The APS Council has endorsed the establishment, contingent on funding, of the

Herman Feshbach Prize in Nuclear Physics

To recognize and encourage outstanding research in theoretical nuclear physics. The prize will consist of $10,000 and a certificate citing the contributions made by the recipient. The prize will be presented biannually or annually-depends on your contributions.

Herman Feshbach was a dominant force in Nuclear Physics for many years. He co-authored two seminal textbooks, provided the theoretical basis for nuclear reaction theory, and originated the ``Feshbach resonance" used to control the interactions between atoms in ultracold gases. He also made many administrative contributions.

The establishment of this prize depends entirely on the contributions of institutions, corporations and individuals associated with Nuclear Physics. So far, significant pledges have been made by MIT, the DNP, Elsevier, ORNL/U.Tenn, JSA/SURA, LANL, TUNL, and BSA,MSU,TRIUMF many individuals. But the collection of contributions has begun. Please make a contribution by going online at http://www.aps.org/ Look for the support banner and click APS member or non-member. Another way is to send a check, made out to "The American Physical Society", with a notation indicating the purpose is the Feshbach Prize Fund, to

Darlene Logan
Director of Development
American Physical Society
One Physics Ellipse
College Park, MD 20740-3844

If annual- number of experimentalists winning Bonner prize goes up by >50%

If you have any questions please contact G. A. (Jerry) Miller UW, miller@uw.edu.

Recent Results on the Proton Radius Puzzle

Gerald A. Miller, University of Washington

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

80 citations

muon H: r_p=0.84184(67) fm

electron H: r_p=0.8768(69)

X. Zhan et al

arXiv:1102.0318

electron scattering

$$r_p = \langle r_p^2 \rangle^{1/2} = 0.875 \pm 0.010 \text{ fm}$$

$$\langle r_{\rm p}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \Rightarrow \text{slope of } G_E \text{ at } Q^2 = 0$$

Why atomic physics to learn proton radius? Why μ H?

- Probability for lepton to reside in the proton: proton to atom volume ratio
- $\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p\ \alpha)^3\ \mathrm{m}^3$
- Muon to electron mass ratio 205! factor is about 8 million times larger for muon

Theme of this talk: muon mass

Electron-proton interaction in atoms

Coon and Bawin

Phys. Rev. C 60, 025207 (1999

Proton current

$$J^\mu = \bar{u}(p')\left(\gamma^\mu F_1(-q^2) + i\frac{\sigma^{\mu\nu}}{2M}q_\nu F_2(-q^2)\right)u(p),\ \ q \equiv p' - p$$

non-relativistic limit $J^0 \rightarrow G_E(\mathbf{q}^2) = F_1(\mathbf{q}^2) - \frac{\mathbf{q}^2}{4M^2}F_2(\mathbf{q}^2)$

change in Coulomb due to finite size

$$\Delta V_c(\mathbf{r}) = 4\pi\alpha\int\frac{d^3q e^{i\mathbf{q}\cdot\mathbf{r}}}{(2\pi)^3\mathbf{q}^2}(G_E(\mathbf{q}^2) - 1),\ \ G_E(\mathbf{q}^2) - 1 \approx 1 - \mathbf{q}^2 r_p^2/6$$

$r_p^2/6$: negative slope of G_E, not proton radius

$$\Delta V_C(\mathbf{r}) \approx -\frac{2\pi\alpha}{3}\delta(\mathbf{r})r_p^2,\ \ \Delta E = \langle\psi_S|\Delta V_C|\psi_S\rangle = \frac{2}{3}\pi\alpha|\psi_S(0)|^2 r_p^2$$

Karplus, Klein, Schwinger

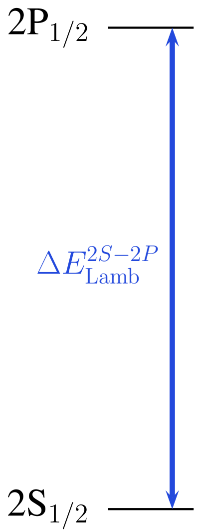
S-states only

next order term in q^2 down by $(r_p/a_B)^2$

Experiment: Basic idea

The Experiment

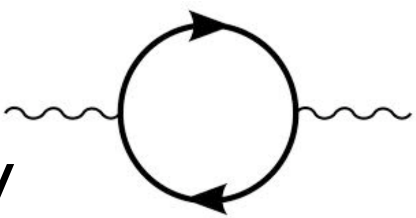
Muonic Hydrogen



$2S_{1/2}, 2P_{1/2}$ states are degenerate–
Schroedinger, Dirac eqns.

The Lamb shift is the splitting of the degenerate $2S_{1/2}$ and $2P_{1/2}$ eigenstates, due to vacuum polarization

Dominant in μH
205 of 206 meV



Dominant in eH

The experiment

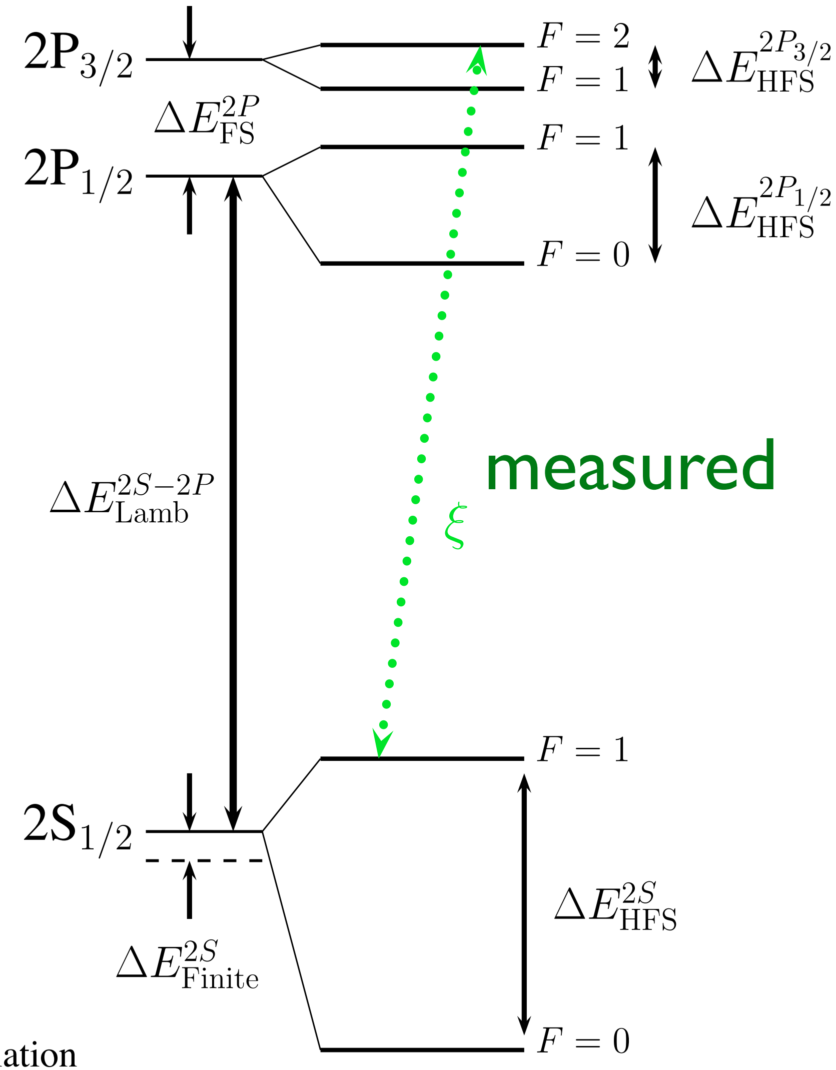
1% of stopped muons populate 2S state

2S → 2P transitions induced by laser

2P → 1S via E1 1.9 keV gamma ray

detect gamma in coincidence with laser

Fine structure and hyperfine structure corrections needed to get to Lamb shift-these OK



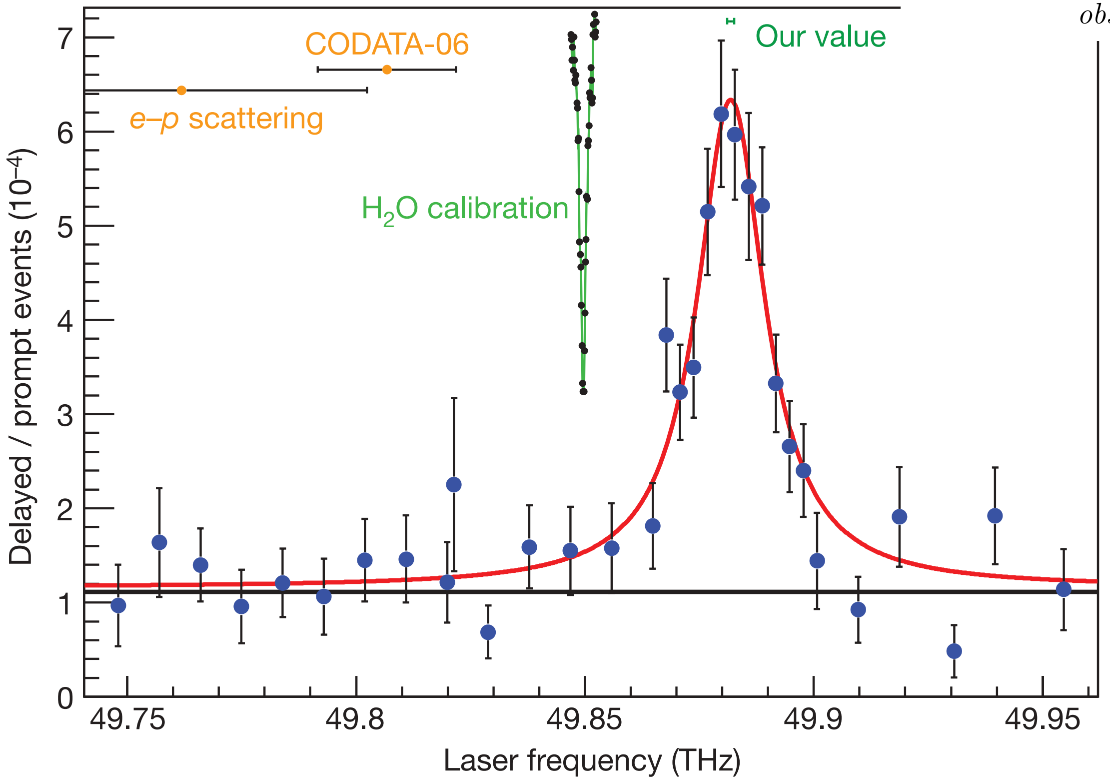
arXiv:1104.2971 Title: Non-Perturbative Relativistic Calculation of the Muonic Hydrogen Spectrum

Authors: J. D. Carroll, A. W. Thomas, J. Rafelski, G. A. Miller

Phys.Rev. A84 (2011) 012506

The experiment:
results disagree with previous measurements & world average

"The 1S-2S transition in H has been measured to 34 Hz, that is, 1.4×10^{-14} relative accuracy. Only an error of about 1,700 times the quoted experimental uncertainty could account for our observed discrepancy."



Rock Solid!

Experimental summary

Pulsed laser spectroscopy

“measure a muonic Lamb shift of 49,881.88(76) GHz. On the basis of present calculations[11–15] of fine and hyperfine splittings and QED terms, we find $r_p = 0.84184(67)$ fm, which differs by 5.0 standard deviations from the CODATA value[3] of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by −110 kHz/c (4.9 standard deviations), or the calculations of the QED effects in atomic hydrogen or muonic hydrogen atoms are insufficient.”

- Rydberg is known to 12 figures

$$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c} = 1.097\,373\,156\,852\,5\,(73) \times 10^7\ \mathrm{m}^{-1},$$

- Puzzle- why muon H different than e H?

Pohl's Table of calculations

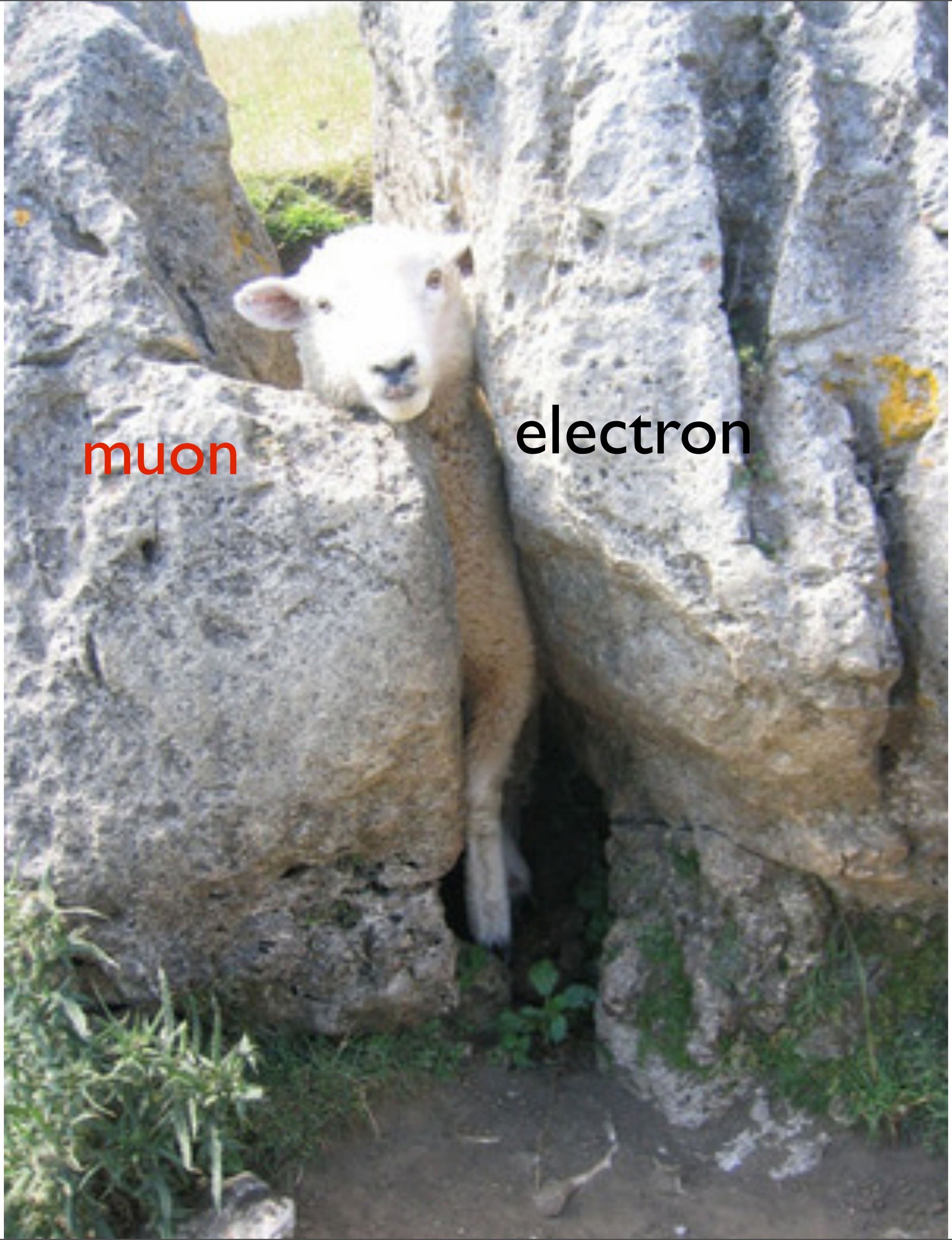
Lamb shift: vacuum polarization many, many terms

#	Contribution	Ref.	Our selection Value	Our selection Unc.	Pachucki[1–3] Value	Pachucki[1–3] Unc.	Borie[5] Value	Borie[5] Unc.
1	NR One loop electron VP	1,2			205.0074			
2	Relativistic correction (corrected)	1–3,5			0.0169			
3	Relativistic one loop VP	5	205.0282				205.0282	
4	NR two-loop electron VP	5,14	1.5081		1.5079		1.5081	
5	Polarization insertion in two Coulomb lines	1,2,5	0.1509		0.1509		0.1510	
6	NR three-loop electron VP	11	0.00529					
7	Polarisation insertion in two and three Coulomb lines (corrected)	11,12	0.00223					
8	Three-loop VP (total, uncorrected)				0.0076		0.00761	
9	Wichmann-Kroll	5,15,16	−0.00103				−0.00103	
10	Light by light electron loop contribution (Virtual Delbrück scattering)	6	0.00135	0.00135			0.00135	0.00015
11	Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	1,2	−0.00500	0.0010	−0.006	0.001	−0.005	
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	17–19	−0.00150					
13	Mixed electron and muon loops	20	0.00007				0.00007	
14	Hadronic polarization $\alpha(Z\alpha)^4 m_r$	21–23	0.01077	0.00038	0.0113	0.0003	0.011	0.002
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	22,23	0.000047					
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	22,23	−0.000015					
17	Recoil contribution	24	0.05750		0.0575		0.0575	
18	Recoil finite size	5	0.01300	0.001			0.013	0.001
19	Recoil correction to VP	5	−0.00410				−0.0041	
20	Radiative corrections of order $\alpha^n(Z\alpha)^k m_r$	2,7	−0.66770		−0.6677		−0.66788	
21	Muon Lamb shift 4th order	5	−0.00169				−0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m}{M} m_r$	2,5–7	−0.04497		−0.045		−0.04497	
23	Recoil of order α^6	2	0.00030		0.0003			
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m_r$	1,2,7	−0.00960		−0.0099		−0.0096	
25	Nuclear structure correction of order $(Z\alpha)^5$ (Proton polarizability contribution)	2,5,22,25	0.015	0.004	0.012	0.002	0.015	0.004
26	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	23	0.00019					
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	23	−0.00001					
	Sum		206.0573	0.0045	206.0432	0.0023	206.05856	0.0046

Table 1: All known radius-**independent** contributions to the Lamb shift in μp from different authors, and the one we selected. We follow the nomenclature of Eides *et al.*[7] Table 7.1. Item # 8 in Refs.[2,5] is the sum of items #6 and #7, without the recent correction from Ref.[12]. The error of #10 has been increased to 100% to account for a remark in Ref.[7]. Values are in meV and the uncertainties have been added in quadrature.

Contribution	Ref.	our selection		Pachucki[2]	Borie[5]
Leading nuclear size contribution	26	−5.19745	$< r_p^2 >$	−5.1974	−5.1971
Radiative corrections to nuclear finite size effect	2,26	−0.0275	$< r_p^2 >$	−0.0282	−0.0273
Nuclear size correction of order $(Z\alpha)^6 < r_p^2 >$	1,27–29	−0.001243	$< r_p^2 >$		
Total $< r_p^2 >$ contribution		−5.22619	$< r_p^2 >$	−5.2256	−5.2244
Nuclear size correction of order $(Z\alpha)^5$	1,2	0.0347	$< r_p^3 >$	0.0363	0.0347

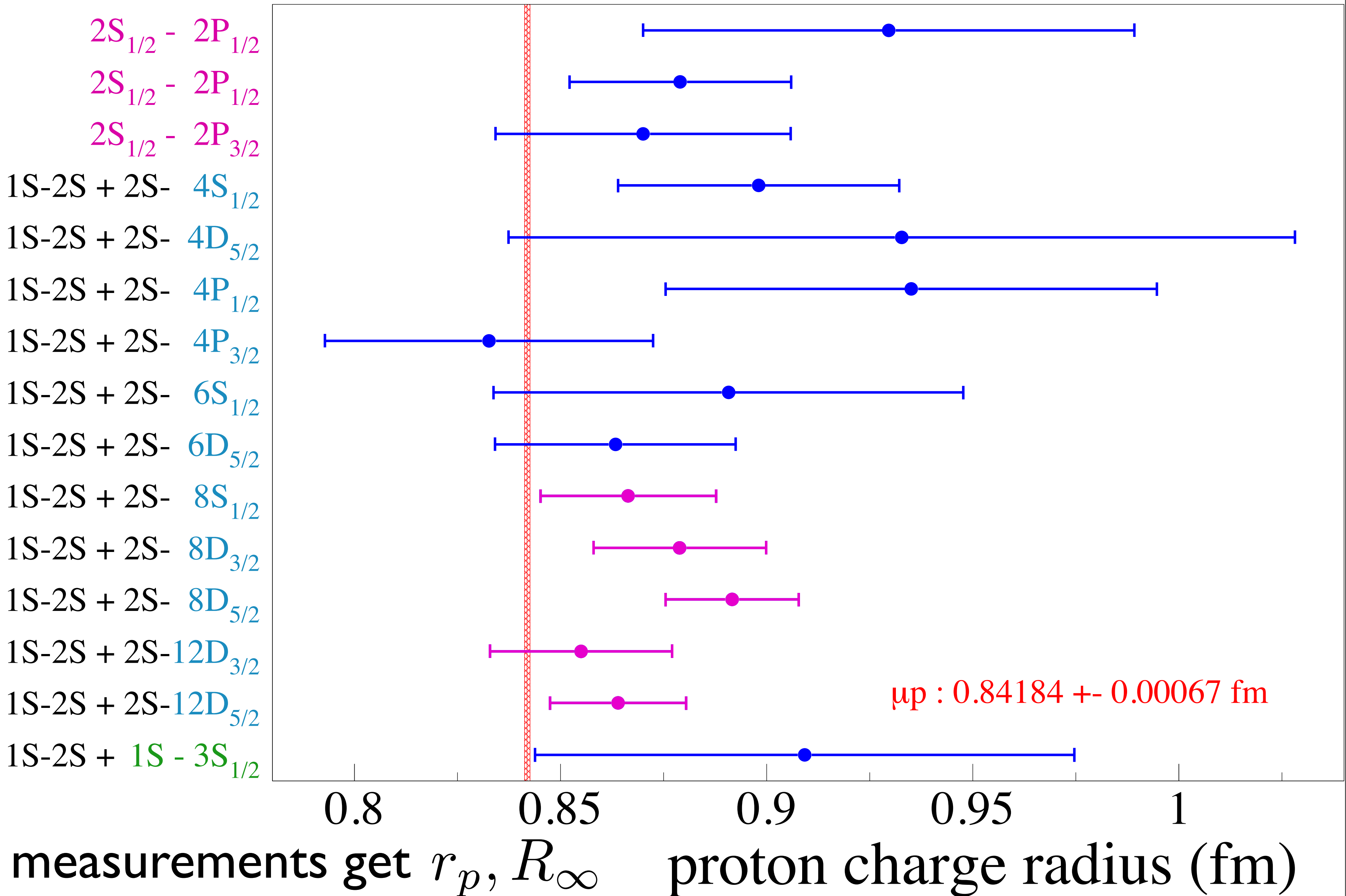
Table 2: All relevant radius-**dependent** contributions as summarized in Eides et al.[7], compared to Refs.[2,5]. Values are in meV and radii in fm.


muon
electron

Possible resolutions

- electron experiments not so accurate
- muon interacts differently than electron
- Strong interaction effect in loop diagram

Electronic Hydrogen -Pohl



2 measurements get r_p, R_∞

$\mu \neq \mathrm{e}$

- Marciano, INT Talk summer 2010-massive photon, violate mu-e universality, matter effects in neutrino oscillations too big by 10000
- Barger et al "We consider exotic particles that couple preferentially to muons, and mediate an attractive nucleon-muon interaction. Many constraints from low energy data disfavor new spin-0, spin-1 and spin-2 particles as an explanation.PRL **106, 153001**
- Brax, Burrage "Combining these constraints with current particle physics bounds, the contribution of a scalar field to the recently claimed discrepancy in the proton radius is negligible."Phys.Rev.D83:035020,2011
- Batell, McKeen, Pospelov **PRL 107,081802** New force differentiates between lepton species. Models with gauged right-handed muon number, contain new vector and scalar force carriers at the 100 MeV scale or lighter. Such forces would lead to an enhancement by several orders-of-magnitude of the parity-violating asymmetries in the scattering of low-energy muons on nuclei. Related to muon g-2
- Barger et al, PRL**108, 081802,** previous BMP model is constrained by K decays if new particles are long lived
- Carlson, Rislow, arXiv:1206.3587 Conclusions: New physics with fine tuned couplings may be entertained as a possible explanation for the Lamb shift discrepancy.

Experimental analysis

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

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

three computed numbers

To explain puzzle:

increase 206.0573 meV by 0.31 meV= 3.1×10^{-10} MeV

Our idea I- bound proton is off its mass shell in two photon exchange

Miller, Carroll, Thomas, Rafelski Phys.Rev. A84 (2011) 012506

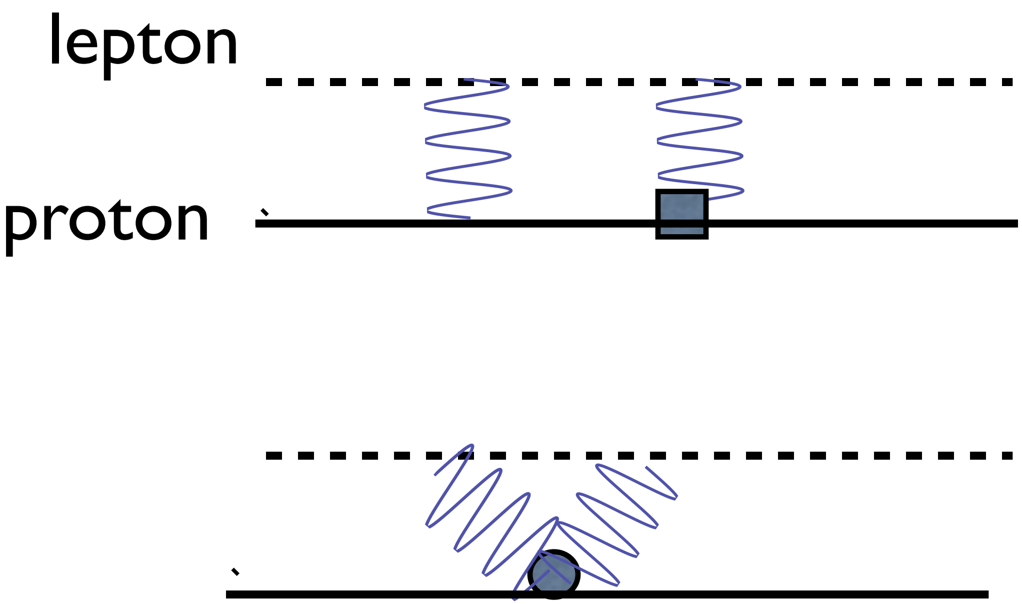
- form factor contains terms containing

  $p \cdot \gamma - M,\ p^2 - M^2$ Inverse propagator

- ``virtuality'' terms important for EMC effect, Strikman Frankfurt, Kulagin, Petti, Melnitchouk ...

- Old idea-Zemach in 50's
- Bincer 1960, Naus & Koch (1987)
- (half-on) vertex function has 4 invariant functions

Idea behind calculation



$$\frac{1}{(p+q)^2 - M^2}\left((p+q)^2 - M^2\right)$$

Lamb shift goes as lepton mass to the fourth power

Our idea-specifics

$$\Gamma^\mu(p',p) = \gamma_N^\mu F_1(-q^2) + F_1(-q^2)F(-q^2)\mathcal{O}^\mu_{a,b,c} \qquad q = p' - p$$

$$\mathcal{O}^\mu_a = \frac{(p+p')^\mu}{2M}[\Lambda_+(p')\frac{(p\cdot\gamma_N - M)}{M} + \frac{(p'\cdot\gamma_N - M)}{M}\Lambda_+(p)]$$

$$\mathcal{O}^\mu_b = ((p^2 - M^2)/M^2 + (p'^2 - M^2)/M^2)\gamma_N^\mu$$

$$\mathcal{O}^\mu_c = \Lambda_+(p')\gamma_N^\mu\frac{(p\cdot\gamma_N - M)}{M} + \frac{(p'\cdot\gamma_N - M)}{M}\gamma_N^\mu\Lambda_+(p)$$

$$\lambda F(-q^2) = \frac{-\lambda q^2/b^2}{(1 - q^2/\widetilde{\Lambda}^2)^{1+\xi}}.$$

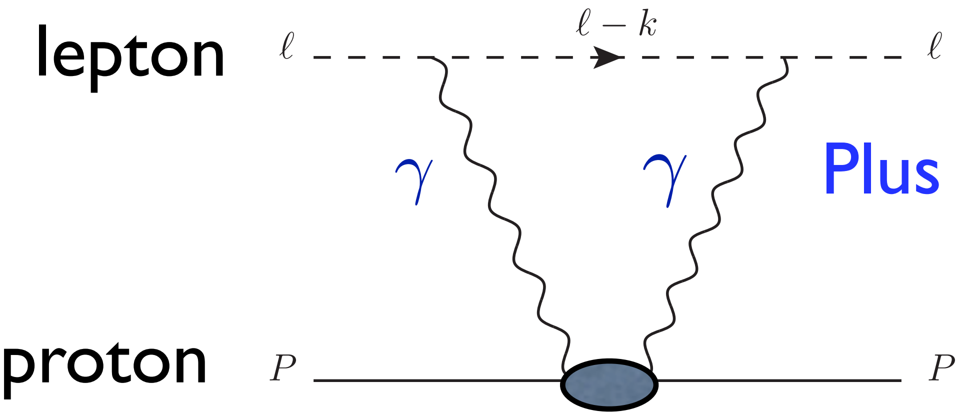
F(0)=0,
off-shell proton charge = proton charge
gauge invariance

parameters $\lambda/b^2,\ \tilde{\Lambda} = \Lambda,\ \xi = 0$

- Ball Chiu (1980) qed

Many many more models are possible!

Evaluate diagram



Plus crossed photon graph

$$\mathcal{O}_a \to \quad \mathcal{M}_{\rm Off} = \frac{e^4}{2M^2}\int \frac{d^4k}{(2\pi)^4}\frac{F_1^2(-k^2)F(-k^2)}{(k^2+i\epsilon)^2}\,\lambda \qquad (4)$$
$$\times(\gamma_N^\mu(2p+k)^\nu + \gamma_N^\nu(2p+k)^\mu)$$
$$\times\left[\gamma_\mu\frac{(l\cdot\gamma - k\cdot\gamma + m)}{k^2-2l\cdot k+i\epsilon}\gamma_\nu + \gamma_\nu\frac{(l\cdot\gamma + k\cdot\gamma + m)}{k^2+2l\cdot k+i\epsilon}\gamma_\mu\right],$$

$l_{\mu\nu}$ lepton tensor gives factor m

Model a

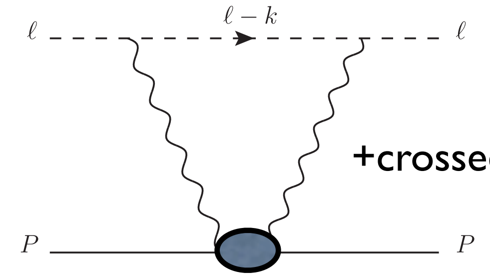
gauge invariant, $\mathcal{M}_{\rm Off} \approx$ constant

$\to \delta(\vec{r})V_0$ coordinate space

Vary λ to obtain needed 0.31 meV shift.

The Controversy- our effect is 20 times that of Pachucki, Martynenko... Carlson & Vanderhaeghan 1101.5965

Conventional approach $\sim$ Pachucki



+crossed photons

$$\Delta E \propto \alpha^5 m^3 \int \frac{d^4q}{q^4} T^{\mu\nu} l_{\mu\nu}(m)$$

$T^{\mu\nu}$ is forward virtual-photon proton scattering amplitude,

$l_{\mu\nu}(m)$ is lepton-tensor

$$T^{\mu\nu}(q,P) = -i \int d^4x e^{iq\cdot x} \langle P|T(j^\mu(x) j^\nu(0)|P\rangle$$

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

$Im(T_{1,2}) \propto W_{1,2}$ Measured structure functions

Cauchy plus data $\longrightarrow$ answers –rock solid (?)

$$T_{1,2}(q \cdot P/M, q^2) = T_{1,2}(q_0, Q^2)$$

$$T_{1,2}(q \cdot P/M, q^2) = T_{1,2}(q_0, Q^2)$$

$$Im T_{1,2} \sim W_{1,2}$$

$$W_2 \sim 1/\nu, \; W_1 \sim \nu \text{ large } \nu$$

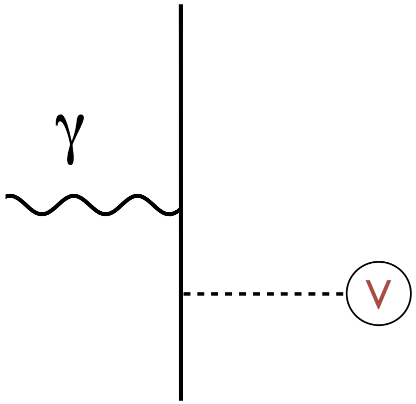
- Dispersion integral involving W_2 converges
- Dispersion integral involving W_1 diverges- subtraction needed at all Q^2

Features

- need subtracted dispersion relation for T_1
- subtraction function ($q^0 = 0$, all q^2) largely unknown $\overline{T}_1(0, Q^2)$
- Assume our model is OK, look for tests

- Quasielastic scattering, Coulomb sum rule
- 2 photon exchange term in ep scattering
- etc

Nuclear modification of form factor

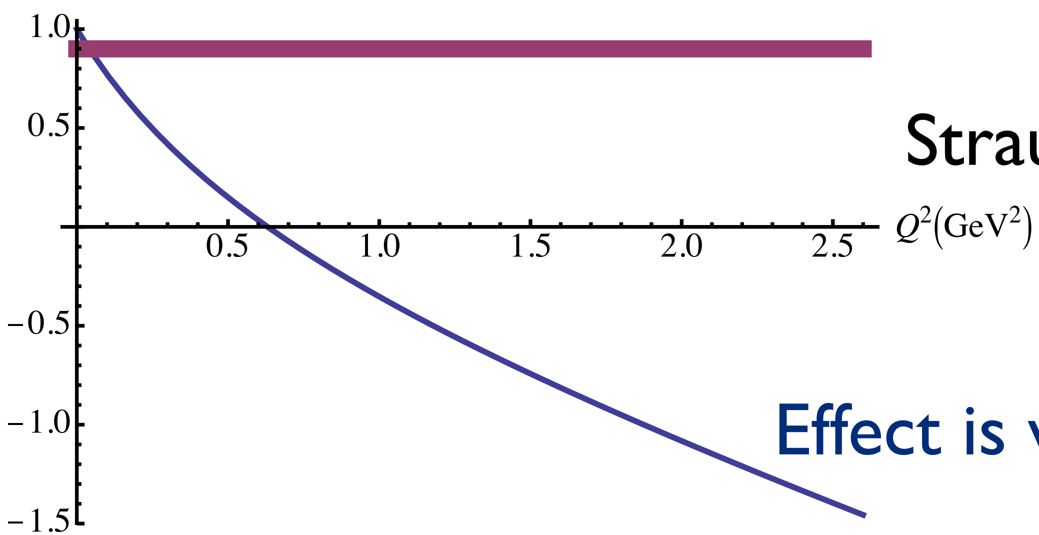


$$\Delta F_1 = -\Delta F_2$$

$$\bar{u}(p')\Gamma^{\mu}_{\rm med}u(p) \;=\; F_1(q^2)\bar{u}(p')\left[\gamma^{\mu}(1+f(Q^2)) - i\frac{\sigma^{\mu\nu}q_{\nu}}{2M}f(Q^2)\right]u(p),$$ +F_2 term

f proportional to λV V=8 MeV

Ratio of G_E/G_M medium to free



Data

Strauch et al ^{4}He

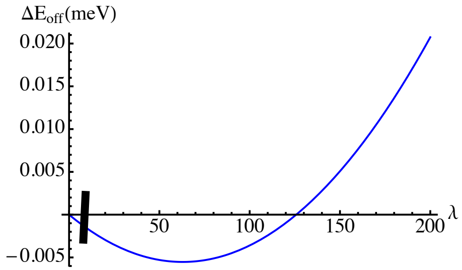
Effect is way too big

Miller, Thomas, Carroll arXiv:1207.0549

Fix: change the operator

$$\mathcal{O}^\mu = \lambda F(Q^2)[F_1(Q^2)(\gamma^\mu - \frac{\not{q}\, q^\mu}{q^2}) + i\frac{\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)]\,\frac{(\not{p}^{\rm off} - M)}{M}.$$

- F_1 and F_2 changed the same.
- No change to ratios of form factors!
- Compute Lamb shift, needs large value of λ



- Magnitude of quasi-elastic scattering hugely changed
- Strike 2! Is 2 photon exchange dead?-No

Unknown subtraction function $\overline{T}_1(0,Q^2)$ **Does not use off-shell idea**

arXiv:1209.4667
Proton Polarizability Contribution: Muonic Hydrogen Lamb Shift and Elastic Scattering
Gerald A. Miller

Pachucki

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

$$h(Q^2) = \left(1 - \frac{Q^2}{2m^2}\right)\left(\left(1+\frac{4m^2}{Q^2}\right)^{1/2} - 1\right) + 1$$

$$\sim 2m^2/Q^2 \text{ large } Q^2,\ \overline{T}_1(0,Q^2) = \frac{Q^2}{\alpha}\beta_M$$ log divergence

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

Pachucki, Martynenko, Carlson & Vanderhaeghen: form factor $F_{\rm loop}(Q^2)$ cuts off integral

Birse & McGovern 2012 $\overline{T}_1^{BM}(0,Q^2) \simeq \frac{\beta_M}{\alpha} Q^2 \left(1 - \frac{Q^2}{M_\beta^2} + \mathcal{O}(Q^4)\right) \to \frac{\beta_M}{\alpha} Q^2 \frac{1}{\left(1+\frac{Q^2}{2M_\beta^2}\right)^2}$

$M_\beta = 460 \pm 50$ MeV, $\Delta E^{subt} = 4.1\mu$ eV

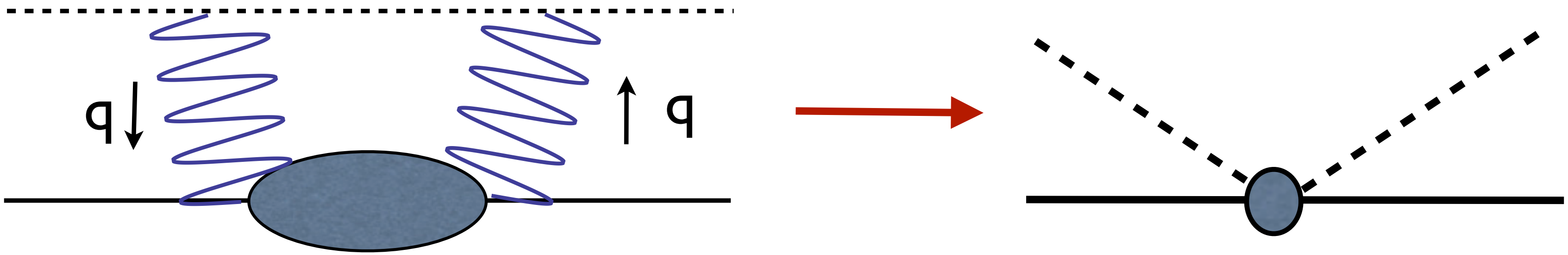
New here: $F_{\rm loop}(Q^2) = \frac{Q^4}{M_\gamma^4}\frac{1}{(1+aQ^2)^3},\ 1/a = 5.65\ \text{GeV}^2$

$M_\gamma = 500$ MeV

$\Delta E^{subt} = 0.31$ meV

EFT of μp interaction

- Compute Feynman diagram, remove log divergence using dimensional regularization
- include counter term in Lagrangian



$$\mathcal{M}_2^{DR} = \frac{3}{2} i\, \alpha^2 m \frac{\beta_M}{\alpha} \left[\frac{2}{\epsilon} + \log\frac{\mu^2}{m^2} + \frac{5}{6} - \gamma_E + \log 4\pi\right] \overline{u}_f u_i \overline{U}_f U_i,$$

$$= i\, \alpha^2 m \frac{\beta_M}{\alpha} (\lambda + 5/4)\, \overline{u}_f u_i \overline{U}_f U_i$$

Choose λ to get 0.31 meV shift

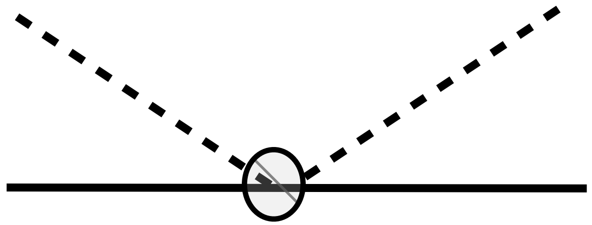
$$\Delta E^{DR} = \alpha^2 m \frac{\beta_M}{\alpha} \phi^2(0)(\lambda + 5/4).$$

$$\Delta E^{DR} = 0.31 \text{ meV} \rightarrow \lambda = 769$$

λ seems large but β_M (mag. polarizability) $= 3.1 \times 10^{-4}$ fm^3 very small

Natural units $\beta_M/\alpha \sim 4\pi/(4\pi f_\pi)^3$ Butler & Savage '92

$$\mathcal{M}_2^{DR} = i\, 3.95\, \alpha^2 m \frac{4\pi}{\Lambda_\chi^3} \overline{u}_f u_i \overline{U}_f U_i.$$



3.95 =natural

So what?

A Proposal for the Paul Scherrer Institute πM1 beam line

Studying the Proton "Radius" Puzzle with μp Elastic Scattering

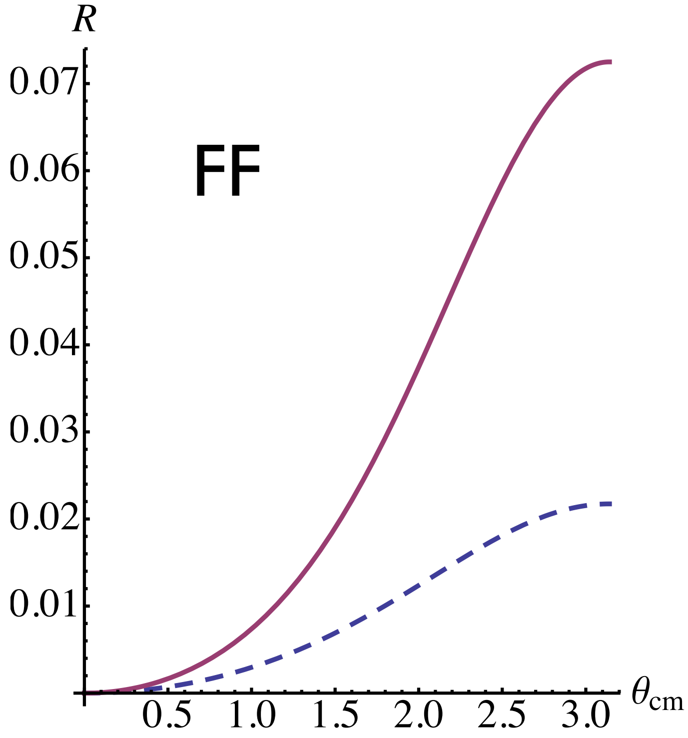
J. Arrington,[1] F. Benmokhtar,[2] E. Brash,[2] K. Deiters,[3] C. Djalali,[4] L. El Fassi,[5] E. Fuchey,[6] S. Gilad,[7] R. Gilman (Contact person),[5] R. Gothe,[4] D. Higinbotham,[8] Y. Ilieva,[4] M. Kohl,[9] G. Kumbartzki,[5] J. Lichtenstadt,[10] N. Liyanage,[11] M. Meziane,[12] Z.-E. Meziani,[6] K. Myers,[5] C. Perdrisat,[13] E. Piasetzsky (Spokesperson),[10] V. Punjabi,[14] R. Ransome,[5] D. Reggiani,[3] A. Richter,[15] G. Ron,[16] A. Sarty,[17] E. Schulte,[6] S. Strauch,[4] V. Sulkosky,[7] A.S. Tadapelli,[5] and L. Weinstein[18]

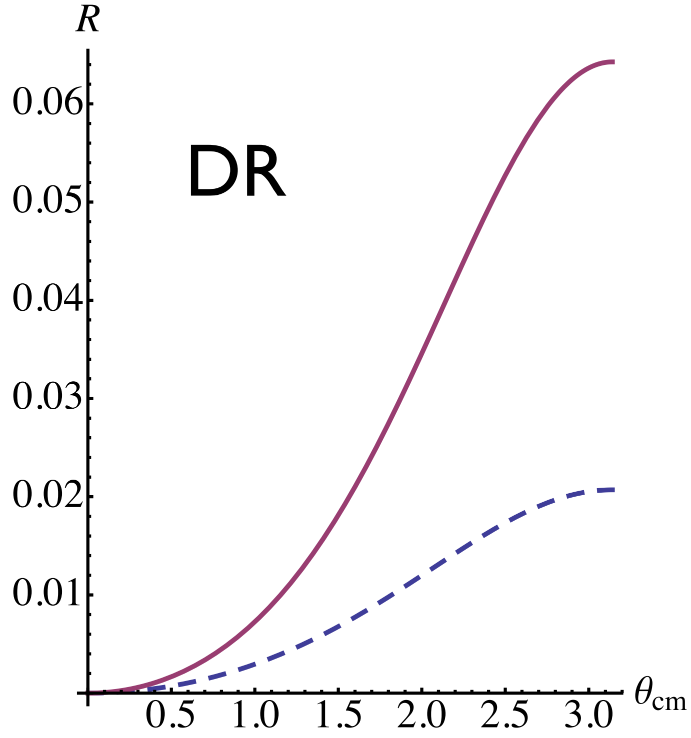
PSI proposal R-12-01.1

2 photon exchange idea is testable

Observable Effect in $\mu^- p$ Scattering

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





Summary

- Logarithmic divergence in the integrand that determines the value of ΔE^{subt}.
- The uncertainty in evaluation large enough to account for the proton radius puzzle.
- Logarithmic divergence controlled via form factor or dimensional regularization
- Either method account for the proton radius puzzle
- Either method predicts (same) observable few % effect- low energy $\mu - p$ scattering.

Explanations for the proton radius puzzle:

- Electronic-hydrogen experiments might not be as accurate as reported
- $\mu - e$ universality might be violated
- strong interaction effect important for muonic hydrogen, but not for electronic

Which correct ???

Strong-interaction effect discussed here is testable experimentally