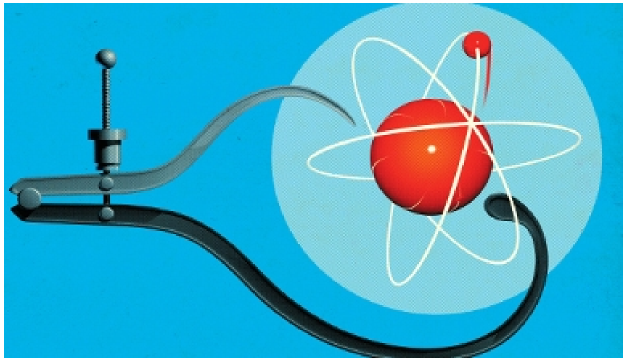
On the proton radius puzzle



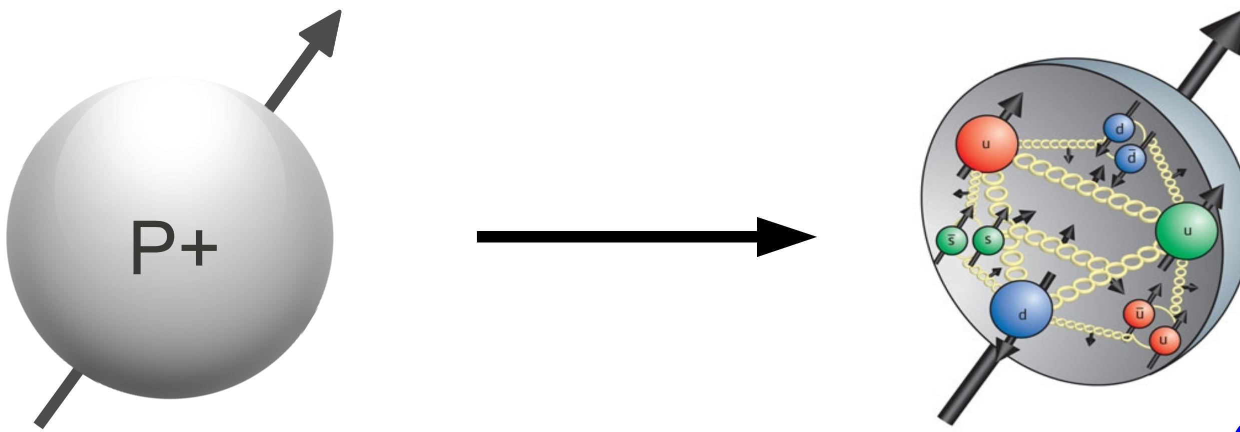
Clara Peset

19th March, 2014

Outline

- What is the proton radius?
- The puzzle
- Measurements
  - in hydrogen
  - in muonic hydrogen
- Possible Issues
  - muonic hydrogen experiment
  - theory of the muonic hydrogen
  - theory of the hydrogen levels
  - beyond the Standard Model
- Conclusions

The proton and its charge radius

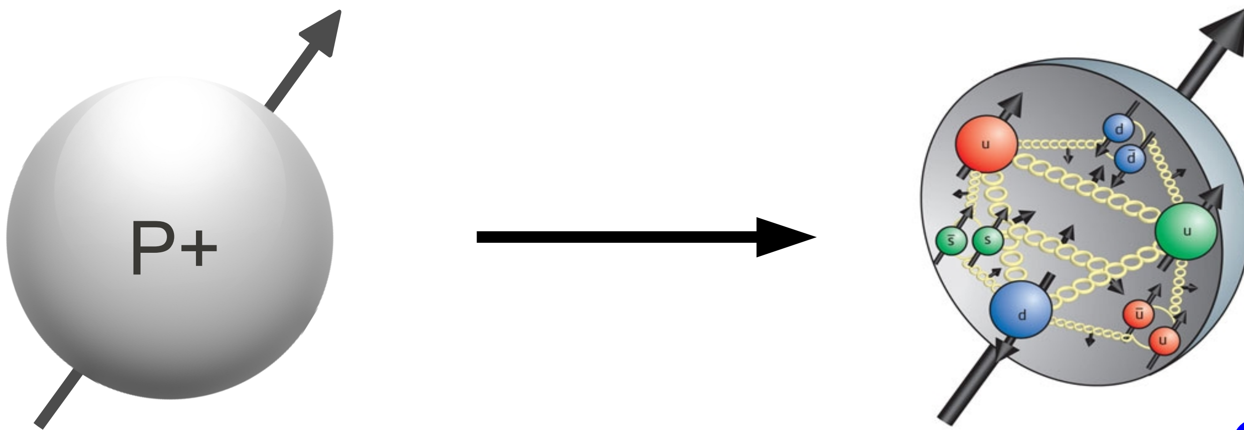


Rutherford 1917-20

QCD

Stable baryon: $\tau_p > 10^{34}$ *years*

The proton and its charge radius



Rutherford 1917-20

QCD

Stable baryon: $\tau_p > 10^{34}$ *years*

What is the proton radius?

EFT (NRQED)

$$r_p^2 = 6\frac{dG_{p,E}(q^2)}{dq^2}\Big|_{q^2=0}$$

$$c_D^{(p)}(\nu) - c_{D,point}^{(p)}(\nu) \equiv \frac{4}{3}m_p^2 r_p^2$$

IR divergent!

The proton radius puzzle

Value obtained from muonic-H:

$r_p = 0.84184(67)$ fm *(Nature '10)*

$r_p = 0.84087(39)$ fm *(Science '13)*

$r_p = 0.8433(17)$ fm *(CP, Pineda '14)*

CODATA value:

$r_p = 0.8768(32)$ fm

$5-7\sigma$ away!

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Probability of the lepton being *within* the volume of the proton

$$\left(\frac{r_p}{a_B}\right)^3 = \left(\alpha\, m_r r_p\right)^3 \qquad m_\mu \approx 200\, m_e$$

8 million times larger for muonic hydrogen!

What is going on?

Experimental measurements wrong?

Theoretical predictions missing a big contribution?

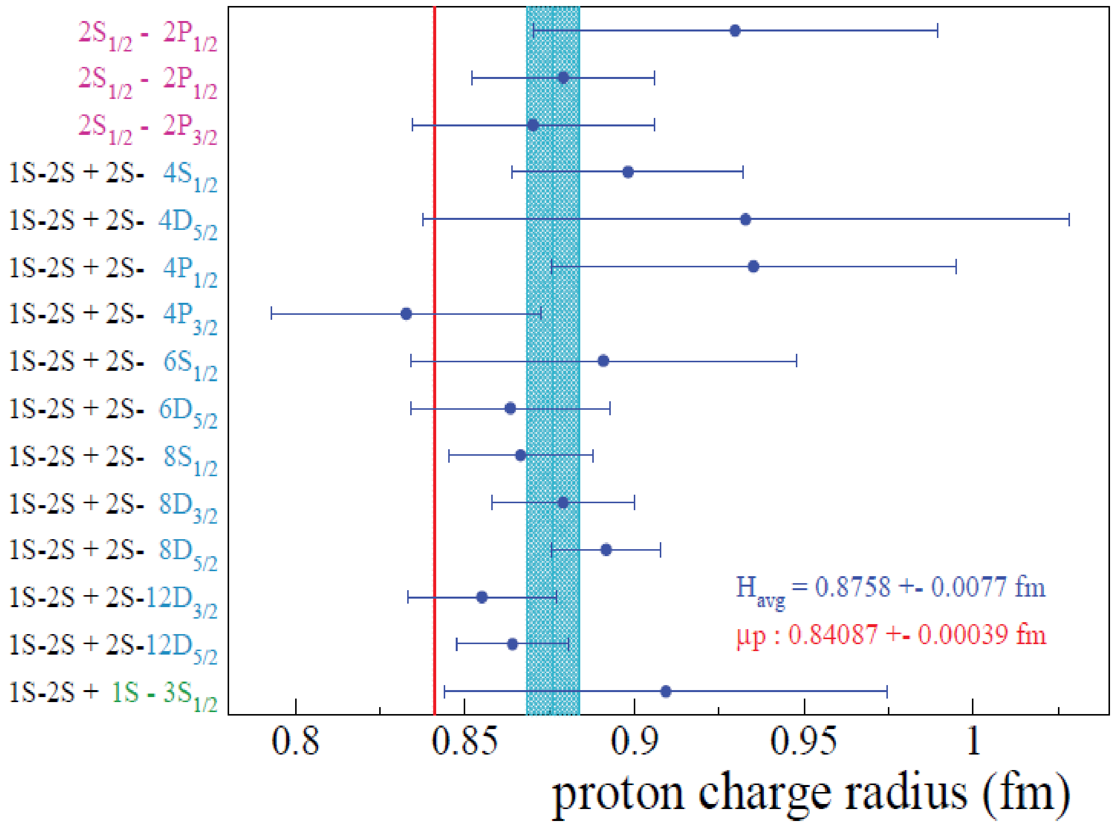
Interaction of the proton with the muon different from the interaction with the electron?

How can we accommodate this within our known theory?

It's a puzzle!

Measurement in hydrogen spectroscopy

Large number of experiments:



Hadronic structure:

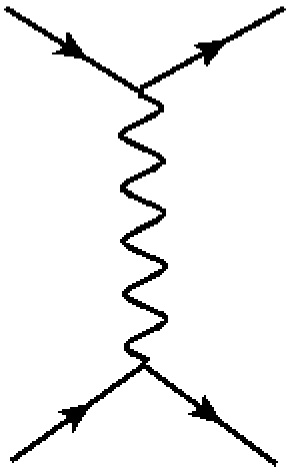
Lamb shift $\approx r_p^2$

EFT counting:

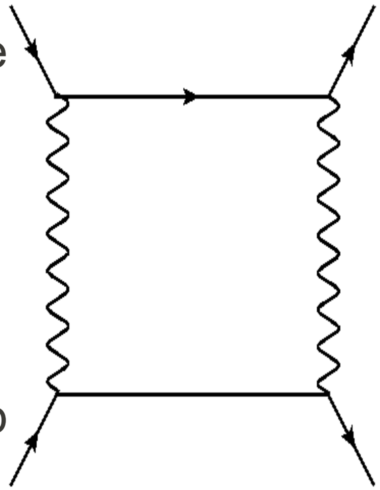
$$O\left(m_e \alpha^4 \frac{m_e^2}{m_p^2}\right) \approx O\left(m_e \alpha^6\right)$$

1S-2S transition measured to accuracy $\dfrac{4}{10^{15}}$

Measurement in p-e scattering



$$\frac{d\sigma}{d\Omega} \approx \frac{d\sigma}{d\Omega}_{point}\left(1-\frac{q^2}{4m^2}\right)\left(G_E^2(q^2)-\frac{q^2}{4m^2}G_M^2(q^2)\right)$$

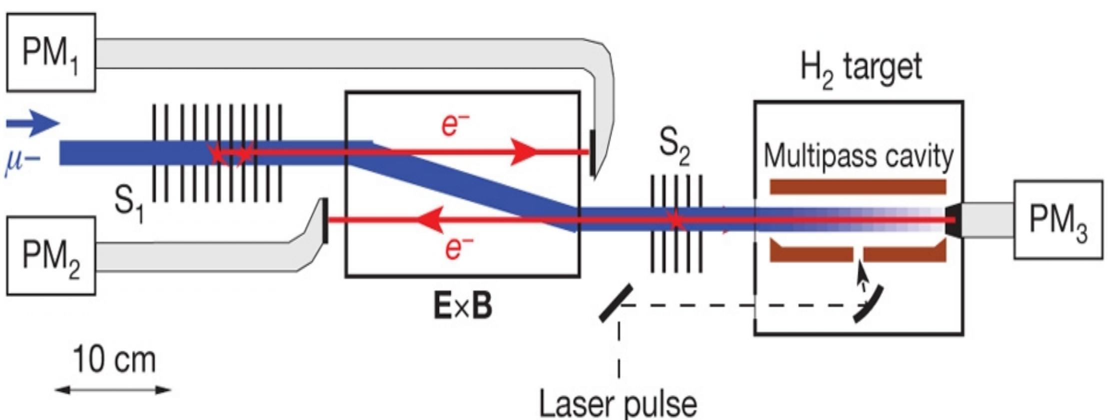


More complicated measurement:

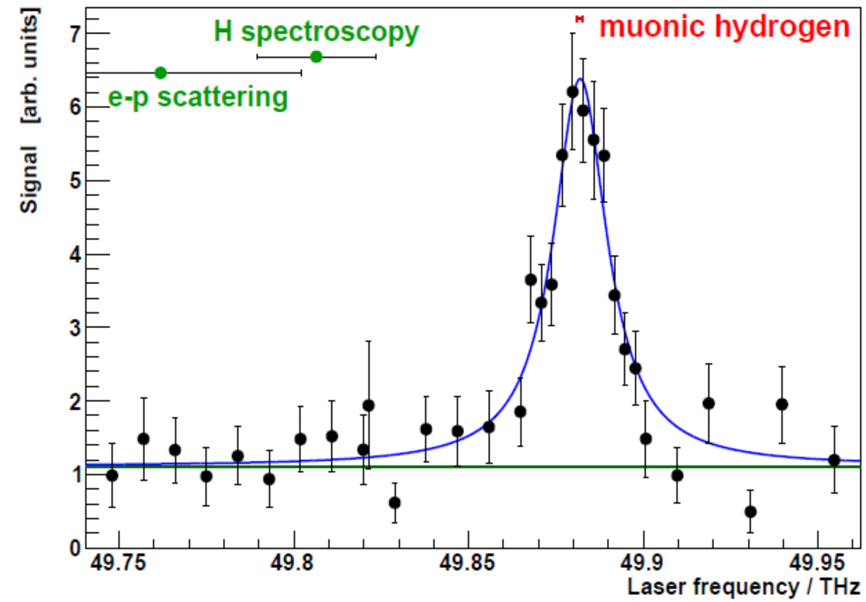
- Experimental uncertainties
- Fit of absolute normalization
- Radius sensitive to low q^2 data
- Errors truncating: $G_E^2(q^2)=1+q^2 r_p^2/6+q^4 r_p^4/120...$
- Higher order effects

off-shell structure of the proton!

Muonic hydrogen experiment



πE5 beam-line



Distance resonance centre from CODATA ~ 4 times resonance width

Not likely covered by statistical or systematic effects

laser calibration, Doppler shifts...

Presence of an electron:
ion (μpe) instead of (μp) → (μpe) is not stable!

Theory of the muonic hydrogen

$2S_{1/2} \rightarrow 2P_{3/2}$ → LAMB SHIFT+ FINE STRUCTURE + HYPERFINE STRUCTURE

Theoretical equation for the Lamb Shift:

$$\Delta E_L = 206.0243(30) - 5.2271(7)\frac{r_p^2}{\mathrm{fm}^2} + 0.0633(144) + \mathcal{O}(m_r\alpha^6)\,\mathrm{meV}$$

CP, Pineda

pure QED

Hadronic effects

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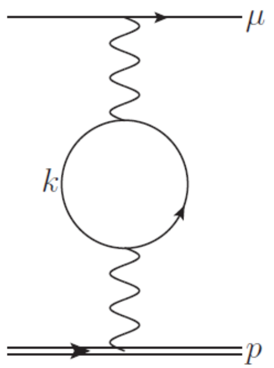


μH QED leading contribution: ELECTRON VACUUM POLARIZATION

(vs H where it is electron self energy)

HADRONIC EFFECTS encoded in δ(r) potential

EFT

H: $O(m_e\alpha^6)$

μH: $O(m_\mu\alpha^4)$

EFT for bound states (μp)

Scales in bound states | **Muonic hydrogen (Coulomb interaction)**

- Hard scale: $m_r \longrightarrow m_r$
- Soft scale: $|\mathbf{p}| \longrightarrow m_r\alpha$
- Ultrasoft scale: $E \longrightarrow m_r\alpha^2$

$\Rightarrow$ Well separated scales!

pNRQED

Scales in μH: $m_p \sim m_\rho, \quad m_\mu \sim m_\pi \sim m_r, \quad m_r\alpha \sim m_e$

→ Small expansion parameters: $\frac{m_\pi}{m_p} \sim \frac{m_\mu}{m_p} \approx \frac{1}{9}, \quad \frac{m_e}{m_r} \sim \frac{m_r\alpha}{m_r} \sim \alpha \approx \frac{1}{137}$

Energy levels:

$$E(\mu p) = \frac{-m_r\alpha^2}{2n^2}\left(1 + c_1\alpha + c_2\alpha^2 + c_3\alpha^3 \ldots\right)$$

$c_1 \sim c_1\left(\frac{m_\mu\alpha}{m_e}\right)$ pure QED, and $c_n \sim \sum_{j=0}^{\infty} c_n^{(j)}\left(\frac{m_\pi}{m_p}\right)^j; \quad c_n^{(j)} \sim c_n^{(j)}\left(\frac{m_r}{m_\mu}, \frac{m_\mu}{m_\pi} \ldots\right)$

Hadronic Effects

$$\delta\mathcal{L} = \frac{d_2}{m_p^2} F_{\mu\nu} D^2 F^{\mu\nu} - e\frac{c_D^{(p)}}{m_p^2} N_p^\dagger \nabla \cdot \mathbf{E} N_p + \frac{c_3}{m_p^2} N_p^\dagger N_p \mu^\dagger \mu$$

Hadronic contribution encoded in the delta potential:

$$\delta V^{had} = \frac{D_d^{had}}{m_p^2} \delta^{(3)}(\mathbf{r})$$

Contributes to energy levels as:

$$E_{nl}^{had} = \frac{D_d^{had}}{m_p^2} \frac{(m_r\alpha)^3}{\pi n^3} \delta_{l,0}$$

Dependence on the matching coefficients:

$$D_d^{had} \equiv -c_3^{had} - 16\pi\alpha d_2^{had} + \frac{\pi\alpha}{2} c_D^{had}$$

polarizability + Born effects

Hadronic VP

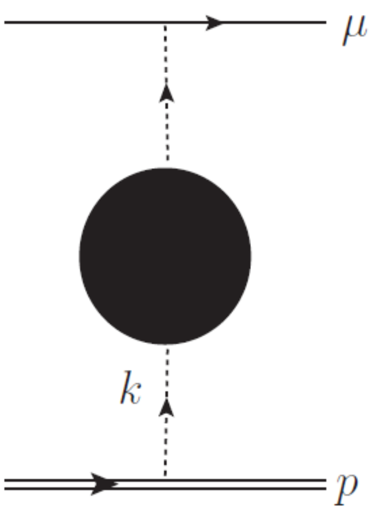
definition of the proton radius!

Hadronic vacuum polarization

$$d_2 = d_{2,R} + \frac{m_p^2}{4} \Pi'_{h,\pi}(0) = \frac{m_p^2}{4} \Pi'_h(0)$$

pion vacuum polarization:

$$\delta E_\pi = \frac{m_r \alpha^5}{24\pi} \frac{m_r^2}{m_\pi^2} = 0.00121 \text{ meV}$$



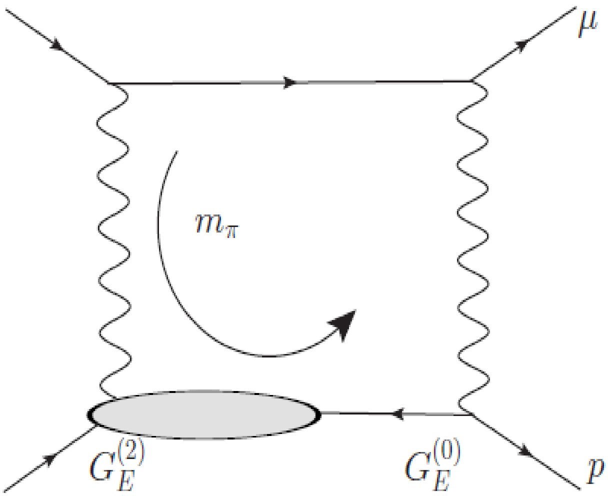
Energy shift determined from dispersion relations: $\delta E = 0.0111(2)$ meV F. Jegerlehner

(large contribution from ρ even if supressed by counting)

The error small enough so that this computation does not alter general result

Born effect

$$c_3^{\text{had}} = c_3^{\text{Born}} + c_3^{\text{pol}}$$



$$c_3^{\text{Born}} = \frac{\pi}{2}\alpha^2 m_p^2 m_\mu \langle r_p^3 \rangle$$

Zemach third momentum

$$\frac{\langle r_p^3 \rangle}{\text{fm}^3} = \frac{96}{\pi}\int d^{D-1}k \frac{1}{\mathbf{k}^6} G_E^{(0)} G_E^{(2)}$$

Large contribution from Δ(1232): $\delta E = 0.0101 + 0.0056 .. = 0.0192$ meV

- the Δ and the proton are degenerate in the large-Nc limit

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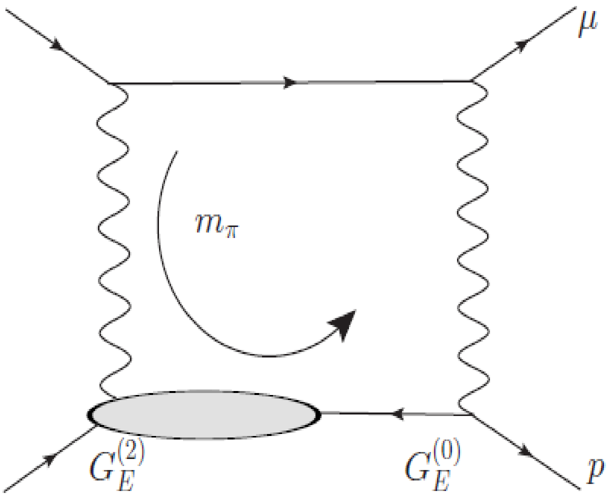

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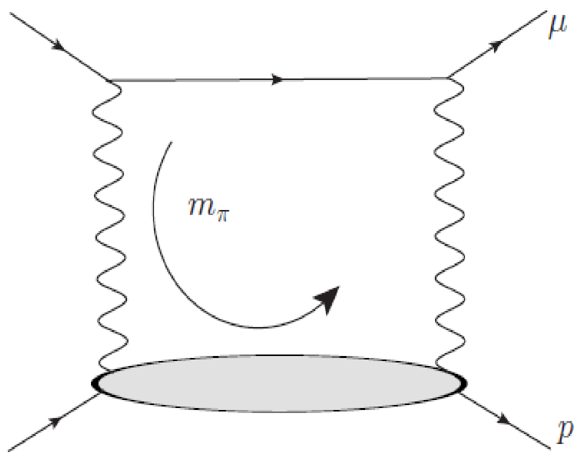
Energy shift determined from dispersion relations: $\delta E = 0.0255(10)$ meV

30% difference in compliance with higher order effects

Proton polarizability

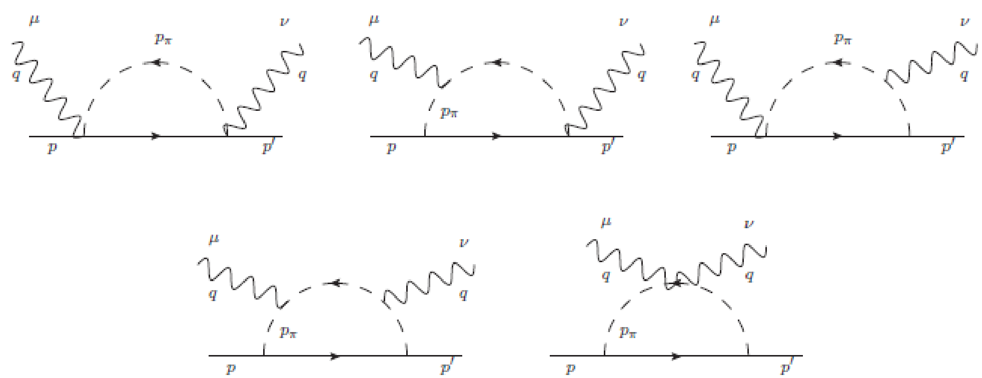
$$c_3^{\rm had} = c_3^{\rm Born} + c_3^{\rm pol}$$



Fit to experiment (model dependent):

$\delta E = 0.012(2)$ meV Pachucki

$= 0.015(4)$ meV Borie



Chiral + Δ computations:

$\delta E = 0.0185 + 0.0080 = 0.0265$ meV

CP, Pineda

+corrections suppressed by $\frac{m_\mu}{m_\rho}$ → 30% uncertainty expected

More accurate SM results can vary this result but not enough to account for the difference

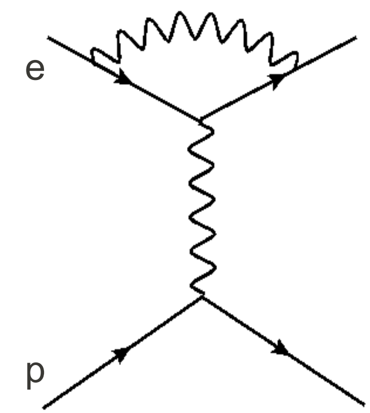
Theory of hydrogen levels

EFT for the Lamb shift:

Scales in H: $m_p \sim m_\rho, \quad m_r \sim m_e$

→ Small expansion parameters: $\frac{m_e}{m_p} \sim \frac{m_r}{m_p} \approx \frac{1}{2000}, \quad \alpha \approx \frac{1}{137}$

Energy levels: $E_{nl} \sim \sum m_r \alpha^s \left(\frac{m_e}{m_p}\right)^t$



H QED leading contribution: ELECTRON SELF ENERGY

HADRONIC EFFECTS mainly from the finite size

→ other proton structure effects suppressed by $\frac{m_e}{m_\rho}$

LIKELY RIGHT: has been *thoroughly* computed by *many* authors

Beyond the Standard Model

Are *μp* and *ep* different interactions?

- supported by: the measurement of the **proton radius**
  the **muon g-2** experiment (3-σ discrepancy)

- constrained **universality** of lepton interactions

Exciting possibility:

- **new** gauge interaction that differenciates *μ and e*

DARK MATTER CANDIDATE!

- need for further assumptions and lots of further constrains
- still a feasable possibility!

Need for further experiments

Quantum gravity?

Future perspectives

New electron scattering experiments

- higher precision and/or smaller q^2 → technical issues
- Jefferson Lab (2014-2015)

Elastic muon-proton scattering

- MUSE at PSI (2016)

Spectroscopy of electronic atoms & ions

- improve measurement of R_∞ to measure r_p from 1S-2S transition
- Several projects going on for different processes

Spectroscopy of exotic atoms

- test pure QED contributions from purely leptonic bound states
- also cross check the measurement with μHe and μD

Summary

The puzzle:

from μH: $r_p = 0.8433(17)$ fm

CODATA value (from H): $r_p = 0.8768(32)$ fm

$6.4\,\sigma$ away!

Possible sources:

- Electron experiments → Several already
- Muon experiments → Cross check
- Hadronic effects of μH theory → Not likely much larger
- Beyond SM physics → Model dependence

On the theoretical side, still possible that we are missing contributions: have to be examined

On the experimental side, more experiments are needed to reinforce the observations


THANK YOU!