### 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 coauthored 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,  $\left[\frac{\text{SA}}{\text{SUAA}}\right]$ , LANL, TUNL, and 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 BSA,MSU,TRIUMF

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 Recent results on the proton recent results on the proton results of the proton results of the proton radius o<br>Recent results of the proton radius of the proton relationship in the proton radius of the proton radius of th  $\frac{on the}{b}$

## Gerald A. Miller, University of Washington The publication: Pohl et al Nature 466,213 (8 July 2010)



**X. Zhan et al**

. **Zhan et al**  
\n
$$
r_p = \langle r_p^2 \rangle^{1/2} = 0.875 \pm 0.010 \text{ fm}
$$
\n
$$
r_p = \langle r_p^2 \rangle^{1/2} = 0.875 \pm 0.010 \text{ fm}
$$

• electron scattering

slope of G<sup>E</sup> at Q<sup>2</sup> = 0

**arXiv:1102.0318** 0.920 electron scattering Electron scattering:

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

Why atomic physics to learn proton radius? Why μH?

Probability for lepton to reside in the proton: proton to atom volume ratio

$$
\sim \left(\frac{r_p}{a_B}\right)^3 = \left(r_p \; \alpha\right)^3 \, \mathsf{m}^3
$$

•

• 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**

Proton current **Phys. Rev. C** 60, 025207 (1999

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

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

S-states only  $\Delta V_C({\bf r})\approx-\frac{2\pi\alpha}{3}\delta({\bf r})r_p^2,\ \Delta E=\langle\psi_S|\Delta V_C|\psi_S\rangle=\frac{2}{3}\pi\alpha|\psi_S(0)|^2r_p^2$ Karplus, Klein, Schwinger

next order term in  $\mathsf{q}^2$  down by  $\ (r_p/a_B)^2$ 

## Experiment: Basic idea

### The Experiment

Muonic Hydrogen



## The experiment  $2P_{3/2}$

1% of stopped muons populate 2S state  $2S \rightarrow 2P$  transitions induced by laser 2P IS 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](http://arxiv.org/abs/1104.2971) Title: Non-Perturbative Relativistic Calculation of the Muonic Hydrogen Spectrum Authors: [J. D. Carroll,](http://arxiv.org/find/physics/1/au:+Carroll_J/0/1/0/all/0/1) [A. W. Thomas,](http://arxiv.org/find/physics/1/au:+Thomas_A/0/1/0/all/0/1) [J. Rafelski,](http://arxiv.org/find/physics/1/au:+Rafelski_J/0/1/0/all/0/1) [G. A. Miller](http://arxiv.org/find/physics/1/au:+Miller_G/0/1/0/all/0/1) **Phys.Rev. A84 (2011) 012506**

#### The experiment: results disagree with previous measurements & world average Line experiment. ground amplitude include the variety of  $\alpha$ r<sup>p</sup> 5 0.84184(36)(56) fm, where the first and second uncertainties originate respectivelyfrom the experimental uncertainty of 0.76 GHz and  $ave  $l$$ mainly the proton polarizability term, gives the dominant contri-The Experiment

the laser frequency. In the laser frequency, we have measured  $50$  events in the res-s-s-s-s-s-s-s-s-s-s-s-s-s-s-s-



data points, top left). Our result is also shown ('our value'). All error bars are

using CERN's ROOT analysis tool accounted for the statistics at each  $\frac{2L}{100}$  is the 1s-2s that is, 1.4 × 10<sup>-14</sup> relative accuracy. "The 1S-2S transition in H has been measured to Only an error of about  $1,700$  times the quoted experimental uncertainty could account for our observed discrepancy."

large discrepancy is not known.

J. Carroll — Proton Radius Puzzle — Slide 13

This frequency corresponds to an energy of DE 5 206.2949(32) meV. 206.2949(32) meV. 206.2949(32) meV. 206.2949(32) From equation (1), we deduce an r.m.s. proton charge radius of

 $\frac{1}{2}$  is extended from H spectroscopy. accurate, but 3.1s smaller, than the accepted hydrogen-independent hydrogen-independent hydrogen-independent  $\mathcal{L}_1$  $v_{\rm eff}$  and  $v_{\rm eff}$  is the origin of the origin of this origin of this origin of this origin of this origin of

 $\mathbb{E} \left[ \mathcal{L} \left( \mathcal{L} \right) \right]$  were defined by wrong or missing, and the distinguished term as  $0.31$ required to match our measurement with the CODATA value of rp.  $W_{\rm eff}$  is 64 times that  $0.31$ 

 $T_{\rm eff}$  determination of  $\sigma$ as adjusting the input parameters r<sup>p</sup> and R' (the Rydberg constant) to match the QED calculations8 to the measured transition frequencies4–7

in H: 1S–2S on the one hand, and 2S on the one hand, and 2S on the one hand, and 2S  $\mu$ 

 $T_{\rm eff}$  transition in H  $_{\rm eff}$  $1.4$  3  $10214$  relative accuracy. Only an error of about 1,700 times the about 1,700 tim  $q$ uoted experimental uncertainty could account for our observed discrepancy. The 2S{n' transitions have been measured to accuracies between 1/100 (2S–8D) (refs 6, 7) and 1/10,000 (2S1/2–2P1/2 Lamb  $s_{\rm 1D}$  of the respective line widths. In principle, such an accuracy  $\sim$ could make these data subject to unknown systematic shifts. We note, however, that all of the (2S) measurements (for a list, see, for a l

laser frequency. The fit (red) is a Lorentzian on top of a flat background, and **Rock Solid!** 

#### Experimental summary  $\overline{a}$ DEI IN TEHLAI SUNT  $\mathbb{P}$  cordinates much smaller by a negative multiplier  $\mathbb{P}$ pared to ordinary atomic hydrogen causes  $\mathcal{L}_{\mathcal{A}}$  atomic hydrogen causes enhancement of effects enhancement of effects in muonic hydrogen is the sum of radiative, recoil, and proton struc- $\overline{\phantom{a}}$ ture contributions, and the fine splittings for  $\overline{\phantom{a}}$ tial v  $\overline{1}$

 $s_{\rm eff}$  is total predicted. The total predicted  $2S_{\rm eff}$ 

(1) is given in Supplementary Information.

 $\frac{1}{2}$ 

rD E is given in fm. A detailed derivation of equation

The first term in equation (1) is dominated by vacuum polarization, which causes the 2S states than the 2S states to be more tightly bound than the 2P states (Fig. 1). The mp fine and hyperfine splittings (due to spin–orbit and spin-spin interactions) are an order of magnitude smaller than order of  $\alpha$  $\mathcal{L}_\mathrm{L}$  is the uncertainty of  $\mathcal{L}_\mathrm{L}$ dominated by the proton polarizability term  $\mathcal{A}$ The second and third terms in equation (1) are the finite size con- $\tau_{\rm eff}$  and  $\tau_{\rm eff}$  amount to 1.8% of DE $_{\rm eff}$ 

 $\mathcal{F}_{\mathcal{F}}$  more than for the mass  $\mathcal{F}_{\mathcal{F}}$ been considered one of the fundamental experiments in atomic spectroscopy, but only recent progress in muon beams and laser techno-beams and laser techno-beams and laser technology made such an experiment feasible. We report the first successful

allowed optical 2S–2P transitions. All transitions are spectrally well transitions. All transitions are spectrally well as  $\sim$ 

 $L$ astler Brossel, E`cole Normale Supe $\mathcal{L}$  P. et  $M$  et  $M$ 

Institut fu¨r Strahlwerkzeuge, Universita¨t Stuttgart, 70569 Stuttgart, Germany. <sup>7</sup>

De´partement de Physique, Universite´ de Fribourg, 1700 Fribourg, Switzerland. <sup>9</sup>

Princeton University, Princeton, New Jersey 08544-1009, USA. 10Dausinger & Giesen GmbH, Rotebu¨hlstr. 87, 70178 Stuttgart, Germany. 11Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland. 12Institut fuïr Teilchenphysik, ETH Zuürich, 8093 Zuürich, Switzerland. {Present addresses: Deuts<br>Switzerland. {Present addresses: Deutsches Zentrum fuïr Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

The experiment was performed at the pE5 beam-line of the pE5 beam-line of the pE5 beam-line of the proton of the proton of the proton of the pE5 beam-line of the pE5 beam-line of the pE5 beam-line of the pE5 beam-line of accelerator at the Paul Scherrer Institute (PSI) in Switzerland. We

I3N, Departamento de Fı´sica, Universidade de Aveiro, 3810-193 Aveiro, Portugal.

 $3=2$  states of mp atoms has been determined by  $\mathcal{L}$ 

#### Pulsed laser spectroscopy  $\mathbf{r}$  as a performance we use the we use  $\mathbf{r}$

measure a muonic Lamb shift of 49,881.88(76) GHz. On the basis of """ ("4) present calculations<sup>11–15</sup> of fine and hyperfine splittings and QED terms, we find  $r_p = 0.84184(67)$  fm, which differs by 5.0 standard terms, we find  $r_p = 0.84184(67)$  fm, which differs by 5.0 standard deviations from the CODATA value<sup>3</sup> of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by  $-110 \text{ kHz/c}$  (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 Rydberg is known to 12 figures  $t_{\text{y}} = t_{\text{y}}$  , precision of H atoms $\sigma$ 

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

#### • Puzzle- why muon H different than e H?  $\mathsf{D}_1$  and  $\mathsf{D}_2$  and thus relies on bound-state  $\mathsf{D}_2$  $\blacksquare$  also why muon  $\blacksquare$  different than  $e \sqcap s$

### Pohl's Table of calculations

Lamb shift: vacuum polarization many, many terms



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



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



# Possible resolutions

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

## **Hydrogen -Pohl**





- 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](http://arxiv.org/find/hep-ph/1/au:+Batell_B/0/1/0/all/0/1)[, McKeen](http://arxiv.org/find/hep-ph/1/au:+McKeen_D/0/1/0/all/0/1)[, Pospelov](http://arxiv.org/find/hep-ph/1/au:+Pospelov_M/0/1/0/all/0/1) **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-ofmagnitude 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  $\xi$  to the following sum of contributions:

 $\xi$ =206.2949(32) meV -One measured number

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

three computed numbers

To explain puzzle:

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



Lamb shift goes as lepton mass to the fourth power

### Our idea-specifics <u>| Uur iuca-specifics</u>

$$
\Gamma^{\mu}(p',p) = \gamma^{\mu}_{N} F_{1}(-q^{2}) + F_{1}(-q^{2}) F(-q^{2}) \mathcal{O}^{\mu}_{a,b,c} \qquad q = p' - p
$$

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

$$
{\cal O}^{\mu}_b=((p^2-M^2)/M^2+(p^{\prime^2}-M^2)/M^2)\gamma^{\mu}_N
$$

is empirically well represented as a dipole F1(−q2) = (1−q2) = (1−q2) = (1−q2) = (1−q2) = (1−q2) = (1−q2) = (1−

 $\Box$ 

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

$$
\lambda F(-q^2) = \frac{-\lambda q^2/b^2}{(1-q^2/\widetilde{\Lambda}^2)^{1+\xi}}.
$$
 off-shell proton charge = proton charge  
gauge invariance

interference between one on-shell and one off-shell part

of the vertex function. The invariant am-

evaluated between fermion spinors, is given in the rest

where the lepton momentum is larger than  $\mathcal{O}(m, 0)$ 

tual photon momentum is k and the nucleon momentum

p = (M, 0, 0, 0). The intermediate proton propagator

 $p$ 

e4

2M<sup>2</sup>

 $T = \text{parameter } \lambda / h^2 \quad \tilde{\Lambda} = \Lambda \quad \epsilon = 0$ parameter  $\lambda$  is  $\lambda$  is  $\lambda$  is  $\lambda$  is expected to be of the theorem to be of the theorem to be of the theorem to be  $\lambda$  $\text{parameters} \,\,\lambda/b^2, \,\tilde{\Lambda} = \Lambda, \; \xi = 0$ 

order of the pion mass, because these longest range com-

• Ball Chiu (1980) qed **Ponents of the nucleon are least bound are least bound are least bound are least bound are suscep-** $M_{\text{env}}$  menture perchanged per percipi  $\Gamma$  itally many more models are possible Many many more models are possible!



 $\mathcal{L}(\mathcal{L}^{(k)})$  (k2)  $\mathcal{L}^{(k)}$  (k2) (k2) (k2) (k2) (k2)

l Vary demanded by current conservation as expressed through  $\lambda$  to obtain needed 0.31 meV shift. Vary  $\lambda$   $\,$  to obtain needed 0.31 meV shift.

tion correction correction correction correction term in the subtraction term in the subtraction term in the subtraction term in the subtraction  $\mathcal{L}_\mathcal{S}$ 

(2π)<sup>4</sup>

2M<sup>2</sup>

 $\mathbf{L}$ 

 $\frac{1}{2}$ 

 $\mathbf{u}$ 

 $\mathbb{R}^n$ . The ratio,  $\mathbb{R}^n$ 

the Ward-Takahashi identity [24, 25]. We assume

 $\mathsf{L}$ 

 $\mathbb{R}^n$ 

N



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



tion correction corresponding to a subtraction term in the

tible to the external perturbations putting the nucleon

 $\mathbb{E}_{\mathcal{L}}[Z]$ . The ratio,  $\mathcal{L}[\mathcal{L}]$  effects to on-shell effects to on-sh

 $T_{1,2}(q \cdot P/M, q^2) = T_{1,2}(q_0, Q^2)$  $ImT_{1,2} \sim W_{1,2}$  $W_2 \sim 1/\nu$ ,  $W_1 \sim \nu$  large  $\nu$ 

- Dispersion integral involving  $W_2$  converges
- Dispersion integral involving W<sub>1</sub> divergessubtraction needed at all  $Q^2$



- 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

as<br>fft  $Eqa(6)$  and  $Eqa(7)$ . The medium modified ratio is given by **Nuclear** measured the ratio of the ratio of the ratio of the <sup>4</sup>He nucleus to that of a nucleon for **Second the ratio of the ratio of the ratio of a nucleon** for Figure 3  $\frac{1}{2}$  changed in the  $(8)$  $\mathcal{F}_{1,2}$  indicated by<br> $\mathcal{F}_{2,3}$  $\frac{\tilde{G}_E}{\sqrt{G_E}} = \frac{G_E + F_1 f(Q^2)(1 + \frac{Q^2}{2N\ell^2})}{G_E + F_1 f(Q^2)(1 + \frac{Q^2}{2N\ell^2})} + \frac{G_E}{\sqrt{N\ell^2}} \left[1 + \frac{F_1}{G_E} f(Q^2)(1 + \frac{Q^2}{2N\ell^2})\right] \cdot \sigma^{\mu\nu} q_k(9)$ values of  $f$  are<br> $\lvert$  nuclear binding GELIO25 times the and the amplitude of  $\frac{16}{5}$ . If the addition  $\frac{1}{4}$  of  $\frac{1}{2}$ , and  $\frac{1}{2}$  reduction  $\frac{1}{2}$  defined  $\frac{1}{2}$  defined  $\frac{1}{2}$  and  $\frac{1}{2}$  defined  $\frac{1}{2}$  defined  $\frac{1}{2}$  defined  $\$ Otherwise, the allow  $V$  to have<br>lead to a larger  $0.007$  minimizes V  $\sigma_{\text{L}}^2 = \sigma_{\text{L}}^2 + \sigma_{\text{L}}^2 + \sigma_{\text{L}}^2$ altrate the function f. Our aim is to see if the *m*ullest possible values  $\frac{dV}{dt}$  are  $\frac{1}{2}$ with observations. Therefore we take  $\epsilon$  to be the ratio  $\alpha$  shown is to sh efor**e** we take  $\epsilon$  to be the extractive dependence nuclearly extend to  $\epsilon \approx -0.007$ . Using Eq. (2), we find  $\frac{1}{3}$  to the Lamb shift large enough to  $\Omega^2$ es between -0.6 and -1.3 as  $Q^2$  *x*aries between 0.4 and 2.6 GeV<sup>2</sup>. The intervalues  $\text{R}^{\text{max}}$  is the second term of  $\text{R}^{\text{max}}$  in the initial protons and final protons are on the ductions  $\text{H}^{\text{max}}$ ratio of polarization observables is a true medium modification. Otherwise, the  $\mathcal{G}$  we will be easily a large and  $-1.3$  as  $O^2$  varies between 0.4 and  $\mathbb{Q}$  for  $\mathcal{G}$  which is in ild argue that the model used to evaluate the nuclear effect, taking  $W_{\rm w}$  to by  $V_{\rm w}$  . E $\cup$  $\frac{1}{2}$  too simple to be used. The most exident improvement would allow  $\frac{1}{2}$  to have  $10$  for  $10$ vd stalar<del>pterno langza u pansyegotolo loppis wsmytghisi wangleadowydealo</del>wychygon. Uther *y* feator and we use the complete on-between these terms that lead to the  $\frac{1}{20}$ ,  $\frac{1}{$ *u* + (*p* + *p* + *p*<sub>0</sub><br>
(*p* + *p*<sub>0</sub><br>
(*p* + *p*<sup>0</sup>)<br>
(*p* + *p*<sup>0</sup>) 11 O<sub>v</sub> um. .Even w<br>evident *c M* this miniatur<br>provement 10 16 tours<br>District o <sup>6</sup>*p*<sup>o</sup>↵ *· <sup>M</sup> <sup>V</sup>* \<br>*u*(*p*) *File Calle n*<sub>2</sub>  $\frac{1}{2}$  *b*<sub>2</sub>  $\frac{1}{2}$  *b*<sub>2</sub>  $\frac{1}{2}$  *y*<sub>2</sub>  $\frac{1}{2}$  binding energy<sub>1</sub>of 7 MeV per nucleon would be disrupted. Using  $V/M = -0.007$  minimizes  $\mathbf{r}$  $\frac{1}{2}$ ard **f**orm factor of polarization transfer in the <sup>4</sup>He nucleus to that of a nucleon for is changed in the angle of the ratio of  $\mathcal{L}(\mathbf{X}_M)$  is changed in the angle of  $\mathcal{L}(\mathbf{X})$  is a strong of  $\mathcal{L}(\mathbf{X})$  is c where  $\frac{G}{4M^2}F_2$ ;  $4M^2$  $G_M =$ Example of that ratio Recall the definitions<br>  $G_E = \oint_{1}^{2} \frac{1}{4M^2} F_2$ ;  $G_M = F_1 + F_2$ . (8)<br>  $G_E = F_1 - \frac{1}{4M^2} F_2$ ;  $G_M = F_1 + F_2$ . (8) 1 + *<sup>Q</sup>*<sup>2</sup>*/*⇤<sup>2</sup> *.* (5)  $\Delta F_1 = -\Delta F_2$  $\bar{u}(p')$  $\sqrt{1}$  $\gamma^{\mu}$ ( $\overline{A}^{\mu}$  +  $\$  $q_1^{\mu\nu}q_\nu$  $\frac{1+4\frac{W^{2}Y}{2}}{2M^{4}Y^{2}} \left( \frac{Q^{2}}{2} \right)$  $\overline{\phantom{a}}$  $u(p),\;$  <del>(</del>F<sub>2</sub> term  $\; \; |$ and the nuclear mass (7 Wey for <sup>4</sup>He); so  $\epsilon \approx -007$ . Us<br>consi**f** entity the observations **IThereford** we take  $\epsilon$  to **F**  $\int_{0}^{\frac{\pi}{2}} f(x^2) \frac{dx}{x^2} dx = \int_{1}^{\frac{\pi}{2}} f(x^2) dx$ , so  $\epsilon \approx -0.007$ . Using Eq. (<del>f</del>*d*) we find **Ratio**<sub>25</sub> times the construction  $\frac{f_1(z)}{z} \approx -1.8 - \frac{1}{1 + (z^2 + 1)}$  reduction  $\mathcal{L}$  **at a** (10) **of the low**ble ratio of polarization observables is a true medium modification. Otherwise, the<br>**Of the distribution of polarization** observables is a true medium modification. Otherwise, the 4He nucleon for a nucleon for which ranges between 10.6 and -1.5 as  $\varphi$  varies between 0.4 and **States of the all with a**<br>6 and 25 tumes that the effect observed by [2]. It one asserts that, the entire 10% reduction of **are property to** simple to be exect. The most extent improvement would allow the ratio discrete the ratio of the ratio of the ratio of the ratio of  $\Omega$  is a measurement of  $\Omega$  is a measurement of  $\Omega$  in the ratio  $\Omega$  discorrepted coffers to be the variation of the variation of the variation of the variation of the definition of the definition of the definition of the definition of the call the definition of the definition of the defin  $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R}}\right\}$   $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R}}\right\}$   $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R}}\right\}$   $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R}}\right\}$   $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R}}\right\}$   $\frac{G_{\text{R}}}{G_{\text{R}}}\left\{\text{G}_{\text{R$  $f$  ent with observations. IT recefor  $\frac{1}{2}$  we ded by the nucleon mass  $\frac{1}{2}$  we ded by the nucleon mass  $\frac{1}{2}$  we ded to  $\frac{1}{2}$  $\Delta F_1 = -\Delta F_2$ We aim to see if such modifications are consistent with present observations. Strauch *et.* 0*.*4 *< Q*<sup>2</sup> *<* 2*.*6 GeV<sup>2</sup>. They observed a decrease of about 10%. If final state interactions medium. We therefore study the variation of that ratio. Recall the definitions The medium mandified form factors  $\tilde{G}$  given are a intentive different the changes in  $F_{1,2}$  indicated by  $\text{Eq}_\text{Q}(\mathfrak{g})$  and  $\text{Eq}_\text{Q}(\mathfrak{g})$  oth that  $\tilde{\mathfrak{G}}_{\text{M}} = G_M$ . *G*˜*E G*˜*<sup>M</sup>*  $\frac{G_E + F_{1f}(Q^2) + F_{2M}^2}{G_E + G_1 f(Q^2))} + \frac{G_E}{\overline{G}W^2}$ *G<sup>M</sup>* <sup>=</sup> *<sup>G</sup><sup>E</sup> G<sup>M</sup>* P  $1 f +$ *F*1 *G<sup>E</sup>*  $\frac{1}{2} \int_{0}^{1} (Q^2)^2 \left(1 + \frac{q \omega^2}{\sigma^2} \right)$  $\frac{4}{4}$  M<sub>2</sub> )  $\overline{\lambda}$  $^{2})$  |  $u(p)$ ,  $\overline{4}$ We has been what observations. Therefore we cake a best flatio of the average increar binding<br>We mow by the microsoft magic weak for 4D at aim is the see if the superficient possible values of *f* are consistent with observations. Therefore we take  $\epsilon$  to be the ratio of the average nuclear binding divided by the nucleon mass  $(\vec{q}^2)$  <u>of  $\vec{q}$   $\vec{q}$ </u>, so  $\epsilon \approx -0.07$ . Using Eq.  $(\vec{q})$  we find  $\frac{1}{2}$   $\approx$   $\frac{1}{2}$   $\approx$   $\frac{1}{2}$   $\approx$   $\frac{1}{2}$   $\approx$   $\frac{1}{2}$   $\approx$   $\frac{1}{2}$   $\approx$   $\frac{1}{$  $Q^2$ which ranges between  $-0.6$  and  $-1.3$  as  $Q^2$  varies between  $0.4$  and  $2.6$  GeV<sup>2</sup>. This is between which ranges between  $\theta$  *we and -1.3 as*  $Q^2$  *varies between* 0.4 and  $\mathcal{R}\theta$  GeV<sub>2</sub>. This is between  $6$  and  $25$  times the e $1$ ect observed by  $\frac{12}{10}$ , if one asserts that the equation of then double ratio <del>fine anization systems langer with pennedium a</del> to diverge . Otherwise, the d iscreptancyfextond use to can lally ev  $\Theta$ nes couley argue that the emodel used to evaluate the nuclear effect, taking  $V/M$  to be a constant, is too simple to be using Eq. (1) in the most medium: Even with this immaturization.<br>Constant, its too simple to be used electric to be need only funnity expendit, would allow *V* to have computed effect because the cancellation between these terms that lead to the small average the size of the e $\mathcal{L}_{\text{ext}}$  of using  $E_{\text{ext}}$  (1) in the nuclear medium. Even with this miniaturization,  $F_1(Q^2) = F_1(Q^2)f(Q^2)$ ,  $\delta F_2(Q^2) = F_1(Q^2)f(Q^2)$   $f(Q^2)$   $f(Q^2)$ We aim to see if such modifications are consistent with present observations. Strauch *et. al* [2] measured the ratio of polarization transfer in the <sup>4</sup>He nucleus to that of a nucleon for 0*.*4 *< Q*<sup>2</sup> *<* 2*.*6 GeV<sup>2</sup>. They observed a decrease of about 10%. If final state interactions are properly accounted for, this is a measurement of how the ratio *GE/G<sup>M</sup>* is changed in the edium. We therefore study the variation of that ratio. Recall the definitions  $\tilde{G}_{\!\mathcal{\bar{E}}}$ *G*˜*<sup>M</sup>*  $=\frac{G_E + F_1 f(Q^2)(1 + \frac{Q^2}{2M^2})}{G_E + G_1 f(Q^2)}$ *G<sup>M</sup>*  $\frac{C}{\sqrt{2}}$ *G<sup>M</sup>*  $\sqrt{2}$  $\frac{1}{1} + \frac{F_1}{\sqrt{1}}$  $Q_{\!\perp\!4}^{\prime\prime}$  $f_{\rm c}(\phi^2)(1+f_{\rm max}^{Q^2})$  $\left(\frac{1}{2M}\right)$ 1  $\sigma^{\mu\nu}q_{\mu}q_{\beta}$ We now evaluate the function *f*. Our aim is to see if the smallest possible values of  $f^*$  are  $\epsilon$  consistent with observations. Therefore we take  $\epsilon$  to be the ratio of the average nuclear binding divided by the nucleon mass (7 MeV for 4He), so  $\epsilon \approx -0.07$ . Using Eq. (2) we find  $f(Q^2)$ <sup>1</sup>  $Q^2$  1.8 *Q*<sup>2</sup>  $\underline{\mathbf{\hat{X}}^{\mathbf{\hat{M}}}}\mathbf{\hat{H}}\underline{\mathbf{e}}$ , so  $\epsilon \approx -.007$ . Using Eq.  $\left(\frac{2}{10}\right)$  $aL$ 1025 times the e $a$  even become as to  $E$ , if  $C$  if  $C$  asserts the entire  $\mu$ the double ratio of polarization observables is a true medium modification. Otherwise, the **discrepancy would be even larger.** One could argue that the model used to evaluate the nuclear effect, taking *V*/M to be a constant, is too simple to be used. The most evident improvement would allow *V* to have an GOULDERVE SELIATP<del>TETIND LANAZEP TEDALISYES PENTSI JAPIS "WSIMBLANISI WOULD LEAD CHILLEN</del> sorrepted effect obelow the chycancellation between these terms that lead to the small average bi**e e**nergy of 7 MeV per the emovel be disrupted. Using the nuclear effect, real the size of the effect of using  $Eq. (1)$  in the nuclear medium. Even with this miniaturization, the predicted modification of the ratio of electric to magnetic form factors is too large. 12 a Goullar and Conception of the Conce  $-\frac{1}{2}$  scalar term and a repulsive vector term. Efter this would lead to a larger **BelleplancylowOrld** 0.5 Ration 5 detween  $-0.6$  and  $-1.3$  as  $Q^2$  varies between  $0.4$  and  $2.6$  GeV<sup>2</sup>. This is between  $\Omega$  at  $\Omega$  $\mathsf{of}$  Ge depile medium <sub>no</sub> Strawch het alu<del>del</del>e  $\sqrt{\frac{1}{2}}$  MeV

and  $\overline{r}$  medium modifies both  $\overline{r}$  and  $\overline{$ 

### Fix: change the operator Miller, Thomas, Carroll arXiv:1207.0549 *<sup>µ</sup>*⌫*q*⌫  $\sigma$  and contribute the matrix of  $\sim$  $T_{\text{max}}$  the desired operator in initial on-shell states that final on-shell states the form:

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

the constraints of Eq. (12)–Eq. (12)–Eq. (12)–Eq. (14). This can be done if we include an e $\Gamma$ 

- $F_1$  and  $F_2$  changed the same. **There is also also also an operator which acts between an initial on-shell and initial on-shell and initial on-shell states, but an initial on-shell states, but an initial on-shell states, but an initial on-shell states,** this is not needed for the calculations presented here. CC is explicitly satisfied by both terms.
- No change to ratios of form factors! acts between ¯*u*(*p* + *q*) and *u*(*p*), see Eq. (4). With Eq. (16) we have
	- Compute Lamb shift, needs large value of Lamb shift, needs large value of  $\lambda$  $\mathbb{R}$



- Magnitude of quasi-elastic scattering hugely changed *<sup>|</sup>|F*(*Q*<sup>2</sup> ) *<* 7*,* (18) for *Q*<sup>2</sup> *<* 10 GeV<sup>2</sup>. Quasi-elastic experiments have not been performed for larger values of *Q*<sup>2</sup>. FIG. 2: The energy shift *E*o↵ as a function of the parameter , using Eq. (34).  $\sim$   $\sim$   $\sim$
- **•** Strike 2! Is 2 photon exchange dead?-No Nothing Allie Library in the Strike Team Eq. (3) in the Strike to Get the Strike to Get the Strike to Get the *T*<sup>1</sup> <sup>+</sup> *Z*<sup>1</sup> <sup>=</sup> *F*(*K*<sup>2</sup>) *F*<sup>2</sup> <sup>2</sup> *K*<sup>2</sup> + 4*F*<sup>2</sup> <sup>1</sup> *M*<sup>2</sup> *<sup>F</sup>*<sup>2</sup>*F*<sup>2</sup>  $\overline{\phantom{a}}$ *F*2  $\overline{\phantom{a}}$ *K*<sup>2</sup> sin<sup>2</sup>  $\overline{\phantom{a}}$ + 2*F*1*K*<sup>2</sup>  $\overline{\phantom{a}}$

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

[arXiv:1209.4667](http://arxiv.org/abs/1209.4667)

Proton Polarizability Contribution: Muonic Hydrogen Lamb Shift and Elastic Scattering [Gerald A. Miller](http://arxiv.org/find/nucl-th/1/au:+Miller_G/0/1/0/all/0/1)

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

$$
h(Q^2) = (1 - \frac{Q^2}{2m^2}) \Big( (1 + \frac{4m^2}{Q^2})^{1/2} - 1 \Big) + 1
$$
  
~ 2m<sup>2</sup>/Q<sup>2</sup> large Q<sup>2</sup>,  $\overline{T}_1(0, Q^2) = \frac{Q^2}{\alpha} \beta_M \log \text{ divergence}$ 

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

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

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

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

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

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

## $\Box$  EFT of  $\mu p$  interaction

larizability contributions, that enter in the two-photon enter in the two-photon exchange term, see Fig. 1, ca<br>1, can be two-photon exchange term, see Fig. 1, can be two-photon exchange term, see Fig. 1, can be two-photon

• Compute Feynman diagram, remove log divergence using dimensional regularization divergence using dimensional regularization **In the fourth power of the fourth power is compute Feynman diagram, remove log** 

symptom that an inefficient technique has been used [27]. A more efficient way to pro-

 $\bullet$  include counter term in Lagrangian

is chosen so that the result is independent of *µ*. Eq. (14) corresponds to using the *MS*

scheme because the term log(4*p*) *g<sup>E</sup>* is absorbed into *l*.



limit that *e* goes to zero. In EFT one removes the divergent piece by adding a contact

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

where  $\ell$  is determined by fitting to the Lamb shift. Eq. (15) corresponds to using the  $\ell$ 

lepton-proton interaction of natural size that is proportional to the lepton mass.

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

 $\lambda$  seems large but  $\beta_M$  (mag. polarizability) = 3.1 × 10 <sup>+</sup> im<sup>3</sup> very small due to a cancel between between between  $\beta_M$ paramagnetic effects of an intermediate D and diamagnetic effects of the pion cloud [30].  $\lambda$  seems large but  $\beta_M$  (mag polarizability)  $=3.1 \times 10^{-4}$  fm<sup>3</sup> yery small paramagnetic effects of an intermediate D and diamagnetic effects of the pion cloud  $\beta$ 0. The pion cloud  $\beta$  $\int$  Natural units  $\rho_M/\alpha \sim 4\pi/(4\pi J_\pi)$  **b** *c*,  $\frac{1}{2}$  *c*  $\frac{1}{2}$  *c*  $\frac{1}{2}$  *c*  $\lambda$  seems large but  $\beta_M$  (mag. polarizability) =  $3.1 \times 10^{-4}$  fm<sup>3</sup> very small Natural units  $\beta_M/\alpha \sim 4\pi/(4\pi f_\pi)^3$  Butler & Savage '92

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

 $\rho$  or  $\rho$  decay constant). Then  $\mathcal{P}$  $\sqrt{3.95 - m}$ 3.95 =natural

The corresponding contribution to the corresponding contribution to the Lamb shift is given by  $\mathcal{L}_\mathbf{X}$ 

# So what?

A Proposal for the Paul Scherrer Institute  $\pi$ M1 beam line

### Studying the Proton "Radius" Puzzle with  $\mu p$  Elastic Scattering

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#### $\overline{DCI}$  is used as all  $\overline{D}$ ,  $12.01.1$ PSI proposal R-12-01.1

2 Rhoton exchange idea is testable 2 photon exchange idea is testable

<sup>8</sup>Jefferson Lab, Newport News, Viginia, USA

## Observable Effect in  $\mu^- p$  Scattering





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