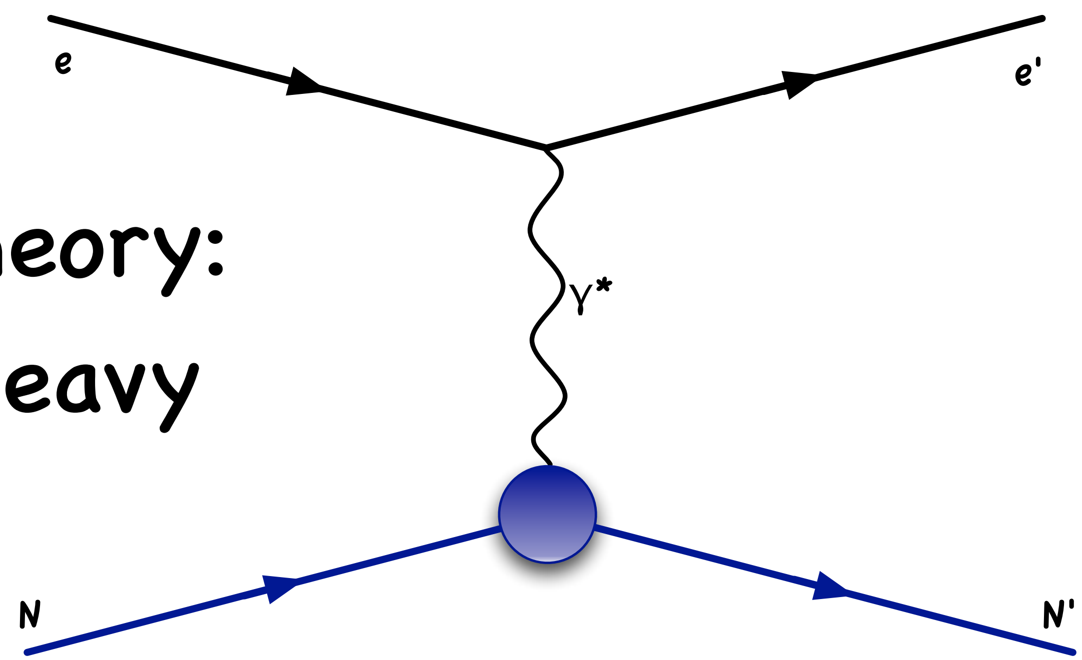
The charge distribution of the nucleon.

Why is that interesting?

Generally: fundamental property of nucleons - but most of the interest is at large Q^2.

Except: ongoing issues with radii and two-photon exchange. Impact on hyperfine theory uncertainties. Suggestions of structures in form factors. Etc.

ep Elastic Scattering Theory



Introductory NR QM scattering theory:
Charge scattering from infinitely heavy charge distribution

$$M = \langle \psi' | V_{int} | \psi \rangle \sim \int e^{-i\vec{q}\cdot\vec{r}} \frac{\rho(r)}{r} dV$$

(A Fourier transform)

Assume spherical symmetry, integrate over angular coordinates, expand for small q

$$G_E(q^2) \sim M \sim 1 - q^2 \left\langle r^2 \right\rangle /6 + q^4 \left\langle r^4 \right\rangle /120 - ...$$

ep Elastic Scattering Theory

In the limit m<<E, m<<M, we have the Rosenbluth formula:

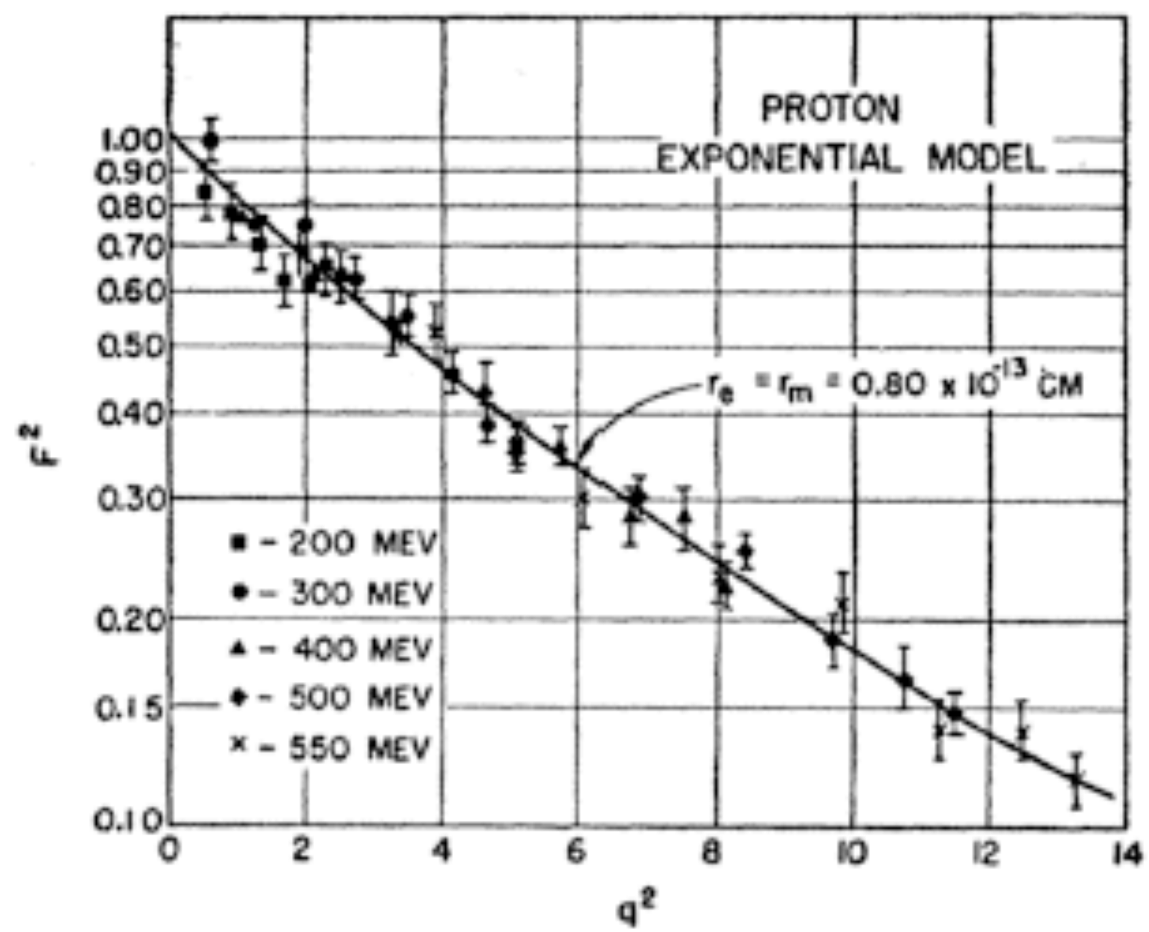
$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2(\theta/2)\right]$$

$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2}\frac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}\frac{1}{1+\frac{2E}{M}\sin^2\frac{\theta}{2}}$$

See Preedom & Tegen, PRC36, 2466 (1987) for the exact formula.

Scattering done since 1950s

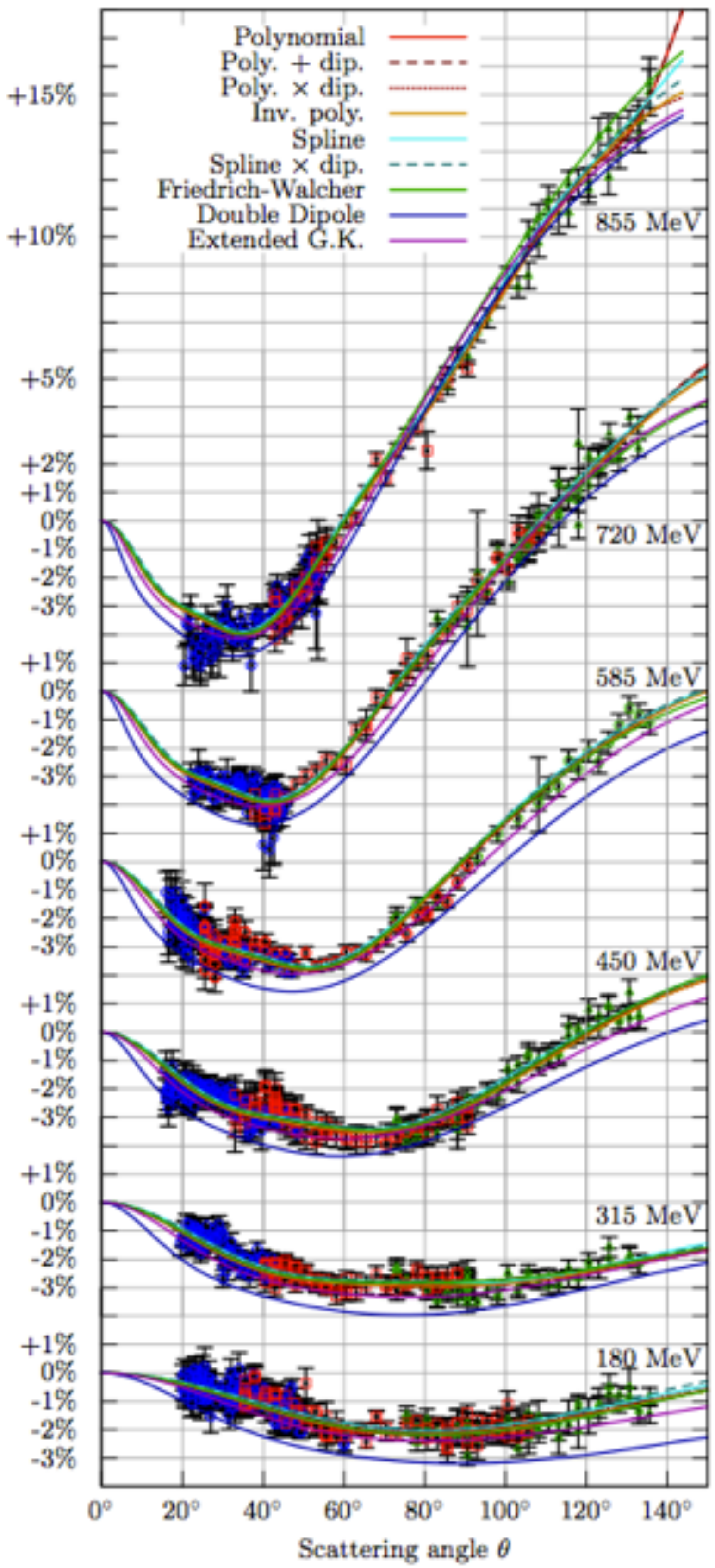
Chambers and Hofstadter,
Phys Rev 103, 14 (1956)



crude approximation:

$G_E,\ G_M/\mu \approx (1+Q^2/0.71)^{-2}$

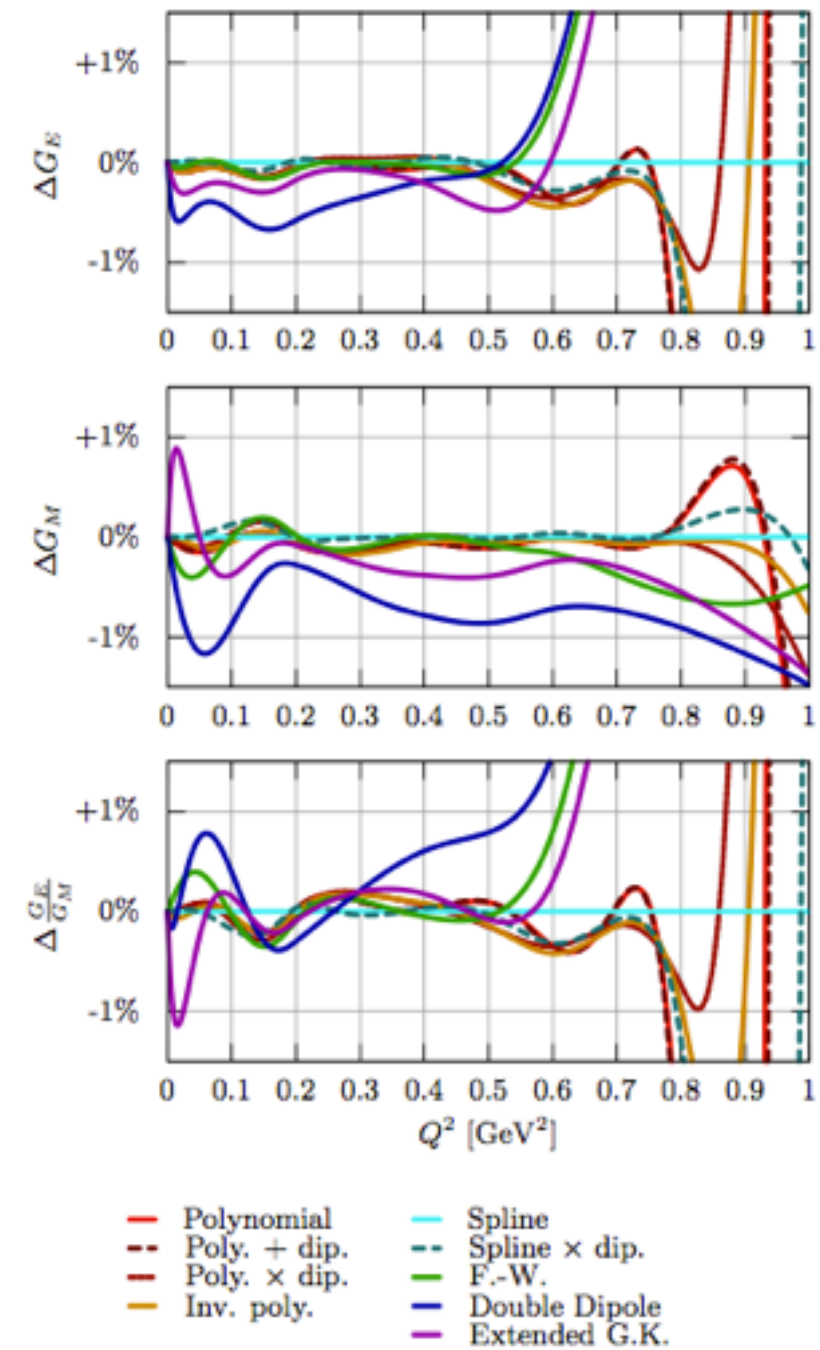
J. Bernauer et al., PRL 105, 242001 (2010)



Largest & best ep data set ever

Left: Various fits vs. cross sections, all relative to "standard dipole"

Right: variation in fits to data, relative to spline. Some fits have poor χ^2, so uncertainty less than variation.



$r_p = 0.879 \pm 0.008$ fm

What is the issue?

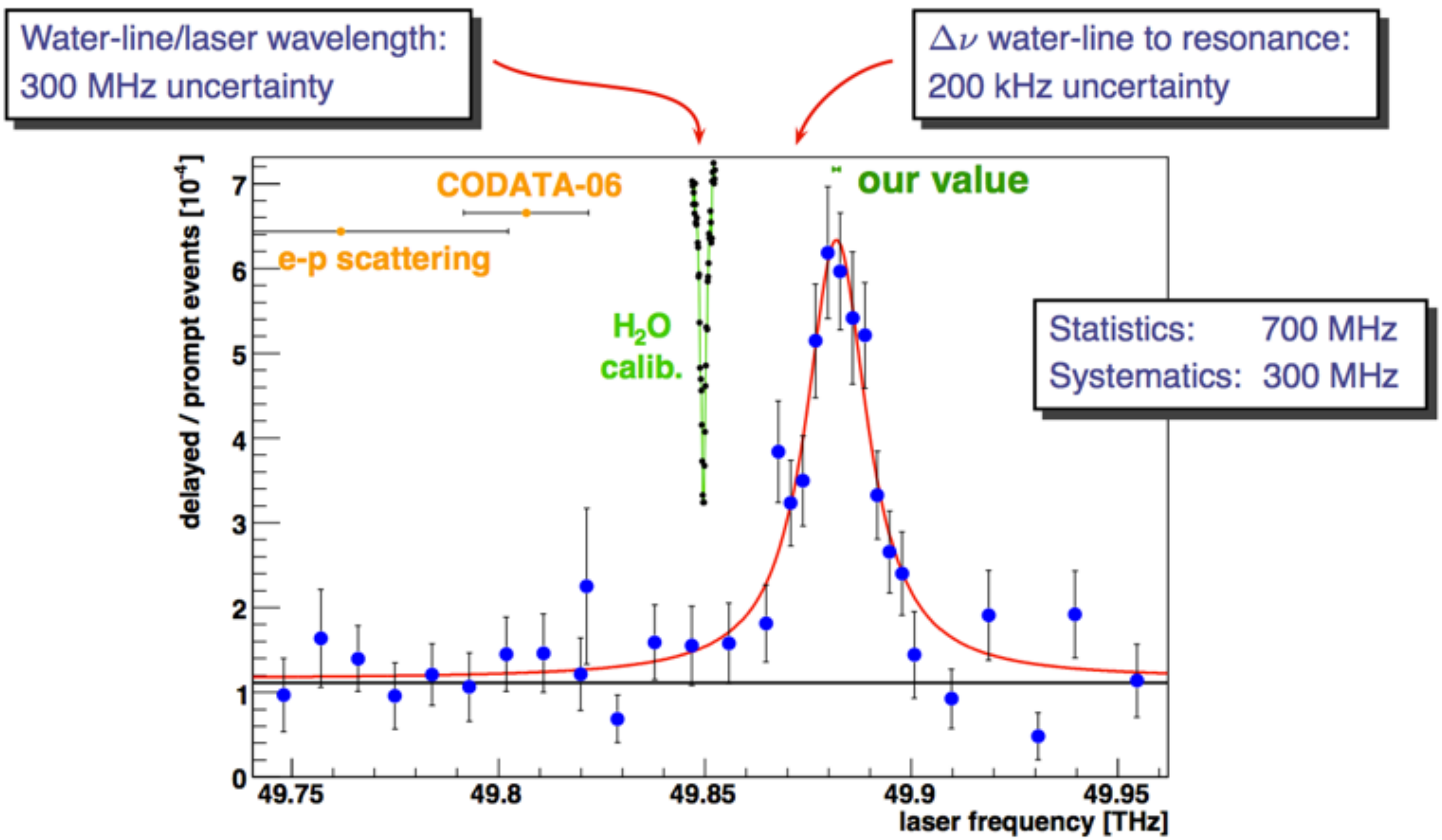
Muonic hydrogen gives a different radius - Proton Radius Puzzle.

Electron scattering has its own magnetic radius puzzle.

What is the Proton Radius Puzzle?

From R. Pohl et al., Nature (2010)

Measurement of a muonic Hydrogen transition frequency depends on proton size



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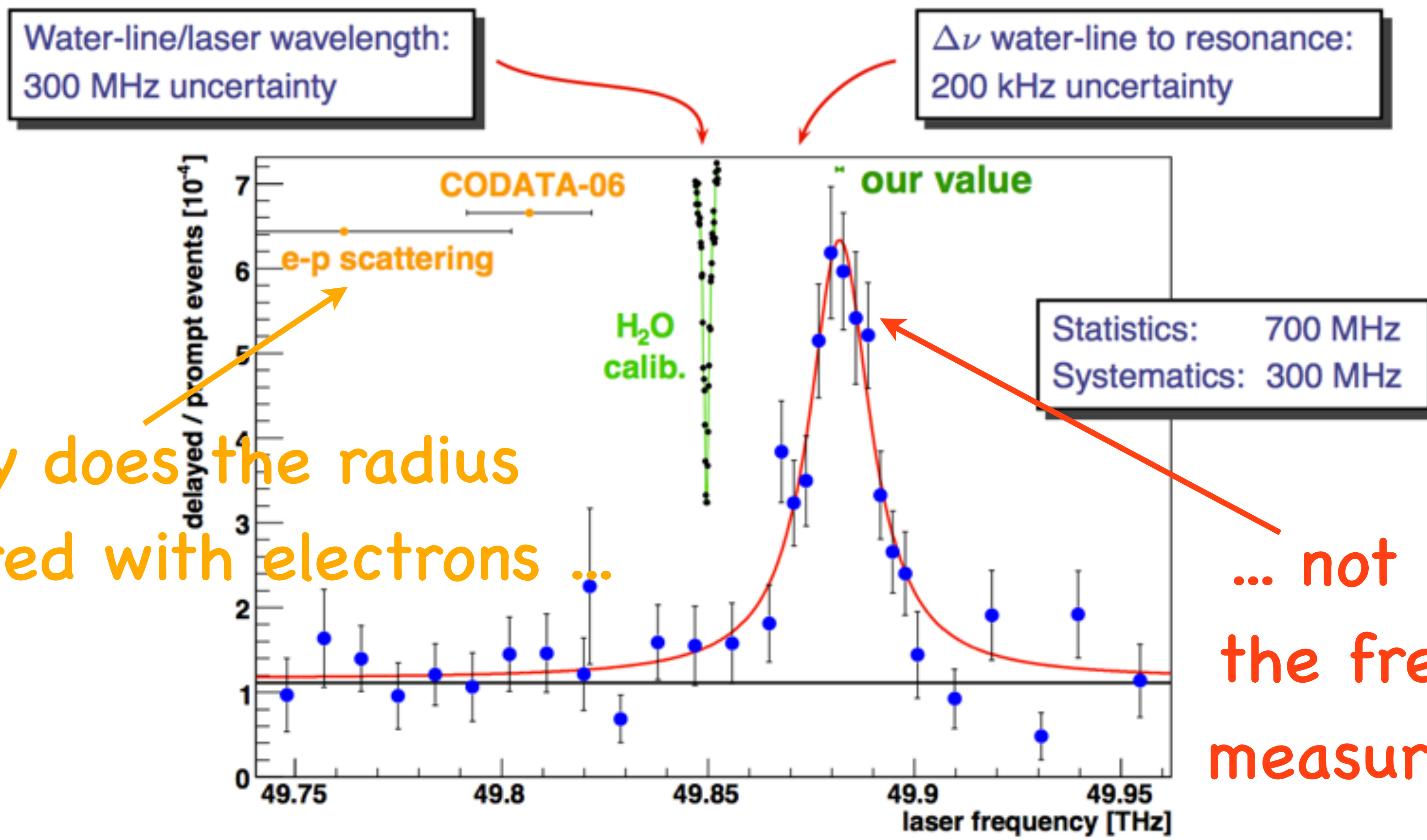
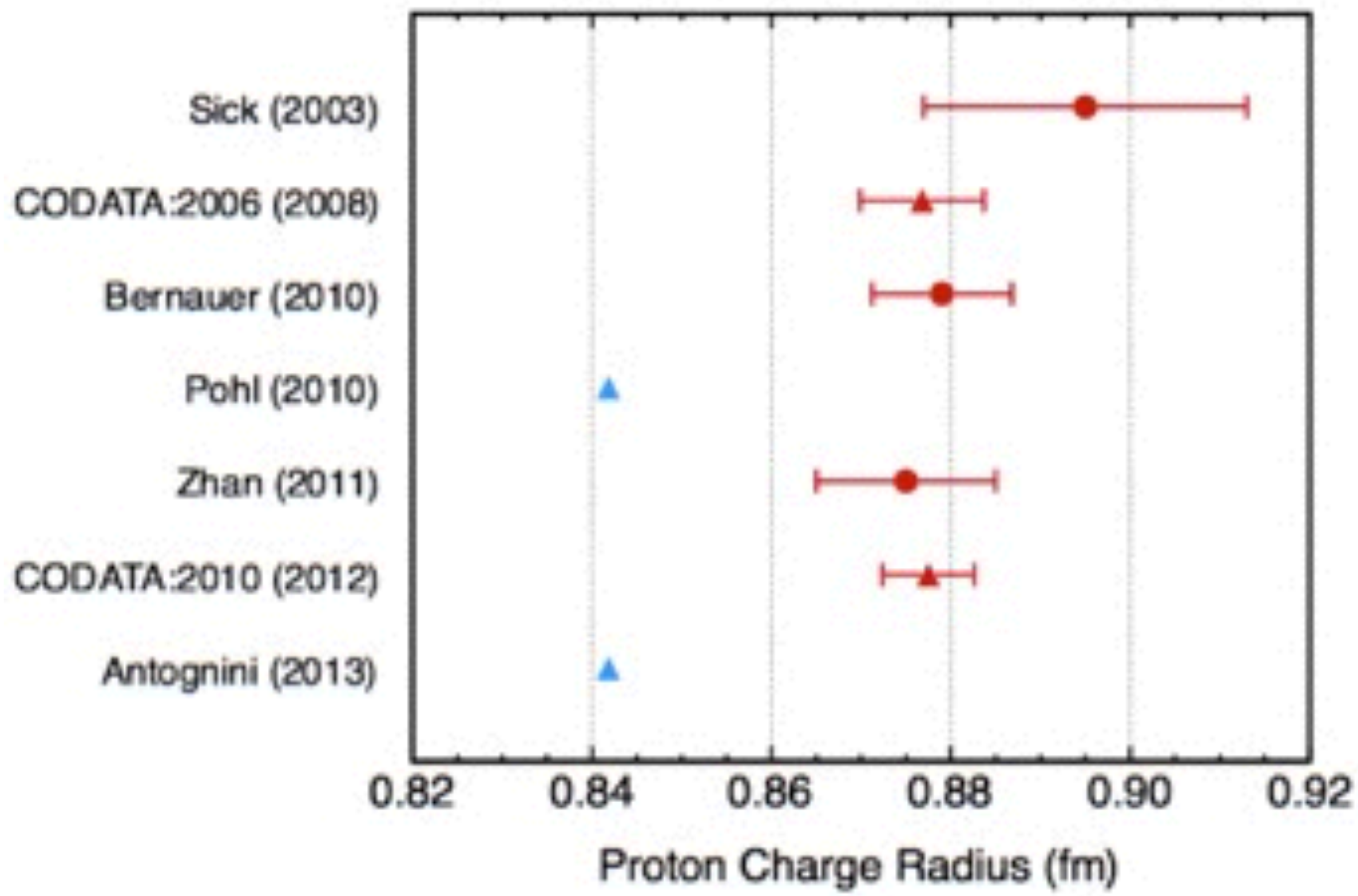


Why does the radius measured with electrons ...

... not predict the frequency measured with muons?

Current Experiment Summary



CODATA 2010: 0.8775 ± 0.0051 – 7.2σ difference

Either radii from some experiments are wrong, or there is some interesting physics

Current Experiment Summary

r_p (fm)	atom	scattering
electron	0.8779 ± 0.0094 (Pohl)	0.879 ± 0.008 (Mainz) 0.875 ± 0.009 (JLab)
muon	0.84087 ± 0.00039 (Antognini)	?

CODATA 2010: 0.8775 ± 0.0051 – 7.2σ difference

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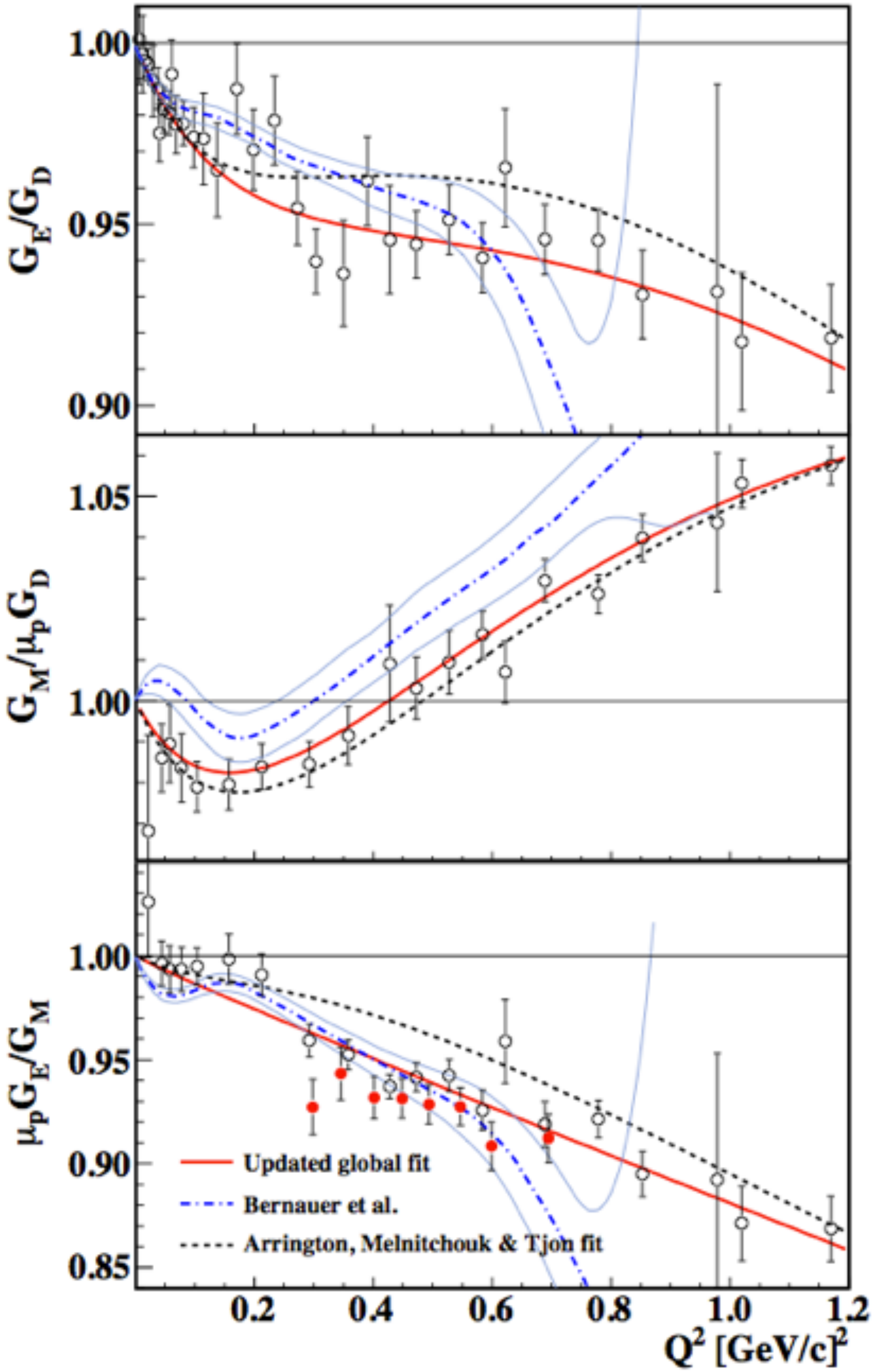
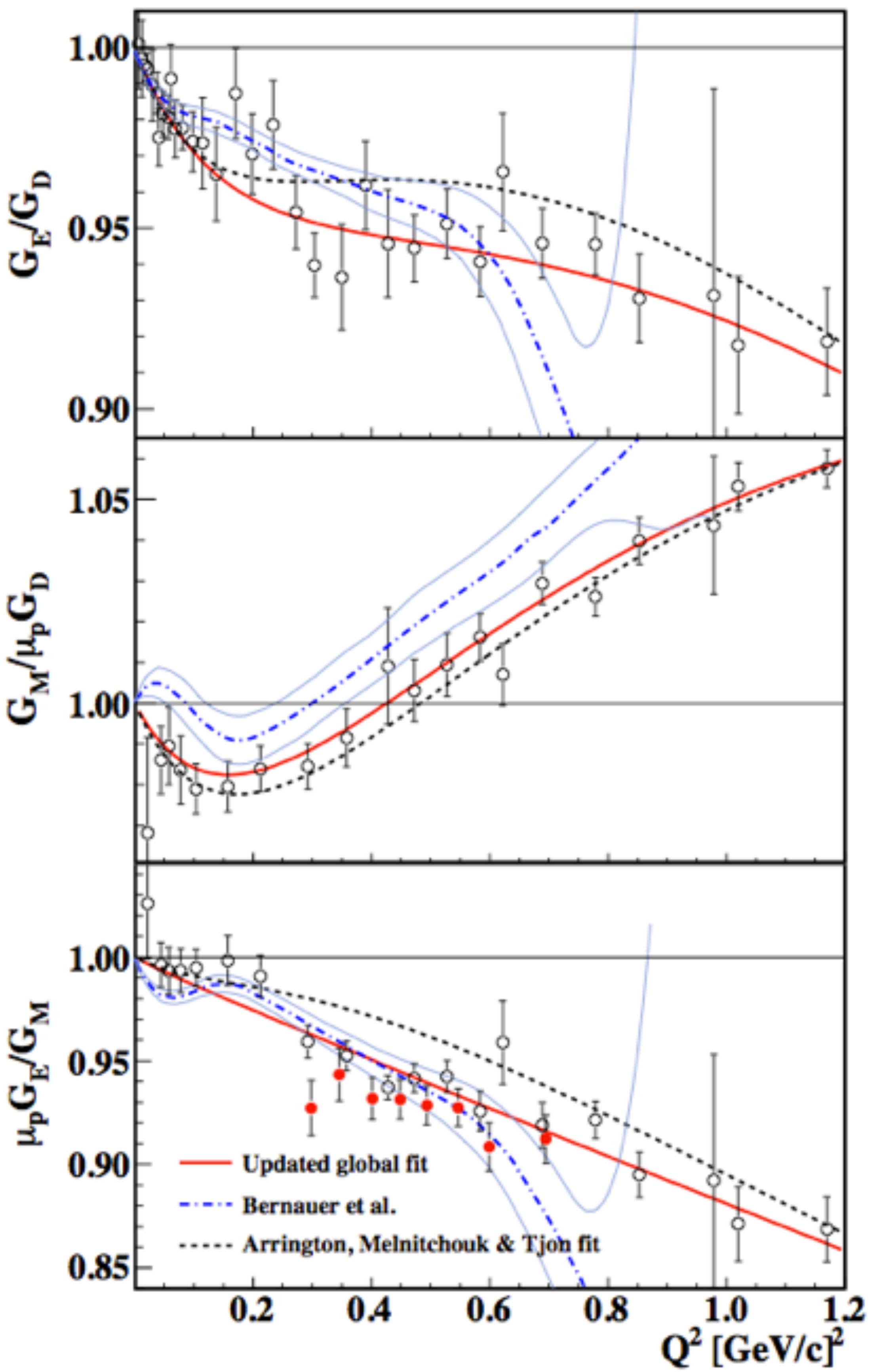
Magnetic Radius Puzzle



Jefferson Lab E08-007, part I (X. Zhan et al., PLB 705, 59,2011):
Recoil polarization measurement, + fit including all non-Mainz world data

Jefferson Lab E08-007, part II, Polarized target+beam asymmetries, at much smaller Q^2, under analysis
G. Ron, M. Friedman, et al.

Magnetic Radius Puzzle



Mainz and JLab agree on charge r_p.

Mainz and JLab agree on G_E/G_M.

Mainz and JLab do not agree on magnetic r_p. (Some part of this is RC.)

Mainz and JLab have 1-2% differences for G_E and for G_M.

Low Q^2 Puzzles

Given the disagreements in G_E and G_M, and r_M, and r_p with muons, it would be good to have new and improved low Q^2 data!

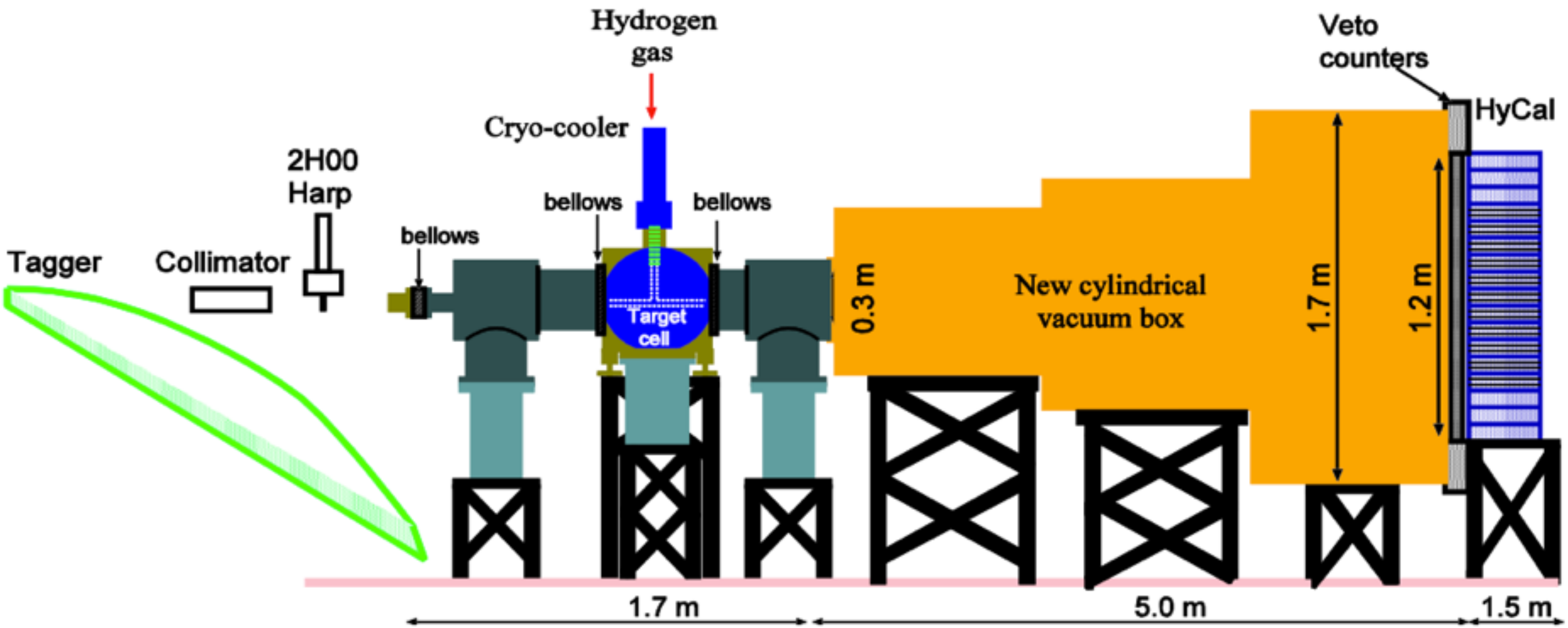
Lots of things underway because of PRP:

- muonic atoms
- new hydrogen atomic physics
- PRAD - low Q^2 scattering at JLab - closest to this idea
- MUSE - low Q^2 ep and mup at PSI

Depending on why we have a PRP, these might resolve it, or might not.

PRAD: 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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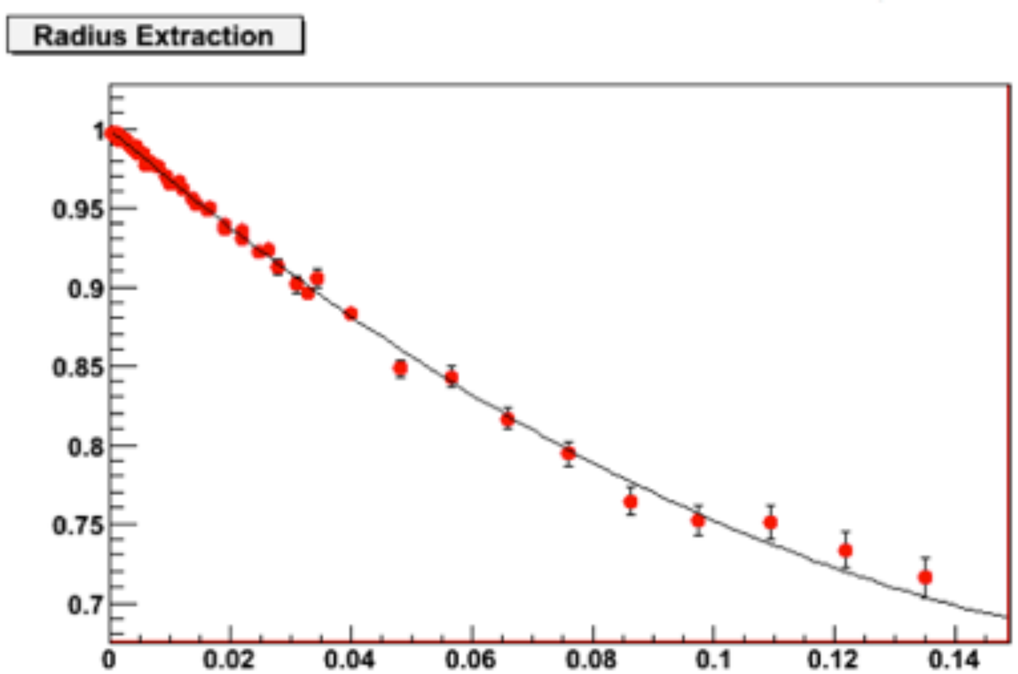
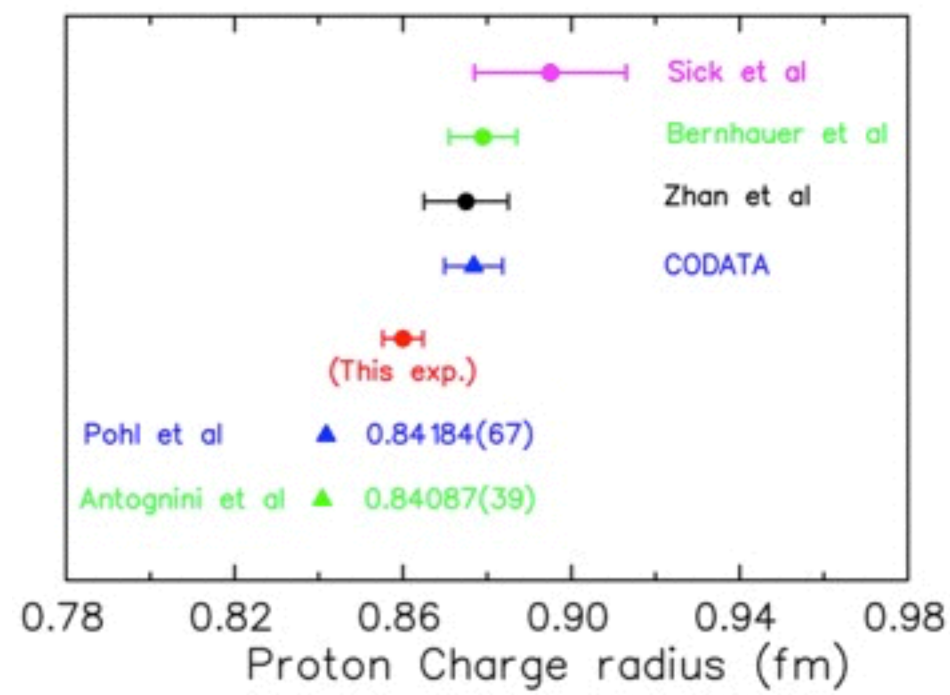


G_E vs Q^2 data simulated, to show radius out = radius in



Projected result

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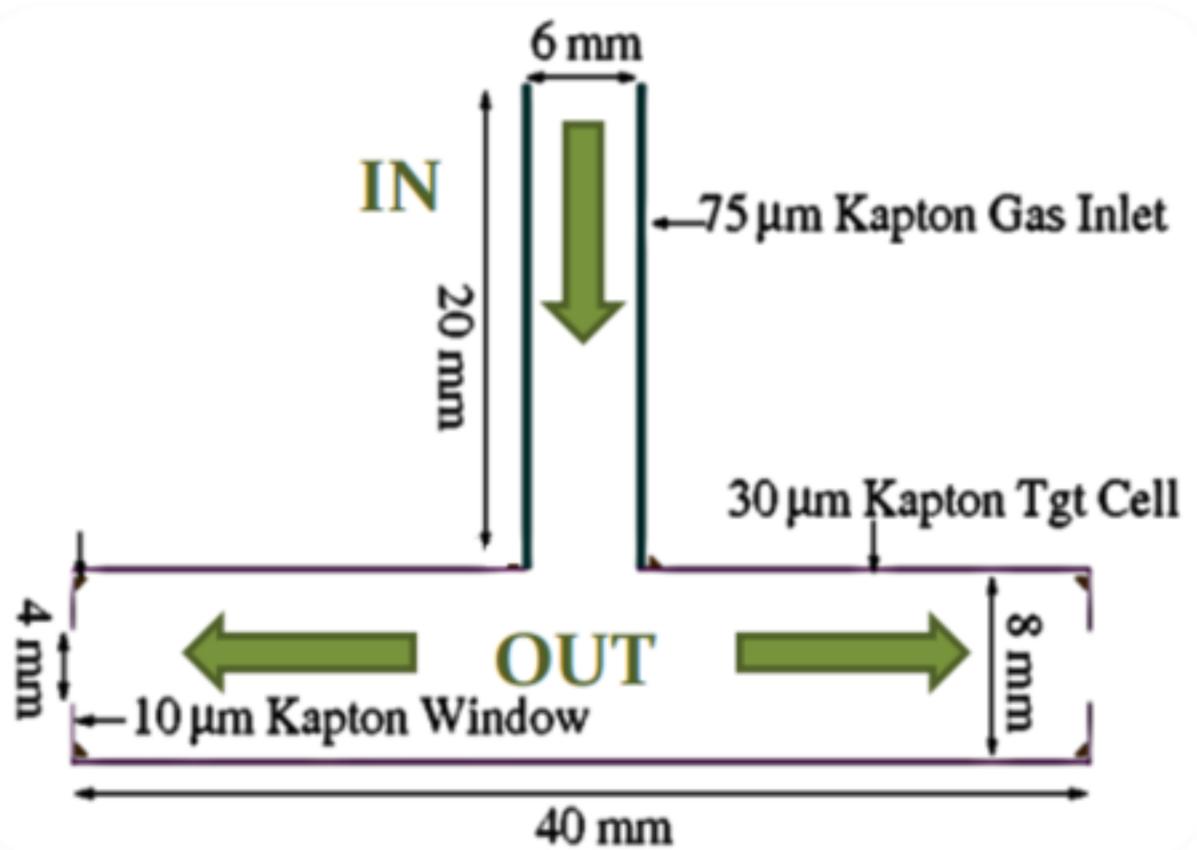
PRAD

JLab Hall B PRAD has A priority.
Expected to run in 2016.
"10 nA" beam on a 25 K cooled gas target, 10^{18} atoms/cm^2.
L ≈ 10^{29}/cm^2/s



Note: this sort of technique first used with 100-200 mA, 2-GeV electron in VEPP-3, with cell increasing target density x15 from about 10^{11}/cm^2 to 3×10^{12}/cm^2.
Drifilm coating kept cell atoms highly polarized.
R. Gilman et al., PRL 65 (1990)
(Authors alphabetical.)

Cornell vs. PRAD

How would intense Cornell electron beam be better than PRAD type experiment?

- Increase beam about 6 orders of magnitude, reduce target thickness, get equal or better rate.
- Beam is polarized - go to polarized atomic source and get similar rates to PRAD, but with added benefit of form factor ratio measurements from asymmetries, as well as cross section measurements.
- With polarized beam+target, measure directly form factor ratio and relative cross sections. Limits effect of certain radiative corrections, which are important to get right to get G_M at low Q^2.

Note also using a gas or atomic beam target minimizes the external radiative corrections.

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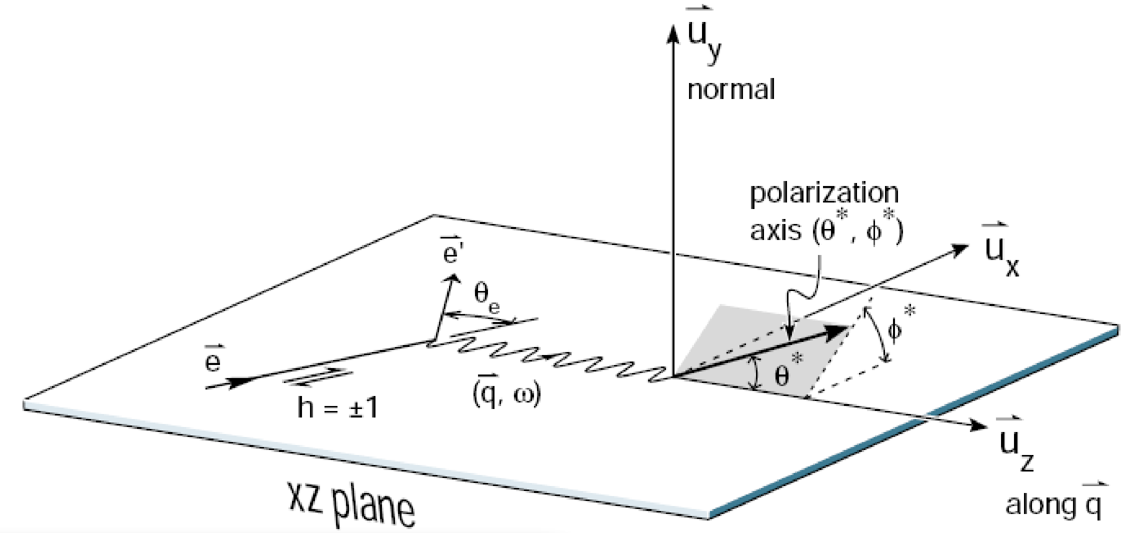
Polarized Beam - Polarized Target Asymmetry Notes



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

a, b, c, d are kinematic factors

$\theta = \pi/2$: A_{LT} term proportional to form factor ratio $R = \mu G_E/G_M$

$\theta = 0$: A insensitive to R, mostly sensitive to kinematic factors

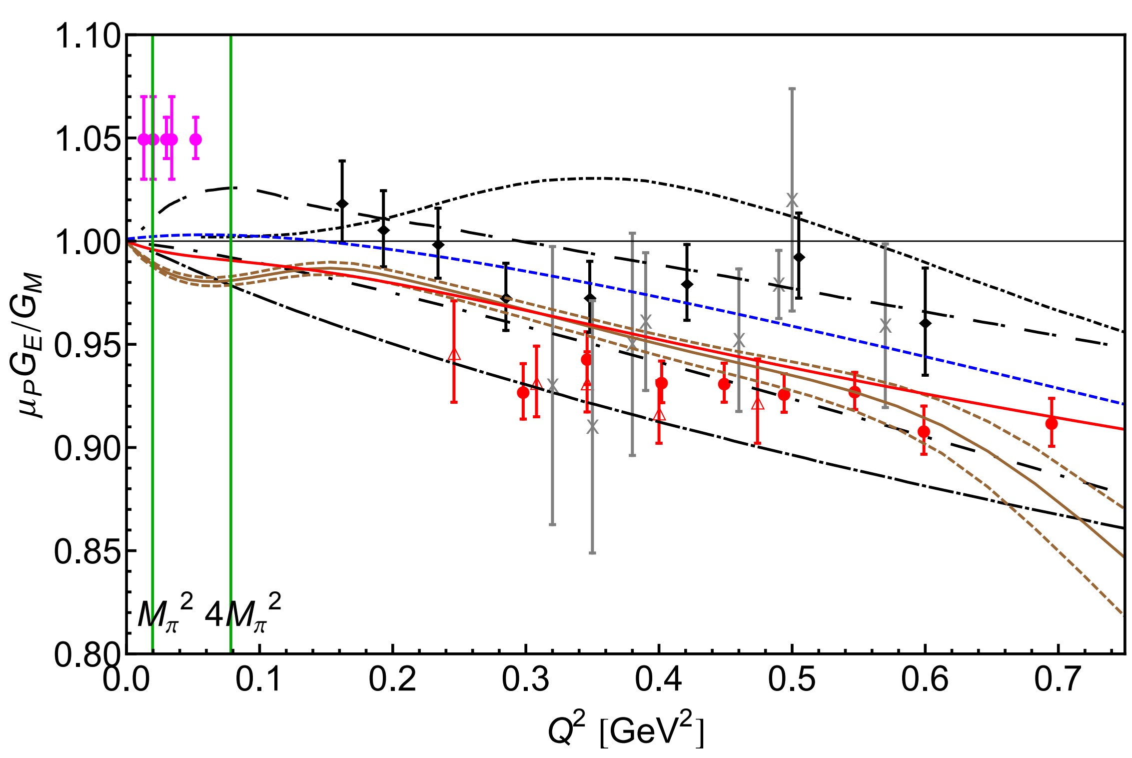
For a single polarization measurement, uncertainties can be limited by polarimetry, to a few percent. But for two simultaneous polarization measurements, these uncertainties can cancel in the ratio of the two.

A leading systematic uncertainty is replaced by a statistical one + a smaller systematic (polarization direction), which is checked by the asymmetry variation.

Polarizations

Technique used before, in Bates BLAST measurements (black points below) and in JLab Hall A E08-007 Part II (magenta points - projected uncertainties). Recoil polarimetry at JLab widely used (red points), mainly at higher Q^2.

A similar story for the deuteron.
Could also be done for ^3H, ^3He.



What kinematic range is possible with 10 mA, 500 MeV beam?

Angle	Q^2 (GeV^2)	ε	rate - $10^{11}/cm^2$ polarized atomic beam	rate - $10^{18}/cm^2$ cell
1	10-4	1	3	30 MHz
10	0.0075	0.985	30 mHz	300 kHz
100	0.361	0.242	10 μHz	100 Hz

Adjust target thickness to optimize data taking for different Q^2 regions?

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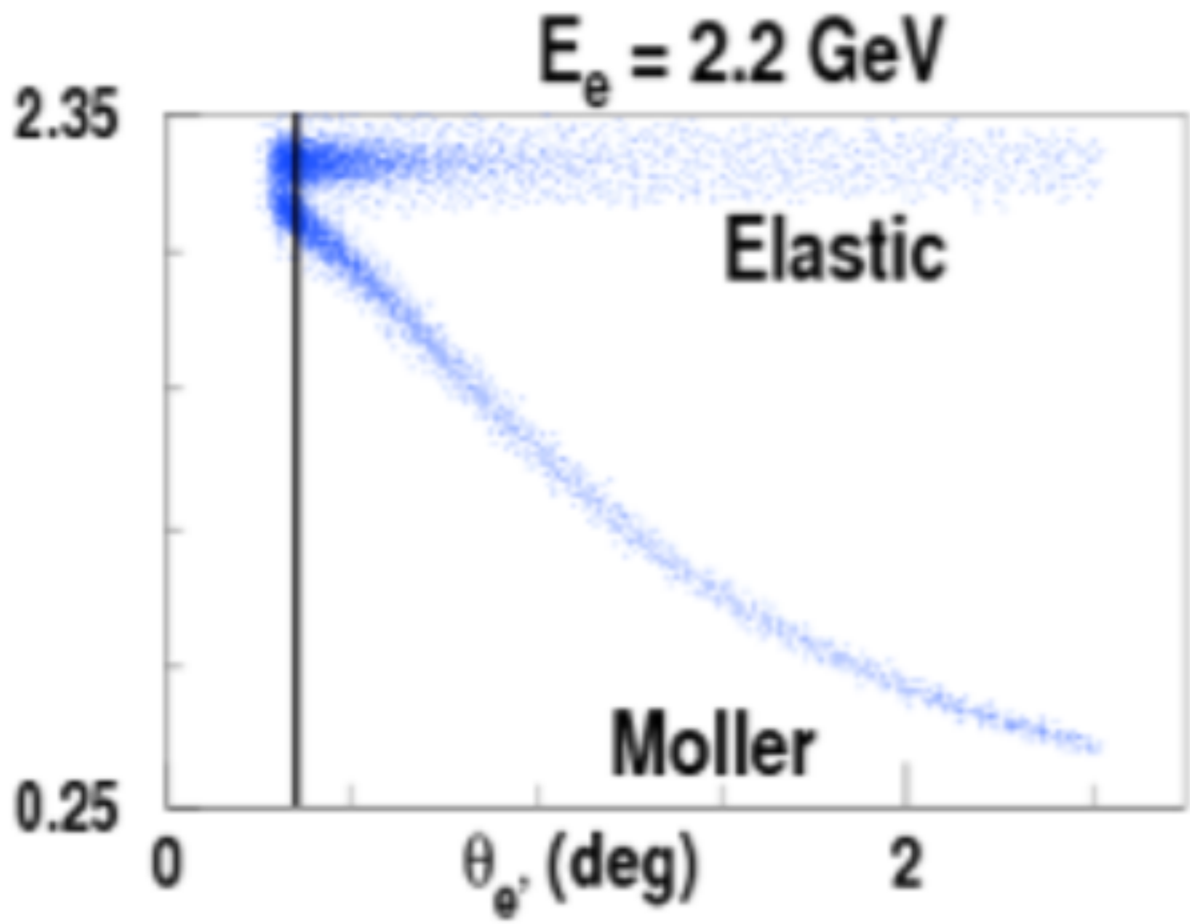
What are the main physics background issues?

Target cell backgrounds - depends on beam properties.
Moller scattering at forward angles.
Pion electro-production (generally small).



PRAD simulation

What are the main experimental issues?

System to handle widely varying rates - lots of interesting technologies to consider if the $ are available.

At this point the experiment would be most compelling - and most able to request significant $ - if in a few years the new PRP results show continued issues with no resolution.

For now, my opinion is: we should just keep in mind whether any system built can measure precise relative cross sections, and asymmetries. Perhaps with simple modifications.

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Summary

Polarized beam + target to obtain precise form factor ratios and relative cross sections can help improve knowledge of form factors.

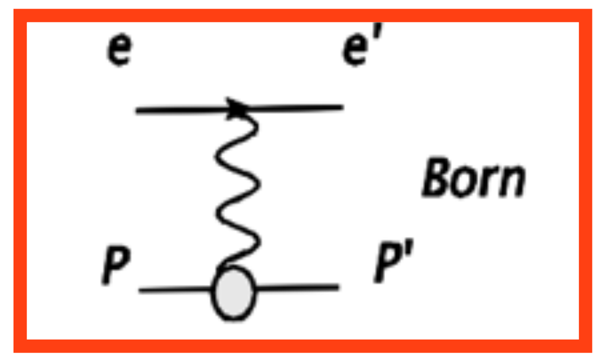
Long established physics, so absent a puzzle does not command large resources.

For now, we should just keep in mind whether any system built can measure precise relative cross sections, and asymmetries.

Radiative Corrections

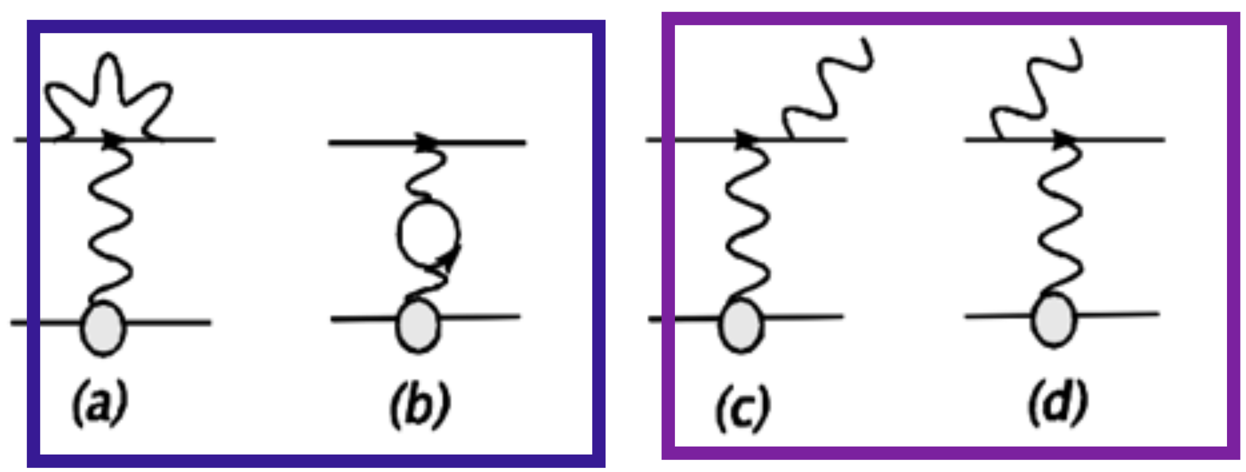
Experiments measure cross sections, which determine form factors. But corrections are needed.

This term determines the form factors.



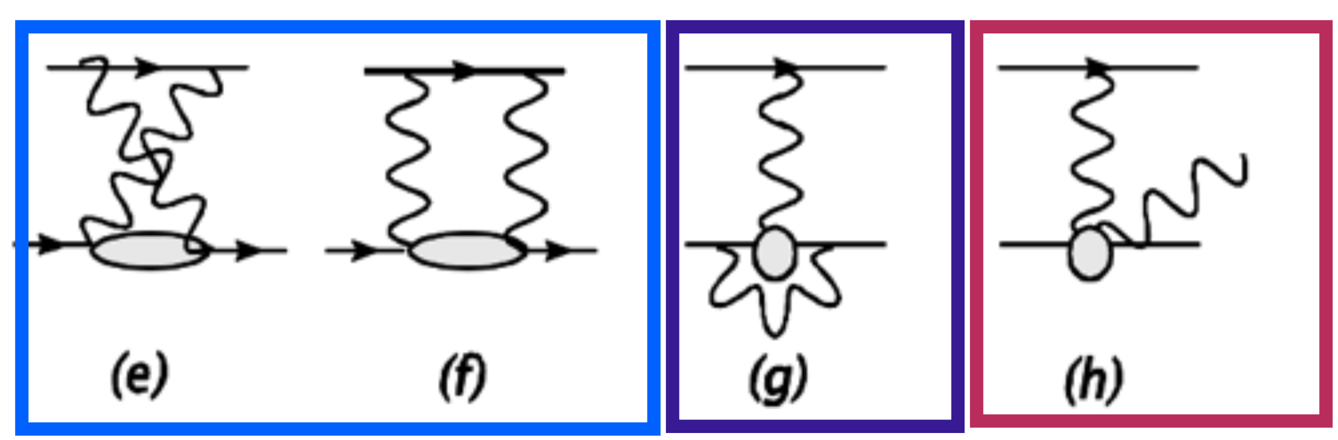
Vertex corrections, vacuum polarization – under control

Bremsstrahlung – conventional, calculable

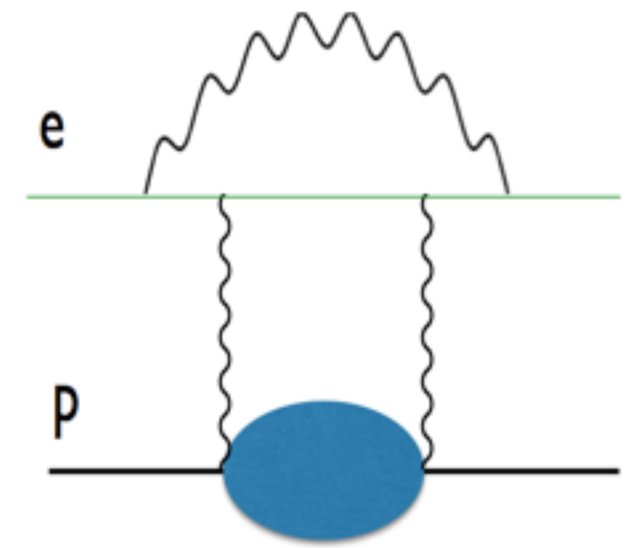


TPE: more problematic – OK if 1 soft photon

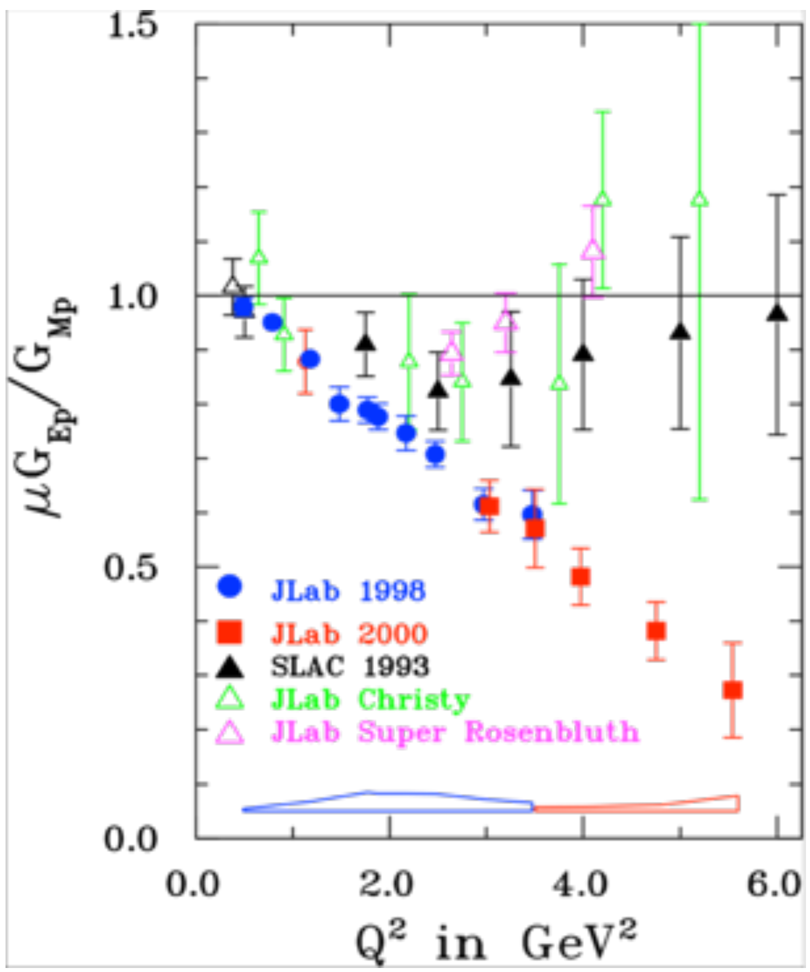
Virtual Compton scattering – small and hard to measure.



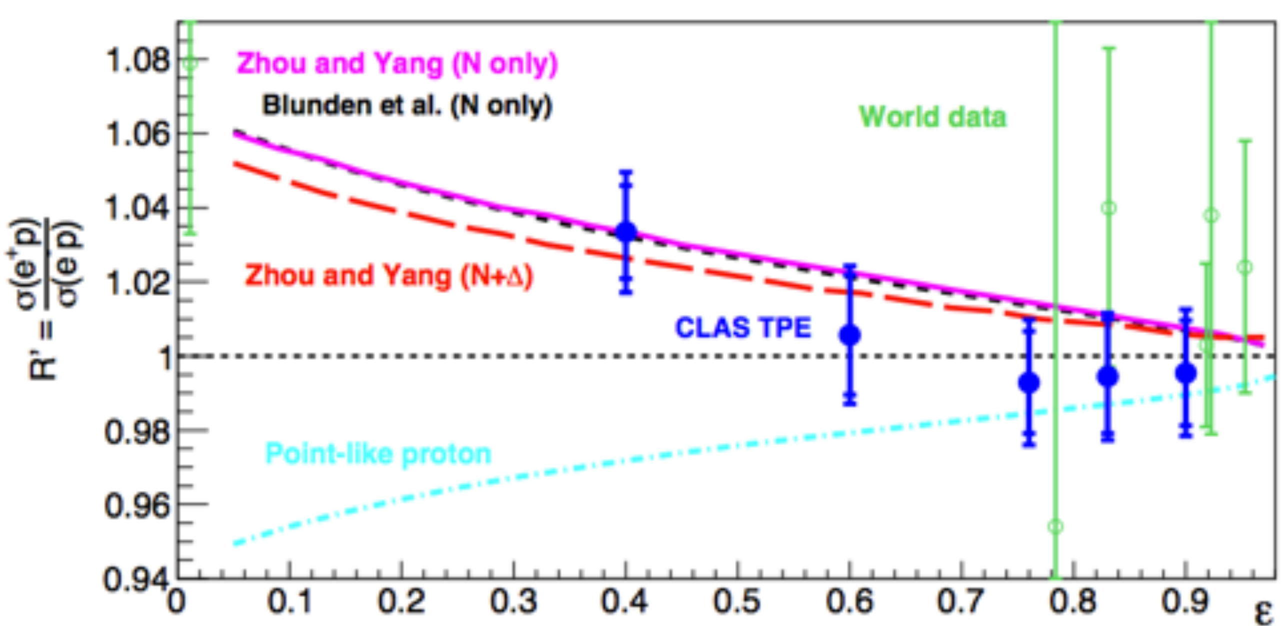
TPE Warning



Long a subject of interest in the EM community - why do proton form factor polarization and cross section measurements disagree?



Our conventional explanation: TPE. But recent experimental results indicate that TPE is smaller than estimated and not well understood.



Possibly an issue at low Q^2 as well?