Muonic hydrogen spectroscopy

Randolf Pohl
for the
CREMA collaboration

CREMA collaboration 2013

Charge Radius Experiment with Muonic Atoms

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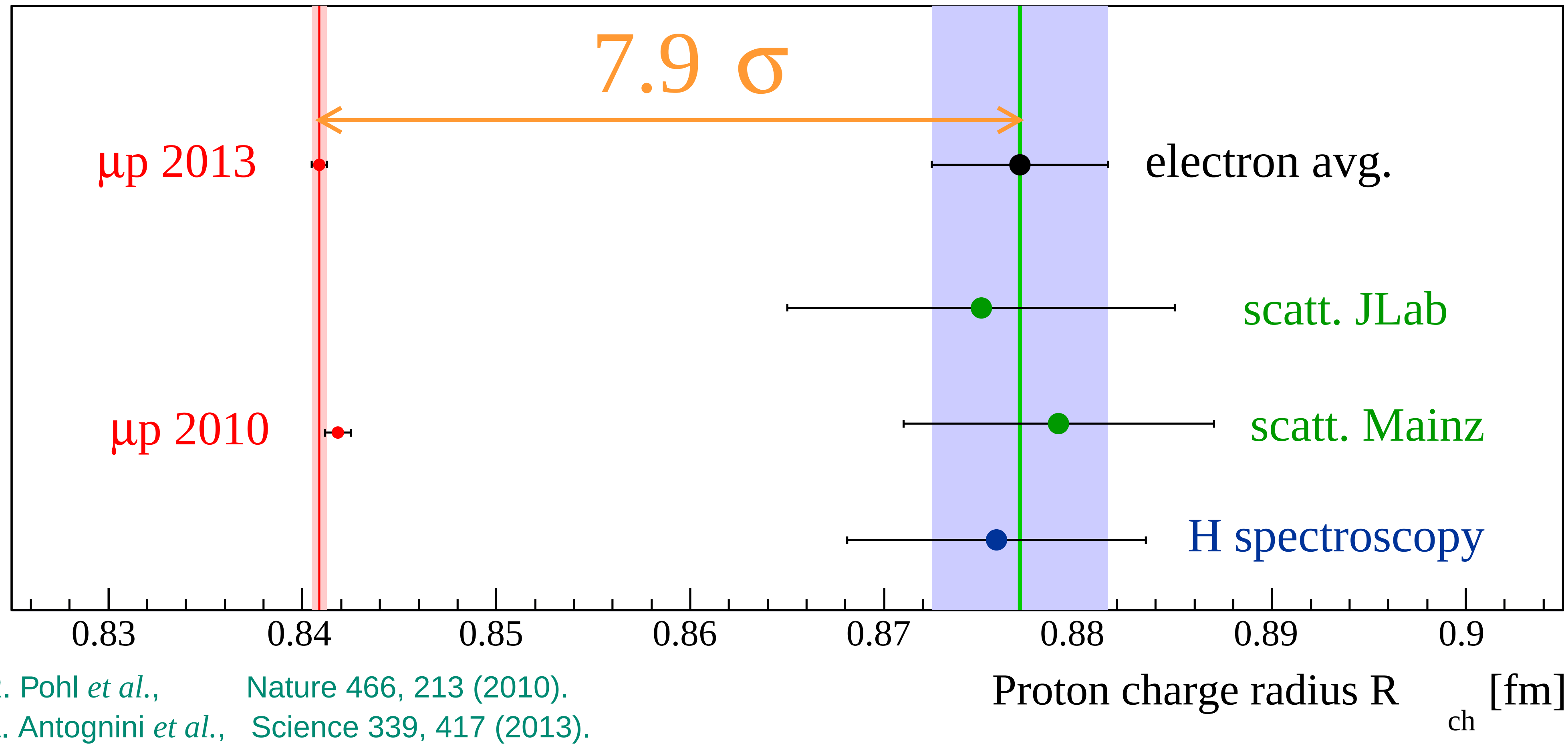
J.P. Santos	Uni Lisbon, Portugal

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

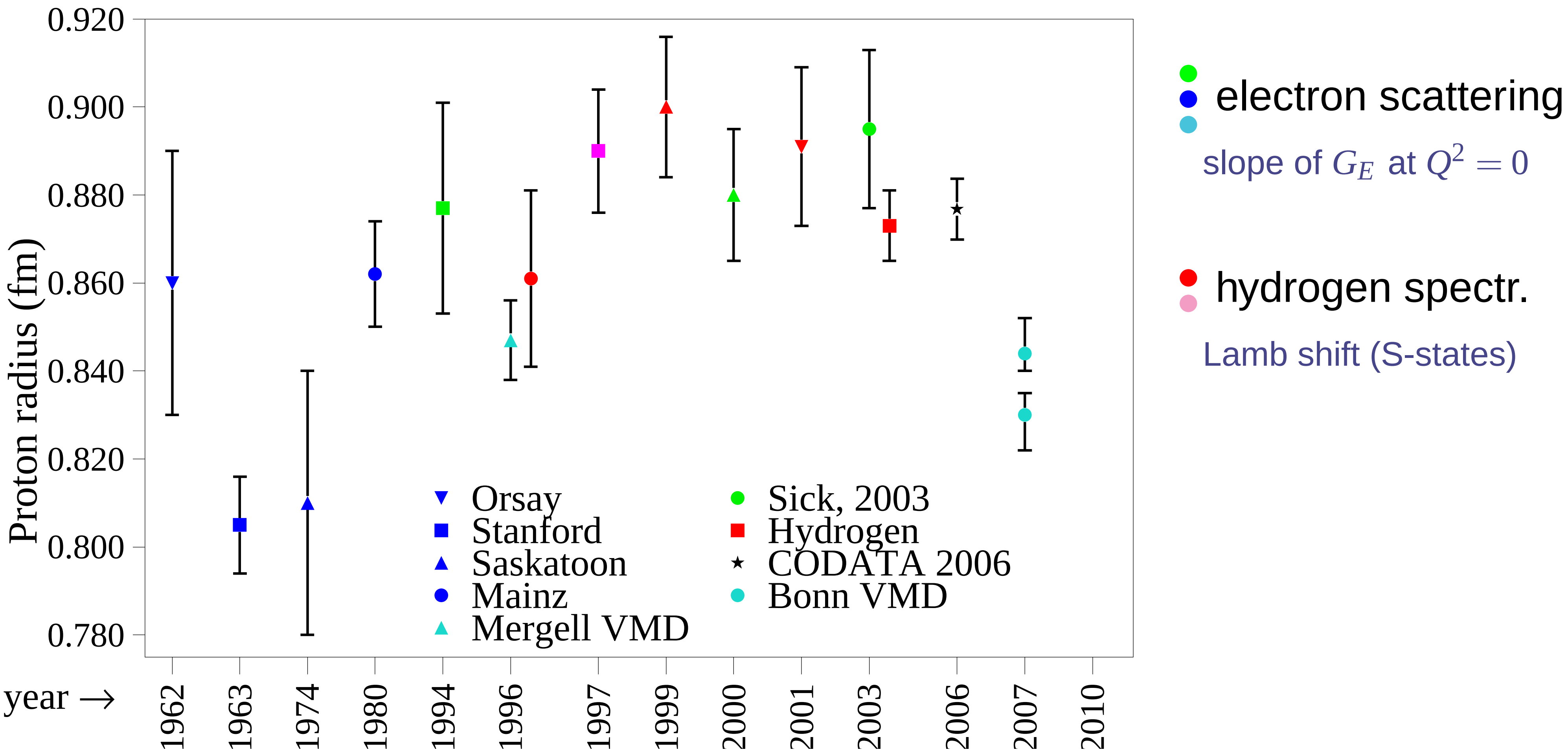
muons: 0.8409 ± 0.0004 fm



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

Proton radius vs. time

The proton rms charge radius is not the most accurate quantity in the universe.



e-p scattering: r_p = 0.895(18) fm ($u_r = 2\,\%$)

Hydrogen: r_p = 0.8760(78) fm ($u_r = 0.9\,\%$)

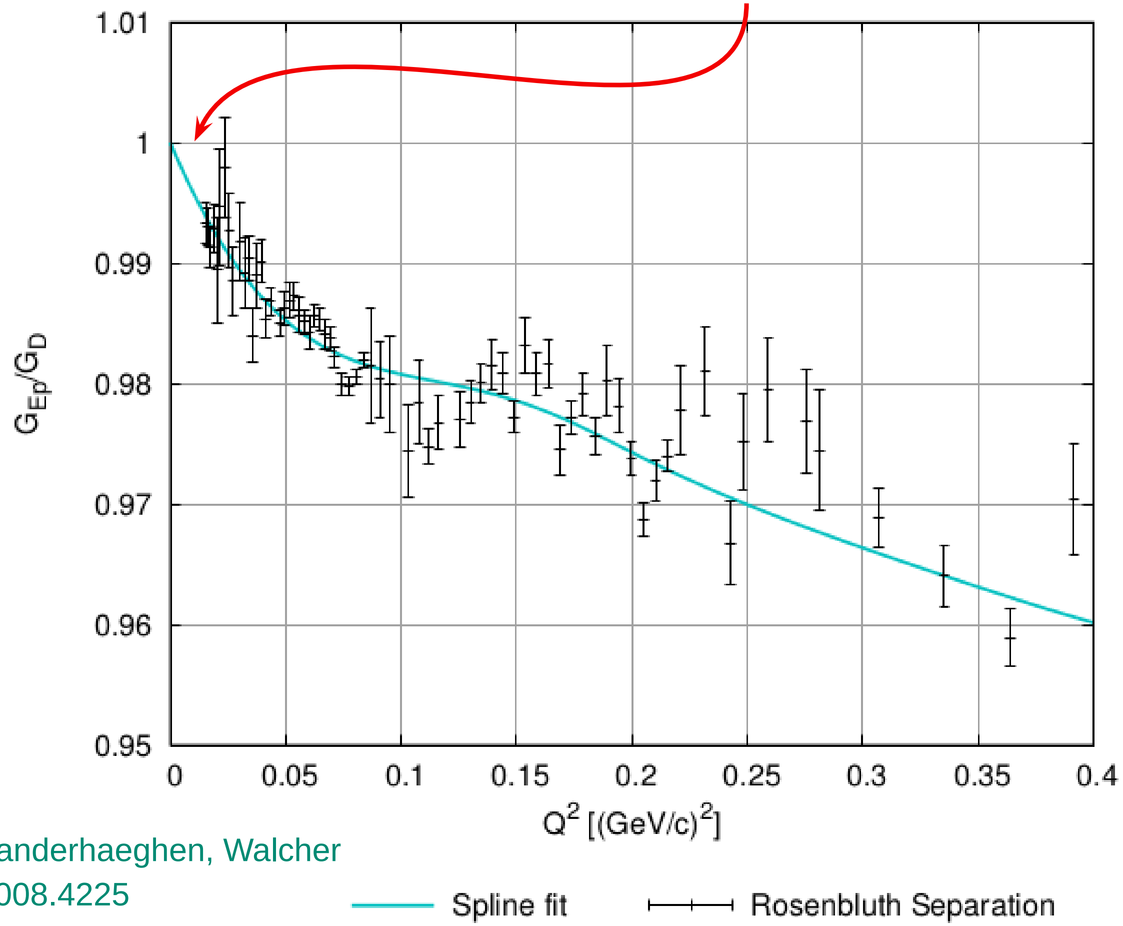
Proton radius vs. time

The proton rms charge radius is not the most accurate quantity in the universe.

0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
Proton radius (fm)
year
e-p
Hy

Electron scattering:

$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \quad \Rightarrow \quad \text{slope of } G_E \text{ at } Q^2 = 0$$



Vanderhaeghen, Walcher
1008.4225

- electron scattering

slope of G_E at $Q^2 = 0$

- hydrogen spectr.

Lamb shift (S-states)

Proton radius vs. time

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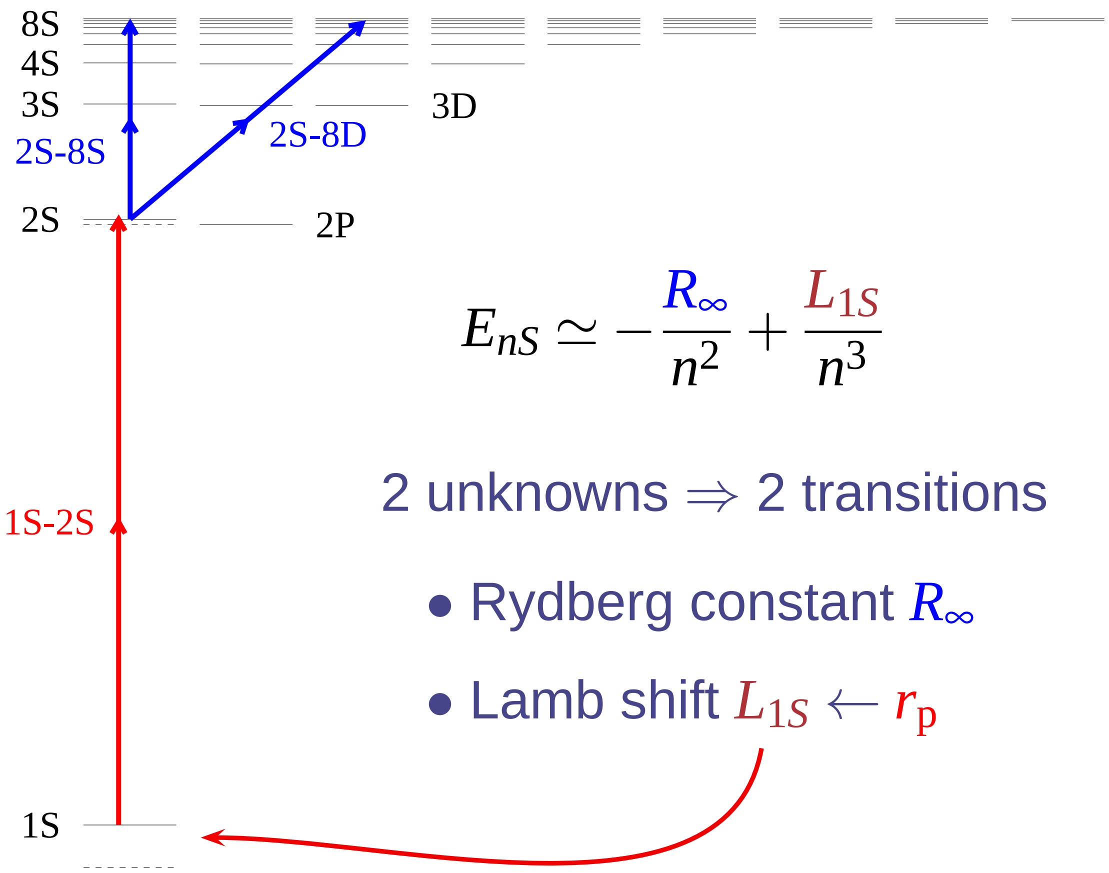
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
Proton radius (fm)
year

e-p
Hy

Hydrogen spectroscopy (Lamb shift):

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



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

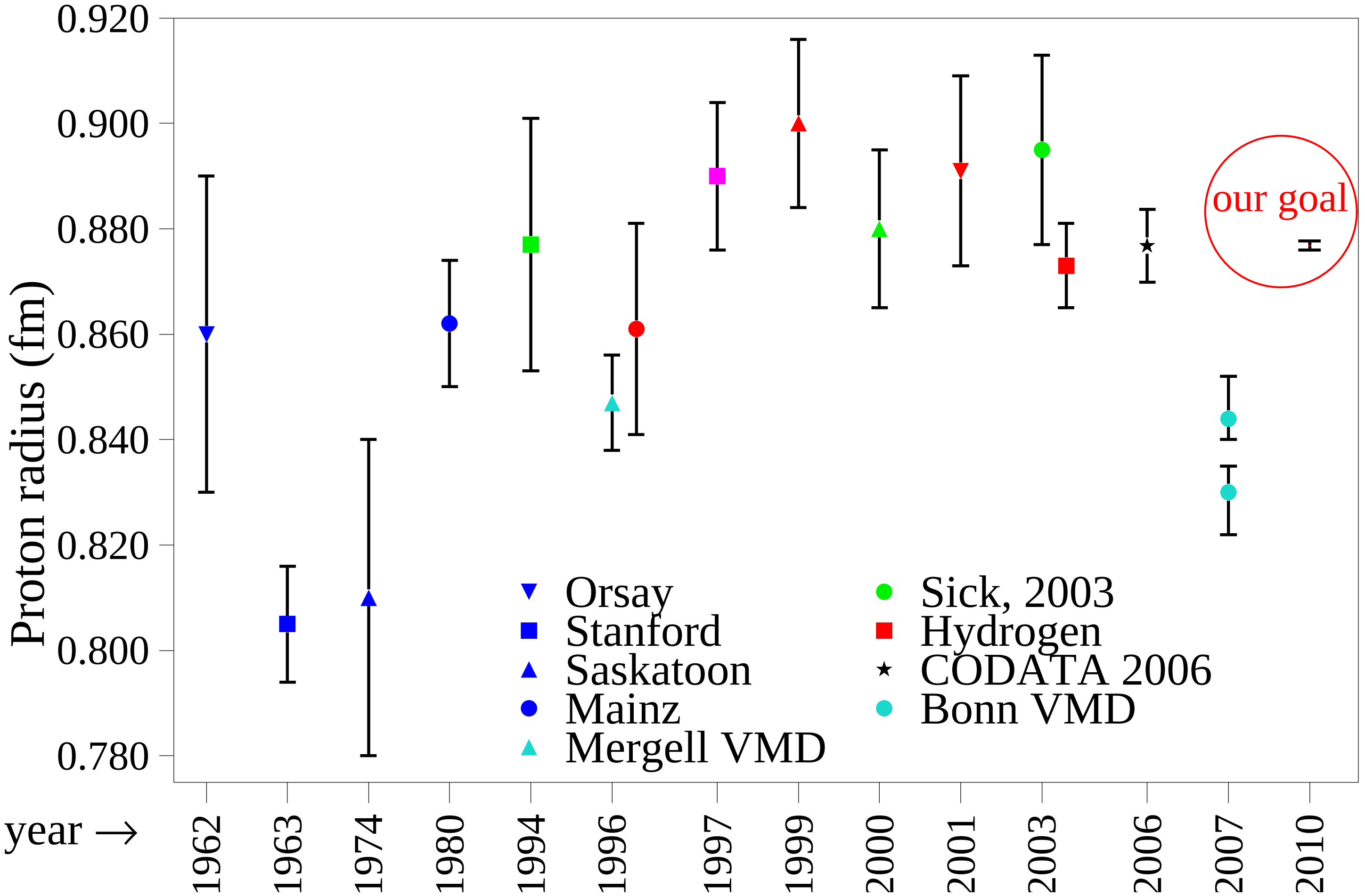
2 unknowns $\Rightarrow$ 2 transitions

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

- electron scattering
  slope of G_E at $Q^2 = 0$
- hydrogen spectr.
  Lamb shift (S-states)

Proton radius vs. time

The proton rms charge radius is not the most accurate quantity in the universe.



electron scattering

slope of G_E at $Q^2 = 0$

hydrogen spectr.

Lamb shift (S-states)

e-p scattering: r_p = 0.895(18) fm ($u_r = 2\,\%$)

Hydrogen: r_p = 0.8760(78) fm ($u_r = 0.9\,\%$)

muonic hydrogen goal (1998): $u_r = 0.1\,\%$

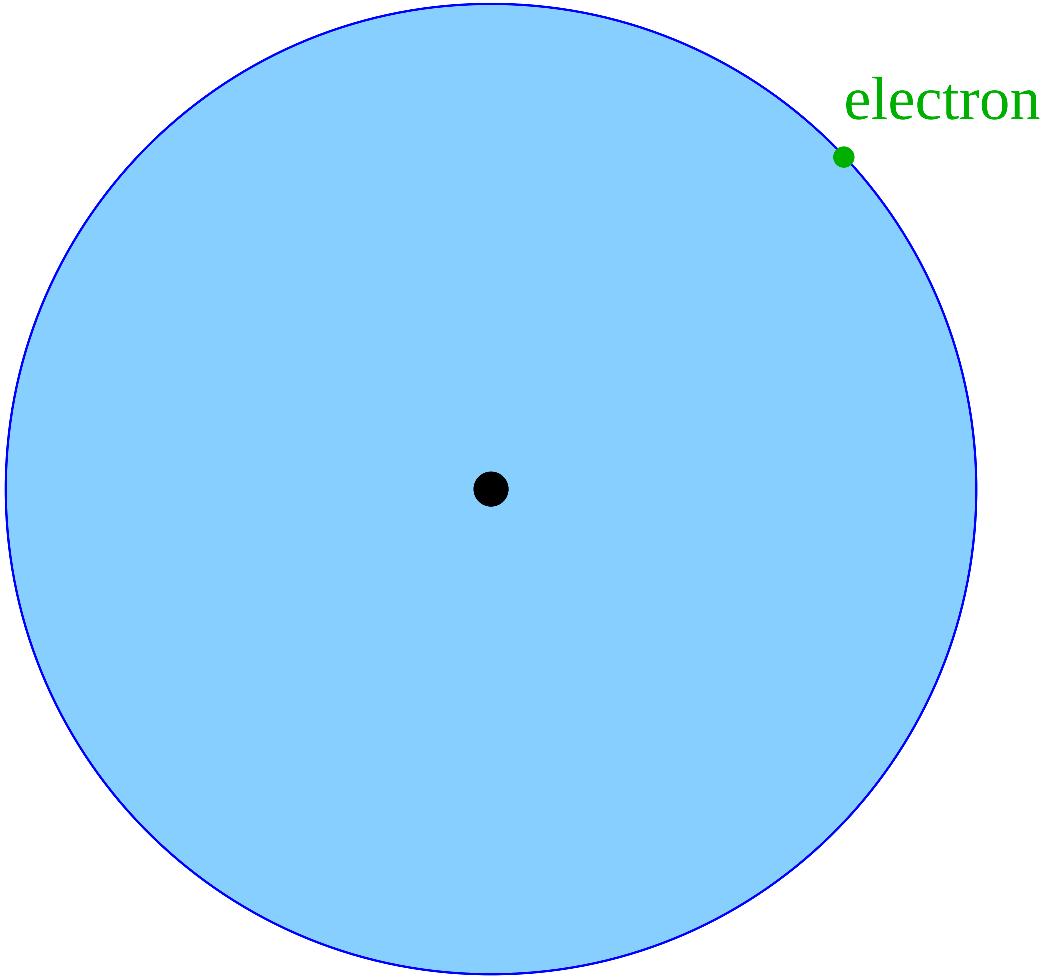
20x improvement

(aim: 10x better QED test in H)

Muonic hydrogen

Regular hydrogen:

electron e^- + proton p



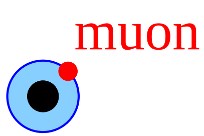
Muonic hydrogen:

muon μ^- + proton p

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

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

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



muon **much** is more sensitive to r_p

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:

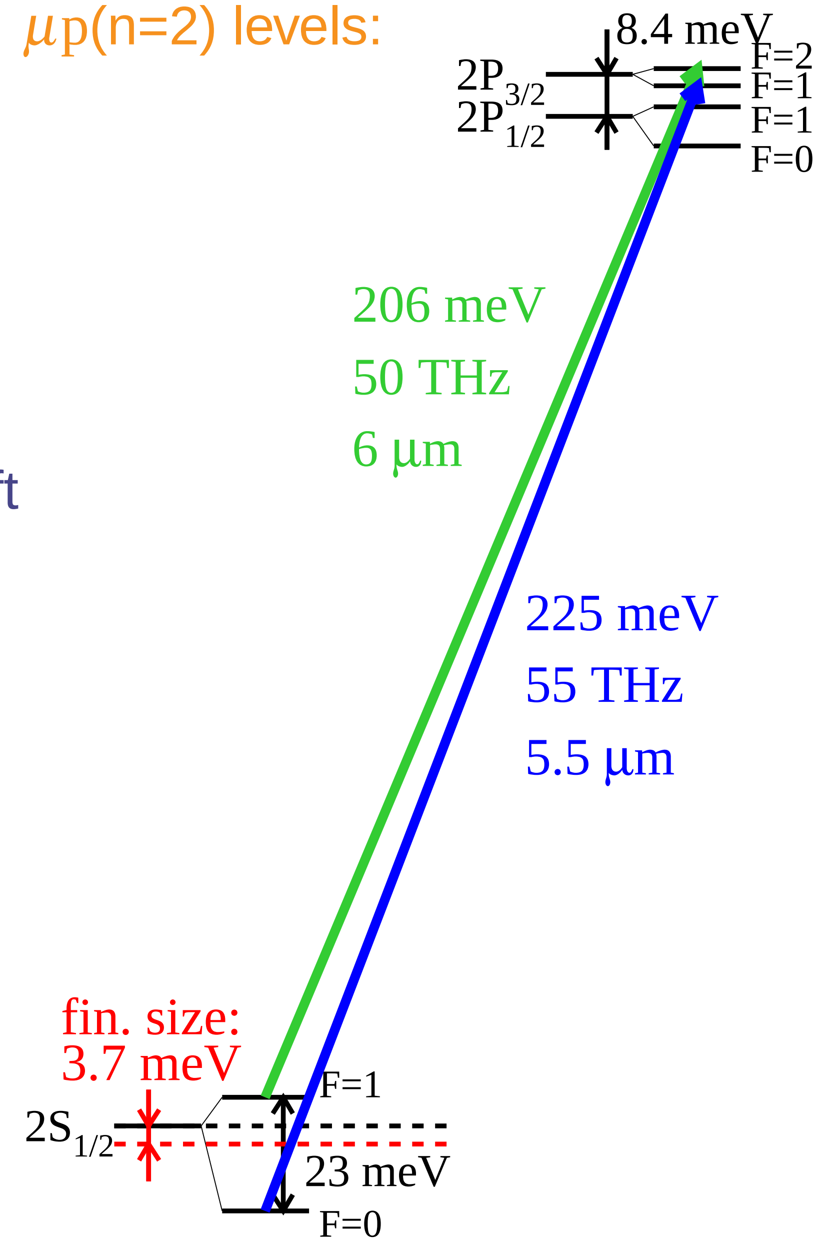
R. Pohl *et al.*, Nature 466, 213 (2010).

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

Theory summary:

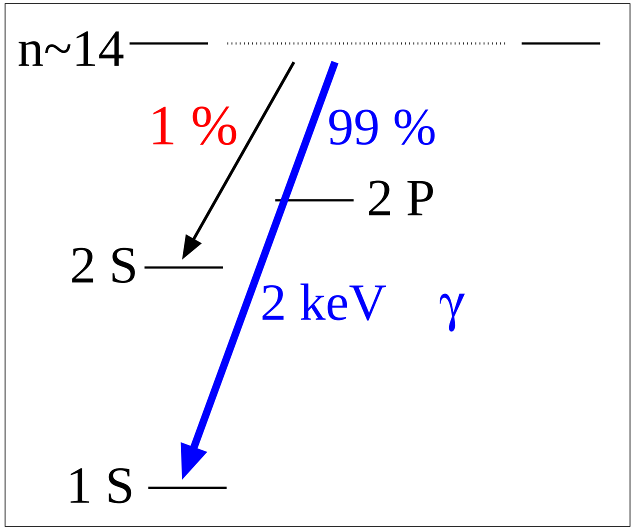
A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

μp(n=2) levels:

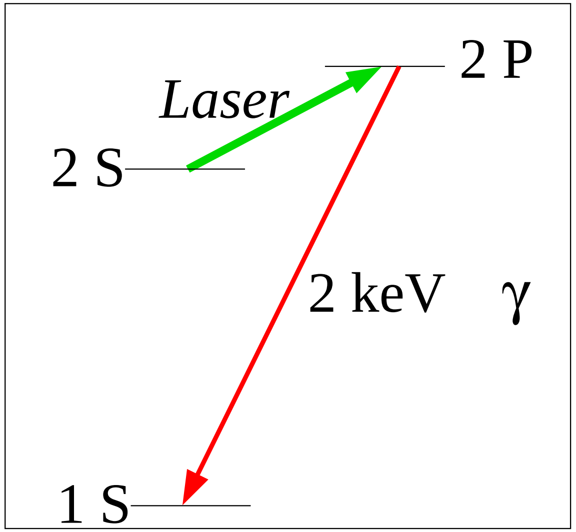


μp Lamb shift experiment: Principle

"prompt" ($t \sim 0$)



"delayed" ($t \sim 1\,\mu$s)



μ^- stop in H_2 gas
$\Rightarrow$ μp^* atoms formed ($n \sim 14$)

99%: cascade to μp(1S),
emitting prompt K_α, K_β ...

1%: long-lived μp(2S) atoms

lifetime $\boxed{\tau_{2S} \approx 1\,\mu s}$ at 1 mbar H_2

R. Pohl *et. al.*, Phys. Rev. Lett. 97, 193402 (2006).

fire laser ($\lambda \approx 6\,\mu$m, $\Delta E \approx 0.2$ eV)

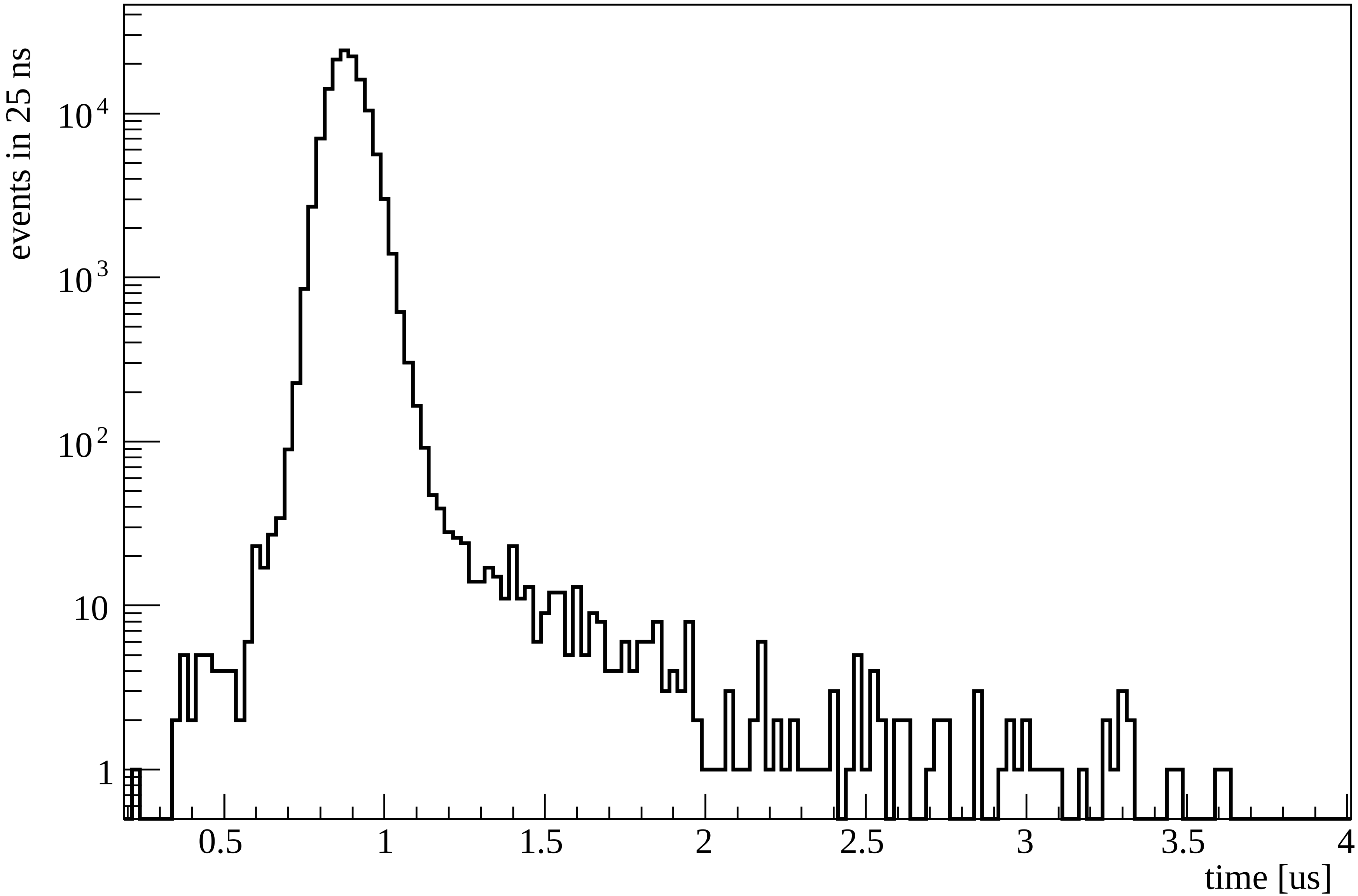
$\Rightarrow$ induce μp(2S) $\rightarrow$ μp(2P)

$\Rightarrow$ observe delayed K_α x-rays

$\Rightarrow$ normalize $\dfrac{\text{delayed } K_\alpha}{\text{prompt } K_\alpha}$ x-rays

μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays (∼ 13 hours of data @ 1 laser wavelength)



μp Lamb shift experiment: Principle

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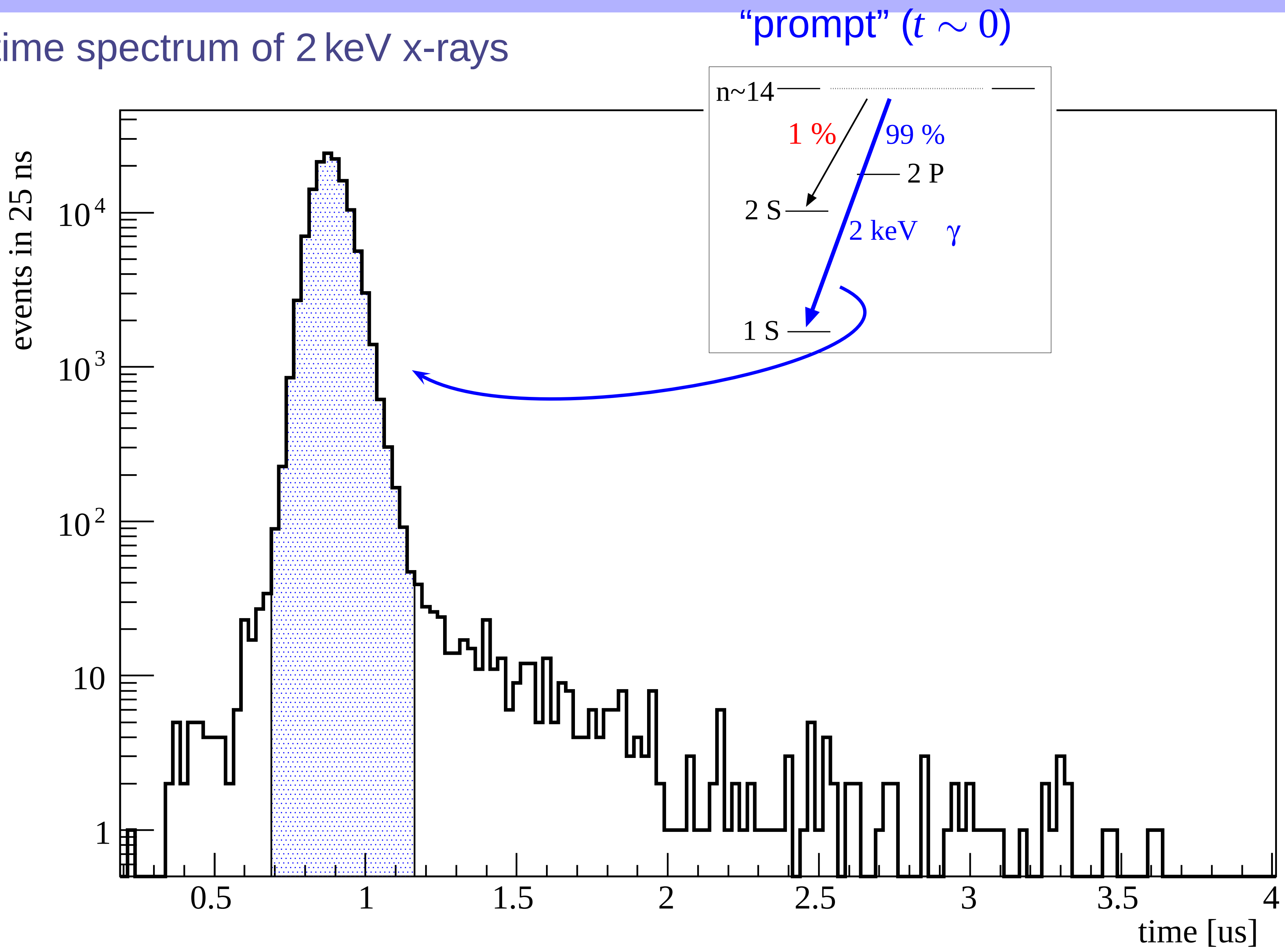

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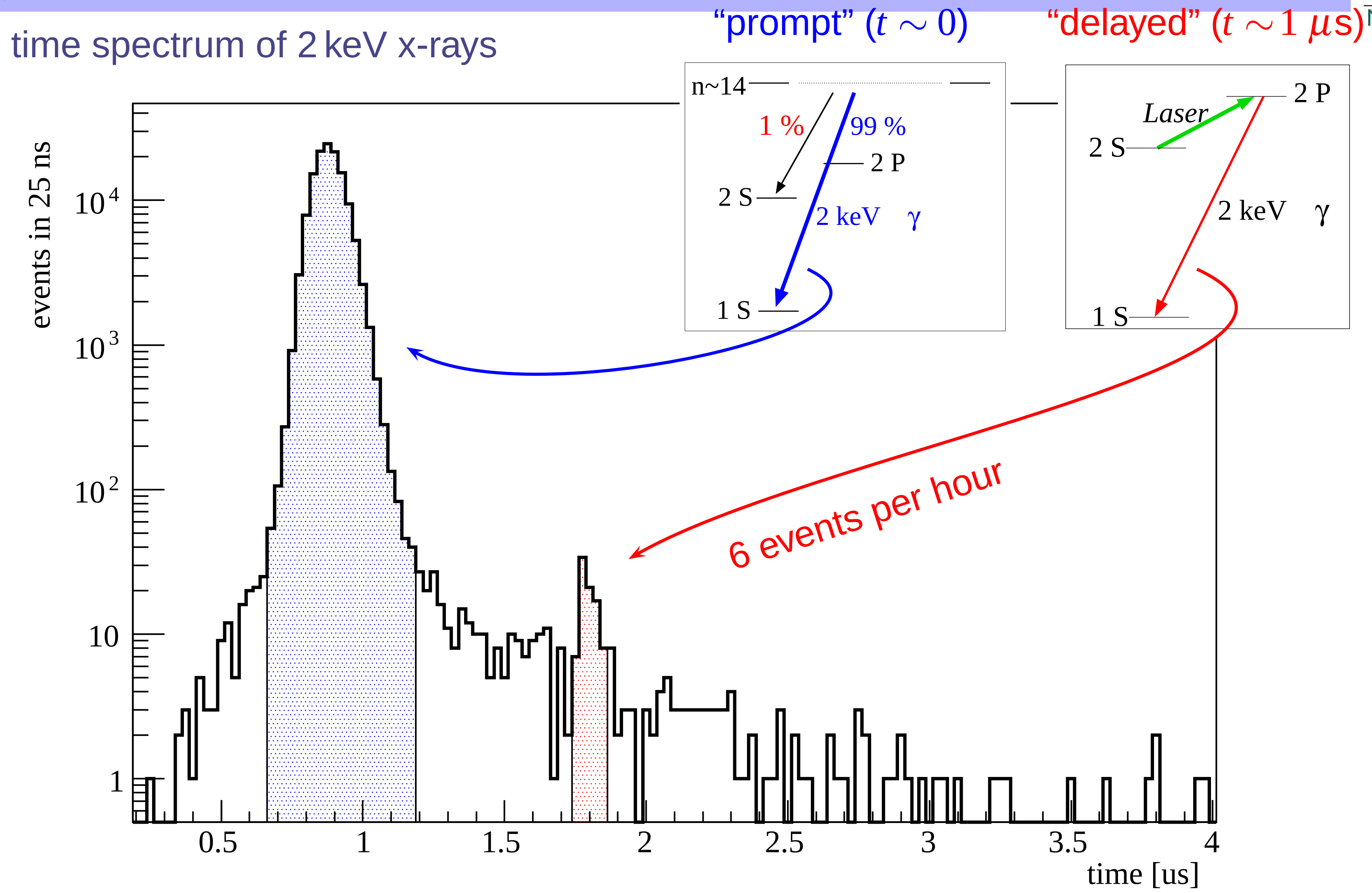

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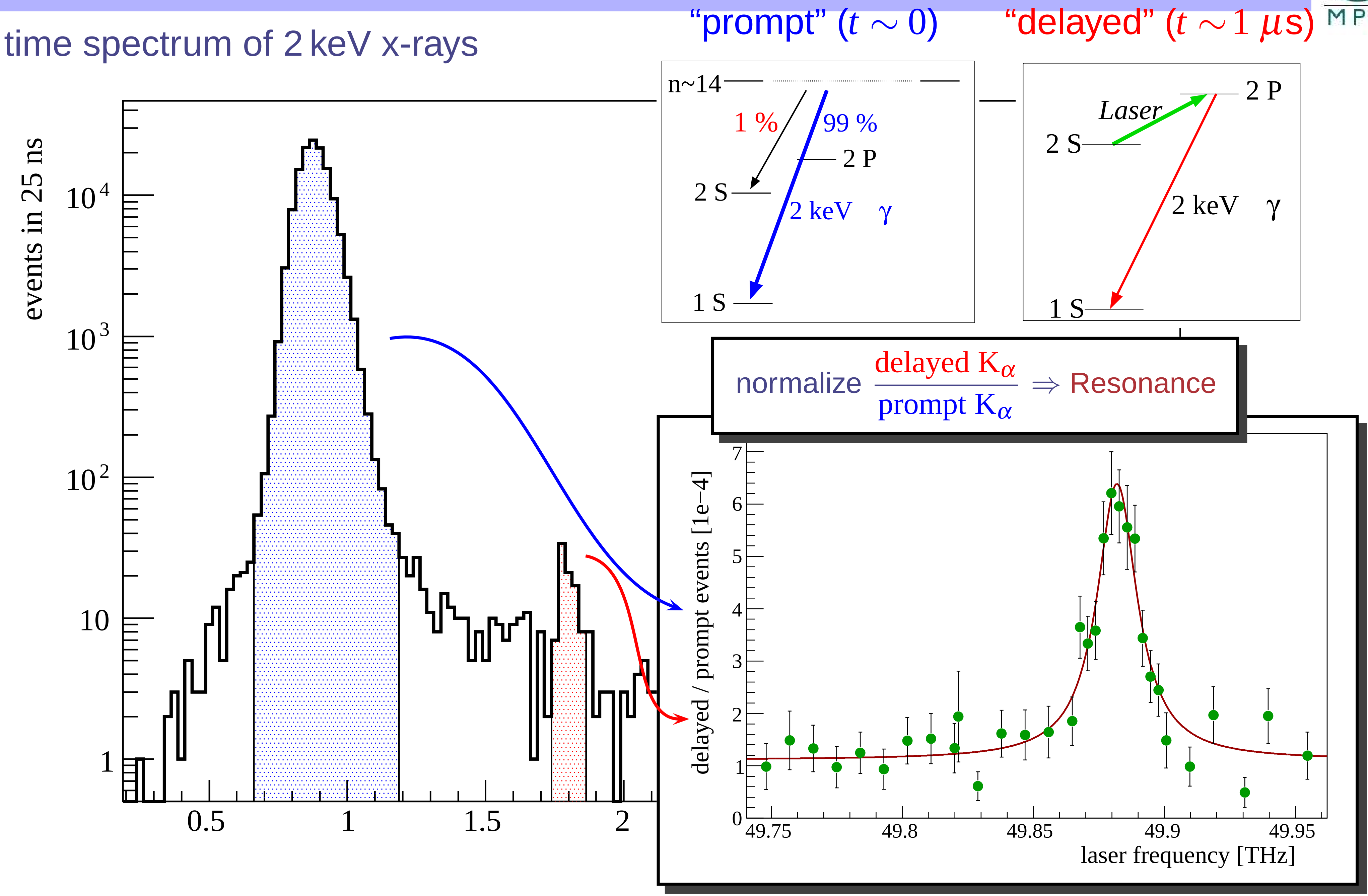
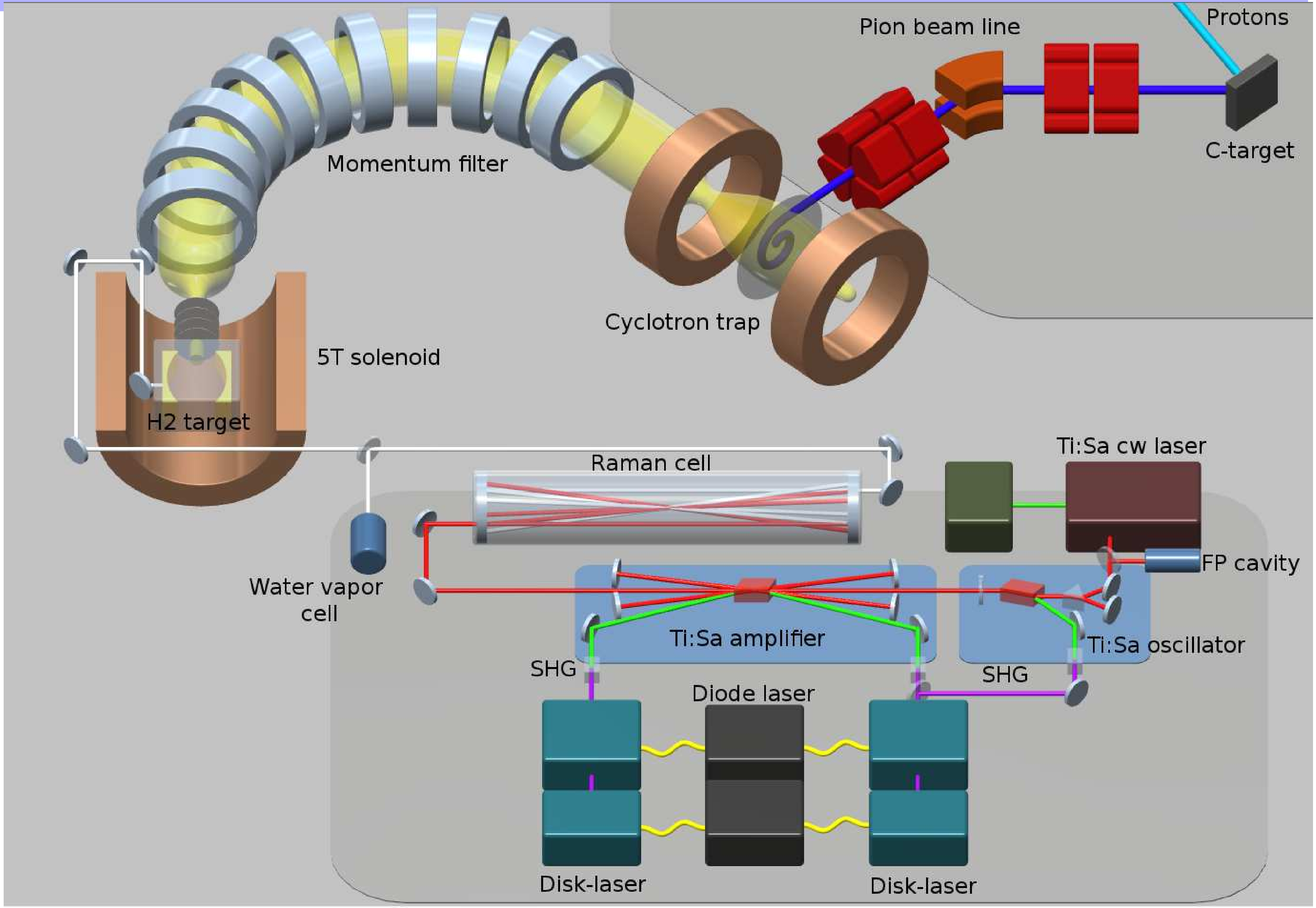


Setup

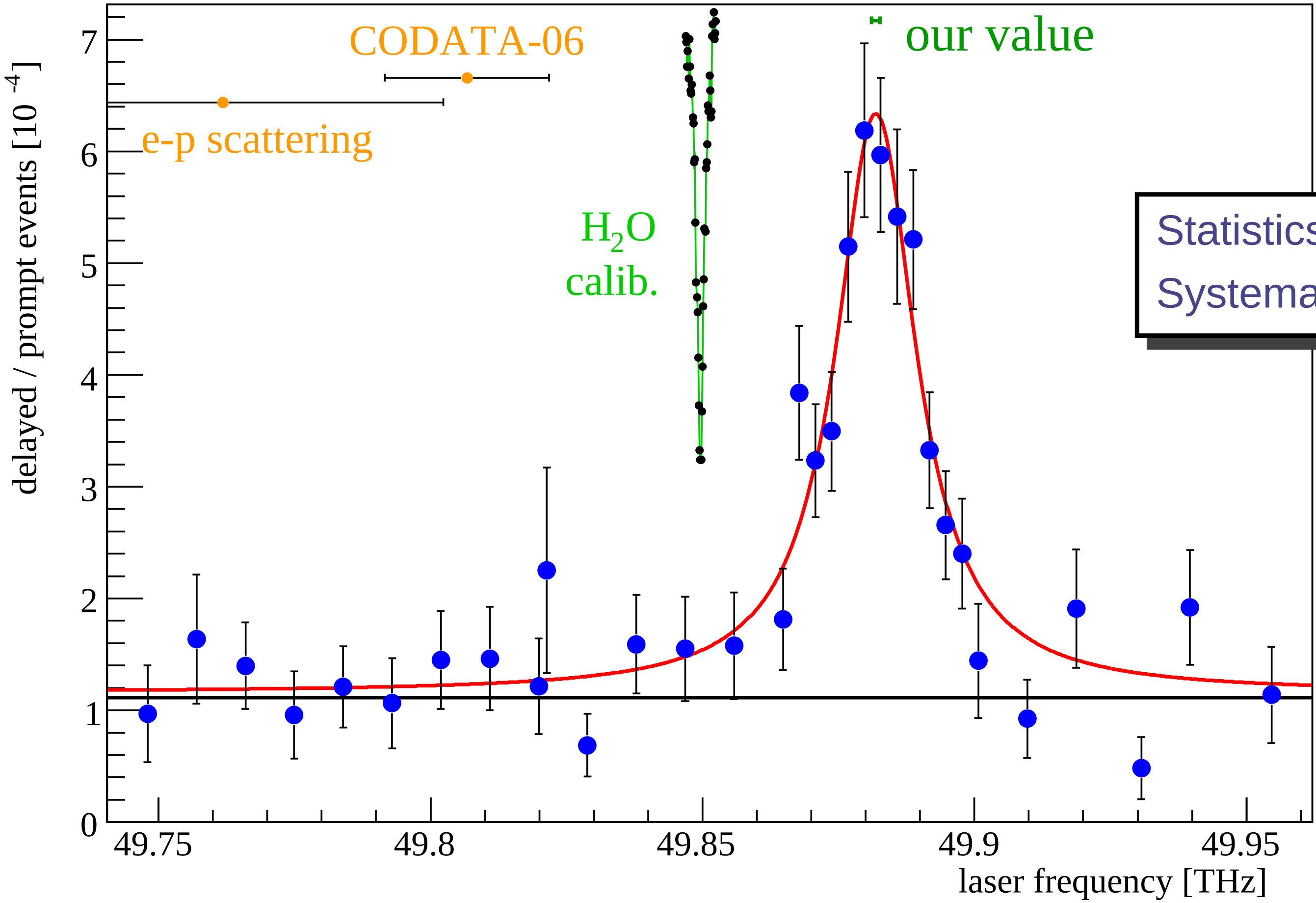


Protons
Pion beam line
C-target
Momentum filter
Cyclotron trap
5T solenoid
H2 target
Raman cell
Ti:Sa cw laser
FP cavity
Water vapor
cell
Ti:Sa amplifier
Ti:Sa oscillator
SHG
SHG
Diode laser
Disk-laser
Disk-laser

The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

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

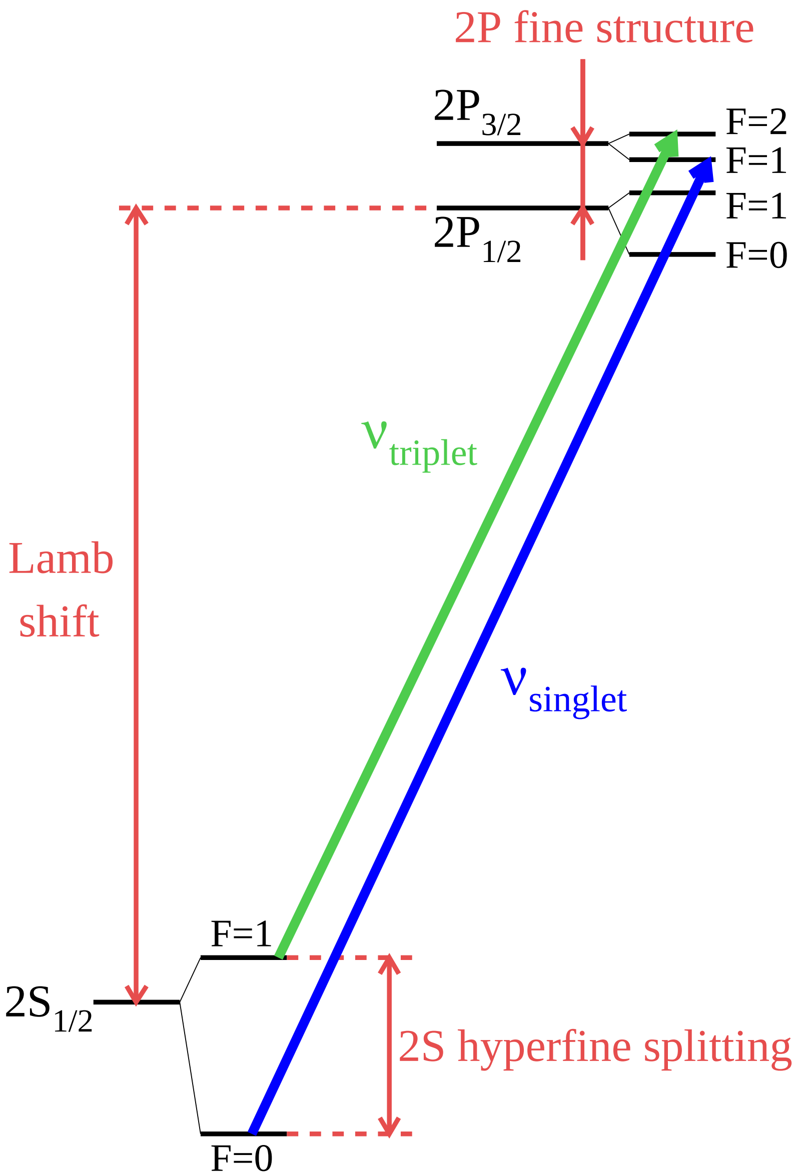


Statistics: 700 MHz
Systematics: 300 MHz

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).

We have measured two transitions in μp



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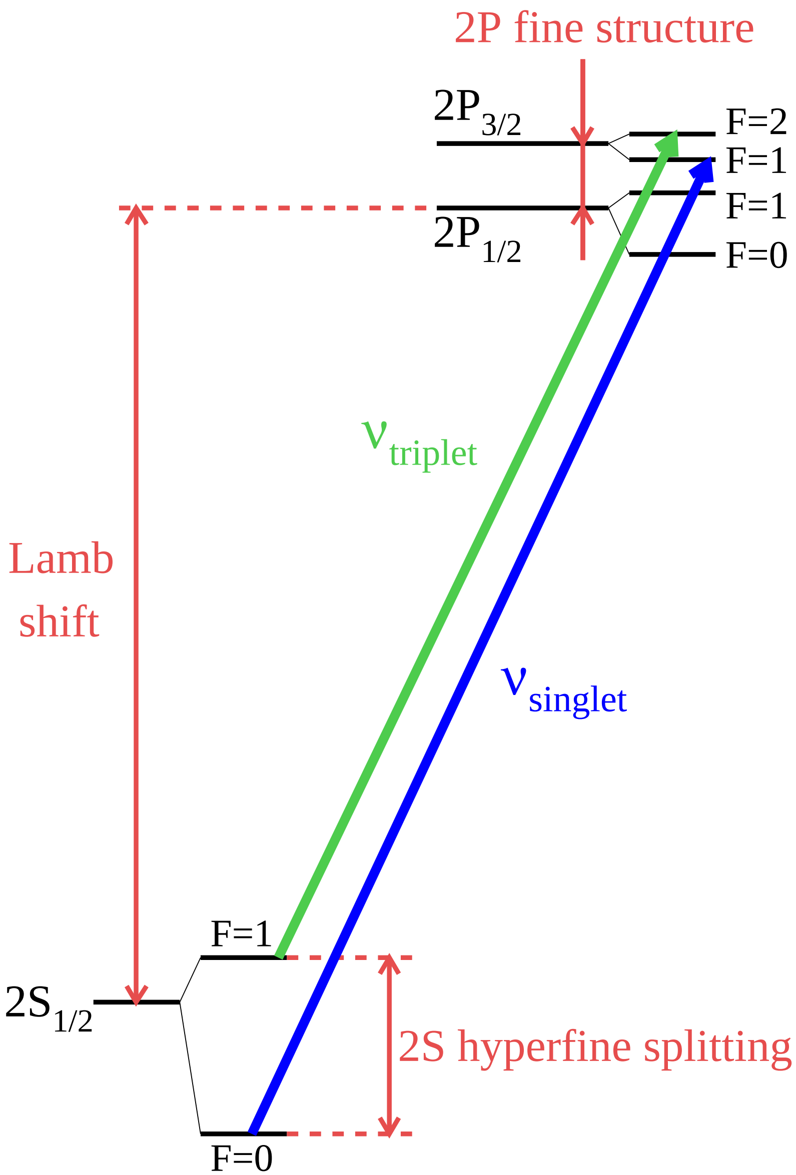

- Consider the two measurements **separately**

Two independent determinations of r_p

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

Consistent results !!!

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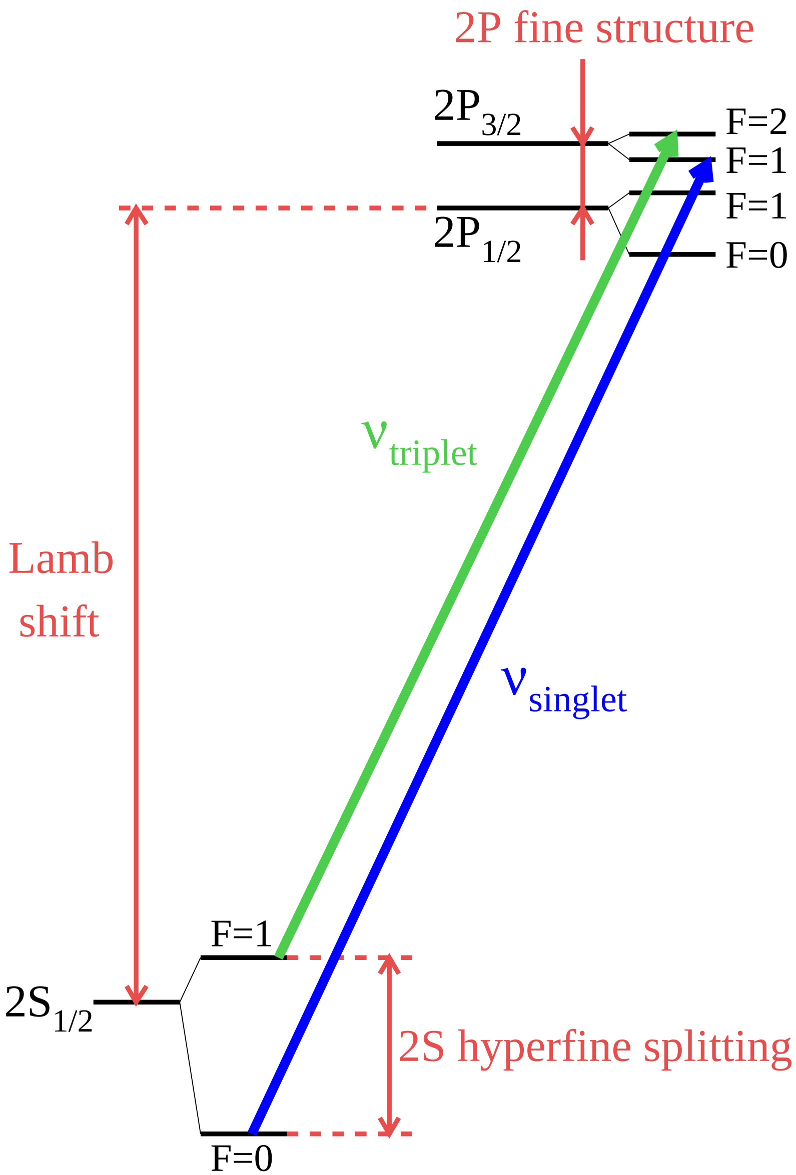


- Consider the two measurements **separately**

Two independent determinations of r_p

$(\nu_t \to r_p\ ,\ \nu_s \to r_p)$ **Consistent results !!!**

- Combine the two measurements

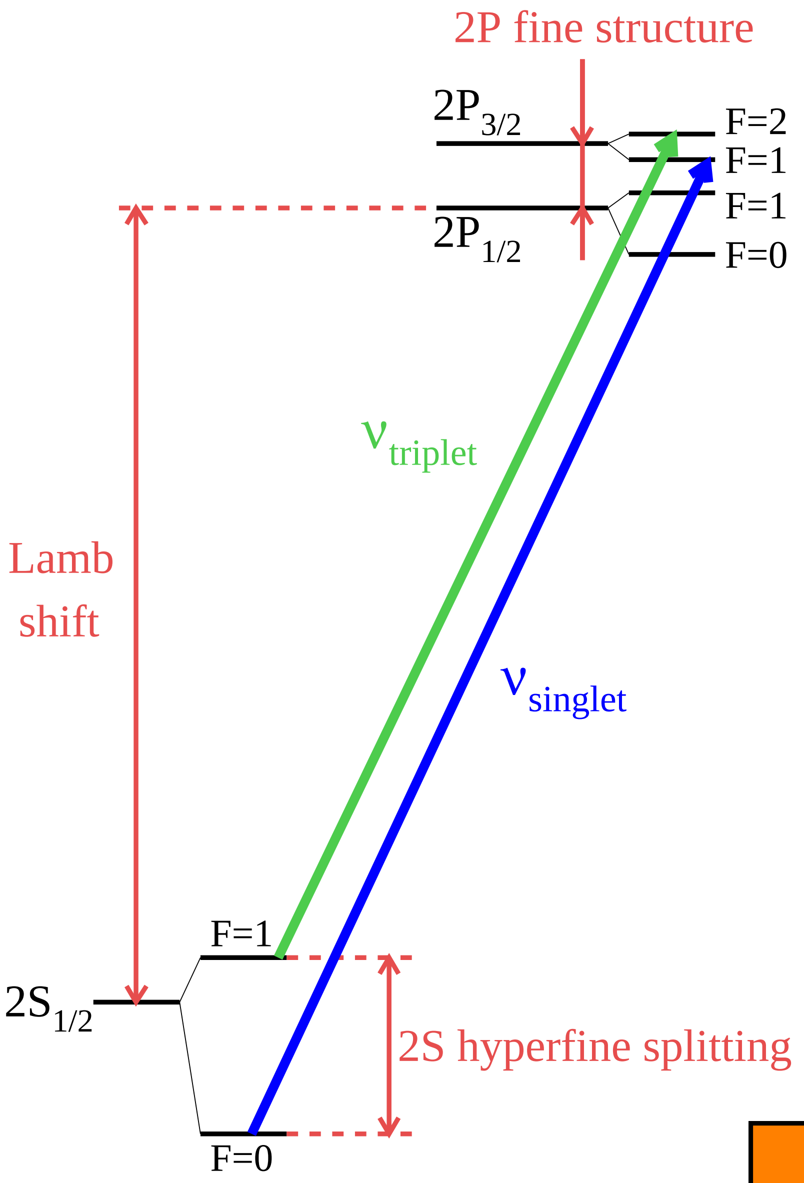
Two measurements $\to$ determine two parameters

$\nu_t, \nu_s \to \Delta E_L, \Delta E_{HFS} \to$ r_p, r_Z

Zemach radius $r_Z = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$

$$\begin{aligned} \tfrac{3}{4}\nu_t + \tfrac{1}{4}\nu_s &= \Delta E_L(r_p) + 8.8123\ \text{meV} \\ \nu_s - \nu_t &= \Delta E_{HFS}(r_Z) - 3.2480\ \text{meV} \end{aligned}$$

We have measured two transitions in μp



- Consider the two measurements **separately**

  Two independent determinations of r_p

  $(\nu_t \to r_p \,,\, \nu_s \to r_p)$ **Consistent results !!!**

  Using the 2S-HFS prediction

- Combine the two measurements

  Two measurements $\to$ determine two parameters

  $\nu_t, \nu_s \to \Delta E_L, \Delta E_{HFS} \to$ r_p, r_Z

  Zemach radius $r_Z = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$

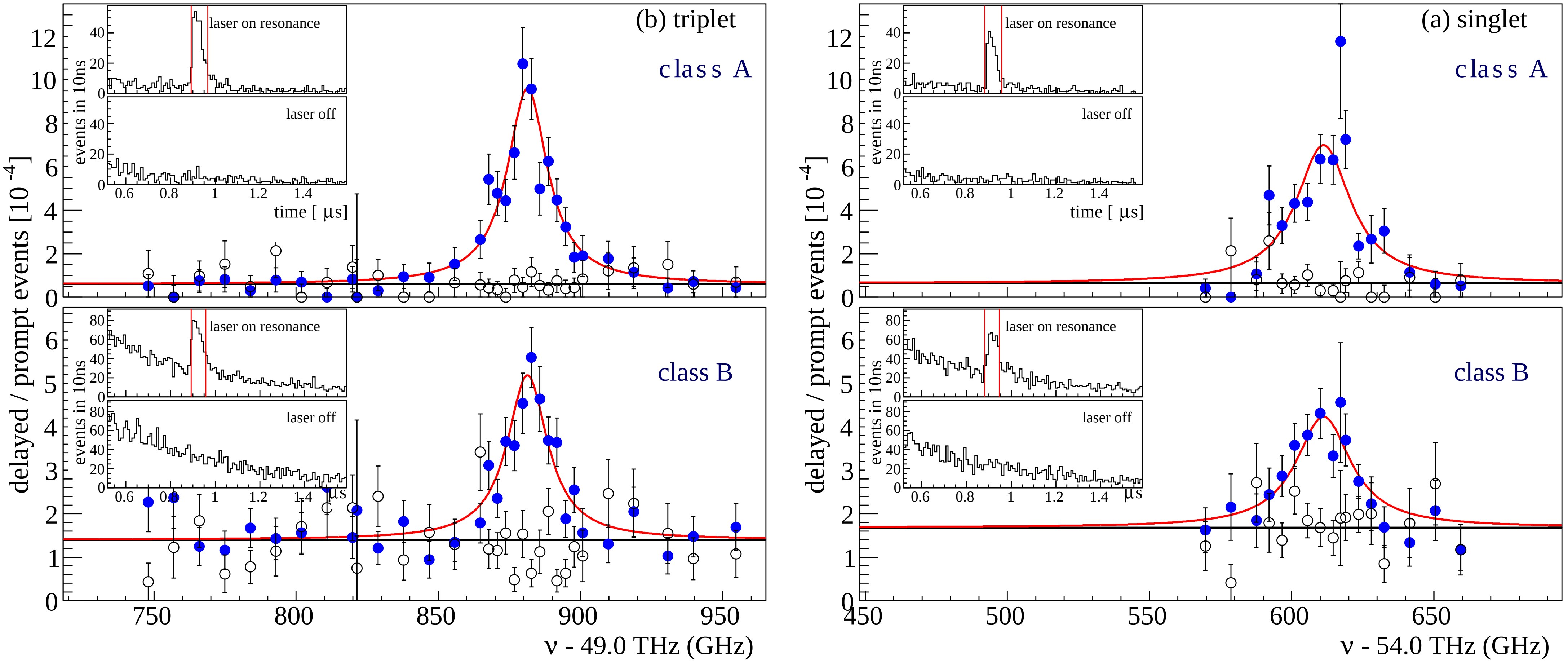
$$\begin{aligned} \tfrac{3}{4}\nu_t + \tfrac{1}{4}\nu_s &= \Delta E_L(r_p) + 8.8123 \text{ meV} \\ \nu_s - \nu_t &= \Delta E_{HFS}(r_Z) - 3.2480 \text{ meV} \end{aligned}$$

New r_p does NOT dependend on 2S-HFS prediction

We have measured two transitions in μp!

$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$ at $\lambda = 6.0\ \mu$m

$\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$ at $\lambda = 5.5\ \mu$m



Both resonances are 0.3 meV away from predictions using r_p from CODATA

Results on muonic hydrogen

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

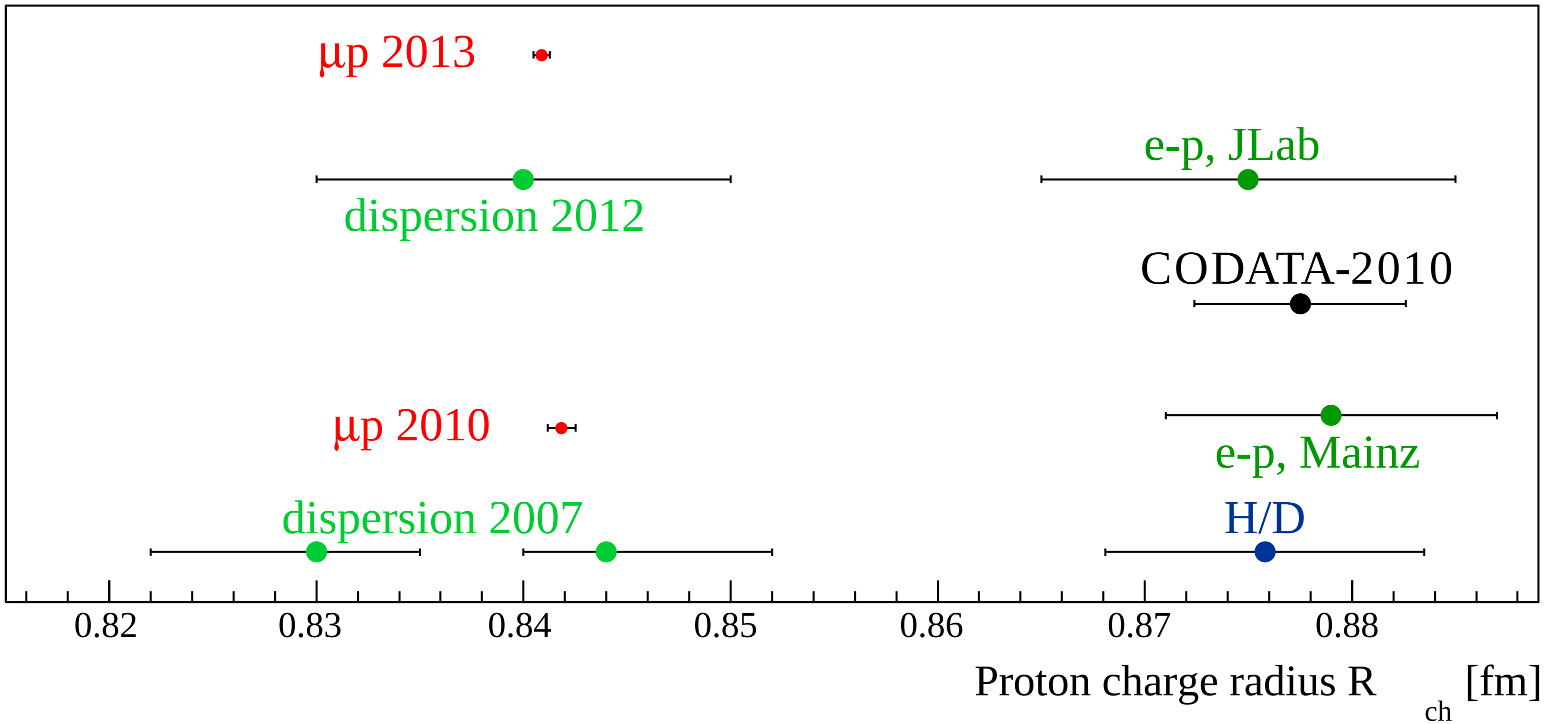
49881.35(65) GHz

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

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

Proton charge radius: $r_p = 0.84087\,(26)_{exp}\,(29)_{th} = 0.84087\,(39)$ fm

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



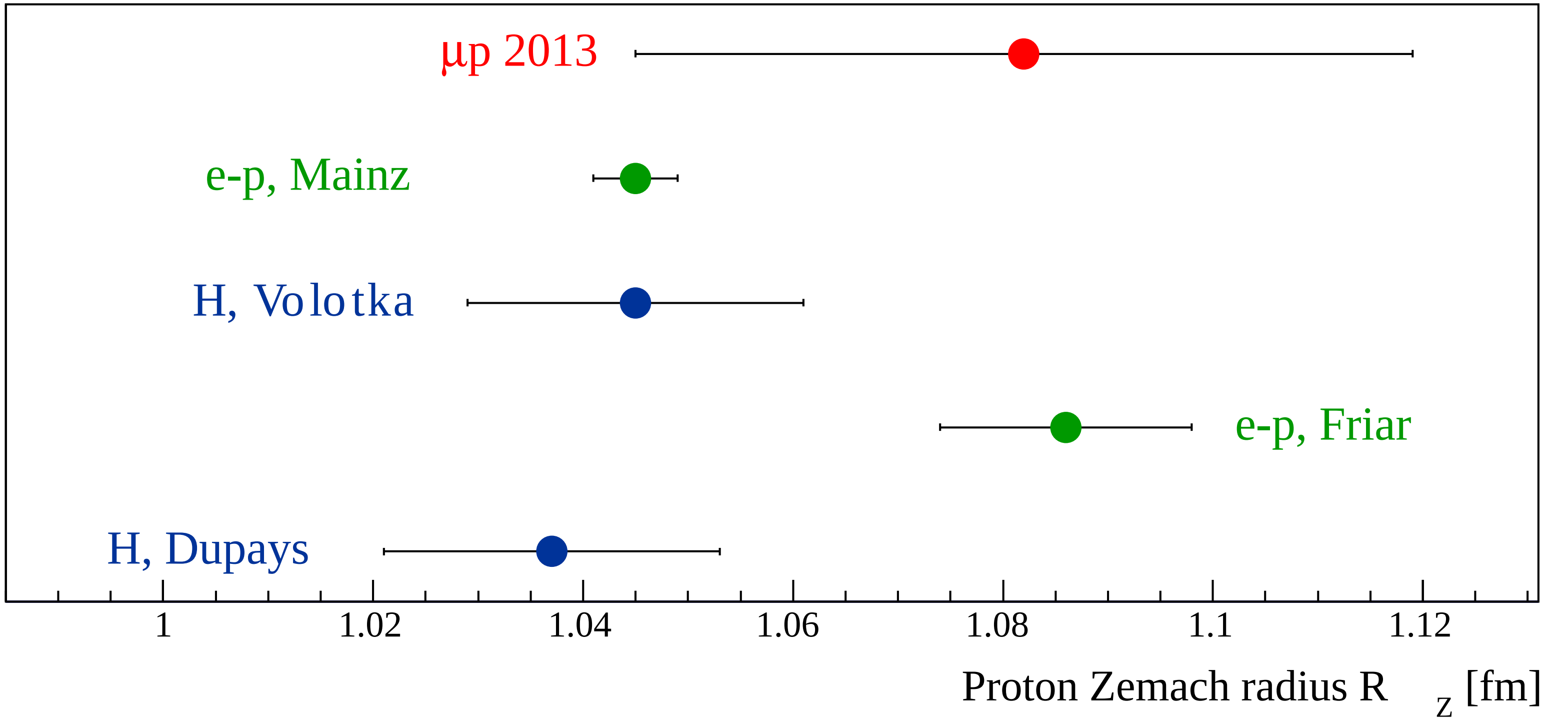
The Zemach radius

2S hyperfine splitting in μp is: $\Delta E_{\rm HFS} = 22.8089(51)$ meV

gives a proton Zemach radius $R_Z = \int d^3r \int d^3r' \, r \, \rho_E(r) \, \rho_M(r - r')$

r_Z = 1.082 (31)$_{\rm exp}$ (20)$_{\rm th}$ = 1.082 (37) fm

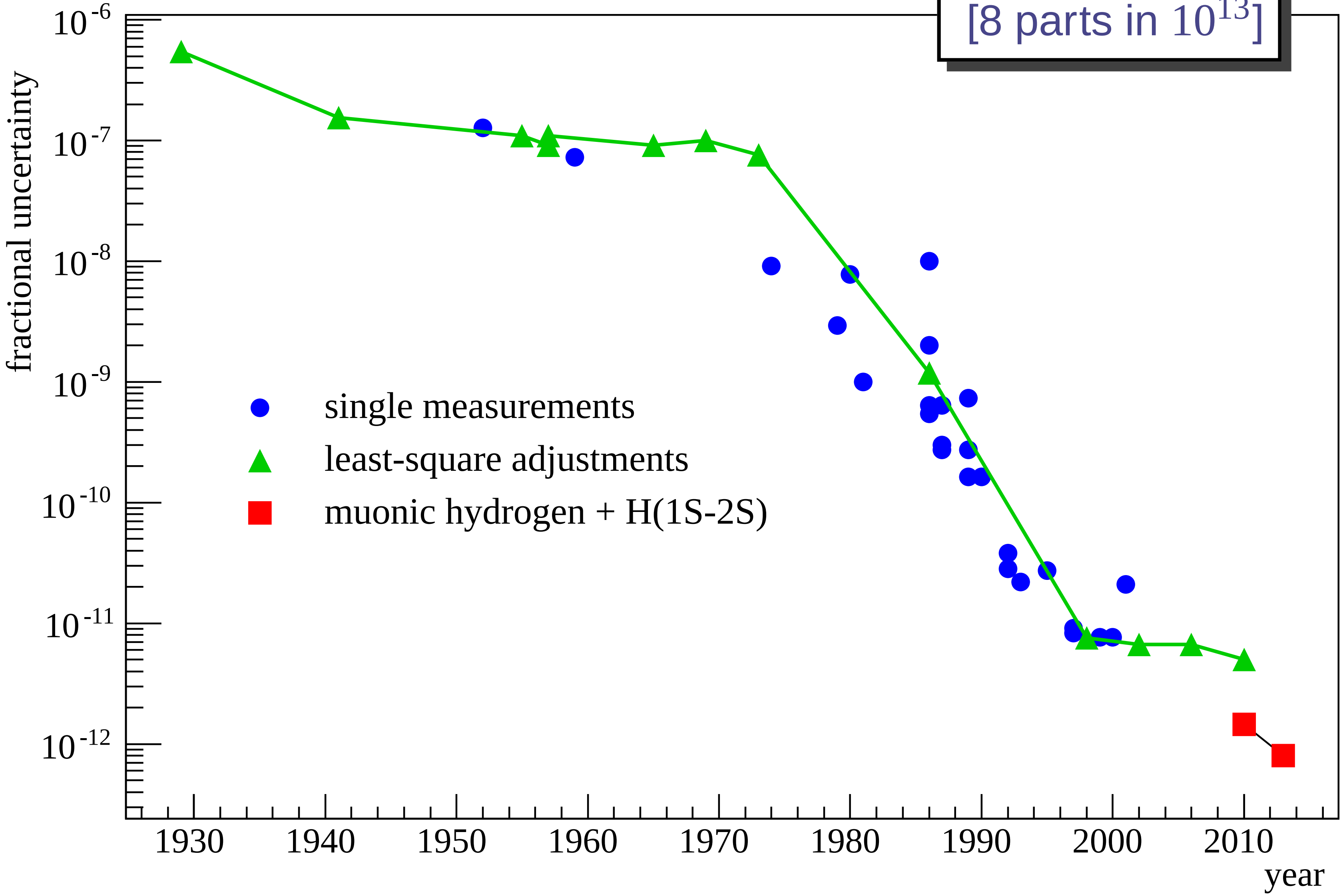
A. Antognini, RP *et al.*, Science 339, 417 (2013).



Rydberg constant 2013

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

[8 parts in 10^{13}]



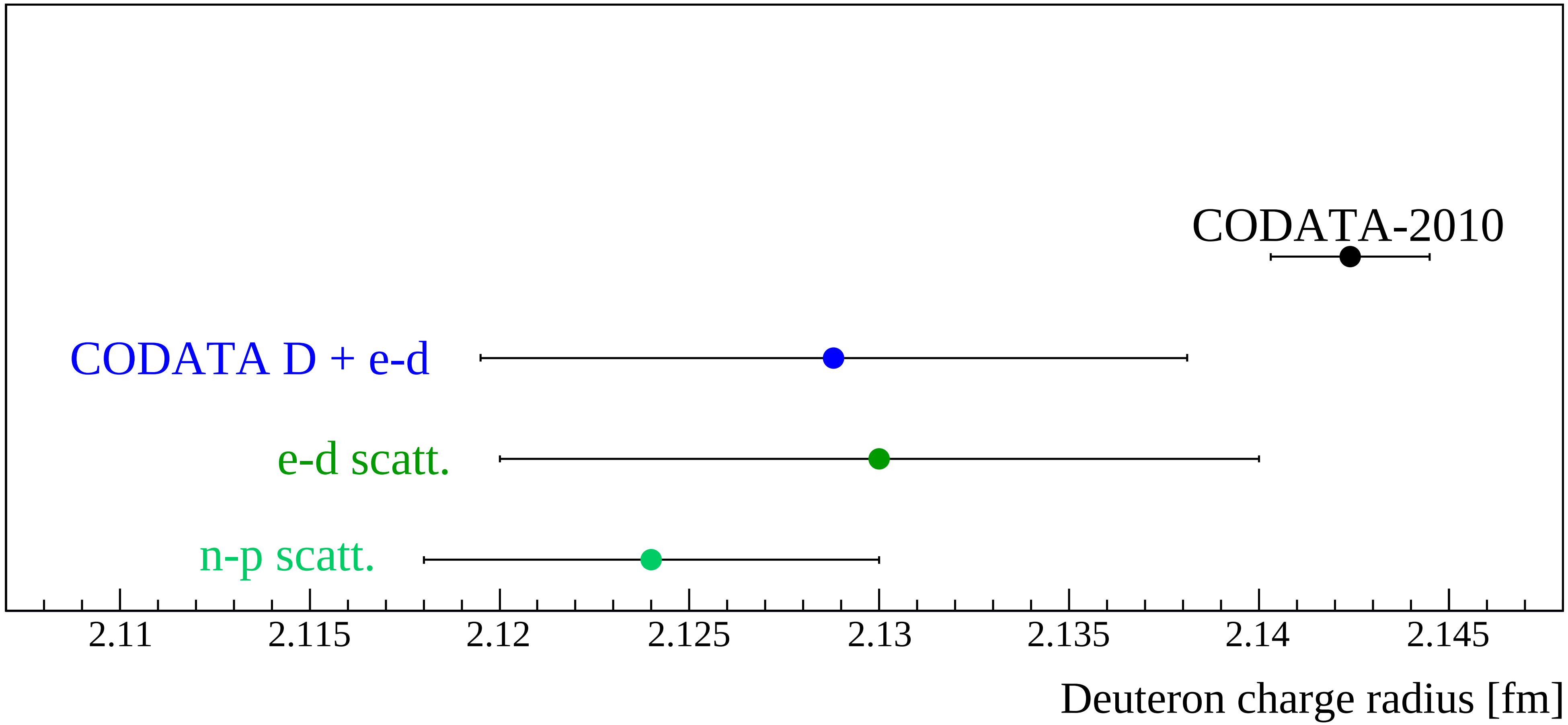
H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011).

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

Deuteron charge radius

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

CODATA 2010 r_d = 2.1424(21) fm



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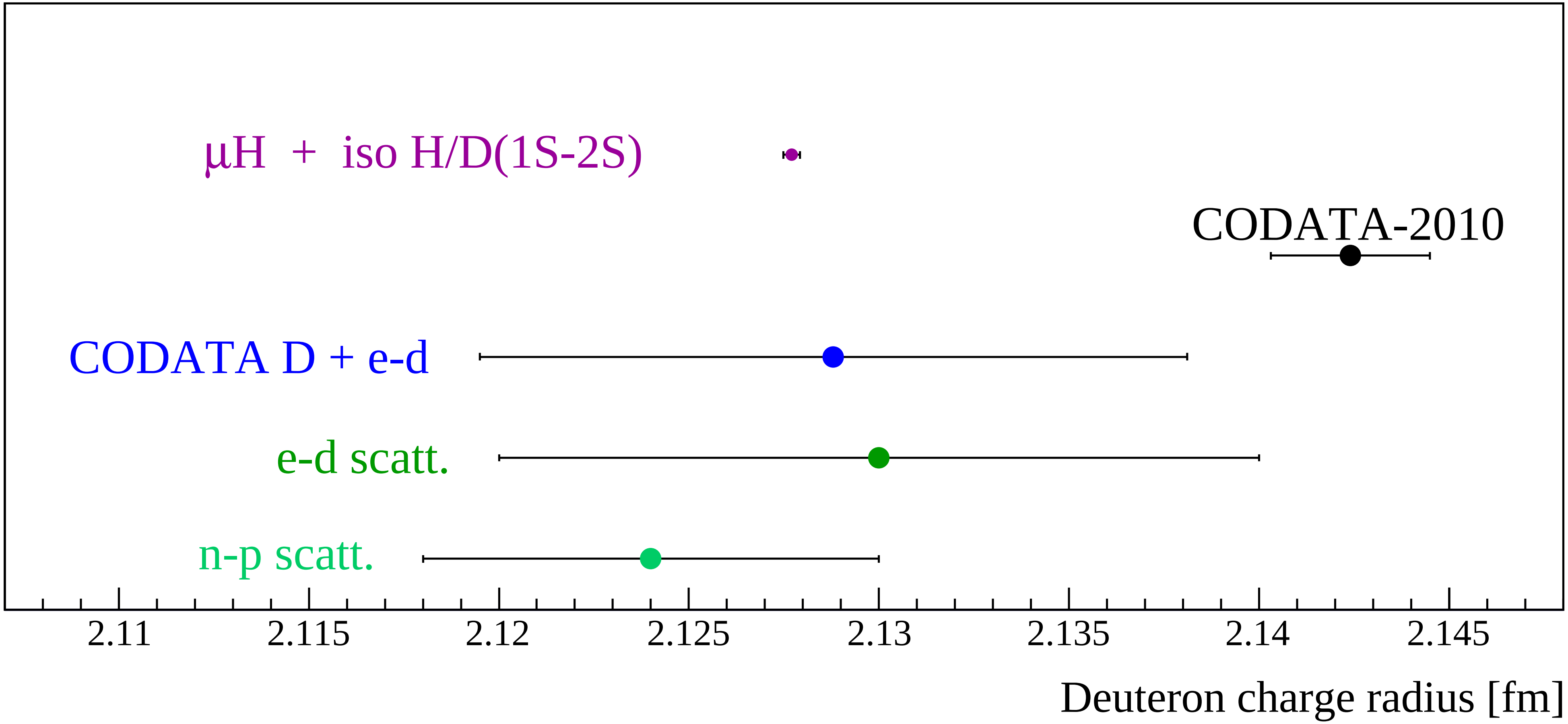
r_p= 0.84087(39) fm from μH gives r_d = 2.12771(22) fm



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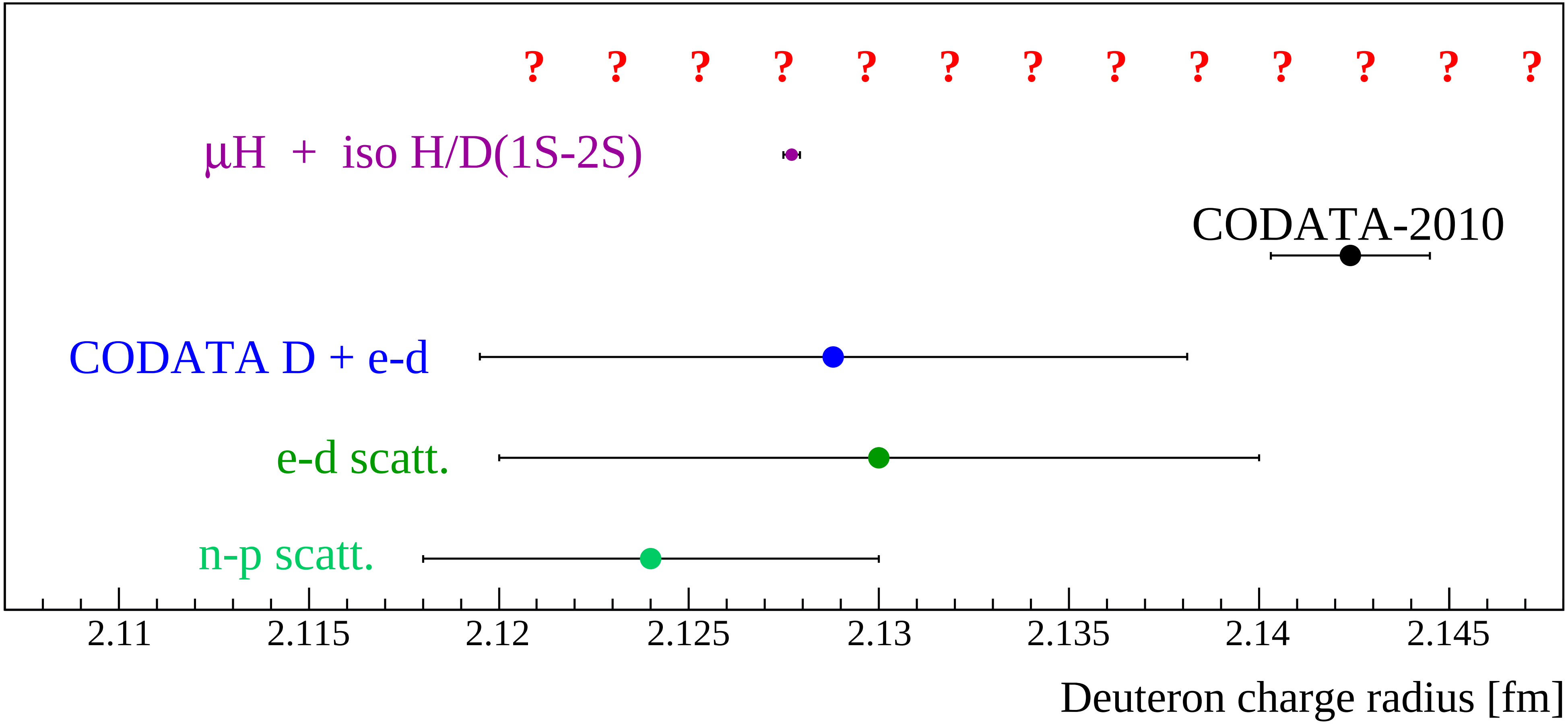
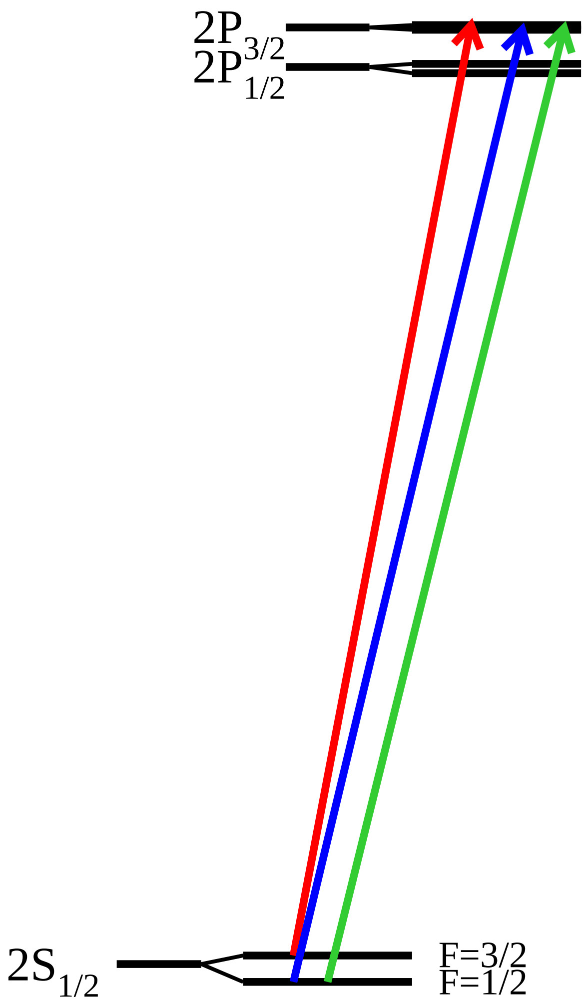
Lamb shift in muonic DEUTERIUM



muonic deuterium



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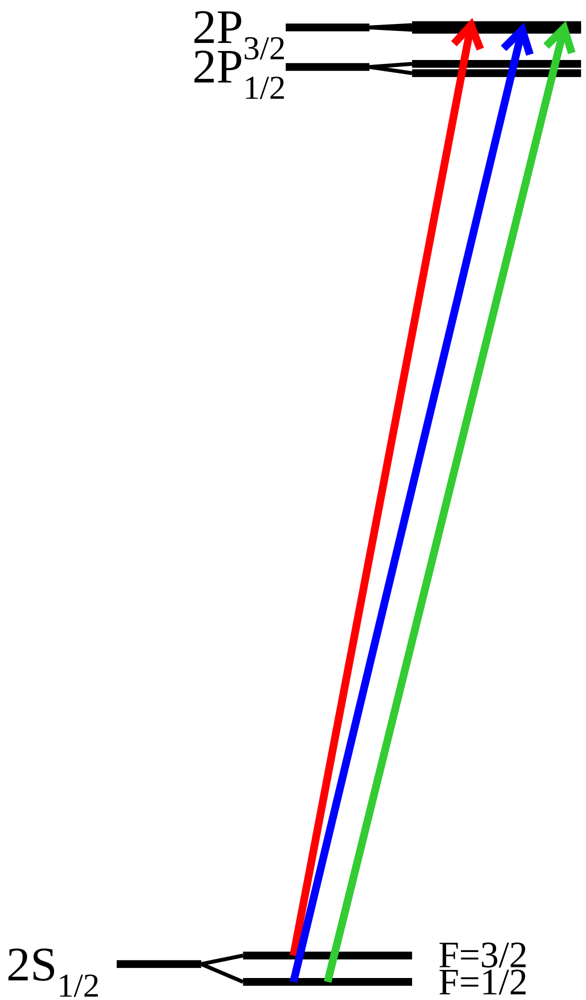
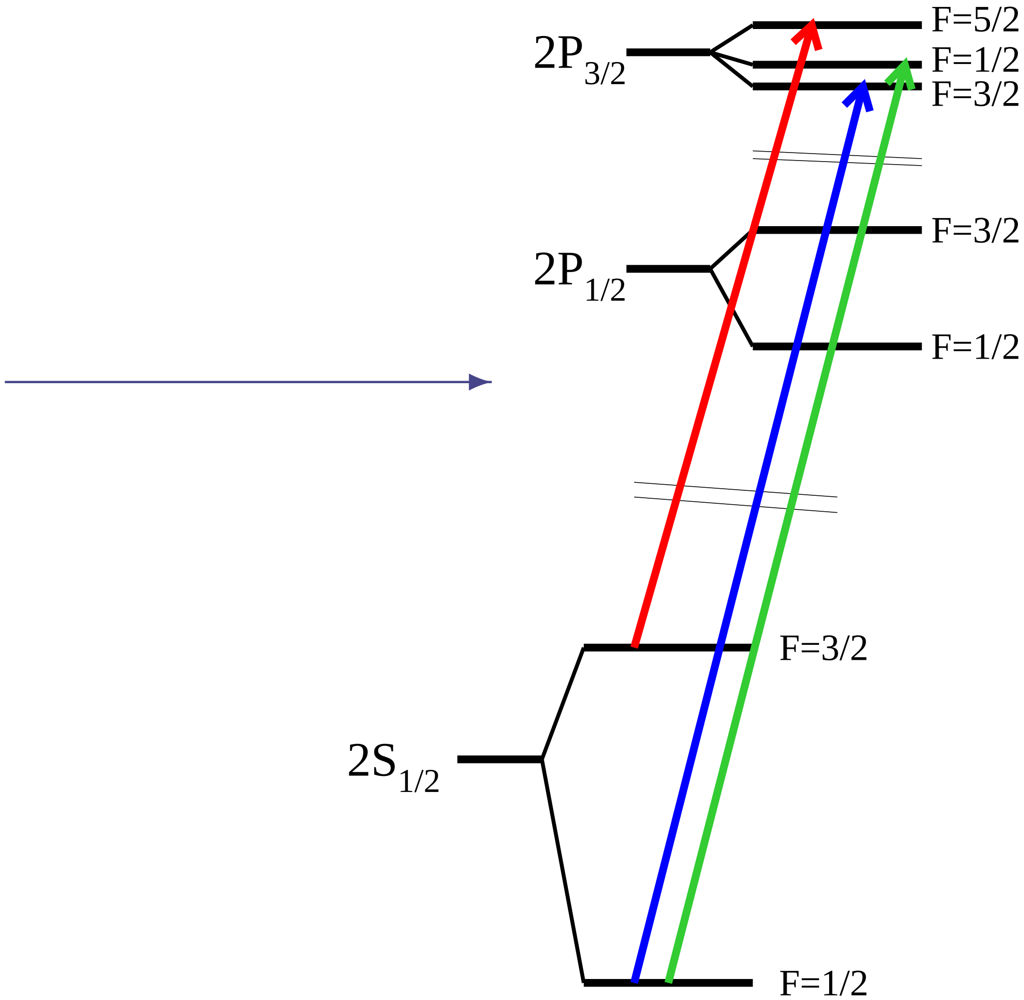
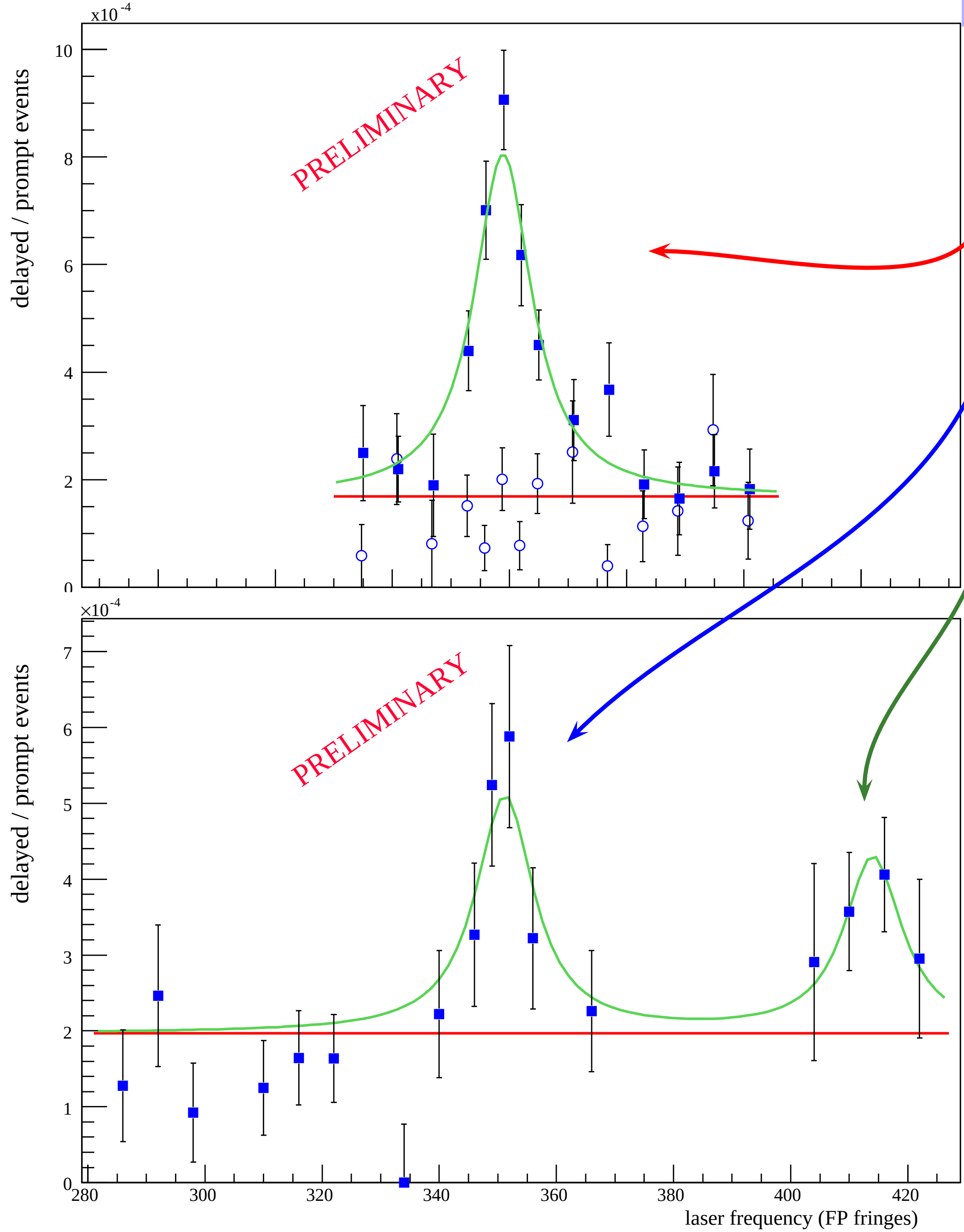


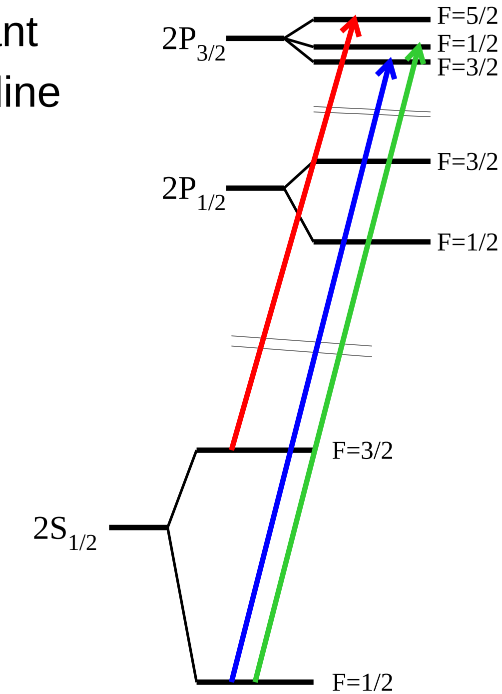


Muonic DEUTERIUM



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



Deuteron radius from μd (preliminary)

- Three transitions frequencies measured in μd
- 2P fine and hyperfine contributions from theory (no nucl. structure contributions)
  Borie, Martynenko

$\Rightarrow$ Fit Lamb shift and 2S-HFS

μd:	$\Delta E_{LS}^{exp} = 202.8759(34)$ meV (prel.!)
(μp:	$\Delta E_{LS}^{exp} = 202.3706(23)$ meV)

$\rightarrow$ similar exp. uncertainty

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Theory		QED	fin. size	TPE		
μp: ΔE_{LS}^{th}	=	206.0336(15)	- 5.2275(10) r_p^2	+ 0.0332(20) meV		
μd: ΔE_{LS}^{th}	=	228.7711(15)	- 6.1085(10) r_d^2	+ 1.6800(160) meV		Martynenko+Pachucki
	=	228.7972(15)	- 6.1094(10) r_d^2	+ 1.6800(160) meV		Borie + Pachucki
				+ 0.018 meV	relat. corr.	Ji *et al.* arXiv 1307.6577
				+ 0.040 meV	neutron pol.	Friar, arXiv 1306.3269
				+ 0.029 meV	nucleon fin.size	and Friar, priv. comm.
μd: ΔE_{LS}^{th}	=	228.7711(15)	- 6.1085(10) r_d^2	+ 1.7670(300) meV		our choice

Deuteron radius from μd (preliminary)

MPQ

- Three transitions frequencies measured in μd
- 2P fine and hyperfine contributions from theory (no nucl. structure contributions)
  Borie, Martynenko

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- Pachucki, Ji et al., and Friar agree on the 2% level
- Carlson, Gorchtein and Vanderhaegen: ongoing work using inelastic data and dispersion relations.
- to do: polarizability contribution to HFS (determined by exp.!)

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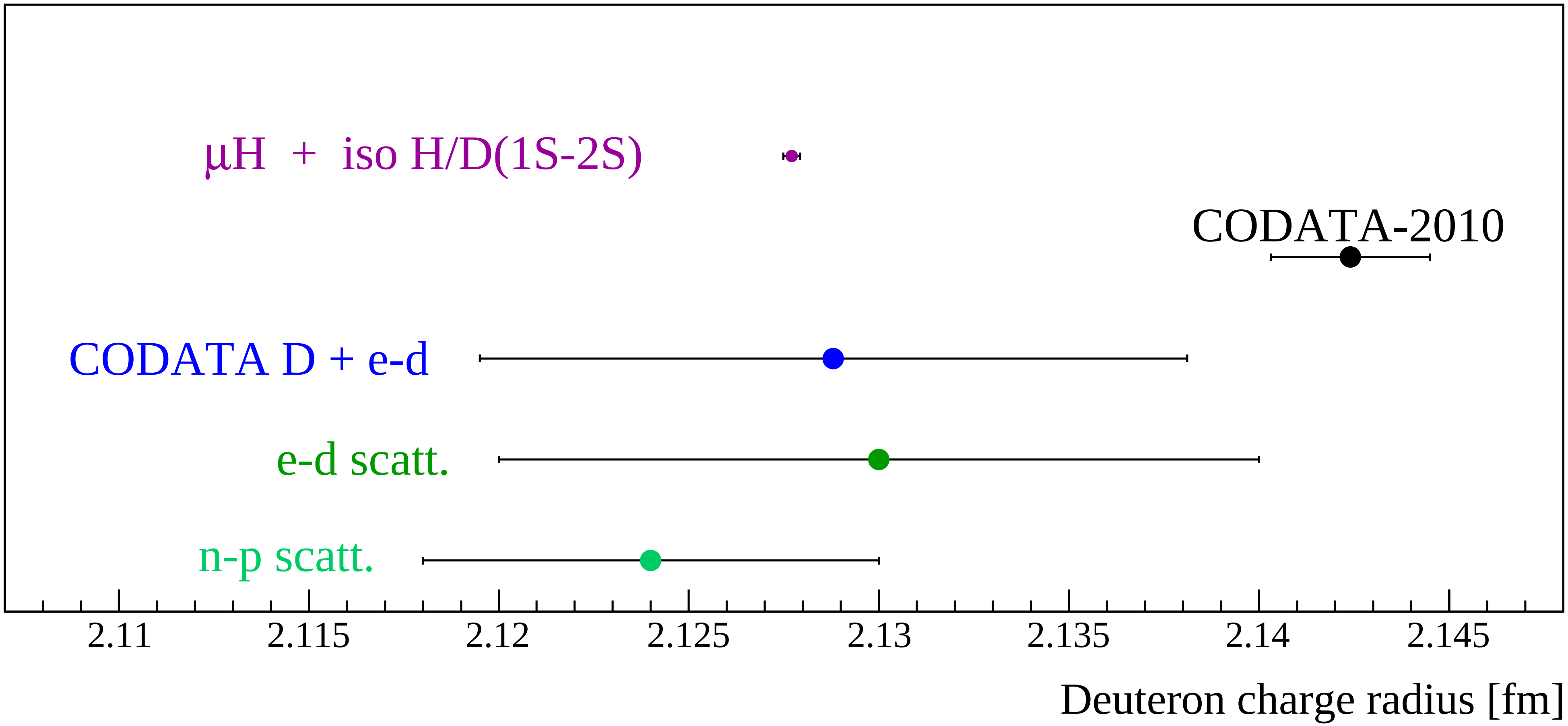


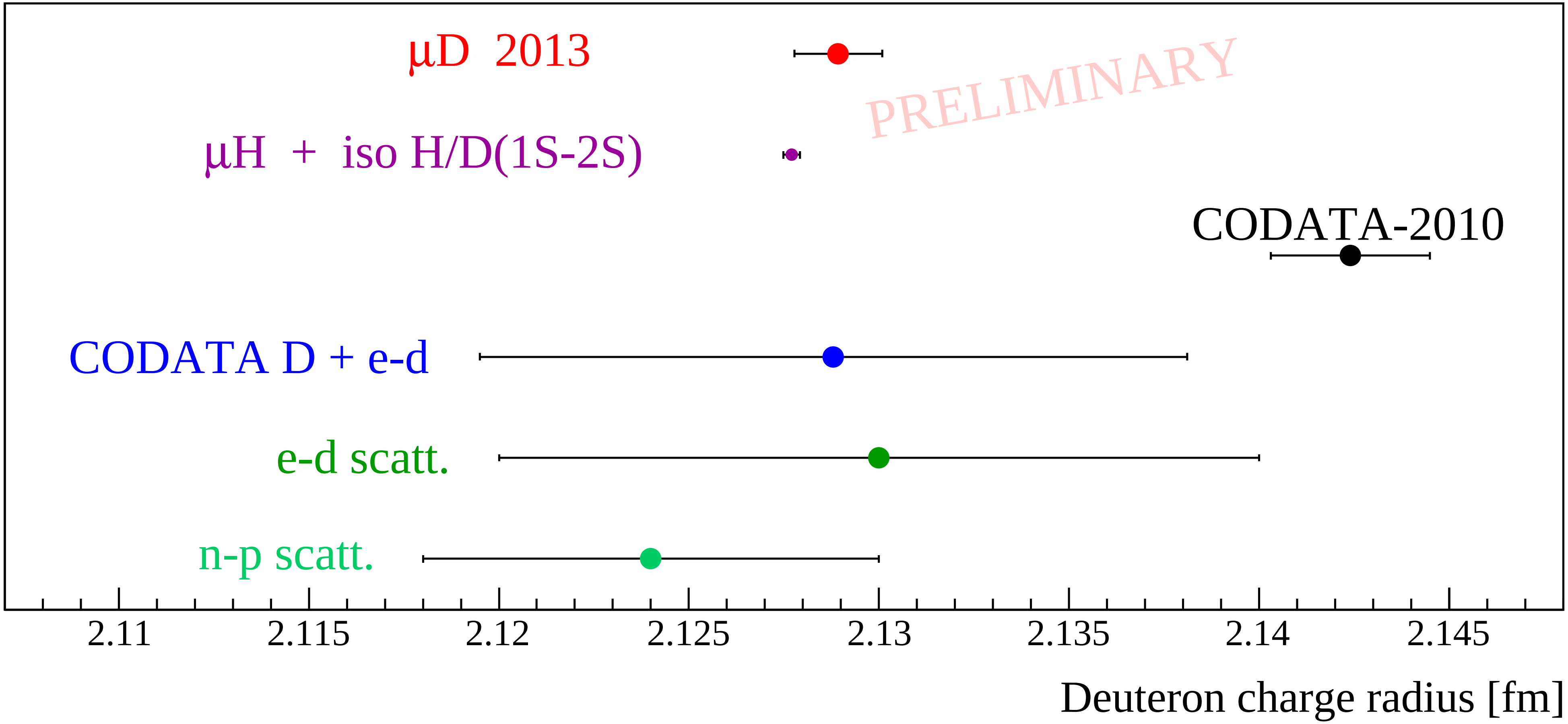
Deuteron charge radius

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

CODATA 2010 r_d = 2.1424(21) fm

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

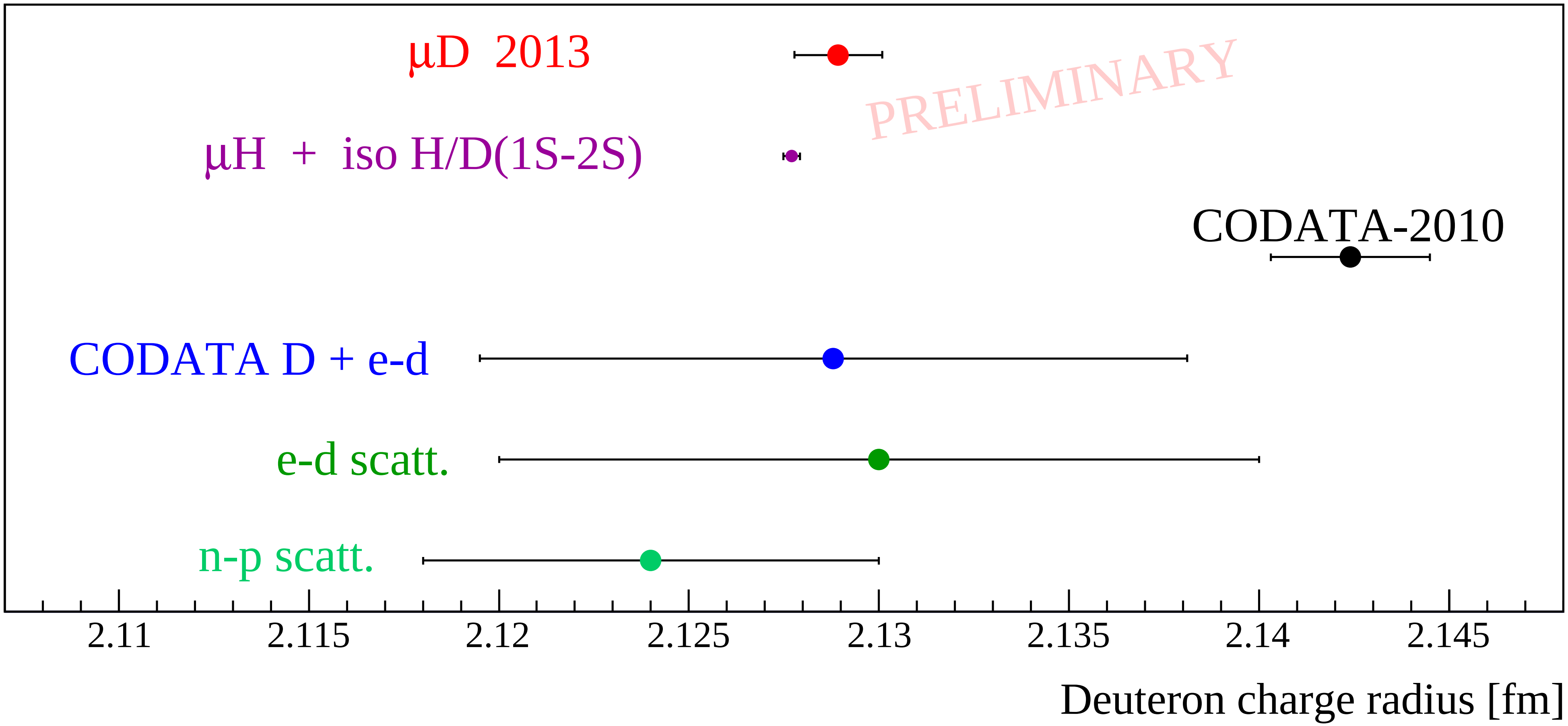
Lamb shift in muonic DEUTERIUM r_d = 2.1289(12) fm PRELIMINARY!



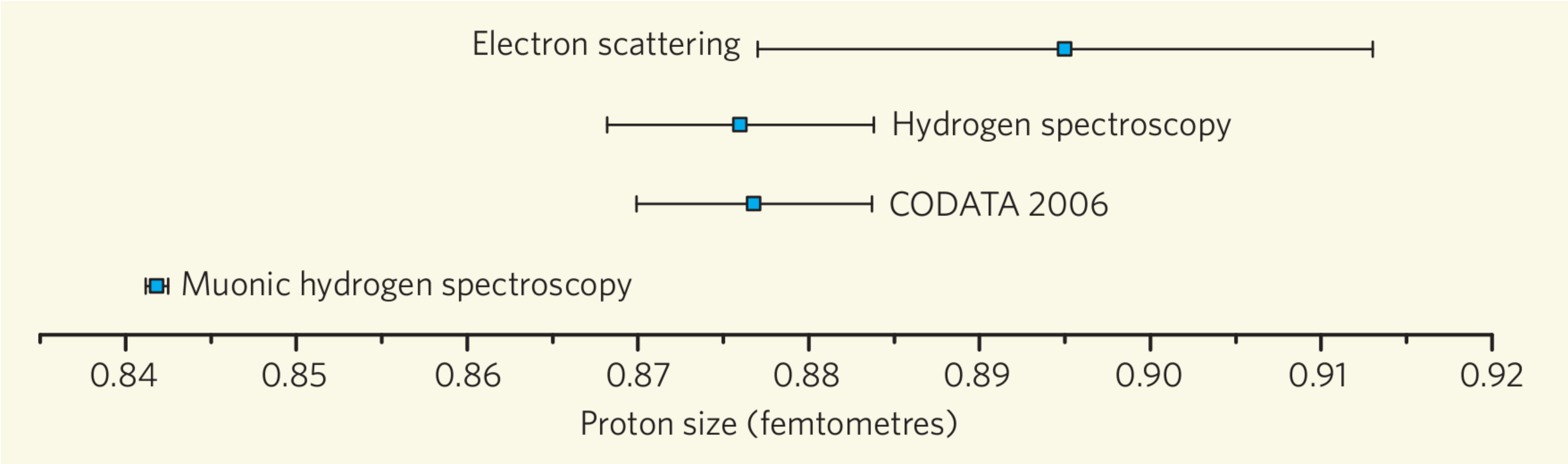
Deuteron charge radius

- μH and μD are **consistent!**

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

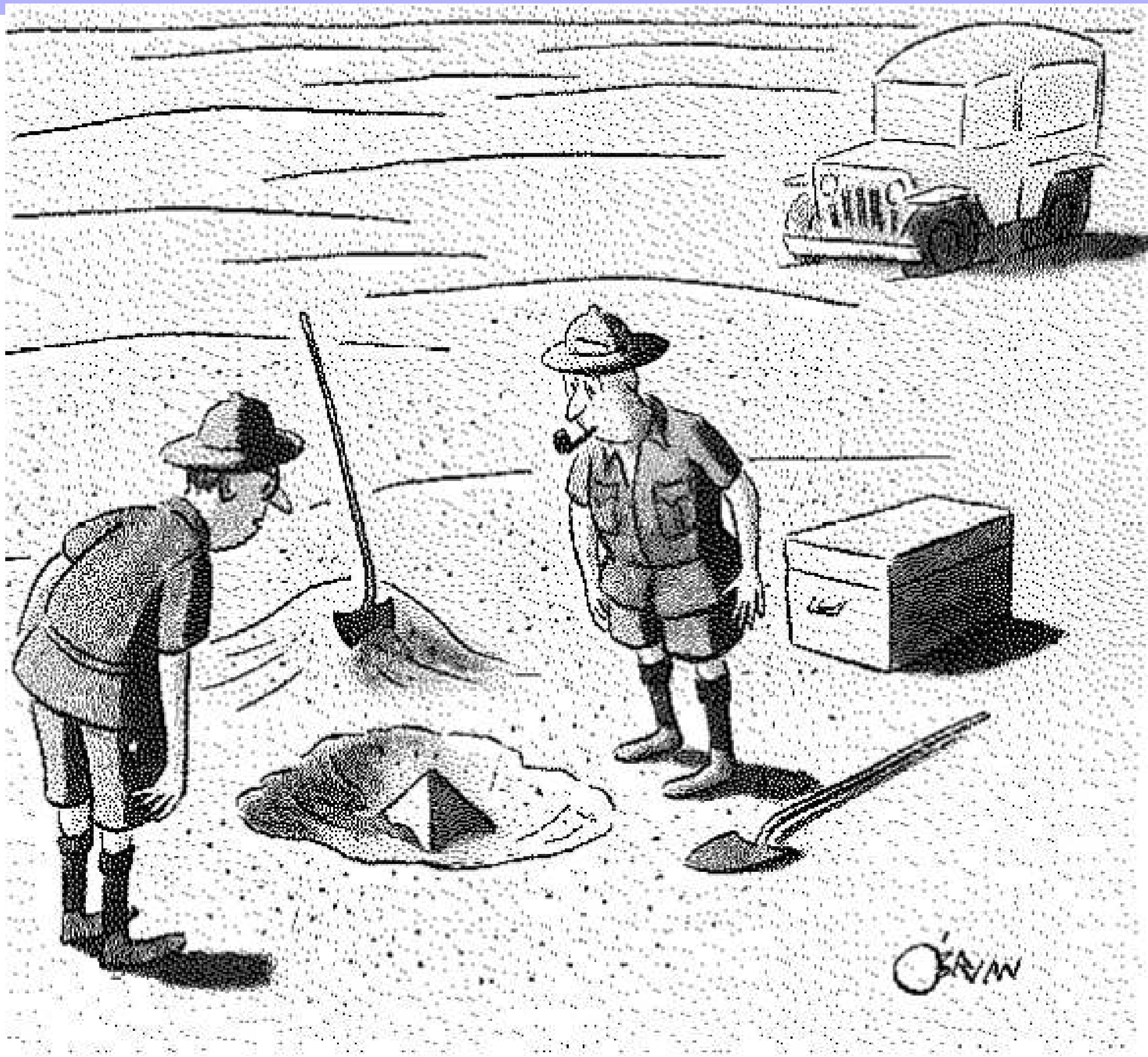


The proton radius puzzle



J. Flowers, News & Views, Nature 466, 195 (2010)

The proton radius puzzle



"This could be the discovery of the century. Depending, of course, on how far down it goes."

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. (accepted)
(arXiv 1301.0905)

What may be wrong?

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

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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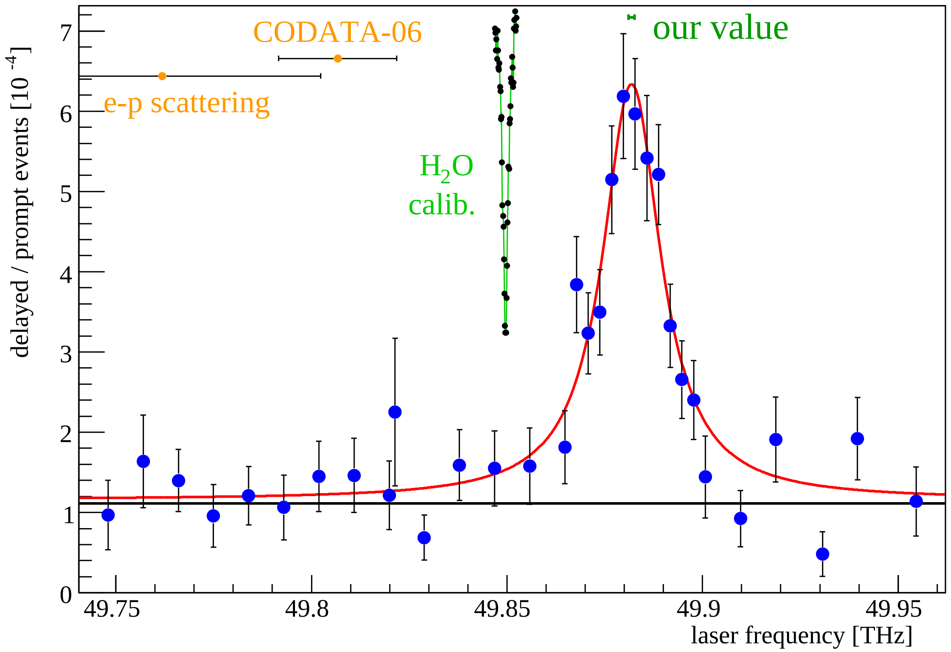
μp experiment wrong?

- Frequency mistake by 75 GHz ($\Leftrightarrow$ 0.15%)?

That is > 100 $\delta(\mu p)$! σ_{tot} = 650 MHz, [570 MHz_{stat}, 300 MHz_{syst}]

4 line widths ! Γ = 19 GHz

2 resonances in μp give the same r_p



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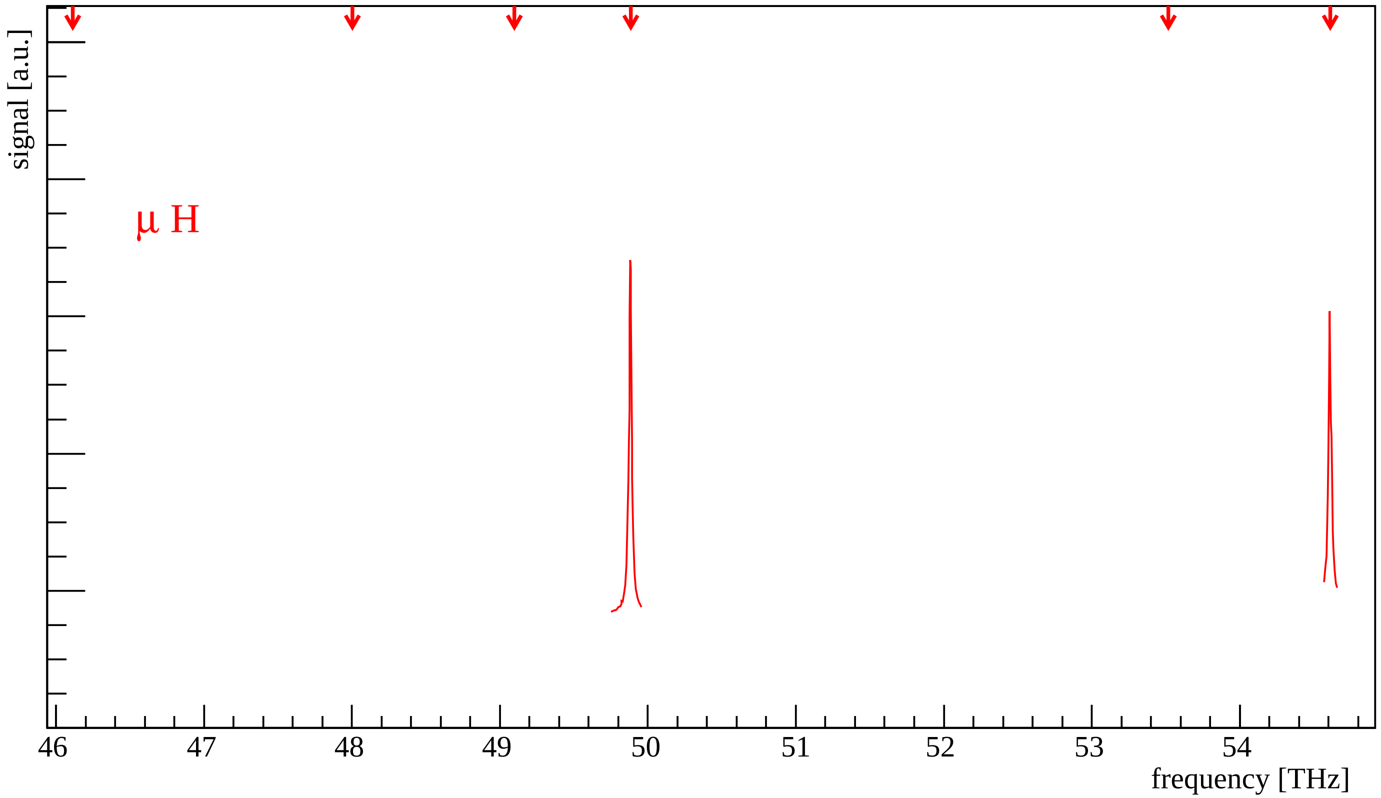
- Wrong transition?

FS, HFS huge.

Next transition:
$\sim$ 1 THz away.



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- Wrong transition?
- Systematic error?

Laser frequency ($H_2$0 calibration)	300 MHz
intrinsic H_2O uncertainty	2 MHz
AC and DC stark shift	< 1 MHz
Zeeman shift (5 Tesla)	< 30 MHz
Doppler shift	< 1 MHz
Collisional shift	2 MHz
	300 MHz

μp atom is small and not easily perturbed by external fields.

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- Wrong transition?
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- Molecular effects?

  $p\ \mu\ e$ molecular ion? U.D. Jentschura, Annals of Physics 326, 516 (2011).

  Does not exist! J.-P. Karr, L. Hilico, PRL 109, 103401 (2012).

  Experimentally:

  - only 1 line observed ($>$ 80 % population)
  - expected width
  - $pp\mu$ ion short-lived R. Pohl *et al.*, PRL 97, 193402 (2006).

What may be wrong?

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- Frequency mistake by 75 GHz ($\Leftrightarrow 0.15\%$)?
- Wrong transition?
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- Molecular effects?
- Gas imputities?

  Target gas contained 0.55(5) % air (leak).

  Back-of-the-envelope calculation:

  collision rate $\lambda \approx 6 \cdot 10^3 s^{-1}$
  2S lifetime $\tau(2S) = 1\,\mu$s

  $\Rightarrow$ Less than 1% of all μp(2S) atoms see any N_2

What may be wrong?

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μp experiment probably not wrong by 100 σ

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$$\Delta E = 206.0668(25) - 5.2275(10)\, r_p^2 \ \text{[meV]}$$

Discrepancy = 0.31 meV
Theory uncert. = 0.0025 meV

$\Longrightarrow$ $120\delta(\text{theory})$ deviation

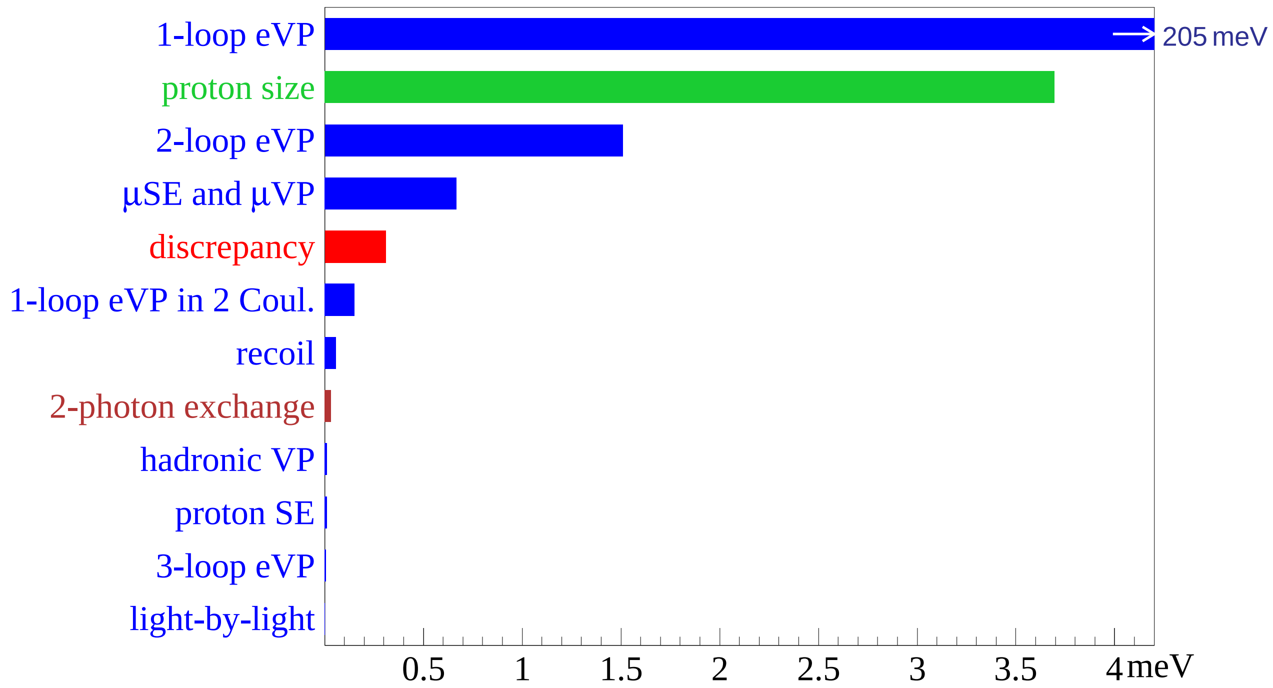
double-checked by many groups

5$^{\text{th}}$ largest term!

Theory summary:

A. Antognini, RP *et al.*
Annals of Physics 331, 127 (2013)

Some contributions to the μp Lamb shift



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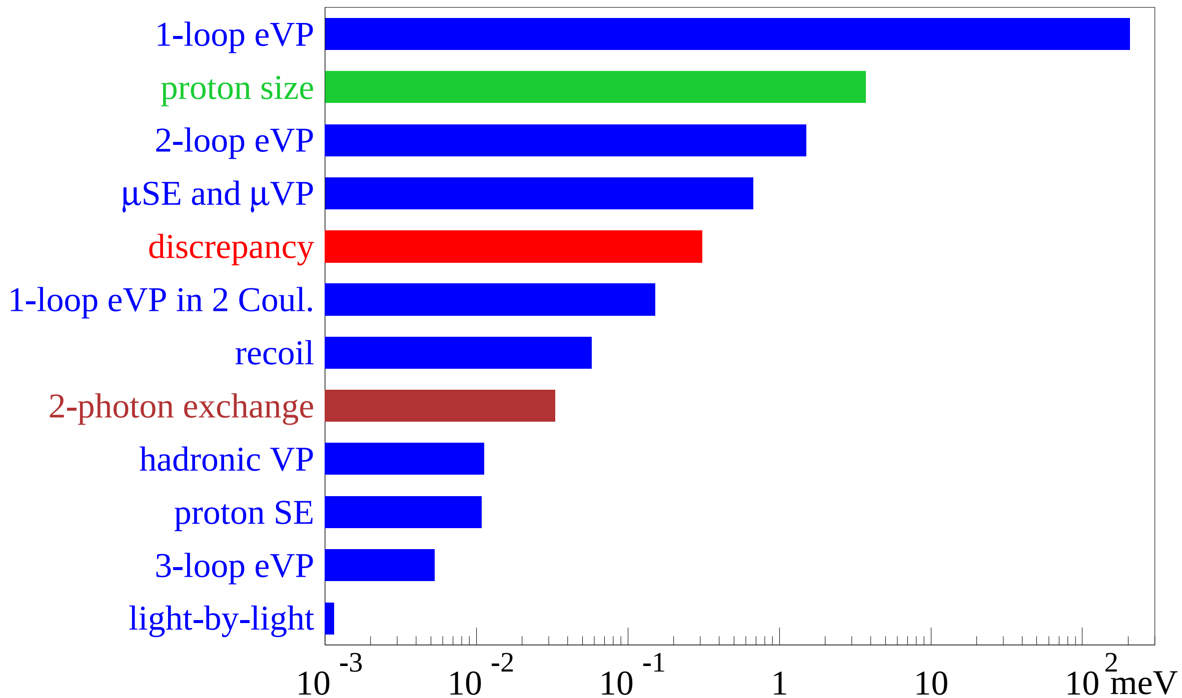

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Discussions: 3rd Zemach moment

- PLB **693**, 555 De Rujula: *"QED is not endangered by the proton's size"* *(1008.3861)*

  A large third Zemach moment $\langle r_p^3 \rangle_{(2)} = \int d^3r_1\, d^3r_2\, \rho(r1)\, \rho(r_2)\, |r_1 - r_2|^3$

  of the proton can explain all three measurements: μp, H, e-p

  $\rho(r)$ is not a simple Dipole, but has "core" and "tail"

- PRC **83**, 012201 Cloet, Miller: *"Third Zemach moment of the proton"* *(1008.4345)*

  Such a large third Zemach moment is impossible.

  $\langle r_p^3 \rangle_{(2)}$ (De Rujula) = 36.6 ± 6.9 fm^3

  $\langle r_p^3 \rangle_{(2)}$ (Sick) = 2.71 ± 0.13 fm^3

- PLB **696**, 343 Distler *et al*: *"The RMS radius of the proton and Zemach moments"* (1011.1861)

  $\langle r_p^3 \rangle_{(2)}$ (Mainz 2010) = 2.85 ± 0.08 fm^3

Discussions: New Physics

- PRD **82**, 125020 (2010) Jaeckel, Roy:
  "Spectroscopy as a test of Coulomb's law - A probe of the hidden sector" (1008.3536)

  hidden photons, minicharged particles $\rightarrow$ deviations from Coulomb's law.

  μp transition can NOT be explained this. (contradicts Lamb shift in H)

- Ann. Phys. **326**, 516 (2011) Jentschura:
  "Lamb shift in muonic hydrogen – II. Analysis of the discrepancy of theory and experiment" (1011.5453)

  no millicharged particles, no unstable neutral vector boson

- PRL **106**, 153001 (2011) Barger, Chiang, Keung, Marfatia:
  "Proton size anomaly" (1011.3519)

  decay of Υ, J/ψ, π^0, η, neutron scattering, muon g-2, μ^{24}Mg, μ^{28}Si

  $\Rightarrow$ It's NOT a new flavor-conserving spin-0, 1 or 2 particle

- PRD **83**, 101702 (2011) Tucker-Smith, Yavin:
  "Muonic hydrogen and MeV forces" (1011.4922)

  MeV force carrier can explain discrepancies for r_p and $(g\text{-}2)_\mu$
  IF coupling to e, n is suppressed relative to coupling to μ, p
  prediction for μHe$^+$, $\mu^+\mu^-$

Discussions: New Physics

- PRL **107**, 011803 (2011) Batell, McKeen, Pospelov:
  "New Parity-violating muonic forces and the proton charge radius" (1103.0721)

  10...100 MeV heavy photon ("light Higgs") can explain r_p and $(g\text{-}2)_\mu$
  prediction for μHe$^+$, enhanced PNC in muonic systems

- PRL **108**, 081802 (2011) Barger, Chiang, Keung, Marfatia:
  "Constraint on Parity-violating muonic forces" (1109.6652)

  No missing mass events observed in leptonic Kaon decay.
  $\Rightarrow$ contraints on light Higgs.

- PRD **86**, 035013 (2012) C.E. Carlson, B.C. Rislow:
  "New physics and the proton radius problem" (1206.3587)

  "New physics with fine-tuned couplings may be entertained as a possible explanation for the Lamb shift discrepancy."

Discussions: New Physics

- 1303.4885 Wang, Ni: *“Proton puzzle and large extra dimensions”*

  Large Extra Dimensions

  “Extra gravitational force between the proton and the muon at very short range provides an energy shift which accounts for the discrepancy...”

- 1303.5146 Li, Chen: *“Can large extra dimensions solve the proton radius puzzle?”*

  “We find that such effect could be produced by four or more large extra dimensions which are allowed by the current constraints from low energy physics.”

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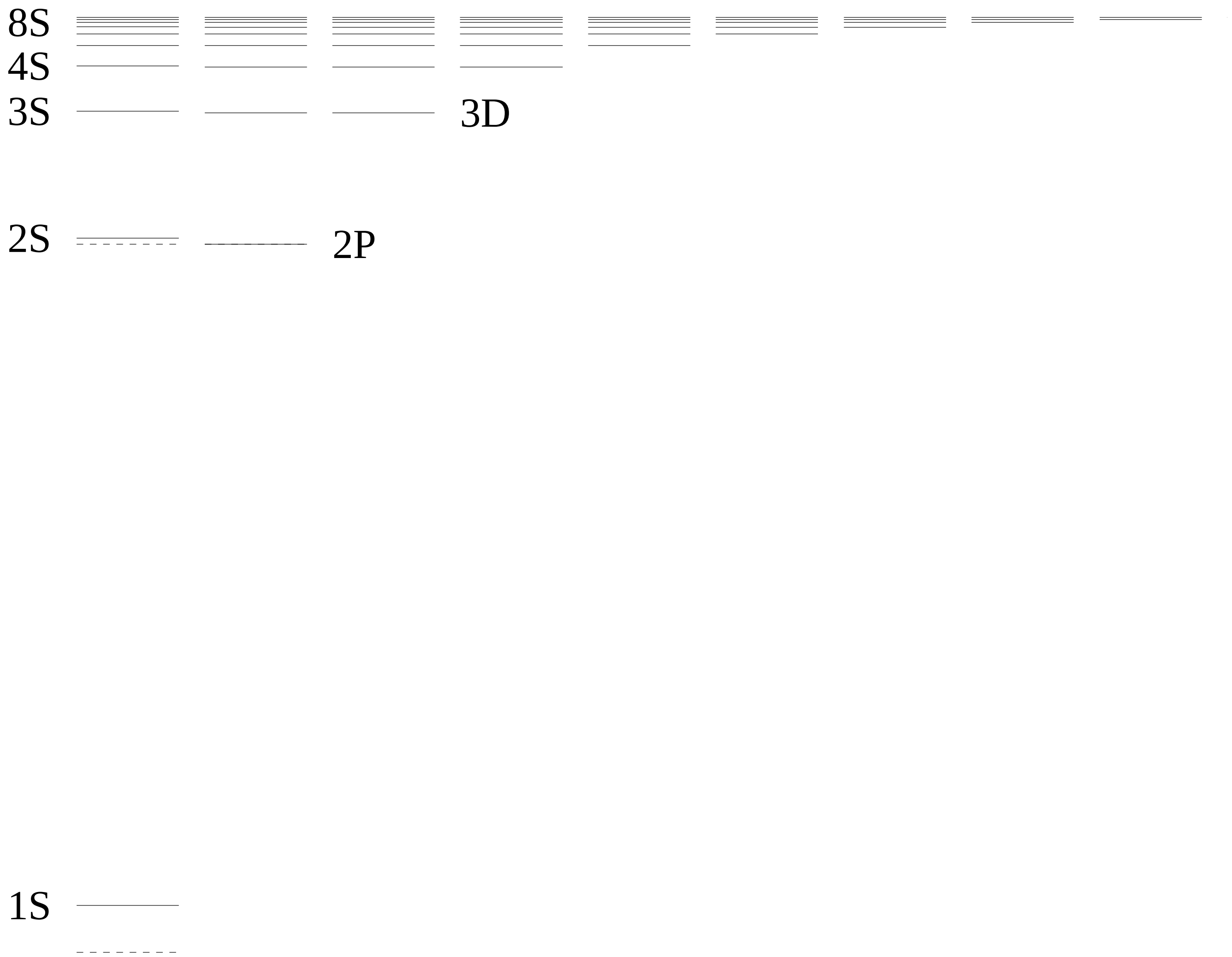
Hydrogen spectroscopy

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

$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$



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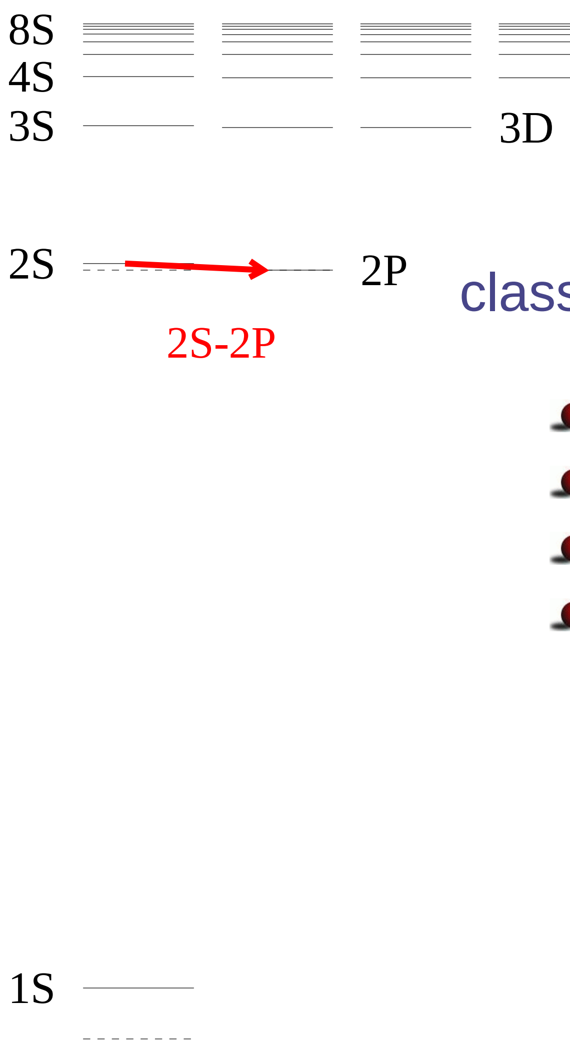
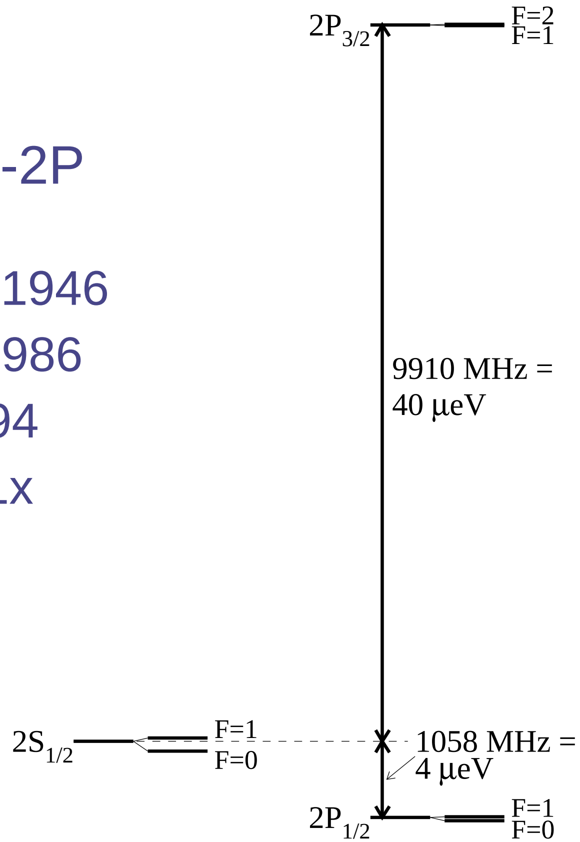


classical Lamb shift: 2S-2P

- Lamb, Retherford 1946
- Lundeen, Pipkin 1986
- Hagley, Pipkin 1994
- Hessels *et al.*, 201x



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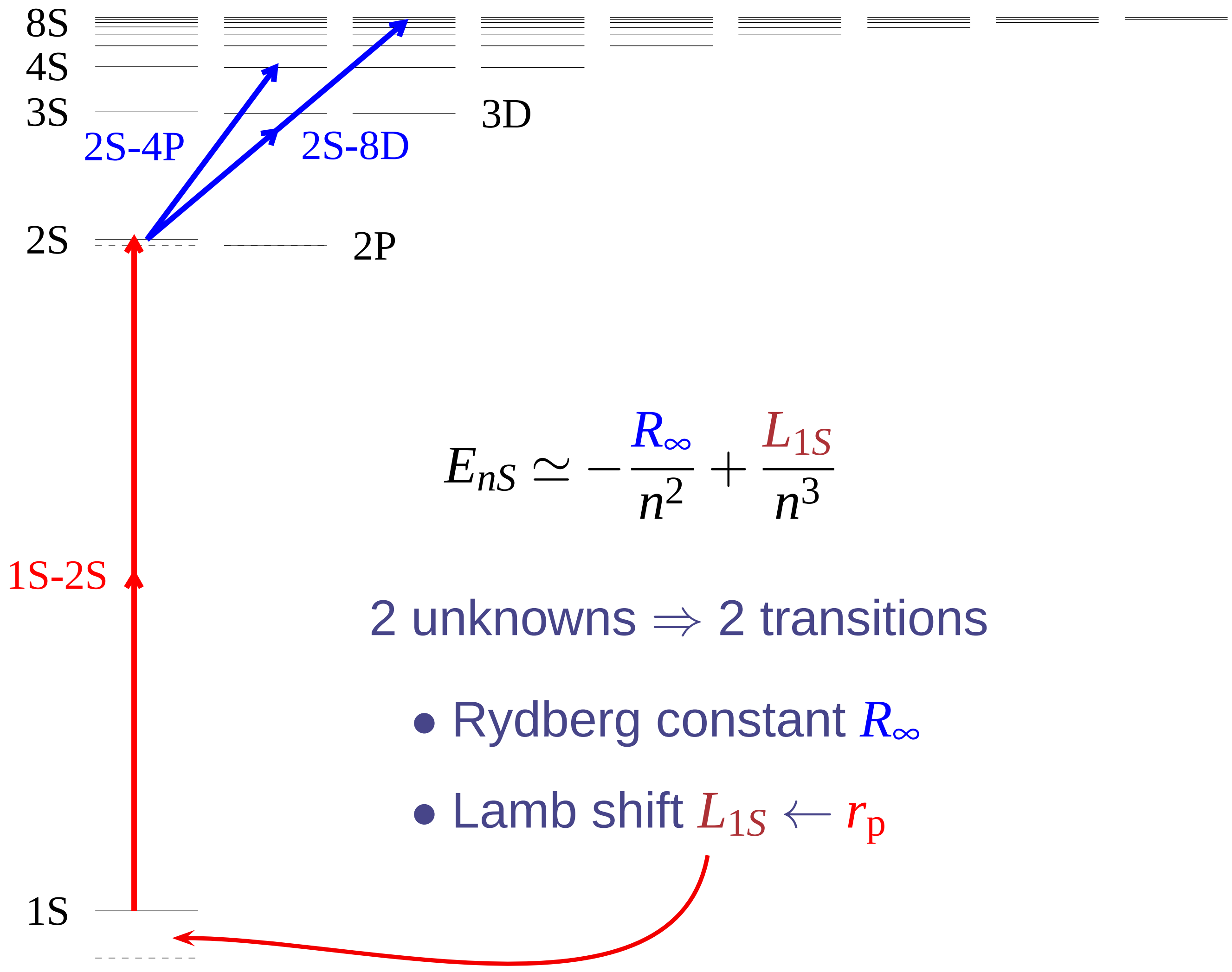
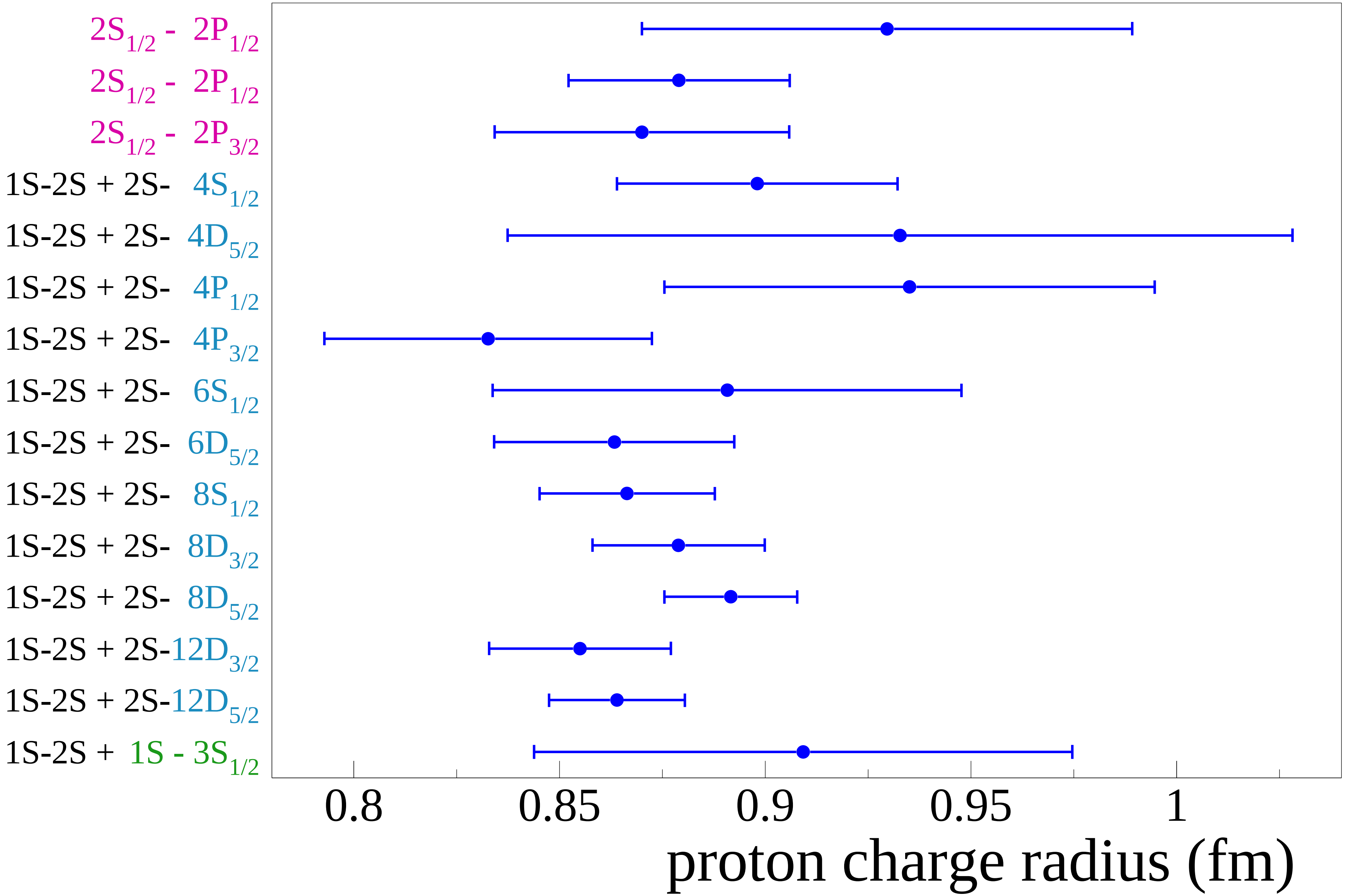


$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns $\Rightarrow$ 2 transitions

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

Hydrogen spectroscopy



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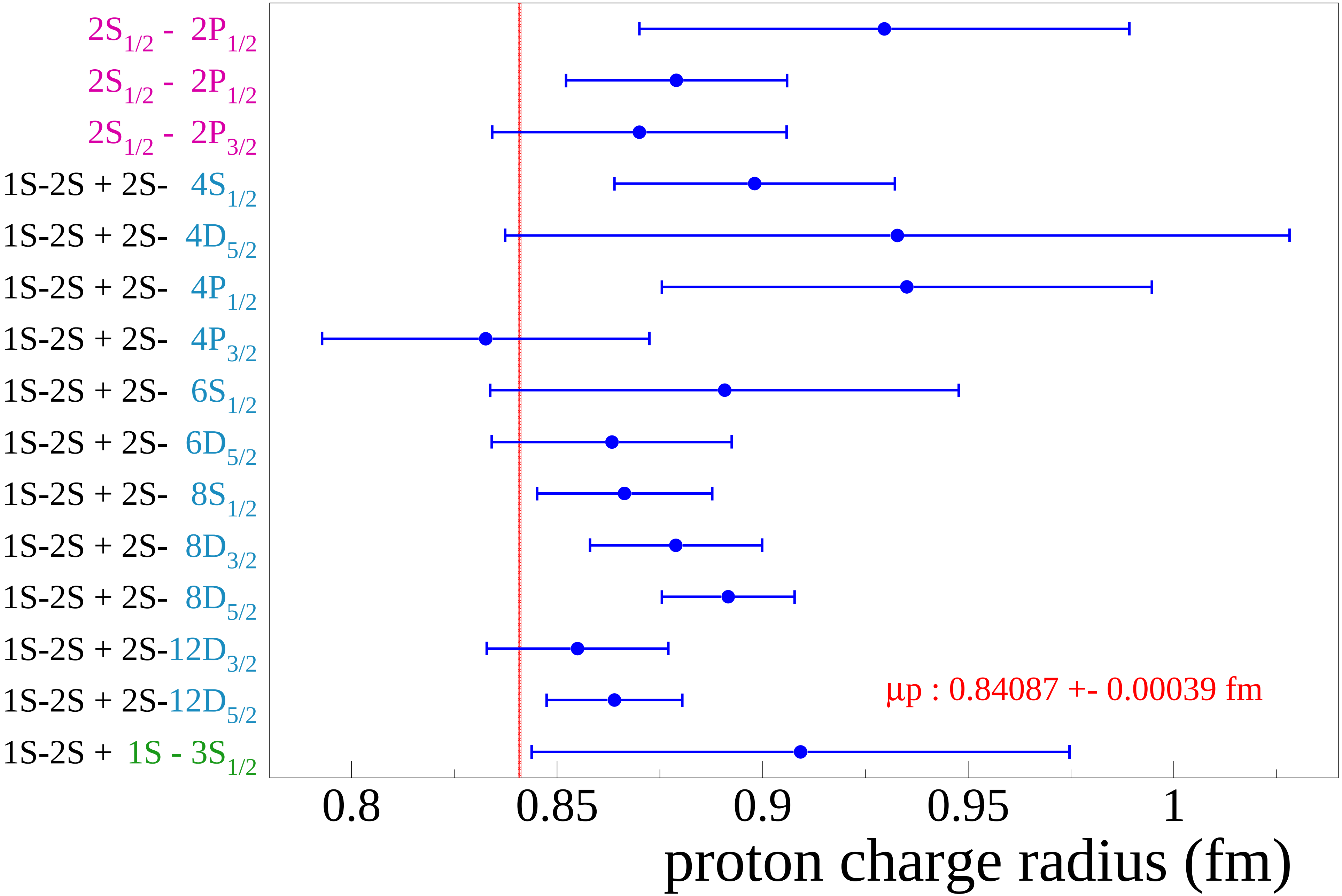

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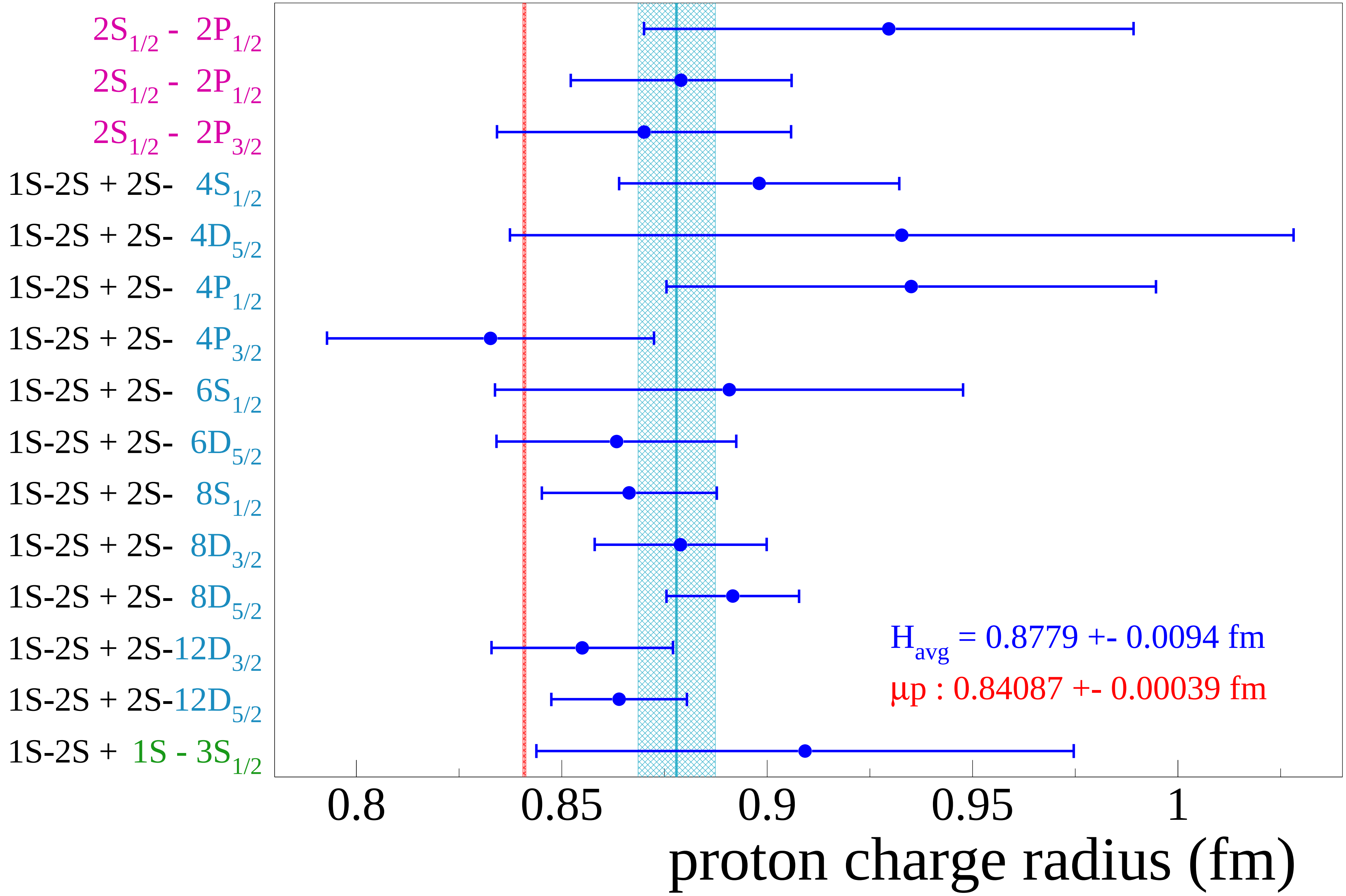

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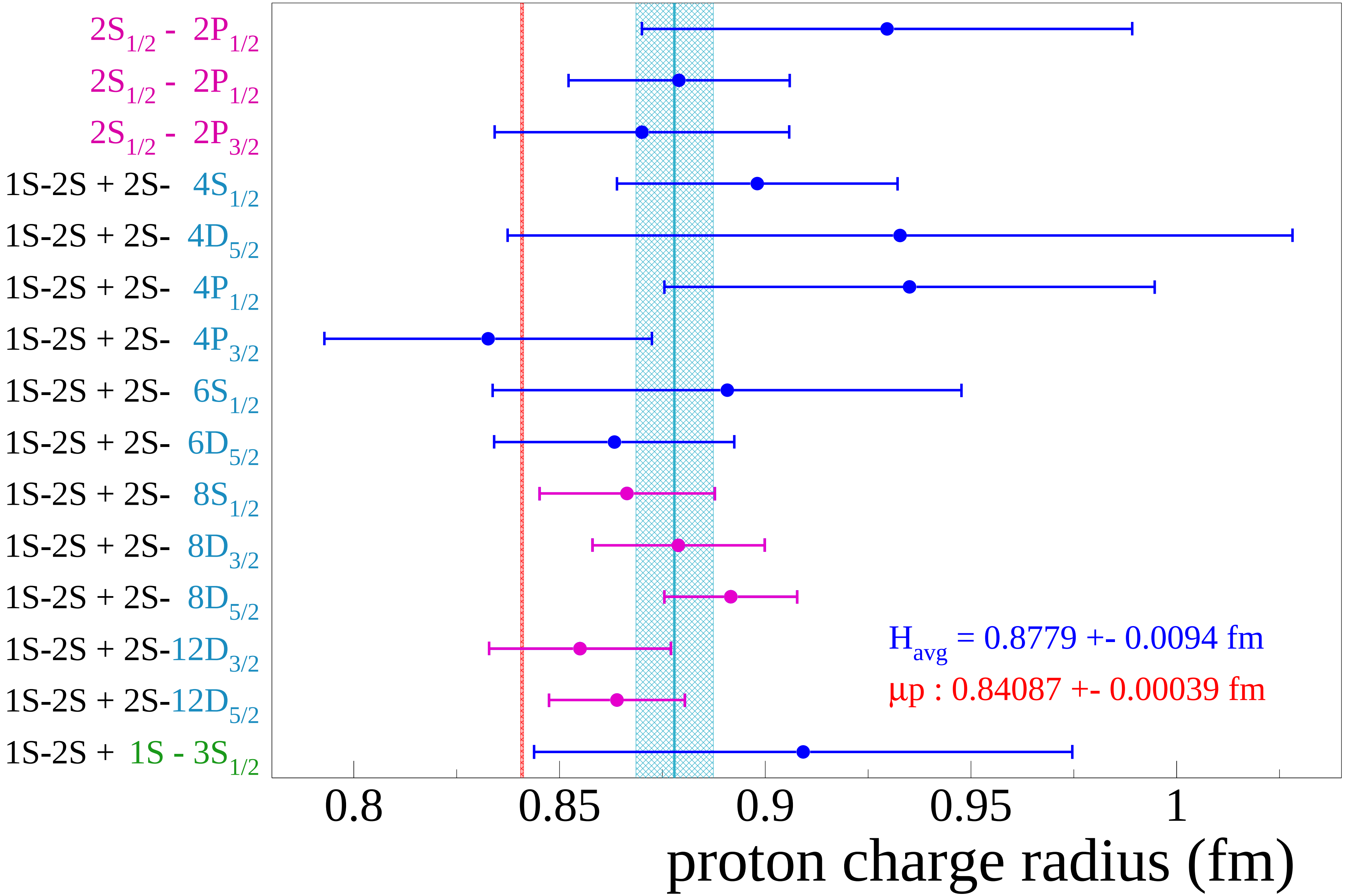

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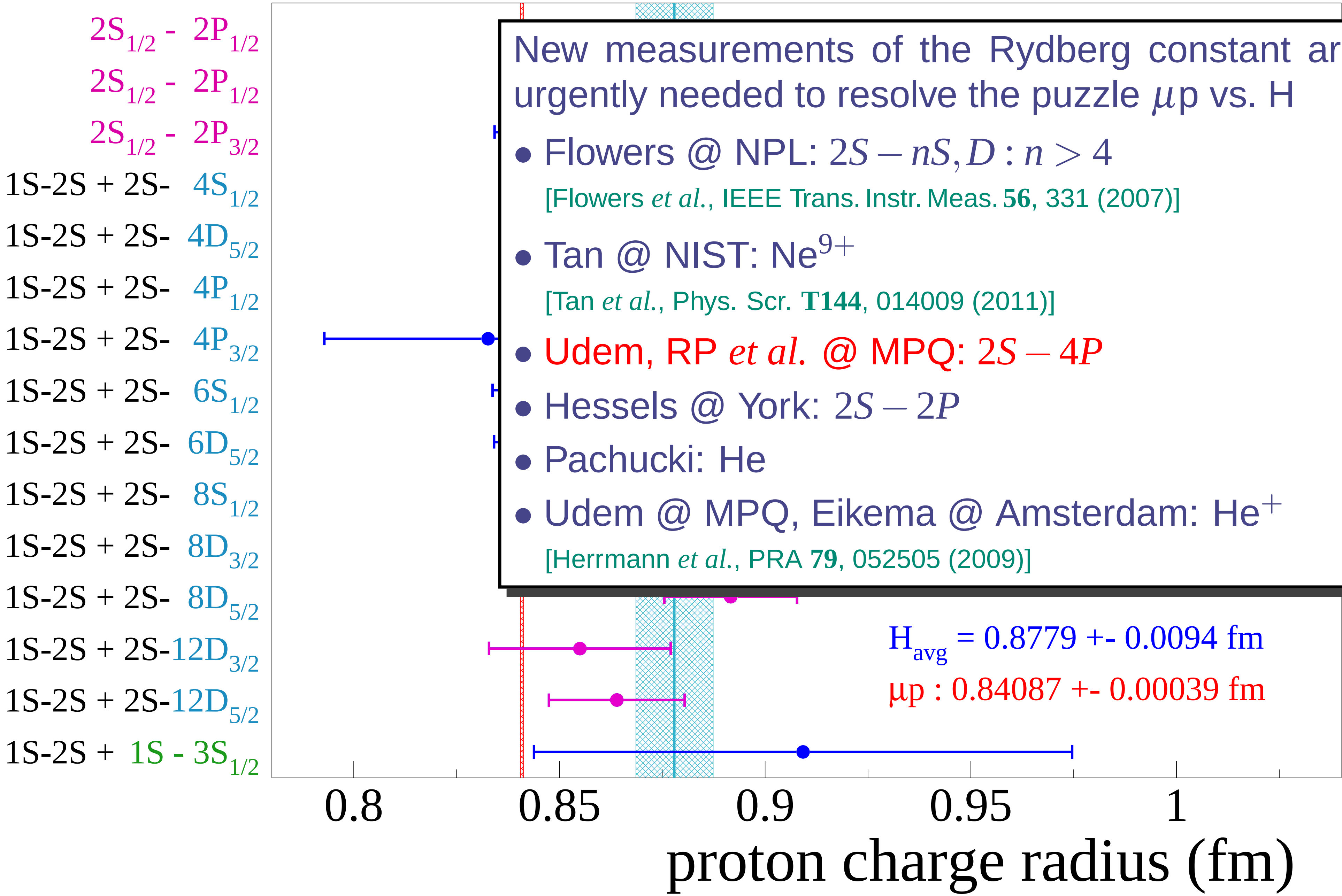
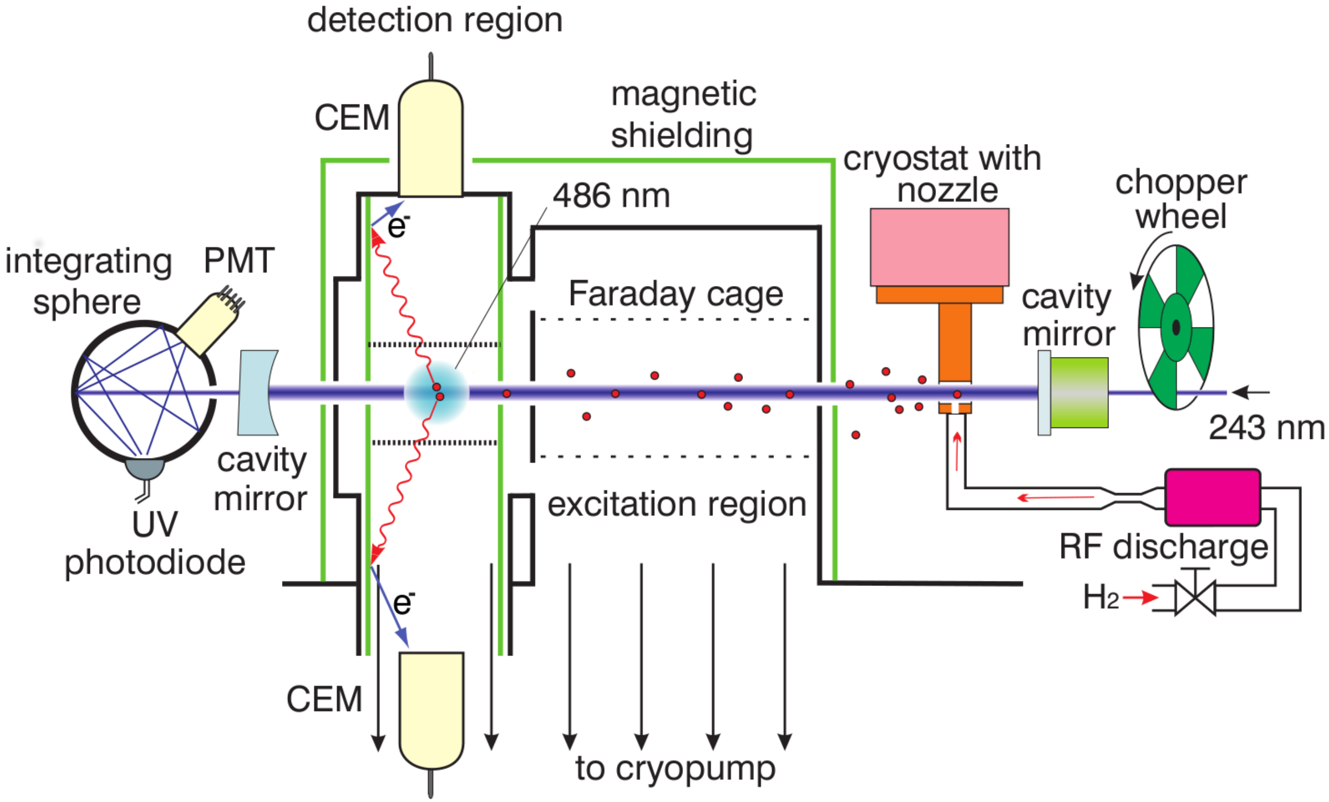


New measurements of the Rydberg constant are urgently needed to resolve the puzzle μp vs. H

- Flowers @ NPL: $2S - nS, D : n > 4$
  [Flowers *et al.*, IEEE Trans. Instr. Meas. **56**, 331 (2007)]
- Tan @ NIST: Ne^{9+}
  [Tan *et al.*, Phys. Scr. **T144**, 014009 (2011)]
- Udem, RP *et al.* @ MPQ: $2S - 4P$
- Hessels @ York: $2S - 2P$
- Pachucki: He
- Udem @ MPQ, Eikema @ Amsterdam: He^{+}
  [Herrmann *et al.*, PRA **79**, 052505 (2009)]

Rydberg constant from hydrogen



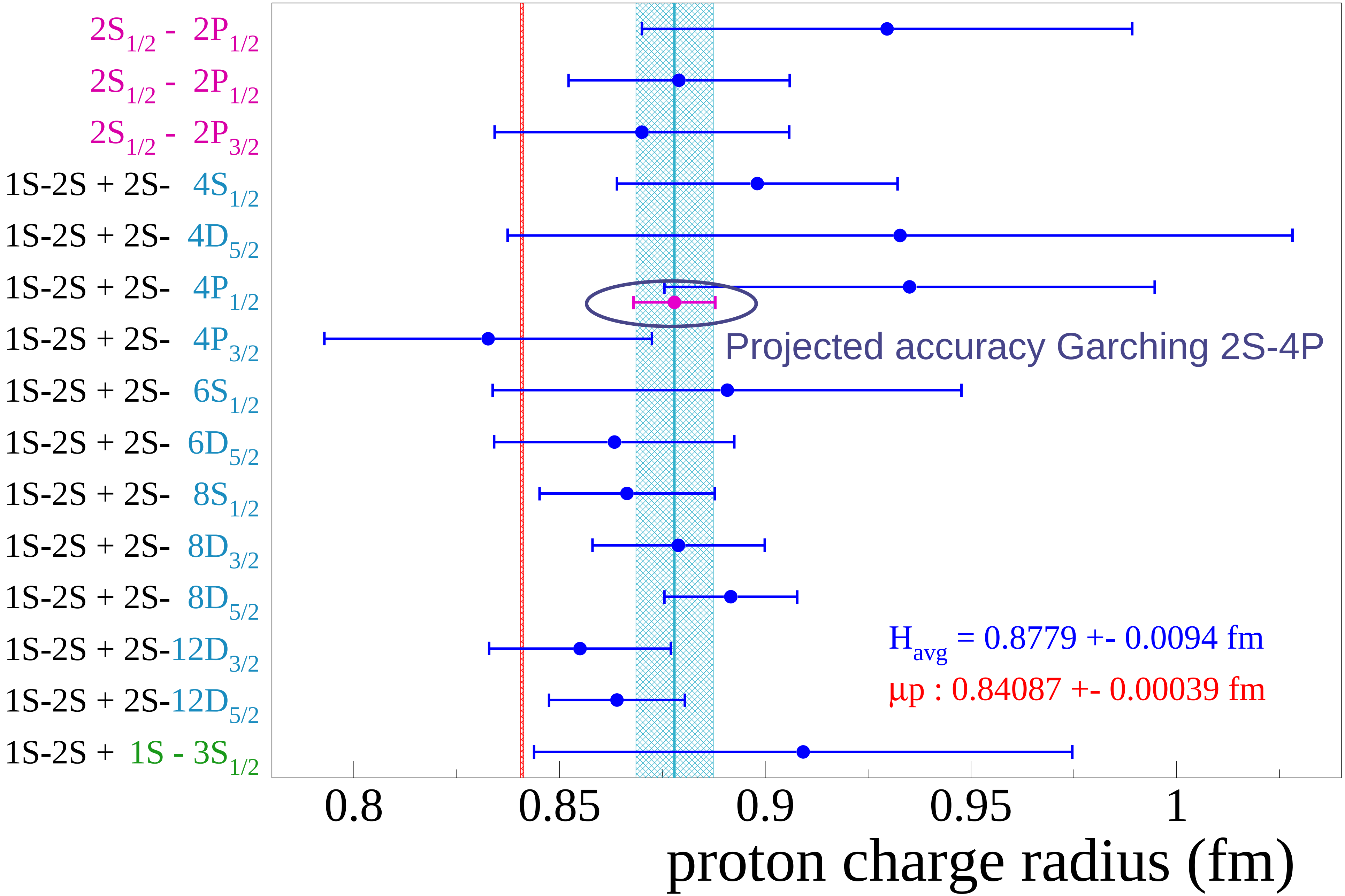
A. Beyer, C.G. Parthey, A. Matveev, J. Alnis, RP, N. Kolachevsky, Th. Udem and T.W. Hänsch

- Apparatus used for H/D(1S-2S)

  C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)
  C.G. Parthey, RP *et al.*, PRL **107**, 203001 (2011)

- 486 nm at 90° + Retroreflector $\Rightarrow$ Doppler-free 2S-4P excitation
- 1st oder Doppler vs. ac-Stark shift
- $\sim$ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic** H beam, **optical** excitation to 2S

Hydrogen spectroscopy



Summary

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

    $$R_\infty = 3.289\,841\,960\,249\,5\;(10)^{\mathrm{radius}}\;(25)^{\mathrm{QED}}\;\times 10^{15}\;\mathrm{Hz/c}$$
  - Deuteron charge radius: r_d = 2.12771 (22) fm from μH + H/D(1S-2S)
- muonic deuterium: r_d = 2.1289(12) fm from μD (PRELIMINARY!)
- Proton radius puzzle persists. New data needed!
  - 2S-4P in regular hydrogen: check R_∞
  - muonic helium: beam time Oct.-Dec. 2013
  - New low-Q^2 measurements on the proton
  - Mainz low-Q^2 measurement on the deuteron
  - MUSE (muon scattering experiment) @ PSI
  - ...

Outlook: Lamb shift in muonic helium

- CREMA collaboration: Charge Radius Experiment with Muonic Atoms
- Exp. R10-01 approved at PSI in Feb. 2010
- ERC Starting Grant #279765
- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He
- $\Rightarrow$ alpha particle and helion charge radius to 3×10^{-4} (0.0005 fm)

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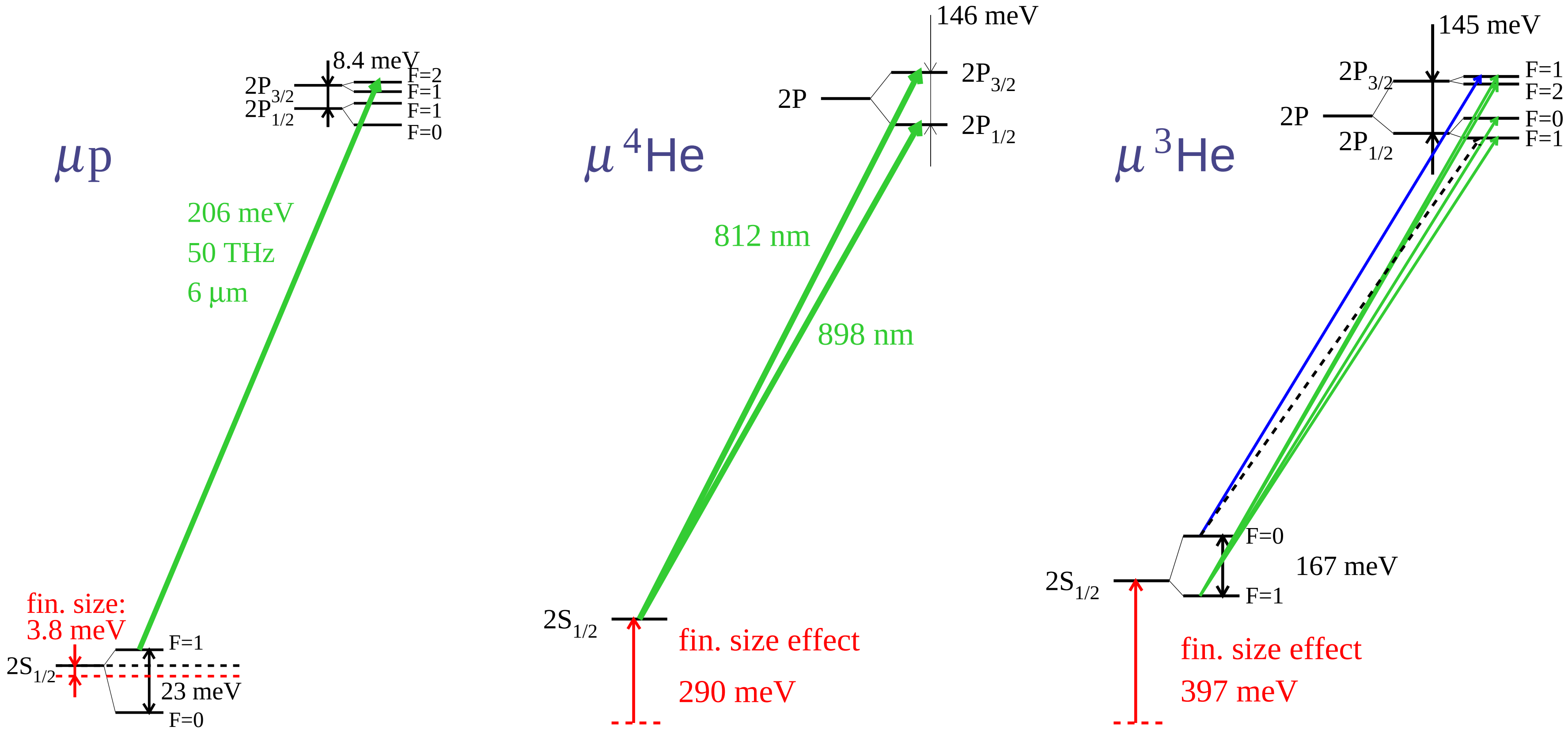

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  - absolute charge radii of helion, alpha
  - low-energy effective nuclear models: ^{1}H, ^{2}D, ^{3}He, ^{4}He
  - QED test with He$^+$(1S-2S) [Udem @ MPQ, Eikema @ Amsterdam]

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Proton Size Investigators thank you for your attention