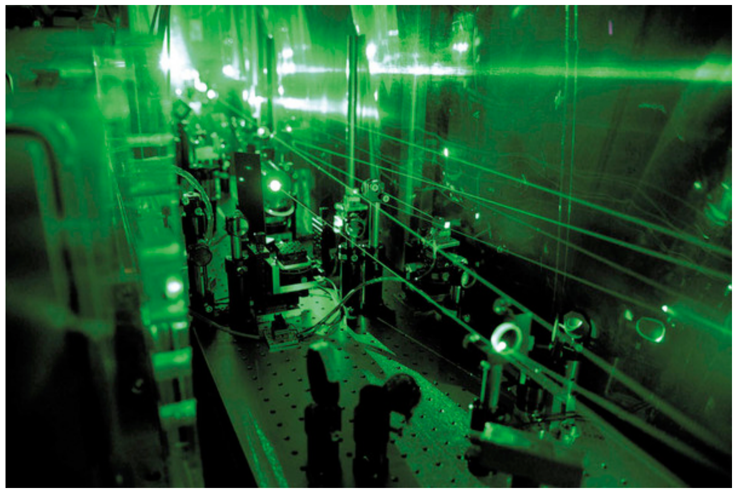
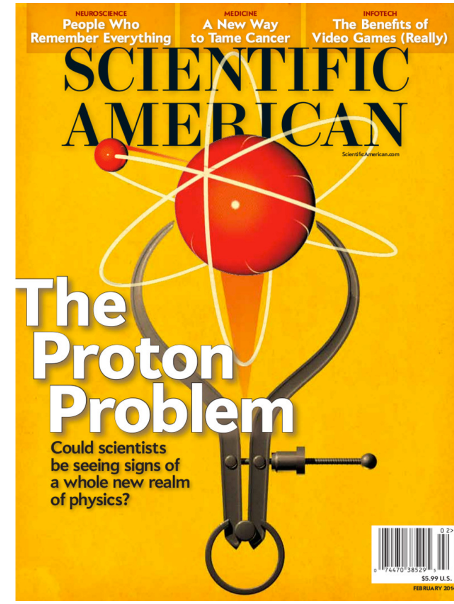
Electrophobic scalar boson and muonic puzzles

Gerald A. Miller, University of Washington

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





Feb. 2014

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

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

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

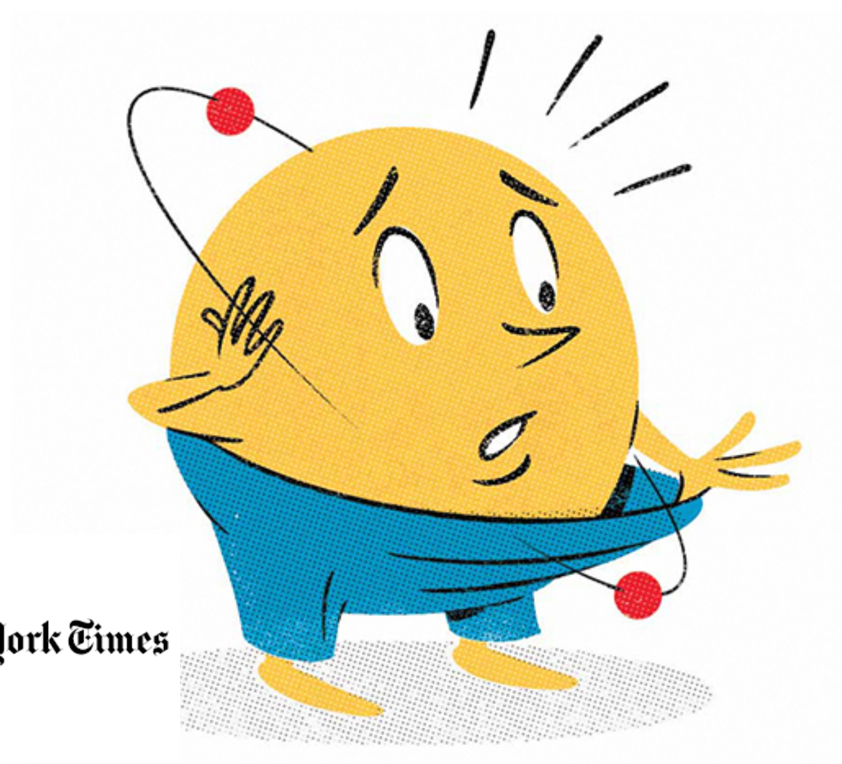
PRad at JLab- lower Q^2

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



The New York Times

Another muon opportunity-anomalous moment

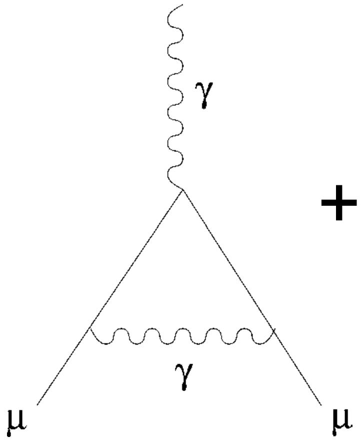


Figure 1 The first-order QED correction to g-2 of the muon.

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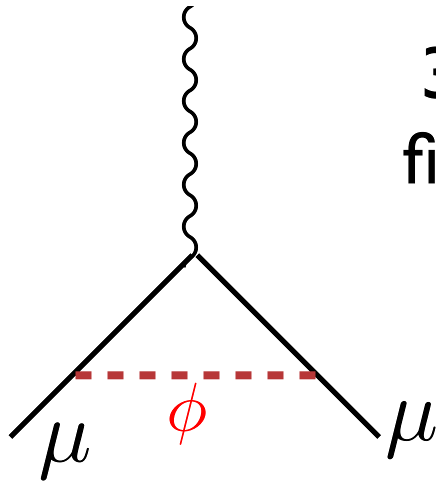
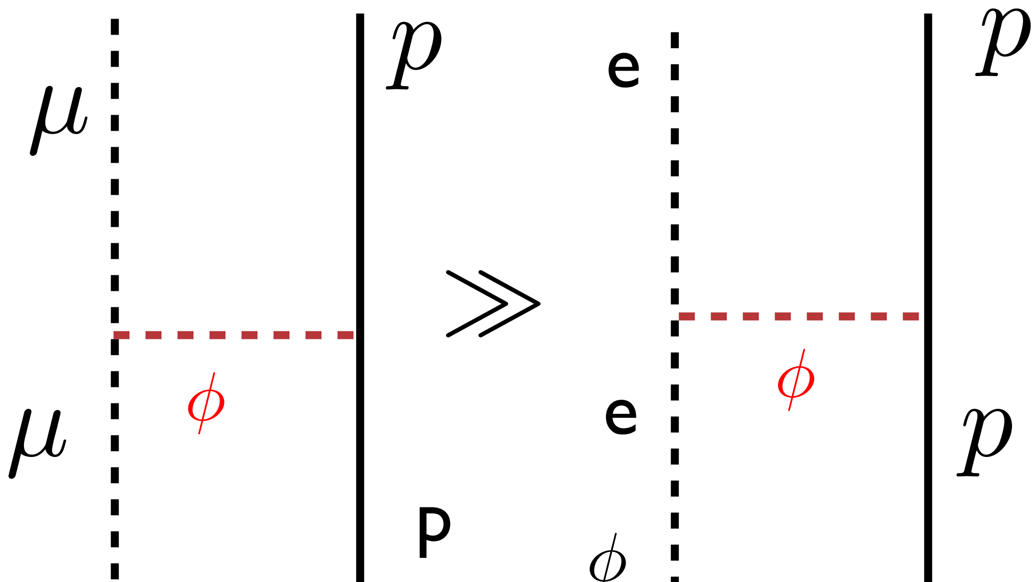


3.6 st. dev anomaly now
fix: add new scalar boson
interacts preferentially with muon

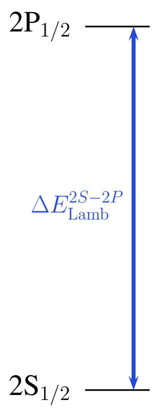
Muon data is g-2 - BNL exp't, Hertzog...

Lamb shift



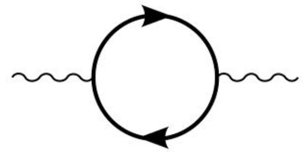
Maybe dark matter, energy particles show up as mediator in muon physics!

muonic hydrogen experiment



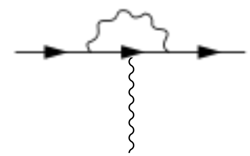
The Lamb shift is the splitting of the degenerate $2S_{1/2}$ and $2P_{1/2}$ eigenstates

Dominant in μH



vacuum polarization 205 of 206 meV

Dominant in eH



electron self-energy

Proton radius in Lamb shift

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

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

Recoil effects included:
interaction computed for moving fermions

Deuteron, ^{4}He: new experiments

- muonic deuteron atom- CREMA
- electronic deuteron isotope shift -two photon spectroscopy PRL104,23301
- same deuteron radius if `small' r_p is used
- $\delta E_L^{\mu D} = -0.368\,(78)\,\mathrm{meV}$

^{4}He radii extracted from Lamb shift require contribution of new effect (scalar boson) to be zero within error

$$\delta E_L^{\mu He} = -1.4(1.5)\,\mathrm{meV}$$

- muon and electron experiments agree for deuteron radius if 'small' r_p is used
- either r_p is really small and eH experiments wrong or
- proposed combination of non-standard model effects on p and n must accoun for μ D data as well as μ H and μ He

Possible resolutions

- QED bound-state calculations not accurate-very unlikely- this includes recoil effects
- Electron experiments not so accurate -new ones ongoing
- Strong interaction effect in two photon exchange diagram— soft proton Miller PLB 2012
- Muon interacts differently than electron!- scalar boson

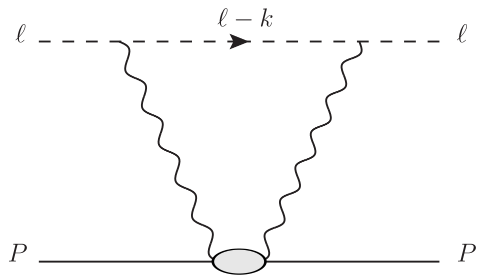
Analysis of Experiment-one example

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

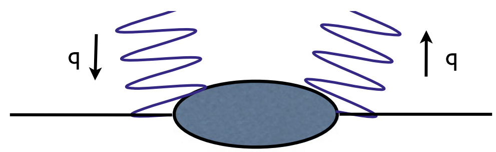
computed

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

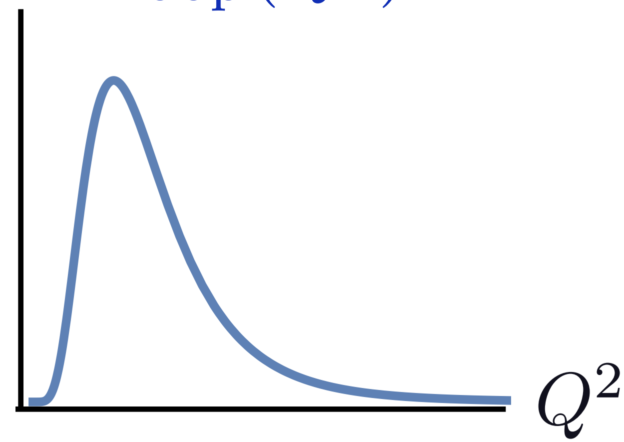
Large virtual photon energy ν, $W_1 \sim \nu$ integral over energy diverges

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

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



number of

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

Lamb shift proportional to m_l^4

Recast in EFT- parameters seems 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

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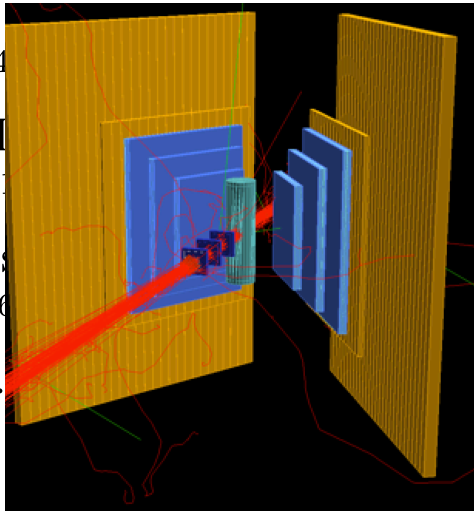
Ilieva,[4] M. Kohl,[9] G. Kumbartzki,[5] J. Lichtenstadt,[10] N. Liyanage,
Z.-E. Meziani,[6] K. Myers,[5] C. Perdrisat,[13] E. Piasetzsky (Spoke
Punjabi,[14] R. Ransome,[5] D. Reggiani,[3] A. Richter,[15] G. Ron,[16
E. Schulte,[6] S. Strauch,[4] V. Sulkosky,[7] A.S. Tadapelli,[5] and L.



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

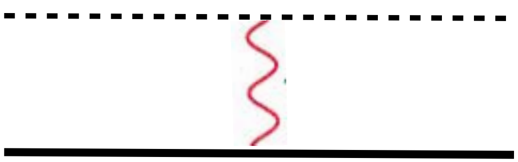
PSI proposal R-12-01.1

2 photon exchange idea is testable

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

muon scattering

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



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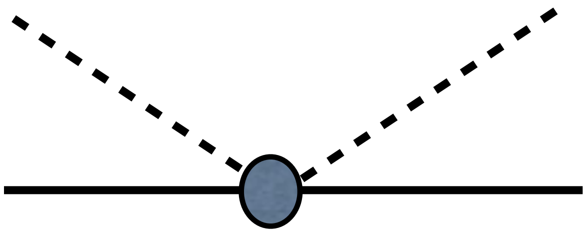
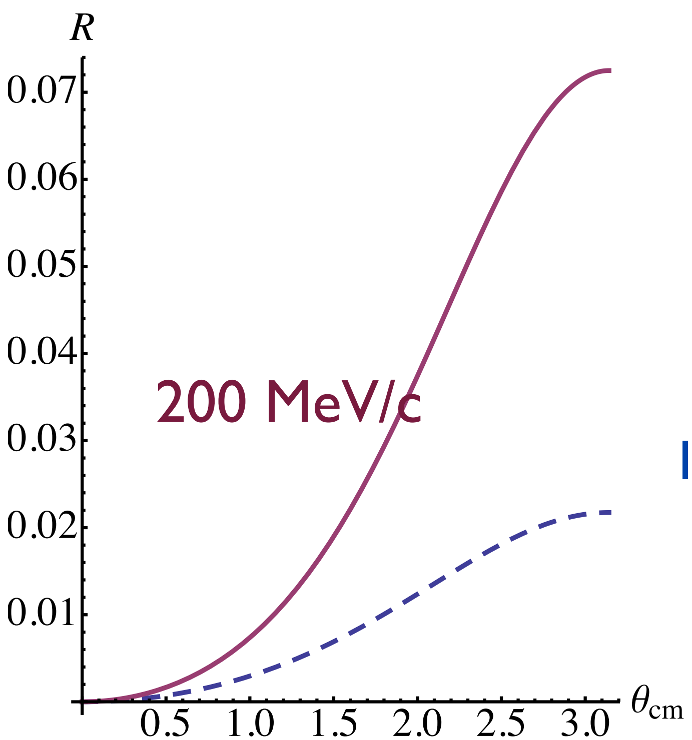




$$R = 2\frac{\mathrm{Re}[(\mathcal{M}^{(1)})^{*}\mathcal{M}^{(2)}]}{|\mathcal{M}^{(1)}]|^{2}}$$

~5 % effect should be seen

~10 % for ratio +/-

Radians

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 E_p (on proton) E_n (on neutron)

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

Size of nucleus

Nuclear shift

Square of wave fun

Counting

My model: ~0.3 meV (8)(2) =-4.8 meV about 3 st. dev off

assuming there is no soft neutron effect, must be careful

Outline of new scalar boson ϕ analysis now E_p and E_n caused by new scalar boson

- parameters must describe muonic atom lamb shift and muon g-2
- discuss processes that constrain coupling constants
- constrain mass of ϕ and coupling to electrons
- assess possible new experiments
- phenomenological approach -work backwards from the data

Notation

Couplings of ϕ to standard model fermions, f:

$$\mathcal{L} \supset e\epsilon_f \phi \bar{f} f, \ \epsilon_f \equiv g_f/e$$

$e =$ electric charge of the proton, f is particle label.

One scalar boson exchange potential between flavor 1 and 2:

$$V(r) = -\epsilon_{f_1}\epsilon_{f_2}\alpha e^{-m_\phi r}/r$$

Others pursued this idea, using further assumptions:

TuckerSmith (2010) uses $\epsilon_p = \epsilon_\mu,\ \epsilon_n = 0$
Izaguirre (2014), assume mass-weighted couplings & $\epsilon_n = 0$

Here: NO assumptions re signs or magnitudes of coupling constants.
Lamb shift $\rightarrow \epsilon_\mu \epsilon_p > 0$ take $\epsilon_\mu, \epsilon_p > 0$. Then $\epsilon_{e,\mu}, \epsilon_n$: either sign

- muonic g-2 and proton Lamb shift

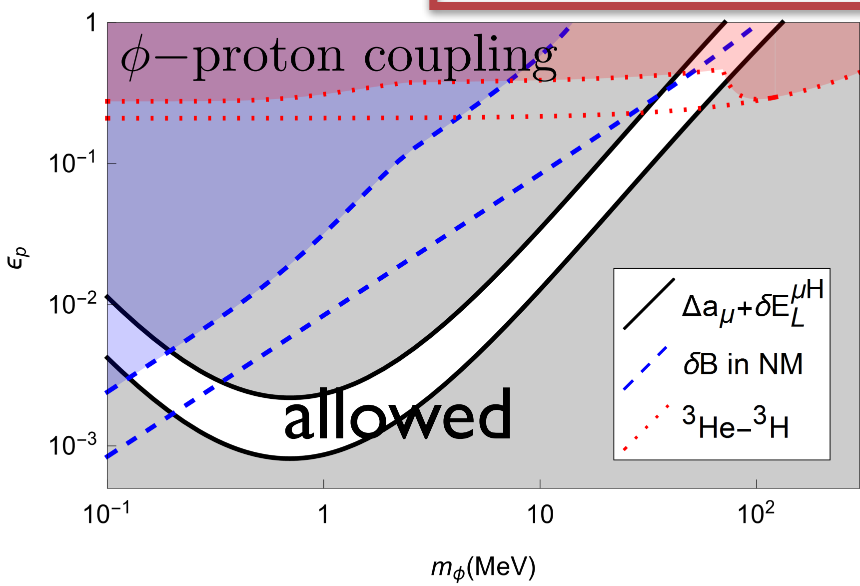
$$\Delta a_\ell = \frac{\alpha \epsilon_\ell^2}{2\pi} \int_0^1 dz \frac{(1-z)^2(1+z)}{(1-z)^2 + (m_\phi/m_\ell)^2 z}.$$

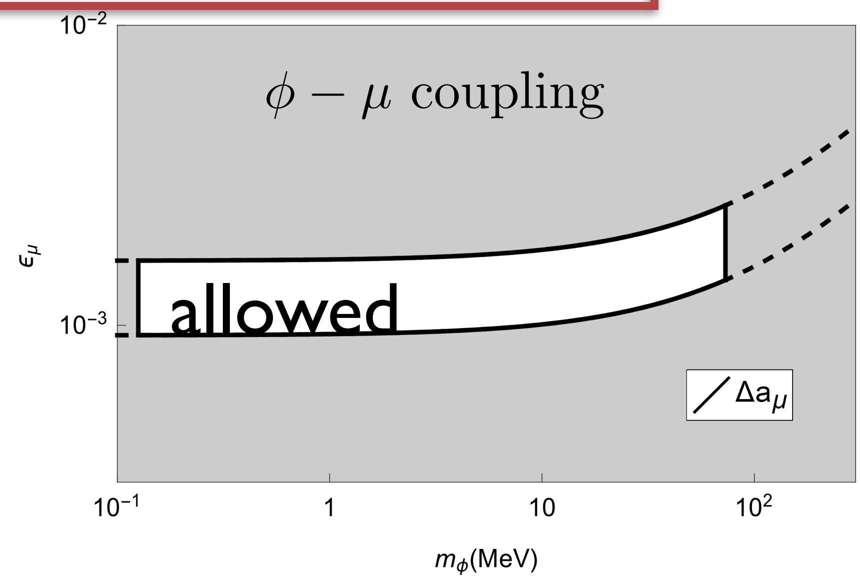
Lamb Shift

$$\delta E_L^{\ell \mathrm{N}} = -\frac{\alpha}{2 a_{\ell \mathrm{N}}} \epsilon_\ell [Z\epsilon_p + (A-Z)\epsilon_n] f(a_{\ell \mathrm{N}} m_\phi)$$

$$f(x) = x^2/(1+x)^4$$

$$\boxed{\Delta a_\mu = 287(80) \times 10^{-11},\ \delta E_L^{\mu \mathrm{H}} = -0.307(56)\ \mathrm{meV}}$$





Yavin-&Tucker-Smith assume coupling to neutron = proton

n- Pb(208) impose severe restriction, but why =?

Nuclear Physics Constraints

Low energy n Pb scattering constrains g_N

$$\frac{g_N^2}{e^2} \to \frac{A-Z}{A}\epsilon_n^2 + \frac{Z}{A}\epsilon_p\epsilon_n$$

Cancellation possible

Isospin breaking of nucleon-nucleon scattering

$1/2(V_{nn}+V_{pp})-V_{np}$ is constrained to be small via scattering length difference <1.6 fm

Binding energy difference between ^{3}He and ^{3}H: V_{pp}-V_{nn} change in binding energy difference < 30 keV

Binding energy in infinite nuclear matter: change in binding energy <1 MeV

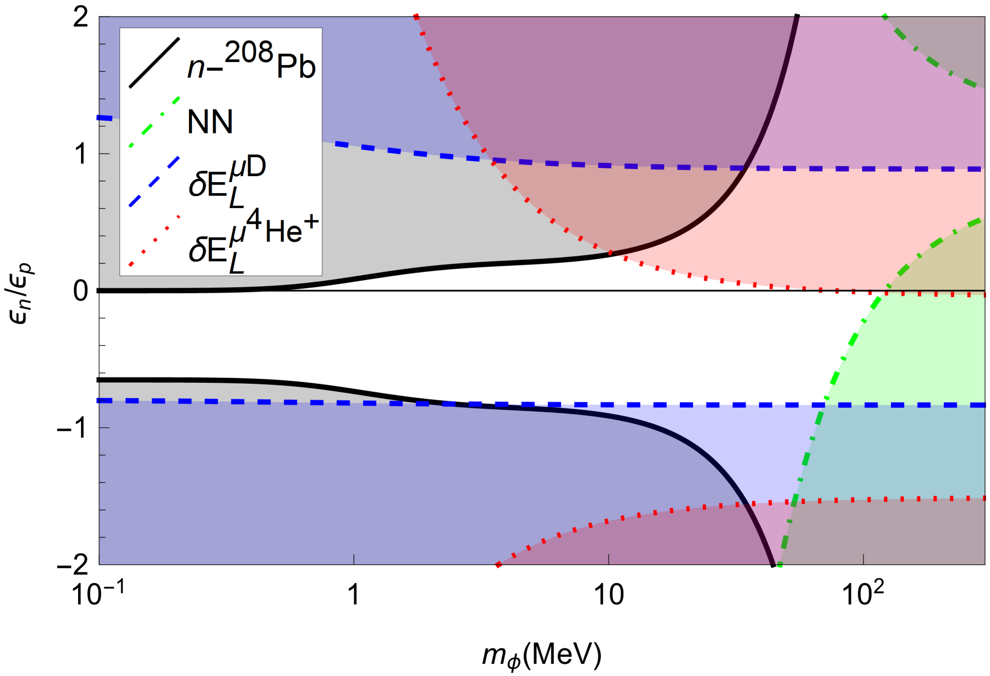
$$\delta B = \frac{\delta B_p + \delta B_n}{2} = \frac{(g_p+g_n)^2\rho}{4m_\phi^2}$$

mu D and mu He constraints

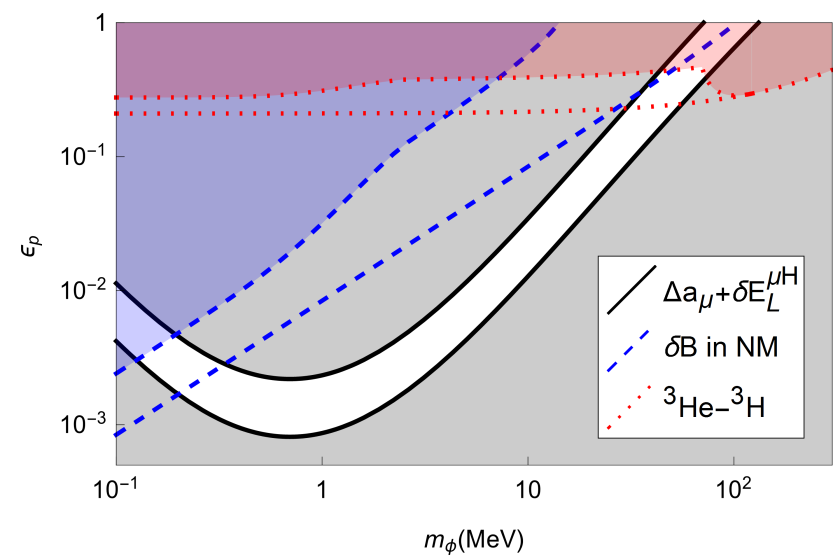
- $\delta E_L^{\mu D} = -0.368\,(78)\,\text{meV}$ (Preliminary) from talk, 3 st. dev.
- $\delta E_L^{\mu He} = -1.4(1.5)\,\text{meV}$ (Preliminary) from talk, 3 st. dev

Combine $\mu H, \mu D, \mu^4 He$ to get ϵ_p/ϵ_n independent of ϵ_μ and ϵ_p

Combining nuclear and muonic atom results



Shaded regions excluded

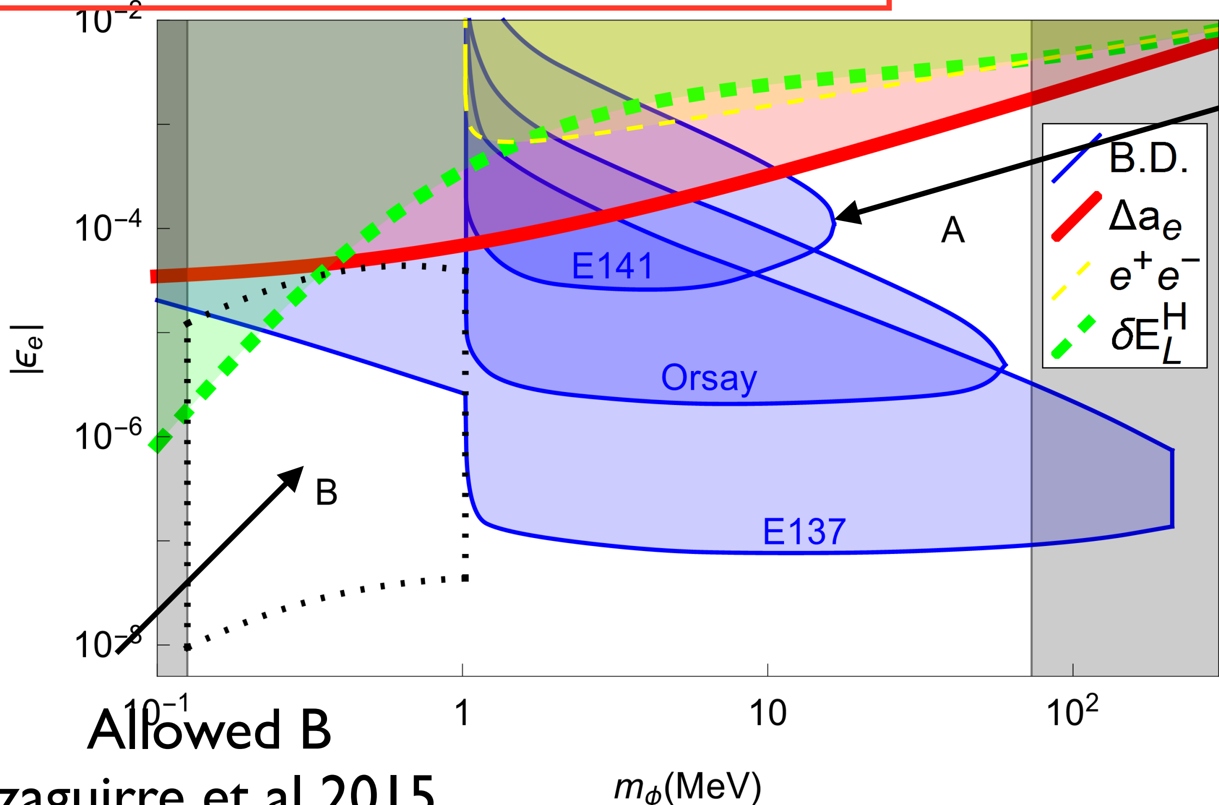


Allowing opposite sign widens allowed region

Constrain coupling to electron (analysis similar to dark photon)

- anomalous magnetic moment of electron- used to determine α, needs value obtained free of possible scalar boson effects- ratio of Planck constant to mass of Rb: Bouchendira et al PRL 106 080801
- Bhabha (e^+e^-) scattering sensitive to resonance at cm energy = m_ϕ Bhabha scattering in the MeV range Tsertos et al PRD40, 1397
- Beam dump experiments- phi decays to e+e- or $\gamma\gamma$ pairs. We provide exact evaluation of phase space integral
- Lamb shift in hydrogen <14 kHz (Eides reviews)
- Stellar cooling limits see An et al PLB725,190 (we have same limits for masses less than 200 keV). Supernova cooling -g_P large enough to keep scalar trapped

Coupling to electrons



Allowed A

Allowed couplings to electrons are small

Allowed B

Izaguirre et al 2015

- Wide range $130\,\mathrm{keV} < m_\phi < 73\,\mathrm{MeV}$ from $\epsilon_p \neq \epsilon_\mu$
- $\epsilon_n \neq 0,\ \epsilon_n/\epsilon_p < 0$ opens up parameter space
- Max $|\epsilon_e(m_\phi = 1\,\mathrm{MeV})|$ decreased by 10^2- beam dump expts
- $m_\phi \approx 70$ MeV 'large' couplings:
  $|\epsilon_e| < 1.8 \times 10^{-3}$, $\epsilon_\mu < 2 \times 10^{-3}$, $-0.3 < \epsilon_p < 0.4$
  testable ??

So far no UV completion, for leptons some guidance exists

- lepton-scalar coupling gives flavor changing neutral currents
- Yukawa matrix proportional to that of Higgs avoids problem Minimal flavor violation Cirigliano et al (2005)
- $|\epsilon_\mu/\epsilon_e| = (m_\mu/m_e)^n$ Combine electron and muon constraints:
- Region A $(0 < n \leq 1)$, Region B $(1 < n < 2)$

Possible new experiments

- Publish muon D and muon ^{4}He results (big impact on soft proton)
- proton and or muon beam dump experiments for large mass region
- low mass region Izaguirre et al underground nuclear decays
- $pp \to pp\phi$ detect protons
- improve neutron-nucleus experiments
- If scalar boson solves proton radius problem, MUSE will detect same `large radius' for positively and negatively charge electrons and muons
- muon beam dump (COMPASS)
- new muon anomalous moment measurement
- Goudelis et al PRL 116, 211303 particle of mass 1.6 to 20 MeV may provide solution to understanding cosmological abundance of 7Li

Summary

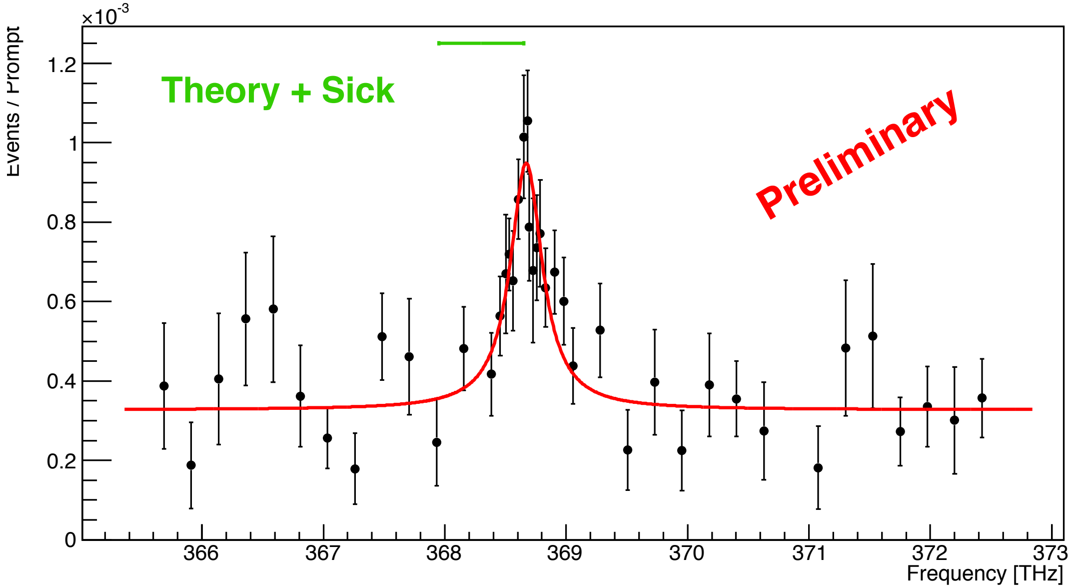
- If all of the experiments relevant to r_p, and their analyses, are correct some unusual or BSM physics occurs
- Either soft proton (almost ruled out) or
- new scalar boson
- Searching over a wide range of experiments a new scalar boson could account for both muonic puzzles and exist in the allowed parameter space.

Liu McKeen Miller 1605.04612

Spares follow

Secret results!

^{4}He from Antonioni talk



- The transition has been found at the expected position i.e., whithin the uncert. given by $r_{\rm He}$ from $e-$He scattering.
- ~~New physics model of Pospelov excluded~~
- Zavattini value from old $\mu\,{\rm He}^+$ experiment excluded

Need to summarize all 2S-2P contributions

^{4}He nuclear charge radius

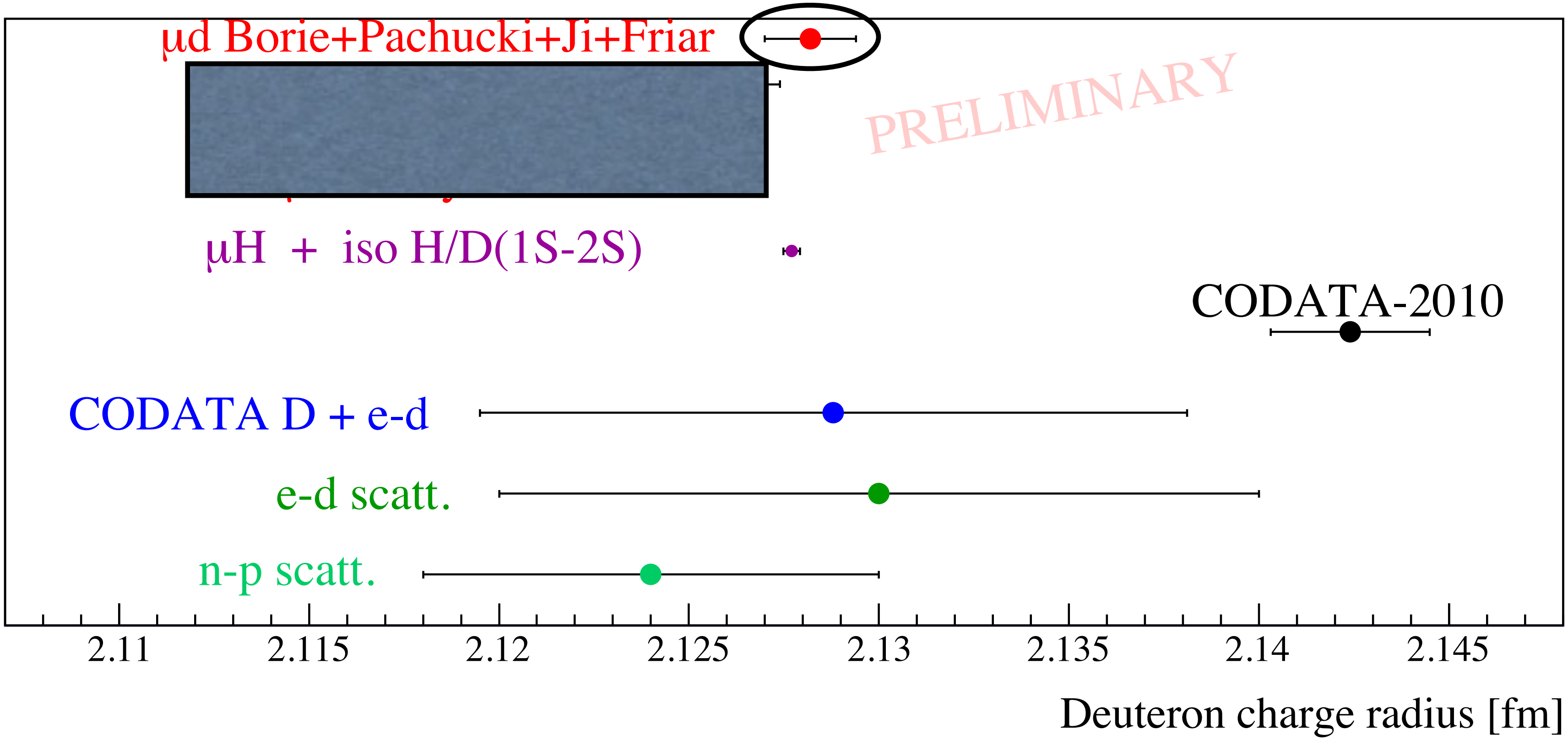
$1.681(4)$ fm	$u_r = 2\times10^{-3}$	[Sick]
$1.677(1)$ fm	(VERY preliminary)	[$\mu\,{\rm He}^+$]

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

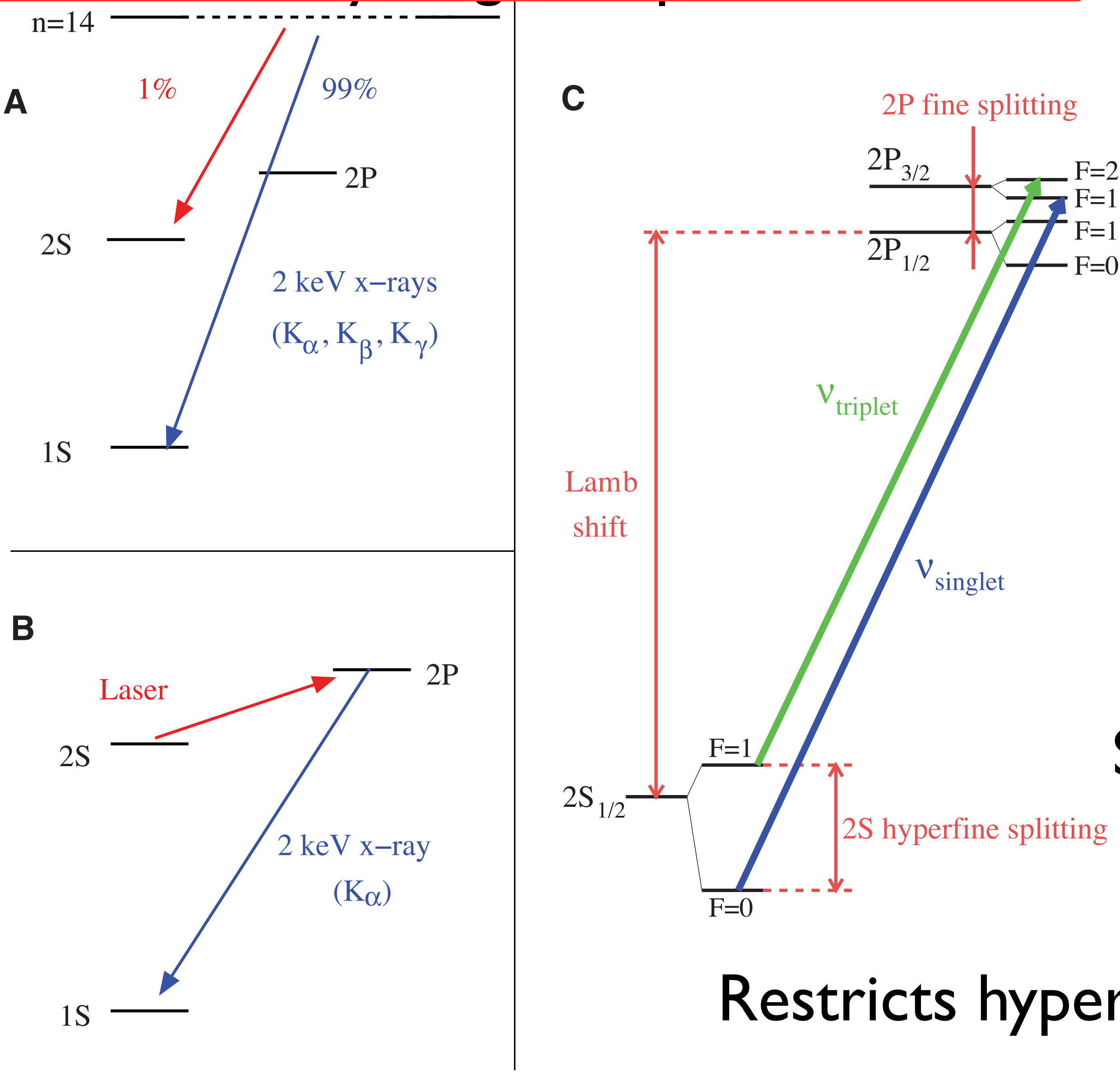
Deuteron charge radius

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



Muonic Hydrogen Experiment



From 2013 Science paper

Restricts hyperfine effects

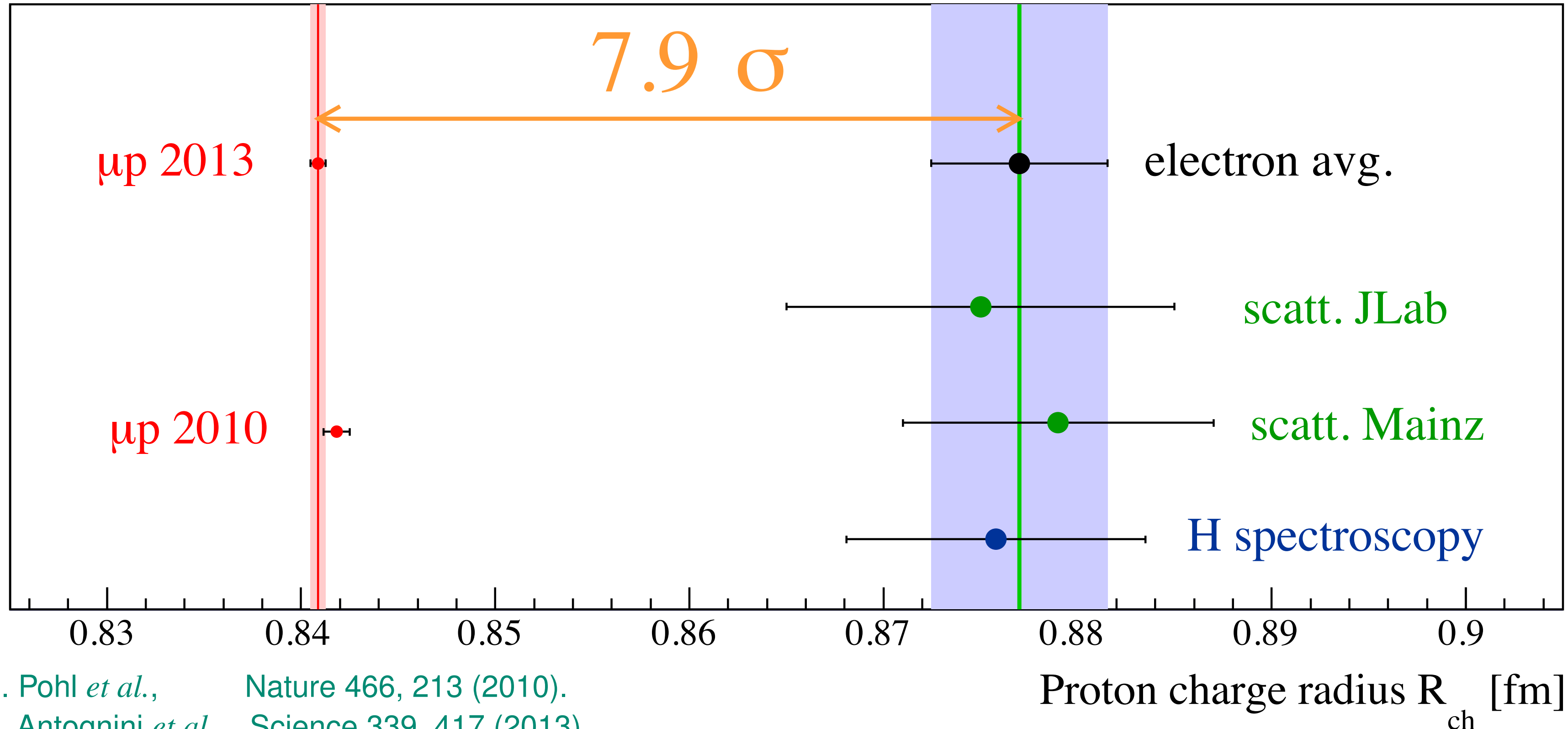
Fig. 1. (**A**) Formation of μp in highly excited states and subsequent cascade with emission of "prompt" $K_{\alpha,\ \beta,\ \gamma}$. (**B**) Laser excitation of the 2S-2P transition with subsequent decay to the ground state with K_α emission. (**C**) 2S and 2P energy levels. The measured transitions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

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

muons: 0.8409 ± 0.0004 fm

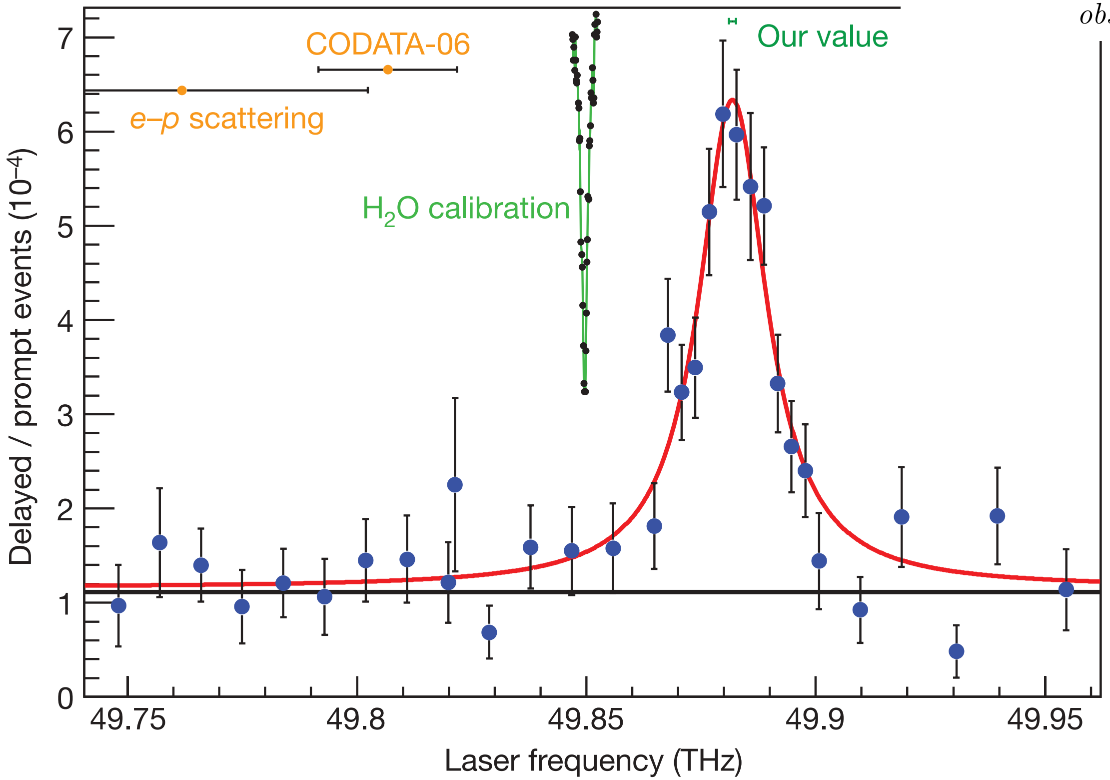


R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini *et al.*, Science 339, 417 (2013).

The experiment:
results disagree with previous measurements & world average

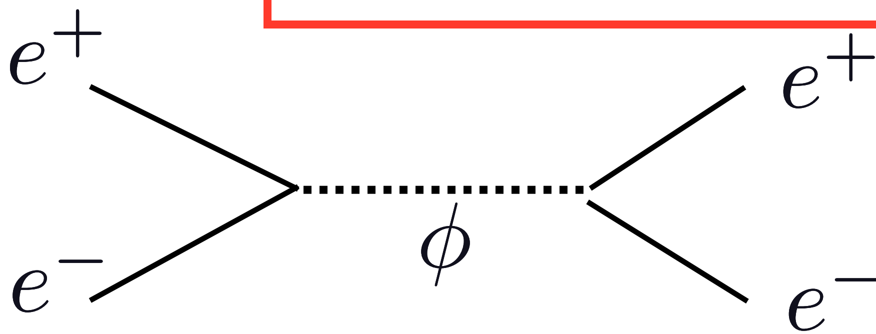
2010 Rock Solid!

"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."



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

e^+e^- resonant (?) scattering



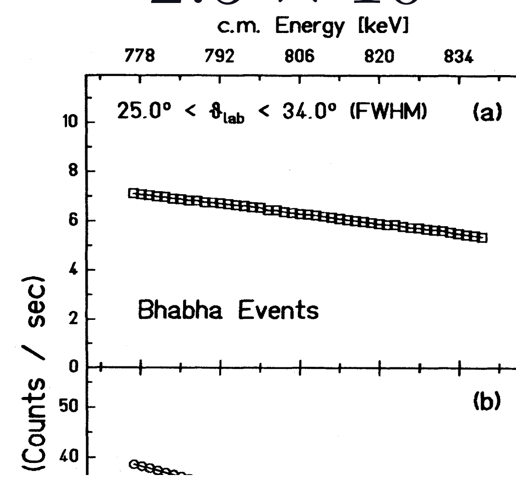
Tsertos et al PRD 40, 1397
claim experimental sensitivity of 0.5 b eV/sr

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



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

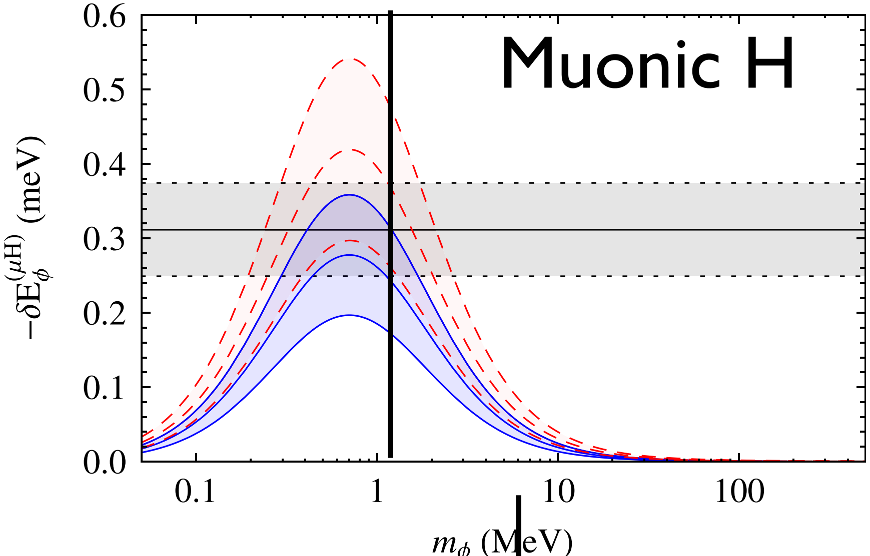
Improve experiment by a factor of 4?

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

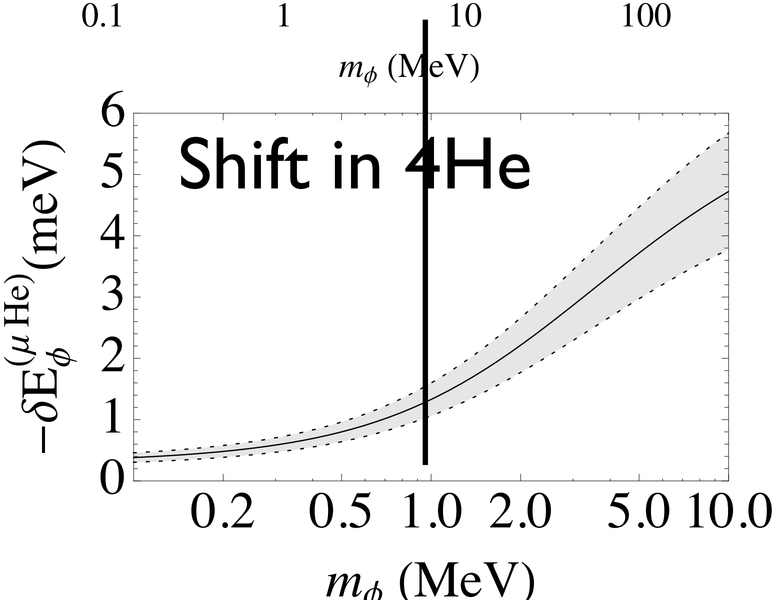
Tucker-Smith & Yavin PRD83, 101702(R)

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



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

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

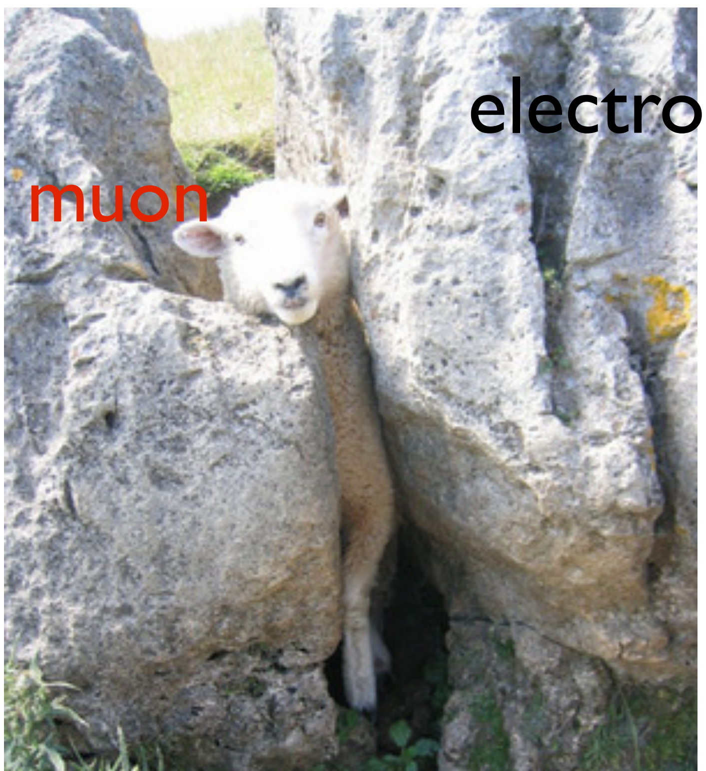


1 meV shift is OK

Vertical line- e^+e^- threshold

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

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

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

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

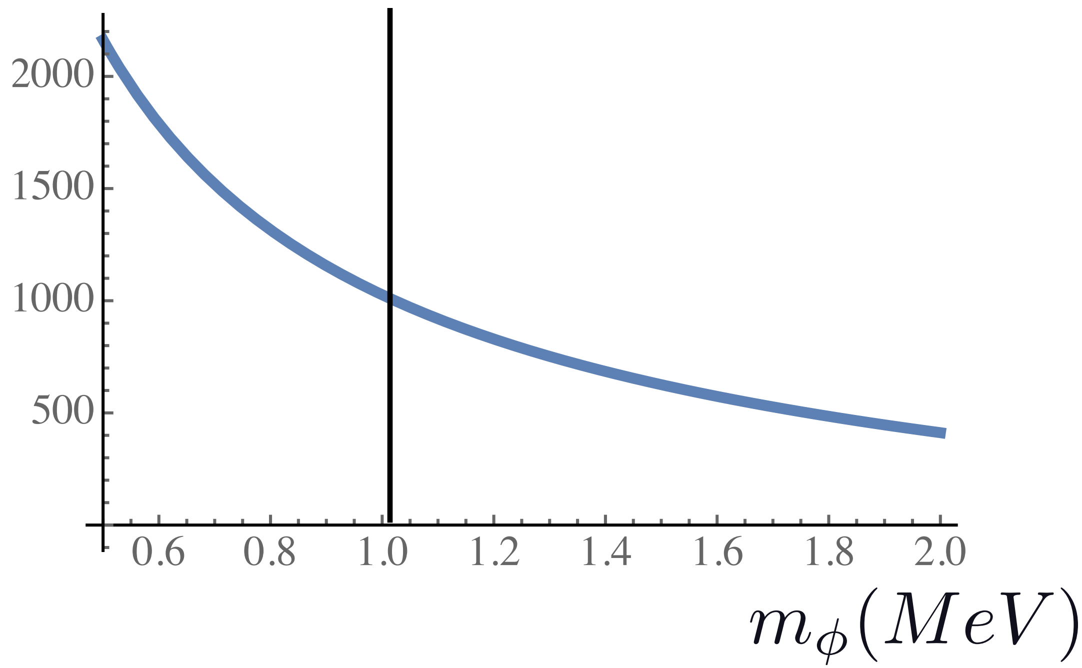
$$^{16}O(6.05, 0^+) \rightarrow ^{16}O(\mathrm{GS}, 0^+) + \phi, \quad \text{No single photon decay}$$

From electron g-2

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

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

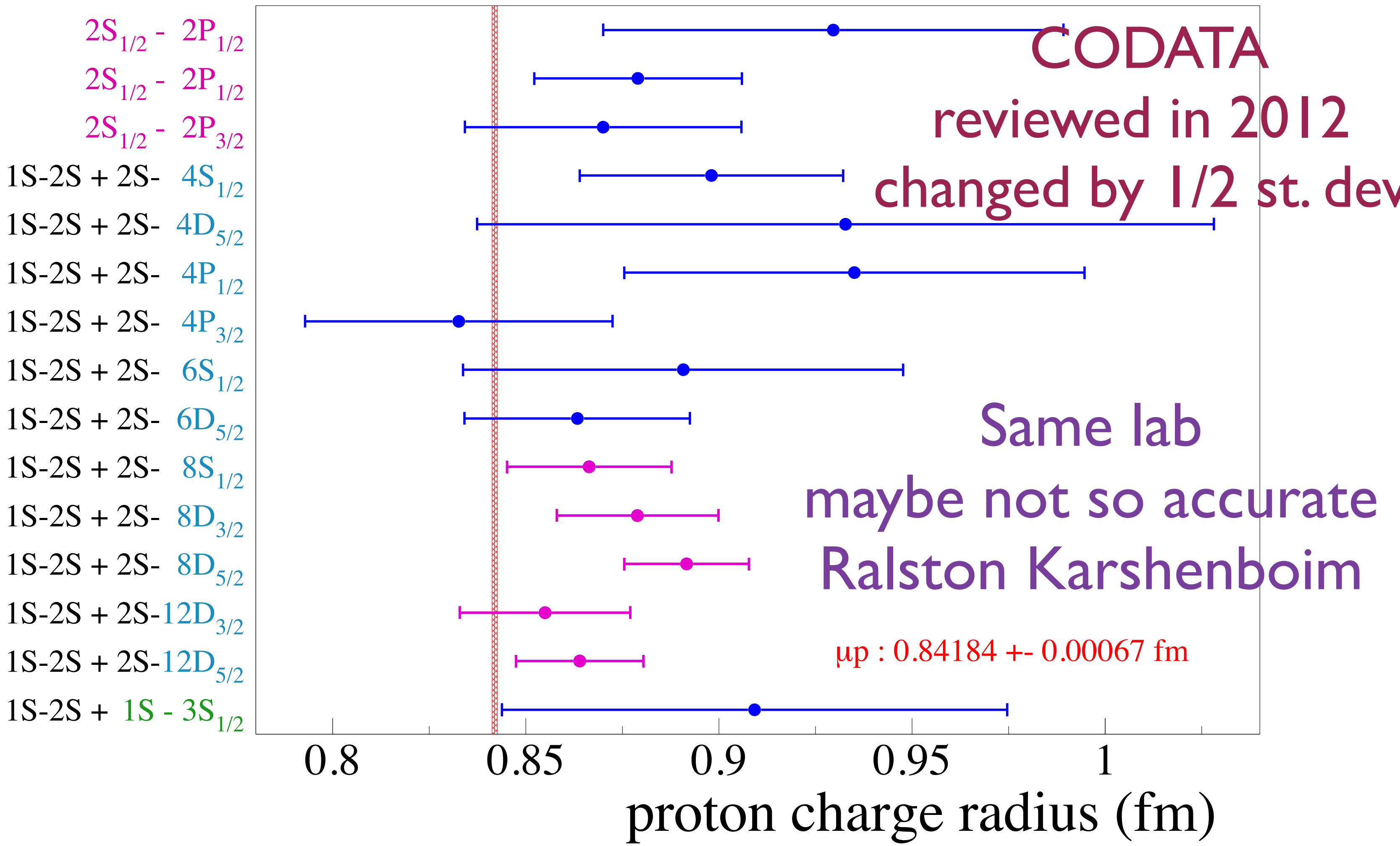
Decay length (m)
nuclear emission of
scalar boson



Electronic Hydrogen -Pohl

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

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



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

Arbitrary functions

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

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

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

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

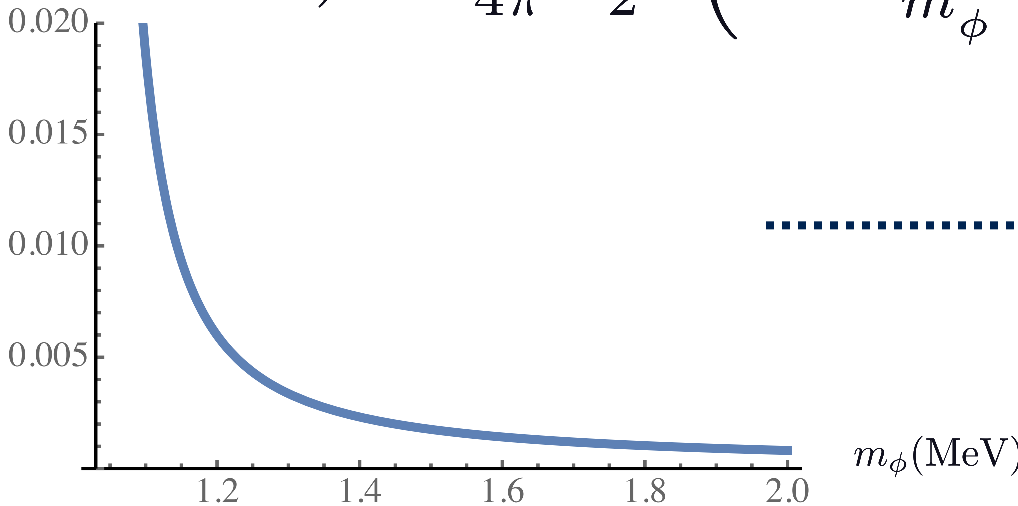
3 parameters: n, N, a $\quad (M_0 = M_\beta)$

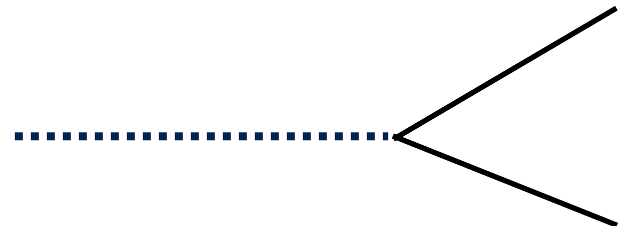
Choose parameters such that shift in proton mass < electromagnetic uncertainty of 0.5 MeV

ϕ Decay modes

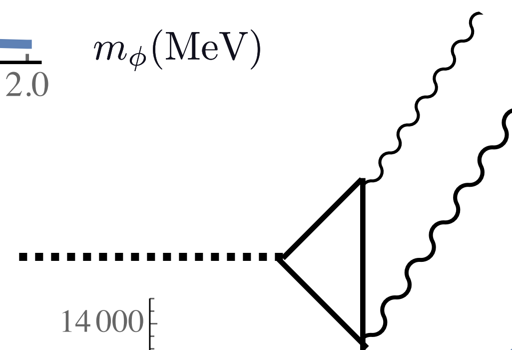
$$\Gamma(\phi \to e^+e^-) = \frac{g_{\phi e}^2}{4\pi}\frac{m_\phi}{2}\left(1 - \frac{4m_e^2}{m_\phi^2}\right)^{3/2}, m_\phi > 2m_e$$

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

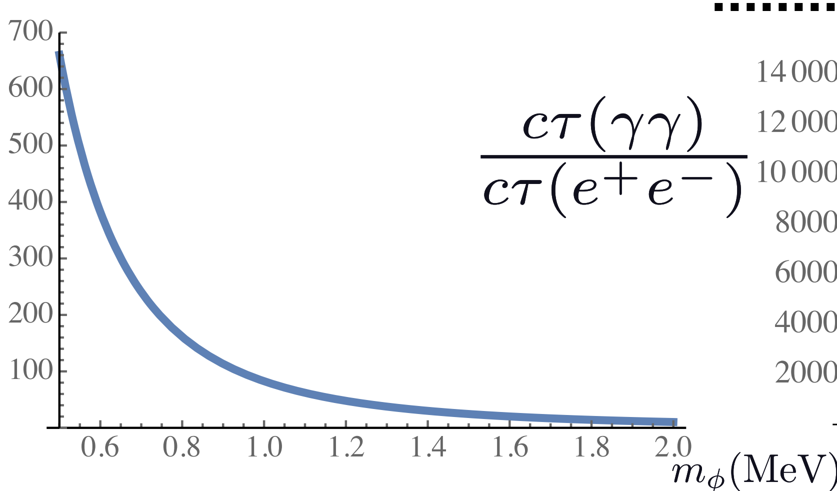




$$\Gamma(\phi \to \gamma\gamma) = g_{\phi e}^2 \frac{\alpha^2}{144\pi^3}\frac{m_\phi^3}{m_e^2}$$



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



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