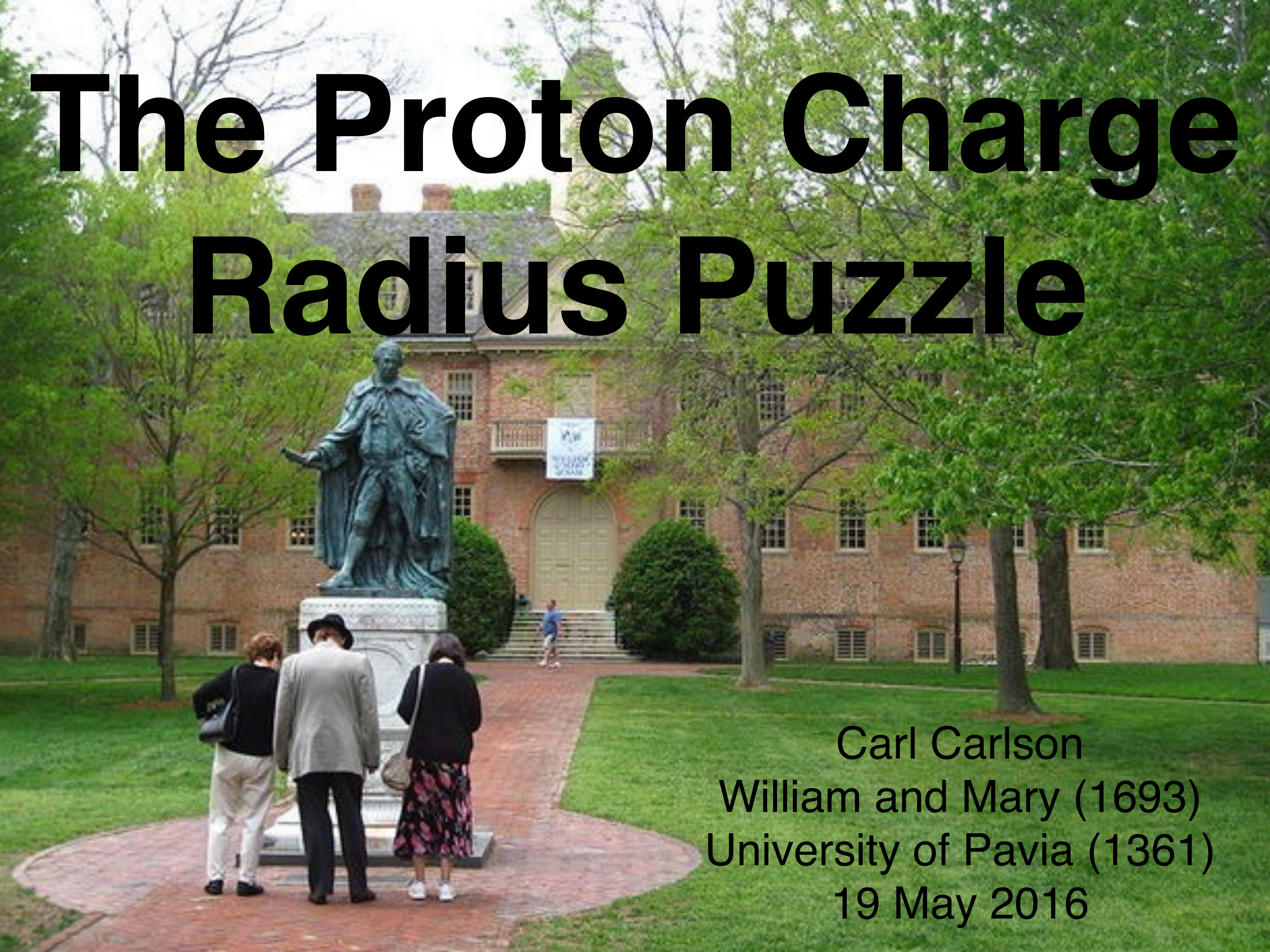

# The Proton Charge Radius Puzzle

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19 May 2016

# The puzzle

- Measure charge radius of the proton different ways, get different answers
- Difference is 7 s.d.
(was 5 s.d. when first announced, 2010)
- Why?  Don't yet know.

# This talk

1. The measurements:
   where the differences came from

2. Suggested explanations

    A. Ordinary explanations

        - Maybe some things are harder than they seem

    B. Exotic explanations

        - Will discuss: Is it Physics Beyond the Standard Model?

        - Will mention: other possibilities (later)

3. Highlight: List of coming relevant data

# This talk

1. The measurements:
   where the differences came from

2. Suggested explanations

   A. Ordinary explanations

      - Maybe some things are harder than they seem

   new stuff here

   B. Exotic explanations

      - Will discuss: Is it Physics Beyond the Standard Model?

      - Will mention: other possibilities (later)

   and here too

3. Highlight: List of coming relevant data

some arriving in 2016 (maybe!)

# Measuring proton radius

- Two methods: scattering or atomic spectroscopy
- Two probes: electrons or muons
- *I.e.*,
    - *e*-*p* elastic scattering
    - *μ*-*p* elastic scattering
    - spectroscopy of electronic Hydrogen
    - spectroscopy of muonic Hydrogen
- 4 categories of measurements, 3 done with sufficient accuracy (and more data coming), *μ*-*p* scattering coming

# $e$-$p$ scattering

- Measure differential cross section, fit results to form factors,

$$\frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)$$

$$\left[\tau = Q^2/4m_p^2\,; \quad 1/\epsilon = 1 + 2(1+\tau)\tan^2(\theta_e/2)\right]$$

- Low $Q^2$, mainly sensitive to $G_E$.

- Extrapolate to $Q^2 = 0$, whence

$$R_E^2 = -6\left(dG_E/dQ^2\right)_{Q^2=0}$$

# Extra: What is the proton radius?

- By this I mean, what is the definition?
- NR, easy. Given w. f., obtain RMS radius,

$$R^2 = \langle r^2 \rangle = \int d^3r\, r^2\, |\psi(r)|^2$$

- In concept, obtaining proton radius by electron scattering same as obtaining radius of H-atom w. f. by scattering an external electron off the bound electron. Worked out by Bethe in 1930's
- Rutherford scattering cross section off pointlike target,

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \left( \frac{k\,q\,Q}{4E\sin^2(\theta/2)} \right)^2$$

Straight out of Taylor's UG Classical Mechnics text

# More extra: Def'n of proton radius

- is modified for scattering off extended target, but just becomes

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} \times \left(G(Q^2)\right)^2$$

- Q = momentum transfer in scattering
- $G(Q^2)$ is "form factor", given NR by

$$G(Q^2) = \int d^3r\, e^{i\vec{Q}\cdot\vec{r}}\, |\psi(r)|^2$$

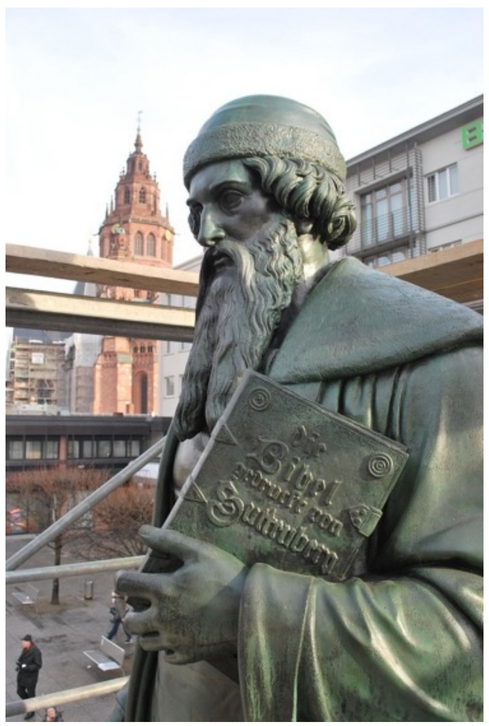
- easy:

$$G(Q^2) = 1 - \frac{1}{6}\langle r^2\rangle Q^2 + \ldots$$

De facto: measure radius by measuring form factor at small momentum transfer and looking at expansion

# Low-$Q^2$ scattering data

- Most extensive current data comes from Mainz, which has an electron accelerator, and is also city of Gutenberg



- Data, Jan Bernauer *et al.*, PRL 2010 (and later articles).
- marked by low $Q^2$ data, range 0.004 to 1 GeV$^2$
- From their analysis,

$$R_E = 0.879(8)\ \mathrm{fm}$$

# Atomic energy level splittings

- Basic: Schrödinger equation, H-atom, point protons

$$E = -\frac{\mathrm{Ryd}}{n^2}\,, \quad \text{where} \quad \mathrm{Ryd} = \frac{1}{2} m_e \alpha^2 \approx 13.6\mathrm{eV}$$

- plus QED corrections

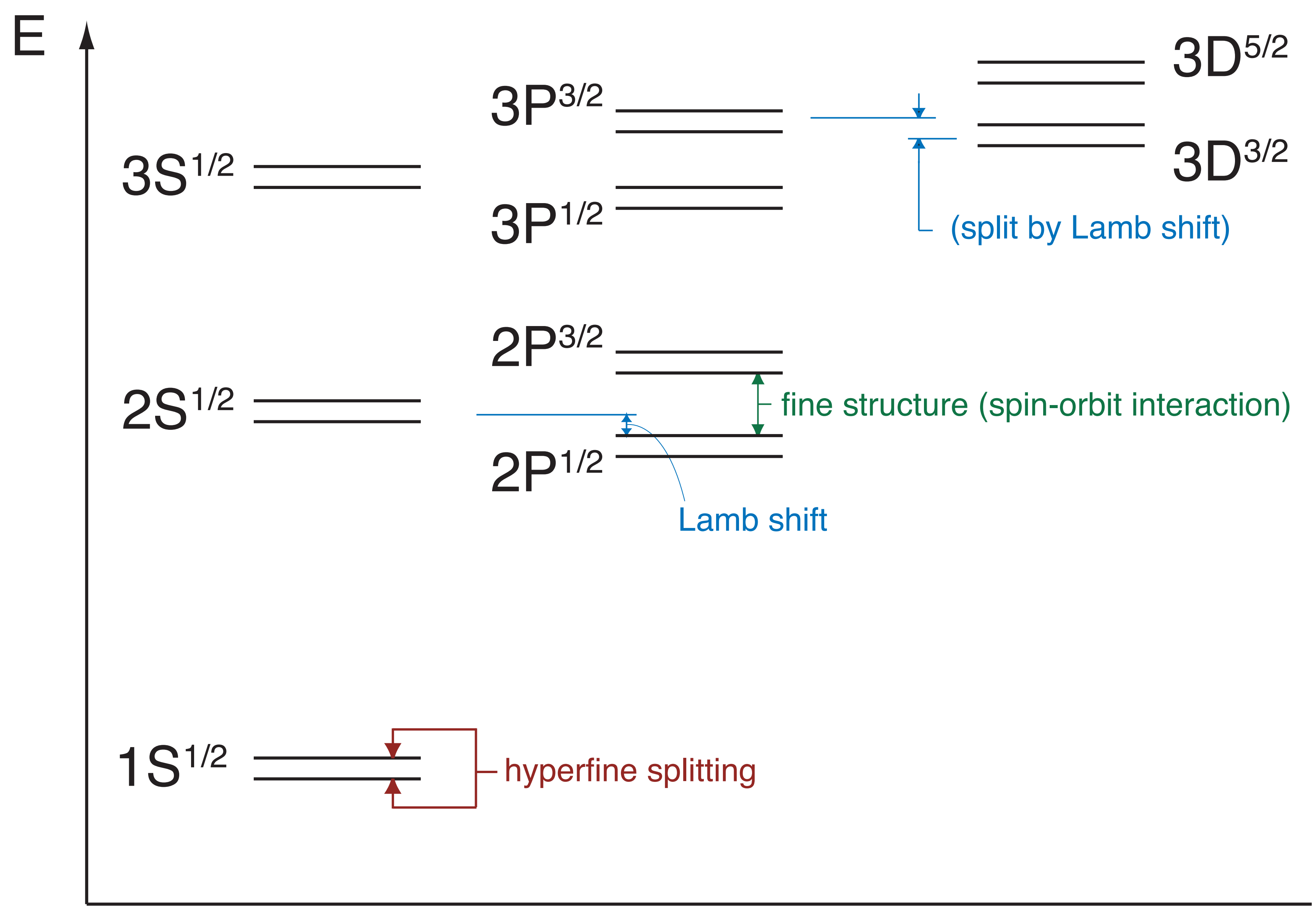
- plus finite size proton, pushing energy upward a bit.

$$\Delta E_{\text{finite size}} = \frac{2\pi\alpha}{3} \phi_{nS}^2(0) R_E^2$$

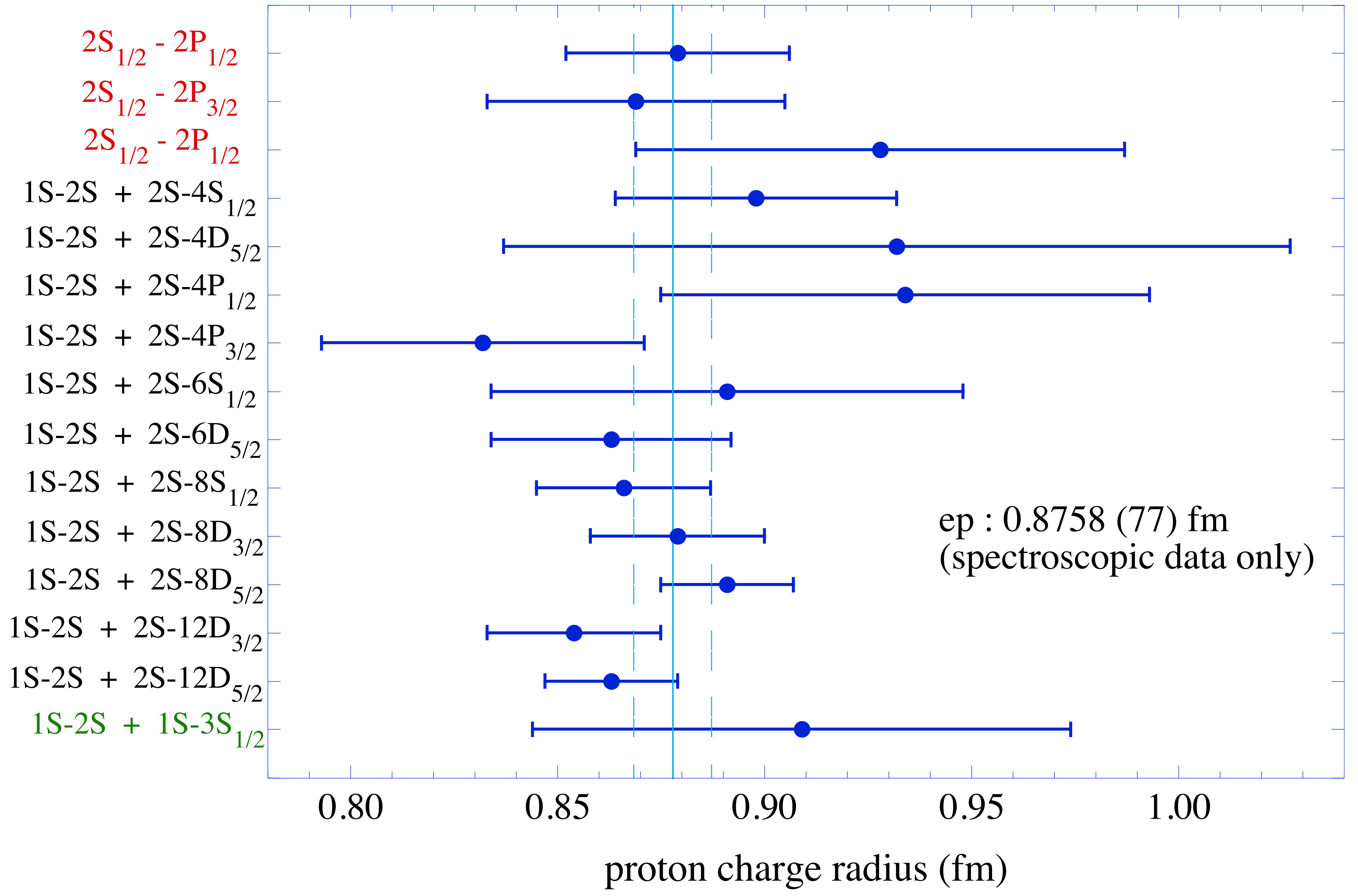
fine print: $\phi_{nS}^2(0) = (m_r \alpha)^3 / (n^3 \pi)$

# measure energy accurately $\iff$ measure radius

- Reminder, H-atom energy levels (diagram not to scale)



# Atomic results



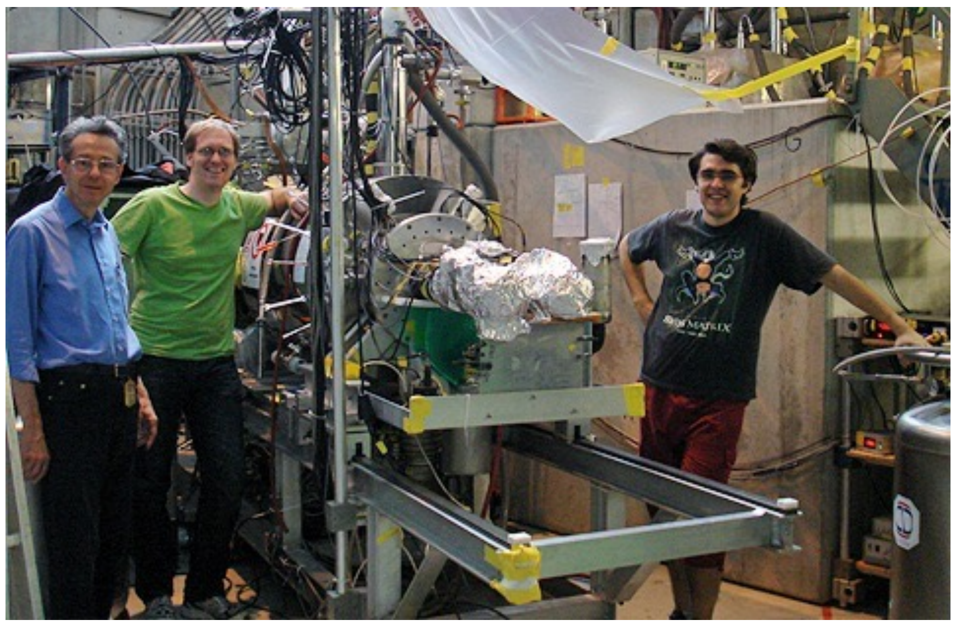
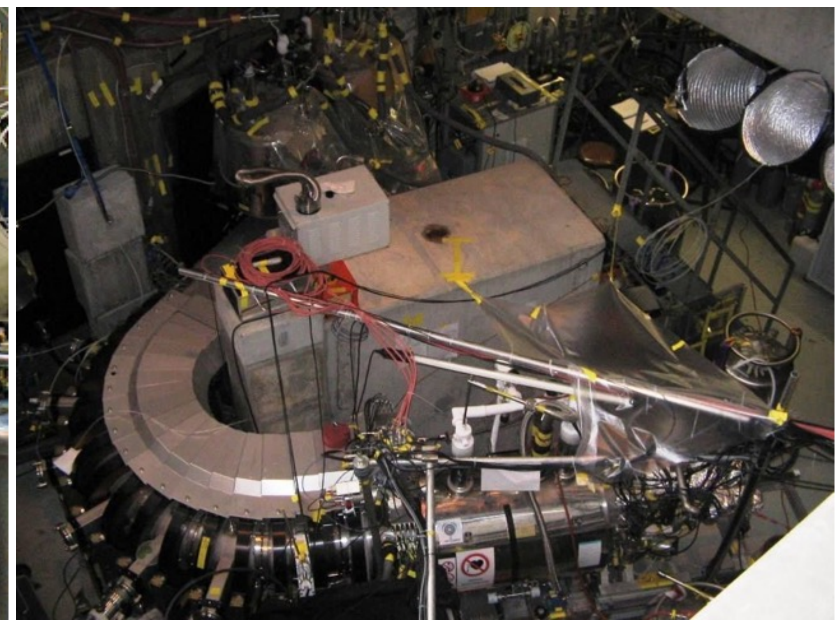
# All electron results

- Consistent
- Combined by Committee on Data in Science and Technology (CODATA, 2014 value),

$$R_E = 0.8751(61)\ \text{fm}$$

# Then in 2010 …

- CREMA = Charge Radius Experiment with Muonic Atoms

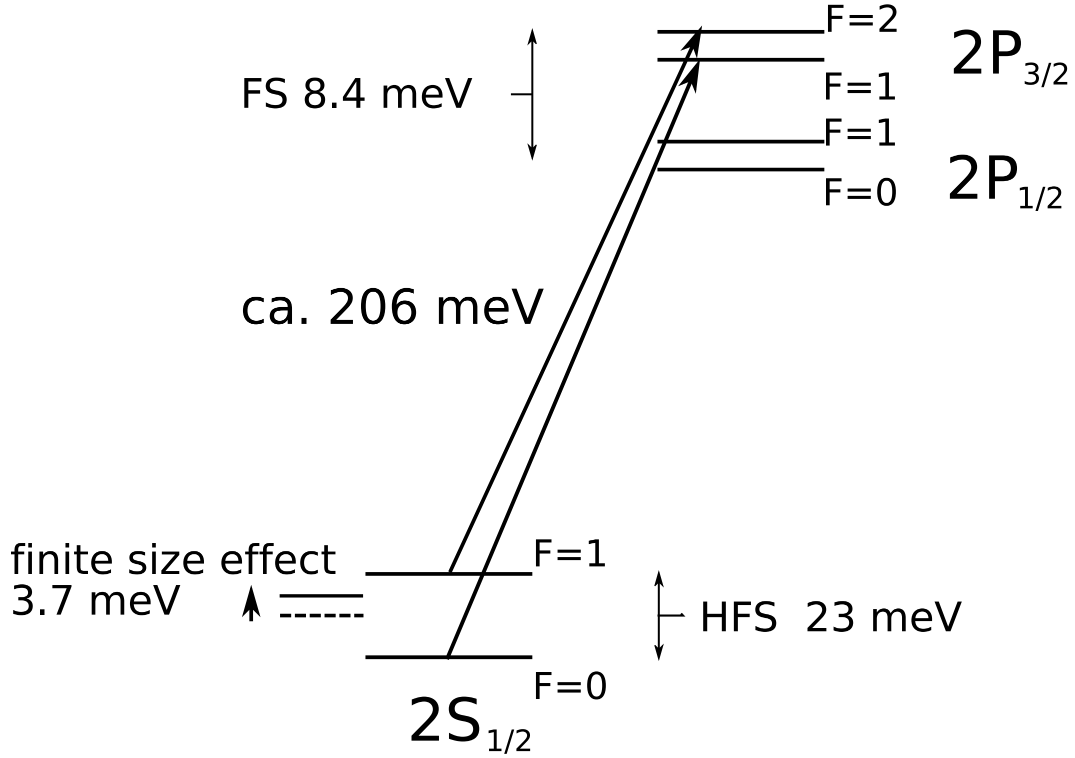




- Did atomic physics, specifically Lamb shift, with muons (muon = electron, but weighs 200 times more, orbits 200 times closer).

- Goal: measure proton radius with factor 10 smaller uncertainty

# CREMA

- $2S$-$2P$ Lamb shift in $\mu$-H.
- Measured two lines,




- pubs:
  upper line, Pohl *et al.*, Nature 2010
  other line Antognini *et al.*, Science 2013

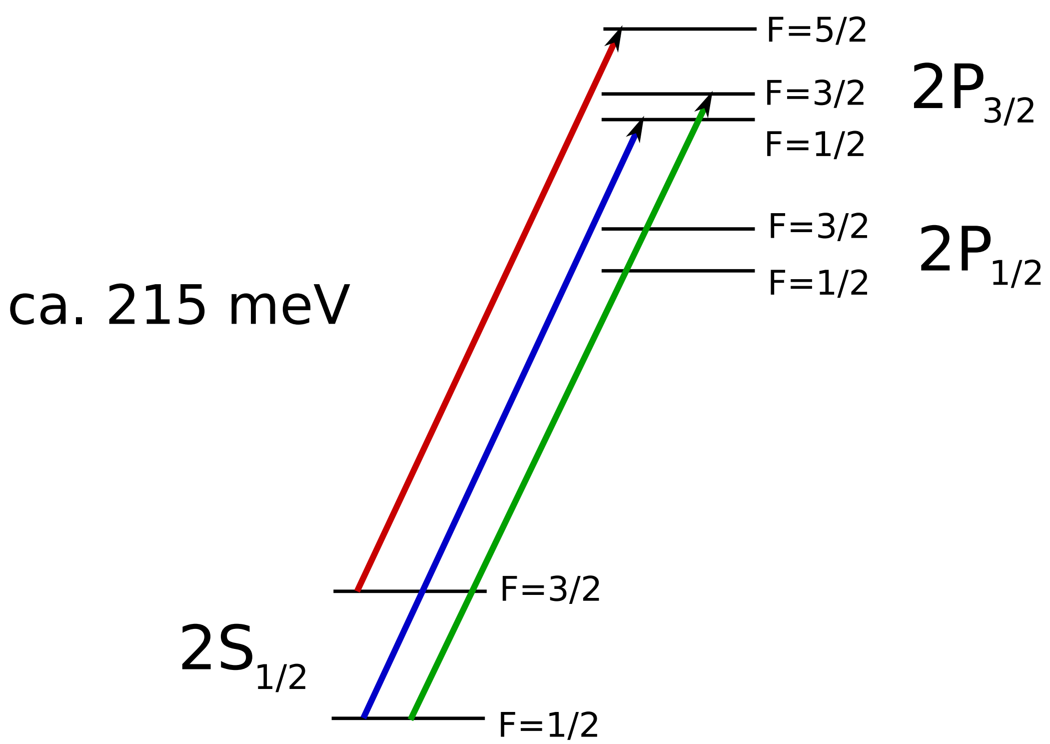
- Interpreting finite size effect in terms of proton radius,

$$R_E = 0.84087(39)\ \mathrm{fm}$$

- Whoops: result 4% or 7σ small

# Other data-deuteron

- Reported at conferences 2013
- 2015 experimenters circulate draft of theory paper!
- Measured three lines




- Quick summary: if proton radius is shrunken, the deuteron radius is also.

# Other data — Helium

- New 2013/2014 data
- $\mu$-$^4$He at Mainz Proton Radius Workshop, 2014
- $\mu$-$^3$He at Gordon Conference, N.H., 2014
- Quick summary: He radii from $\mu$ Lamb shift <u>in accord with</u> electron scattering radii.

# Explanations?

- Hard to see problems with $\mu$ experiment
  - Hard to get working
  - But once working, easy to analyze
- Problems with analysis of electron experiments? But there are a lot of them.
- BSM explanations?
  - If so, further tests?

# Review *e*-*p* scattering data

- Point: Measurements at finite $Q^2$. Need to extrapolate to $Q^2 = 0$ to obtain charge radius. (Mainz group itself: $R_E = 0.879(8)$ fm.)

- Because of importance, others have tried, using different ways of fitting data. Three recent fits found "big" values:

- Graczyk & Juszczak (2014), using Bayesian ideas and pre-Mainz world data, obtained

$$R_E = 0.899(3) \text{ fm.}$$

- Lee, Arrington, & Hill (2015) using Mainz data and neat mapping ideas to ensure convergence of expansions, obtained

$$R_E = 0.895(20) \text{ fm.}$$

- Arrington & Sick (2015) found

$$R_E = 0.879(11) \text{ fm.}$$

# But…

- Several recent fits found "small" values (*i.e.*, compatible with muonic Lamb shift experiment):

- Lorenz, Meißner, Hammer, & Dong (2015 and earlier), dispersive ideas, also using timelike data, obtained
  $R_E = 0.840(15)$ fm.

- Horbatsch and Hessels (1509.05644)

- Carlson, Griffioen, Maddox (1509.06676)

- Higinbotham, Kabir, Lin, Meekins, Norum, Sawatzky (1510.01293)

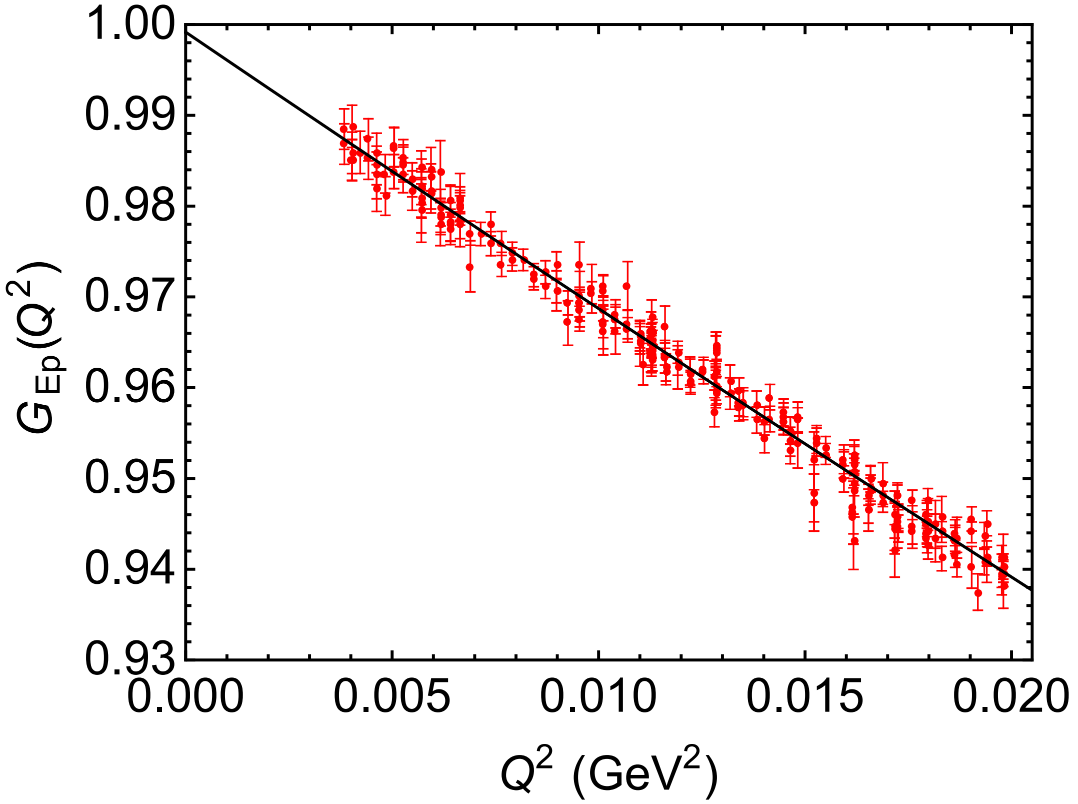
# Recent *e*-*p* analyses, I

- Maddox et al. (1509.06676)

- First viewpoint: Charge radius is a $Q^2 = 0$ concept, should be able to obtain just from low $Q^2$ data.

- Technical: Form factor is analytic function of $Q^2$, except for cut starting at $4m_\pi^2$. Hence, polynomial expansion in $Q^2$ converges for $Q^2 < 4m_\pi^2$.

- For low $Q^2$ data, use
  $Q^2 < 0.02$ GeV$^2$
  (243 data points)
  linear plus quadratic in $Q^2$ ,
  get $R_E = 0.850(19)$ fm

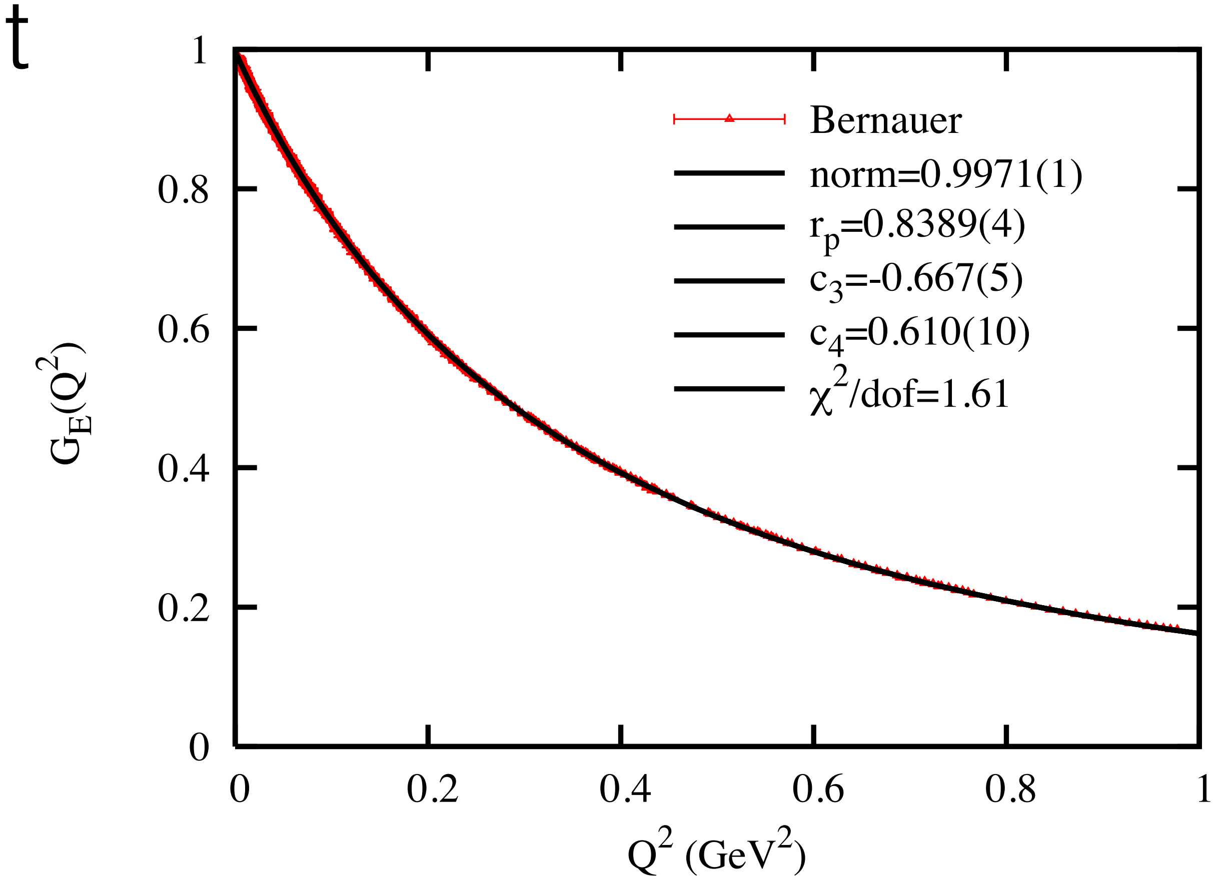


# Recent *e*-*p* analyses, I

- Second viewpoint: fitting whole Q2 data range with complicated (i.e., many parameters) function leads to dangers in extrapolation.

- Fit whole Mainz 2010 data set with simpler functions (i.e., 4 or so parameters), that extra-polate more reliably. From collection of such fits quote

$$R_E = 0.840(16)\ \text{fm}$$



# Recent *e*-*p* analyses, II

- Higinbotham, Kabir, Lin, Meekins, Norum, Sawatzky (1510.01293)

- Also emphasized use of low $Q^2$ range data.

- Additional contribution: resurrecting Saskatoon 1974 and Mainz 1980 data. Excellent data. $Q^2 < 0.031$ and $< 0.055$ GeV$^2$, resp.

- Excellent discussion of statistics relevant to deciding how many parameters to use. Argued for reliability of even linear fits in this data range.

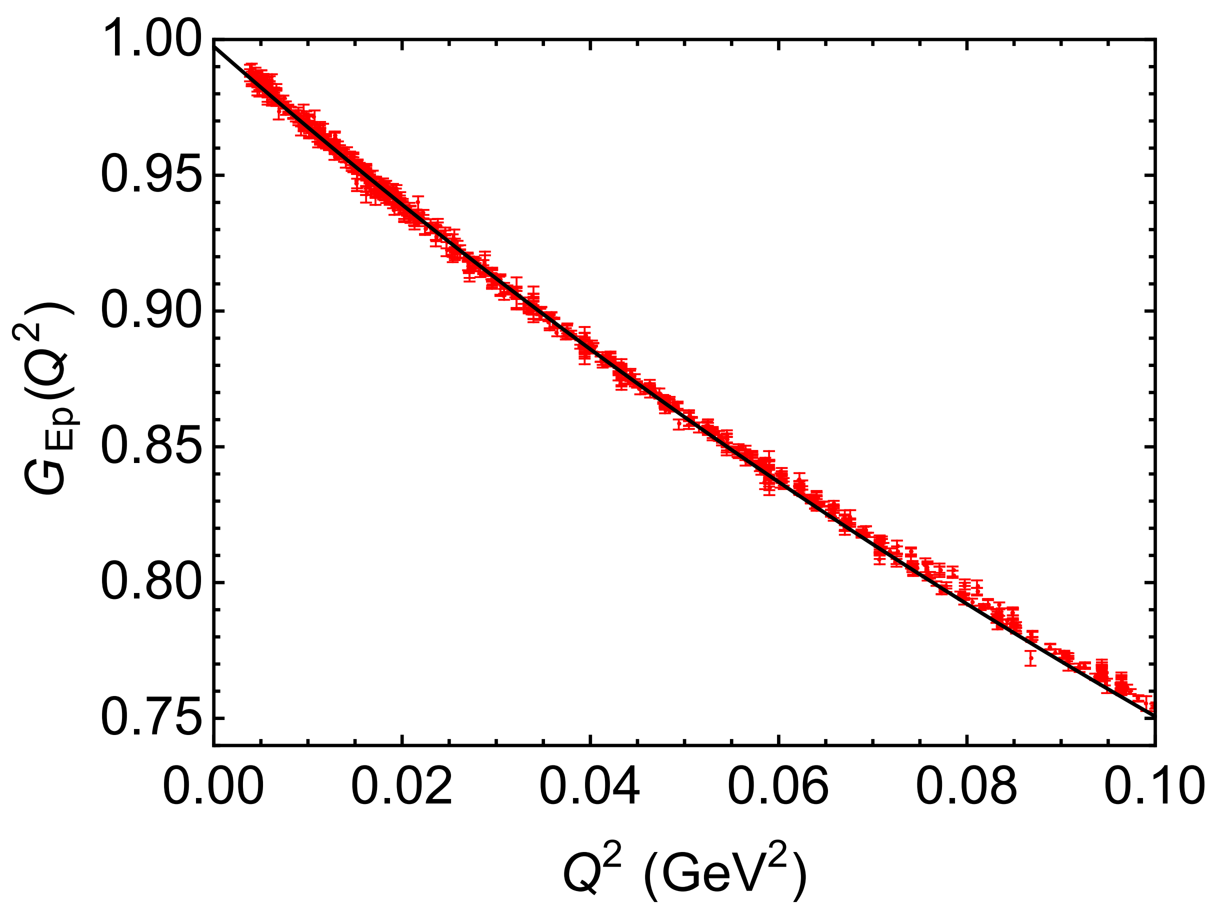
- Obtained $R_E$ compatible with muonic atomic data, 0.84 fm

# Recent *e*-*p* analyses, III

- Horbatsch and Hessels (1509.05644)
- Also believe “the rms charge radius of the proton is a small-$Q^2$ concept. Thus, if possible, it should be determined from low-$Q^2$ data.”
- Look at Mainz 2010 data restricting $Q^2 < 0.1$ GeV$^2$. Analyze two ways, get bifurcated result.
- their take-away conclusion: scattering data can’t help
- proton radius problem remains, but between electron atomic physics and muon atomic physics

# H. H.

- dipole fit: $G_E = (1 + R_E^2\ Q^2\ /12)^{-2}$, similarly for $G_M$
- Got $R_E = 0.842(2)$ fm and $R_M = 0.800(2)$ fm
- Fits look o.k.



# H. H.

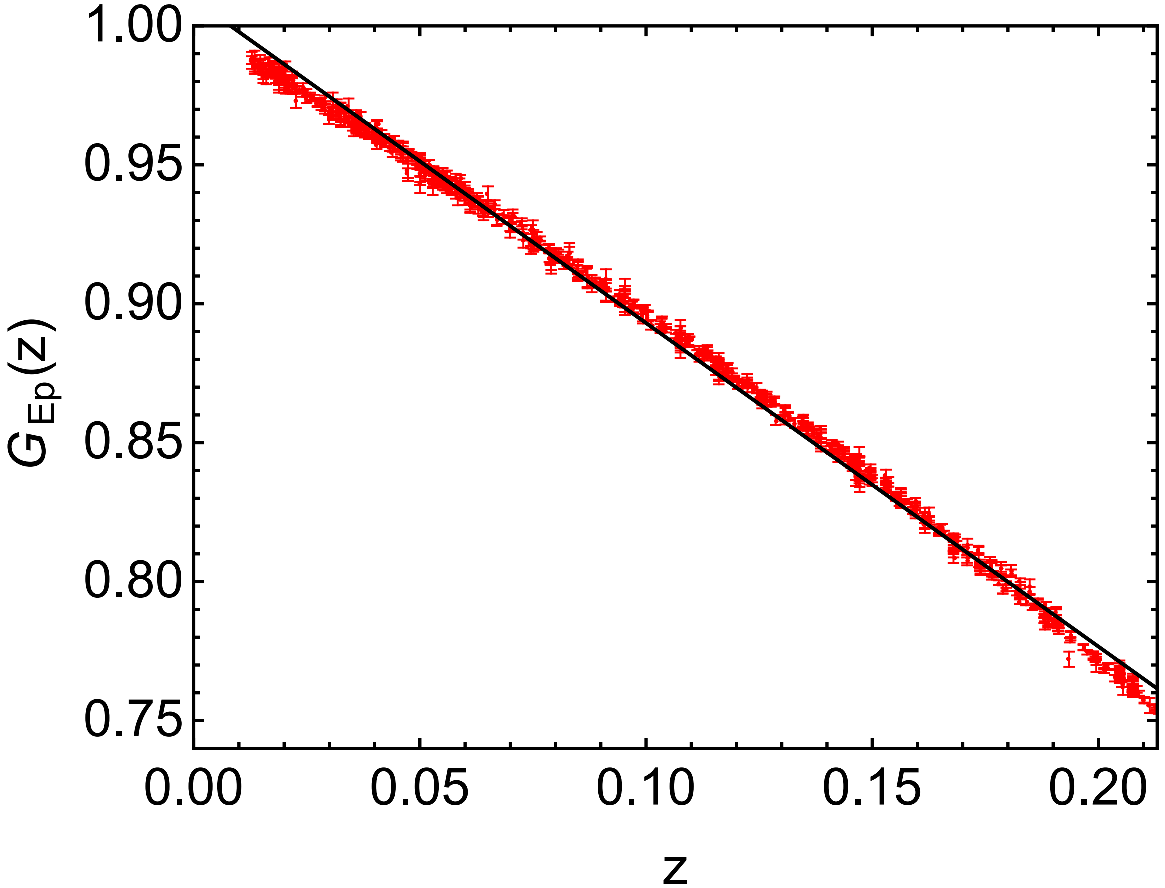
- *z* variable expansion, $$z = \frac{\sqrt{4m_\pi^2 + Q^2} - 2m_\pi}{\sqrt{4m_\pi^2 + Q^2} + 2m_\pi}$$

- reason: for functions like $G_E$, polynomial expansion in *z* converges for all $0 < z < 1$, *i.e.*, all spacelike $Q^2$

- Expansion linear in *z*, $G_E = 1 - (8/3) m_\pi^2 R_E^2 \, z$

- Now got $R_E$ = 0.888(1) fm and $R_M$ = 0.874(2) fm

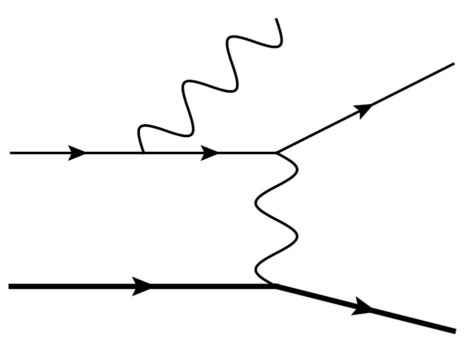
# H. H.




- Fit looks not good
- This is $Q^2 < 0.1$ GeV$^2$ data
- Concavity when plotted in this variable not well fit by linear polynomial
- Overly large $R_E$ not surprise
- (Plot is mine; theirs would look better, but principal problem remains. Can explain.)
- My take-away 1: should include $z^2$ term if doing this way. My result when doing so is $R_E = 0.838$ fm.
- My take-away 2: low $R_E$ o.k., high $R_E$ not o.k.

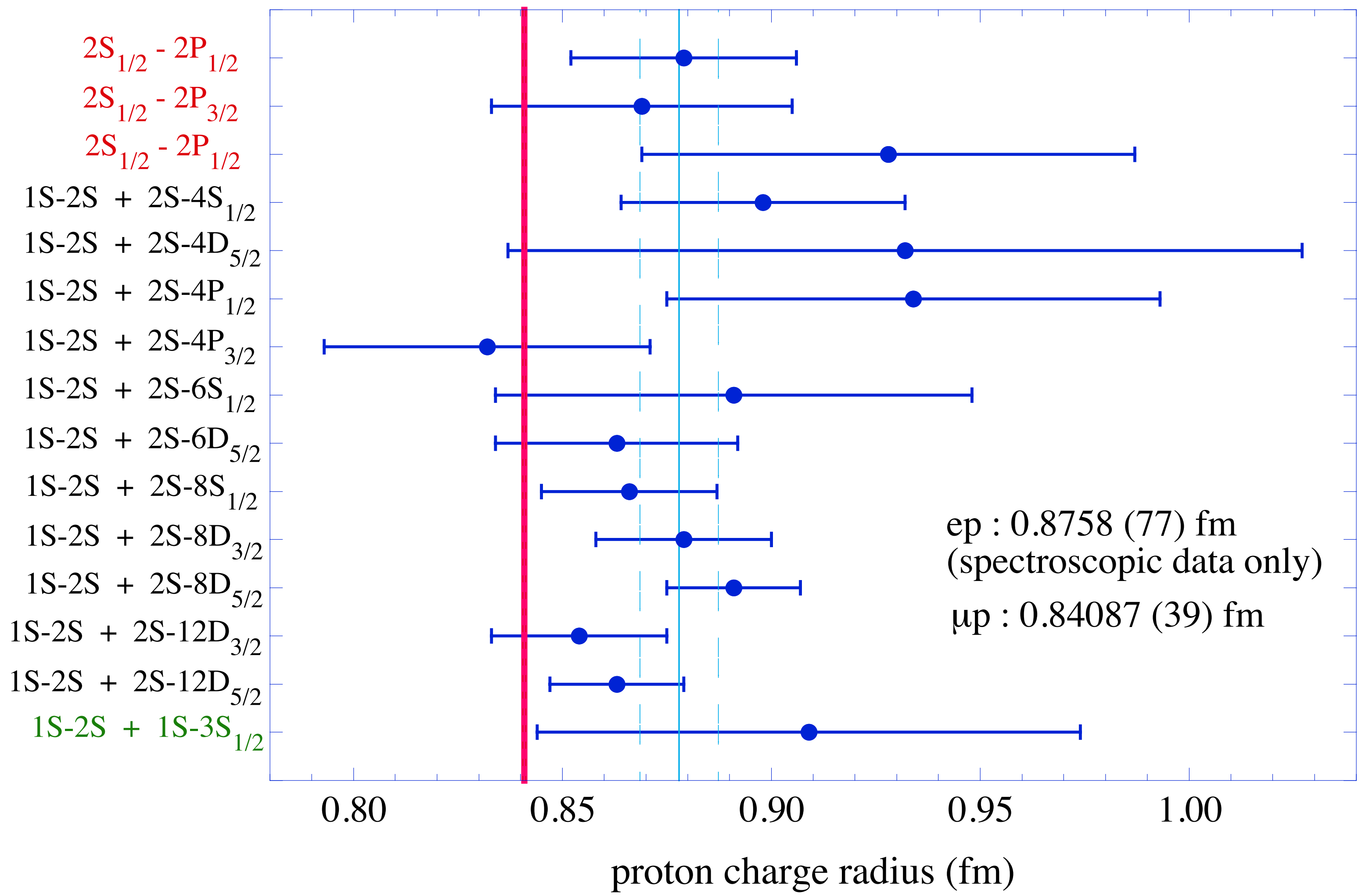
# Scattering future

- *A:* Continue discussing statistics and extrapolations
- *B:* Do further experiments to lower lowest $Q^2$, and also do $\mu$ scattering
- *1:* PRad at JLab: Just target and detector screen, allowing very small scattering angles. Anticipate $Q^2|_{\mathrm{low}} \approx 0.0002\ \mathrm{GeV}^2$. Running now!



- *2:* ISR (Initial State Radiation) at Mainz. Photon radiation takes energy out of electron, allowing lower $Q$ at given scattering angle. Anticipate $Q^2|_{\mathrm{low}} \approx 0.0001\ \mathrm{GeV}^2$. Data taken, more data to be taken; under analysis.
- *3:* MUSE = Muon scattering experiment at the PSI. Anticipate $Q^2|_{\mathrm{low}} \approx 0.002\ \mathrm{GeV}^2$. Production runs 2017/2018.

# Back to atomic spectroscopy




- Same plot, but $\mu$-H value added
- Possible: correlated systematic errors. There are more measurements than independent expt'l groups.

# Short term future

- Several independent groups are doing more precise experiments. The first 3 (at least) can individually get the proton radius to under 1%.
  - York University (Canada): Ordinary hydrogen 2*S*-2*P* Lamb shift
    (“We have run into some systematic effects that we want to understand better”)
  - MPI Quantum Optics (Garching): 2*S*-4*P* transition
    (“…about 2S-4P: things are progressing great, but you haven't missed anything concerning publications. I will be happy to let you know as soon as there is some news from our side.”)
  - Laboratoire Kastler Brossel (Paris): 1*S*-3*S* transition
    (“…In parallel, we have another failure with a RF amplifier, we put another which has failed after one week… We are fighting with a little bit of luck I hope to get a result for 1S-3S before the end of this year.”)
  - NIST (USA): Measure Rydberg using “Rydberg” states, very high *n* states, uncontaminated by proton size. (Very relevant: recall previous discussion.)
  - + National Physical Lab (U.K.), several 2S–*nS*,*D* transitions
- Under way, may see results soon. Will be important, one way or another.

# Exotic possibilities

- Breakdown of Lorentz invariance? (Gomes, Kostelecky, & Vargas, 2014)
- Unanticipated QCD corrections? (G. Miller, 2013)
- Higher-dimensional gravity(?) (1509.08735, Dahia and Lemos)
- Renormalization group effects for effective particles (Glazek, 2014)
- Will consider breakdown of muon-electron universality. New particle coupling to muons and protons. Small or no coupling to other particles.
- References (optimistic or neutral): Tucker-Smith & Yavin (2011), Batell, McKeen, & Pospelov (2011), Brax & Burrage (2011), Rislow & Carlson (2012, 2014), Marfatia & Keung (2015), Pauk & Vanderhaeghen (2015)
- References (pessimistic): Barger, Chiang, Keung, Marfatia (2011, 2012), Karshenboim, McKeen, & Pospelov (2014)

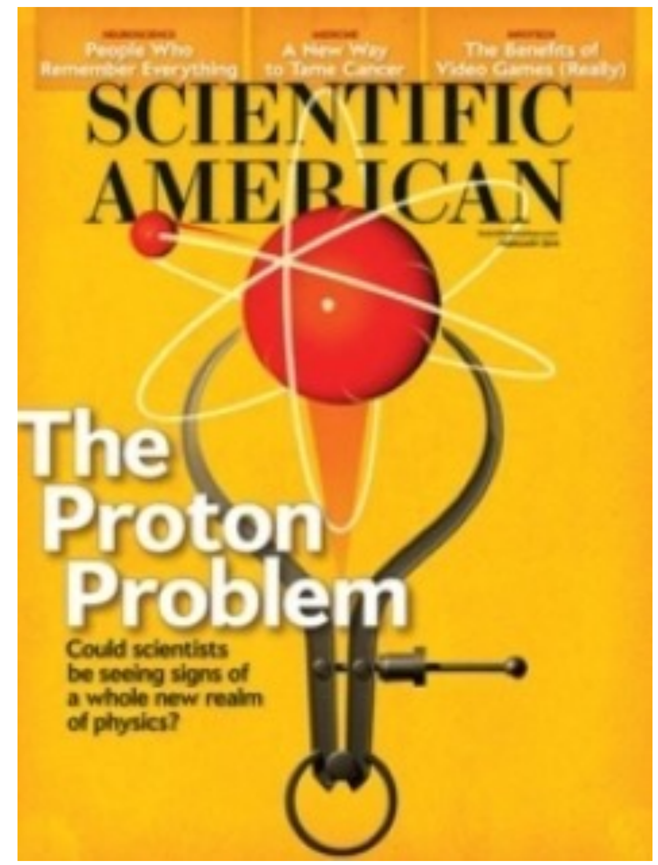
# $\mu$-H Lamb shift

- Point: Experimenters do not directly measure proton radius. Measure energy deficit, 310 μeV. Interpret as proton radius deficit.

- Idea: Proton radius unchanged. Energy deficit due to new force, carried by exchange of new particle.

- New particle is scalar or vector. Pseudoscalar or axial vector have little effect on Lamb shift for similar couplings.


nature
OIL SPILLS
There's more to come
PLAGIARISM
It's worse than you think
CHIMPANZEES
The battle for survival
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent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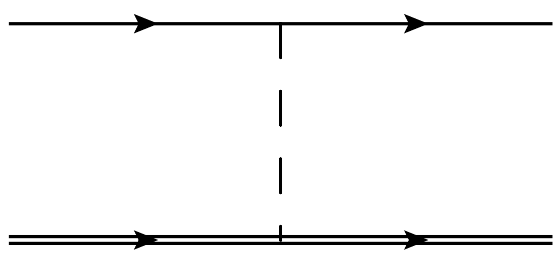
The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?

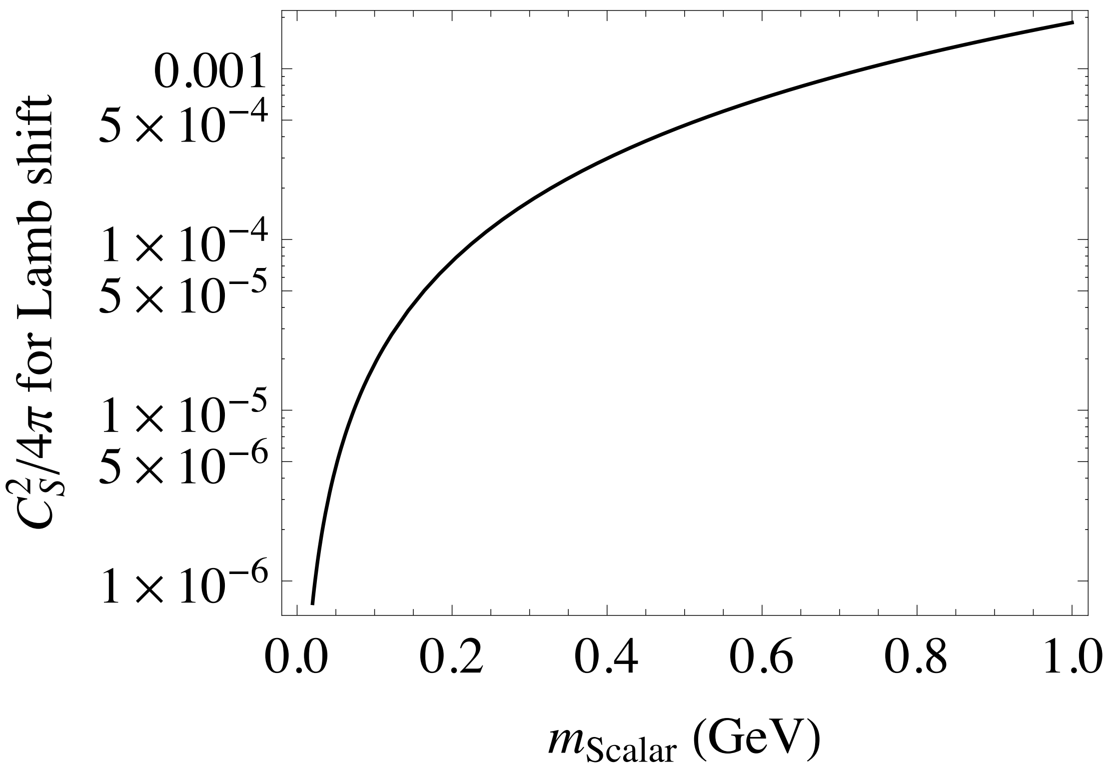
# Energy shift

- e.g., scalar case



$$V(r) = -\frac{C_S^{\mu} C_S^{p}}{4\pi r} e^{-Mr}$$

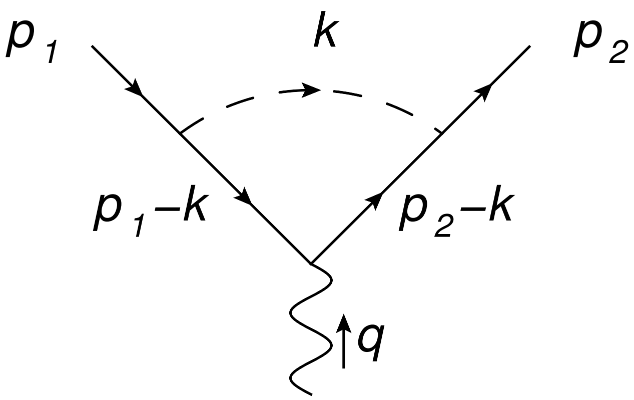
- Pick $C_S^{\mu}\, C_S^{p}$ to give 320 μeV for given $m_\phi$. (Plot for $C_S^{\mu} = C_S^{p}$.)



# Other muon processes

- Worry about other processes where new particle couples to muons. *First:*
  - Loop corrections to $\mu$ magnetic moment
  - (Reminder: 3 σ discrepancy between measured and standard model calculated $(g\text{-}2)_\mu$.)
  - If new exchange particle light, effect on $(g\text{-}2)_\mu$ small enough (Tucker-Smith & Yavin). Otherwise, need to fix by fine tuning.

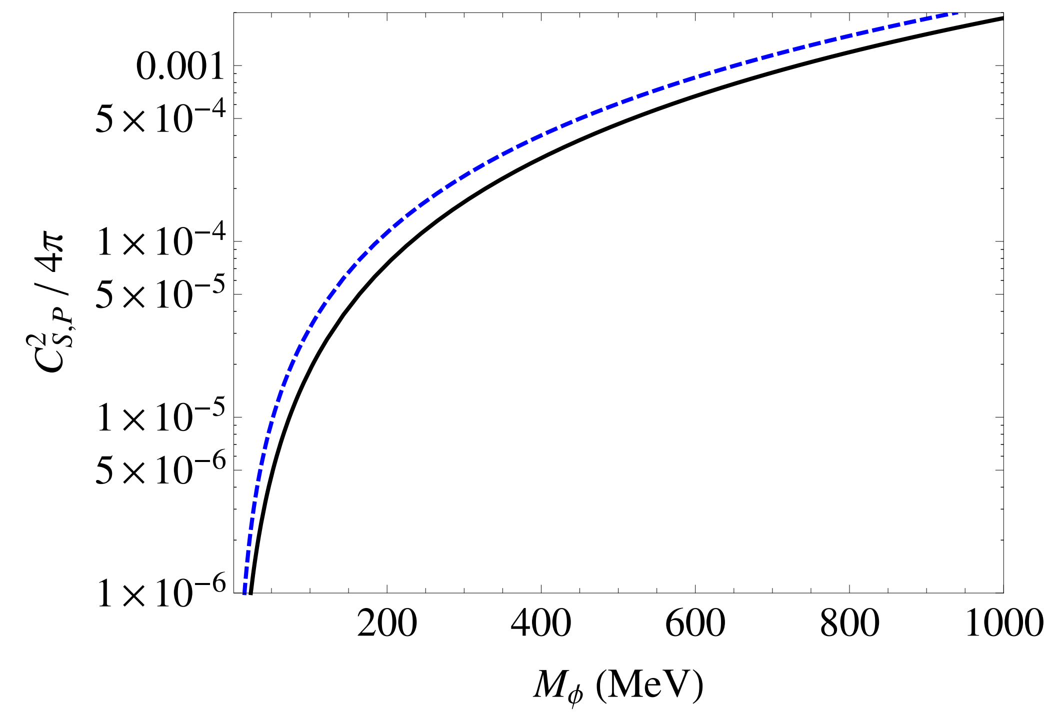
# Fixing $(g\text{-}2)_\mu$




- Will need extra particle and fine tuning
- Lucky break: corrections to (g-2) from regular vector and axial vector have opposite sign. Same is true of scalar and pseudoscalar.

- With extra particle, have new coupling, say $C_P^j$. Choose coupling to cancel in $(g\text{-}2)_\mu$. Does not much affect Lamb shift.
- Couplings now fixed, albeit mass sensitive. Hence predictions for other processes fixed.

# (Fine tuning plot)

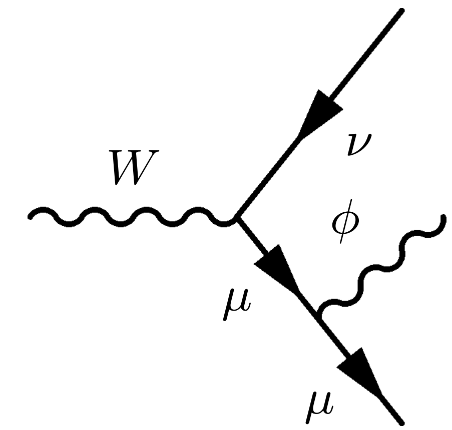



- Above for scalar-pseudoscalar
- Low enough mass, cancellation not needed (TSY)
- Couplings now fixed, albeit mass sensitive.
- ∴ Predictions for other processes now fixed.

# BSM problems

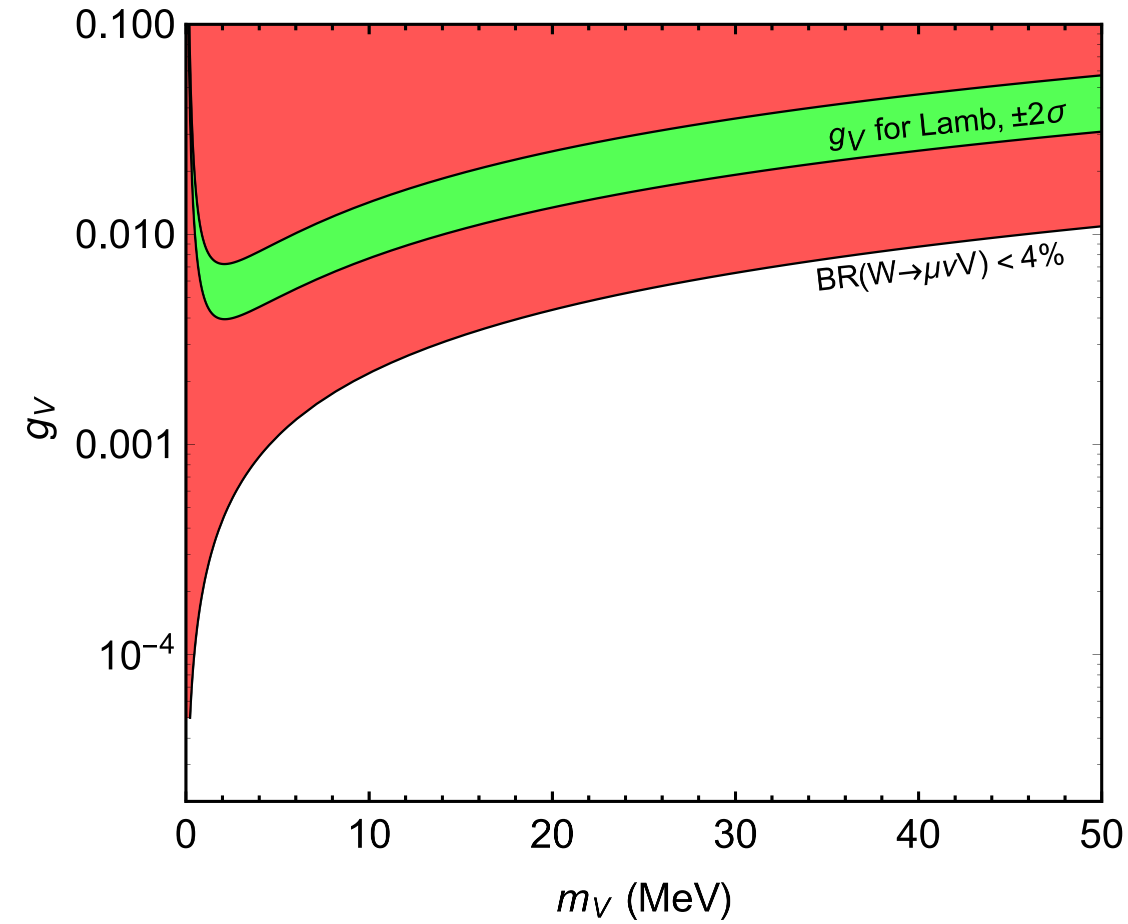
1. Radiative corrections to W-decay
2. Non-effect in He

# W decay




- Remark of Karshenboim, McKeen, and Pospelov: fast growth with energy of amplitudes involving massive vector particles

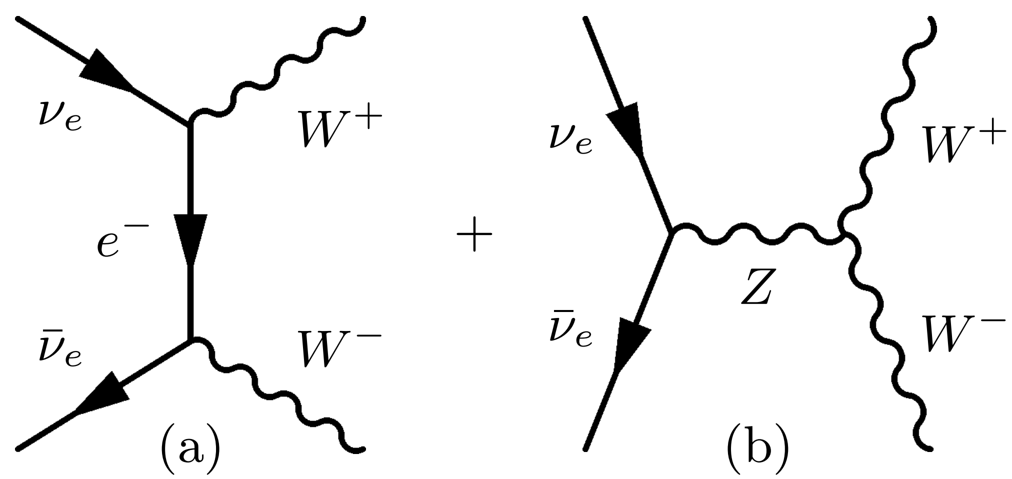
- If light new particle $\boldsymbol{\phi}$ *or V* coupling to muon, it gives large radiative correction to *W* decay via $W \rightarrow \boldsymbol{\mu\nu} V$, larger than measured error in *W* decay rate.




Red: forbidden
Fig. based on
Karshenboim et al. (2014)

# W decay

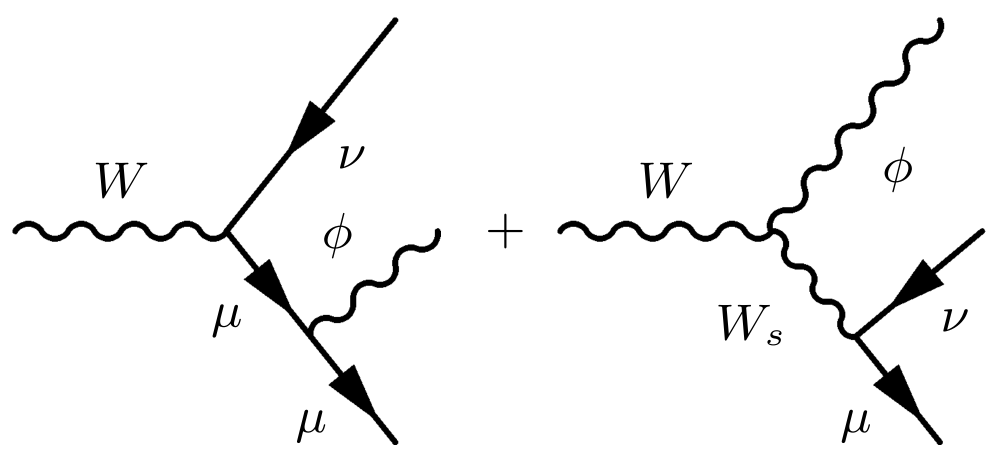
- Reminiscent of (from early days of W.S. model),




- Left diagram grew unpleasantly at high energy, right diagram cancelled it at high energy, was small at lower energy

# Here

- Should have interaction also with *W* to make theory renormalizable.




- Problem ameliorated (see Freid and me (2015))

# Helium Lamb shift

- A pair ($^3$He & $^4$He) of non-contradictory results.
- He radii measured in electron scattering, to about 1/4%. These radii go into prediction for Lamb shift.
- Preliminary data on $\mu$-He Lamb shift agrees with prediction, to about 1σ. If due to heavy BSM particle exchange, should disagree by about 5σ.
- How does mass creep in?

# Heavy atom Lamb shift

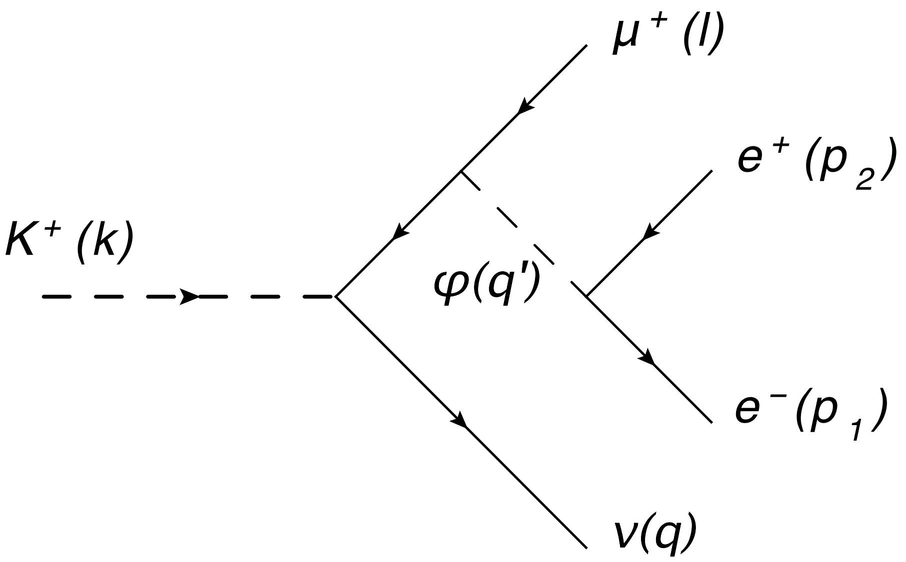
- Physics: Range of potential is controlled by mass. Light mass, long range, like Coulomb potential, does not split S and P states.

- Application: Z=2 helium has orbital muons closer to nucleus than Z=1 hydrogen. What looks like long range to helium is short range to hydrogen, if mass chosen correctly.

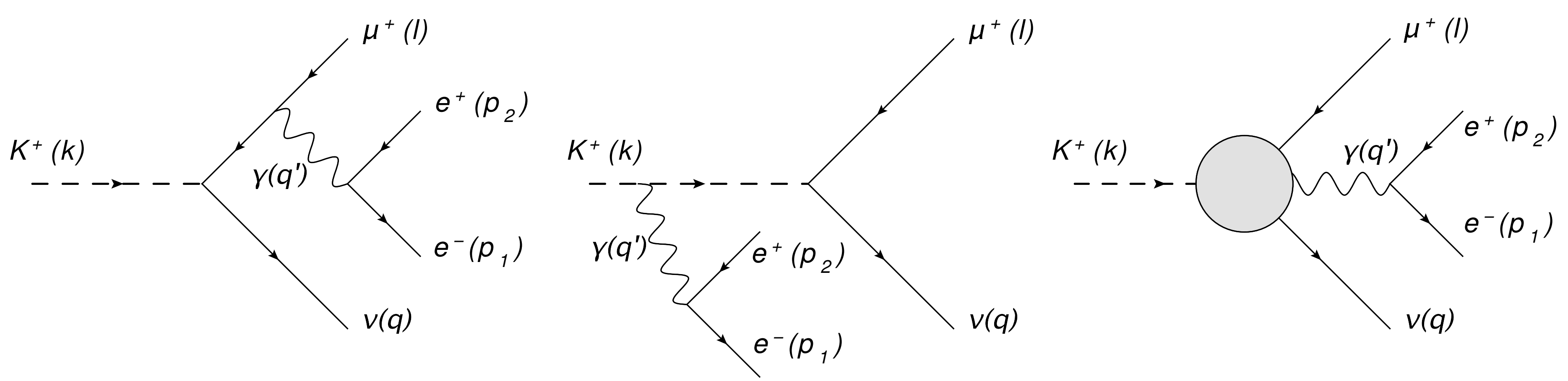
- Quick bottom line: Get result for proton big enough and for He small enough if $m_\phi \approx 1$ MeV.

# New force seen elsewhere?

- Older suggestion: correction to *K*-decay, *viz.*, $K \to \mu\, \nu\, e^+ e^-$ as correction to $K \to \mu\, \nu$.

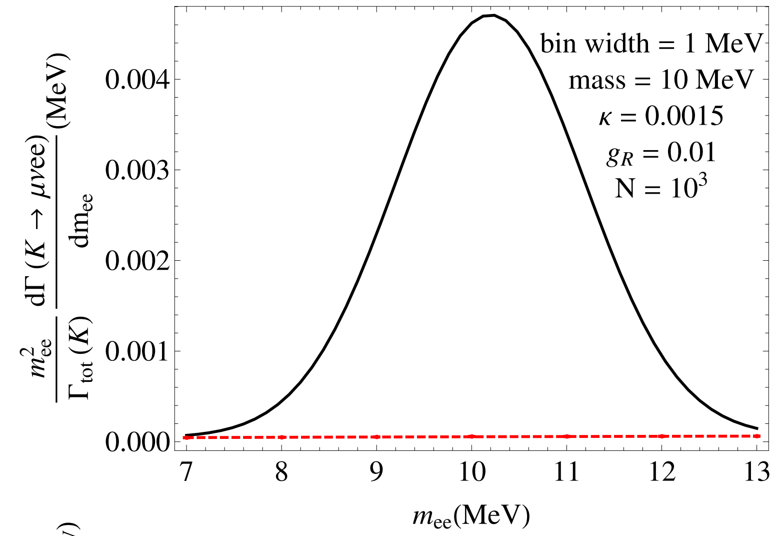


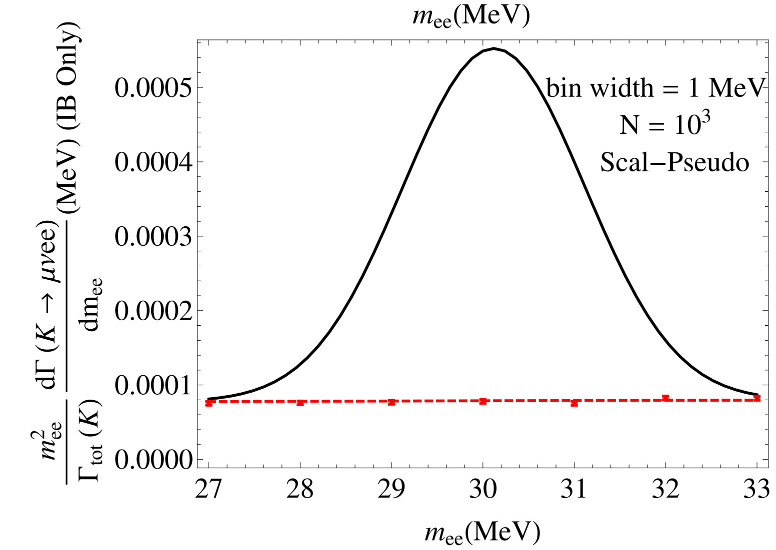

- Of course, QED gives same final state, with smooth (calculable) spectrum of $e^+ e^-$.



# $\varphi$ visible?

- $\varphi$ (new BSM particle) will give bump. Size calculable.
- Is it observable?
  Wow, Yes. (If it exists.)
  [Red = QED background,
  solid = bump from $\varphi$]




- Note: TREK experiment (E36) at JPARC (Japan) will observe $10^{10}$ kaon decays, or about 200,000 $K\to\mu\nu e^+e^-$ events, about 1000 per MeV bin in the mass range we are considering. (Thanks to M. Kohl)



Plots from Rislow and me (2014)

# Reminder: new data coming

- New CREMA measurements (out at conferences, 2013/14)
- 3 scattering expts. underway or coming
- Electron deuteron scattering (Griffioen *et al.*, Mainz) (data taken)
- 5 atomic energy level measurements
- TREK at JPARC
- Maybe also: Trumuonium ($\mu^+\mu^-$) at JLab



(14 experiments)

# Ending

- Remarkable: 6 years after the first announcement, the problem persists.
- Interestingly little discussion of the correctness of the $\mu$-H Lamb shift data.
- Serious and good new data coming.
- Opinion: Either
  - All radii correct, and BSM—muonic specific force—is explanation despite problems, or
  - The electron based radius measurements will reduce to the muonic value.
- Comment: the theory for $(g\text{-}2)_\mu$ cannot be considered settled until the proton radius problem is settled. Further, there may be striking corrections to other processes that involve muons.

The end for now!