The Proton Radius Puzzle

Carl Carlson
William and Mary

QCD for New Physics at the Precision Frontier
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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

      - Somebody screwed up

   B. Exotic explanations

      - Will discuss: Physics Beyond the Standard Model (BSM)

      - Will mention: other possibilities later

3. Highlight: List of coming relevant data

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 (and with more data coming), *μ*-*p* scattering in preparation

e-*p* scattering

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

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

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

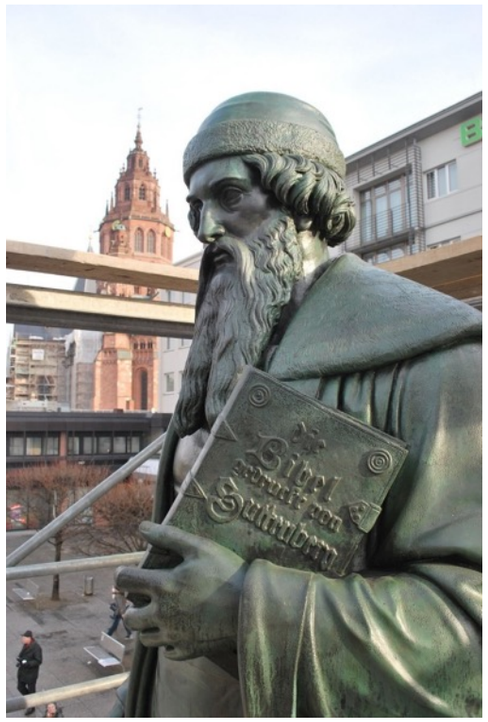
- Low Q^2, mainly sensitive to G_E.

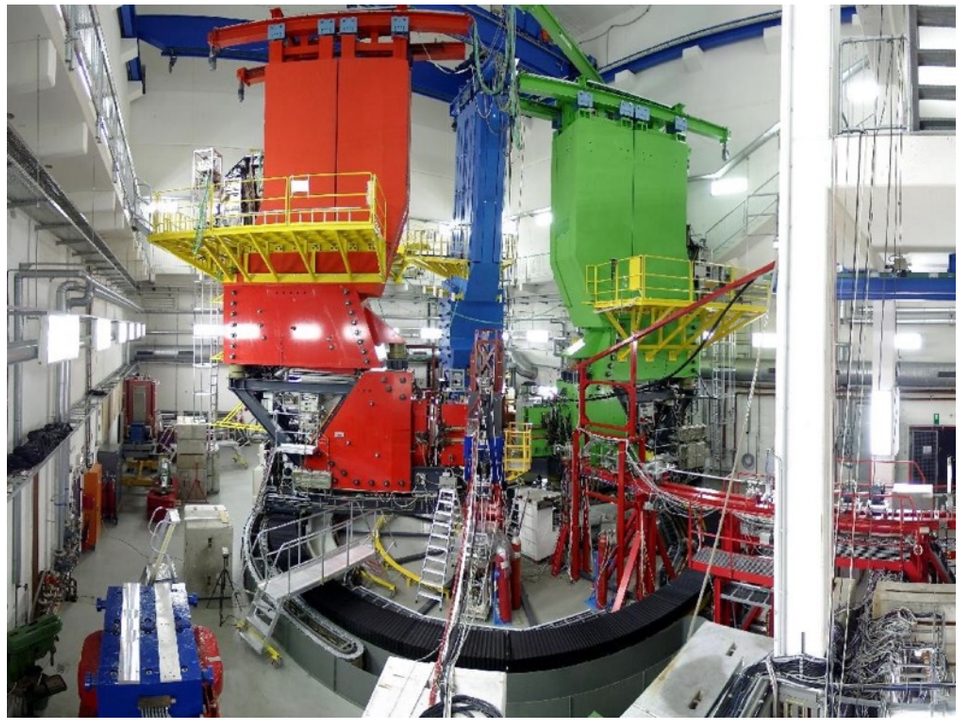
- Extrapolate to $Q^2 = 0$, whence

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

Low-Q^2 scattering data

- Mainz has Gutenberg plus an electron accelerator





- Great data, Jan Bernauer *et al.*, PRL 2010 (and later articles).

- Q^2 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

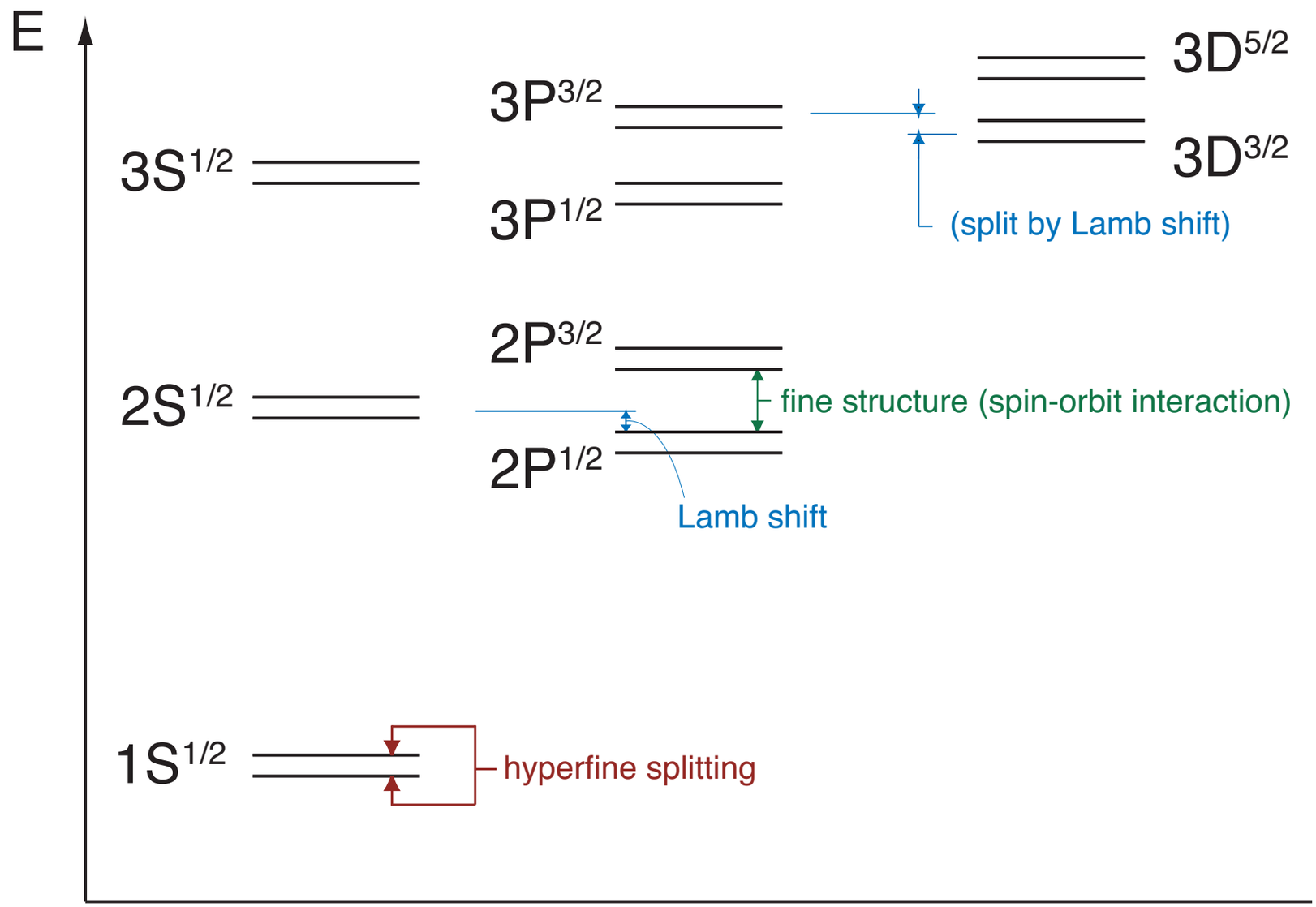
- plus finite size proton, pushing energy upward a bit.

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

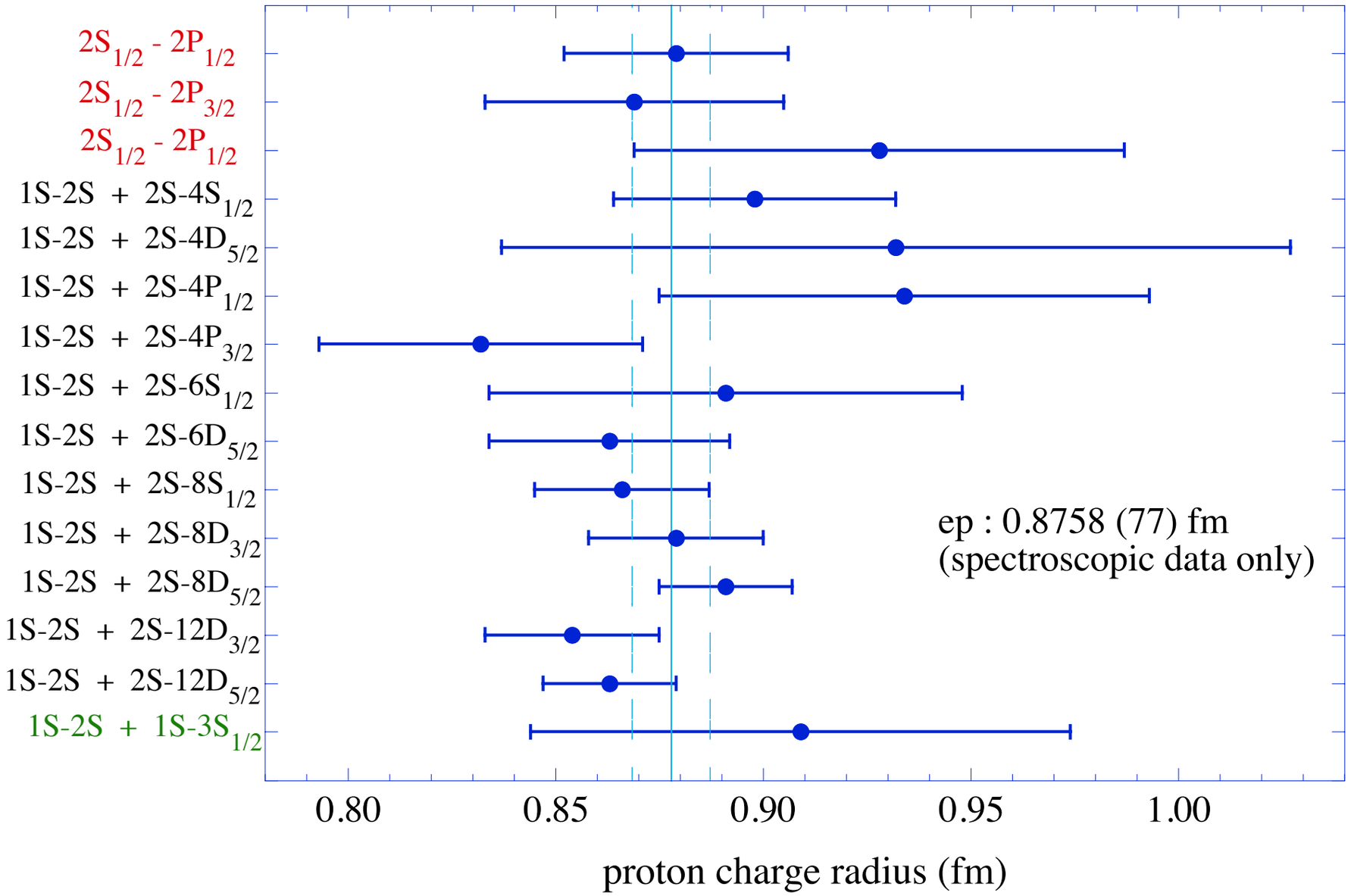
fine print: $\phi_{nS}^2(0) = (m_r \alpha)^3/(n^3\pi)$

measure energy accurately
$\Longleftrightarrow$ measure radius

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



Atomic results



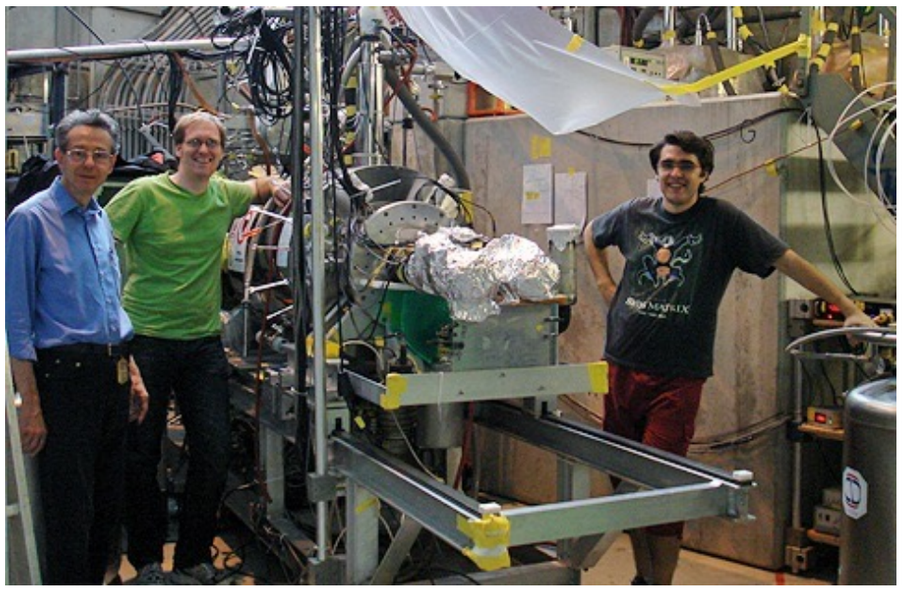
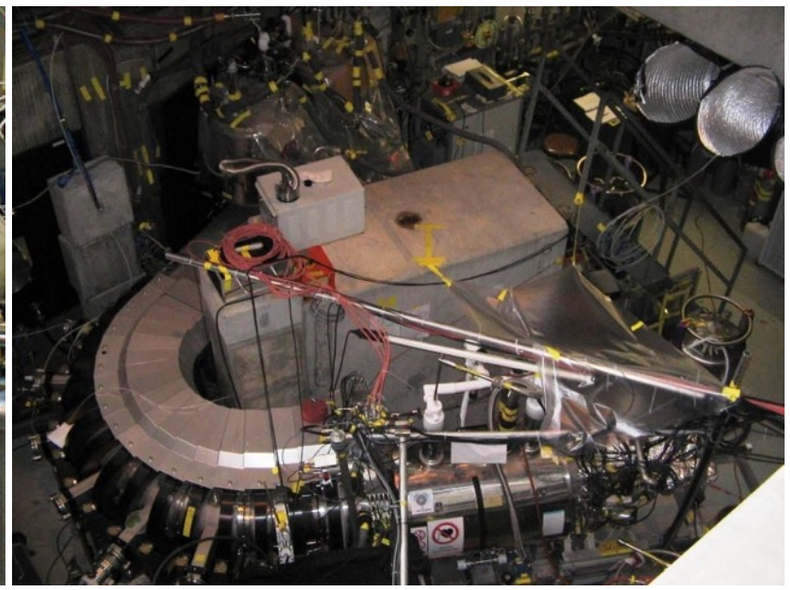
All electron results

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

$$R_E = 0.8775(51)\,\mathrm{fm}$$

Then came 2010

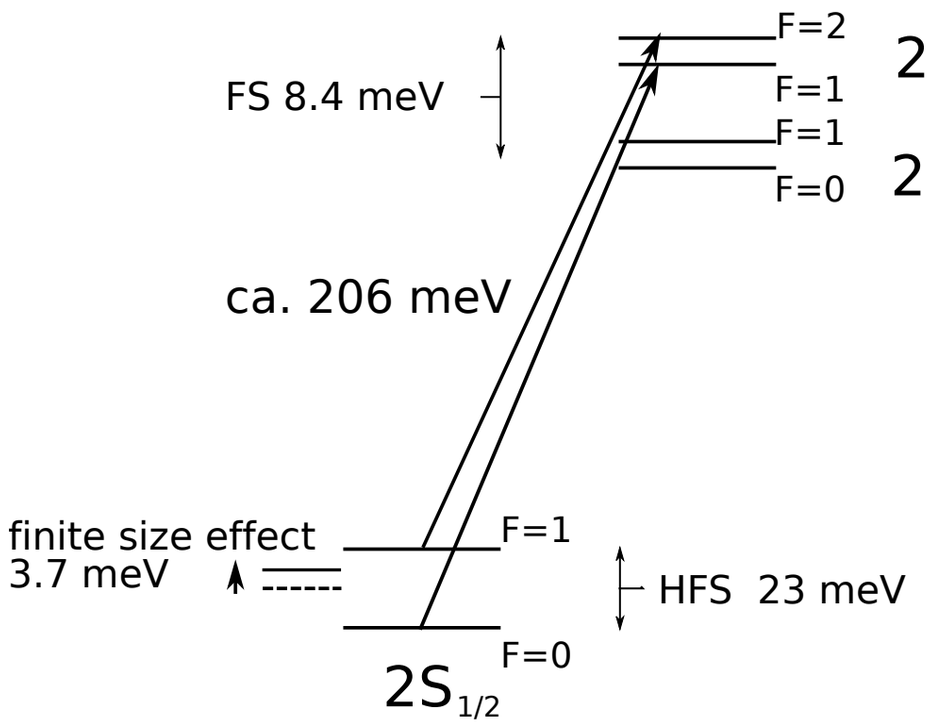
- CREMA = Charge Radius Experiment with Muonic Atoms


- Did atomic physics, specifically Lamb shift, with muons (muon= electron, but weighs 200 times more).
- Orbits 200 times closer: proton looks 200 times bigger
- Goal: measure proton radius with factor 10 smaller uncertainty

CREMA

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



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

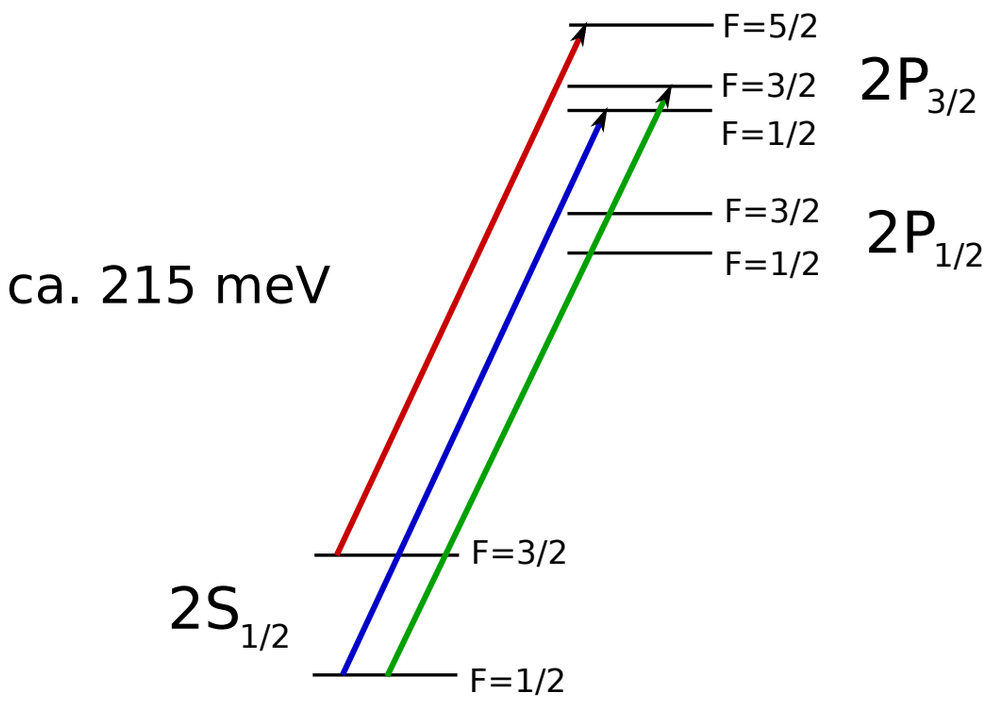
- Interpreting finite size effect in terms of proton radius,

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

- 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
- μ-^{4}He at Mainz Proton Radius Workshop, 2014
- μ-^{3}He at Gordon Conference, N.H., 2014
- Quick summary: He radii from μ Lamb shift <u>in accord with</u> electron scattering radii.

Explanations?

- Hard to see problems with μ 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

  $R_E = 0.899(3)$ 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.

Contrarian view

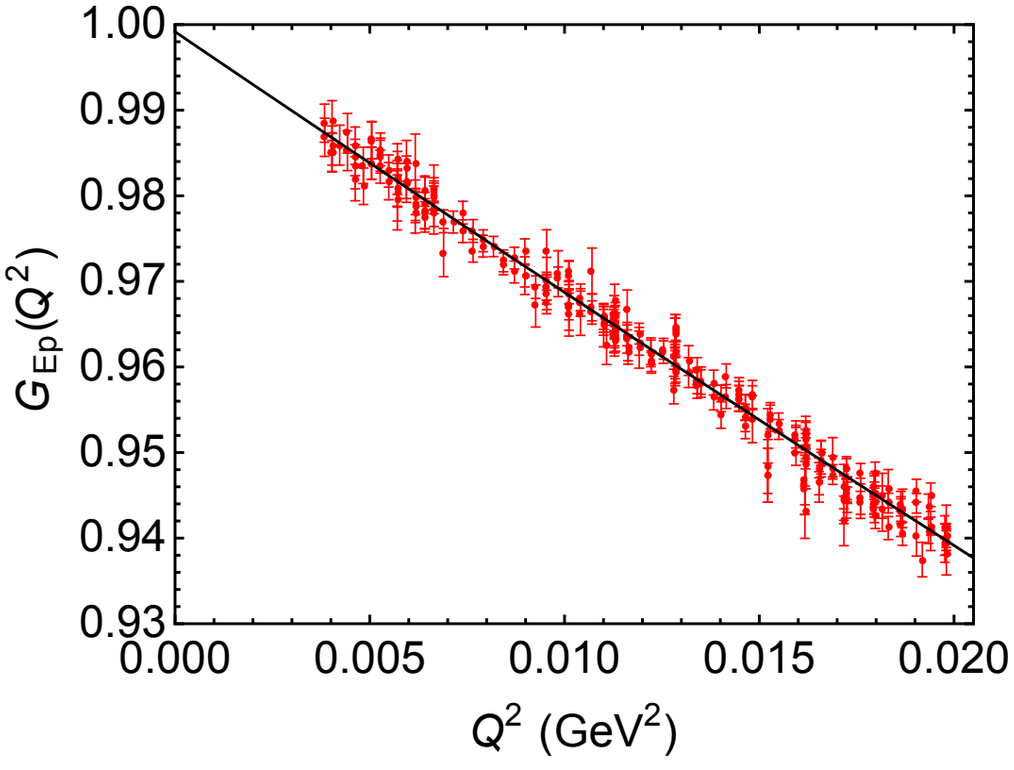
- Two “low” values of R_E from *e-p* scattering data

- 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.



Further remarks

- 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 $Q^2 < 4m_\pi^2$.

- Do so. Keep enough terms so χ^2 acceptable but few enough so that each term is well determined.

- Obtain “low” proton radius.

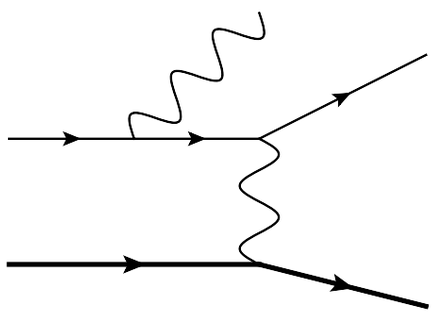
- Detail: Use the 243 data points for $Q^2 < 0.02$ GeV^2, got $G_E = 1 - Q^2 (0.850(19)\text{ fm})^2/6 + Q^4 (4.5(5.6))\text{ GeV}^4$.

- See Griffioen, Maddox, and me.

Scattering future

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

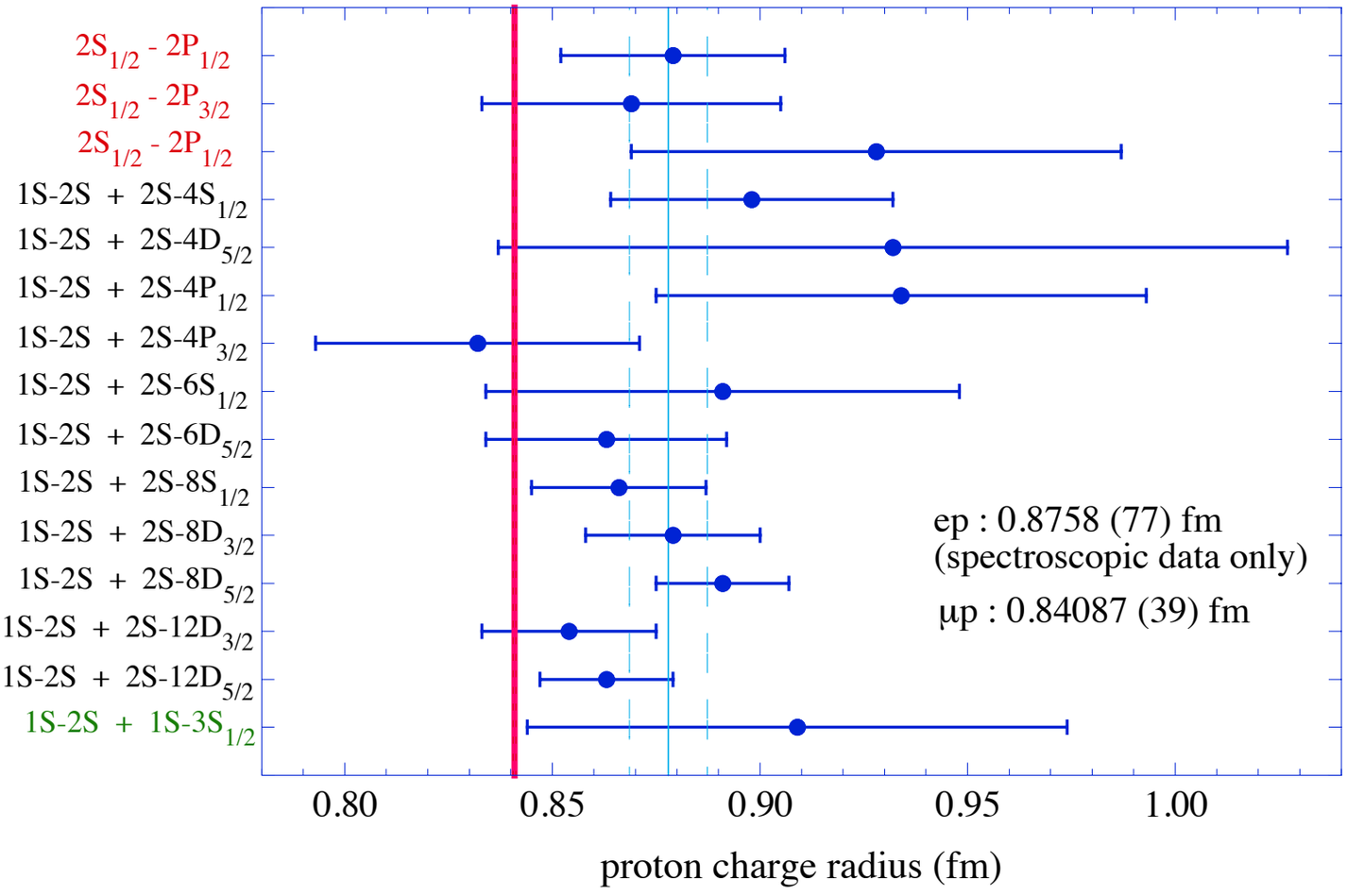
- PRad at JLab: Just target and detector screen, allowing very small scattering angles. Anticipate $Q^2|_{low} \approx 0.0002$ GeV^2. Hope running soon.



- 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.

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

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 2*S*-2*P* Lamb shift
  - MPI Quantum Optics (Garching): 2*S*-4*P* transition
  - Laboratoire Kastler Brossel (Paris): 1*S*-3*S* transition
  - + National Physical Lab (U.K.), several 2S–*nS*,*D* transitions
- Under way, may see results soon. (All had hoped for delivery before end of 2014.)

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

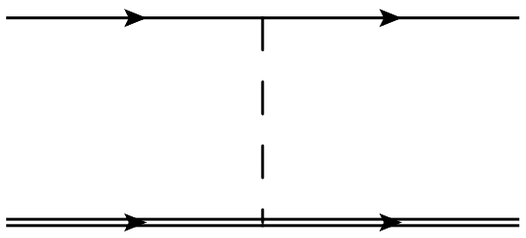
- Point: Experimenters do not directly measure proton radius. Measure energy deficit, 320 μeV. Interpret as proton radius deficit.

- 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.

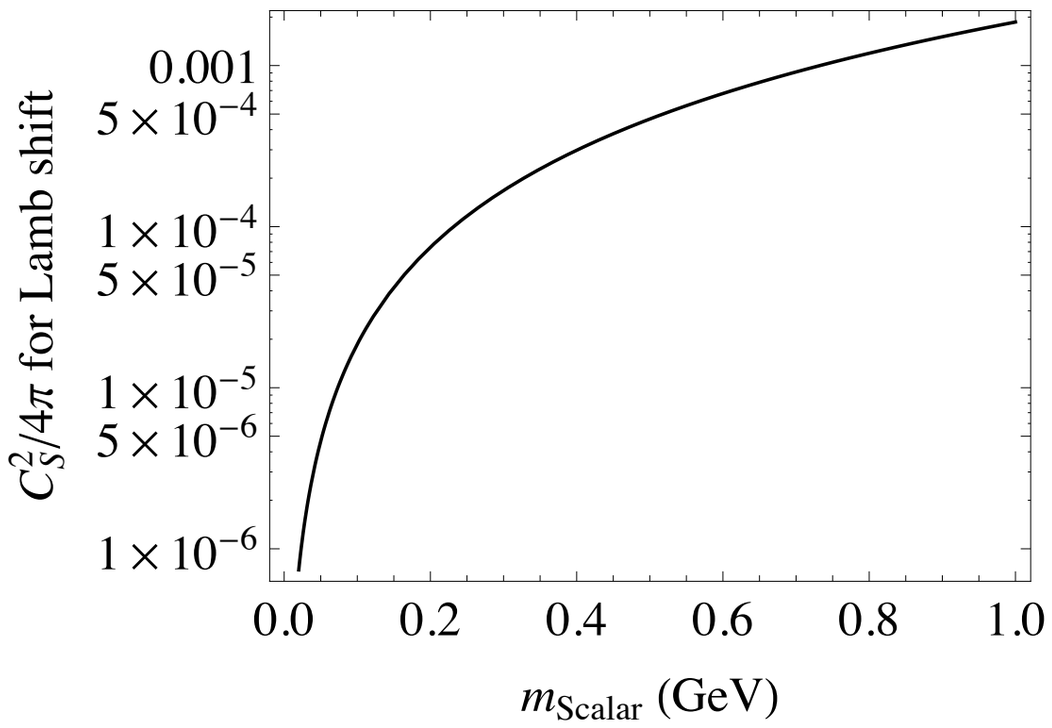
Energy shift

- 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

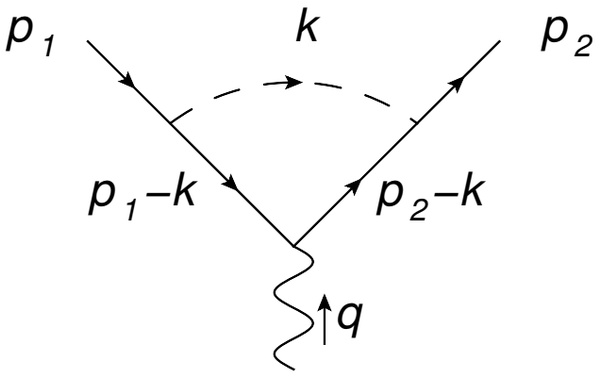
- Worry about other processes where new particle couples to muons. *First:*

  - Loop corrections to μ magnetic moment

  - (Reminder: 3 σ discrepancy between measured and standard model calculated $(g\text{-}2)_\mu$.)

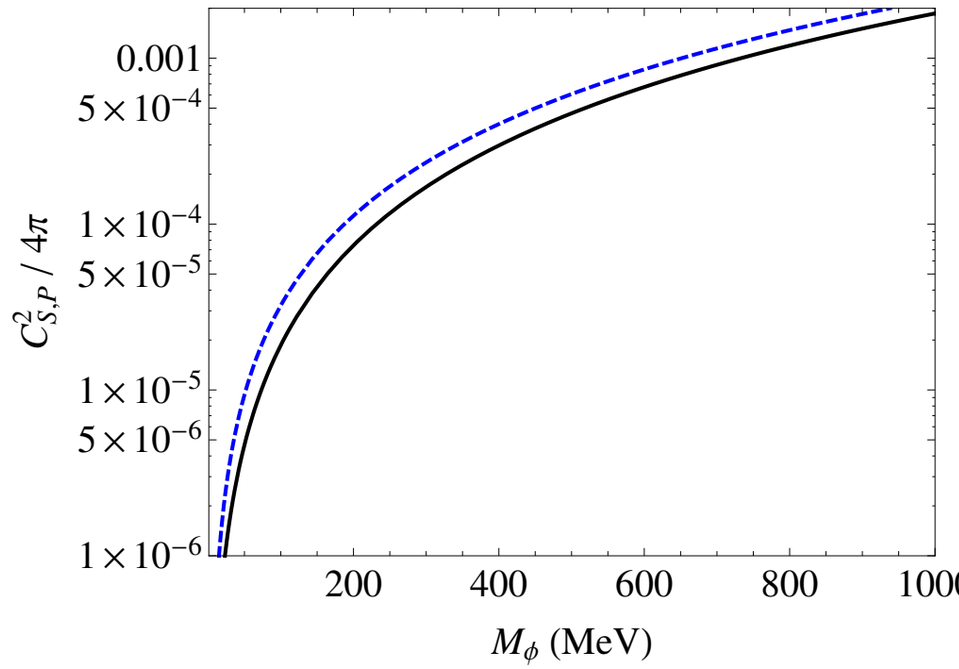
  - If new exchange particle light, effect on $(g\text{-}2)_\mu$ small enough (Tucker-Smith & Yavin). Otherwise, need to fix by fine tuning.

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)



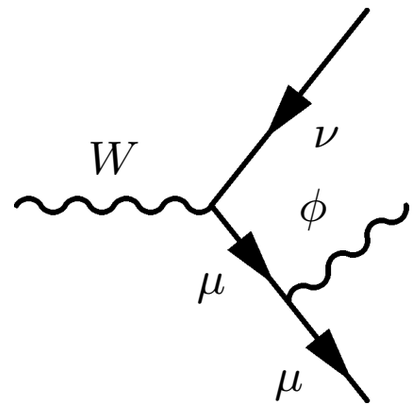
- Above for scalar-pseudoscalar
- Low enough mass, cancellation not needed (TSY)
- Couplings now fixed, albeit mass sensitive.
- ∴ Predictions for other processes now fixed.

BSM problems

1. Radiative corrections to W-decay

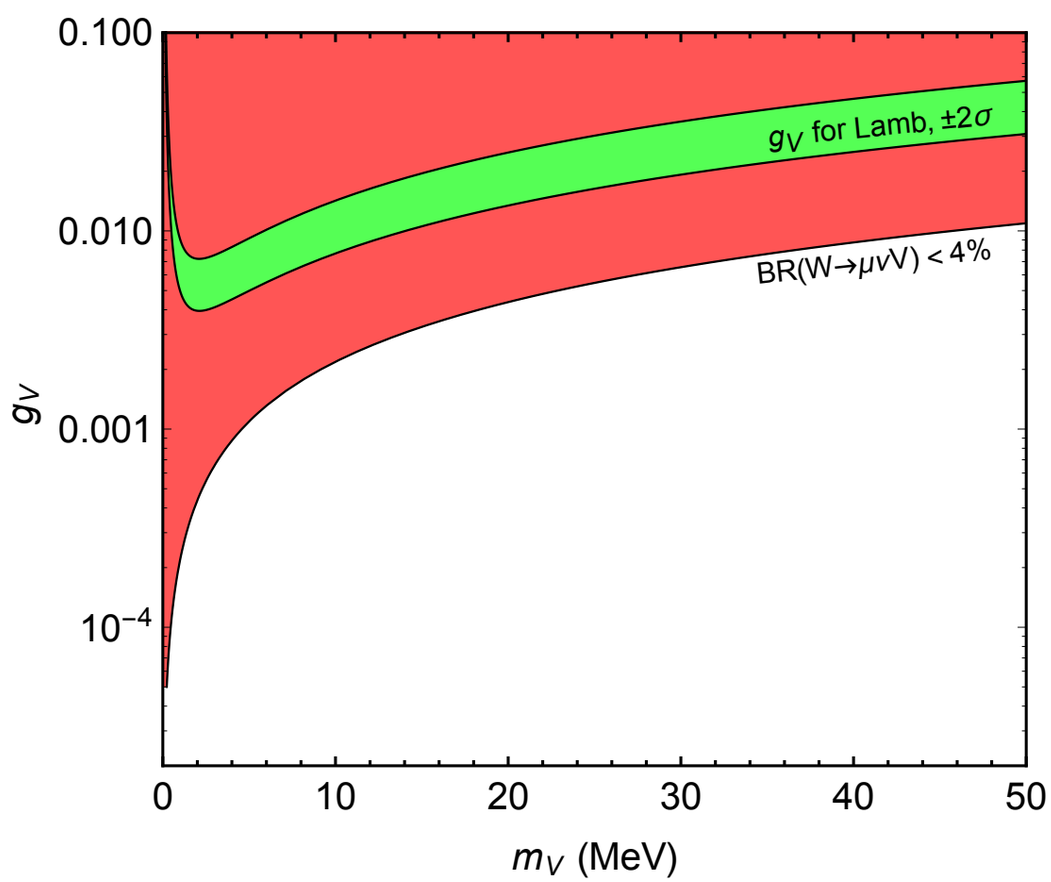
2. Non-effect in He

W decay



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

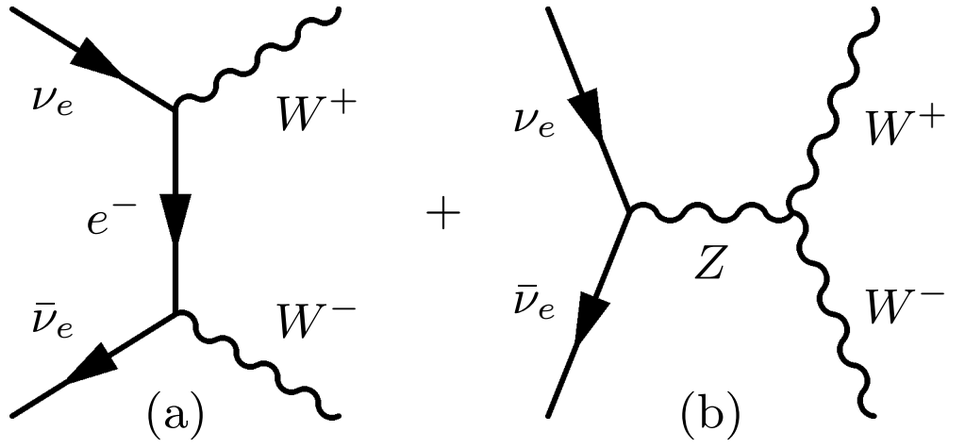
- If light new particle ϕ *or V* coupling to muon, it gives large radiative correction to *W* decay via $W \to \mu\nu V$, larger than measured error in *W* decay rate.



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

W decay

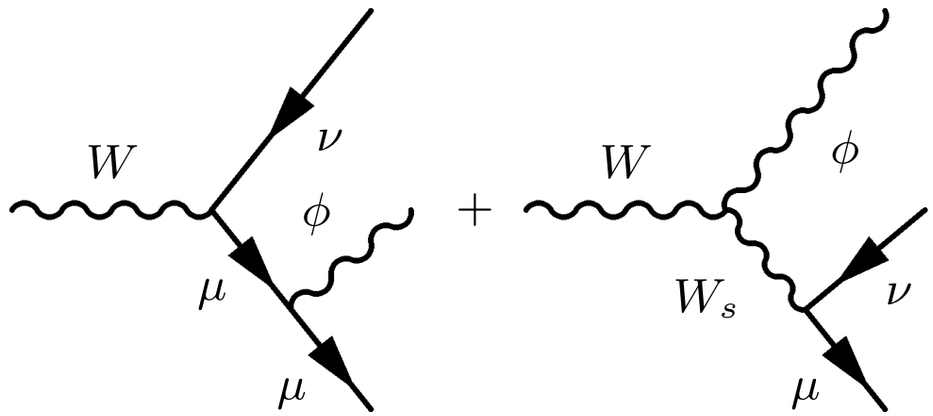
- Reminiscent of (from early days of W.S. model),



- 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

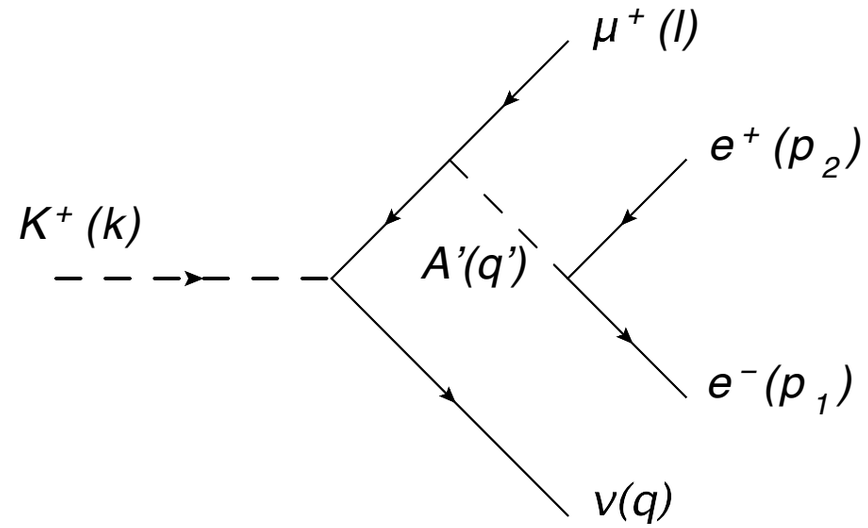
- Physics: Range of potential is controlled by mass. Light mass, long range, like Coulomb potential, does not split S and P states.

- 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.

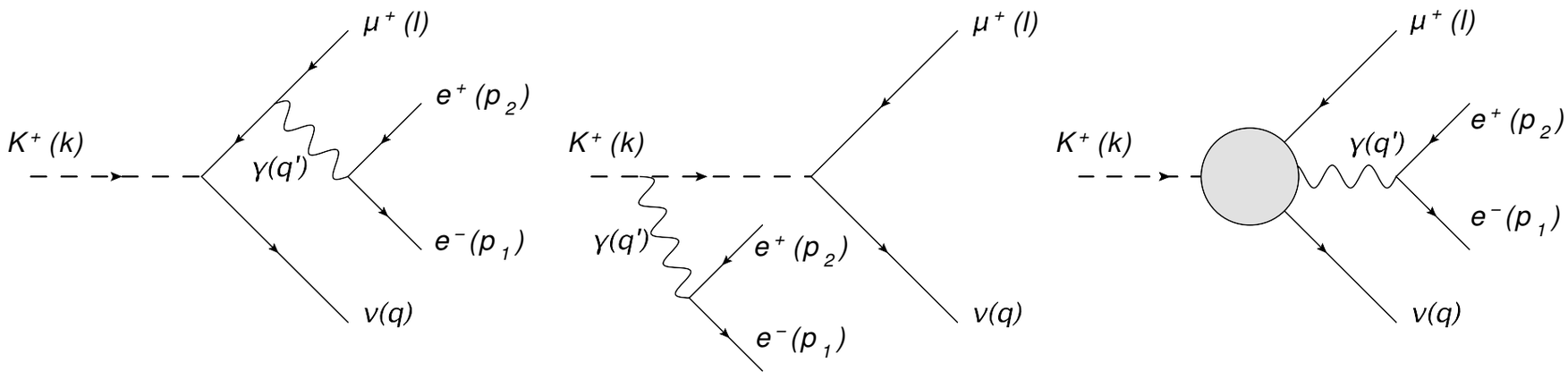
- Quick bottom line: Get result for proton big enough and for He small enough if $m\phi \approx 1$ MeV.

New force seen elsewhere?

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

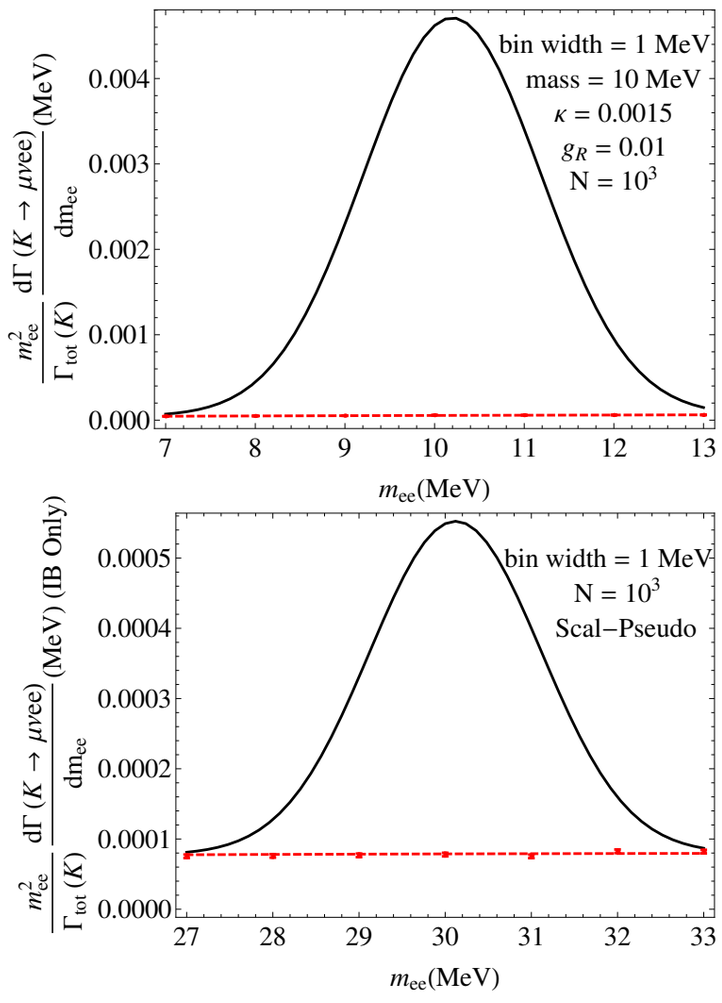


- Of course, QED gives same final state, with smooth (calculable) spectrum of e^+e^-.



A’ visible?

- A’ (name of new particle here) will give bump. Size calculable.



- Is it observable?
  Wow, Yes. (If it exists.)

- 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)

- 3+ atomic energy level measurements
- TREK at JPARC
- Maybe also: Trumuonium ($\mu^+\mu^-$) at JLab

End

- 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.
- One impact: 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!