WILLIAM & MARY
CHARTERED 1693

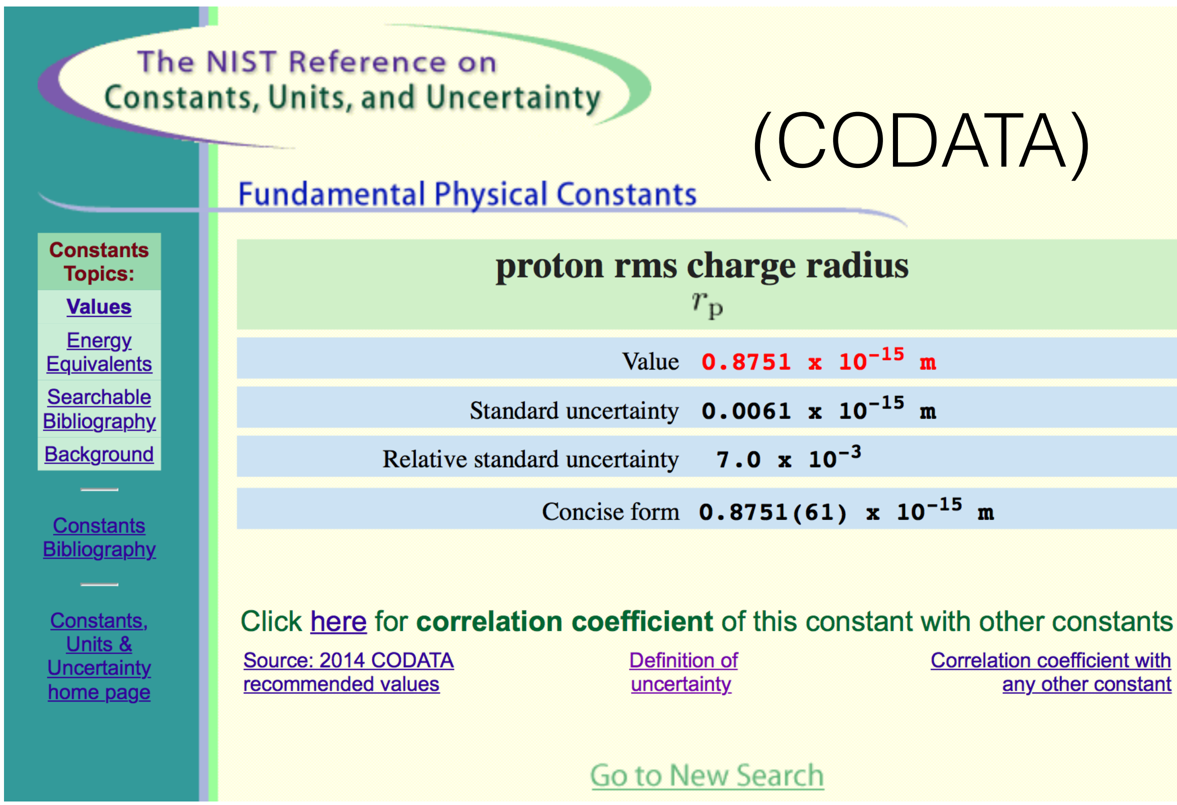
Extractions of the proton and deuteron charge radii from scattering experiments

Hadronic Contributions to New Physics Searches
25-30 Sept. 2016, Tenerife, Spain

Keith Griffioen
College of William & Mary griff@physics.wm.edu

The Proton Size Puzzle

Until 2010, conventional wisdom had the proton's rms radius r_p= 0.875(6) fm



The NIST Reference on Constants, Units, and Uncertainty

Fundamental Physical Constants

Constants Topics: Values | Energy Equivalents | Searchable Bibliography | Background | Constants Bibliography | Constants, Units & Uncertainty home page

proton rms charge radius
r_p

Value	0.8751×10^{-15} m
Standard uncertainty	0.0061×10^{-15} m
Relative standard uncertainty	7.0×10^{-3}
Concise form	$0.8751(61) \times 10^{-15}$ m

Click here for **correlation coefficient** of this constant with other constants

Source: 2014 CODATA recommended values | Definition of uncertainty | Correlation coefficient with any other constant

Go to New Search

(CODATA)

This came both from electron scattering and hydrogen Lamb shift measurements

In 2010, muonic hydrogen Lamb shift measurements found

rp = 0.84184(67) fm

Size Puzzle Solution?

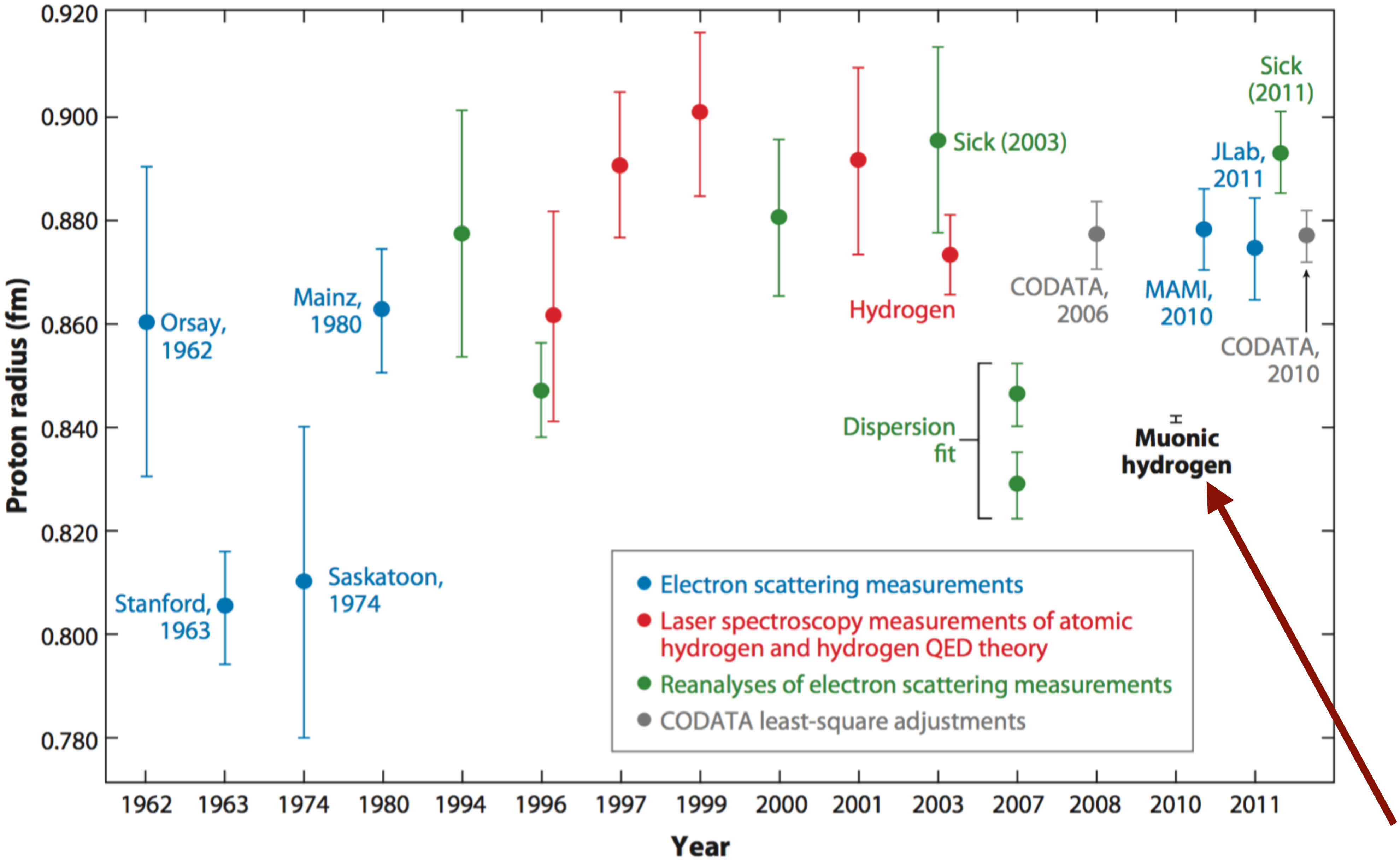
Either some extractions of the radius from data are wrong or there is new physics

If the muon, for example, couples to a yet unknown particle, possibly dark matter, and the electron doesn’t, this could explain the discrepancy

Everyone hopes for new physics, but it has been hard to find

r_p History

Pohl, doi:10.1146/annurev-nucl-102212-170627



The Stakes

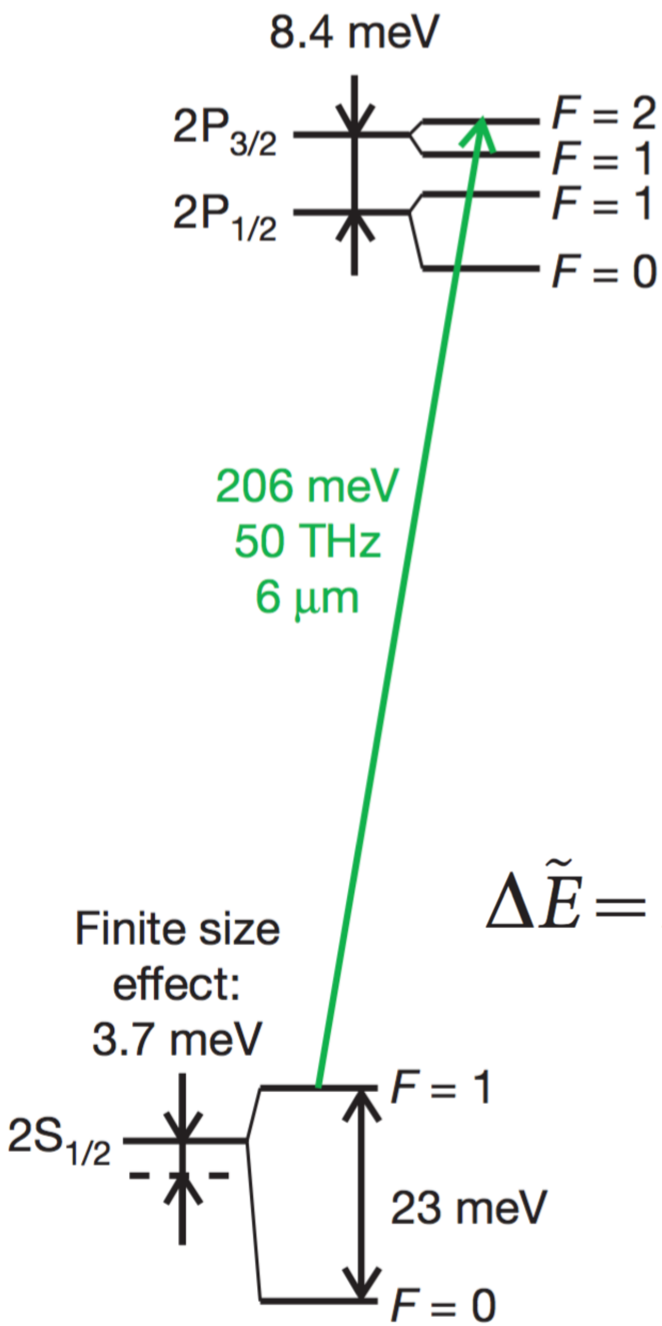
Can we really determine the proton's radius by electron scattering experiments?

If so, what have we been missing?

The answer, perhaps, lies not in the realm of new physics, but in the mundane mechanics of modeling real and imperfect experimental data

How to Measure r_p with μH

Pohl, doi:10.1038/nature09250



Schematic level structure of muonic hydrogen for n = 2.

$$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2} =$$

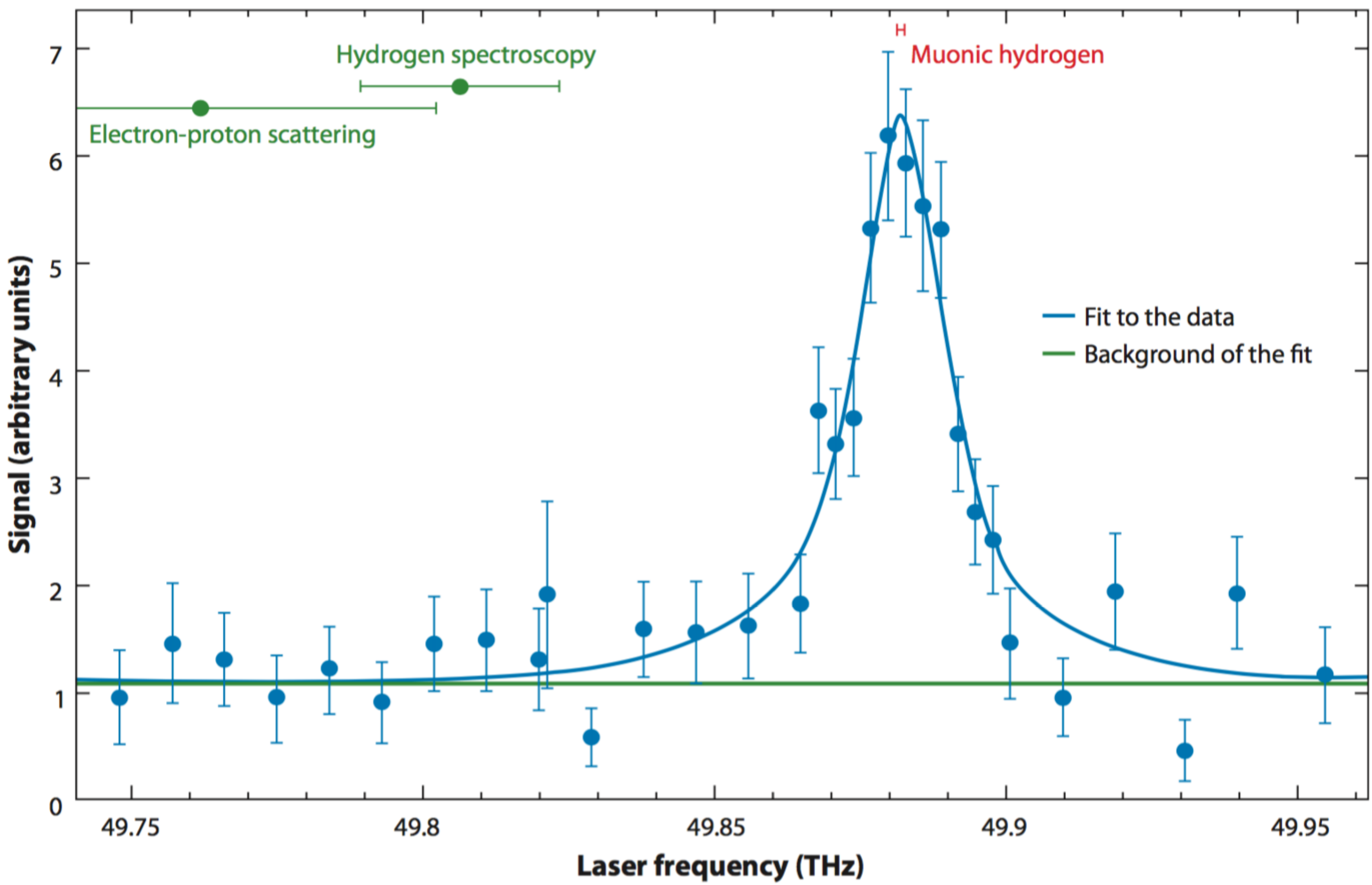
$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_{\mathrm{p}}^{2} + 0.0347\ r_{\mathrm{p}}^{3}\ \mathrm{meV}$$

rp = 0.84184(67) fm

WILLIAM & MARY
CHARTERED 1693

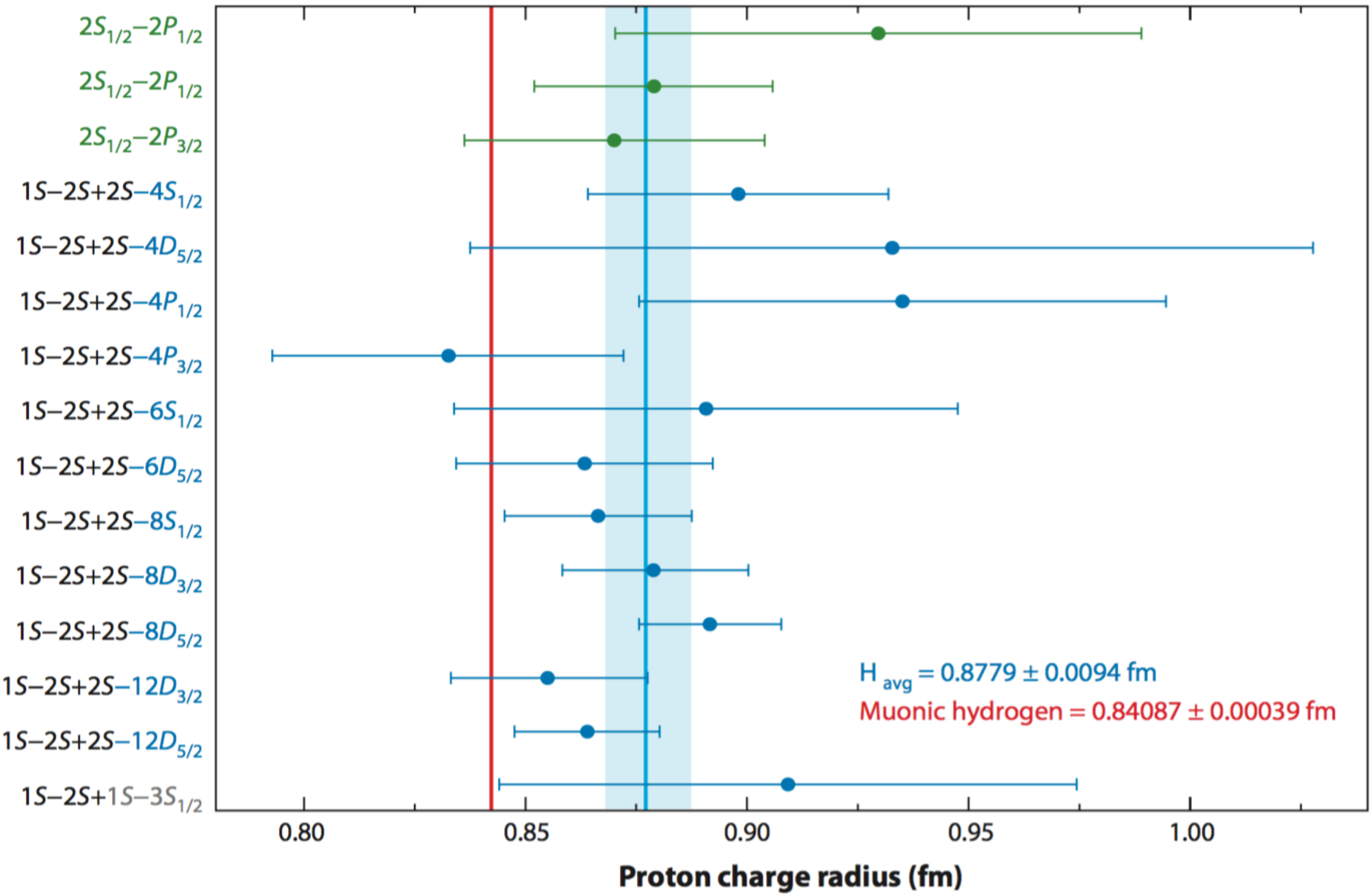
Muonic Hydrogen

Pohl, doi:10.1146/annurev-nucl-102212-170627



Hydrogen Lamb Shift

Pohl, doi:10.1146/annurev-nucl-102212-170627



How to Measure r_p with *ep*

$$G_E(Q^2)=1-[r_p^2/6]Q^2 + cQ^4 + \ldots$$

r_p is gotten from the slope of $G_E(Q^2)$ at $Q^2 = 0$

This definition of r_p is consistent with that measured in Lamb-Shift atomic transitions

Determining the proton's rms radius from *ep* elastic scattering is as easy and as hard as determining the slope of $G_E(Q^2)$ at $Q^2 = 0$

The problem is nobody can measure at $Q^2 = 0$, so everyone must extrapolate.

Fitting $G_E(Q^2)$

Can't we just fit G_E to a power series in Q^2 and extract the linear term?

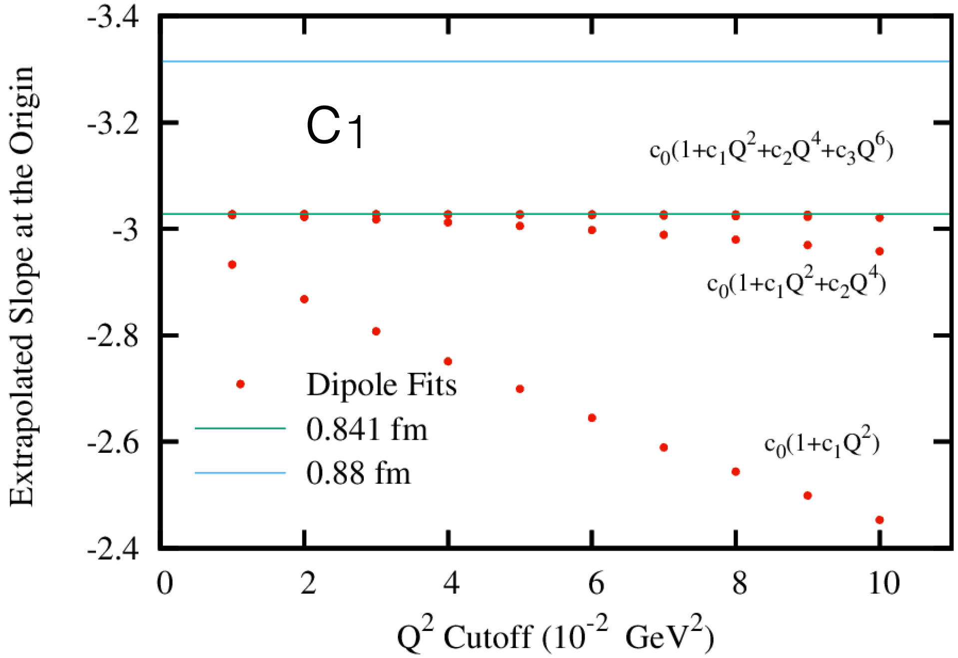
Yes, but…

One must match the power series to the correct range of Q^2 in order to extrapolate well to $Q^2=0$

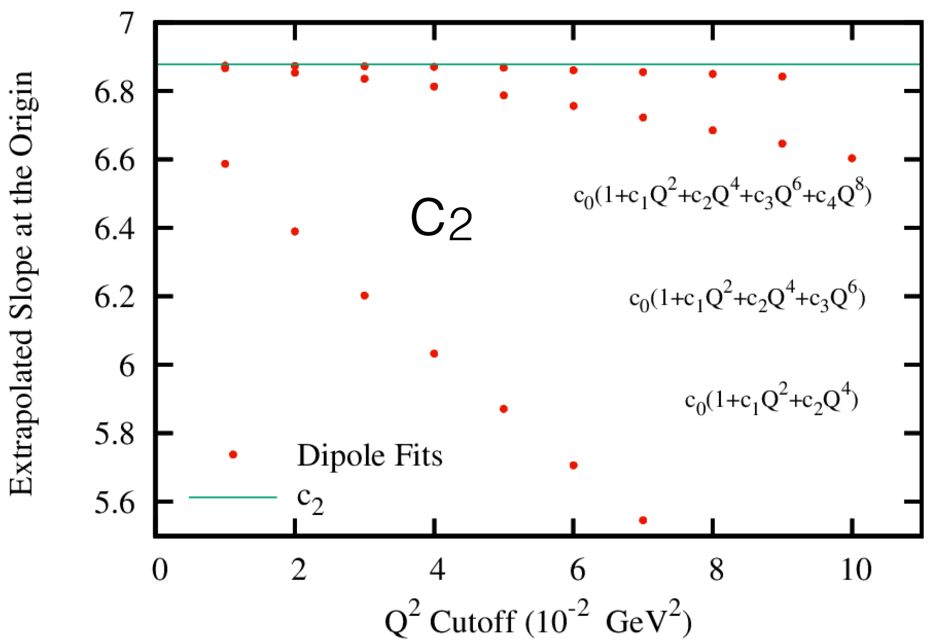
No…

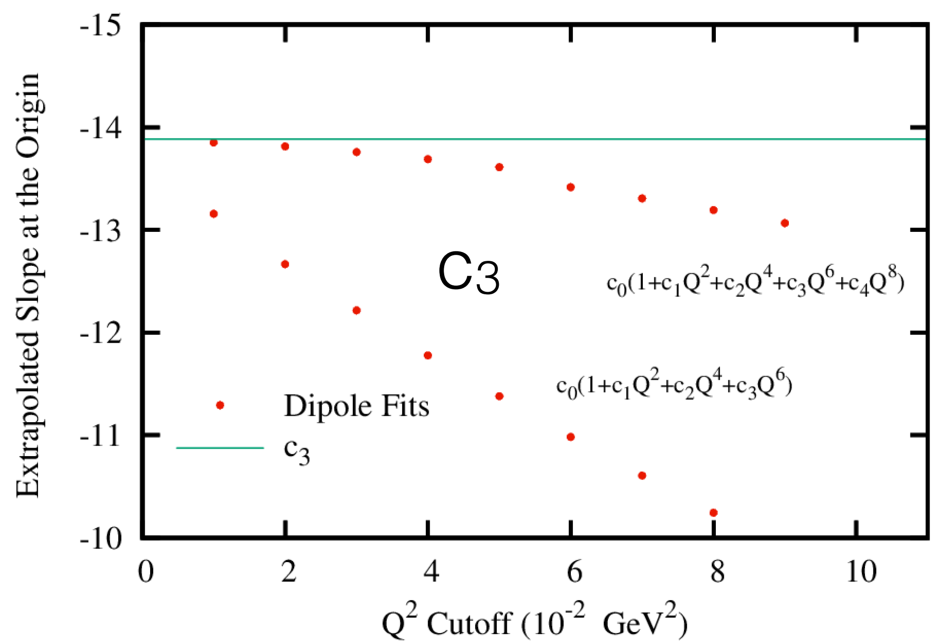
A global fit that includes regions of G_E where the linear term is small can skew the fit at the origin

Fit Bias

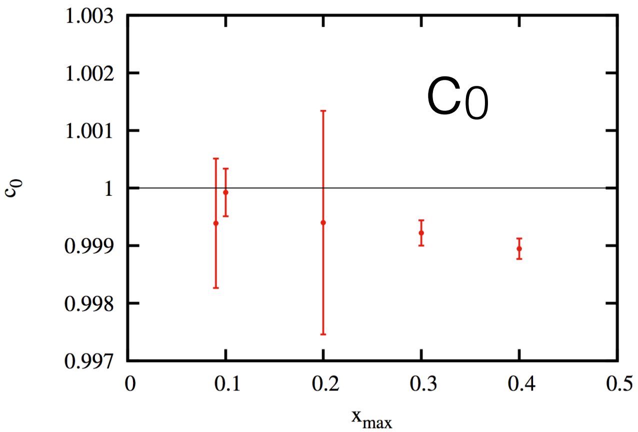


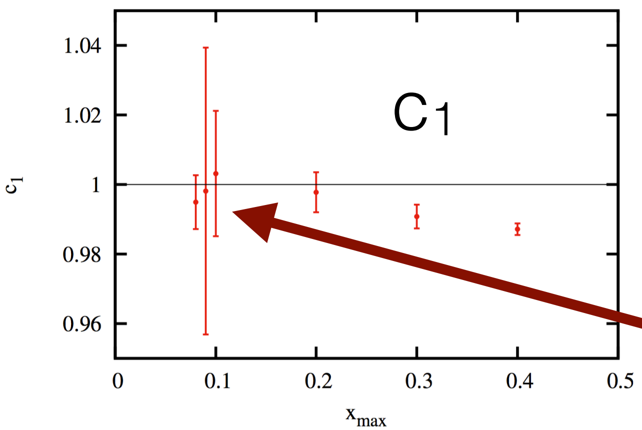
- Dipole form
- $f(Q^2)=(1+Q^2/\Lambda^2)^{-2}$
- $\Lambda^2=0.660$ ($r_p=0.84$ fm) Perfect Data
- Fit to Polynomial
- Bias for low order plus large cutoff

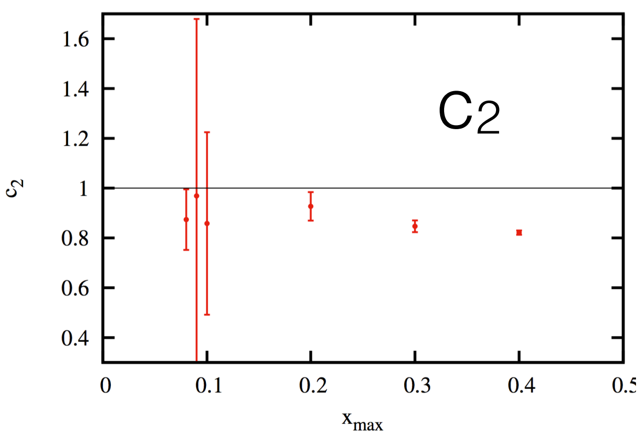


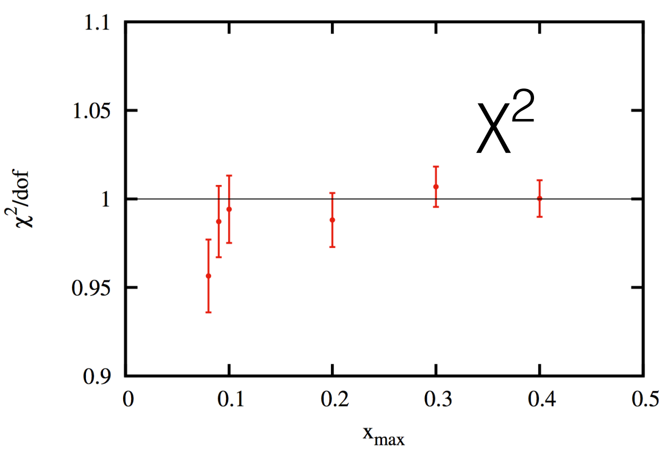


Fit Bias with Statistical Data









Generated: $f(x)=e^{-x}$ [0,1]

Fit: $f(x)=c_0[1+c_1Q^2+c_2Q^4]$

[0.02,0.1] 15 trials of 10^9 events

[0.02,0.1] 50 trials of 10^7 events

[0.00,0.1] 50 trials of 10^7 events

[0.02,0.2-4] 50 trials of 10^7 events

No bias in slope

For region where data drop by 10% [0,0.1]
c_1 is true
c_2 is slightly low

A Safe Model

From Monte Carlo Studies we conclude that fits of the form

$$c_0 G_E(Q^2) = c_0[1 - c_1 Q^2 + c_2 Q^2]$$

applied over a range where G_E drops by 10%
from unity at $Q^2=0$
yield an unbiased c_1 (*i.e.* an unbiased radius)

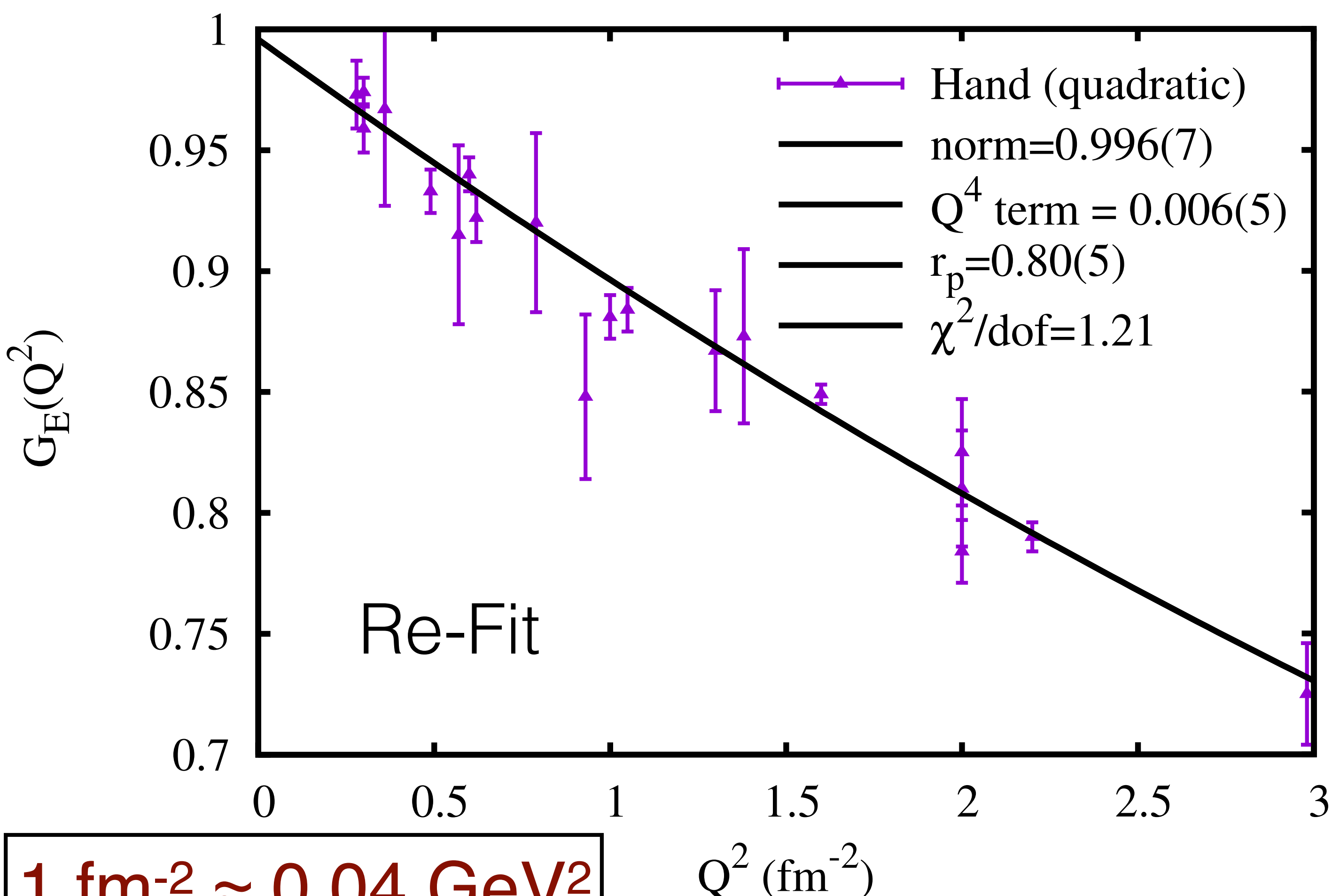
Let's apply this to data going back to early 1960s
and to what happens

Hand *et al.* 1963

REVIEWS OF MODERN PHYSICS VOLUME 35, NUMBER 2 APRIL 1963

Electric and Magnetic Form Factors of the Nucleon*

L. N. HAND, D. G. MILLER, AND RICHARD WILSON
Cyclotron Laboratory, Harvard University, Cambridge, Massachusetts

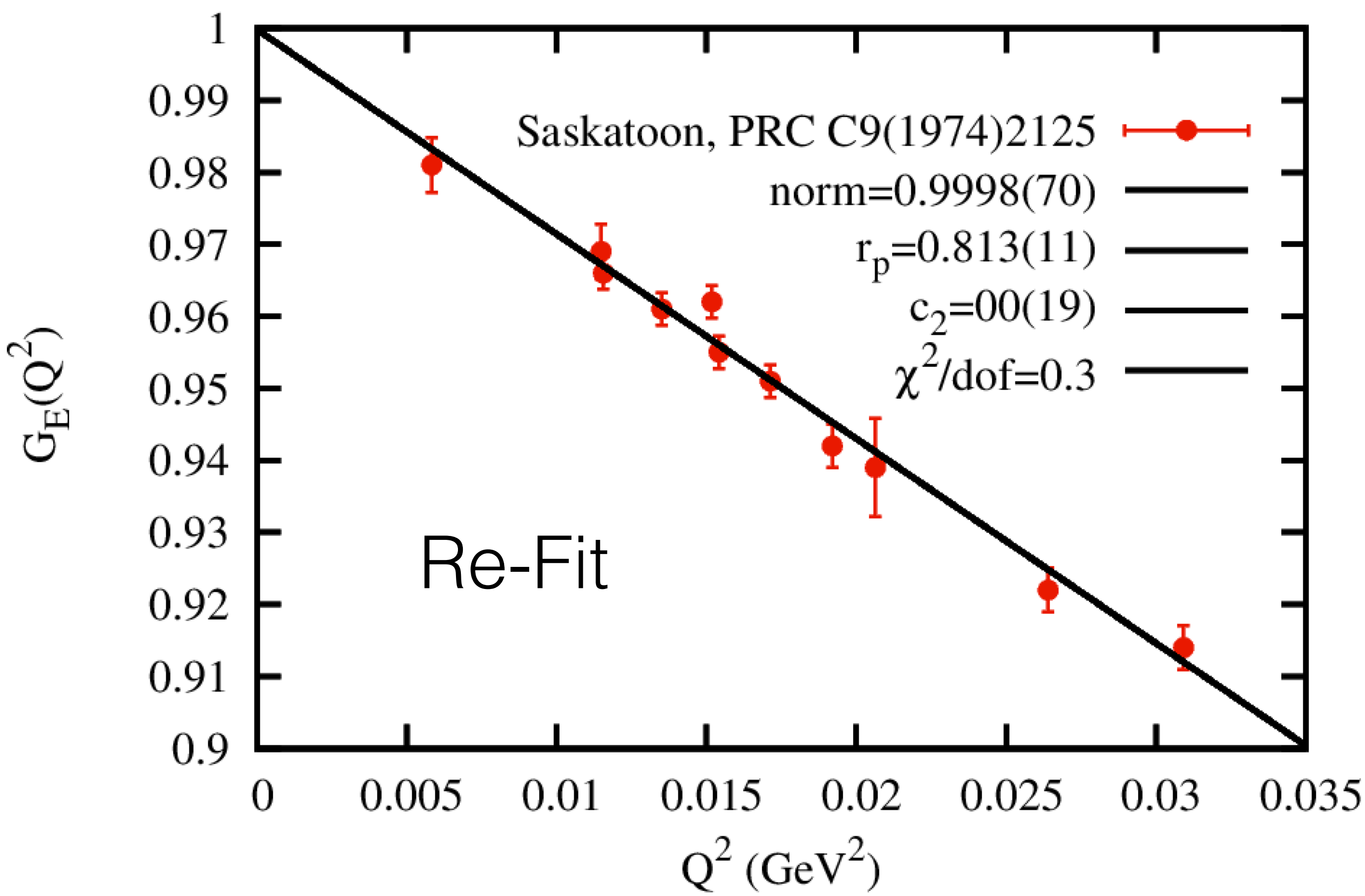


- Fit to all G_E data at the time with $Q^2 < 3$ fm^{-2} (0.012 GeV^2)
- Re-creation on left
- Quadratic term raises r_p from 0.74 to 0.80 fm^{-1} with no increase in χ^2
- Overall scale factor is essential

1 $fm^{-2} \approx$ 0.04 GeV^2

r_p=0.80(5) fm

Saskatoon 1974



Linear fit has the same χ^2

r_p=0.82(1) fm

Systematic errors, added linearly, overestimate the statistical fluctuations

Mainz 1975

ELECTROMAGNETIC FORM FACTORS OF THE PROTON AT LOW FOUR-MOMENTUM TRANSFER (II)

Nuclear Physics B93 (1975) 461--478

F. BORKOWSKI, G.G. SIMON, V.H. WALTHER and R.D. WENDLING*
Institut für Kernphysik der Universität Mainz, D-65 Mainz, Germany

Received 5 March 1975
(Revised 28 April 1975)

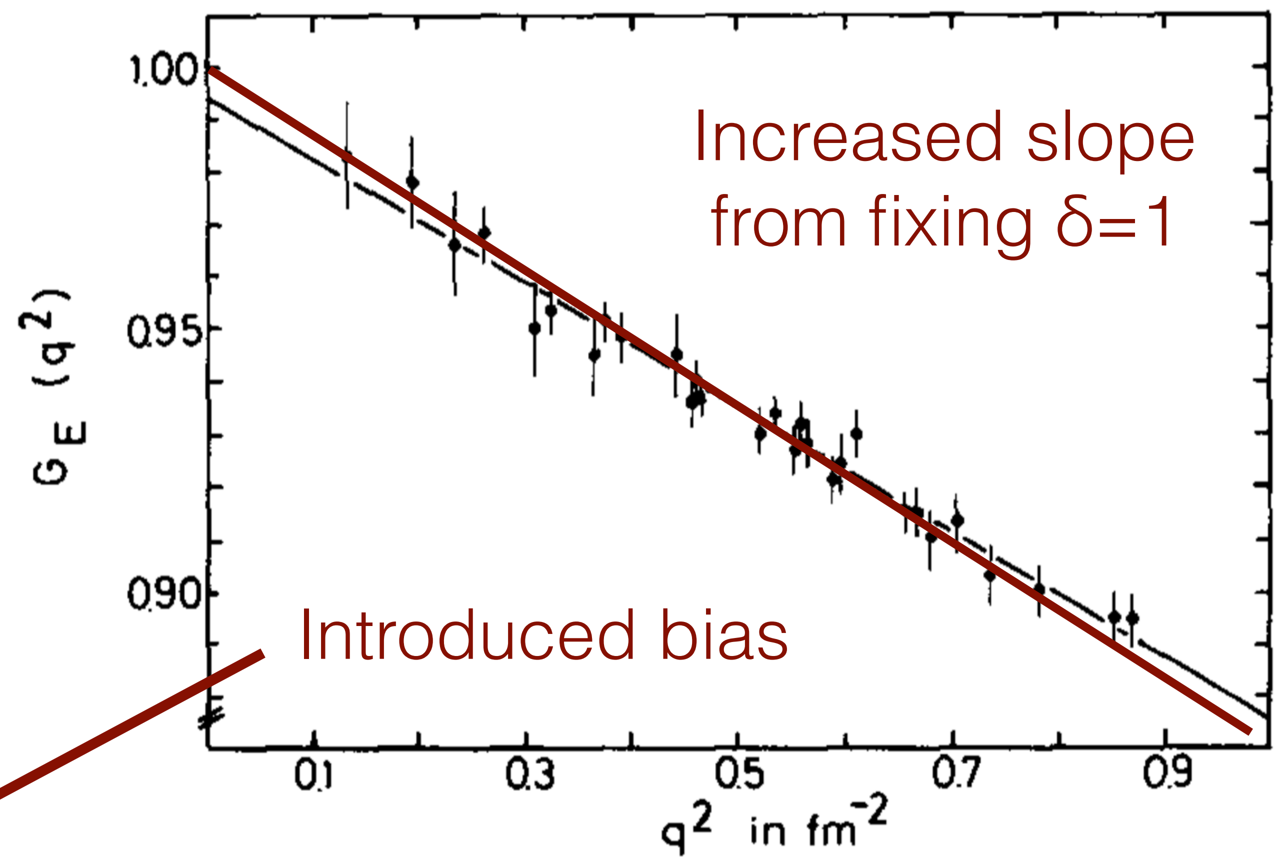
$$G_E(q^2) = \delta + \beta q^2$$

$$\delta = 0.994 \pm 0.002$$

$$\beta = -0.118 \pm 0.004 \text{ fm}^2$$

The reduced χ^2 was 0.5.

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.84 \pm 0.02 \text{ fm}$$



(i.e. $\delta = 1.0$), we obtain a proton r.m.s. radius of 0.88 fm

$1 \text{ fm}^{-2} \approx 0.04 \text{ GeV}^2$

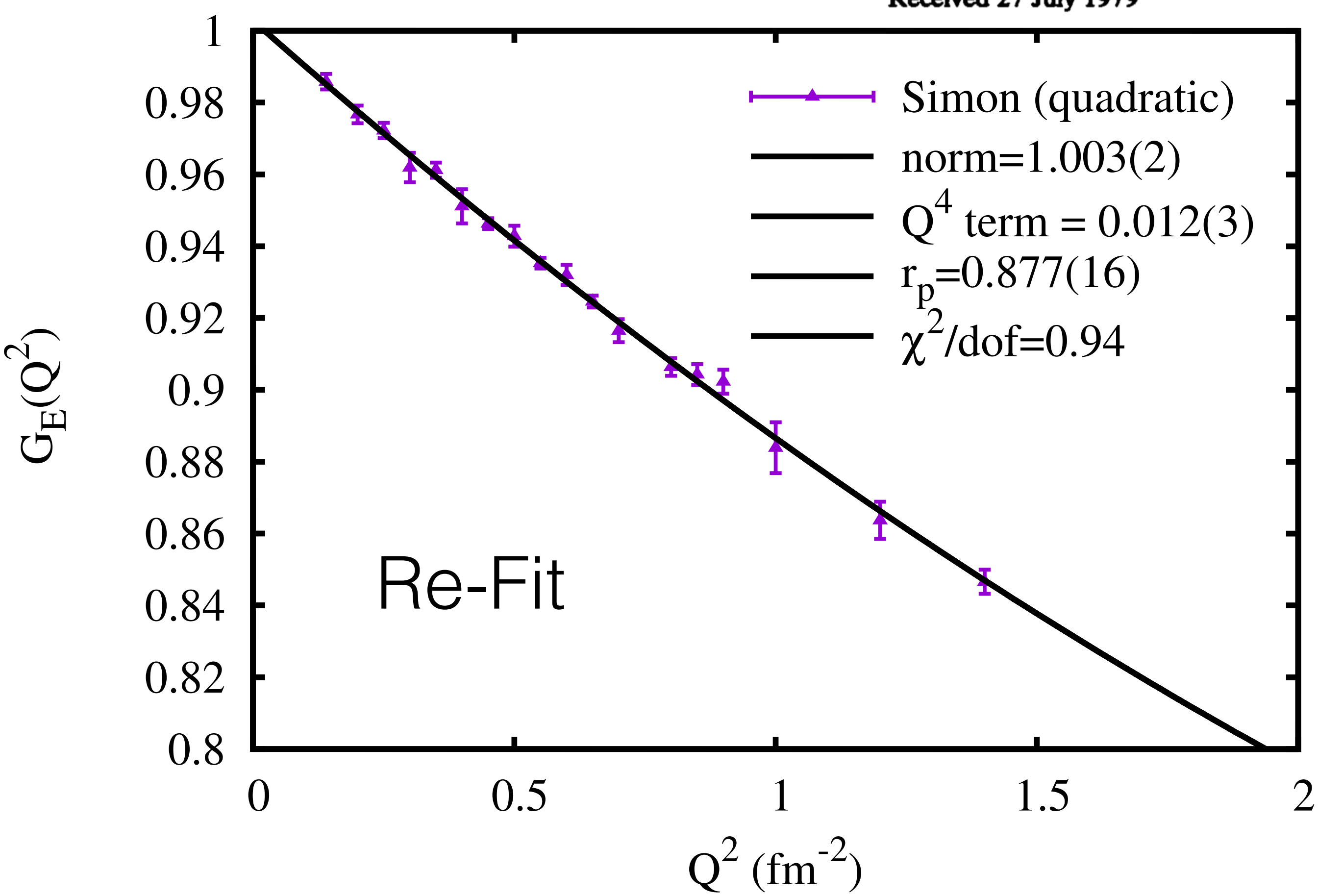
Simon 1979

Nuclear Physics **A333** (1980) 381–391 © *North-Holland Publishing Co., Amsterdam*

ABSOLUTE ELECTRON–PROTON CROSS SECTIONS AT LOW MOMENTUM TRANSFER MEASURED WITH A HIGH PRESSURE GAS TARGET SYSTEM

G. G. SIMON, Ch. SCHMITT, F. BORKOWSKI and V. H. WALTHER
Institut für Kernphysik, Universität Mainz, D-6500 Mainz

Received 27 July 1979



Quadratic fit yields r_p=0.88±0.02

Linear fit yields r_p=0.88(2) fm and same χ^2

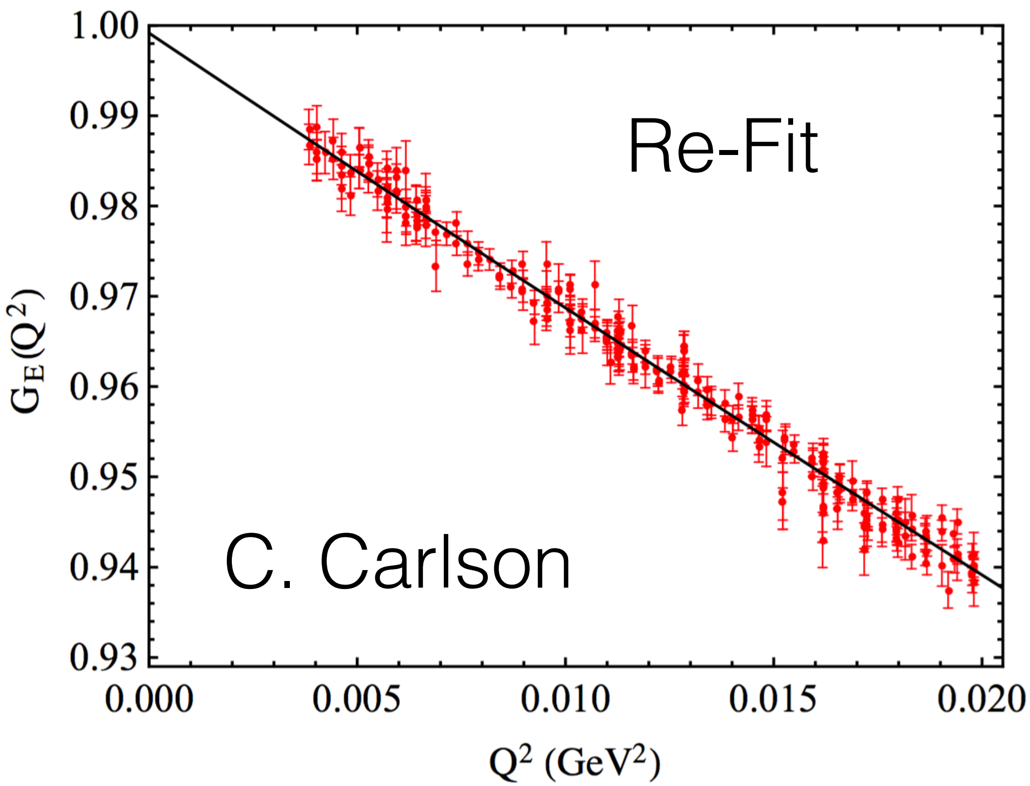
1 fm^{-2} ≈ 0.04 GeV^2

Mainz 2010

PRL **105,** 242001 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]



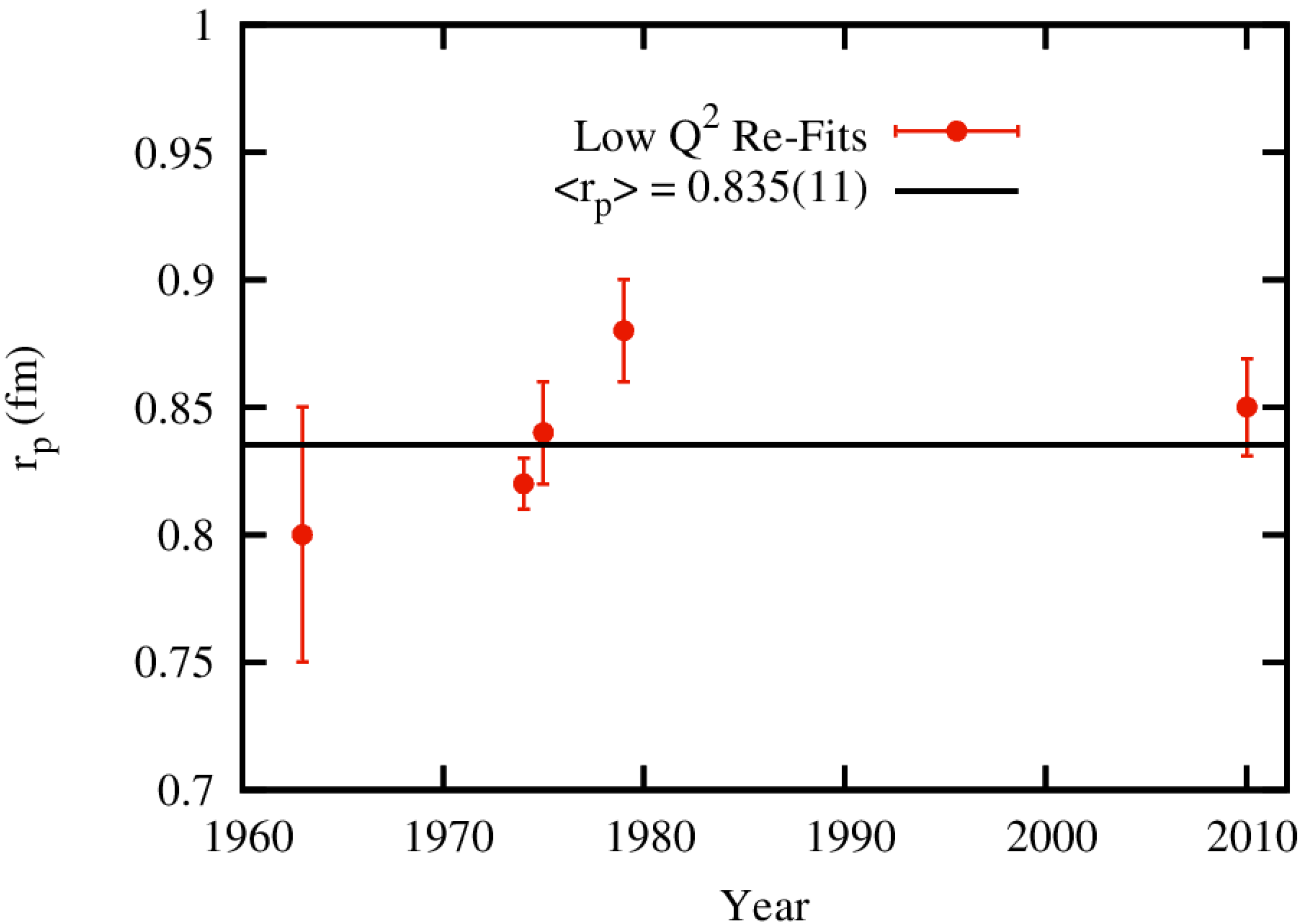
c_0=0.9992(3)

r_p = 0.850(19) fm

Low Q^2 Mainz 2010 data

WILLIAM & MARY
CHARTERED 1693

r_p Time History



r_p from Higinbotham

- Stepwise regression
- F tests
- Akaike information criterion
- Multivariate error estimates.
- Systematical determination of predictive variables for a give of electron scattering data

Higinbotham *et al.*

DOI: 10.1103/PhysRevC.93.055207

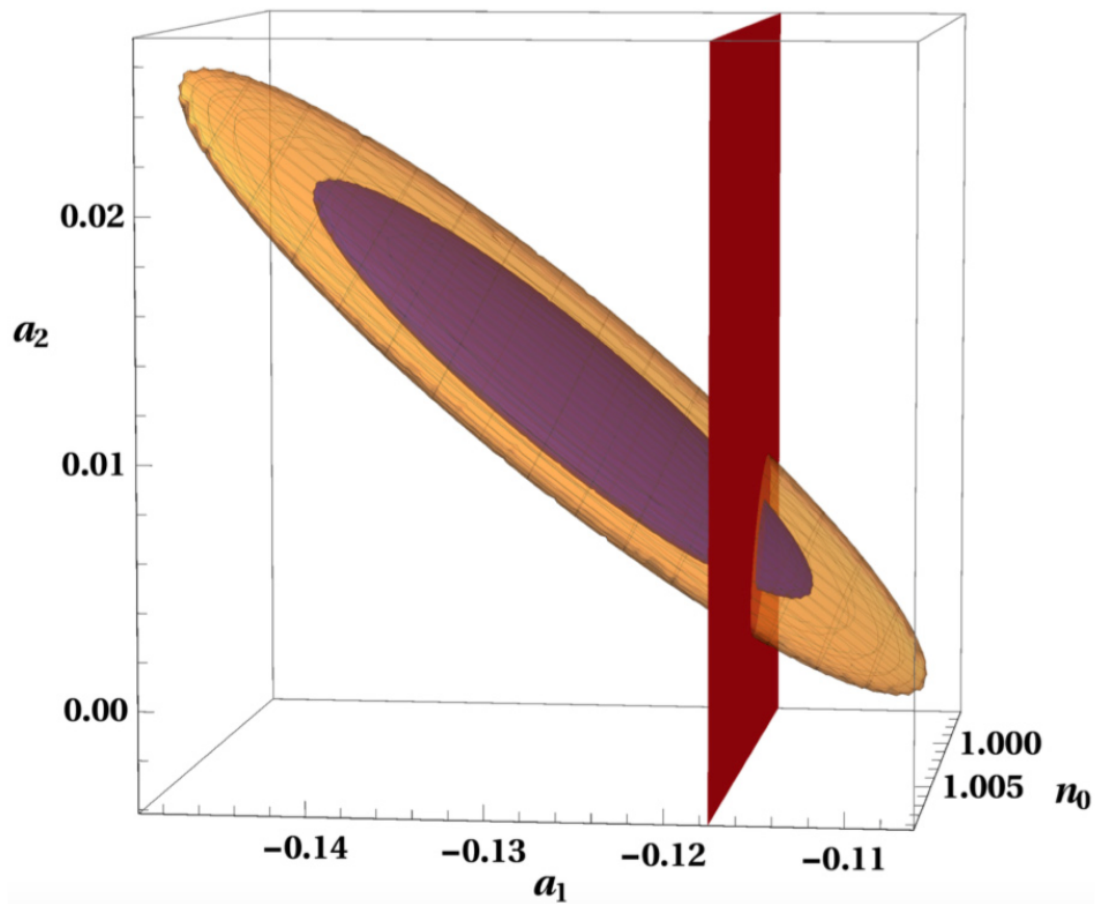
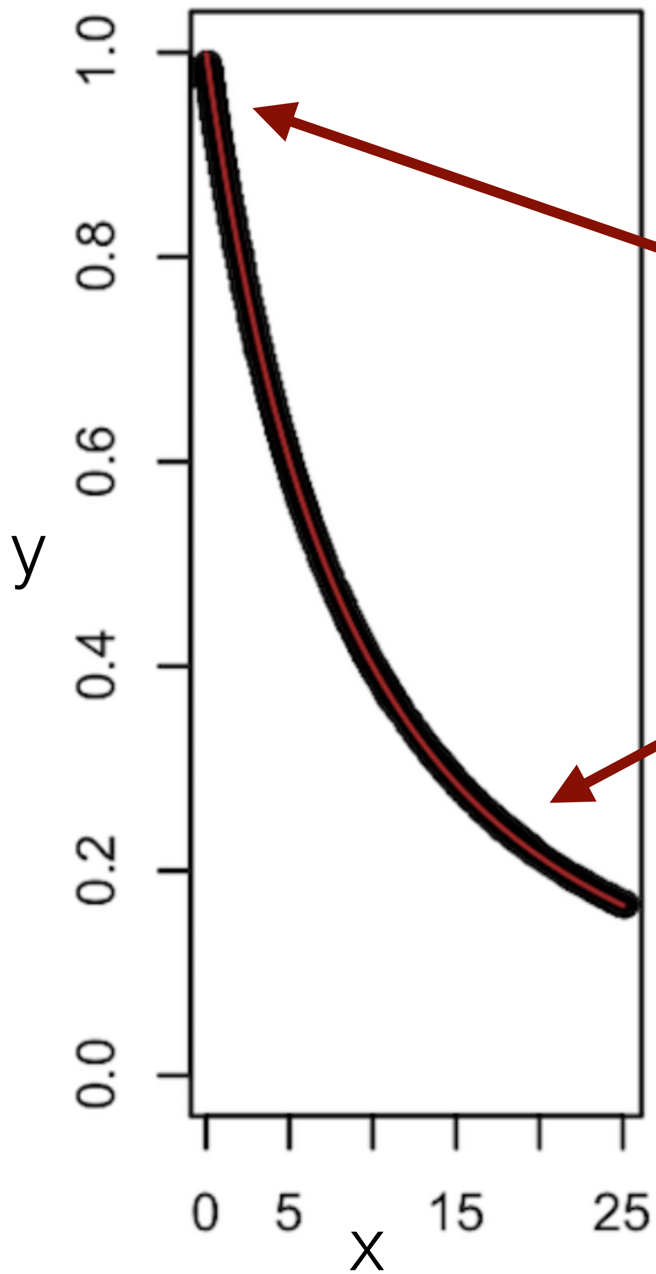


FIG. 1. The 68% (inner) and 95% (outer) confidence ellipsoids associated with the covariance matrix from the three-parameter fit of the Mainz80 and Saskatoon74 data. The plane representing the muonic Lamb shift result of rp = 0.84 fm is shown at its corresponding a1 value of −0.1176 fm^2 and is clearly not ruled out by this fit.

Global Fitting Models



$(a_0+a_1x+a_2x^2+\ldots)$

~x

~x^{-1}

$1/(1+b_1x+b_2x^2+\ldots)$

Padé Approximates

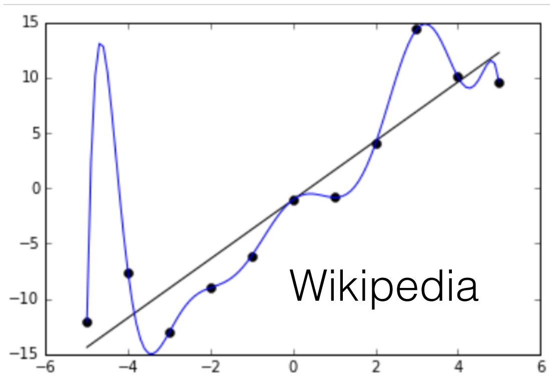
$$R(x) = \frac{\sum_{j=0}^{m} a_j x^j}{1 + \sum_{k=1}^{n} b_k x^k}$$

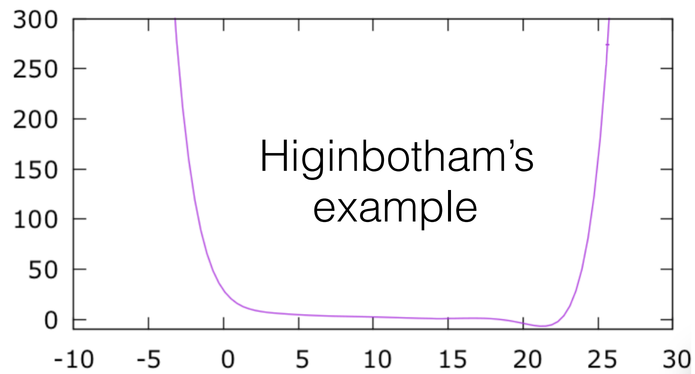
Continued Fraction

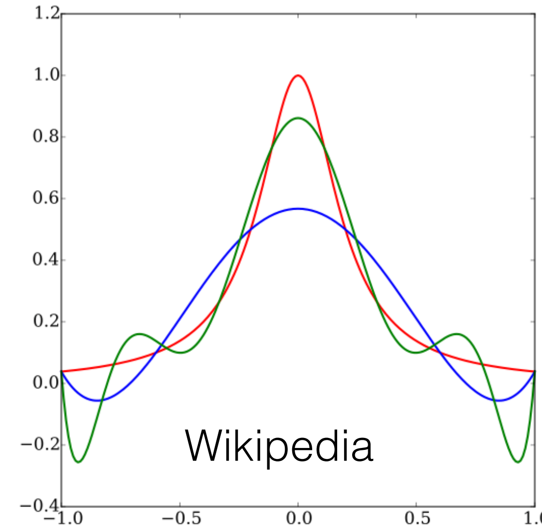
$$f(Q^2) = \frac{c_1}{1 + \frac{c_2 Q^2}{1 + \frac{c_3 Q^2}{1 + \frac{c_4 Q^2}{1 + \ldots}}}}$$

Polynomials?

High-order polynomials are a bad idea







- Over-fitting
- Quick divergence outside the fit range
- Oscillations at the edges (Runge Phenomena)

If you're going to extrapolate, use low-order polynomials or Padé approximates

Refit of Mainz 2010

PHYSICAL REVIEW C **93**, 065207 (2016)

Consistency of electron scattering data with a small proton radius

Keith Griffioen, Carl Carlson, and Sarah Maddox
Physics Department, College of William and Mary, Williamsburg, Virginia 23187, USA
(Received 26 October 2015; published 17 June 2016)

We determine the charge radius of the proton by analyzing the published low momentum transfer electron-proton scattering data from Mainz. We note that polynomial expansions of the form factor converge for momentum transfers squared below $4m_\pi^2$, where m_π is the pion mass. Expansions with enough terms to fit the data, but few enough not to overfit, yield proton radii smaller than the CODATA or Mainz values and in accord with the muonic atom results. We also comment on analyses using a wider range of data, and overall obtain a proton radius $R_E = 0.840(16)$ fm.

DOI: 10.1103/PhysRevC.93.065207

Extract G_E from Mainz 2000 Cross sections
Fit!

Extracting G_E

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

$$\frac{\sigma}{\sigma_D} = \frac{\varepsilon G_E^2 + \tau G_M^2}{\varepsilon G_D^2 + \tau \mu_p^2 G_D^2}$$

$$\tau = \frac{\nu^2}{Q^2} = \frac{Q^2}{4M^2}$$

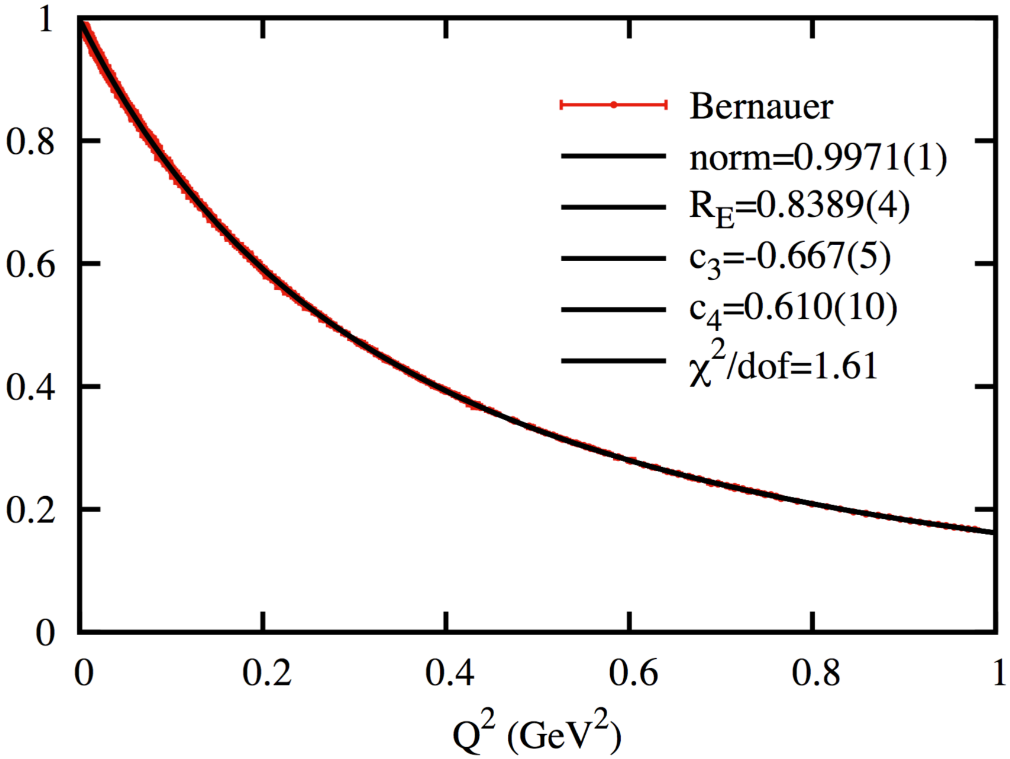
$$G_E(Q^2) = G_D(Q^2)\left(\frac{\sigma}{\sigma_D}\right)^{1/2}\left[1 + \tau\mu_p^2 \frac{G_M^2/(\mu_p G_E)^2 - 1}{\varepsilon + \tau\mu_p^2}\right]^{-1/2}$$

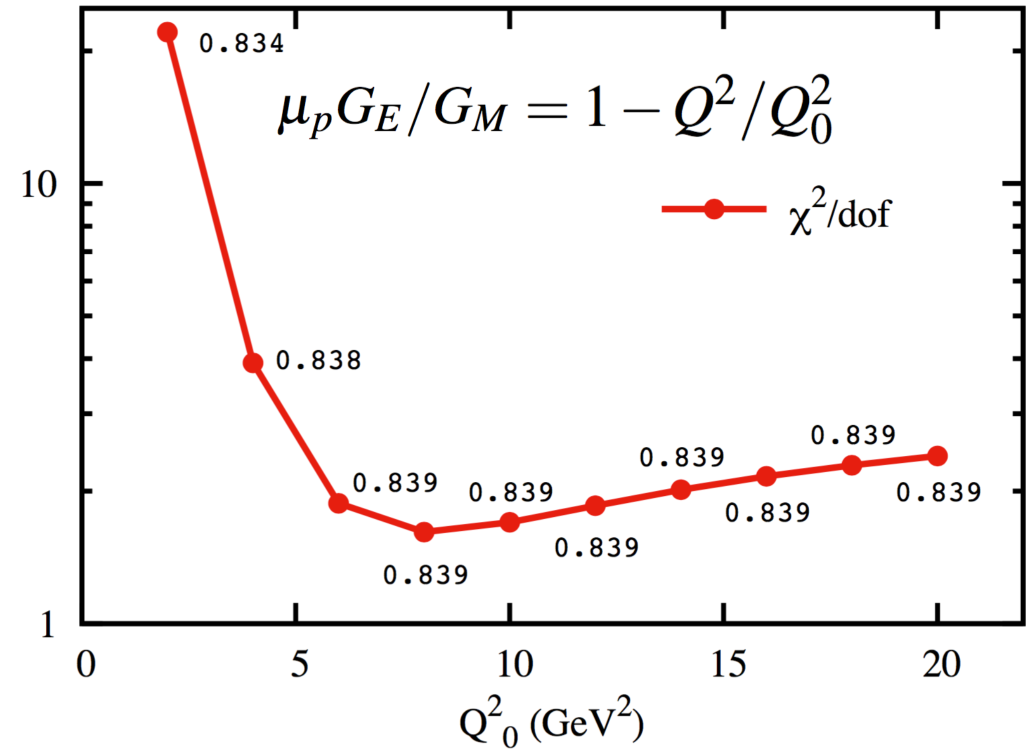
$$\mu_p G_E / G_M = 1 - Q^2/Q_0^2$$

$$Q_0^2 = 8.02 \pm 0.05 \text{ with } \chi^2/\text{dof} = 2.3$$

Fit to world data

Full-Range Fits



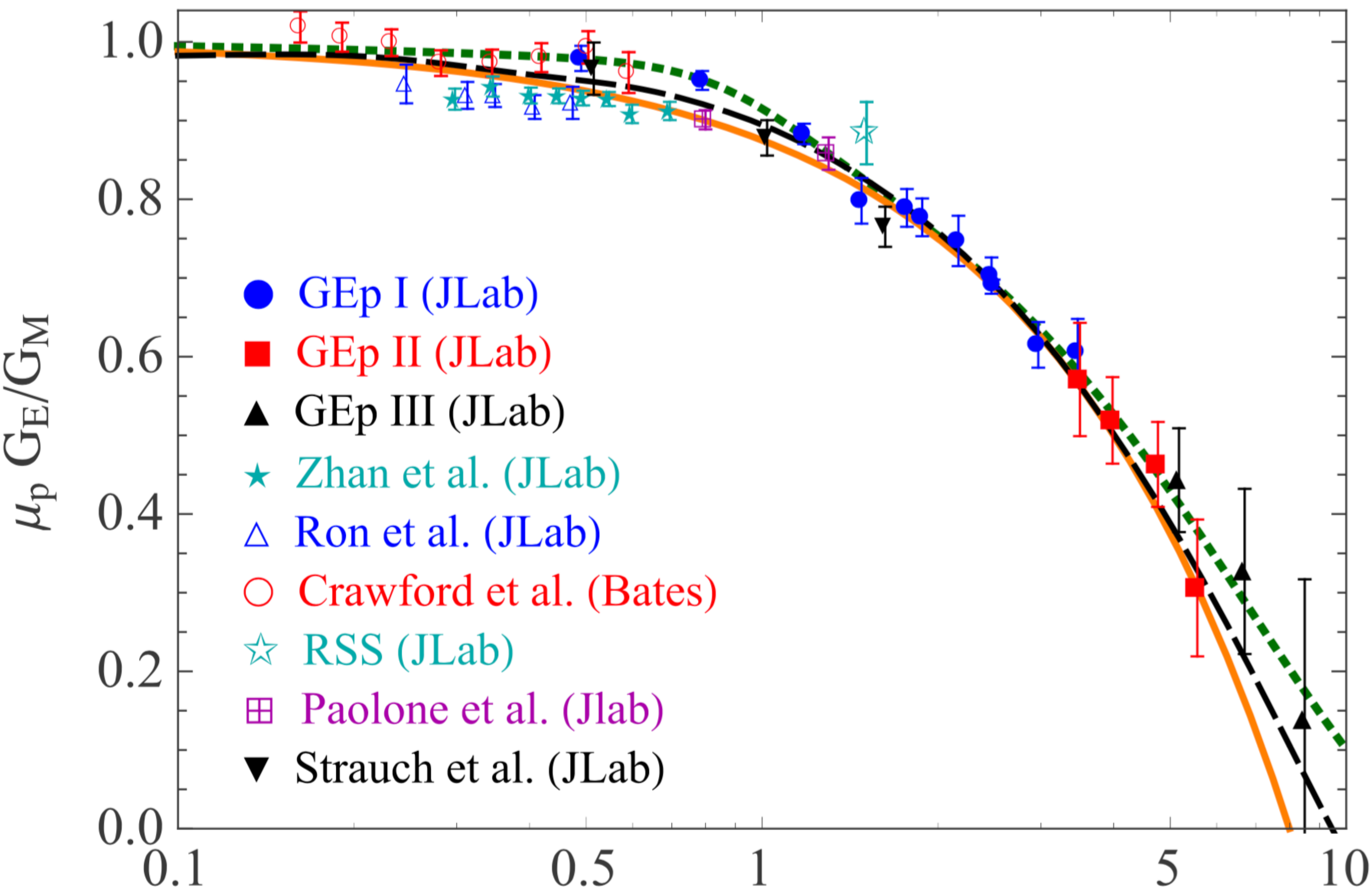


A continued Fraction with 4 parameters fits the data well. Extracted r_p=0.8389(4)

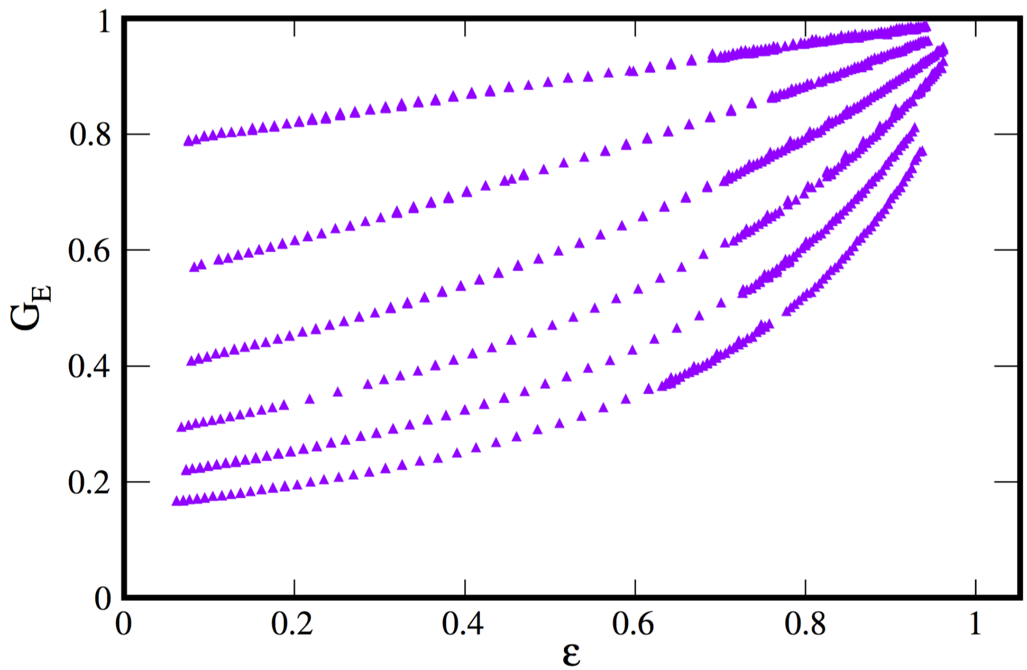
Extracting G_E by adjusting Q_0 in G_E/G_M yields best value of 8 GeV^2

World G_E/G_M

Orange: $1-Q^2/(8.02\ GeV^2)$

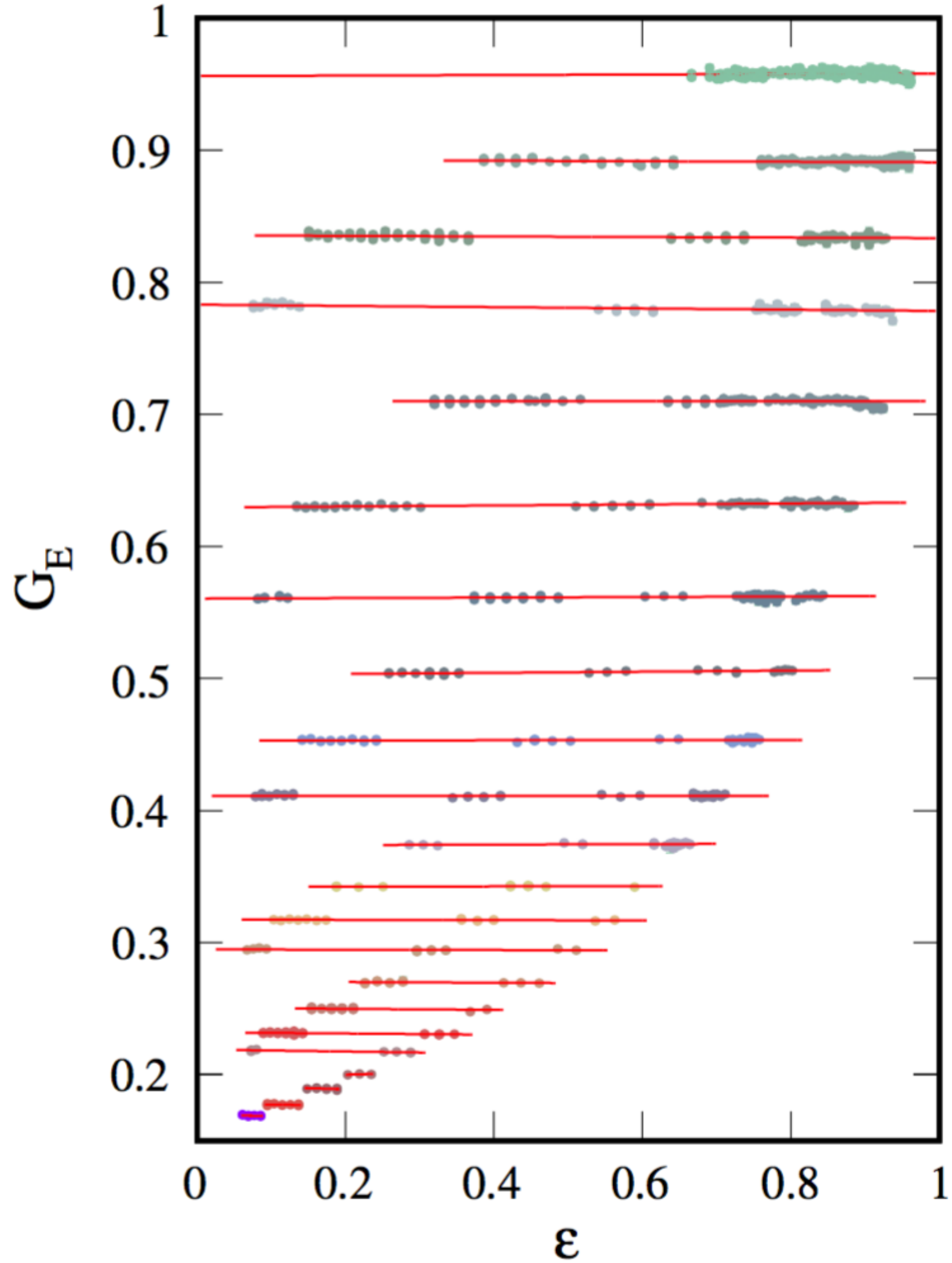


ε

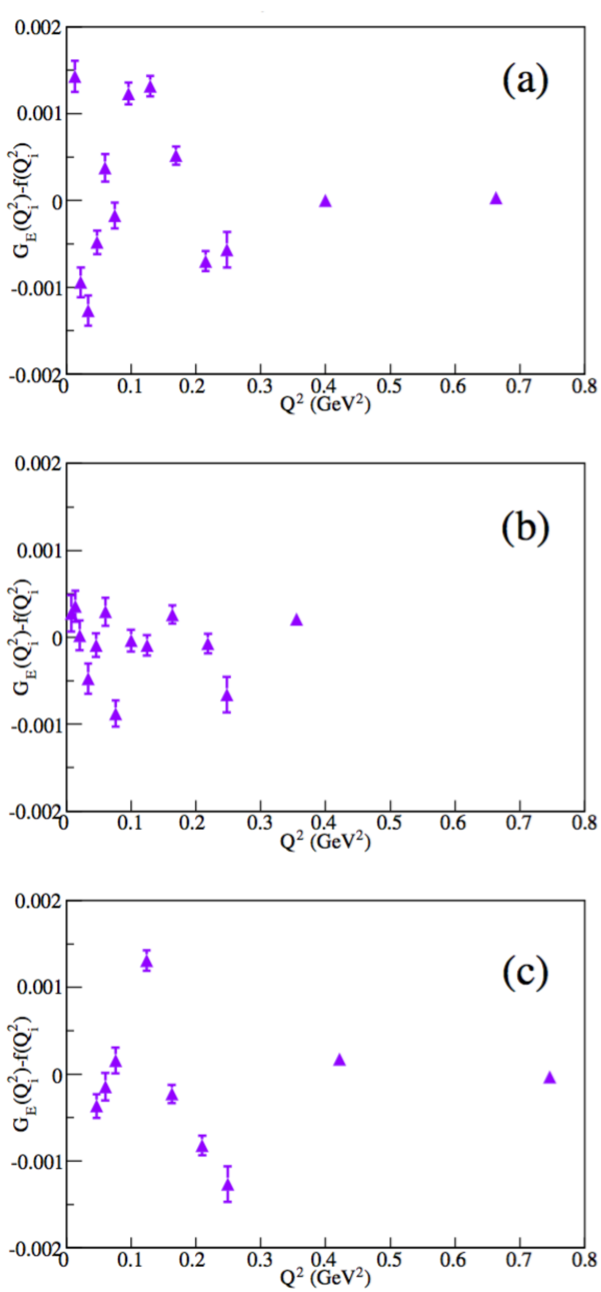


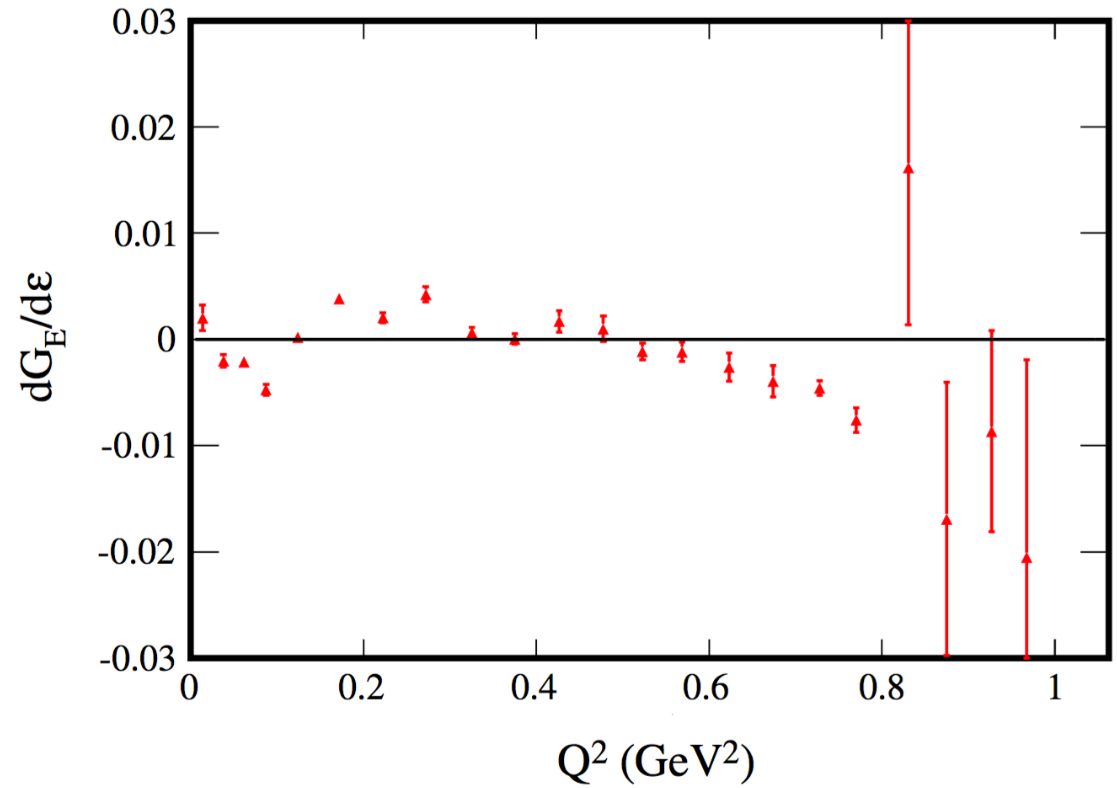
Low Q^2 → high ε where 2-photon effects are small

No observable ε-dependence in G_E



Fluctuations?

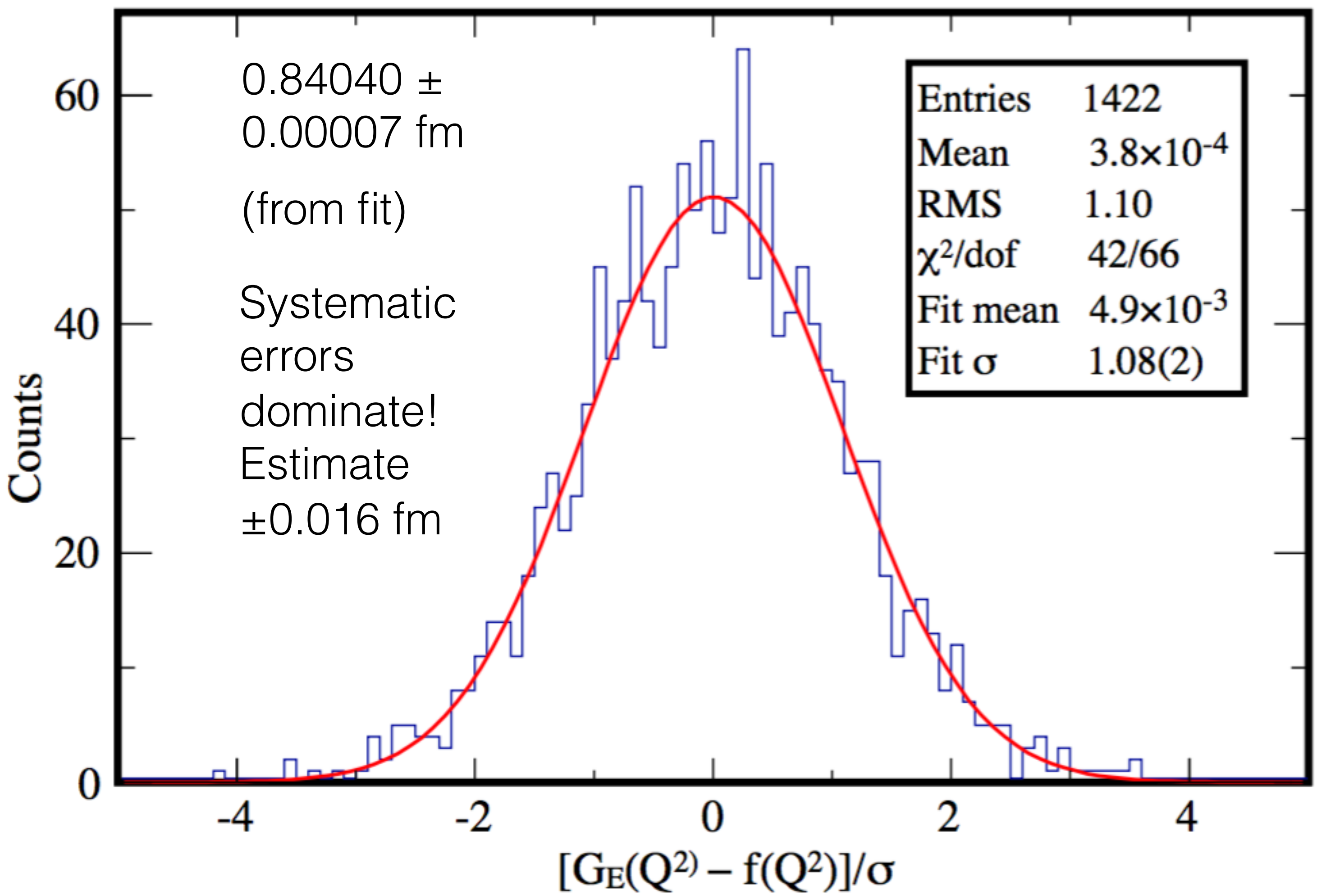




Slope of G_E with ε is consistent with no strong 2-photon effects

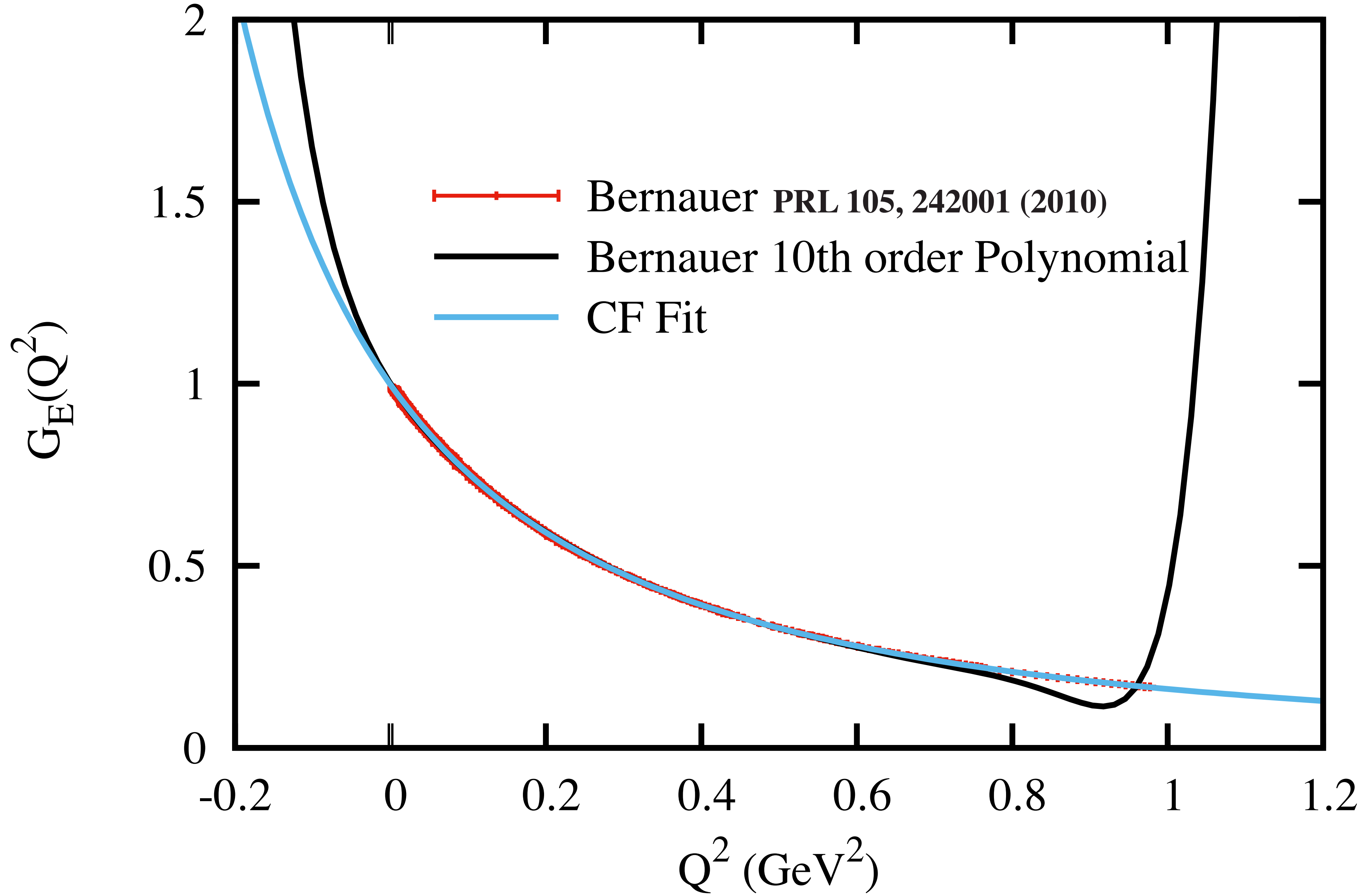
No consistency in G_E-fit for Spec. A, B and C separately.

Statistics

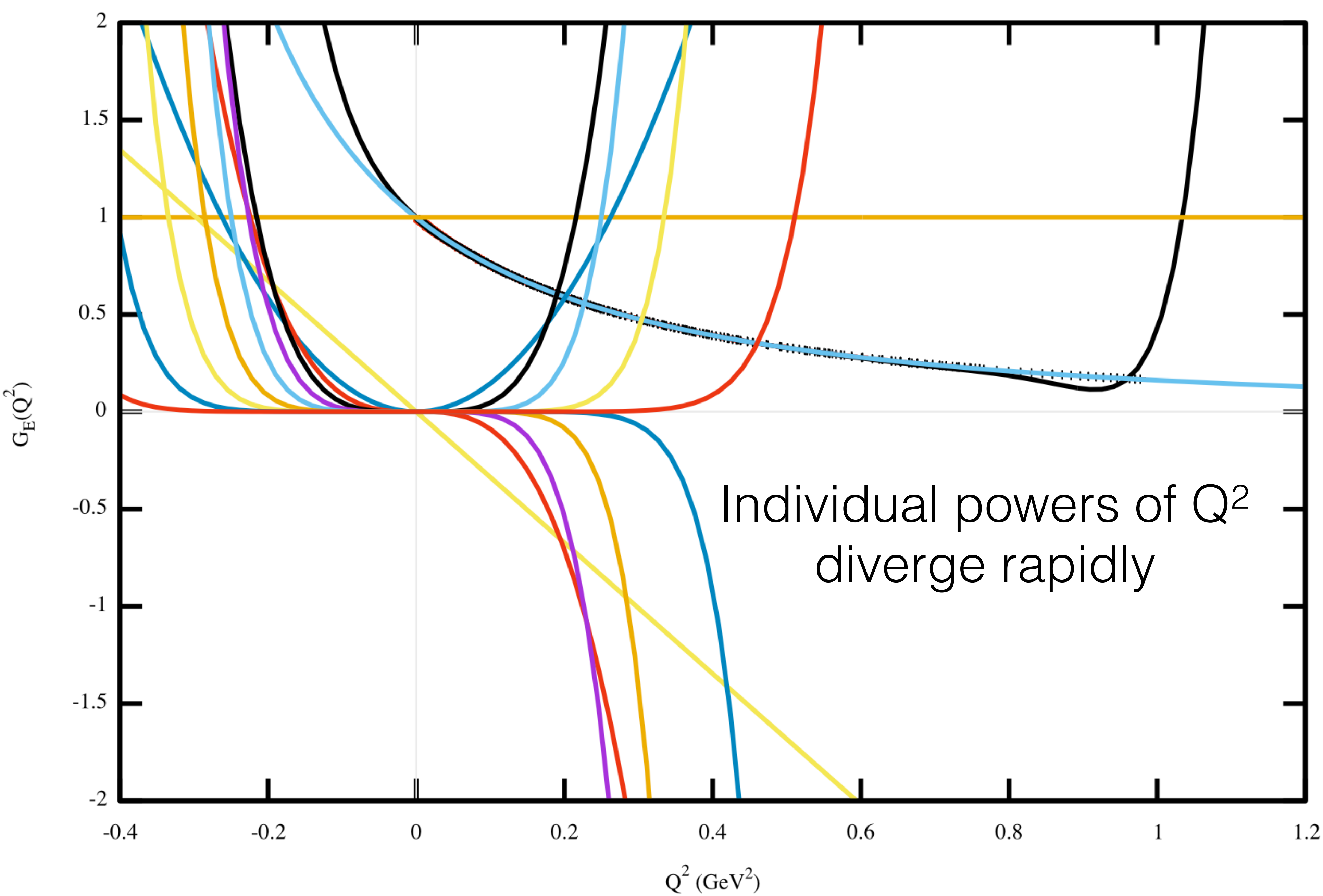


With errors on G_E are inflated by 15% the full 1422 points obey perfect statistics

Same Data, Different r_p



Polynomial Terms



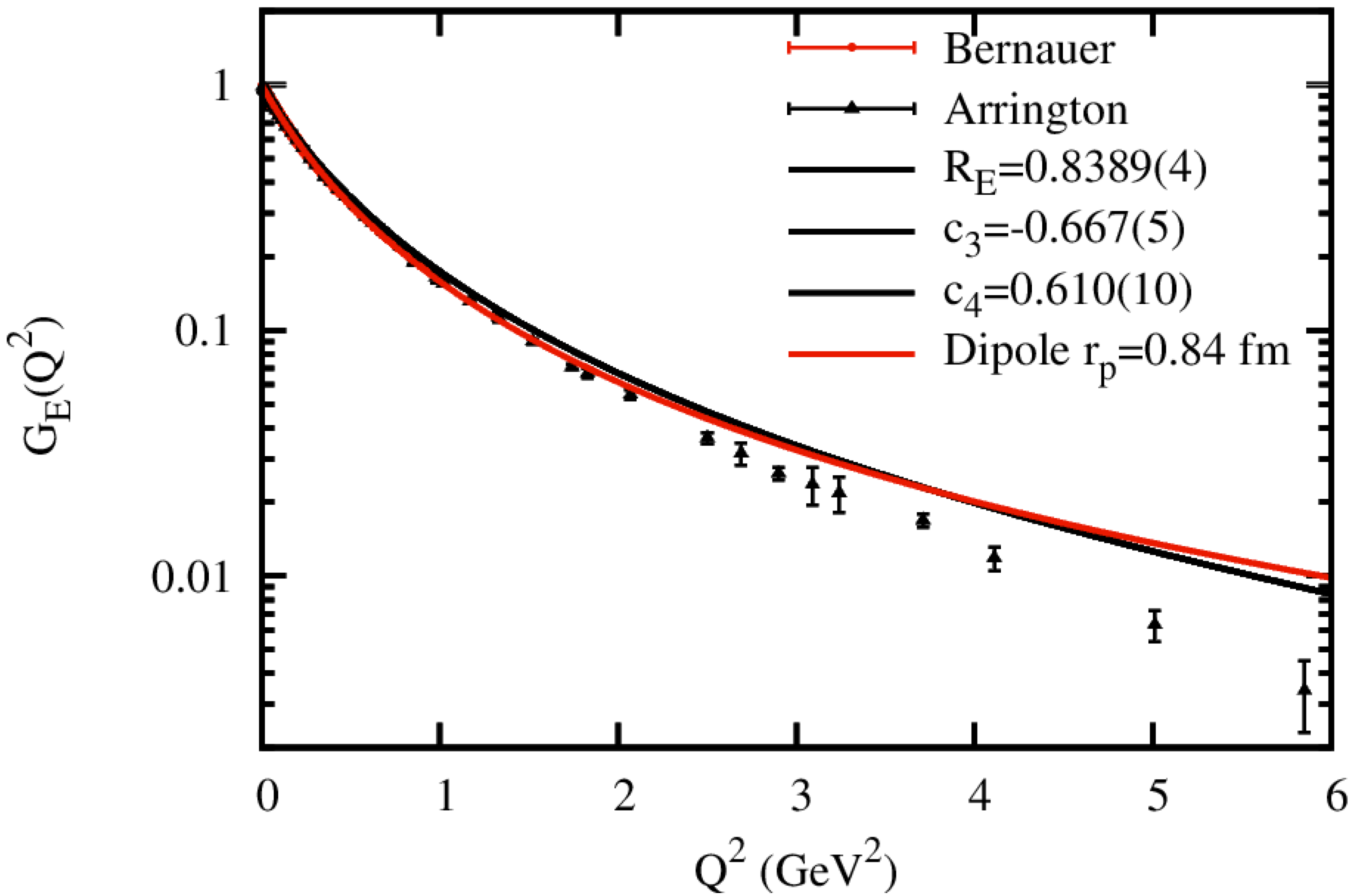
Wider Q^2

Arrington

DOI: 10.1103/PhysRevC.71.015202

World G_E data corrected *ad hoc* for 2-photon effects

Our fit extrapolates well

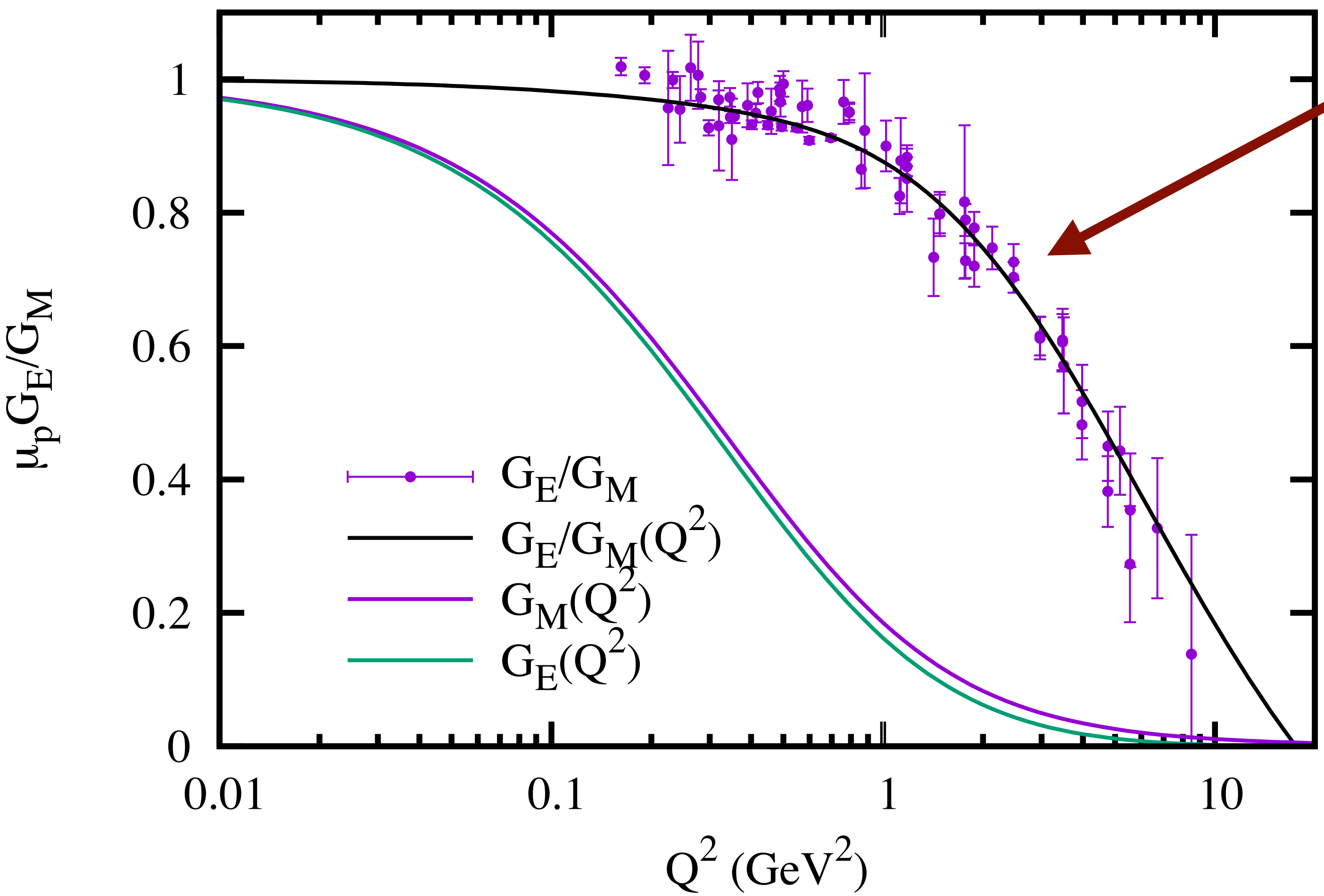


WILLIAM & MARY
CHARTERED 1693

CF Fit to G_M using G_E/G_E

variance of residuals (reduced chisquare) = WSSR/ndf : 2.41576
p-value of the Chisq distribution (FIT_P) : 1.39377e-09

Final set of parameters		Asymptotic Standard Error	
f	= 0.807636	+/- 0.01165	(1.442%)
g	= -0.690034	+/- 0.09996	(14.49%)
h	= 0.898897	+/- 0.1637	(18.22%)



World Recoil Polarization data

G_E fixed from CF fit

Three Recent r_p's

- Muonic Hydrogen Lamb Shift: **r_p = 0.84087(39) fm**

CREMA Collaboration

- Electron Scattering **r_p = 0.840(16) fm**

Griffioen, Carlson, Maddox
Reanalysis of the Mainz 2010 data

- Hydrogen Lamb Shift: **r_p = 0.8297(91) fm**

L. Maisenbacher, A. Beyer, et al.

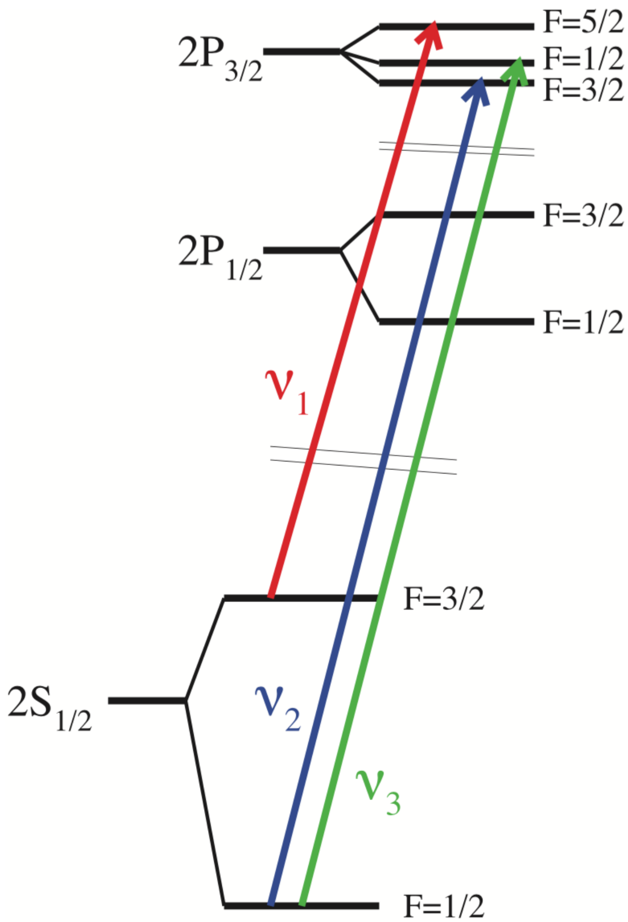
Max-Planck-Institut für Quantenoptik,
Garching, Germany

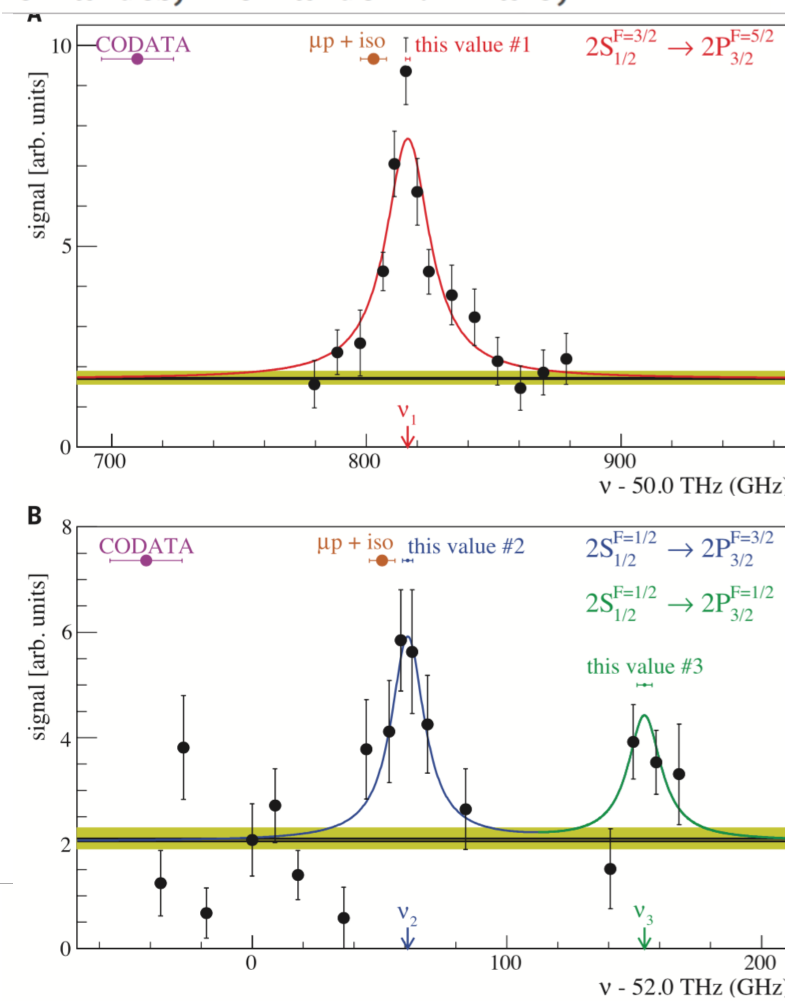
CREMA Collaboration

Laser spectroscopy of muonic deuterium

Science
12 AUGUST 2016 • VOL 353 ISSUE 6300 669

Randolf Pohl,[1,2*] François Nez,[3] Luis M. P. Fernandes,[4] Fernando D. Amaro,[4]





Lamb Shift

$$\Delta E_{\mathrm{LS}}^{\mathrm{theo}} = 228.7766(10)\ \mathrm{meV} + \Delta E_{\mathrm{LS}}^{\mathrm{TPE}}$$

$$-6.1103(3)\, r_{\mathrm{d}}^2\ \mathrm{meV}/\mathrm{fm}^2$$

$$\Delta E_{\mathrm{LS}}^{\mathrm{TPE}}(\mathrm{theo}) = 1.7096(200)\ \mathrm{meV}$$

$$\Delta E_{\mathrm{LS}}^{\mathrm{exp}} = 202.8785(31)_{\mathrm{stat}}(14)_{\mathrm{syst}}\ \mathrm{meV}$$

Isotope Shift

$$\delta^{(2)}(\mathrm{H},\mathrm{D}) \equiv r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.82007(65)\ \mathrm{fm}^2$$

$$r_\mathrm{p}(\mu\mathrm{d} + \mathrm{iso}) = 0.8356(20)\,\mathrm{fm}$$

$$r_\mathrm{p}(\mu\mathrm{p}) = 0.84087(39)\ \mathrm{fm}$$

r_d

$$r_{\rm d}(\text{D spectroscopy}) = 2.1415(45)\ \text{fm}$$

$$r_{\rm d}(\text{CODATA}) = 2.1424(21)\ \text{fm}$$

$$r_{\rm d}(\mu\text{p} + \text{iso}) = 2.12771(22)\ \text{fm}$$

$$r_{\rm d}(\mu\text{d}) = 2.12562(13)_{\rm exp}(77)_{\rm theo}$$

Smaller than CODATA

WILLIAM & MARY
CHARTERED 1693

HFS and TPE

$$\Delta E^{\mathrm{pol}}_{\mathrm{HFS}}(\mathrm{exp}) = 0.2178(74)\,\mathrm{meV}$$

$$\Delta E^{\mathrm{pol}}_{\mathrm{HFS}}(\mathrm{theo}) = 0.2226(49)\,\mathrm{meV}$$

$$\Delta E^{\mathrm{TPE}}_{\mathrm{LS}}(\mathrm{exp}) = 1.7638(68)\,\mathrm{meV}$$

$$\Delta E^{\mathrm{TPE}}_{\mathrm{LS}}(\mathrm{theo}) = 1.7096(200)\,\mathrm{meV}$$

μ Hyperfine Splitting

PHYSICAL REVIEW A **83**, 042509 (2011)

Proton-structure corrections to hyperfine splitting in muonic hydrogen

Carl E. Carlson,[1,2] Vahagn Nazaryan,[3] and Keith Griffioen[2]
[1]Helmholtz Institut Mainz, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
[2]Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA
[3]Center for Advanced Medical Instrumentation, Department of Physics, Hampton University, Hampton, VA
(Received 7 February 2011; published 19 April 2011)

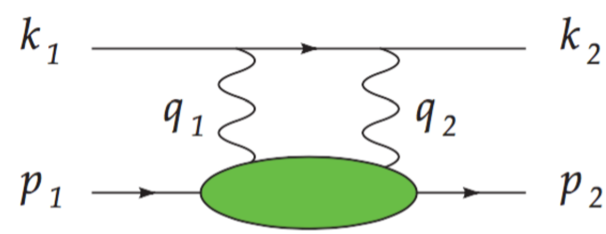
$$\Delta_S = \Delta_Z + \Delta_R + \Delta_{\text{pol}} = \frac{E_{2\gamma}^{\text{box}}}{E_F} - \frac{8\alpha m_r}{\pi}\int_0^\infty \frac{dQ}{Q^2}$$

$$\Delta_Z = \frac{8\alpha m_r}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa_p} - 1\right) \equiv -2\alpha m_r r_Z,$$

$$\Delta_1 = \int_0^\infty \frac{dQ^2}{Q^2}\left\{\beta_1(\tau_\ell)F_2^2(Q^2) + 4m_p\int_{\nu_{th}}^\infty \frac{d\nu}{\nu^2}\frac{Q^4\beta_1(\tau) - 4m_\ell^2\nu^2\beta_1(\tau_\ell)}{Q^4 - 4m_\ell^2\nu^2} g_1(\nu,Q^2)\right\},$$

$$\Delta_2 = -12m_p^2\int_0^\infty \frac{dQ^2}{Q^2}\int_{\nu_{th}}^\infty \frac{d\nu}{\nu^2}\frac{Q^4[\beta_2(\tau) - \beta_2(\tau_\ell)]}{Q^4 - 4m_\ell^2\nu^2} g_2(\nu,Q^2)$$

$$\Delta_{\text{pol}} = \frac{\alpha m_\ell}{2(1+\kappa_p)\pi m_p}(\Delta_1 + \Delta_2)$$



$$\beta_1(\tau) = -3\tau + 2\tau^2 + 2(2-\tau)\sqrt{\tau(\tau+1)}$$

$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)},$$

The hyperfine splittings in μH depend on proton form factors G_E and G_M proton spin structure functions g_1 and g_2

Two-Photon Effects

PHYSICAL REVIEW A **89**, 022504 (2014)

Nuclear-structure contribution to the Lamb shift in muonic deuterium

Carl E. Carlson
College of William and Mary, Physics Department, Williamsburg, Virginia 23187, USA

Mikhail Gorchtein* and Marc Vanderhaeghen
Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany
and PRISMA Cluster of Excellence, Johannes Gutenberg-Universität, Mainz, Germany
(Received 3 December 2013; published 4 February 2014)

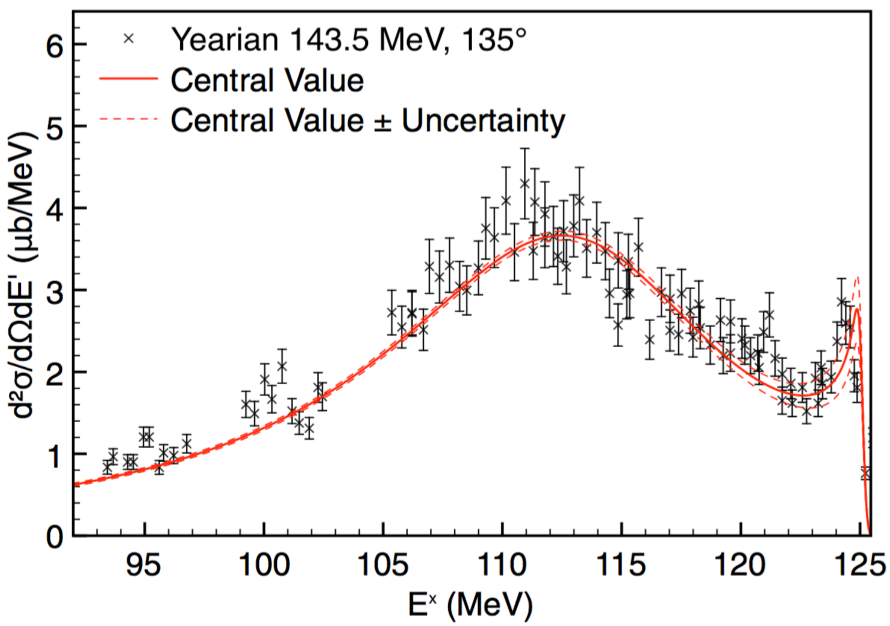
We consider the two-photon exchange contribution to the $2P-2S$ Lamb shift in muonic deuterium in the framework of forward dispersion relations. The dispersion integrals are evaluated using experimental data on elastic deuteron form factors and inelastic electron-deuteron scattering, both in the quasielastic and hadronic range. The subtraction constant that is required to ensure convergence of the dispersion relation for the forward Compton amplitude $T_1(\nu,Q^2)$ is related to the deuteron magnetic polarizability $\beta(Q^2)$. Based on phenomenological information, we obtain for the Lamb shift $\Delta E_{2P-2S} = 2.01 \pm 0.74$ meV. The main source of the uncertainty of the dispersion analysis is due to lack of quasielastic data at low energies and forward angles. We show that a targeted measurement of the deuteron electrodesintegration in the kinematics of upcoming experiments A1 and MESA at Mainz can help in quenching this uncertainty significantly.

DOI: 10.1103/PhysRevA.89.022504 PACS number(s): 31.30.jr, 13.40.Gp, 14.20.Dh, 36.10.Ee

TPE

TABLE I. TPE corrections to the $2S_{1/2}$ energy level in muonic deuterium in units of meV.

$\Delta \bar{E}^{el}$	$-0.417(2)$
ΔE^{PWBA}	$-1.616(739)$
ΔE^{FSI}	$-0.391(44)$
$\Delta E^{\perp}$	$-0.322(3)$
ΔE^{hadr}	$-0.028(2)$
ΔE^{β}	$0.740(40)$
ΔE^{Th}	$0.023(1)$
$\Delta E_{\mathrm{total}}$	$-2.011(740)$



Precise quasi-elastic data at low Q^2 is needed for TPE. Mainz A1 has data being analyzed

Monterey1973

Volume 47B, number 4 PHYSICS LETTERS 26 November 1973

Measured D/p Ratio

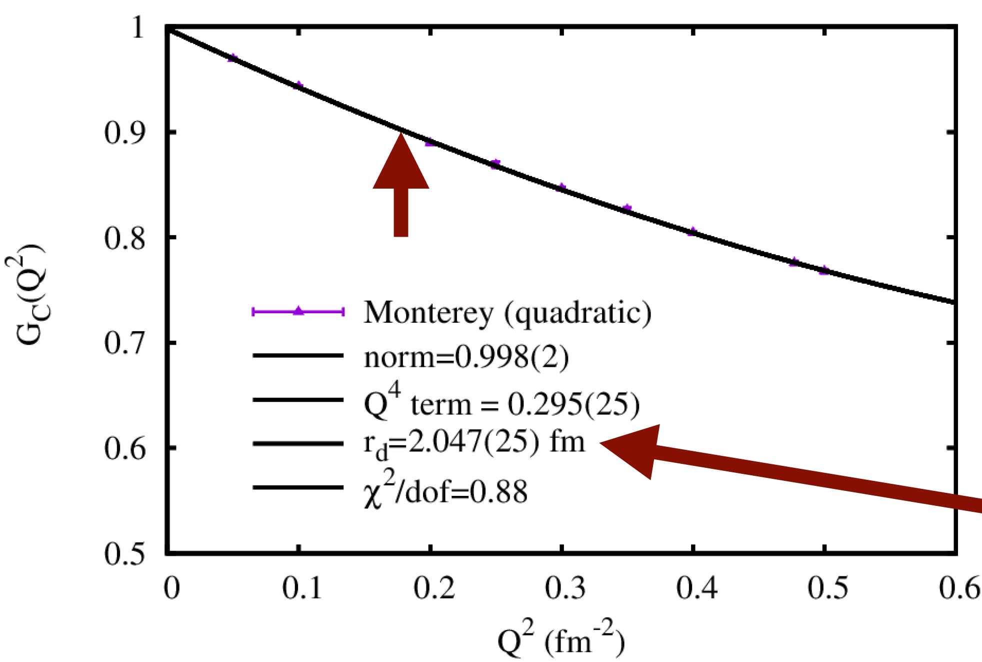
ELASTIC ELECTRON DEUTERON SCATTERING

R.W. BERARD, F.R. BUSKIRK, E.B. DALLY, J.N. DYER,
X.K. MARUYAMA, R.L. TOPPING and T.J. TRAVERSO
Naval Postgraduate School, Monterey, California, USA

Received 3 October 1973

Measurements of the ratio of the deuteron to proton electric form factors were made for low q. The rms radius of the deuteron structure factor was found to be 1.9635 ± 0.0045 fm, yielding an rms charge radius of 2.095 ± 0.006 fm.

Form factor drops much faster than for the proton



Slope at origin is underestimated assuming r_p=0.84 fm

Mainz 1981

Measured D/p Ratio

$$r_c = 2.116 \pm 0.006 \text{ fm}$$

Nuclear Physics **A364** (1981) 285–296

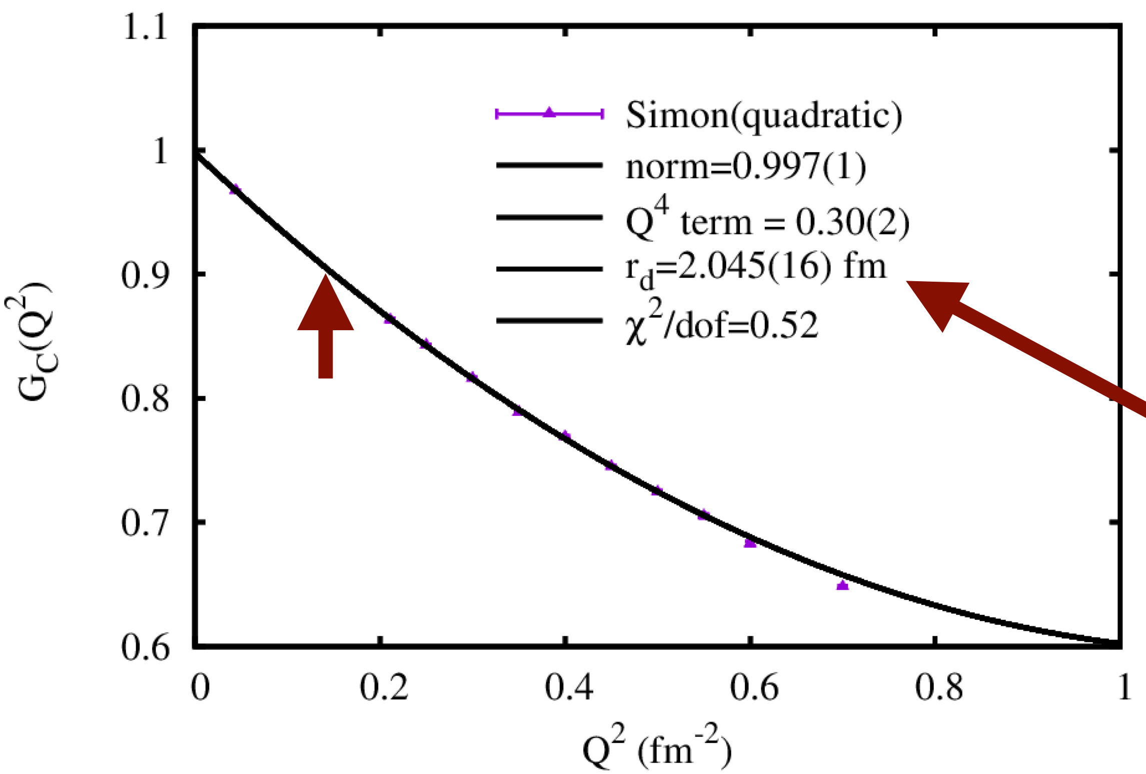
ELASTIC ELECTRIC AND MAGNETIC e-d SCATTERING AT LOW MOMENTUM TRANSFER

G.G. SIMON, CH. SCHMITT and V.H. WALTHER

Institut für Kernphysik, Johannes Gutenberg-Universität, D-6500 Mainz, Federal Republic of Germany

Received 5 December 1980

Abstract: Up to $q^2 = 4$ fm^{-2} differential cross sections for elastic electron–deuteron scattering have been measured for a wide range of scattering angles. Using a combination of high pressure gas target and liquid target systems we have obtained high-accuracy data for the ratio e-p to e-d scattering and a small normalization error for backward scattering data. For extreme low momentum transfer the elastic structure deuteron rms radius has been extracted: $r_d = 1.9660 \pm 0.0068$ fm. This quantity, which is a characteristic parameter of the nucleon–nucleon potential was compared with the results of different models. The analysis of the isoscalar form factor indicates no significant contribution of a non-resonant three-pion state. The high-accuracy data of the electric neutron form factor could be extended to higher q^2. All nucleon form factors are described with a consistent ansatz. The magnetic scattering data indicate the important role of isobar configuration in nucleon–nucleon interactions.



Form factor drops much faster than for the proton

Slope at origin is underestimated assuming r_p=0.84 fm

WILLIAM & MARY
CHARTERED 1693

New D Measurements

Schlimme et al., DOI: 10.1051/epjconf/2016113 04017

A1 Mainz, Elastic/Quasi-Elastic eD scattering

Currently being analyzed

Deuteron form factor measurements at low momentum transfers

B. S. Schlimme[1,a], P. Achenbach[1], J. Beričič[2], R. Böhm[1], D. Bosnar[3], L. Correa[4], M. O. Distler[1], A. Esser[1], H. Fonvieille[4], I. Friščić[3], K. A. Griffioen[5], Y. Huan[5], S. Kegel[1], Y. Kohl[1], H. Merkel[1], M. Mihovilovič[1], J. Müller[1], U. Müller[1], J. Pochodzalla[1], M. Schoth[1], F. Schulz[1], C. Sfienti[1], S. Širca[2,6], S. Štajner[2], M. Thiel[1], and A. Weber[1]

[1] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[2] *Jožef Stefan Institute, SI-1000 Ljubljana, Slovenia*
[3] *Department of Physics, University of Zagreb, HR-10002 Zagreb, Croatia*
[4] *Clermont Université, Université Blaise Pascal, F-63000 Clermont-Ferrand, France*
[5] *College of William and Mary, Williamsburg, VA 23187, USA*
[6] *Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia*

Abstract. A precise measurement of the elastic electron-deuteron scattering cross section at four-momentum transfers of $0.24\,\mathrm{fm}^{-1} \leq Q \leq 2.7\,\mathrm{fm}^{-1}$ has been performed at the Mainz Microtron. In this paper we describe the utilized experimental setup and the necessary analysis procedure to precisely determine the deuteron charge form factor from these data. Finally, the deuteron charge radius r_d can be extracted from an extrapolation of that form factor to $Q^2 = 0$.

Conclusions

- Low Q^2 electron scattering data are consistent with the muonic Lamb shift value r_p=0.84 fm.
- Several experiments including **PRAD** at JLab and **MUSE** at PSI will weigh in on this issue int he coming years.
- More precision low-Q^2 G_E, G_M, F_1, F_2, g_1 and g_2 data are needed for improving the nuclear physics contributions to atomic transitions. Mainz deuteron data will contribute to this. Some JLab data on g_1 and g_2 have yet to be published.