Proton Size Puzzle: Thick or Thin?

“Thick and Thin” famous Anton Chekhov novel

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Introduction
Experimental data
On 2-photon contributions
Conclusions

1) Phys.Part.Nucl.Lett. 14 (2017) 857
2) Phys.Lett. B776 (2018) 105;
3) EPJA 54 (2018) 131
4)PRA98 (2018) 042501

In 2010 the CREMA (Charge Radius Experiments with Muonic Atoms) Collaboration measured very precisely the Lamb shift of muonic hydrogen. It has opened the new era of the precise investigation of the spectrum of simple muonic atoms.

In the new experiments by this Collaboration with muonic deuterium and ions of muonic helium a charge radii of light nuclei were obtained with very high precision.

For muonic hydrogen and muonic deuterium it was shown that obtained values of the charged radii are significantly different from those which were extracted from spectra of electronic atoms and in the scattering of the electrons with nucleon and were recommended for using by CODATA, so-called, "PROTON CHARGE RADIUS PUZZLE".

Several experimental groups plan to measure the hyperfine structure of various muonic and electronic atoms with more high precision.

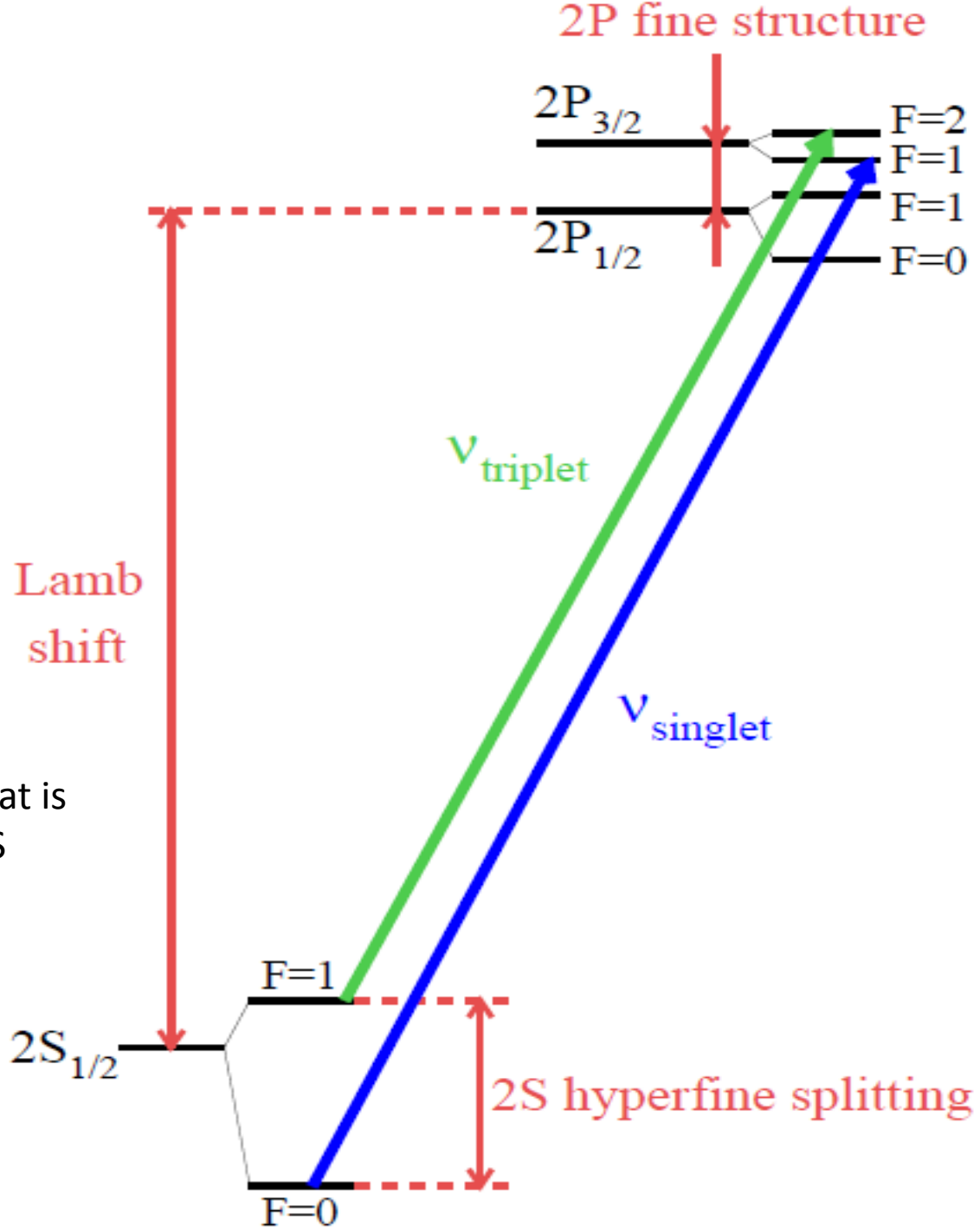
One can consider experiments with muonic atoms as a smoking gun for:

Precise measurements of the proton charge radius and other parameters

Test of the Standard Model with greater accuracy

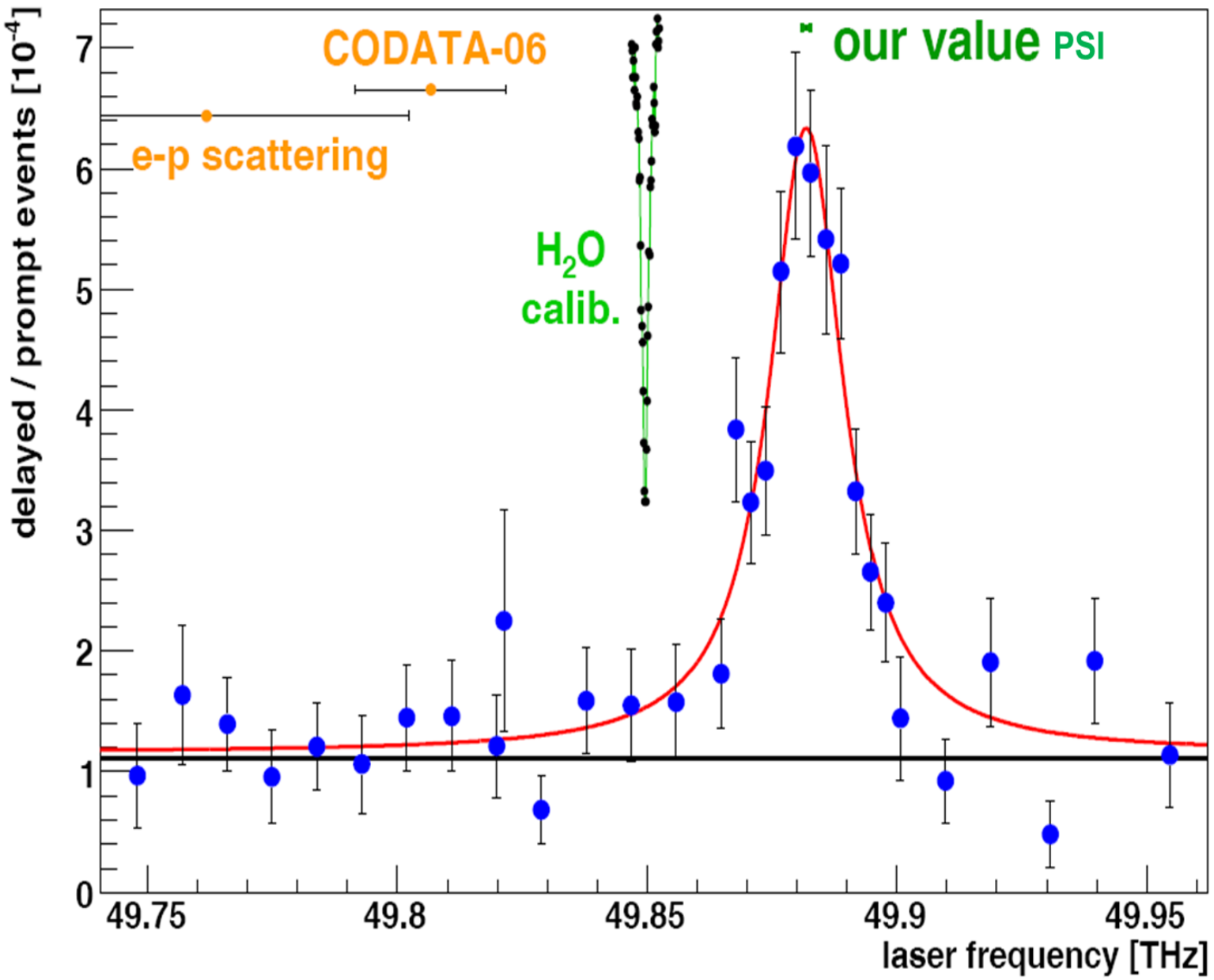
and, possibly, to reveal the source of previously unaccounted interactions between the particles forming the bound state in QED.

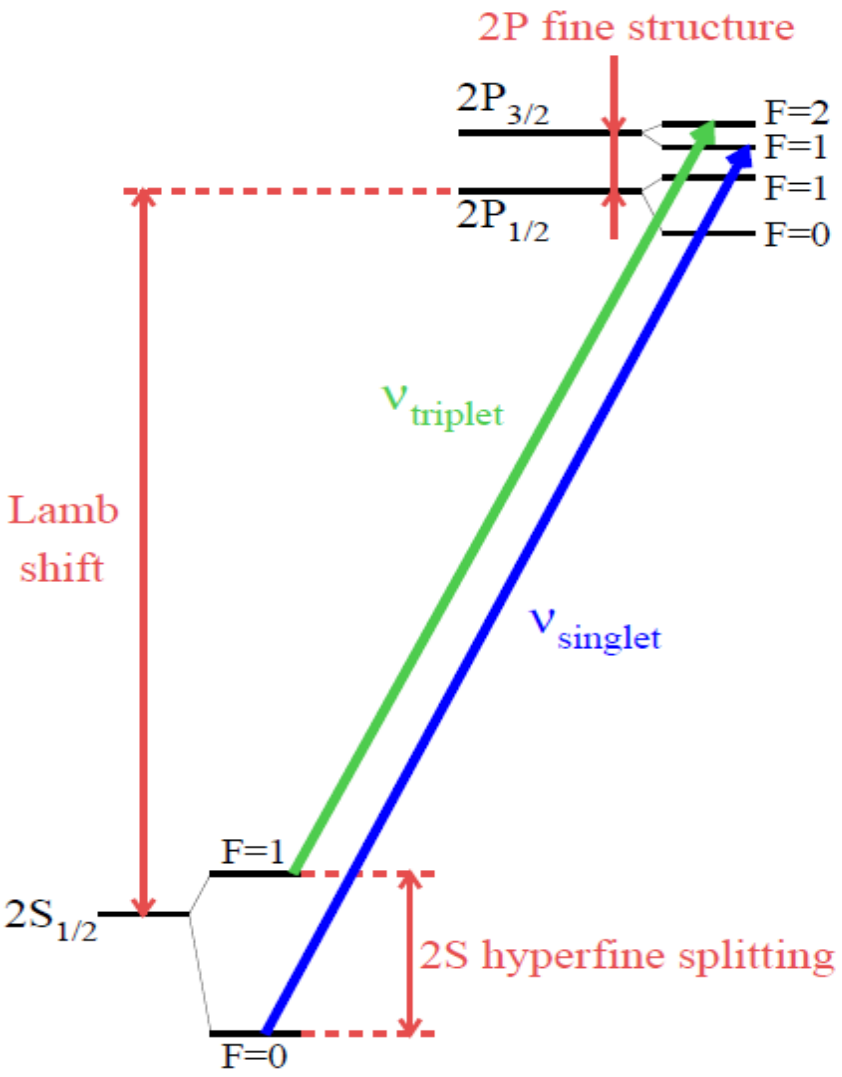
The HFS requires the spin-spin coupling that is the interaction between the nuclear spin S and the lepton total angular momentum j, where F = j + S is the atom total angular momentum



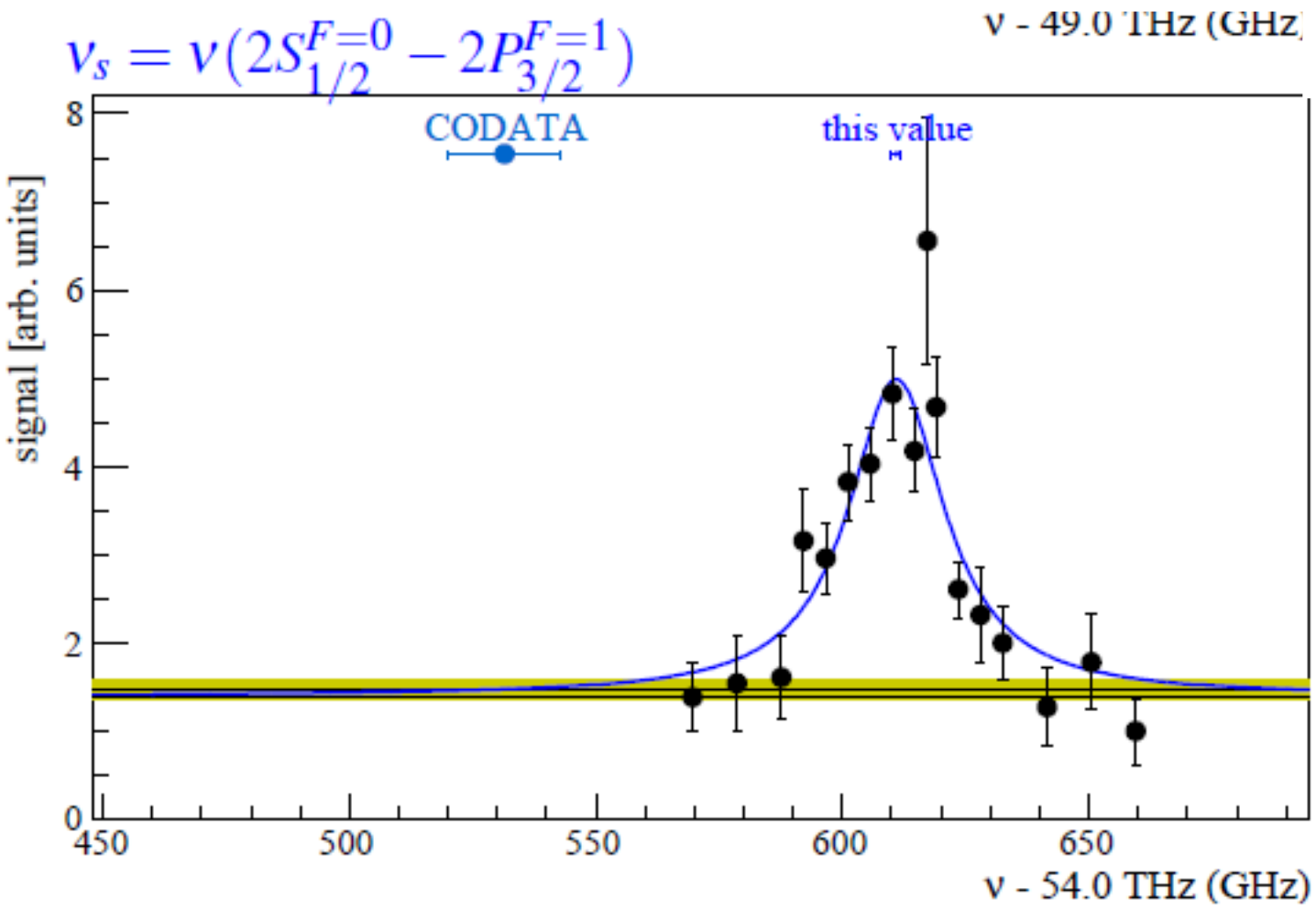
$$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$$

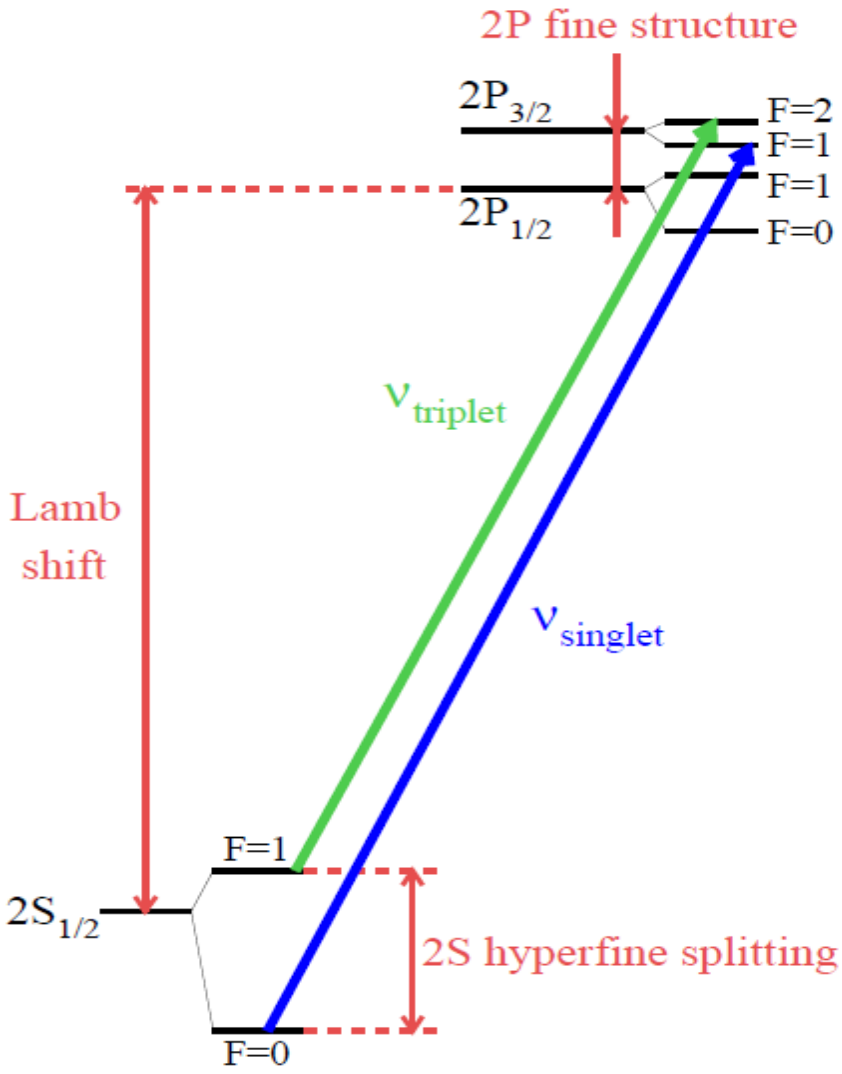
CREMA-10-13





CREMA-13


$\nu_s = \nu(2S^{F=0}_{1/2} - 2P^{F=1}_{3/2})$
ν - 49.0 THz (GHz)
CODATA
this value
signal [arb. units]
0
2
4
6
8
450
500
550
600
650
ν - 54.0 THz (GHz)


2P fine structure
$2P_{3/2}$
$2P_{1/2}$
F=2
F=1
F=1
F=0
$\nu_{triplet}$
$\nu_{singlet}$
Lamb shift
$2S_{1/2}$
F=1
F=0
2S hyperfine splitting

Two transitions measured

$$\nu_T = 49881.35(\ 65)\ \text{GHz}$$
$$\nu_S = 54611.16(1.05)\ \text{GHz}$$

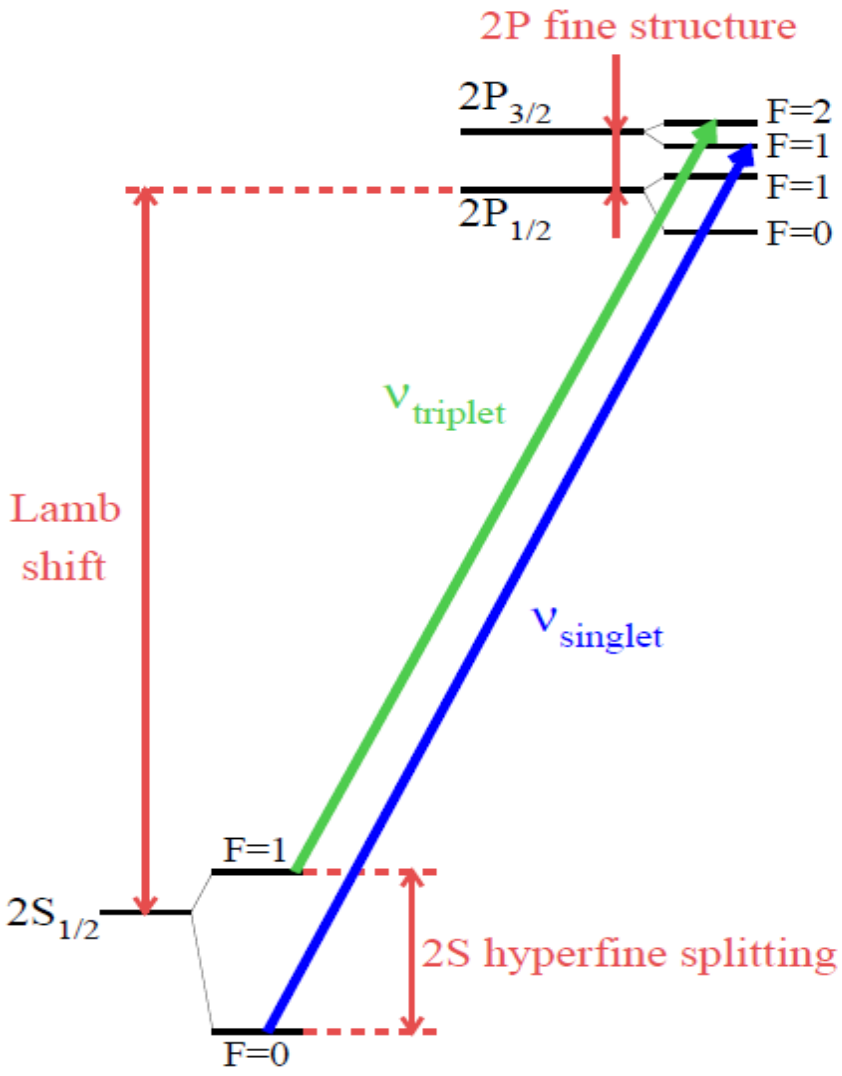
From these two transition measurements, one can independently deduce both the Lamb shift $\Delta E_L = \Delta E(2P_{1/2}-2S_{1/2})$ and the 2S-HFS splitting (ΔE_{HFS}) by the linear combinations

$$\frac{1}{4}h\nu_s + \frac{3}{4}h\nu_t = \Delta E_L + 8.8123(2)\text{meV}$$

$$h\nu_s - h\nu_t = \Delta E_{HFS} - 3.2480(2)\text{meV}$$

Then one get

$$\Delta E_{LS}^{exp} = 202.3706(23)\ \text{meV}$$
$$\Delta E_{HFS}^{exp} = 22.8089(51)\ \text{meV}$$



Proton Size Puzzle

$$r_p = 0.8751(61)\,\text{fm}\ (\text{CODATA-2014})$$

From spectrum of electronic atoms and
the scattering of the electrons with nuclei

Lamb shift in muonic Hydrogen (μp) (a proton orbited by a negative muon)

muon mass $m_\mu \approx 200 \times m_e$

Bohr radius $r_\mu \approx 1/200 \times r_e$

μ inside the proton: $200^3 \approx 10^7$

μp *has much smaller Bohr radius compared to electronic hydrogen and so is much more sensitive to the finite size of the proton*

$$\Delta E_{\text{LS}}^{\text{exp}} = 202.3706(23)\ \text{meV}$$

CREMA experiment **Nature 2010; Science 2013**
(0.05% precision)

$$\Delta E_{\text{LS}} = 206.0668(25) - 5.2275(10)\langle r_p^2 \rangle + O\left(\langle r_p^2 \rangle^{3/2}\right)[\text{meV}]$$

Theory summary: Antognini et al. AnnPhys 2013
(2% effect)

$$r_p = 0.84087(39)\,\text{fm}\ (\text{CREMA coll. Antognini et al., 2013})$$

5.6 σ deviation!

$$r_E^2 = \int d^3r\, r^2\, \rho_E(r)$$

MAMI 1905.11182

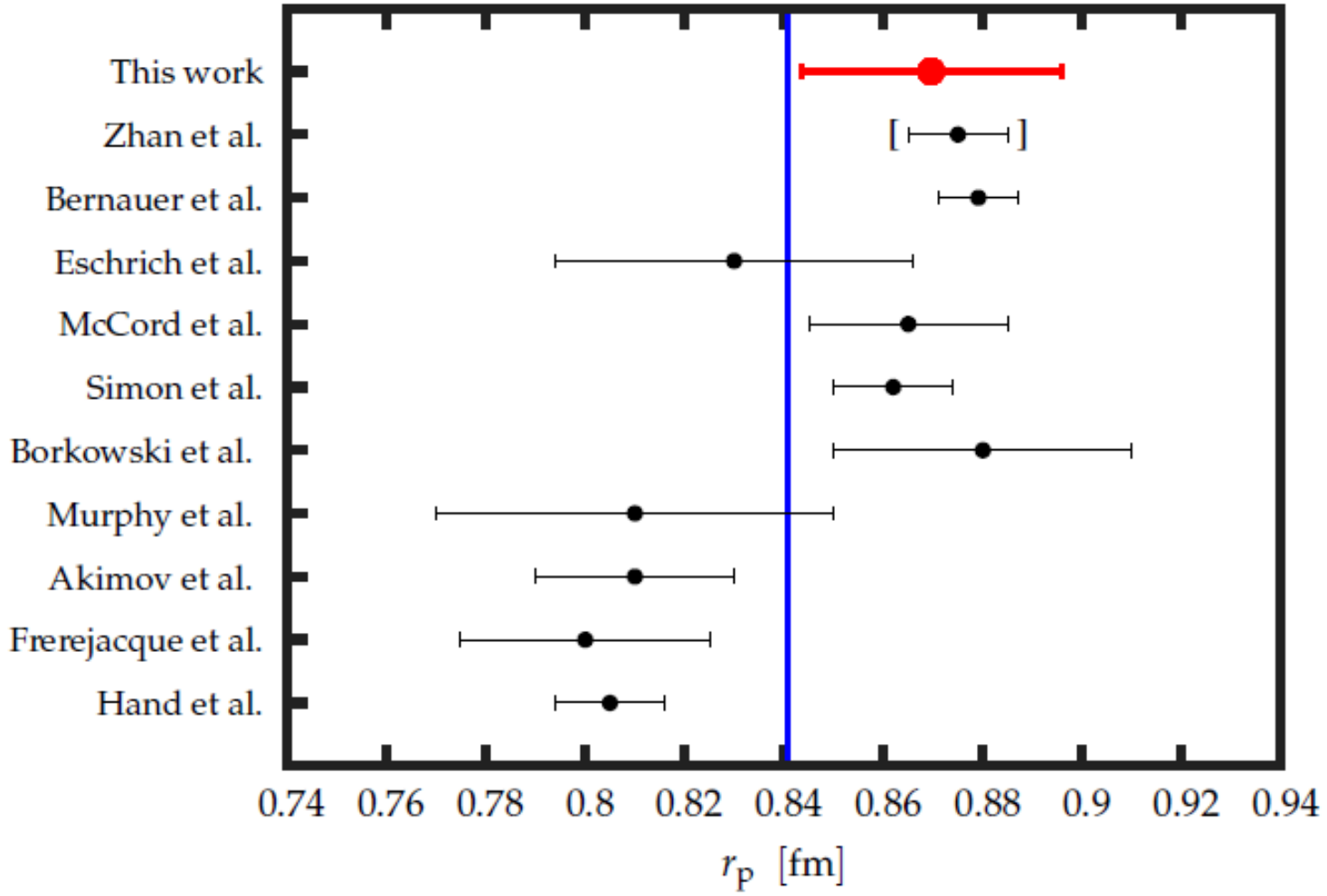
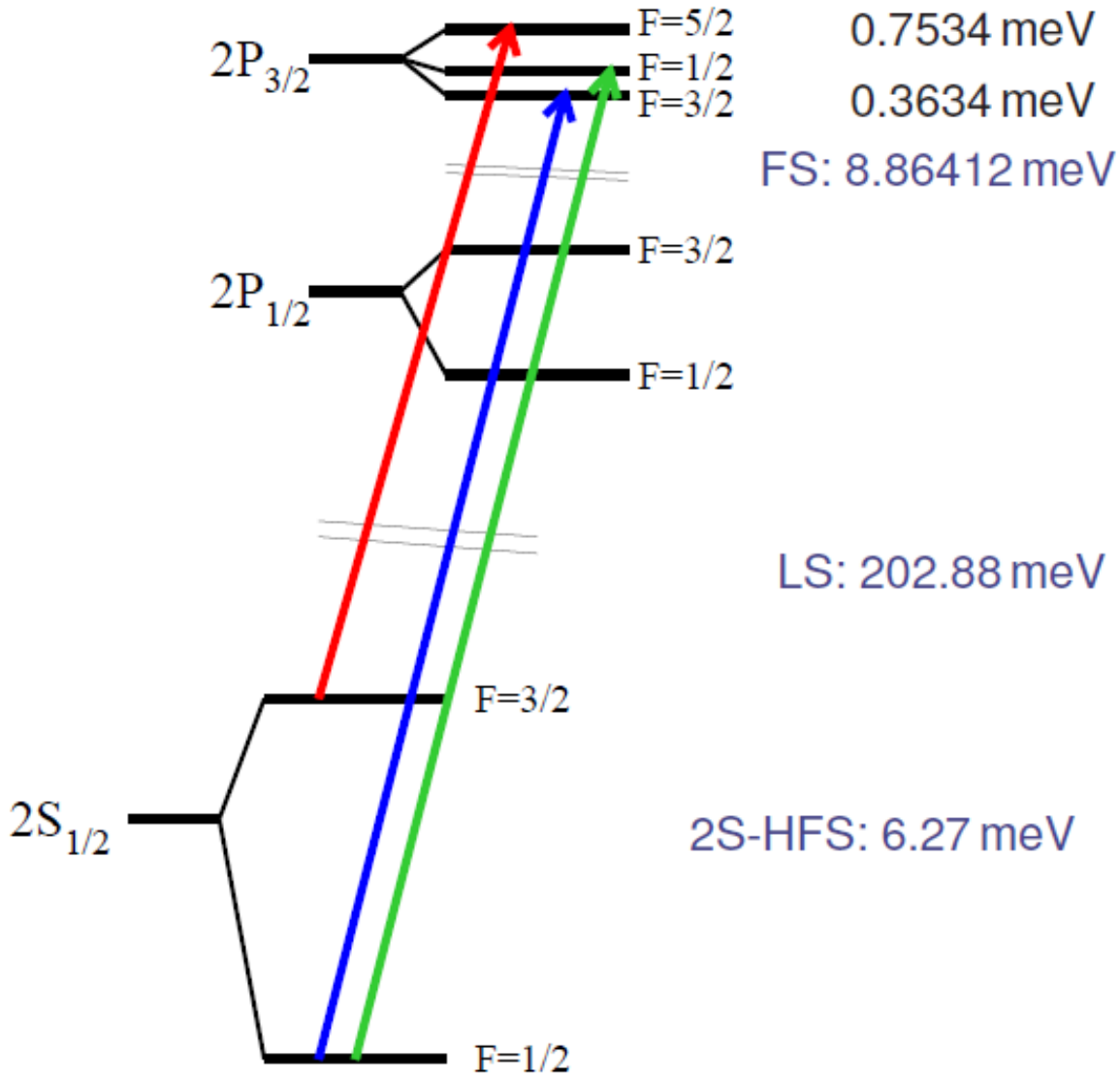


Figure 5: The proton charge radius extracted from the ISR experiment together with previous electron scattering measurements [17–25], where the data point of Zhan et al., enclosed by square brackets, is not an independent measurement of the radius [26]. The value obtained from the Lamb shift measurements in muonic hydrogen is shown by the blue line for the comparison.

Muonic deuterium CREMA-16



Deutron charge radius

$$\Delta E_{\rm LS}^{\rm exp} = 202.8785(34)\ \text{meV}$$

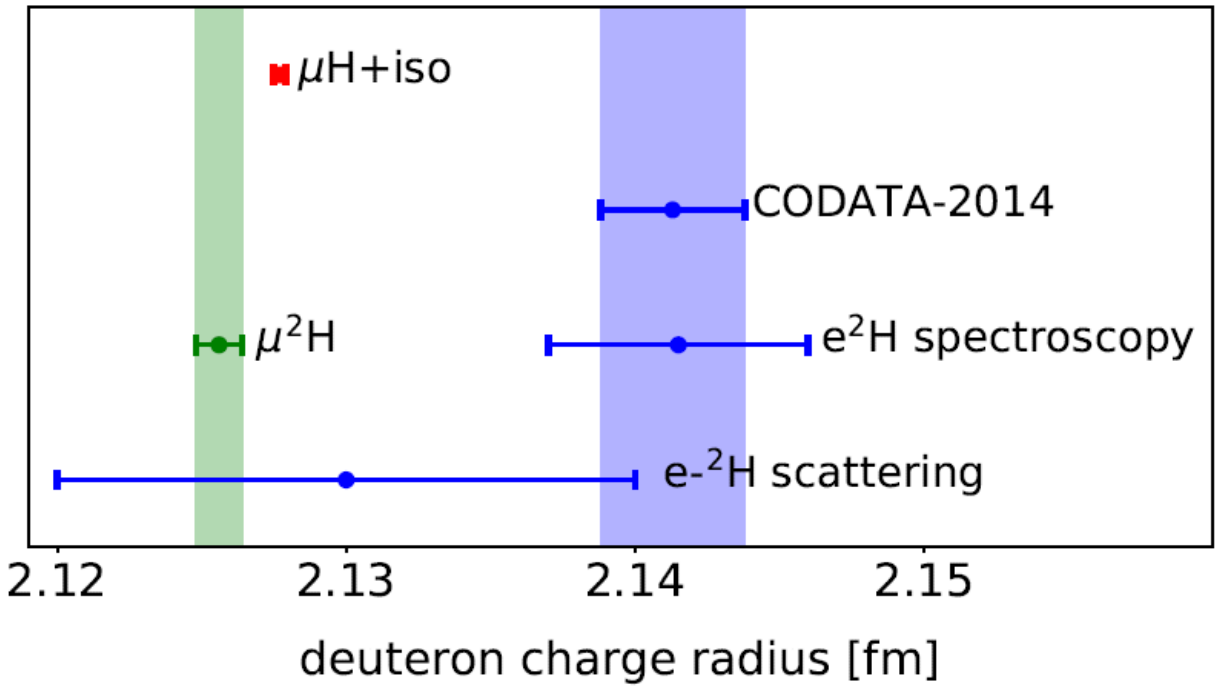
$$\Delta E_{\rm LS}^{\rm th} = 228.7766(10)\ \text{meV (QED)} + 1.7096(200)\ \text{meV (TPE)} - 6.1103(3)\, r_{\rm d}^2\ \text{meV/fm}^2$$

$$\mu\text{D} \Rightarrow r_{\rm d} = 2.12562(78)\ \text{meV}\ \ (\text{CREMA 2016})$$

H/D isotope shift: $r_{\rm d}^2 - r_{\rm p}^2 = 3.82007(65)\ \text{fm}^2$

$r_{\rm p}$ from μH gives $r_{\rm d} = 2.12771(22)$ fm $\leftarrow 5.4\sigma$ from $r_{\rm p}$

CODATA 2014 $r_{\rm d} = 2.14130(250)$ fm



r_d is 7.5 σ smaller than CODATA-2010 (99% correlated with r_p !)

3.5 σ smaller than r_d (D spectrosopy)

The leading contribution to the hyperfine splitting (HFS) in muonic hydrogen is coming from one-photon exchange [AP Martynenko, RN Faustov 2004]

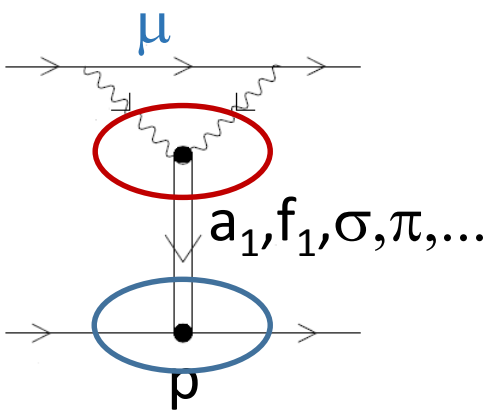
$$\Delta V_B^{hfs} = \frac{8\pi\alpha\mu_p}{3m_\mu m_p}(\mathbf{S}_p\mathbf{S}_\mu)\delta(\mathbf{r}) - \frac{\alpha\mu_p(1+a_\mu)}{m_\mu m_p r^3}\left[(\mathbf{S}_p\mathbf{S}_\mu) - 3(\mathbf{S}_p\mathbf{n})(\mathbf{S}_p\mathbf{n})\right] +$$

$$\frac{\alpha\mu_p}{m_\mu m_p r^3}\left[1 + \frac{m_\mu}{m_p} - \frac{m_\mu}{2m_p\mu_p}\right](\mathbf{L}\mathbf{S}_p)$$

We calculate further the contribution to HFS coming from light pseudoscalar and axial-vector meson exchanges

New theoretical contributions to the Lamb shift and HF structure of muonic hydrogen μP:

Meson exchanges through the anomalous two-photon vertex



Axial-Vector and Pseudoscalar mesons contribution to HFS of muonic hydrogen

mesons	$I^G(J^{PC})$	Λ_A in MeV	$F^{(0)}_{AV\gamma^*\gamma^*}(0,0)$ in GeV^{-2}	$\Delta E^{hfs}(1S)$ in meV	$\Delta E^{hfs}(2S)$ in meV
$f_1(1285)$	$0^+(1^{++})$	1040	0.266	-0.0093 ± 0.0033	-0.0012 ± 0.0004
$a_1(1260)$	$1^-(1^{++})$	1040	0.591	-0.0437 ± 0.0175	-0.0055 ± 0.0022
$f_1(1420)$	$0^+(1^{++})$	926	0.193	-0.0013 ± 0.0008	-0.0002 ± 0.0001
π^0	$1^-(0^{-+})$	776		-0.0017 ± 0.0001	-0.0002 ± 0.00002
Sum				-0.0560 ± 0.0178	-0.0071 ± 0.0024

$$\Delta E^{\text{exp}}_{\text{2S-HFS}} = 22.8089(51)\ \text{meV}$$

$$\Delta E^{\text{th}}_{\text{2S-HFS}} = 22.9843(30) - 0.1621(10) r_Z\ \text{meV}$$

$$r_Z = 1.082(37)\,\text{fm}\ (\text{CREMA coll. Antognini et al., 2013})$$

0.001 meV → 0.006 fm

$$r_Z = 1.040(37)\,\text{fm}$$

Scalar mesons contribution to the Lamb shift of muonic hydrogen

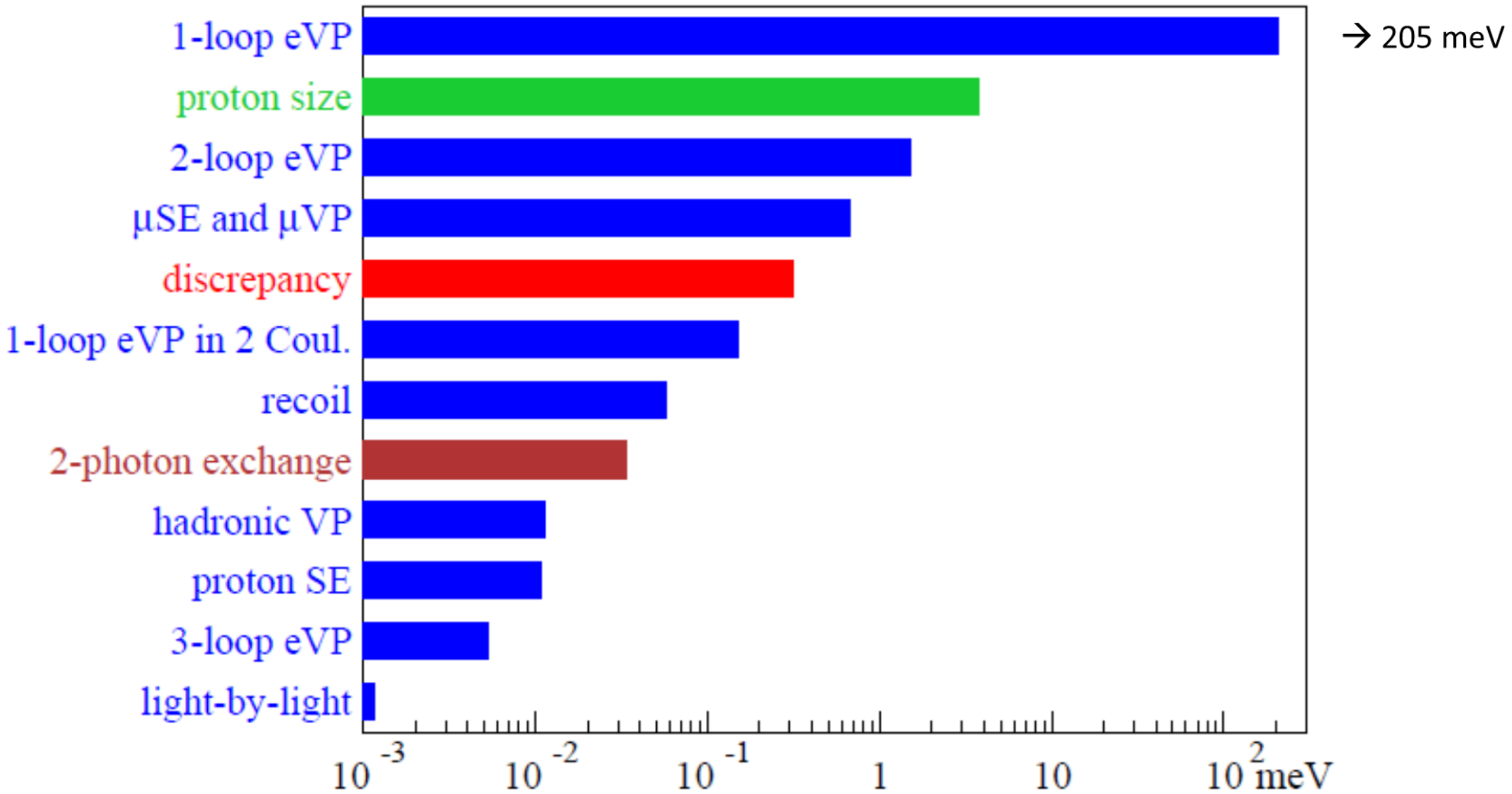
Scalar meson	$I^G(J^{PC})$	$\Gamma_{\gamma\gamma}^{exp}$ in keV	Λ_S in MeV	A_S in GeV^{-1}	$\Delta E^{Ls}(2P-2S)$ in μeV
$\sigma(550)$	$0^+(0^{++})$	4.5	2000	-0.299	17.05
$f_0(980)$	$0^+(0^{++})$	0.33	2000	-0.034	0.72
$a_0(980)$	$1^-(0^{++})$	0.30	2000	-0.032	0.53
$f_0(1370)$	$0^+(0^{++})$	4.5	2000	-0.075	0.81

$$\Delta E_{\mathrm{LS}}^{\mathrm{exp}} = 202.3706(23)\ \mathrm{meV}$$

$$\Delta E_{\mathrm{LS}} = 206.0668(25) - 5.2275(10)\left\langle \mathrm{r}_{\mathrm{p}}^2 \right\rangle + \mathrm{O}\left(\left\langle \mathrm{r}_{\mathrm{p}}^2 \right\rangle^{3/2} \right) [\mathrm{meV}]$$

$$r_p = 0.84087(39)\,\mathrm{fm}\ (\mathrm{CREMA\ coll.\ Antognini\ et\ al.,\ 2013})$$

Hierarchy of contributions to Lamb shift



Conclusions

From CREMA experiment side:

"Proton radius puzzle" is in fact "Z=1 radius puzzle" $r_p = 0.84087(39)\,\mathrm{fm}$ $r_Z = 1.082(37)\,\mathrm{fm}$

Muonic helium-3 and -4 ions show (preliminary) no big discrepancy

New projects are ongoing, one of them FAMU (Fisica Atomi MUonici) with accuracy 2 ppm

In our theoretical work:

A new **large** contribution to the HFS of muonic hydrogen is found, that
Induced by **pseudoscalar**, **axial-vector and scalar** couplings to two photon state.

In particular these results provide diminishing of the Zemach radius
(compare with $r_Z = 1.040(37)\,\mathrm{fm}$ $r_Z = 1.082(37)\,\mathrm{fm}$

It should be taking into account for the interpretation of the new data on HFS in this atom.

There are still a number of uncertainties in phenomenological input used in our calculations and some other new effects unaccounted by us. (Work is in progress)

This mechanism is very important to obtain the total value of the HFS in **μP** with high precision and needs to be account in current experiments (CREMA (PSI), FAMU (GB), …)