# News from the "Proton Radius Puzzle"

Randolf Pohl

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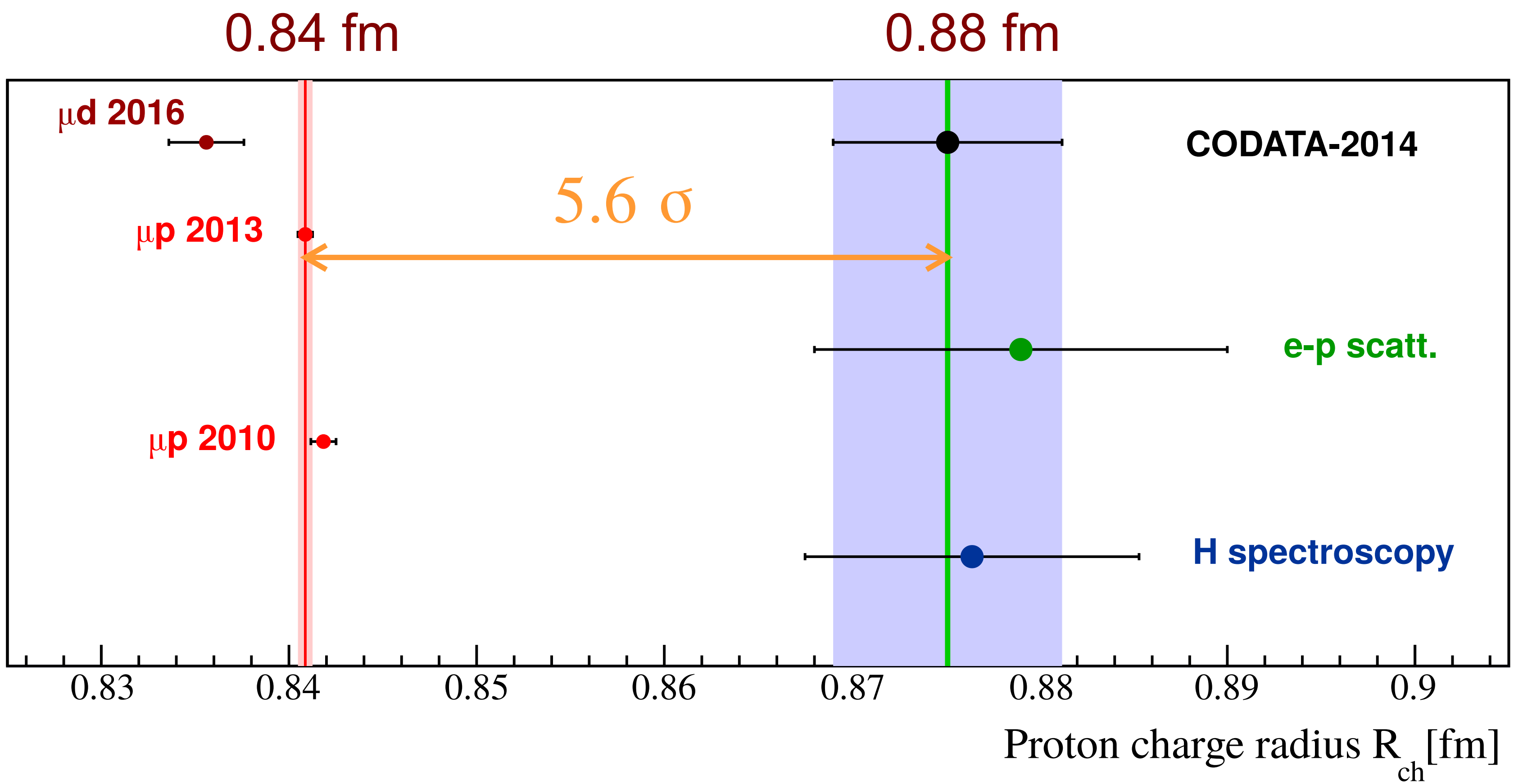
before: Max-Planck Institute of Quantum Optics, Garching

Bormio
Jan. 22, 2019

# The “Proton Radius Puzzle”

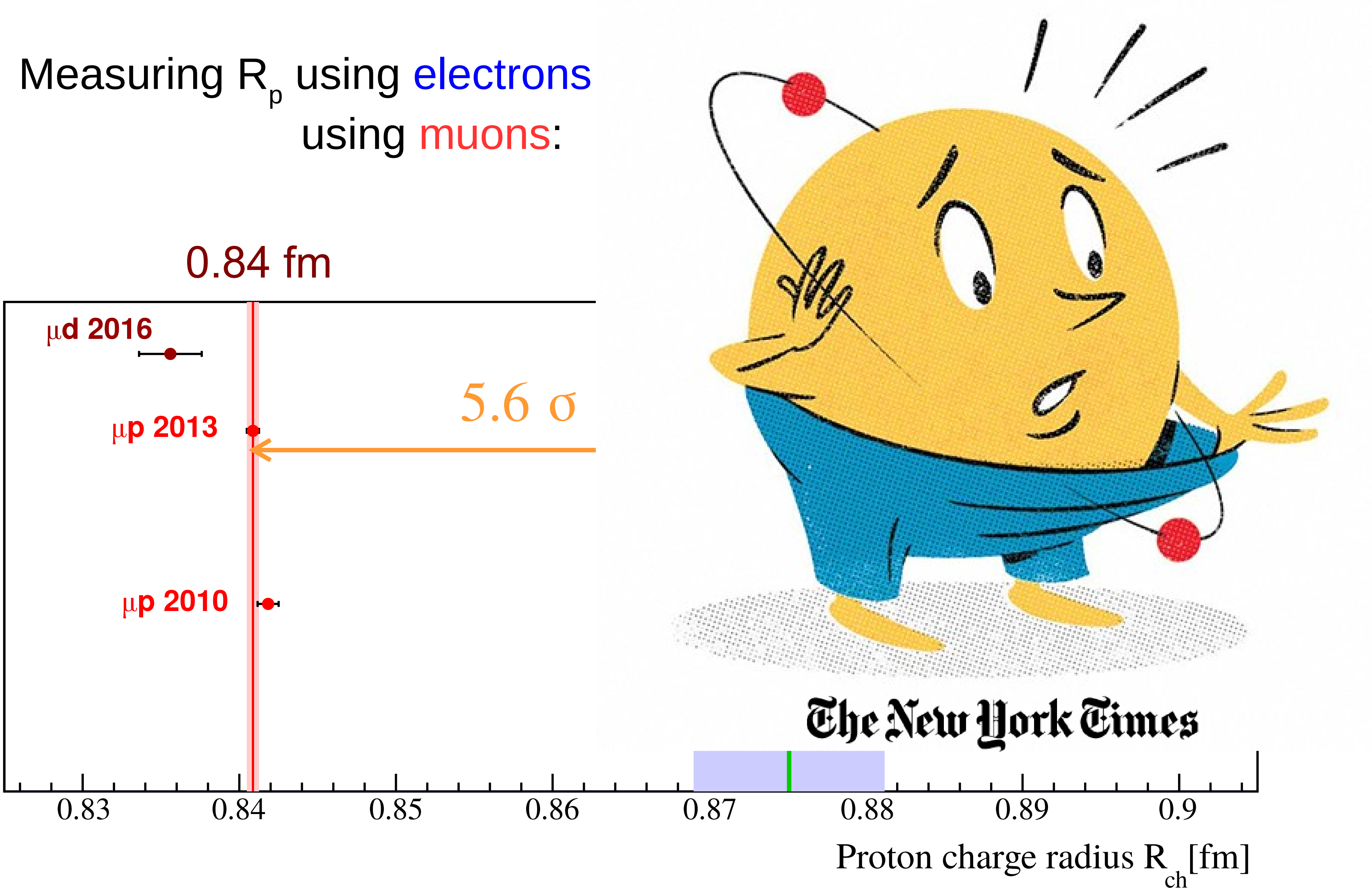
Measuring $R_p$ using electrons: 0.88 fm ( +- 0.7%)
using muons: 0.84 fm ( +- 0.05%)




μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

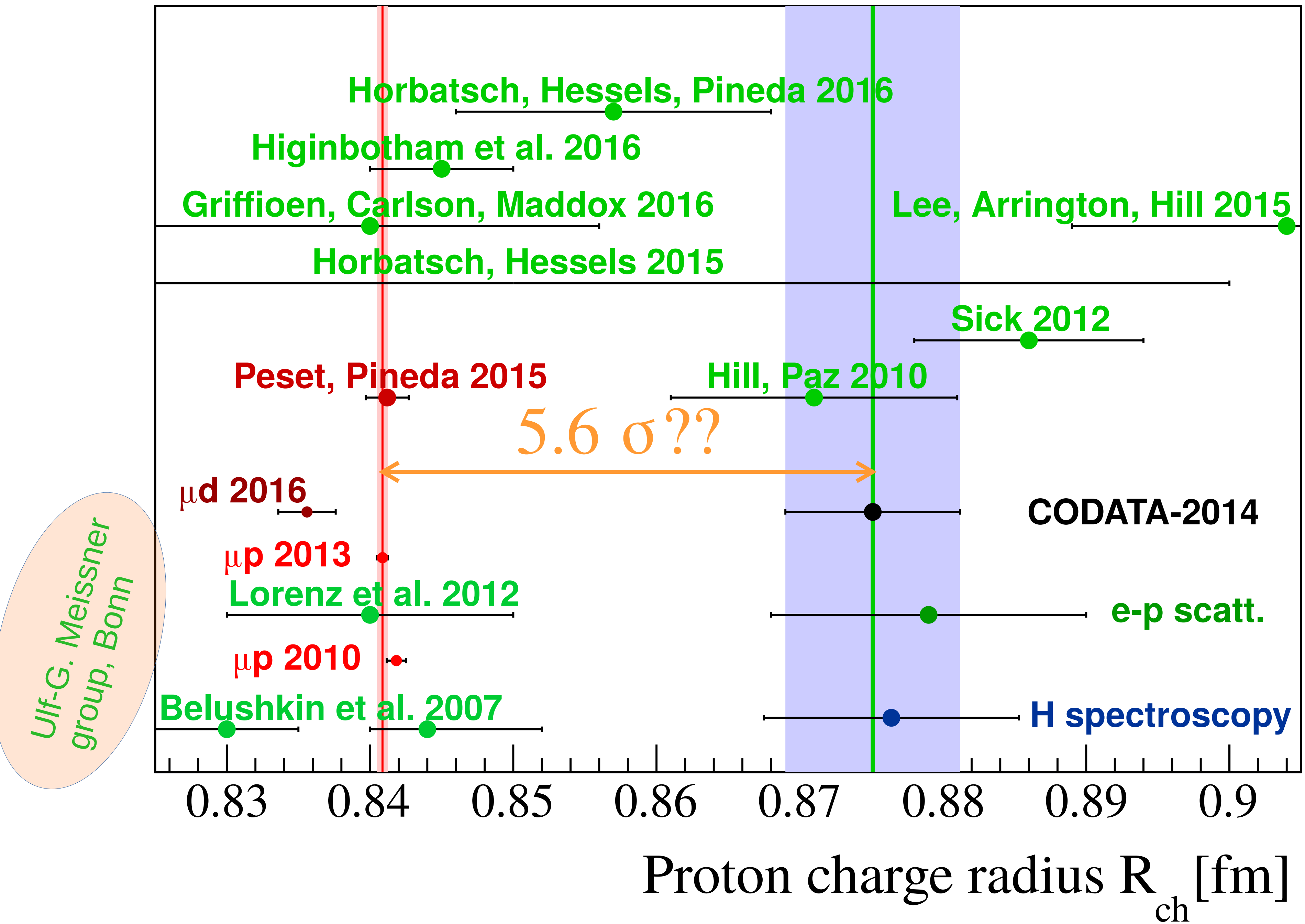
# The "Proton Radius Puzzle"

Measuring $R_p$ using electrons
using muons:



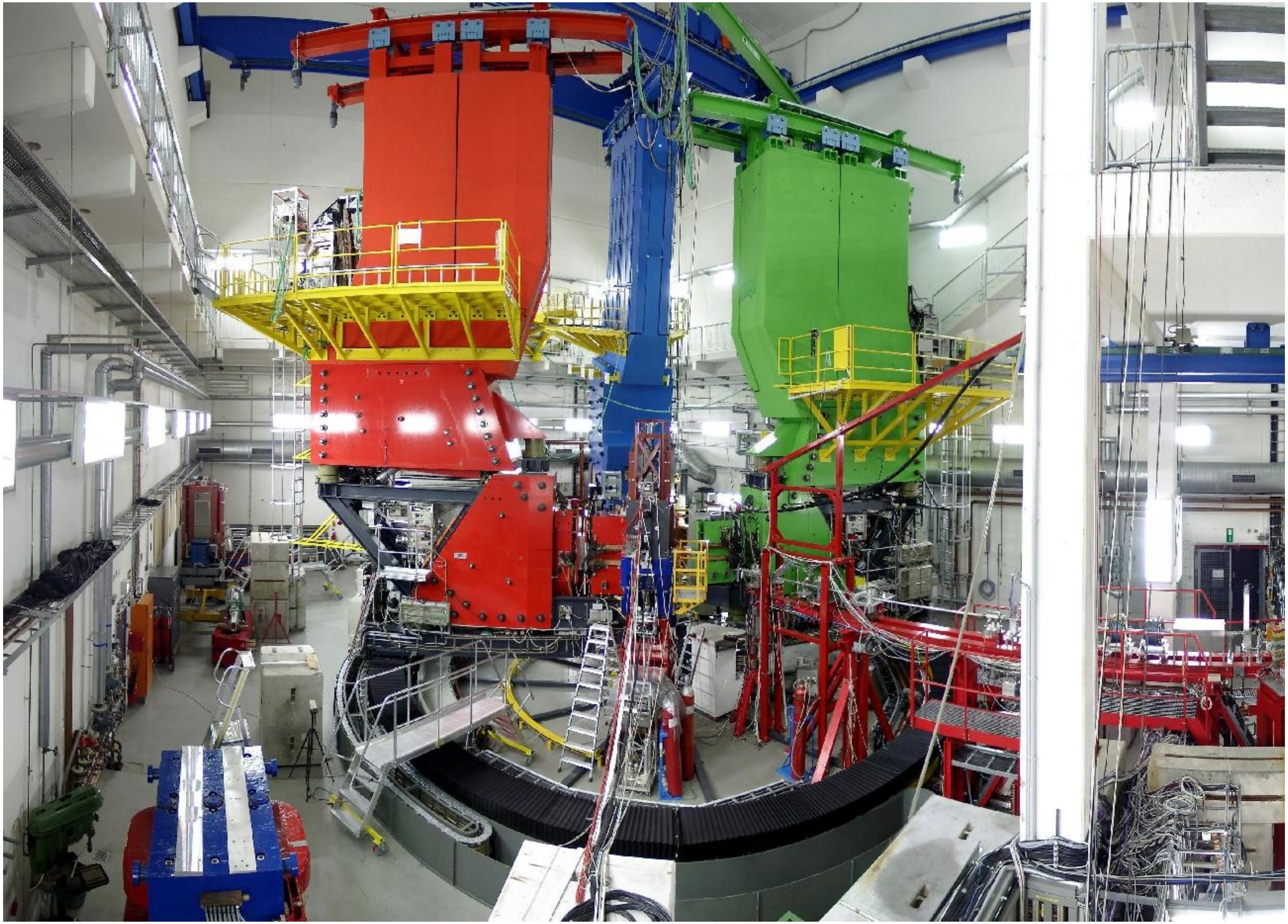

µd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
µp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

# A “Proton Radius **Puzzle**” ??

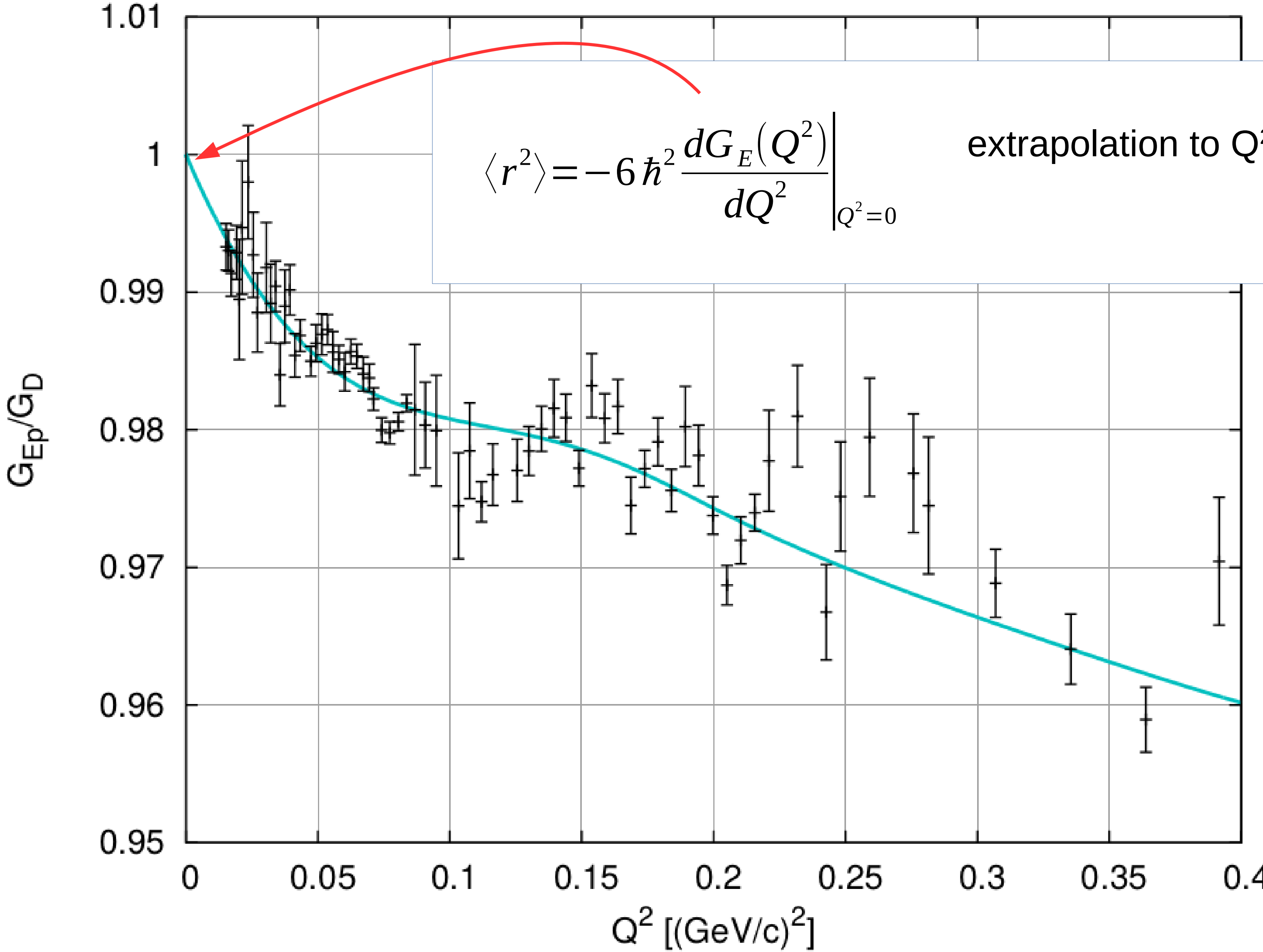


# Electron scattering

# Mainzer Microtron MAMI



# Electron scattering




$$\langle r^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

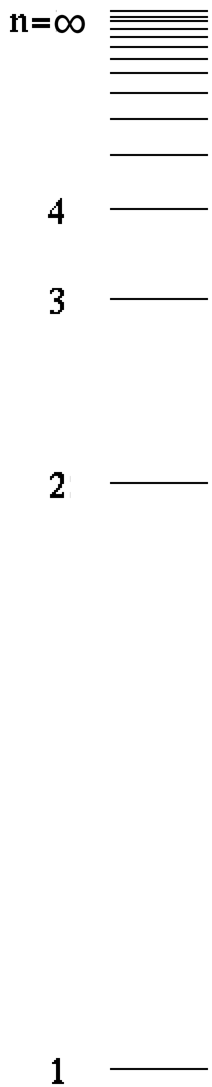
extrapolation to $Q^2 = 0$ required

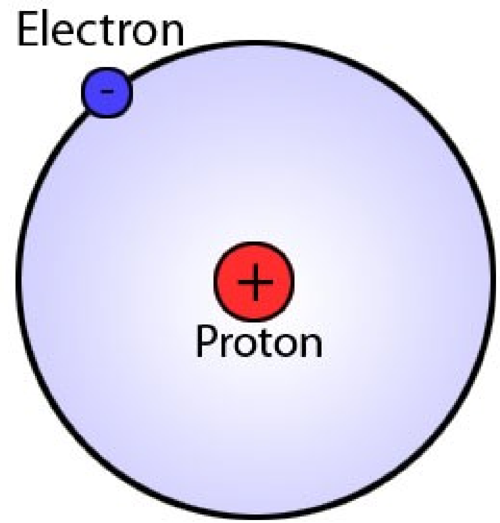
Mainz MAMI data 2010

Vanderhaeghen, Walcher: 1008.4225

# Hydrogen

# Energy levels of hydrogen

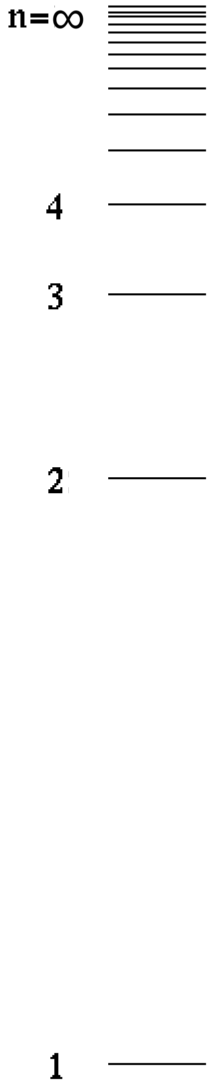



$$E_n \approx -\frac{R_\infty}{n^2}$$

Bohr formula

# Energy levels of hydrogen

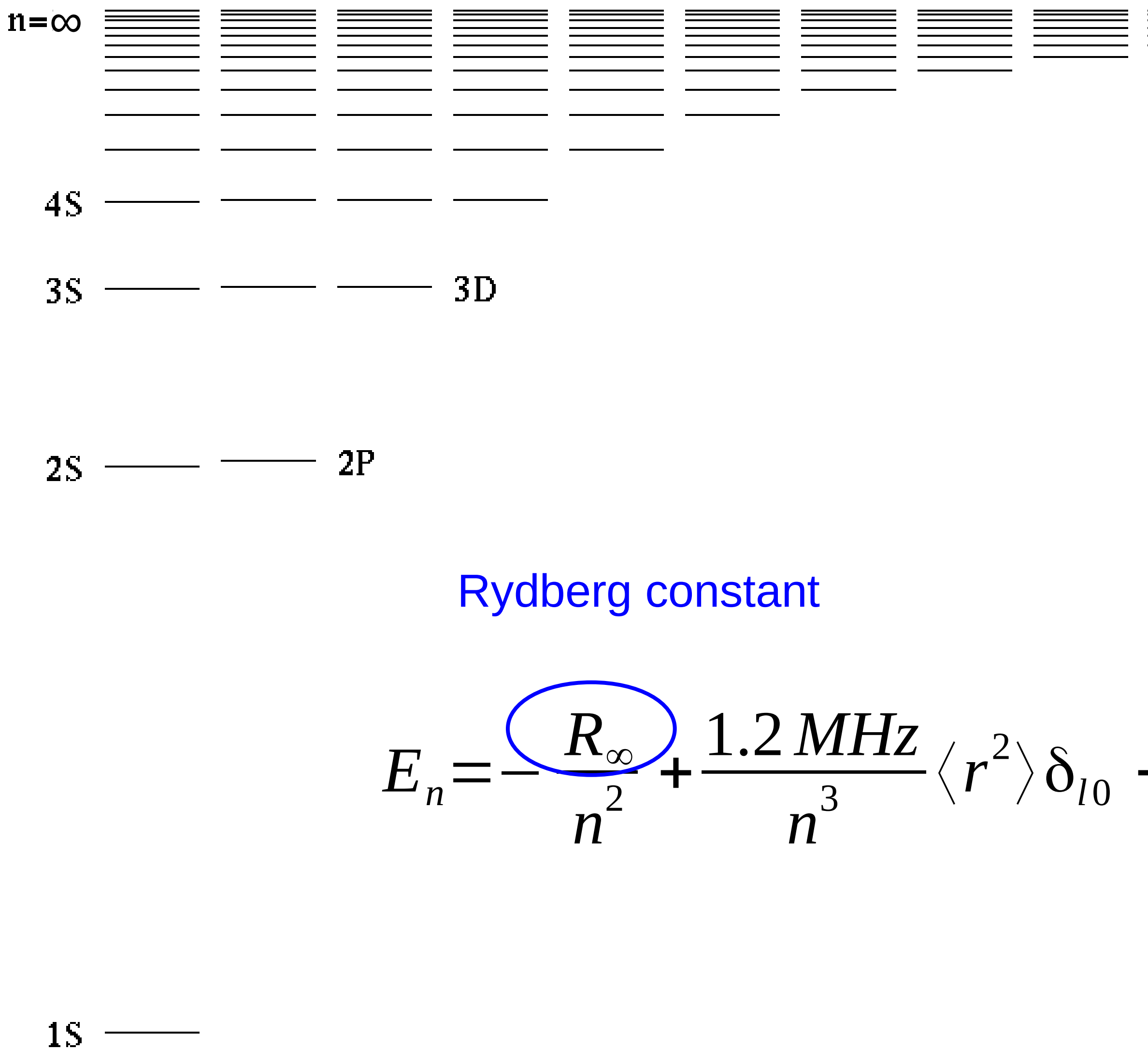



Rydberg constant

$$E_n \approx -\frac{R_\infty}{n^2}$$

Bohr formula

# Energy levels of hydrogen

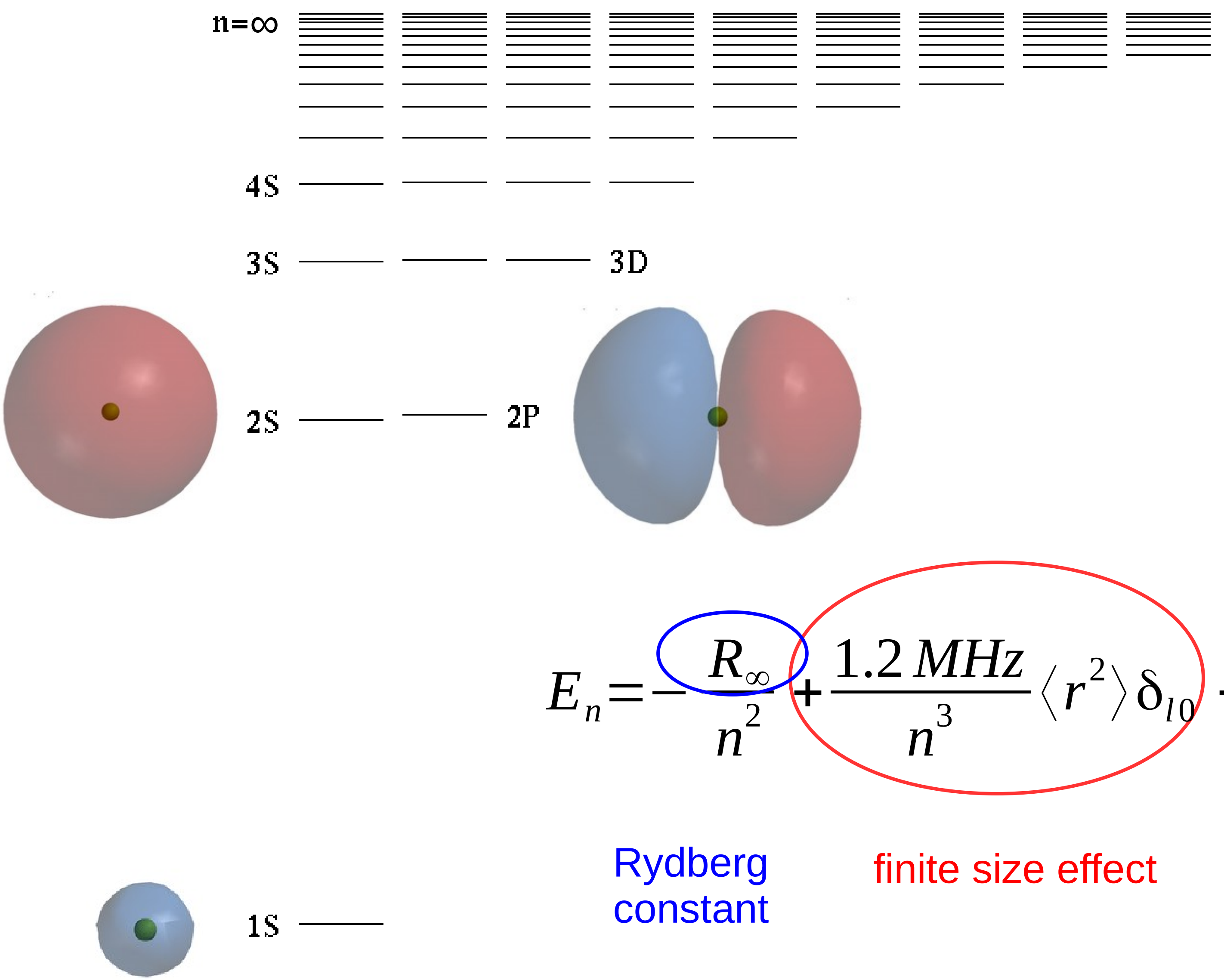



Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n, l, j)$$

RP et al., Metrologia 54, L1 (2017)

# Energy levels of hydrogen

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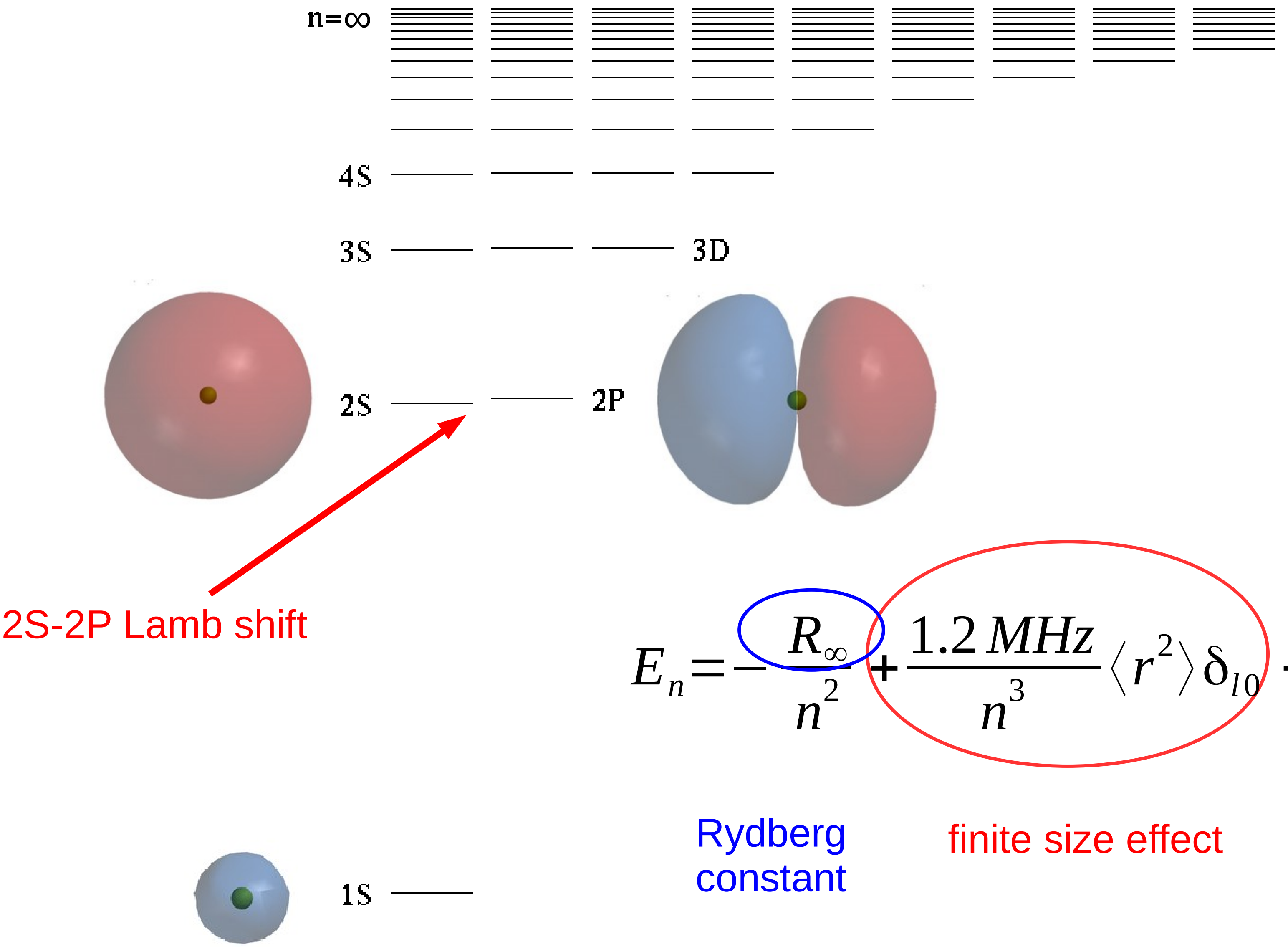
Rydberg constant

finite size effect

RP et al., Metrologia 54, L1 (2017)

# Energy levels of hydrogen

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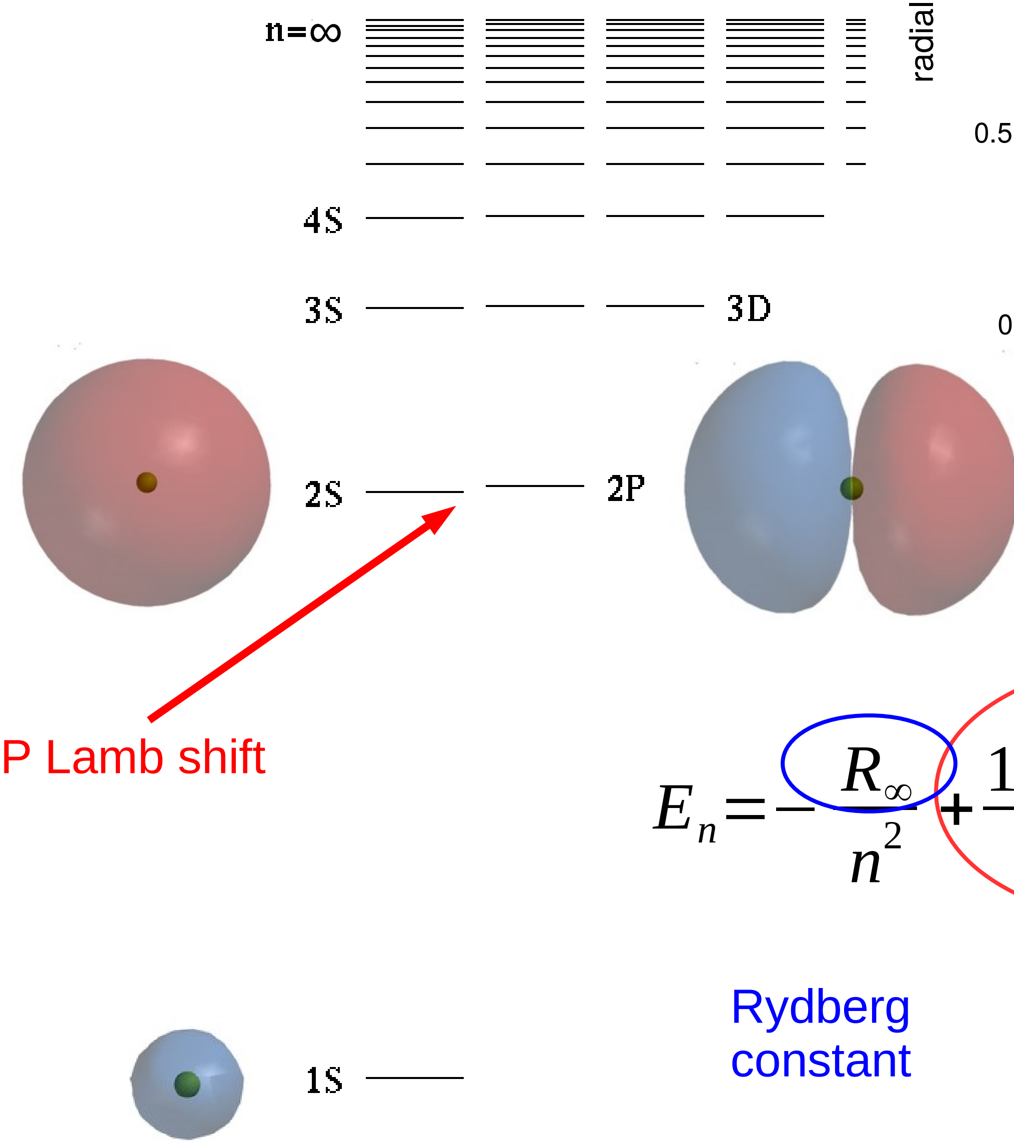
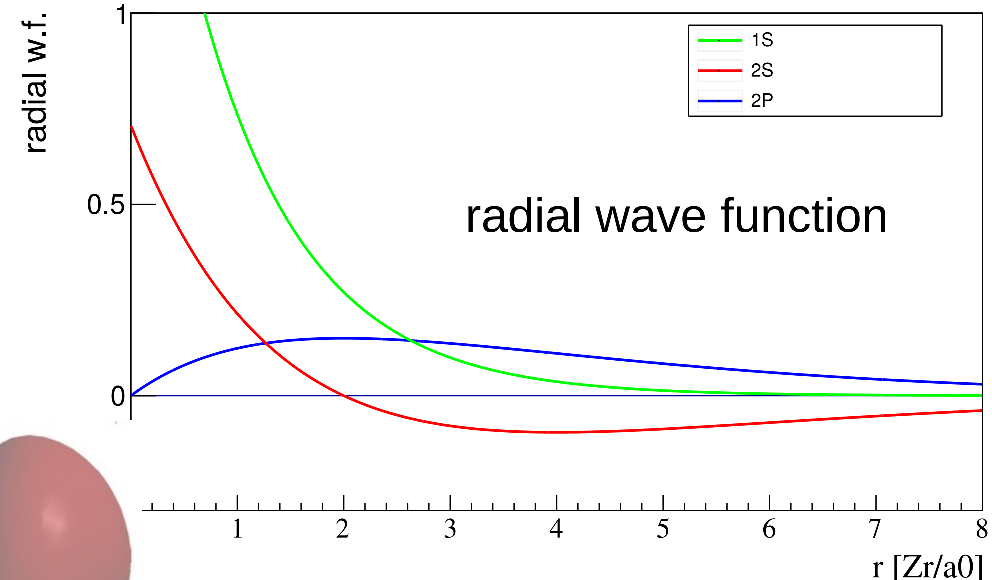



2S-2P Lamb shift

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

Rydberg constant

finite size effect

RP et al., Metrologia 54, L1 (2017)

# Muonic Hydrogen

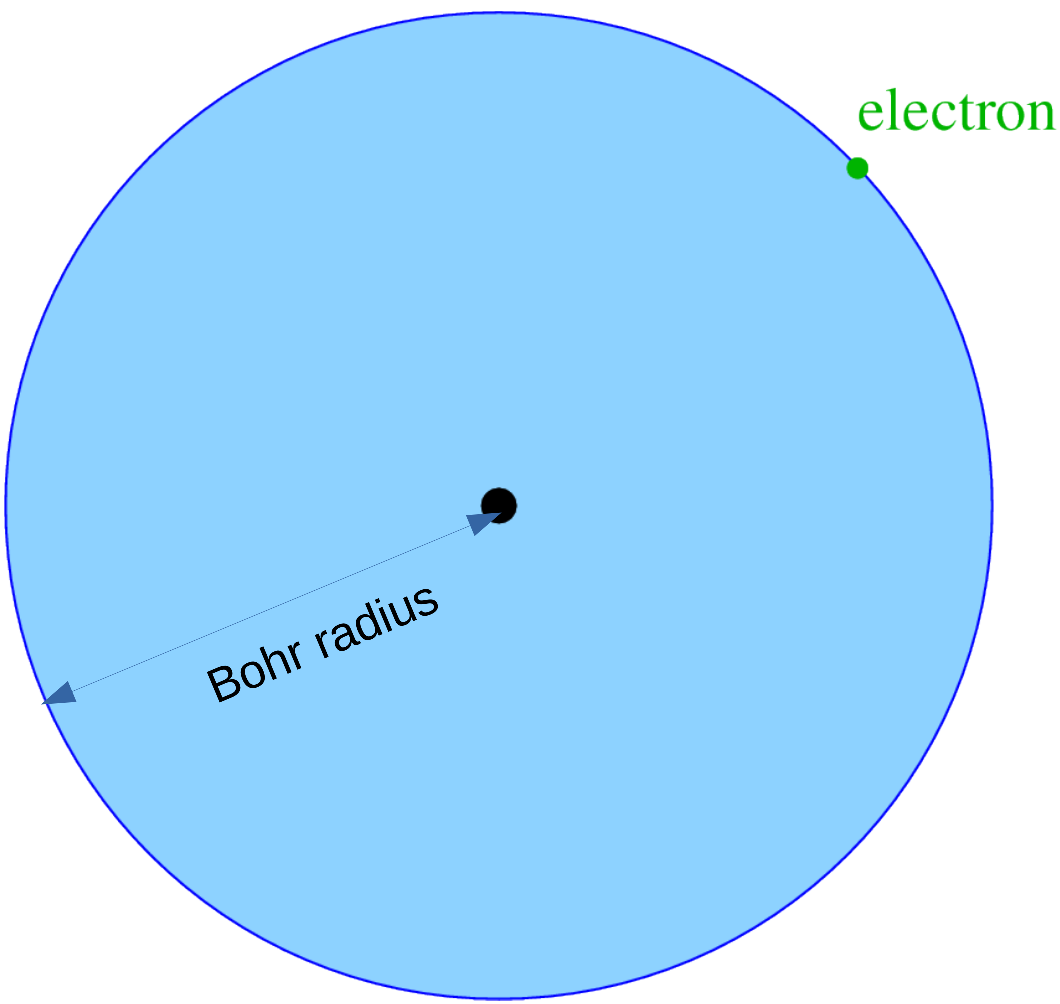
# Muonic Hydrogen

A proton, orbited by a **negative muon.**

# Electronic and muonic atoms

## Regular hydrogen:

Proton + Electron




## Muonic hydrogen:

Proton + Muon

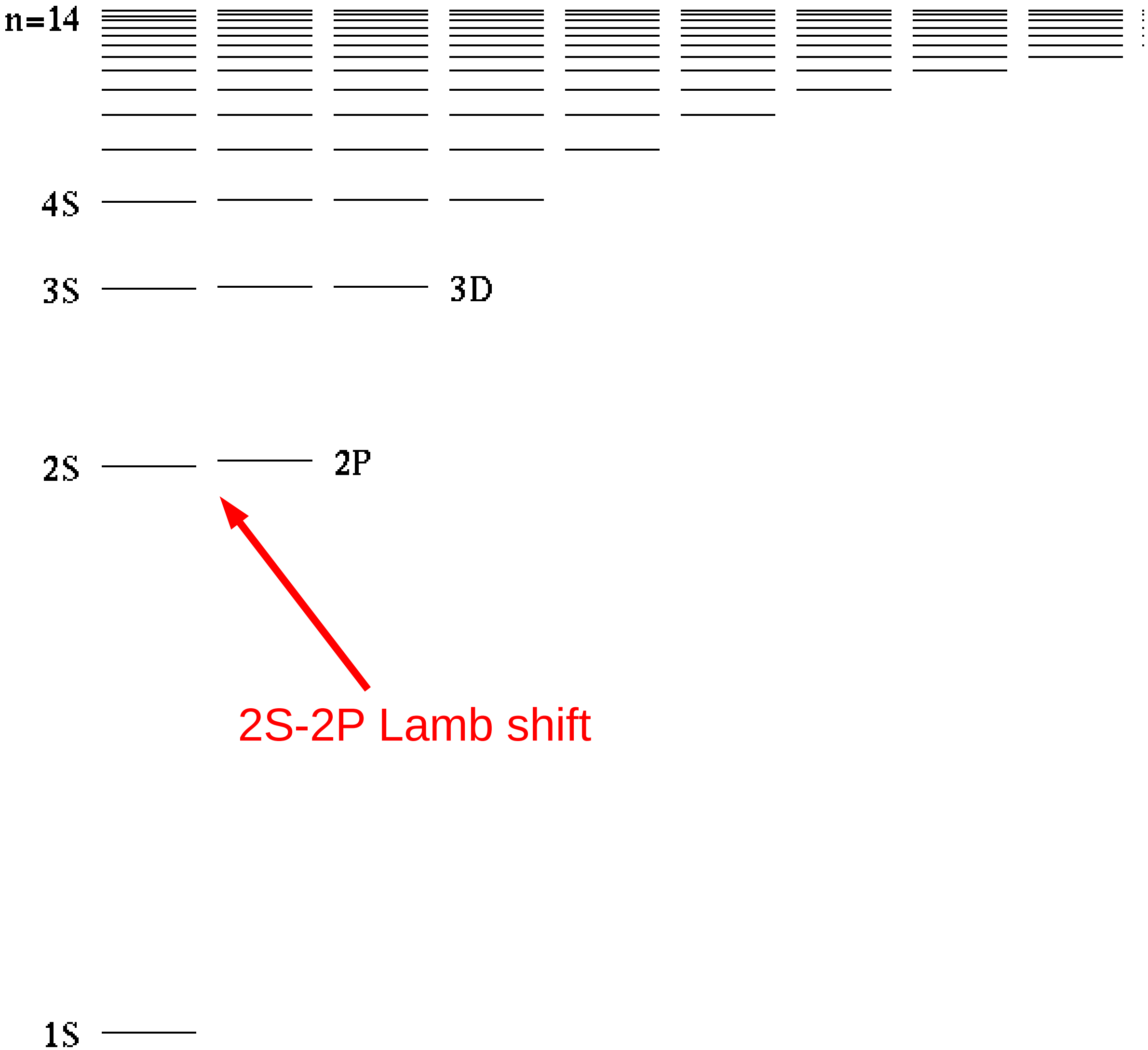
Muon **mass** = **200** * electron mass

Bohr **radius** = **1/200** of H

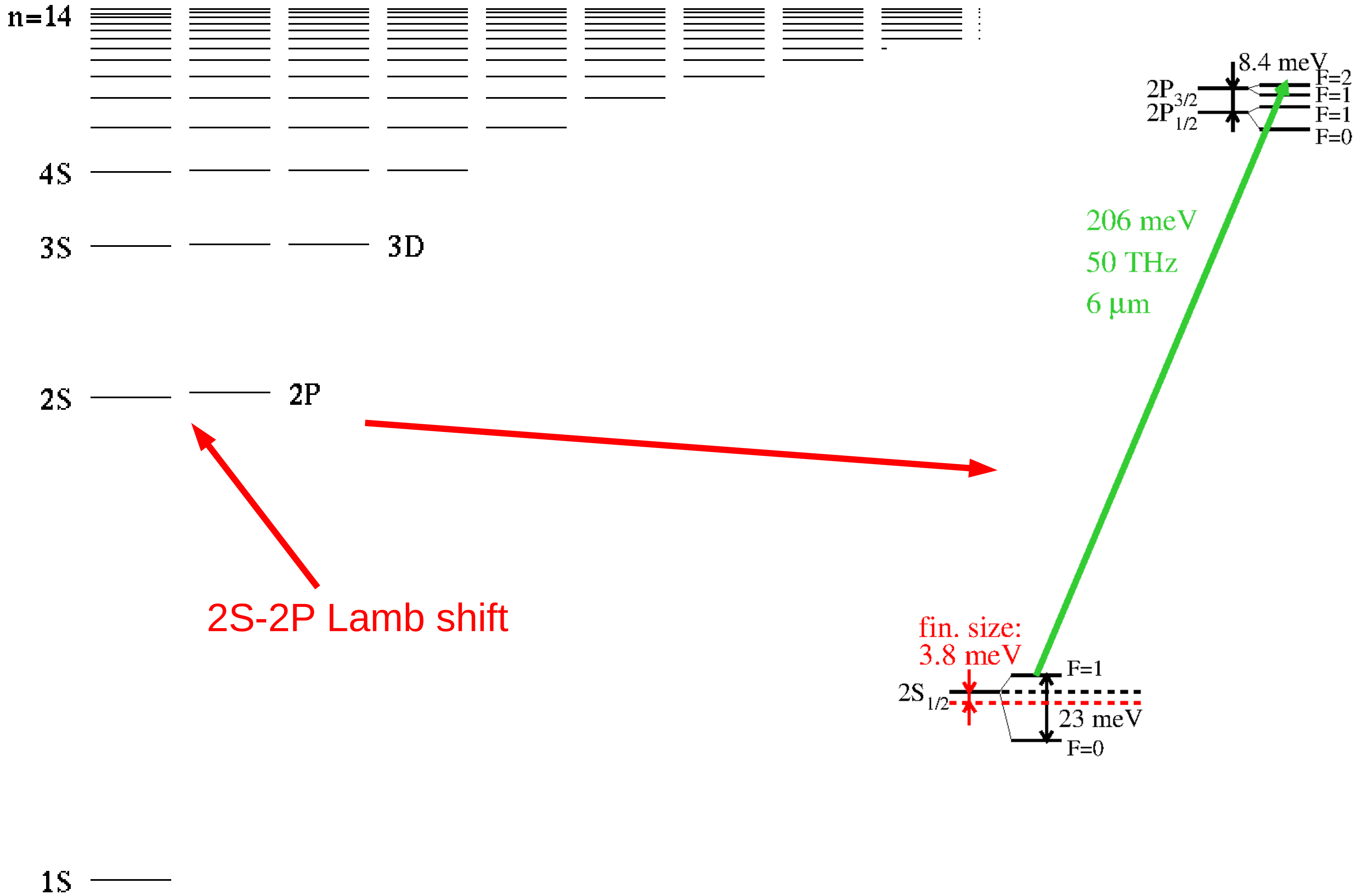
$\mathbf{200^3}$ = a **few million times** more sensitive to proton size


Vastly not to scale!!

# Muonic Hydrogen



# Muonic Hydrogen



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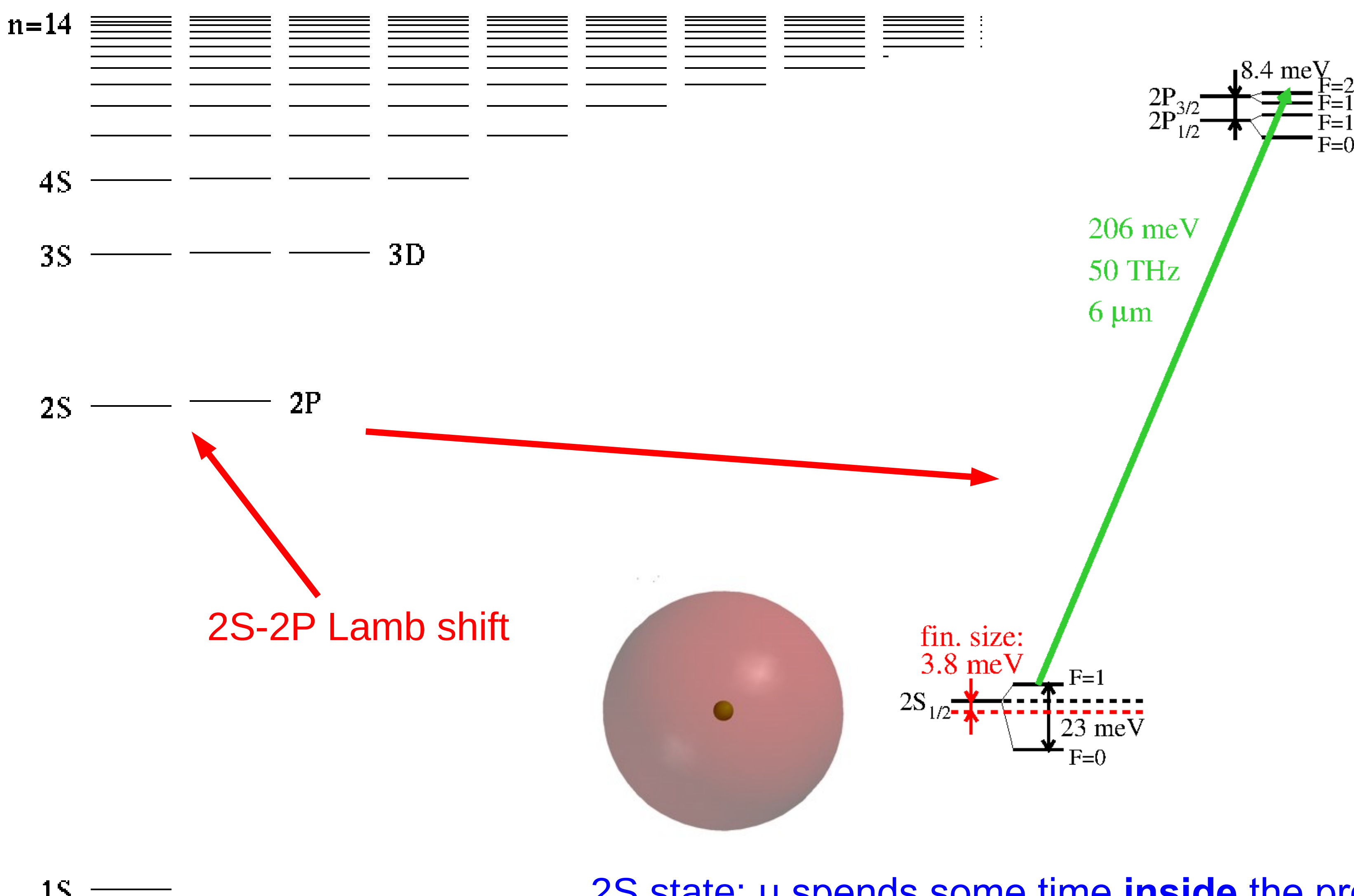
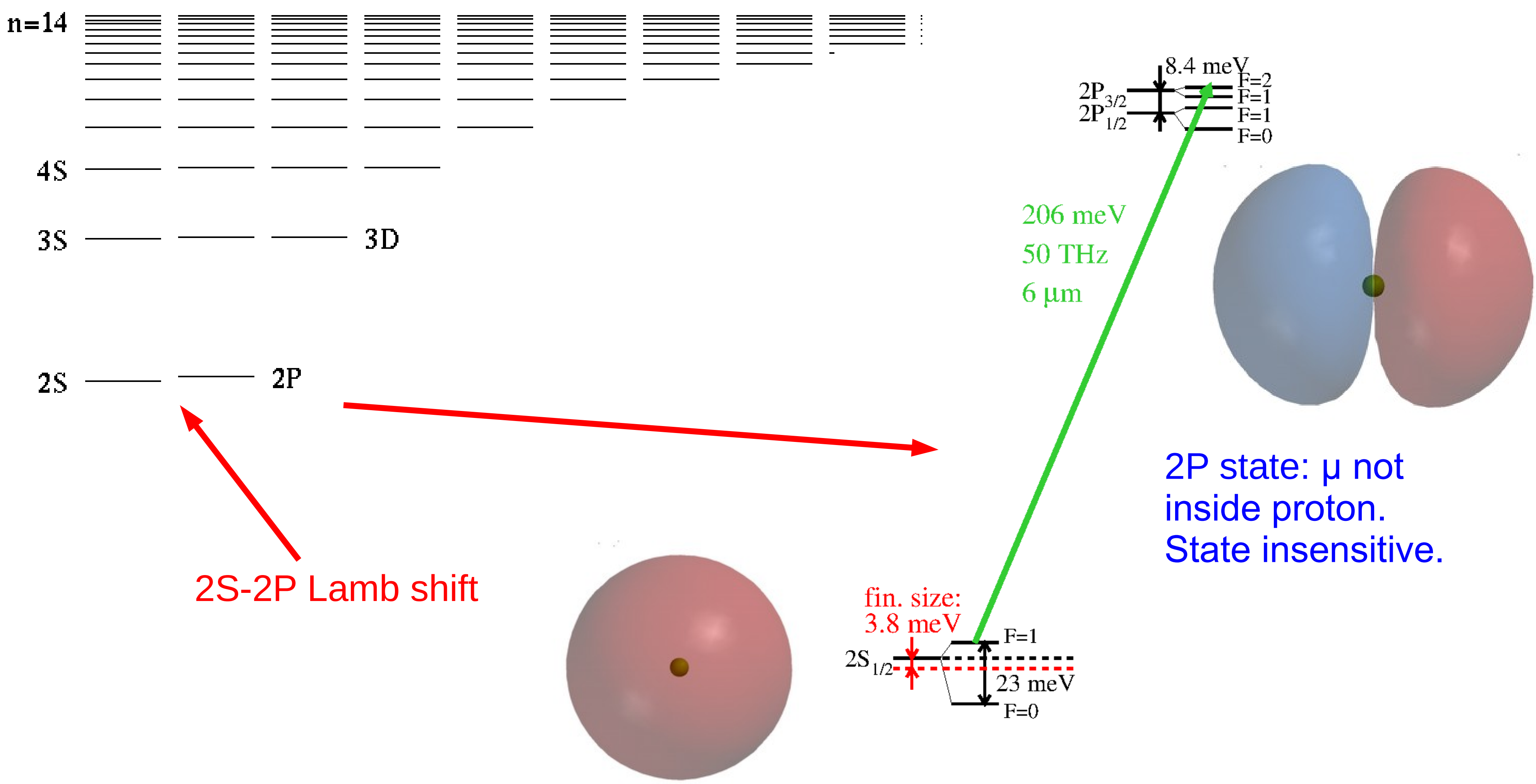



2S state: µ spends some time **inside** the proton!
State is sensitive to the proton size.

# Muonic Hydrogen

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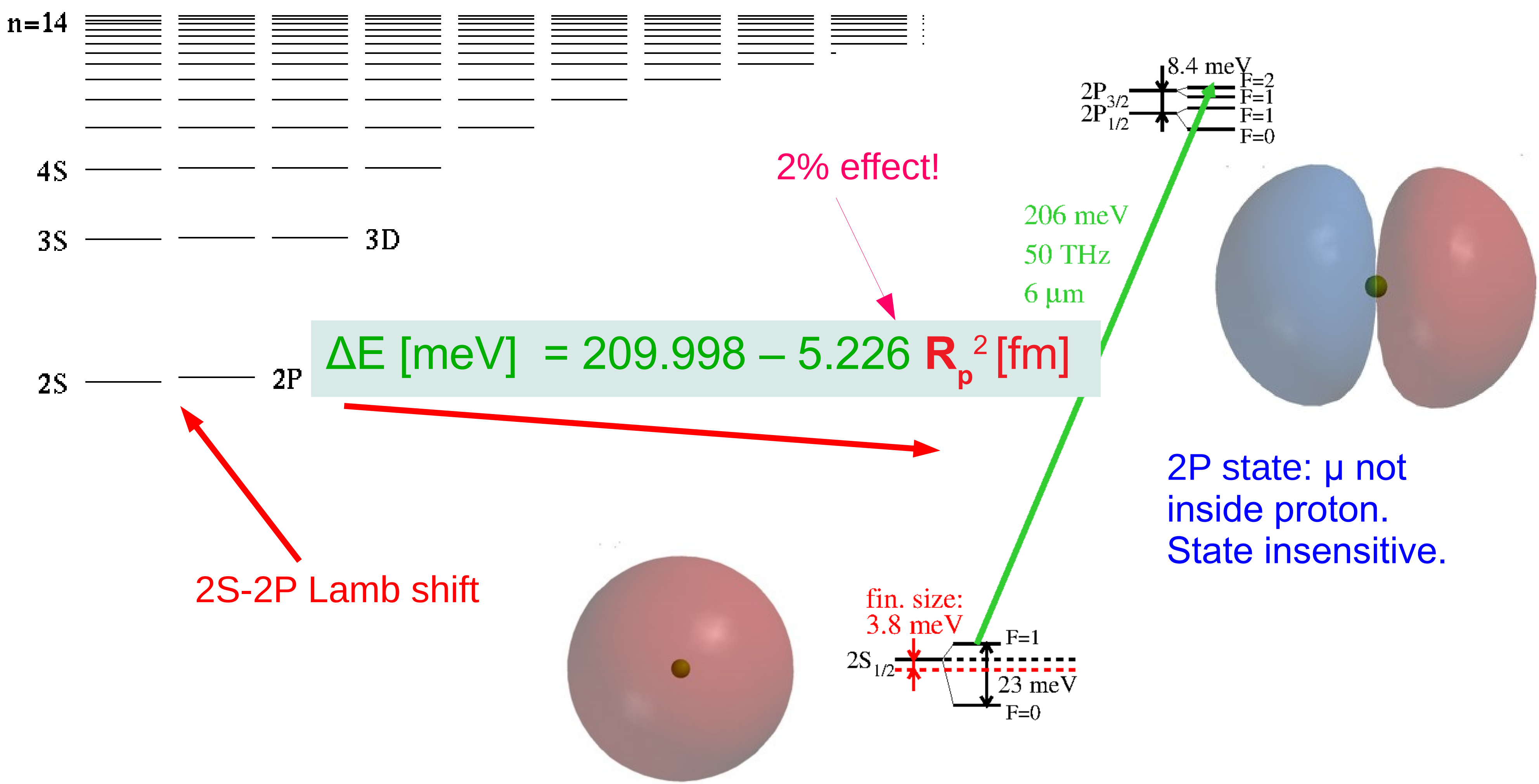
# Muonic Hydrogen

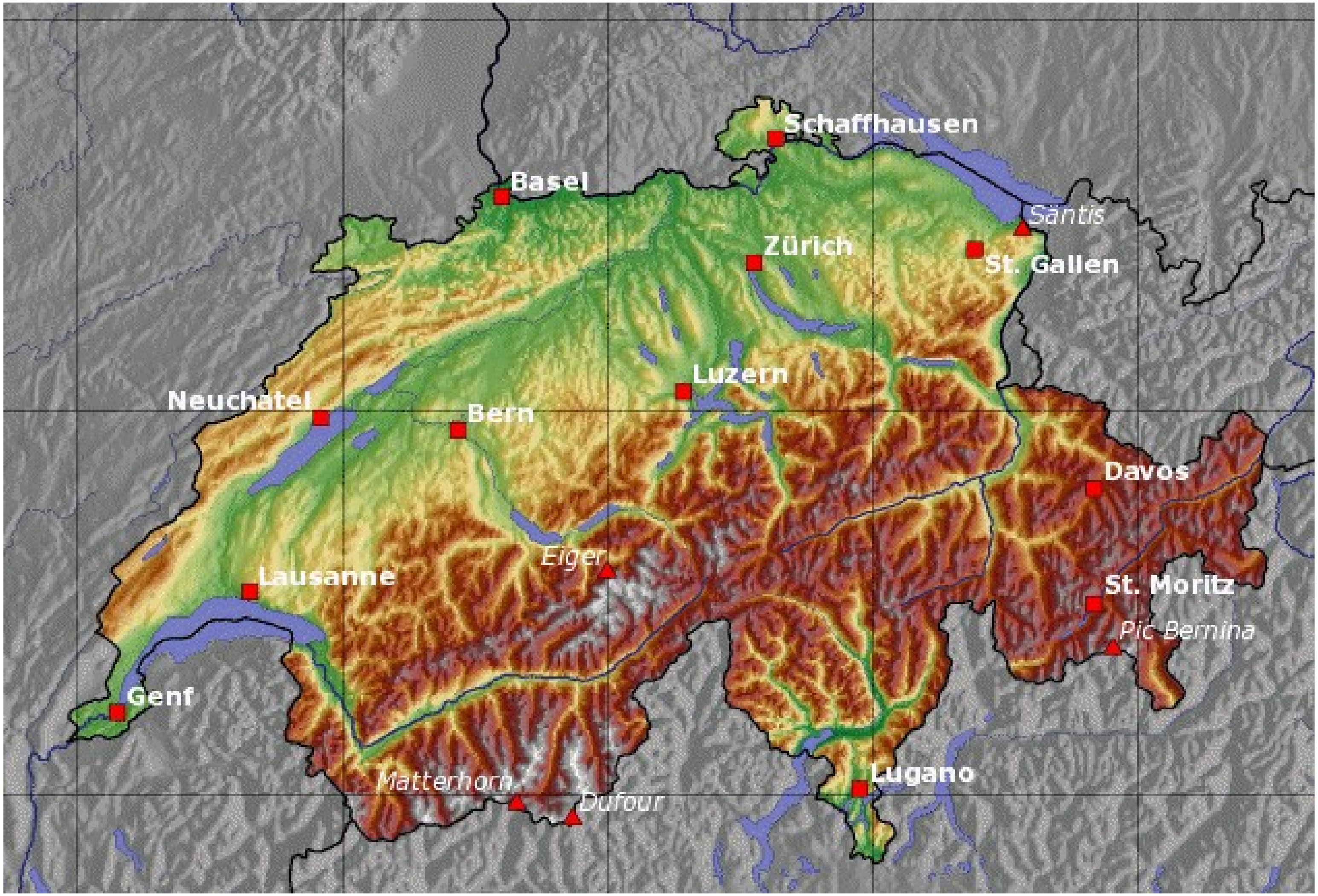



$$\Delta E\ [\mathrm{meV}] = 209.998 - 5.226\ R_p^{\,2}\ [\mathrm{fm}]$$

2P state: µ not inside proton. State insensitive.

2S state: µ spends some time **inside** the proton! State is sensitive to the proton size.

# The accelerator at PSI



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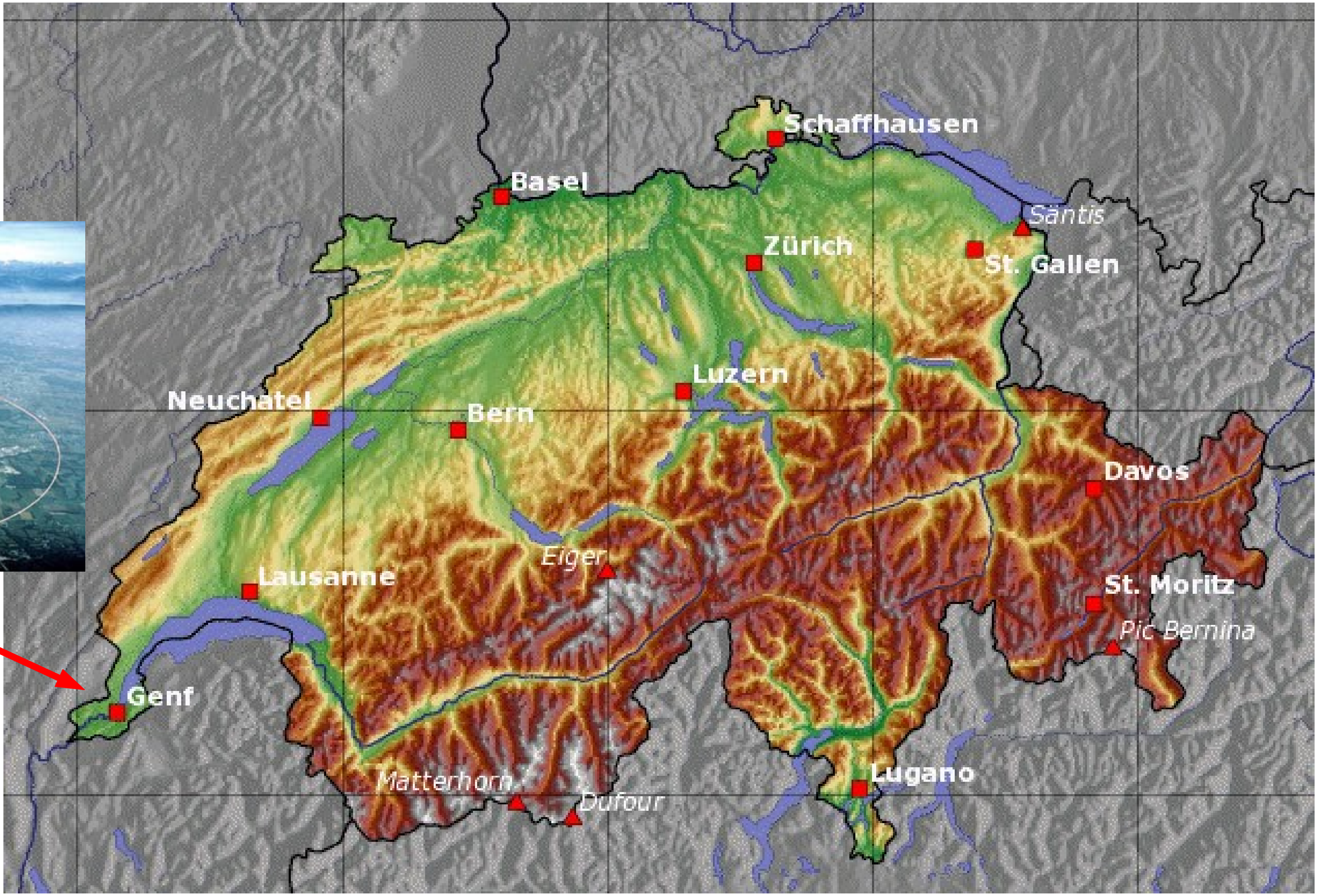

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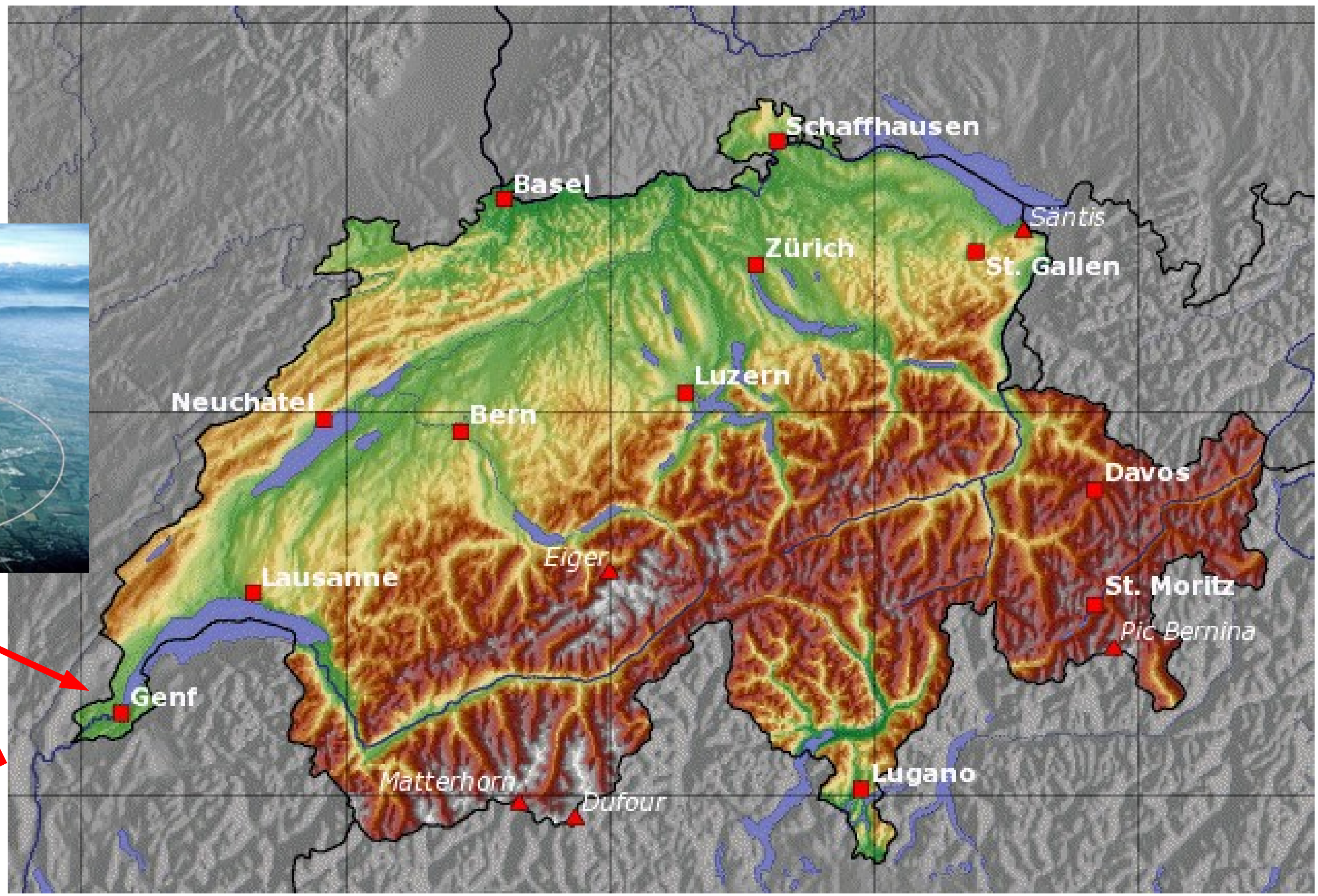
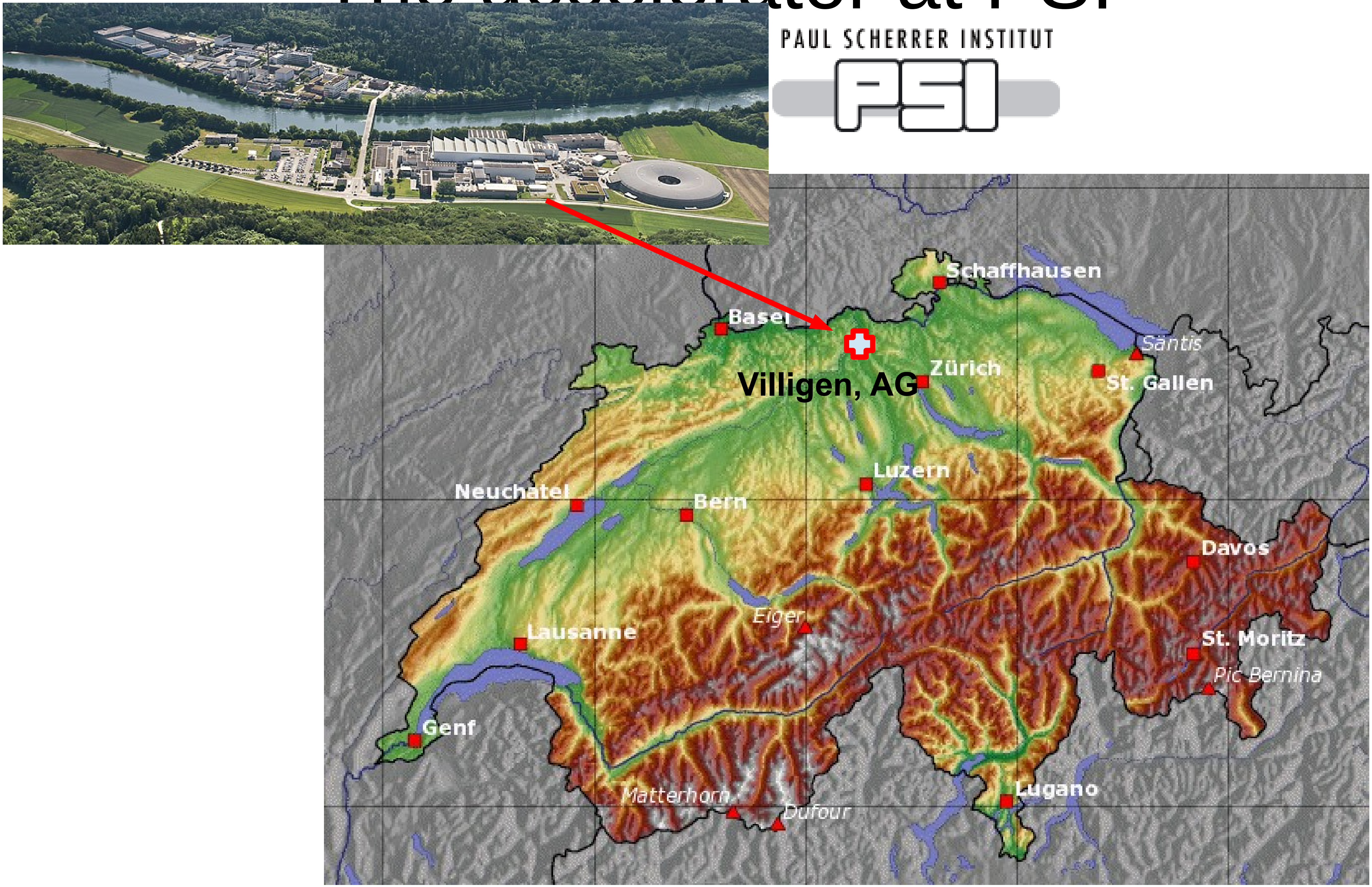
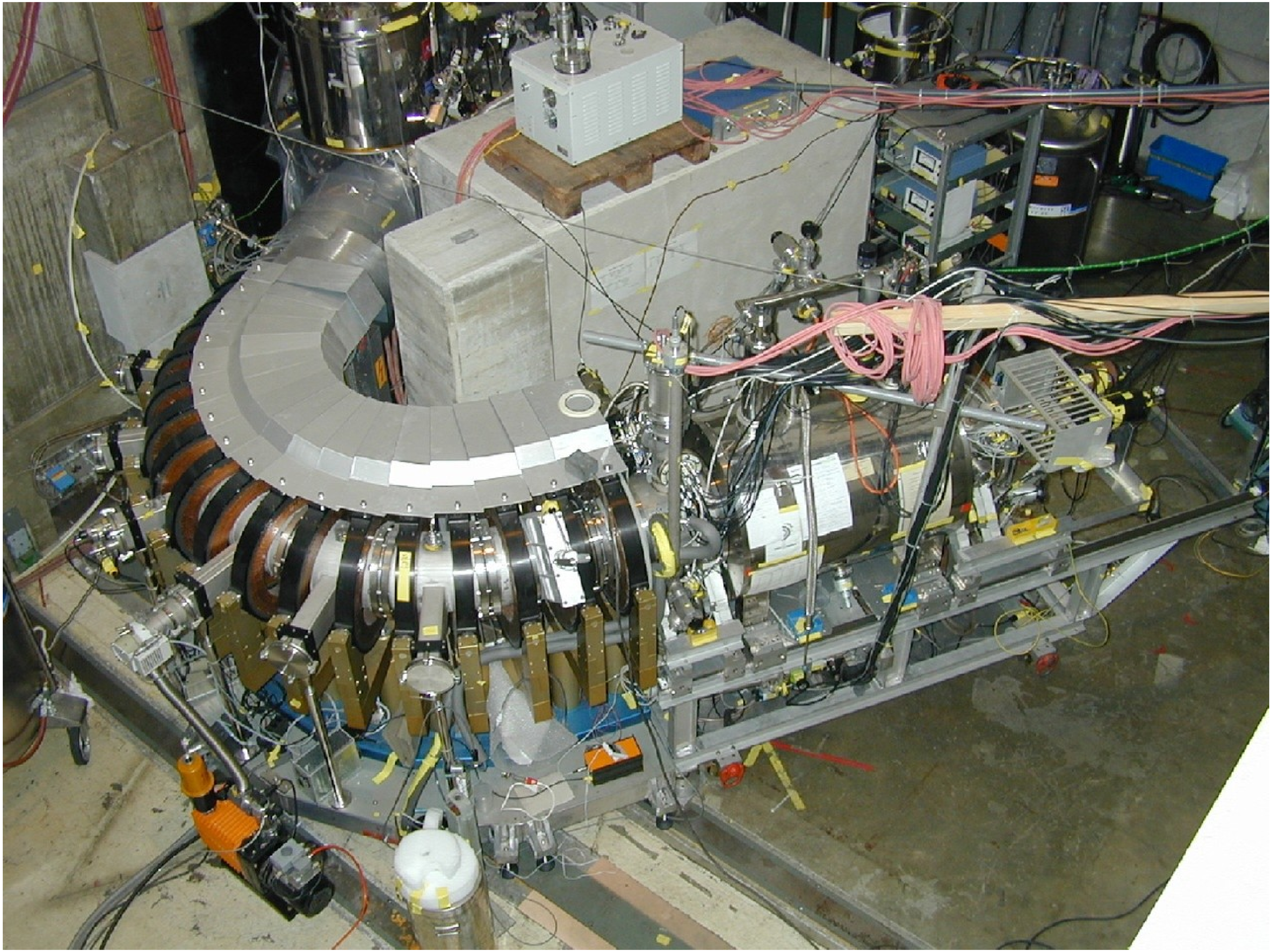


# The accelerator at PSI

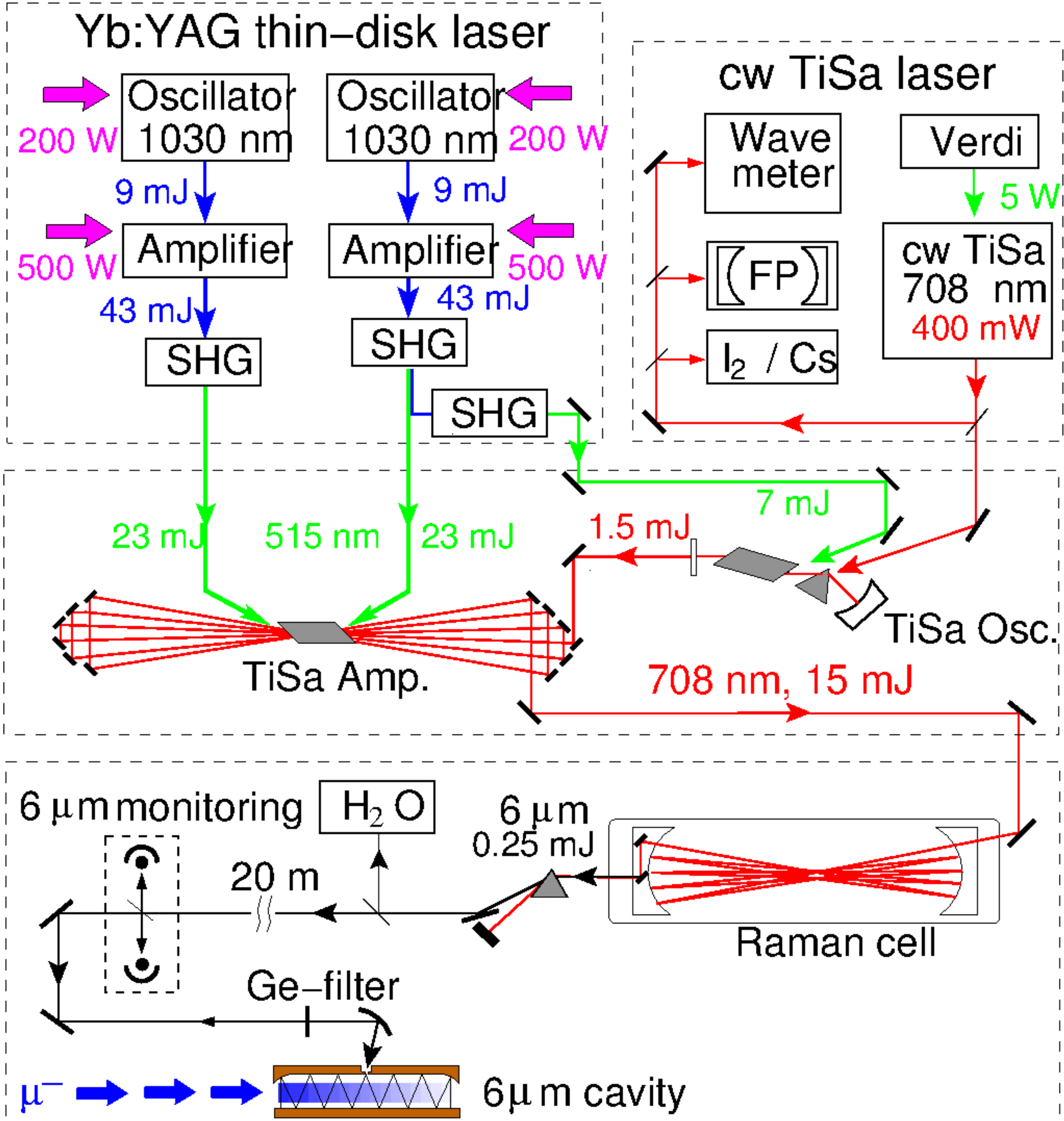
PAUL SCHERRER INSTITUT



# The muon beam line in πE5



# The laser system




Yb:YAG Disk laser
→ fast response on µ

Frequency doubling (SHG)
→ green light to pump Ti:sapphire laser

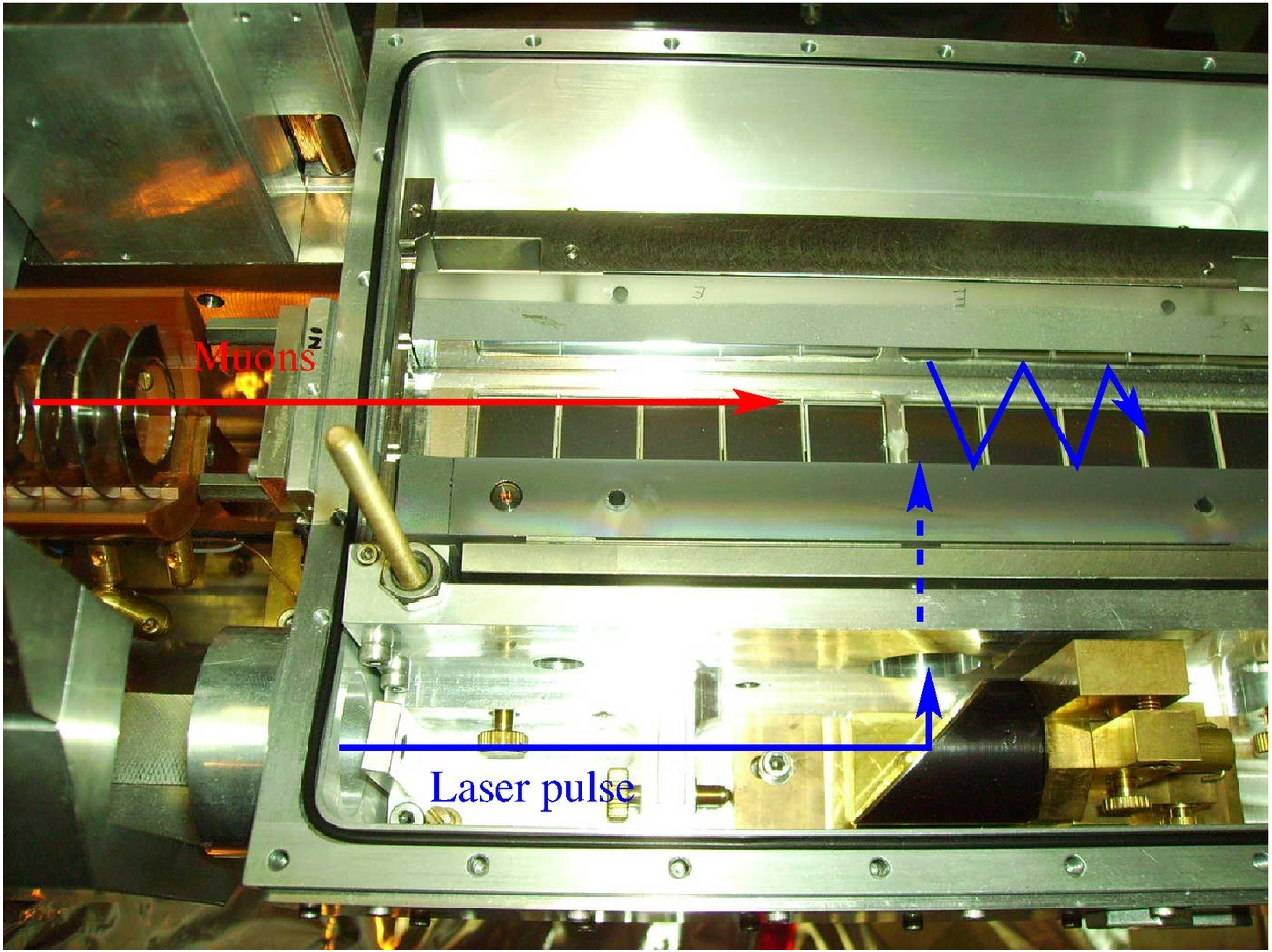
Ti:sapphire cw laser
→ determines laser frequency

Ti:sapphire MOPA
→ high pulse energy (15 mJ)

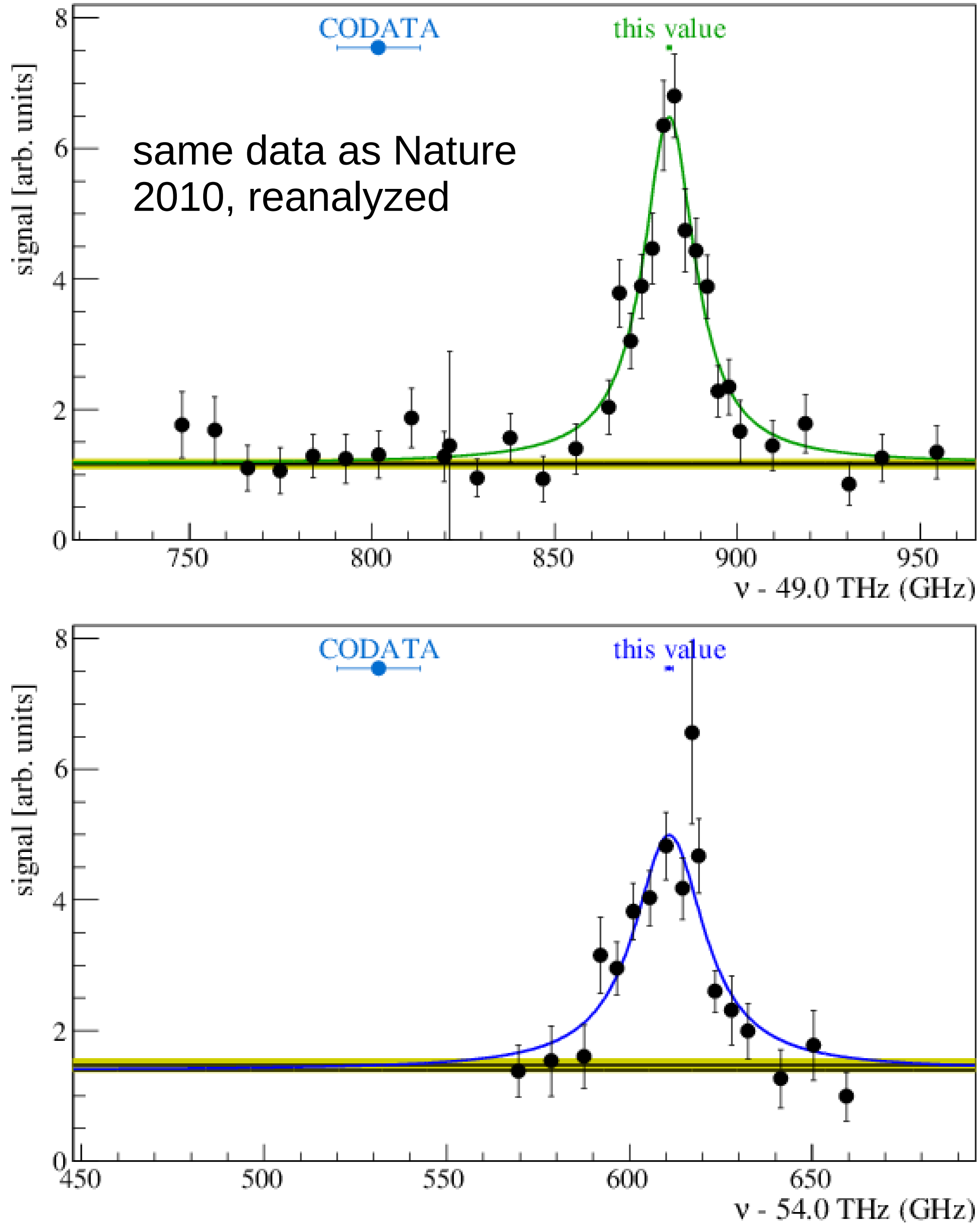
Raman cell
→ 3 sequential stimulated Raman Stokes shifts Laser wave length → 6 µm

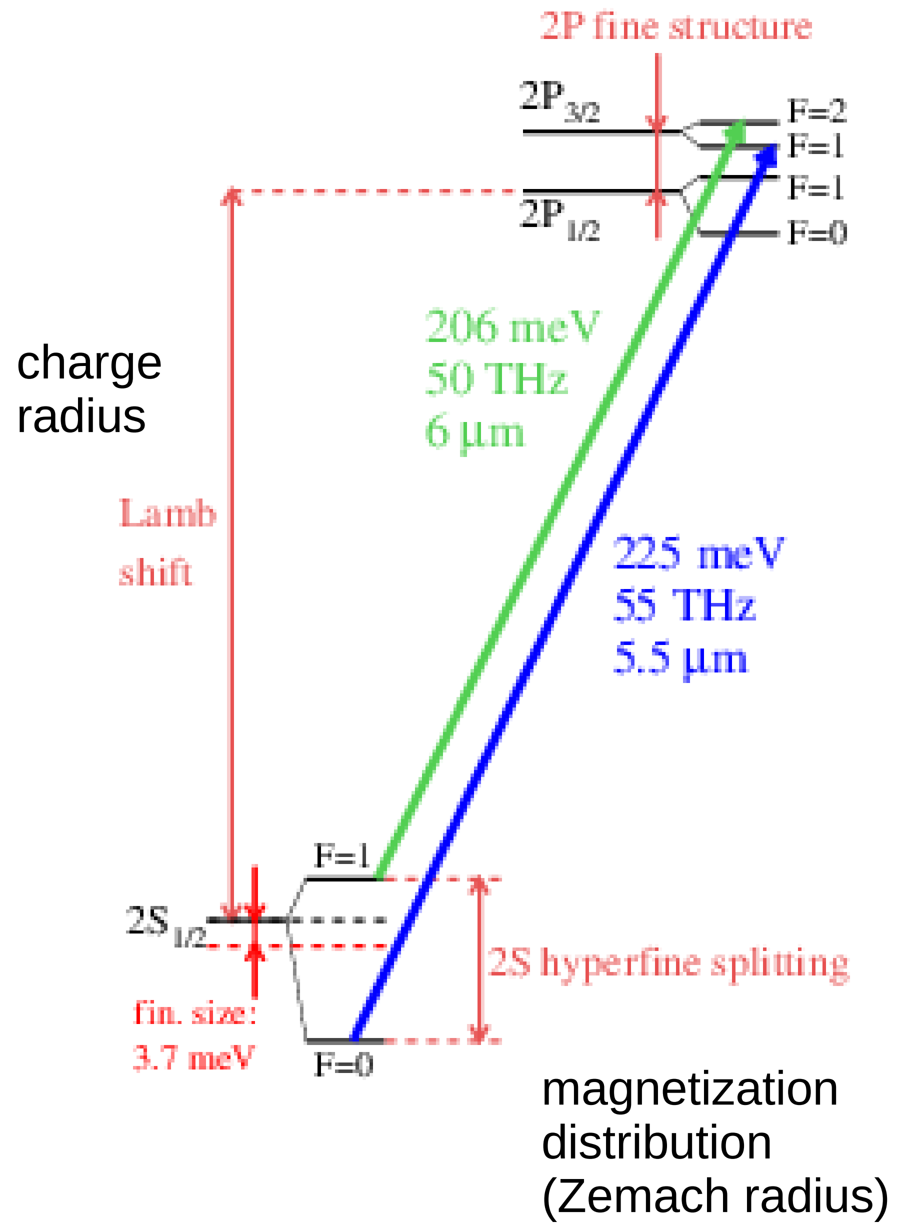
Target Cavity
→ Mirror system to fill the muon stop volume ($H_2$)

# The hydrogen target



# 2 transitions in muonic H



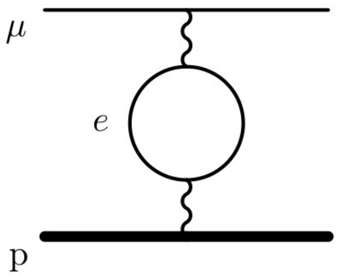




Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

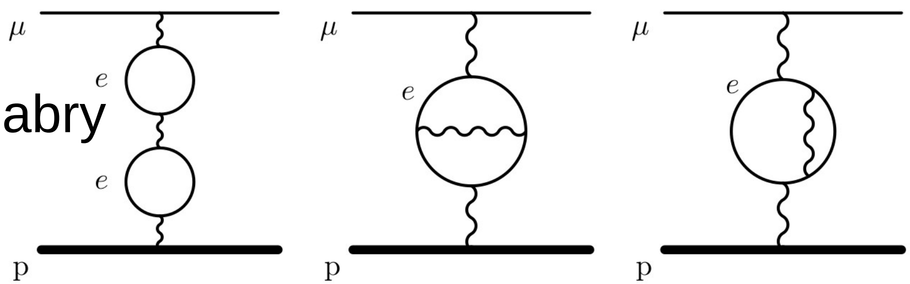
# Theory in muonic H

$$\Delta E_{Lamb} = 206.0336\ (15)\ \mathrm{meV}_{QED} + 0.0332\ (20)\ \mathrm{meV}_{TPE} - 5.2275\ (10)\ \mathrm{meV/fm}^2 * R_p^{\,2}$$

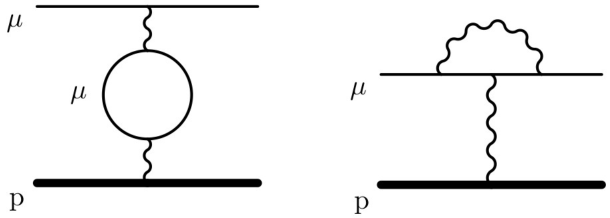
Uehling



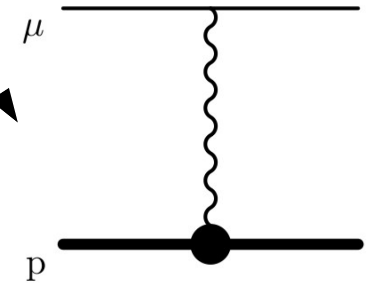

Källen-Sabry



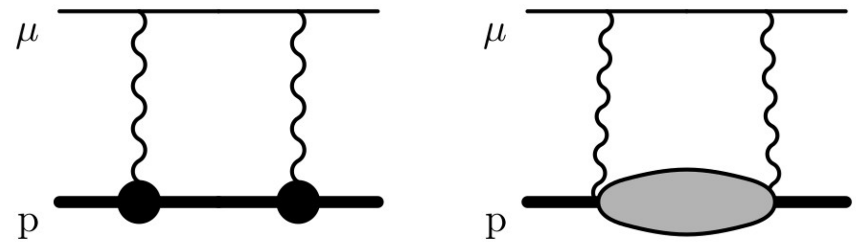

Muon SE+VP




and 20+ more….




Proton form factor

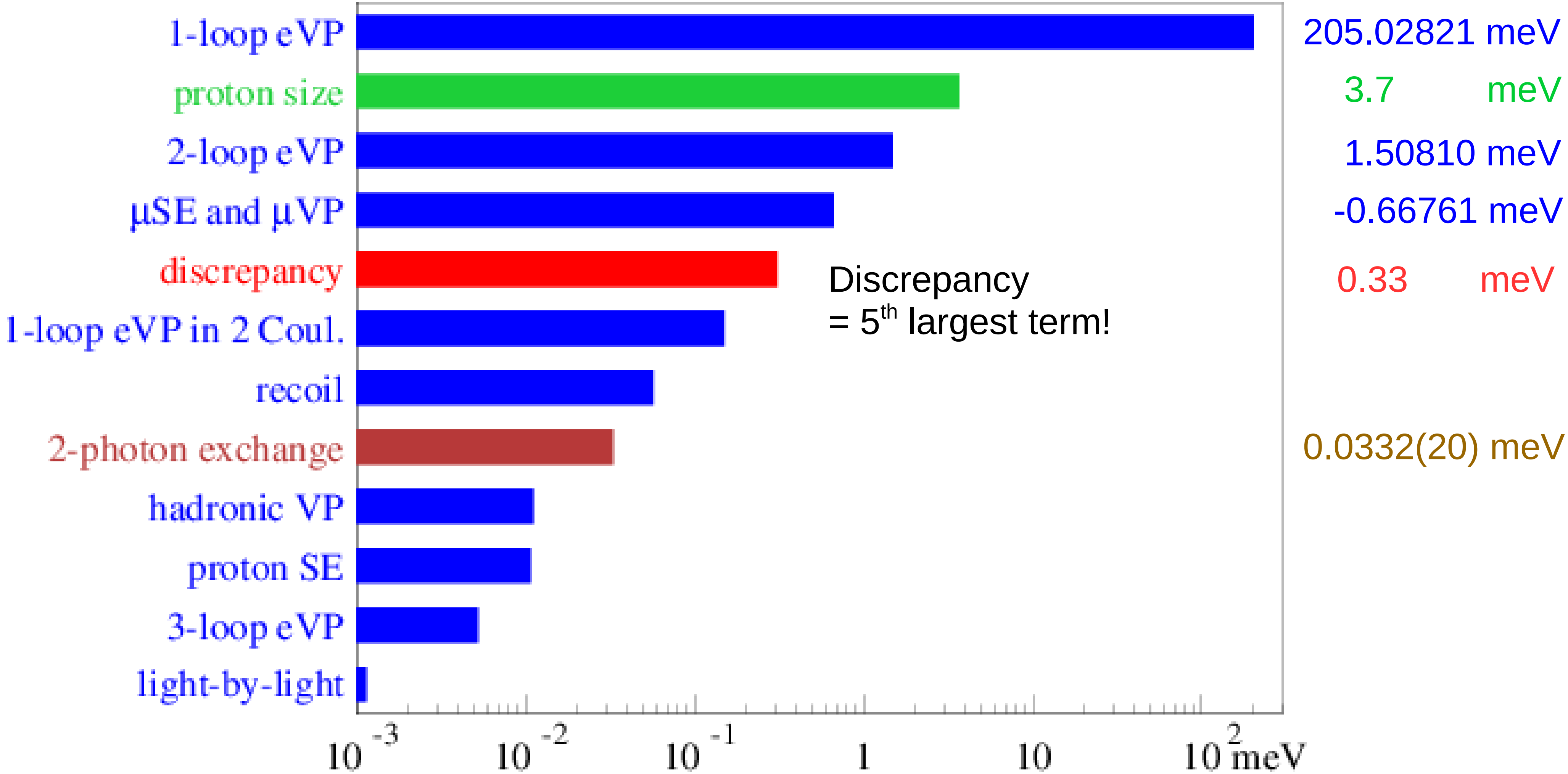



elastic and inelastic two-photon exchange
(Friar moment and polarizability)

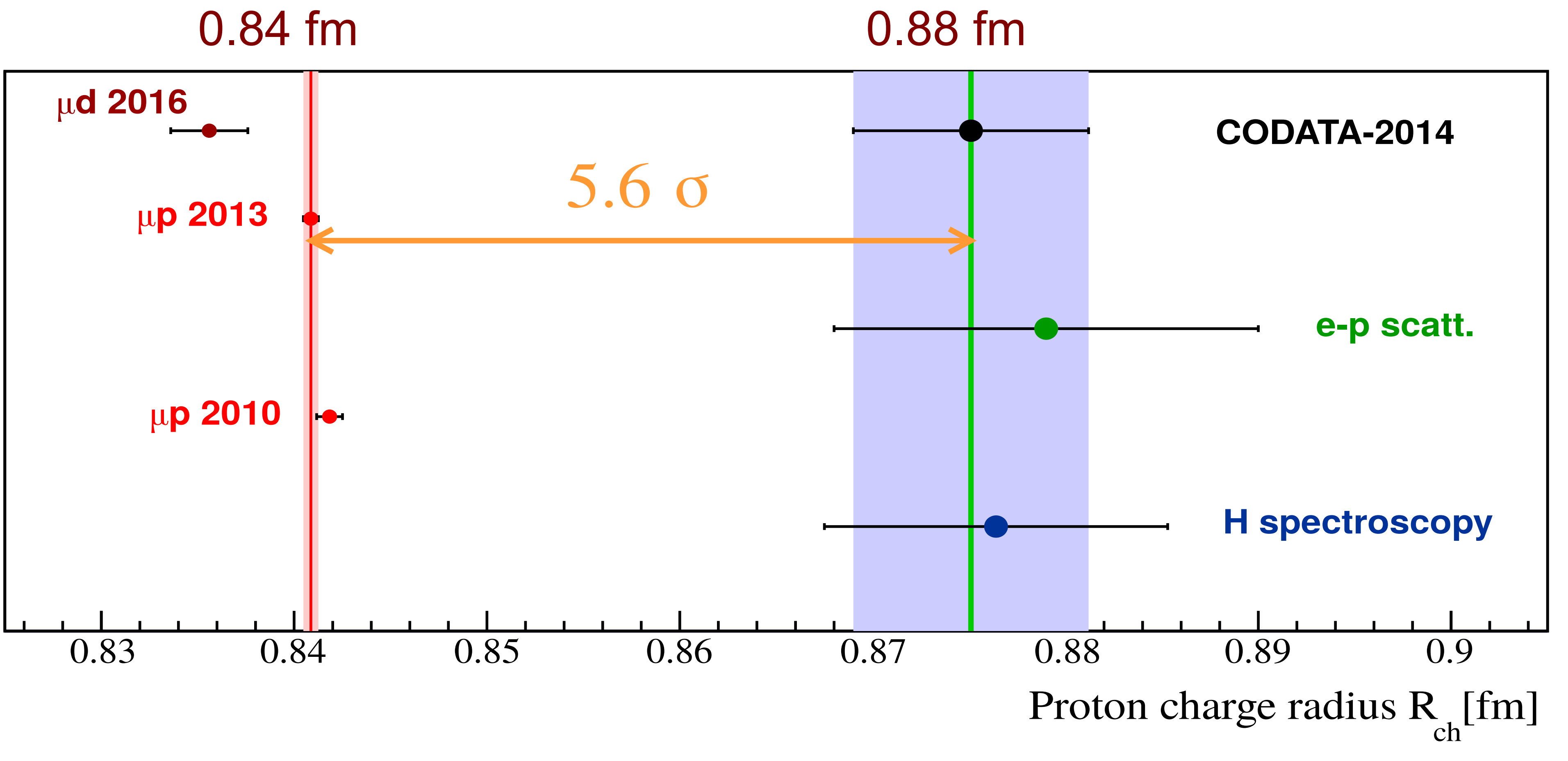
# Theory in muonic H

$\Delta E_{Lamb}$ = 206.0336 (15) $meV_{QED}$ + 0.0332 (20) $meV_{TPE}$ – 5.2275 (10) meV/fm$^2$ * $\mathbf{R_p^2}$

Nice hierarchy



# Muonic Hydrogen




muonic hydrogen: 0.8409 ± 0.0004 fm

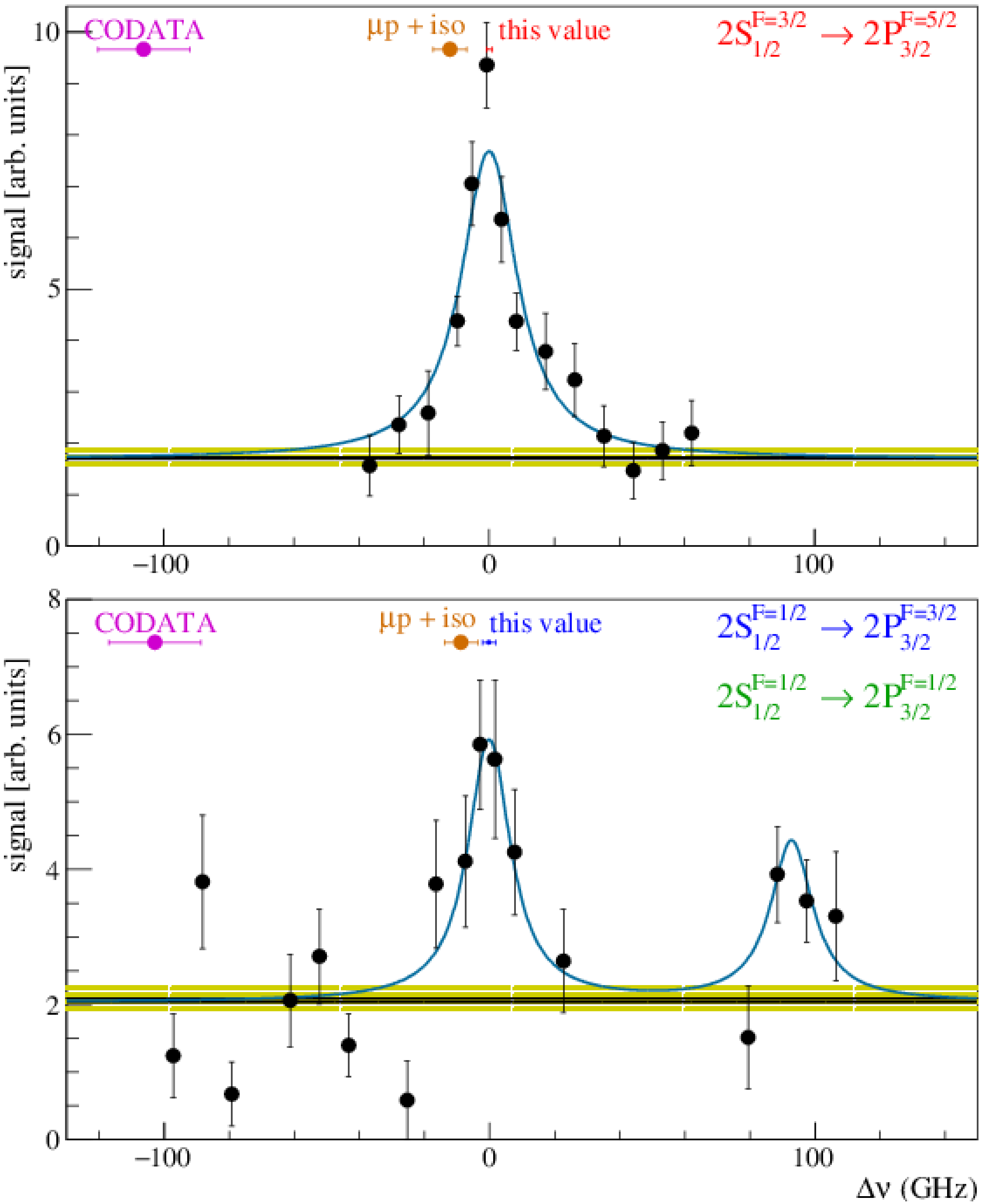
electronic hydrogen: 0.876 ± 0.008 fm

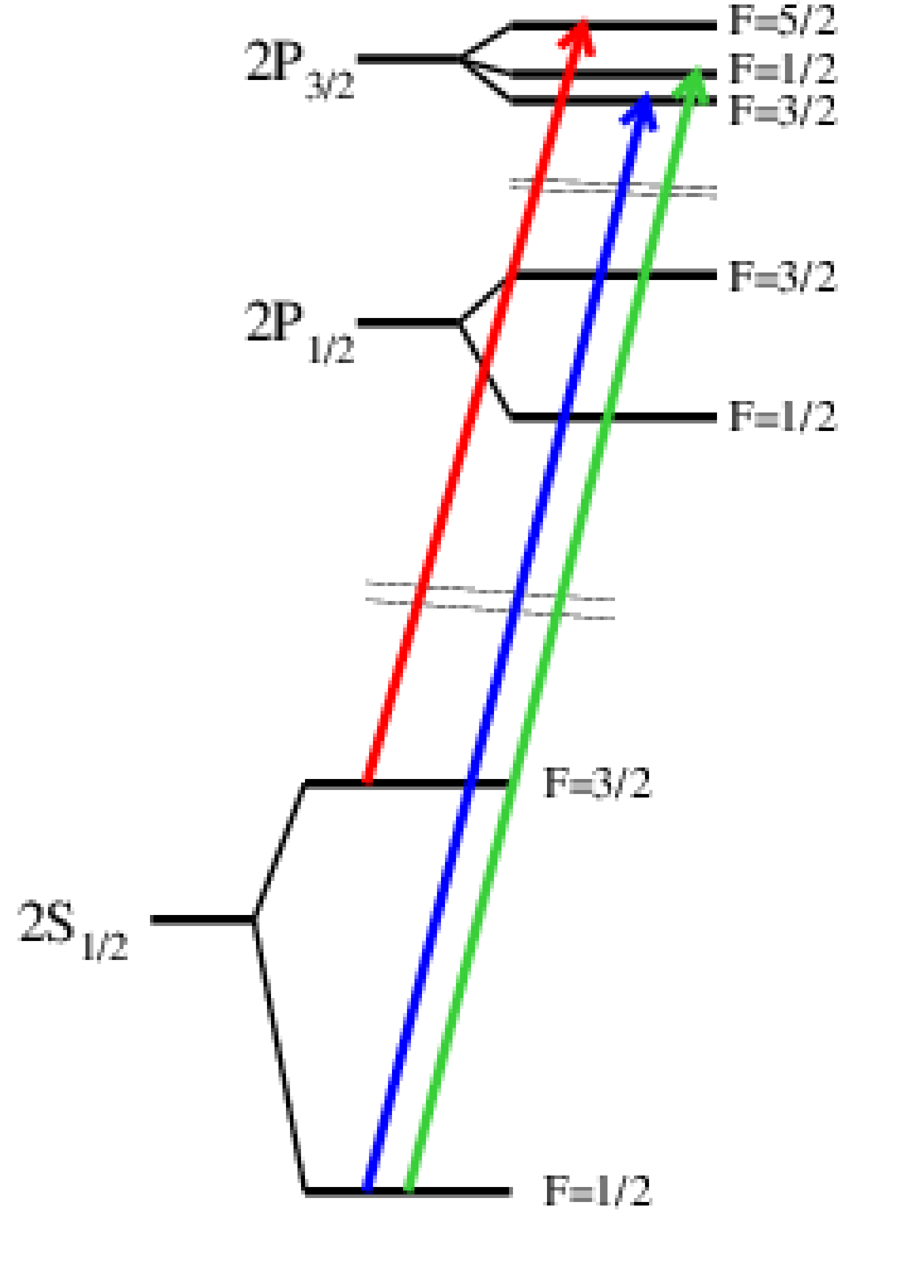
electron scattering 0.879 ± 0.011 fm

20x more precise

# Muonic Deuterium

# 2.5 transitions in muonic D




Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

# Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ \mathrm{meV}_{QED} + 1.7500\ (\mathbf{210})\ \mathrm{meV}_{TPE} - 6.1103\ (3)\ \mathrm{meV/fm^2} * \mathbf{R_d}^{\mathbf{2}}$$

$$\Delta E^{\mu H}_{Lamb} = 206.0336\ (15)\ \mathrm{meV}_{QED} + 0.0332\ (20)\ \mathrm{meV}_{TPE} - 5.2275\ (10)\ \mathrm{meV/fm^2} * \mathbf{R_p}^{\mathbf{2}}$$

Annals of Physics 331 (2013) 127–145

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Annals of Physics

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Theory of the 2S–2P Lamb shift and 2S h
splitting in muonic hydrogen

Aldo Antognini [a,*], Franz Kottmann [a], François Birab
François Nez [b], Randolf Pohl [c]

[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Laboratoire Kastler Brossel, École Normale Supérieure, CNRS and Université P. et M. Cu
[c] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Annals of Physics 366 (2016) 168–196

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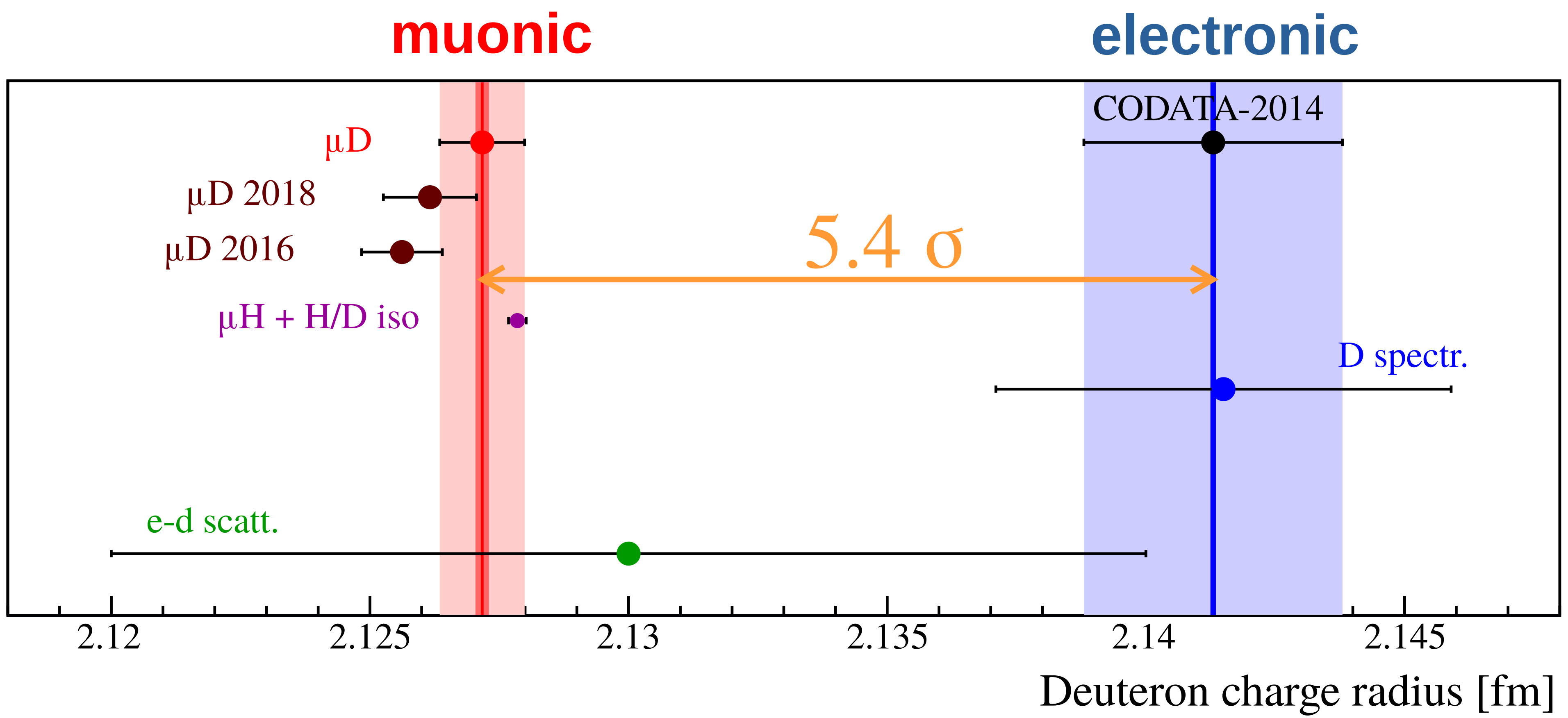
Theory of the $n = 2$ levels in muonic deuterium

Julian J. Krauth [a,*], Marc Diepold [a], Beatrice Franke [a],
Aldo Antognini [b,c], Franz Kottmann [b], Randolf Pohl [a]

Summarizes original work by: Bacca, Barnea, Birse, Borie, Carlson, Eides, Faustov, Friar, Gorchtein, Hernandez, Ivanov, Jentschura, Ji, Karshenboim, Korzinin, Krutov, Martynenko, McGovern, Nevo~Dinur, Pachucki, Shelyuto, Sick, Vanderhaeghen, et al.

Newer work: Pachucki et al., PRA 97, 062511 (2018), Hernandez et al., PLB 778, 377 (2018)

# Muonic Deuterium



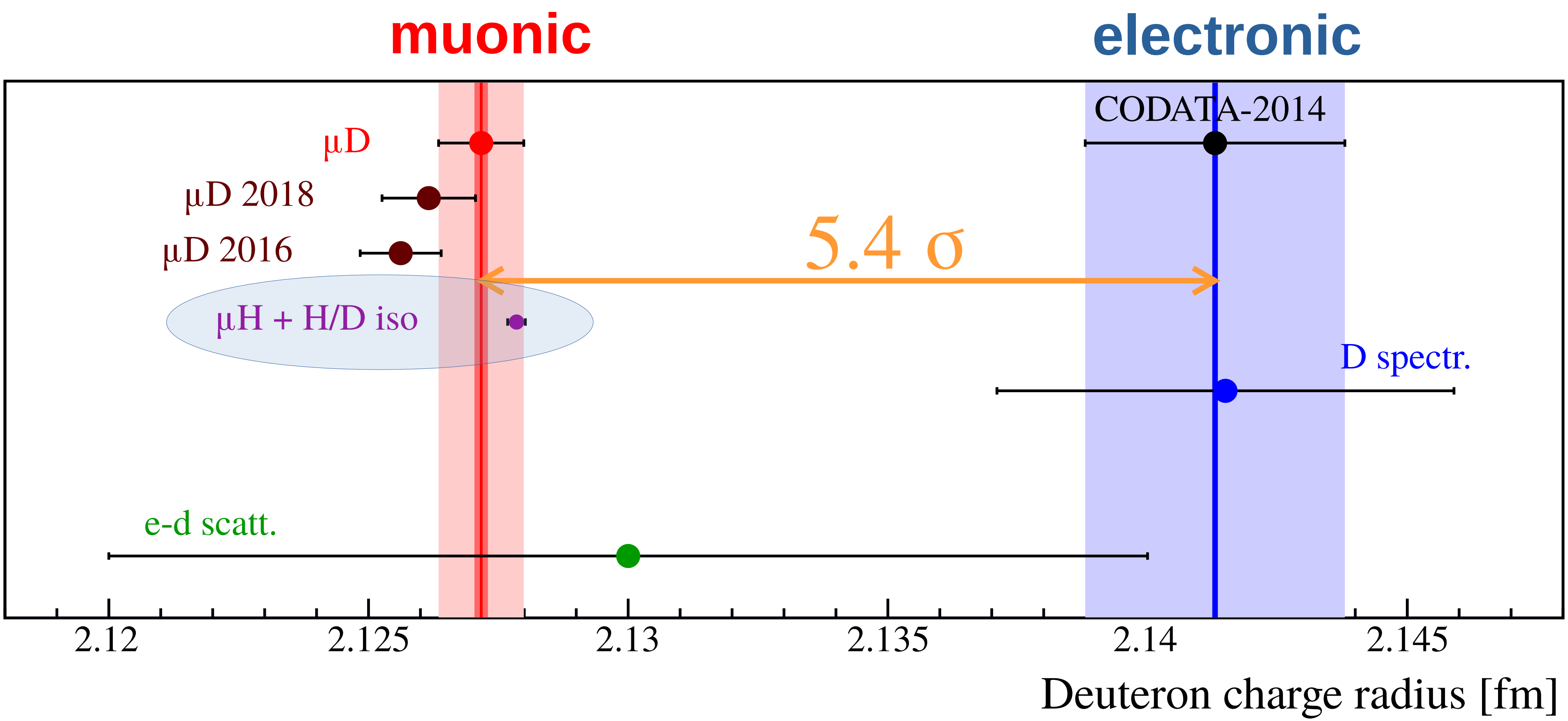

μD: 2.12717 $(13)_{exp}$ $(81)_{theo}$ fm (theo = nucl. polarizability)

CODATA-2014: 2.1**4**130 (250) fm

RP et al. (CREMA Coll.), Science 353, 559 (2016)

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)
+ Kalinowski, arXiv 1812.10993

# Muonic Deuterium




μD: 2.12717 $(13)_{exp}$ $(82)_{theo}$ fm (theo = nucl. polarizability)

μH + H/D(1S-2S): 2.12785 (17) fm

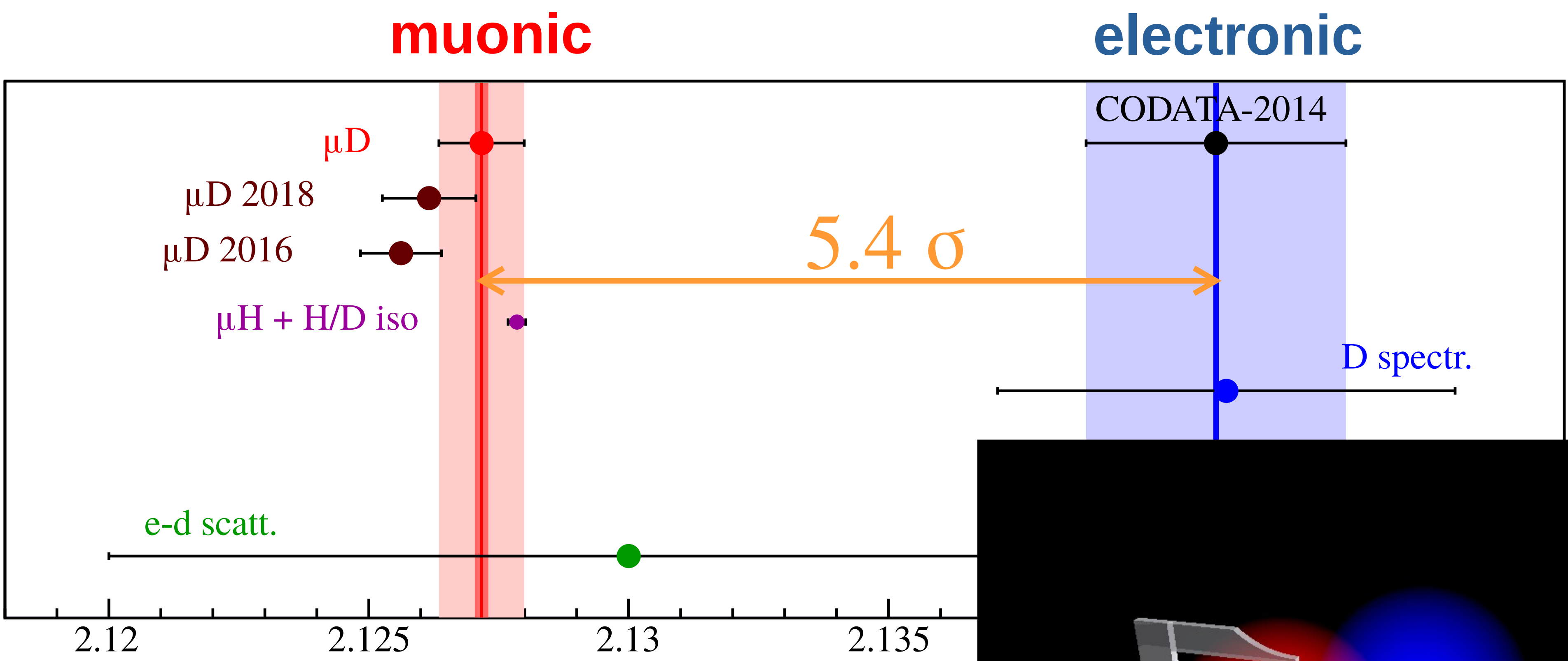
CODATA-2014: 2.1**4**130 (250) fm

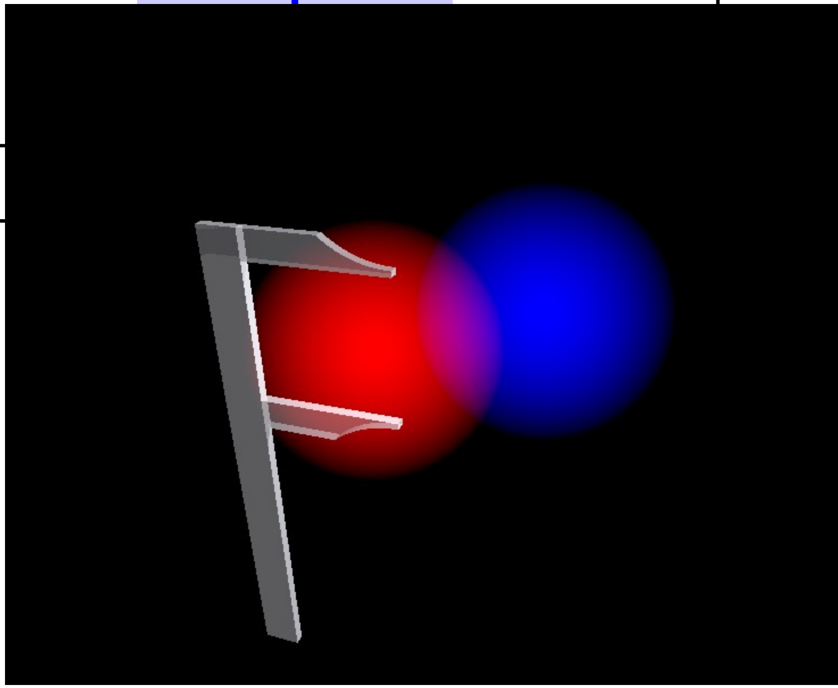
H/D 1S-2S isotope shift:
$r_d^2 - r_p^2 = 3.82070(31)\ fm^2$

Pachucki et al., PRA 97, 062511 (2018)

H/D 1S-2S. Parthey, RP et al. (MPQ Garching), PRL 104, 233001 (2010)
PRL 107, 203001 (2011)

# Muonic Deuterium



Deuteron is CONSISTENTLY smaller!

$$R_d^2 = R^2_{struct} + R_p^2 + R_n^2 \ (+ DF)$$

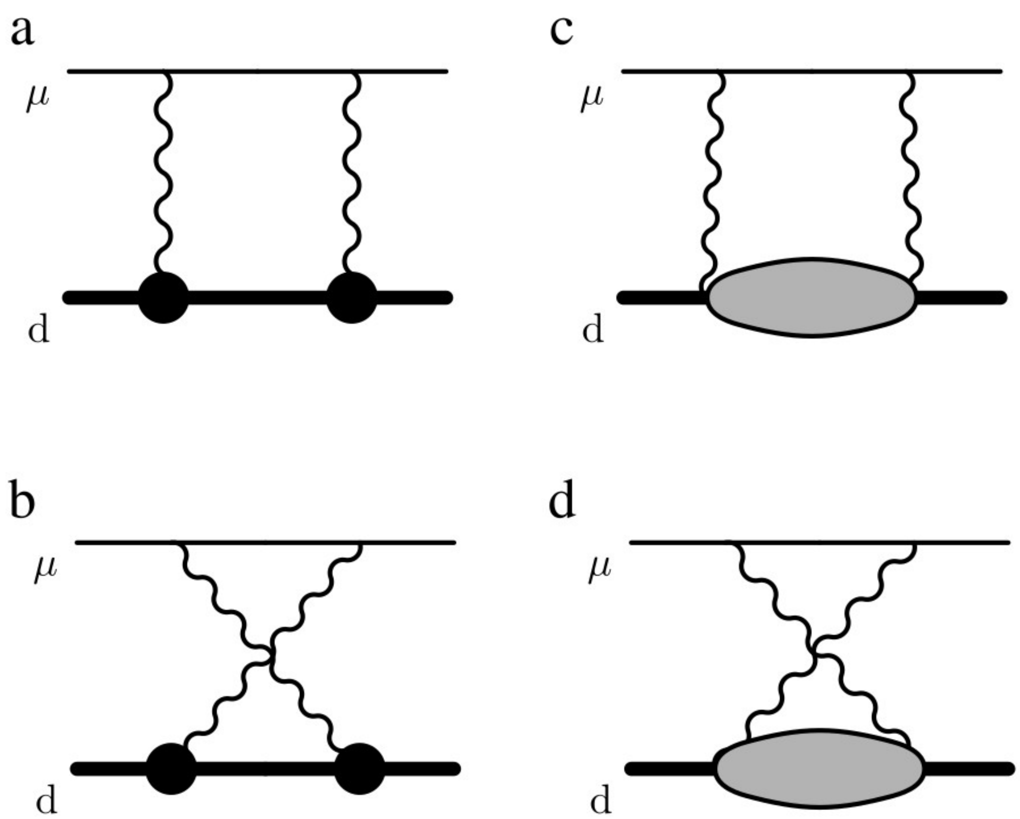
Pohl et al. (CREMA), Science 353, 669 (2016)

# Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\,(13)\ \mathrm{meV}_{QED} + 1.7500\,(\mathbf{210})\ \mathrm{meV}_{TPE} - 6.1103\,(3)\ \mathrm{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$$

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)
+ Kalinowski, arXiv 1812.10993

Two-photon nuclear structure contributions to the Lamb shift in muonic deuterium.



# Theory in muonic D

$\Delta E^{\mu D}_{Lamb}$ = 228.7854 (13) meV$_{QED}$ + 1.7500 (**210**) meV$_{TPE}$ – 6.1103 (3) meV/fm$^2$ * $\mathbf{R_d^2}$

**$\Delta E_{TPE}$ (theo) = 1.7500 +- 0.0210 meV** (Kalinowski, 2018)

**vs. +- 0.0034 meV experimental uncertainty**

(1) **charge radius**, using **calculated TPE**

$r_d$ (μD) = 2.12717 ( 13) $_{exp}$ ( 82) $_{theo}$ fm vs.

$r_d$ (CODATA-14) = 2.1**4**130 (250) fm

(2) **polarizability**, using **charge radius from isotope shift**

$\Delta E_{TPE}$ (theo) = 1.7500 ( 210) meV vs.

$\Delta E_{TPE}$ (exp) = 1.7591 ( 59) meV 3.5x more accurate

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018) + Kalinowski (2018)

# Muonic Helium-3 and -4

# Theory in muonic He-3

$$\Delta E^{\mu^3He}_{Lamb} = 1644.4820(149)_{QED} + 15.3000(\mathbf{5200})_{TPE} - 103.5184(10) * \mathbf{R_h}^{\mathbf{2}} /fm^2 \quad [meV]$$

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)_{QED} + 1.7500(\ 210)_{TPE} - 6.1103\ (\ 3) * \mathbf{R_d}^{\mathbf{2}} /fm^2 \quad [meV]$$

$$\Delta E^{\mu H}_{Lamb} = 206.0336\ (15)_{QED} + 0.0332(\ 20)_{TPE} - 5.2275(10) * \mathbf{R_p}^{\mathbf{2}} /fm^2 \quad [meV]$$

Annals of Physics 331 (2013) 127–145

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Theory of the 2
splitting in mu

Aldo Antognini [a,*],
François Nez [b], Ra

[a] Institute for Particle Physics, E
[b] Laboratoire Kastler Brossel, Éc
[c] Max-Planck-Institut für Quan

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Theory of t

Julian J. Kraut
Aldo Antogni

Eur. Phys. J. D (2017) 71: 341
DOI: 10.1140/epjd/e2017-80296-1

THE EUROPEAN PHYSICAL JOURNAL D

Topical Review

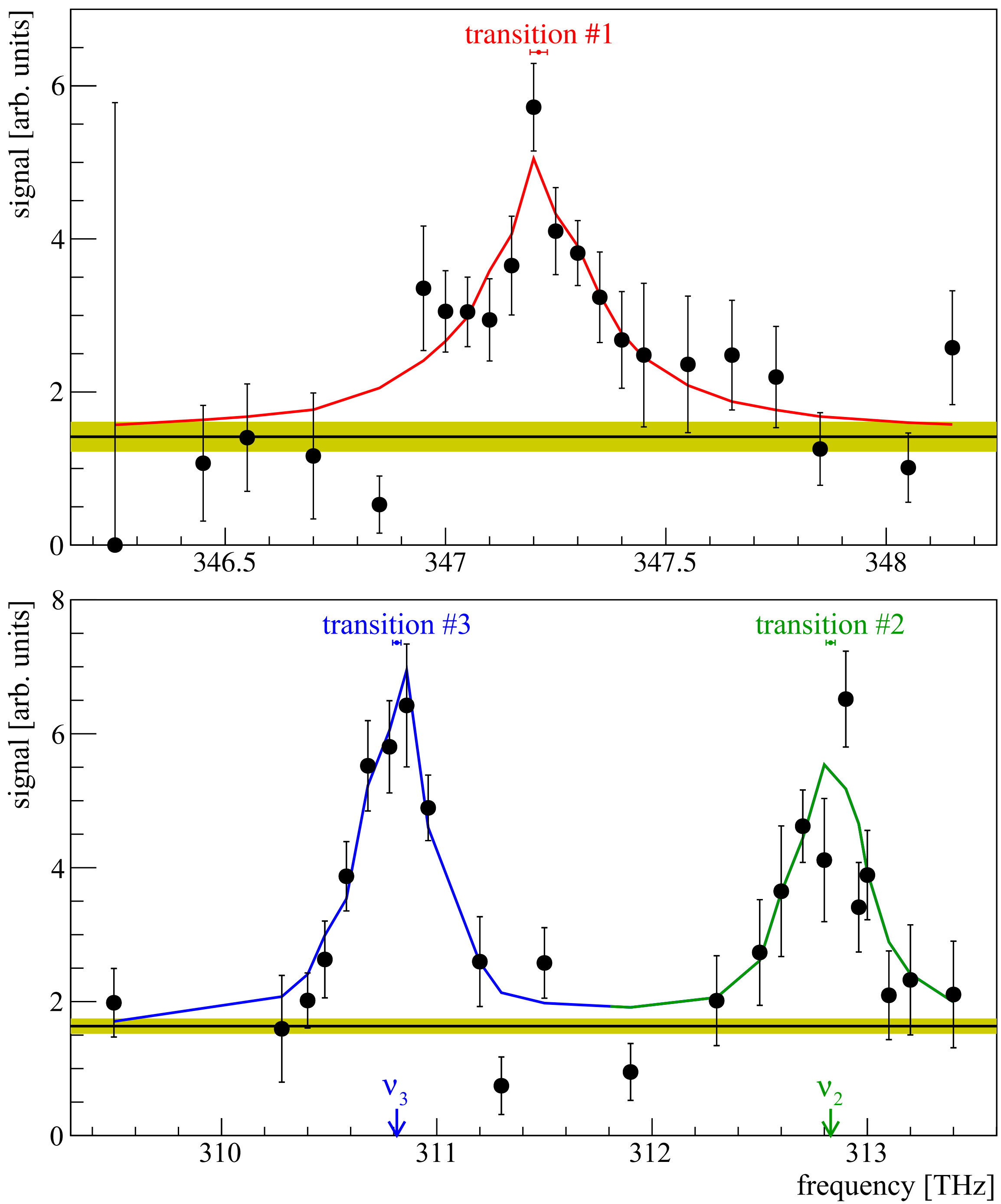
## Theory of the $n = 2$ levels in muonic helium-3 ions

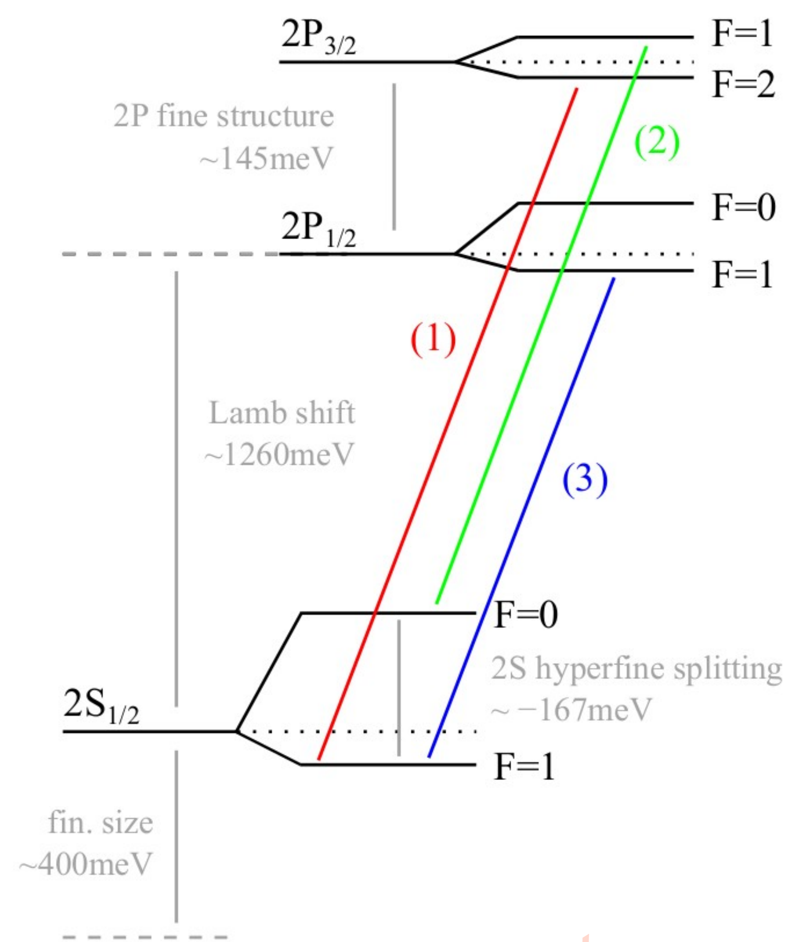
Beatrice Franke[1,2,a], Julian J. Krauth[1,3,b], Aldo Antognini[4,5], Marc Diepold[1], Franz Kottmann[4], and Randolf Pohl[3,1,c]

[1] Max–Planck–Institut für Quantenoptik, 85748 Garching, Germany
[2] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[3] Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA, 55099 Mainz, Germany
[4] Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland
[5] Paul Scherrer Institute, 5232 Villigen, Switzerland

**Three-photon contribution still missing** (Pachucki et al., PRA 97, 052511 (2018))

# muonic $^3$He ions



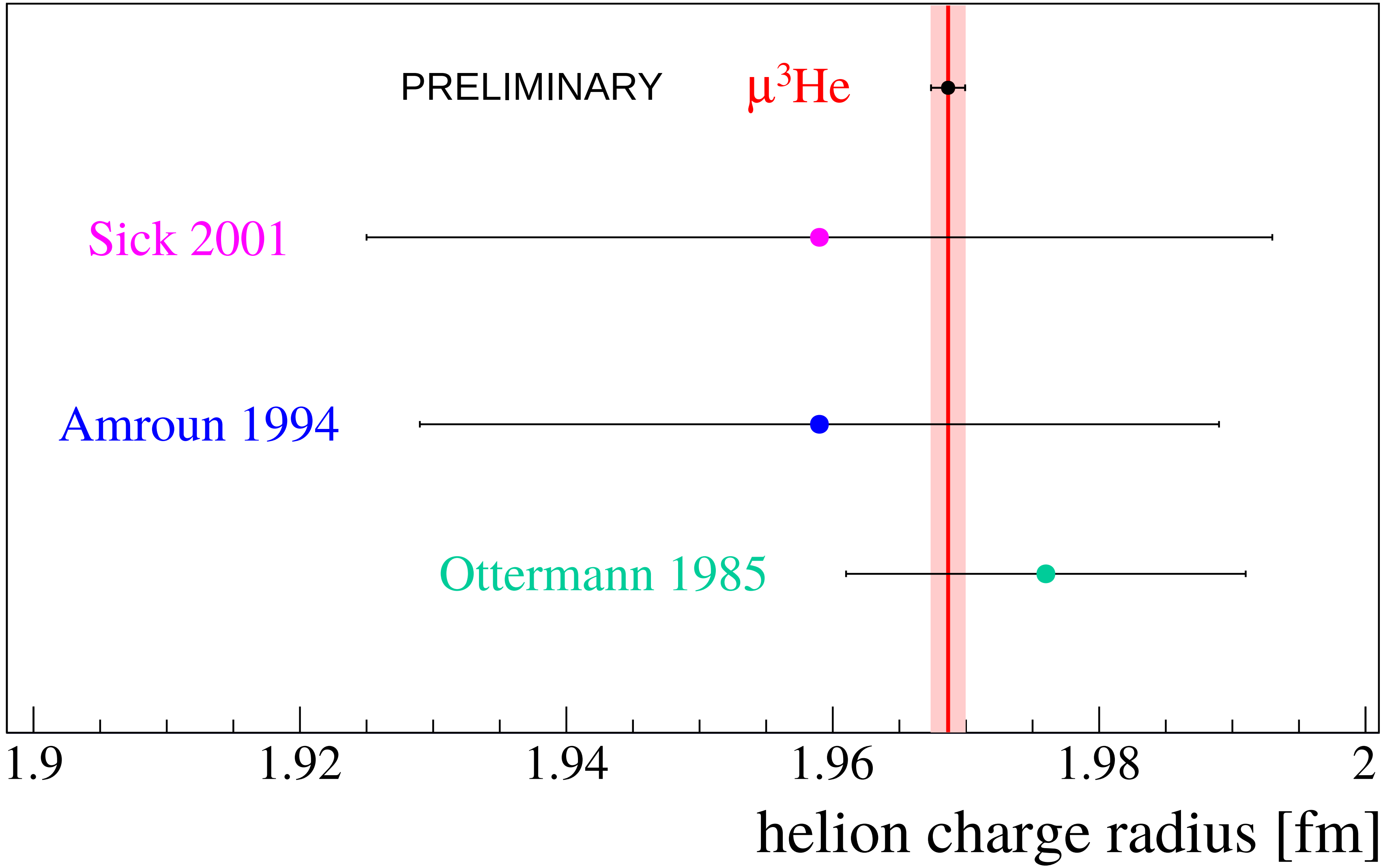




$R(^3He) = 1.96866\,(12)_{exp}\,(128)_{theo}$ fm

PRELIMINARY

Theory: Franke et al., EPJD (2017),
but 3-photon (Pachucki et al.) ?!?!

# Muonic Helium-3




prel. accuracy: exp **+- 0.00012** fm, theo **+- 0.00128** fm (nucl. polarizability)

Theory: see Franke et al. EPJ D 71, 341 (2017) [1705.00352]

# Theory in muonic He-4

$$\Delta E^{\mu^4He}_{Lamb} = 1668.5670(178)_{QED} + 9.9000(\mathbf{2800})_{TPE} - 106.3540(80) * R_\alpha^2 /fm^2 \quad [meV]$$

$$\Delta E^{\mu^3He}_{Lamb} = 1644.4820(149)_{QED} + 15.3000(5200)_{TPE} - 103.5184(10) * R_h^2 /fm^2 \quad [meV]$$

$$\Delta E^{\mu D}_{Lamb} = 228.7854\,(13)_{QED} + 1.7500(\,210)_{TPE} - 6.1103\,(\,3) * R_d^2 /fm^2 \quad [meV]$$

$$\Delta E^{\mu H}_{Lamb} = 206.0336\,(15)_{QED} + 0.0332(\,20)_{TPE} - 5.2275(10) * R_p^2 /fm^2 \quad [meV]$$

Annals of Physics 331 (2013) 127–145

ELSEVIER

Theory of the ... splitting in mu...

Aldo Antognini[a,*], ...
François Nez[b], Ra...
[a] Institute for Particle Physics, E...
[b] Laboratoire Kastler Brossel, Éc...
[c] Max-Planck-Institut für Quan...

Annals o...

ELSEVIER

Eur. Phys. J. D (2017) 71: 34...
DOI: 10.1140/epjd/e2017-802...

Topical Review

Theory of the ...

Beatrice Franke[1,2,a], Julian ...
and Randolf Pohl[3,1,c]
[1] Max–Planck–Institut für Qu...
[2] TRIUMF, 4004 Wesbrook M...
[3] Johannes Gutenberg-Unive... 55099 Mainz, Germany
[4] Institute for Particle Physic...
[5] Paul Scherrer Institute, 523...

Theory of t...

Julian J. Kraut...
Aldo Antogni...

Annals of Physics 396 (2018) 220–244

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Annals of Physics

journal homepage: www.elsevier.com/locate/aop

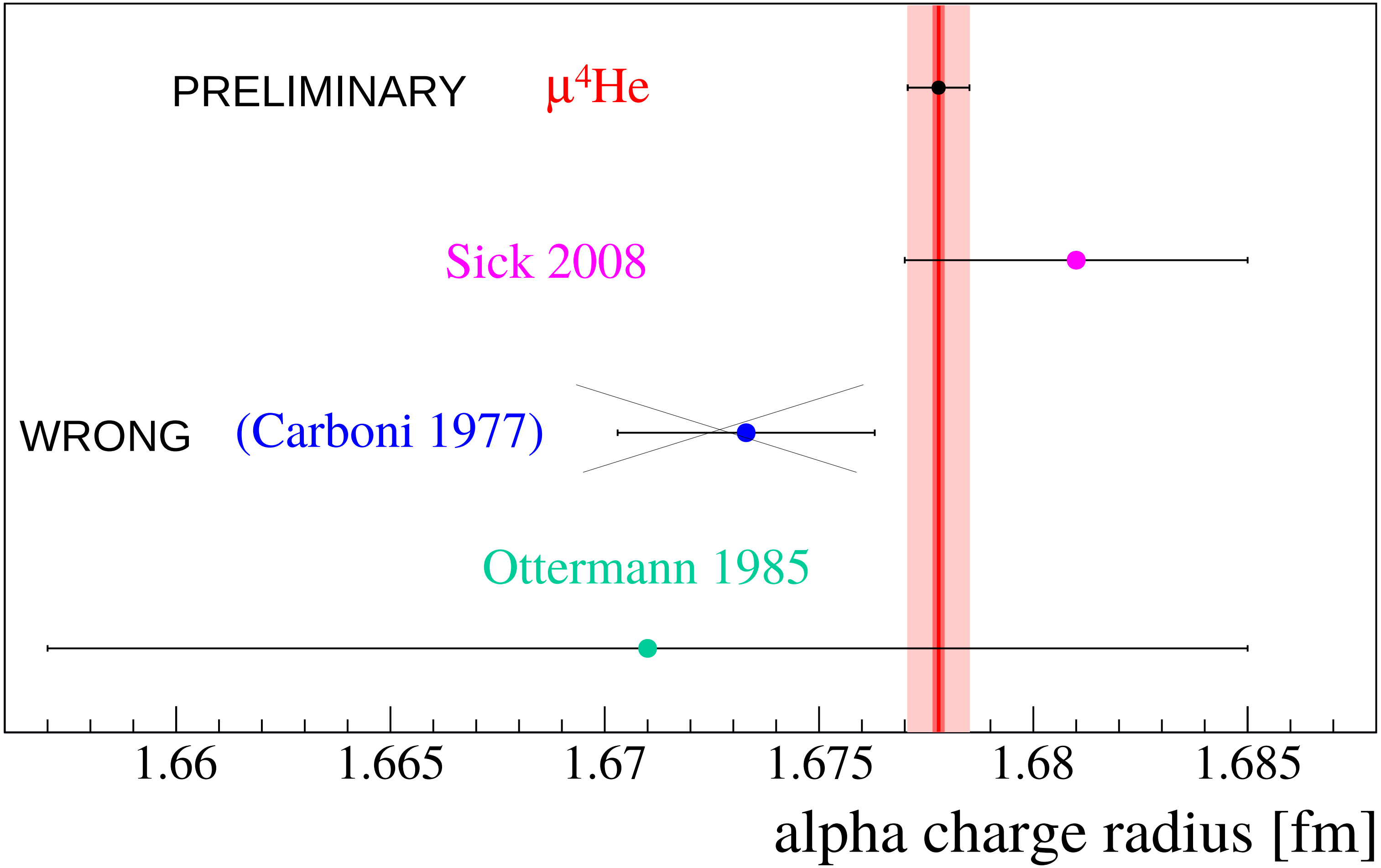
ELSEVIER

Theory of the Lamb Shift and fine structure in muonic $^4$He ions and the muonic $^3$He–$^4$He Isotope Shift

Marc Diepold[a], Beatrice Franke[a,b], Julian J. Krauth[a,c,*], Aldo Antognini[d,e], Franz Kottmann[d], Randolf Pohl[c,a]

**Three-photon contribution still missing** (Pachucki et al., PRA 97, 052511 (2018))

# Muonic Helium-4

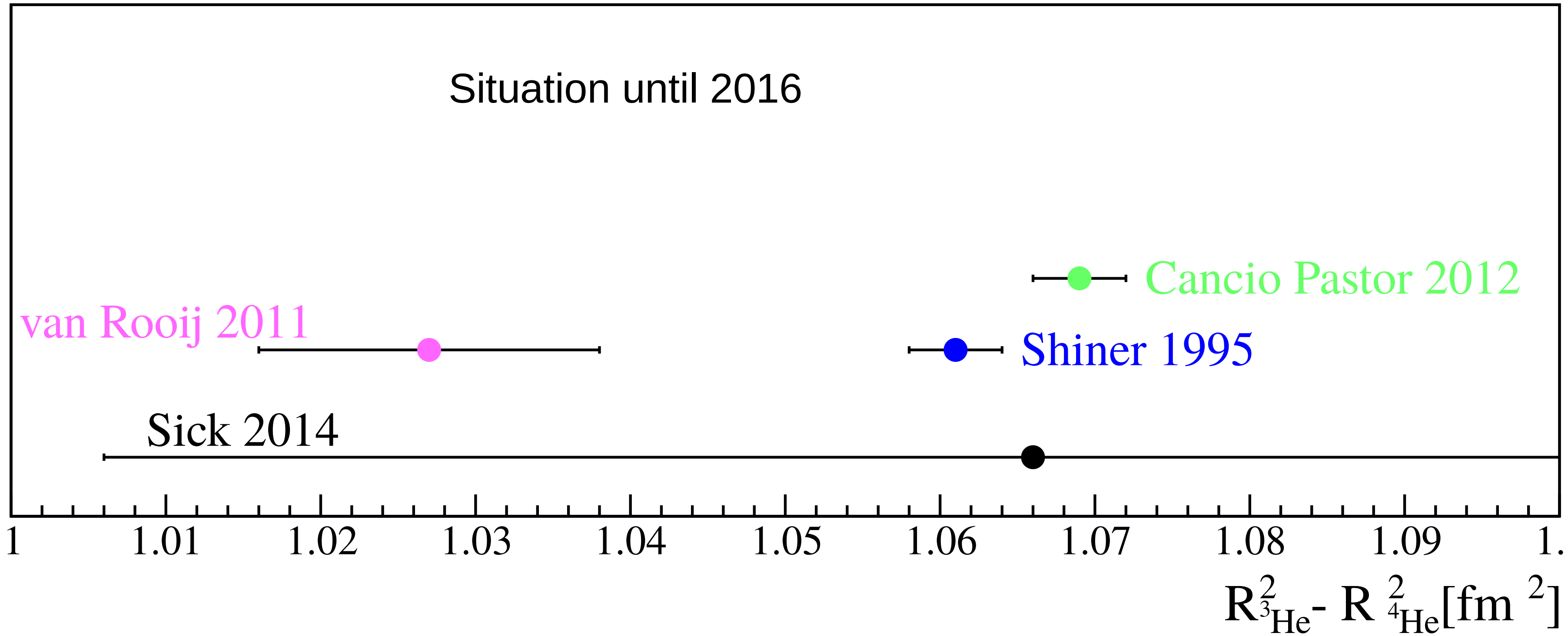



prel. accuracy: exp **+- 0.00019** fm, theo **+- 0.00058** fm (nucl. polarizability)

Theory: M. Diepold, RP et al. Ann. Phys. (N.Y.) 396, 220 (2018)
(arxiv 1606.05231 (sic!))

# The $^3$He – $^4$He isotope shift

$^3$He / $^4$He (squared) charge radius difference



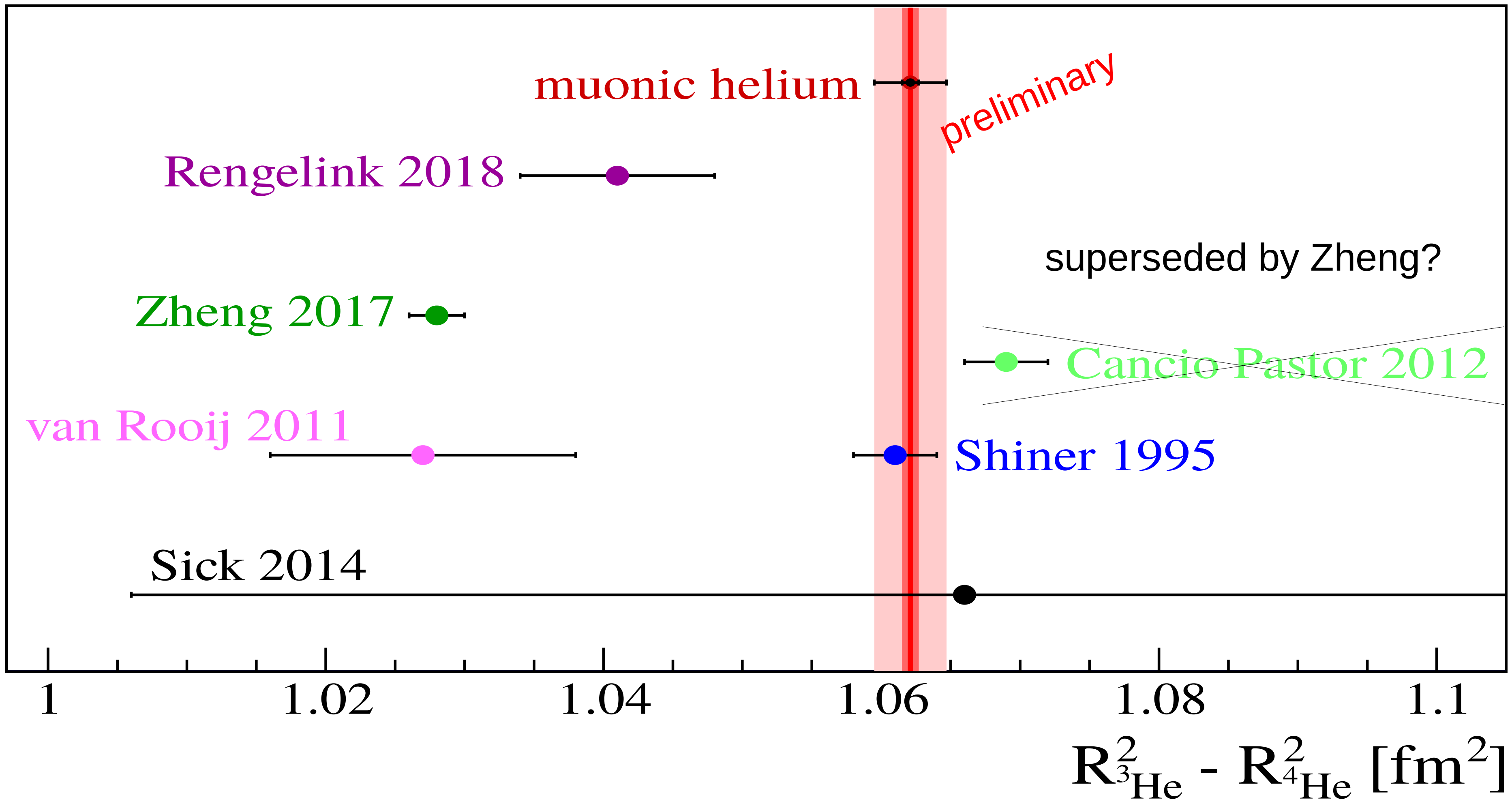

Shiner et al., PRL 74, 3553 (1995)
vanRooij, Science 333, 196 (2011)
Cancio Pastor et al., PRL 108, 143001 (2012)

**all evaluated with recent theory by Pachucki et al.**

Sick, PRC 90, 064002 (2014)

# The $^3$He – $^4$He isotope shift

$^3$He / $^4$He (squared) charge radius difference



# Part 2: The Rydberg constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

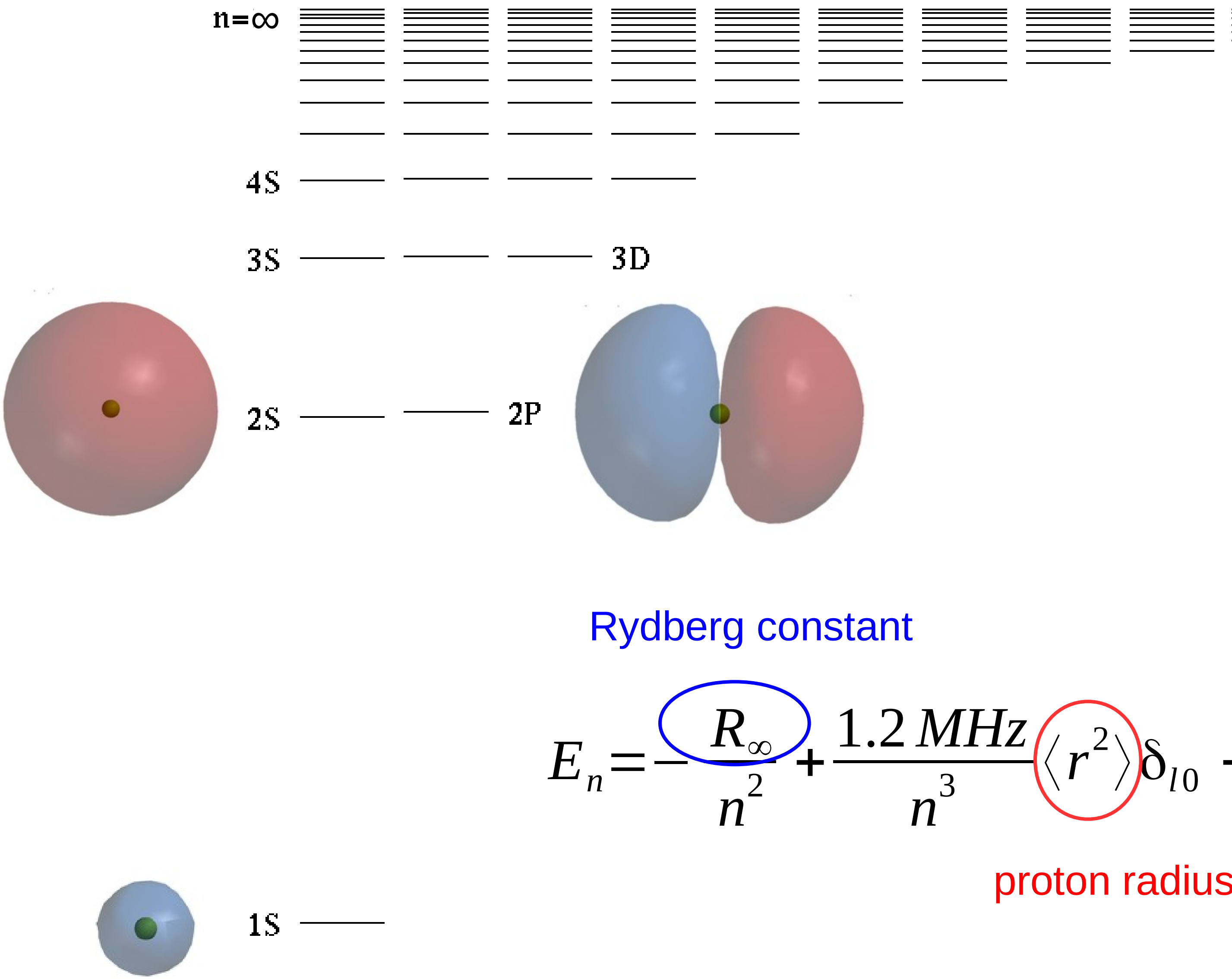
- most accurately determined fundamental constant $u_r = 5.9 * 10^{-12}$
- corner stone of the CODATA LSA of fundamental constants

  links fine structure constant α, electron mass $m_e$, velocity of light c and Planck's constant *h*
- correlation coefficient with proton radius: 0.9891

  → The "proton radius puzzle" could be a "Rydberg puzzle"

- $R_\infty$ is a "unit converter": atomic units → SI (Hertz)

# Energy levels of hydrogen

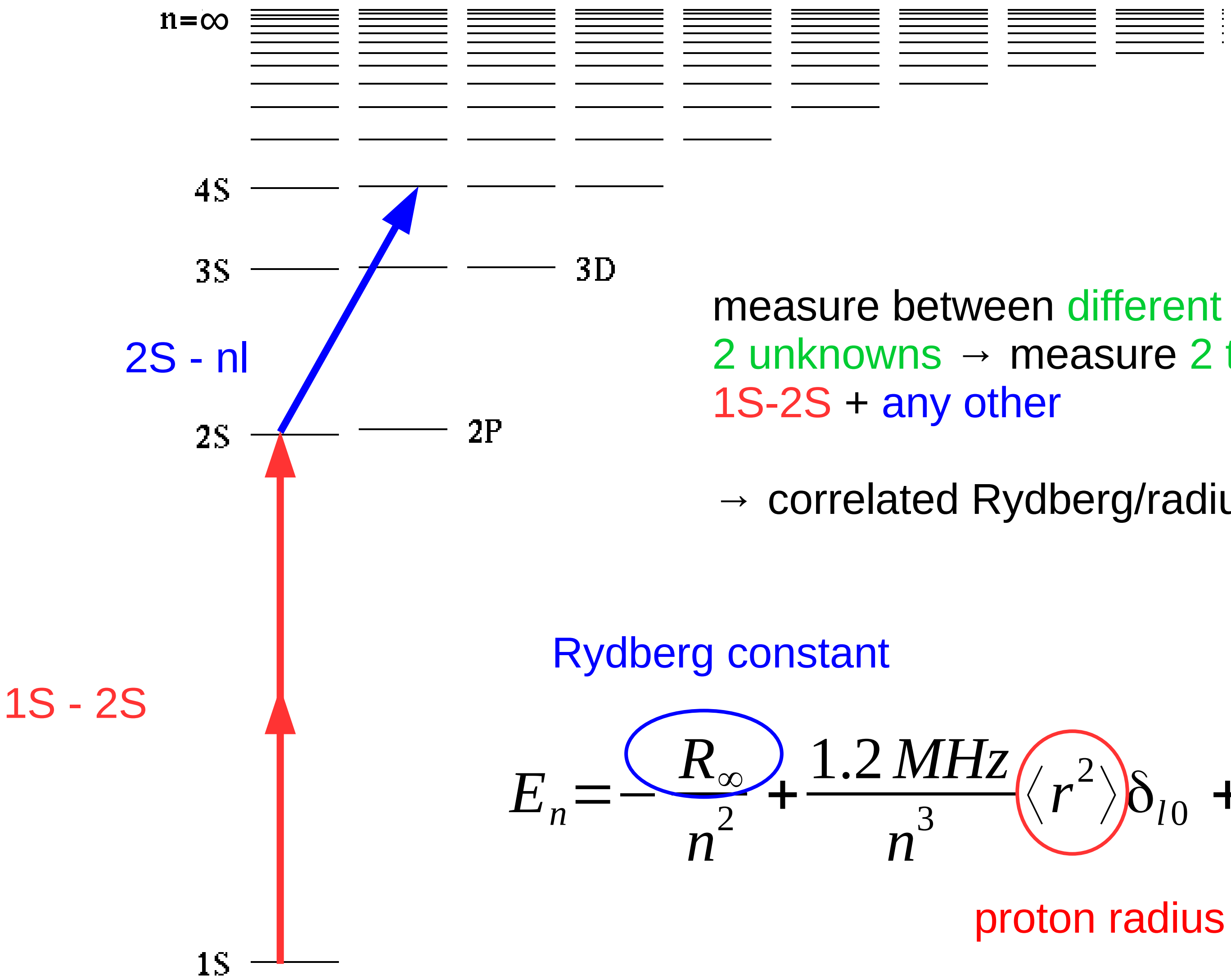



Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

# Energy levels of hydrogen




measure between different **n**
2 unknowns → measure 2 transitions:
1S-2S + any other

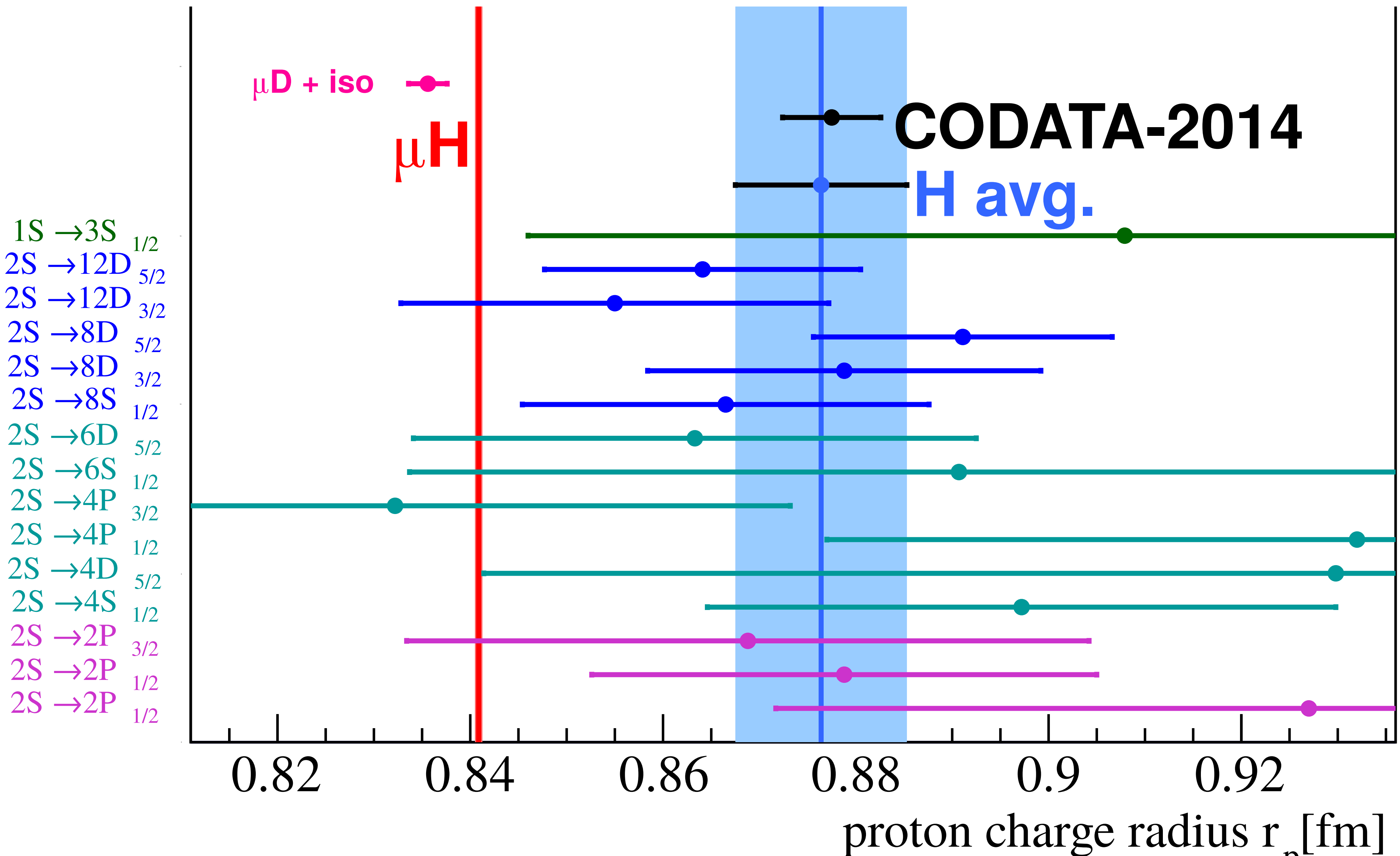
→ correlated Rydberg/radius pairs

Rydberg constant

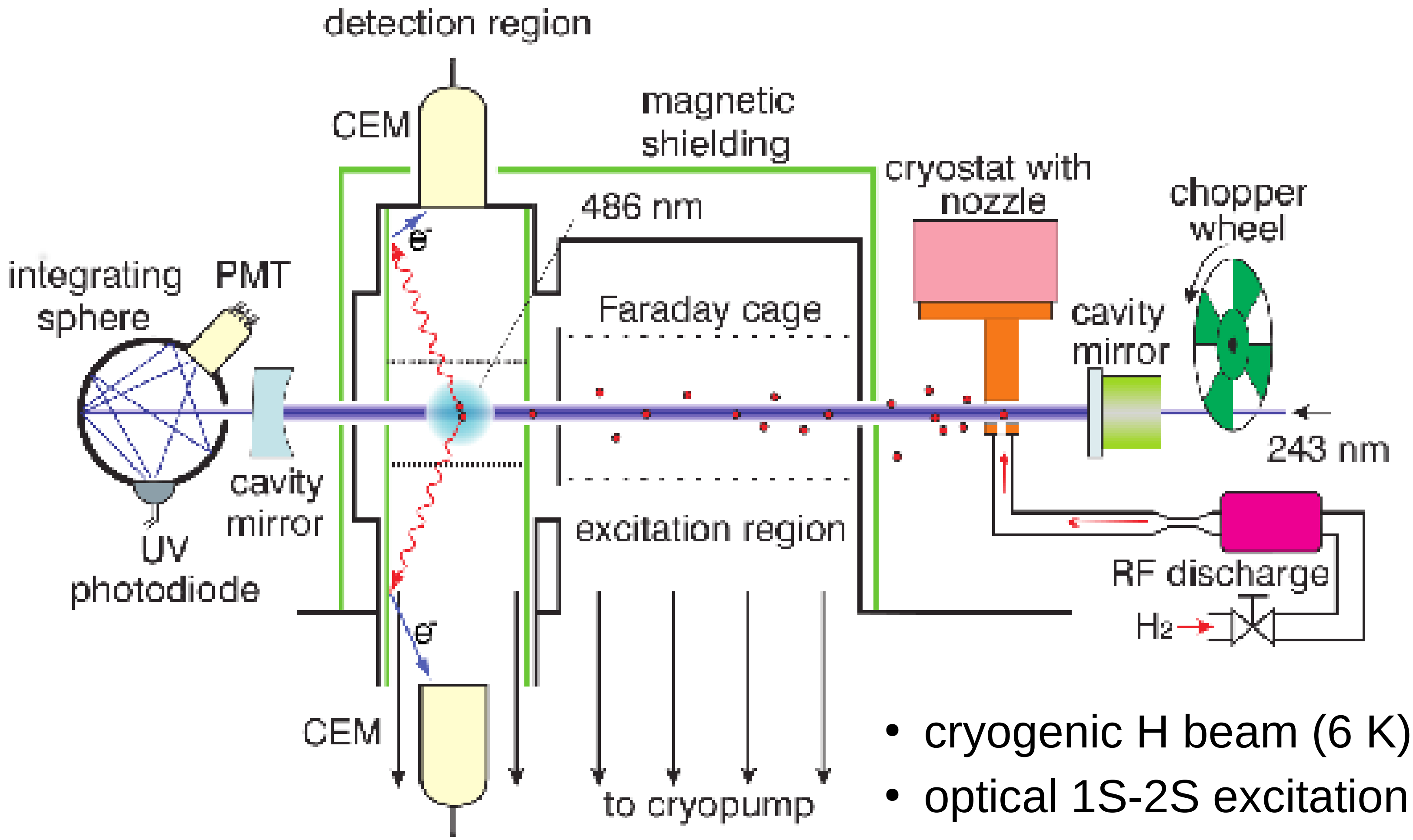
$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

# Rp from H spectroscopy



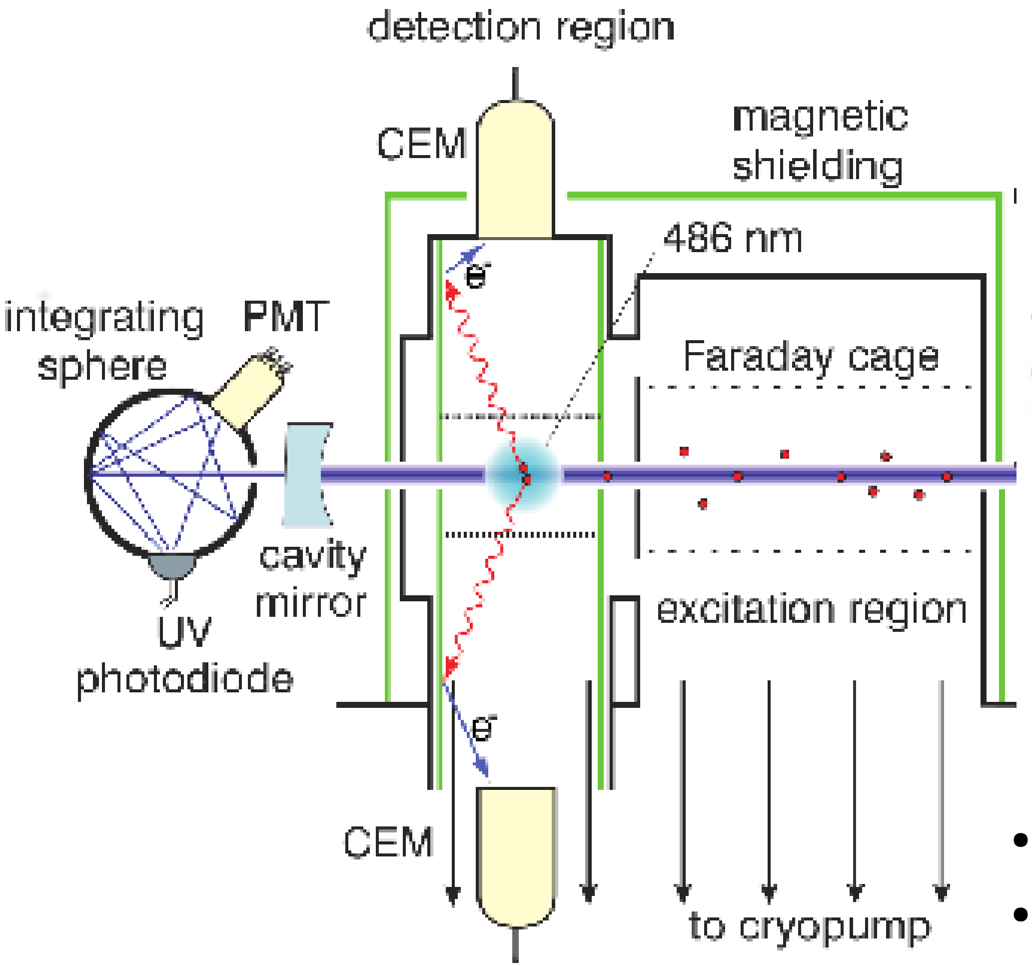
# Garching H(2S-4P)



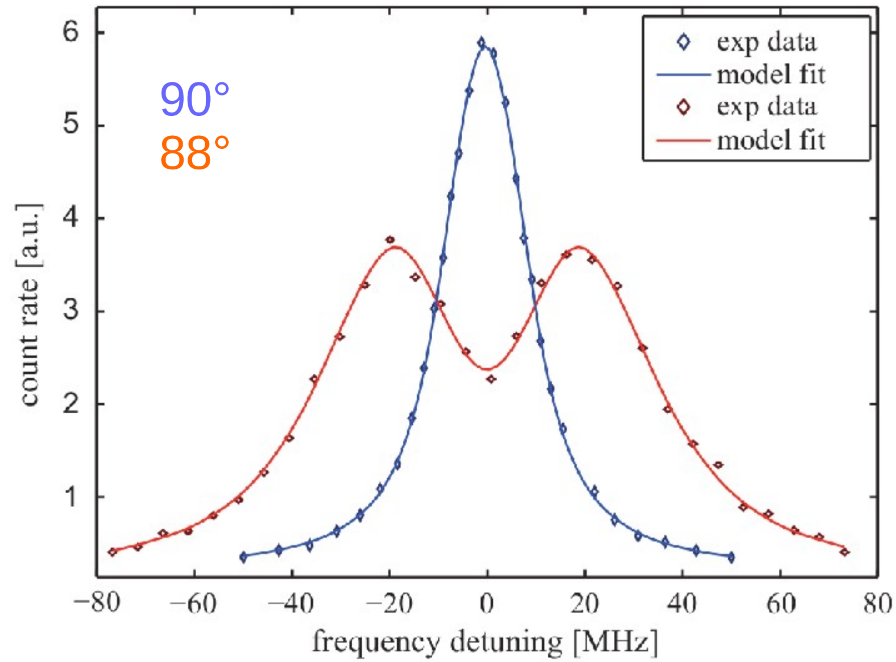

- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to $10^{-4}$ !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

# Garching H(2S-4P)




1st order Doppler cancellation

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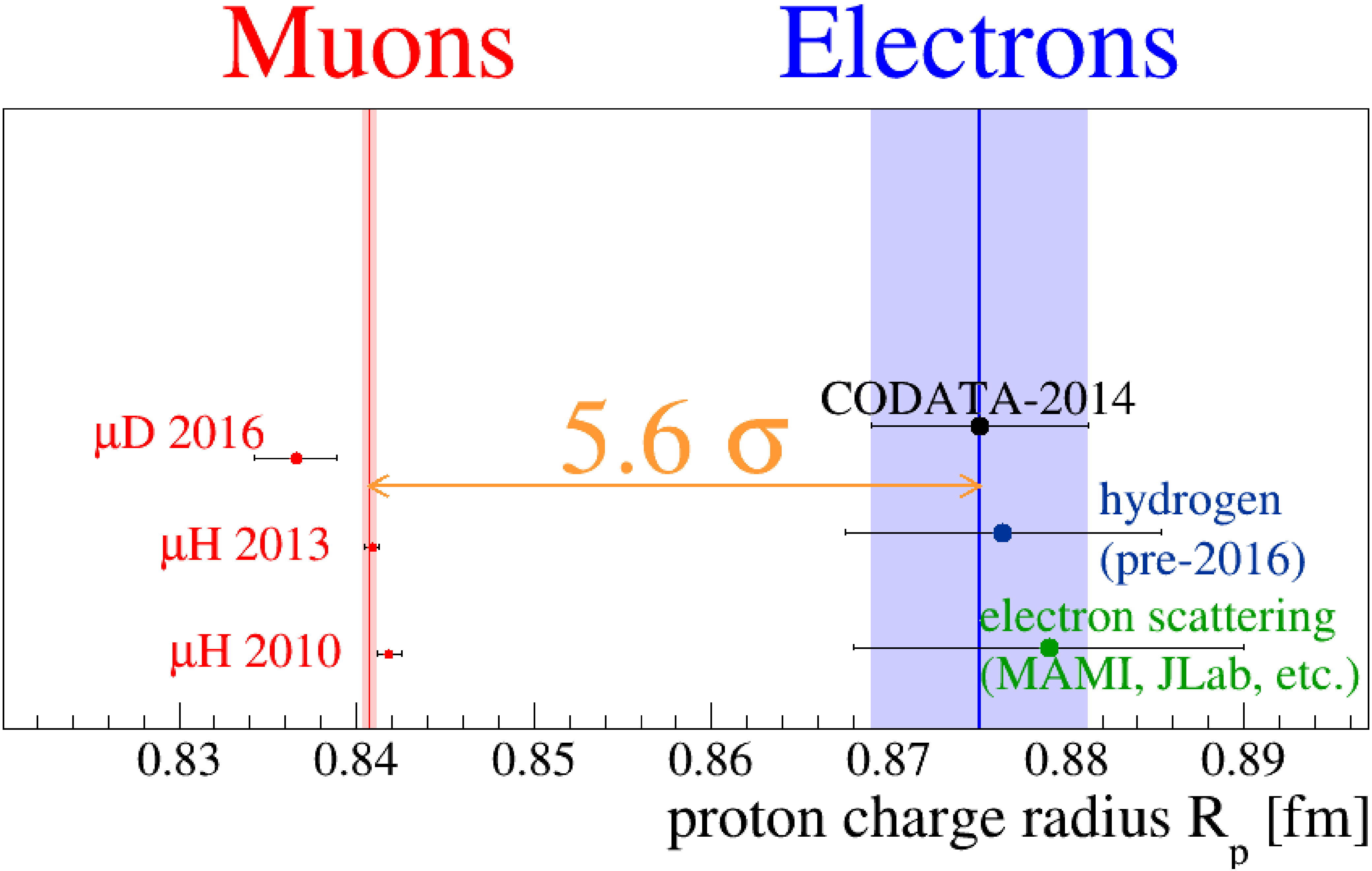
Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

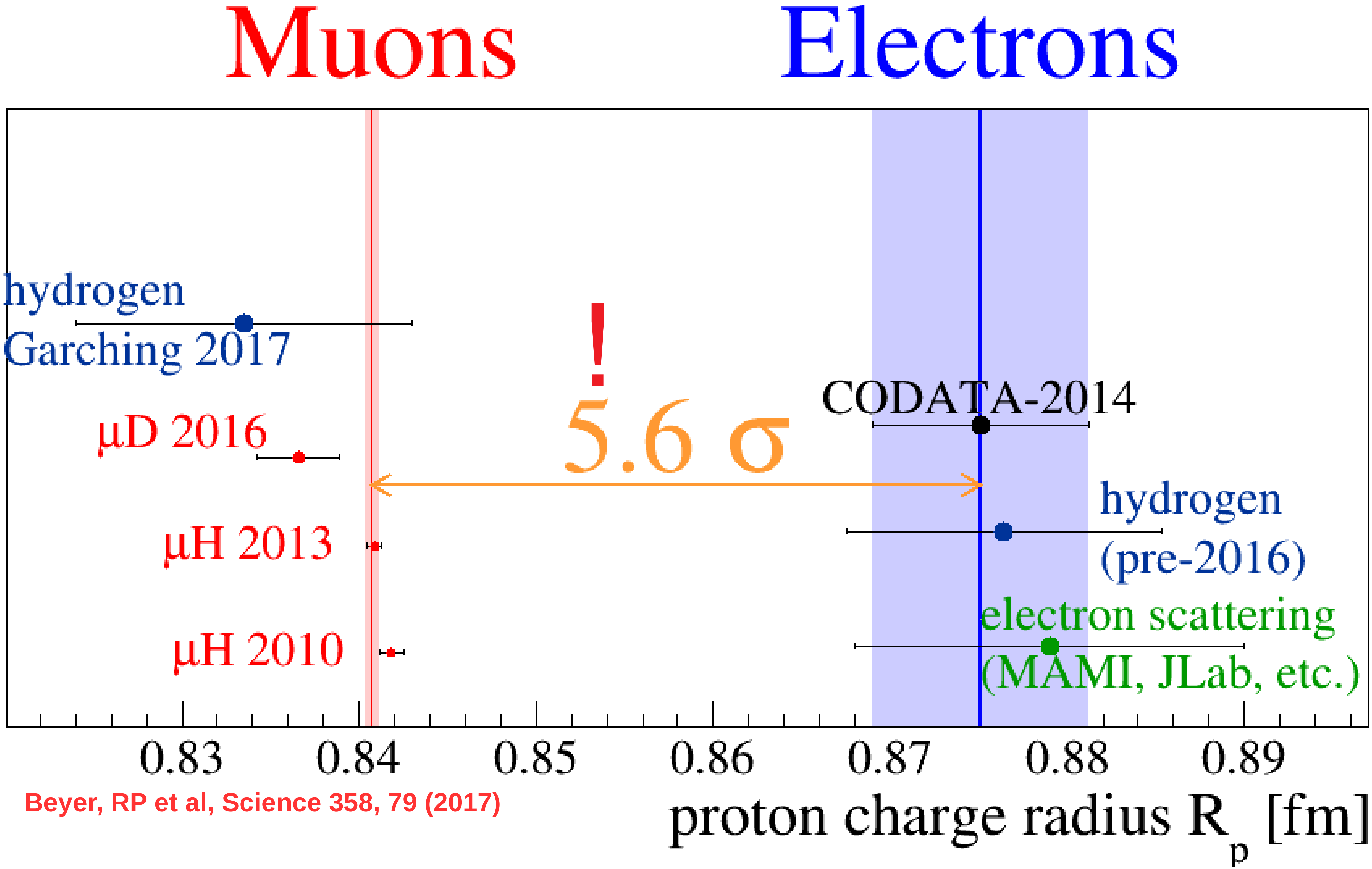
# Systematics

| Contribution | Δν (kHz) | σ (kHz) |
|---|---|---|
| Statistics | 0.00 | 0.41 |
| First-order Doppler shift | 0.00 | 2.13 |
| Quantum interference shift | 0.00 | 0.21 |
| Light force shift | –0.32 | 0.30 |
| Model corrections | 0.11 | 0.06 |
| Sampling bias | 0.44 | 0.49 |
| Second-order Doppler shift | 0.22 | 0.05 |
| dc-Stark shift | 0.00 | 0.20 |
| Zeeman shift | 0.00 | 0.22 |
| Pressure shift | 0.00 | 0.02 |
| Laser spectrum | 0.00 | 0.10 |
| Frequency standard (hydrogen maser) | 0.00 | 0.06 |
| Recoil shift | –837.23 | 0.00 |
| Hyperfine structure corrections | –132,552.092 | 0.075 |
| Total | –133,388.9 | 2.3 |

# The “Proton Radius Puzzle”



# New Measurements: Garching 2S-4P




Beyer, RP et al, Science 358, 79 (2017)

# New Rp from Paris: 1S-3S

PHYSICAL REVIEW LETTERS **120,** 183001 (2018)

## New Measurement of the $1S-3S$ Transition Frequency of Hydrogen: Contribution to the Proton Charge Radius Puzzle

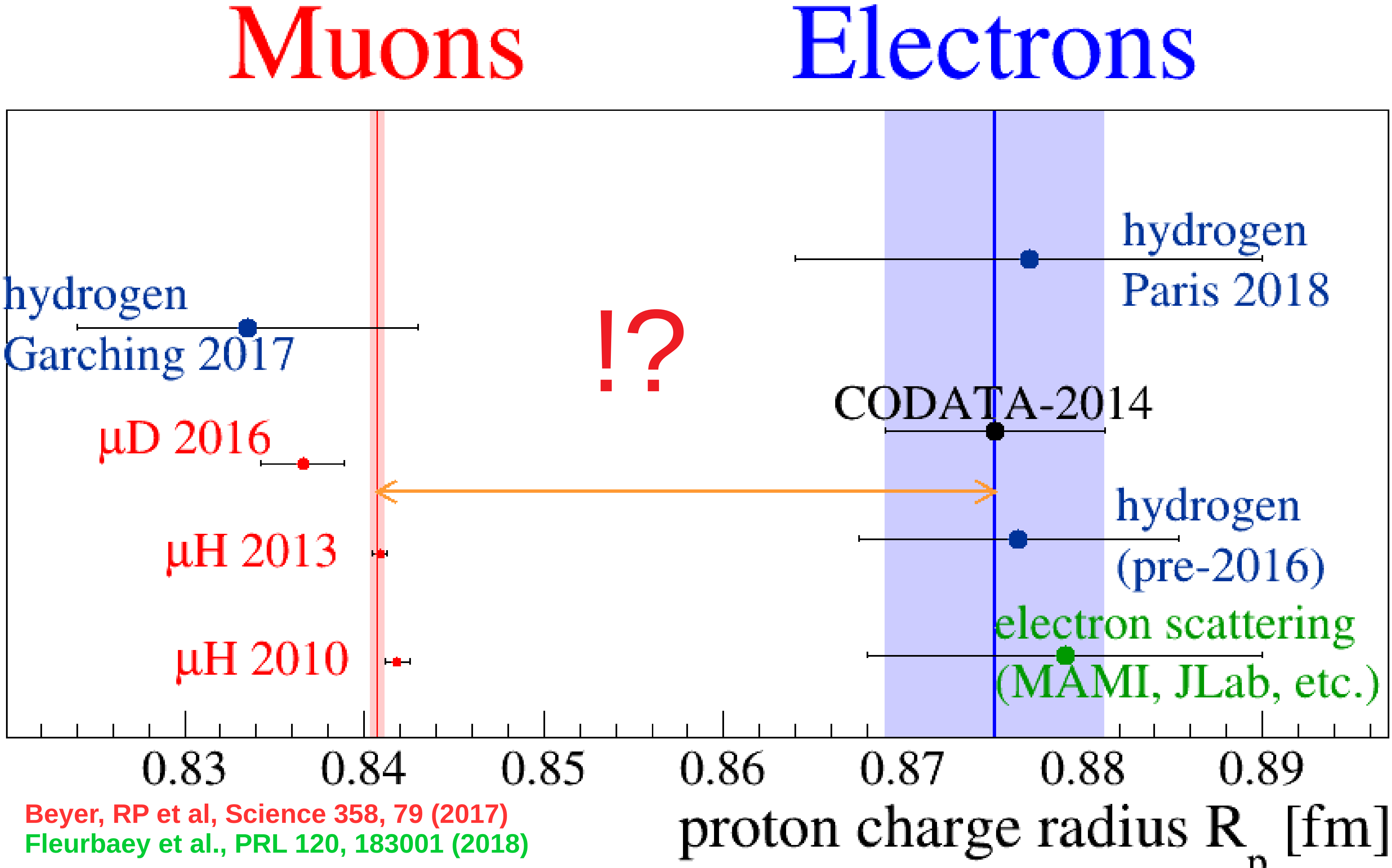
Hélène Fleurbaey, Sandrine Galtier,* Simon Thomas, Marie Bonnaud,
Lucile Julien, François Biraben, and François Nez
*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL,
Collège de France, 4 place Jussieu, Case 74, 75252 Paris Cedex 05, France*

Michel Abgrall and Jocelyne Guéna
*LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS,
Sorbonne Université, 61 avenue de l'Observatoire, 75014 Paris, France*

(Received 8 December 2017; revised manuscript received 9 March 2018; published 4 May 2018)

We present a new measurement of the $1S-3S$ two-photon transition frequency of hydrogen, realized with a continuous-wave excitation laser at 205 nm on a room-temperature atomic beam, with a relative uncertainty of $9 \times 10^{-13}$. The proton charge radius deduced from this measurement, $r_p = 0.877(13)$ fm, is in very good agreement with the current CODATA-recommended value. This result contributes to the ongoing search to solve the proton charge radius puzzle, which arose from a discrepancy between the CODATA value and a more precise determination of $r_p$ from muonic hydrogen spectroscopy.

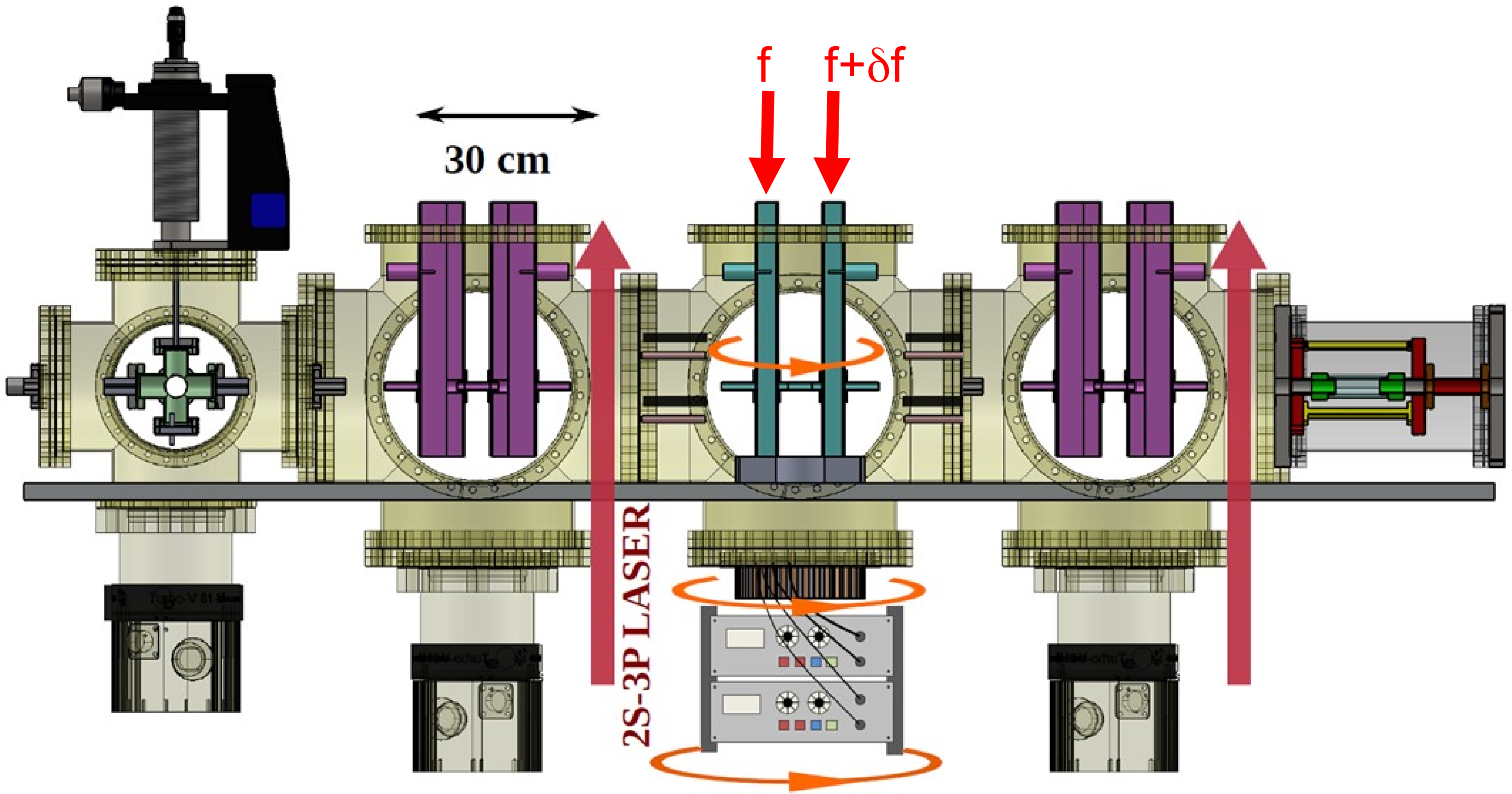
# New Measurements: Paris 1S-3S




Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)

# Lamb shift

**We are using a new Frequency-offset SOF technique (FOSOF)**
(AC Vutha and EA Hessels Phys. Rev. A052504 (2015))




E.A. Hessels, ECT Trento 2016

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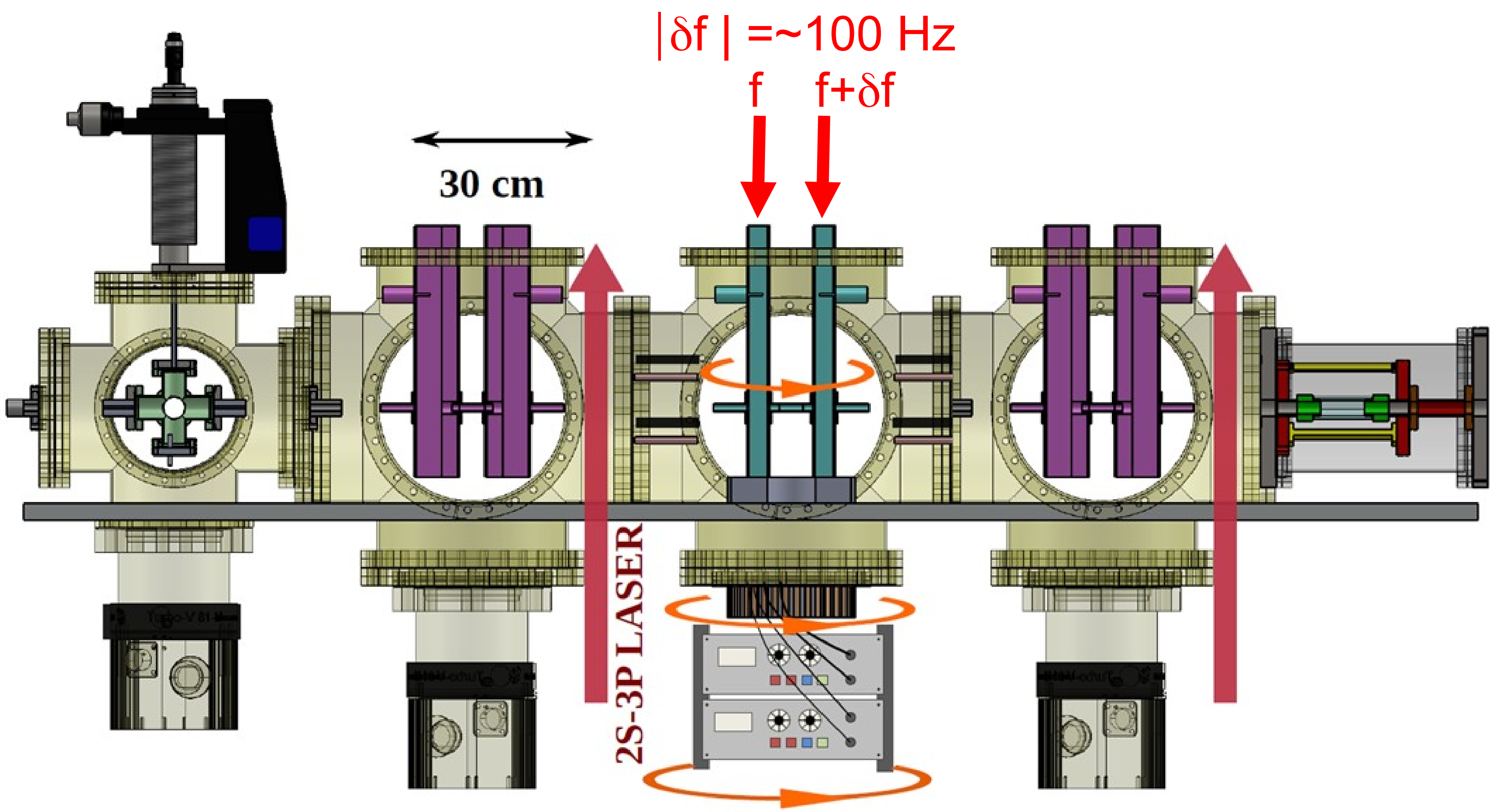
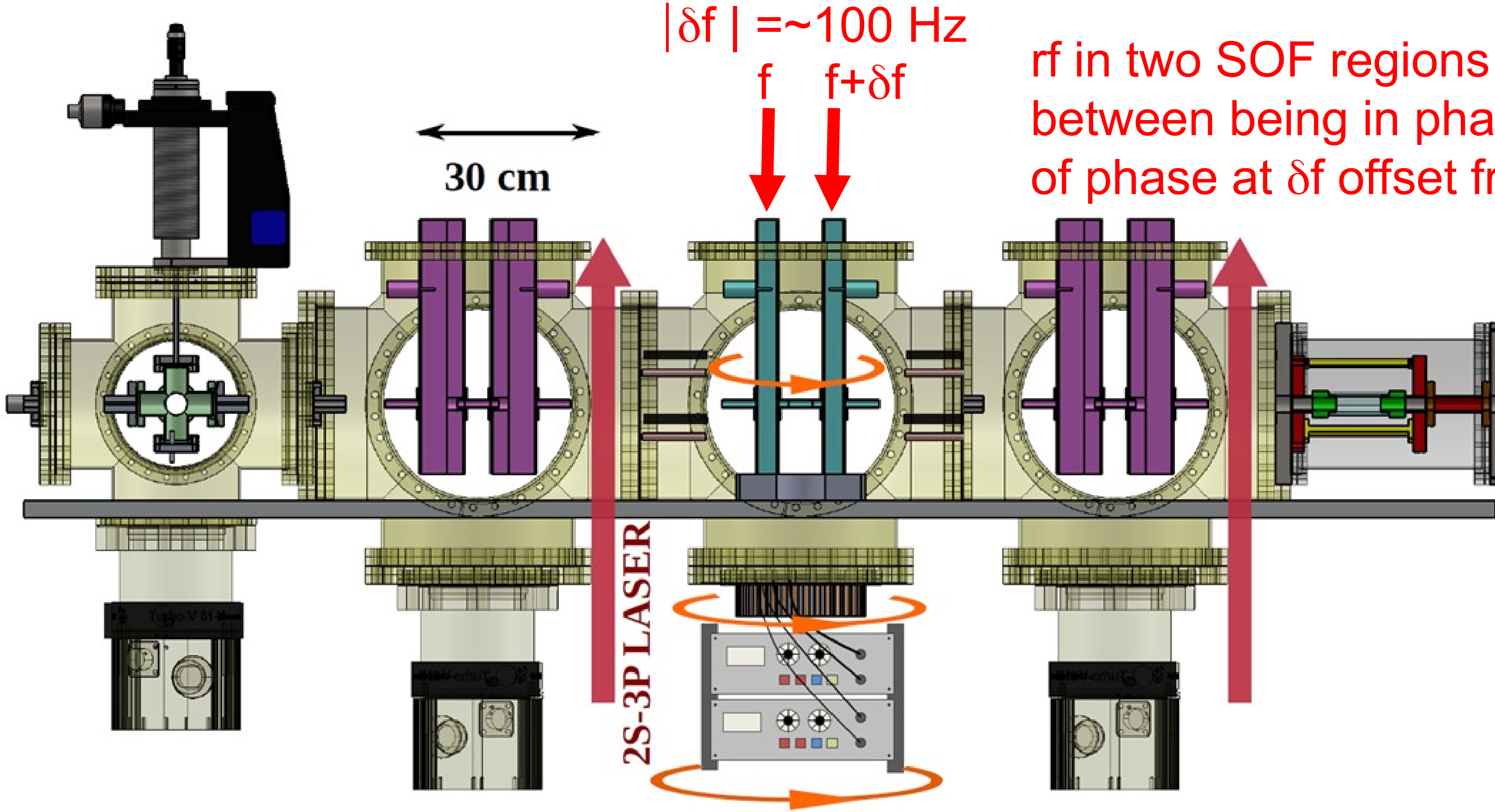


# Lamb shift

**We are using a new Frequency-offset SOF technique (FOSOF)**
(AC Vutha and EA Hessels Phys. Rev. A052504 (2015))

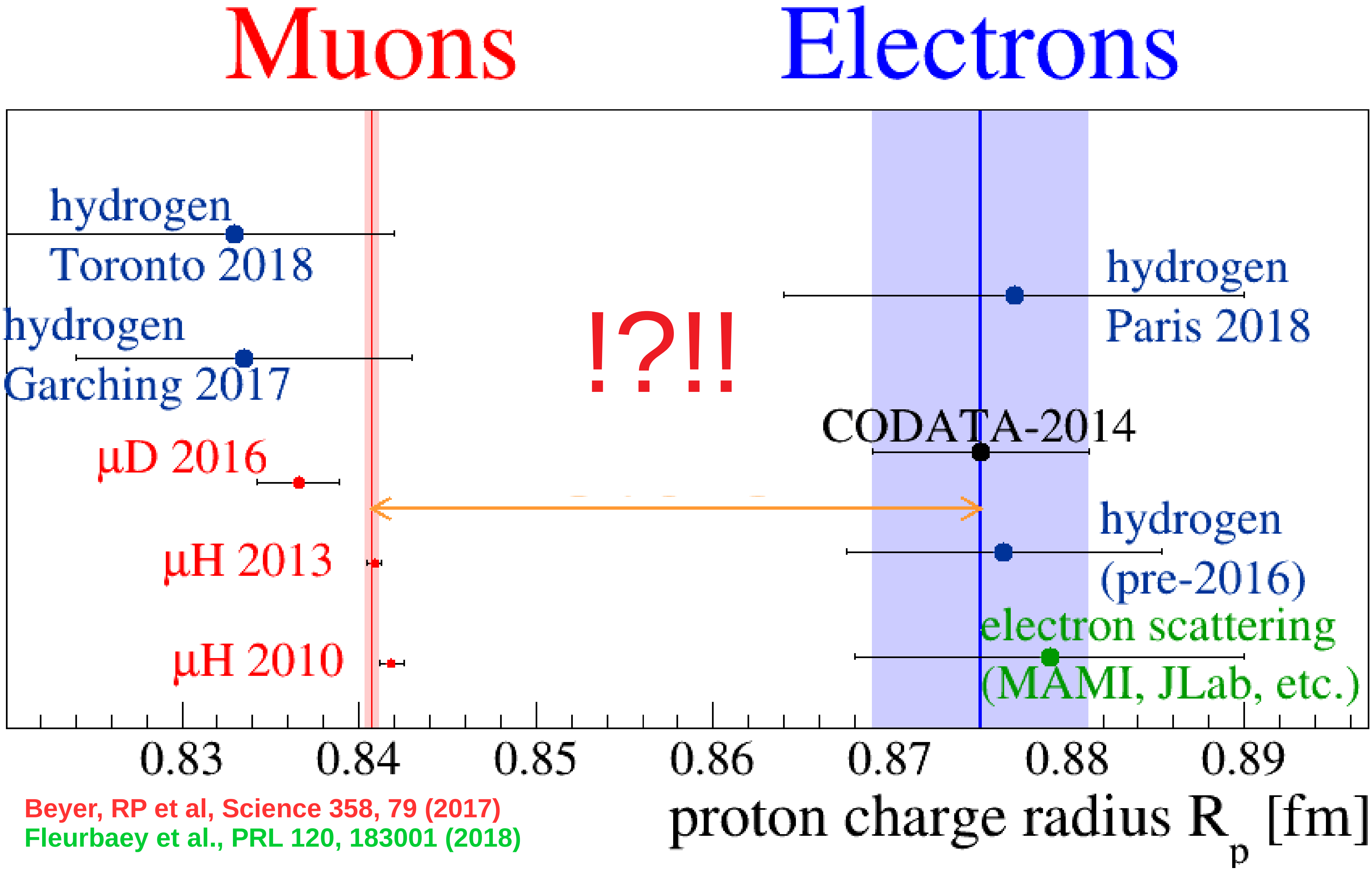
|δf | =~100 Hz

rf in two SOF regions oscillate between being in phase and out of phase at δf offset frequency




E.A. Hessels, ECT Trento 2016

# New Measurements: Toronto 2S-2P




Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)

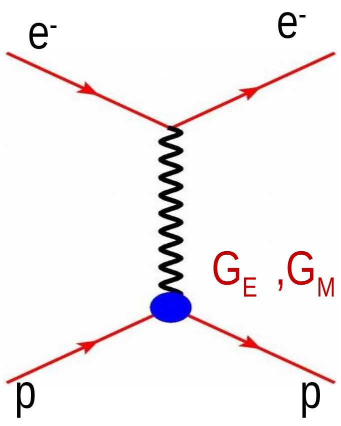
# Electron scattering

# Proton Radius from ep → ep Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

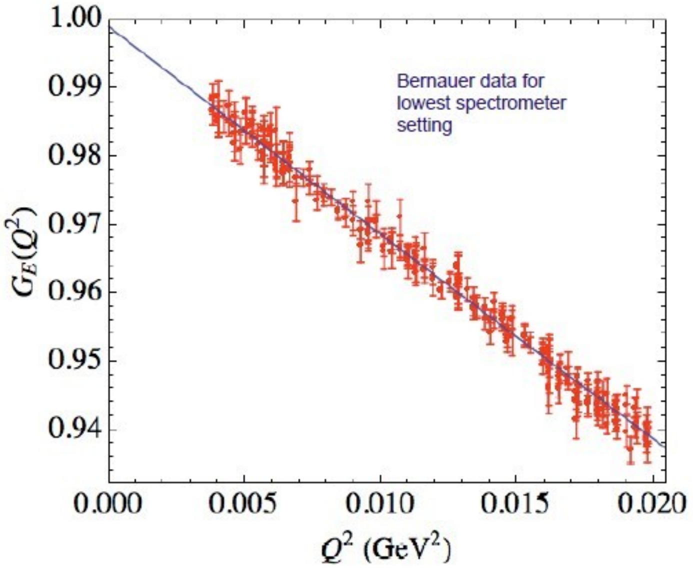
$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$




- Structureless proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2\left[1-\beta^2\sin^2\frac{\theta}{2}\right]}{4k^2\sin^4\frac{\theta}{2}}$$

- $G_E$ and $G_M$ were extracted using Rosenbluth separation (or at extremely low $Q^2$ the $G_M$ can be ignored, like in the PRad experiment)




Mainz low $Q^2$ data set
Phys. Rev. C 93, 065207, 2016

- The Taylor expansion at low $Q^2$:

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

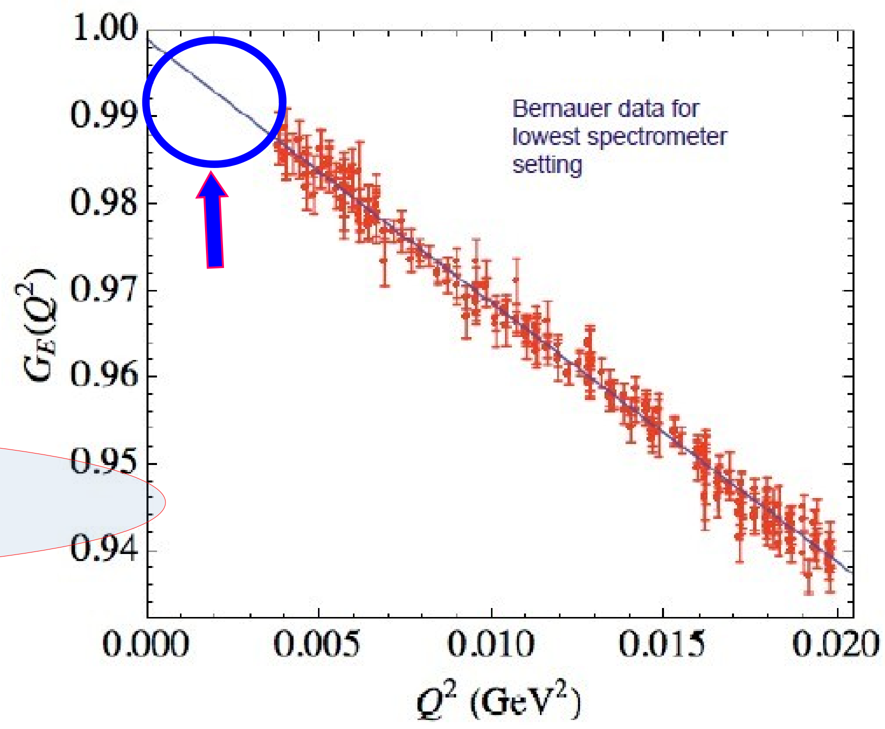
derivative in $Q^2 \to 0$ limit:

$$\langle r^2\rangle = -6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2=0}$$

# The PRad Experimental Approach

- PRad initial goals:
  - large $Q^2$ range in one experimental setting
  - reach to very low $Q^2$ range (~ $10^{-4}$ GeV/C$^2$)
  - reach to sub-percent precision in cross section

- PRad suggested solutions:
  - use high resolution high acceptance calorimeter:
    - ✓ reach smaller scattering angles: ($\theta_e = 0.7^0 - 7.0^0$ ) ($Q^2 = 2\text{x}10^{-4} \div 6\text{x}10^{-2}$ ) GeV/c$^2$ ;
    - ✓ large $Q^2$ range in one experimental setting!;
    - ✓ simultaneous detection of $ee \rightarrow ee$ Moller scattering (best known control of systematics).
  - use high density windowless $H_2$ gas flow target:
    - ✓ beam background under control;
    - ✓ minimize experimental background.

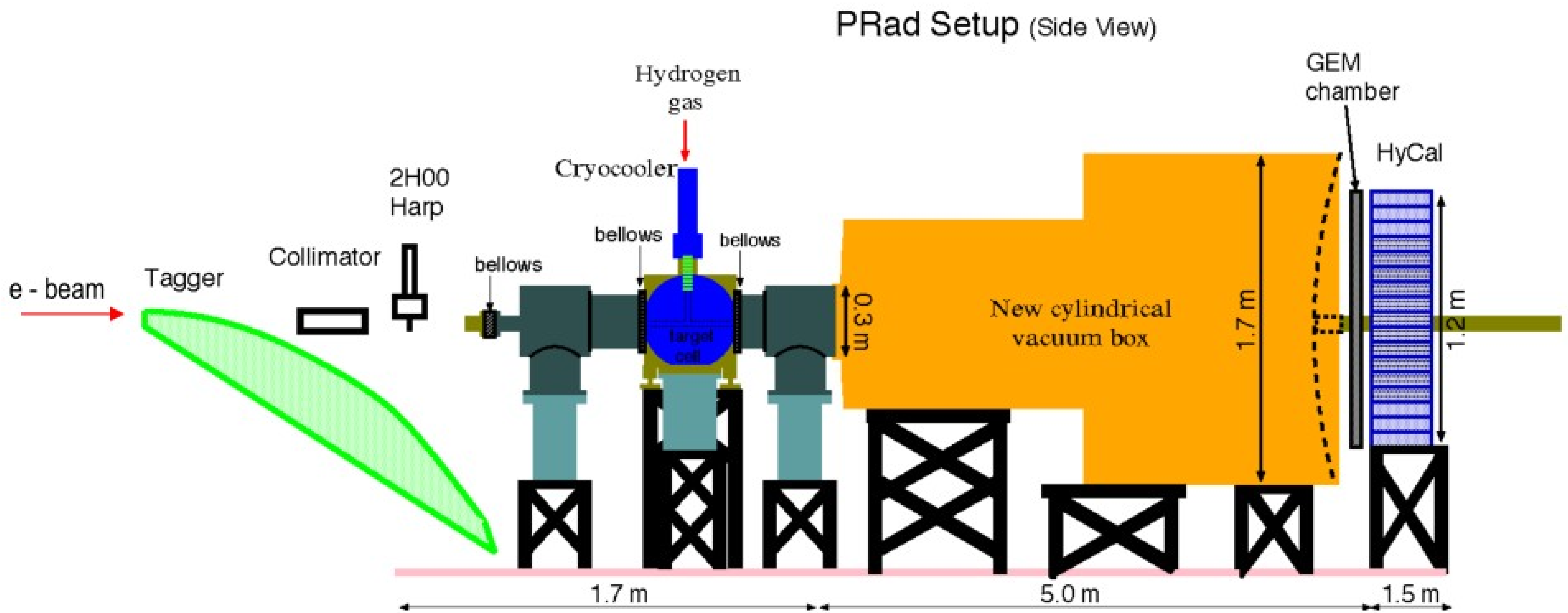



Mainz low $Q^2$ data set
Phys. Rev. C 93, 065207, 2016

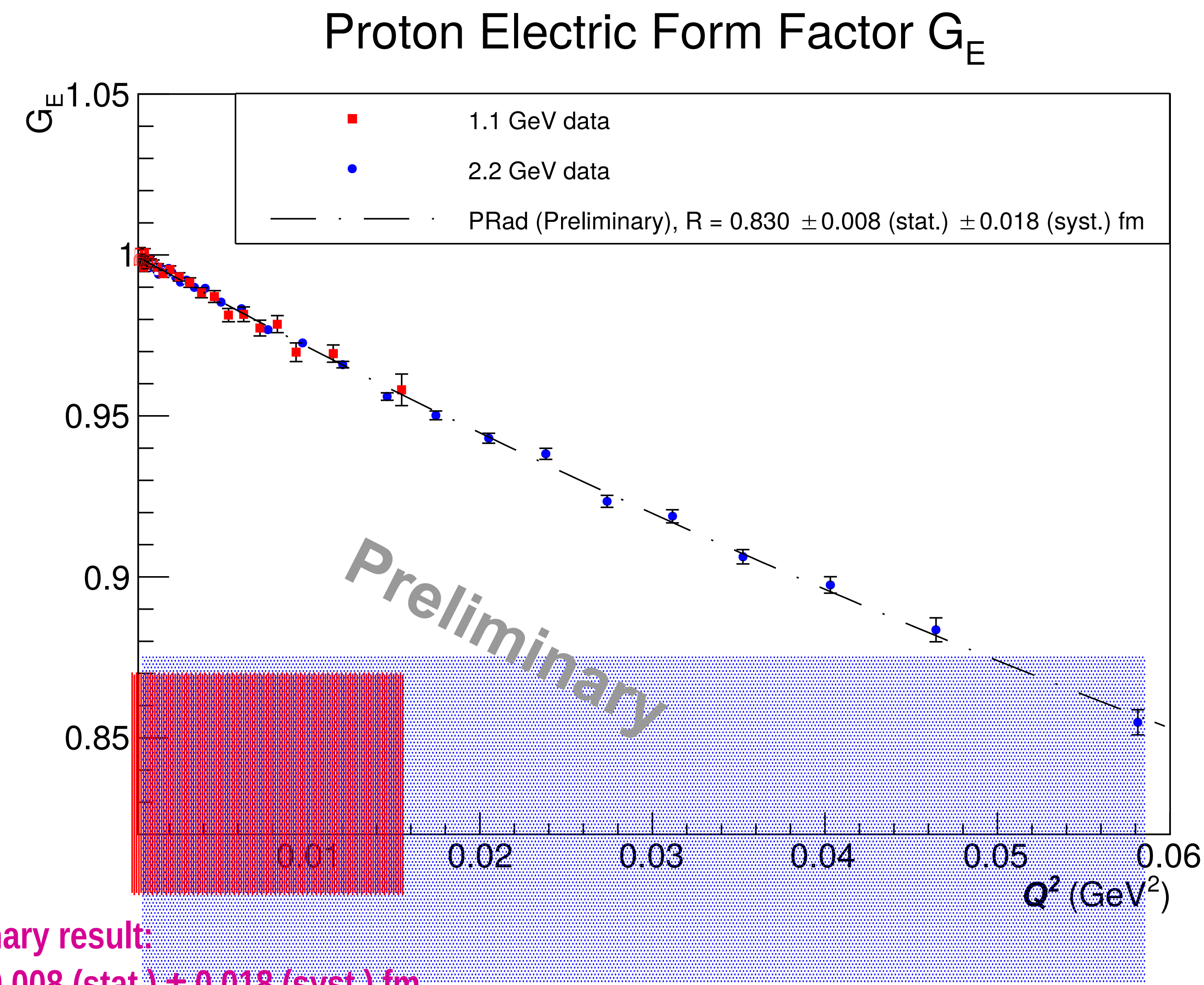
- Two beam energies: $E_0$ = 1.1 GeV and 2.2 GeV to increase $Q^2$ range.
- Approved by JLab PAC39 (June, 2012) with high "A" scientific rating.

# PRad Experimental Setup in Hall B at JLab (schematics)

- Main detector elements:
  - windowless $H_2$ gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal
- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for $e^-$ beam halo "cleanup")
  - Harp 2H00
  - pipe connecting Vacuum Window through HyCal

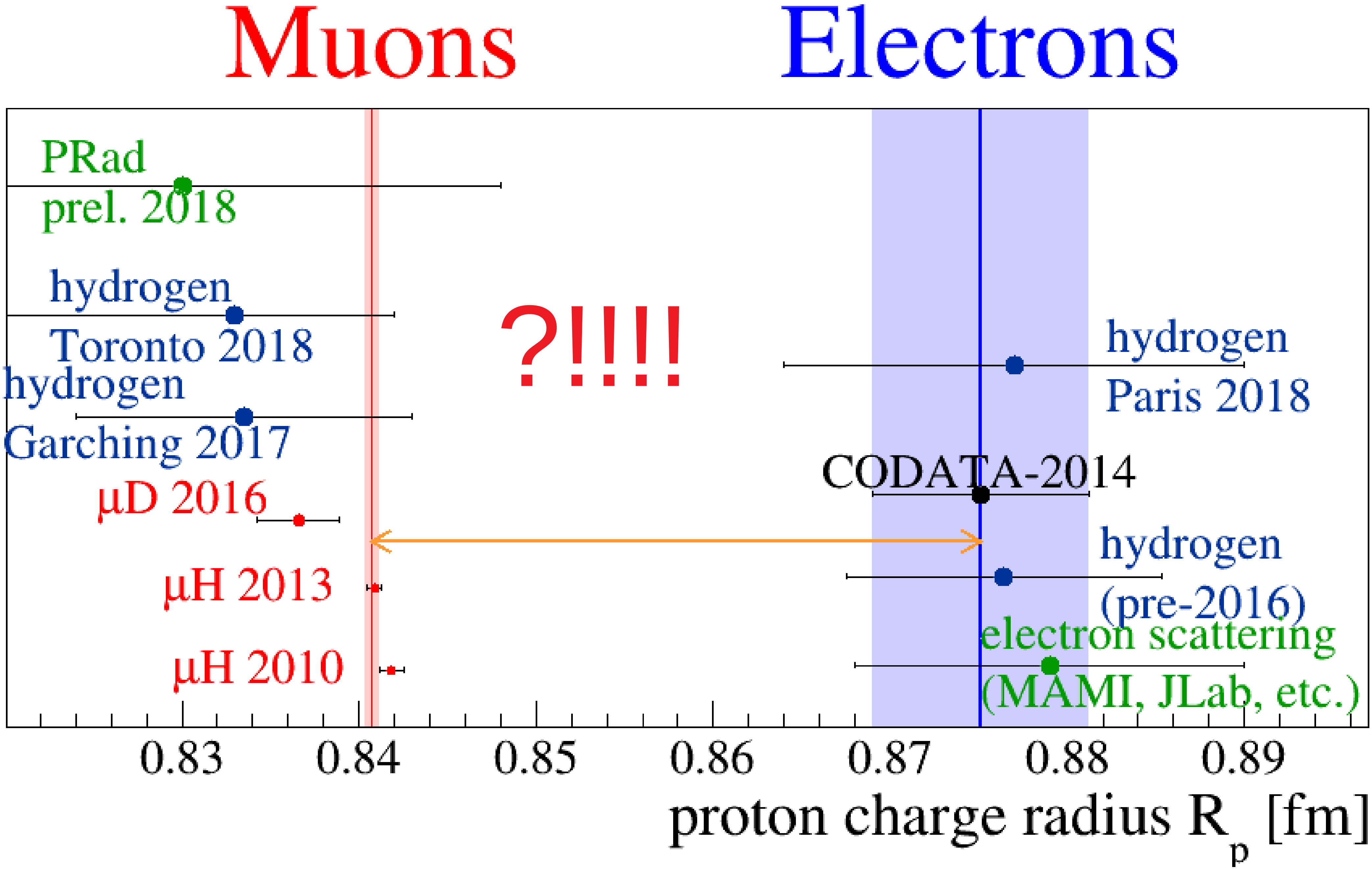


# Our Fit of the Extracted $G_E$ (Preliminary)




**PRad Preliminary result:**
**$R_p$ = 0.830 ± 0.008 (stat.) ± 0.018 (syst.) fm**

# New Measurements: PRad

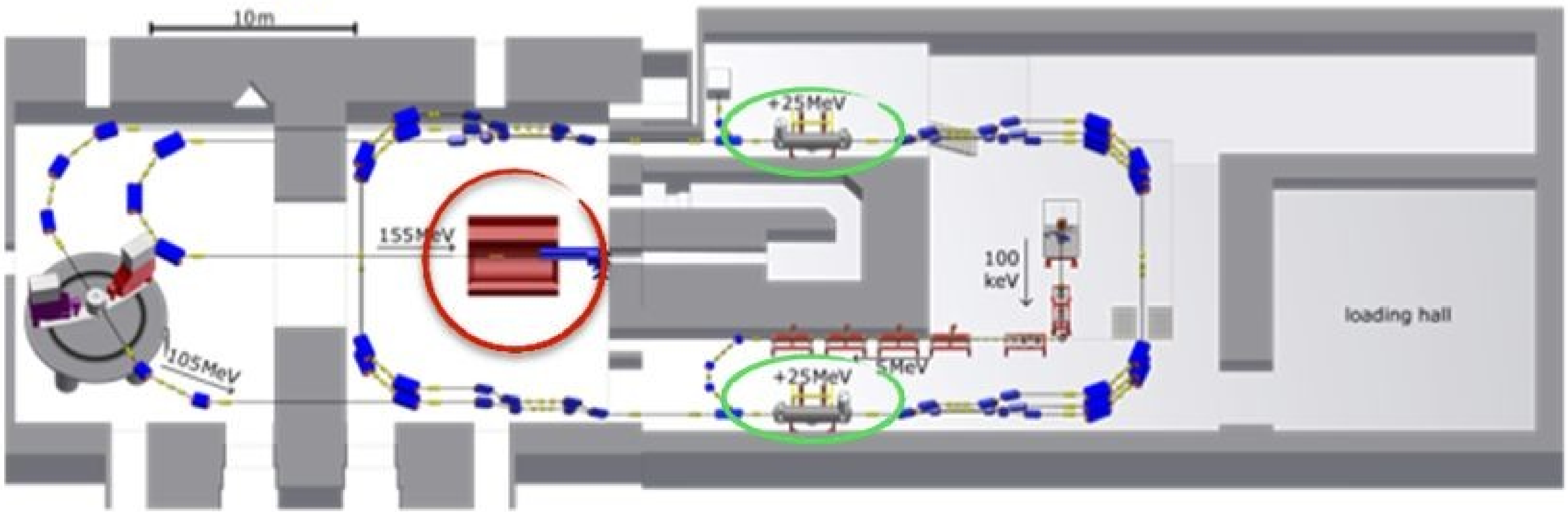


# New Mainz electron accelerator **MESA**

Kurt Aulenbacher

MESA — "**M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator

Beam energy: 105 MeV / 155 MeV Current: 1–2 mA




Being built on **Campus of JGU Mainz**

Cluster of Excellence **PRISMA**, since 27.9. also **PRISMA+ !!!**

# Conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**

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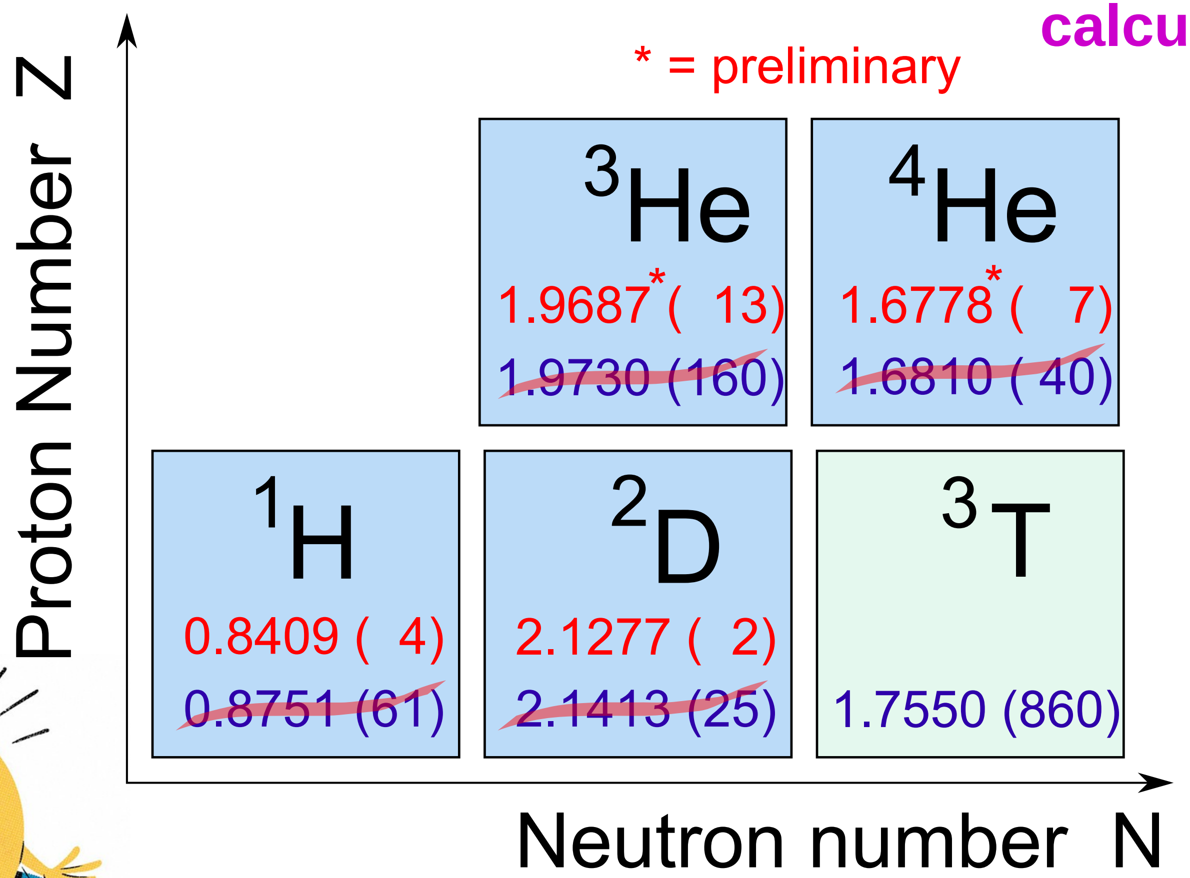


# Conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**

- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

**Muonic atoms are a novel tool for proton and new-nucleon properties!**

# Conclusions

Proton radius situation:

- smaller radii from muonic **hydrogen** and **deuterium** imply a smaller Rydberg constant
- new H(2S-4P) gives a smaller proton radius
- new H(1S-3S) however confirms large proton radius

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More data needed:

- H(2S – 6P, 8P, 9P, …) and D(2S-nl) underway in Garching and Colorado
- H(1S – 3S, 4S, ..) underway in Paris and Garching
- H(2S-2P) (Hessels @ Toronto)
- Muonium at PSI, J-PARC
- Positronium (Cassidy @ UCL, Crivelli @ ETH)
- $He^+$(1S-2S) underway in Garching (Udem) and Amsterdam (Eikema)
- $HD^+$, $H_2$, etc. in Amsterdam (Ubachs @ Amsterdam) and Paris (Hilico, Karr @ Paris)
- He (Vassen @ Amsterdam), $Li^+$ (Udem @ Garching)
- HCI, e.g. H-like Ne (Tan @ NIST)
- Rydberg-atoms, e.g. Rb (Raithel @ Ann Arbor)
- new low-$Q^2$ electron scattering at MAMI, JLab, MESA
- muon scattering: MUSE @ PSI, COMPASS @ CERN

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- muon scattering: MUSE @ PSI, COMPASS @ CERN

Compare Rydberg values to test QED and SM

# Up next: Hyperfine structure in μp

The 21 cm line in hydrogen (1S hyperfine splitting) has been **measured** to 12 digits (0.001 Hz) in 1971:

$$\boldsymbol{\nu_{exp} = 1\,420\,405.\,751\,766\,7 \pm 0.000\,001\ \mathrm{kHz}}$$

Essen et al., Nature 229, 110 (1971)

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$$\nu_{exp} = 1\ 420\ 405.\ 751\ 766\ 7 \pm 0.000\ 001\ \mathrm{kHz}$$

Essen et al., Nature 229, 110 (1971)

**QED test** is limited to 6 digits (800 Hz) because of proton structure effects:

$$\nu_{theo} = 1\ 420\ 403.\ 1 \pm 0.6_{\text{proton size}} \pm 0.4_{\text{polarizability}}\ \mathrm{kHz}$$

Eides et al., Springer Tracts 222, 217 (2007)

# Proton Zemach radius

HFS depends on "Zemach" radius:

$$\Delta E = -2(Z\alpha) m \langle r \rangle_{(2)} E_F$$

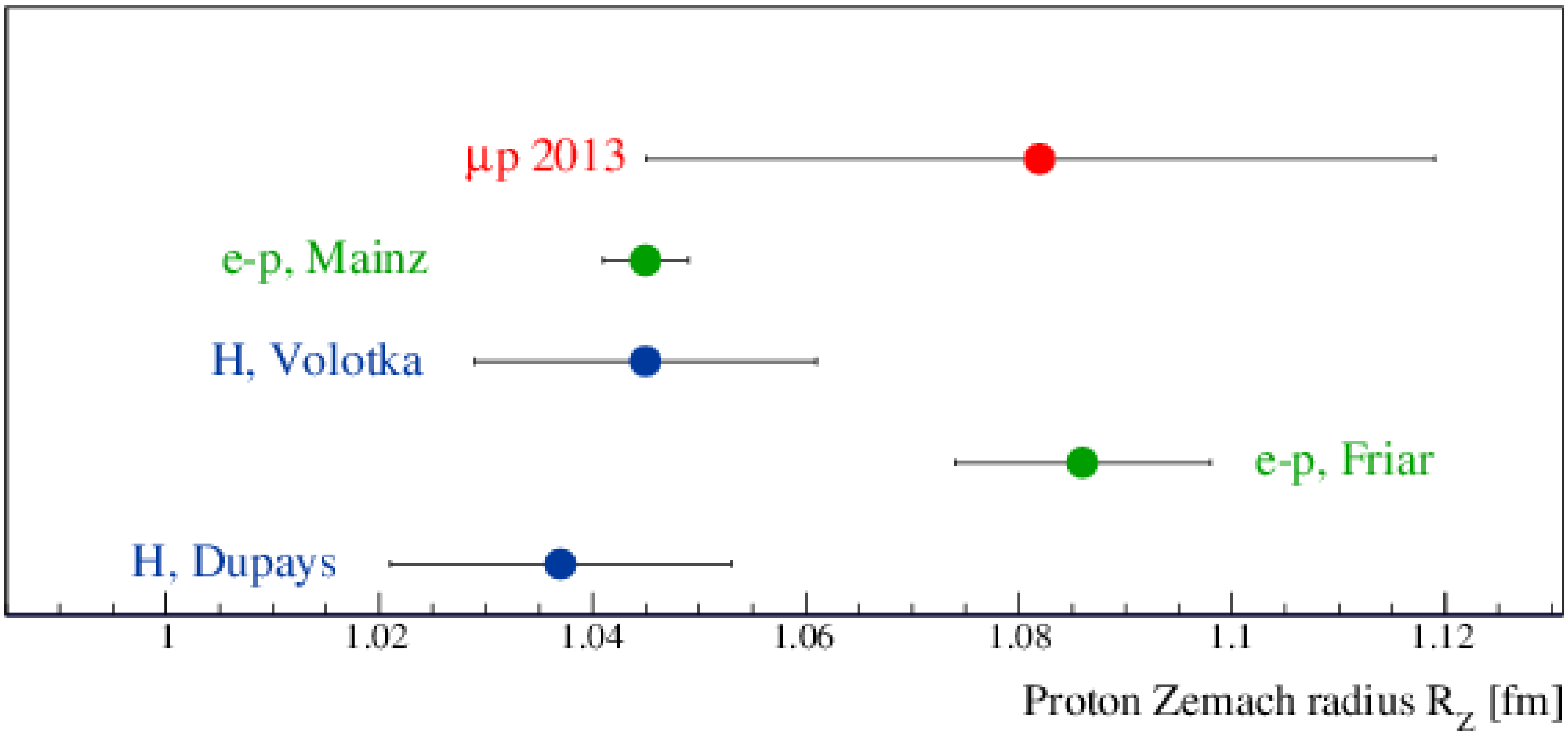
$$\langle r \rangle_{(2)} = \int d^3 r \, d^3 r' \, \rho_E(r) \, \rho_M(r') |r - r'|$$

Zemach, Phys. Rev. 104, 1771 (1956)

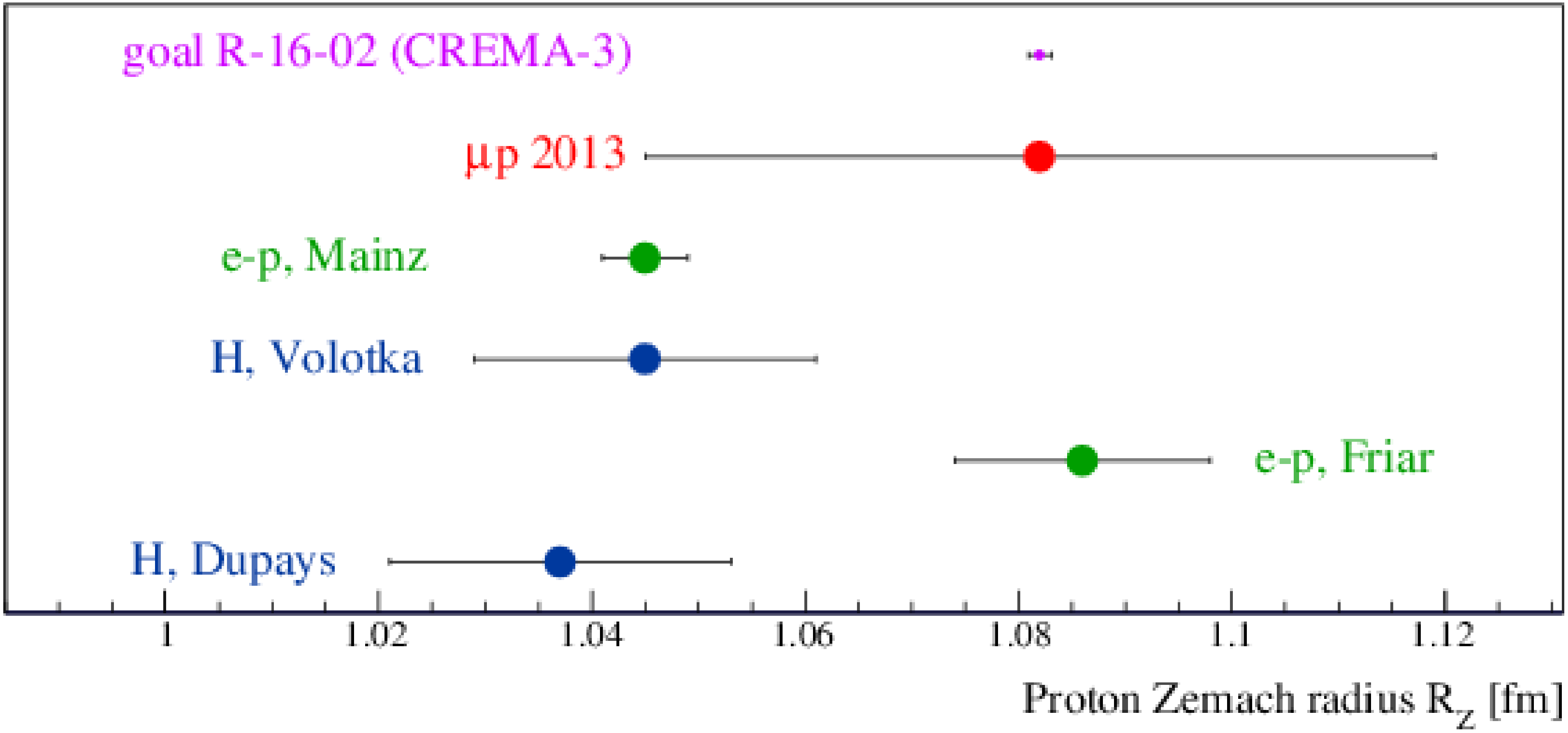
Form factors and momentum space

$$\Delta E = \frac{8(Z\alpha)m}{\pi n^3} E_F \int_0^\infty \frac{dk}{k^2} \left[ \frac{G_E(-k^2) G_M(-k^2)}{1+\kappa} \right]$$

# Proton Zemach radius from μp



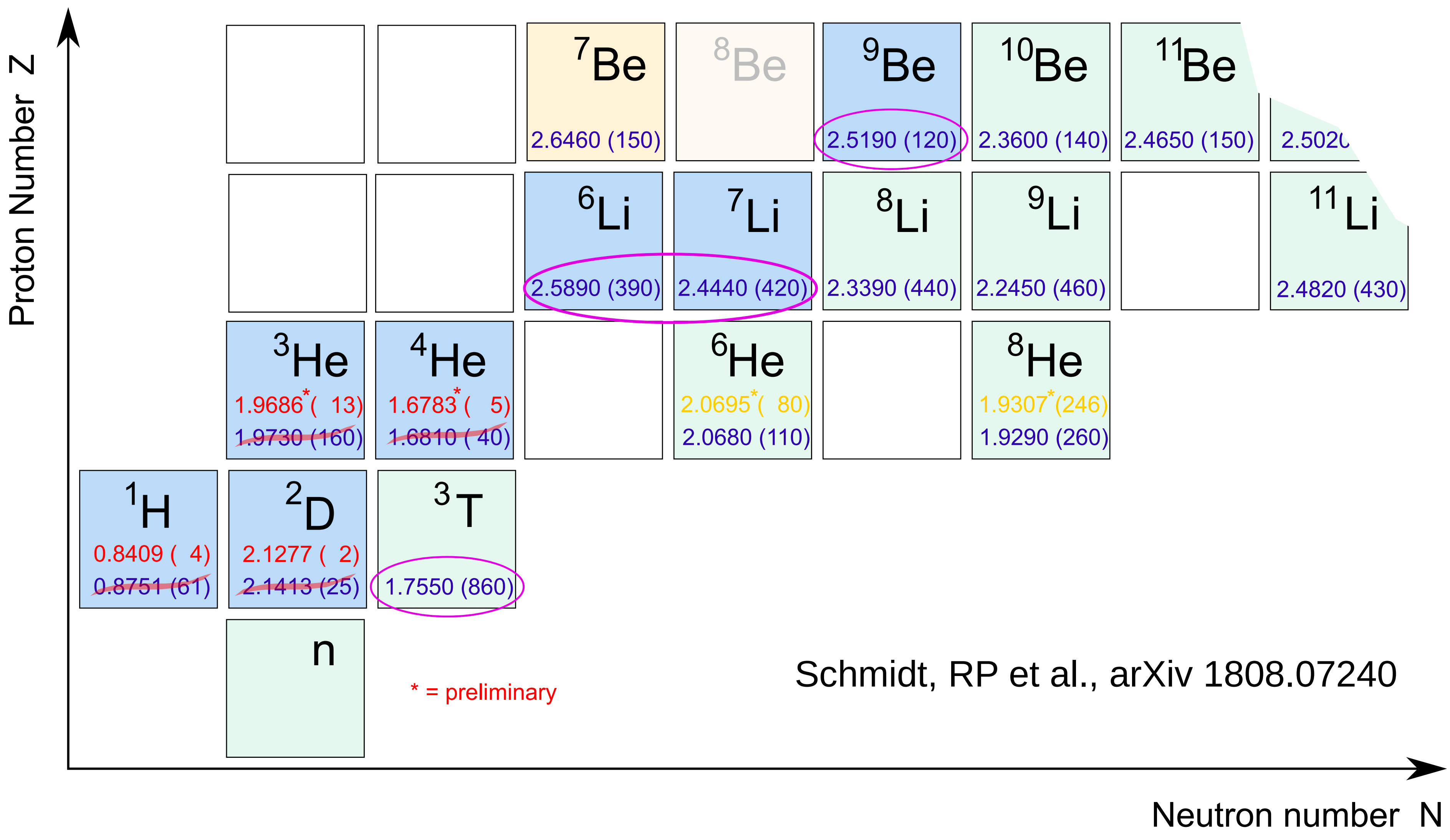
# Proton Zemach radius from μp



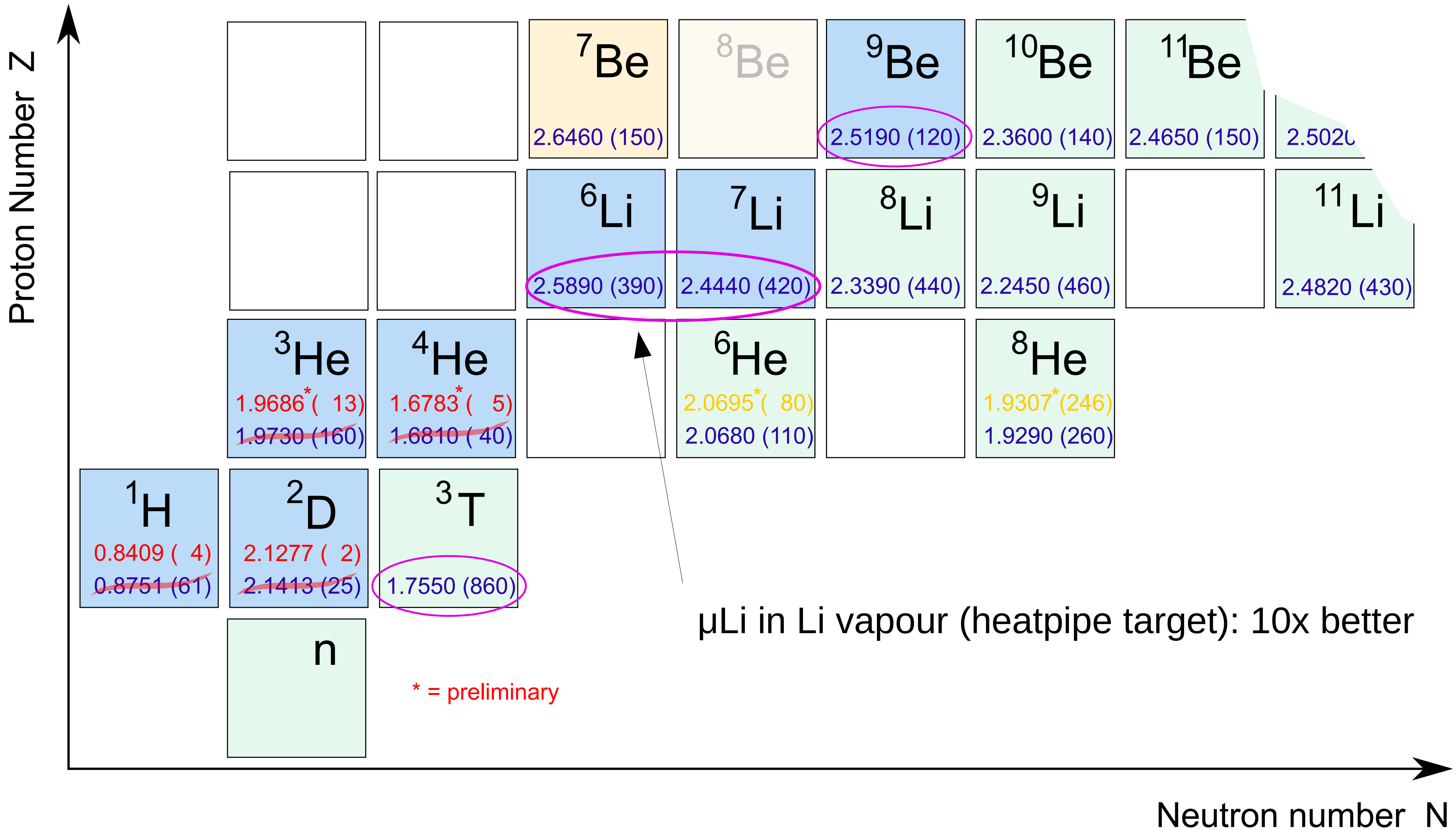

PSI Exp. R-16-02: Antognini, RP et al. (CREMA-3 / HyperMu)

see e.g. Schmidt, RP et al., arXiv 1808.07240

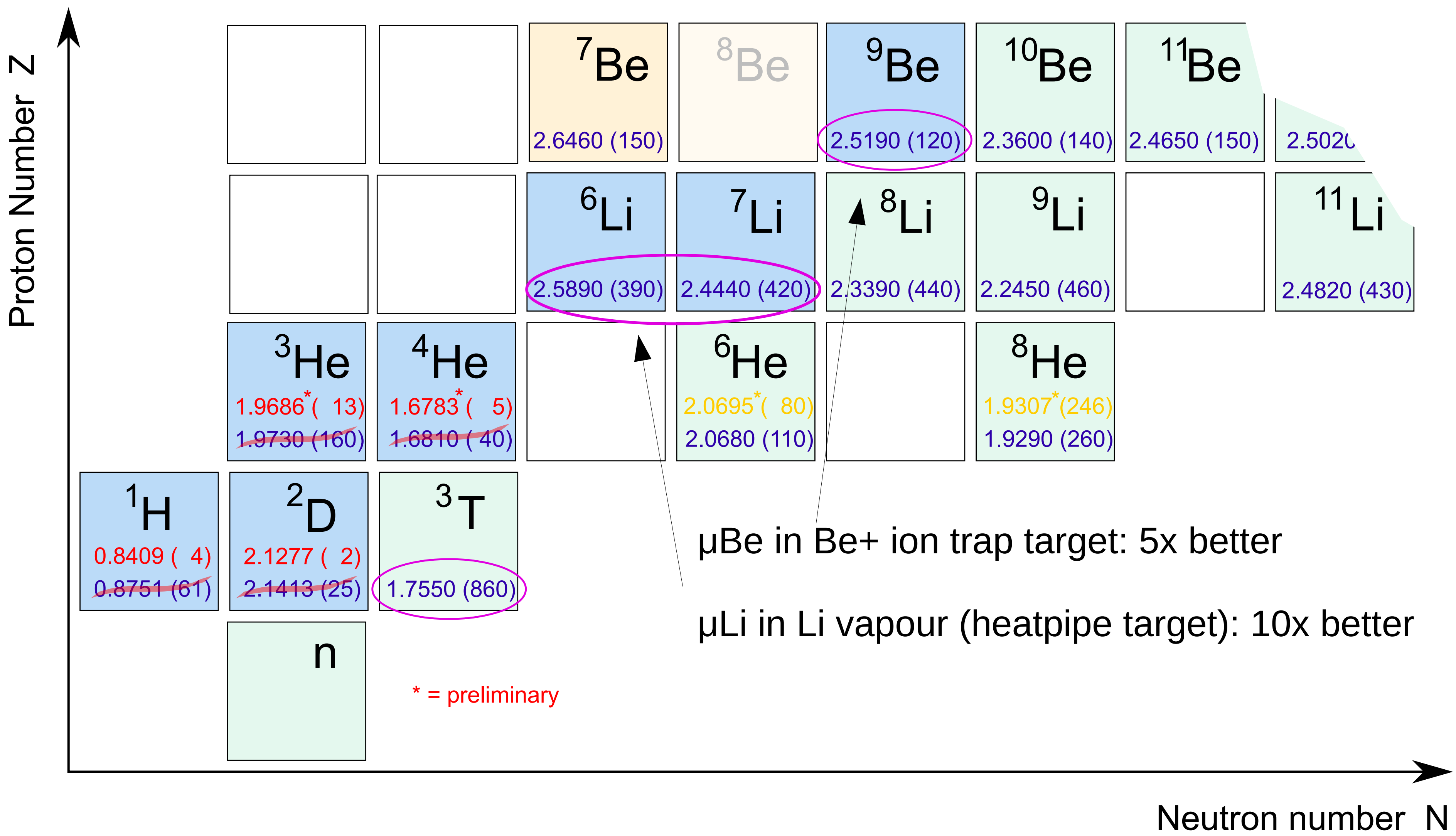
# Charge radii: The future



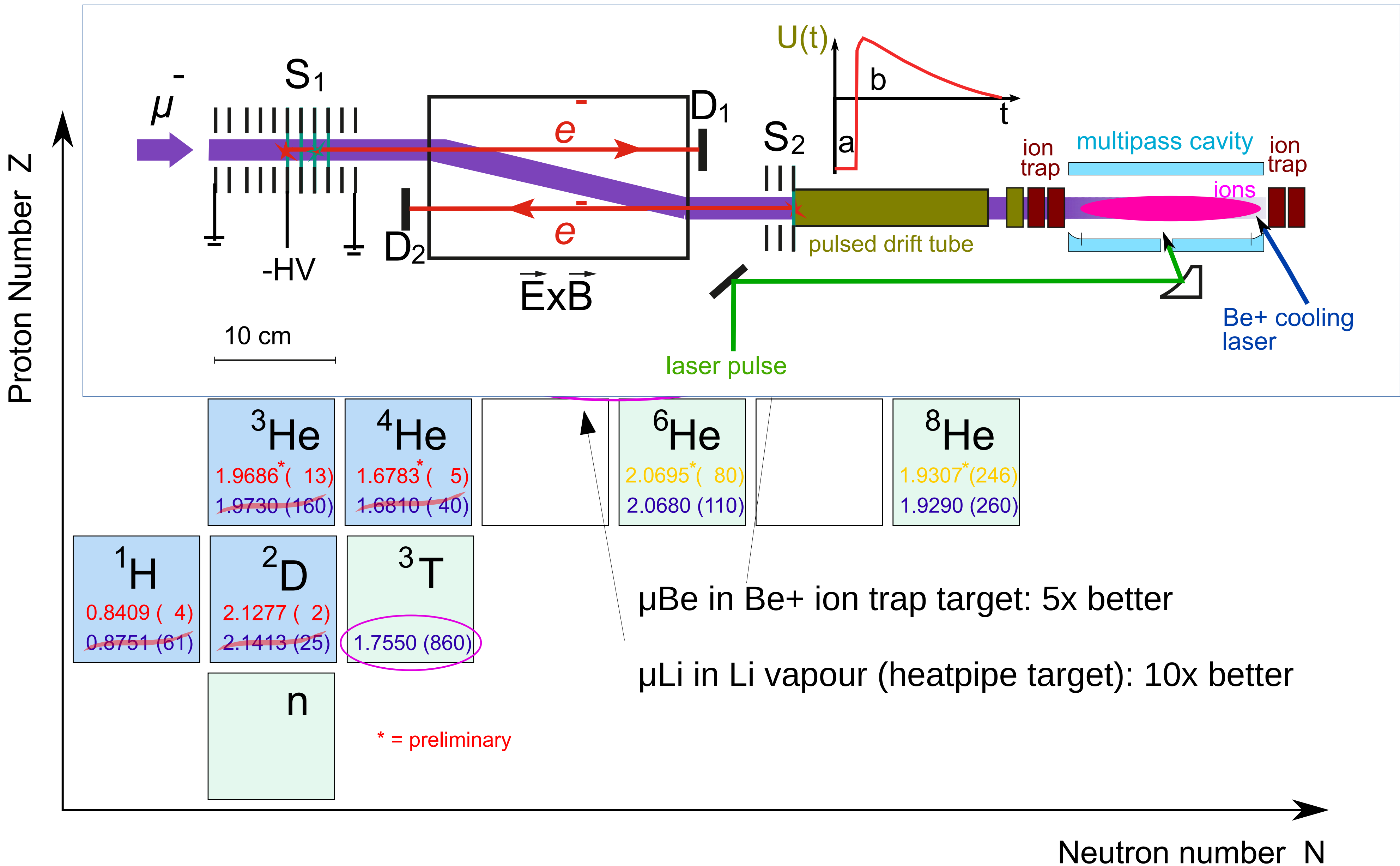
# Charge radii: The future



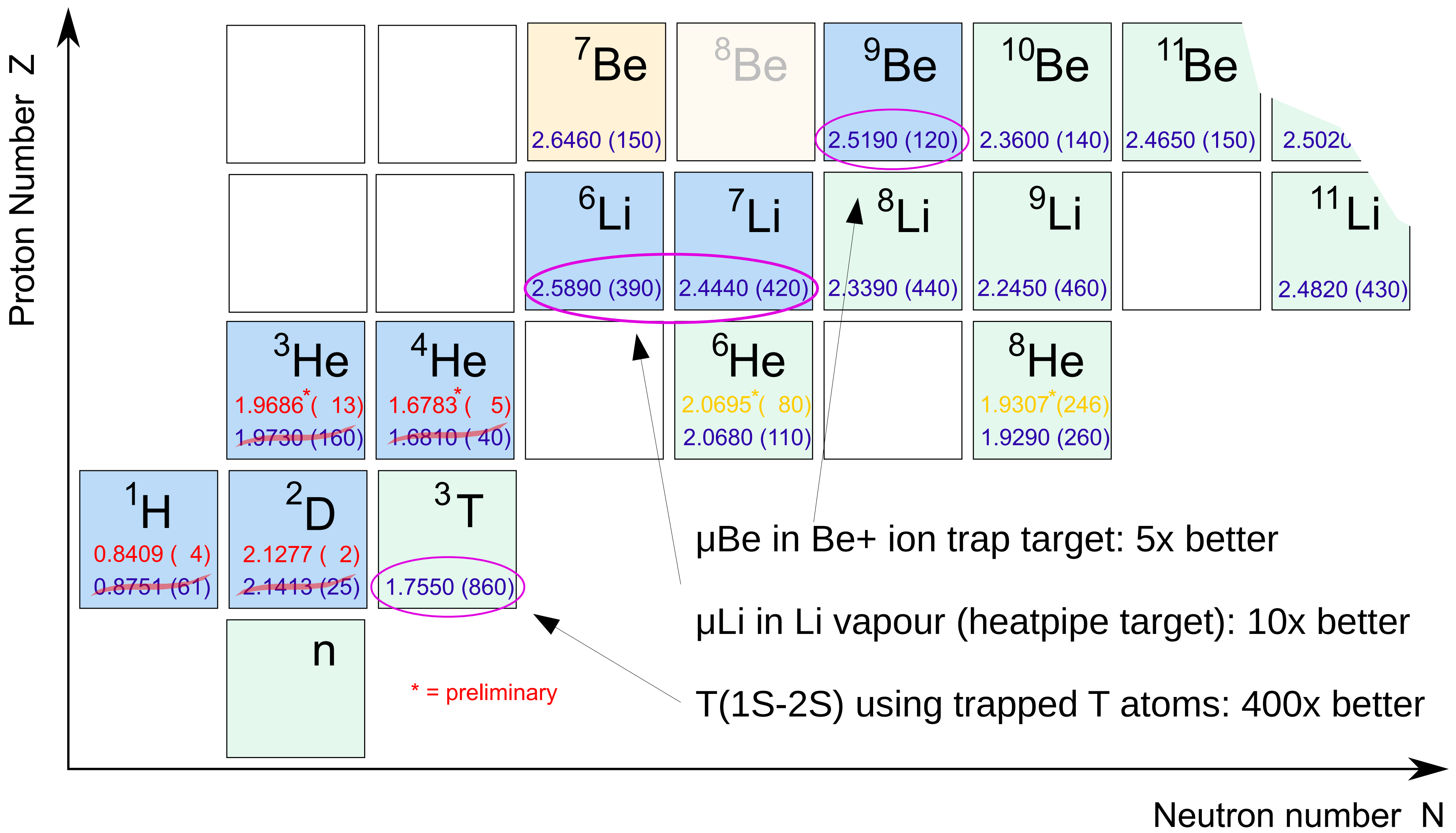
# Charge radii: The future



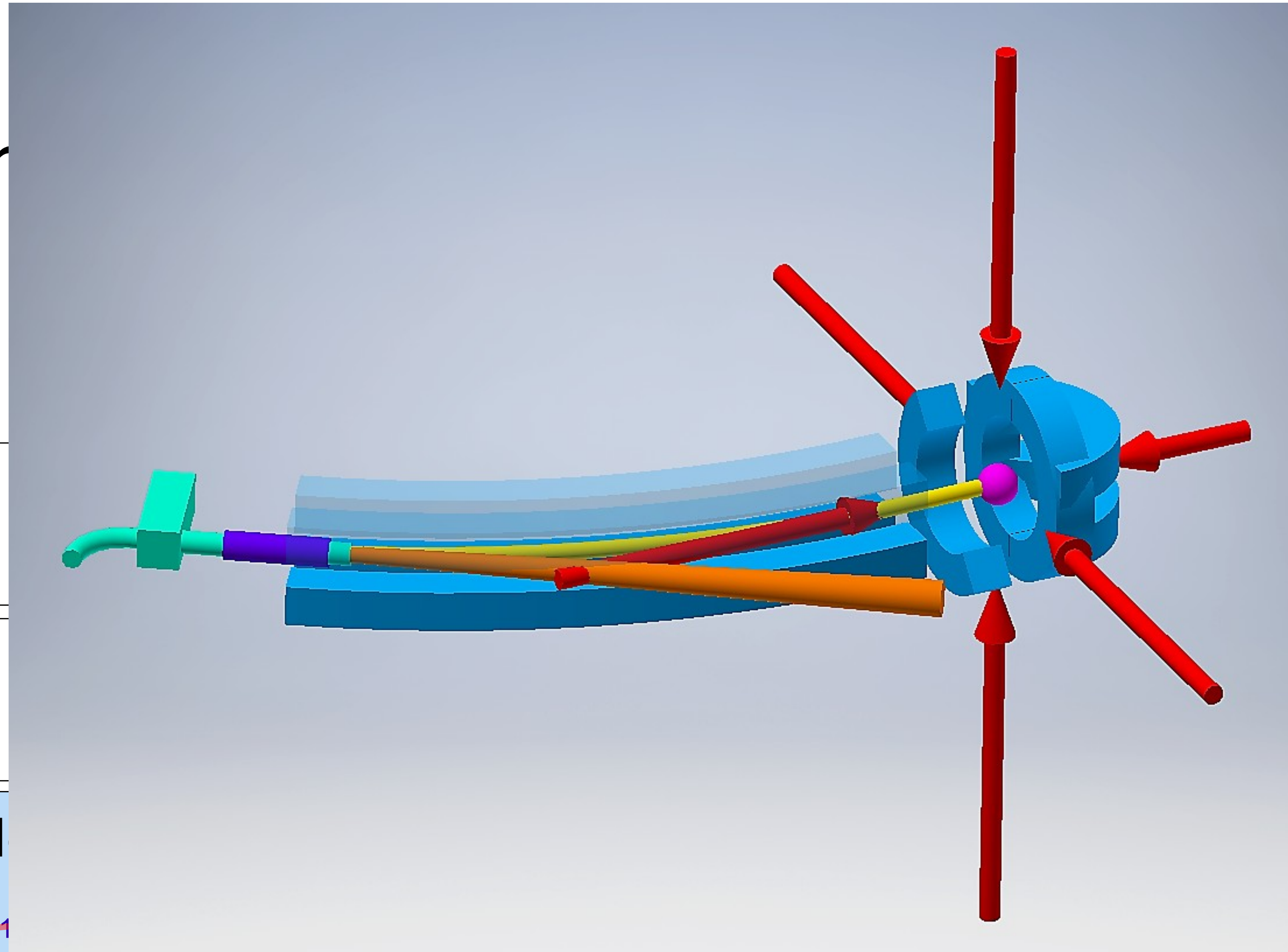
# Charge radii: The future

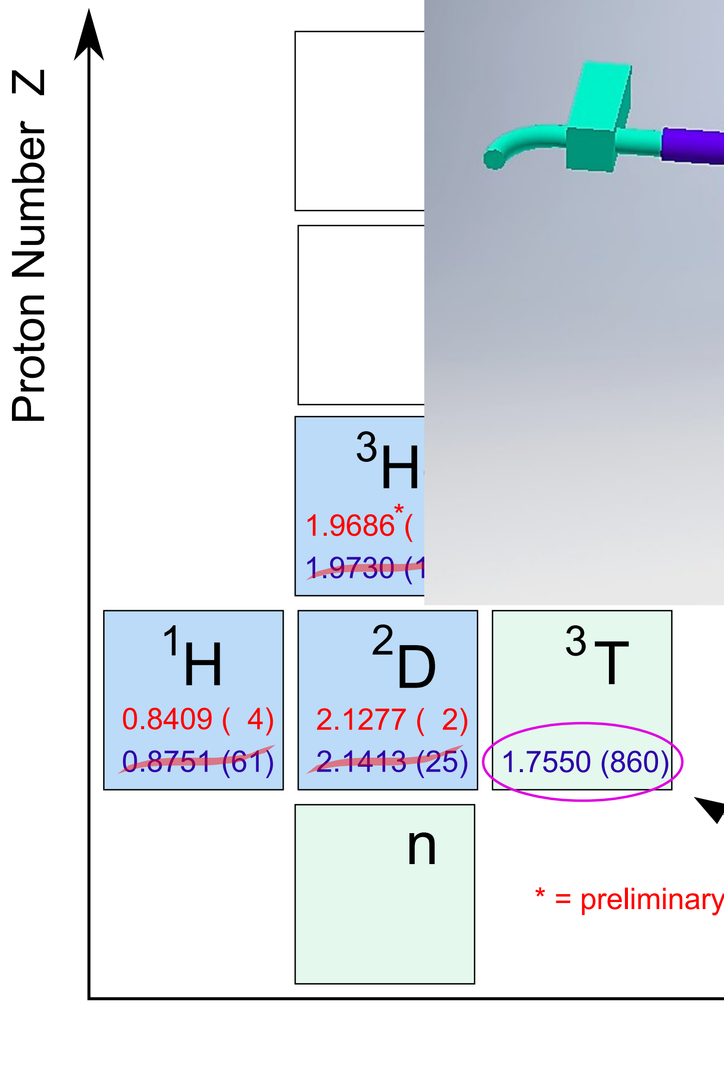


# Charge radii: The future



# Ch






μBe in Be+ ion trap target: 5x better

μLi in Li vapour (heatpipe target): 10x better

T(1S-2S) using trapped T atoms: 400x better

# Thanks a lot for your attention

The Garching Hydrogen Team:

Axel Beyer, Lothar Maisenbacher, Arthur Matveev, RP,
Ksenia Khabarova, Alexey Grinin, Tobias Lamour, Dylan C. Yost,
Theodor W. Hänsch, Nikolai Kolachevsky, Thomas Udem

The CREMA Collaboration:

Aldo Antognini, Fernando D. Amaro, François Biraben, João M. R. Cardoso, Daniel S. Covita, Andreas Dax, Satish Dhawan, Marc Diepold, Luis M. P. Fernandes, Adolf Giesen, Andrea L. Gouvea, Thomas Graf, Theodor W. Hänsch, Paul Indelicato, Lucile Julien, Paul Knowles,Franz Kottmann, Juilian J. Krauth, Eric-Olivier Le Bigot, Yi-Wei Liu, José A. M. Lopes, Livia Ludhova, Cristina M. B. Monteiro, Françoise Mulhauser, Tobias Nebel, François Nez, Paul Rabinowitz, Joaquim M. F. dos Santos, Lukas A. Schaller, Karsten Schuhmann, Catherine Schwob, David Taqqu, João F. C. A. Veloso, RP

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The Garching

Axel ,
Ksenia K . Yost,
Theo em


**Open Positions!**

**pohl @ uni-mainz.de**


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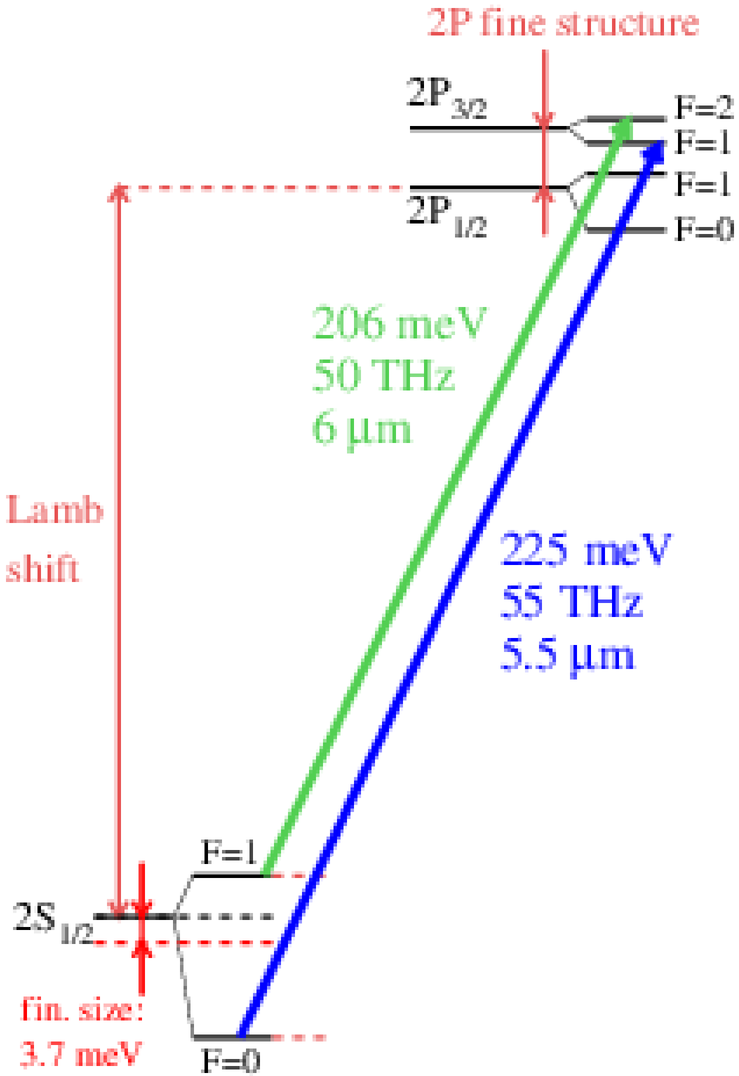
# Group at JGU Mainz

...

# Theory in muonic H

$$\Delta E_{Lamb} = 206.0336\,(15)\ meV_{QED} + 0.0332\,(20)\ meV_{TPE} - 5.2275\,(10)\ meV/fm^2 * R_p^{\,2}$$

**Simple-looking formula**
**based on decades of work by**
E. Borie, M.C. Birse, P. Blunden, C.E. Carlson,
M.I. Eides, R. Faustov, J.L. Friar, G. Paz,
A. Pineda, J. McGovern, K. Griffioen, H. Grotch,
F. Hagelstein, H.-W. Hammer, R.J Hill, P.Indelicato,
U.D. Jentschura, S.G. Karshenboim, E.Y. Korzinin,
V.G. Ivanov, I.T. Lorenz, A.P. Martynenko,
G.A. Miller, U.-G. Meissner, P.J. Mohr,
K. Pachucki, V. Pascalutsa, J. Rafelski,
V.A. Shelyuto, I. Sick, A.W. Thomas,
M. Vanderhaeghen, V. Yerokhin,
…..
(shout if I missed your name!)




Antognini, RP at al., Ann. Phys. (N.Y.) 331, 127 (2013)

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Annals of Physics 331 (2013) 127–145

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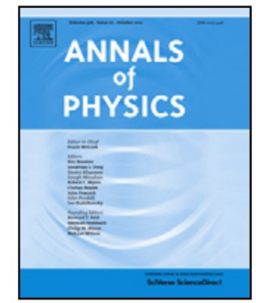



## Theory of the 2S–2P Lamb shift and 2S hyperfine splitting in muonic hydrogen

Aldo Antognini [a,*], Franz Kottmann [a], François Biraben [b], Paul Indelicato [b], François Nez [b], Randolf Pohl [c]

[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Laboratoire Kastler Brossel, École Normale Supérieure, CNRS and Université P. et M. Curie, 75252 Paris, CEDEX 05, France
[c] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Our attempt to summarize all the original work by many theorists….

# Theory I: “pure” QED

**Table 1**
All known radius-*independent* contributions to the Lamb shift in $\mu$p from different authors, and the one we selected. Values are in meV. The entry # in the first column refers to Table 1 in Ref. [13]. The “finite-size to relativistic recoil correction” (entry #18 in [13]), which depends on the proton structure, has been shifted to Table 2, together with the small terms #26 and #27, and the proton polarizability term #25. SE: self-energy, VP: vacuum polarization, LBL: light-by-light scattering, Rel: relativistic, NR: non-relativistic, RC: recoil correction.

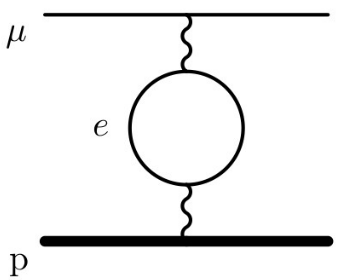
| # | Contribution | Pachucki [10,11] | Nature [13] | Borie-v6 [79] | Indelicato [80] | Our choice | Ref. |
|---|---|---|---|---|---|---|---|
| 1 | NR one-loop electron VP (eVP) | 205.0074 | | | | | |
| 2 | Rel. corr. (Breit–Pauli) | 0.0169[a] | | | | | |
| 3 | Rel. one-loop eVP | | 205.0282 | 205.0282 | 205.02821 | 205.02821 | [80] Eq. (54) |
| 19 | Rel. RC to eVP, $\alpha(Z\alpha)^4$ | (incl. in #2)[b] | $-0.0041$ | $-0.0041$ | | $-0.00208$[c] | [77,78] |
| 4 | Two-loop eVP (Källén–Sabry) | 1.5079 | 1.5081 | 1.5081 | 1.50810 | 1.50810 | [80] Eq. (57) |
| 5 | One-loop eVP in 2-Coulomb lines $\alpha^2(Z\alpha)^5$ | 0.1509 | 0.1509 | 0.1507 | 0.15102 | 0.15102 | [80] Eq. (60) |
| 7 | eVP corr. to Källén–Sabry | 0.0023 | 0.00223 | 0.00223 | 0.00215 | 0.00215 | [80] Eq. (62), [87] |
| 6 | NR three-loop eVP | 0.0053 | 0.00529 | 0.00529 | | 0.00529 | [87,88] |
| 9 | Wichmann–Kroll, “1:3” LBL | | $-0.00103$ | $-0.00102$ | $-0.00102$ | $-0.00102$ | [80] Eq. (64), [89] |
| 10 | Virtual Delbrück, “2:2” LBL | | 0.00135 | 0.00115 | | 0.00115 | [74,89] |
| New | “3:1” LBL | | | $-0.00102$ | | $-0.00102$ | [89] |
| 20 | $\mu$SE and $\mu$VP | $-0.6677$ | $-0.66770$ | $-0.66788$ | $-0.66761$ | $-0.66761$ | [80] Eqs. (72) + (76) |
| 11 | Muon SE corr. to eVP $\alpha^2(Z\alpha)^4$ | $-0.005(1)$ | $-0.00500$ | $-0.004924$[d] | | $-0.00254$ | [85] Eq. (29a)[e] |
| 12 | eVP loop in self-energy $\alpha^2(Z\alpha)^4$ | $-0.001$ | $-0.00150$ | | | [f] | [74,90–92] |
| 21 | Higher order corr. to $\mu$SE and $\mu$VP | | $-0.00169$ | $-0.00171$[g] | | $-0.00171$ | [86] Eq. (177) |
| 13 | Mixed eVP + $\mu$VP | | 0.00007 | 0.00007 | | 0.00007 | [74] |
| New | eVP and $\mu$VP in two Coulomb lines | | | | 0.00005 | 0.00005 | [80] Eq. (78) |
| 14 | Hadronic VP $\alpha(Z\alpha)^4 m_r$ | 0.0113(3) | 0.01077(38) | 0.011(1) | | 0.01121(44) | [93–95] |
| 15 | Hadronic VP $\alpha(Z\alpha)^5 m_r$ | | 0.000047 | | | 0.000047 | [94,95] |
| 16 | Rad corr. to hadronic VP | | $-0.000015$ | | | $-0.000015$ | [94,95] |
| 17 | Recoil corr. | 0.0575 | 0.05750 | 0.0575 | 0.05747 | 0.05747 | [80] Eq. (88) |
| 22 | Rel. RC $(Z\alpha)^5$ | $-0.045$ | $-0.04497$ | $-0.04497$ | $-0.04497$ | $-0.04497$ | [80] Eq. (88), [74] |
| 23 | Rel. RC $(Z\alpha)^6$ | 0.0003 | 0.00030 | | 0.0002475 | 0.0002475 | [80] Eq. (86)+Tab.II |
| New | Rad. (only eVP) RC $\alpha(Z\alpha)^5$ | | | | | 0.000136 | [85] Eq. (64a) |
| 24 | Rad. RC $\alpha(Z\alpha)^n$ (proton SE) | $-0.0099$ | $-0.00960$ | $-0.0100$ | | $-0.01080(100)$ | [43][h] [74] |
| | Sum | 206.0312 | 206.02915 | 206.02862 | | 206.03339(109) | |

Antognini, RP at al., Ann. Phys. (N.Y.) 331, 127 (2013)

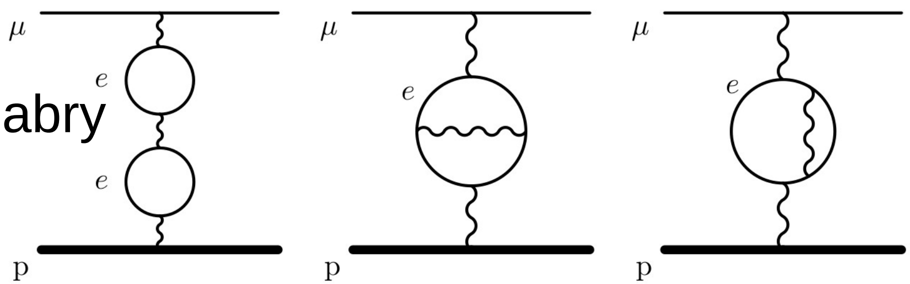
# Theory in muonic H

$\Delta E_{Lamb}$ = 206.0336 (15) $meV_{QED}$ + 0.0332 (20) $meV_{TPE}$ – 5.2275 (10) meV/fm$^2$ * $\mathbf{R_p^{\,2}}$

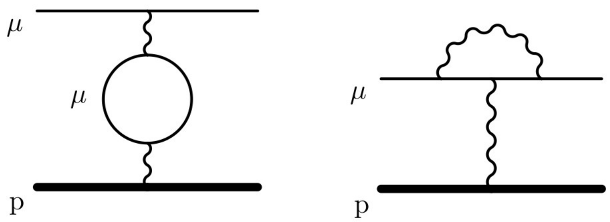
Uehling



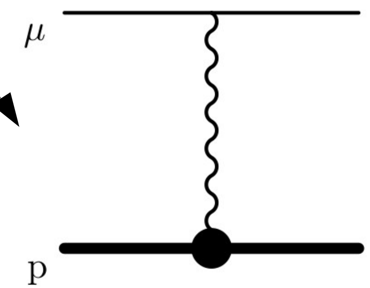

Källen-Sabry



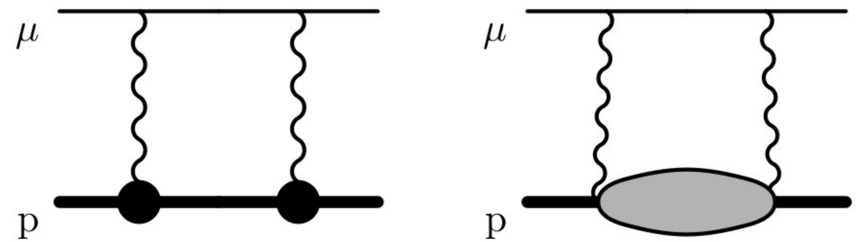

Muon SE+VP




and 20+ more….




Proton form factor




elastic and inelastic two-photon exchange
(Friar moment and polarizability)

# Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ \text{meV}_{QED} + 1.7150\ (\mathbf{230})\ \text{meV}_{TPE} - 6.1103\ (3)\ \text{meV/fm}^2 * \mathbf{R_d^2}$$

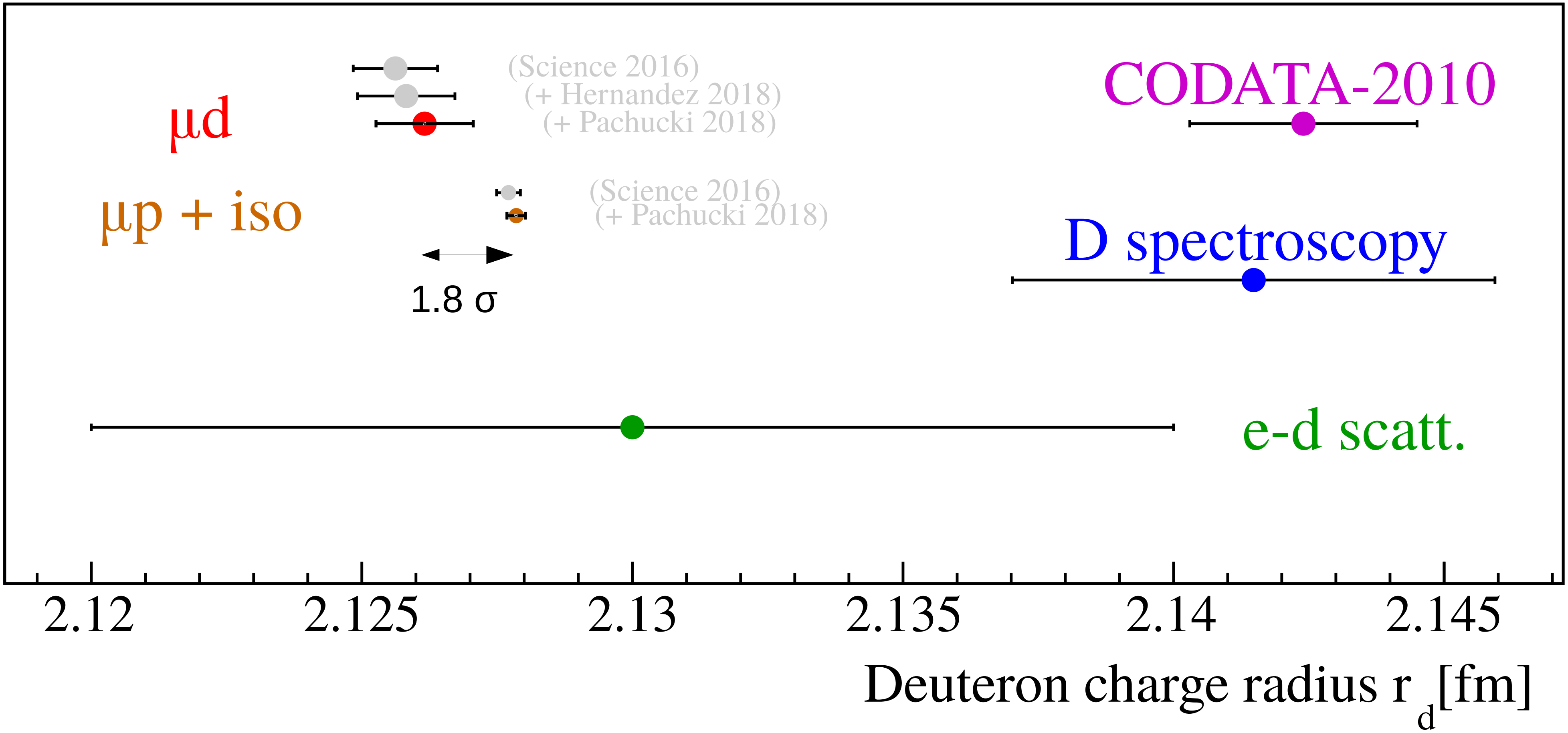
Nuclear structure contributions to the Lamb shift in muonic deuterium.

| Item | Contribution | Pachucki [55] AV18 | | Friar [60] ZRA | | Hernandez *et al.* [58] AV18 | N$^3$LO † | | Pach.& Wienczek [65] AV18 | | Carlson *et al.* [64] data | Our choice value | | source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Source | 1 | | 2 | | 3 | 4 | | 5 | | 6 | | | |
| p1 | Dipole | 1.910 | $\delta_0 E$ | 1.925 | Leading C1 | 1.907 | 1.926 | $\delta^{(0)}_{D1}$ | 1.910 | $\delta_0 E$ | | 1.9165 | ± 0.0095 | 3-5 |
| p2 | Rel. corr. to p1, longitudinal part | −0.035 | $\delta_R E$ | −0.037 | Subleading C1 | −0.029 | −0.030 | $\delta^{(0)}_{L}$ | −0.026 | $\delta_R E$ | | | | |
| p3 | Rel. corr. to p1, transverse part | | | | | 0.012 | 0.013 | $\delta^{(0)}_{T}$ | | | | | | |
| p4 | Rel. corr. to p1, higher-order | | | | | | | | 0.004 | $\delta_{HO} E$ | | | | |
| sum | Total rel. corr., p2+p3+p4 | −0.035 | | −0.037 | | −0.017 | −0.017 | | −0.022 | | | −0.0195 | ± 0.0025 | 3-5 |
| p5 | Coulomb distortion, leading | −0.255 | $\delta_{C1} E$ | | | | | | −0.255 | $\delta_{C1} E$ | | | | |
| p6 | Coul. distortion, next order | −0.006 | $\delta_{C2} E$ | | | | | | −0.006 | $\delta_{C2} E$ | | | | |
| sum | Total Coulomb distortion, p5+p6 | −0.261 | | | | −0.262 | −0.264 | $\delta^{(0)}_{C}$ | −0.261 | | | −0.2625 | ± 0.0015 | 3-5 |
| p7 | El. monopole excitation | −0.045 | $\delta_{Q0} E$ | −0.042 | C0 | −0.042 | −0.041 | $\delta^{(2)}_{R2}$ | −0.042 | $\delta_{Q0} E$ | | | | |
| p8 | El. dipole excitation | 0.151 | $\delta_{Q1} E$ | 0.137 | Retarded C1 | 0.139 | 0.140 | $\delta^{(2)}_{D1D3}$ | 0.139 | $\delta_{Q1} E$ | | | | |
| p9 | El. quadrupole excitation | −0.066 | $\delta_{Q2} E$ | −0.061 | C2 | −0.061 | −0.061 | $\delta^{(2)}_{Q}$ | −0.061 | $\delta_{Q2} E$ | | | | |
| sum | Tot. nuclear excitation, p7+p8+p9 | 0.040 | | 0.034 | C0 + ret-C1 + C2 | 0.036 | 0.038 | | 0.036 | | | 0.0360 | ± 0.0020 | 2-5 |
| p10 | Magnetic | −0.008 ◇ [a] | $\delta_M E$ | −0.011 | M1 | −0.008 | −0.007 | $\delta^{(0)}_{M}$ | −0.008 | $\delta_M E$ | | −0.0090 | ± 0.0020 | 2-5 |
| SUM_1 | Total nuclear (corrected) | 1.646 | | 1.648 [b] | | 1.656 | 1.676 | | 1.655 | | | 1.6615 | ± 0.0103 | |
| p11 | Finite nucleon size | | | 0.021 | Retarded C1 f.s. | 0.020 ◇ [c] | 0.021 ◇ [c] | $\delta^{(2)}_{NS}$ | 0.020 | $\delta_{FS} E$ | | | | |
| p12 | n p charge correlation | | | −0.023 | pn correl. f.s. | −0.017 | −0.017 | $\delta^{(1)}_{np}$ | −0.018 | $\delta_{FZ} E$ | | | | |
| sum | p11+p12 | | | −0.002 | | 0.003 | 0.004 | | 0.002 | | | 0.0010 | ± 0.0030 | 2-5 |
| p13 | Proton elastic 3rd Zemach moment | } 0.043(3) | $\delta_P E$ | 0.030 | $\langle r^3 \rangle^{pp}_{(2)}$ | | | | } 0.043(3) | $\delta_P E$ | | 0.0289 | ± 0.0015 | Eq.(13) [d] |
| p14 | Proton inelastic polarizab. | | | | | } 0.027(2) | | $\delta^N_{\text{pol}}$ [64] | | | } 0.028(2) $\Delta E^{\text{hadr}}$ | } 0.0280 | ± 0.0020 | 6 |
| p15 | Neutron inelastic polarizab. | | | | | | | | 0.016(8) | $\delta_N E$ | | | | |
| p16 | Proton & neutron subtraction term | | | | | | | | | | | −0.0098 | ± 0.0098 | Eq.(15) [e] |
| sum | Nucleon TPE, p13+p14+p15+p16 | 0.043(3) | | 0.030 | | 0.027(2) | | | 0.059(9) | | | 0.0471 | ± 0.0101 | [f] |
| SUM_2 | Total nucleon contrib. | 0.043(3) | | 0.028 | | 0.030(2) | | | 0.061(9) | | | 0.0476 | ± 0.0105 | |
| | **Sum**, published | 1.680(16) | | 1.941(19) | | 1.690(20) | | | 1.717(20) | | 2.011(740) | | | |
| | **Sum**, corrected | | | 1.697(19) [g] | | 1.714(20) [h] | | | 1.707(20) [i] | | 1.748(740) [j] | **1.7096** | **± 0.0147** | |

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)

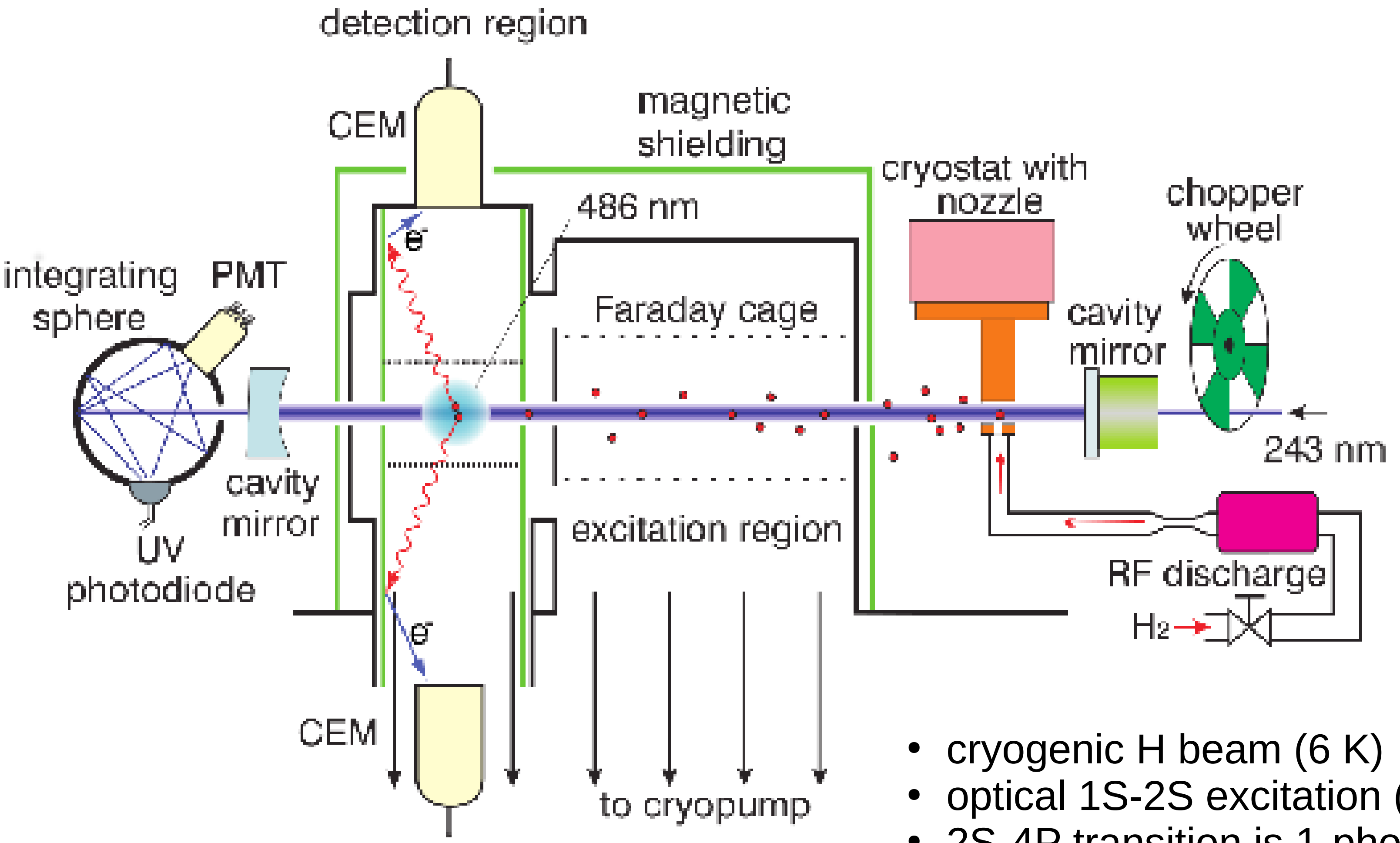
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

# Deuteron radius




Hernandez et al, Phys. Lett. B 778, 377 (2018)
Pachucki et al., PRA 97, 062511 (2018)

# Garching H(2S-4P)




- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to $10^{-4}$ !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

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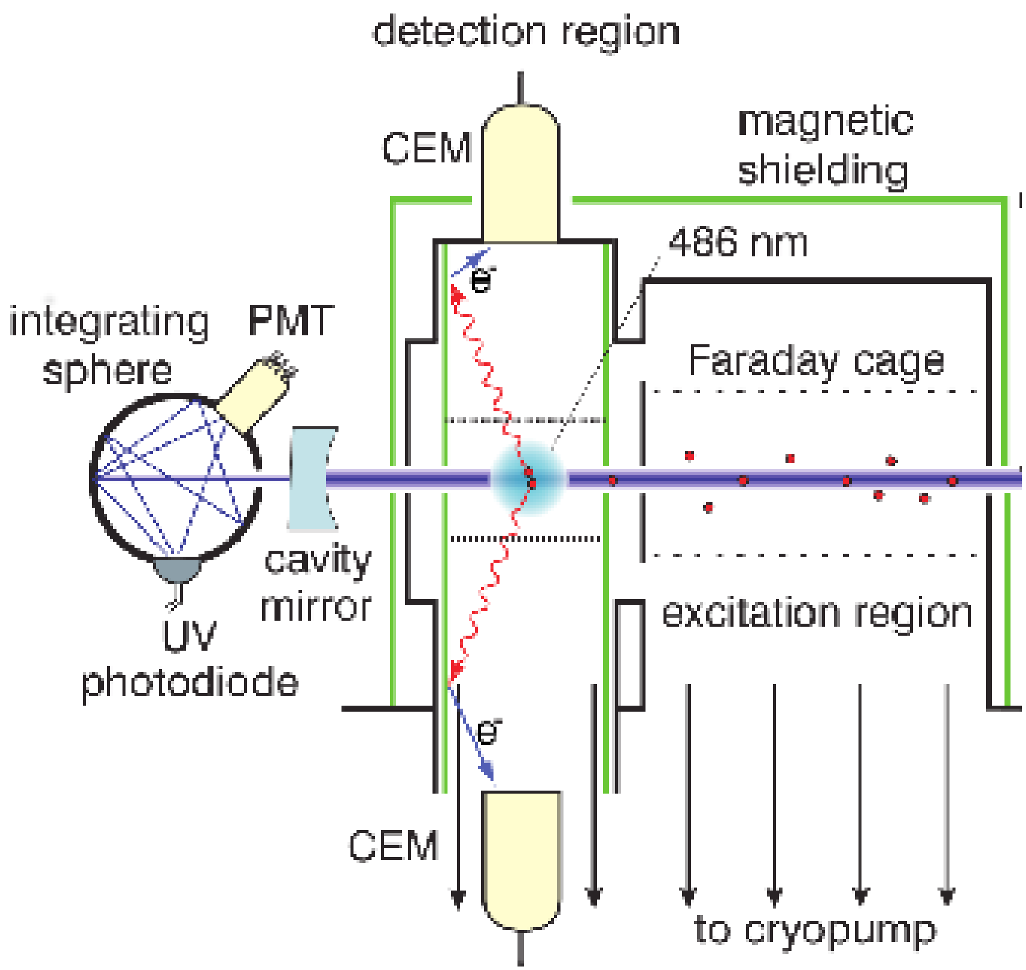
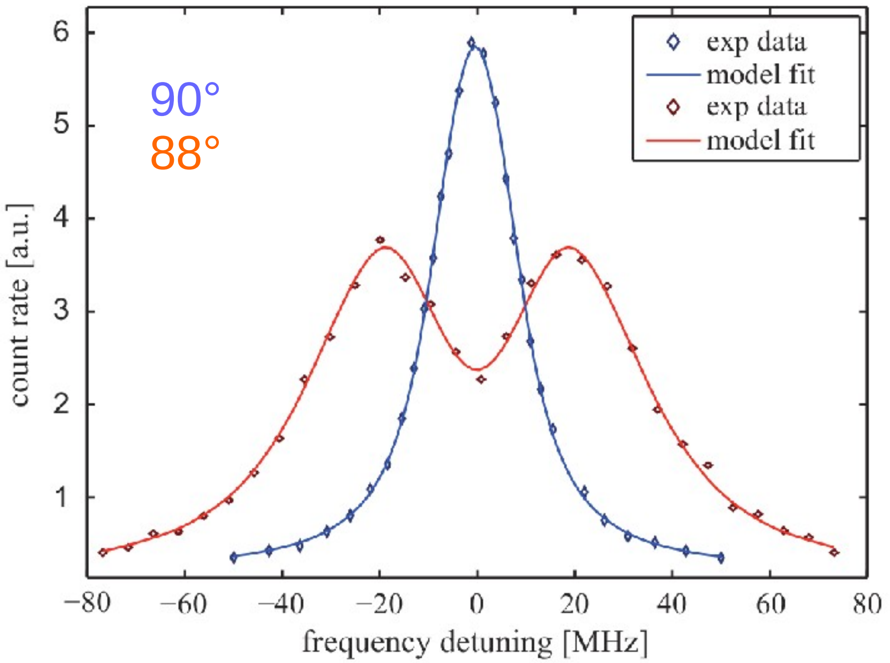



1st order Doppler cancellation

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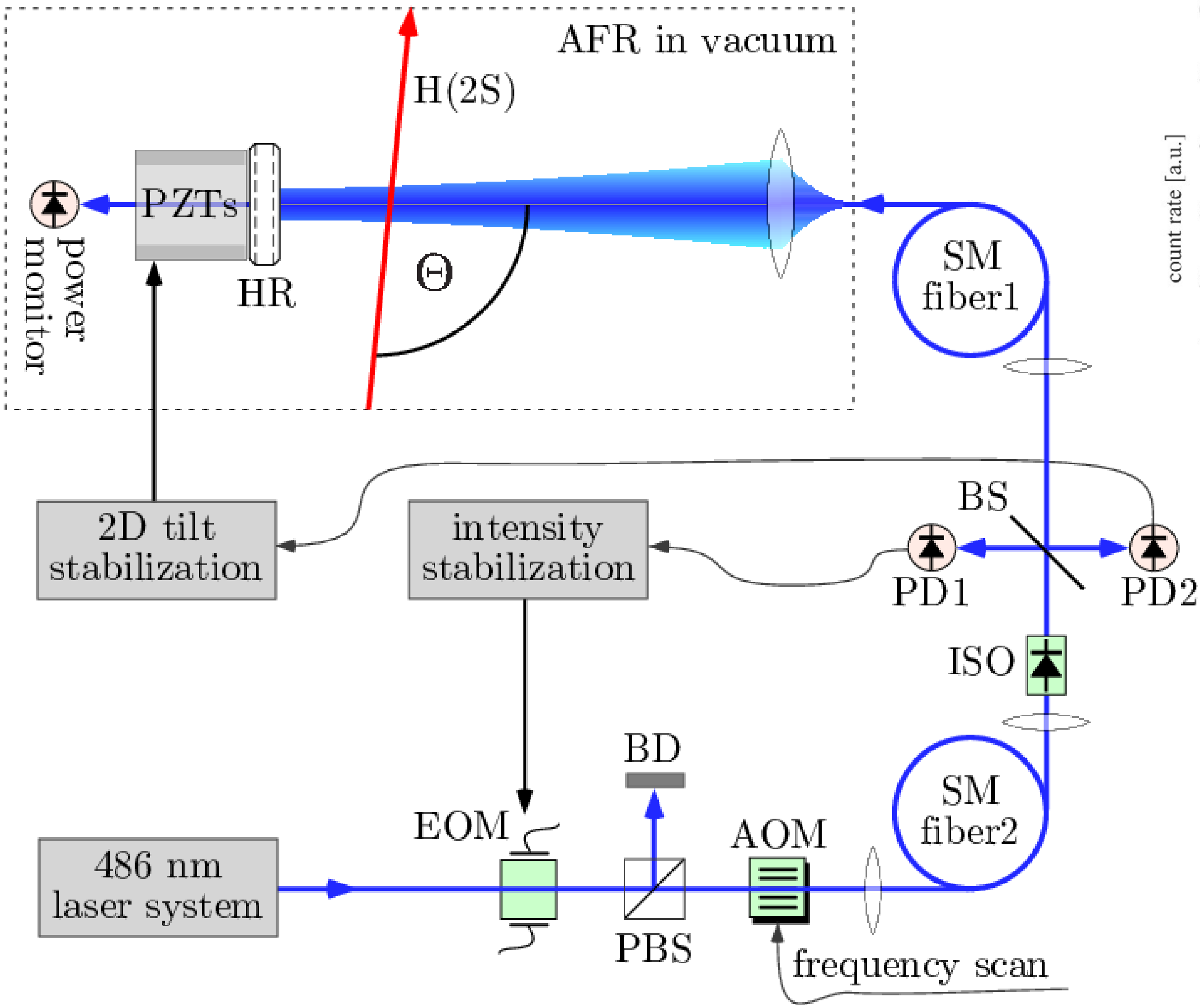
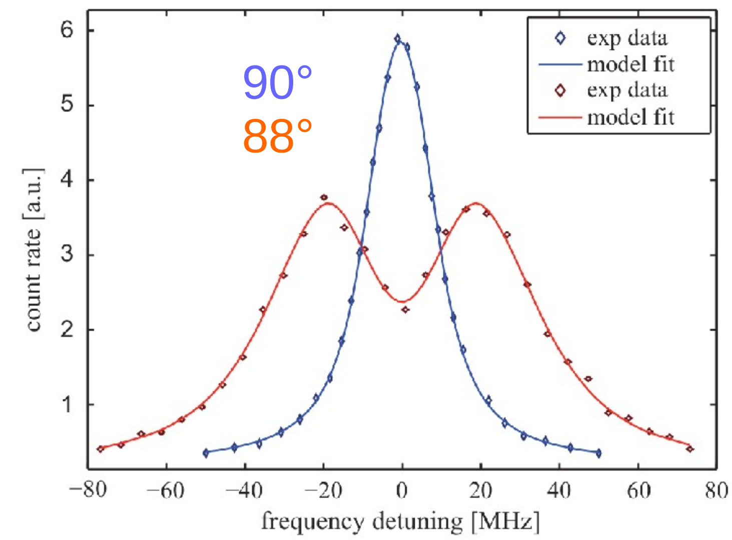
- large systematics

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

# 1$^{st}$ order Doppler shift

AFR: Active Fiber-based Retroreflector




Beyer, RP et al, Opt. Expr. 24, 17470 (2016)

# Systematics

| Contribution | Δν (kHz) | σ (kHz) |
|---|---|---|
| Statistics | 0.00 | 0.41 |
| First-order Doppler shift | 0.00 | 2.13 |
| Quantum interference shift | 0.00 | 0.21 |
| Light force shift | −0.32 | 0.30 |
| Model corrections | 0.11 | 0.06 |
| Sampling bias | 0.44 | 0.49 |
| Second-order Doppler shift | 0.22 | 0.05 |
| dc-Stark shift | 0.00 | 0.20 |
| Zeeman shift | 0.00 | 0.22 |
| Pressure shift | 0.00 | 0.02 |
| Laser spectrum | 0.00 | 0.10 |
| Frequency standard (hydrogen maser) | 0.00 | 0.06 |
| Recoil shift | −837.23 | 0.00 |
| Hyperfine structure corrections | −132,552.092 | 0.075 |
| Total | −133,388.9 | 2.3 |

# New Rp from Paris: 1S-3S

PHYSICAL REVIEW LETTERS **120,** 183001 (2018)

## New Measurement of the $1S-3S$ Transition Frequency of Hydrogen: Contribution to the Proton Charge Radius Puzzle

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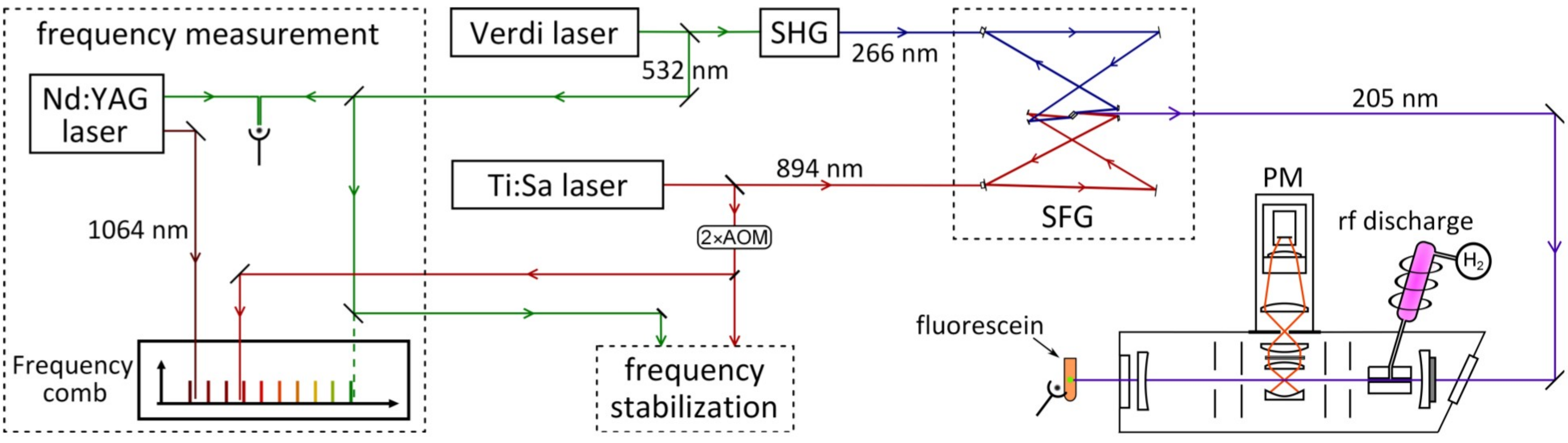
We present a new measurement of the $1S-3S$ two-photon transition frequency of hydrogen, realized with a continuous-wave excitation laser at 205 nm on a room-temperature atomic beam, with a relative uncertainty of $9 \times 10^{-13}$. The proton charge radius deduced from this measurement, $r_p = 0.877(13)$ fm, is in very good agreement with the current CODATA-recommended value. This result contributes to the ongoing search to solve the proton charge radius puzzle, which arose from a discrepancy between the CODATA value and a more precise determination of $r_p$ from muonic hydrogen spectroscopy.

# New Rp from Paris: 1S-3S

arXiv: 1801.08816

Setup:



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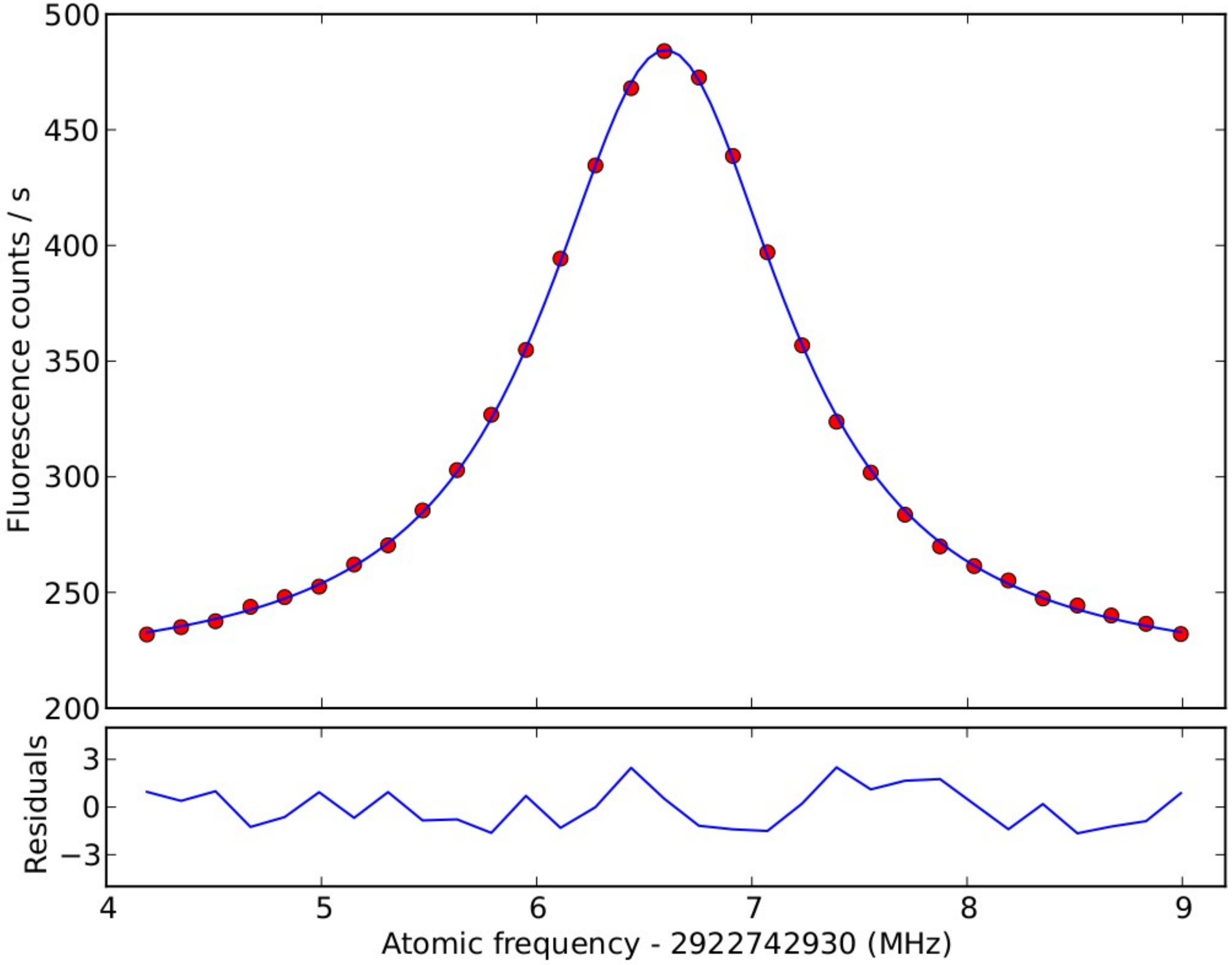
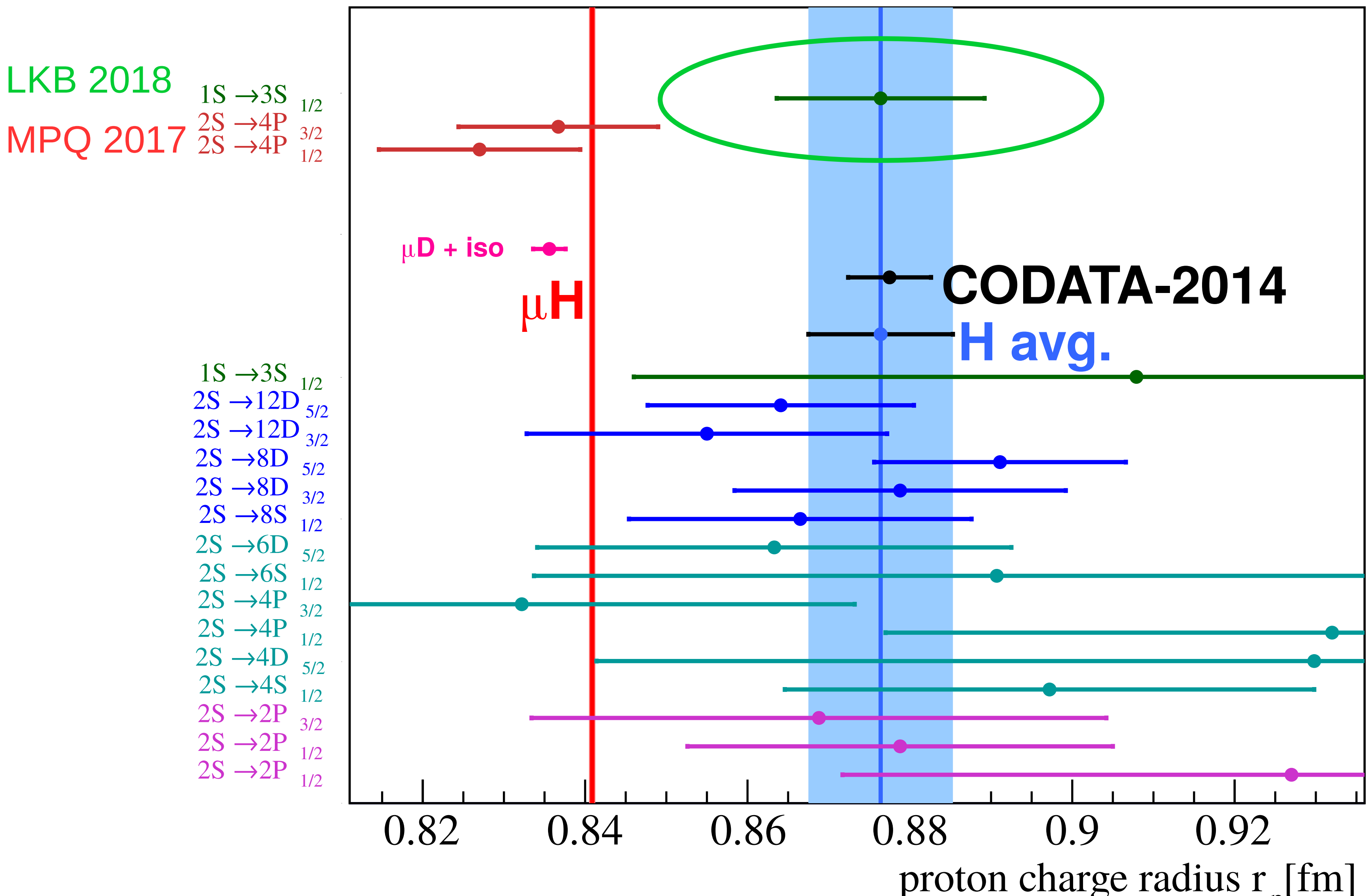



Data:
Average of 47 recordings
(4 hours of integration)

Fit with theoretical line profile

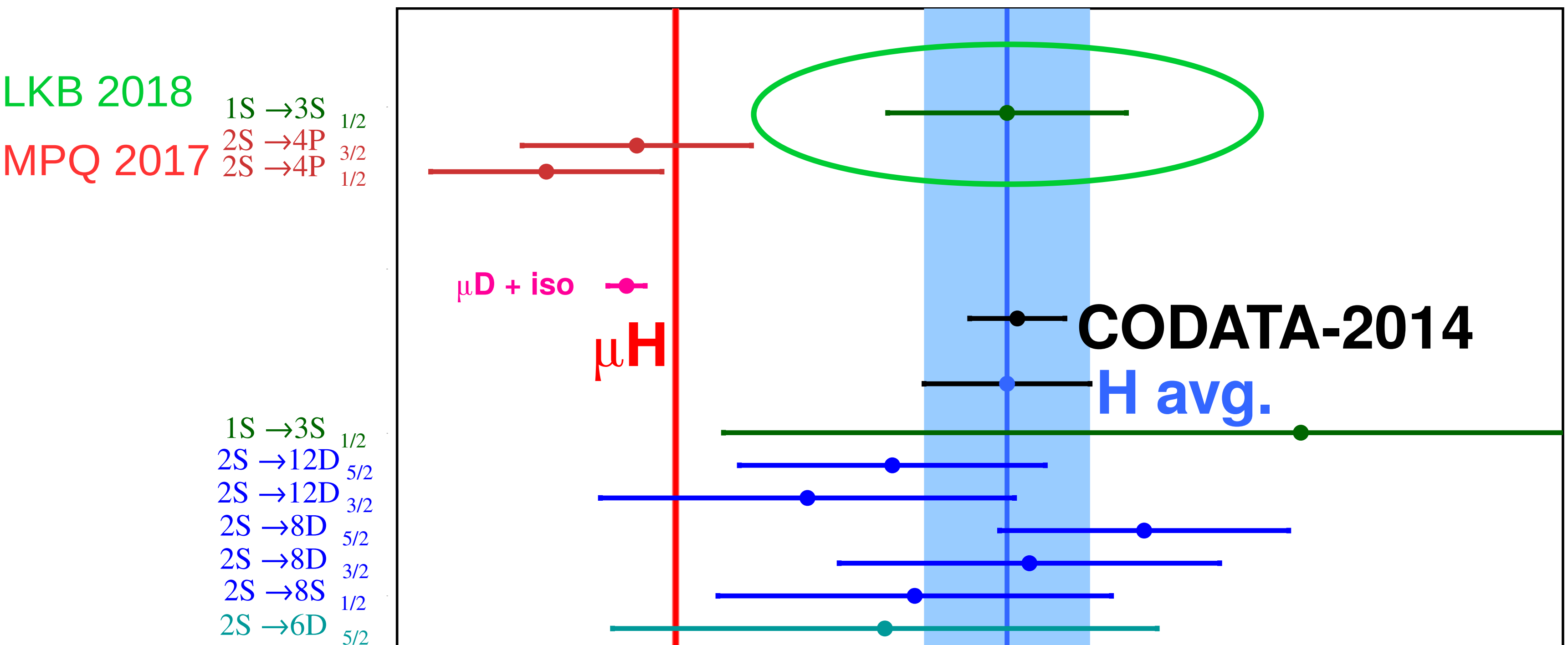
Obs. linewidth = 1.35 MHz
Nat. linewidth = 1 MHz

# Rp from H spectroscopy




**Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)**
**Fleurbaey et al., PRL 120, 183001 (2018)**

# Rp from H spectroscopy

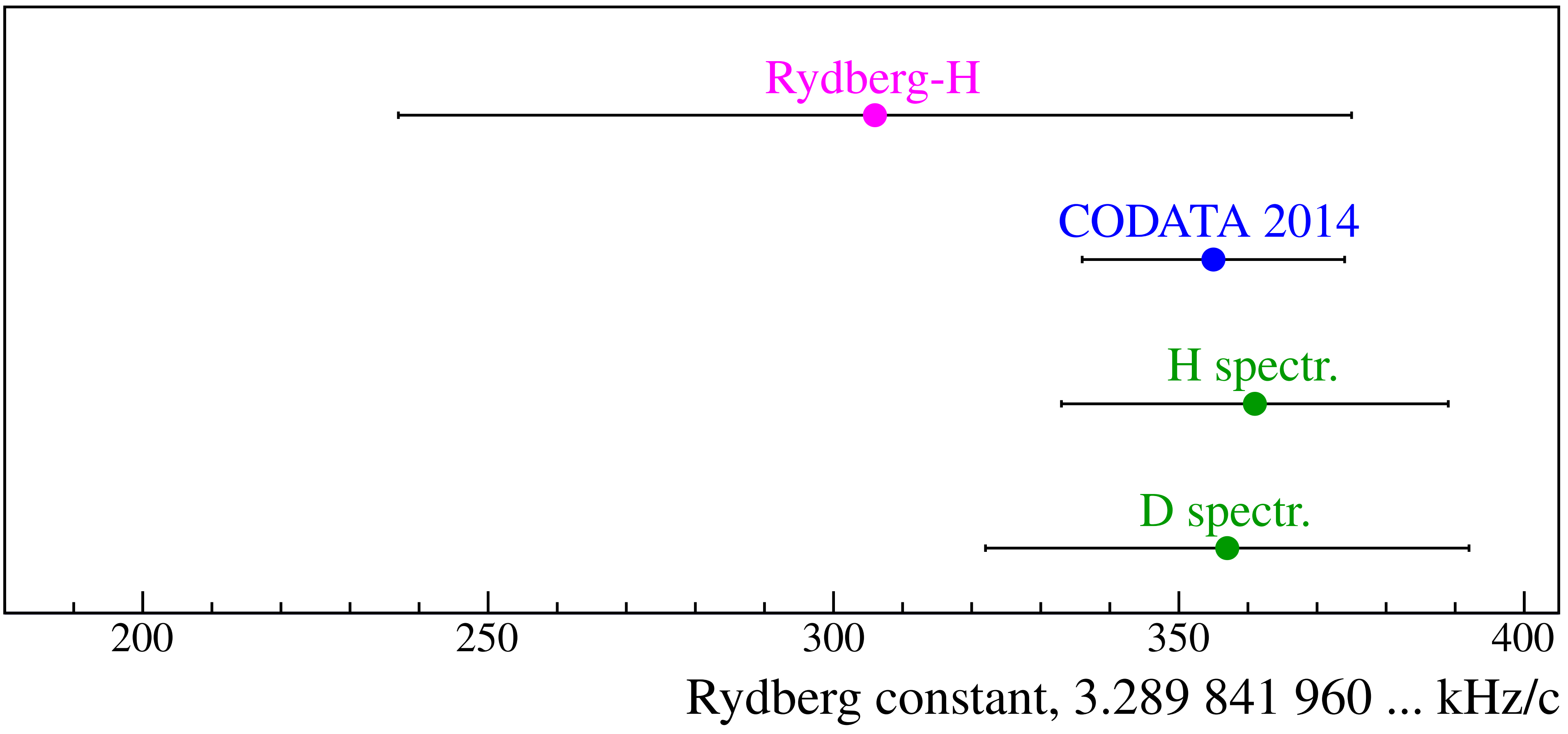



Proton Radius Puzzle is NOT “solved” !!

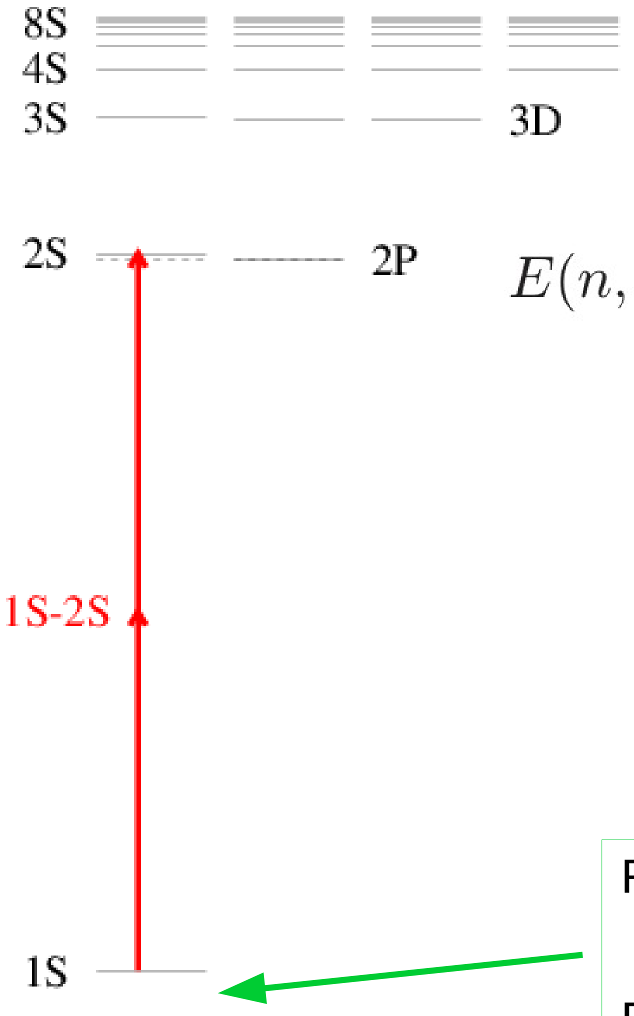
We have a “Rydberg problem” now → need more data!

**Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)**
**Fleurbaey et al., PRL 120, 183001 (2018)**

# Rydberg constants from H/D



# And now with ***muonic*** charge radii



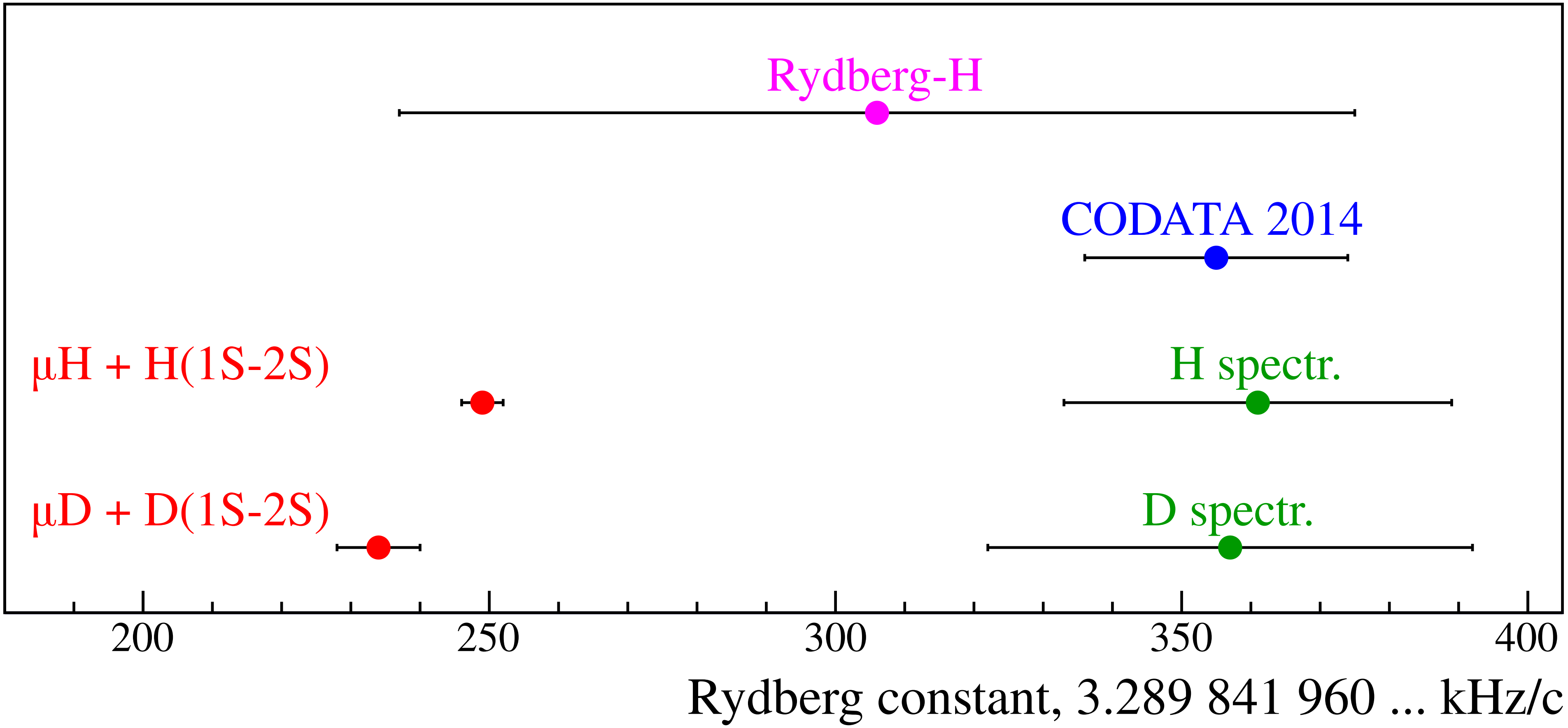

$$E(n,\ell,j)/h = -\frac{cR_\infty}{n^2}\frac{m_{\rm red}}{m_e} + \frac{E_{NS}}{n^3}\,\delta_{\ell 0} + \Delta(n,\ell,j). \quad (7)$$

$$\nu(1S-2S) \approx \frac{3}{4} R_\infty - \frac{7}{8} E_{NS}$$

$R_{\mathbf{p}}$(μp) into H(1S-2S)
or
$R_{\mathbf{d}}$(μd) into D(1S-2S)

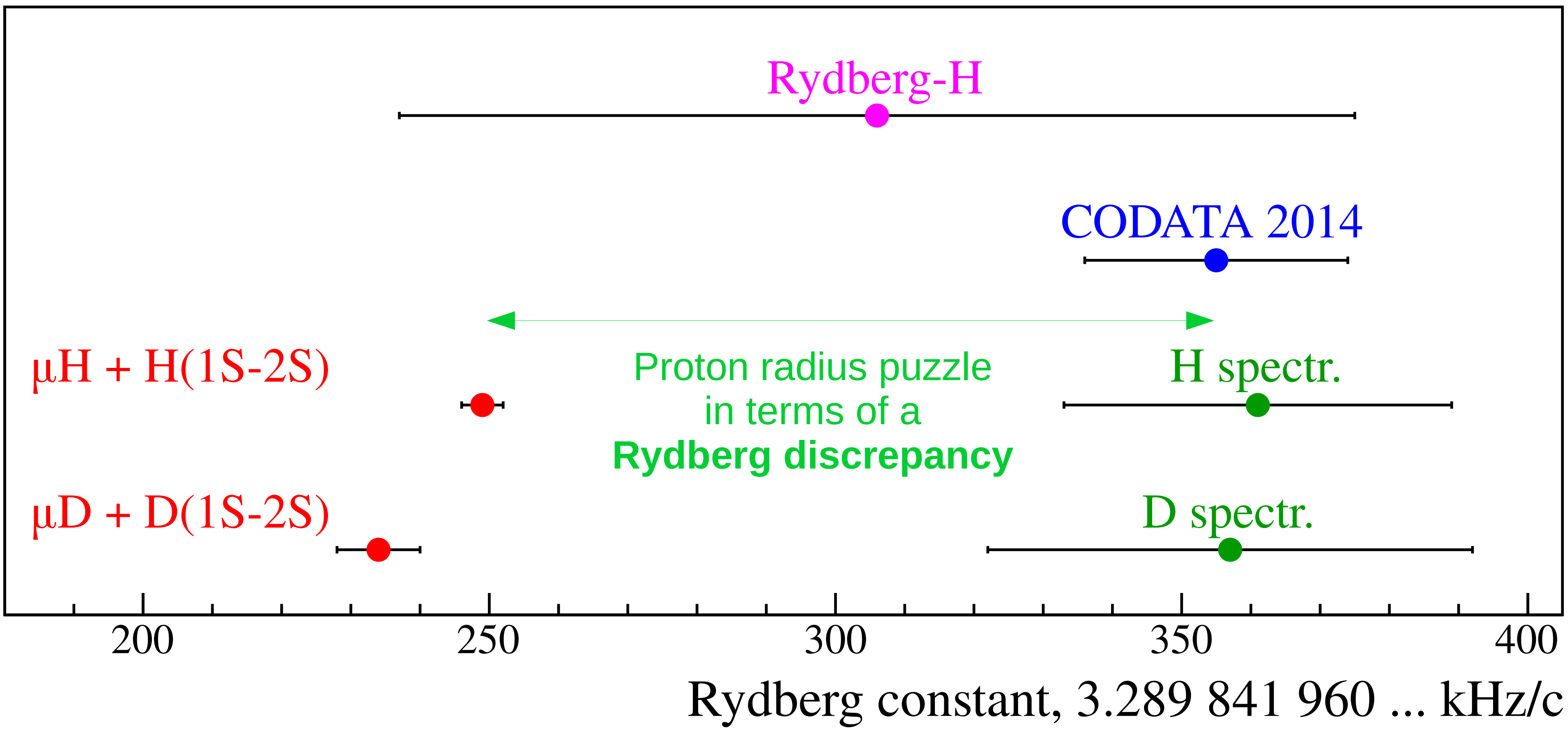
μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

# Rydberg constants from e/μ H/D



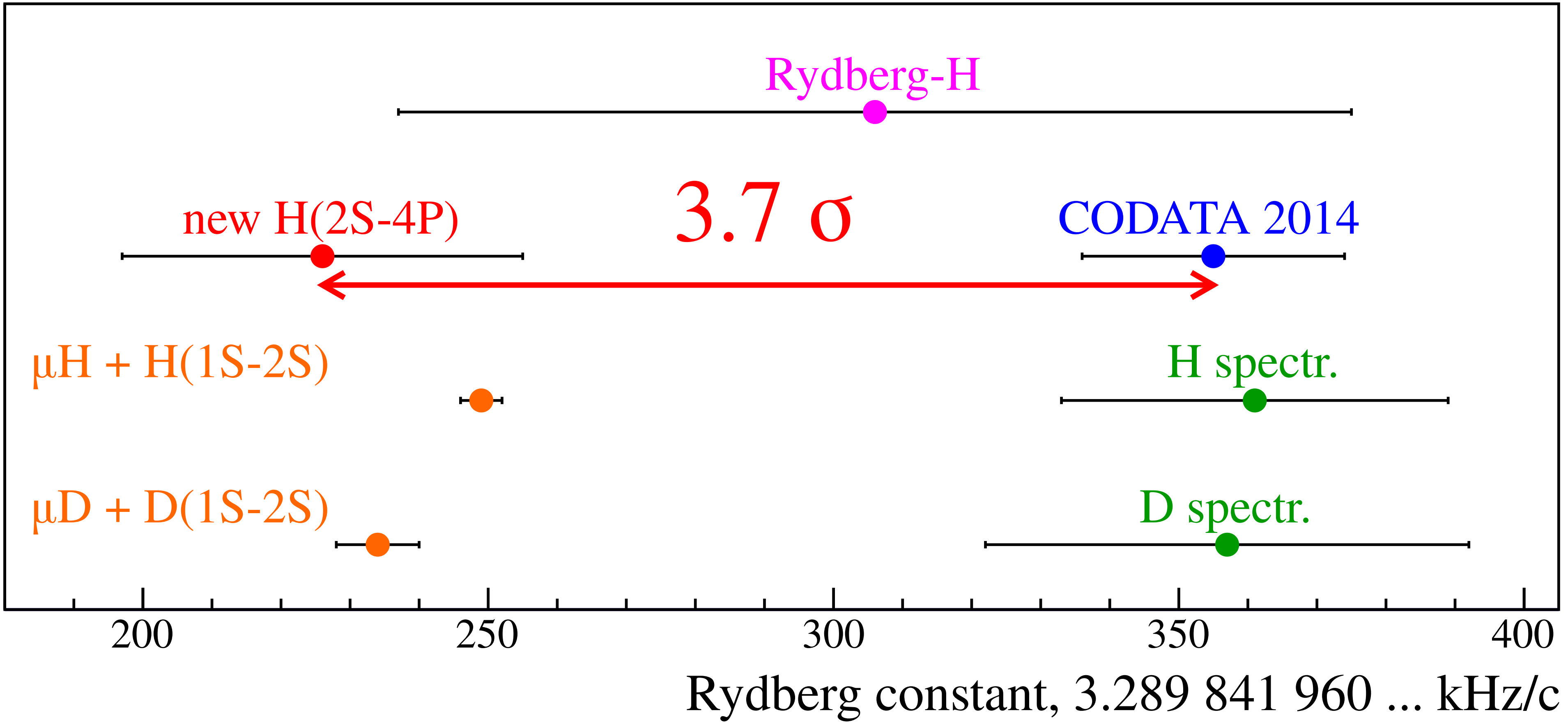

$R_\infty$ [μH + H(1S-2S)] = 3.289 841 960 249 **(1.0)** $^{Rp}$ **(2.5)** $^{QED}$ kHz/c

# Rydberg constants from e/μ H/D




$R_\infty$ [μH + H(1S-2S)] = 3.289 841 960 249 **(1.0)** Rp **(2.5)** QED kHz/c

# Rydberg constant from H(2S-4P)

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