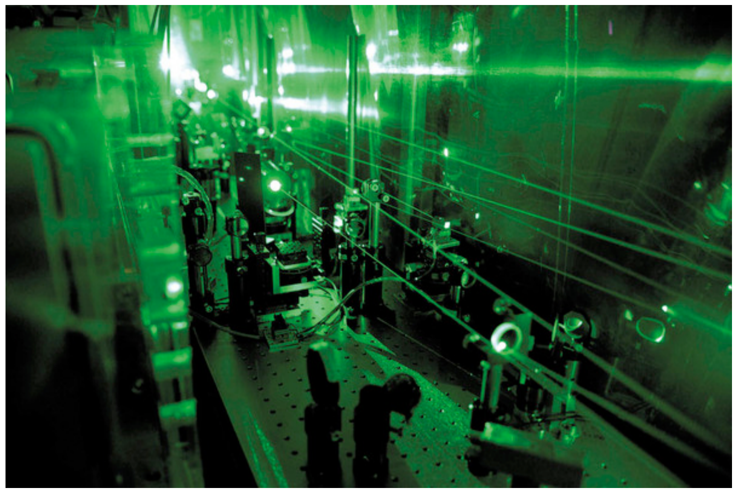
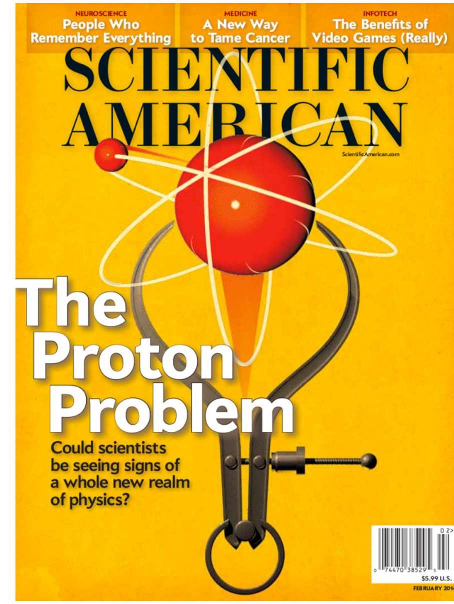
The Proton Radius Puzzle

Gerald A. Miller, University of Washington

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





Feb. 2014

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

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

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

PRad at JLab- lower Q^2

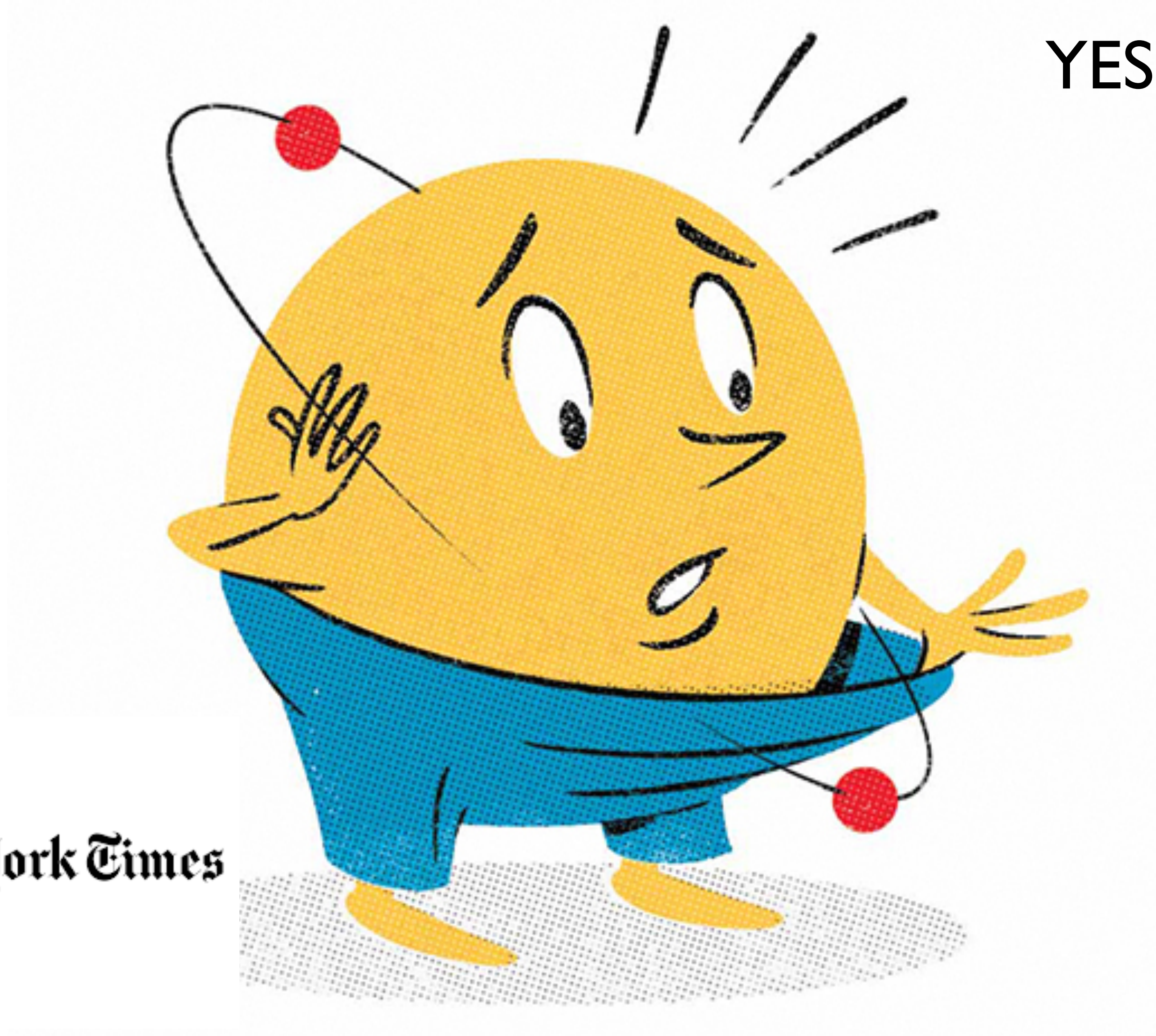
4 % Difference

4 % in radius: why care?

- Can’t be calculated to that accuracy
- 1/2 cm in radius of a basketball

Is the muon-proton interaction the same as the electron-proton interaction? - many possible ramifications

Does 4% matter?



YES

The New York Times

Summary/Outline

- If all of the experiments, and their analyses, are correct a new scalar boson of mass ~1 MeV must exist
- Direct detection is needed.: detection seems to be difficult:

David McKeen, Yu-Sheng Lu

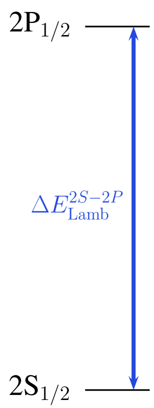
$$p(1.88\,\mathrm{MeV}) +^{19} F \rightarrow \alpha +^{16} O^*(6.05)$$
$$^{16}O^*(6.05) \rightarrow^{16} O(GS) + \phi$$

0+ to 0+ (no photon emission)

Electron-positron resonant elastic scattering

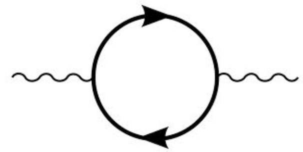
Beam dump experiments, muon facilities

muonic hydrogen experiment



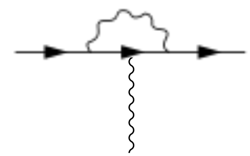
The Lamb shift is the splitting of the degenerate $2S_{1/2}$ and $2P_{1/2}$ eigenstates

Dominant in μH



vacuum polarization 205 of 206 meV

Dominant in eH



electron self-energy

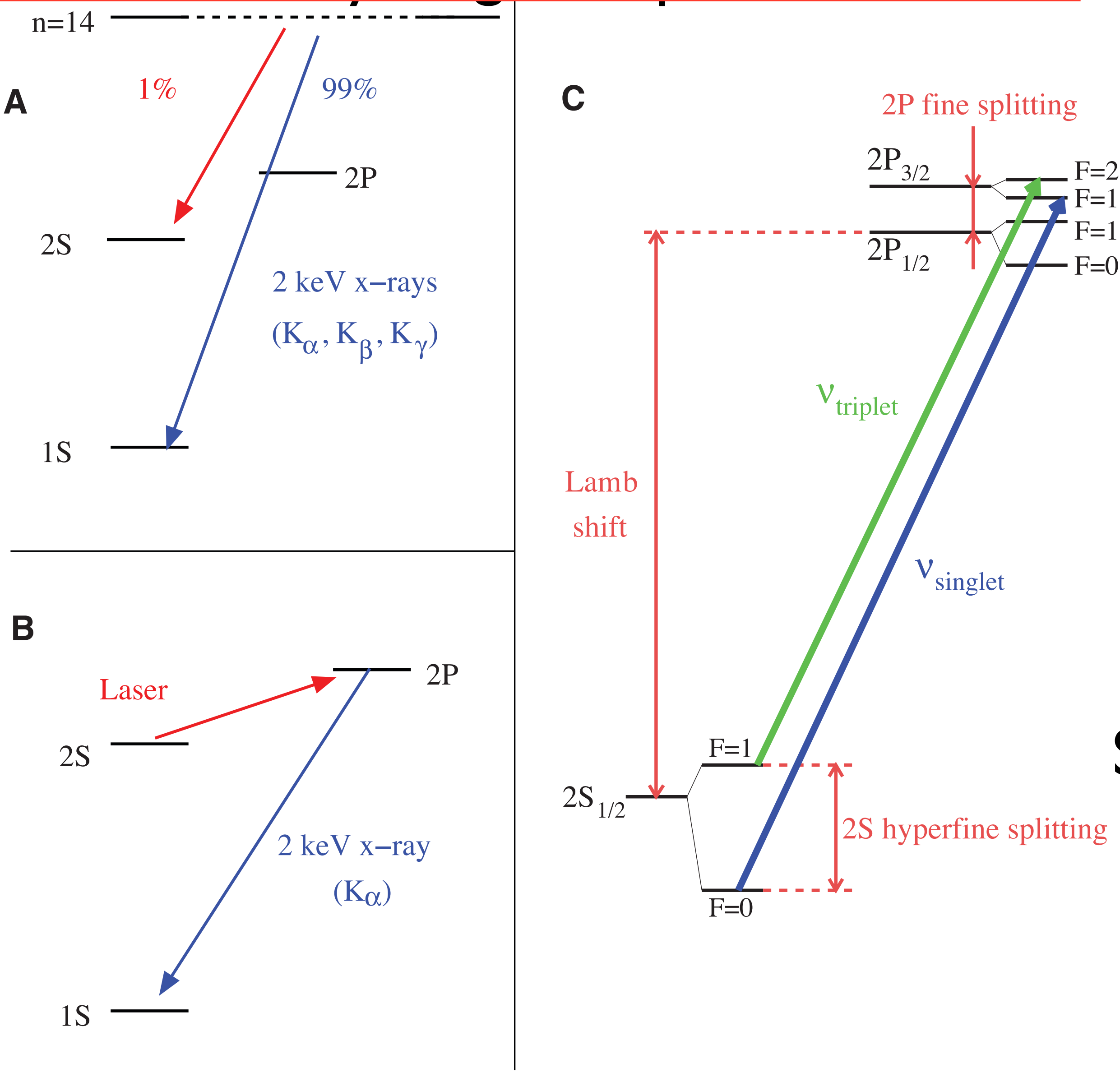
Proton radius in Lamb shift

$$\Delta E = \langle \Psi_S | V_C - V_C^{\rm pt} | \Psi_S \rangle = \frac{2}{3}\pi\alpha |\Psi_S(0)|^2 (-6 G_E'(0))$$

Muon/electron mass ratio 205! 8 million times larger for muon

Recoil effects included:
interaction computed for moving fermions

Muonic Hydrogen Experiment



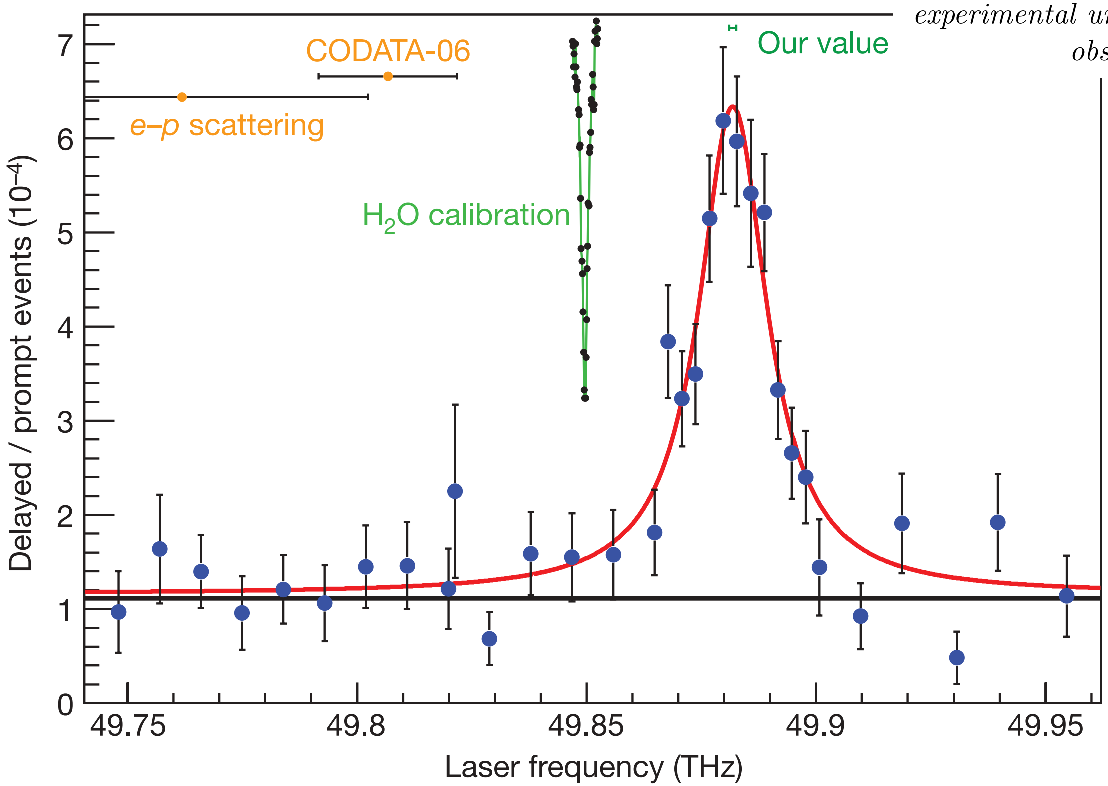
From 2013 Science paper

Fig. 1. (**A**) Formation of μp in highly excited states and subsequent cascade with emission of "prompt" $K_{\alpha,\ \beta,\ \gamma}$. (**B**) Laser excitation of the 2S-2P transition with subsequent decay to the ground state with K_α emission. (**C**) 2S and 2P energy levels. The measured transitions ν_s and ν_t are indicated together with the Lamb shift, 2S-HFS, and 2P-fine and hyperfine splitting.

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."

2010 Rock Solid!



7 standard deviation difference in r_p- or value of Rydberg constant has to be shifted- (12 figures) or new physics!

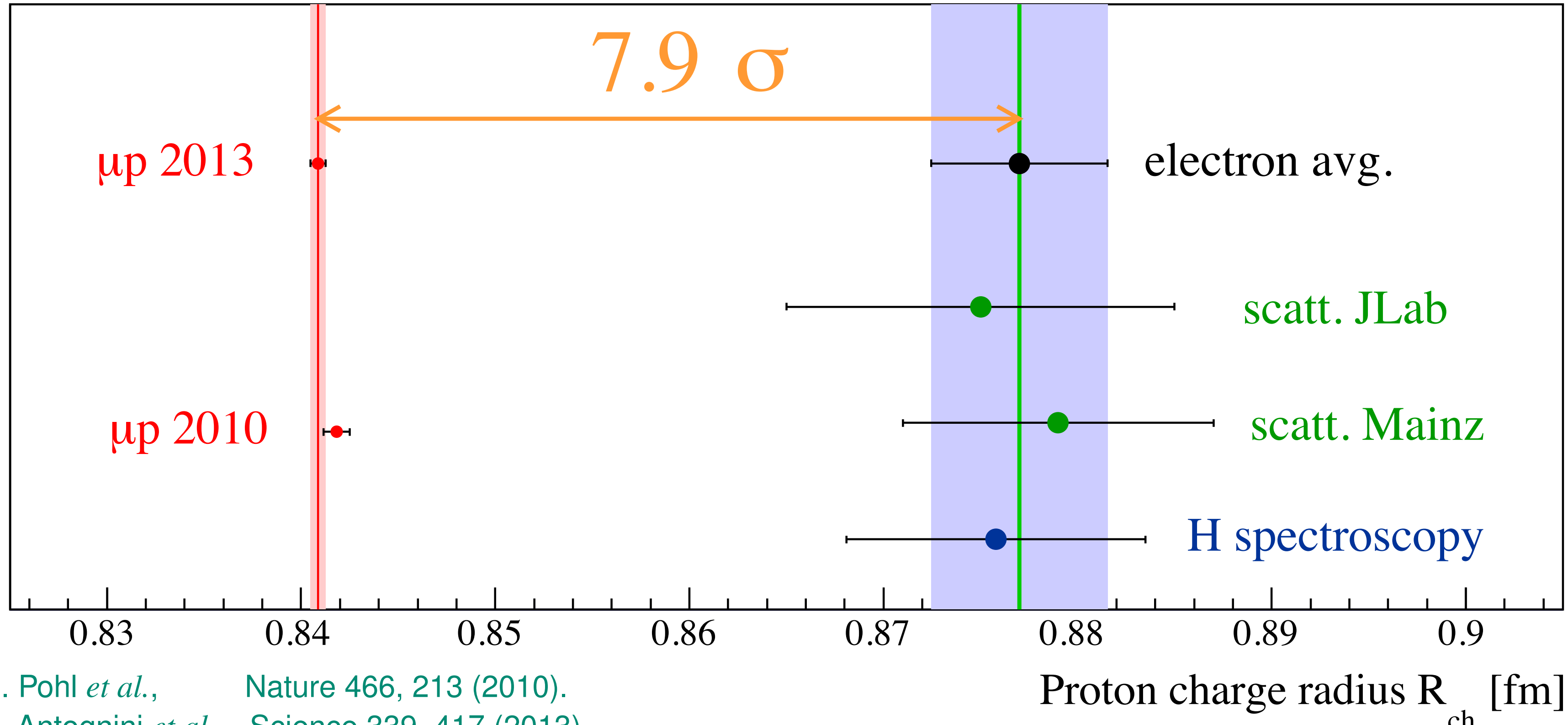
The proton radius puzzle

In a picture

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

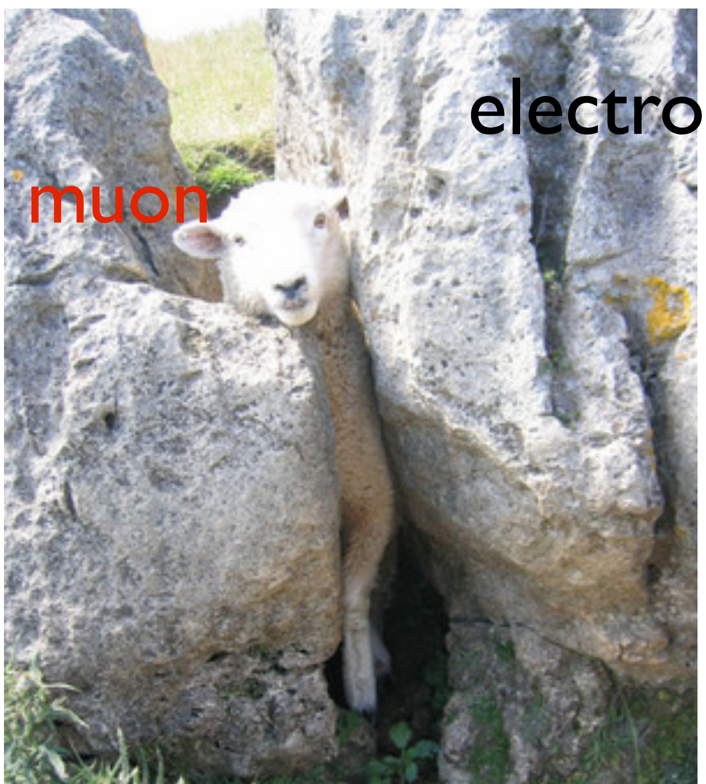
muons: 0.8409 ± 0.0004 fm



R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini *et al.*, Science 339, 417 (2013).

QED theory ?

- Pohl et al table 32 terms!
- Most important -HFS- measured Jan ’13
- QED theory not responsible-



A new effect on mu-H energy shift must vary at least as fast as lepton mass to the fourth power, if short-ranged

An effect on electron, but not muon free of this constraint

New data- more problems

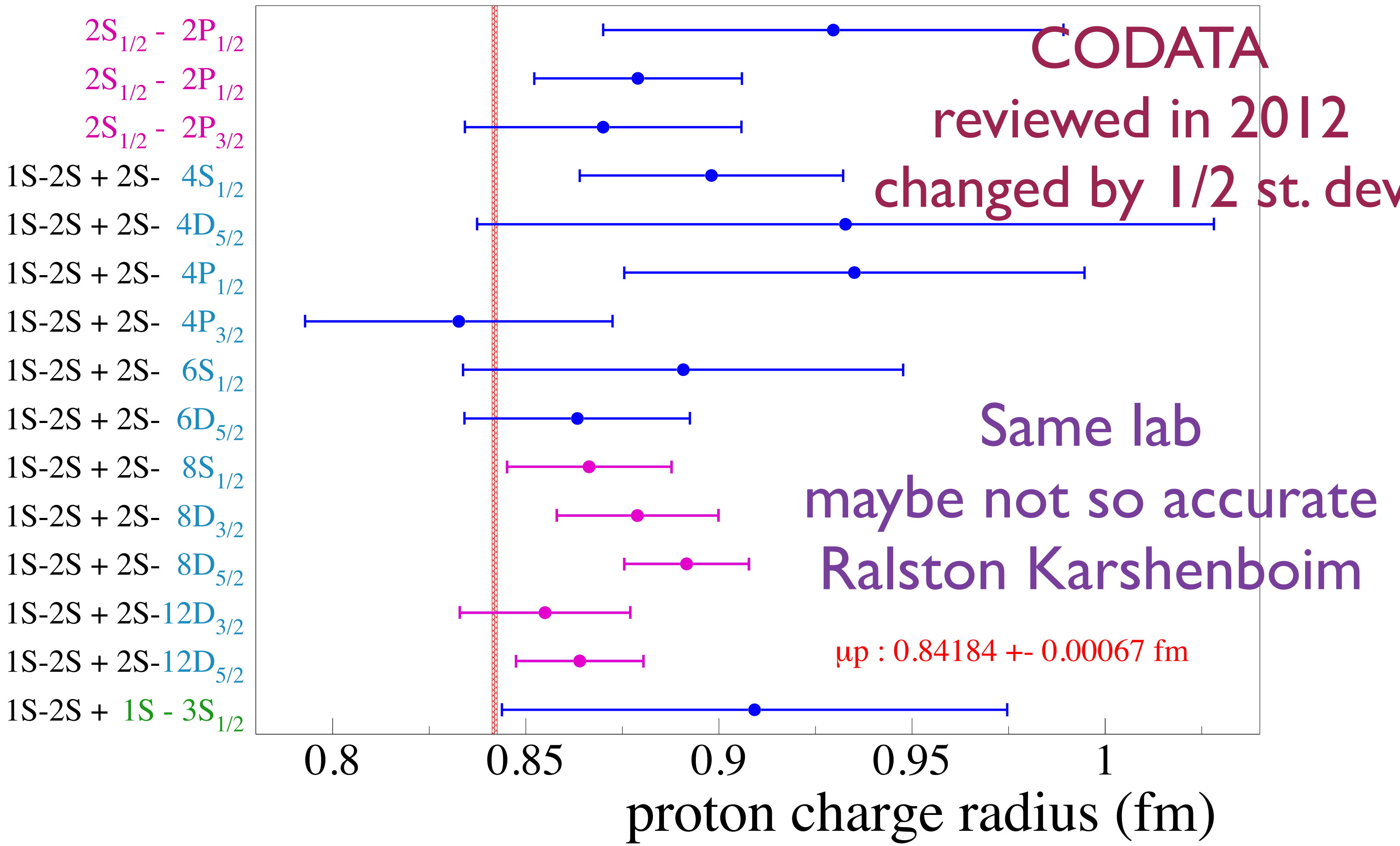
Possible resolutions

- ~~QED bound-state calculations not accurate~~- very unlikely- this includes recoil effects
- Electron experiments not so accurate
- Strong interaction effect in two photon exchange diagram
- soft proton
- ~~More e^+e^- pairs than $\mu^+ \mu^-$ pairs in the proton~~
- Muon interacts differently than electron!-new particles, gravity, ~~non-commutative geometry~~

Electronic Hydrogen -Pohl

- Need two levels to get Rydberg and Lamb shift-have ~ 20 available

$$E(nS) \approx \frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$



Deuteron: new experiments

- muonic deuteron atom- CREMA
- electronic deuteron isotope shift -two photon spectroscopy

Improved Measurement of the Hydrogen $1S-2S$ Transition Frequency

Christian G. Parthey,[1,*] Arthur Matveev,[1,*] Janis Alnis,[1] Birgitta Bernhardt,[1] Axel Beyer,[1] Ronald Holzwarth,[1,†] Aliaksei Maistrou,[1] Randolf Pohl,[1] Katharina Predehl,[1] Thomas Udem,[1] Tobias Wilken,[1] Nikolai Kolachevsky,[1,‡] Michel Abgrall,[2] Daniele Rovera,[2] Christophe Salomon,[3] Philippe Laurent,[2] and Theodor W. Hänsch[1,§]

2 photon spectroscopy PRL 104, 233001

Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)$ fm^2

electron experiment
C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010 r_d = 2.1424(21) fm uses ep data

r_p= 0.84087(39) fm from μH gives r_d = 2.1277(2) fm

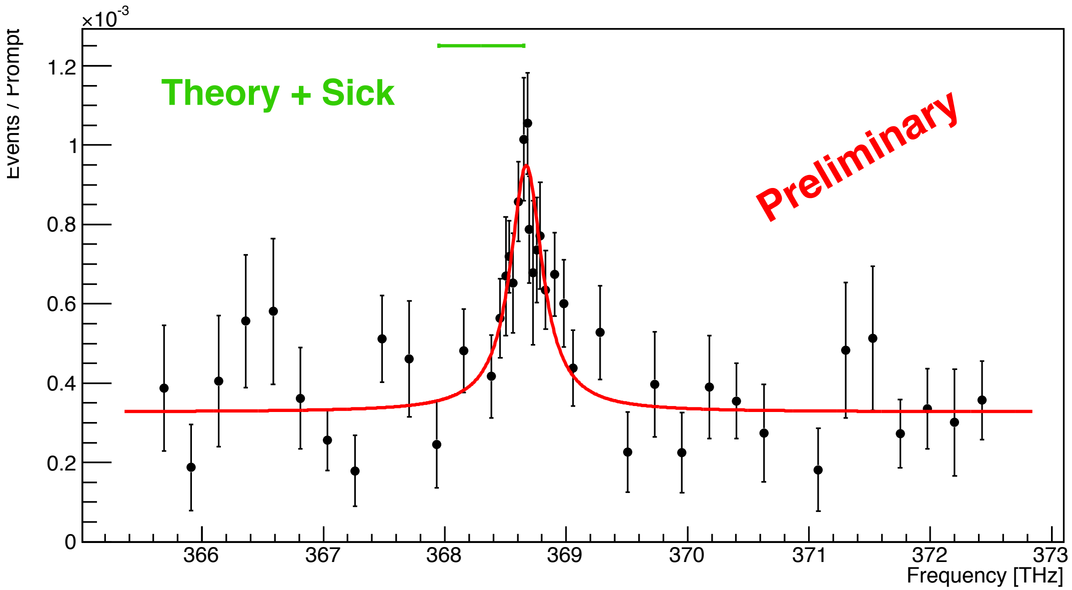
Lamb shift in muonic DEUTERIUM r_d = 2.1282(12) fm PRELIMINARY!

- Deuteron radii measured by electrons and muons is the same, using the proton radius measured in muonic hydrogen!
- Proton radius puzzle reappears in deuterium
- It seems is no new neutron effect on Lamb shift

If your model predicts neutron effect on energy level it is ruled out

Secret results!

^{4}He



- The transition has been found at the expected position i.e., whithin the uncert. given by r_{He} from $e-$He scattering.
- [redacted]
- Zavattini value from old $\mu\,\mathrm{He}^+$ experiment excluded

Need to summarize all 2S-2P contributions

^{4}He nuclear charge radius

$1.681(4)$ fm	$u_r = 2 \times 10^{-3}$	[Sick]
$1.677(1)$ fm	(VERY preliminary)	[$\mu\,\mathrm{He}^+$]

No new effect in ^{4}He within 1 st. dev.

Several new electron experiments planned

- Independent measurement of Rydberg constant. This would change only extracted r_p nothing else
- 2S-6S UK, 2S-4P Germany, 1S-3S France
- 2S-2P classic, Canada
- Highly charged single electron ions NIST
- PRad at Jab electron scattering- calorimeter extends measurement to very small angles
- several others

Possible resolutions

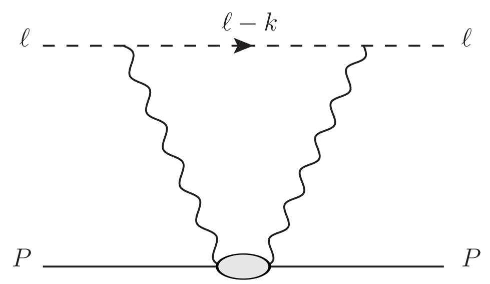
- ~~QED bound-state calculations not accurate-~~ very unlikely- this includes recoil effects
- Electron experiments not so accurate
- Strong interaction effect in two photon exchange diagram-my work- soft proton
- Muon interacts differently than electron!-new particles, gravity, ~~non-commutative geometry~~

Analysis of Experiment-one example

Measured =206.2949(32)= 206.0573(45)-5.2262 r_p^2+0.0347 r_p^3 meV
computed

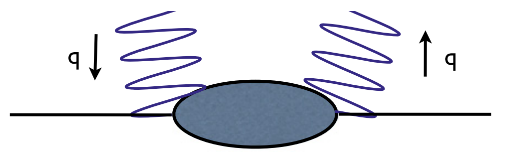
Explain puzzle with radius as in H atom increase 206.0573 meV by 0.31 meV-attractive effect on 2S state needed

Our idea



energy shift proportional to lepton mass[4]

$T^{\mu\nu} =$



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

Dispersion relation: $Im[T_1] \propto W_1$ measured

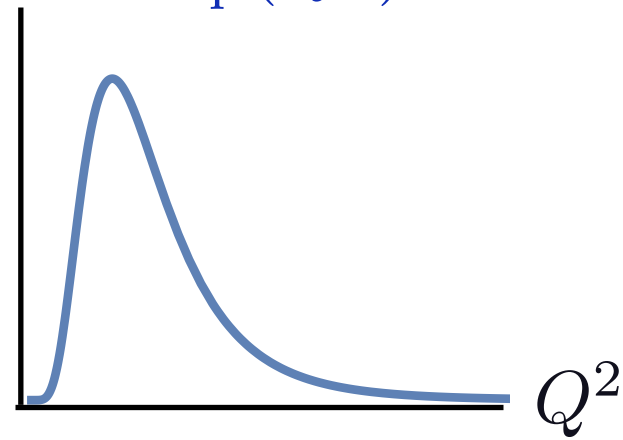
Large virtual photon energy ν, $W_1 \sim \nu$ integral over energy diverges

Subtraction function needed: $\bar{T}_1(0, Q^2)$ zero energy

Hill & Paz- big uncertainty in dispersion approach

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

$$\Delta E^{\rm subt} \sim \frac{\alpha^2}{m}\Psi_S^2(0)\int^\infty \frac{dQ^2}{Q^2}\cdots \quad F_{\rm loop}(Q^2)$$



Choose $F_{\rm loop}(Q^2)$ give 0.31 meV satisfy all constraints

Recast in EFT- parameters seem natural

Soft proton

e^+/e^- and μ^+/μ^- scattering on proton

So what? MUSE expt

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]
Fuchey,[6] S. Gilad,[7] R. Gilman (Contact person),[5] R. Gothe,[4] D. H
Ilieva,[4] M. Kohl,[9] G. Kumbartzki,[5] J. Lichtenstadt,[10] N. Liyanage,
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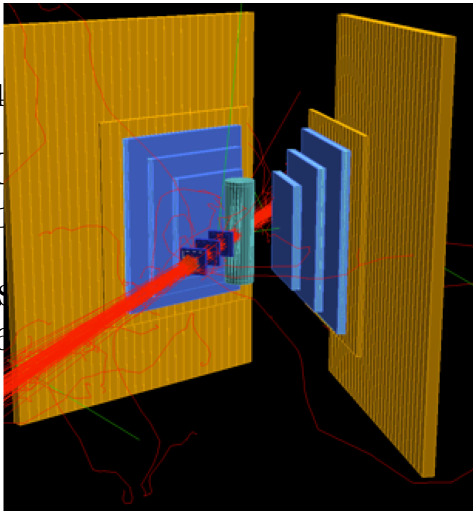
Punjabi,[14] R. Ransome,[5] D. Reggiani,[3] A. Richter,[15] G. Ron,[16]
E. Schulte,[6] S. Strauch,[4] V. Sulkosky,[7] A.S. Tadapelli,[5] and L.



determining the proton radius through muon scattering, with simultaneous electron scattering measurements.

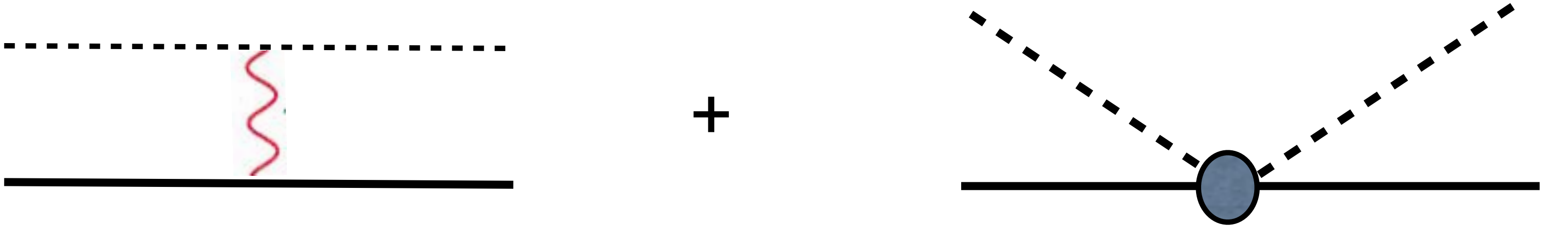
PSI proposal R-12-01.1

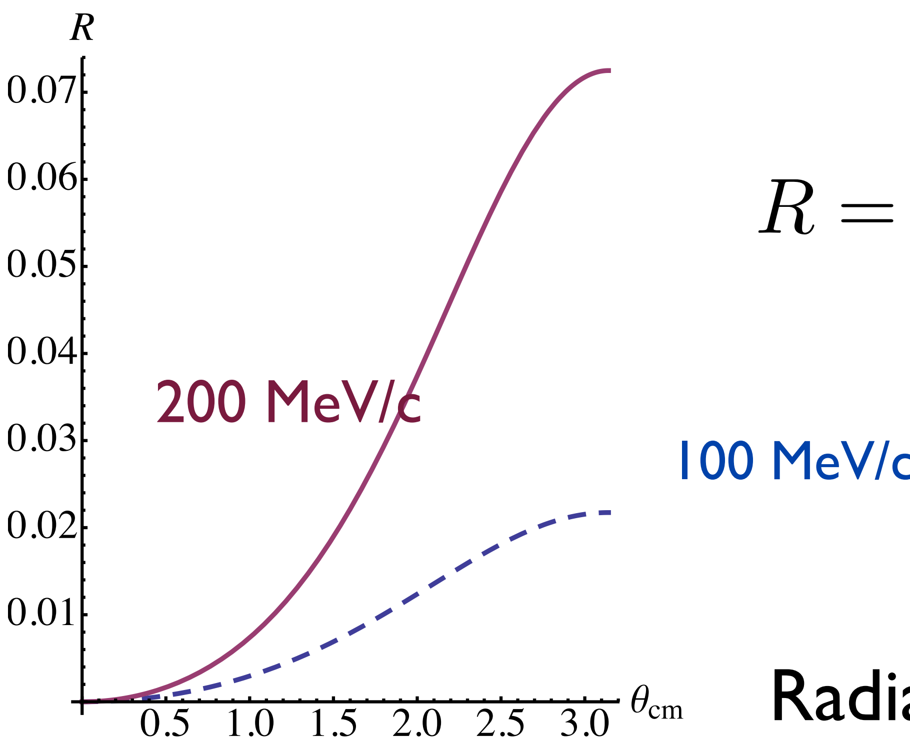
http://www.physics.rutgers.edu/~rgilman/elasticmup/

2 photon exchange idea is testable

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 +/-

Radians

Soft proton idea

- explains muon Lamb shift
- no change to electron Lamb shift
- no hyperfine interaction
- no effect on neutron so Deuteron is OK
- easily testable in muon-proton scattering
- easily testable in heavy muonic atoms

Nuclear dependence of short-ranged mu-p effects

- Energy shift is proportional to square of muon wave function at the origin

GAM
1501.01036

- Suppose you have effect that gives energy shifts Ep (on proton) En (on neutron)

$$E_A = \left(\frac{1+\frac{m_\mu}{m_p}}{1+\frac{m_\mu}{Am_p}}\right)^3 Z^3 (ZE_p + NE_n)\left(1 - \mathcal{O}(\frac{R_A^2}{a_\mu^2})\right) \approx \left(\frac{1+\frac{m_\mu}{m_p}}{1+\frac{m_\mu}{Am_p}}\right)^3 Z^3 (ZE_p + NE_n),$$

Nuclear shift

Square of wave fun

Counting

Size of nucleus

My model: ~0.3 meV (8)(2) =-4.8 meV about 5 st. dev off

Soft proton idea is testable- advantage

Assume D, He data correct

- Deuteron says no neutron effect -
- ^{4}He- Effect goes as $Z * Z^3 = Z^4$
- This is a 5 st. dev effect NOT seen- RIP for pol idea
- Moral- any new short-ranged muon-nucleon interaction ruled out by He data
- RIP - enhanced e+e- pairs, short-ranged gravity, ...

Possible resolutions

- ~~QED bound-state calculations not accurate- very unlikely- this includes recoil effects~~
- Electron experiments not so accurate
- ~~Strong interaction effect in two photon exchange diagram-my work- soft proton~~
- ~~More e^+e^- pairs than $\mu^+ \mu^-$ pairs in the proton~~
- Muon interacts differently than electron!-new particles, ~~gravity, non-commutative geometry~~

Another muon opportunity-anomalous moment

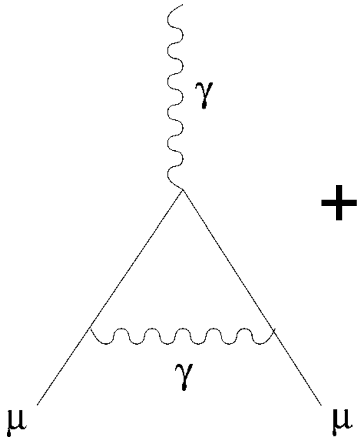


Figure 1 The first-order QED correction to g-2 of the muon.

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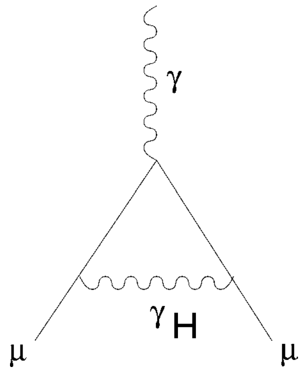


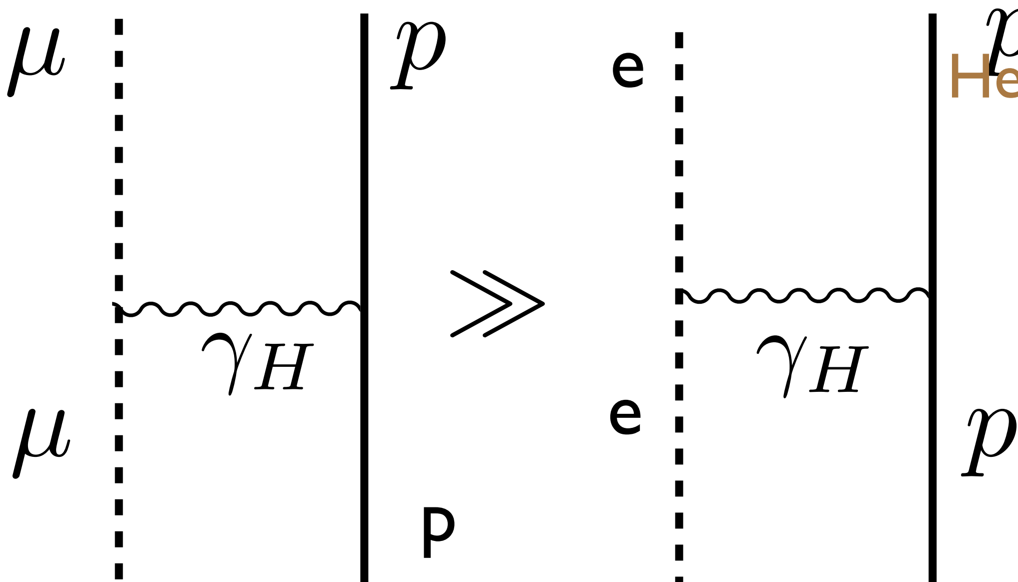
Figure 1 The first-order QED correction to g-2 of the muon.

3.6 st. dev anomaly now
fix add heavy photon
interacts preferentially with
muon

Muon data is g-2 - BNL exp't,

… Hertzog

Lamb shift



Hertzog- Kammel
new Flab

Out
R Essig '15 AP

Maybe dark matter, energy particles show up in muon physics!

Lepton-universality violating one boson exchange

- Tucker-Smith & Yavin PRD83, 101702 new particle scalar or vector coupling
- Brax & Burrage scalar particles PRD 83, 035020 &'14
- Batell, McKeen & Pospelov PRL 107, 011803 new gauge boson kinetically mixing with $F^{\mu\nu}$ plus scalar for muon mag. mom. 1401.6154 W decays enhanced
- Carlson Rislow PRD 86, 035013 fine tune scalar pseudoscalar or polar and axial vector couplings
- Barger et al PRL106,153001 - new particles ruled out but assumes universal coupling
- Kaon decays provide constraints

New scalar bosons must

ϕ

- give μ-p Lamb shift
- almost no hyperfine in μ proton
- almost no effect for D, ^{4}He
- consistent with g-2 of μ and electron

Scalar ok with all constraints using

$$g_{\phi e} \leq 2.3 \times 10^{-4} e, \quad g_{\phi\mu} \leq 1.3 \times 10^{-3}$$

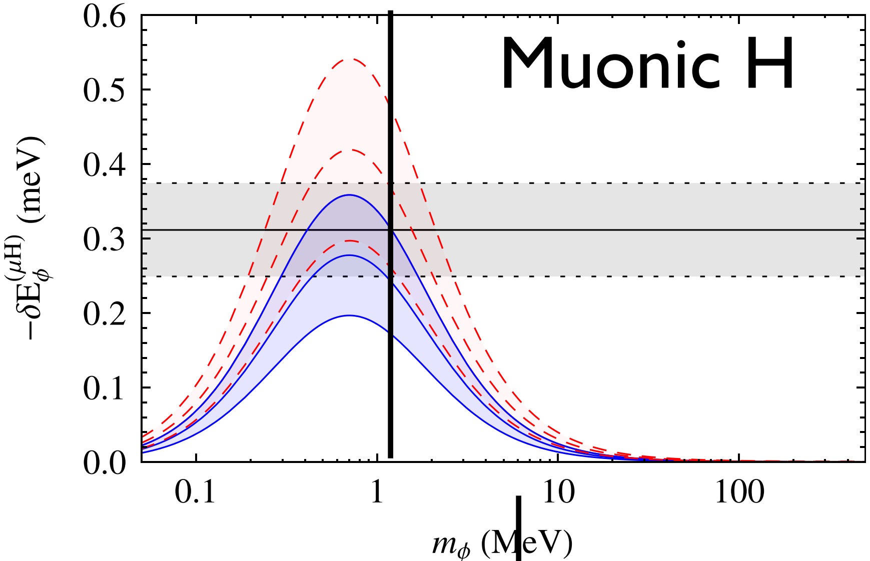
$$\frac{g_{\phi e}^2}{4\pi} \leq 5.3 \times 10^{-8} \alpha, \quad \frac{g_{\phi\mu}^2}{4\pi} \leq 1.7 \times 10^{-6} \alpha$$

Tucker-Smith & Yavin (PRD83,101702(R))

- be found

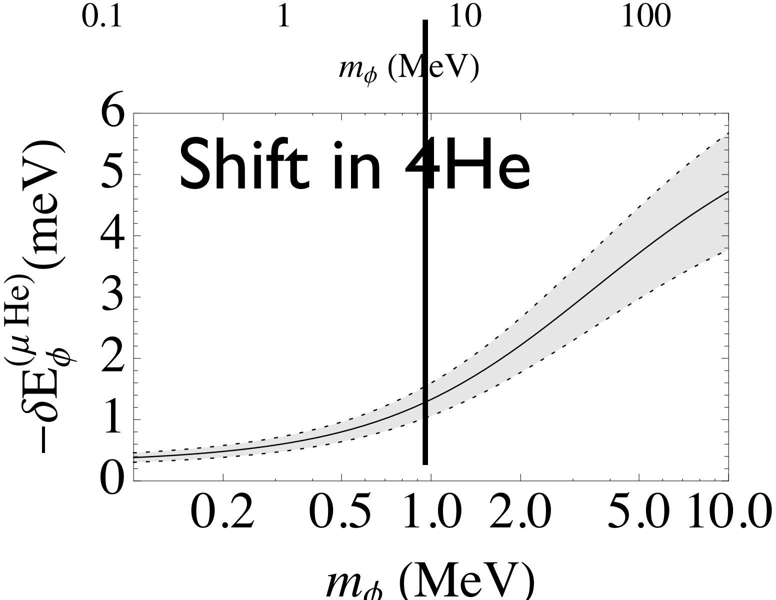
Tucker-Smith & Yavin PRD83, 101702(R)

ϕ couplings to μ, p greater than to e, n



Solid is scalar
dashed is vector
central curve gives
g-2 of muon

$$V_\phi(r) = -1.7 \times 10^{-6}\, \alpha \frac{e^{-m_\phi r}}{r}$$



1 meV shift is OK

Vertical line- e^+e^- threshold

~1 MeV scalar consistent

- muonic Lamb shifts H,D, 4He
- no hyperfine
- K decays (Carlson 2015 review)
- Upsilon decay
- neutron scattering by model assumption
- g-2 of muon
- muonic atom (^{24}Mg ^{28}Si) transitions

MUSE and ~1 MeV scalar

$$V_\phi(r) = -1.7 \times 10^{-6}\,\alpha \frac{e^{-m_\phi\, r}}{r}$$

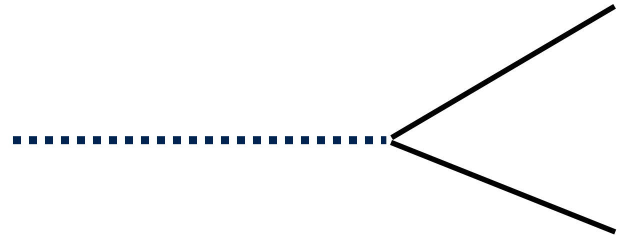
- No spin-independent scattering experiment can detect a coupling this weak

Liu & Miller 1507.04399

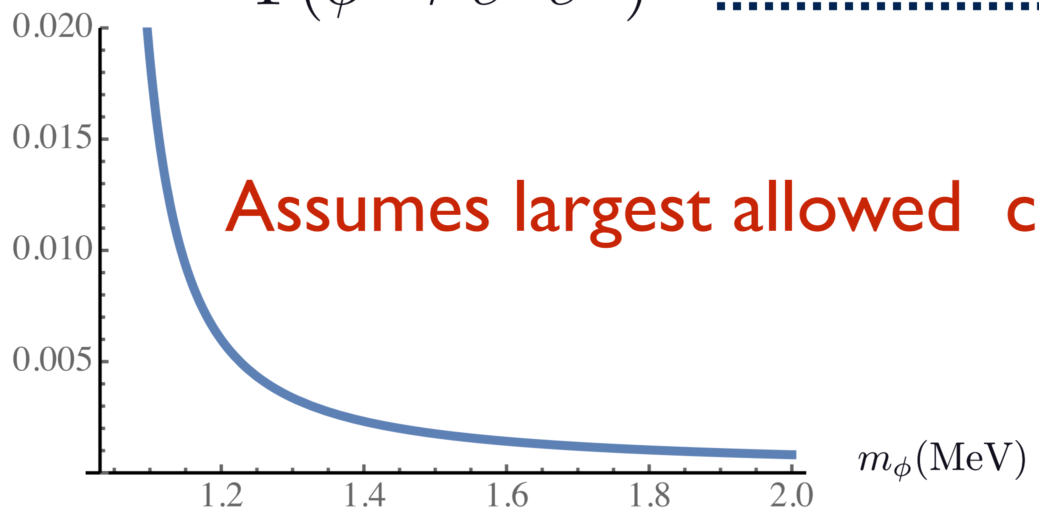
- If this scalar exists (and other experiments correct) MUSE will find electrons/positrons see the same large radius and
- muons and anti-muons will see the same large radius
- Needs some other way to detect

ϕ Decay modes

$\Gamma(\phi \to e^+e^-)$

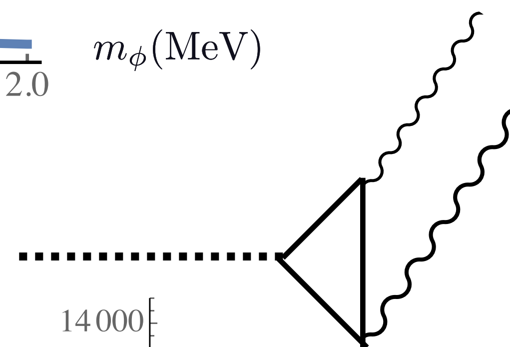


$c\tau(\mathrm{m})$

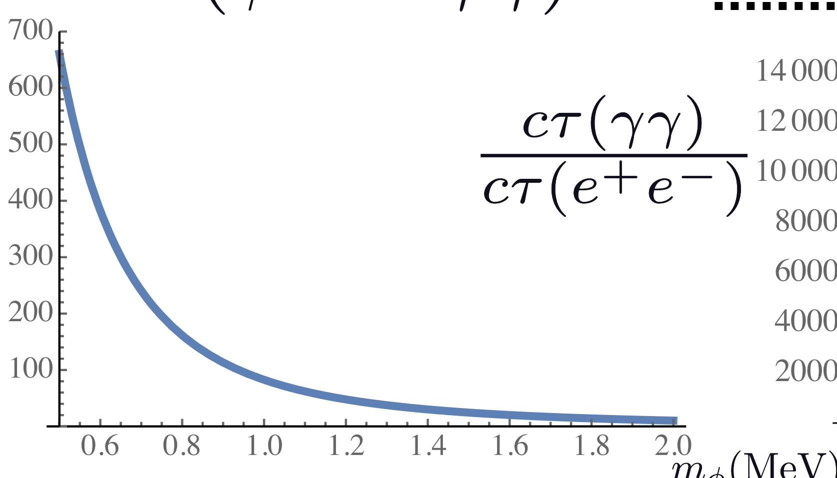


Assumes largest allowed coupling to electron

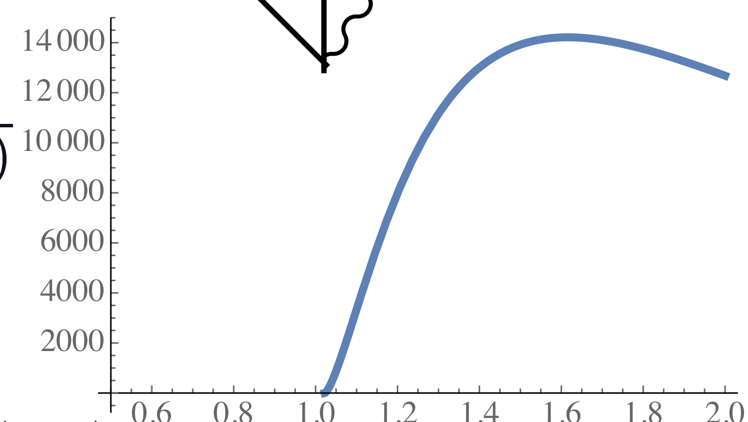
$\Gamma(\phi \to \gamma\gamma)$



$c\tau(\mathrm{m})$



$\frac{c\tau(\gamma\gamma)}{c\tau(e^+e^-)}$



Probing new physics with underground accelerators and radioactive sources

PLB 740, 61

Eder Izaguirre [a], Gordan Krnjaic [a,*], Maxim Pospelov [a,b]

Focus is on mass range $250\ \text{keV} \leq m_\phi \leq 2m_e$

Discusses motivation and existing constraints BUT

The region with mass greater than 2 electron masses is NOT really studied anywhere, till now

- Focus here on detecting electron-positron decays of ϕ
- make ϕ with proton induced reaction or positron-electron scattering

$$p(1.88\,\mathrm{MeV}) +^{19} F \rightarrow \alpha +^{16} O^*(6.05)$$
$$^{16}O^*(6.05) \rightarrow^{16} O(GS) + \phi$$

Kohler et al PRL 33, 1628 (1974) rules out mass range > 1.03 MeV for coupling const,. 40 times larger than what is needed now

- resonance at 1.88 MeV- reaction discovered excited state of ^{16}O (1939)
- shielded scintillation detector -detects ϕ
- decaying to pairs- signal is approximate that of 6.05 gamma ray
- 30 hours running 0.04 C on target
- need to improve by 1600

Freedman et al. PRL 52, 240 rules out mass >3 MeV

$$p +^3 H \rightarrow^4 He(20.1) \rightarrow 4He(GS) + \phi$$

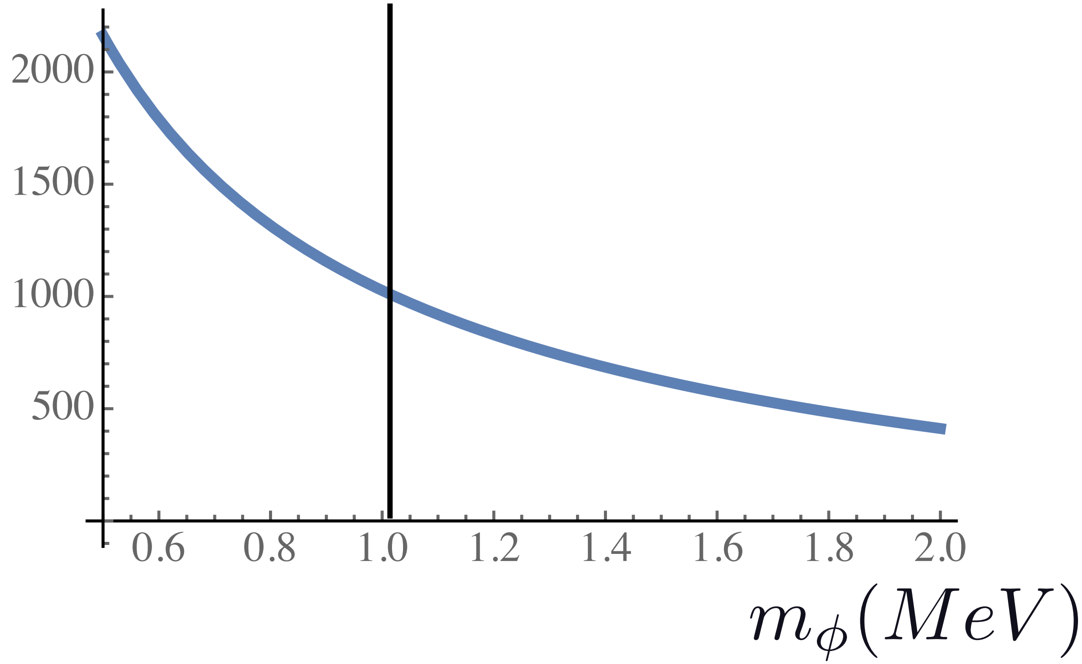
$$^{16}O(6.05, 0^+) \rightarrow ^{16} O(\mathrm{GS}, 0^+) + \phi, \quad \text{No single photon decay}$$

From electron g-2

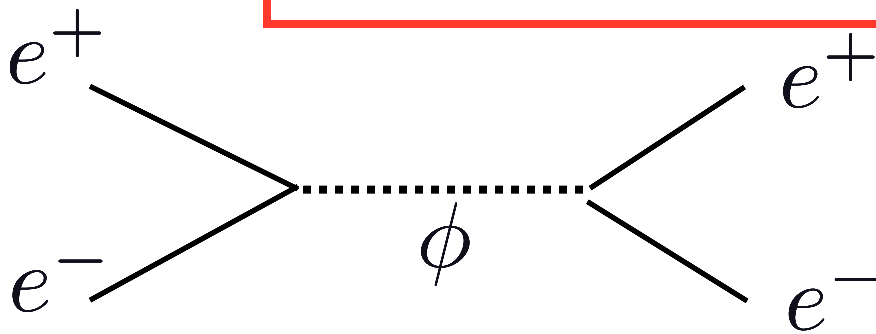
$$\frac{\tau(A^* \to A + e^+ e^-)}{\tau(A^* \to A + \phi} = 3.3 \times 10^3 \frac{g^2_{\phi e \bar{e}}}{e^2} \left(1 - \left(\frac{m_\phi}{6\mathrm{MeV}}\right)^2\right)^{5/2}$$

$$\tau(A^* \to A + e^+ e^-) : \quad \text{lifetime is } 10^{-10}\mathrm{s}$$

Decay length (m) nuclear emission of scalar boson



e^+e^- resonant (?) scattering

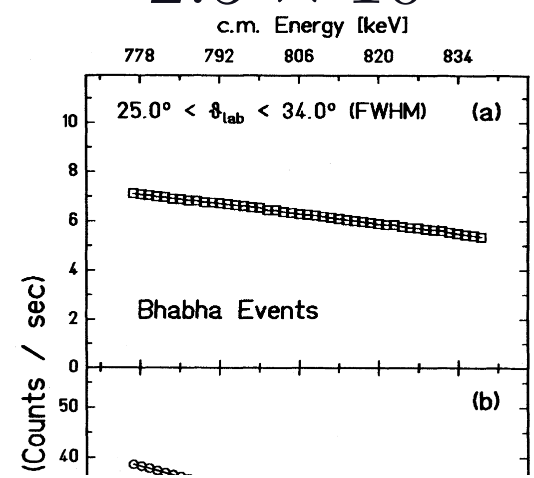


Tsertos et al PRD 40, 1397
claim experimental sensitivity of 0.5 b eV/sr
rule out Mass 1.8 MeV

$$\text{Ratio to usual } \left(\frac{g_{\phi e}^2}{e^2}\right)^2 = (5.3 \times 10^{-8})^2 = 2.5 \times 10^{-15}$$

monoenergetic beam on Be

Our parameters



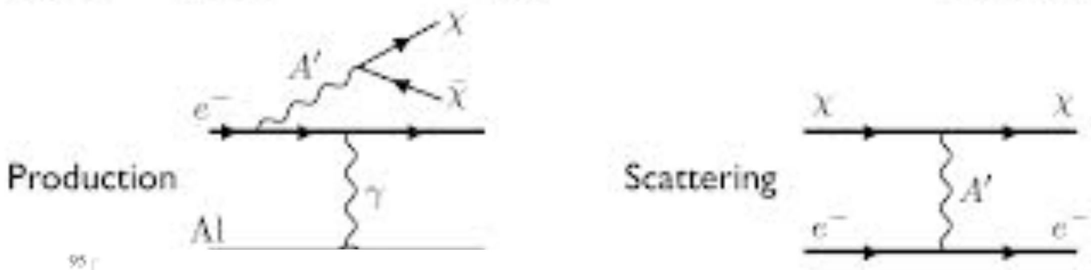
$$\int \frac{d\sigma}{d\Omega} dE = 0.14\left(1 - \frac{4m^2}{m_\phi^2}\right)^{1/2} \leq 0.14 \text{ b eV}$$

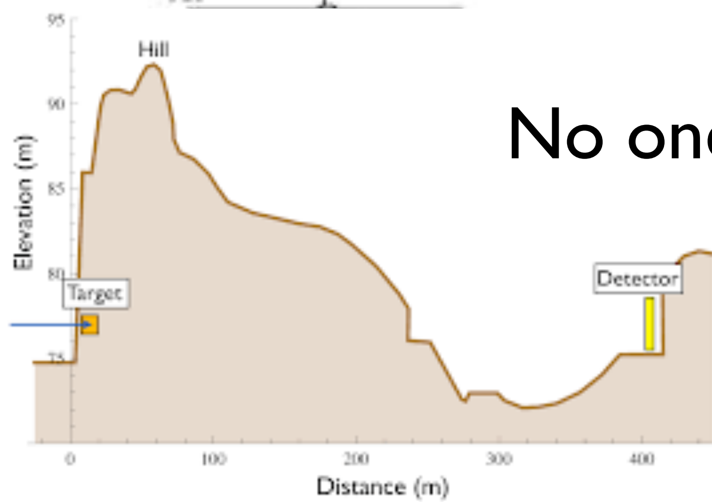
Improve experiment by a factor of 4?

Beam dump experiments

Dark photons to dark matter

SLAC E137



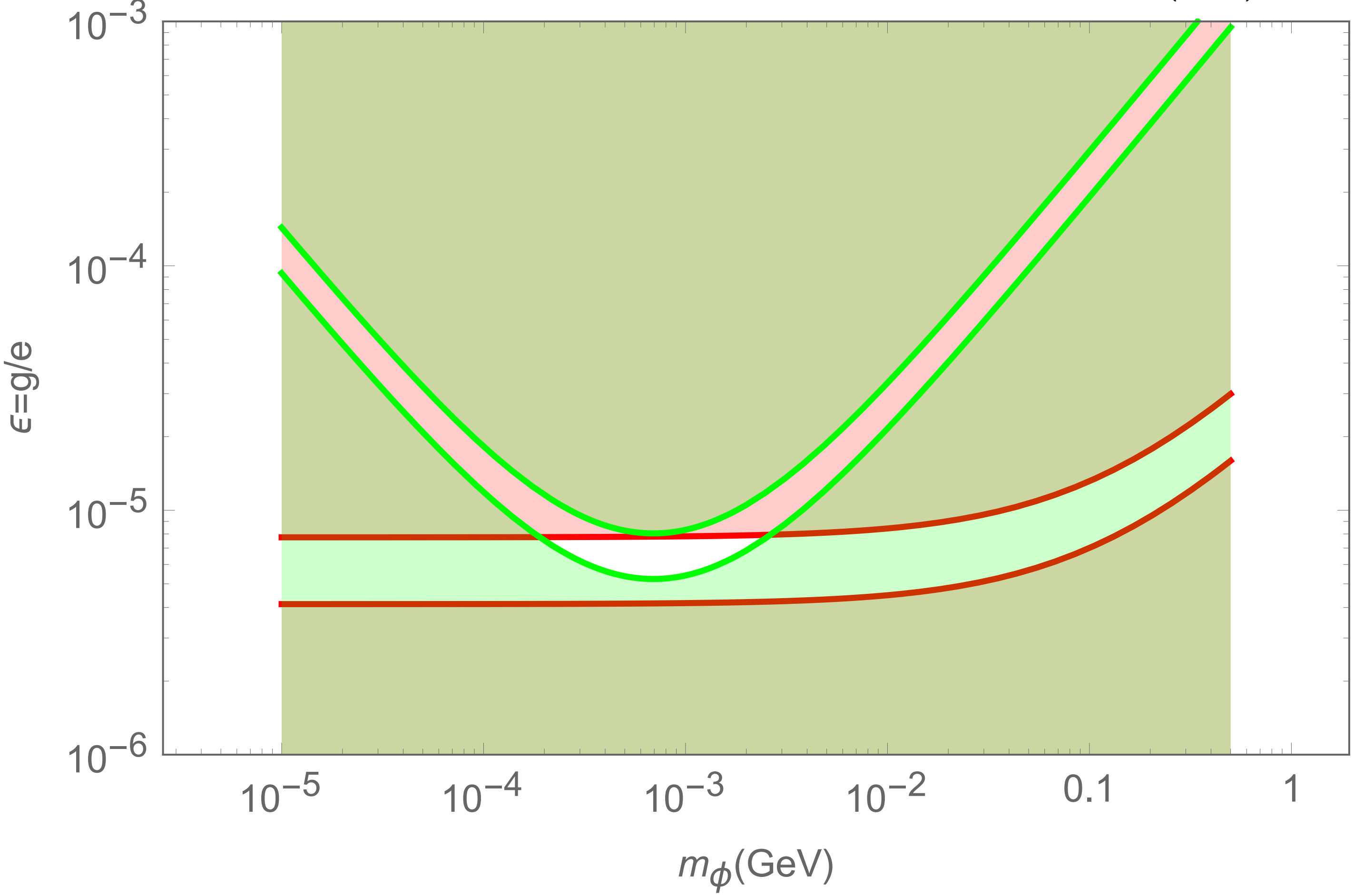


No one has discovered anything, yet

Phys.Rev.Lett. 113 (2014) 17, 171802 arXiv:1406.2698

Exclusion from e,mu g-2, p Lamb shift, assumes

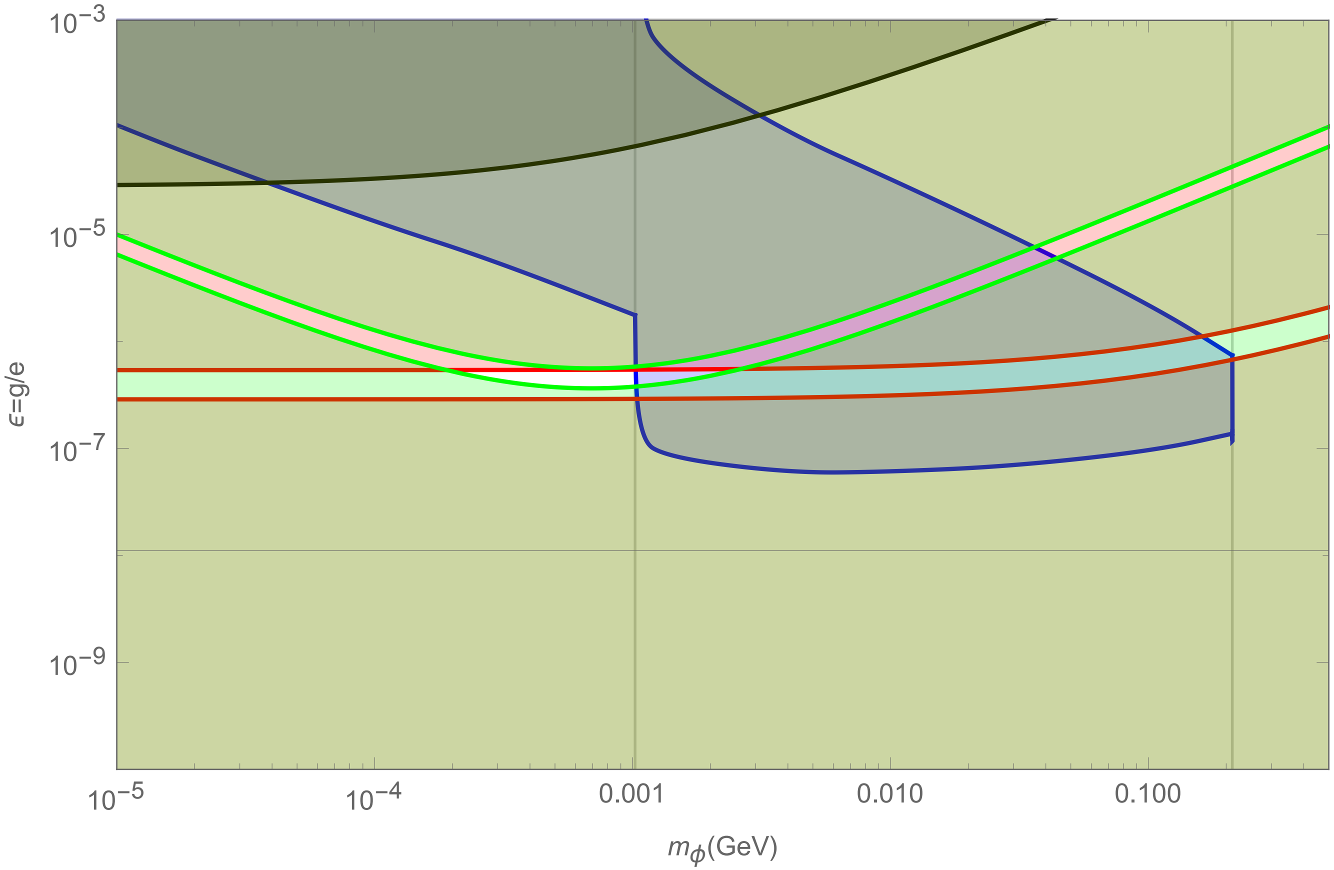
$$\frac{g_\mu}{g_e} = \left(\frac{m_\mu}{m_e}\right) = \frac{g_p}{g_e}$$



Shaded areas excluded white is allowed

Exclusion from e,mu g-2, p Lamb shift, and beam dump E137 assumes $\frac{g_\mu}{g_e} = \left(\frac{m_\mu}{m_e}\right)^{1.5} = \frac{g_p}{g_e}$

$\frac{g}{e}$ is much smaller



scalar boson survives, but much smaller coupling to electrons, see or not in muon or proton beam dump experiments

Summary

- If all of the experiments, and their analyses, are correct a new scalar boson of mass ~1 MeV must exist

- Direct detection is needed: David McKeen, Yu-Sheng Lu

$$p(1.88\,\mathrm{MeV}) +^{19} F \to \alpha +^{16} O^*(6.05)$$

$$^{16}O^*(6.05) \to^{16} O(GS) + \phi$$

$e^+ - e^-$ scattering

Very difficult:

beam dump constrains e-boson coupling

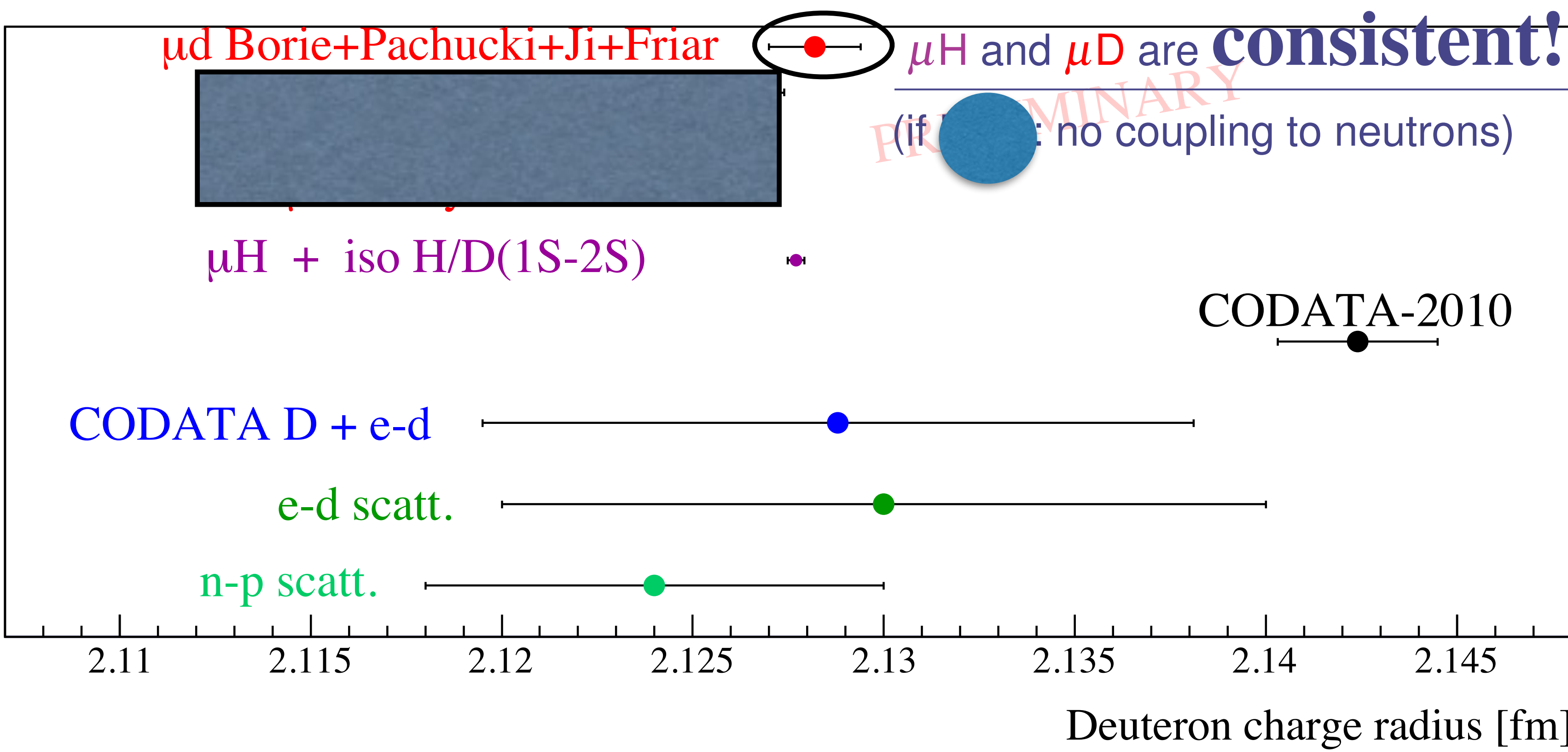
Need to detect from muon and proton interactions

Spares follow

Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \text{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010	r_d = 2.1424(21) fm
r_p= 0.84087(39) fm from μH gives	r_d = 2.1277(2) fm
Lamb shift in muonic DEUTERIUM	r_d = 2.1282(12) fm PRELIMINARY!



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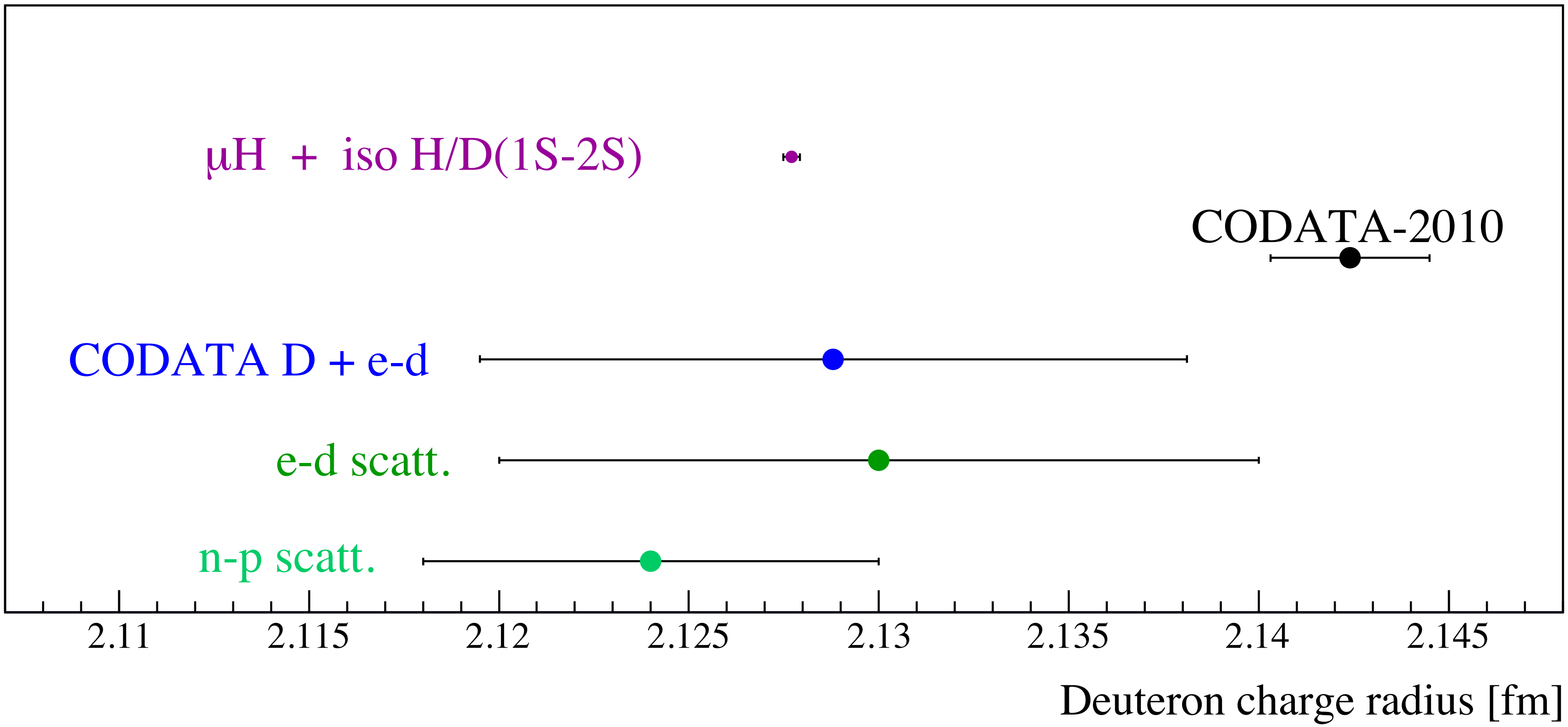


R Essig talk at APS '15

- Dark (heavy) photon is ruled out as explanation of muon g-2
- Complete parameter space has been searched and nothing is found
- But other scalar boson not searched completely

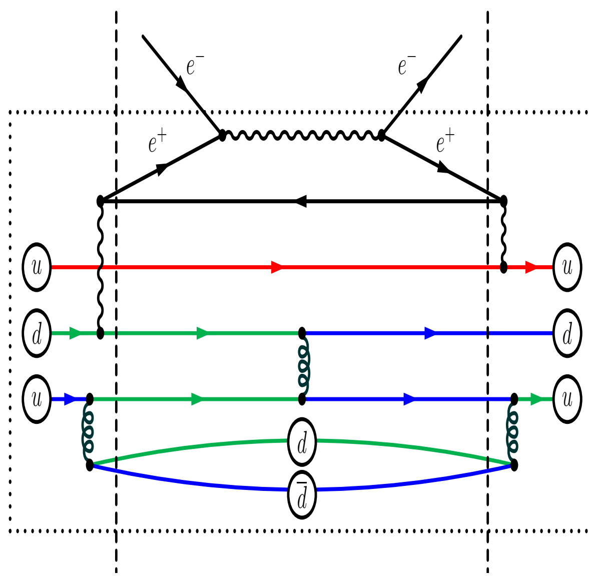
Yes it really is G_E

- Non-relativistic reduction of one-photon exchange leads to the spin independent interaction being $G_E(Q^2)/Q^2$
- All recoil effects properly accounted for:Breit-Pauli Hamiltonian computed for non-zero lepton and proton momentum

Light Sea Fermions in Electron–Proton and Muon–Proton Interactions

U. D. Jentschura   Phys.Rev.A88 (2013) 062514

If we assume an average of roughly 0.7×10−7 light sea positrons per valence quark, then we can show that virtual electron-positron annihilation processes lead to an extra term in the electron-proton versus muon-proton interaction, which has the right sign and magnitude to explain the proton radius discrepancy.



Contribution for electron not muon

Non-perturbative lepton-pair exists in proton wave function. UDJ: energy shift $\propto 1/m_l^2$, from annihilation at rest. GAM: Shift $\propto 1/(\text{constituent quark mass})^2$

Any effect is small and same for electron and muon atoms

arXiv:1501.01036

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

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

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

$\rightarrow$ Logarithmic divergence

Typo bleow

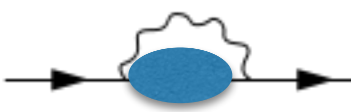
$$\overline{T}_1(0,Q^2) \rightarrow \frac{\beta_M}{\alpha}Q^2 F_{\rm loop}(Q^2)$$ Cuts off integral

Birse & McGovern assume dipole : $\Delta E^{\rm subt} = 0.004\,\text{meV}$ very small

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

Infinite parameter set gets needed 0.31meV, NO constraint on neutron

Choose parameters so shift in proton mass <0.5 MeV (current uncertainty)



Recast in EFT- parameters seem natural

Arbitrary functions

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

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

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

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

3 parameters: n, N, a $\quad (M_0 = M_\beta)$

Choose parameters such that shift in proton mass < electromagnetic uncertainty of 0.5 MeV

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

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

Soft proton

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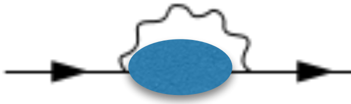
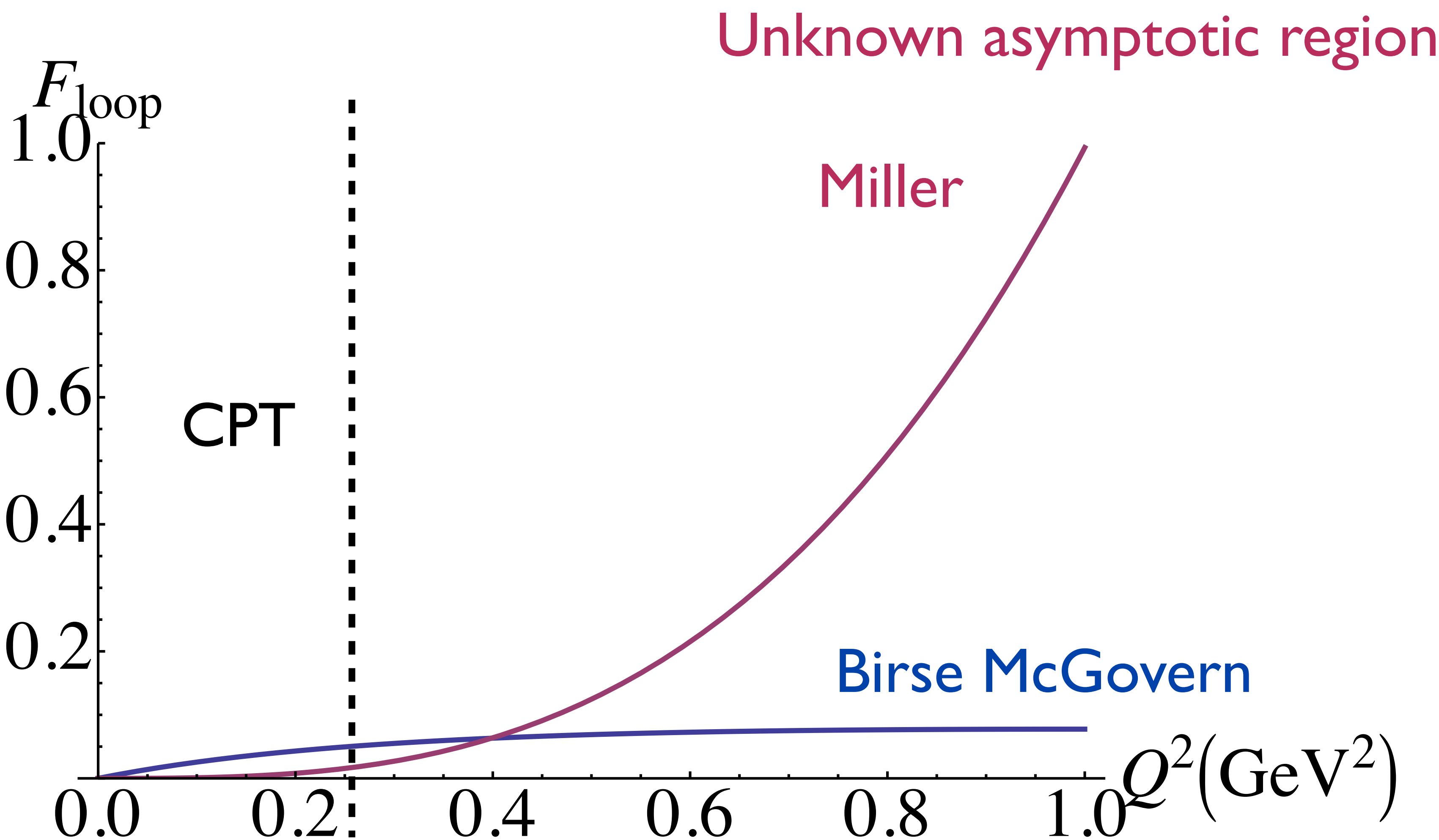


Recast in EFT- parameters seem natural

New 1 MeV scalar boson

- give μ-p Lamb shift
- almost no hyperfine in μ proton
- consistent with g-2 of μ
- almost no effect for D, ^{4}He
- evade existing constraints
- be found

Form factors

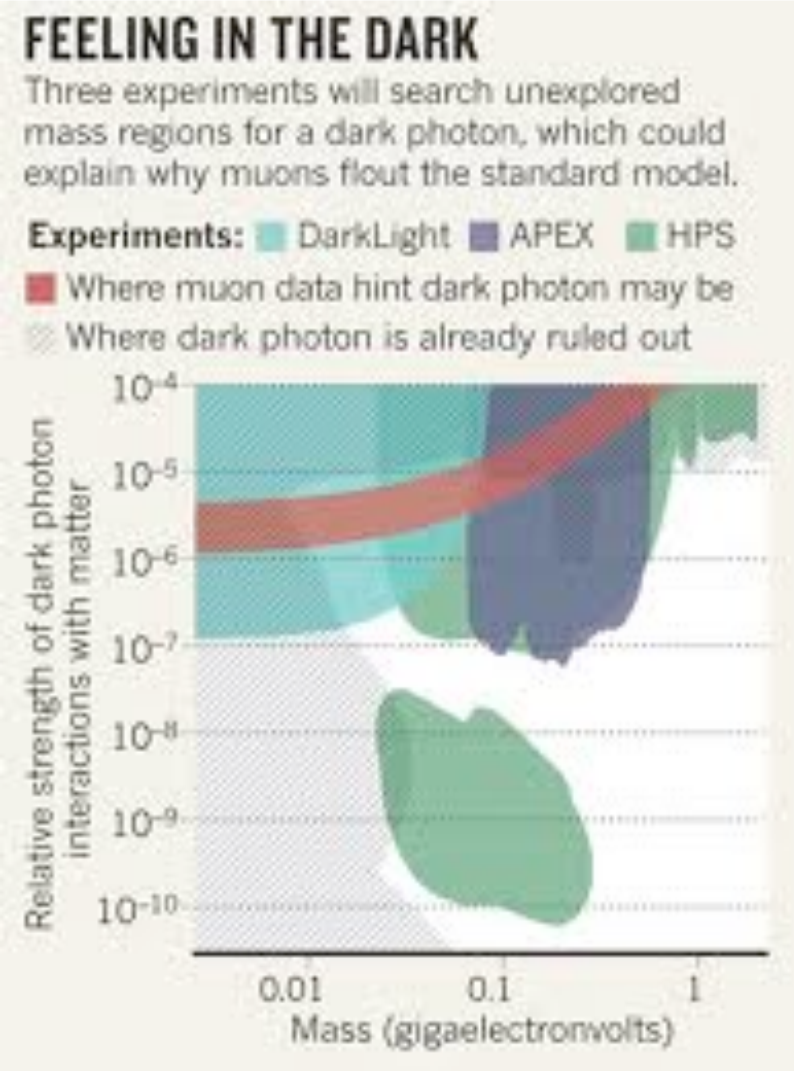


If recast into effective field theory strength seems natural

$$\mu \neq \mathrm{e}$$

- 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--
- Karshenboim, McKeen Pospelov arXiv:1401.6154 Hyperfine effects in muonium> “completely disfavoring the remainder of the parameter space,

No BSM idea solves puzzle at this time, but maybe



Three experiments at JLab

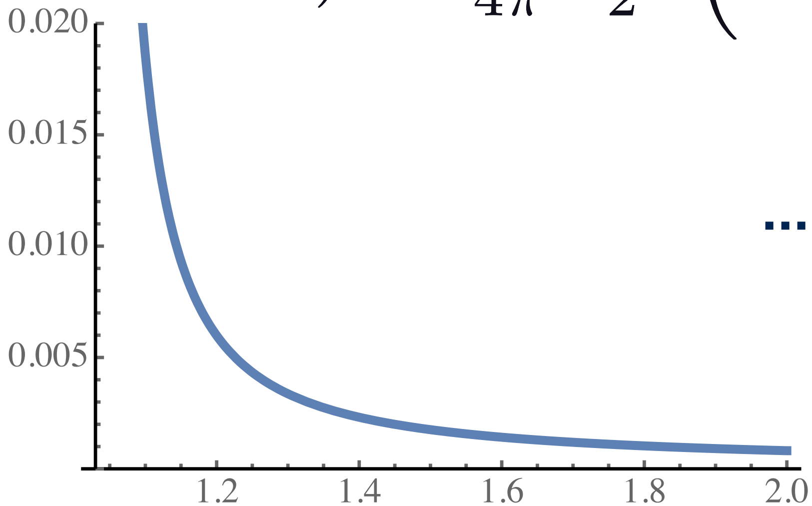
R. Essig

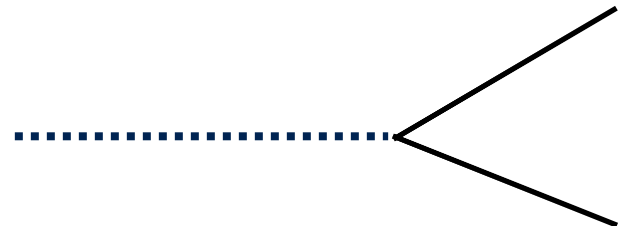
Muon data is g-2 - BNL exp't, Hertzog- Kammel ...

ϕ Decay modes

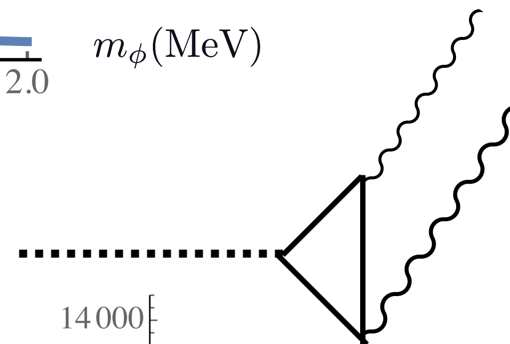
$$\Gamma(\phi \to e^+e^-) = \frac{g_{\phi e}^2}{4\pi}\frac{m_\phi}{2}\left(1-\frac{4m_e^2}{m_\phi^2}\right)^{3/2}, m_\phi > 2m_e$$

$c\tau(\mathrm{m})$

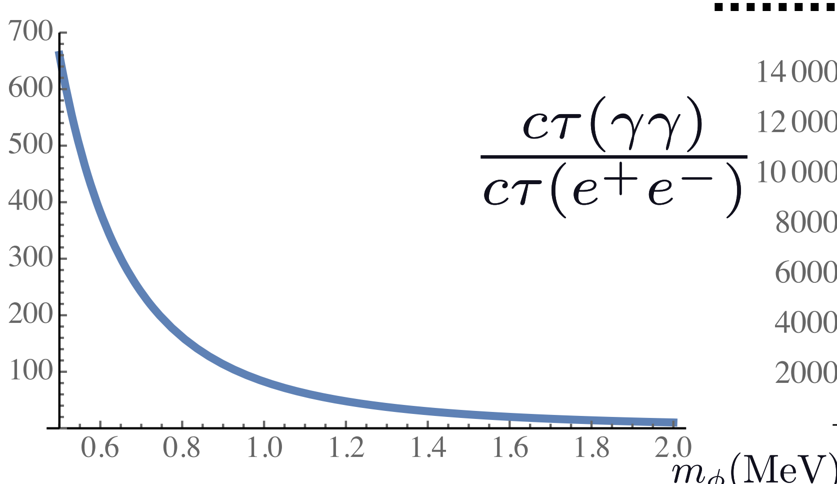




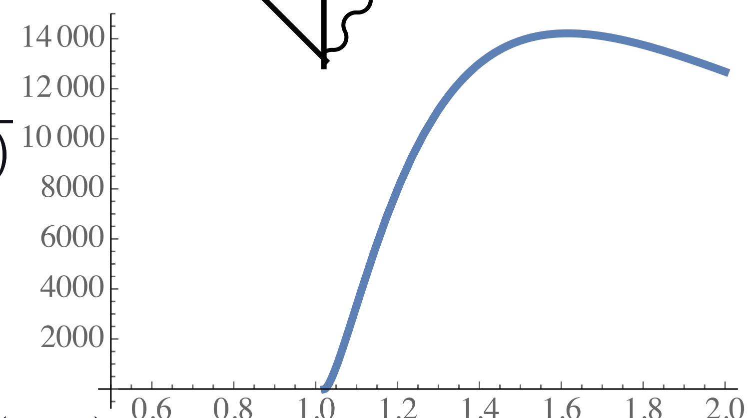
$$\Gamma(\phi \to \gamma\gamma) = g_{\phi e}^2 \frac{\alpha^2}{144\pi^3}\frac{m_\phi^3}{m_e^2}$$



$c\tau(\mathrm{m})$



$$\frac{c\tau(\gamma\gamma)}{c\tau(e^+e^-)}$$



2010 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."

Jan. 2013, 7 st. dev
Antogini -Sci. 339,417

- 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?

The APS Council and the DNP have endorsed the establishment of the

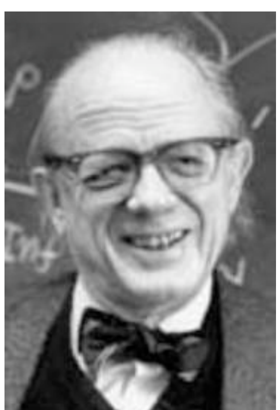
Herman Feshbach Prize in Nuclear Physics

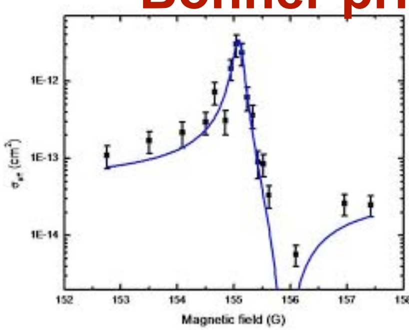
Purpose: To recognize and encourage outstanding research in theoretical nuclear physics. The prize will consist of $10,000 and a certificate citing the contributions made by the recipient. The prize will be presented biannually or annually.

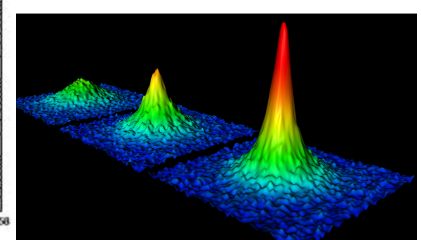
Herman Feshbach was a dominant force in Nuclear Physics for many years.
The establishment of this prize depends entirely on the contributions of institutions, corporations and individuals associated with Nuclear Physics. So far, significant contributions have been made by MIT, the DNP, ORNL/U.Tenn, JSA/SURA, BSA, Elsevier Publishing, TUNL, TRIUMF, MSU, and a number of individuals. More than $150,000 has been raised, primarily through institutional contributions. **It is very important that physicists make contributions to carry the endowment over the $200,000 mark, so that the Prize will be eligible to be awarded annually.** Please help us reach that goal by making a contribution. Go online at http://www.aps.org/ Look for the support banner and click APS member (membership number needed) and look down the list of causes.

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

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







What theorists do

- make up new particles- compute shift
- study constraints -
- non-observation of new particles that couple mainly to muons

Constraints are obtained from the decay of the Y resonances;
neutron interactions with nuclei;
the anomalous magnetic moment of the muon
x-ray transitions in 24Mg and 28Mg, Si atoms;
J/Ψ decay;
neutral pion decay
eta decay

Any time a photon appears can also have a diagram with heavy photon

Pohl et al. Table of calculations

Lamb shift: vacuum polarization many, many terms

Mostly irrelevant- theory replaced by experiment

Resolution 1- QED calcs not OK

QED calcs expand in α

#	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.

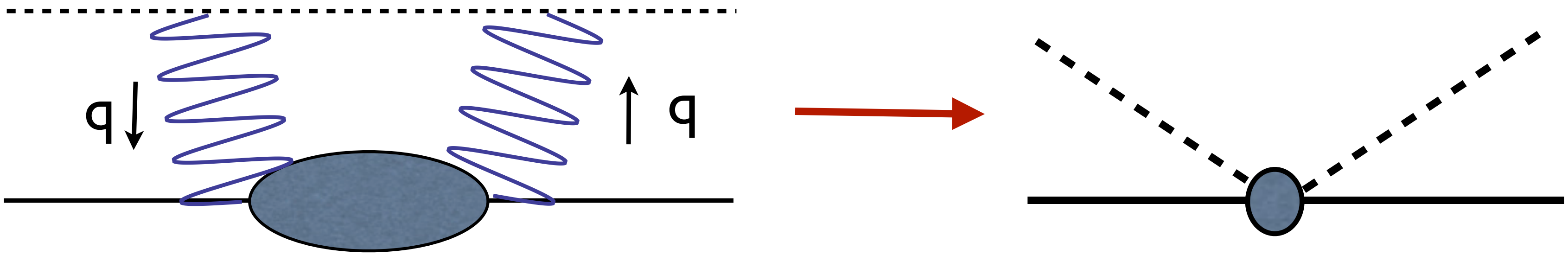
Contribution	Ref.	our selection		Pachucki[2]	Borie[5]
Leading nuclear size contribution	26	−5.19745	$< r_p^2 >$	−5.1974	−5.1971
Radiative corrections to nuclear finite size effect	2,26	−0.0275	$< r_p^2 >$	−0.0282	−0.0273
Nuclear size correction of order $(Z\alpha)^6 < r_p^2 >$	1,27–29	−0.001243	$< r_p^2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

EFT of μp interaction

Caswell Lepage '86

- 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

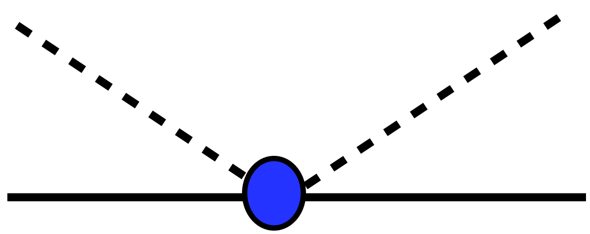
$$\Delta E^{\rm subt}(DR) = \alpha^2 m \frac{\beta_M}{\alpha} \Psi_S^2(0)(\lambda + 5/4)$$

$$\Delta E^{\rm subt}(DR) = 0.31 \text{ meV} \rightarrow \boxed{\lambda = 769}$$

$\beta_M(\text{magnetic polarizability}) = 3.1 \times 10^{-4}\text{fm}^3$ 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

Summary of D

- If there is no new Lamb shift effect on the neutron, muon hydrogen and muon deuterium are consistent
- Moreover, an electronic experiment is consistent with muonic experiments.
- If there is an effect on the neutron, a puzzle remains