Two photon exchange effects: A testable explanation of the proton radius puzzle

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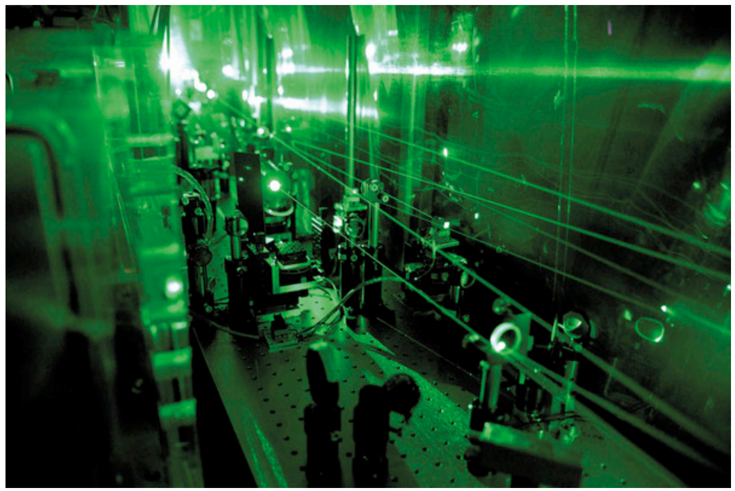
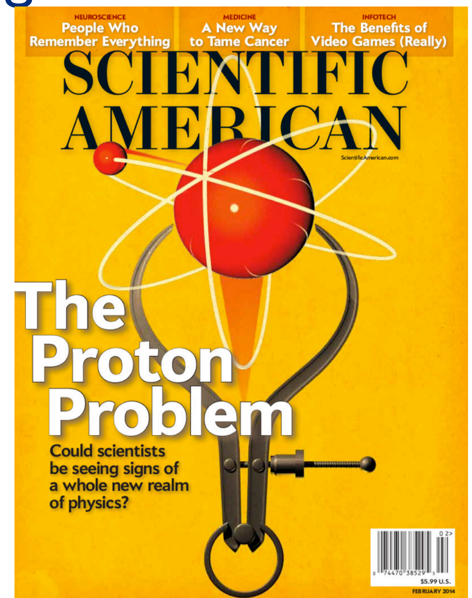
Pohl et al Nature 466, 213 (8 July 2010)





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muon H r_p =0.84184 (67) fm

electron H r_p =0.8768 (69)fm

electron-p scattering r_p =0.875 (10)fm

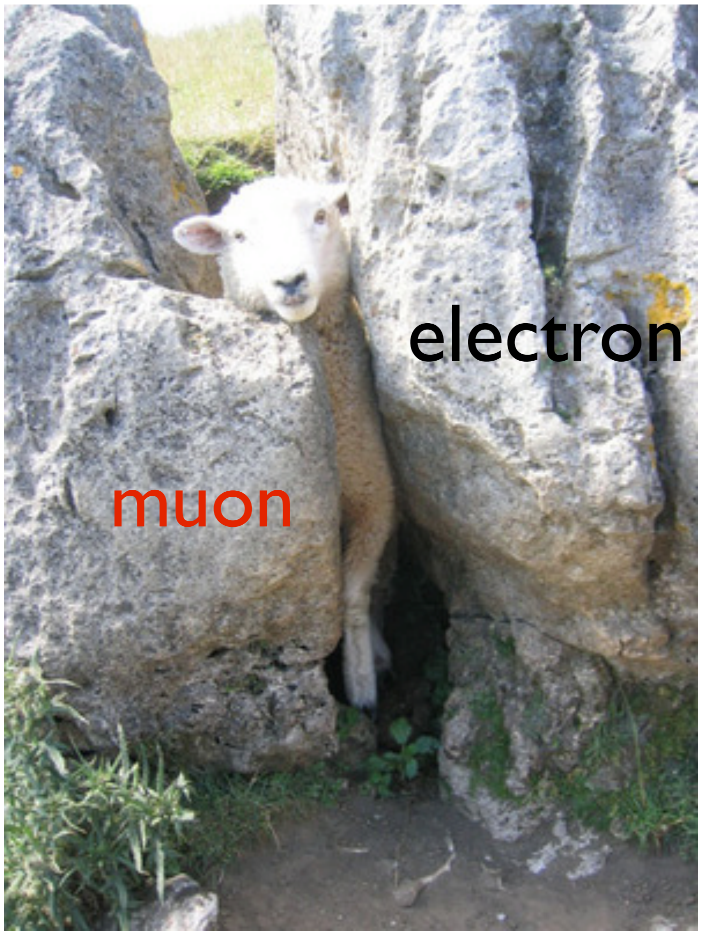
Pohl, Gilman, Miller, Pachucki (ARNPS63, 2013)

$$r_p^2 \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

Facts from Randolf, Aldo

- **proton**: radius from muons differs from radius from electrons
- **deuteron**: neutron has no influence on Lamb shift
- **deuteron**: isotope shifts from electron and muon give same $r_p^2 - r_d^2$
- **^{4}He**: radius from muons and electrons is the same

Resolving the proton puzzle



Effect on muon-H
energy shift
must vary as lepton mass
to the fourth power
otherwise ruin electron-H

Effect must have no
hyperfine
contribution

Analysis of Experiment

Extract the proton radius from the transition energy,

compare measured ξ to the following sum of contributions:

ξ=206.2949(32) meV -One measured number

$$\xi = \boxed{206.0573(45)} - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}$$

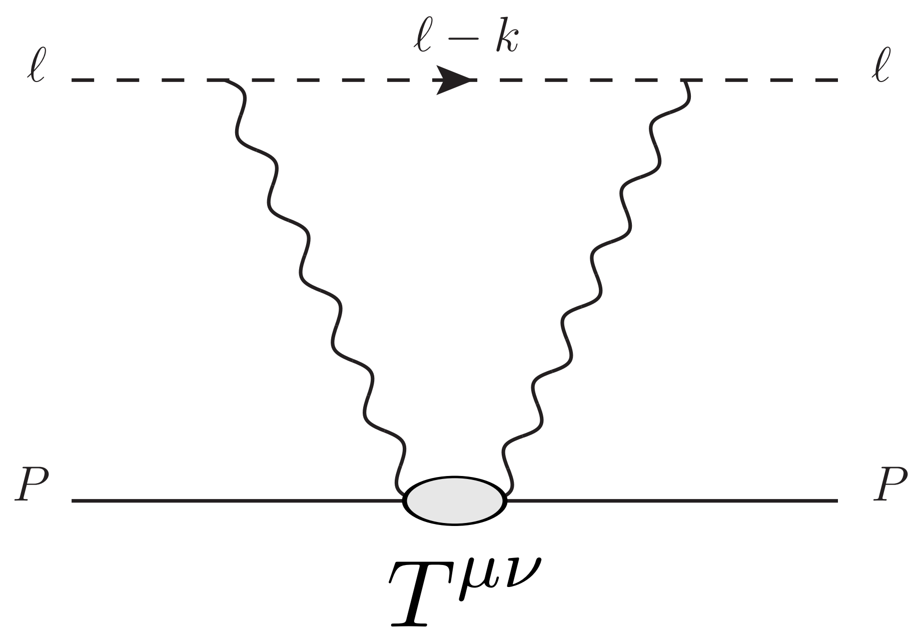
three computed numbers

To explain puzzle:

increase 206.0573 meV by 0.31 meV$= 3.1\times 10^{-10}$ MeV

Then radius is as in H atom

Our idea



lepton

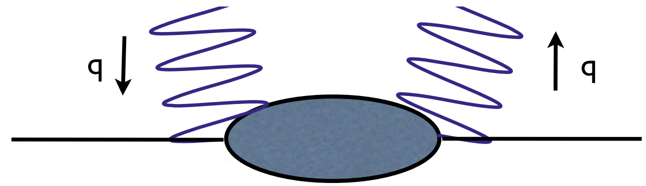
proton

lepton propagator/loop integral provides term so that energy shift is proportional to lepton mass^4

This term is in Pohl et al Table -very small

The Controversy- needed effect is 20 times that of Pachucki, Martynenko... Carlson & Vanderhaeghan 2011

$$T^{\mu\nu} =$$



$$= -(g^{\mu\nu} - \cdots)T_1 + (P^\mu - \cdots)(P^\mu - \cdots)T_2$$

Dispersion relation: $Im[T_i] \sim W_i$ measured

High photon energy (ν) : $W_1 \sim \nu$

Subtraction function needed $\overline{T}_1(\nu = 0, Q^2)$

Hill & Paz 2011 : dispersion approach
uncertainty order of mag larger than stated
My comment -two orders

Almost unknown $\overline{T}_1(0, Q^2)$ Miller PLB 2012

$$\Delta E^{\rm subt} = \frac{\alpha^2}{m}\Psi_S^2(0)\int_0^\infty \frac{dQ^2}{Q^2} h(Q^2)\overline{T}_1(0,Q^2)$$

$m = $ lepton mass

$$\lim_{Q^2 \gg m^2} h(Q^2) \sim \frac{2m^2}{Q^2},\ \text{chiral PT}:\ \overline{T}_1(0,Q^2) = \frac{\beta_M}{\alpha}Q^2 + \cdot$$

$\rightarrow$ Logarithmic divergence

$$\text{Birse \& McGovern}:\ \overline{T}_1(0,Q^2) = \frac{\frac{\beta_M}{\alpha}Q^2}{(1+\frac{Q^2}{2M_\beta^2})^2}$$

$\Delta E^{\rm subt} = .004$ meV very small

High Q^2 behavior is ASSUMED

Arbitrary functions

$$\overline{T}_1(0,Q^2) = \frac{\beta_M}{\alpha} Q^2 F_{\rm loop}(Q^2)\,.$$

$$F_{\rm loop}(Q^2) = \left(\frac{Q^2}{M_0^2}\right)^n \frac{1}{(1+aQ^2)^N},\ n \geq 2,\ N \geq n+3,$$

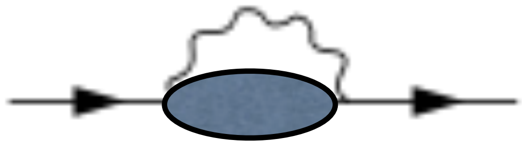
$$\overline{T}_1(0,Q^2) \sim \frac{1}{Q^4} \text{ or faster},\ \beta_M \to \beta$$

$$\Delta E^{\rm subt} \approx 3\alpha^2 m \Psi_S^2(0) \frac{\beta}{\alpha} \gamma^n B(N,n), \gamma \equiv \frac{1}{M_0^2 a}$$

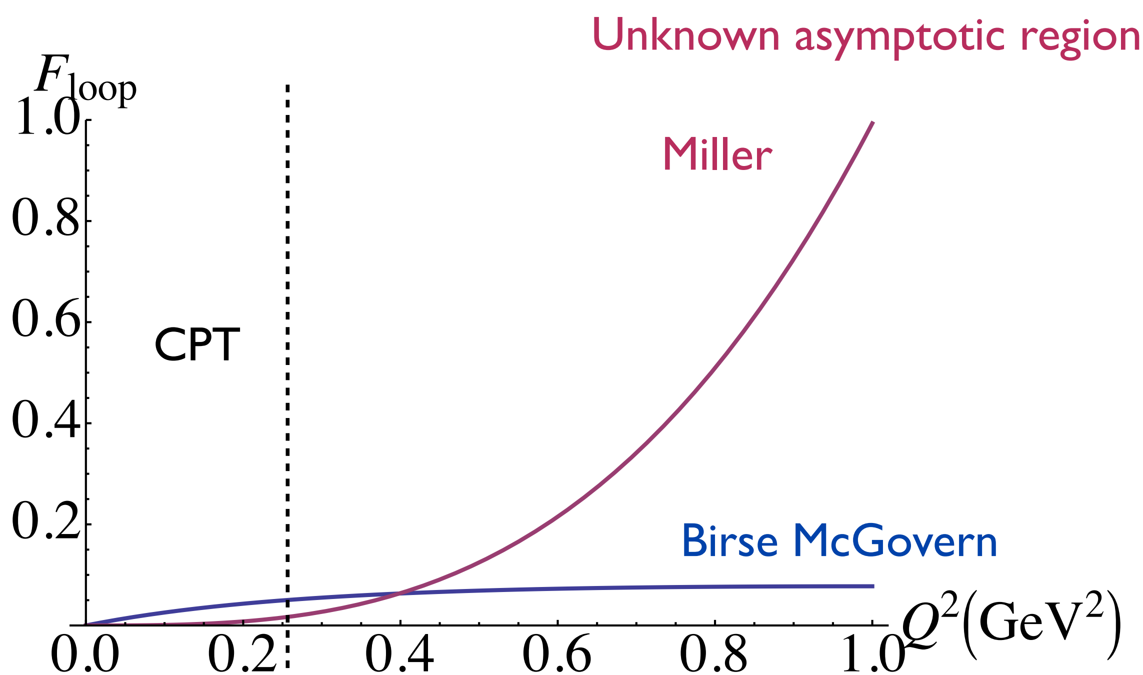
$$(M_0 = M_\beta)$$

3 parameters: n, N, a

Contribution to proton mass

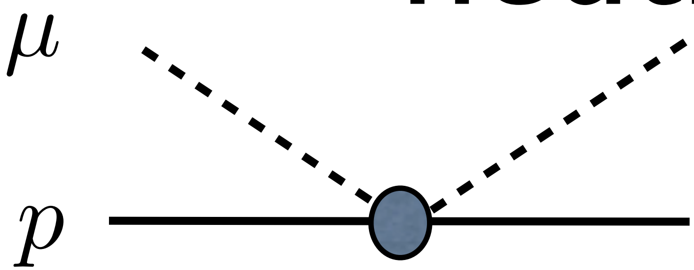


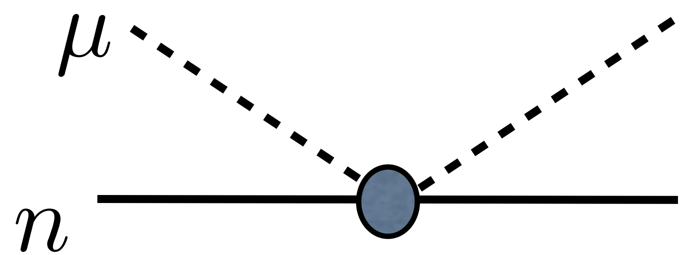
- choose parameters n,N, a to minimize this contribution, and keep **same** Lamb shift



If recast into effective field theory strength seems natural

Relevance: need neutron term



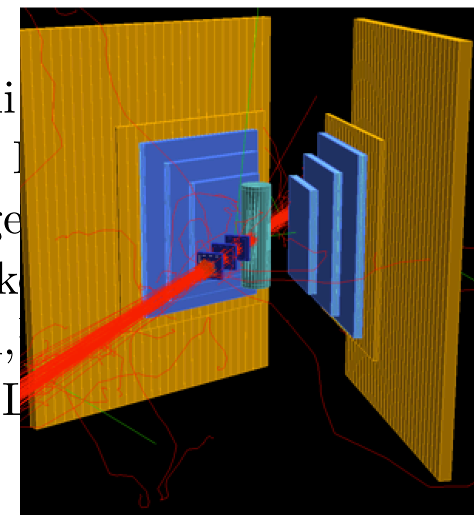


- neutron term is **not** constrained by the neutron-proton mass difference
- can adjust neutron term to get deuteron physics

So what? MUSE expt

A Proposal for the Paul Scherrer Institute πM1 beam line

Studying the Proton "Radius" Puzzle with μp Elastic Scattering



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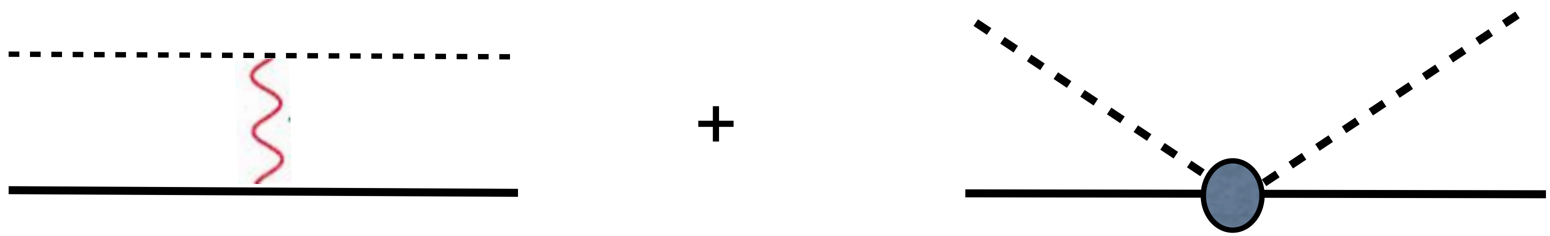
PSI proposal R-12-01.1

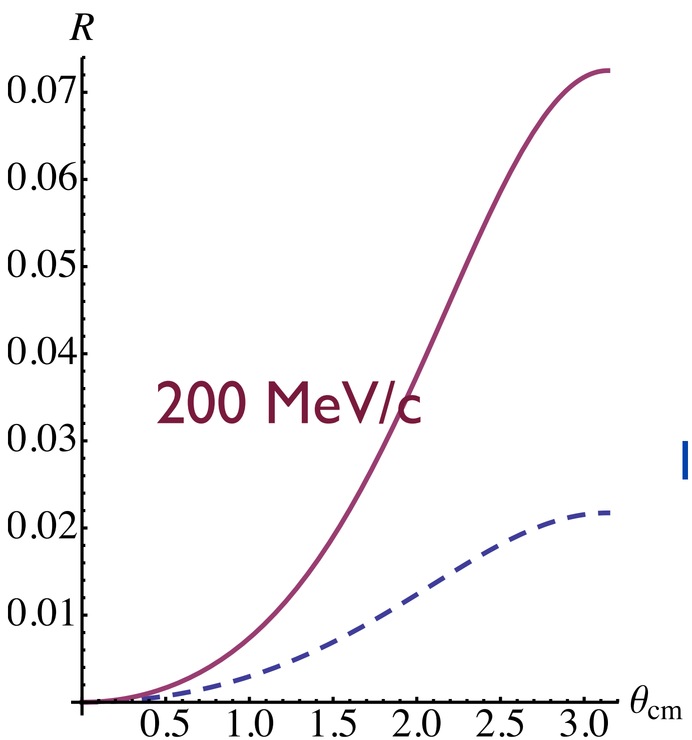
2 photon exchange idea is testable

http://www.physics.rutgers.edu/~rgilman/elasticmup/

muon scattering

$$\mathcal{M} = \mathcal{M}^{(1)} + \mathcal{M}^{(2)}$$





$$R = 2\frac{\mathrm{Re}[(\mathcal{M}^{(1)})^{*}\mathcal{M}^{(2)}]}{|\mathcal{M}^{(1)}]|^{2}}$$

~5 % effect should be seen

~10 % for ratio +/-

Deuteron, He as a test

- Need polarizability effect on neutron
- Use deuteron to determine effect on neutron (could be opposite sign)
- Then predict other nuclei

Nuclear analysis

$\mathcal{M}_{\mu p}$= 0.31 meV, from proton data, need $\mathcal{M}_{\mu n}$

Deuteron

$\Delta E_{LS} = \mathcal{M}_{\mu p} + \mathcal{M}_{\mu n} = 0.4 \pm 0.0034\,\text{meV} \rightarrow \mathcal{M}_{\mu n} = 0.09$ meV

^{4}Helium

$\Delta E_{LS} = Z^3(2\mathcal{M}_{\mu p} + 2\mathcal{M}_{\mu n}) = 8(2(0.31 + 0.09)\text{meV} = 6.4$ meV

Aldo 1 $\sigma \leftrightarrow$ 1.4 meV, so Helium energy is off by 4.6 $\sigma < 7\sigma$

Maybe 4 σ if nuclear structure uncertainties included

So this idea may explain $\leq 1/4 = 25$ % of missing energy

The only way to rule this term out is with data!!

Summary

- No BSM model works now- other ideas?
- In Two Photon Exchange- Flexibility in subtraction function?
- can resolve puzzle for p, d but 4He can't be described unless structure uncertainty is much larger than thought, but is an irritating unknown uncertainty
- Many would say: Most likely explanation at this time is in the electronic hydrogen experiments, but let all of the experiments decide
- mu p- scattering ~5% /10 % effect in mu p scattering, maybe now a ~1.3/2.6 % effect still interesting, and could kill off uncertainty