Size of the proton

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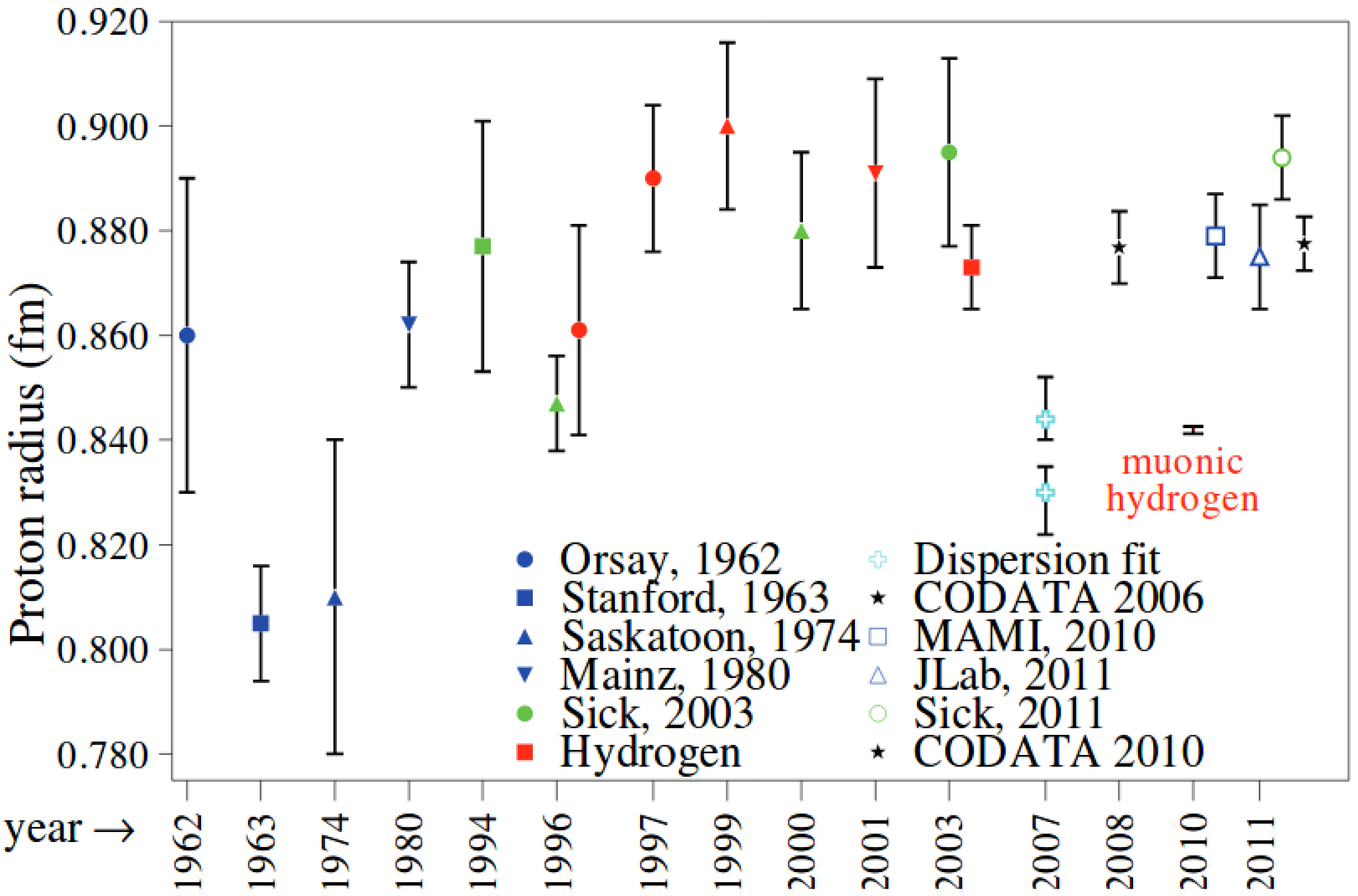
22nd March 2017

Outline

- The puzzle
- Motivation
- Hydrogen spectroscopy
- *ep* elastic scattering
- Muonic Hydrogen
- Possible explanations
- Future
- Summary

The puzzle



0.920
0.900
0.880
0.860
0.840
0.820
0.800
0.780
Proton radius (fm)
year →
1962
1963
1974
1980
1994
1996
1997
1999
2000
2001
2003
2007
2008
2010
2011
muonic
hydrogen
Orsay, 1962
Stanford, 1963
Saskatoon, 1974
Mainz, 1980
Sick, 2003
Hydrogen
Dispersion fit
CODATA 2006
MAMI, 2010
JLab, 2011
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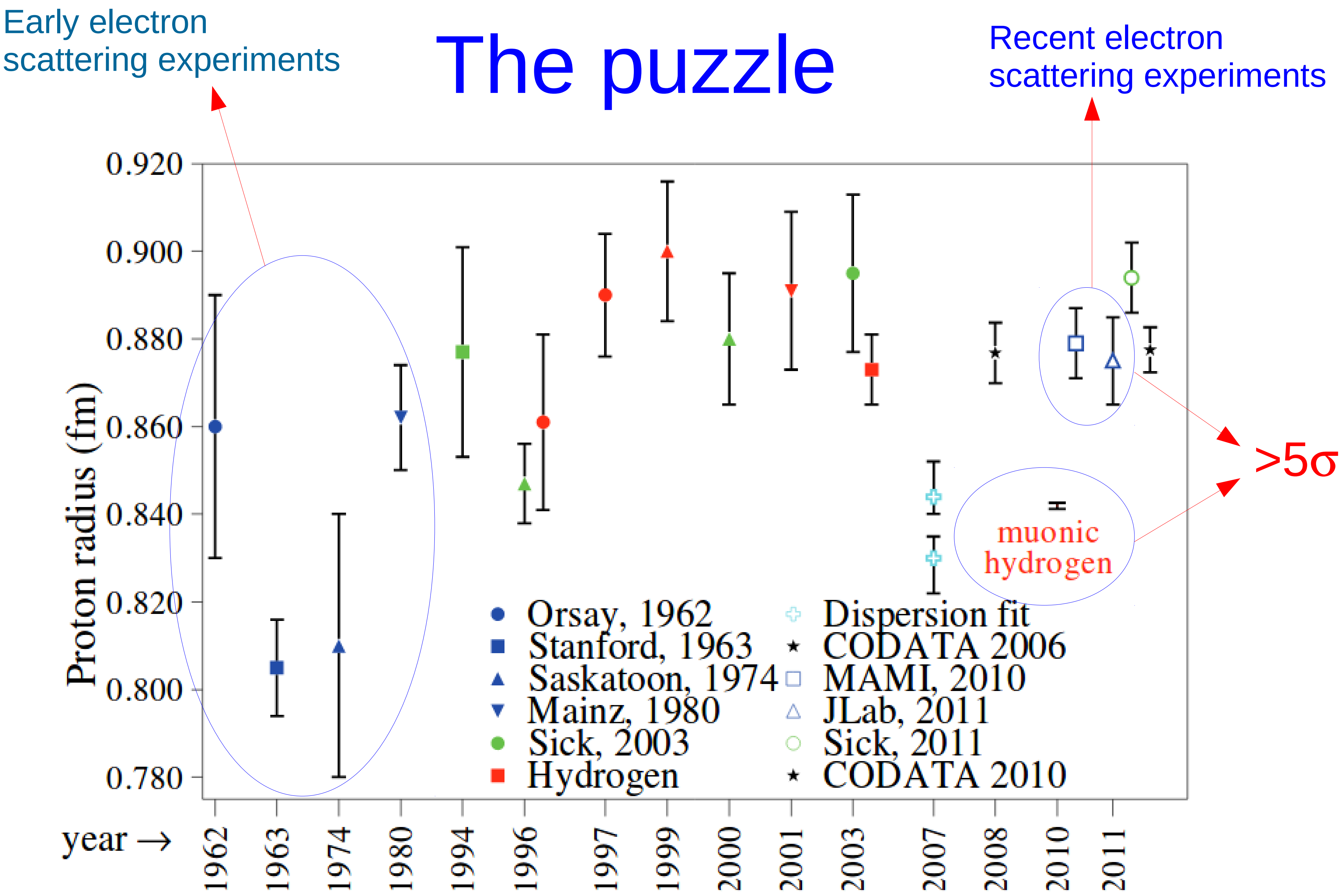
CODATA 2010

The puzzle



Early electron scattering experiments
Recent electron scattering experiments
>5σ
muonic hydrogen
Proton radius (fm)
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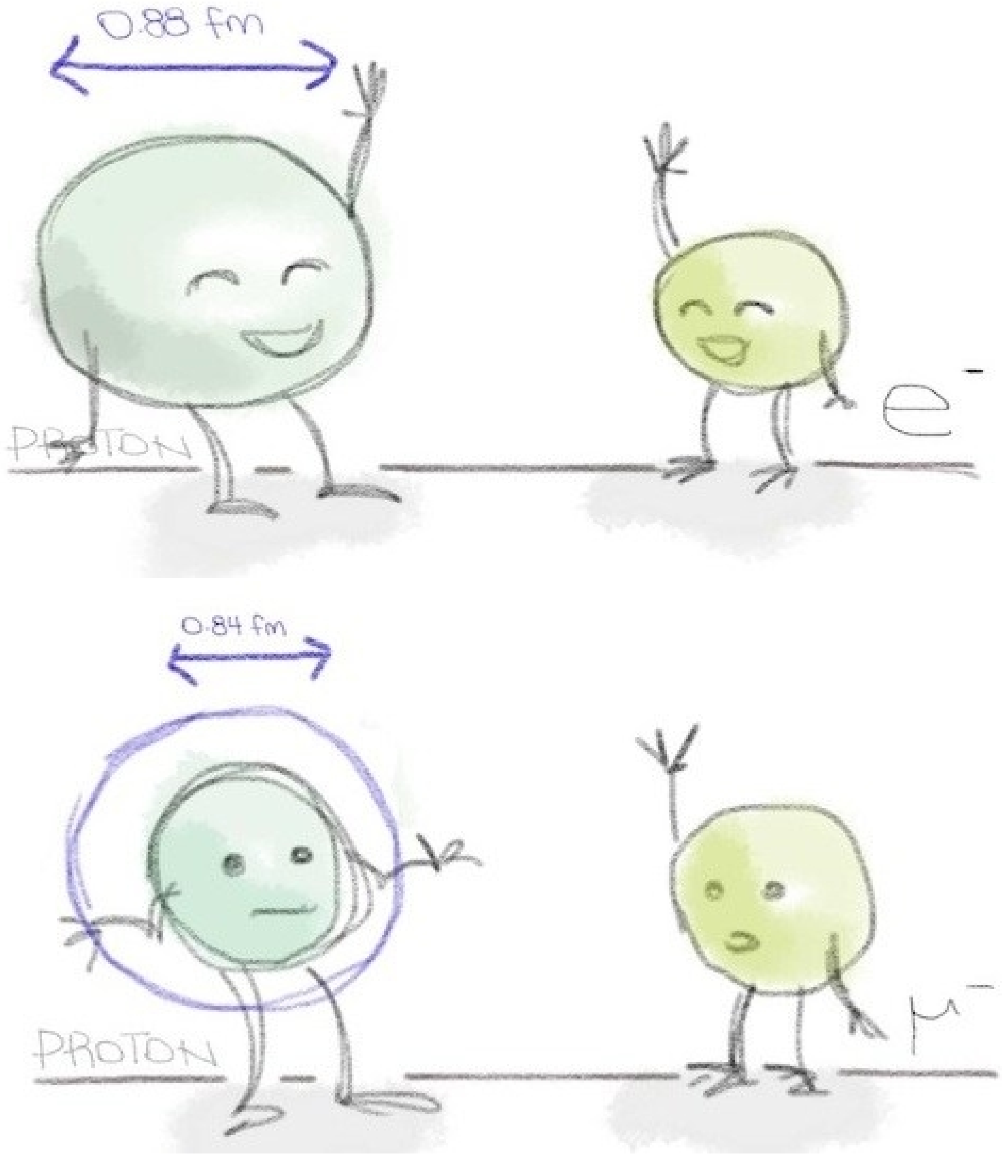
The puzzle (Simplified version)



Motivation

- Hydrogen – simplest atom and perfect for comparison between theory and experiment
- Looking back..

Balmer series → Bohr model and quantum mechanics

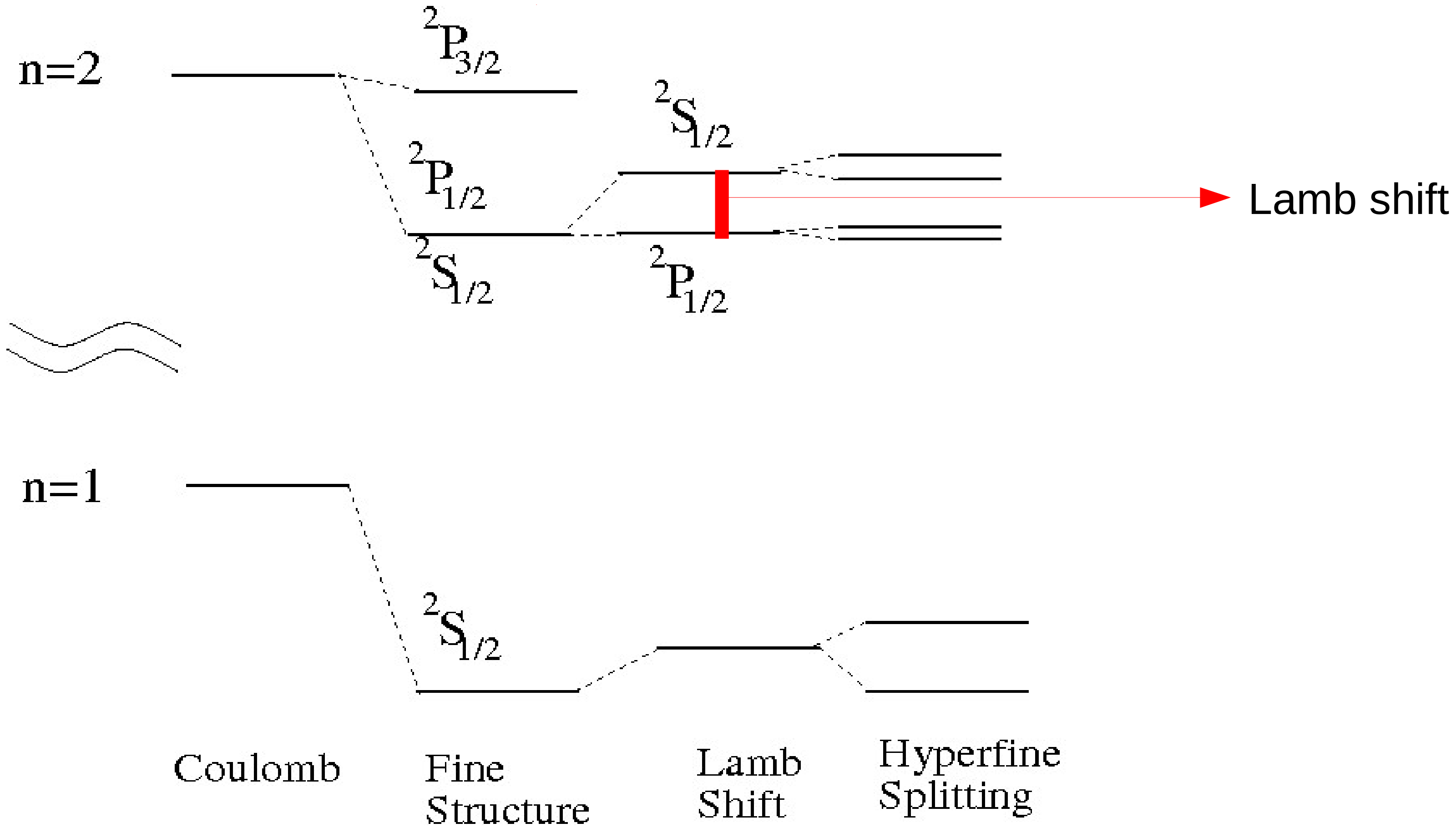
Spin-orbit coupling → Validated Dirac equation

Lamb shift → Quantum Electrodynamics

Proton radius puzzle → ???

Hydrogen spectroscopy

- Lamb shift measurement



- Theoretically, simplified result for Lamb shift for S states can be written as

$$E_{nS} = \frac{R}{n^2} + \frac{f(r_p^2)}{n^3}$$

where R is Rydberg constant

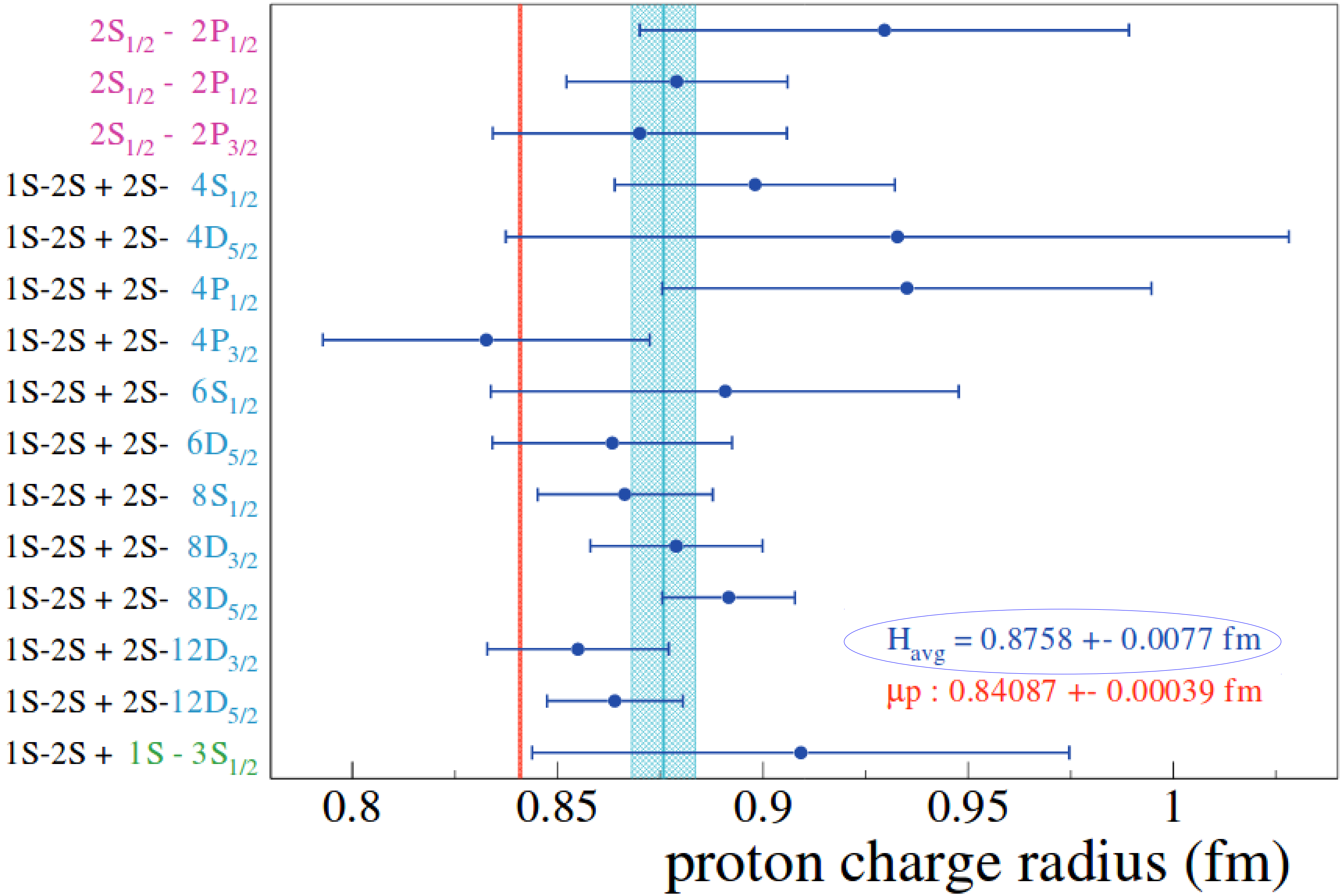
and r_p is the proton radius

$$R_\infty = \frac{\alpha^2 m_e c}{4\pi\hbar}$$

  - What does this tell us?

    1. Lower n ⟶ more sensitive to r_p
    2. Higher n ⟶ Precise measurement of R
    2. You need at least two transitions to comment on r_p from Lamb shift measurements

- Experimentally,



ep elastic Scattering

$$\frac{d\sigma}{d\Omega_{exp}} = \frac{d\sigma}{d\Omega_{point}} \times \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2(\theta/2) G_M^2(Q^2) \right]$$

→ One photon echange

where Q^2 = Momentum transfer

G_E and G_M are electronic and magnetic form factors

$\tau = Q^2/4m^2$

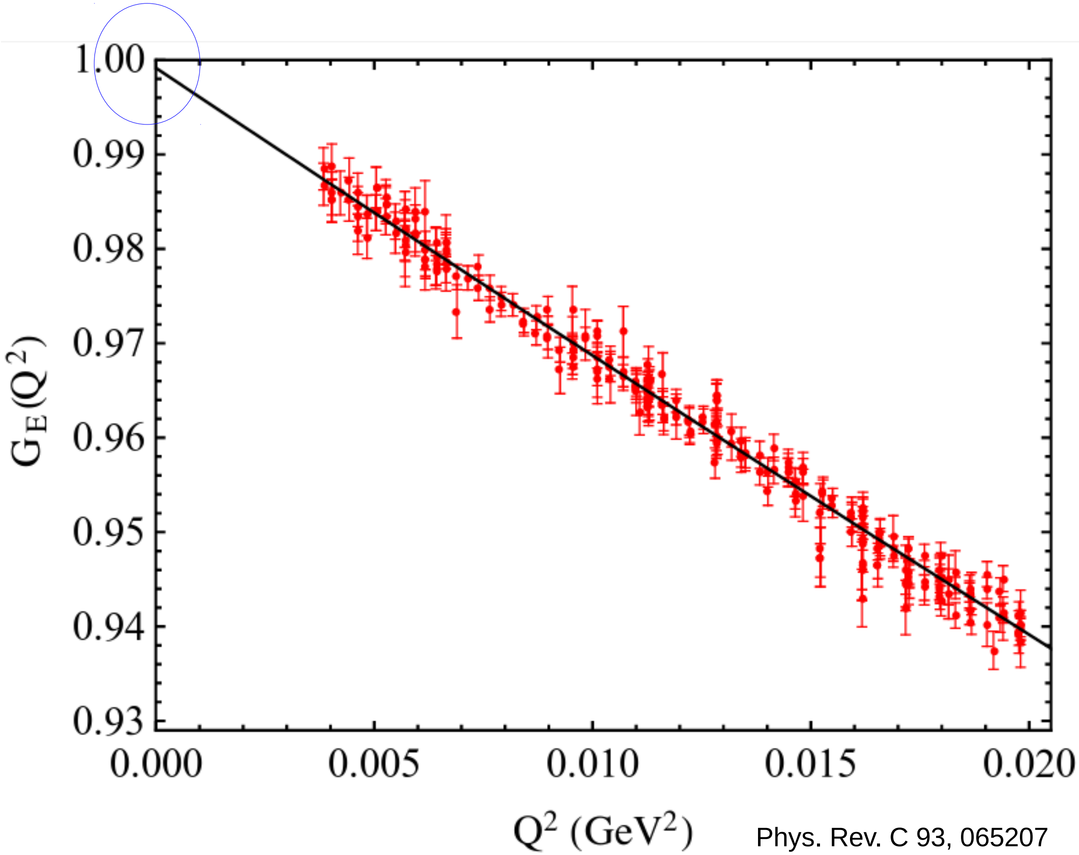
θ = lab scattering angle and

Mott scattering formula:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \frac{\alpha^2}{4p_e^2 \sin^4 \frac{\theta}{2}} \left(\cos^2 \frac{\theta}{2} - \frac{q^2}{2m_p^2} \sin^2 \frac{\theta}{2} \right)$$

Here, proton radius is obtained by finding slope of G_E when Q^2=0

$$G_E = 1 - Q^2 r_p^2/6 + Q^4 r_p^4/120\ldots$$



Phys. Rev. C 93, 065207

Mainz A1 collaboration
r_p = 0.895(20) fm

Modern scattering experiment values are more or less the same.

Muonic hydrogen

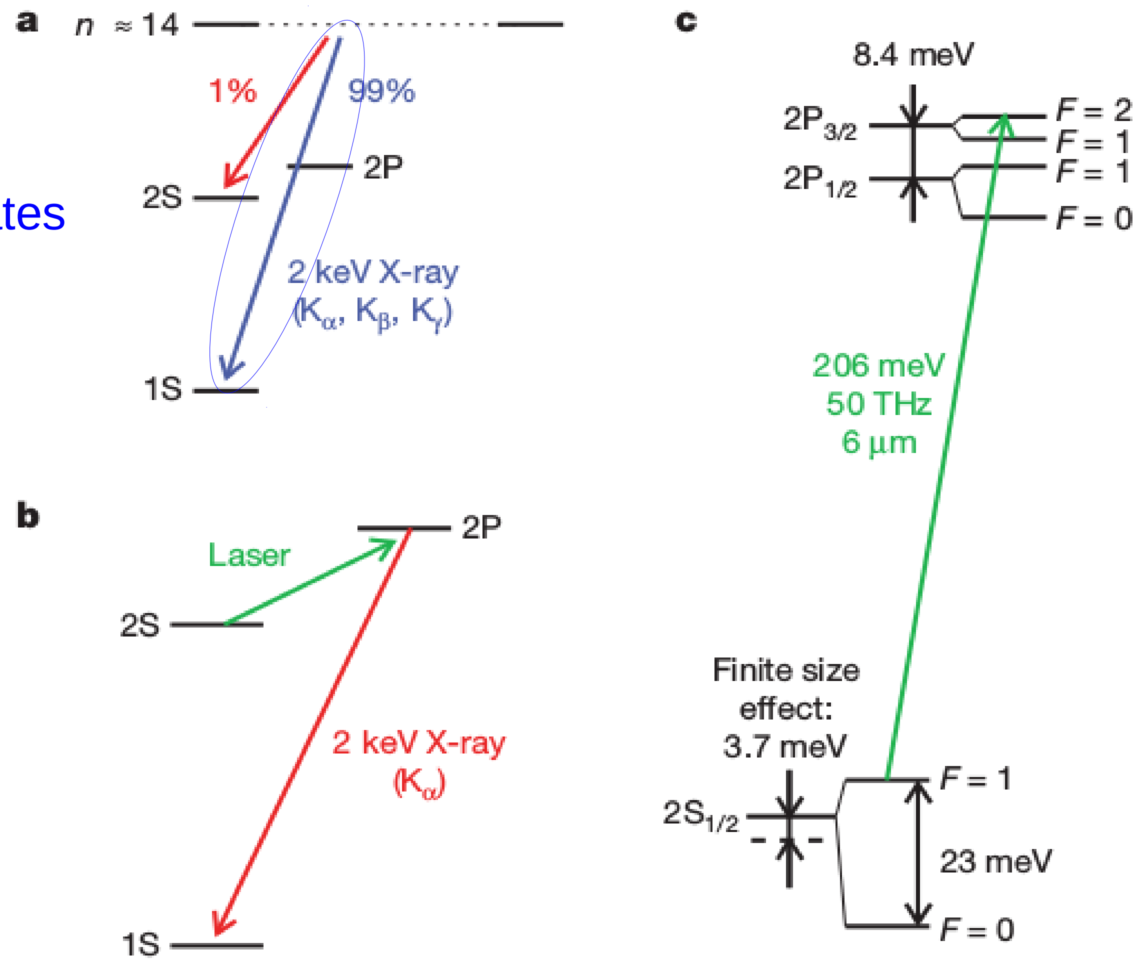
- m_μ ~ 105 MeV and m_e ~ 0.5 MeV
- Back of the envelope calculation:
  - Probability of lepton being inside proton radius =

    $$(r_p/a_B)^3 = (\alpha m_r r_p)^3,$$

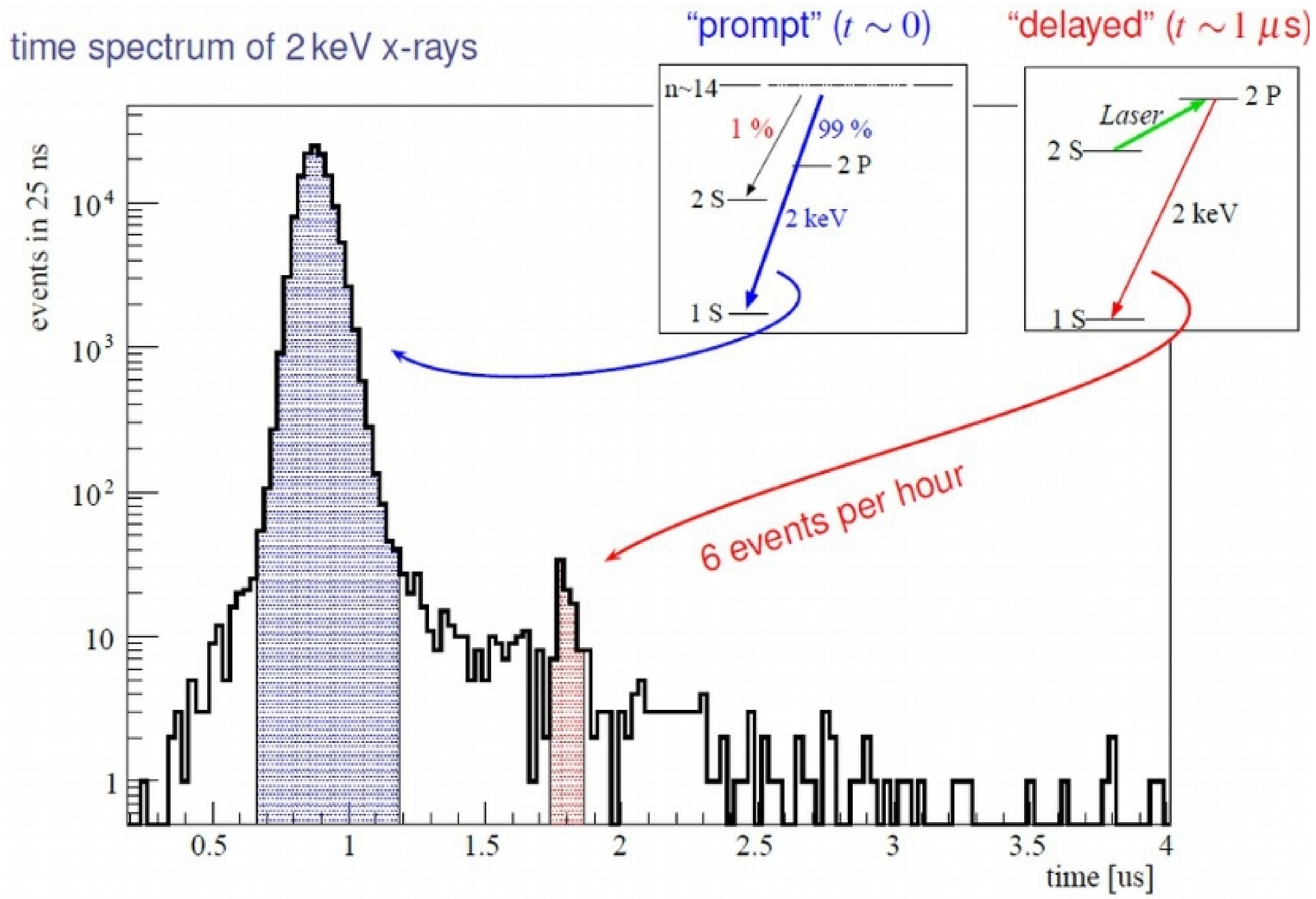
    where m_r = reduced lepton mass
  - Probability of muon being inside proton radius is 8 million times more than electron!
  - Muon must be more sensitive to proton radius.

- Experimentally challenging!

Dominates



2010 experiment



- Using simplified expression for the transition after considering the Lamb shift and hyperfine splitting, the energy expression is

$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ [meV]}$$

- Result: r_p = 0.84184(67) fm

  Previously agreed result: 0.8768(69) fm

  >5σ deviation!! → Experimental artifact?

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  No!

2013 experiment

- Measured same transition in μH and found

  r_p = 0.84087(39) fm

  >7σ deviation!!

Possible explanations

- Depends on which theorist you ask!
  - Quantum gravity
  - Extra dimensions
  - New boson?

  ...

- Experimental error in measuring Rydberg Constant?
  - Error of the order 10^{12} can explain this dicrepancy.

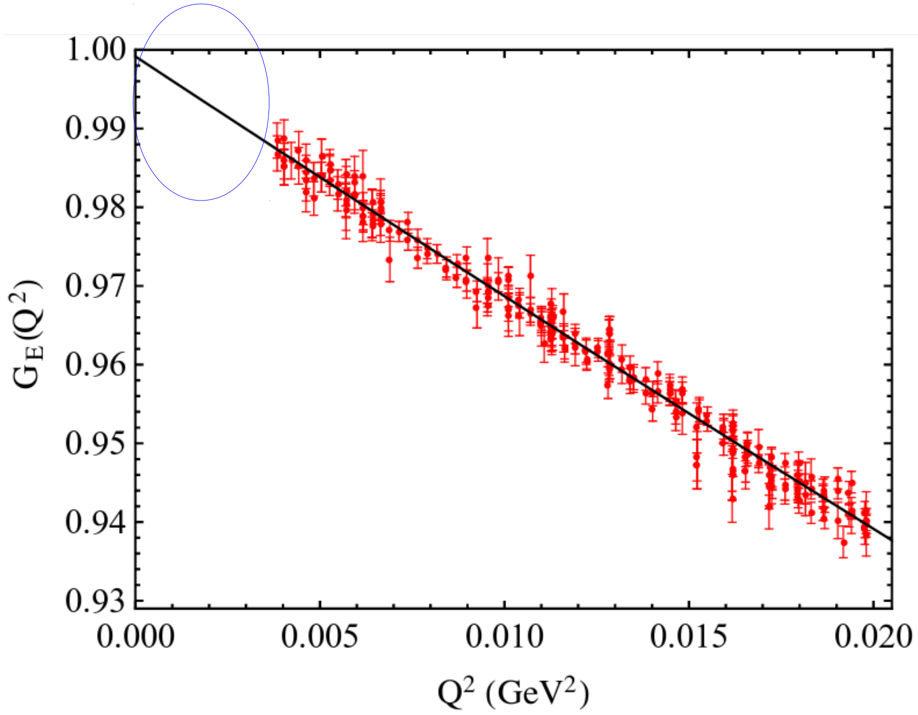
Future

- PRad (New Proton Radius experiment)
- MUSE (MUon Scattering Experiment)
- Spectroscopy of electronic atoms and ions to determine Rydberg constant to very high precision.
- Muonic deuterium
- Muonic helium vs electronic helium

...

PRad

- Experiment at Jlab
- ep elastic scattering method
- Data taken: May-June 2016
- Result: Coming soon!



MUSE

- μp elastic scattering
- This is messy
  - Muon beams have lower flux
  - Need higher acceptance spectrometer
  - Might decay into electrons
  - Higher background due to π, e^-

    ...
- Status: Not operational yet!

Summary

- Proton radius measurement has significant discrepencies.
- Different experiments are using different techniques to make an independent measurement of the radius.
- Many more results to come in the future..
  - which could either resolve the discrepancy or lead to some new physics
- Stay tuned!

References

- Muonic Hydrogen: https://www.jlab.org/indico/event/160/session/0/contribution/97/material/slides/0.pdf
- Nature 466: 213-216, 2010
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- Annu. Rev. Nucl. Part. Sci. Vol 63 (2013)
- Particlebites.com
- https://www.jlab.org/prad/collaboration.html