The Lamb shift, `proton charge radius puzzle' etc.

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Outline

- Different methods to determine the proton charge radius
    - *spectroscopy of hydrogen (and deuterium)*
    - *the Lamb shift in muonic hydrogen*
    - *electron-proton scattering*
- The proton radius: the state of the art
    - *electric charge radius*
    - *magnetic radius*

Electromagnetic interaction and structure of the proton

Quantum electrodynamics:

- kinematics of photons;
- kinematics, structure and dynamics of leptons;
- hadrons as compound objects:
- *hadron structure*
  - *affects details of interactions;*
  - *not calculable, to be measured;*
  - *space distribution of charge and magnetic moment;*
  - *form factors (in momentum space).*

Atomic energy levels and the proton radius

- Proton structure affects
  - the Lamb shift
  - the hyperfine splitting

- The Lamb shift in hydrogen and muonic hydrogen
  - splits $2s_{1/2}$ & $2p_{1/2}$
  - The proton finite size contribution

    $\sim (Z\alpha)\, R_p^2\, |\Psi(0)|^2$
  - shifts all s states

Different methods to determine the proton charge radius

- *Spectroscopy of hydrogen (and deuterium)*

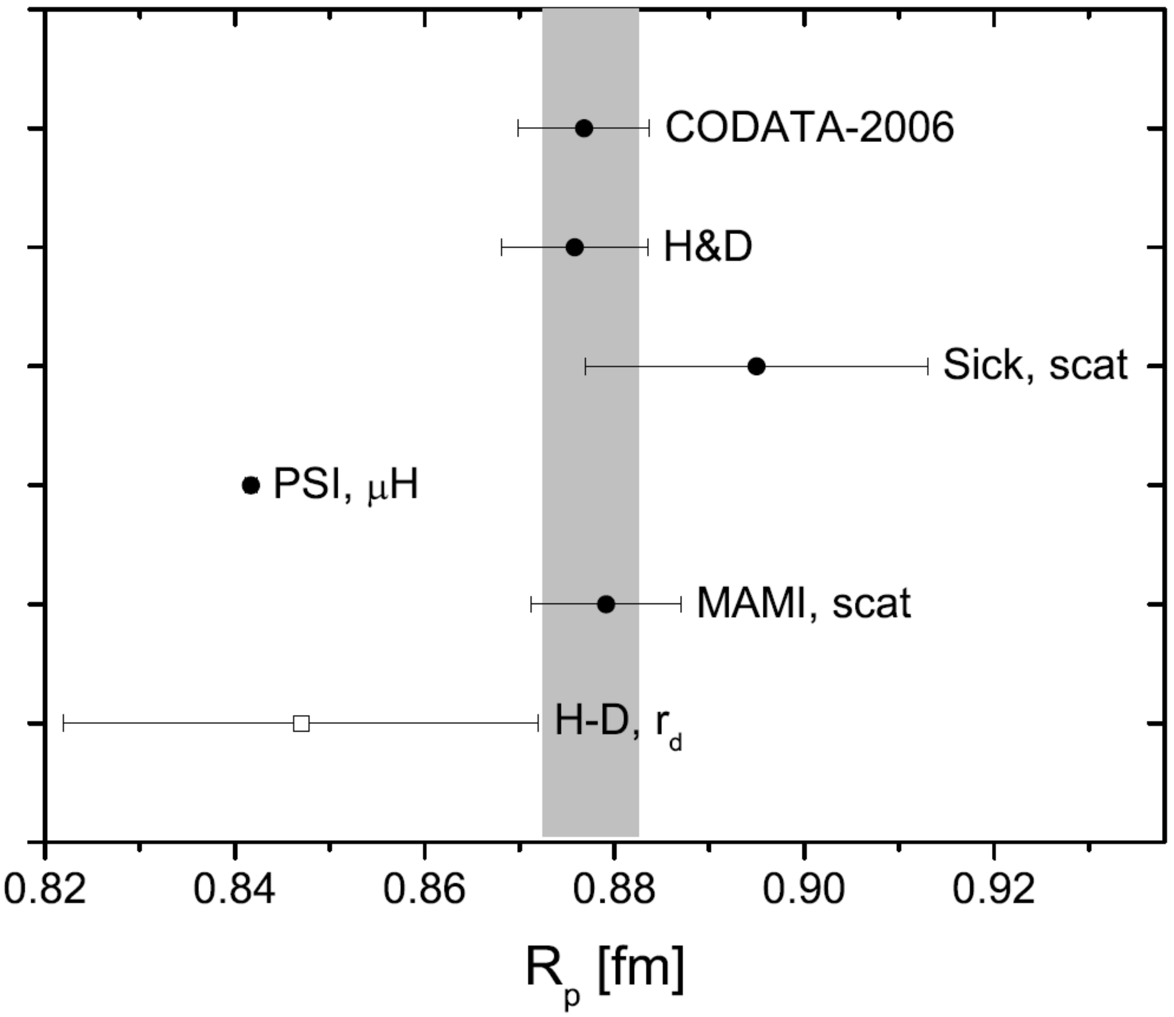
- *The Lamb shift in muonic hydrogen*

Spectroscopy produces a model-independent result, but involves a lot of theory and/or a bit of modeling.

- *Electron-proton scattering*

Studies of scattering need theory of radiative corrections, estimation of two-photon effects; the result is to depend on model applied to extrapolate to zero momentum transfer.

Different methods to determine the proton charge radius



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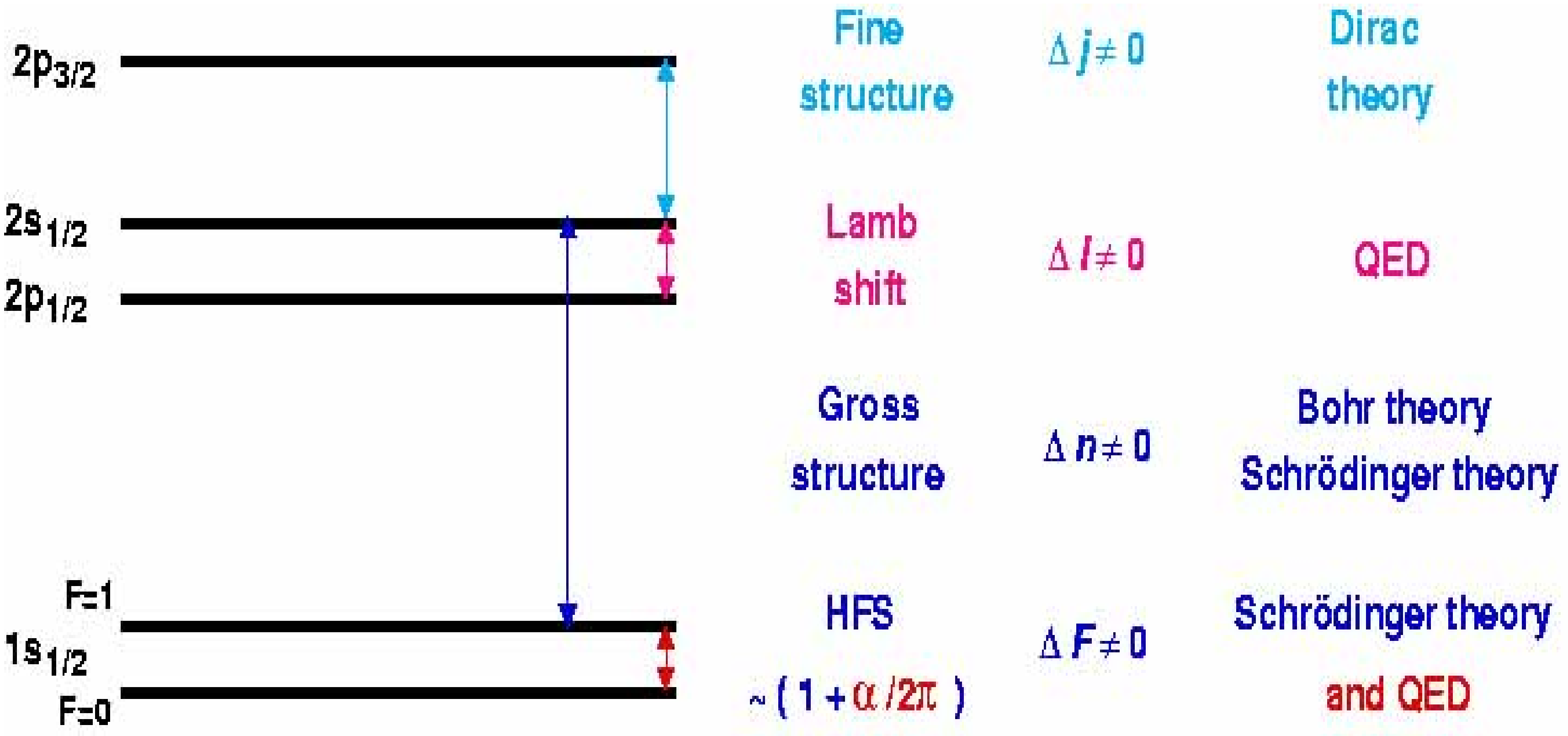
Energy levels in the hydrogen atom



Fine structure	$\Delta j \neq 0$	Dirac theory
Lamb shift	$\Delta l \neq 0$	QED
Gross structure	$\Delta n \neq 0$	Bohr theory Schrödinger theory
HFS $\sim (1+\alpha/2\pi)$	$\Delta F \neq 0$	Schrödinger theory and QED

Three fundamental spectra: *n* = 2

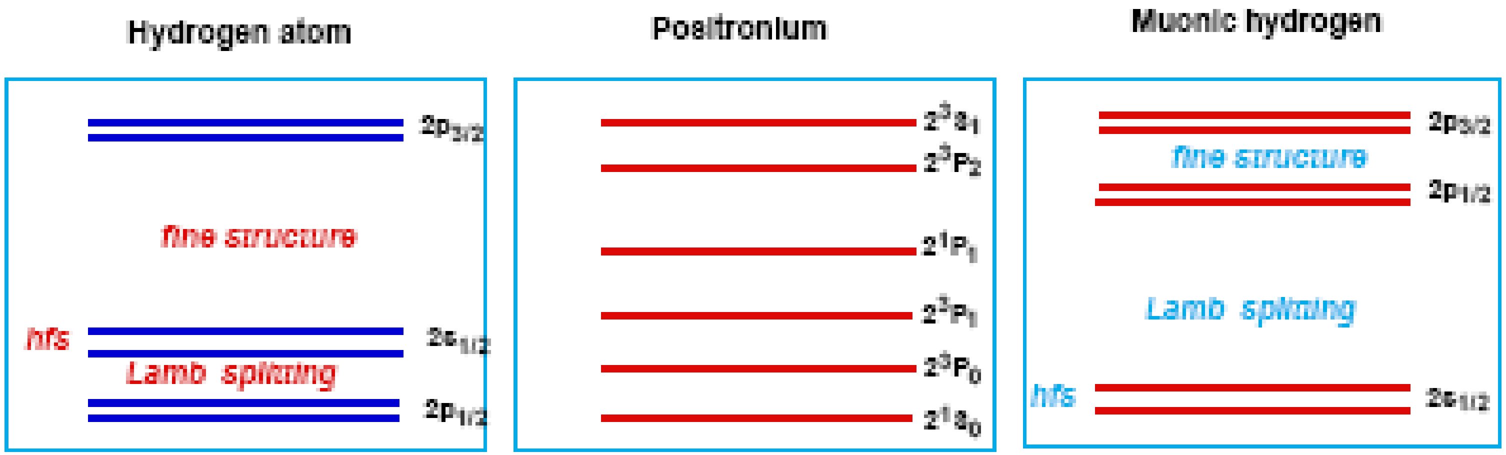
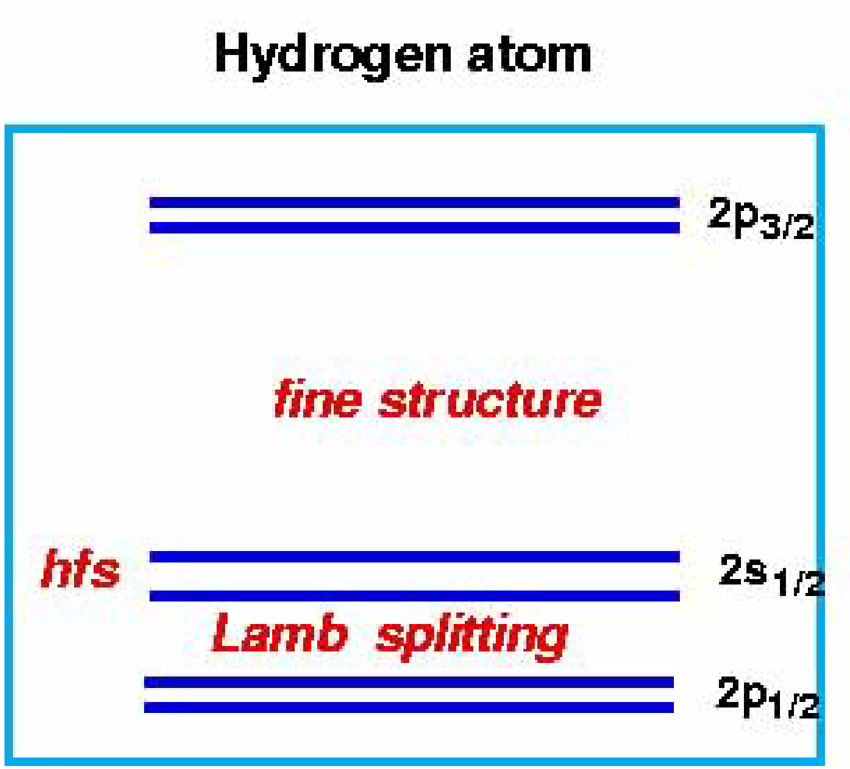


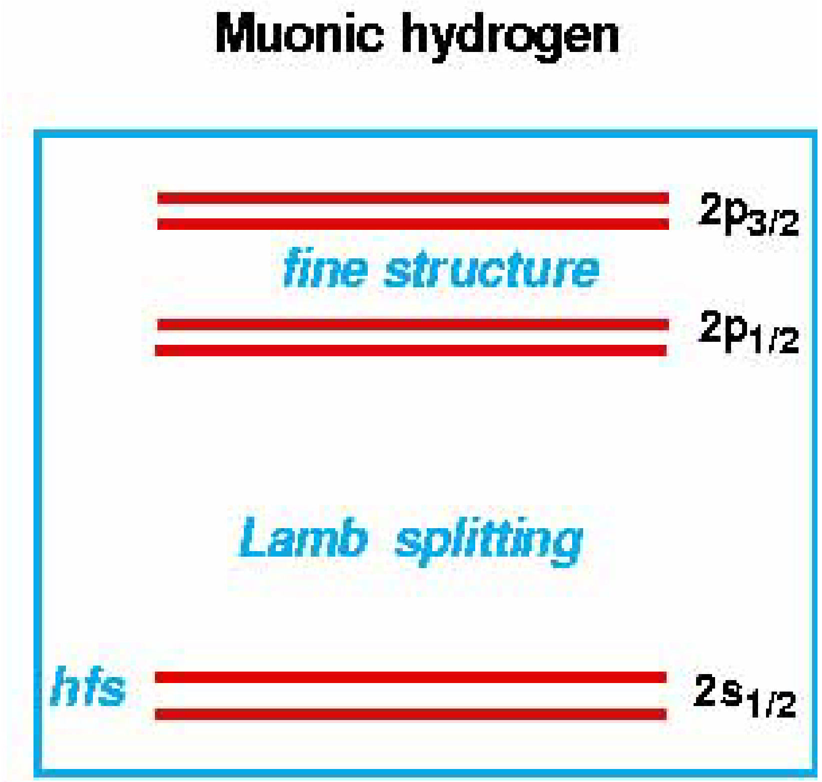
Fig. 6. Scheme of the lowest excited levels ($n = 2$) in different simple atoms (not to scale).

Three fundamental spectra: $n = 2$



- The dominant effect is the fine structure.
- The Lamb shift is about 10% of the fine structure.
- The 2p line width (not shown) is about 10% of the Lamb shift.
- The 2s hyperfine structure is about 15% of the Lamb shift.

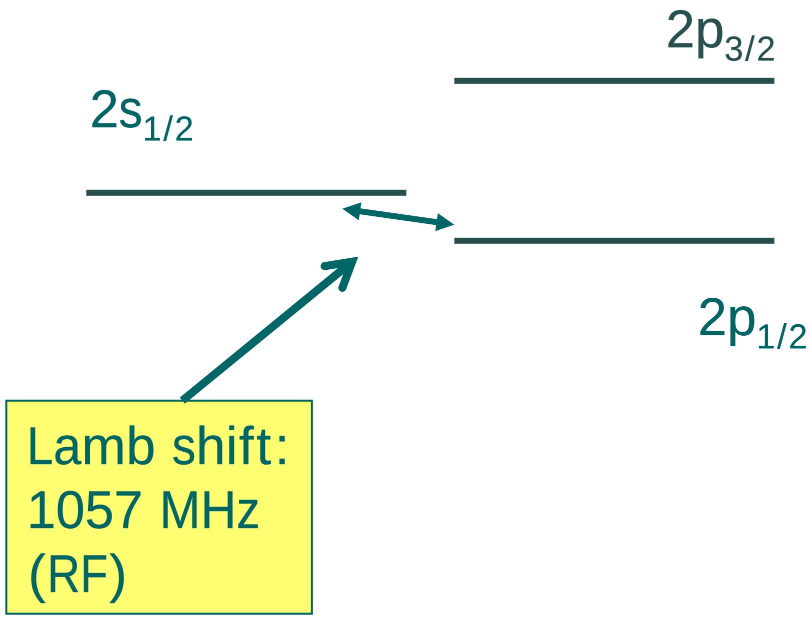
Three fundamental spectra: *n* = 2



- The Lamb shift originating from vacuum polarization effects dominates over fine structure (4% of the Lamb shift).
- The fine structure is larger than radiative line width.
- The HFS is more important than in hydrogen; it is ~ 10% of the fine structure (because $m_\mu/m_p \sim 1/9$).

QED tests in microwave

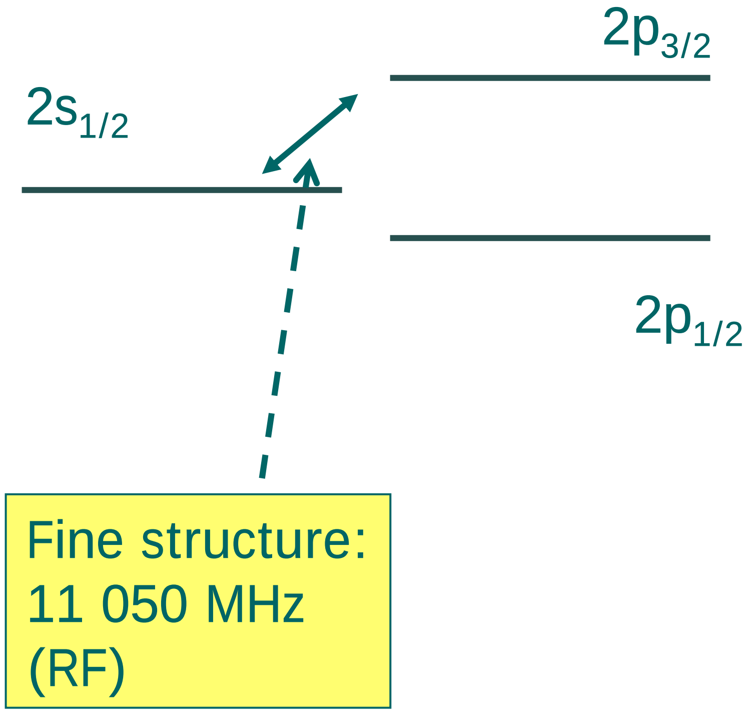
- Lamb shift used to be measured either as a splitting between $2s_{1/2}$ and $2p_{1/2}$ (1057 MHz)



Lamb shift: 1057 MHz (RF)

QED tests in microwave

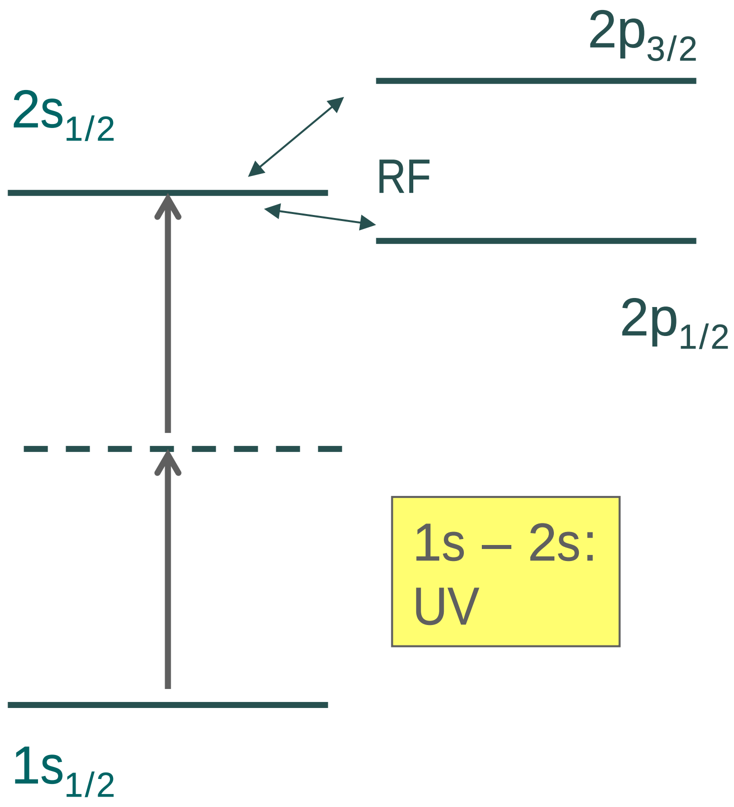
- Lamb shift used to be measured either as a splitting between $2s_{1/2}$ and $2p_{1/2}$ (1057 MHz) or a big contribution into the fine splitting $2p_{3/2} - 2s_{1/2}$ 11 THz (fine structure).



Fine structure:
11 050 MHz
(RF)

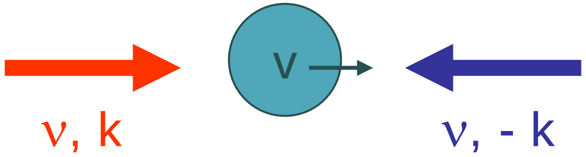
QED tests in microwave & optics

- Lamb shift used to be measured either as a splitting between $2s_{1/2}$ and $2p_{1/2}$ (1057 MHz) or a big contribution into the fine splitting $2p_{3/2}$ – $2s_{1/2}$ 11 THz (fine structure).
- *However, the best result for the Lamb shift has been obtained up to now from UV transitions (such as 1s – 2s).*



Two-photon Doppler-free spectroscopy of hydrogen atom

Two-photon spectroscopy



- is free of linear Doppler effect.
- That makes cooling relatively not too important problem.
- All states but 2s are broad because of the E1 decay.
- The widths decrease with increase of n.
- However, higher levels are badly accessible.
- Two-photon transitions double frequency and allow to go higher.

Spectroscopy of hydrogen (and deuterium)

Two-photon spectroscopy involves a number of levels strongly affected by QED.

In “old good time” we had to deal only with 2s Lamb shift.

Theory for p states is simple since their wave functions vanish at $r=0$.

Now we have more data and more unknown variables.

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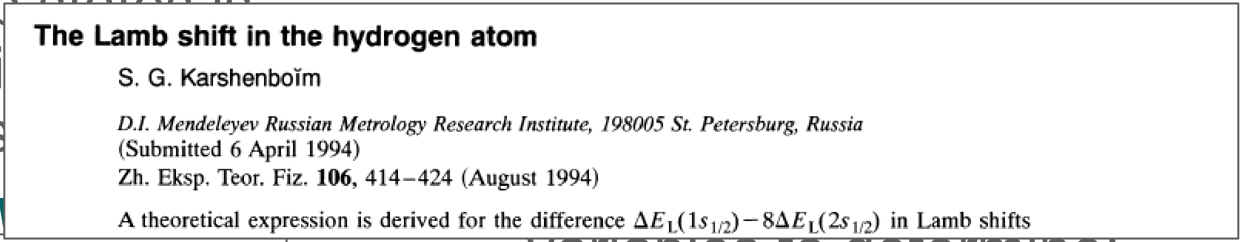
$$\Delta(2) = L_{1s} - 2^3 \times L_{2s}$$

which we understand much better since any short distance effect vanishes for $\Delta(2)$.

variables to determine: the 1s Lamb shift L_{1s} & R_∞.



The Lamb shift in the hydrogen atom

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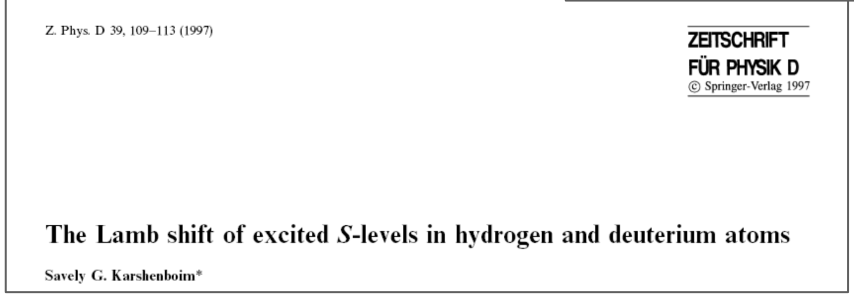
D.I. Mendeleyev Russian Metrology Research Institute, 198005 St. Petersburg, Russia
(Submitted 6 April 1994)
Zh. Eksp. Teor. Fiz. **106**, 414–424 (August 1994)

A theoretical expression is derived for the difference $\Delta E_L(1s_{1/2}) - 8\Delta E_L(2s_{1/2})$ in Lamb shifts



Z. Phys. D 39, 109–113 (1997)

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The Lamb shift of excited *S*-levels in hydrogen and deuterium atoms

Savely G. Karshenboim*

Spectroscopy of hydrogen (and deuterium)

Two-photon spectroscopy involves a number of levels strongly affected by QED.

In “old good time” we had to deal only with 2s Lamb shift.

Theory for p states is simple since their wave functions vanish at $r=0$.

Now we have more data and more unknown variables.

The idea is based on theoretical study of

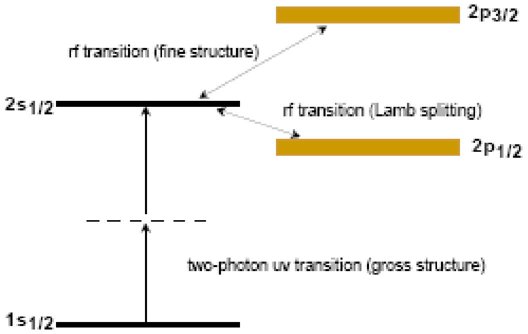
$$\Delta(2) = L_{1s} - 2^3 \times L_{2s}$$

which we understand much better since any short distance effect vanishes for $\Delta(2)$.

Theory of p and d states is also simple.

That leaves only two variables to determine: the 1s Lamb shift L_{1s} & R_∞.

Spectroscopy of hydrogen (and deuterium)



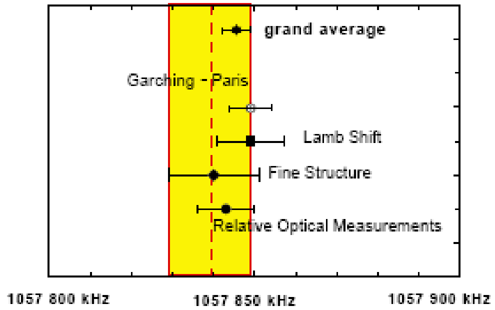


Fig. 9. Measurement of the Lamb shift in the hydrogen atom. The most accurate experimental result comes from a comparison of the $1s-2s$ interval measured at MPQ (Garching) [38] and the $2s-ns/d$ intervals at LKB (Paris) [39], where $n=8,10,12$ (see also [33] for detail). Three more results are shown for the average values extracted from direct *Lamb shift* measurements, measurements of the *fine structure* and a comparison of *two optical* transitions within a *single* experiment (i.e., a relative optical measurement). The filled part is for theory. Theory and evaluation of the experimental data are presented according to Ref. [36].

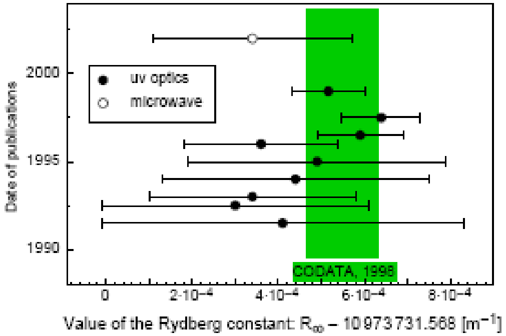
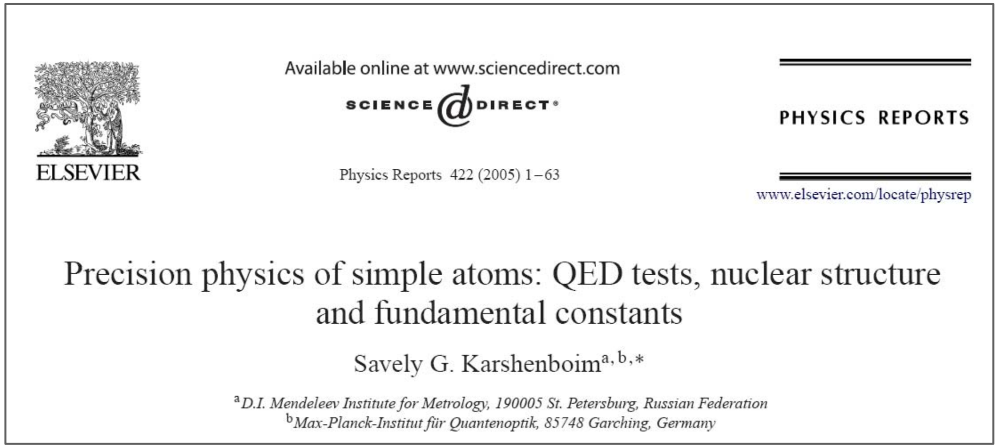


Fig. 8. Progress in determination of the Rydberg constant by means of two-photon Doppler-free spectroscopy of hydrogen and deuterium. The label *CODATA* stands for the recommended value of the Rydberg constant $R_\infty(1998)$ [21] from Eq. (12). The most recent original value is a preliminary result from MIT obtained by microwave means [37].



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Precision physics of simple atoms: QED tests, nuclear structure and fundamental constants

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[b] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

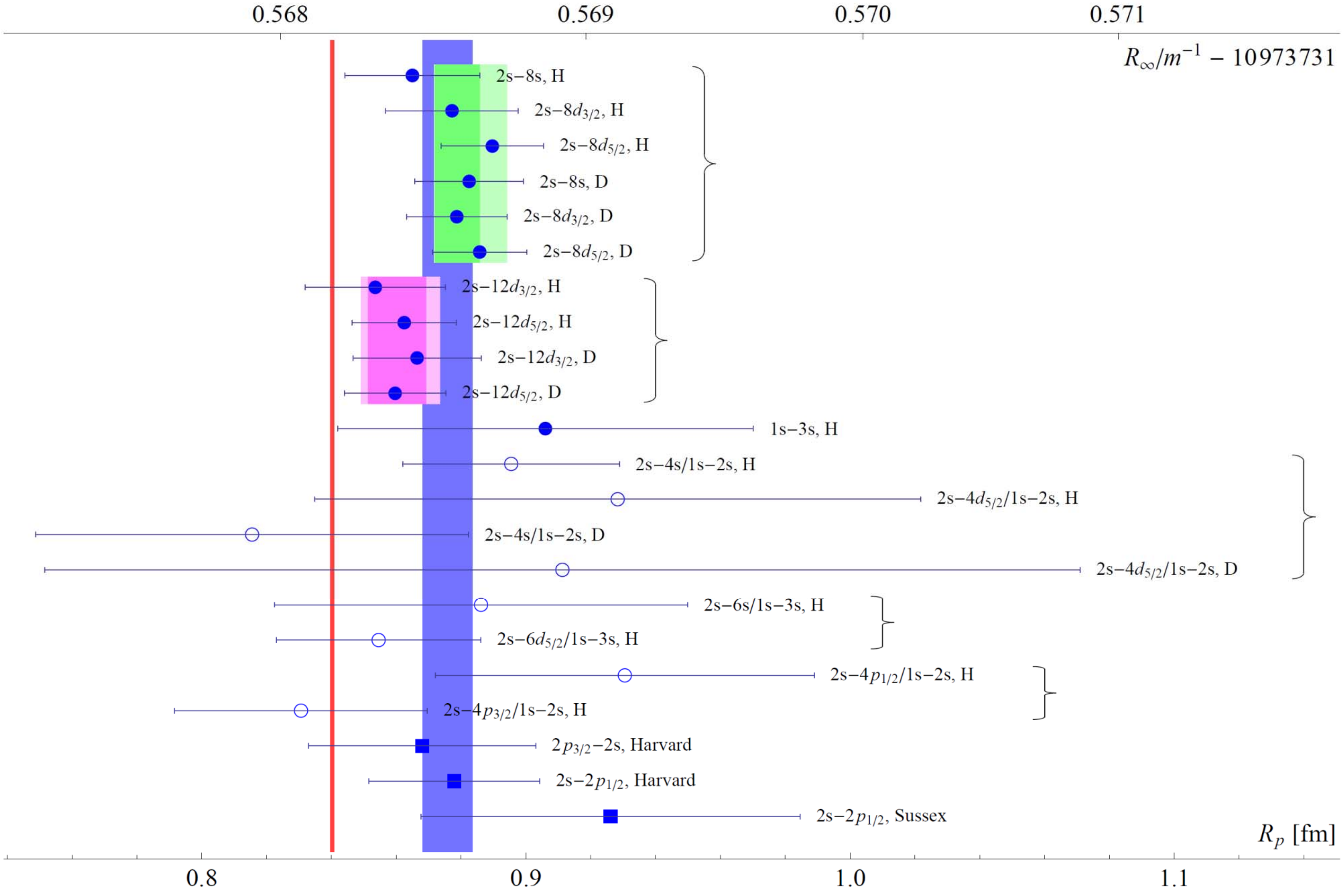
Lamb shift ($2s_{1/2} – 2p_{1/2}$) in the hydrogen atom

Uncertainties:

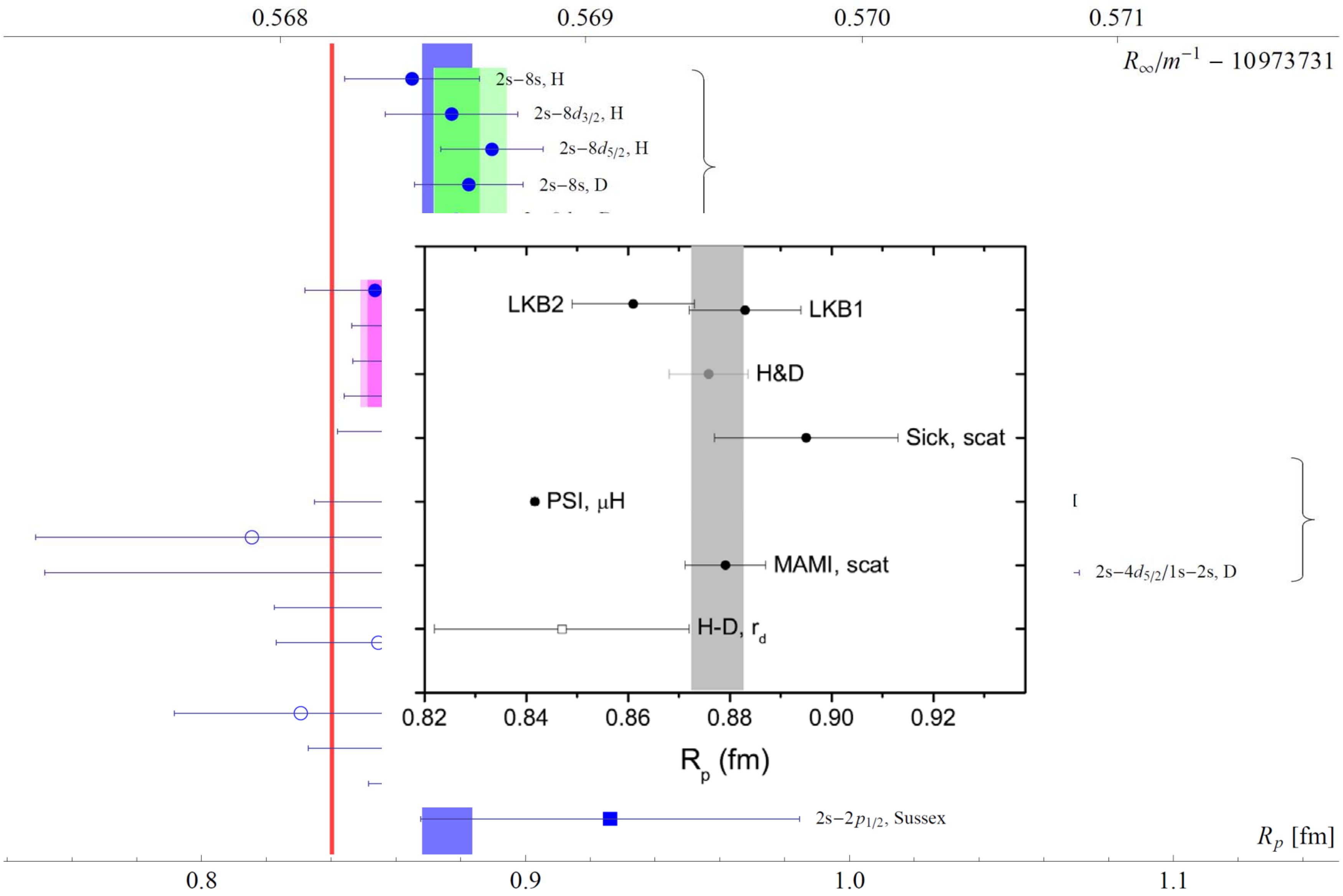
- Experiment: 2 ppm
- QED: < 1 ppm
- Proton size: 2 ppm

There are data on a number of transitions, but most of them are correlated.

Proton radius from hydrogen



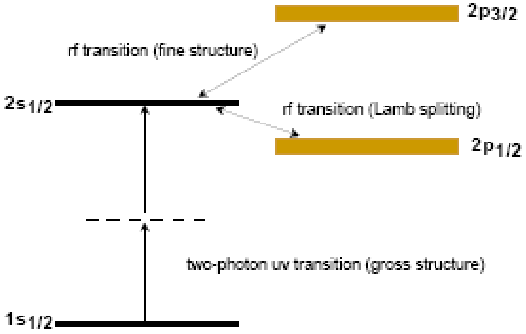
Proton radius from hydrogen



The Lamb shift in muonic hydrogen

- Used to believe: *since a muon is heavier than an electron, muonic atoms are more sensitive to the nuclear structure.*
- Not quite true. **What is important**: scaling of various contributions with *m*.

- Scaling of contributions
  - **nuclear finite size effects**: ~ m^3;
  - standard Lamb-shift QED and its uncertainties: ~ m;
  - width of the 2p state: ~ m;
  - nuclear finite size effects for HFS: ~ m^3



The Lamb shift in muonic hydrogen: experiment

The size of the proton

Randolf Pohl[1], Aldo Antognini[1], François Nez[2], Fernando D. Amaro[3], François Biraben[2], João M. R. Cardoso[3], Daniel S. Covita[3,4], Andreas Dax[5], Satish Dhawan[5], Luis M. P. Fernandes[3], Adolf Giesen[6]†, Thomas Graf[6], Theodor W. Hänsch[1], Paul Indelicato[2], Lucile Julien[2], Cheng-Yang Kao[7], Paul Knowles[8], Eric-Olivier Le Bigot[2], Yi-Wei Liu[7], José A. M. Lopes[3], Livia Ludhova[8], Cristina M. B. Monteiro[3], Françoise Mulhauser[8]†, Tobias Nebel[1], Paul Rabinowitz[9], Joaquim M. F. dos Santos[3], Lukas A. Schaller[8], Karsten Schuhmann[10], Catherine Schwob[2], David Taqqu[11], João F. C. A. Veloso[4] & Franz Kottmann[12]

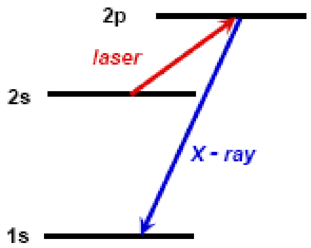


Fig. 16. Level scheme of the PSI experiment on the Lamb shift in a muonic hydrogen [88] (not to scale). The hyperfine structure is not shown.

The Lamb shift in muonic hydrogen: experiment

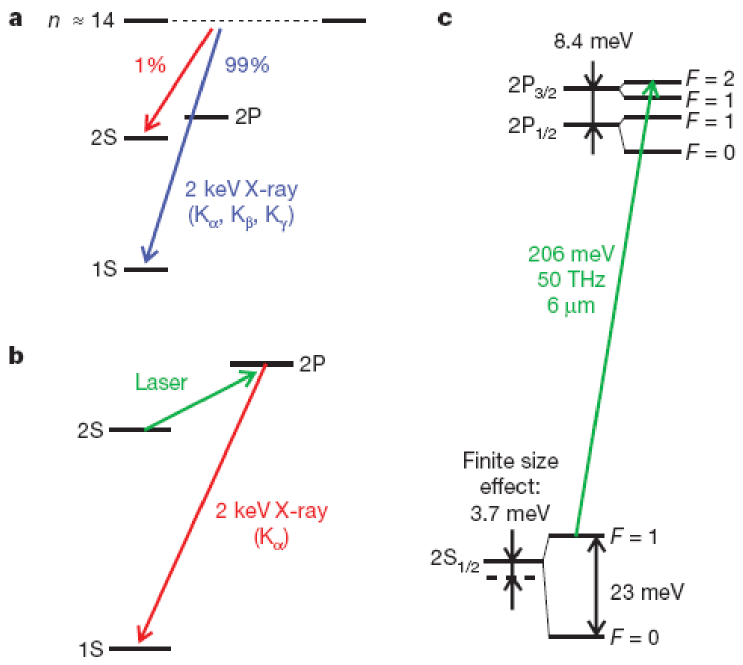


Figure 1 | Energy levels, cascade and experimental principle in muonic hydrogen. **a**, About 99% of the muons proceed directly to the 1S ground state during the muonic cascade, emitting 'prompt' K-series X-rays (blue). 1% remain in the metastable 2S state (red). **b**, The μp(2S) atoms are illuminated by a laser pulse (green) at 'delayed' times. If the laser is on resonance, delayed K_α X-rays are observed (red). **c**, Vacuum polarization dominates the Lamb shift in μp. The proton's finite size effect on the 2S state is large. The green arrow indicates the observed laser transition at $\lambda = 6$ μm.

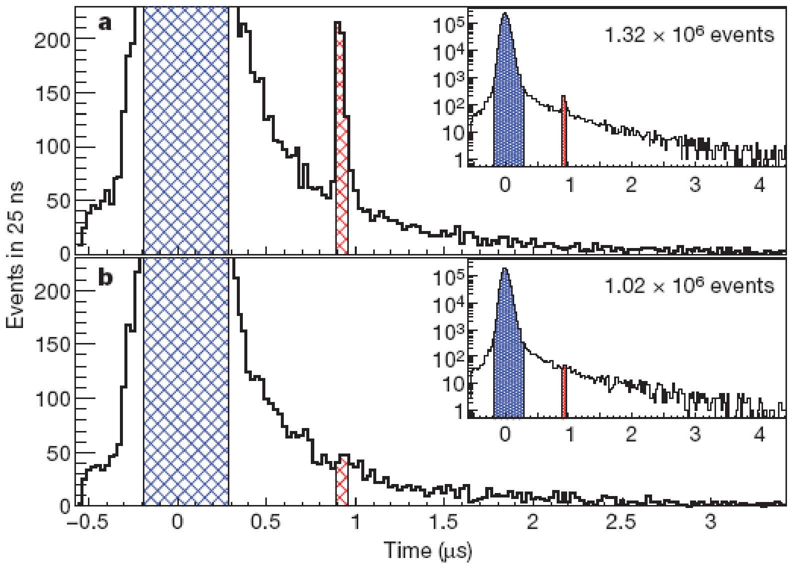


Figure 4 | Summed X-ray time spectra. Spectra were recorded on resonance (**a**) and off resonance (**b**). The laser light illuminates the muonic atoms in the laser time window $t \in [0.887, 0.962]$ μs indicated in red. The 'prompt' X-rays are marked in blue (see text and Fig. 1). Inset, plots showing complete data; total number of events are shown.

The Lamb shift in muonic hydrogen: experiment

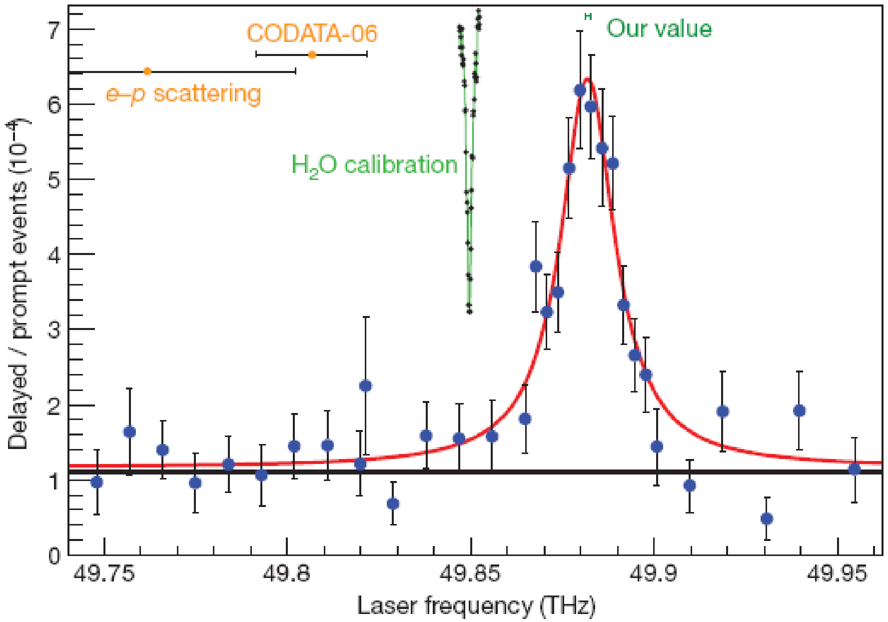
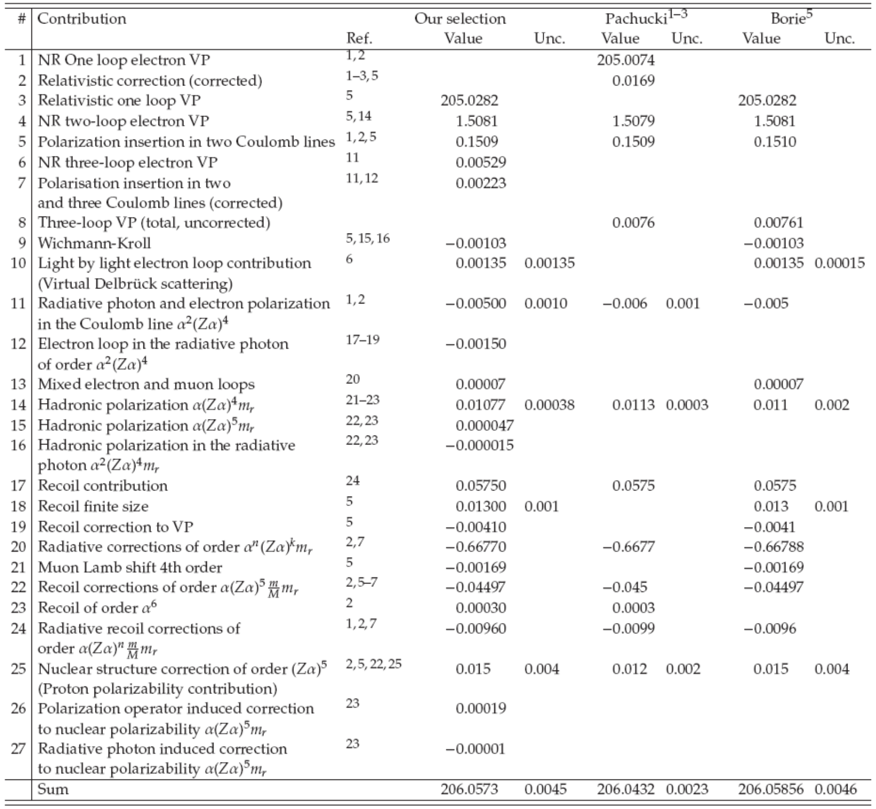


Figure 5 | Resonance. Filled blue circles, number of events in the laser time window normalized to the number of 'prompt' events as a function of the laser frequency. The fit (red) is a Lorentzian on top of a flat background, and gives a χ^2/d.f. of 28.1/28. The predictions for the line position using the proton radius from CODATA[3] or electron scattering[1,2] are indicated (yellow data points, top left). Our result is also shown ('our value'). All error bars are the ±1 s.d. regions. One of the calibration measurements using water absorption is also shown (black filled circles, green line).

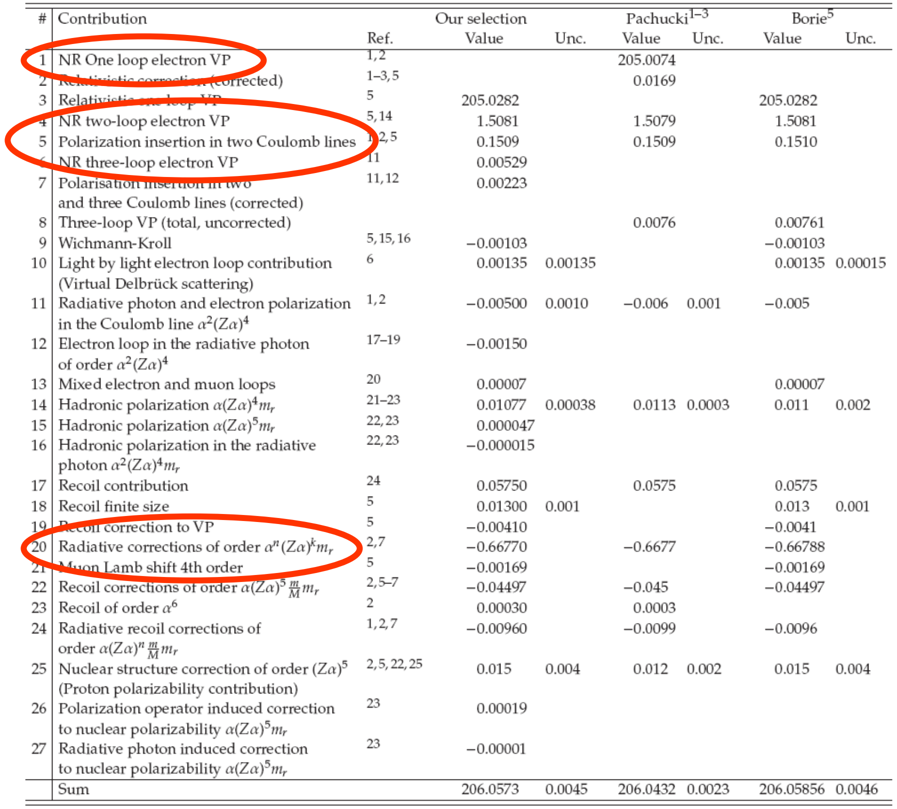
The Lamb shift in muonic hydrogen: theory



#	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.

The Lamb shift in muonic hydrogen: theory



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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					
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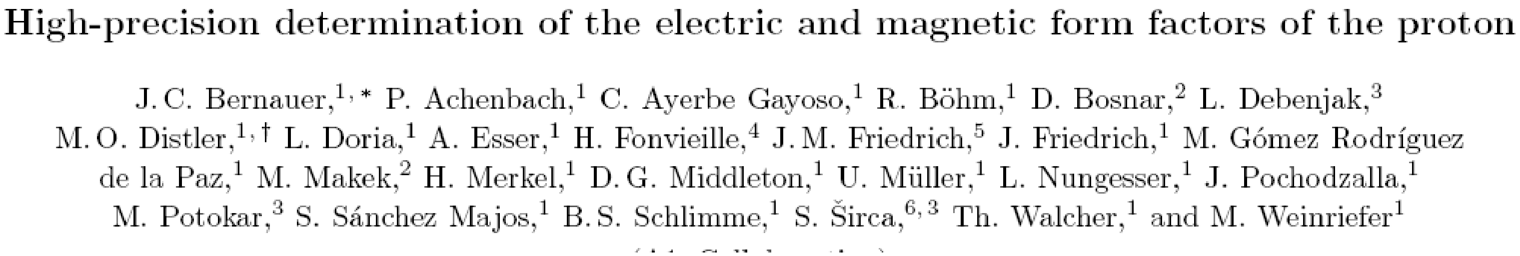
$$\Delta E_{LS} = 206.0573(45) - 5.2262\, r_p^2 + \boxed{0.0347\, r_p^3 \text{ meV}} \quad (1)$$

- Discrepancy ~ 0.300 meV.
- Only few contributions are important at this level.
- **They are reliable.**

Electron-proton scattering: new Mainz experiment



High-precision determination of the electric and magnetic form factors of the proton

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M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez
de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1]
M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.879(5)_{\mathrm{stat.}}(4)_{\mathrm{syst.}}(2)_{\mathrm{model}}(4)_{\mathrm{group}}\ \mathrm{fm},$$

$$\langle r_M^2 \rangle^{\frac{1}{2}} = 0.777(13)_{\mathrm{stat.}}(9)_{\mathrm{syst.}}(5)_{\mathrm{model}}(2)_{\mathrm{group}}\ \mathrm{fm}.$$

Electron-proton scattering: evaluations of `the World data'

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- JLab (similar results also from Ingo Sick)

$$\langle r_E^2\rangle^{1/2} = 0.875 \pm 0.008_{\mathrm{exp}} \pm 0.006_{\mathrm{fit}}\ \mathrm{fm} \qquad (3)$$
$$\langle r_M^2\rangle^{1/2} = 0.867 \pm 0.009_{\mathrm{exp}} \pm 0.018_{\mathrm{fit}}\ \mathrm{fm}, \qquad (4)$$

Magnetic radius does not agree!

- Charge radius:

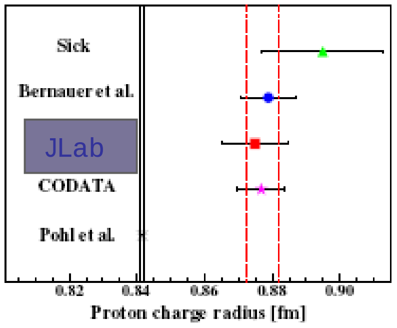
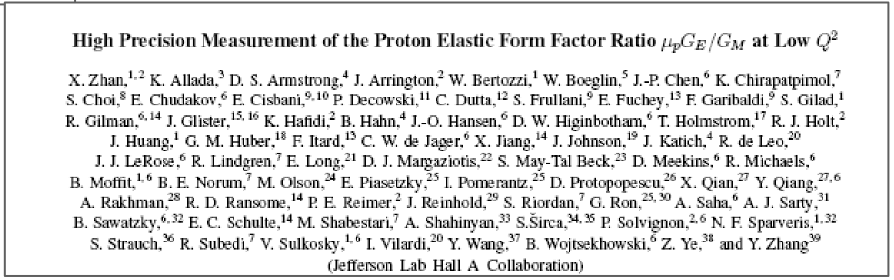


FIG. 3: (Color online) The proton RMS charge radius from previous *ep* scattering analysis (Sick [40]), Mainz low Q^2 measurement (Bernauer *et al.* [37]) and this work compared to the CODATA [41] and muonic hydrogen spectroscopy (Pohl *et al.* [42]). The red dashed lines show the combined results from CODATA, Bernauer *et al.* and this work, while the black dotted lines show the Pohl *et al.* uncertainty.



High Precision Measurement of the Proton Elastic Form Factor Ratio $\mu_p G_E/G_M$ at Low Q^2

X. Zhan,[1,2] K. Allada,[3] D. S. Armstrong,[4] J. Arrington,[2] W. Bertozzi,[1] W. Boeglin,[5] J.-P. Chen,[6] K. Chirapatpimol,[7]
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B. Moffit,[1,6] B. E. Norum,[7] M. Olson,[24] E. Piasetzky,[25] I. Pomerantz,[25] D. Protopopescu,[26] X. Qian,[27] Y. Qiang,[27,6]
A. Rakhman,[28] R. D. Ransome,[14] P. E. Reimer,[2] J. Reinhold,[29] S. Riordan,[7] G. Ron,[25,30] A. Saha,[6] A. J. Sarty,[31]
B. Sawatzky,[6,32] E. C. Schulte,[14] M. Shabestari,[7] A. Shahinyan,[33] S.Širca,[34,35] P. Solvignon,[2,6] N. F. Sparveris,[1,32]
S. Strauch,[36] R. Subedi,[7] V. Sulkosky,[1,6] I. Vilardi,[20] Y. Wang,[37] B. Wojtsekhowski,[6] Z. Ye,[38] and Y. Zhang[39]
(Jefferson Lab Hall A Collaboration)

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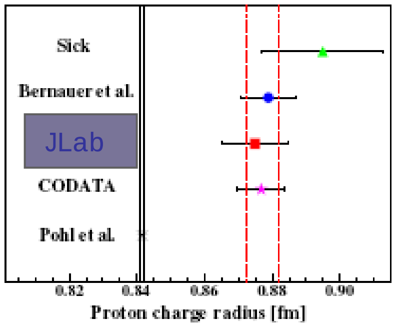

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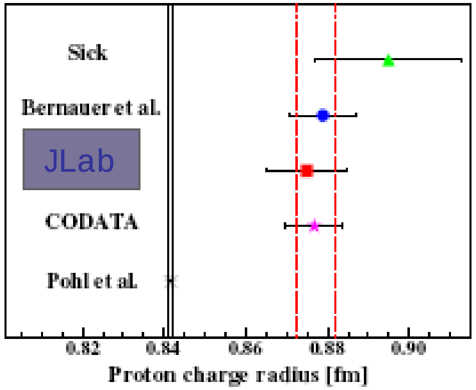
Different methods to determine the proton charge radius

- *spectroscopy of hydrogen (and deuterium)*
- *the Lamb shift in muonic hydrogen*
- *electron-proton scattering*

- Comparison:



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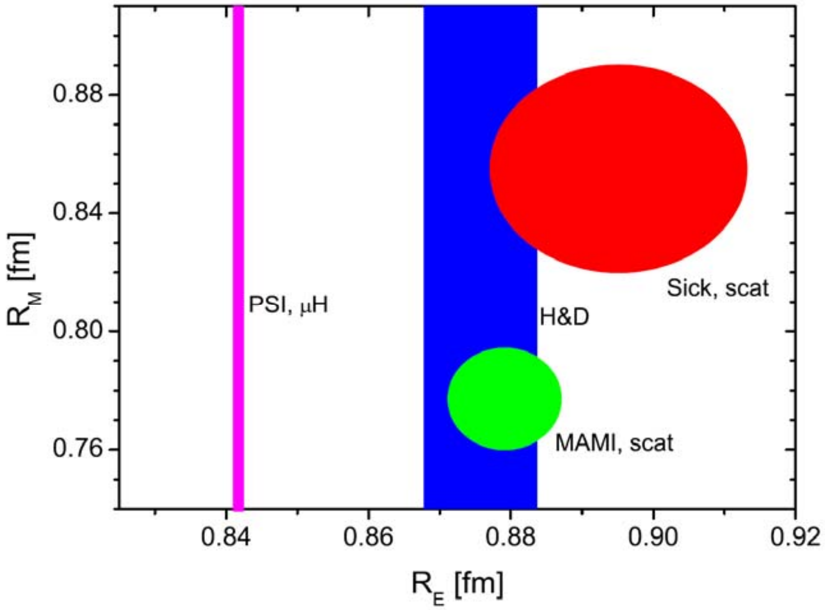
Present status of proton radius: three convincing results

charge radius and the Rydberg constant: a strong discrepancy.

- If I would bet:
  - *systematic effects in hydrogen and deuterium spectroscopy*
  - *error or underestimation of uncalculated terms in 1s Lamb shift theory*
- Uncertainty and model-independence of scattering results.

magnetic radius:

a strong discrepancy between different evaluation of the data and maybe between the data



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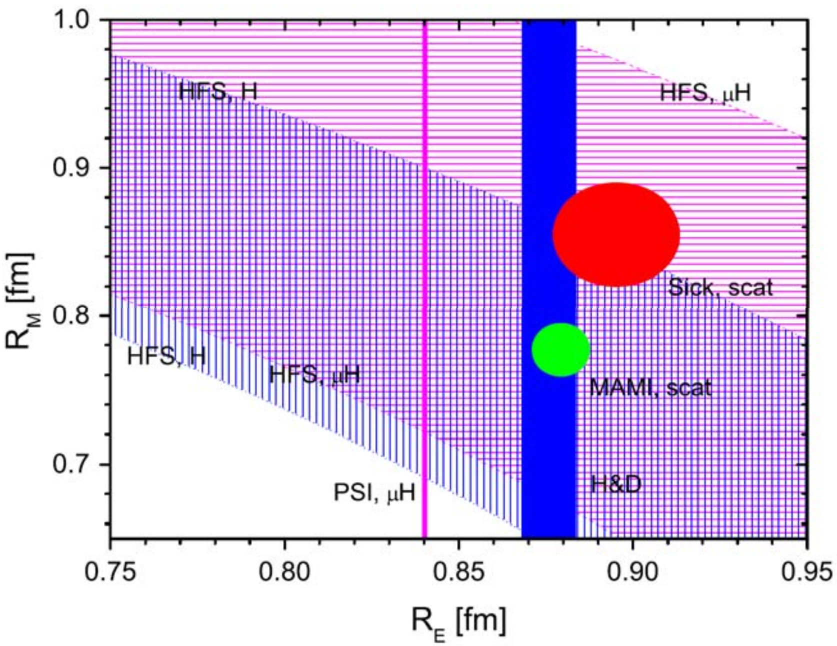
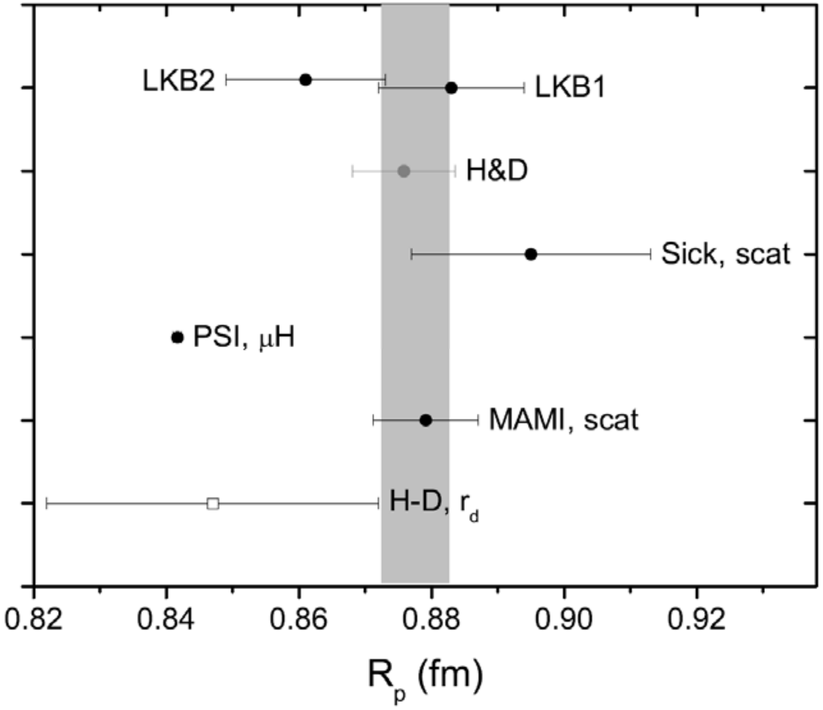


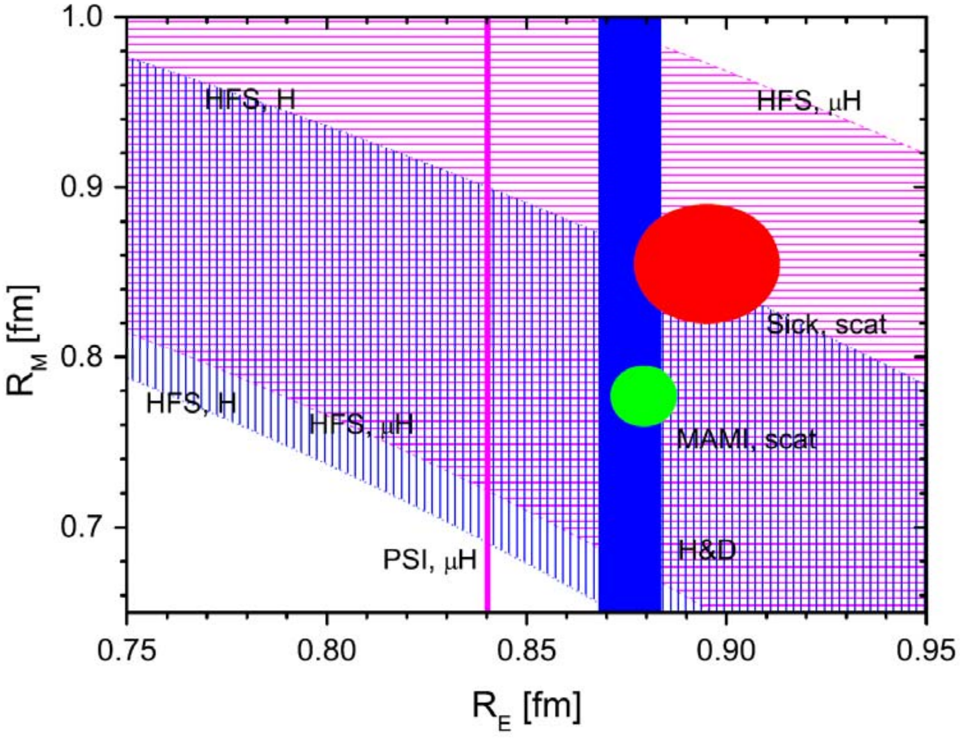
What is next?

- *new evaluations of scattering data (old and new)*
- *new spectroscopic experiments on hydrogen and deuterium*
- *evaluation of data on the Lamb shift in muonic deuterium (from PSI) and new value of the Rydberg constant*

- *systematic check on muonic hydrogen and deuterium theory*

Where we are


LKB2
LKB1
H&D
Sick, scat
PSI, μH
MAMI, scat
H-D, r_d
0.82
0.84
0.86
0.88
0.90
0.92
R_p (fm)


1.0
0.9
0.8
0.7
R_M [fm]
HFS, H
HFS, μH
Sick, scat
HFS, H
HFS, μH
MAMI, scat
PSI, μH
H&D
0.75
0.80
0.85
0.90
0.95
R_E [fm]