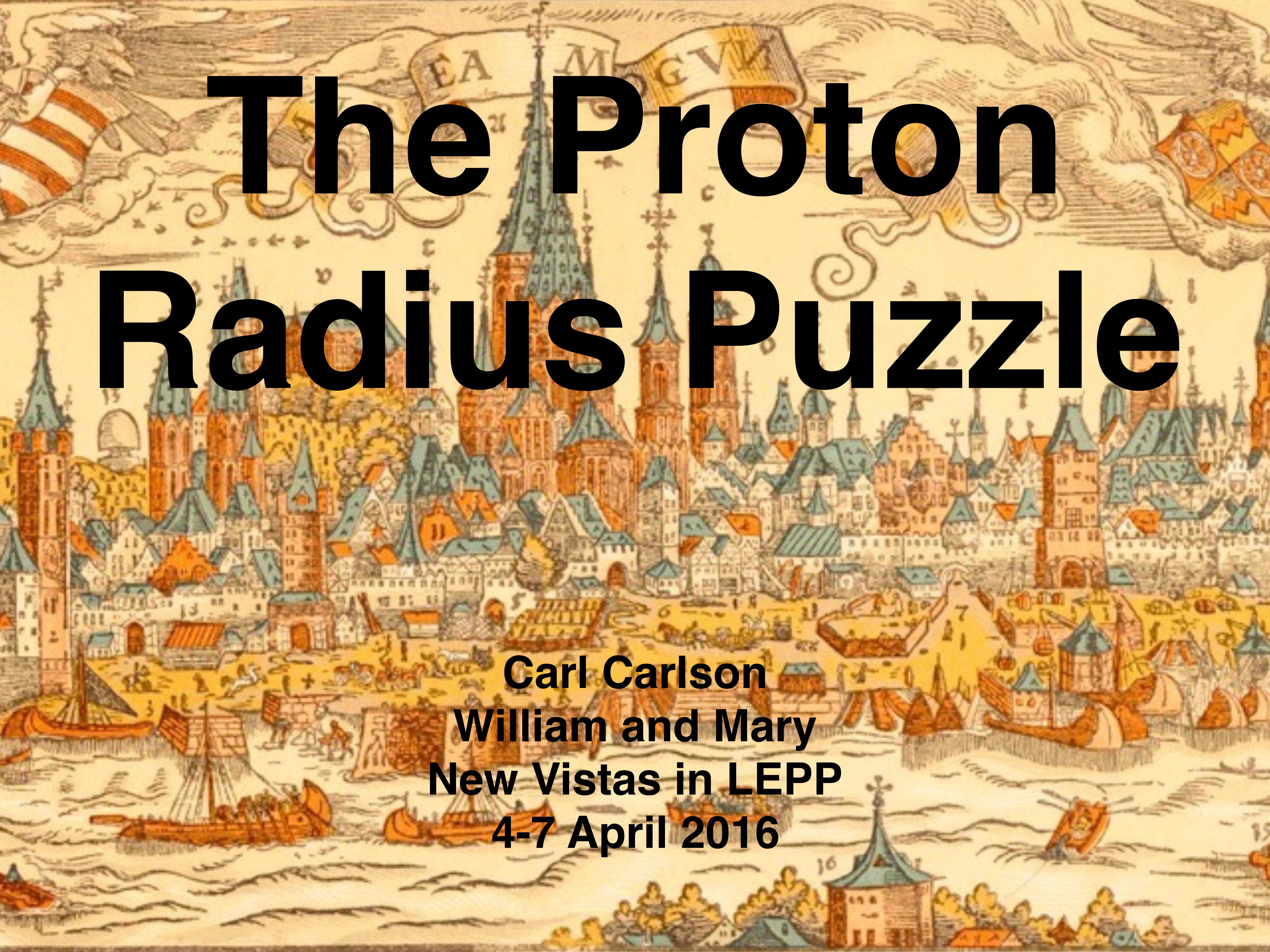

The Proton Radius Puzzle

Carl Carlson
William and Mary
New Vistas in LEPP
4-7 April 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. Exotic explanations
        - Physics Beyond the Standard Model
            - My opinion: likelihood decreasing, but still possible
        - May mention other possibilities (later)
    B. Ordinary explanations
        - Atomic physics: more experiments coming
        - Electron scattering: maybe some things are harder than they seem
3. Highlight: List of coming relevant data

This talk

1. The measurements: where the differences came from
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    A. Exotic explanations

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    B. Ordinary explanations

    - Atomic physics: more experiments coming
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3. Highlight: List of coming relevant data

new stuff here

some arriving in 2016 (maybe)

new stuff here too

some relatively soon

Measuring proton radius

- Methods: scattering or atomic spectroscopy
- 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 adequate accuracy (and more data coming), and new *μ*-*p* scattering experiment in preparation

e-*p* scattering

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

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

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

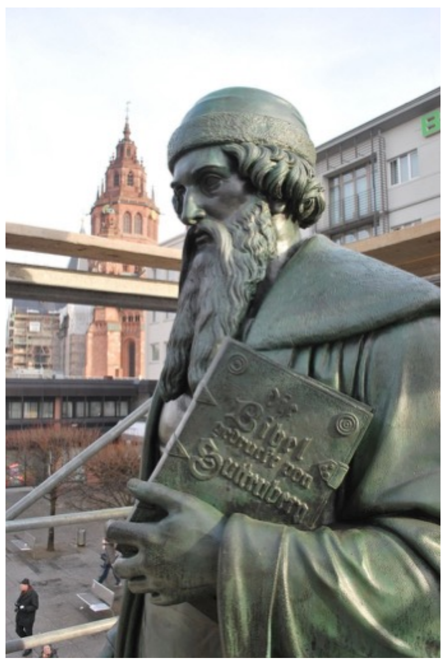
- Low Q^2, mainly sensitive to G_E.

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

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

Low-Q^2 scattering data

- Most extensive current data comes from Mainz, famous for Gutenberg and for electron accelerator.



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

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

- Compatible with Zhan *et al.*, PLB 705 (2011) 59-64.

Atomic energy level splittings

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

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

- plus QED corrections

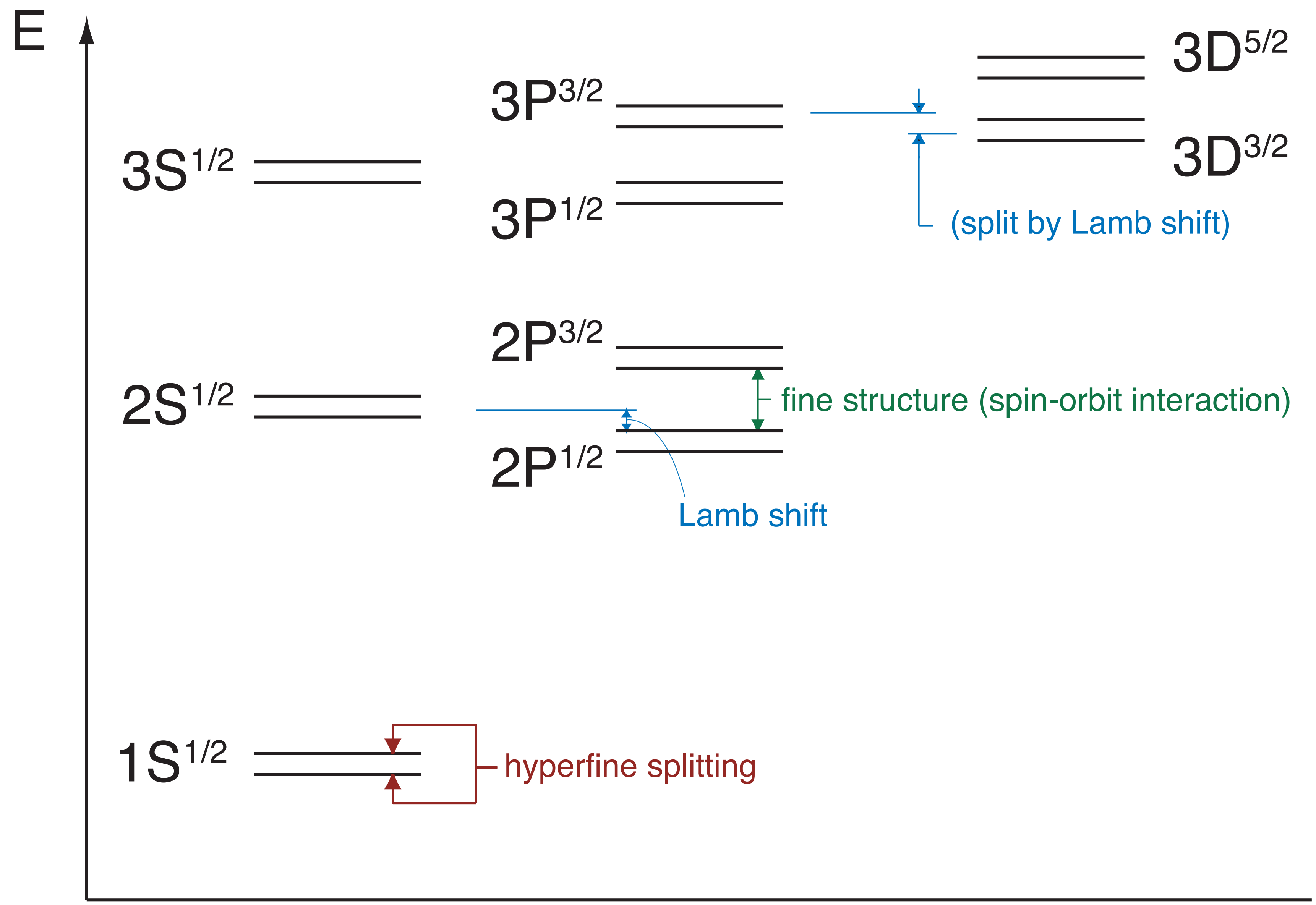
- plus finite size proton, pushing energy upward a bit.

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

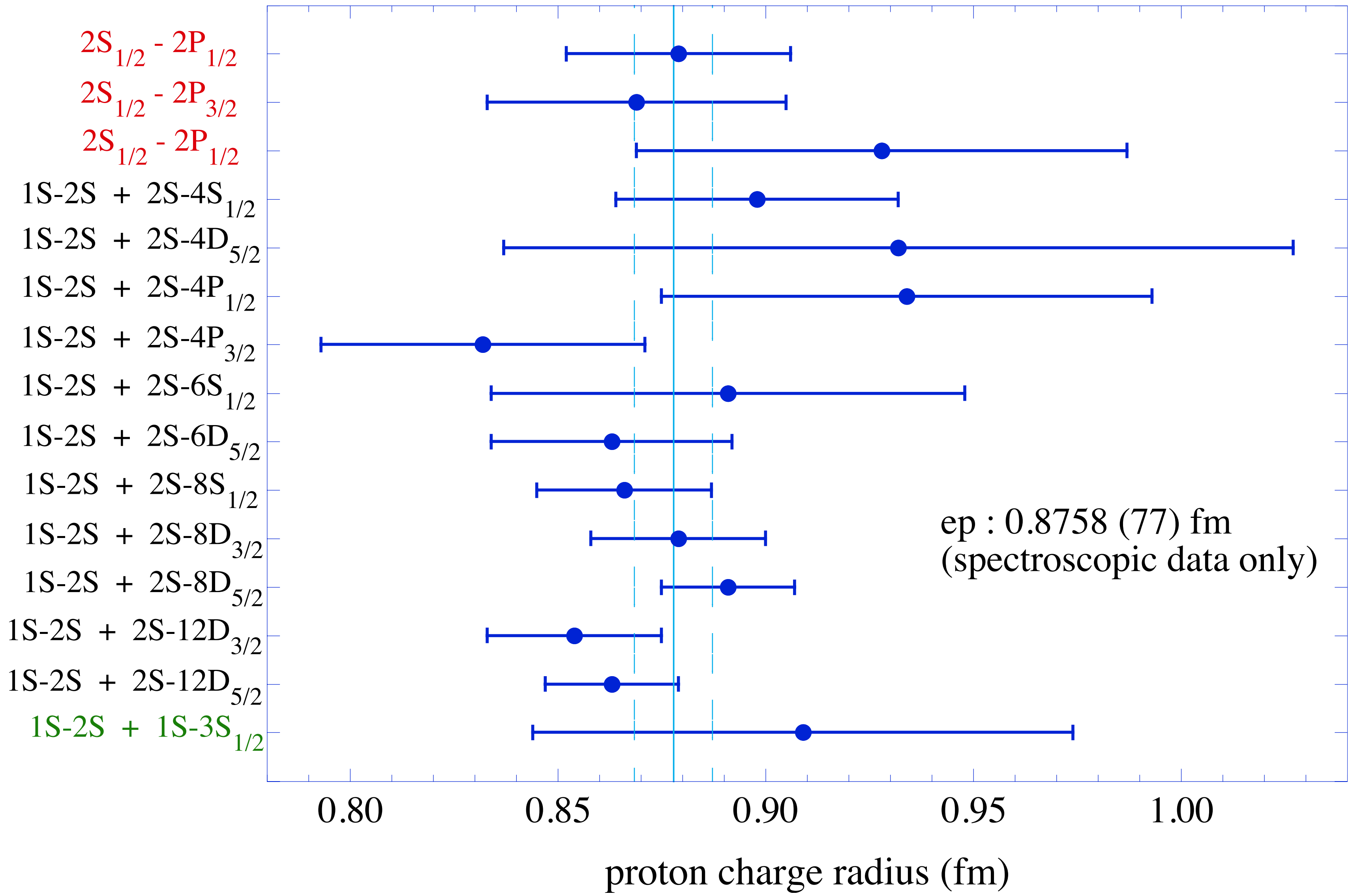
fine print: $\phi_{nS}^2(0) = (m_r \alpha)^3 / (n^3 \pi)$

measure energy accurately $\Longleftrightarrow$ measure radius

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



Atomic results

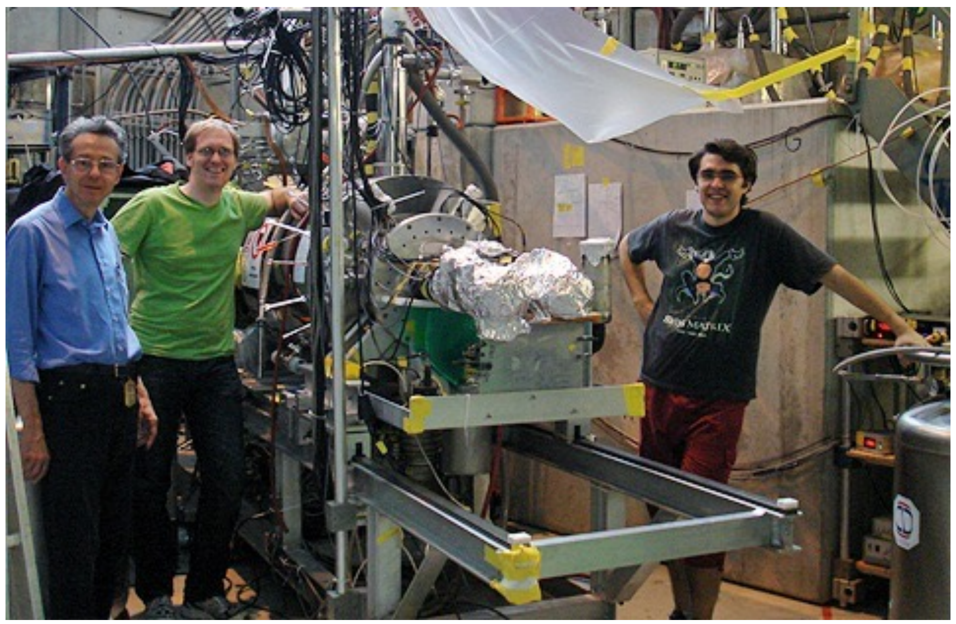
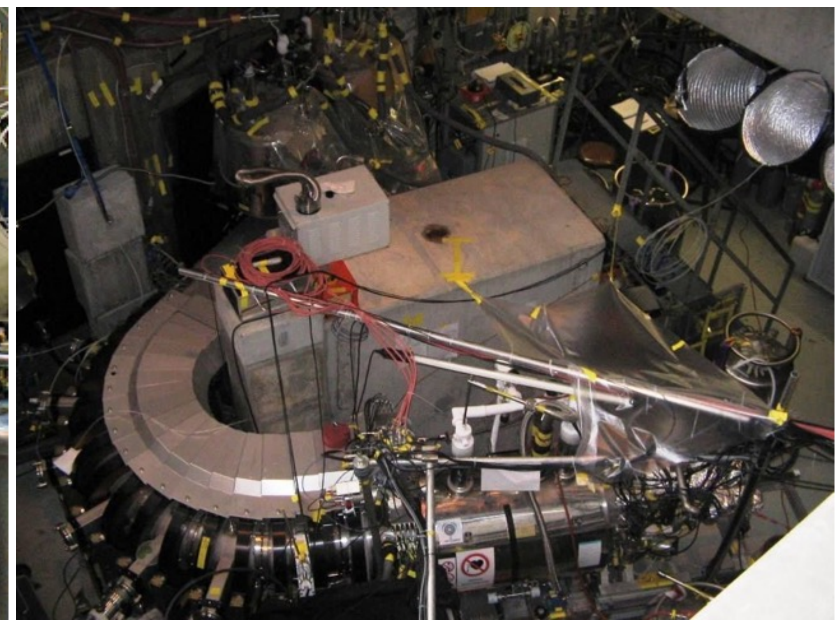


- Scattering and atomic results combined (CODATA, 2014):

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

2010 Revolution

- CREMA = Charge Radius Experiment with Muonic Atoms

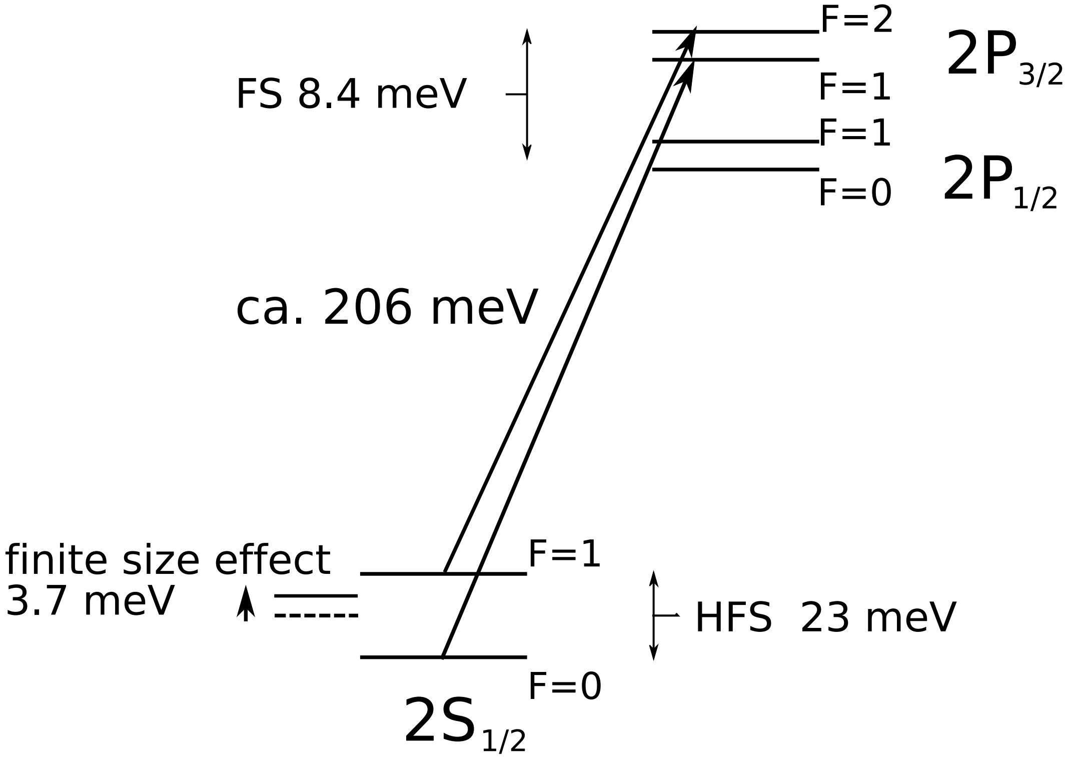




- Did atomic physics, specifically Lamb shift, with muons (muon= electron, but weighs 200 times more, orbits 200 times closer).

- Goal: measure proton radius with factor 10 smaller uncertainty

CREMA

- 2*S*-2*P* Lamb shift in *μ*-H.
- Measured two energy differences,



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

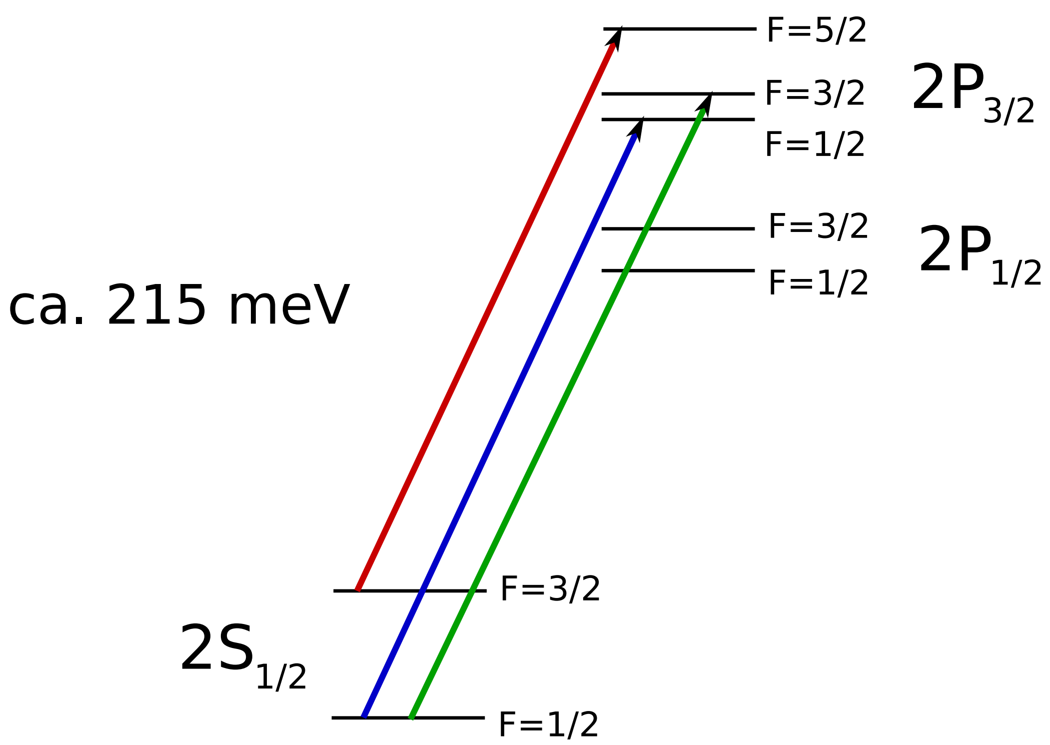
- Interpreting difference from QED as finite size effect, get

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

- Success on uncertainty goal: but 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-deuteron (detail)

- Note: accuracy of current directly measured deuteron radius from electron scattering inadequate for comparison to Lamb shift result. Work ongoing at Mainz.

- Existent atomic result for *d* vs. *p* “isotope shift,”

$$\left(R_E^d\right)^2 - \left(R_E^p\right)^2 = 3.82007(65)\ \mathrm{fm}^2$$

- Measured for electrons. If used for muons, find muonic deuteron radius compatible with muonic proton radius.

Other data — Helium

- New 2013/2014 data
- μ-^{4}He at Mainz Proton Radius Workshop, 2014
- μ-^{3}He at Gordon Conference, N.H., 2014
- Found: He radii from μ Lamb shift in accord with electron scattering radii.

Explanations?

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

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 (positive or neutral side): Tucker-Smith & Yavin (2011), Batell, McKeen, & Pospelov (2011), Brax & Burrage (2011), Rislow & Carlson (2012, 2014), Marfatia & Keung (2015), Pauk & Vanderhaeghen (2015)
- References (less positive): Barger, Chiang, Keung, Marfatia (2011, 2012), Karshenboim, McKeen, & Pospelov (2014)

μ-H Lamb shift

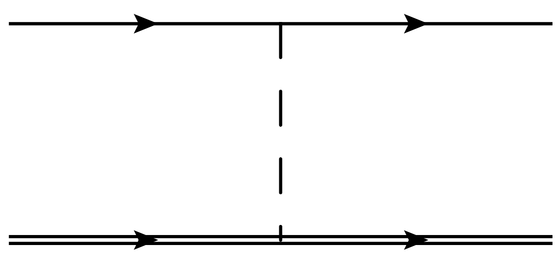
- Point: Experimenters do not directly measure proton radius. Measure energy deficit, 320 μeV. Interpret as proton radius deficit.

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

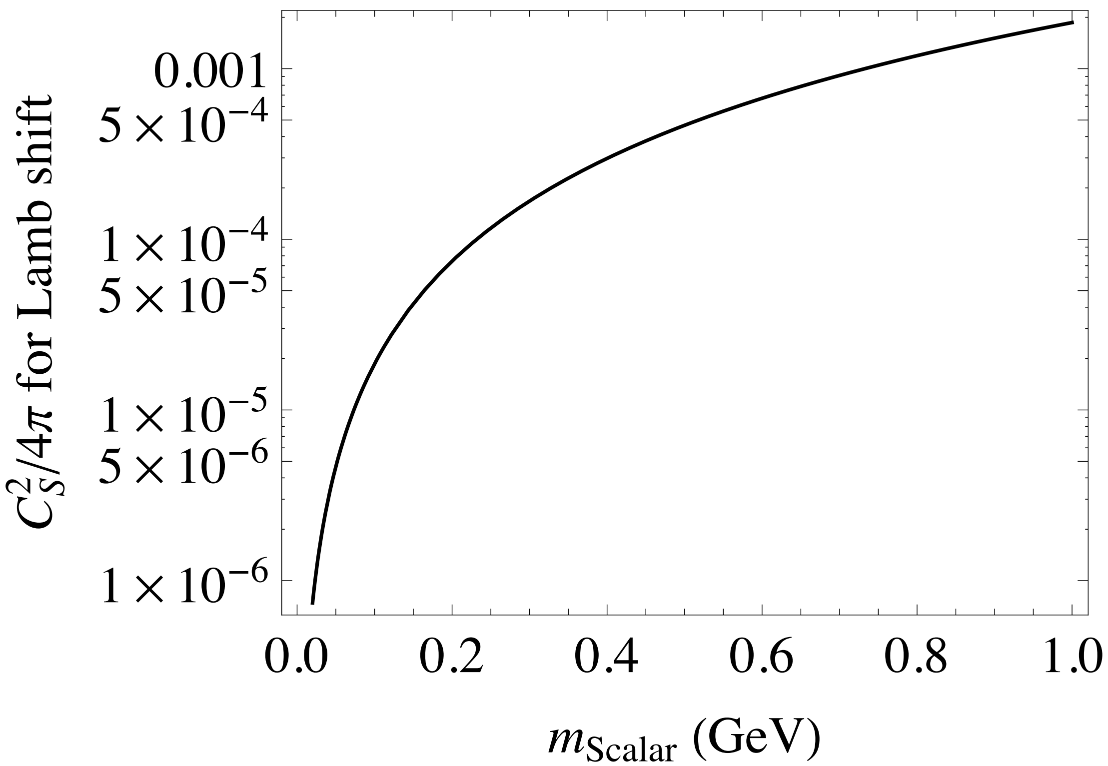
- New particle is scalar or vector. Pseudoscalar or axial vector have little effect on Lamb shift for similar couplings.

Energy shift

- e.g., scalar case



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

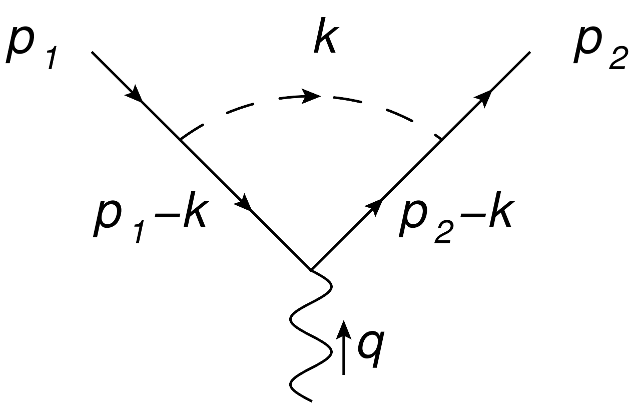


- Pick $C_S^\mu C_S^p$ to give 320 μeV for given m_ϕ. (Plot for $C_S^\mu = C_S^p$.)

Other muon processes

- Worry about other processes where new particle couples to muons. *First:*
  - Loop corrections to μ magnetic moment
  - Reminder: 3 σ discrepancy between measured and standard model calculated $(g-2)_\mu$.
  - If new exchange particle light, effect on $(g-2)_\mu$ small enough (Tucker-Smith & Yavin, 2011). Otherwise, need to fix by fine tuning.

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



- If new particle not light, 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.

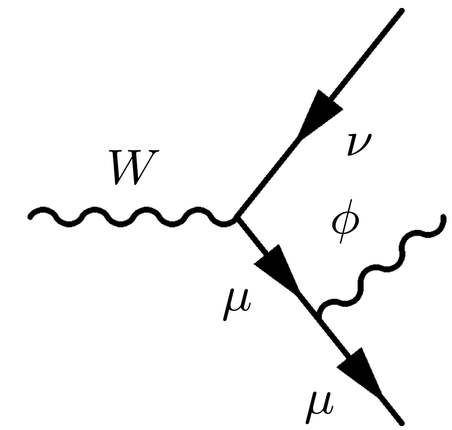
BSM problems

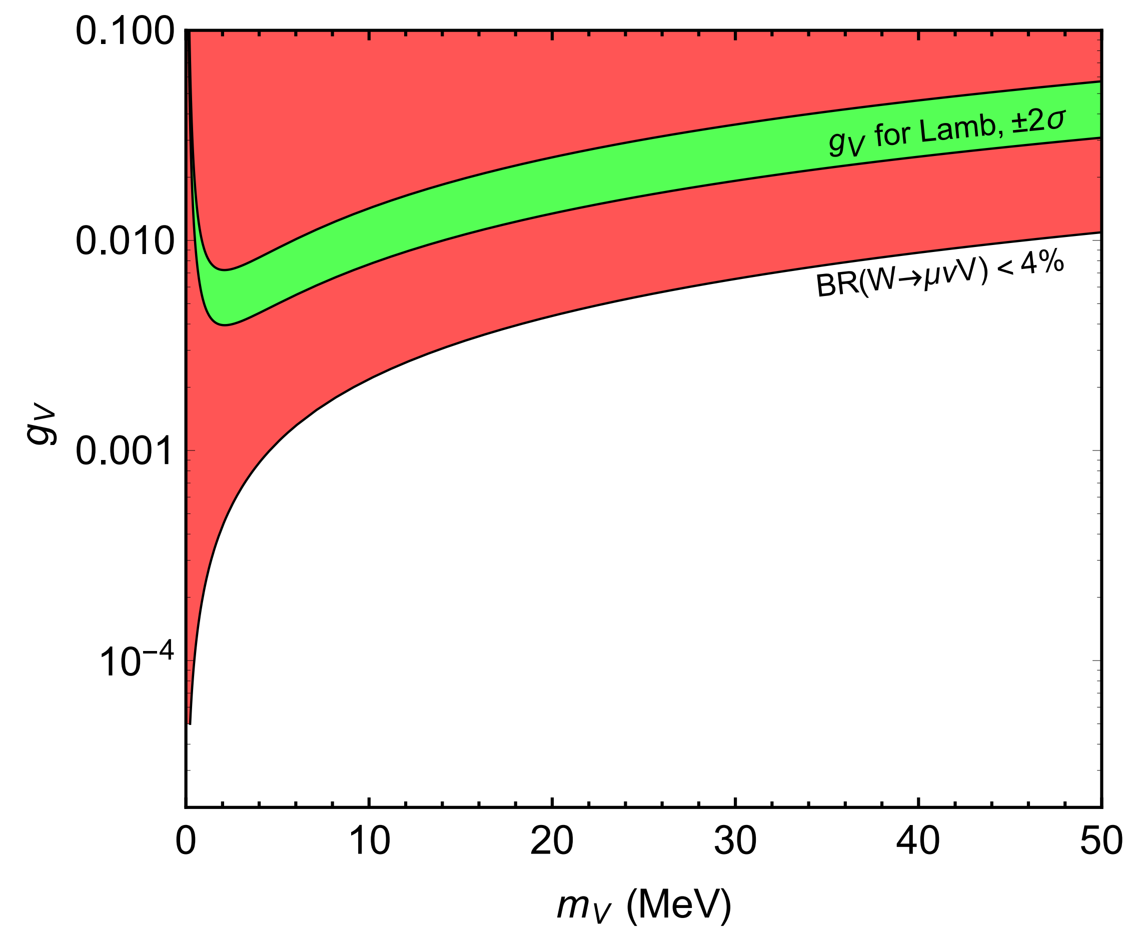
- Come from "other muon processes,"
  1. Radiative corrections to W-decay
  2. Non-effect in He

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.

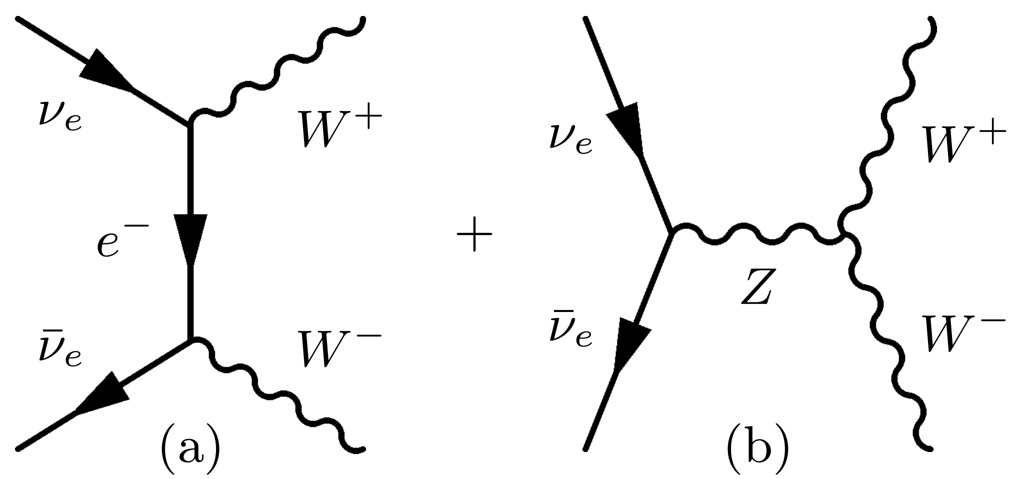




Red: forbidden
Fig. based on
Karshenboim et al. (2014)

W decay

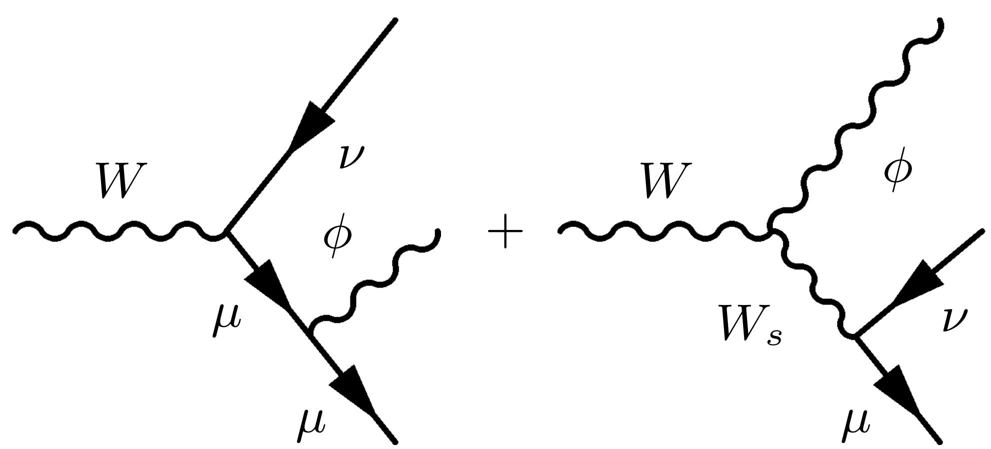
- Reminiscent of (from early days of W.S. model),



- 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 μ-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

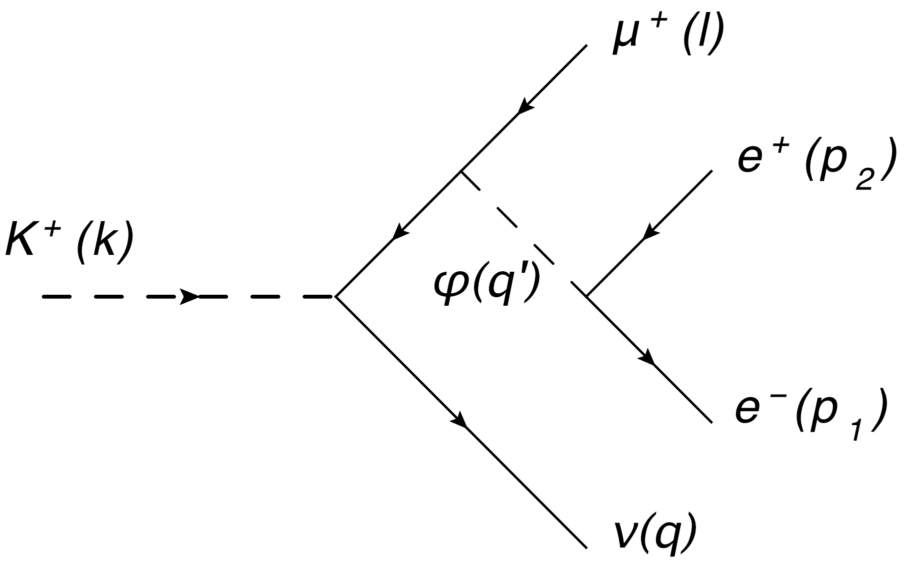
- Physics: Range of potential is controlled by mass. Light mass, long range, like Coulomb potential, does not split S and P states.

- 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.

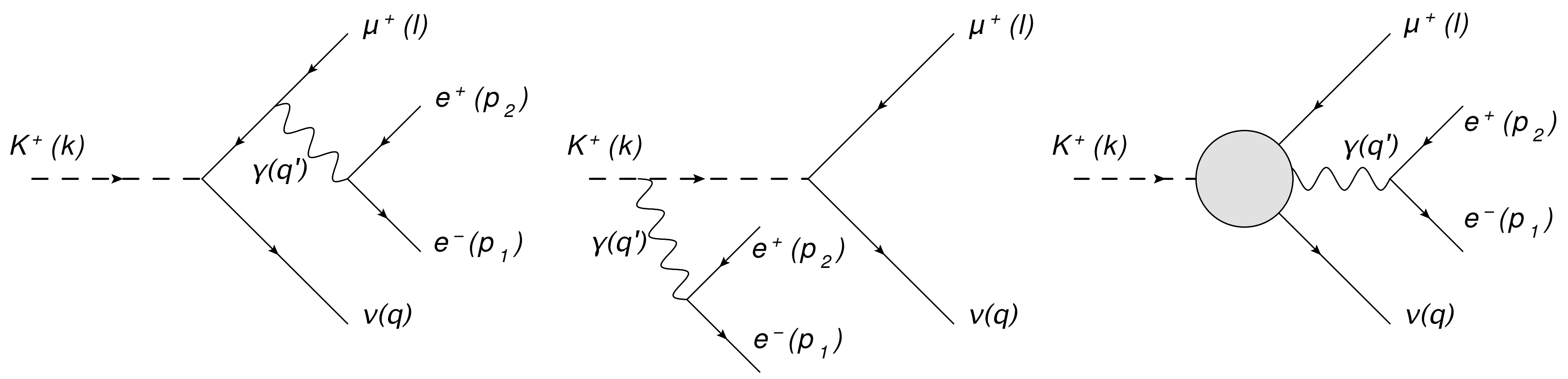
- Quick bottom line: Get result for proton big enough and for He small enough if $m_\phi \approx 1$ MeV.

New force seen elsewhere?

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



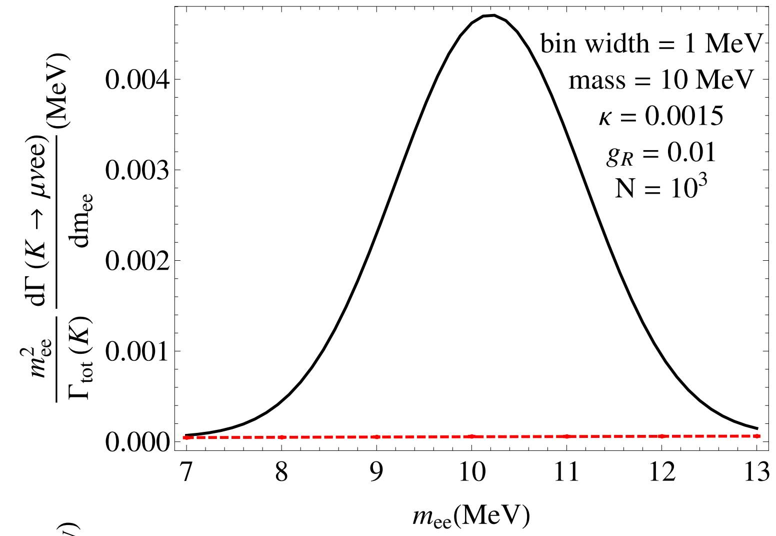
- Of course, QED gives same final state, with smooth (calculable) spectrum of e^+e^-.

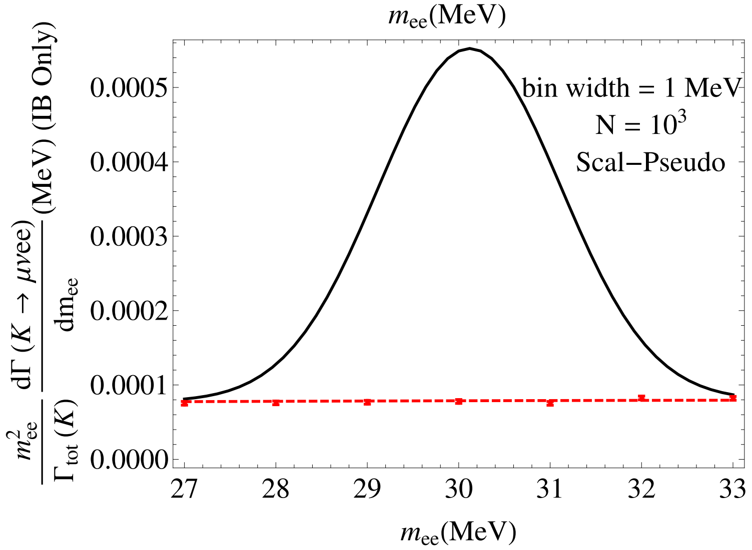


φ visible?

- φ (new BSM particle) will give bump. Size calculable.

- Is it observable? Wow, Yes. (If it exists.) [Red = QED background, solid = bump from φ]

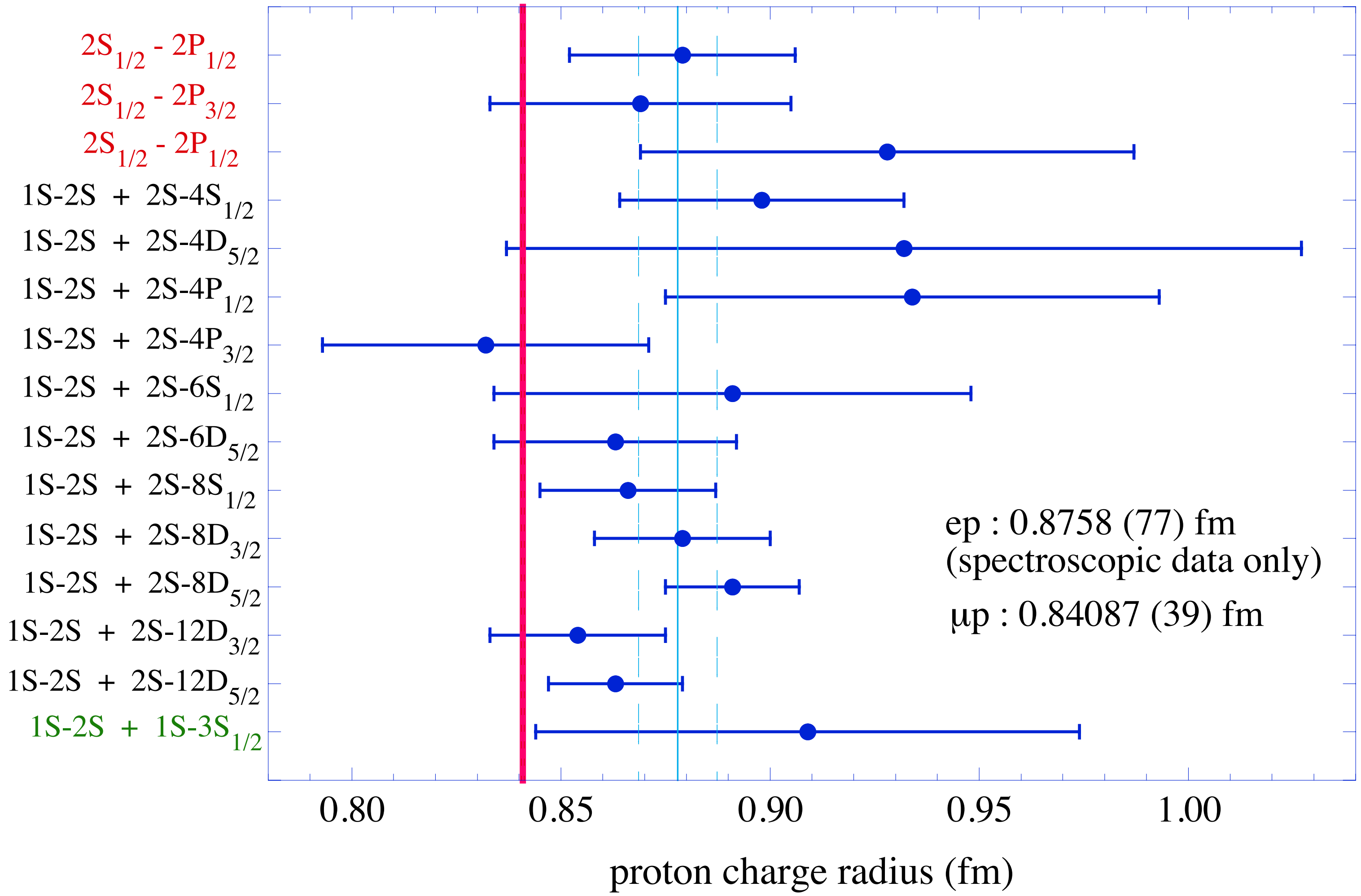




- Note: TREK experiment (E36) at JPARC (Japan) will observe 10^{10} kaon decays, or about 200,000 $K \to \mu\nu e^+e^-$ events, about 1000 per MeV bin in the mass range we are considering. (Thanks to M. Kohl)

Plots from Rislow and me (2014)

Back to atomic spectroscopy



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

Short term future

- 3+ independent groups are doing more precise experiments that will individually get the proton radius to under 1%.
  - York University (Canada): Ordinary hydrogen $2S$-$2P$ Lamb shift
    ("We have run into some systematic effects that we want to understand better")
  - MPI Quantum Optics (Garching): $2S$-$4P$ 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): $1S$-$3S$ transition
    ("…In parallel, we have another failure with a RF amplifier, we put another which has failed after sone 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.")
  - + National Physical Lab (U.K.), several 2S–nS,D transitions
- Under way, may see results soon. Will be important, one way or another.

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

  $R_E = 0.899(3)$ fm.

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

  $R_E = 0.895(20)$ fm.

- Arrington & Sick found

  $R_E = 0.879(11)$ fm.

But…

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

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

- Horbatsch and Hessels (1509.05644)

- Carlson, Griffioen, Maddox (1509.06676)

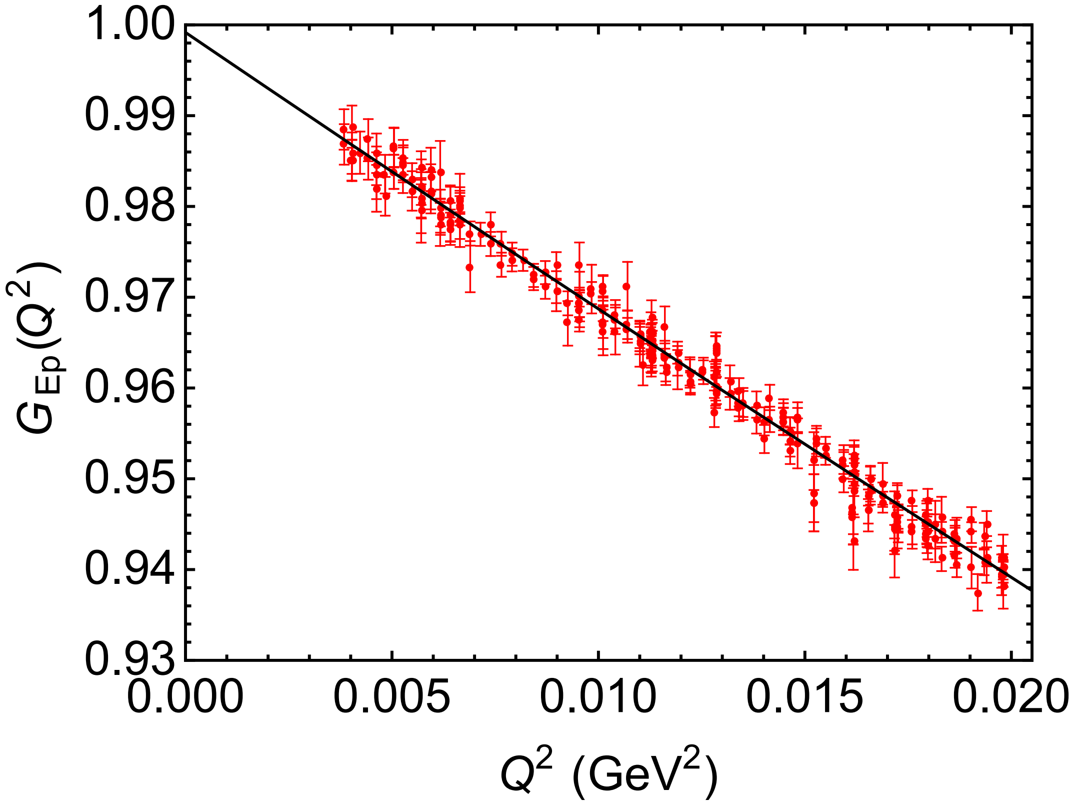
- Higinbotham, Kabir, Lin, Meekins, Norum, Sawatzky (1510.01293)

Contrarian view

- Two "low" values of R_E from *e-p* scattering data

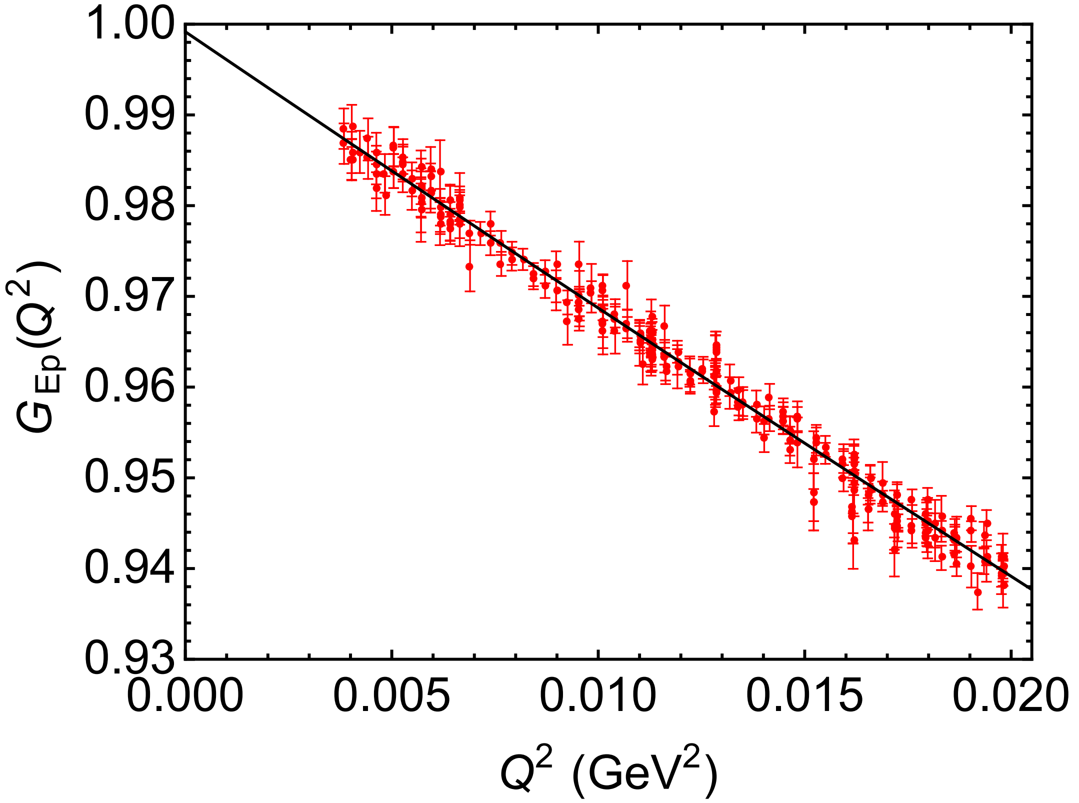
- Lorenz, Meißner, Hammer, & Dong (2015), using dispersive ideas to obtain their fit functions, and also using timelike data, obtained
  $R_E = 0.840(15)$ fm.

- Griffioen, Maddox, and me (1509.06676) believe that one should be able to obtain accurate R_E from just lower-Q^2 data, finding
  $R_E = 0.840(16)$ fm.



Recent *e-p* analyses, I

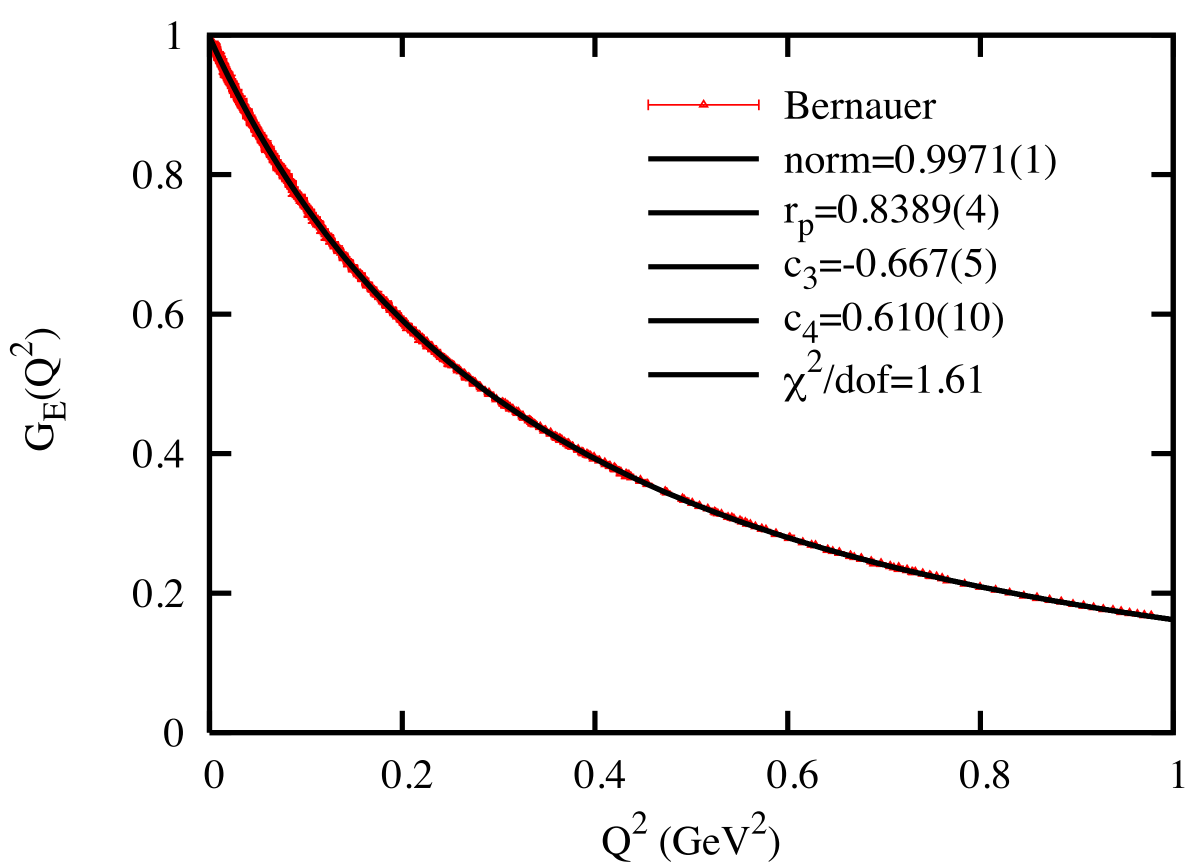
- Maddox et al. (1509.06676)
- Viewpoint: Form factor is analytic function of Q^2, except for cut starting at $4m_\pi^2$. Hence, polynomial expansion in Q^2 converges for $Q^2 < 4m_\pi^2$.
- Fit low Q^2 data,
  $Q^2 < 0.02$ GeV^2
  (243 data points)
  linear plus quadratic in Q^2 ,
  got $R_E = 0.850(19)$ fm



Recent *e*-*p* analyses, I

- Also fit whole Mainz 2010 data set with simpler functions (i.e., 4 or so parameters), that extrapolate 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)

- One contribution: resurrecting Saskatoon 1974 and Mainz 1980 data. Excellent data.
  Overlap region, $0.005 < Q^2 < 0.03$ GeV^2.

- Emphasized correlations among fit parameters

- Used statistical arguments for accuracy of linear fits in this data range

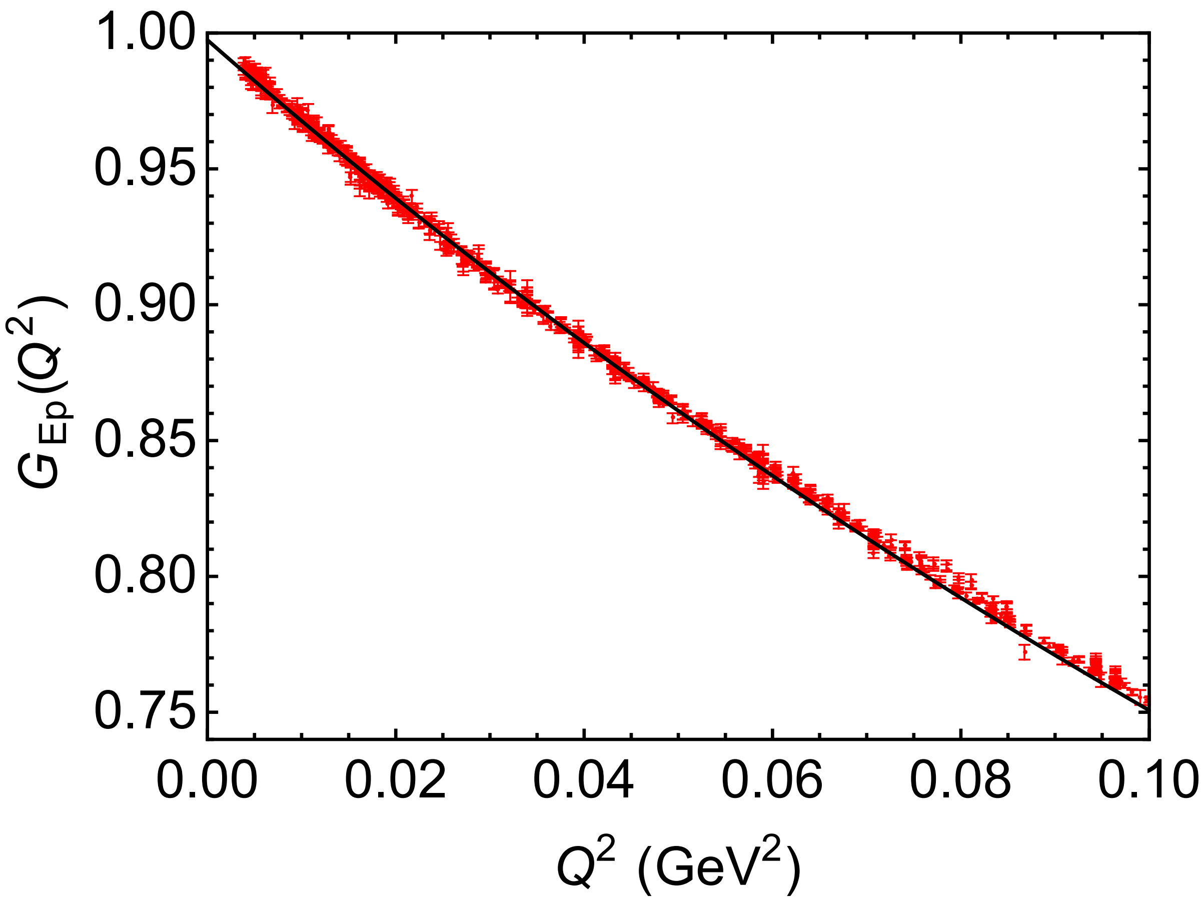
- Obtained R_E compatible with muonic atomic data, 0.84 fm

Recent *e*-*p* analyses, III

- Horbatsch and Hessels (1509.05644)
- 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.

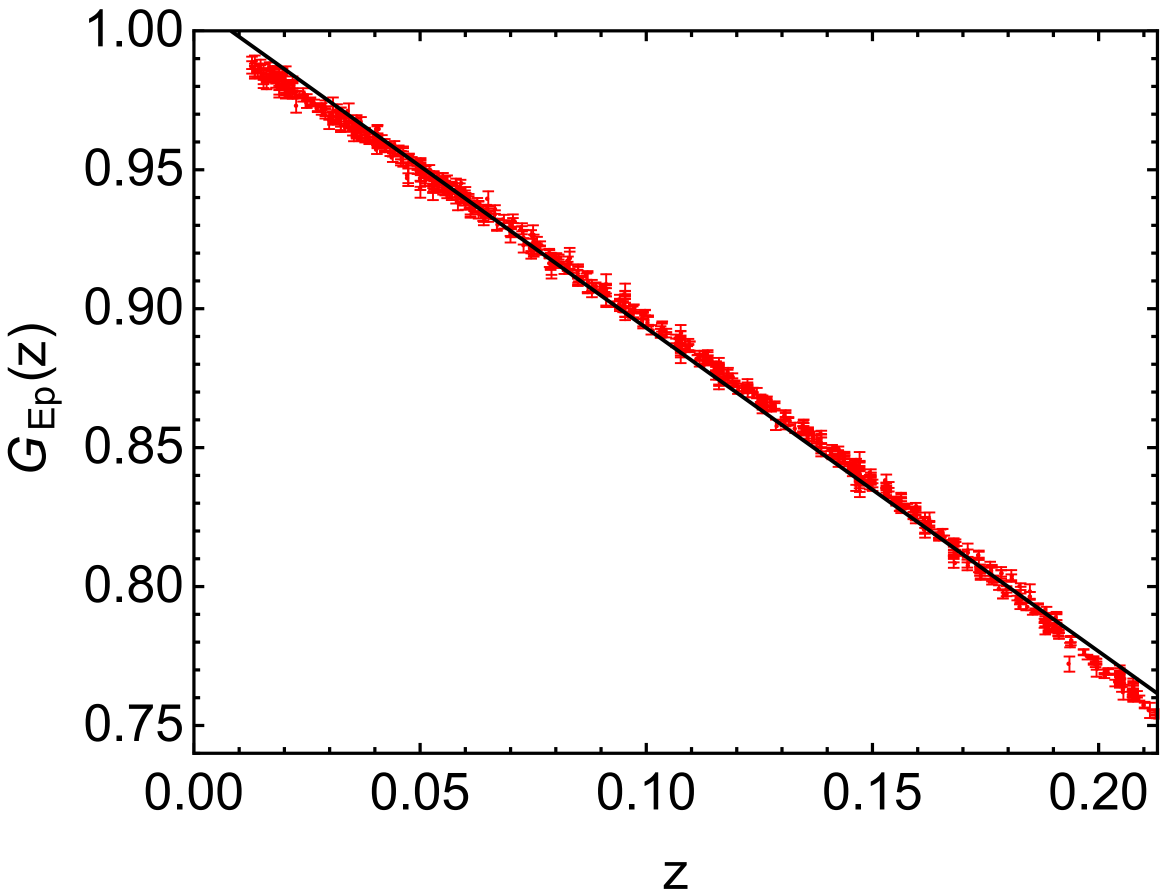
- dipole fit: $G_E = (1 + R_E^2\ Q^2\ /12)^{-2}$, similarly for G_M
- Got R_E = 0.842(2) fm and R_M = 0.800(2) fm
- Fits look o.k.



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
- Fit data with 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.

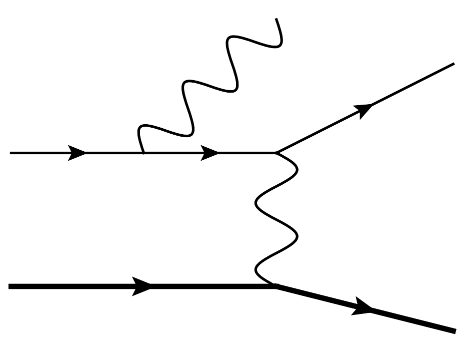


- Fit looks not good
- This is $Q^2 < 0.1$ GeV^2 data
- Concavity when plotted in this variable not well fit by linear polynomial
- Overly large R_E not surprise
- (Plot is mine; theirs would look better, but principal problem remains. Can explain.)
- My take-away 1: should include z term if doing this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

Scattering future

- 3 further experiments lower lowest Q^2, and one will do μ scattering

- PRad at JLab: Just target and detector screen, allowing very small scattering angles. Anticipate $Q^2|_{low} \approx 0.0002$ GeV^2. Hope running soon. (H. Gao talk here.)



- ISR (Initial State Radiation) at Mainz. Photon radiation takes energy out of electron, allowing lower Q at given scattering angle. Anticipate $Q^2|_{low} \approx 0.0001$ GeV^2. Data taken, more data to be taken; under analysis. (M. Mihovilovic talk here.)

- MUSE = Muon scattering experiment at the PSI. Anticipate $Q^2|_{low} \approx 0.002$ GeV^2. Production runs 2017/2018. (G. Ron talk.)

Reminder: new data coming

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

count 13 items,
10 new, some
maybe out this year

Ending

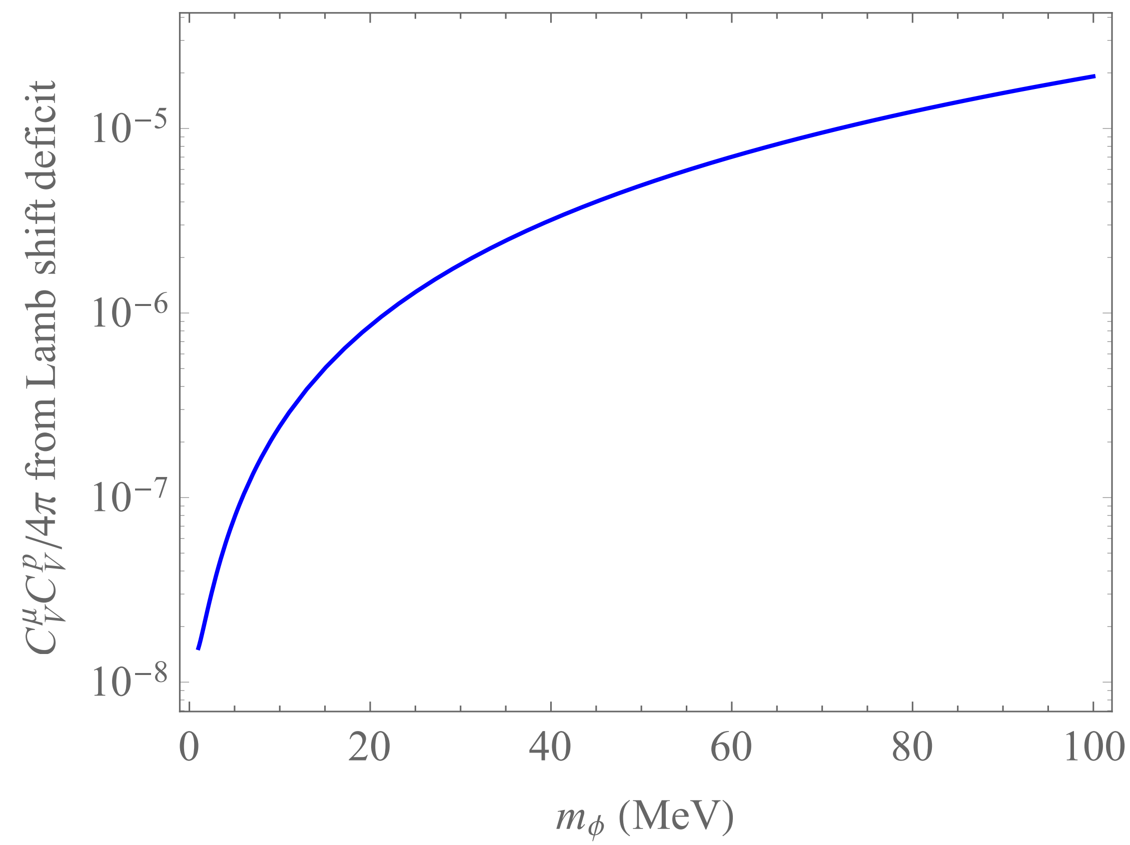
- Remarkable: 5 years after the first announcement, the problem persists.
- Interestingly little discussion of the correctness of the μ-H Lamb shift data.
- Serious and good new data coming.
- Opinion: Either
  - All radii correct, and BSM—muonic specific force—is explanation despite problems, or
  - 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!

Extras

True-muonium

- Reminder: for BSM particle, muonic-H Lamb shift energy deficit implies couplings given mass



- True muonium = $\boldsymbol{\mu}$-$\boldsymbol{\mu}$ bound state. From QED,

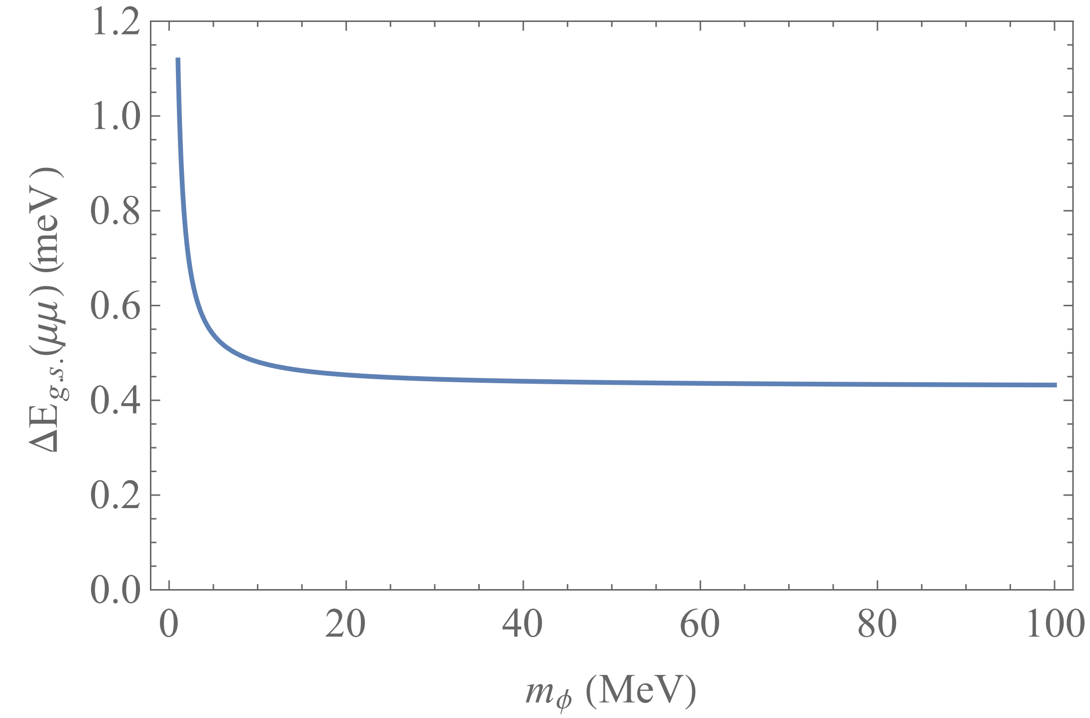
$$E_{g.s.} = \frac{1}{4} m_\mu \alpha^2 = 1.41\ \mathrm{keV}$$

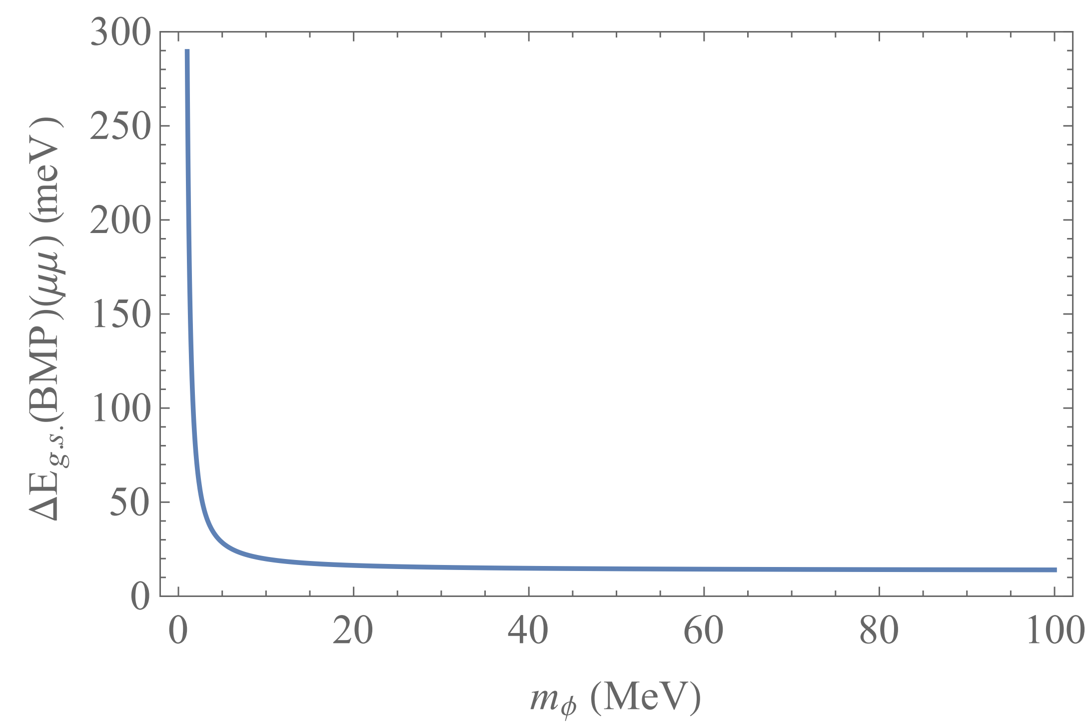
- Extra $\boldsymbol{\mu}$-specific exchange modifies binding.

True-muonium

- For muon-specific BSM exchange shifts to the g.s. energy, if $C_V^\mu = C_V^p$ (Rislow and me), get shifts about ppm.

- More striking are asymmetric couplings from Batell *et al.*/ Karshenboim *et al.*



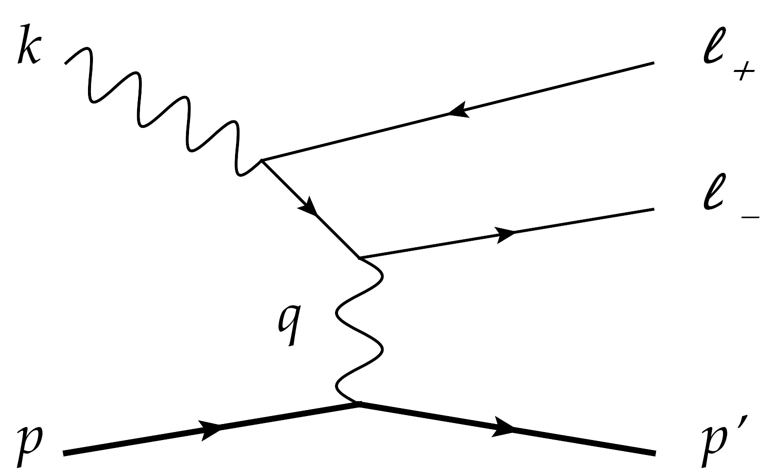


(footnote for me)

- Karshenboim *et al.* have coupling to proton that is dark photon, so same magnitude as to electron. Then get constraints on electron coupling from disturbance to $(g\text{-}2)_e$.

New force seen elsewhere?

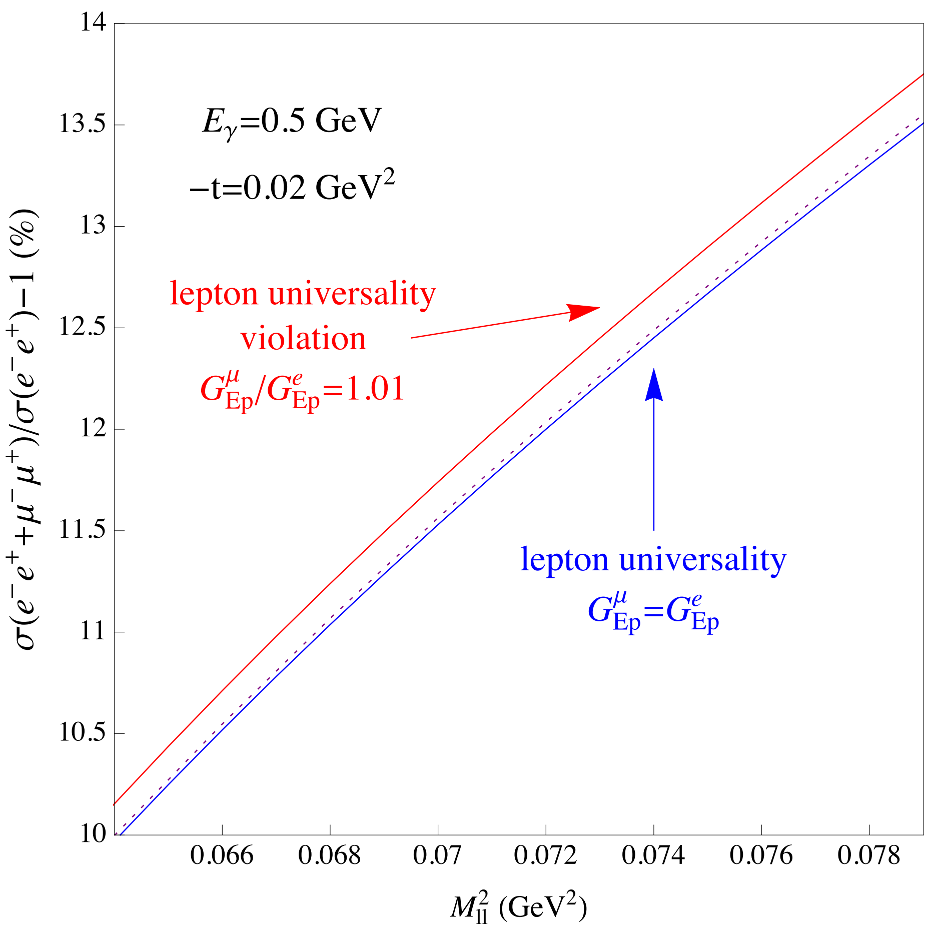
- Recent suggestion: *μ-p* scattering at JLab or Mainz *a.k.a.*, lepton pair photoproduction, $\gamma\, p \rightarrow \ell^+\, \ell^-\, p$. (Pauk & Vanderhaeghen, 2015)



- Extra force, even coupling only to *μ* and *p* will affect muons production. Get normalization by comparing $\mu^+\mu^-$ to e^+e^- production.

- Believe 2% measurement will show effect of extra force consistent with proton radius conflict.

$\gamma\, p \rightarrow \ell^+\, \ell^-\, p$



- Gap between lines corresponds to difference in G_{Ep} suggested by electron- and muon-measured charge radii at Q^2 of 0.02 GeV^2.

- Contribution from timelike Compton process small at this kinematics