News from the Proton Radius Puzzle

muonic deuterium

Randolf Pohl

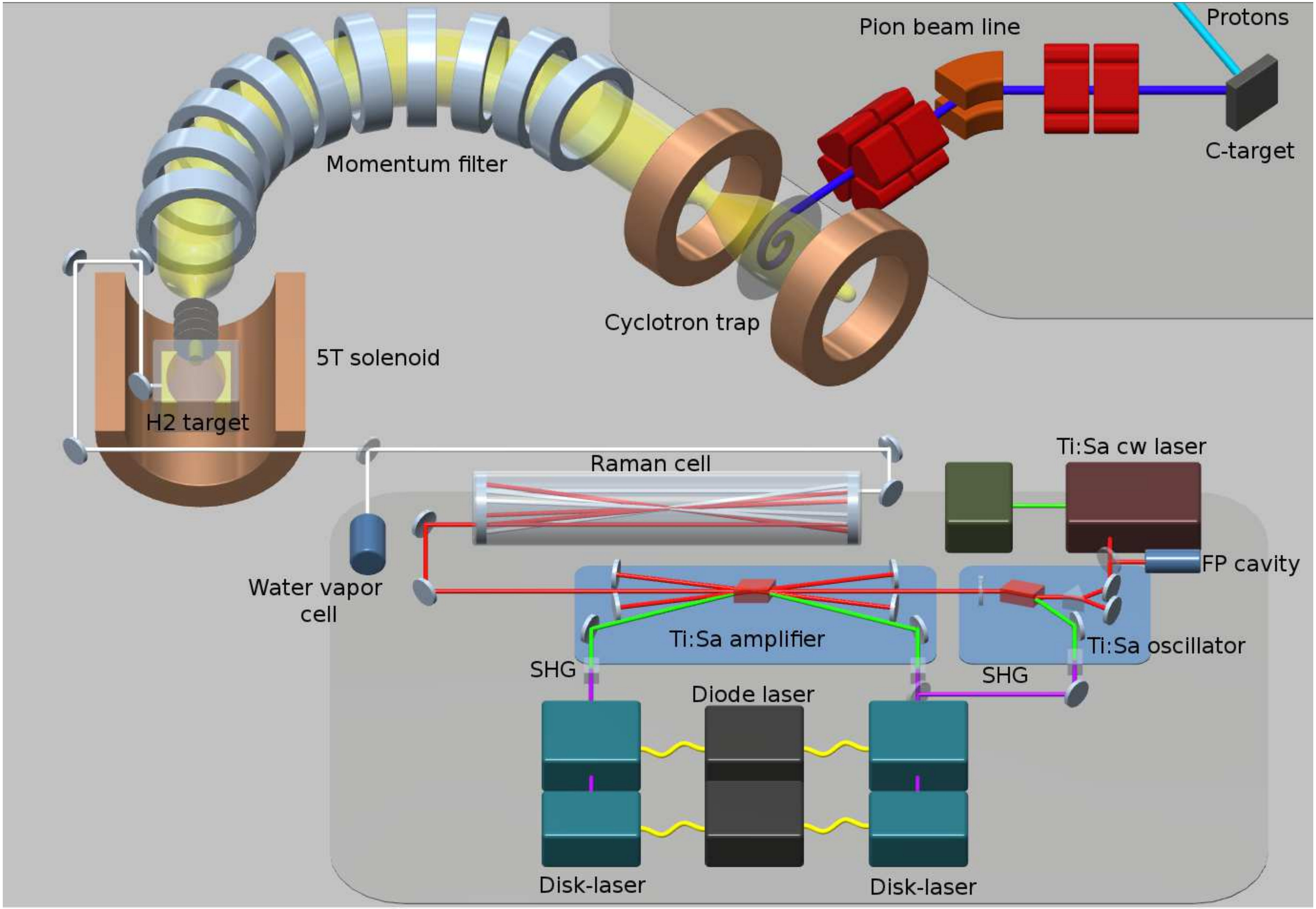
Max-Planck-Institut für Quantenoptik Garching, Germany

Outline

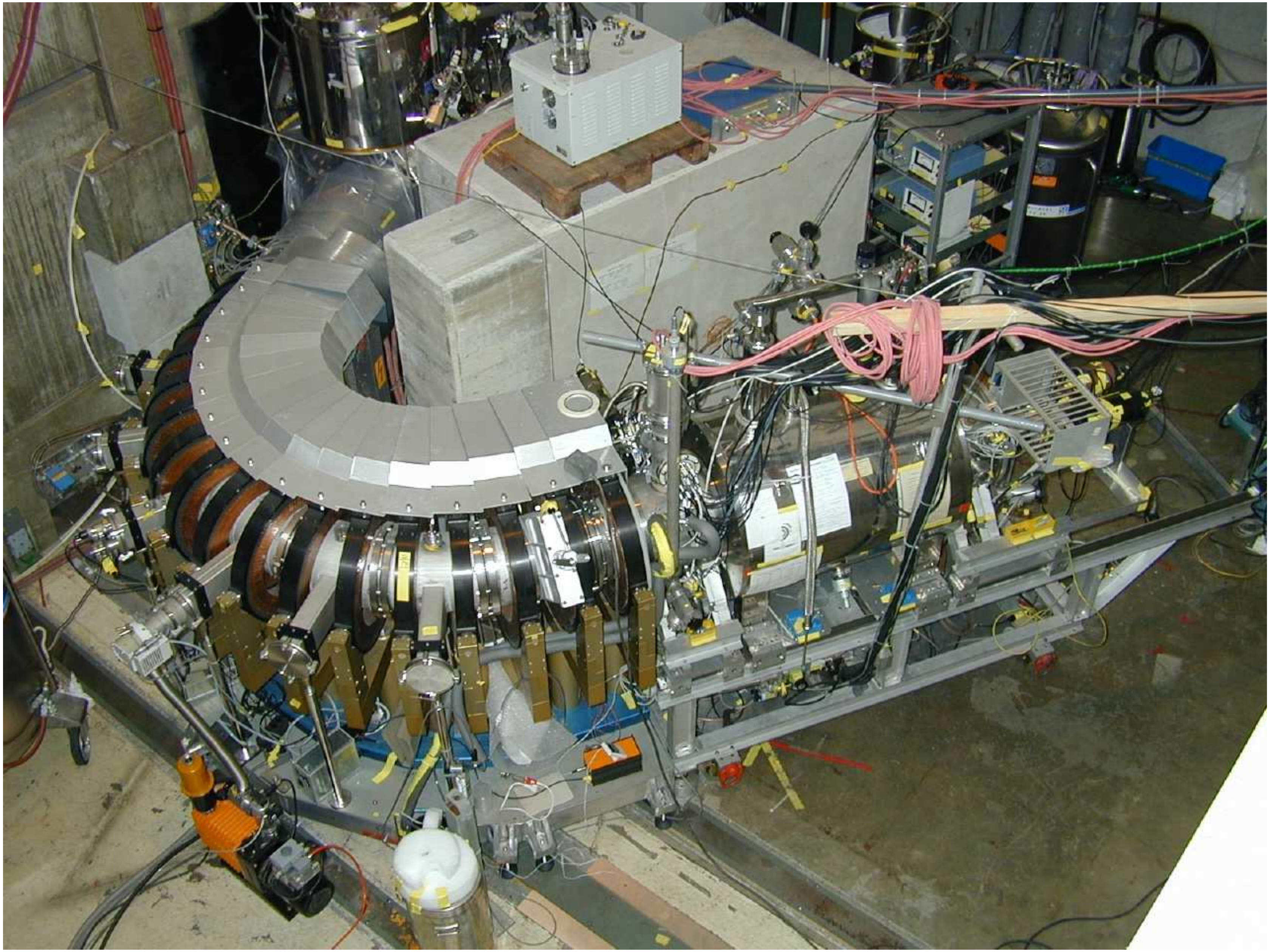
- The problem:
  Proton rms charge radius r_p from muonic hydrogen μp is 4 % smaller
  than the values from elastic electron-proton scattering and
  hydrogen spectroscopy.
  That's 5σ ... 8σ.
  But the $\mu\mathbf{p}$ result is 10 times more accurate than any other measurement.
- Introduction
- Muonic hydrogen
- Muonic deuterium
- Muonic helium
- Muonic future

Muonic measurements.

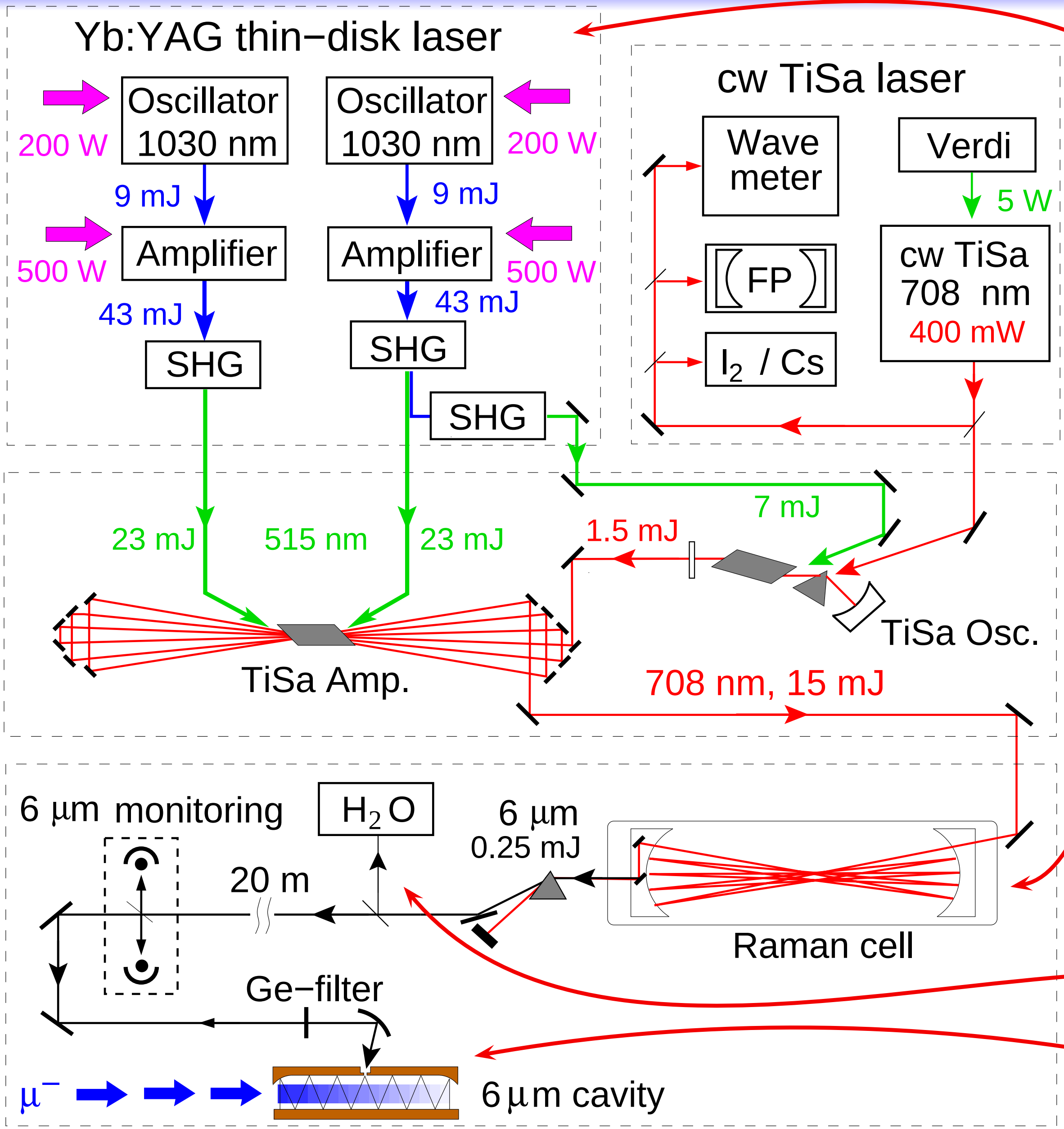
Setup


Pion beam line
Protons
C-target
Momentum filter
Cyclotron trap
5T solenoid
H2 target
Raman cell
Ti:Sa cw laser
Water vapor cell
FP cavity
Ti:Sa amplifier
Ti:Sa oscillator
SHG
SHG
Diode laser
Disk-laser
Disk-laser

Muon beam line



The laser system



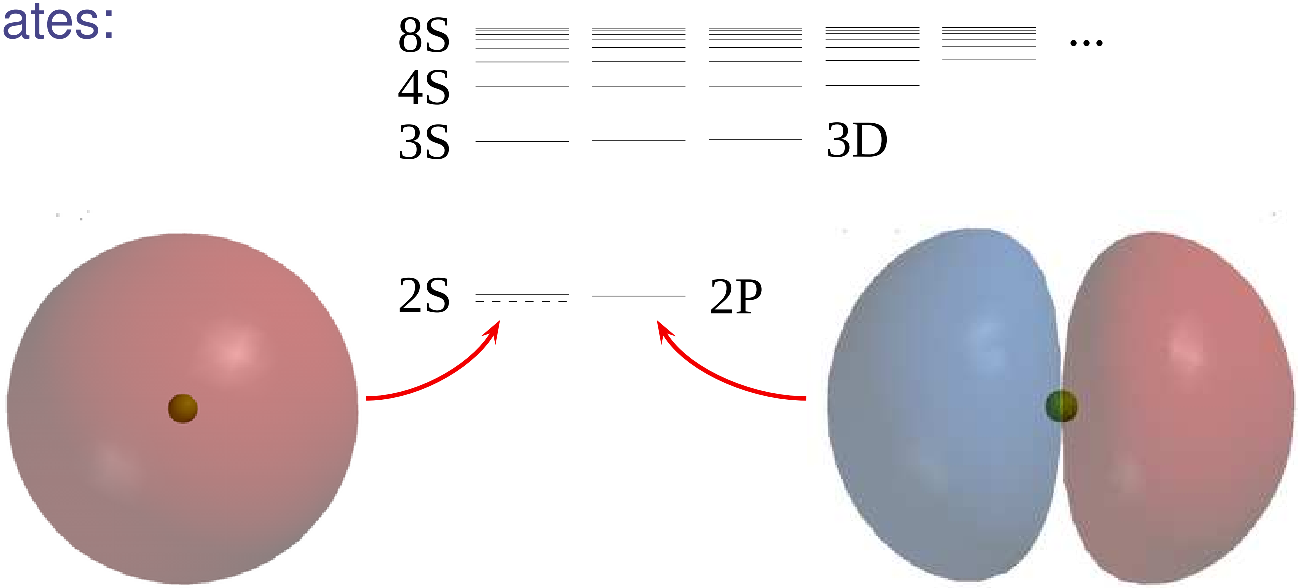
Main components:

- Thin-disk laser
  fast response to detected μ^-
- Frequency doubling
- TiSa laser:
  frequency stabilized cw laser
  injection seeded oscillator
  multipass amplifier
- Raman cell
  3 Stokes: 708 nm $\rightarrow$ 6 μm
- λ calibration
  (1) wavemeter + known Raman shift
  (2) H_2O spectr. at 6 μm
- Target cavity

A. Antognini, RP *et. al.*, Opt. Comm. 253, 362 (2005)

Atomic physics

Wave functions of S and P states:



S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

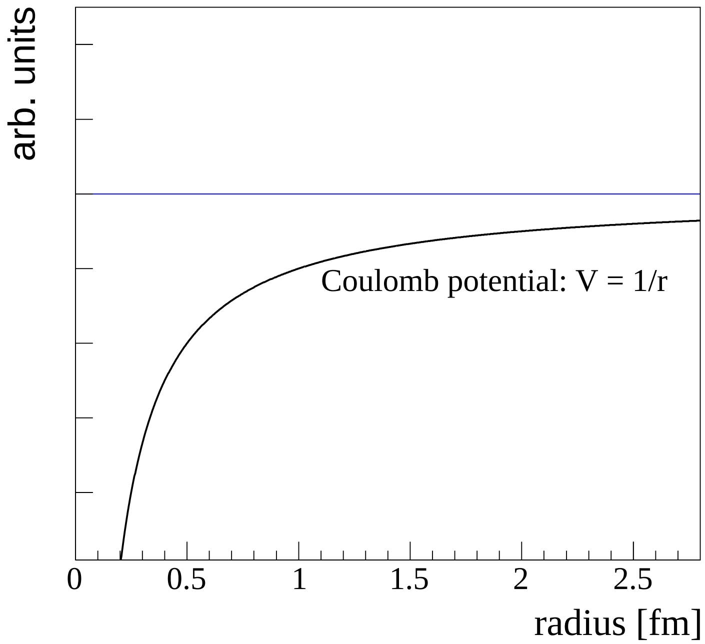
size of the proton

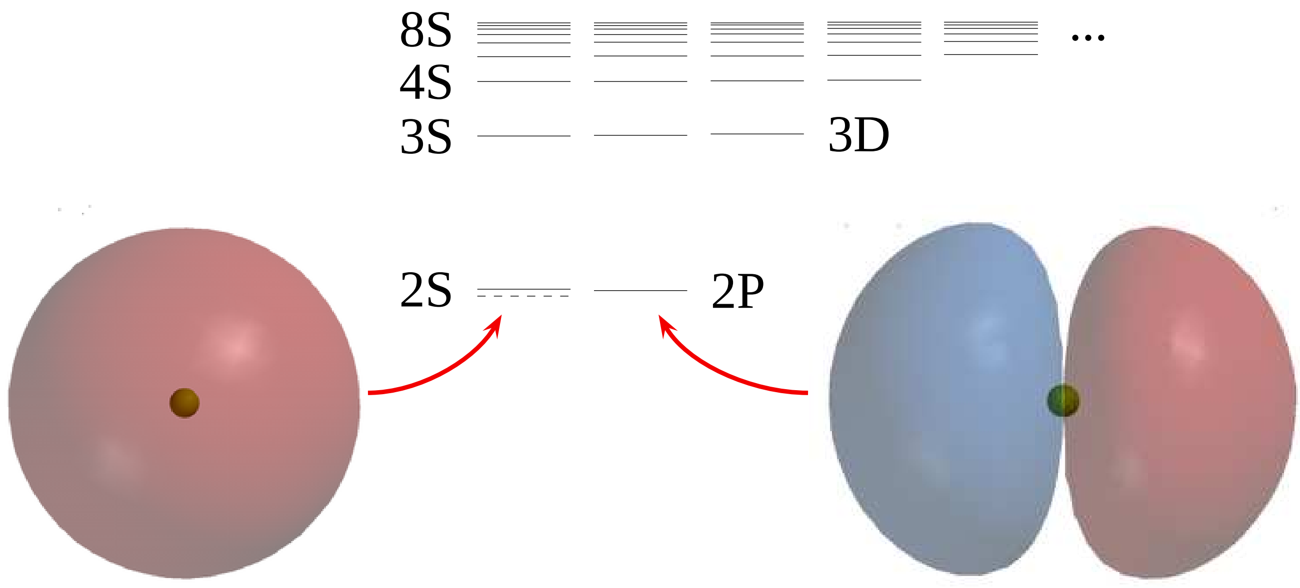
P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

Atomic physics





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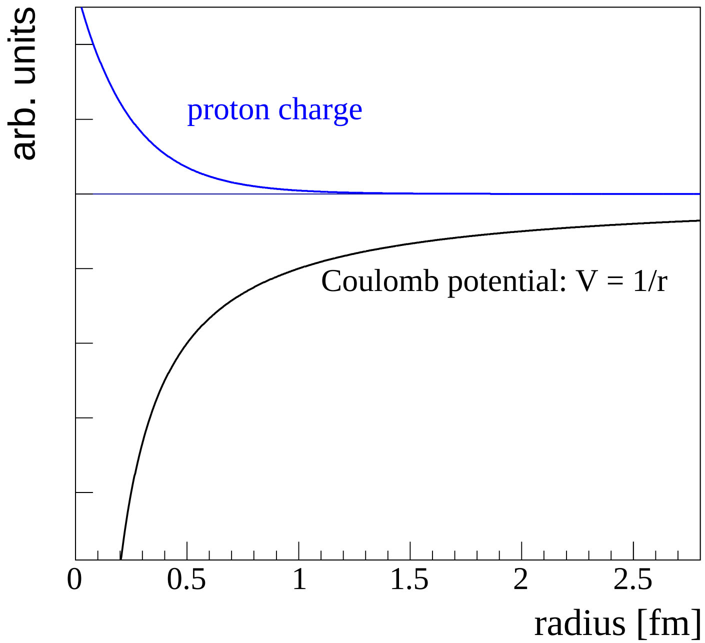
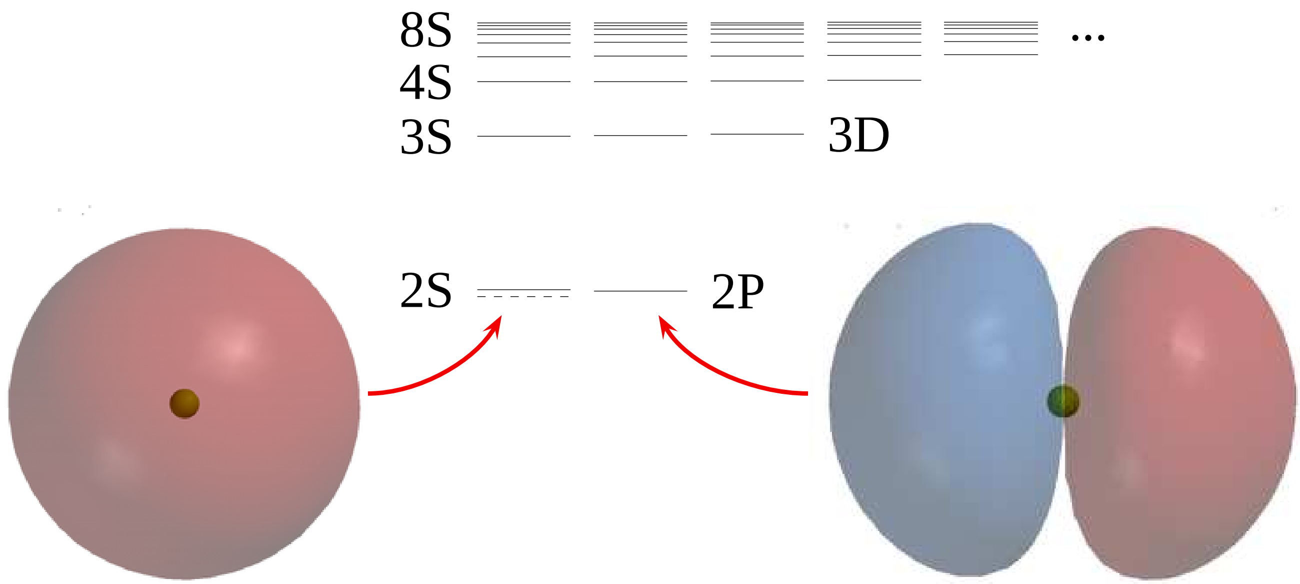
Atomic and nuclear physics





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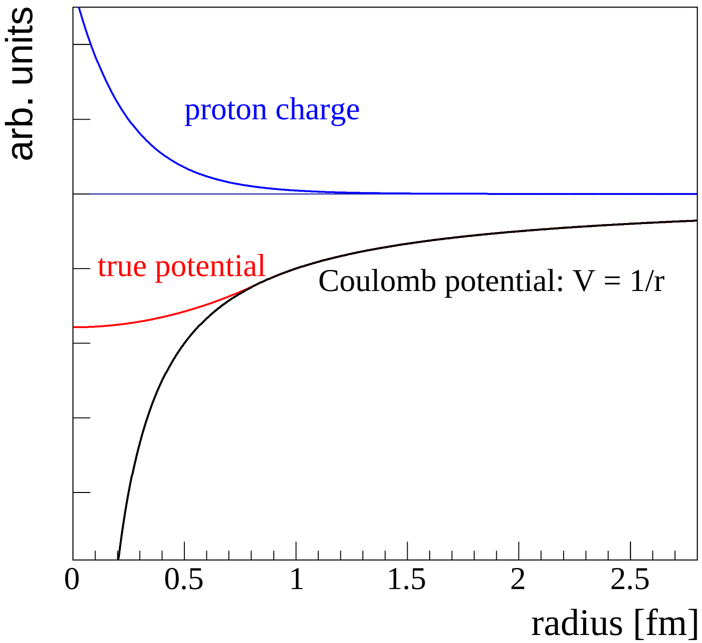

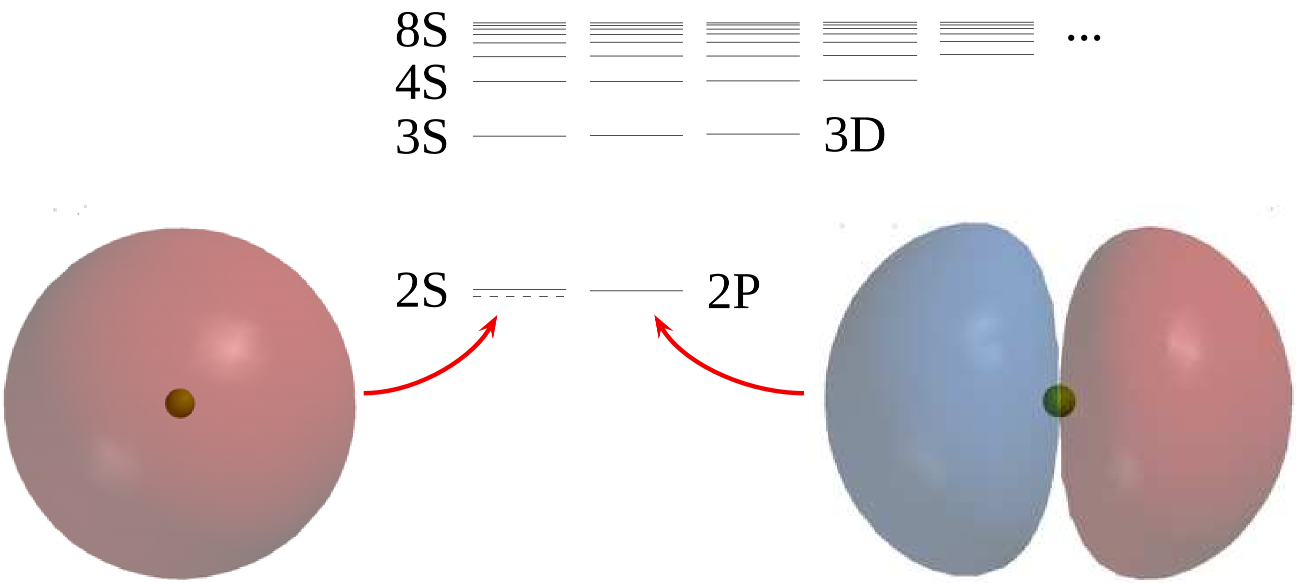

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Orbital pictures from Wikipedia

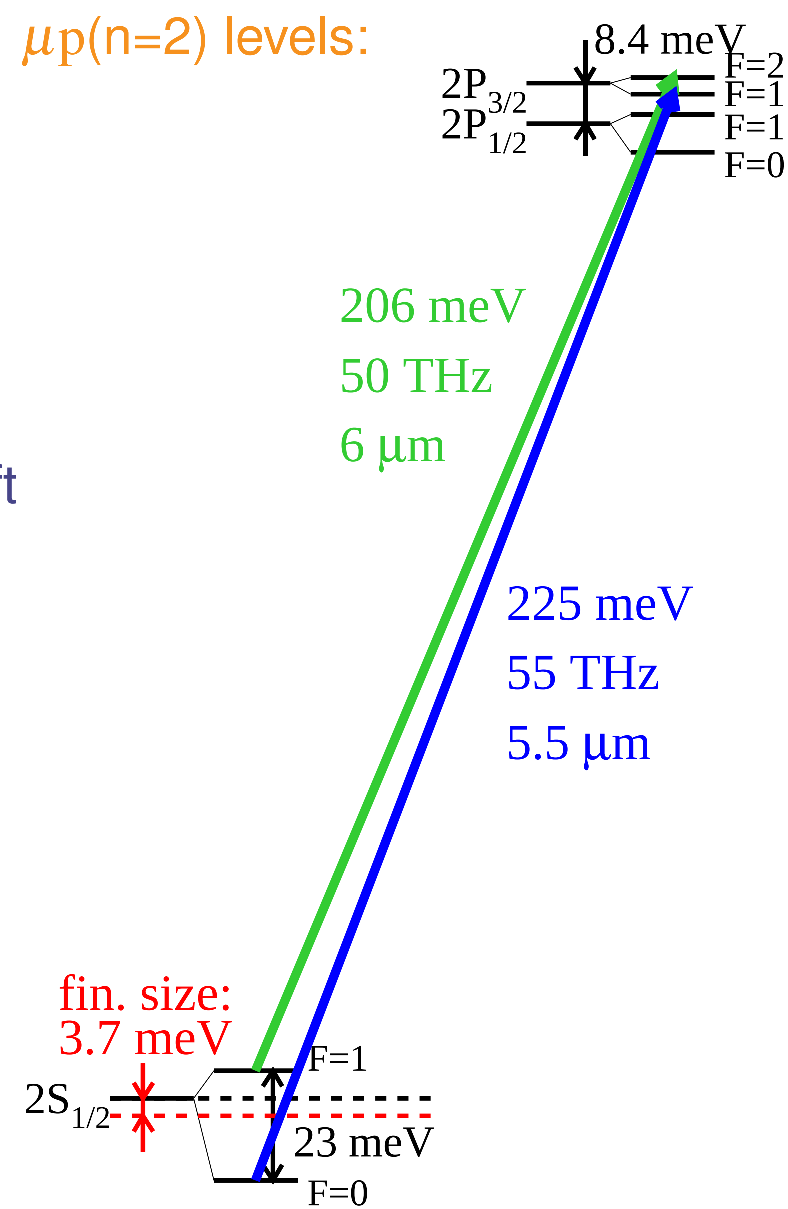
Proton charge radius and muonic hydrogen

Lamb shift in μp [meV]:

$$\Delta E = 206.0668(25) - 5.2275(10)\, r_p^2$$

Proton size effect is 2% of the μp Lamb shift

Measure to 10^{-5} $\Rightarrow$ r_p to 0.05 %



Experiment:

R. Pohl *et al.*, Nature 466, 213 (2010).

A. Antognini, RP *et al.*, Science 339, 417 (2013).

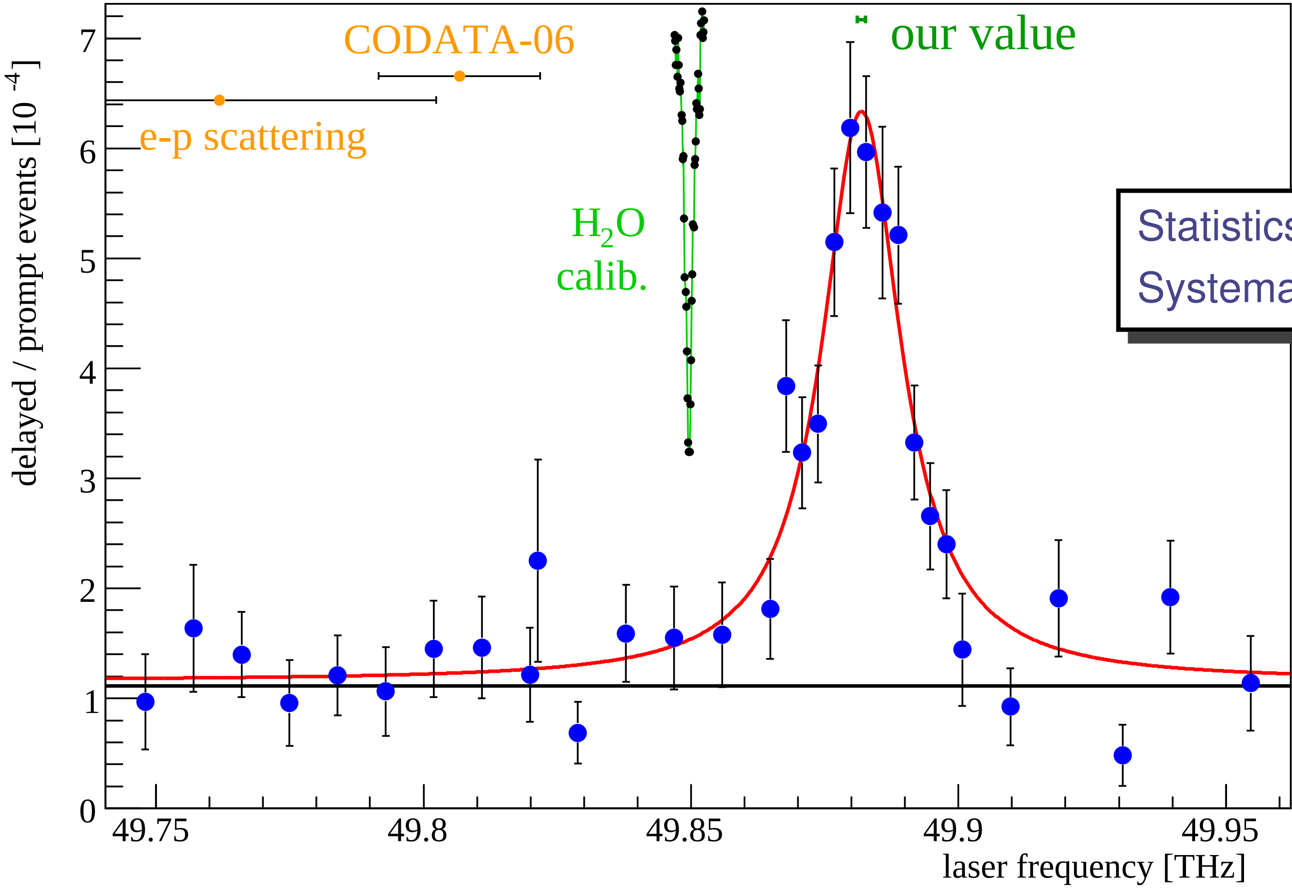
Theory summary:

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty



Statistics: 700 MHz
Systematics: 300 MHz

Discrepancy:
$5.0\sigma \leftrightarrow$ **75 GHz** $\leftrightarrow \delta\nu/\nu = 1.5 \times 10^{-3}$

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

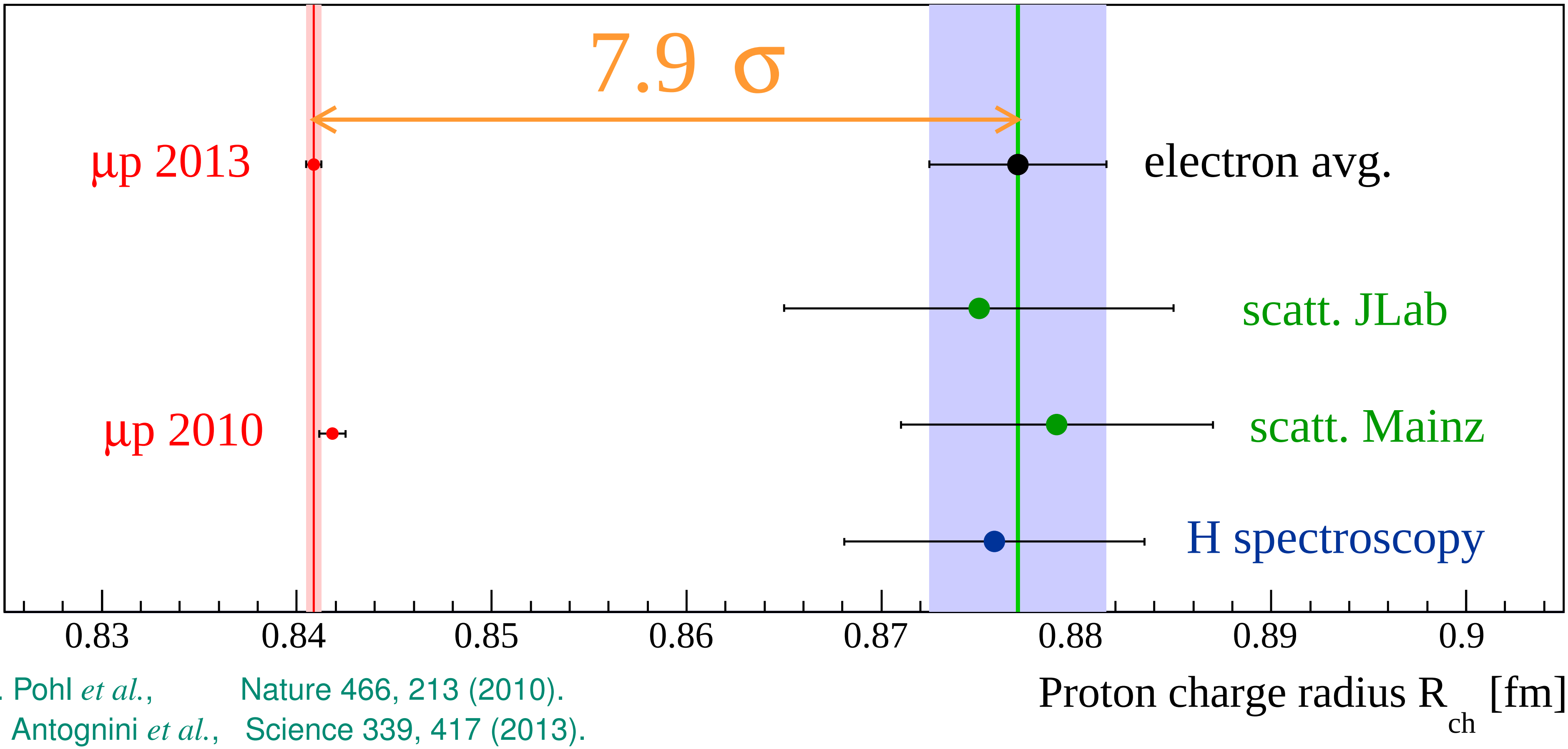
The proton radius puzzle.

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

muons: 0.8409 ± 0.0004 fm



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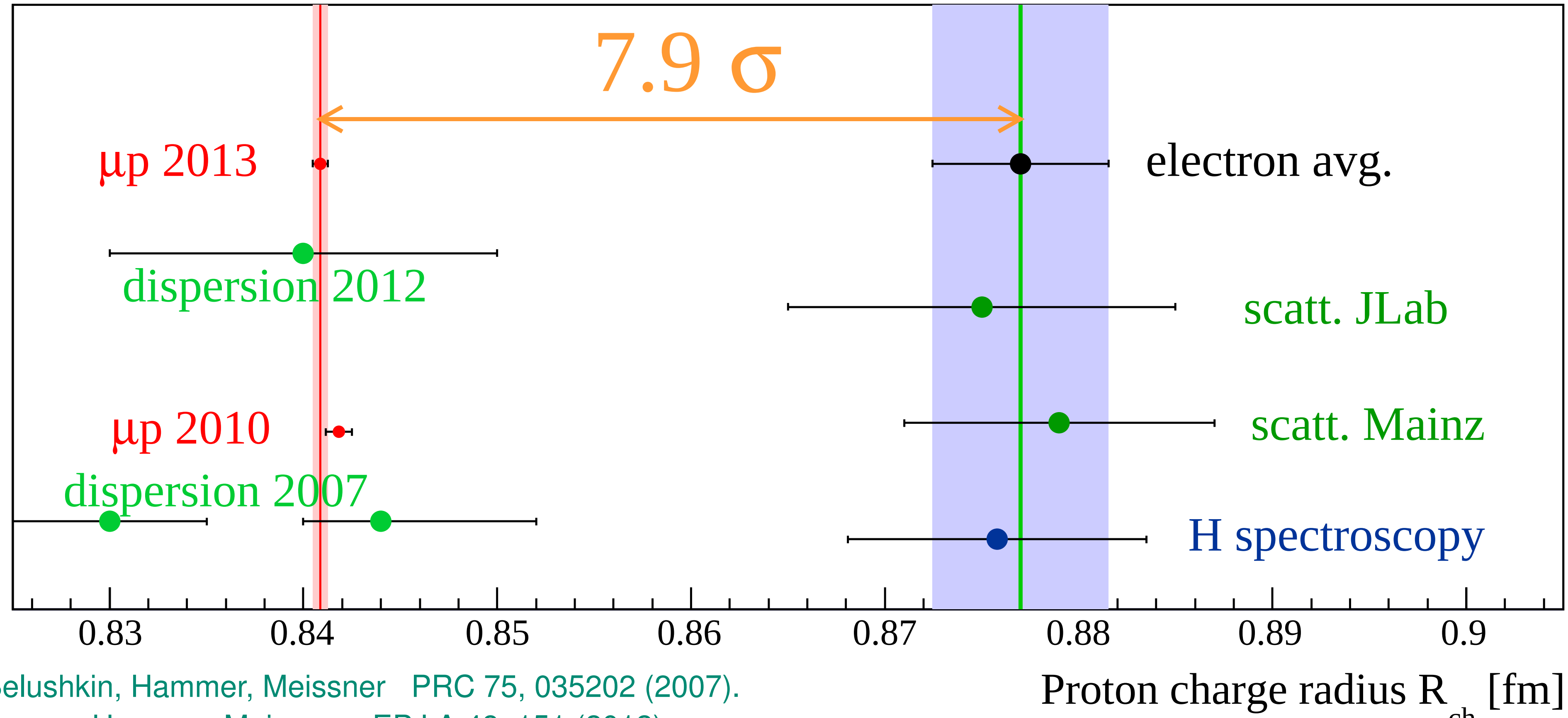

Belushkin, Hammer, Meissner PRC 75, 035202 (2007).

Lorenz, Hammer, Meissner EPJ A 48, 151 (2012).

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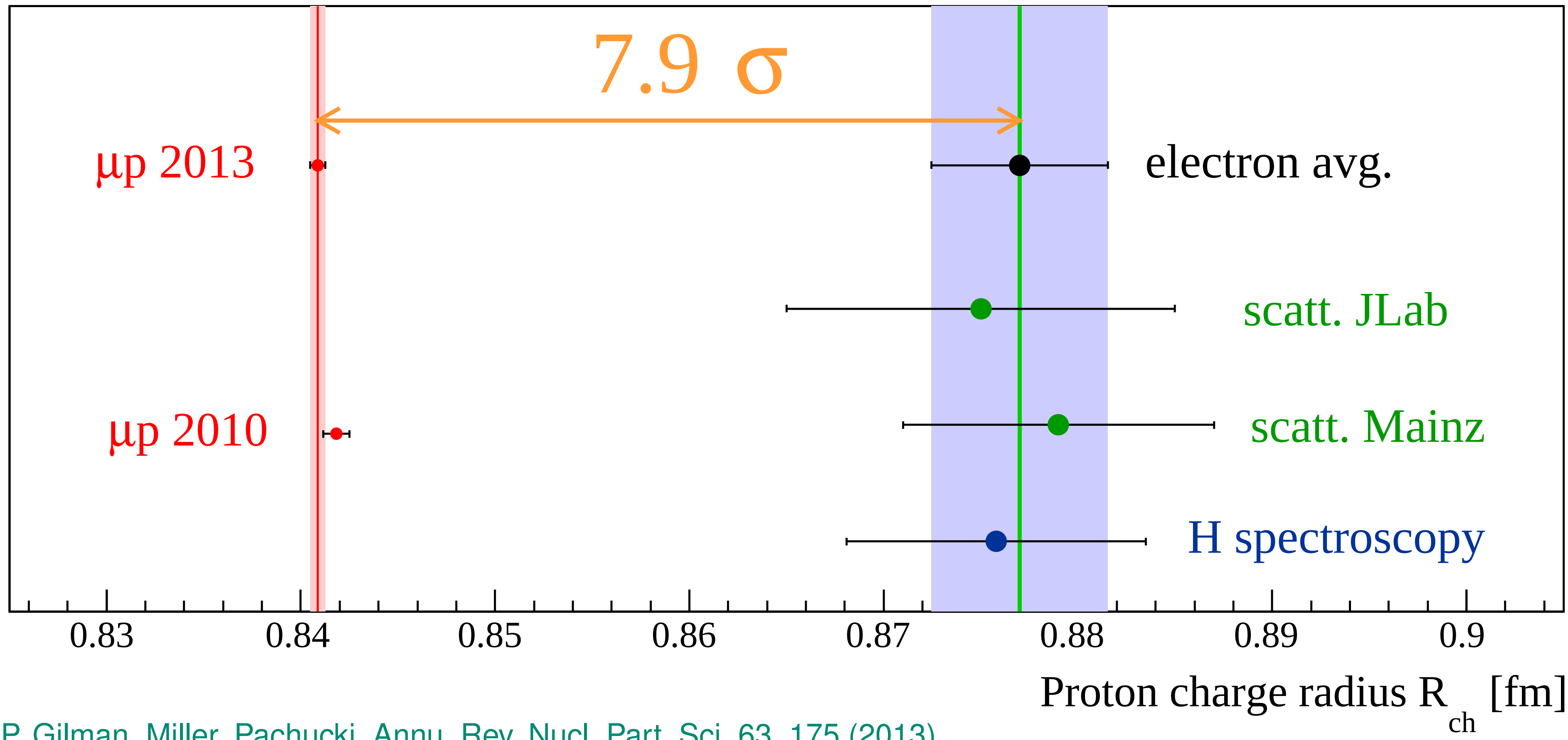

RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

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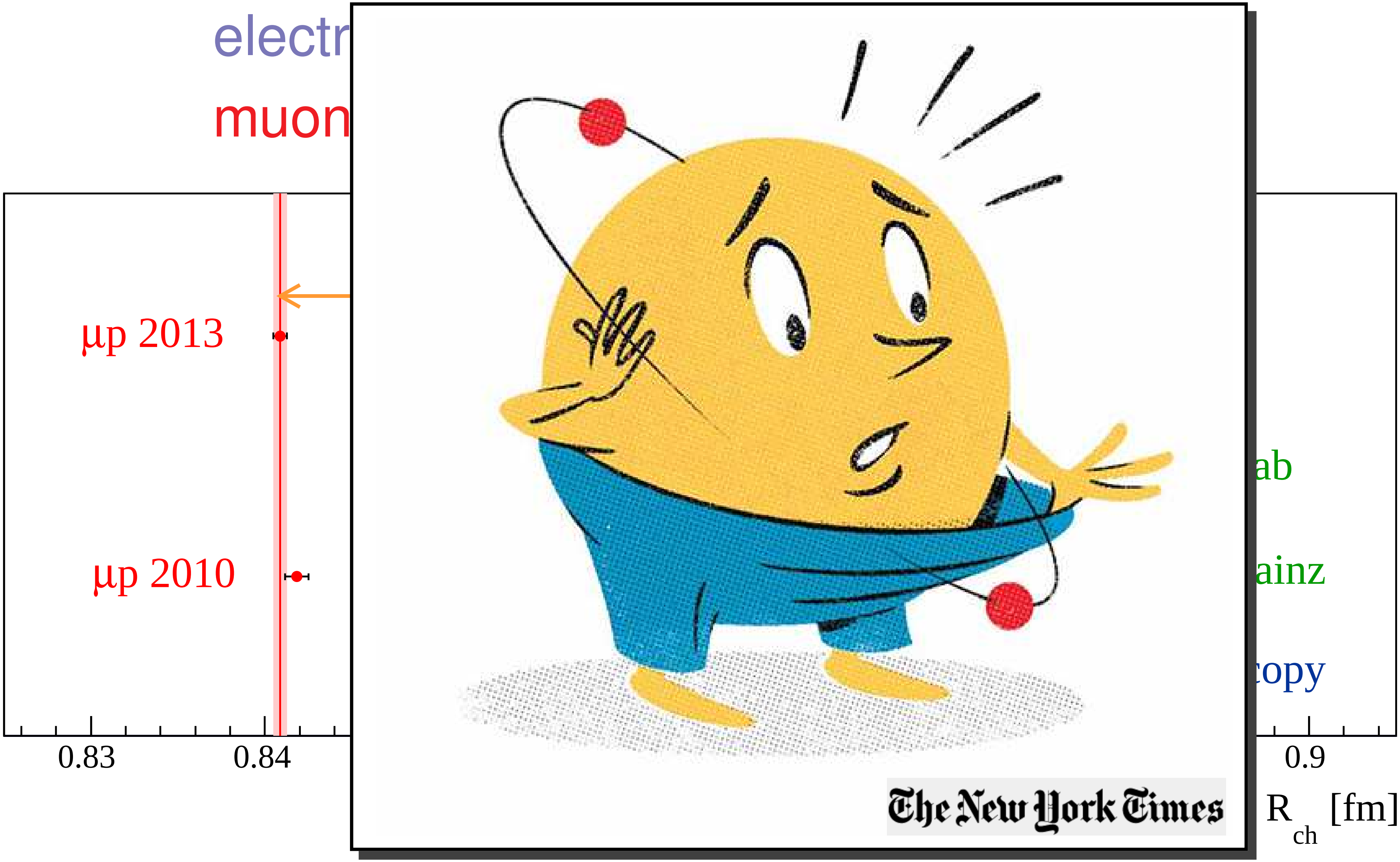
electr

muon



Muons in the news

Muons in the news

Muons in the news

Muons in the news

J. Bernauer, RP

Muons in the news

J. Bernauer, RP

ECT* Workshop

"The Proton Radius Puzzle", Trento, Italy, Oct. 28 - Nov. 2, 2012

G.A. Miller, R. Gilman, RP

47 theorists + experimentalists

- atomic physics
- electron scattering
- nuclear physics
- Beyond SM

38 talks

3 "fighting" sessions

$\Rightarrow$ no solution

voting: more data needed

RP, R. Gilman, G.A. Miller, K. Pachucki, "Muonic hydrogen and the proton radius puzzle",
Annu. Rev. Nucl. Part. Sci. **63**, 175 (2013)
(arXiv 1301.0905)

What may be wrong?

$$\widetilde{L}_{\mu p}^{\mathrm{theo.}}(r_{\mathrm{p}}^{\mathrm{CODATA}}) - \widetilde{L}_{\mu p}^{\mathrm{exp.}} = \begin{cases} 75\ \mathrm{GHz} \\ 0.31\ \mathrm{meV} \\ 0.15\ \% \end{cases}$$

μp theory wrong?

μp experiment wrong?

H theory wrong?

H experiments wrong? $\rightarrow R_\infty$ wrong?

AND e-p scattering exp. wrong?

Standard Model wrong?!?

RP, R. Gilman, G.A. Miller, K. Pachucki, "Muonic hydrogen and the proton radius puzzle", Annu. Rev. Nucl. Part. Sci. **63**, 175 (2013) (arXiv 1301.0905)

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μp theory

New measurements:

- Muonic hydrogen, deuterium, helium ions
- Hydrogen spectroscopy ⇒ Rydberg constant, r_{p}
- Helium ion ⇒ Rydberg constant, QED test
- Elastic electron scattering at lower Q^2, p, d, He
- Muon scattering: MUSE @ PSI

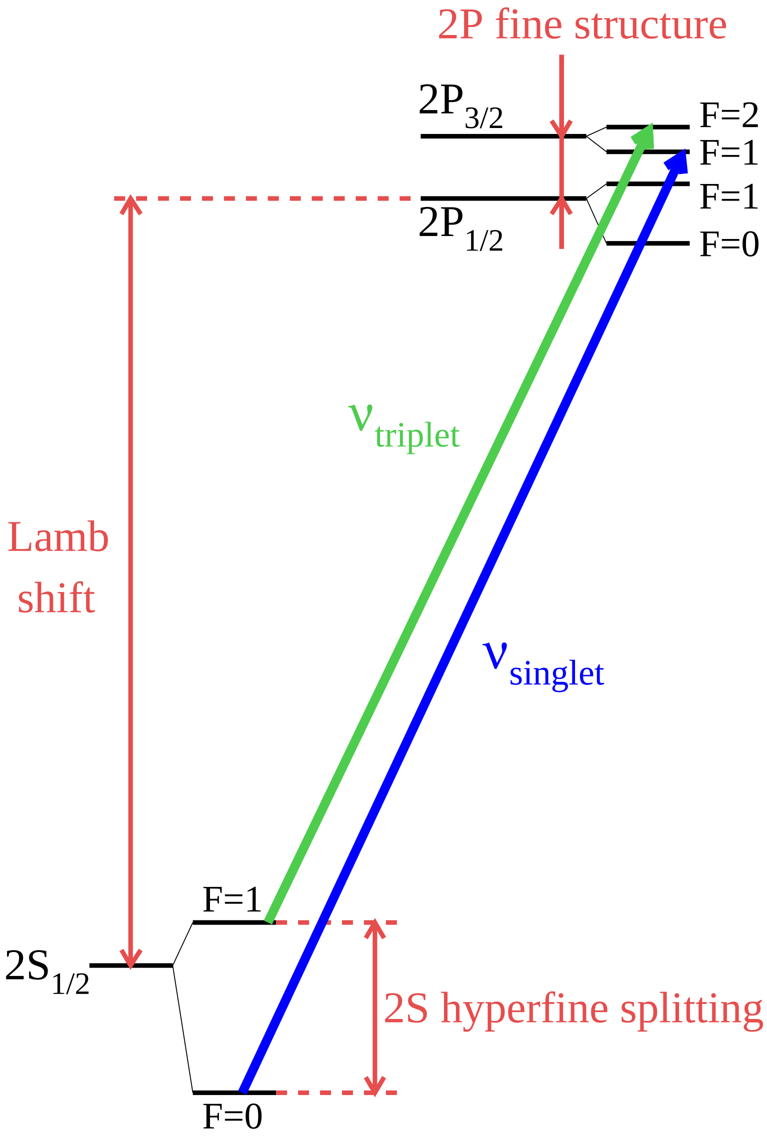
Theory:

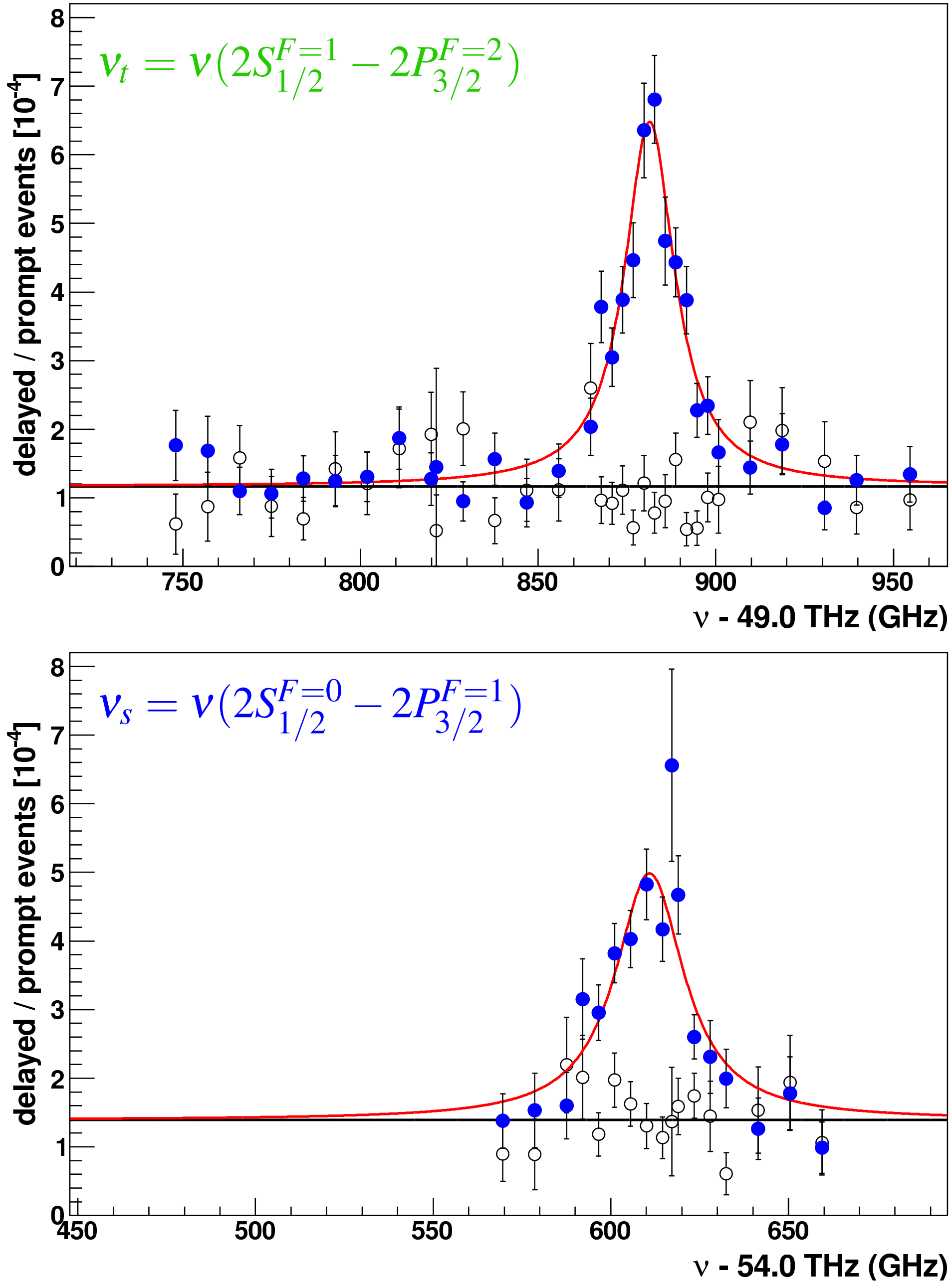
- QED in electronic and muonic atoms
- Nucl. structure effects: p, d, ^{3,4}He, ...
- Electron scattering
- Lattice
- ...

RP, R. Gilm
Annu. Rev. N

Muonic hydrogen

We have measured two transitions in μp





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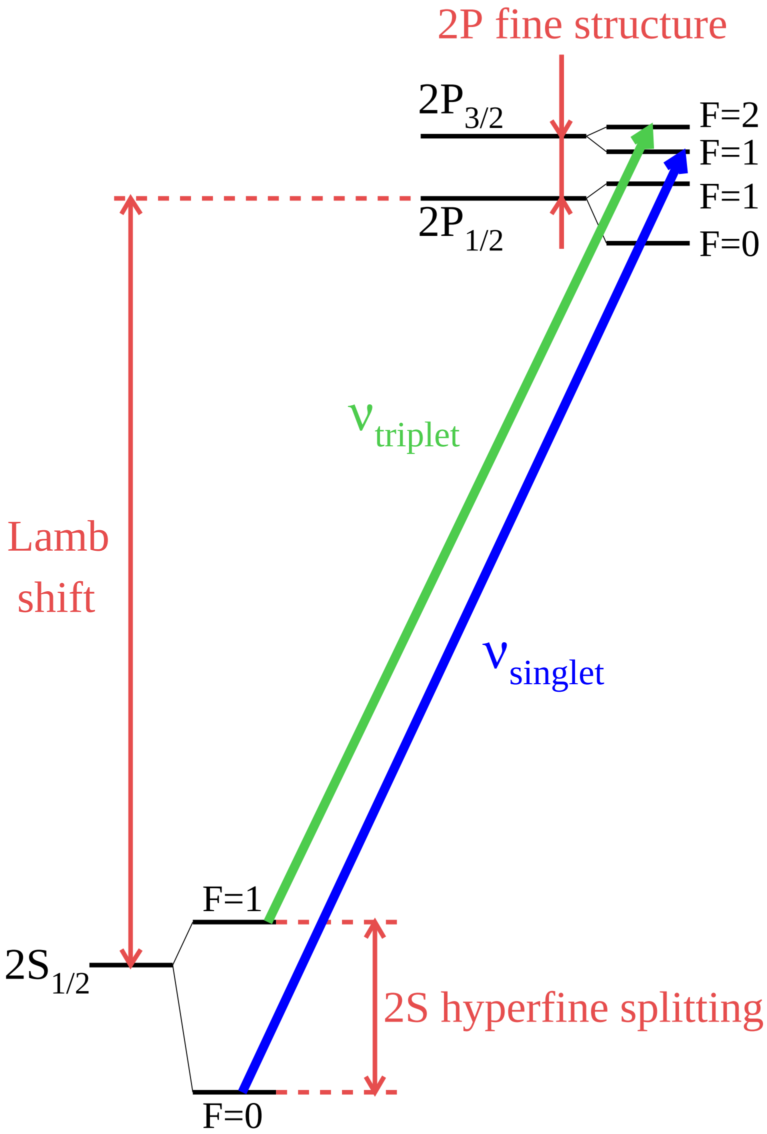

- Consider the two measurements **separately**

Two independent determinations of r_p

$(\nu_t \rightarrow r_p \ , \ \nu_s \rightarrow r_p)$

Consistent results!

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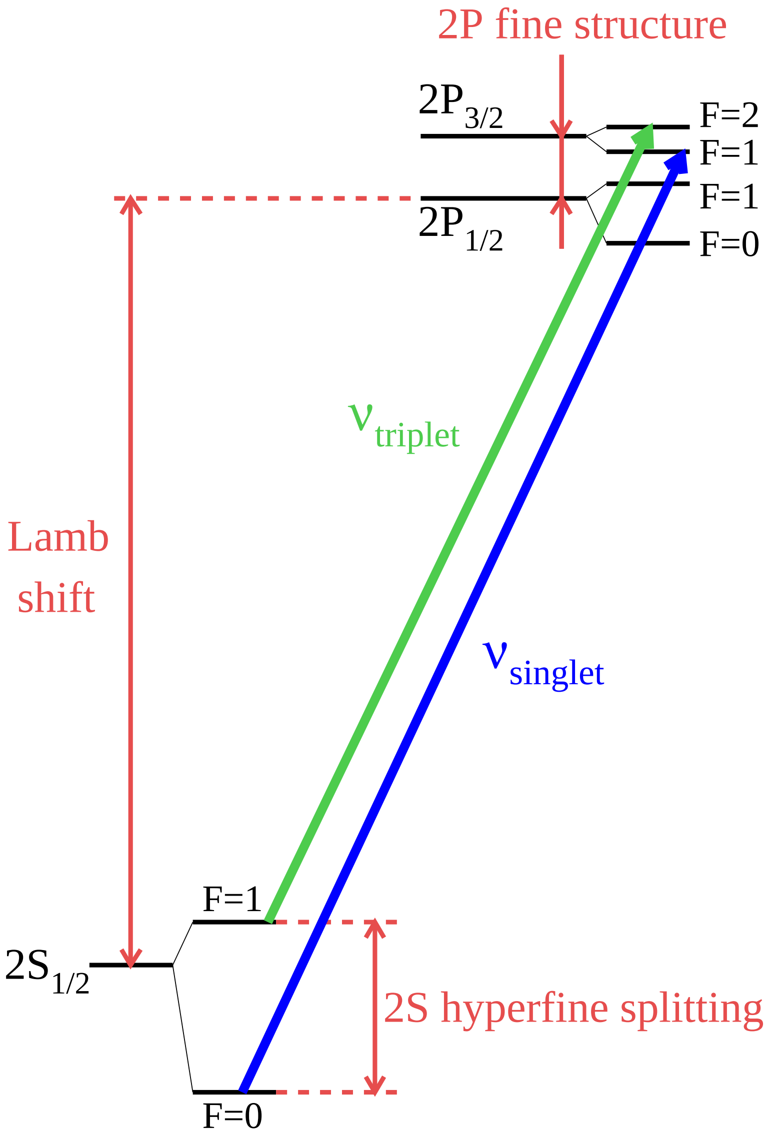


- <u>Consider the two measurements **separately**</u>

  Two independent determinations of r_p

  $(\nu_t \rightarrow r_\mathrm{p} \ , \ \nu_s \rightarrow r_\mathrm{p})$ **Consistent results!**

- <u>Combine the two measurements</u>

  Two measurements $\rightarrow$ determine two parameters

  $\nu_t, \nu_s \rightarrow \Delta E_\mathrm{L}, \Delta E_\mathrm{HFS} \rightarrow$ $r_\mathrm{p}, r_\mathrm{Z}$

$$\begin{aligned} \tfrac{3}{4}\nu_t + \tfrac{1}{4}\nu_s &= \Delta E_\mathrm{L}(r_\mathrm{p}) + 8.8123 \text{ meV} \\ \nu_s - \nu_t &= \Delta E_\mathrm{HFS}(r_\mathrm{Z}) - 3.2480 \text{ meV} \end{aligned}$$

Proton charge radius

$$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2}) = 49881.88(76)\,\text{GHz}$$ R. Pohl *et al.*, Nature 466, 213 (2010)

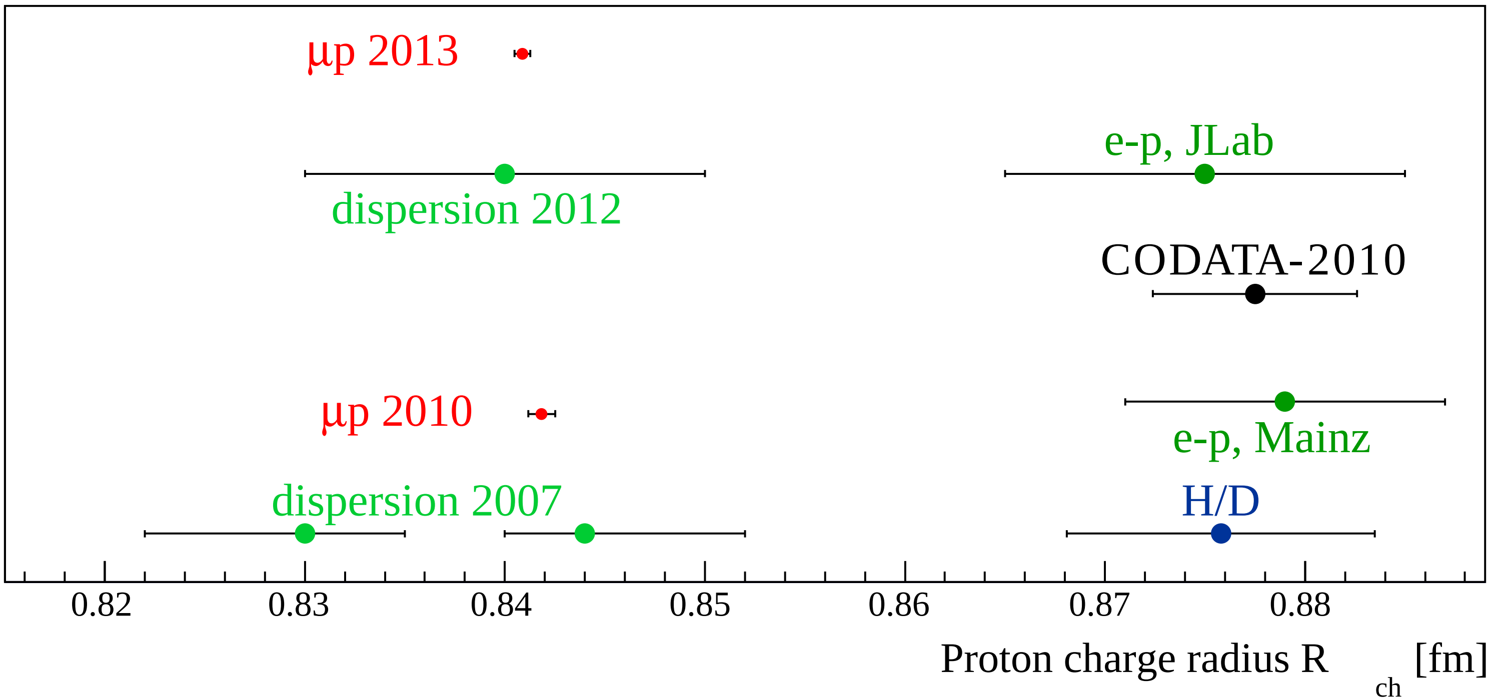
$$49881.35(65)\,\text{GHz}$$

$$\nu(2S_{1/2}^{F=0} \to 2P_{3/2}^{F=1}) = 54611.16(1.05)\,\text{GHz}$$

} A. Antognini, RP *et al.*, Science 339, 417 (2013)

Proton charge radius: $r_\mathrm{p} = 0.84087\ (26)_\mathrm{exp}\ (29)_\mathrm{th} = 0.84087\ (39)\ \mathrm{fm}$

μp theory summary: A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013) [arXiv :1208.2637 (atom-ph)]



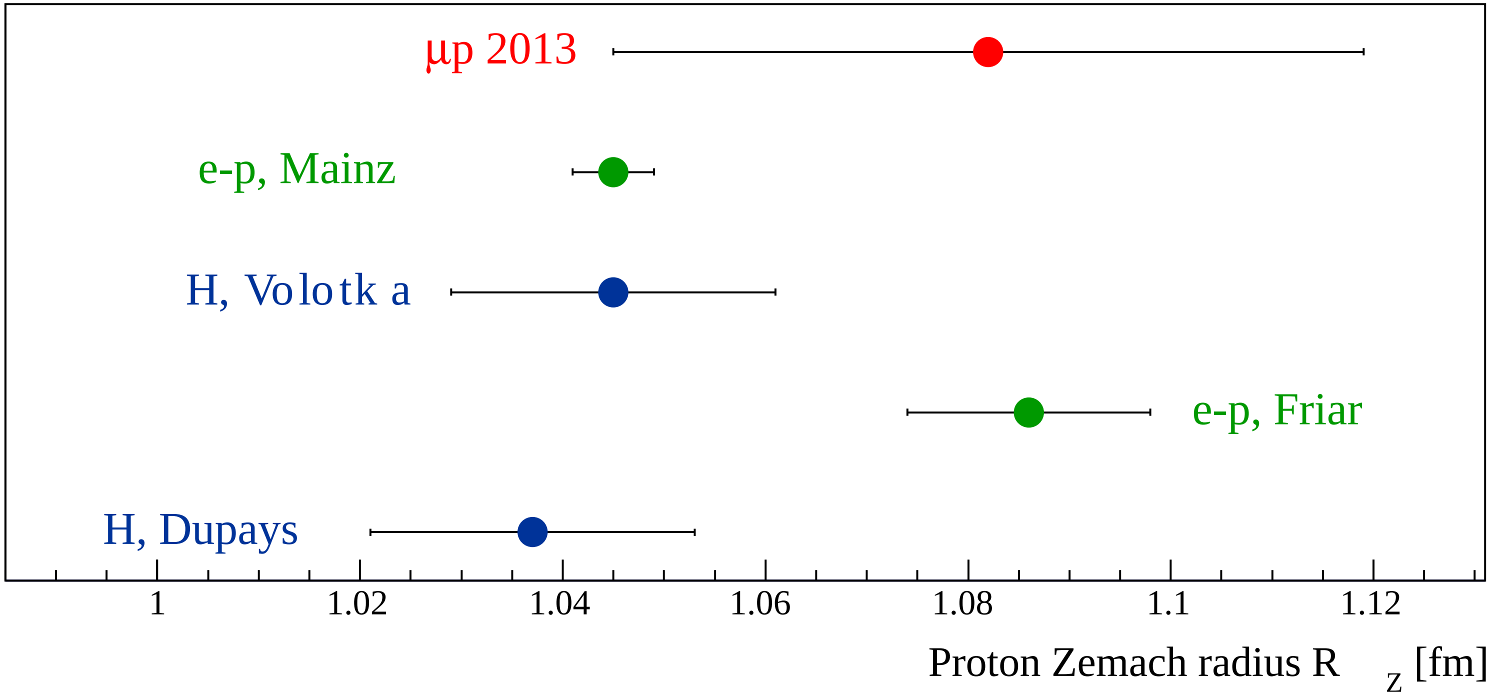
Proton Zemach radius

2S hyperfine splitting in μp is: $\Delta E_{\mathrm{HFS}} = 22.9843(30) - 0.1621(10)\, r_Z\ [\mathrm{fm}]$ meV

with $r_Z = \int d^3r \int d^3r'\ r\, \rho_E(r)\, \rho_M(r-r')$

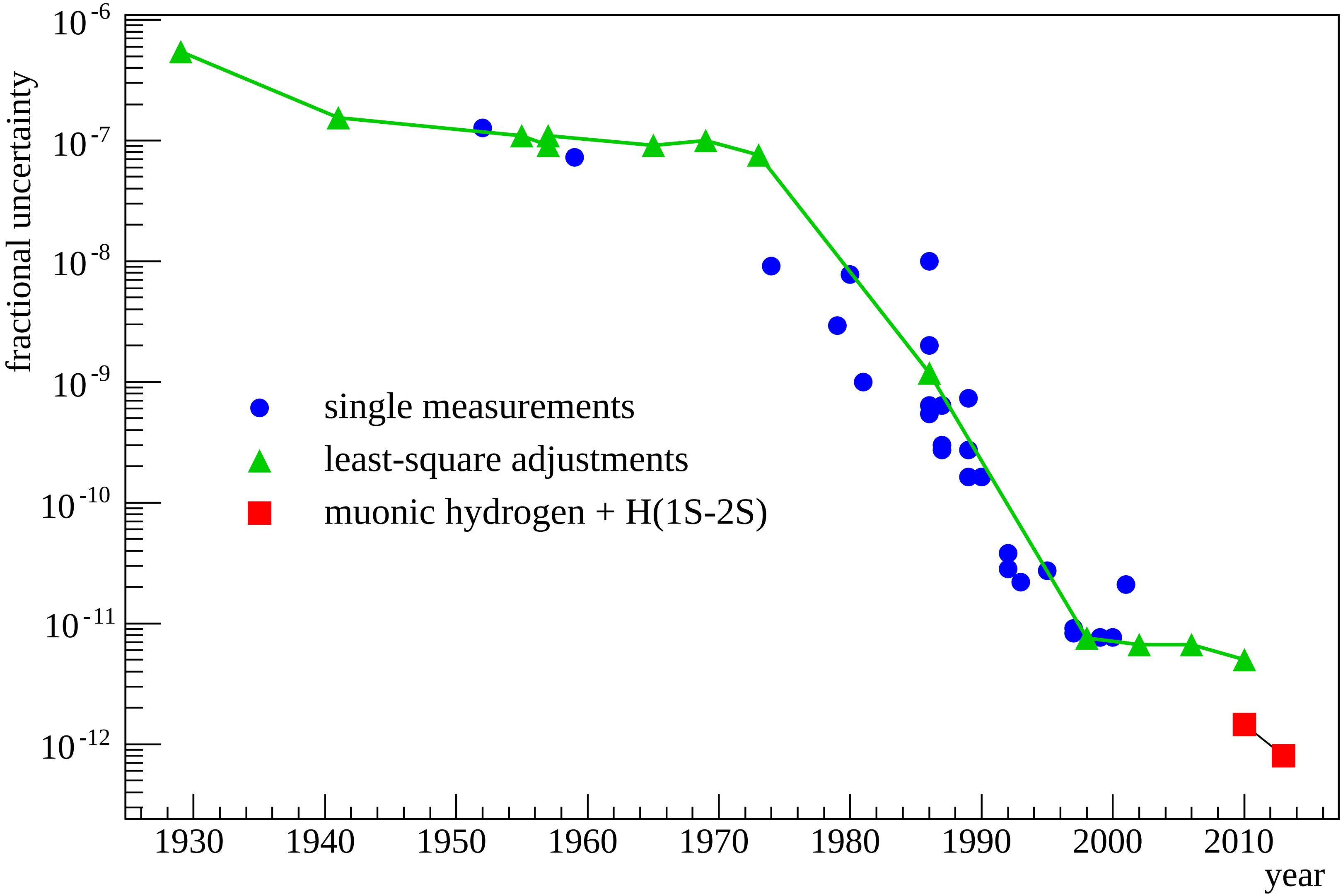
We measured $\Delta E_{\mathrm{HFS}} = 22.8089(51)$ meV

This gives a proton Zemach radius r_Z = 1.082 $(31)_{\mathrm{exp}}$ $(20)_{\mathrm{th}}$ = 1.082 (37) fm



A. Antognini, RP *et al.*, Science 339, 417 (2013)

Rydberg constant



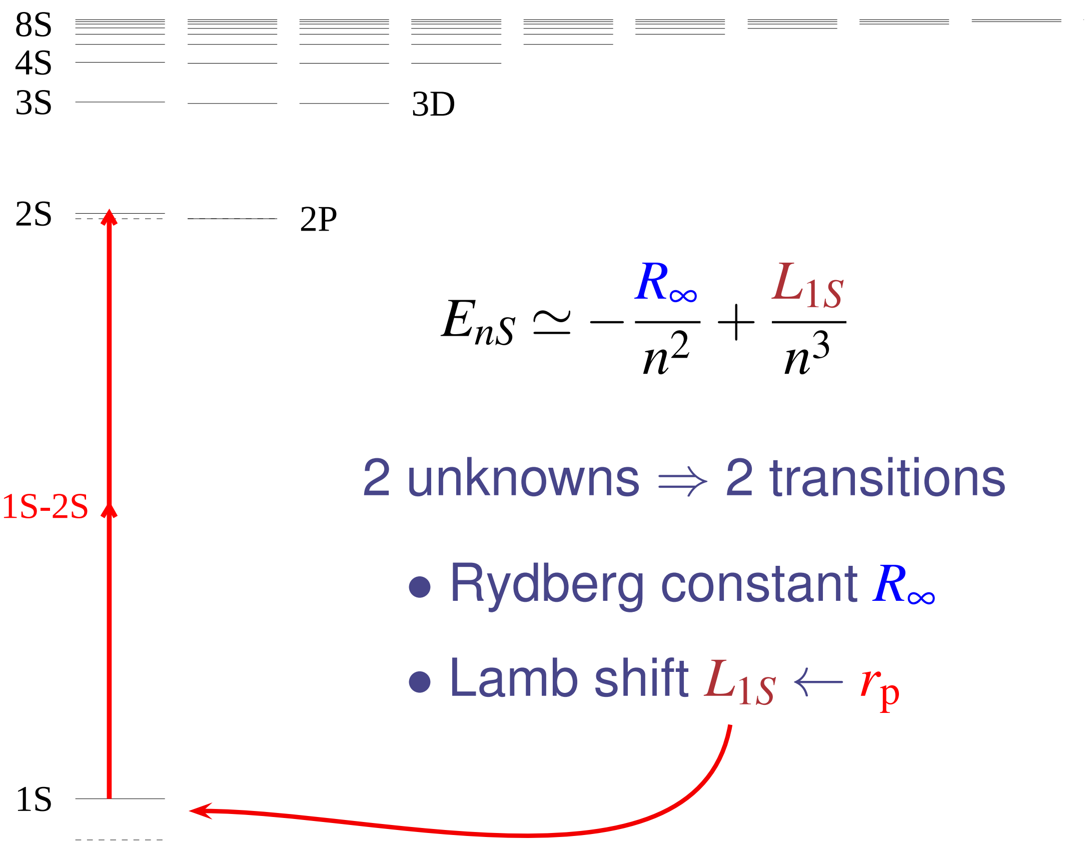
H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011).

r_p: A. Antognini, RP *et al.*, Science 339, 417 (2013).

Rydberg constant

Hydrogen spectroscopy (Lamb shift):

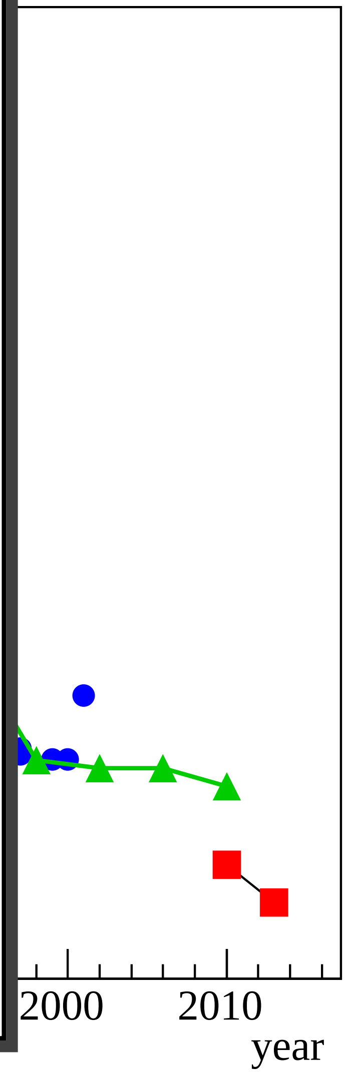
$$L_{1S}(r_p) = 8171.636(4) + 1.5645\,\langle r_p^2 \rangle \quad \text{MHz}$$



$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns ⇒ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$



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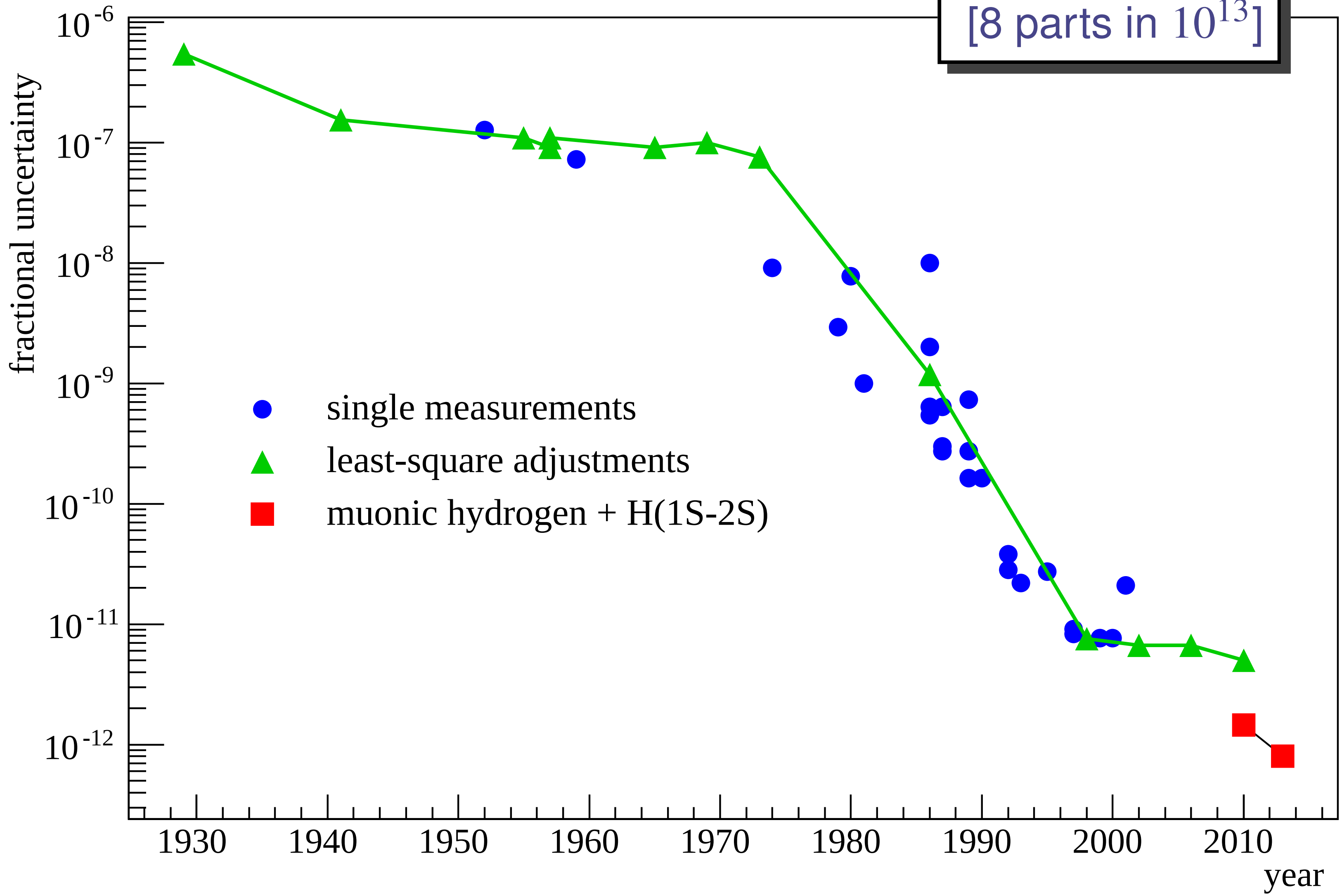
Rydberg constant

$$R_\infty = 3.289\,841\,960\,249\,5\,(10)^{r_p}\,(25)^{\mathrm{QED}} \times 10^{15}\ \mathrm{Hz/c}$$

[8 parts in 10^{13}]



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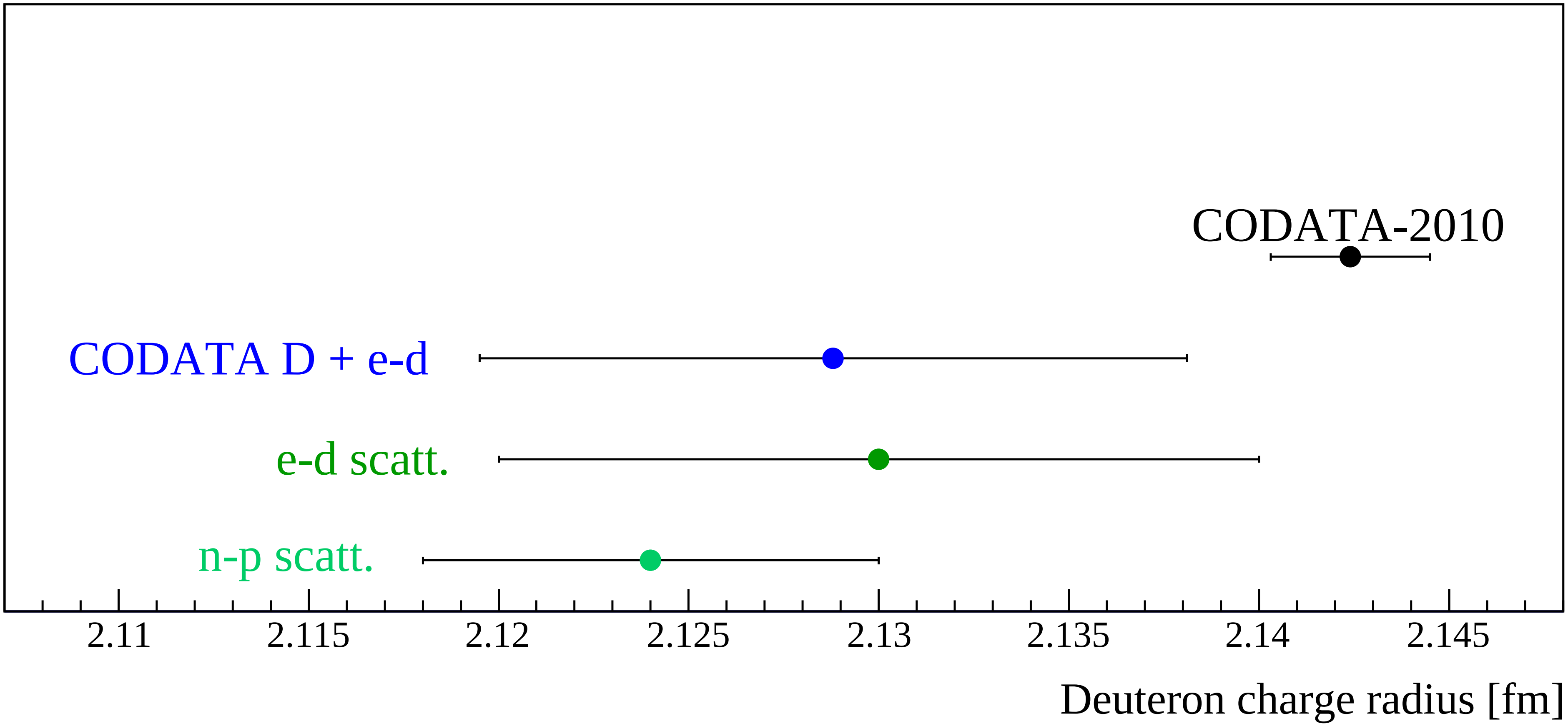
Deuteron charge radius

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

CODATA 2010 r_d = 2.1424(21) fm



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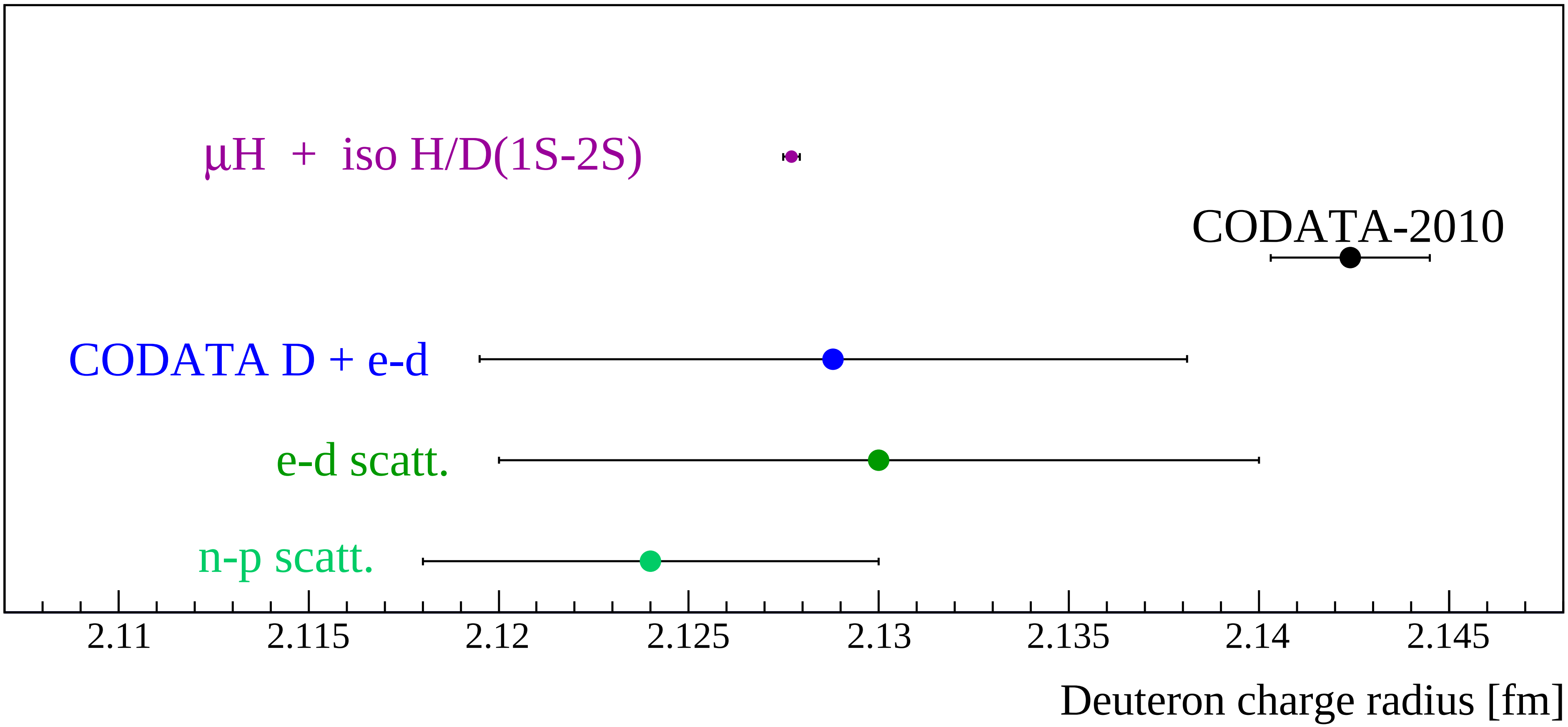
r_p= 0.84087(39) fm from μH gives r_d = 2.12771(22) fm



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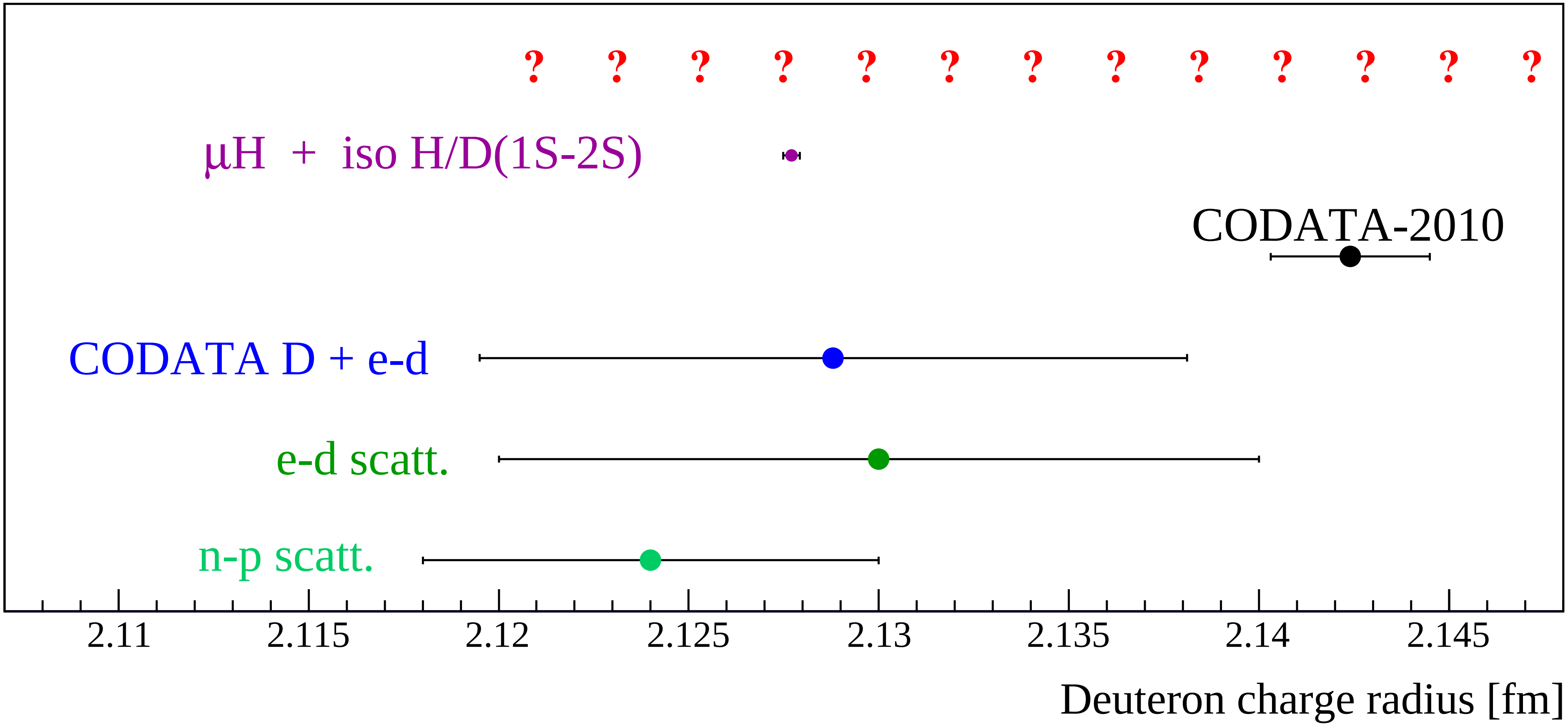
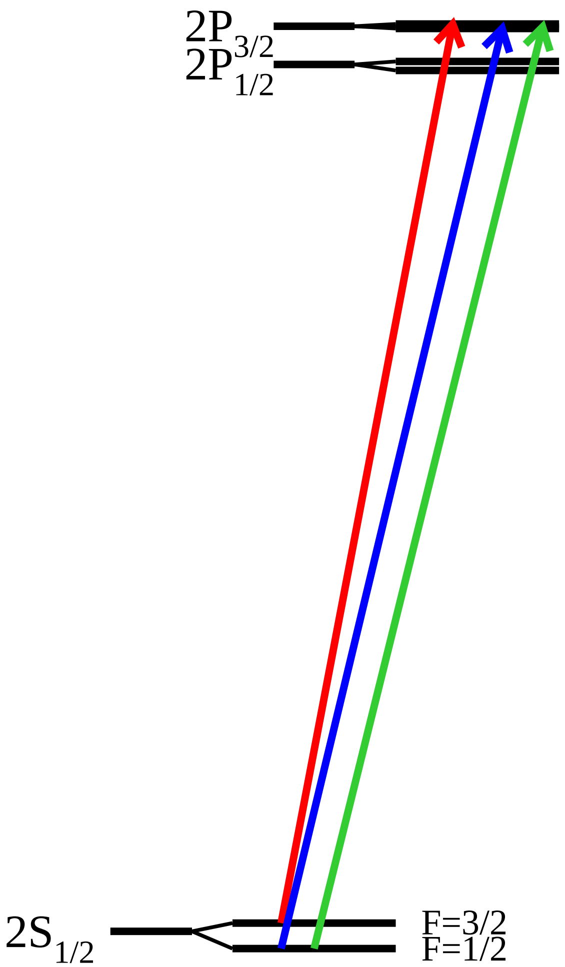
Lamb shift in muonic DEUTERIUM



Muonic deuterium

muonic deuterium



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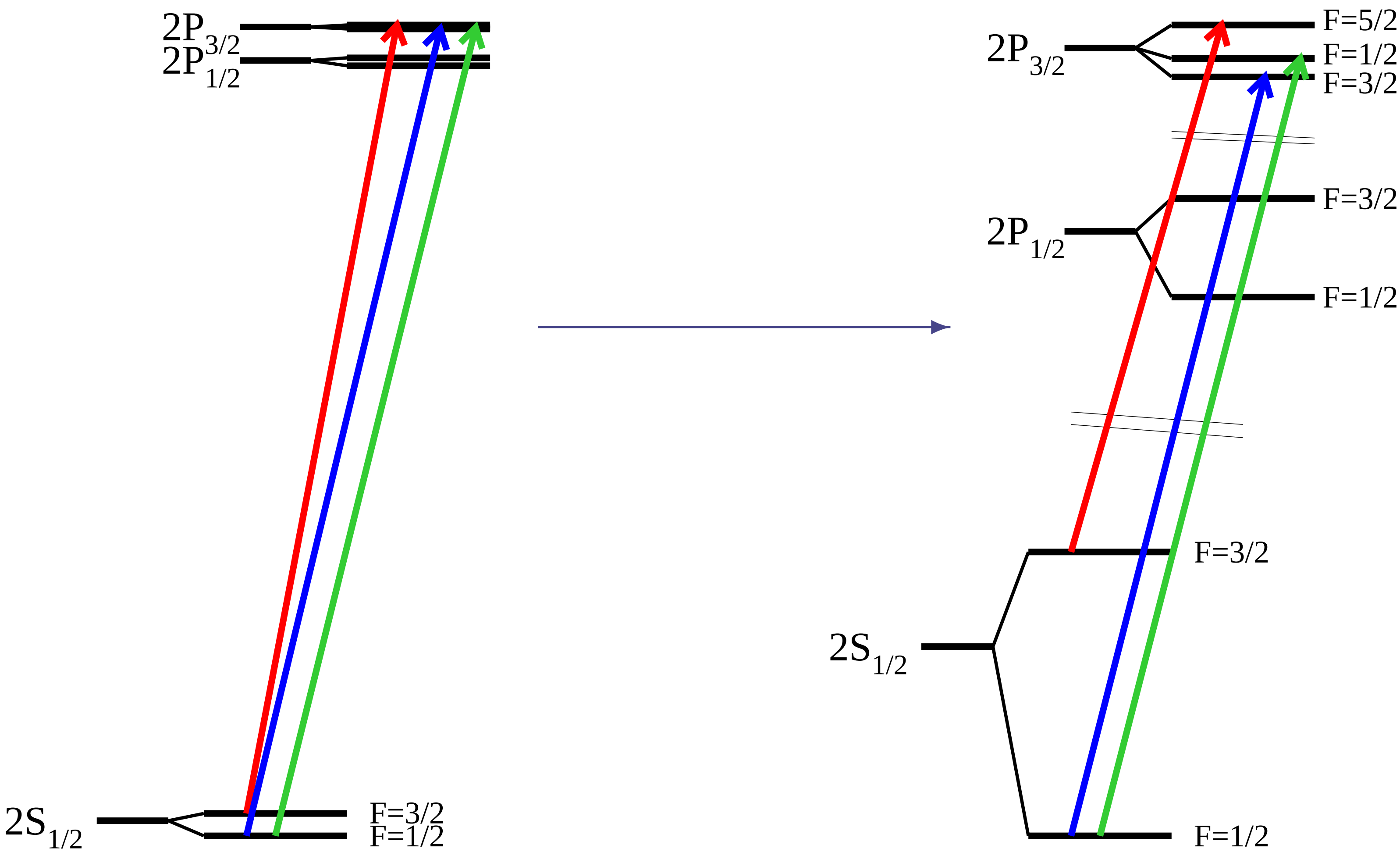
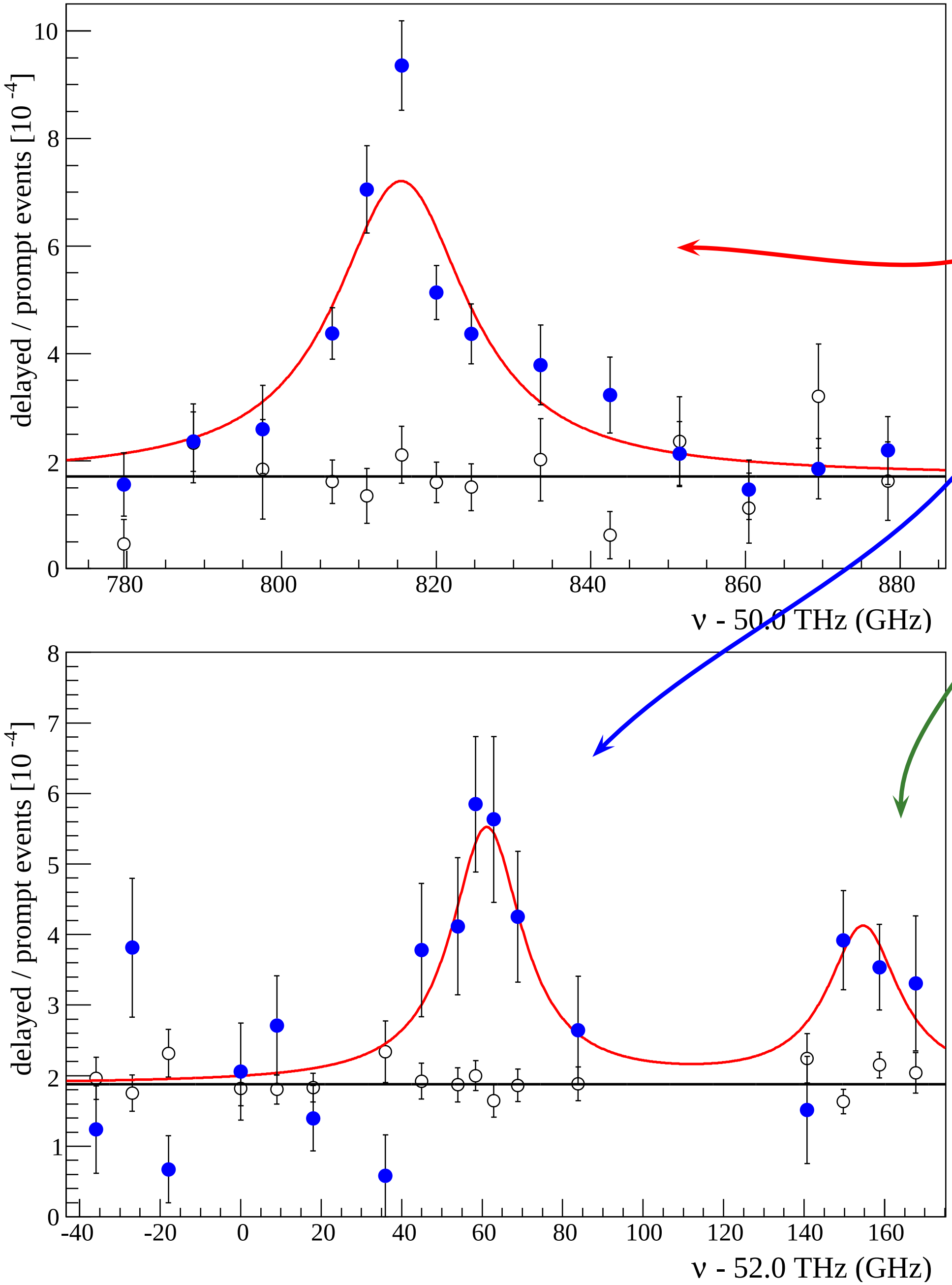
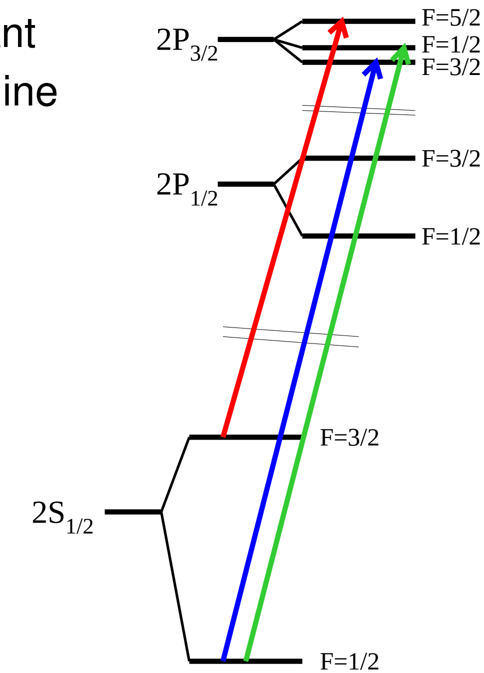


Muonic DEUTERIUM



2.5 resonances in muonic **deuterium**

- μd [$2S_{1/2}$(F=3/2) $\rightarrow$ $2P_{3/2}$(F=5/2)]
  20 ppm (stat., online)
- μd [$2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=3/2)]
  45 ppm (stat., online)
- μd [$2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=1/2)]
  70 ppm (stat., online)
  only 5σ significant
  identifies F=3/2 line



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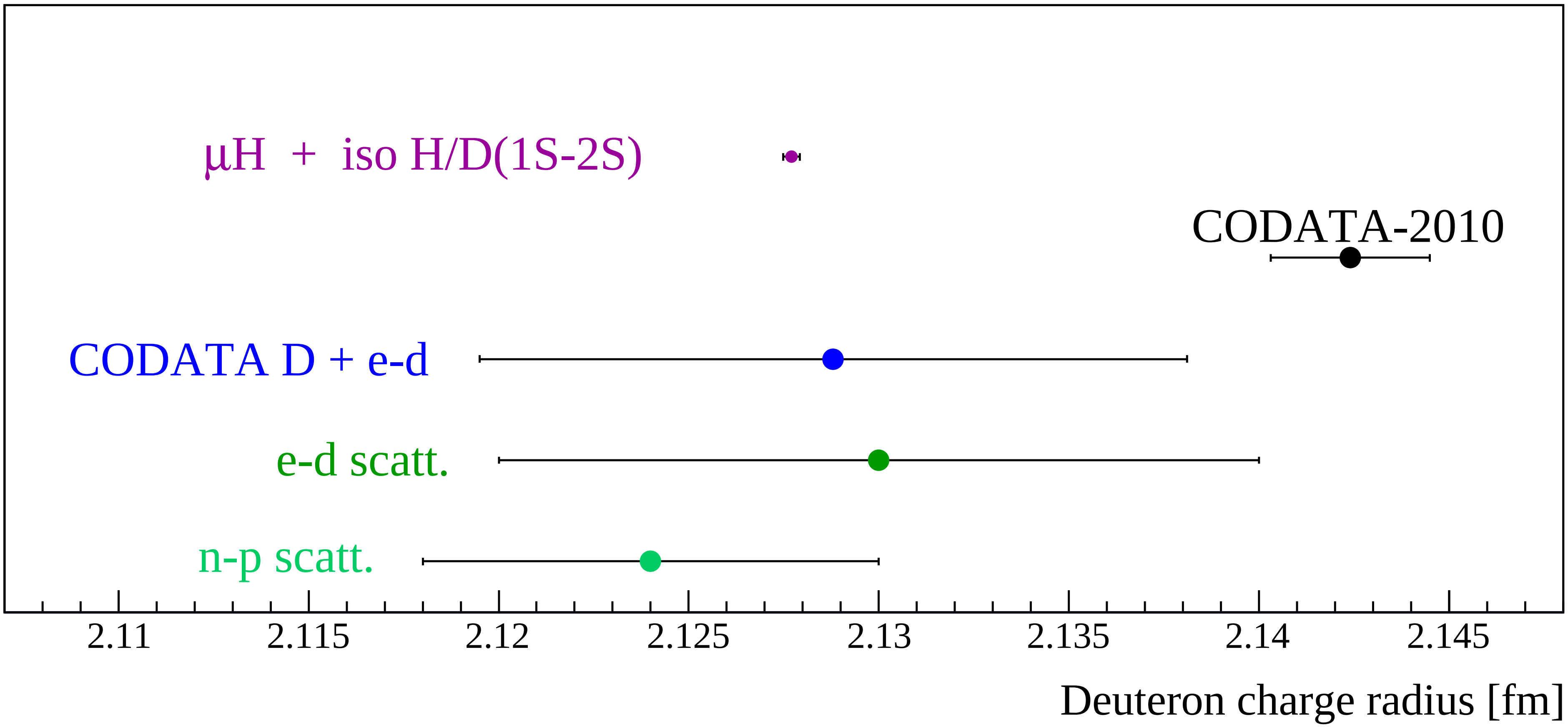

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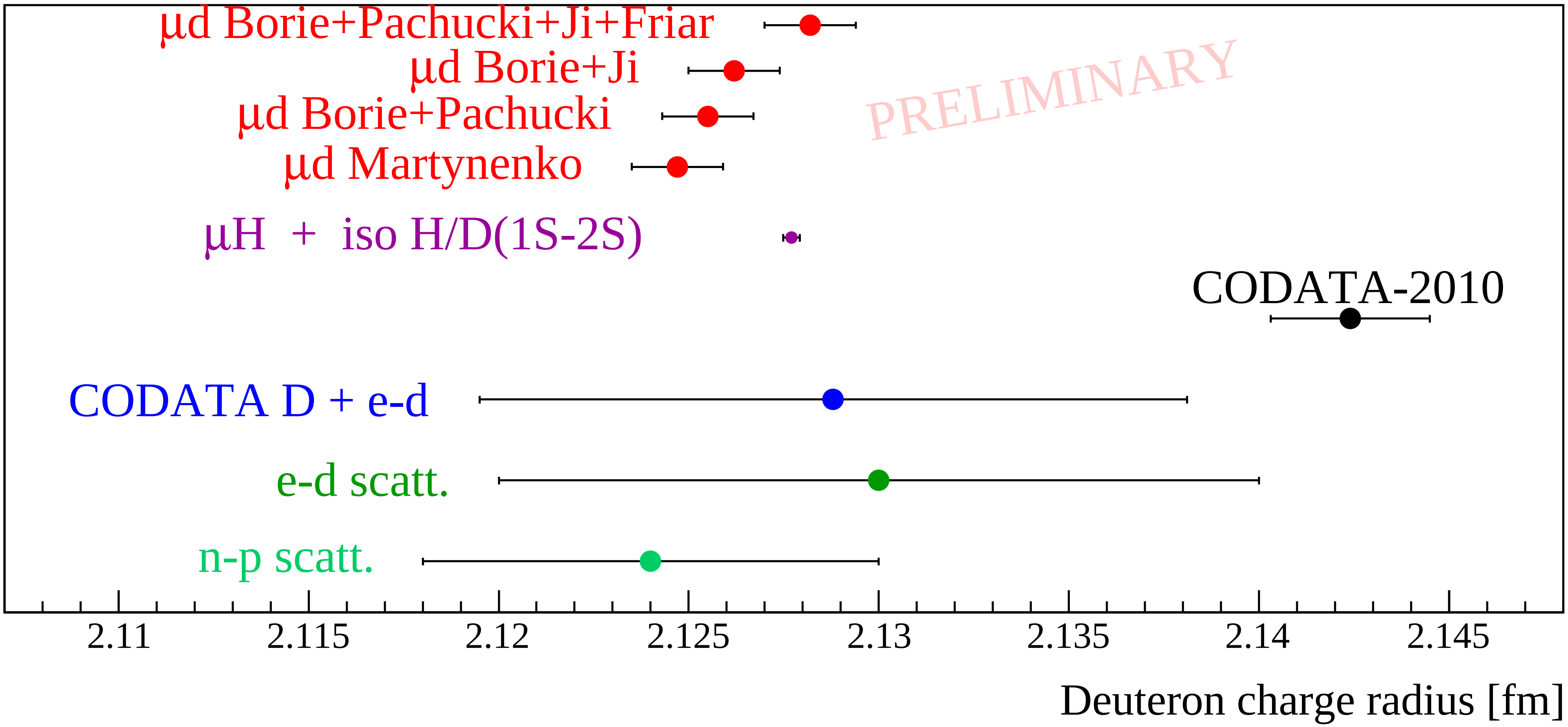
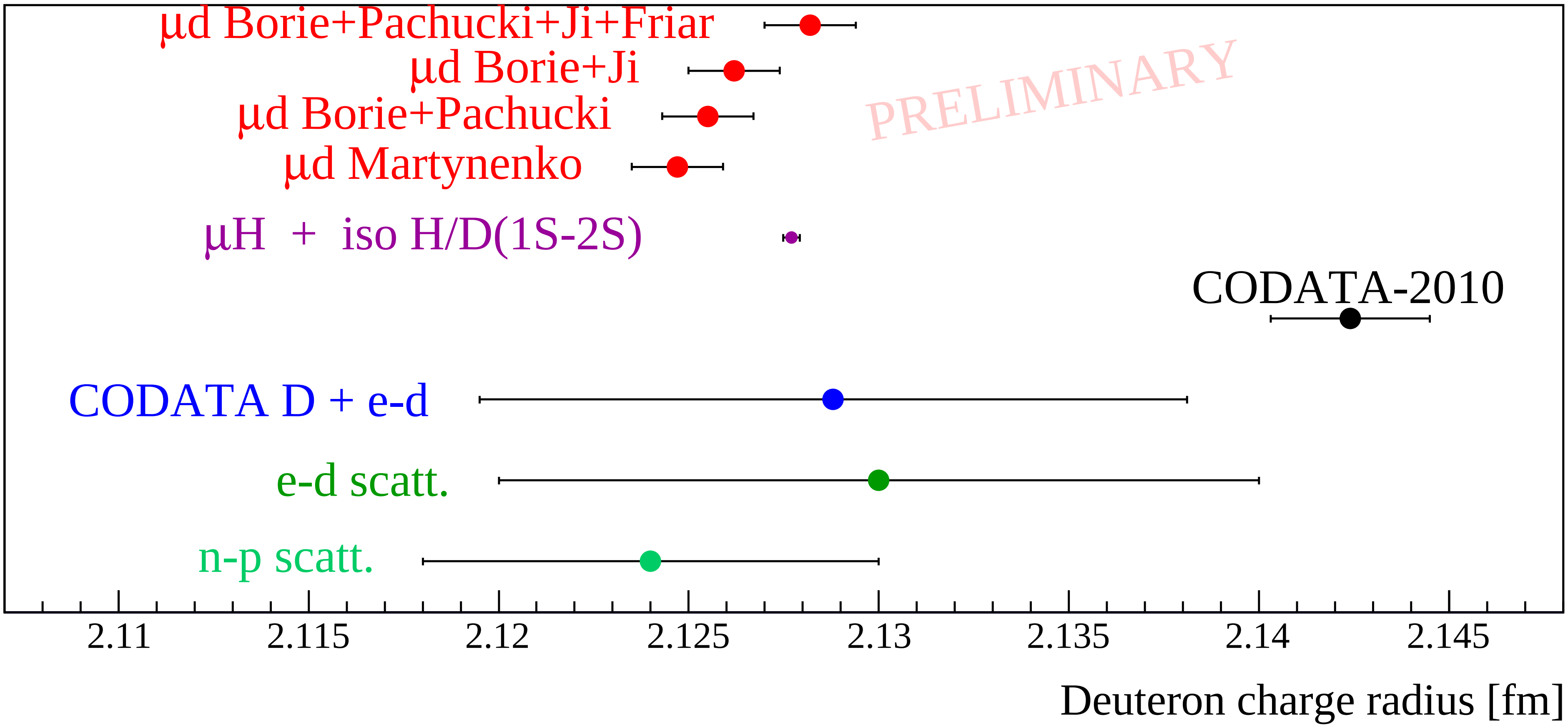
Lamb shift in muonic DEUTERIUM r_d = 2.1282(12) fm PRELIMINARY!



Deuteron charge radius

- μH and μD are **consistent!**

  (if BSM: no coupling to neutrons)
- WIP: deuteron polarizability (theory) complete? double-counting?
- WIP: shift from QM-interference



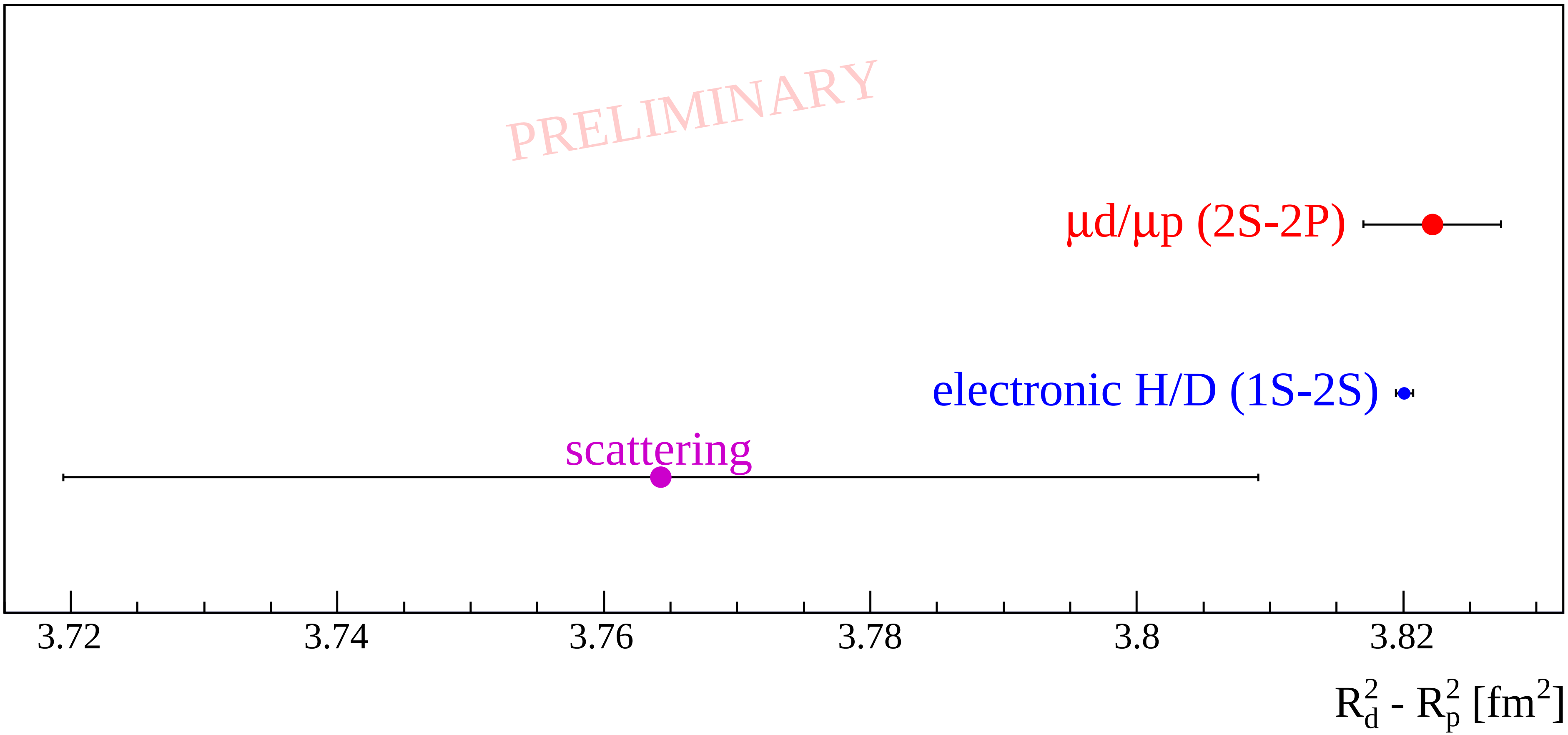
Proton-deuteron isotope shift

In other words: The muonic isotope shift agrees with the electronic one!

$r_d^2 - r_p^2$:

H/D isotope shift	$3.82007 \pm 0.00065\ \mathrm{fm}^2$		
muonic Lamb shift	$3.8221 \pm 0.0052\ \mathrm{fm}^2$	PRELIMINARY!	
scattering	$3.764 \pm 0.045\ \mathrm{fm}^2$		

The muonic error is conservative (nucl. structure terms).



Muonic helium.

Lamb shift in muonic helium

- CREMA collaboration: Charge Radius Experiment with Muonic Atoms
- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He
- ⇒ alpha particle and helion charge radius to 3×10^{-4} (± 0.0005 fm)

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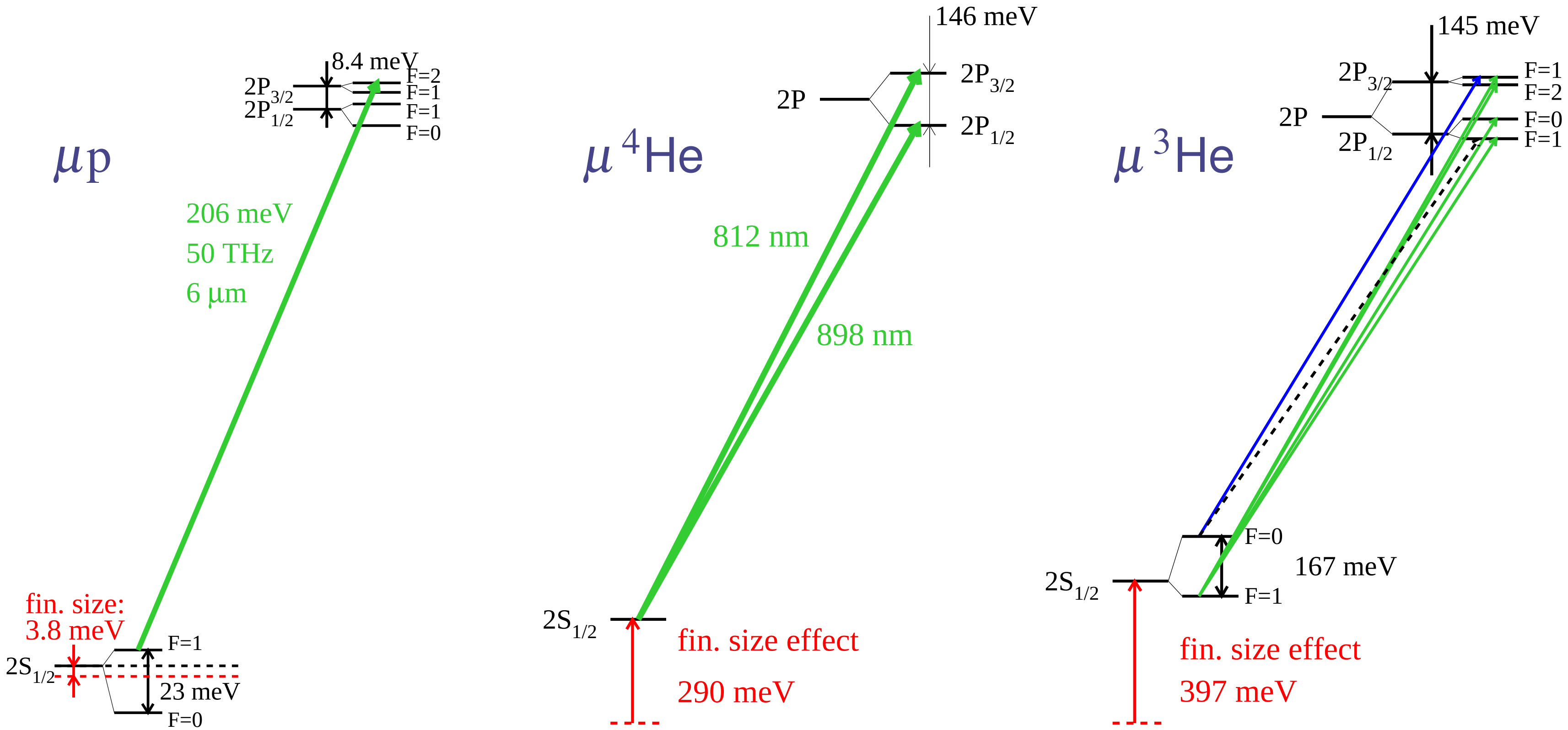

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- aims:
  - help to solve the proton size puzzle
  - absolute charge radii of helion, alpha
  - low-energy effective nuclear models: ^{1}H, ^{2}D, ^{3}He, ^{4}He
  - QED test with He$^+$(1S-2S) [Udem @ MPQ, Eikema @ Amsterdam]

Lamb shift in muonic helium

- CREMA collaboration: Charge Radius Experiment with Muonic Atoms
- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He
- ⇒ alpha particle and helion charge radius to 3×10^{-4}
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  - low-energy effective nuclear models: ^{1}H, ^{2}D, ^{3}He, ^{4}He
  - QED test with He$^+$(1S-2S) [Udem @ MPQ, Eikema @ Amsterdam]

- ^{4}He beam time: Oct.-Dec. 2013
- ^{3}He beam time: May-Aug. 2014

- Talk by Aldo Antognini, tomorrow morning!

Future muonic experiments

- Z=1:
  - Muonic hydrogen: HFS
  - Muonic deuterium: Lamb shift, HFS
  - Muonic tritium
- Z=2:
  - Muonic ^{4}He: Fine structure
  - Muonic ^{3}He: Lamb shift, fine and hyperfine structure
- Z=3, 4, 5:

Lamb shift:	absolute charge radius
	nuclear polarizability
2S-HFS:	Zemach / magnetic radius
	nuclear polarizability

PHYSICAL REVIEW A VOLUME 32, NUMBER 2 AUGUST 1985

Lamb shifts and fine-structure splittings for the muonic ions μ^--Li, μ^--Be, and μ^--B: A proposed experiment

G. W. F. Drake and Louis L. Byer*
Department of Physics, University of Windsor, Windsor, Ontario, Canada N9B 3P4

(Received 28 February 1985)

Detailed calculations are presented for the energy splittings of the states $2s_{1/2}$-$2p_{1/2}$ and $2s_{1/2}$-$2p_{3/2}$ for the muonic ions μ^--Li, μ^--Be, and μ^--B obtained by numerical integration of the Dirac equation. It is shown that there is severe cancellation between the vacuum polarization and finite nuclear size contributions to the energy differences, leading to transition frequencies which lie in the visible region of the spectrum. As a consequence of the cancellation, a measurement of the transition frequency would provide a sensitive probe of nuclear size and structure. The system μ^--^{7}Li appears to offer particularly good possibilities for performing such an experiment.

Future muonic experiments

- Z=1:
  - Muonic hydrogen: HFS
  - Muonic deuterium: Lamb shift, HFS
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- Z=3, 4, 5:

Lamb shift:	absolute charge radius
	nuclear polarizability
2S-HFS:	Zemach / magnetic radius
	nuclear polarizability

TABLE VII. Calculated absorption wavelengths (in Å) for transitions in muonic ions. The first uncertainty listed for the wavelengths is that due to nuclear polarization and the second is that due to the rms nuclear radius R.

Ion	R (fm)	$\lambda(2s_{1/2}\text{-}2p_{1/2})$	$\lambda(2s_{1/2}\text{-}2p_{3/2})$
^{4}He	1.674±0.012	8978.0± 4±27	8118.0± 3±22
^{6}Li	2.56 ±0.05	10 097.0± 33±1072	6275.0± 13±414
^{7}Li	2.39 ±0.03	7473.0± 18±334	5147.0± 9±159
^{9}Be	2.520±0.012	−9520.0±116±703	11 512.0±173±1048
^{10}B	2.45 ±0.12	−1393.0± 3±354	−4033.0± 27±2947
^{11}B	2.42 ±0.12	−1481.0± 4±397	−4887.0± 46±4286

Drake, Byer, PRA 32, 713 (1985)

Future muonic experiments

Lamb shift:	absolute charge radius
	nuclear polarizability
2S-HFS:	Zemach / magnetic radius
	nuclear polarizability

- Z=1:
  - Muonic hydrogen: HFS
  - Muonic deuterium: Lamb shift, HFS
  - Muonic tritium
- Z=2:
  - Muonic ^{4}He: Fine structure
  - Muonic ^{3}He: Lamb shift, fine and hyperfine structure
- Z=3, 4, 5:
  - (Electronic) isotope shifts have been measured very accurately.
    $\Rightarrow$ (squared) charge radius **differences** are very well known.
  - Muonic Lamb shifts provide **absolute** charge radii.
  - Test of few-electron (QED) calculations.
  - *Ab initio* nuclear structure calculations.
- Also: 1S-2S in (electronic) tritium. "Missing link" at A=3

Summary

- Muonic hydrogen gives:
  - Proton charge radius: r_p= 0.84087 (39) fm
  - Proton Zemach radius: R_Z = 1.082 (37) fm
  - Rydberg constant:

    $$R_\infty = 3.289\,841\,960\,249\,5\;(10)^{\text{radius}}\;(25)^{\text{QED}}\;\times 10^{15}\;\text{Hz/c}$$
  - Deuteron charge radius: r_d = 2.12771 (22) fm from μH + H/D(1S-2S)
  - The “Proton radius puzzle”
- muonic deuterium: r_d = 2.1289(12) fm from μD (PRELIMINARY!)

  Lamb shift in muD is ok.
  2S-HFS is missing a large (polarizability) term!
- Proton radius puzzle persists. New data needed!
  - muonic helium
  - hydrogen
  - ...

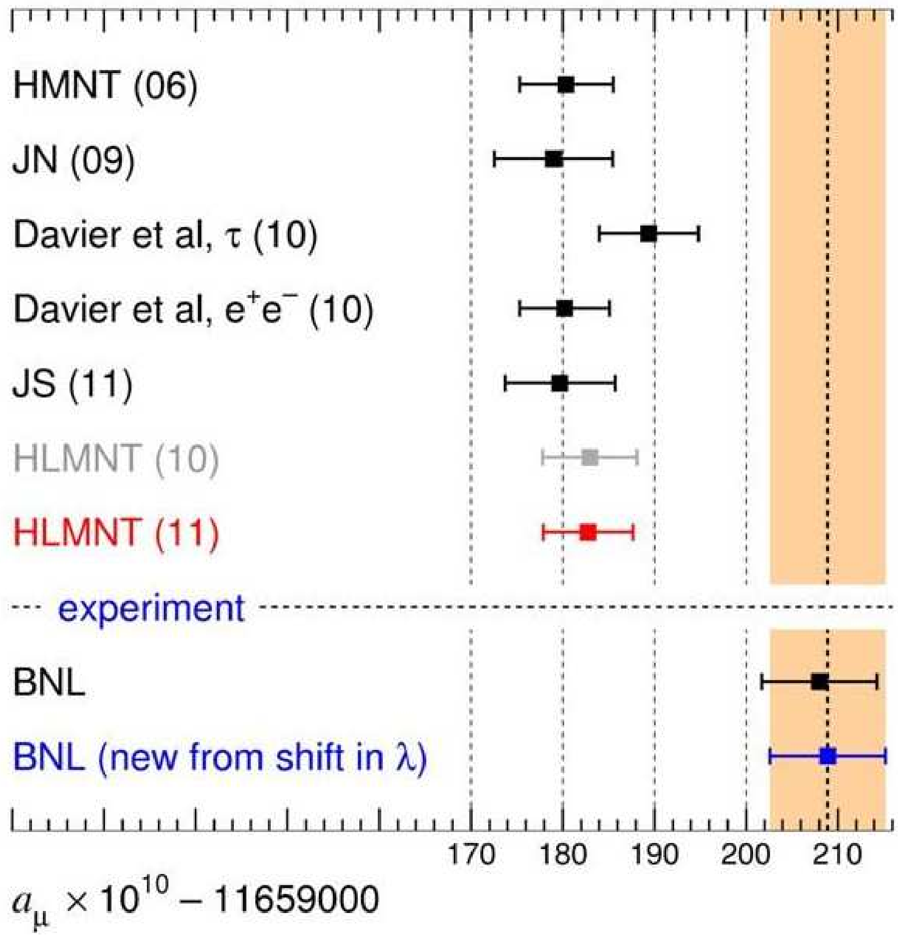
Two muon puzzles

- **Anomalous magnetic moment** of the muon

The measured value of $a_\mu = (g-2)/2$ of the muon has been in disagreement with the SM predictions for

>10 years now!

The discrepancy stands at $\sim 3.6\sigma$



J. Phys. G 38, 085003 (2011).

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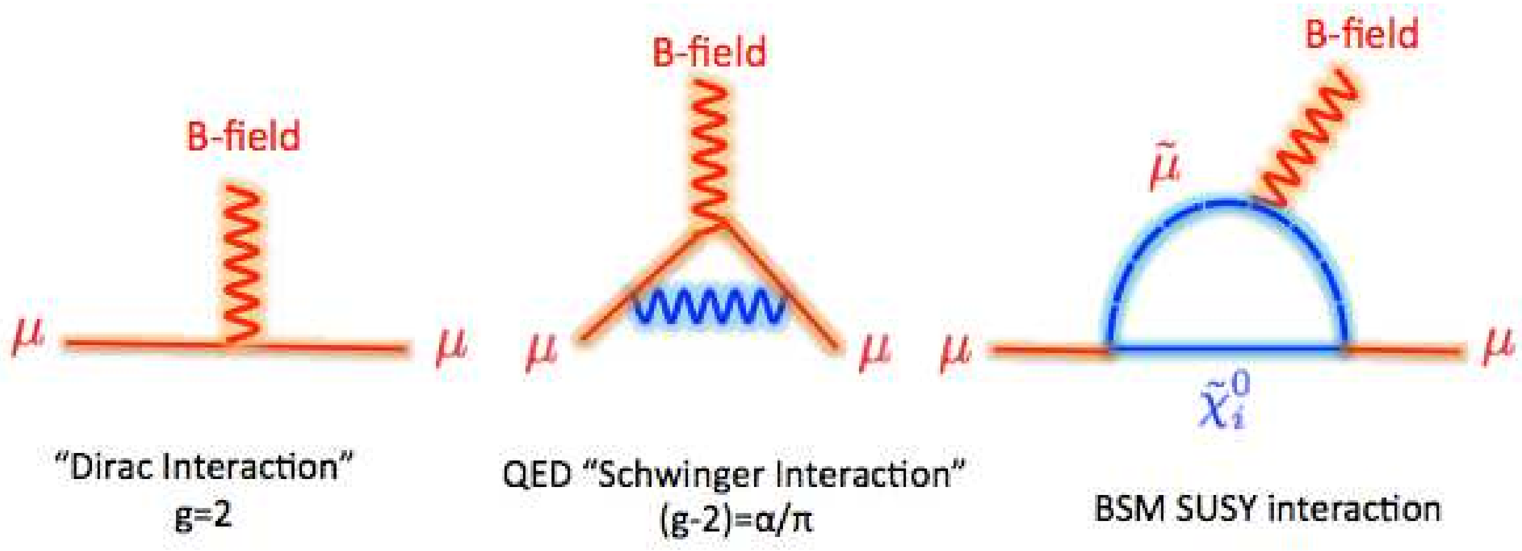
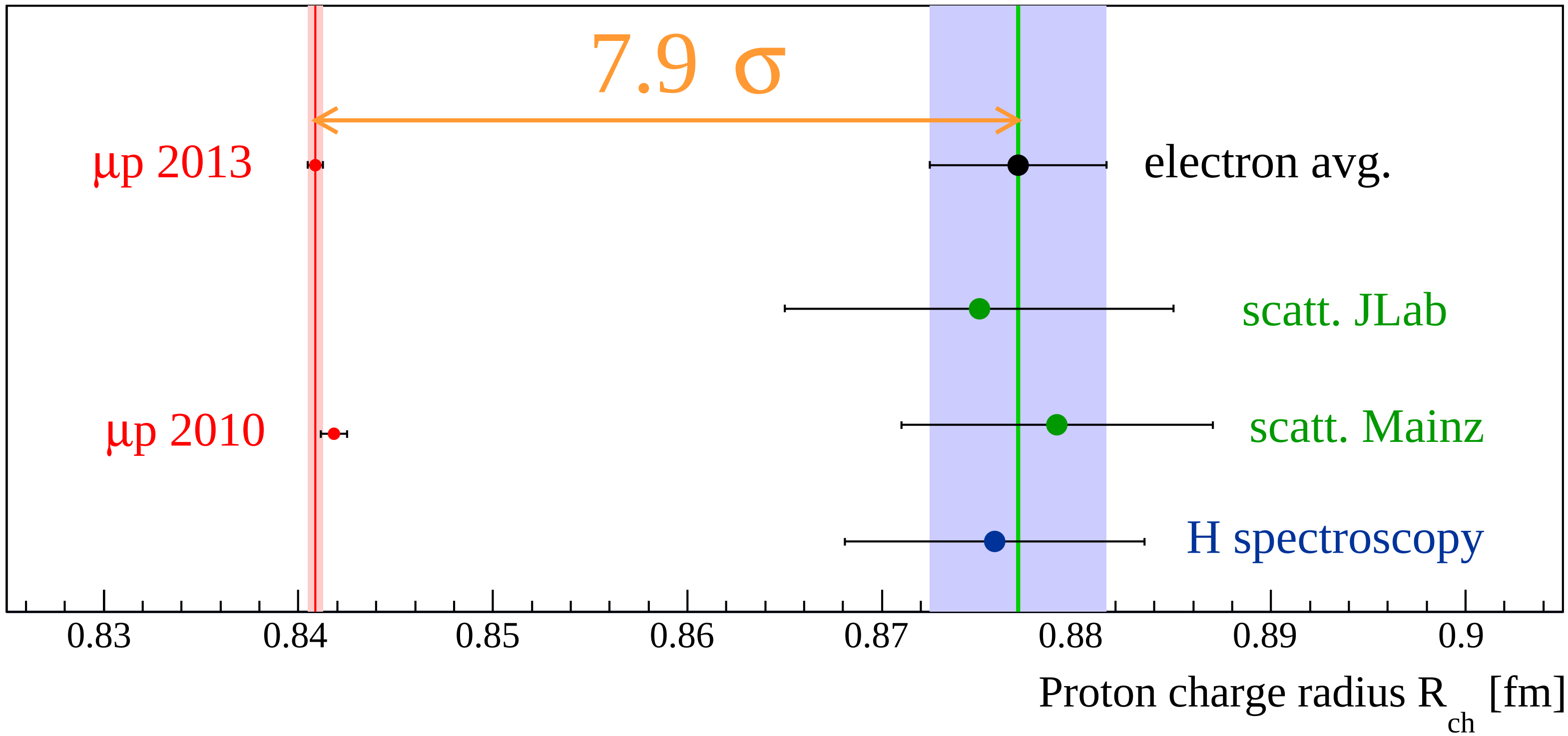


http://www.hep.ucl.ac.uk/muons/g-2/

Two muon puzzles

- **Anomalous magnetic moment** of the muon $\sim 3.6\sigma$
- **Proton radius from muonic hydrogen**

The measured value of the proton rms charge radius from muonic hydrogen μp is 10 times more accurate, but 4% smaller than the value from both **hydrogen spectroscopy** and **elastic electron proton scattering.**



RP et al., Nature 466, 213 (2010); Science 339, 417 (2013); ARNPS 63, 175 (2013).

Two muon puzzles

- **Anomalous magnetic moment** of the muon $\sim 3.6\sigma$
- **Proton radius from muonic hydrogen** $\sim 7.9\sigma$
- These 2 discrepancies may be **connected**.

r_p a_μ

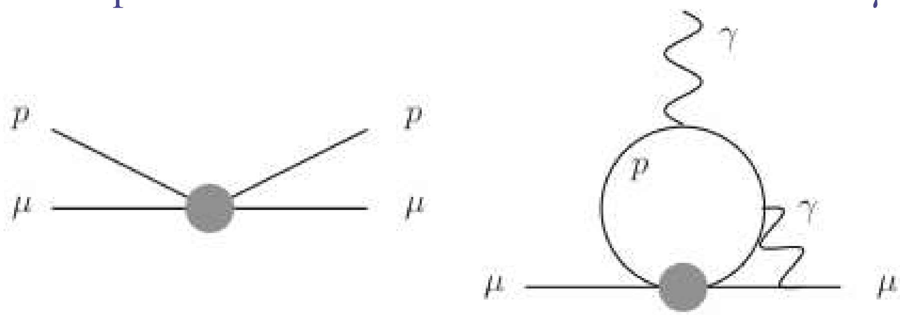
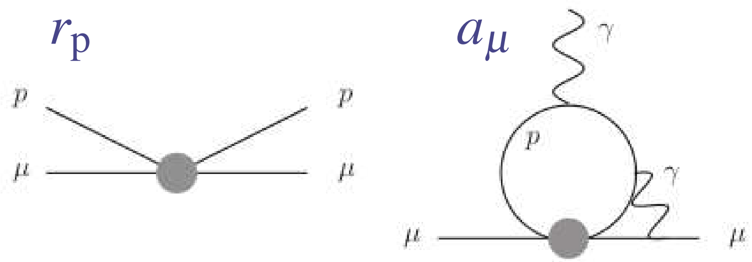


FIG. 1. Left:the effective proton-muon interaction resulting from unexpectedly large QCD effects or new physics that is responsible for the r_p discrepancy. Right: the two-loop contribution to the muon $g-2$ that results from the interaction on the left after integrating out the proton.

Karshenboim, McKeen, Pospelov, arXiv 1401.6156

r_p and a_μ

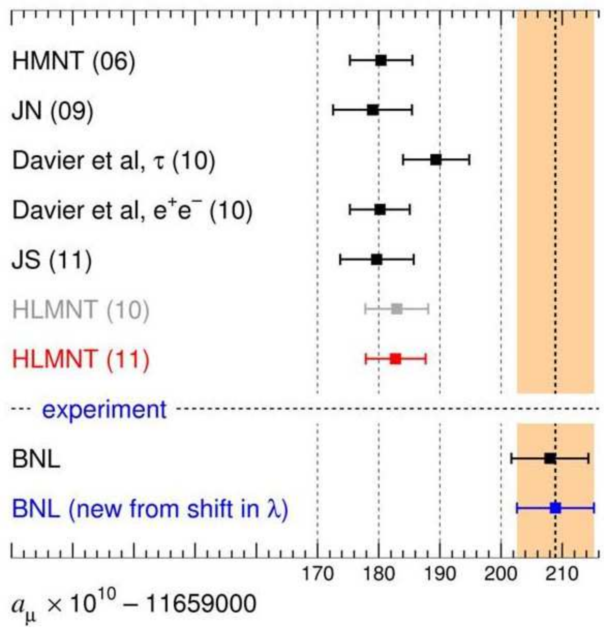
Both the r_p and the a_μ discrepancy could originate from the same new proton structure effect (two-photon-exchange) or “New light Physics” (m≈ MeV)



Fixing r_p could give rise to

$5 \times 10^{-9} < |\Delta(a_\mu)| < 10^{-7}$ (for $\Lambda_{had} = m_\pi \ldots p_p$).

This is **much larger** than the $(g-2)_\mu$ discrepancy of $\sim 1 \times 10^{-9}$.

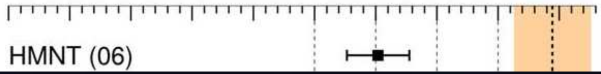


J. Phys. G 38, 085003 (2011).

after Pospelov
Karshenboim, McKeen, Pospelov, arXiv 1401.6156

$r_{\rm p}$ and a_μ

Both the $r_{\rm p}$ and the a_μ discrepancy could originate
from the sa
exchange)



Fixing $r_{\rm p}$ co

$5 \times 10^{-9} <$

This is **muc**

June 22 – July 25, 2013

after Pospelov
Karshenboim, McKeen, Pospelov, arXiv 1401.6156

r_p and a_μ

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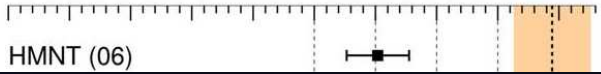

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after Pospelov

Karshenboim, McKeen, Pospelov, arXiv 1401.6156

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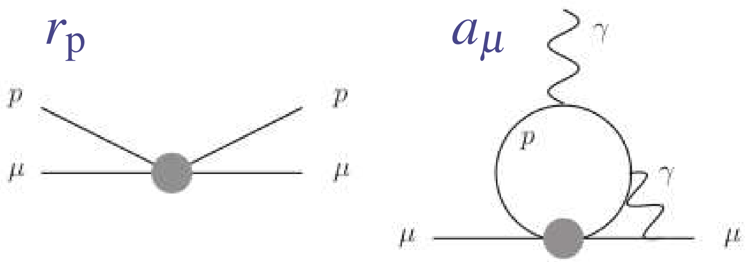

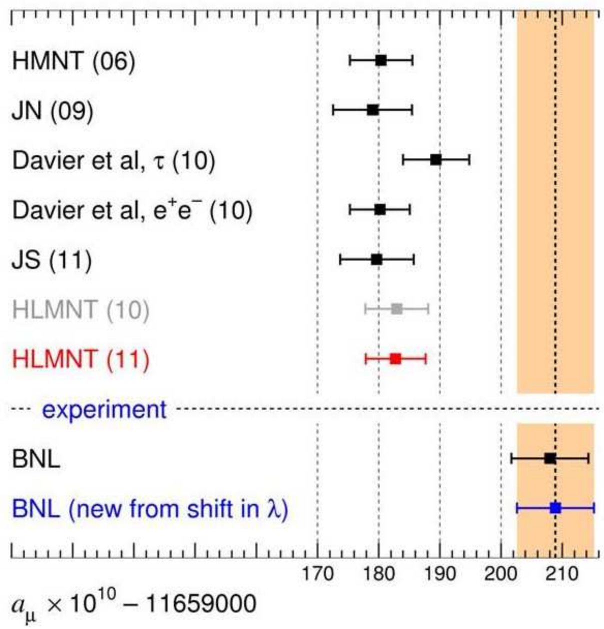

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Maybe one can invert the argument:

a_μ "not so wrong" $\Longrightarrow$ r_p is not due to proton TPE or this kind of BSM

after Pospelov
Karshenboim, McKeen, Pospelov, arXiv 1401.6156

Proton Size Investigators thank you for your attention

CREMA collaboration in 2009

Charge Radius Experiment with Muonic Atoms

F. KOTTMANN	ETH Zürich, Switzerland
D. TAQQU	PSI, Switzerland
A. ANTOGNINI, T.W. HÄNSCH, T. NEBEL, R. POHL	MPQ, Garching, Germany
E.-O. Le BIGOT, F. BIRABEN, P. INDELICATO, L. JULIEN, F. NEZ	Laboratoire Kastler Brossel, Paris, France
A. GIESEN, K. SCHUHMANN	Dausinger + Giesen, Stuttgart, Germany
T. GRAF	Institut für Strahlwerkzeuge, Stuttgart, Germany
F.D. AMARO, J.M.R. CARDOSO, D.S. COVITA, L.M.P. FERNANDES, J.A.M. LOPEZ, C.M.B. MONTEIRO, J.M.F. DOS SANTOS, J.F.C.A. VELOSO	Department of Physics, Coimbra, Portugal
C.-Y. KAO, Y.-W. LIU	National Tsing Hua University, Hsinchu, Taiwan
P. RABINOWITZ	Department of Chemistry, Princeton, USA
A. DAX, P. KNOWLES, L. LUDHOVA, F. MULHAUSER, L. SCHALLER	former members, spent holidays at run 2009

MPQ Laboratoire Kastler Brossel Physique quantique et applications UNIVERSIDADE DE COIMBRA PAUL SCHERRER INSTITUT PSI University of Stuttgart Germany