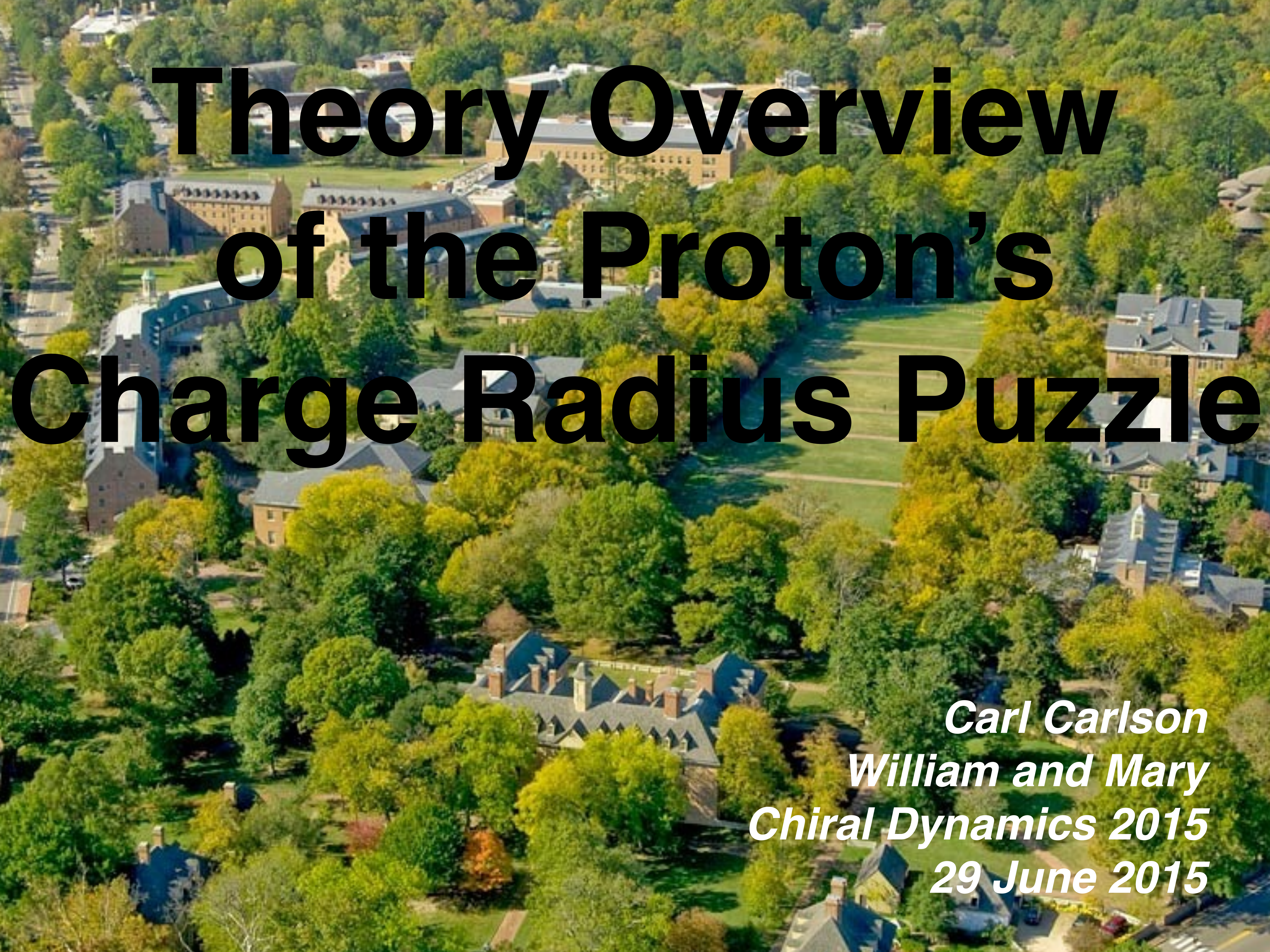


# Theory Overview of the Proton's Charge Radius Puzzle


*Carl Carlson*

*William and Mary*


*Chiral Dynamics 2015*

*29 June 2015*

# 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

      - Physics Beyond the Standard Model (BSM)

3. Highlight: List of coming relevant data

# Measuring proton radius

- Use lepton-proton scattering or use atomic spectroscopy
- Use electrons or muons

| SCORECARD | lepton scattering | atomic energy splittings |
|---|---|---|
| electrons | done—but more coming | done—but more coming |
| muons | not done—but coming | done—one experiment |

# *e*-*p* scattering

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

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

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

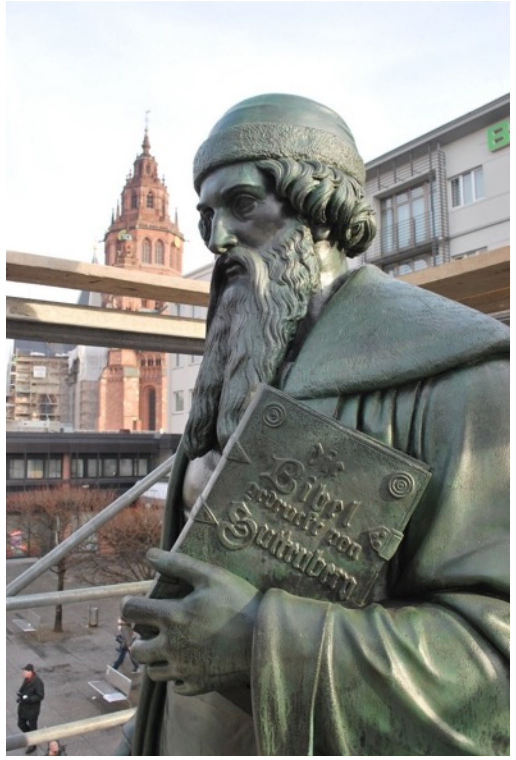
- Low $Q^2$, mainly sensitive to $G_E$.

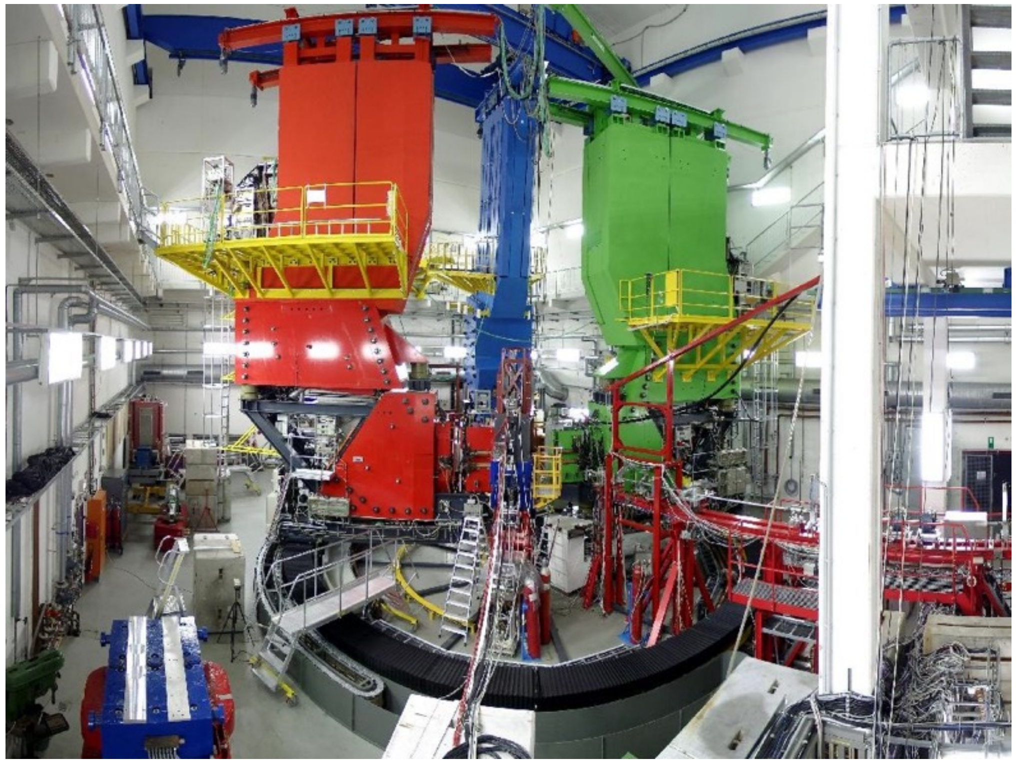
- Extrapolate to $Q^2 = 0$, whence

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

# 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

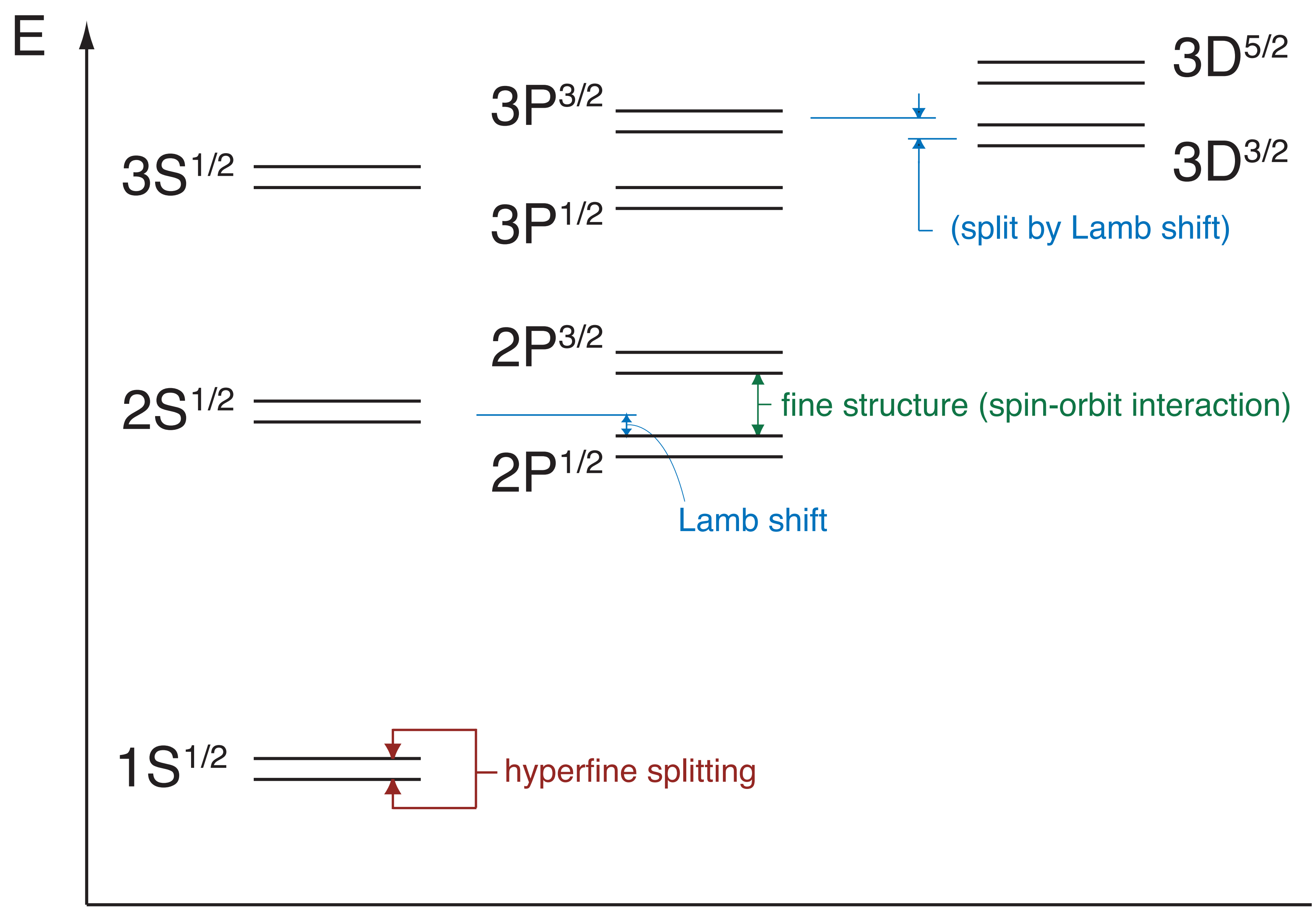
- plus finite size proton, pushing energy upward a bit.

$$\Delta E_{\text{finite size}} = \frac{2\pi\alpha}{3} \phi_{nS}^2(0) R_E^2 \qquad \text{fine print:} \qquad \phi_{nS}^2(0) = (m_r \alpha)^3 / (n^3 \pi)$$

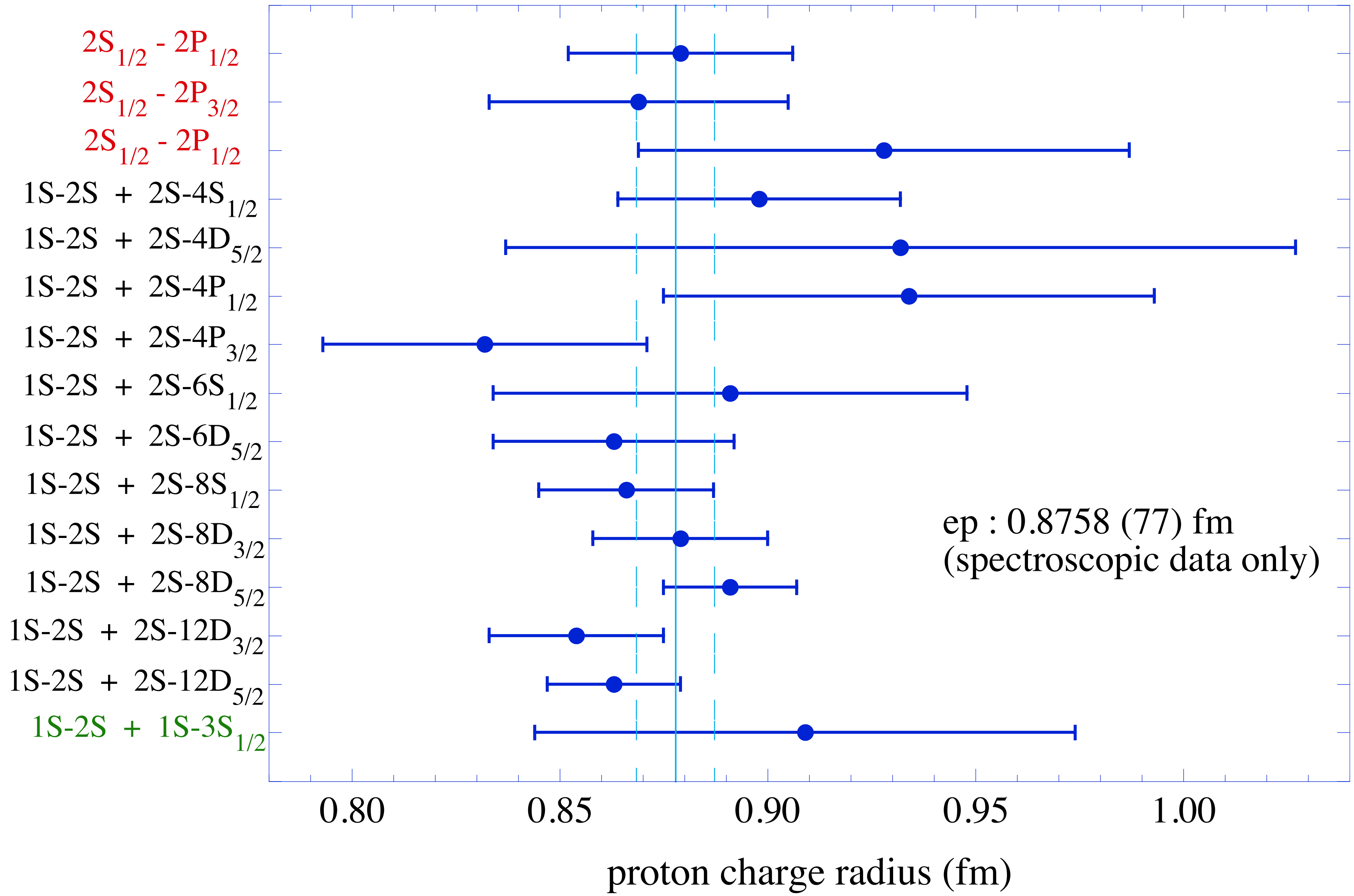
$$\textit{I.e.,} \quad E_{\text{total}} = -\frac{Ryd}{n^2} + \frac{\text{finite size}}{n^3} \delta_{\ell,0}$$

# measure energy accurately $\Longleftrightarrow$ measure radius

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



# Atomic results



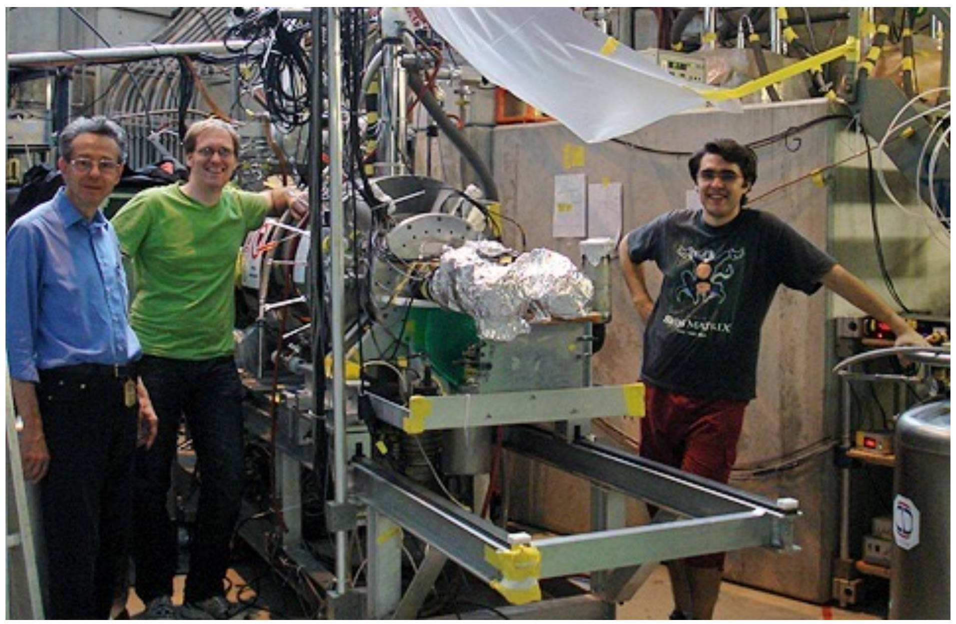
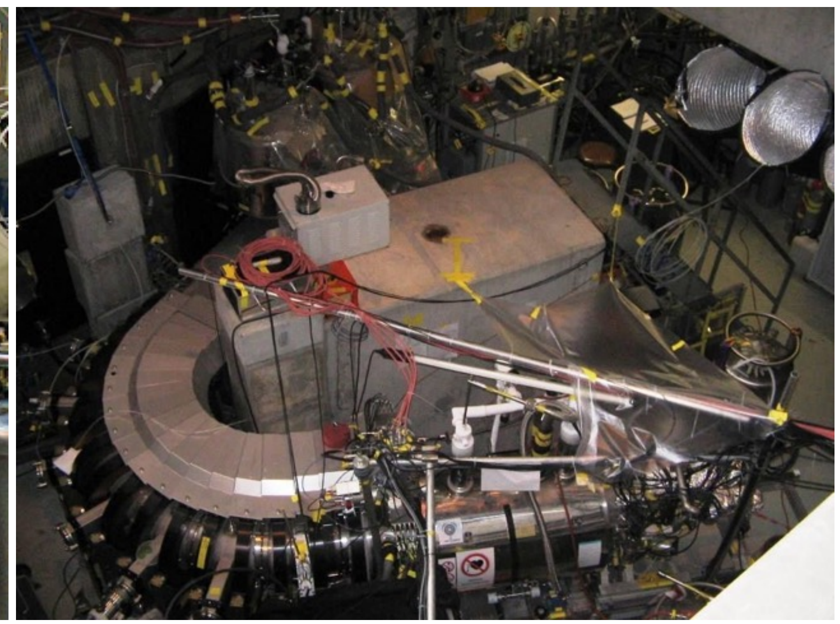
# All electron results

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

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

# Then in 2010

- CREMA = Charge Radius Experiment with Muonic Atoms

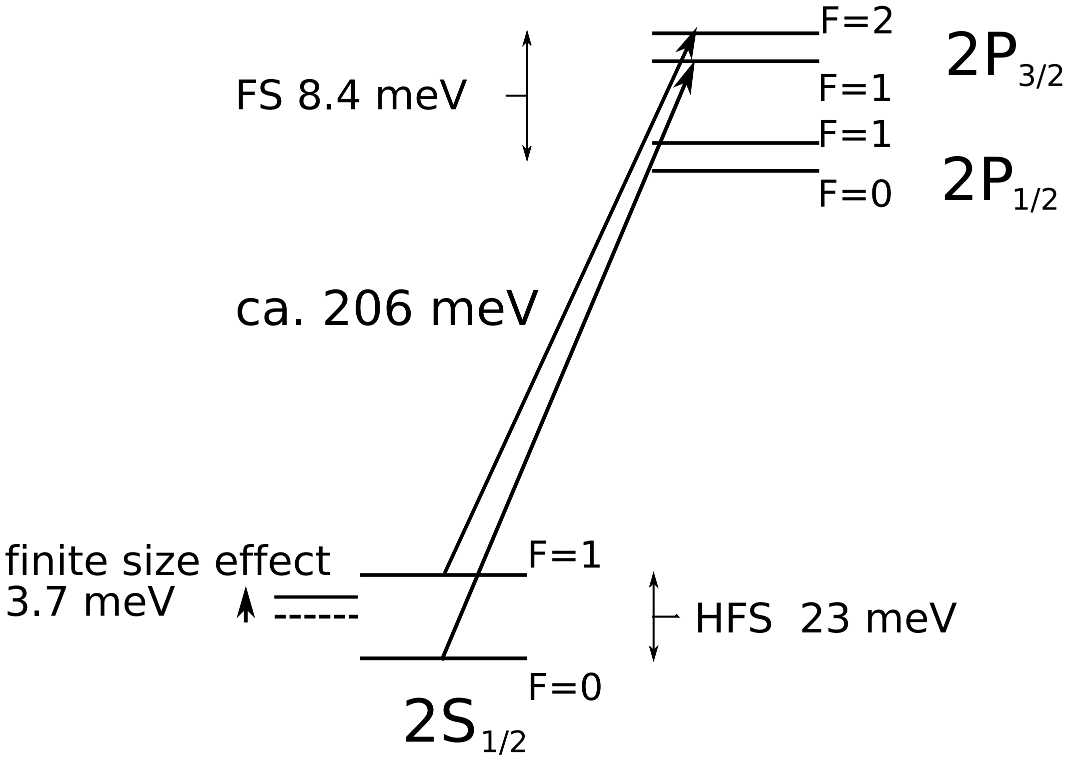
- Did atomic physics, specifically Lamb shift, with muons (muon= electron, but weighs 200 times more).

- Orbits 200 times closer: proton looks 200 times bigger

- Goal: measure proton radius with factor 10 smaller uncertainty

# CREMA

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




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

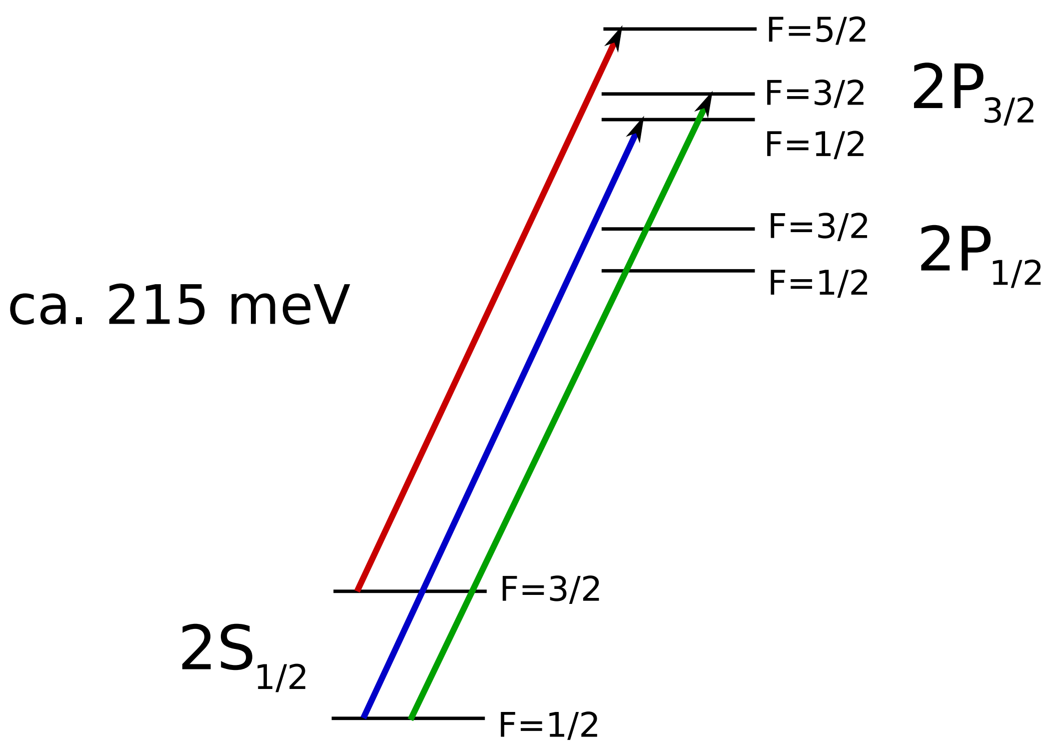
- Interpreting finite size effect in terms of proton radius,

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

- 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?
  Theorists are chipping in here!
  But there are a lot of expeirments.
- 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.)

- Others have tried different analyses regarding the extrapolation

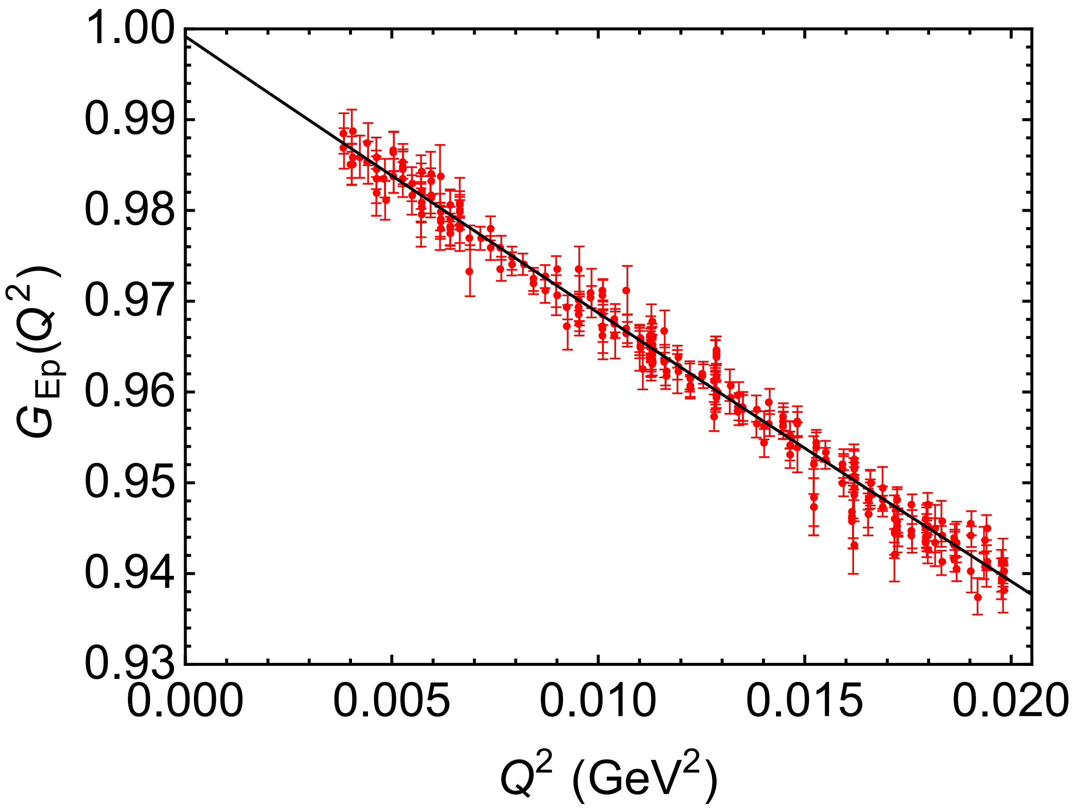
- Graczyk & Juszczak (2014), using Bayesian ideas and pre-Mainz world data, obtained
  $R_E = 0.899(3)$ fm.

- 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

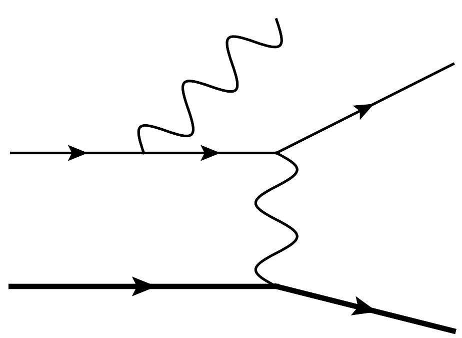
- Can also obtain "low" values of $R_E$ from $e$-$p$ scattering data
- Lorenz, Meißner, Hammer, & Dong (2015), used dispersive ideas to obtain their fit functions, and also used timelike data, and obtained
$$R_E = 0.840(15)\text{ fm.}$$
- Griffioen, Maddox, and me (coming) believe that one should be able to obtain accurate $R_E$ from just lower-$Q^2$ data, finding
$$R_E = 0.840(5)\text{ fm.}$$



# More scattering coming

- Further experiments lower lowest $Q^2$, and will do $\mu$ scattering

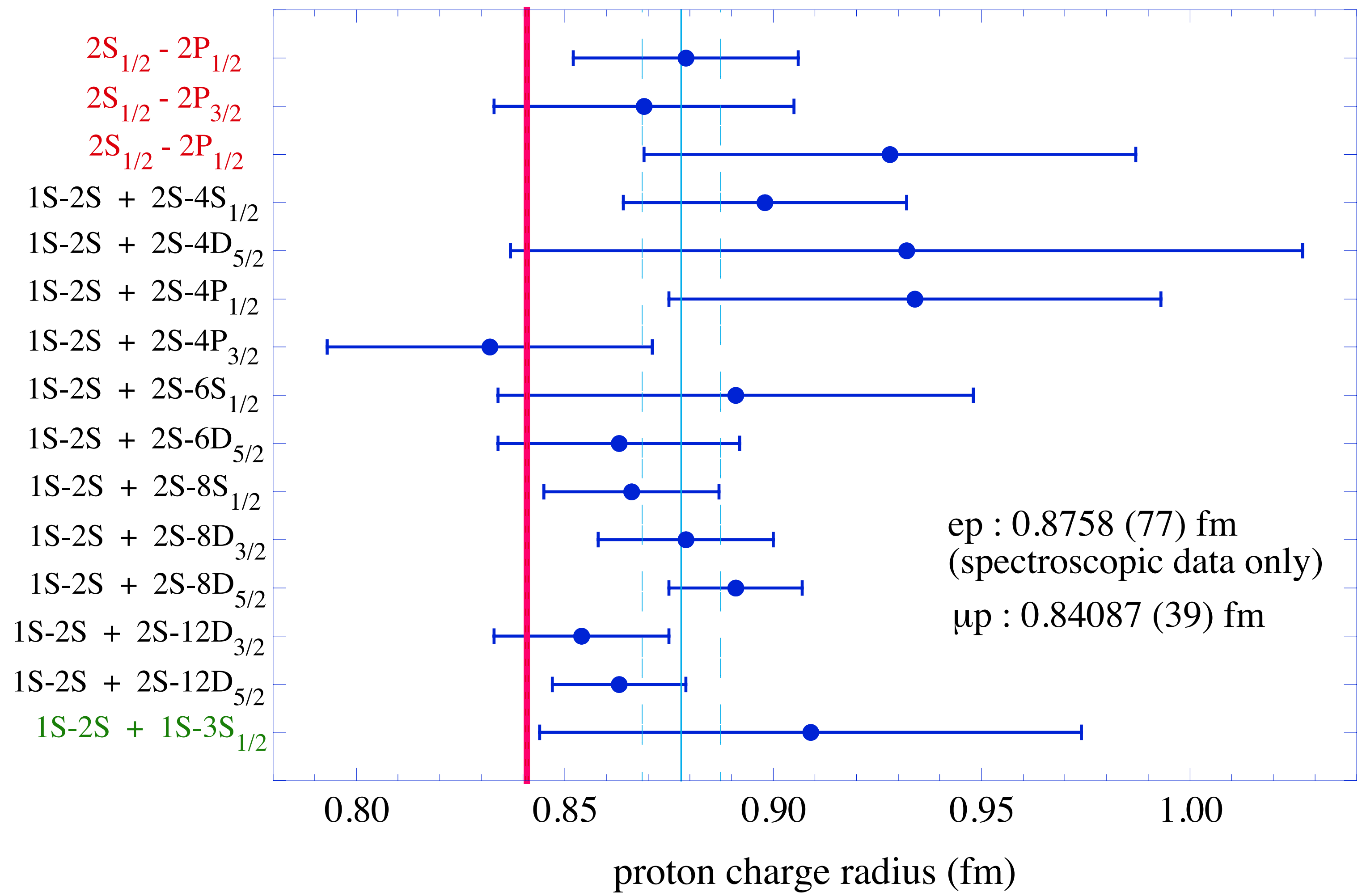
- PRad at JLab: Just target and detector screen, allowing very small scattering angles. Anticipate $Q^2|_{low} \approx 0.0002$ GeV$^2$. Hope running soon.



- 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 for preliminary experiment taken; under analysis; will obtain further data

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

# Short term future

- 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
- 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)
- 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)

# $\mu$-H Lamb shift

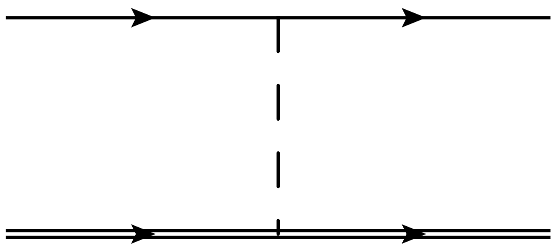
- Point: Experimenters do not directly measure proton radius. Measure energy deficit, 320 μeV. Interpret as proton radius deficit.

- 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.

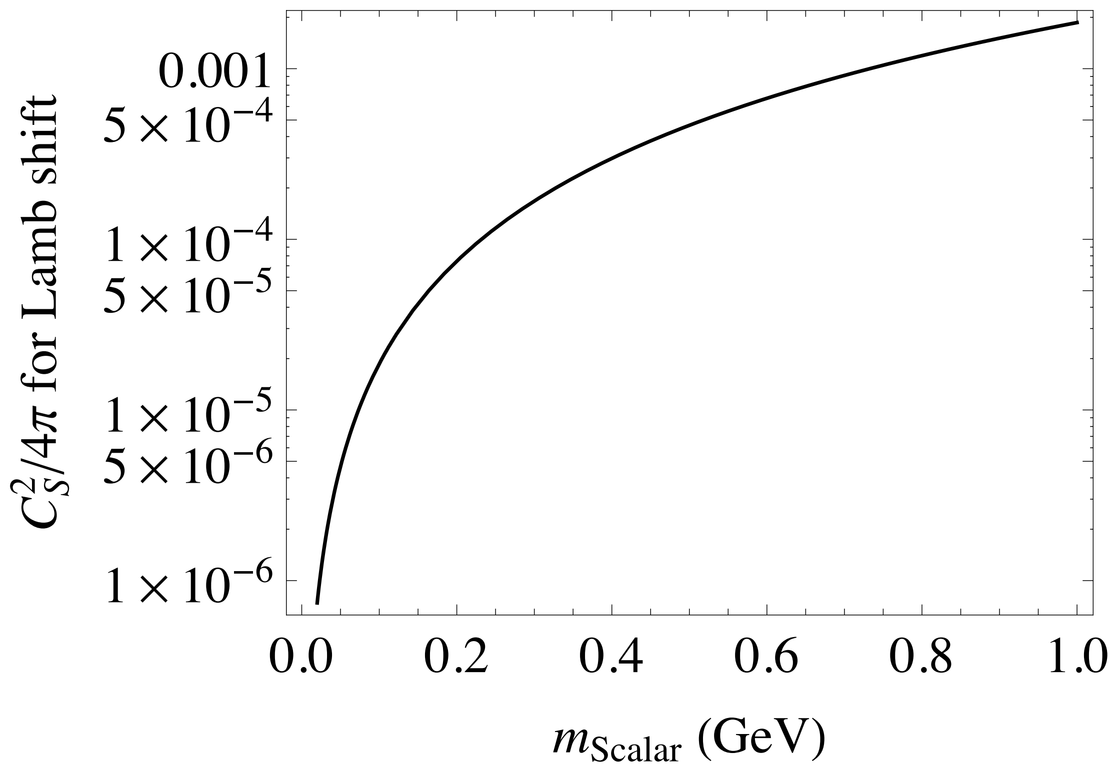
# Energy shift

- e.g., scalar case



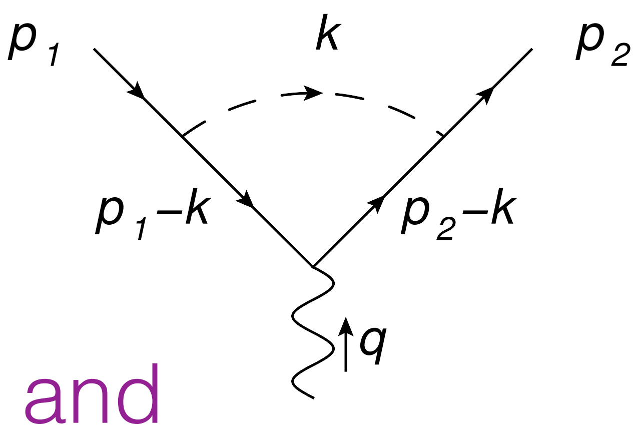
$$V(r) = -\frac{C_S^\mu C_S^p}{4\pi r} e^{-Mr}$$

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



# Other muon processes

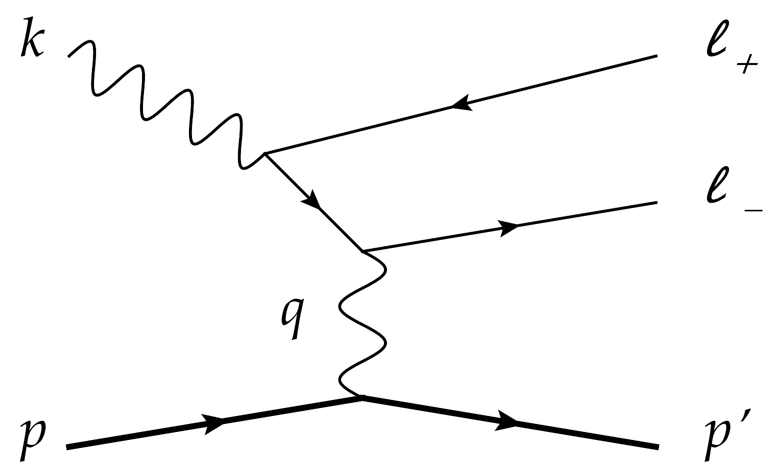
- Worry about other processes where new particle couples to muons. *First:*




  - Loop corrections to $\mu$ magnetic moment
  - (Reminder: 3 discrepancy between measured and standard model calculated $(g\text{-}2)_\mu$. But only at ppm level.)
  - If new exchange particle light, effect on $(g\text{-}2)_\mu$ small enough (Tucker-Smith & Yavin). Otherwise, need to fix adding second new particle and fine tuning. Well understood: Batell, McKeen, Pospelov, or Rislow and me. <u>Couplings still fixed.</u>

# New force seen elsewhere?

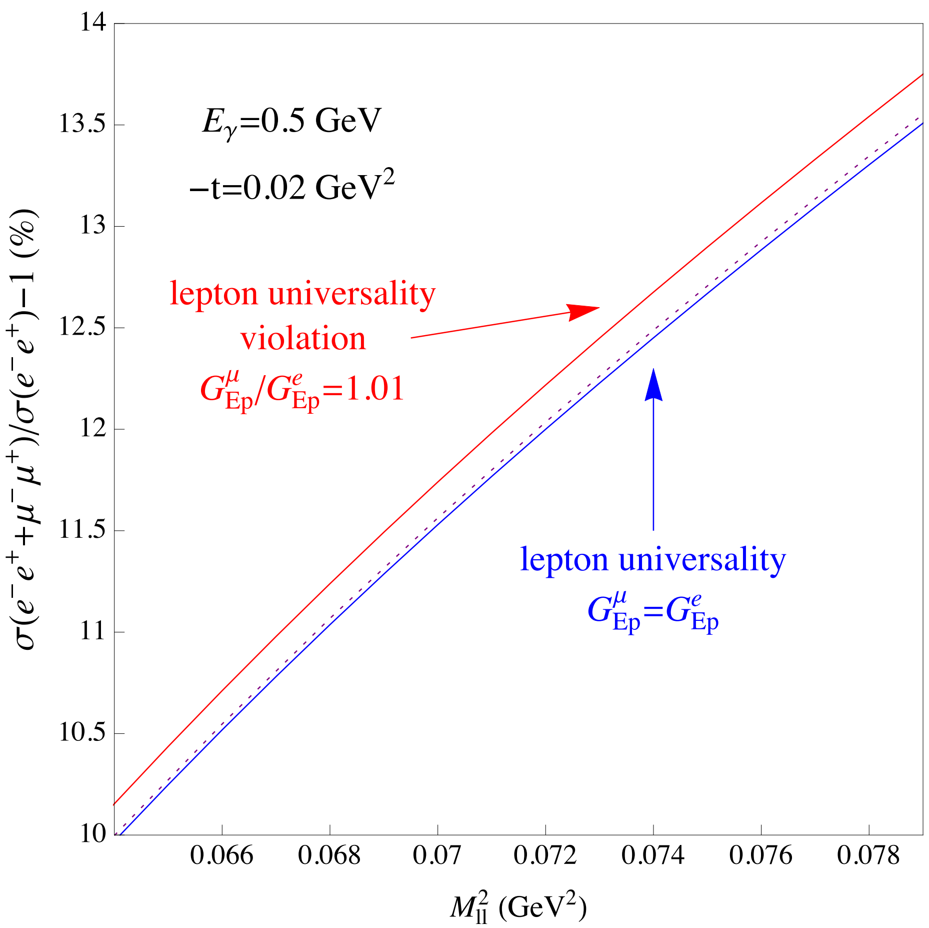
- Recent suggestion: *μ-p* scattering at JLab or Mainz *a.k.a.*, lepton pair photoproduction, $\gamma\, p \to \ell^+ \ell^- p$. (Pauk & Vanderhaeghen, 2015)




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

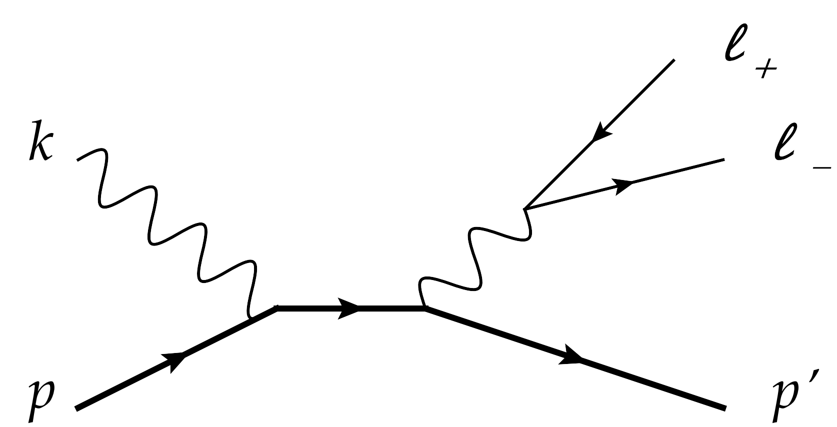
- Believe 2% measurement will show effect of extra force consistent with proton radius conflict.

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




- 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



# Helium Lamb shift

- $^3$He & $^4$He give 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.
- Mass problem!
- 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.

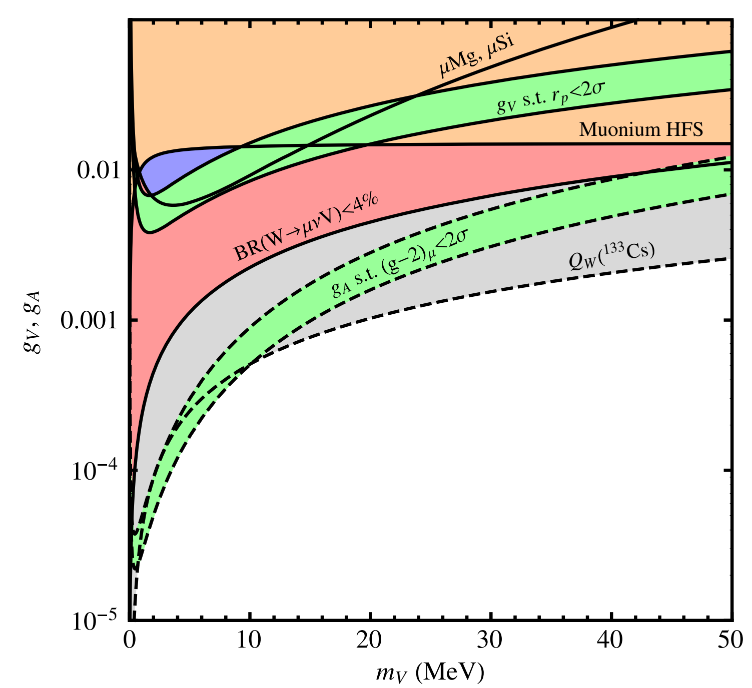
# High energy decay problem

- New particle coupling to $\boldsymbol{\mu}$ gives radiative correction to W decay: $W \rightarrow \boldsymbol{\mu}\ \boldsymbol{\nu}\ V$ or $W \rightarrow \boldsymbol{\mu}\ \boldsymbol{\nu}\ \boldsymbol{\phi}$.

- Given mass, couplings known. Hence calculate.

- Ugh: Result larger than uncertainty in width of $W$

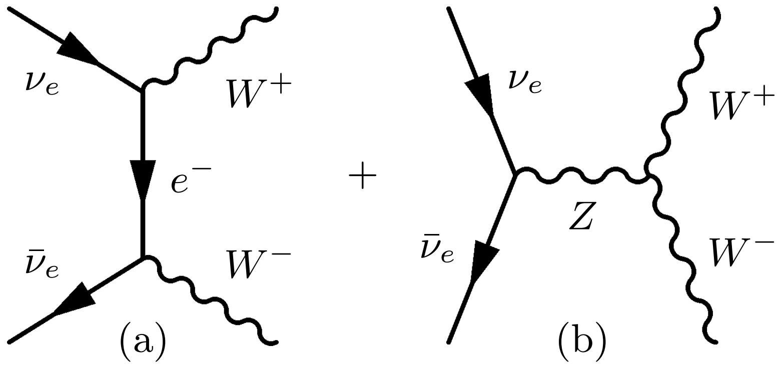
- Plot from Karshenboim *et al.*,



# Hope

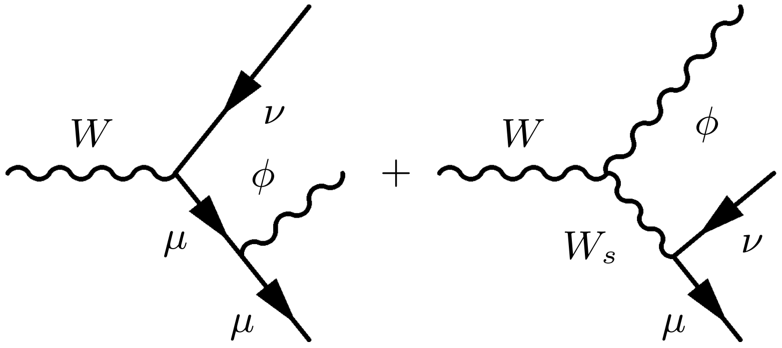
- But new particle not yet part of complete renormalizable model.

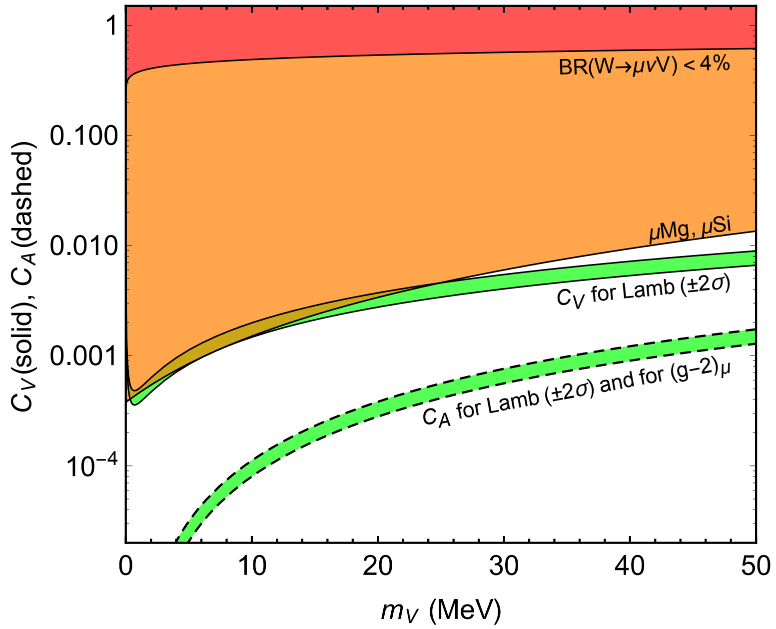
- Analog from past: with just massive vector boson, $\nu\,\bar{\nu} \to W\,W$ has excessive high energy growth




- Fixed by complete (Weinberg-Salam) theory

- Similar here: needs further Weinberg-Salam-like $W$




M. Freid & me, 1506.06631

# Lots of new data coming

- New CREMA measurements (out at conferences, 2013/14)
- MUSE (2017/2018)
- PRad (run 2015)
- ISR form factor meas. (data taken)
- Electron deuteron scattering (Griffioen *et al.*, Mainz) (data taken)
- High precision Lamb shift in *e*-H (York, 2014)
- 2*P*-4*P* *e*-H splitting at Garching (2014)
- 1*S*-3*S* *e*-H splitting at LKB, Paris (2014)
- TREK at JPARC
- Alternative measurements of the Rydberg (NIST, 2018)
- Trumuonium ($\mu^+\mu^-$) at JLab

# End

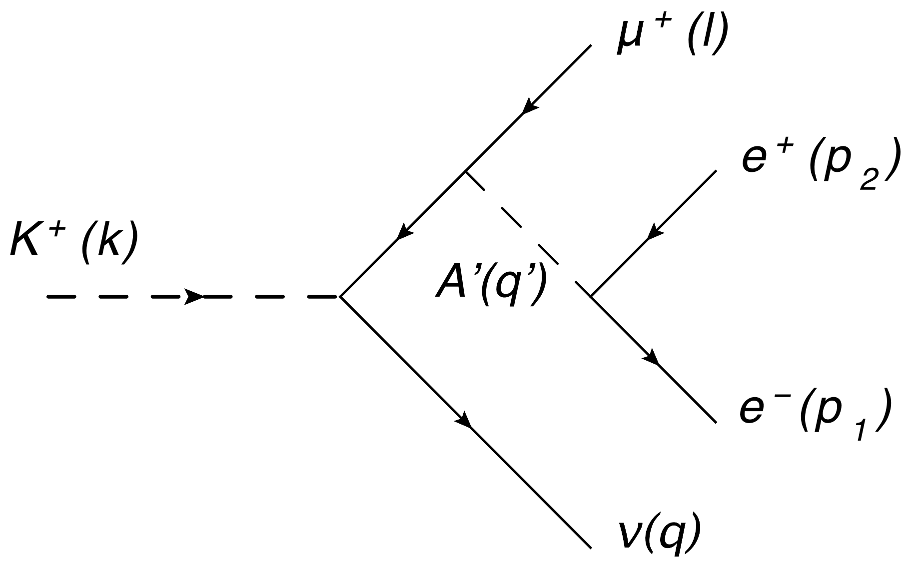
- 5 years after the first announcement, the problem persists.
- Interestingly little discussion of the correctness of the $\mu$-H Lamb shift data.
- Extrapolations that obtain the charge radius from scattering data are unsettled. Theorists should settle. Additionally, more data coming.
- Serious new Hydrogen energy level splitting experiments are in progress.
- Exotic or beyond the standard model explanations face serious constraints, particularly mass contains. But windows are still open.
- 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 this talk!

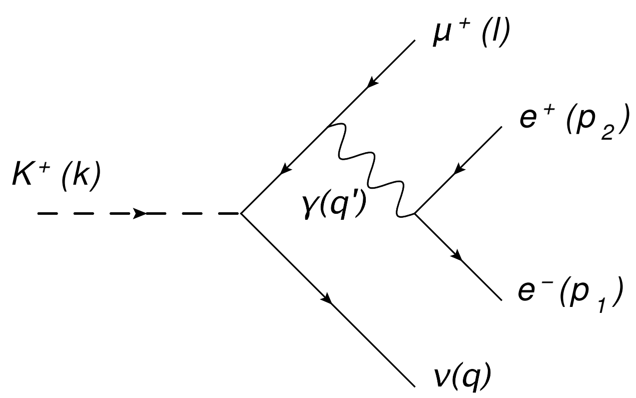
# Extras

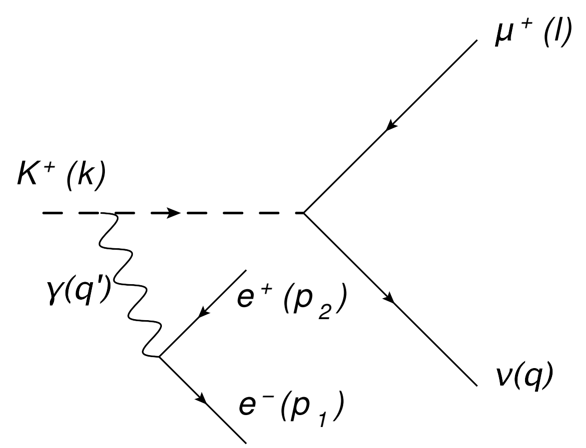
# New force seen elsewhere?

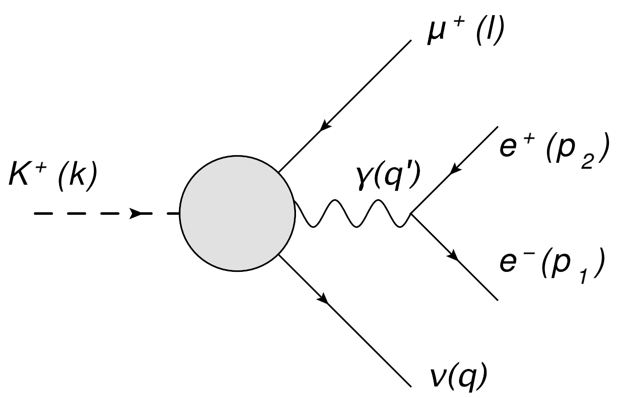
- Older suggestion: correction to $K$-decay, *viz.*, $K \to \mu\, \nu\, e^+ e^-$ as correction to $K \to \mu\, \nu$.




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

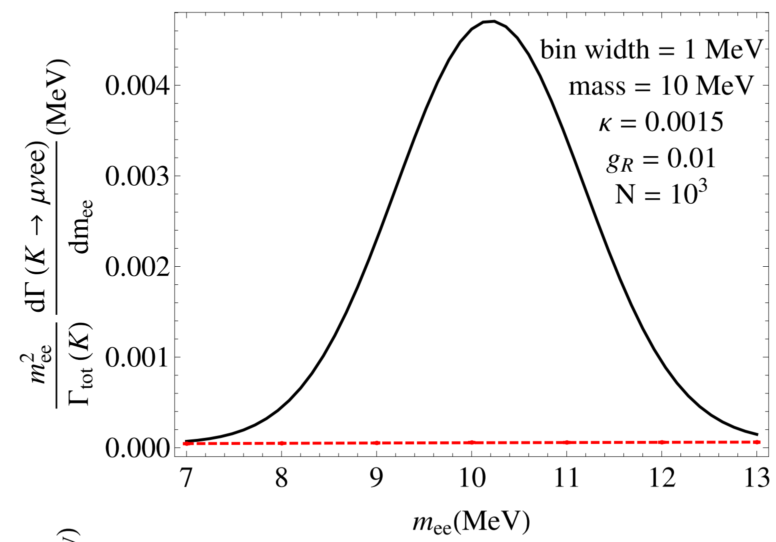


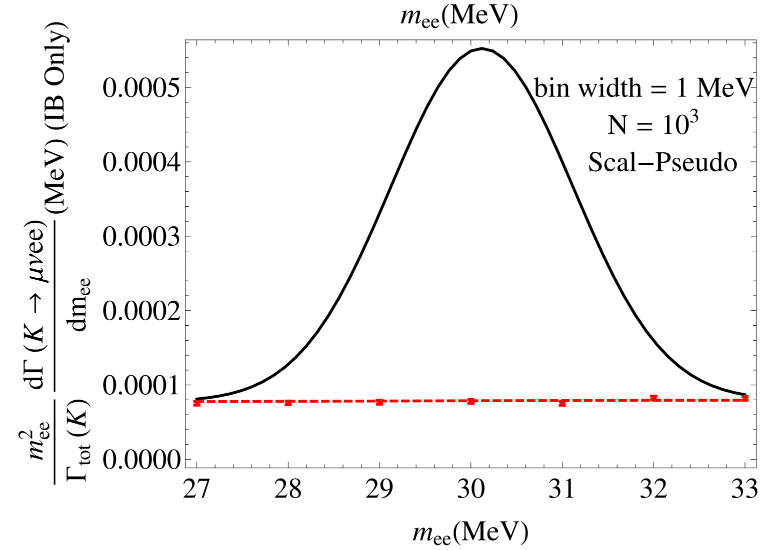



# A’ visible?

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



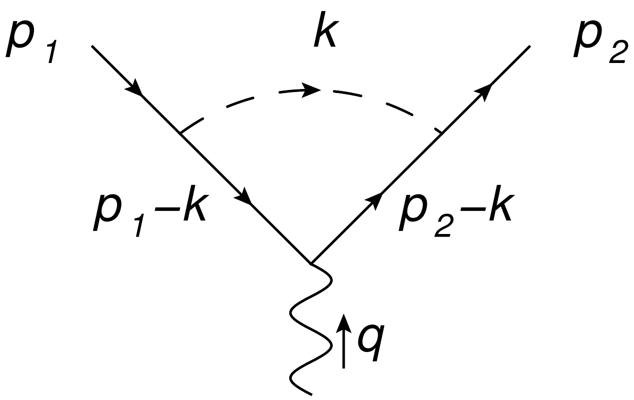

- Is it observable?
  Wow, Yes. (If it exists.)

- 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)

# 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.

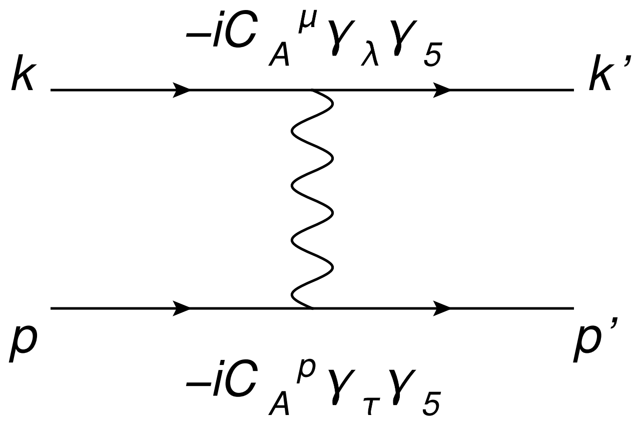
# Mass problems

- Recall measured HFS of 2*S* state of $\mu$-H measured in agreement with standard theory. Data number was,

$$\Delta E_{\mathrm{HFS}}^{\mathrm{exp}} = 22.8089(51)\ \mathrm{meV}$$

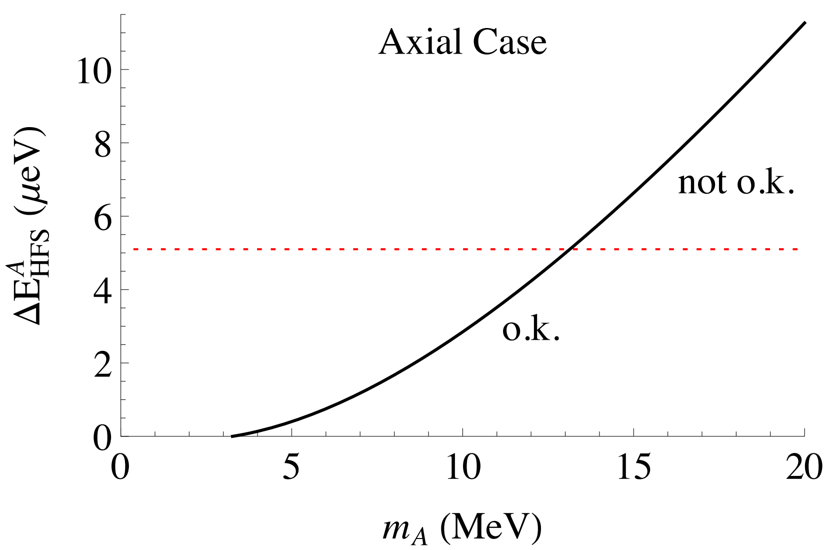
- Any HFS from exotics must be small, say below 5.1 μeV.

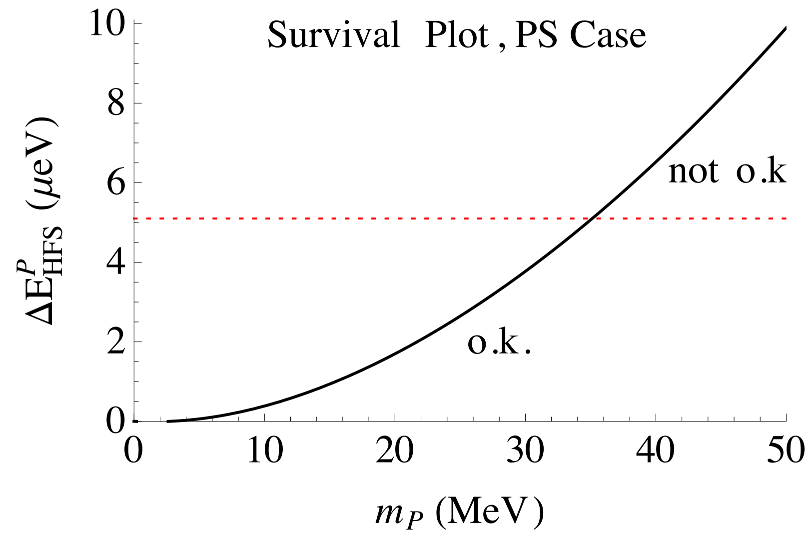
- Axial vector—if needed for fine tuning (g-2)—now problem. Gives contribution to HFS in leading order in NR expansion.




- Straightforward atomic physics calculation

# HFS and mass limits




- Conclude: HFS agreement with SM calculation compatible with new particle exchange if new particle light enough.
- Axial case o.k. if mass below about 13 MeV.
- Analogous pseudoscalar/scalar case has mass limit 35 MeV.

See Marfatia & Keung (2015), Carlson & Rislow (in prep.)

# Numbers note

- Take 1*S*-3*S* as example (the LKB measurement)
- splitting about 2.9 x $10^{12}$ kHz
- difference due to CODATA vs. $\mu$-H proton radii difference about 7.2 kHz
- $\therefore$ need ppt accuracy. Wow.
- Already have (2010) measurement with 13 kHz error bar.

# Lamb shift

- Measure well
- Calculate point proton QED part well
- Difference is due to proton size
- Need to know Rydberg well enough.  Do know it.
- Get proton radius to few %.

# Details

- Splittings between different principal QN (e.g., 2*S*-3*P*)
    - finite size term about $10^{-10}$ of Ryd term
    - need to know Rydberg very well.  Don't.
    - no problem: Take pairs of splittings instead
- Splittings within one energy level (*i.e.*, Lamb shift), finite size term about $10^{-6}$ of Lamb shift, no problem with knowing value of Rydberg accurately enough.

# Electron scattering data

- Mainz 2010 measures differential cross section, has 1422 data points, about 0.3% relative error, about or below 2% absolute error.

- Want slope of $G_E$ at $Q^2 = 0$. Cannot measure to $Q^2 = 0$, so extrapolate.

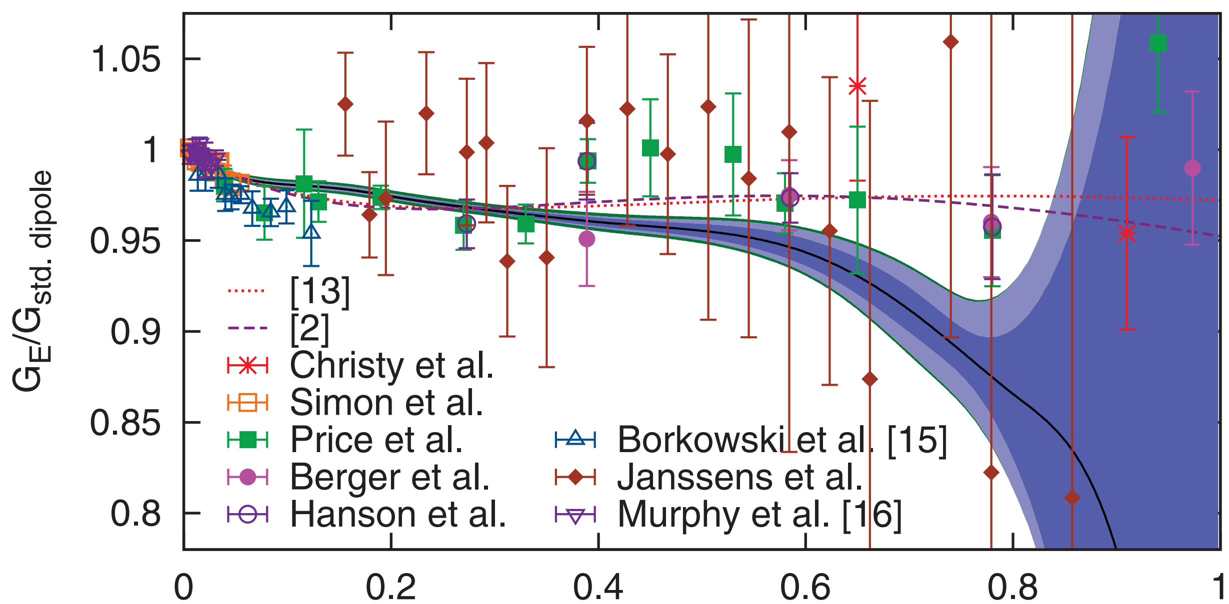
- Mainz data has $0.004 < Q^2 < 1\ \mathrm{GeV}^2$.

# Mainz’s own fit

- The experimenters fit $G_E$ and $G_M$ to their data using polynomials or modified polynomials in $Q^2$.

- Results have small error limits compared to other data.

- Extrapolation to $Q^2 = 0$ gave “big” result quoted already.



# On the other hand

- There is reason to believe polynomial expansion don't converge for $Q^2$ beyond $4m_\pi{}^2 \approx 0.08$ GeV$^2$.
- Lorenz and Meissner did a conformal transformation to a new variable in terms of which a polynomial expansion would be convergent.
- They fit the Mainz data and got

$$R_E = 0.84(1)\ \mathrm{fm}$$

- hmm

# MUSE

- Muon scattering experiment at the PSI.
- Proton radius measurement table

| | **atomic spectroscopy** | **scattering** |
|---|---|---|
| **electron** | yes | yes |
| **muon** | yes | no |

- MUSE will fill in table. Anticipate $Q^2|_{\text{low}} \approx 0.002\ \text{GeV}^2$. Production runs 2017/2018.

# But still

- Hill and Paz also did a fit over a wide range of $Q^2$ using the variable that should allow convergence.

$$R_E = 0.870(23)(12)\ \mathrm{fm}$$

- But they did not use the Mainz 2010 data, only a collection of older data.

# And then there is

- A fit using only low $Q^2$ data, where convergence of a polynomial expansion should not be a problem.

- Low $Q^2$, but still a long enough range to well determine the charge radius upon extrapolation.

$$R_E = 0.840(5)\ \mathrm{fm}$$

- Local product: Griffioen, Maddox, me.

- Conclusion: a bit up in the air.