Scientific Overview

Ron Gilman* (Rutgers University) for
the MUSE Collaboration

The Proton Radius Puzzle is the difference between measurements of the proton radius with electrons vs. with muons. It is unresolved after 4 years, and a very high profile issue.

Most of the suggested explanations of the puzzle to date have been ruled out, and arguably none of the remaining explanations are widely supported in the field. There is wide agreement new measurements are needed to resolve the puzzle.

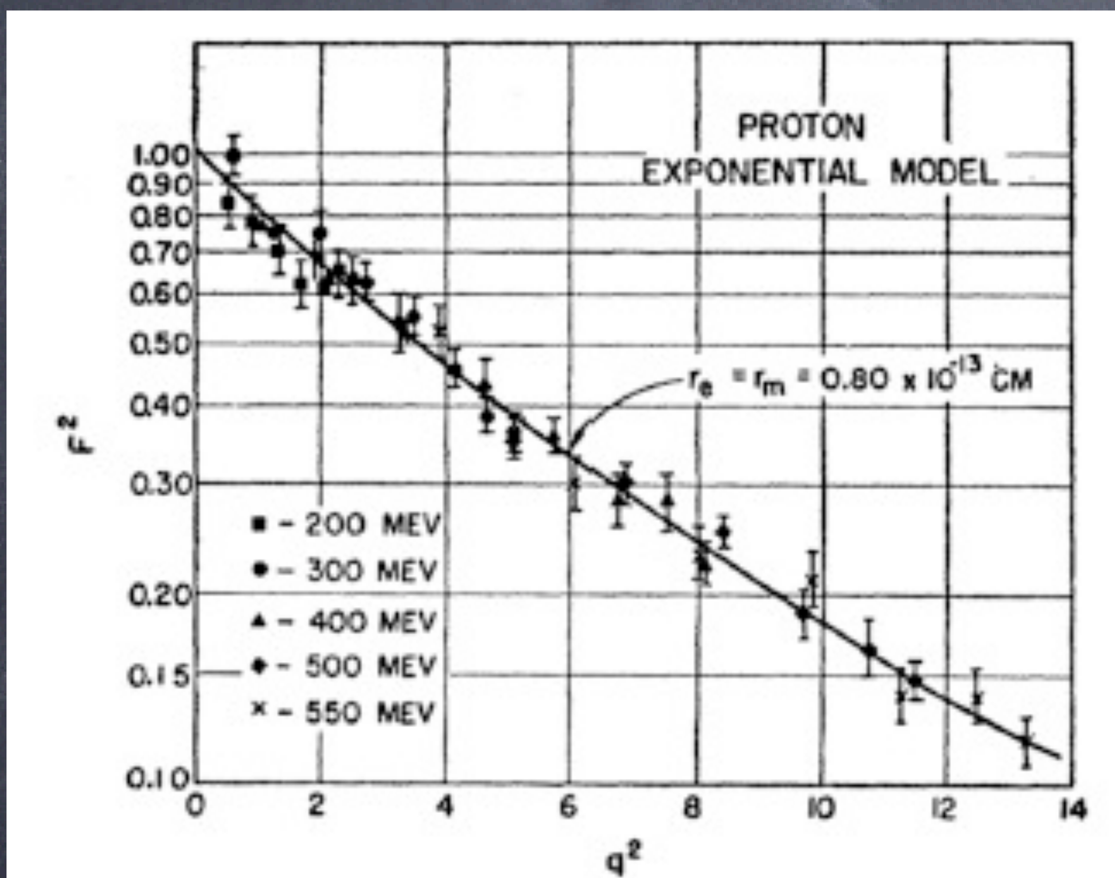
Some new analyses and data are starting to appear, and new suggestions keep arising, but nothing to date clearly points to a resolution of the Puzzle.

*Supported in part by US NSF grant PHY 1306126

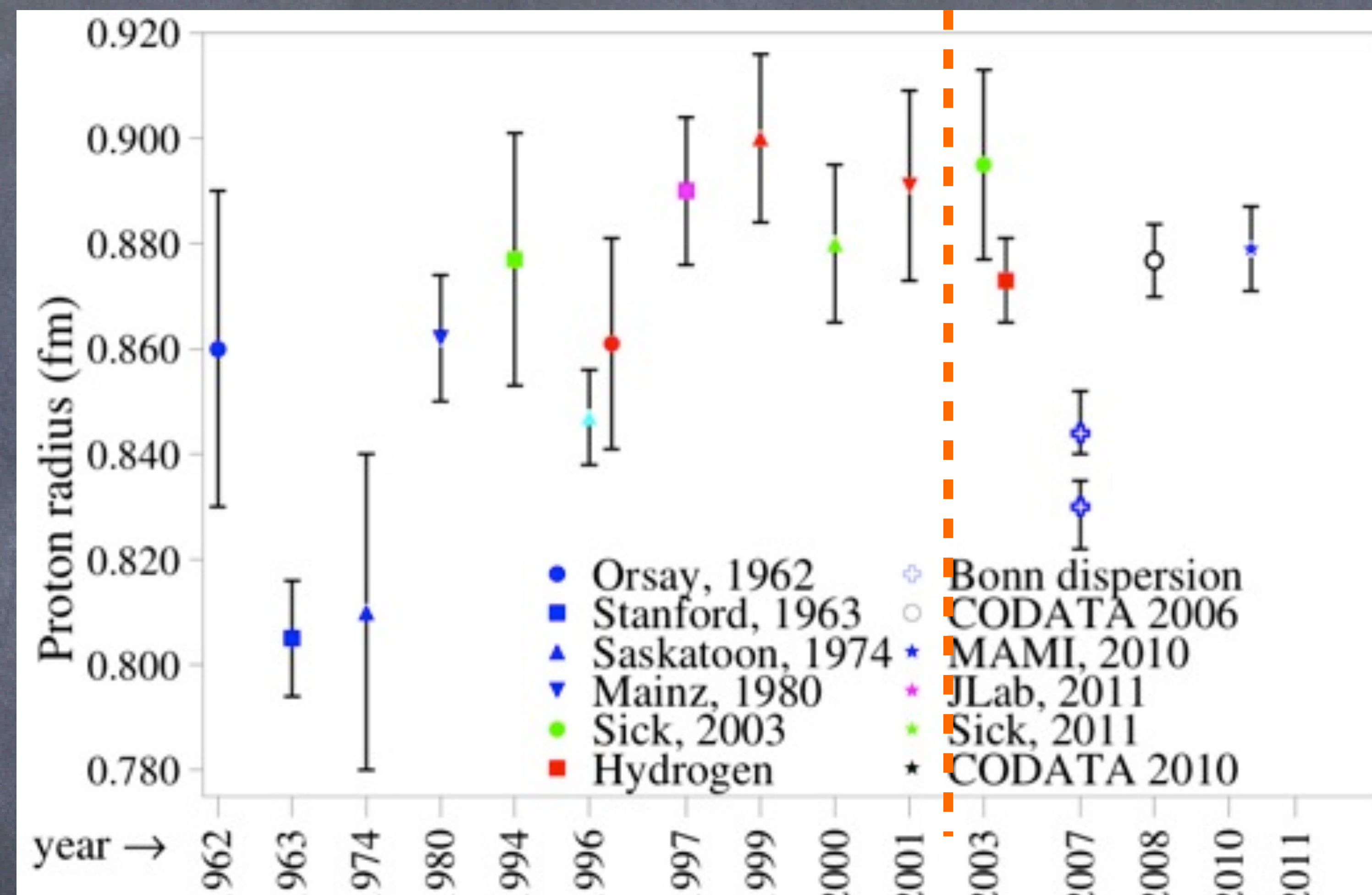
The Puzzle Arises

"Old" Proton Radius Measurements

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



From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, AnnRevNPS 63, 167 (2013), modified



By early 2000s, good agreement between hydrogen and scattering, and fitting issues generally understood, though sometimes ignored.

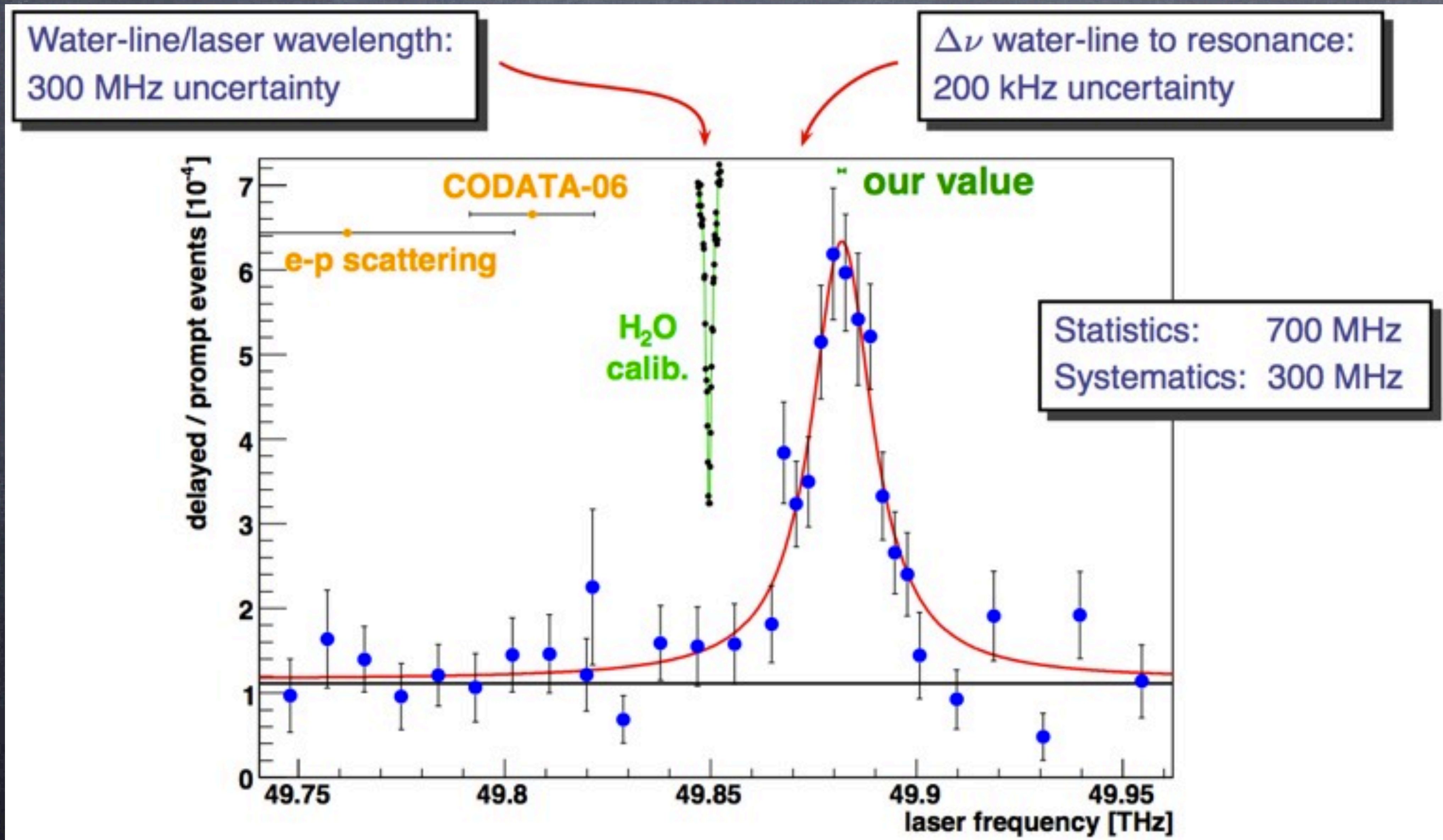
The Proton Radius Puzzle Appears

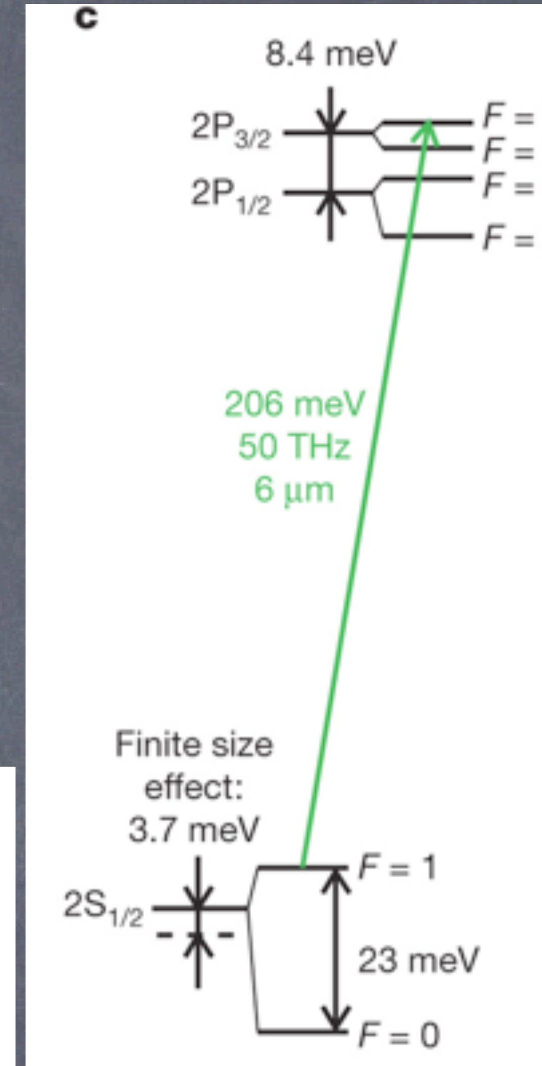
Randolf Pohl et al., Nature 466, 213 (2010):

0.84184 ± 0.00067 fm

5σ off 2006 CODATA

$\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ (meV)





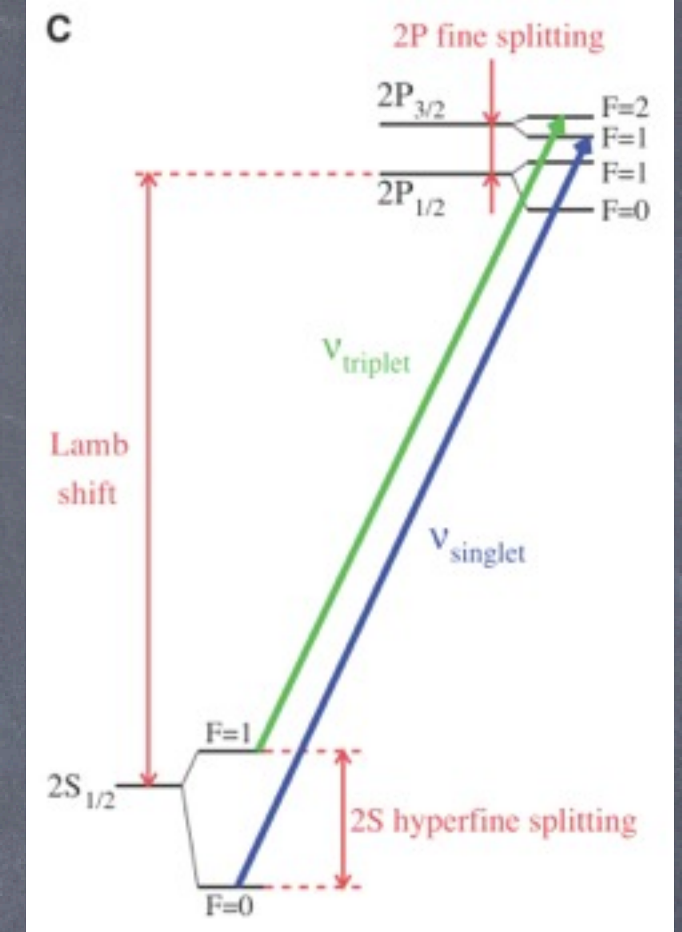
Use laser to excite muons into the 2P state; detect 2P to 1S decay X rays to see that you succeeded

The Proton Radius Puzzle Is Confirmed

Aldo Antognini et al., Science 339, 417 (2013):

0.84087 ± 0.00039 fm

7σ off 2010 CODATA



$$\Delta E = 206.0336(15) - 5.22275(10)r^2 + E_{TPE} \text{ (meV)}$$

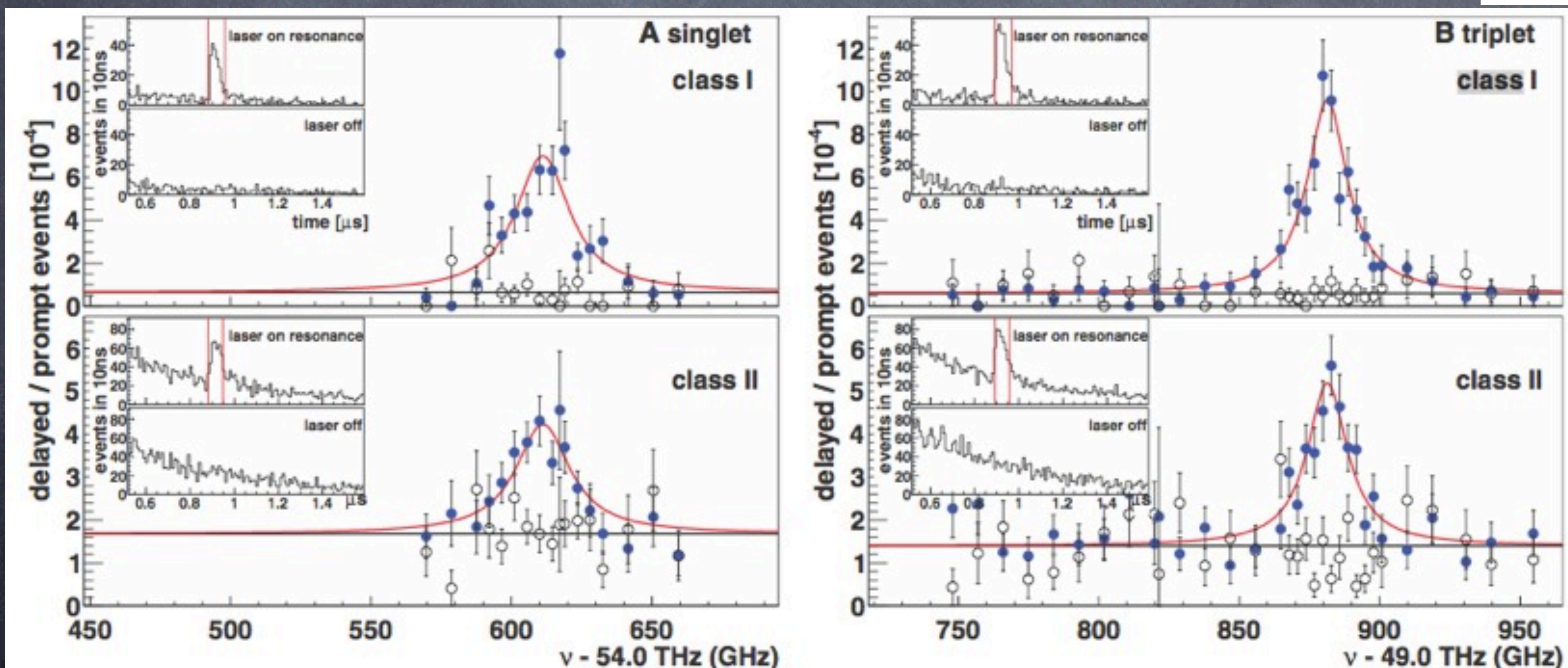
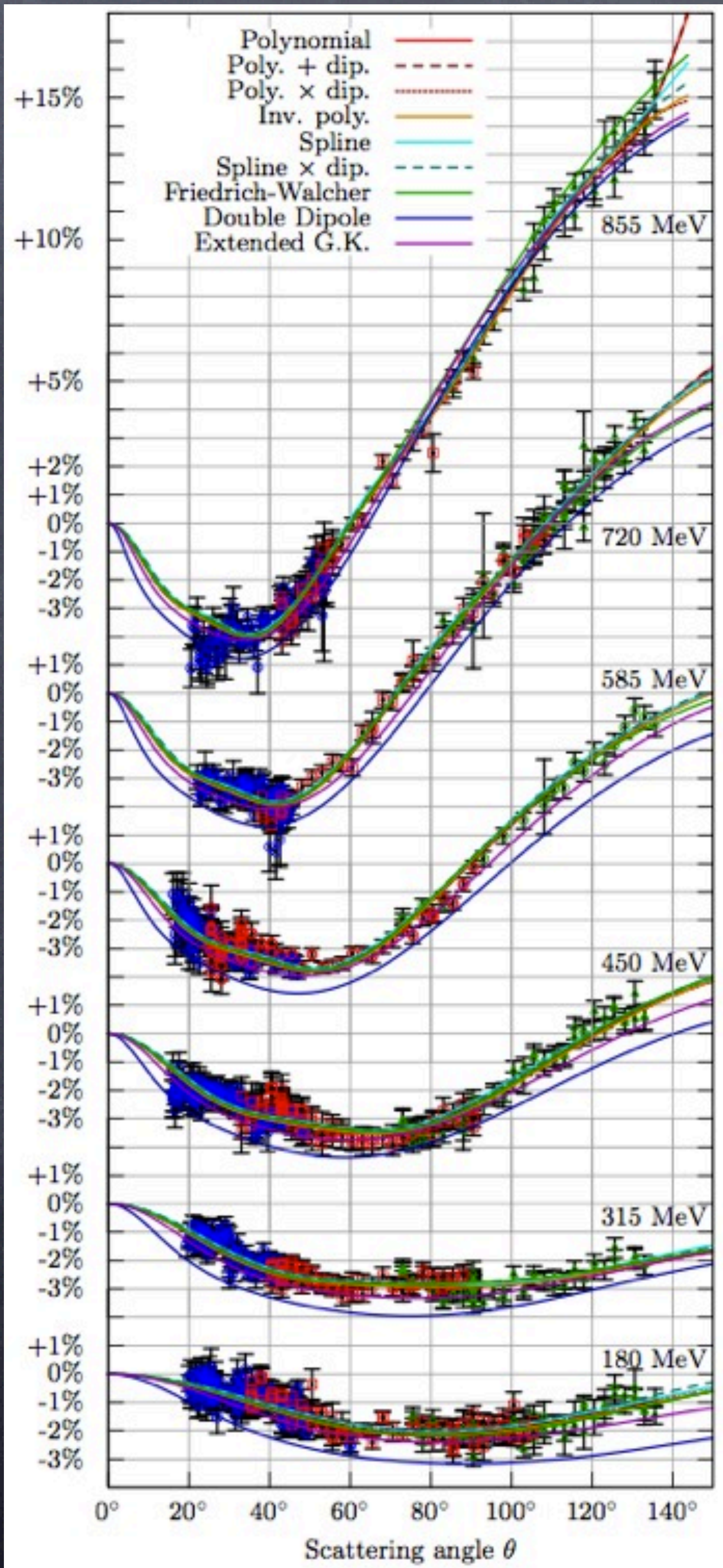


Fig. 3. Muonic hydrogen resonances (solid circles) for singlet ν_s (**A**) and triplet ν_t (**B**) transitions. Open circles show data recorded without laser pulses. Two resonance curves are given for each transition to account for two different classes, I and II, of muon decay electrons (*12*). Error bars indicate the standard error. (Insets) The time spectra of K_α x-rays. The vertical lines indicate the laser time window.

New Mainz ep

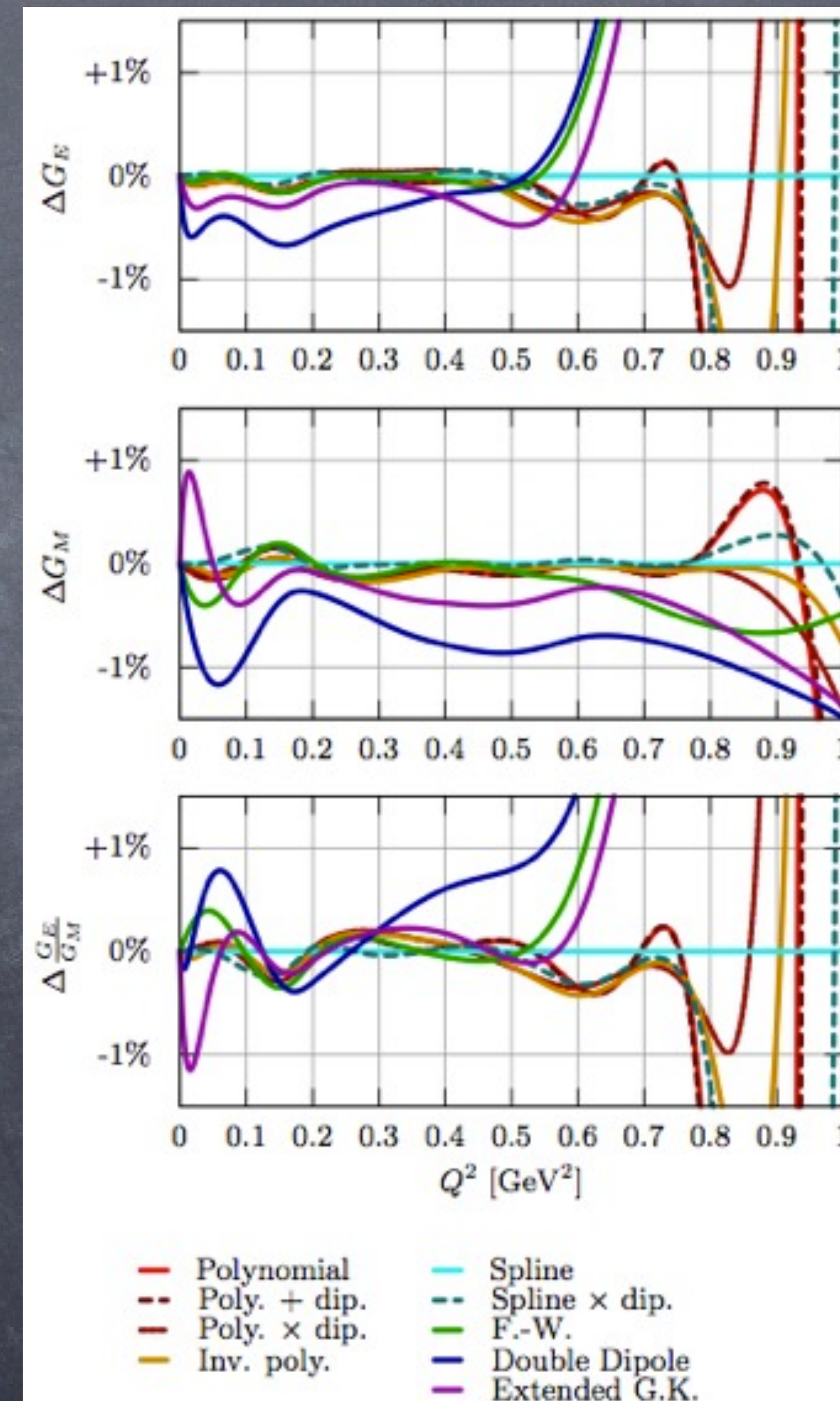
J. Bernauer et al PRL 105, 242001 (2010)

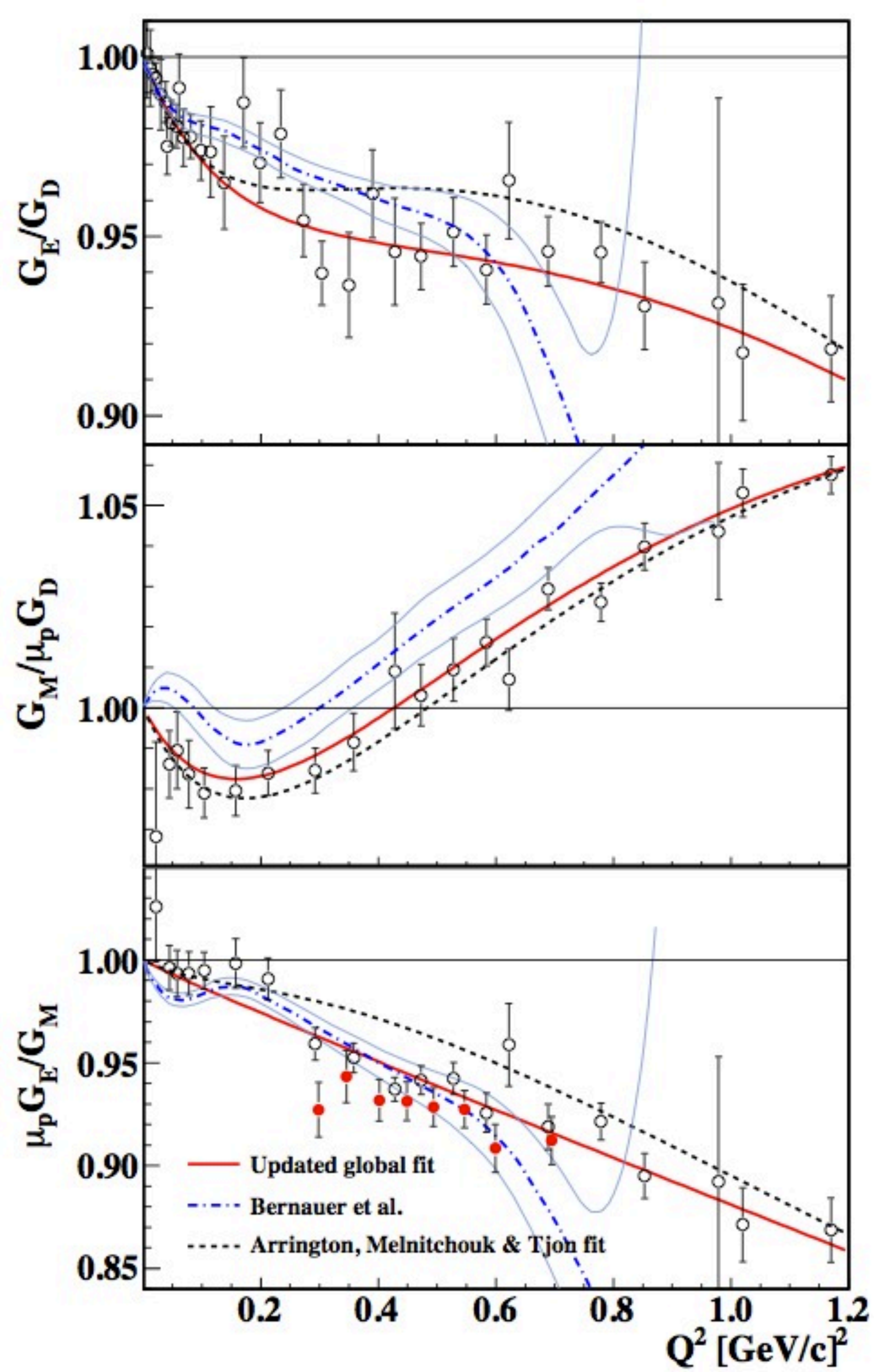
$r_p = 0.879 \pm 0.008$ fm



Left: Cross sections relative to standard dipole

Right: variation in fits to data - some fits have poor χ^2, so uncertainty is overestimated.



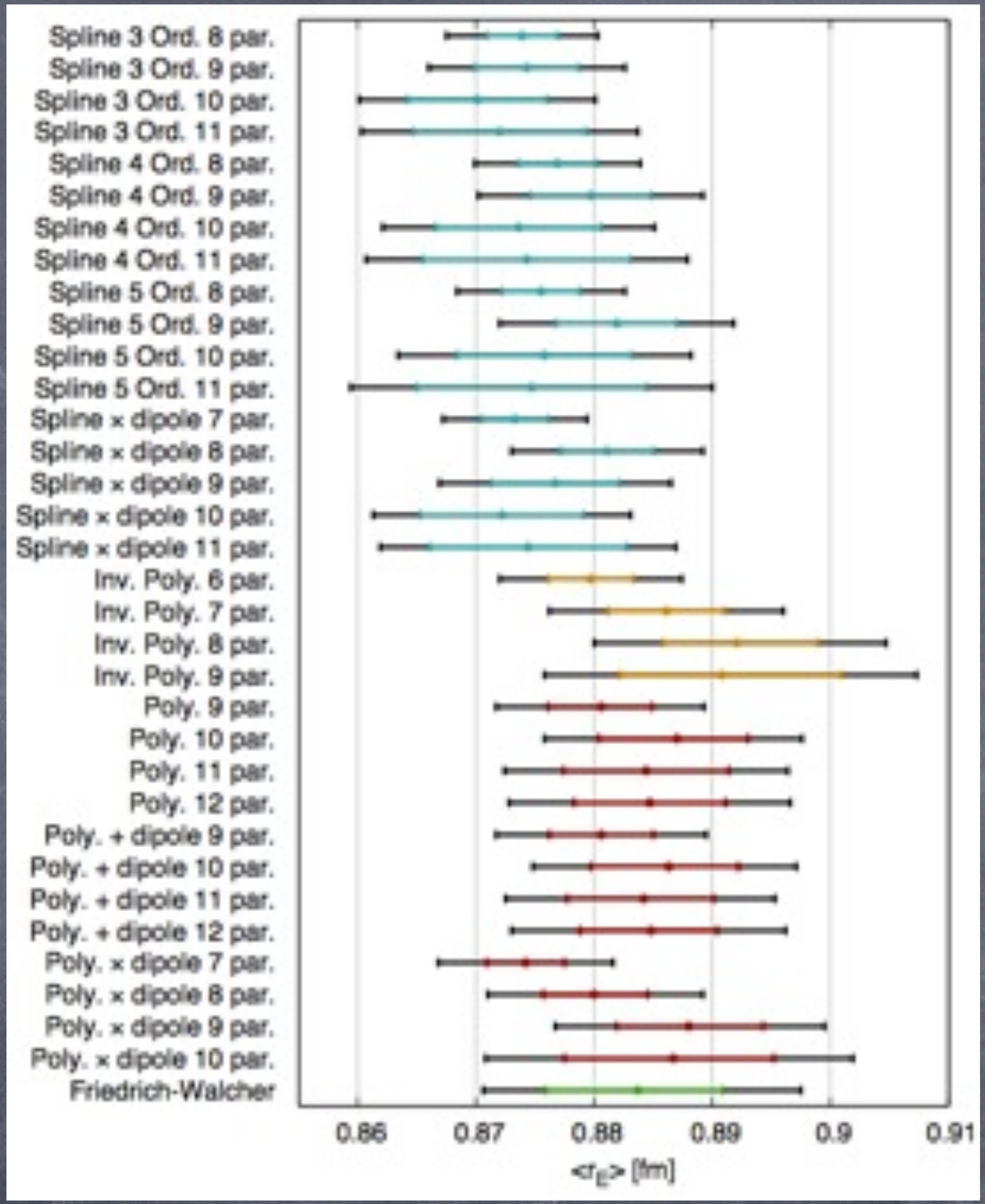


New JLab ep E08-007 Part I (G Ron...)

X. Zhan et al PLB 705, 59 (2011)

$r_p = 0.875 \pm 0.009$ fm

Model Dependence



From J. Bernauer's thesis

The PDG Summary

Most measurements of the radius of the proton involve electron-proton interactions, and most of the more recent values agree with one another. The most precise of these is r_p = 0.879(8) fm (BERNAUER 2010). The CODATA 10 value (MOHR 2012), obtained from the electronic results, is 0.8775(51). However, a measurement using muonic hydrogen finds r_p = 0.84087(39) fm (ANTOGNINI 2013), which is 13 times more precise and seven standard deviations (using the CODATA 10 error) from the electronic results.

...

Until the difference between the ep and μp values is understood, it does not make sense to average the values together. For the present, we give both values. It is up to workers in this field to solve this puzzle.

Proton Charge Radius Summary Table

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 or 7.2σ difference

High Profile

The radius puzzle received a lot of attention, as did its confirmation.

Pohl et al, Nature (2010) ≈ 400 citations

Bernauer et al, PRL 2011 ≈ 60 citations

Zhan et al, PLB 2012 ≈ 50 citations

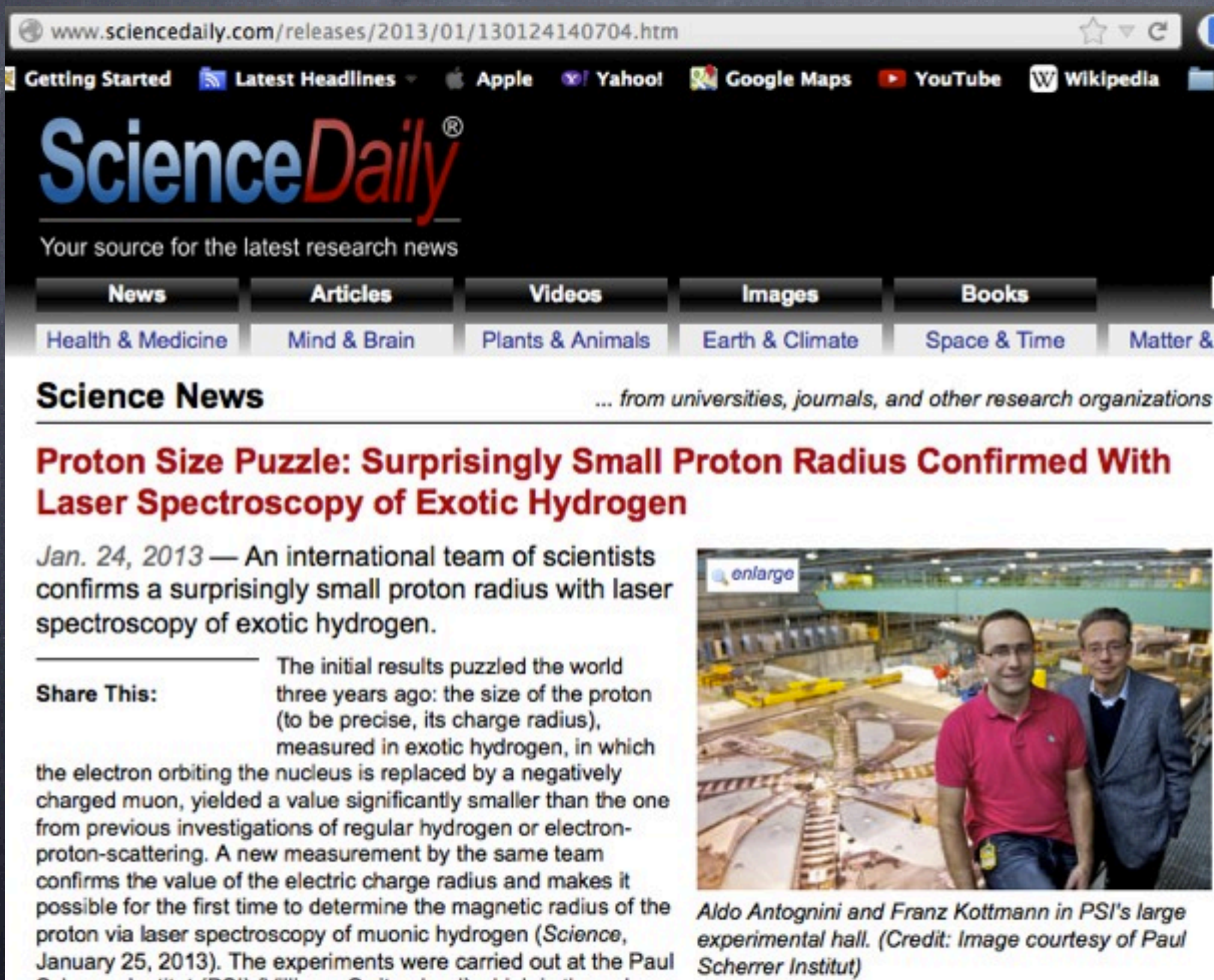
Antognini et al, Science 2013 ≈ 100 citations

Pohl, Gilman, Miller, Pachucki, Ann Rev Nucl Part Sci 63, 167 (2013) ≈ 20 citations

Pohl, Gilman, Miller, Reviews of Modern Physics Colloquium, in preparation

High Profile

The radius puzzle has also received a lot of popular attention.


www.sciencedaily.com/releases/2013/01/130124140704.htm

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Proton Size Puzzle: Surprisingly Small Proton Radius Confirmed With Laser Spectroscopy of Exotic Hydrogen

Jan. 24, 2013 — An international team of scientists confirms a surprisingly small proton radius with laser spectroscopy of exotic hydrogen.

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The initial results puzzled the world three years ago: the size of the proton (to be precise, its charge radius), measured in exotic hydrogen, in which the electron orbiting the nucleus is replaced by a negatively charged muon, yielded a value significantly smaller than the one from previous investigations of regular hydrogen or electron-proton-scattering. A new measurement by the same team confirms the value of the electric charge radius and makes it possible for the first time to determine the magnetic radius of the proton via laser spectroscopy of muonic hydrogen (*Science*, January 25, 2013). The experiments were carried out at the Paul Scherrer Institut (PSI) (Villigen, Switzerland) which is the only

enlarge

Aldo Antognini and Franz Kottmann in PSI's large experimental hall. (Credit: Image courtesy of Paul Scherrer Institut)

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Shrinking proton puzzle persists in new measurement

19:00 24 January 2013 by Lisa Gros

A puzzle at the heart of the atom refuse
measurement yet of the proton's radius
smaller than the laws of physics demar
debated for two years.

The latest finding deepens the need for
explanation, to account for the inconsis
hole is deeper now," says Gerald Miller
Seattle, who was not involved in the ne

The saga of the proton radius began in
Pohl at the Max Planck Institute of Qua
determined the width of the fuzzy ball o
smaller than had been assumed.

Previous teams had inferred the proton
measure directly, by studying how elect
uses the simplest atom, hydrogen, whic
proton. A quirk of quantum mechanics s

www.sciencenews.org/view/generic/id/347775/description/Protons_radius_revised_downward

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07|13|13 ISSUE

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When the atom went

Home / News / February 23, 2013; Vol.183 #4

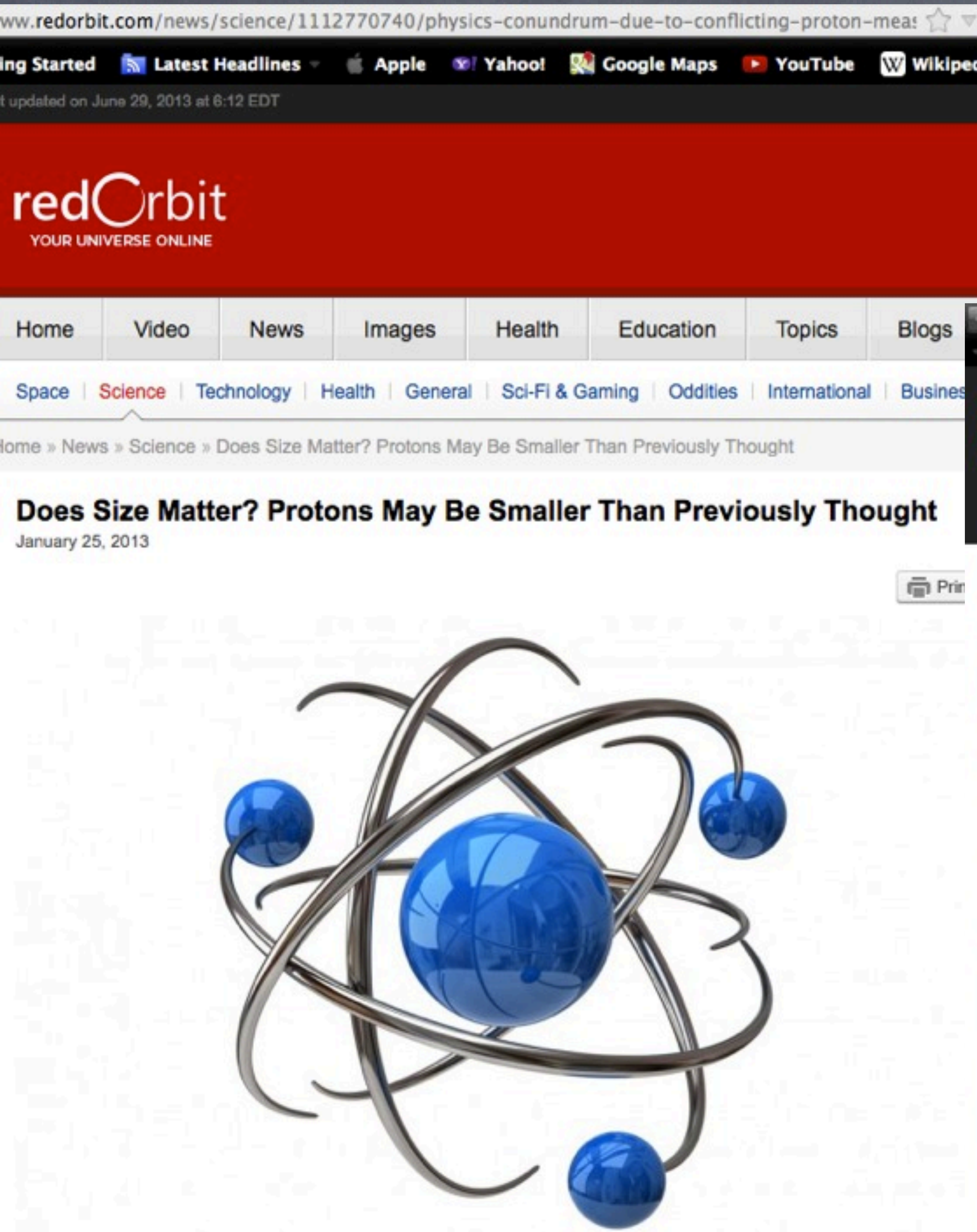
Proton's radius revised downward

Surprise measurement may point to new physics

By Andrew Grant
Web edition: January 24, 2013
Print edition: February 23, 2013; Vol.183 #4 (p. 8)

A+ A-

Only in physics can a few quintillionths of a meter be cause for uneasy
excitement. A new measurement finds that the proton is about 4 perce
smaller than previous experiments suggest. The study, published in the
25 issue of *Science*, has physicists cautiously optimistic that the discrep
between experiments will lead to the discovery of new particles or force



ww.redorbit.com/news/science/1112770740/physics-conundrum-due-to-conflicting-proton-mea

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Does Size Matter? Protons May Be Smaller Than Previously Thought

January 25, 2013

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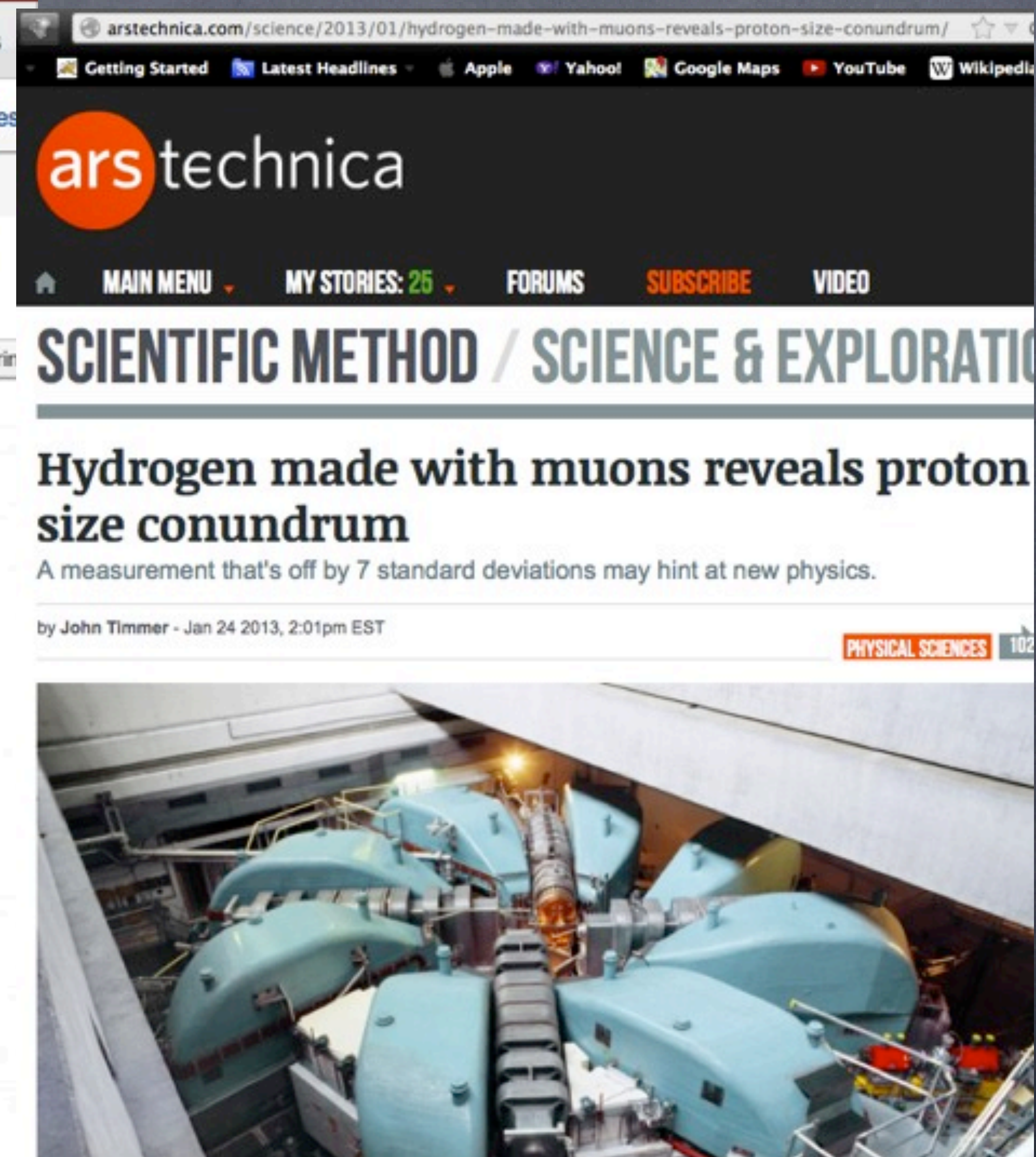

arstechnica.com/science/2013/01/hydrogen-made-with-muons-reveals-proton-size-conundrum/

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Hydrogen made with muons reveals proton size conundrum

A measurement that's off by 7 standard deviations may hint at new physics.

by John Timmer - Jan 24 2013, 2:01pm EST

PHYSICAL SCIENCES

phys.org/news/2013-01-physicists-surprisingly-small-proton-radius.html

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Physicists confirm surprisingly s

Jan 24, 2013

International team of physicists confirms surprisingly small proton
spectroscopy of exotic hydrogen. The initial results puzzled the w
the size of the proton (to be precise, its charge radius), measured
which the electron orbiting the nucleus is replaced by a negatively
yielded a value significantly smaller than the one from previous in
hydrogen or electron-proton-scattering. A new measurement by th
the value of the electric charge radius and makes it possible for th
determine the magnetic radius of the proton via laser spectroscop

The experiments were carried out at the Paul Scherrer Institut (PS
Switzerland) which is the only research institute in the world provi
amount of muons. The international collaboration included the Ma
Quantum Optics (MPQ) in Garching near Munich, the Swiss Fede
Technology ETH Zurich, the University of Fribourg, the Institut für

www.huffingtonpost.com/2013/01/25/proton-radius-smaller-physicists-new-research_n_2549576.h

Proton Radius Is Smaller Than Physicists Had Thought, New Research Shows

Posted: 01/25/2013 8:20 am EST

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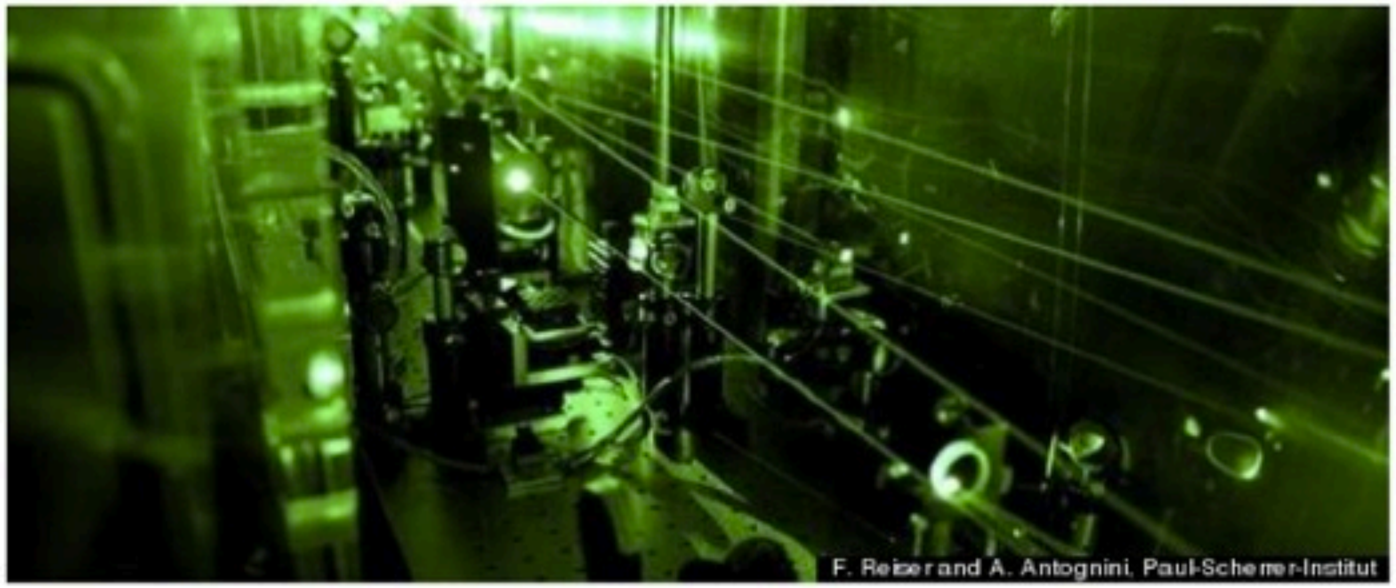

F. Reiser and A. Antognini, Paul-Scherrer-Institut

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By: Jesse Emspak, LiveScience Contributor
Published: 01/24/2013 03:02 PM EST on LiveScience

How many protons can dance on the head of a pin? The answer is nowhere near as straightforward as one may think — and it might offer new insights into one of the most well-tested theories in physics.

www.nature.com/news/shrunken-proton-baffles-scientists-1.12289

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NATURE | NEWS

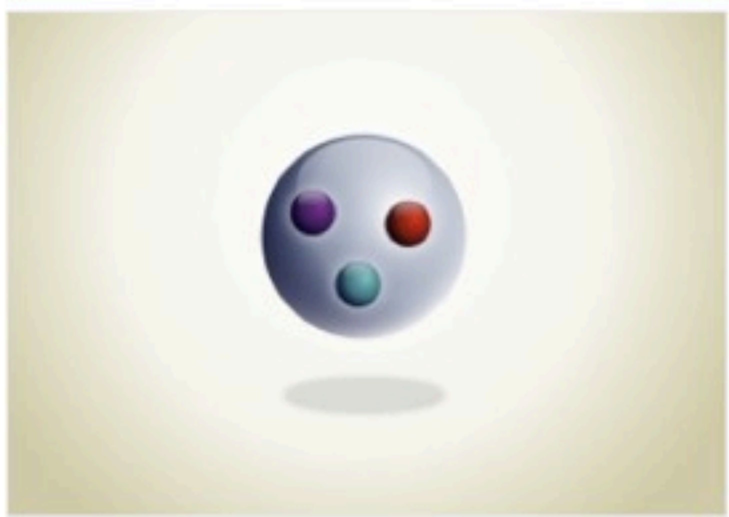
Shrunken proton baffles scientists

Researchers perplexed by conflicting measurements.

Geoff Brumfiel

24 January 2013

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.



The proton's three quarks are (mostly) confined within a region 0.87 femtometres in radius — or is it 0.84?

WESLEY FERNANDES

An experiment published today in *Science*[1] only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

www.scientificamerican.com/article.cfm?id=shrunken-proton-baffles-scientists

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Shrunken Proton Baffles Scientists

Researchers are perplexed by conflicting measurements for one of the universe's most common particles

By Geoff Brumfiel and Nature magazine

One of the Universe's most common particles has left physicists completely stumped. The proton, a fundamental constituent of the atomic nucleus, seems to be smaller than thought. And despite three years of careful analysis and reanalysis of numerous experiments, nobody can figure out why.

Pin it

The proton's three quarks are (mostly) confined within a region 0.87 femtometers wide — or is it 0.84?

Image: Flickr/Argonne National Laboratory

An experiment published today in *Science* only deepens the mystery, says Ingo Sick, a physicist at the University of Basel in Switzerland. "Many people have tried, but none has been successful at elucidating the discrepancy."

Prettiness of graphics inversely correlated with accuracy of physics?

www.newscientist.com/article/mg21929262.100-particle-puzzle-honey-i-shrunk-the-proton.html

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Particle puzzle: Honey, I shrunk the proton

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- Magazine issue 2926. **Subscribe and save**
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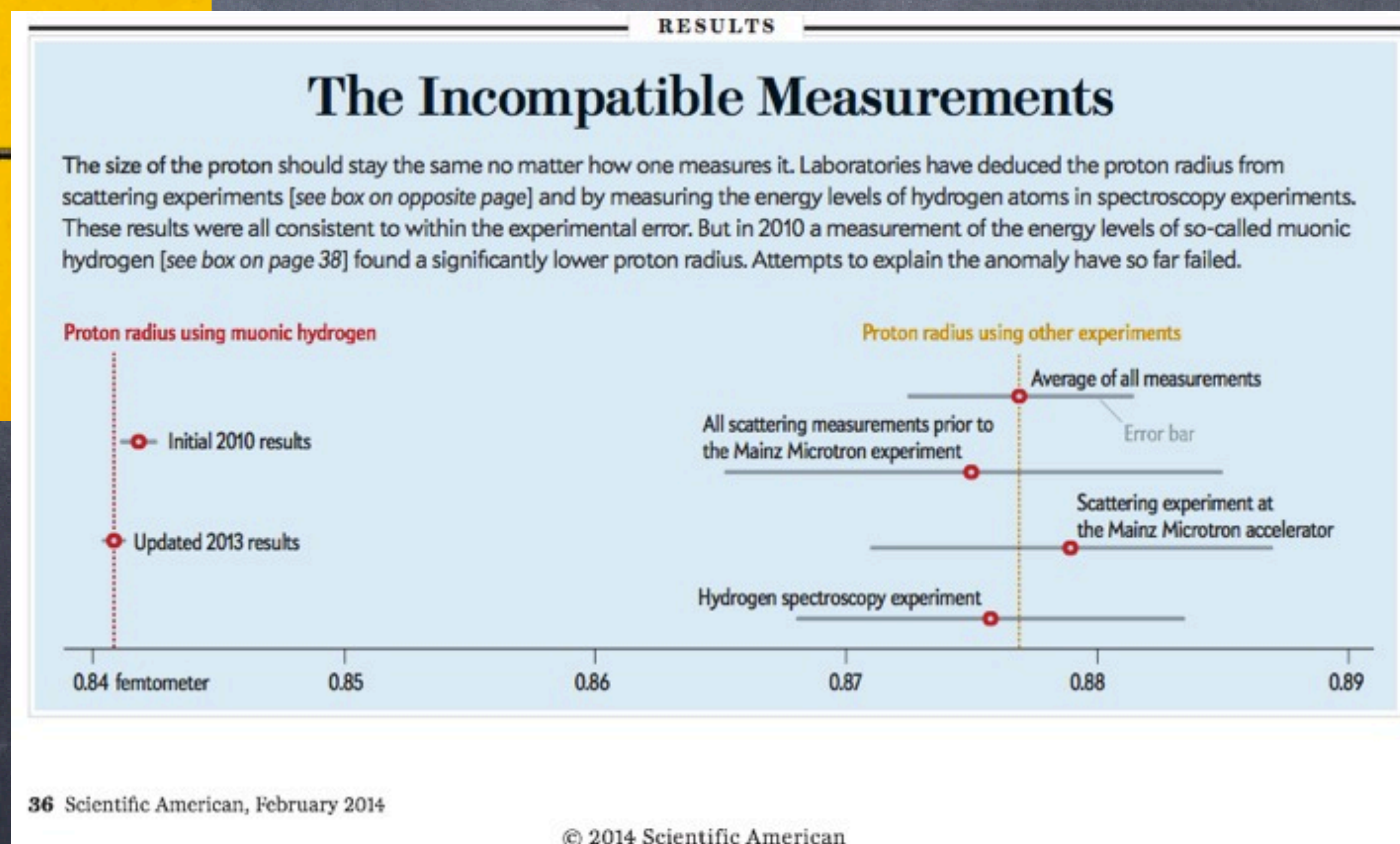
ONE quadrillionth of an inch. If you lost that off your waistline, you wouldn't expect a fuss. Then again, you are not a proton.

Until recently, it was unthinkable to question the size of the proton. Its radius is so well known that it appears on lists of nature's fundamental constants, alongside the speed of light and the charge of an electron. So when Randolf Pohl and his colleagues set out to make the most accurate measurement of the proton yet, they expected to just put a few more decimal places on the end of the official value. Instead this group of more than 30 researchers has shaken the world of atomic physics. Their new measurement wasn't just more accurate, it was decidedly lower. The proton had apparently been on a diet.

Most recently: Scientific American cover story, by R Pohl and J Bernauer


RESULTS

The Incompatible Measurements

The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.

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Mar 4, 2014 ... The resolution of the **Proton Radius** Puzzle is the diffraction pattern, giving another wavelength in case of muonic hydrogen oscillation for the ...
vixra.org/abs/1403.0017 - Similar

The **Radius** of the **Proton** in the Self-Consistent Model - viXra.org
Aug 3, 2012 ... Based on the notion of strong gravitation, acting at the level of elementary particles, and on the equality of the magnetic moment of the **proton** ...
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Feb 4, 2013 ... Recent experiments for **proton radius** measurement, based on muonic hydrogen, confirmed that the proton size obtained by muon interaction is ...
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Jan 25, 2012 ... In experiments for **proton radius** measurement that use muonic hydrogen, the value obtained was four percent below the expected standard ...
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Jan 29, 2013 ... Within the Everlasting Theory I calculated the charge **radius** of **proton** for experiment involving a **proton** and an electron 0.87673 fm.
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viXra.org e-Print archive, viXra:1111.0017, The Incredibly Shrinking ...
Nov 1, 2011 ... The recent discovery that the charge **radius** of **proton** deduced from quantum average of nuclear charge density from the muonic version of ...
vixra.org/abs/1111.0017 - Similar

Support for the Validity of the New, Smaller **Radius** of the **Proton**
Feb 5, 2014 ... Authors: Roger N. Weller. A simple algebraic derivation using the Planck

And, for better or worse, apparently 19 references in viXra.org

Possible Resolutions of the Puzzle

Possible Resolutions of the Puzzle

- Novel physics
  - Beyond Standard Model: new particles, new forces, quantum gravity
  - Conventional - 2 photon exchange
  - Conventional - structures in form factors, e^+e^- proton sea
  - Atomic physics calculations not good enough
  - Experiments do not measure the same physical quantity, or they measure the radius in different frames
- Experimental issues
  - μp is wrong: 3-body effects, ...
  - ep is wrong: underestimated uncertainties, bad radius extractions, ...

Examples of Bad Theory Explanations

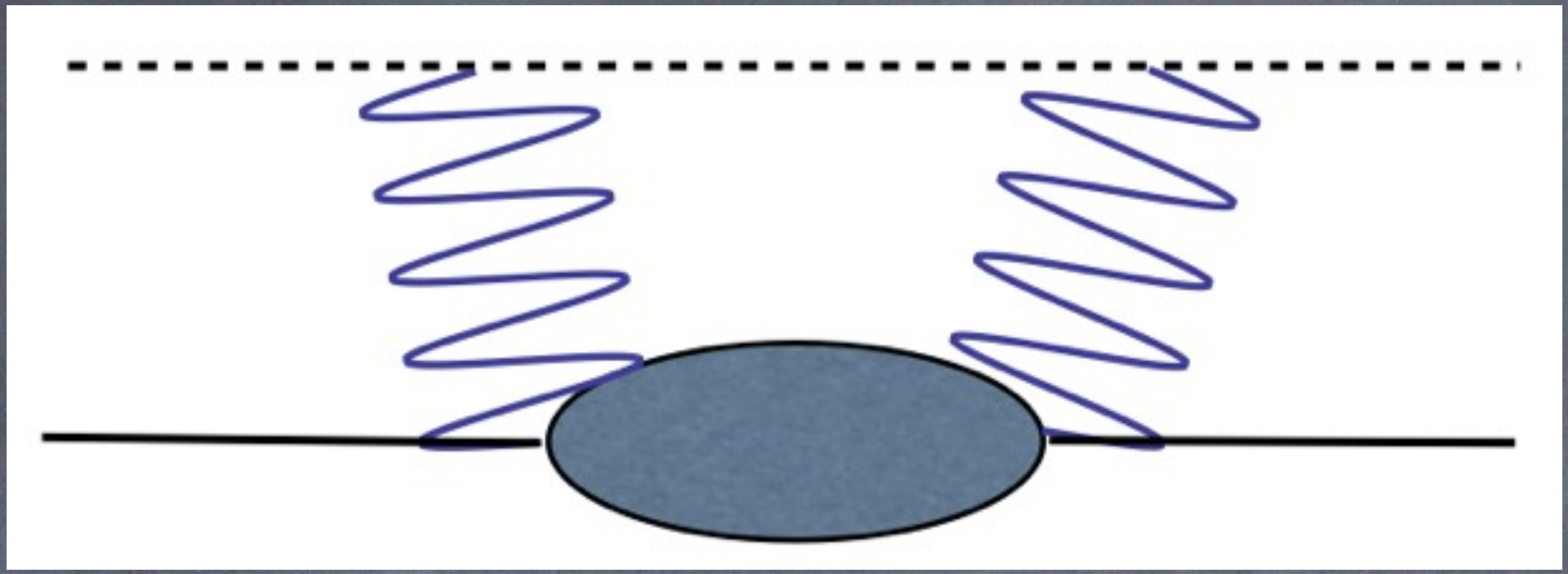
- De Rujula: large 3rd Zemach moment
- Thorns / lumps in form factor
- Quantum gravity!
- Large extra dimensions!
- Mart & Sulaksono: oscillating protons
- Robson: rest frame form factor is not scattering form factor
- Giannini & Santopinto: frame dependence of charge radii

Possibly Viable Theory Explanations

- What are viable theoretical explanations of the Radius Puzzle?
  - Novel Beyond Standard Model Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
  - Novel Hadronic Physics: G. Miller: two-photon correction
  - No explanation with majority support in the community
  - See Trento Workshop on PRP for more details:

http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

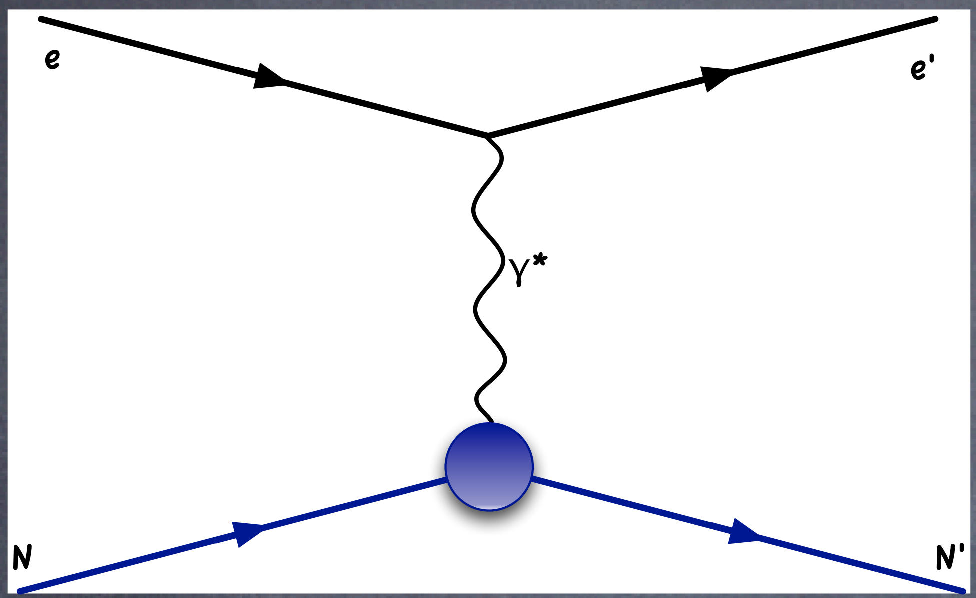
Theory Explanations: Novel Hadronic Physics



- There is a polarizibility correction that depends on m_l^4, affecting muons but not electrons
- Part of the correction is not (strongly) constrained by data or theory; it might resolve puzzle
- Prediction: enhanced 2γ exchange in μ scattering: 2-4%

- Calculations using chiral perturbation theory for the low Q^2 behavior coupled to a pQCD inspired inspired Q^{-4} falloff suggest correction is far too small
- Carlson: the correction also leads to a large EM mass of the proton

Theory Explanations: Novel Beyond Standard Model Physics

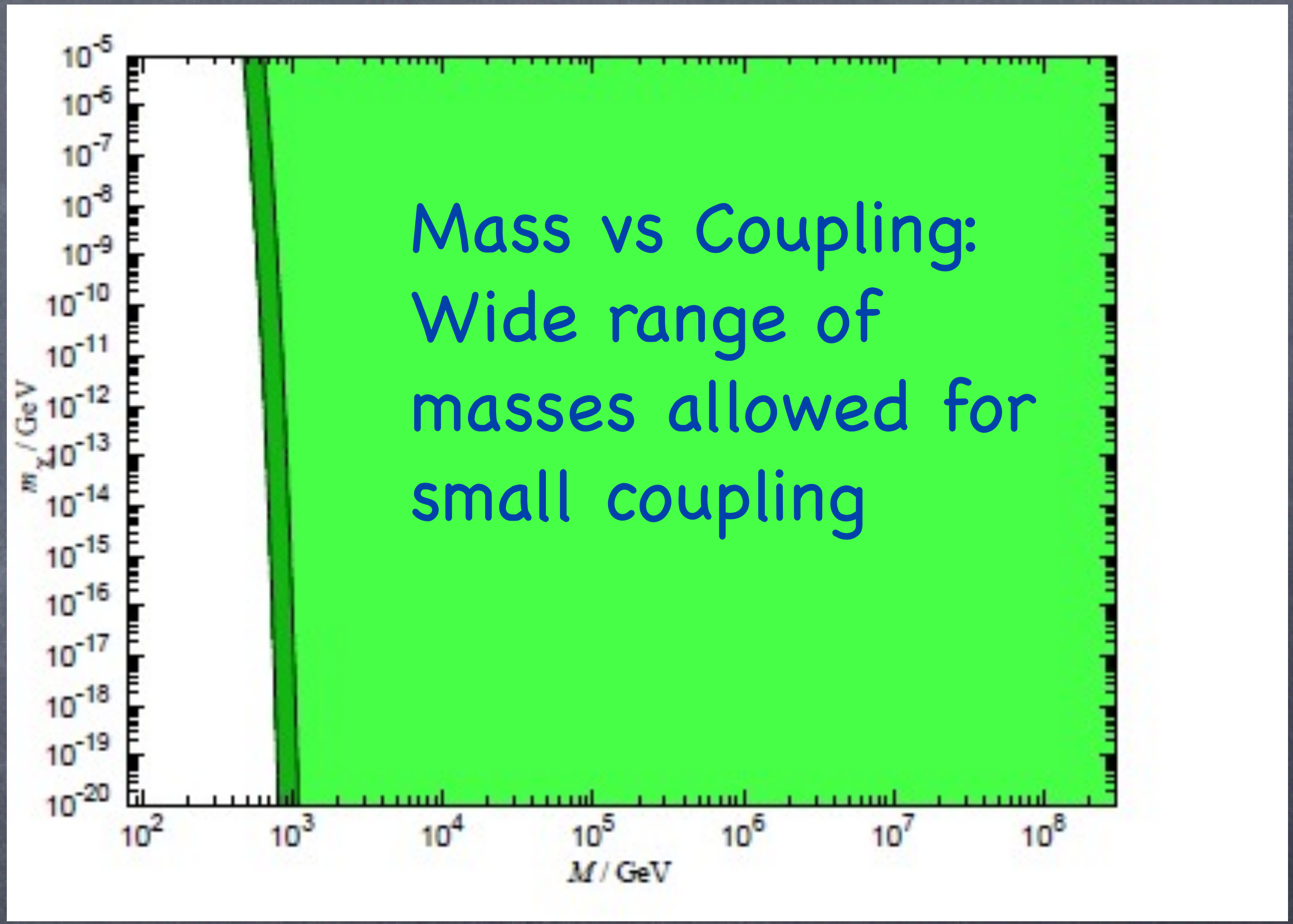


- Ideally, one new (dark photon?) particle explains Proton Radius Puzzle, μ g-2, cosmological positron excess

- But many constraints from existing physics and the 3 issues may be unrelated
- Examples follow…

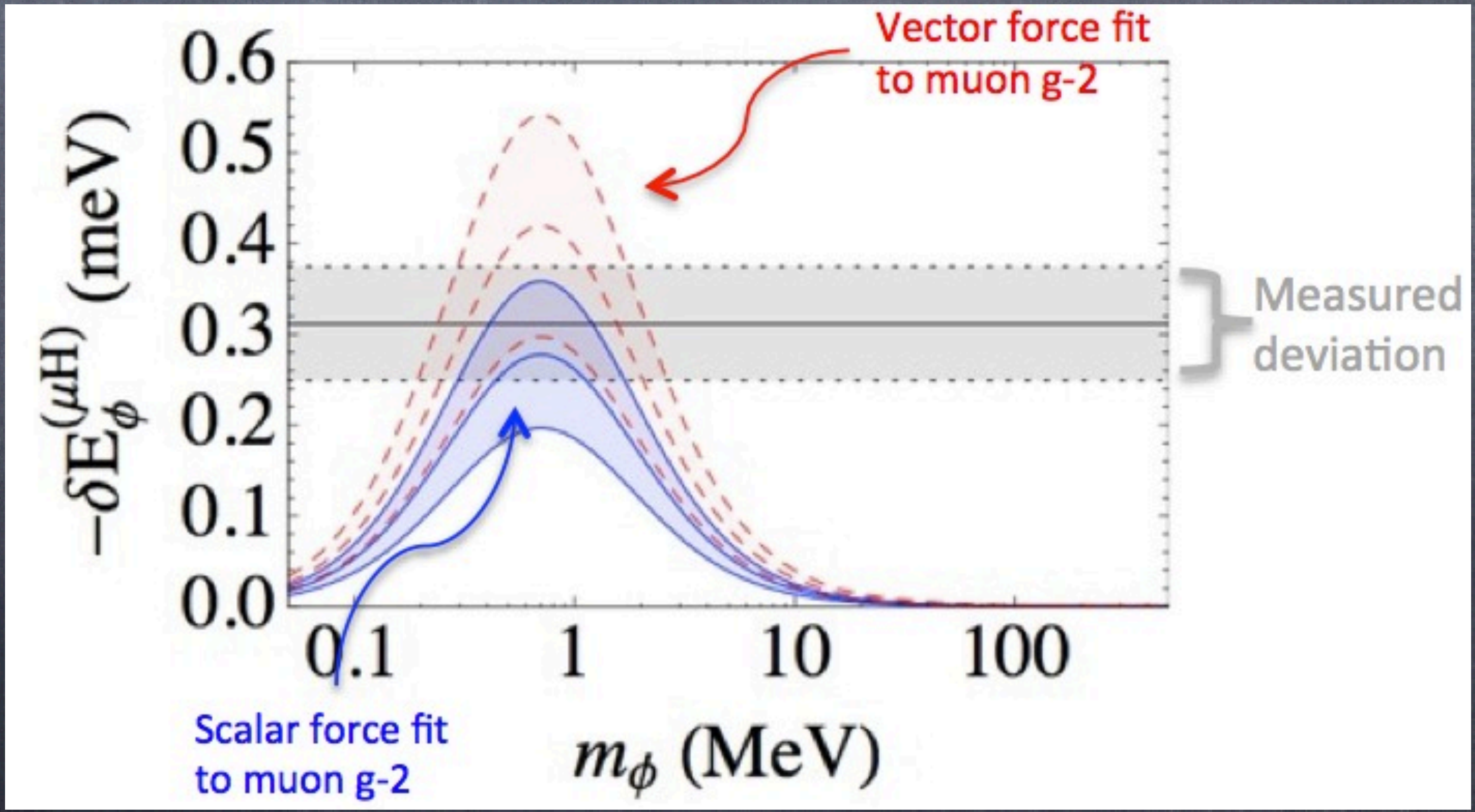
Theory Explanations: Novel BSM Physics

- Brax and Burrage, PRD 83, 035020 (2011)
- New light scalar couples ~ Fermion mass, 10^7 x greater effect in μ than e Lamb shift
- Need m < 1 MeV for PRP, more constraints from Z width, precision tests
- Constraints relaxed if coupling flavor dependent



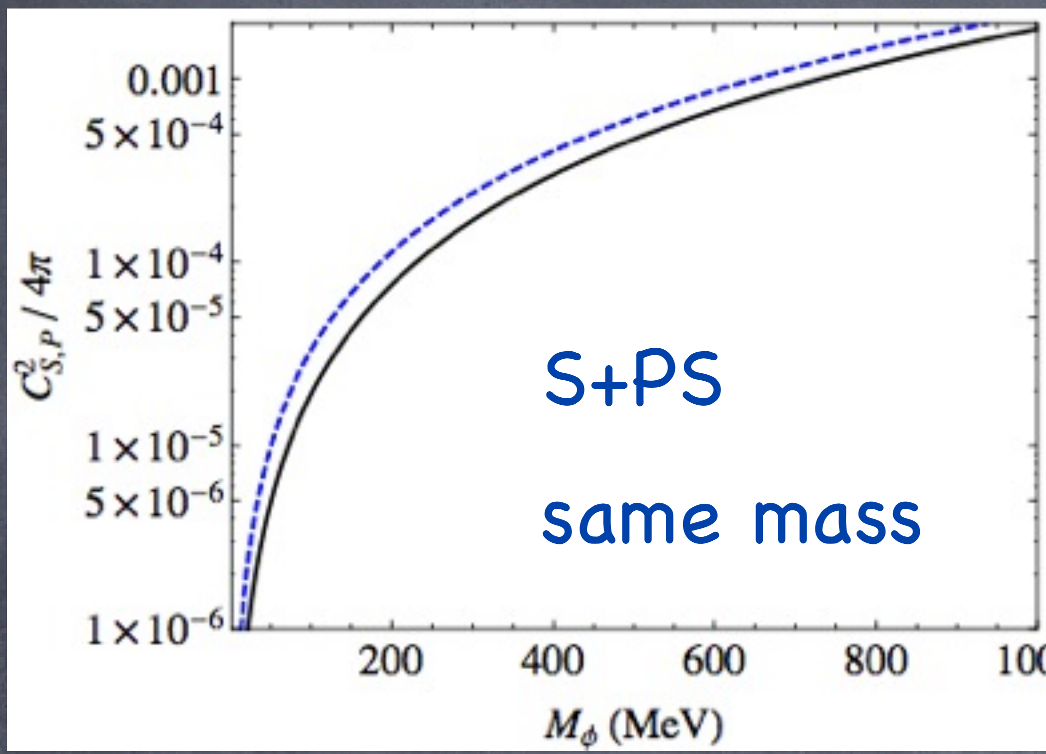
Theory Explanations: Novel BSM Physics

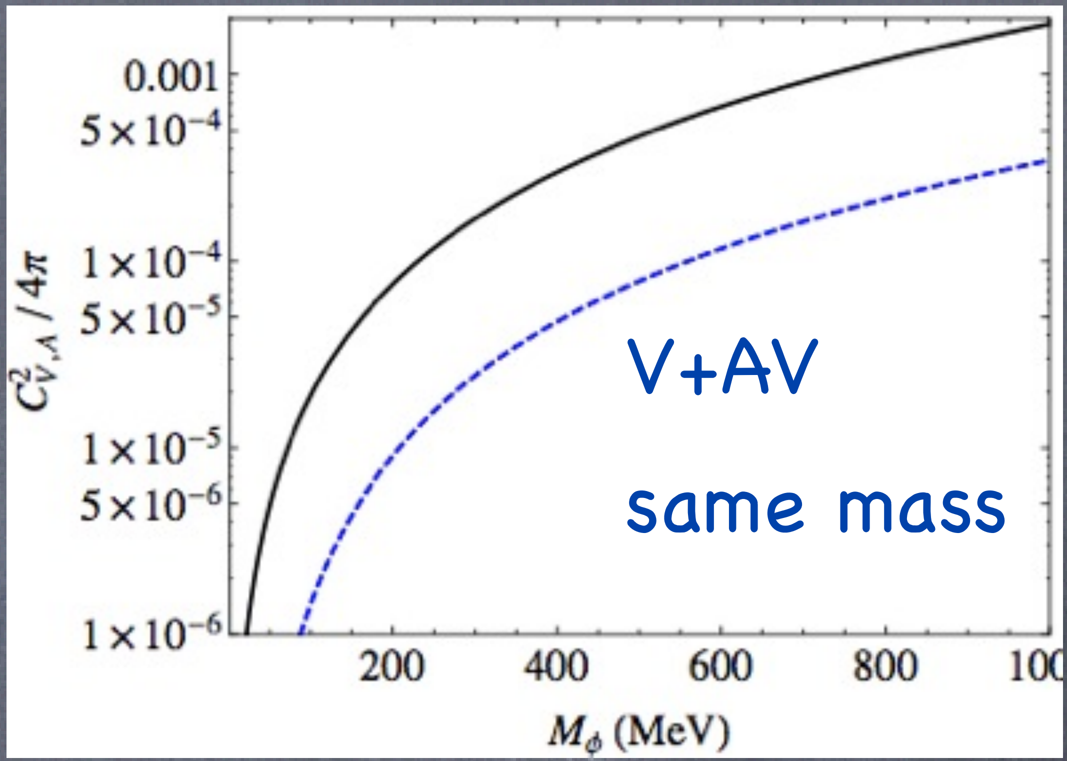
- Tucker-Smith and Yavin, PRD 83, 101702(R) (2011)
- New force with MeV mass particle can explain both PRP and μ g-2
- Various constraints, stronger if flavor independent couplings
- Predict 2x the effect in muonic deuterium, but ...

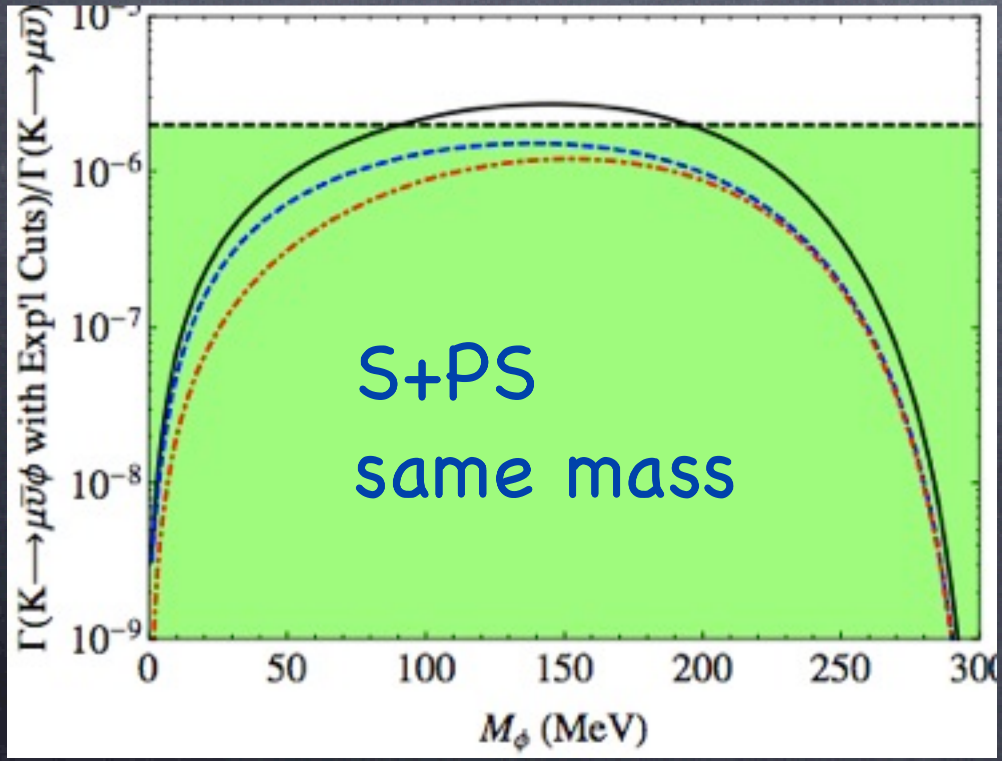


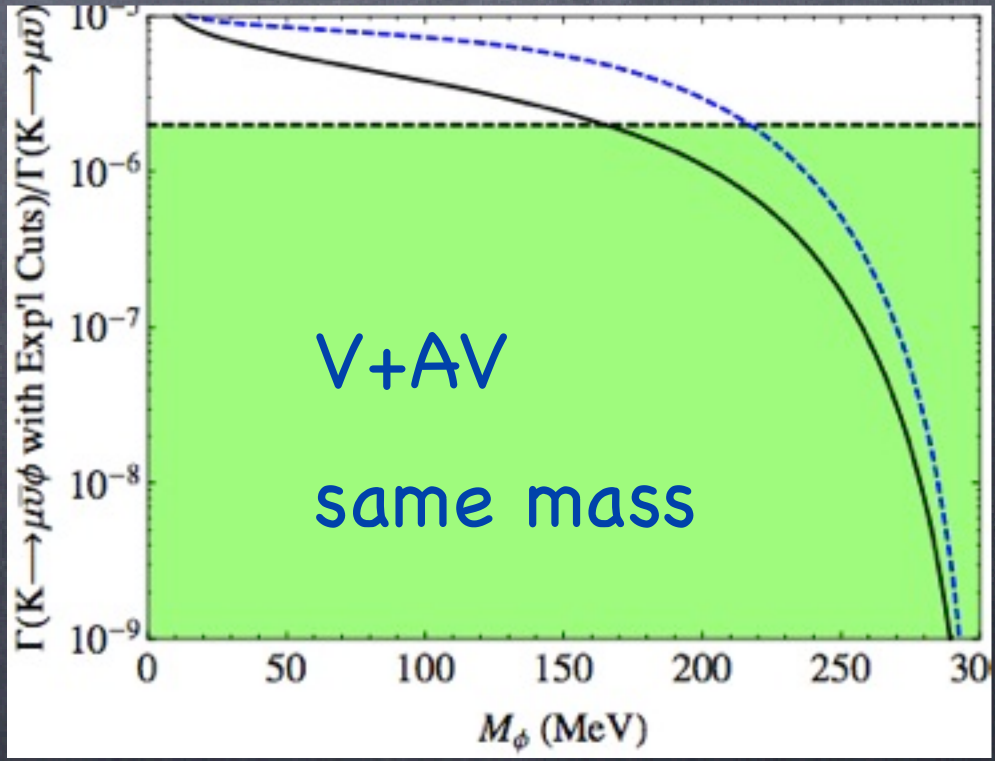
Theory Explanations: Novel BSM Physics

- Carlson and Rislow, PRD 86, 035013 (2012)
- Two new particles scalar + pseudoscaler or vector + axial vector



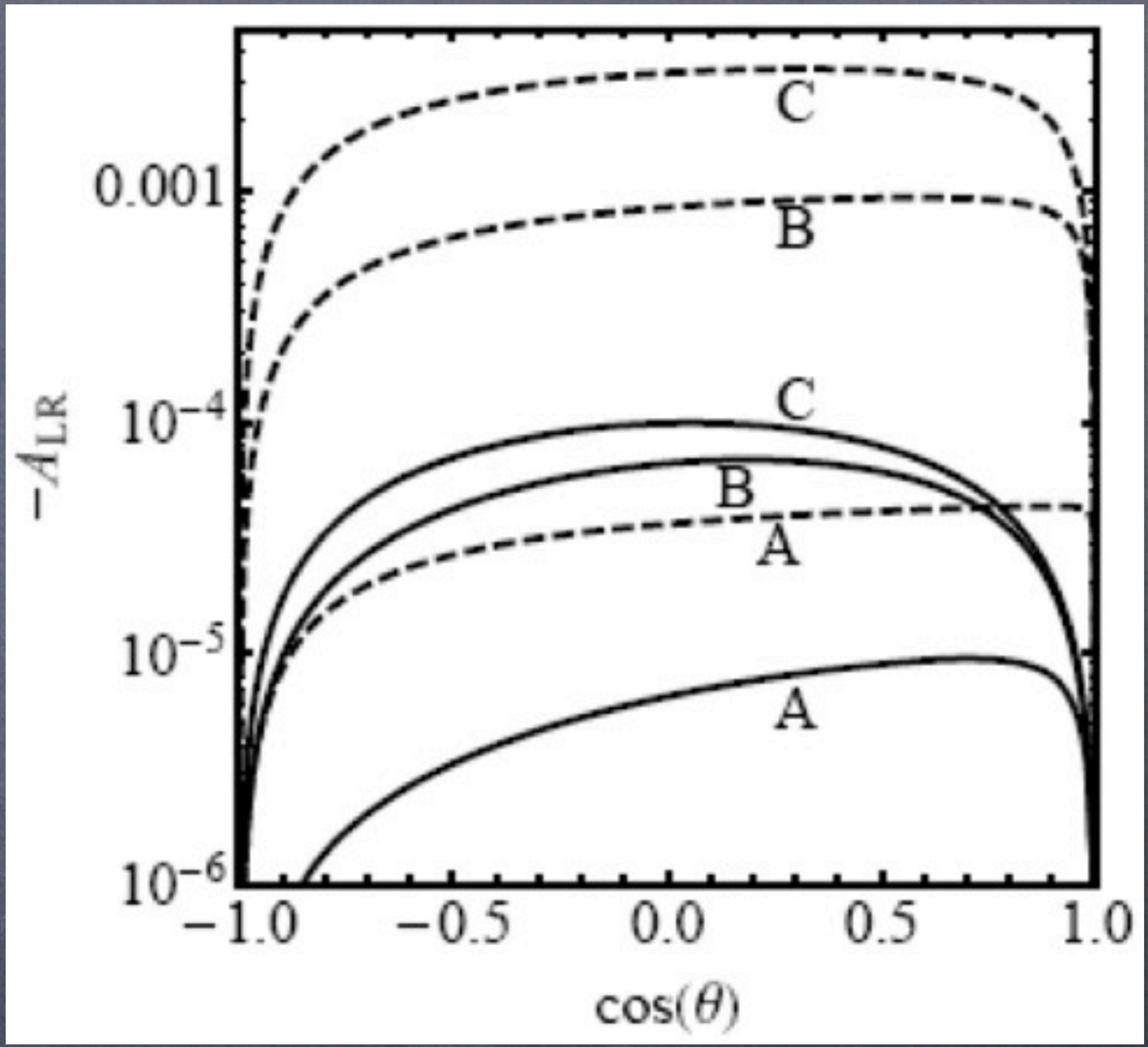






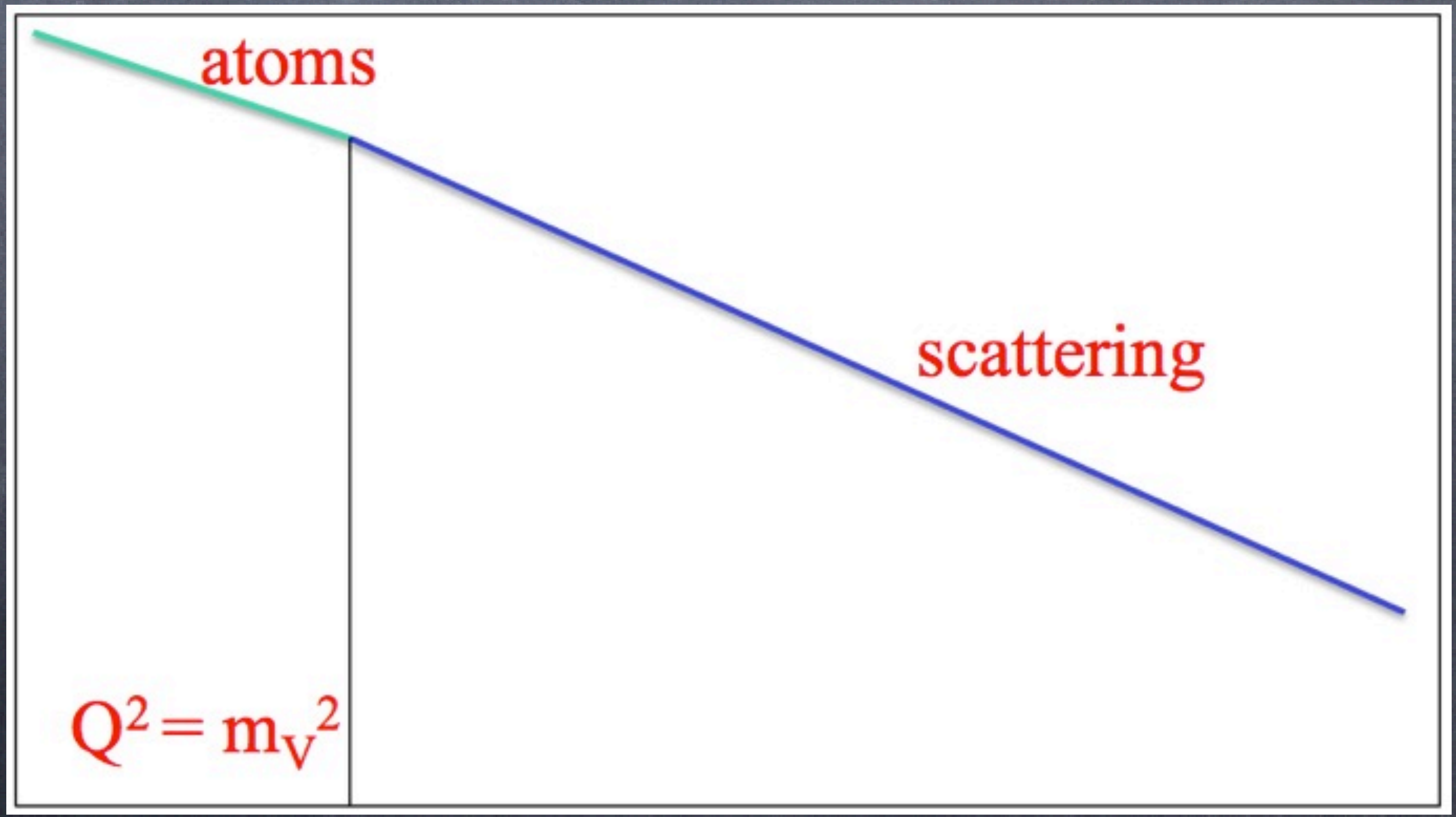
Theory Explanations: Novel BSM Physics

- Batell, McKeen, and Pospelov, PRL 107, 011803 (2011)
- New U(1) force for RH muons. LH coupling "breaks the SM gauge group"
- Muonic vector forces almost invariably lead to large parity violation (29 MeV/c solid and 100 MeV/c dashed)



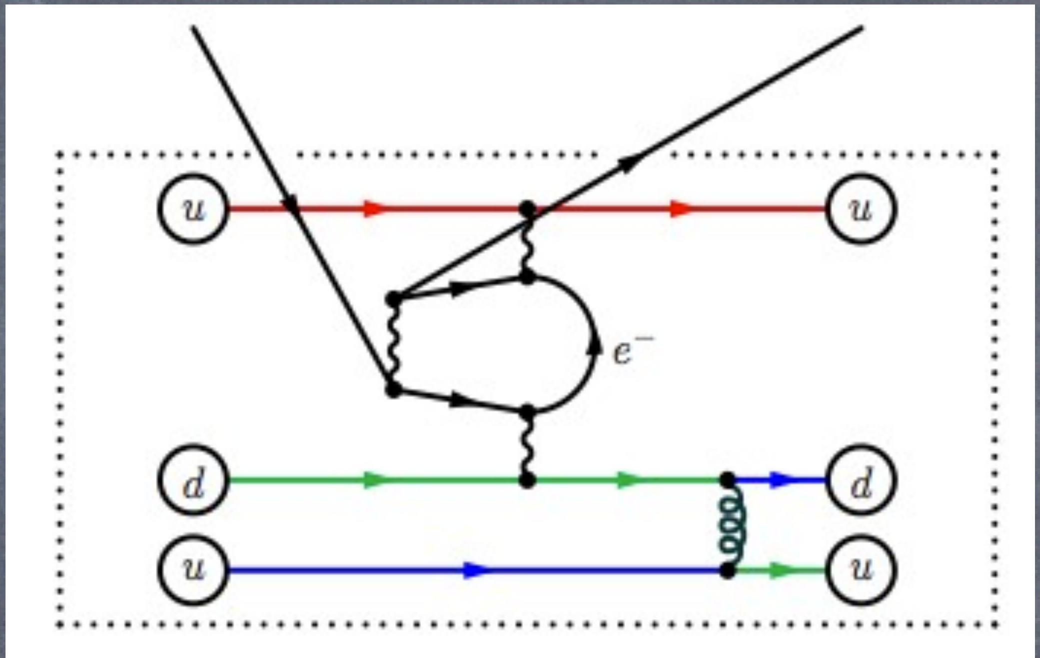
Theory Explanations: Novel BSM Physics

- Pospelov also reminds us of effect on form factors of new dark photon - would explain scattering vs. atom difference, but not hydrogen vs. muonic hydrogen



A Very Recent Nucleon Sea Idea

- Jentschura, PRA 88, 065214 (2013): nonperturbative e^+e^- sea makes proton look bigger



- Perturbative (radiative correction) e^+e^- sea is too small
- The nonperturbative sea would have to be at the level of 10^{-7}
- Attributes old muon scattering data being a few percent small to this effect - almost certainly not right

Theory Summary

- Novel theory is the most exciting possibility, and a number of such theories are not ruled out.
  - BSM
  - Hadronic

- But if it is not theory, it must be experiment... We generally assume the muonic data are fine, but it might be the radius extraction from muonic hydrogen, or the electronic data.

Atomic Physics Again Reconfirmed

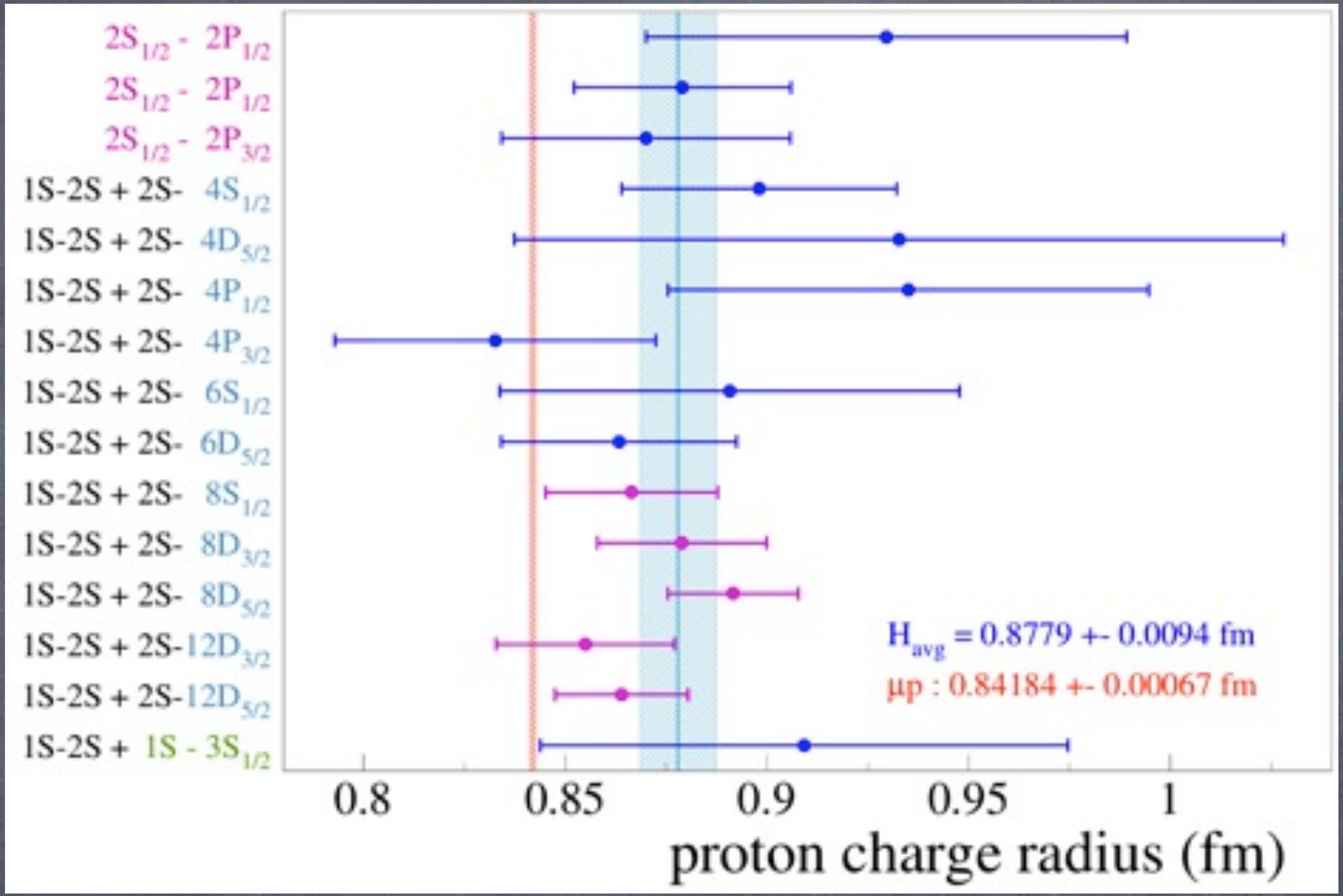
Peset and Pineda recently reconfirmed the muonic hydrogen proton radius extraction in arXiv:1403.3408.

In an effort to have a model-independent extraction, with a well defined expansion scheme for reliable error estimates, they used a combination of Heavy Baryon Effective Theory and (potential) non-relativistic QED.

They suggest $r_p = 0.8433 \pm 0.0017$ vs 0.84087 ± 0.00039 (Antognini).

They comment that the Miller TPE effect requires a model, and is not ruled out by Birse & McGovern. It seems implicit that they think Miller's effect is ruled out by their calculation.

Atomic Hydrogen Uncertainty



Atomic hydrogen summary

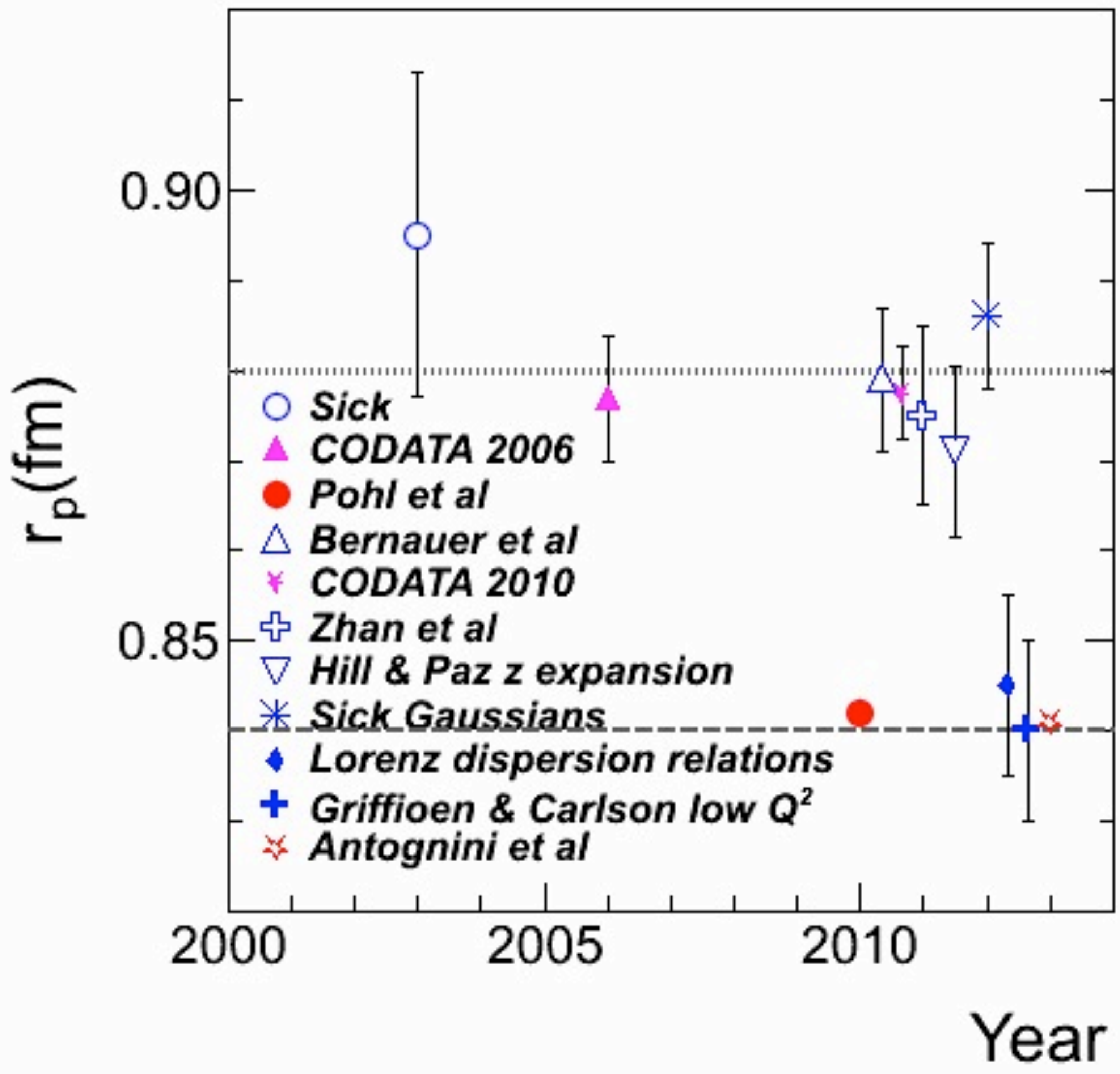
From Pohl, Gilman, Miller, Pachucki review, arXiv: 1301.0905, AnnRevNPS 63, 167 (2013)

Proton Charge Radius Summary Table

r_p (fm)	atom	scattering
electron	0.8779 ± 0.0094 (Pohl)	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

The Proton Radius vs Time



Focusing in on recent results...

There are reasons to think that the scattering analyses giving larger radii are better.

It is a "feature" of the dispersion analyses for ≈20 years that they give smaller radii. They generally have had large χ^2 and do not follow the low Q^2 data well.

The Scattering Experiments

The scattering knowledge is dominated by the recent Bernauer et al Mainz experiment, plus Zhan et al JLab polarization data and older cross section experiments.

Extracting a radius from the scattering data has been a challenge.

Until recently, all analyses ignored most of the following issues:

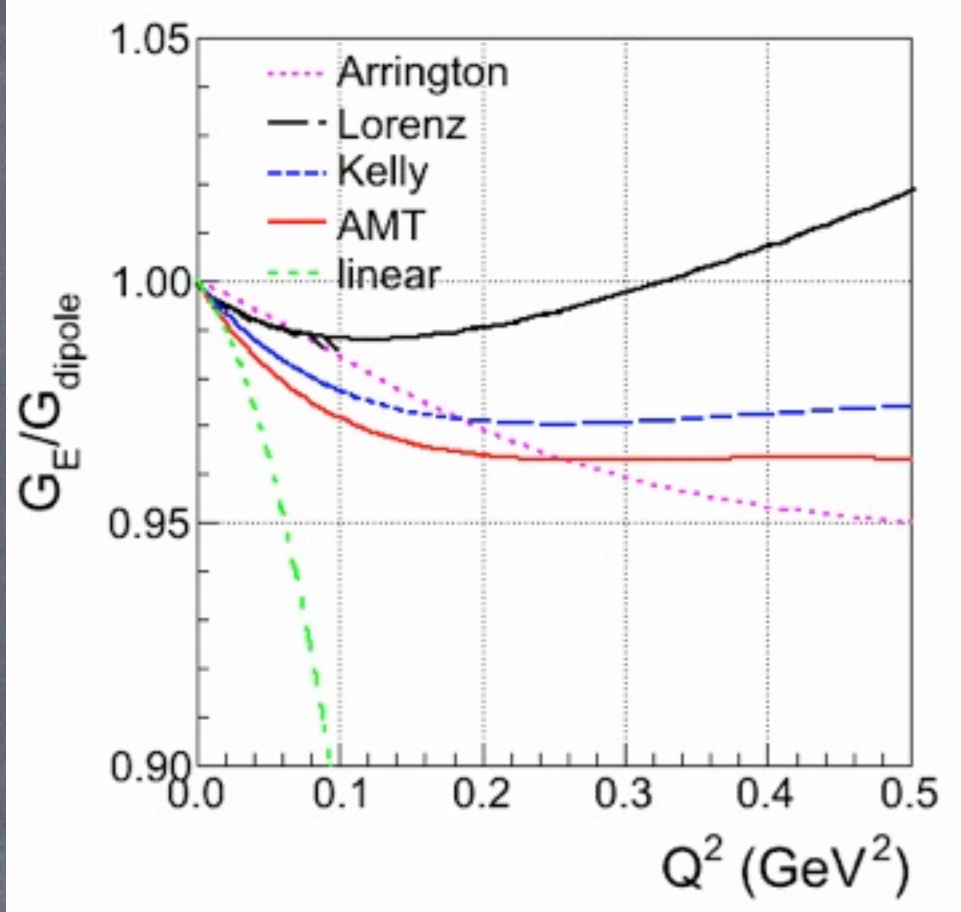
- Coulomb corrections
- Two-photon exchange
- Truncation offsets
- World data fits vs radius fits
- Model dependence
- Treatment of systematic uncertainties
- Fits with unphysical poles
- Including time-like data to ``improve'' radius

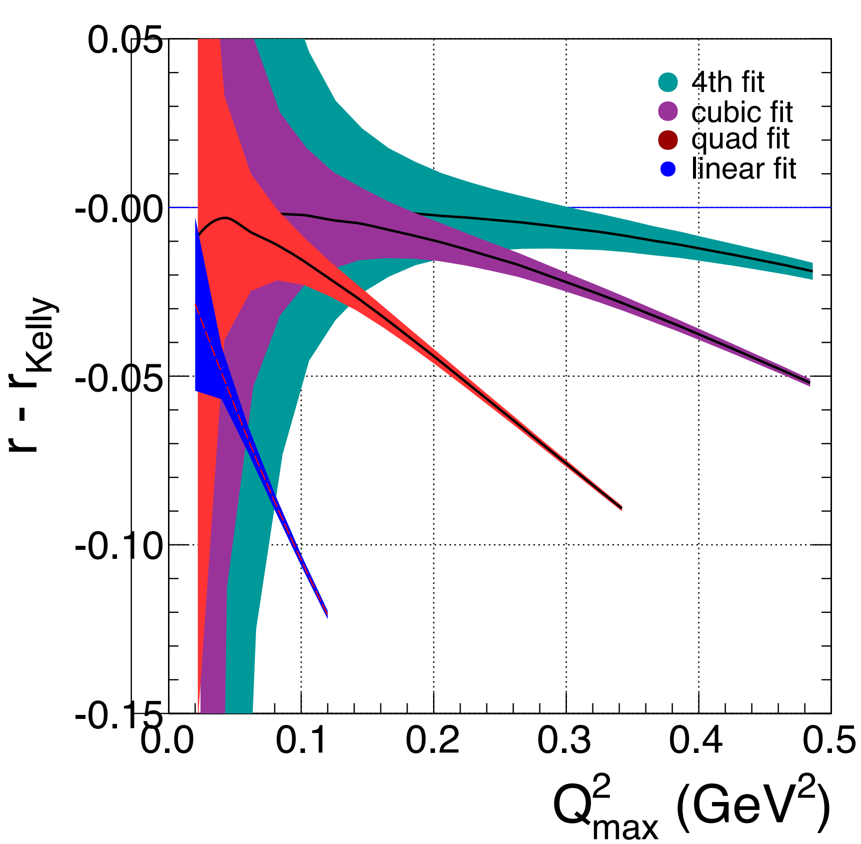
The good modern analyses tend to have fewer issues.

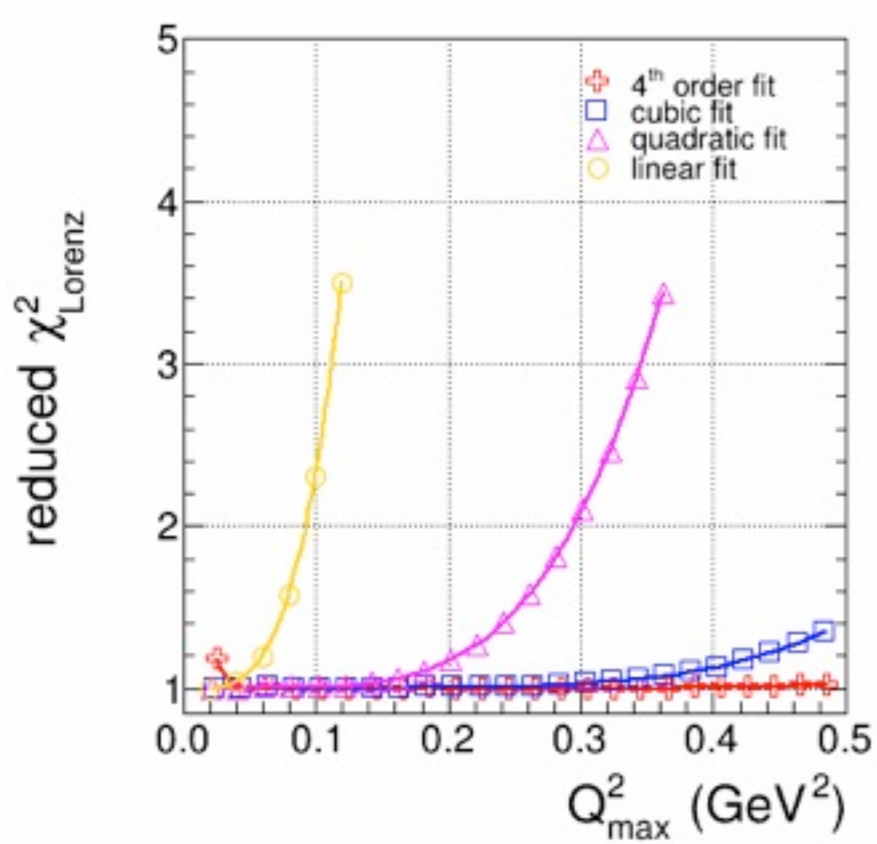
Truncation Errors

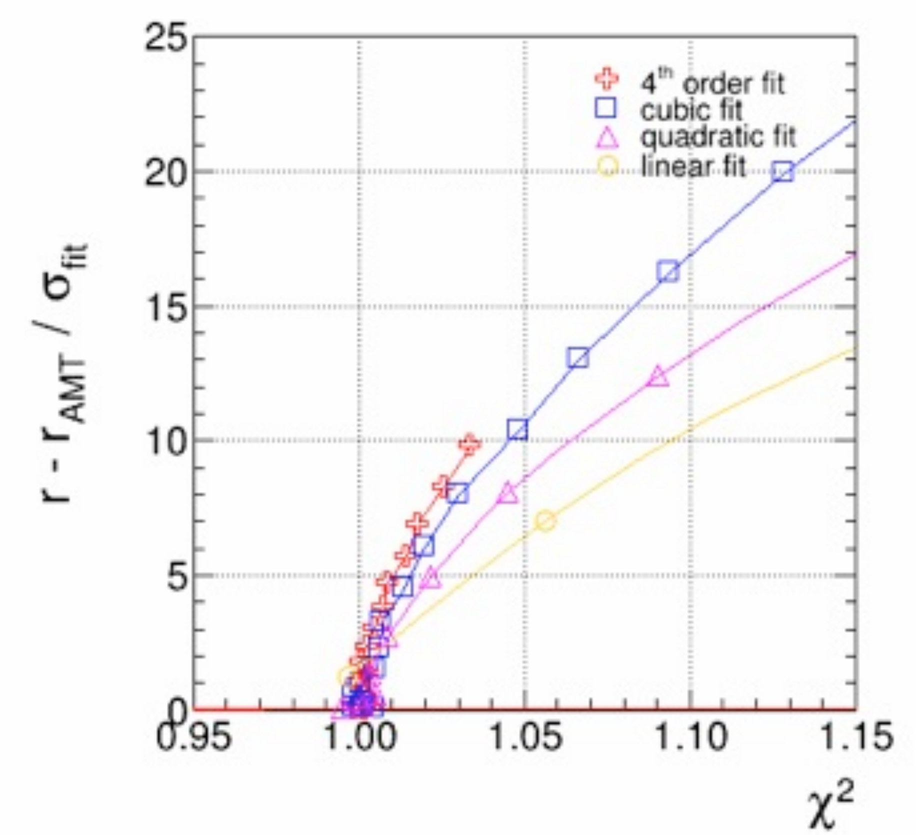
We studied truncation errors in Taylor series expansions by generating pseudodata from 4 world-data fits, and refitting the data, varying the order of the fit and max Q^2. The pseudodata were similar in density and uncertainties to the Mainz Bernauer data.

We found low Q^2 fits are unreliable - and they always underestimate the radius!









Status

- Up to 2010, we were all happy that atomic hydrogen and electron scattering gave the same proton radius.
- Now we are even happier that muonic hydrogen gives a different proton radius!
- Many possible explanations are ruled out, and the remaining explanations all seem unlikely
  - Experimental error: seems unlikely
  - BSM: not ruled out, but somewhat contrived models
  - Hadronic: not ruled out, but much bigger than most theorists find palatable.
- Four years on, I am more puzzled than ever.
- New data are needed

Recent and Upcoming Experimental Results

How do we Resolve the Radius Puzzle

- New data needed to test possible explanations
  - BSM: modify scattering probability for Q^2 up to m^2_{BSM}, enhanced parity violation, e and μ interact differently
  - Hadronic: enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - **Muon scattering!**
  - Also: rare K decays - JPARC TREK

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MUSE tests these

many efforts

CREMA

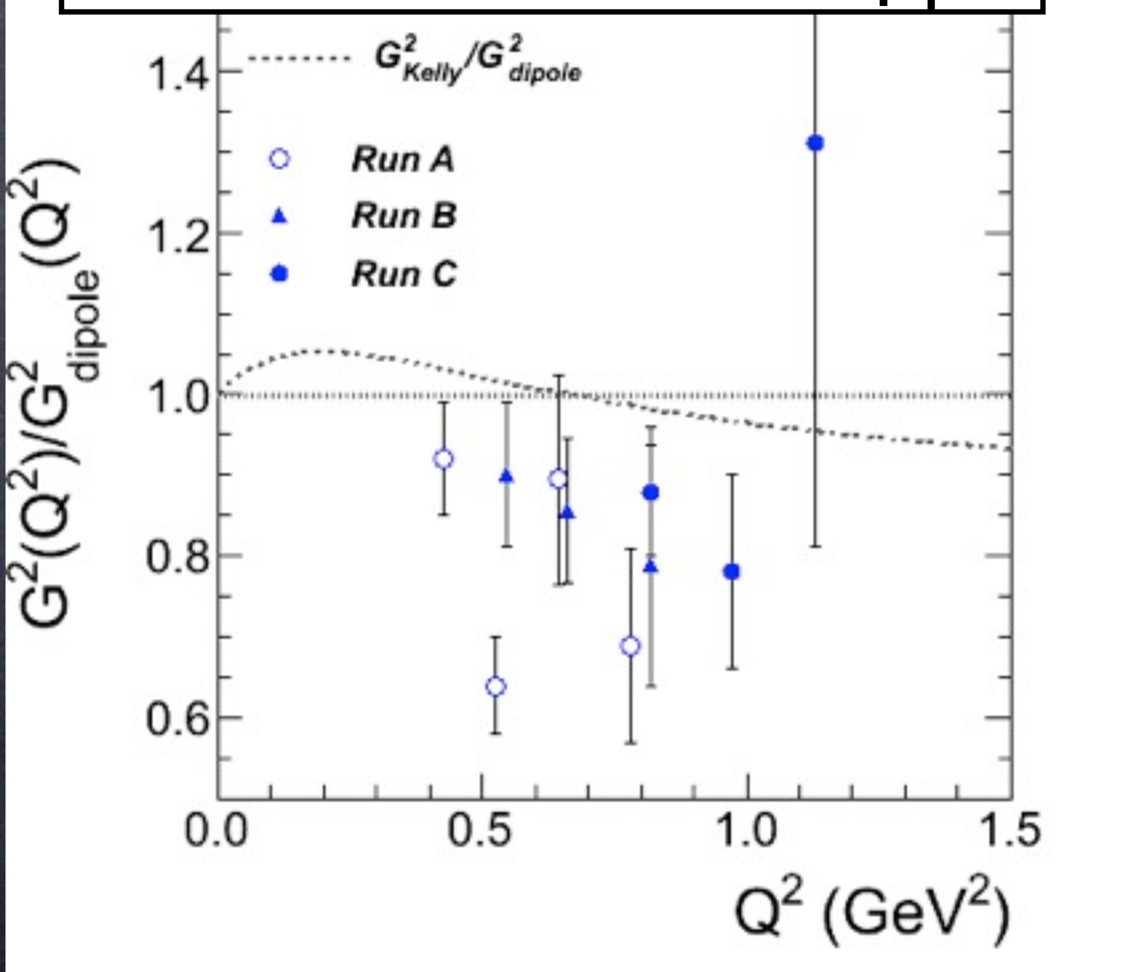
JLab Halls A&B, Mainz

Possible 2nd generation experiment

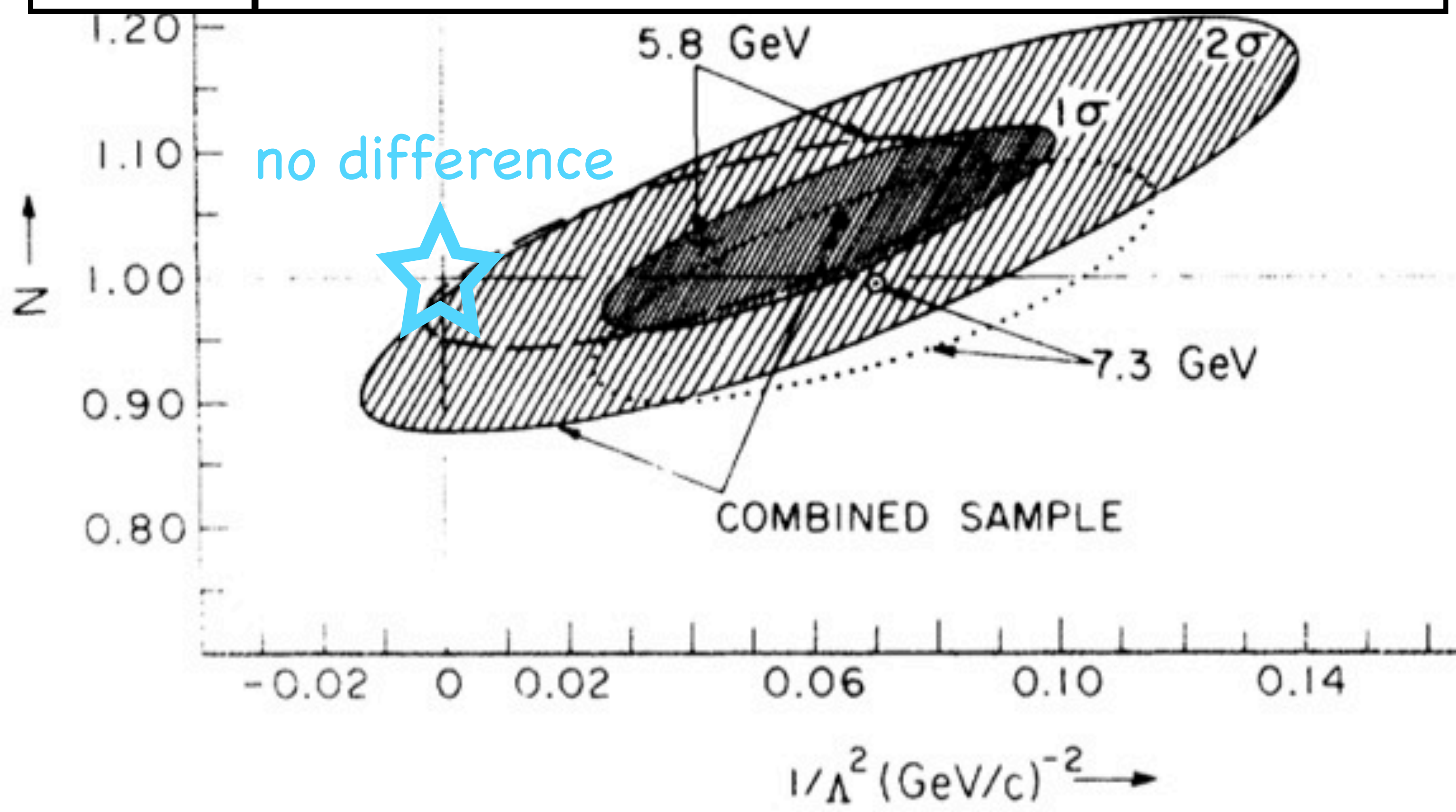
Previous e-μ Scattering Comparisons

In the 1970s / 1980s, several scattering experiments tested whether ep and μp interactions are equal in scattering, to within the 10% precision of the experiments. (Many other tests as well.) In light of the proton ``radius" puzzle, the 10% experiments are not as good as one would like.

Ellsworth et al.: form factors from elastic μp



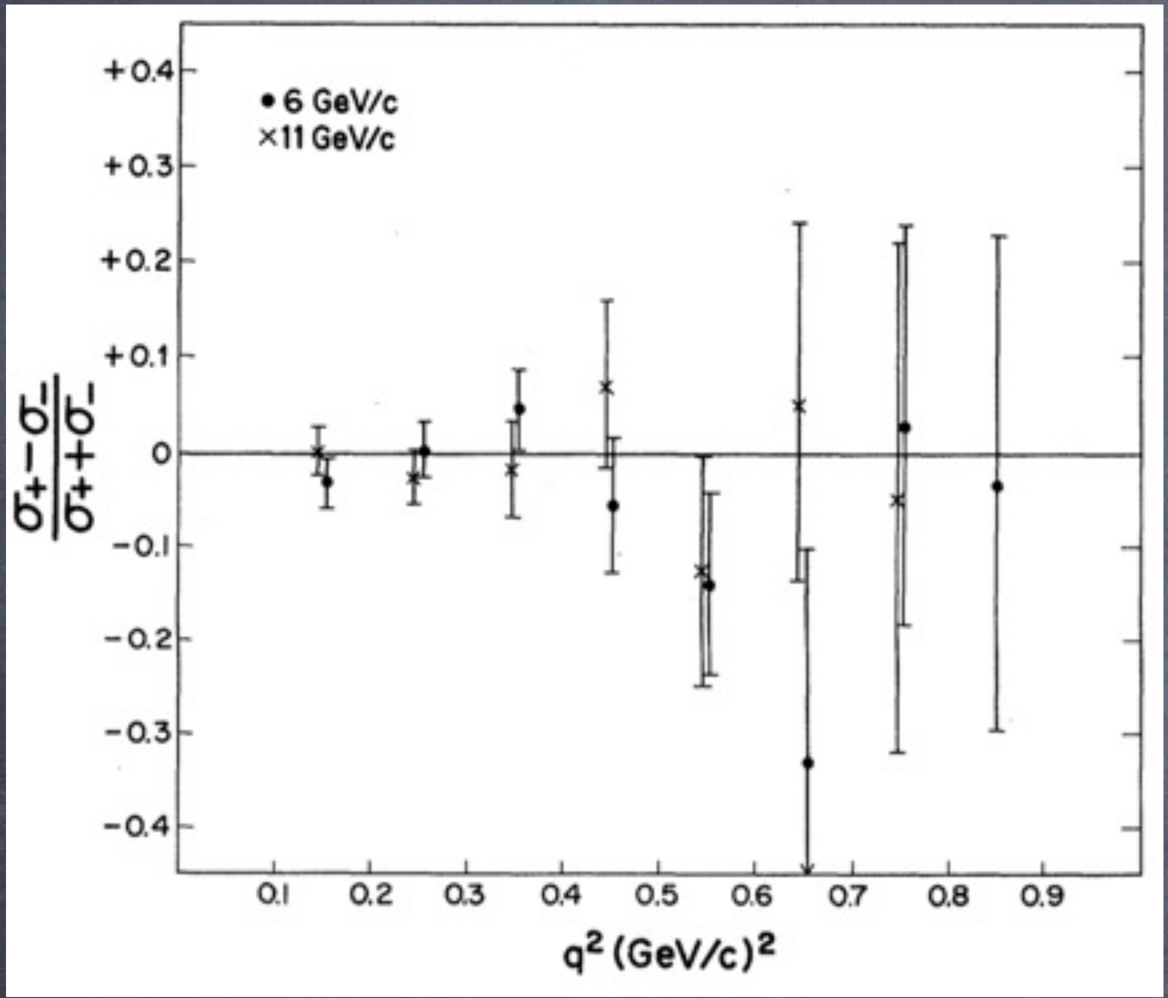
Kostoulas et al. parameterization of μp vs. ep elastic differences



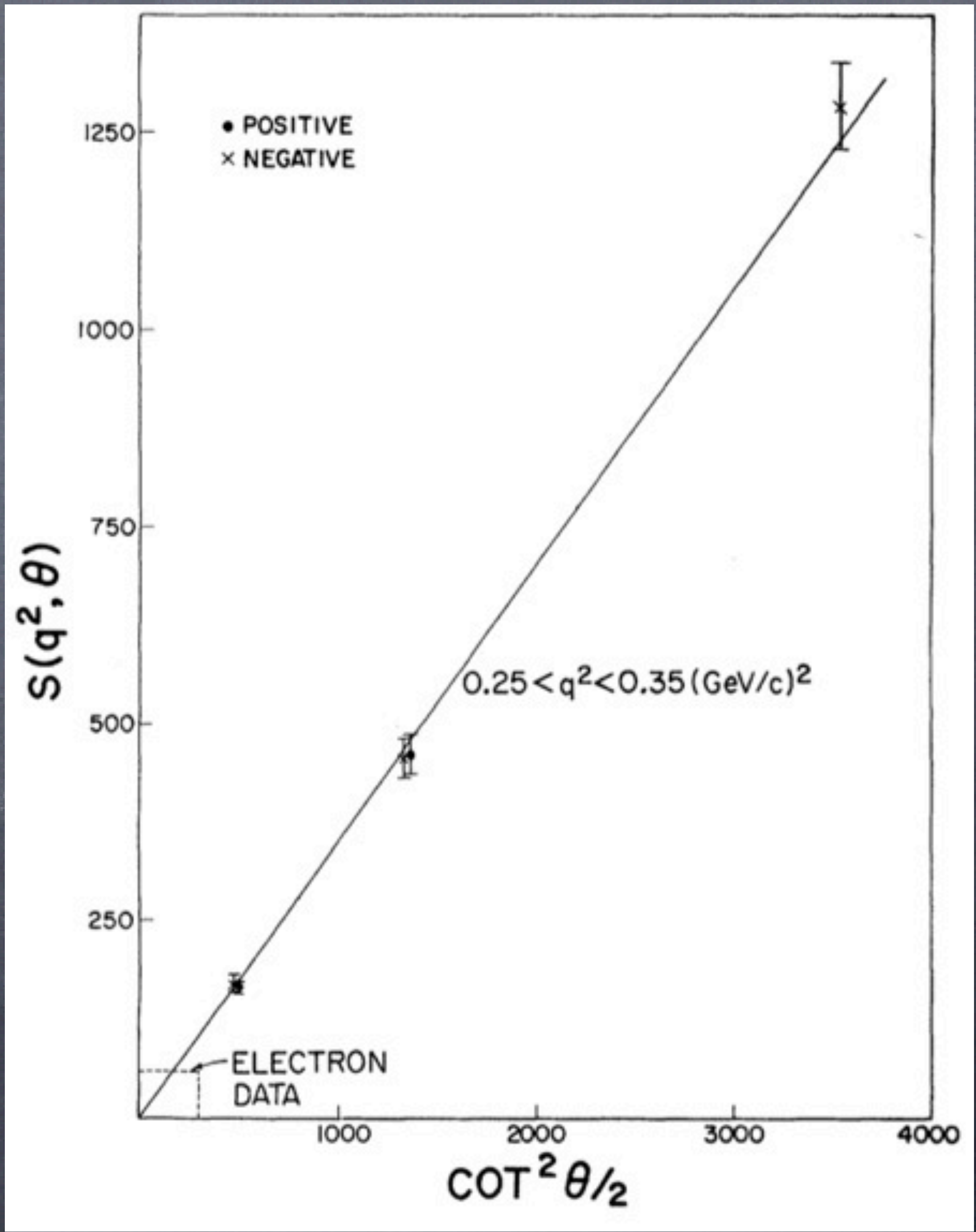
Entenberg et al DIS: $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)

Two-photon exchange tests in μp elastics

Camilleri et al. PRL 23: No evidence for two-photon exchange effects, but very poor constraints by modern standards.



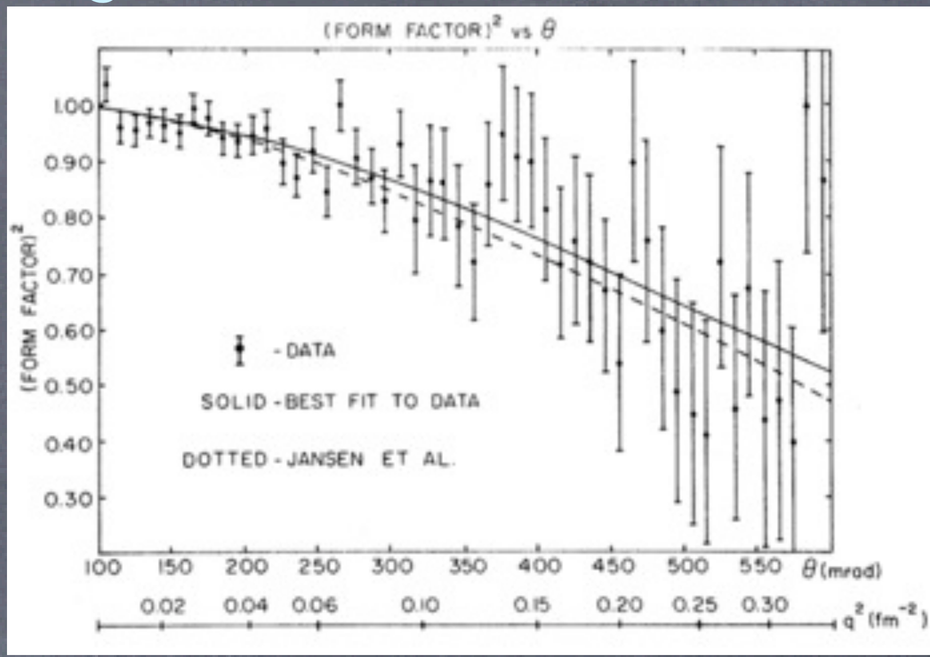
No difference between μ^+p and μ^-p elastic scattering



Rosenbluth plot is linear.

C Radius and e-μ Universality

The ^{12}C radius was determined with eC scattering and μC atoms. The results agree:



Offermann et al. eC: 2.478 ± 0.009 fm

Schaller et al. μC X rays: 2.4715 ± 0.016 fm

Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm

Sanford et al. μC elastic: $2.32\ ^{+0.13}_{-0.18}$ fm

Why the same result in carbon, but difference for proton?

Opposite effects for proton and neutron cancel with carbon?

Jentschura: nuclear radius from nucleon motion, don't see e^+e^- sea

Indelicato: updating constants gives 1.7σ larger muonic radius

Also: A. Antognini et al: Muonic H + eH/D isotope shift ⇨ r_d = 2.12771(22) fm vs. 2.130(10) fm from ed scattering.

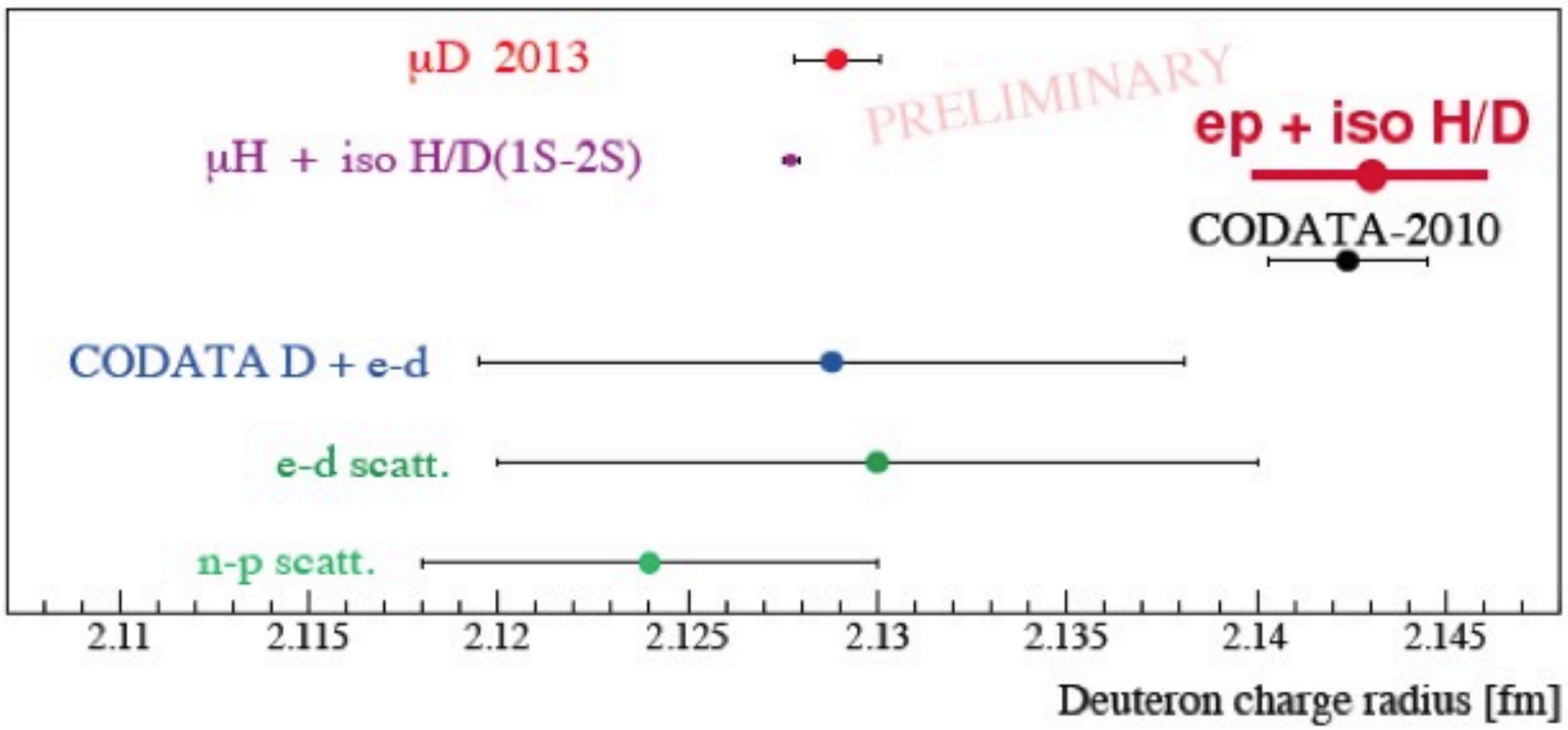
New & Unpublished: Muonic Deuterium, ^{4}He

Proton radius: The challenge continues

Combining H-D isotope shift and e-p elastic scattering:

$$\left.\begin{aligned} r_d^2 - r_p^2 &= 3.82007(65)\,\mathrm{fm}^2 \\ r_p &= 0.879(8)\,\mathrm{fm} \end{aligned}\right\} \Rightarrow r_d = 2.143(3)\,\mathrm{fm}$$

J.C. Bernauer *et al.*, Phys.Rev.Lett. 105 (2010) 242001



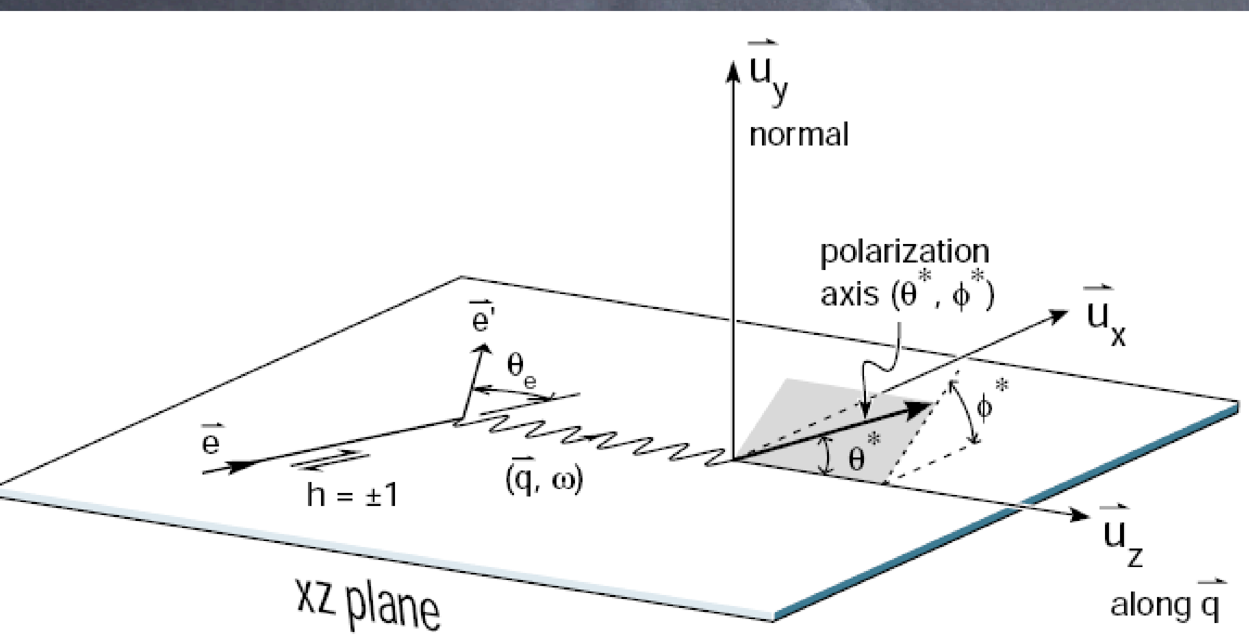
Note: deuteron polarizability correction is large?

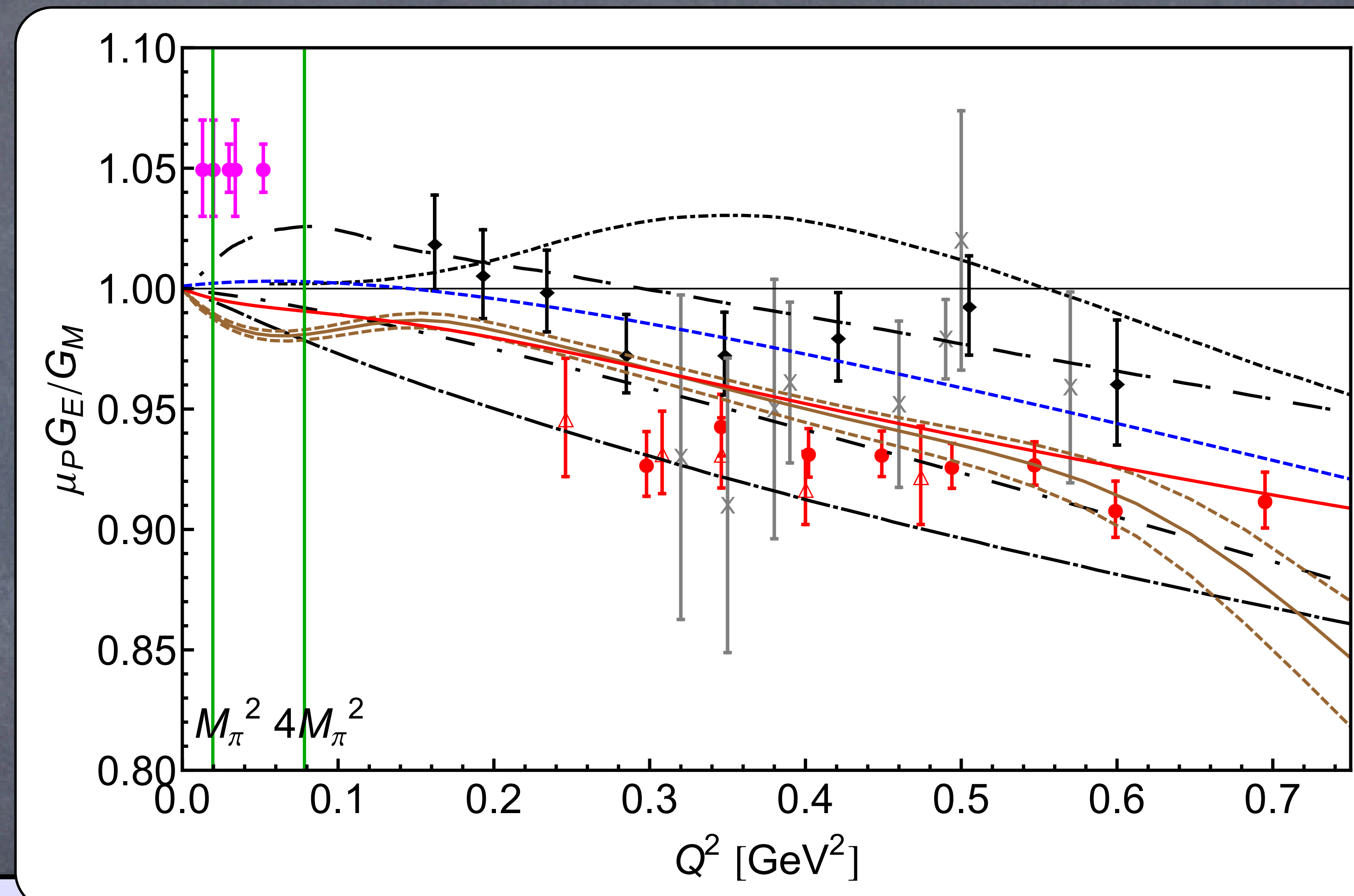
Deuterium radius plot by M. Distler includes unpublished CREMA data (Pohl, Antognini, et al.). Mainz redoing (& unpublished JLab) ed elastics. CREMA also measured muonic helium 4 in Dec 2013.

Electron Scattering Experiments

JLab Hall A E08-007 Part II: G. Ron, M. Friedman et al.

Polarized target - polarized beam asymmetry measurement for proton form factor ratio at $Q^2 < 0.1$ GeV^2





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

Electron Scattering Experiments

Mainz Initial State Radiation Experiment:
Data taken and under analysis
Much of the radiative tail comes from pre-radiation of a photon with lower Q^2 vertex than the asymptotic kinematics, allowing access to lower Q^2 form factors.

JLab Hall B PRAD: to run ?
Small-angle low Q^2 scattering of the JLab beam into the PRIMEX calorimeter, cross calibrating ep to Moller scattering.

Physics Summary

- The proton radius puzzle is a high-profile issue
  - Explanation unclear, if anything more puzzling after 4 years.
  - Several experiments underway.
  - **MUSE is the only experiment that will test:**
    - Are μp and ep interactions different? BSM physics predicts cross sections different ($\mu^+ \approx \mu^- \neq e^-$). Expect up to few percent cross section differences.
    - Also examined with G_E. Expect up to 1 or 2% differences.
    - What are the 2γ exchange effects ($\mu^+ \neq \mu^-$, $e^+ \neq e^-$)? Expect 2-4% effect for muons, vs ≈0.1% for electrons.
    - What is the scattering radius from muons (and electrons)? 0.84 vs 0.88 fm

Broader Impacts

Broader Impacts - Physics

- The proton radius puzzle has attracted broad interest in the popular media, and thus its resolution is likely to also be of general interest.
- The proton size is becoming a limiting uncertainty in some aspects of metrology / fundamental constants. Resolving the radius puzzle will reduce the importance of the uncertainty of the size.
- If the puzzle arises from novel physics, there is great potential for its resolution to help lead to a deeper understanding of nature.

Broader Impacts - Training Personnel I

- MUSE is expected to become the PhD experiment for at least 5 graduate students, with interest from all 7 core institutions (GW, Hampton, Hebrew, Rutgers, South Carolina, Tel Aviv, and Temple) in having a PhD student on the experiment.
- MUSE is expected to be a central project for the training of a similar number of post-doctoral researchers - it has already involved five (J. Bernauer, MIT, A. Liyanage, Hampton, K. Myers Mesick, Rutgers, D. Schott, GW, & V. Sulkosky, MIT & Longwood)
- All will work in an international collaboration with state-of-the-art technologies.

Broader Impacts - Training Personnel II

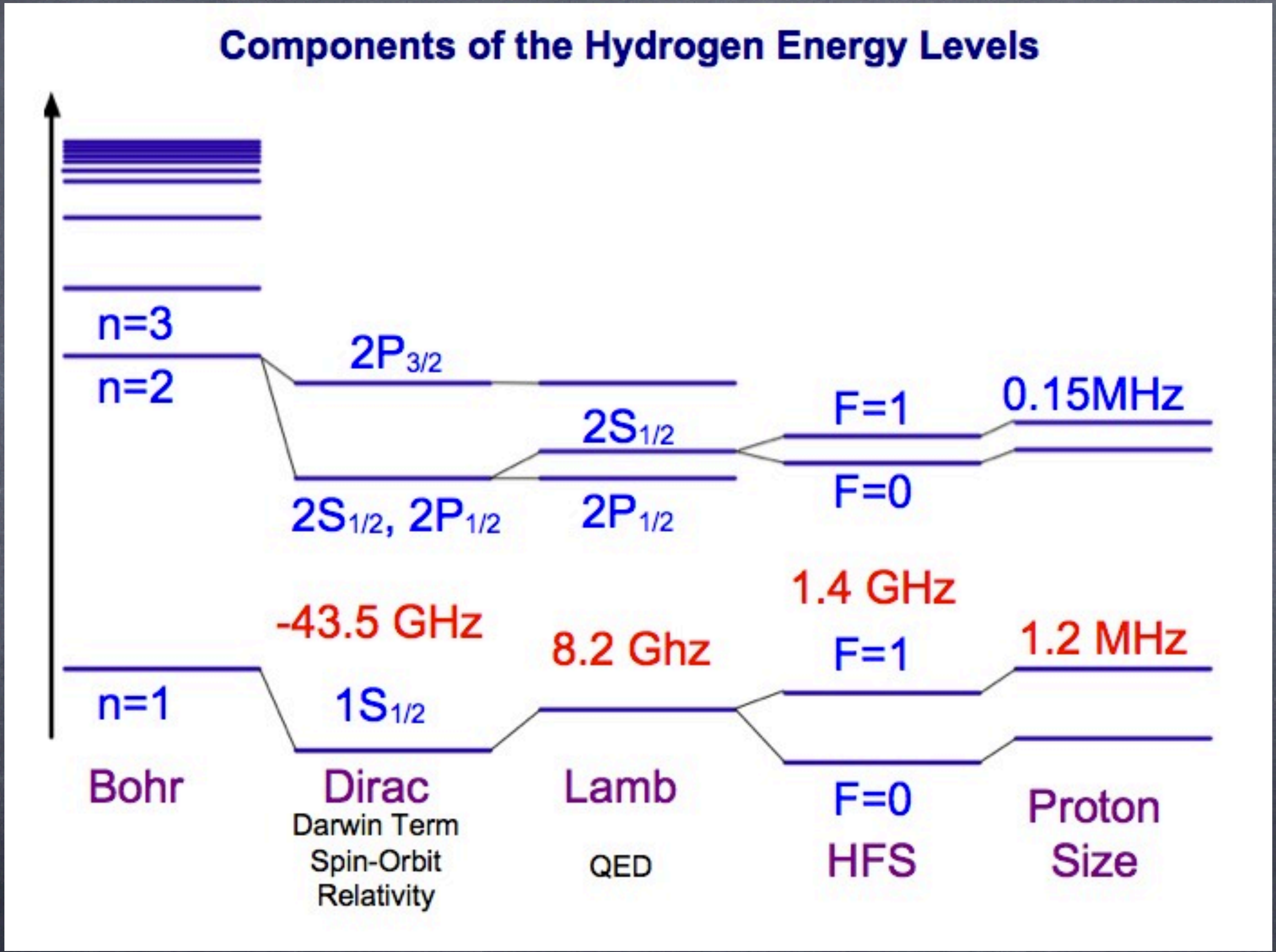
- MUSE is already being used to expose undergraduates and high school students to physics and research. At Rutgers, three students worked on MUSE related projects in summer 2013: one high school student, one Rutgers student, and one REU student.
- We expect to have a Rutgers Aresty student during AY14-15.
- The MUSE core institutions will involve additional students in the construction and project over the next few years.

Broader Impacts - Technology

- While MUSE is not developing new technology, it appears we will be the first experiment to deploy the TRB3 and beam-Cerenkov technologies for production data.
- MUSE will continue the trend towards more complicated FPGA triggers, and it appears we will be the first to do beam particle ID as part of our trigger - and tracking - which might open up other new possibilities.

The End

The complications - from R. Pohl to G. Ron to E. Downie to here



The basic point: the hydrogen atom is not simple, and extracting a radius requires detailed calculations.

The Atomic Physics

The atomic physics calculation is quite detailed and complicated, but basically all aspects of it have been computed by multiple independent groups.

The momentum-space Breit potential, for incorporating proton finite size effects. From Kelkar, Garcia Daza, and Nowakowski, NPB 864, 382 (2012).

$$\begin{aligned}
\hat{U}(\mathbf{p}_X, \mathbf{p}_p, \mathbf{q}) = 4\pi e^2 \Bigg[& F_1^X F_1^p \Bigg(-\frac{1}{\mathbf{q}^2} + \frac{1}{8m_X^2c^2} + \frac{1}{8m_p^2c^2} + \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_p)}{4m_p^2c^2\mathbf{q}^2} \\
& - \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_X)}{4m_X^2c^2\mathbf{q}^2} + \frac{\mathbf{p}_X.\mathbf{p}_p}{m_Xm_pc^2\mathbf{q}^2} - \frac{(\mathbf{p}_X.\mathbf{q})(\mathbf{p}_p.\mathbf{q})}{m_Xm_pc^2\mathbf{q}^4} - \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_X)}{2m_Xm_pc^2\mathbf{q}^2} \\
& + \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_p)}{2m_Xm_pc^2\mathbf{q}^2} + \frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_Xm_pc^2} - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_Xm_pc^2\mathbf{q}^2} \Bigg) \\
& + F_1^X F_2^p \Bigg(\frac{1}{4m_p^2c^2} + \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_p)}{2m_p^2c^2\mathbf{q}^2} - \frac{i\boldsymbol{\sigma}_p.(\mathbf{q}\times\mathbf{p}_X)}{2m_Xm_pc^2\mathbf{q}^2} \\
& - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_Xm_pc^2\mathbf{q}^2} + \frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_Xm_pc^2} \Bigg) \\
& + F_2^X F_1^p \Bigg(\frac{1}{4m_X^2c^2} - \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_X)}{2m_X^2c^2\mathbf{q}^2} + \frac{i\boldsymbol{\sigma}_X.(\mathbf{q}\times\mathbf{p}_p)}{2m_Xm_pc^2\mathbf{q}^2} \\
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& + F_2^X F_2^p \Bigg(\frac{\boldsymbol{\sigma}_X.\boldsymbol{\sigma}_p}{4m_Xm_pc^2} - \frac{(\boldsymbol{\sigma}_X.\mathbf{q})(\boldsymbol{\sigma}_p.\mathbf{q})}{4m_Xm_pc^2\mathbf{q}^2} \Bigg) \Bigg],
\end{aligned}$$

The Atomic Physics

The atomic physics calculation is quite detailed and complicated, but all aspects of it have been computed by multiple independent groups.

Contributions to 2s hyperfine structure, from Indelicato, arXiv 1210.5828

	#	Ref. [40]	Ref. [70]	This work
Fermi energy	1	22.8054	22.8054	
Dirac Energy (includes Breit corr.)	2			22.807995
Vacuum polarization corrections of orders α^5, α^6 in 2nd-order perturbation theory ϵ_{VP1}	3	0.0746	0.07443	
All-order VP contribution to HFS, with finite magnetisation distribution	4			0.07244
finite extent of magnetisation density correction to the above	5		−0.00114	
Proton structure corr. of order α^5	6	−0.1518	−0.17108	−0.17173
Proton structure corrections of order α^6	7	−0.0017		
Electron vacuum polarization contribution+ proton structure corrections of order α^6	8	−0.0026		
contribution of 1γ interaction of order α^6	9	0.0003	0.00037	0.00037
$\epsilon_{VP}2E_F$ (neglected in Ref. [40])	10		0.00056	0.00056
muon loop VP (part corresponding to ϵ_{VP2} neglected in Ref. [40])	11		0.00091	0.00091
Hadronic Vac. Pol.	12	0.0005	0.0006	0.0006
Vertex (order α^5)	13		−0.00311	−0.00311
Vertex (order α^6) (only part with powers of $\ln(\alpha)$ - see Ref. [103])	14		−0.00017	−0.00017
Breit	15	0.0026	0.00258	
Muon anomalous magnetic moment correction of order α^5, α^6	16	0.0266	0.02659	0.02659
Relativistic and radiative recoil corrections with proton anomalous magnetic moment of order α^6	17	0.0018		
One-loop electron vacuum polarization contribution of 1γ interaction of orders α^5, α^6 (ϵ_{VP2})	18	0.0482	0.04818	0.04818
finite extent of magnetisation density correction to the above	19		−0.00114	−0.00114
One-loop muon vacuum polarization contribution of 1γ interaction of order α^6	20	0.0004	0.00037	0.00037
Muon self energy+proton structure correction of order α^6	21	0.001		0.001
Vertex corrections+proton structure corrections of order α^6	22	−0.0018		−0.0018
"Jellyfish" diagram correction+ proton structure corrections of order α^6	23	0.0005		0.0005
Recoil correction Ref. [104]	24		0.02123	0.02123
Proton polarizability contribution of order α^5	25	0.0105		
Proton polarizability Ref. [104]	26		0.00801	0.00801
Weak interaction contribution	27	0.0003	0.00027	0.00027
Total		22.8148	22.8129	22.8111