

Shrinking the Proton

Laser spectroscopy for
nuclear physics and
fundamental constants

Randolf Pohl

JGU, Mainz

MPQ, Garching

for the

CREMA collaboration



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T.-L. Chen, C.-Y. Kao, Y.-W. Liu	Nat. Tsing Hua Uni, Hsinchu, Taiwan
P. Amaro, J.P. Santos	Uni Lisbon, Portugal
L. Ludhova, P.E. Knowles, L.A. Schaller	Uni Fribourg, Switzerland
A. Giesen	Dausinger & Giesen GmbH, Stuttgart, Germany
P. Rabinowitz	Uni Princeton, USA

Hydrogen group at MPQ

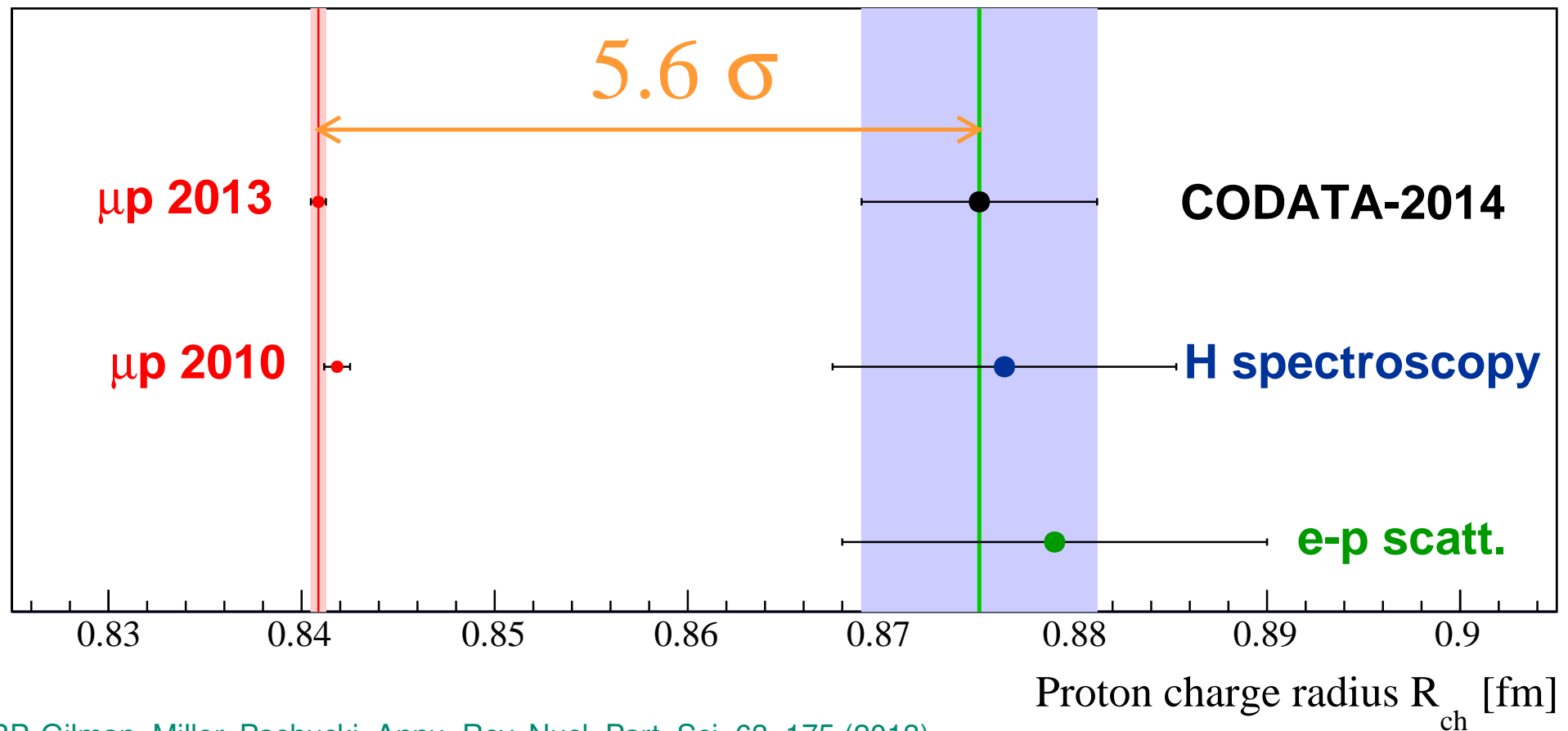
A. Beyer, A. Grinin, L. Maisenbacher, A. Matveev, C.G. Parthey, J. Alnis, D.C. Yost, E. Peters, R. Pohl, Th. Udem, T.W. Hänsch	MPQ, Garching, Germany
K. Khabarova, N. Kolachevksy	Lebedev Inst., Moscow, Russia

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm

muons: 0.8409 ± 0.0004 fm

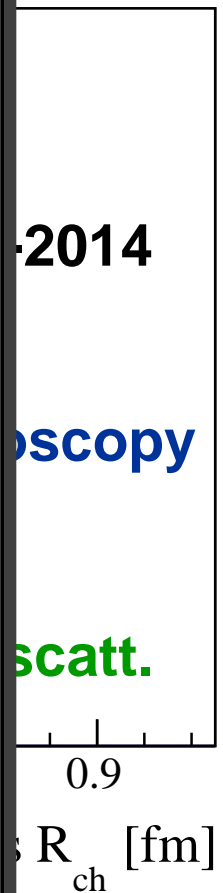
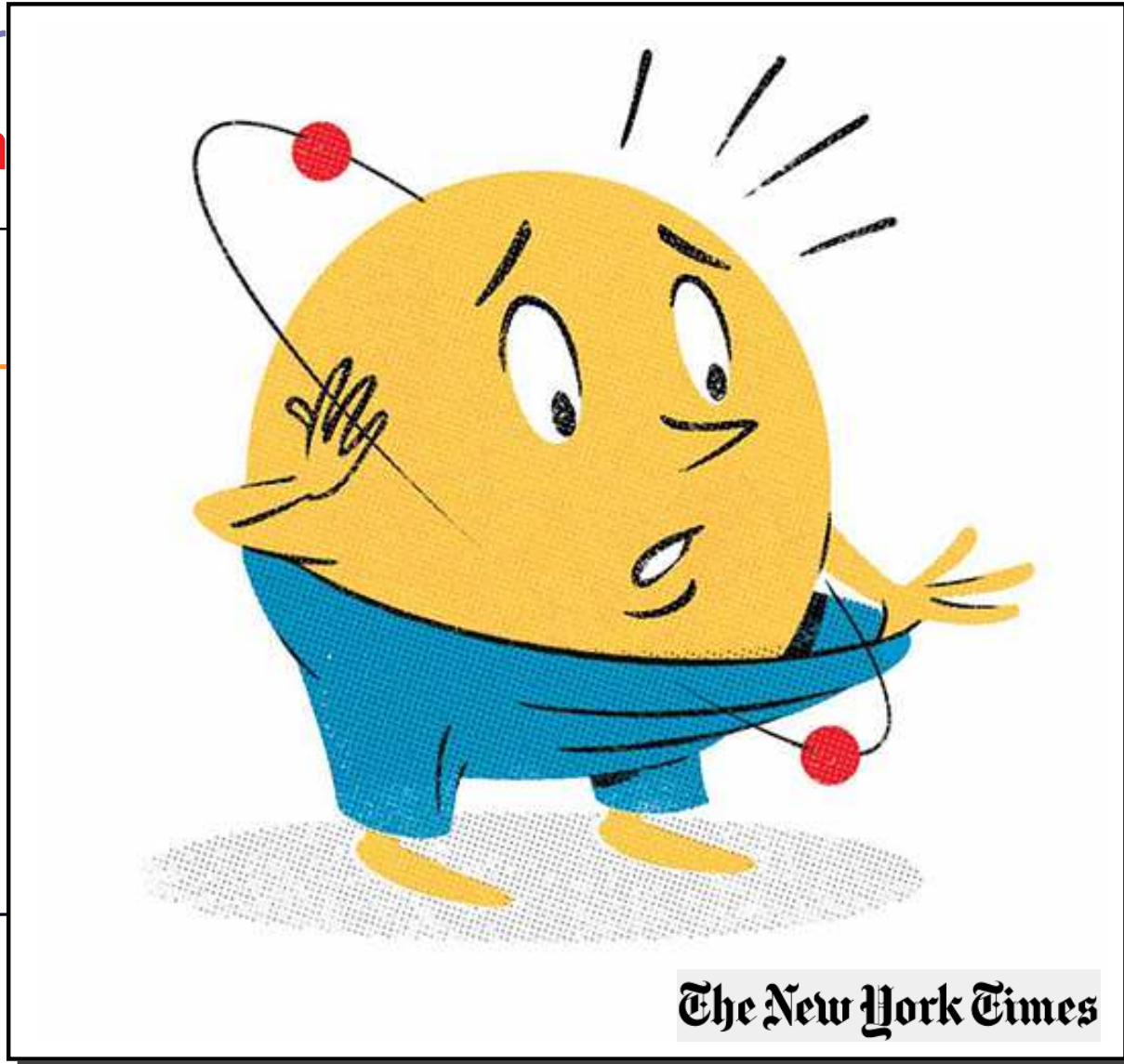
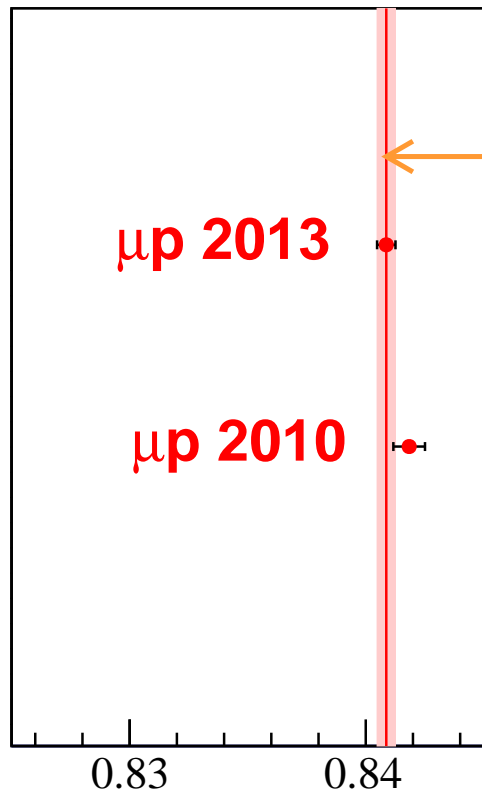


RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

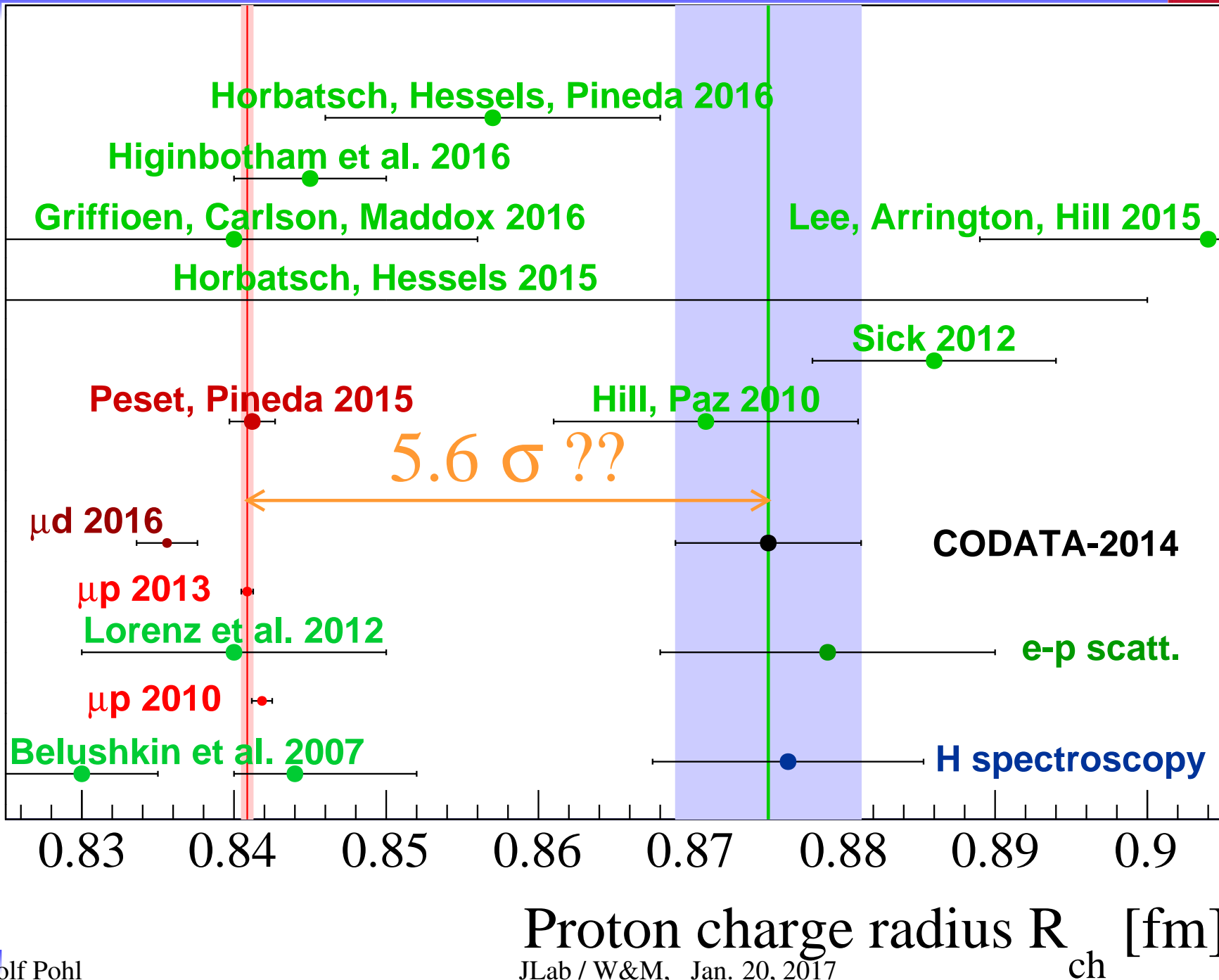
The proton radius puzzle

The proton rms charge radius measured with

electron
muon



The proton radius puzzle???





8 July 2010 | www.nature.com/

na

OIL SPILLS
There's more to come

PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

NATUREJOBS
Researchers for hire

ASSOCIATION OF ASIA PACIFIC PHYSICAL SOCIETIES

AAPPS

Volume 23 | Number 2 | APRIL 2013 **Bulletin**

Proton Size Puzzle Reinforced

Labels in diagram: Momentum filter, Cyclotron trap, Pion beam line, Protons, C-target, ST solenoid, Raman cell, Ti:Sa cw laser, FP cavity, Ti:Sa amplifier, Ti:Sa oscillator, SHG, Diode laser, Disk-laser, Water vapor cell.

ISSN 0218-2203

Feature Articles	Activities and Research News	Institutes in Asia Pacific
<ul style="list-style-type: none">• Neutrino Oscillation and Mixing• Status and Prospect of Telescope Array Experiment	<ul style="list-style-type: none">• Proton Size Puzzle Reinforced• Asia Pacific School/Workshop on Gravitation and Cosmology 2013	<ul style="list-style-type: none">• Department of Physics, Yonsei University• Department of Physics at Korea University



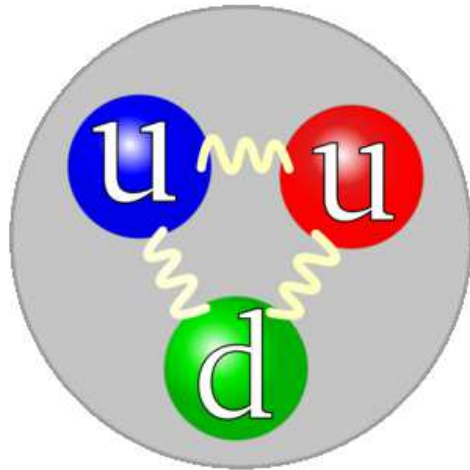


Muons in the news

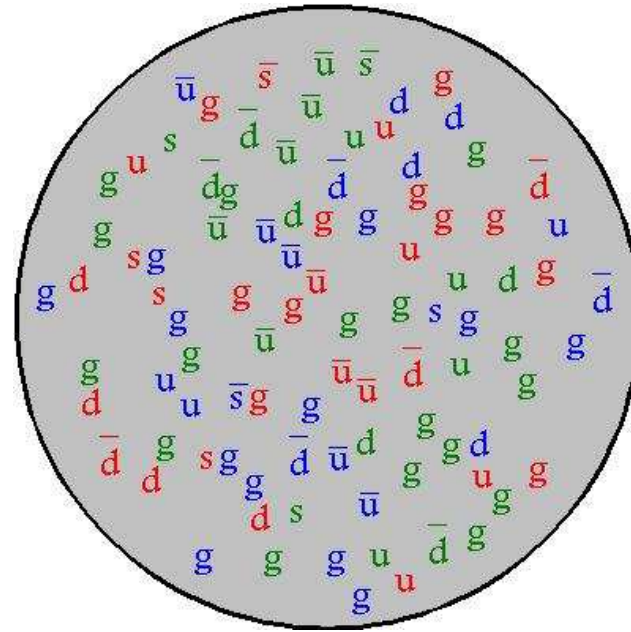
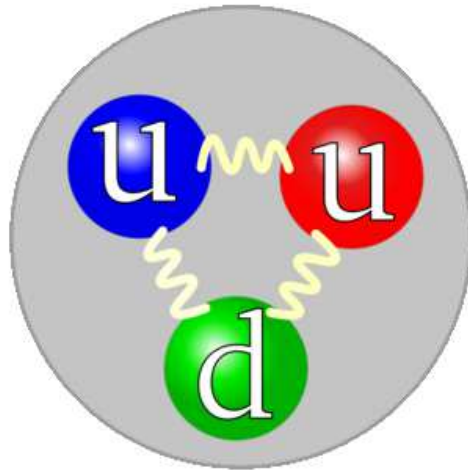


- Introduction:
 - How large are the proton, deuteron, helion, alpha...?
 - Atomic vs. nuclear physics
- Muonic hydrogen:
 - Size does matter!
- Laser spectroscopy of muonic atoms/ions
- New measurements:
 - Muonic deuterium → Another puzzle!
 - Muonic helium
 - Regular hydrogen → New Rydberg constant!
- Future:
 - HFS in muonic hydrogen and helium-3
 - X-ray spectroscopy of radium etc.
 - Lamb shift in muonic Li, Be, ...
 - 1S-2S in regular tritium (triton radius)
 - ...

The Proton



The Proton



Ernest Rutherford (1871 - 1937)



half-life; α and β rays

1908: Nobel prize Chemistry:

"for his investigations into the disintegration of the elements,
and the chemistry of radioactive substances"

Ernest Rutherford (1871 - 1937)

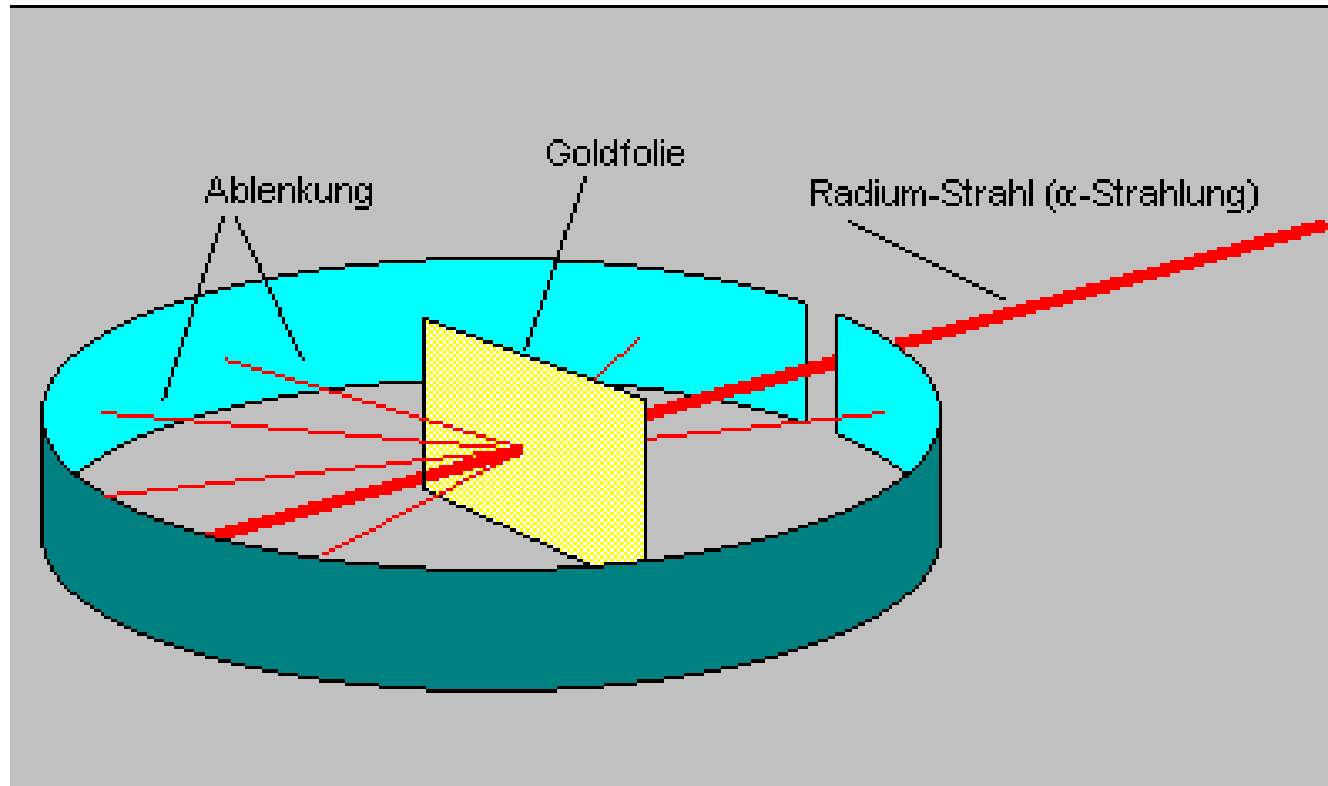


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1911: Most α particles pass a thin gold foil undeflected.



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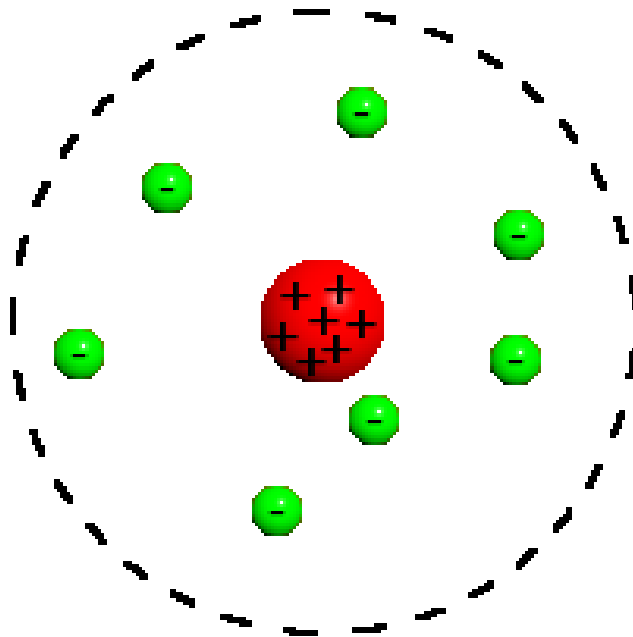
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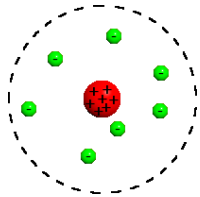
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1917: Discovery of the proton.



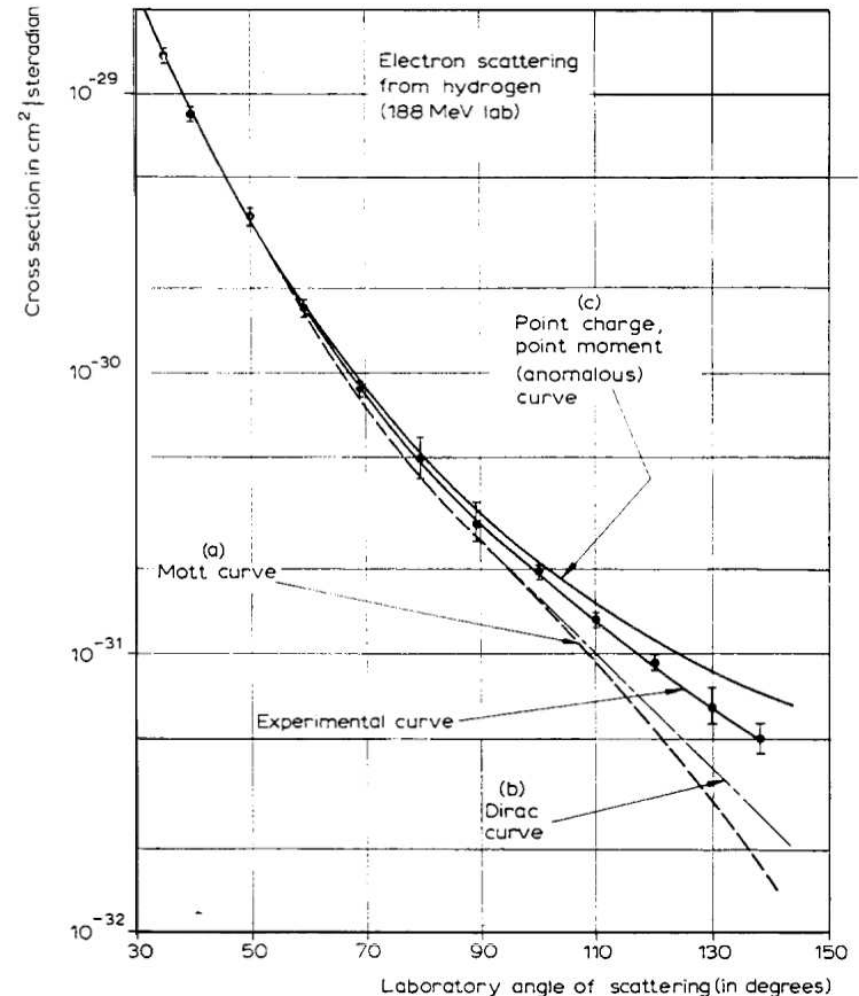
Robert Hofstadter (1915 - 1990)



1961: Nobel prize Physics (with Rudolf Mössbauer):
"for his pioneering studies of **electron scattering**
in atomic nuclei
and for his consequent discoveries concerning the
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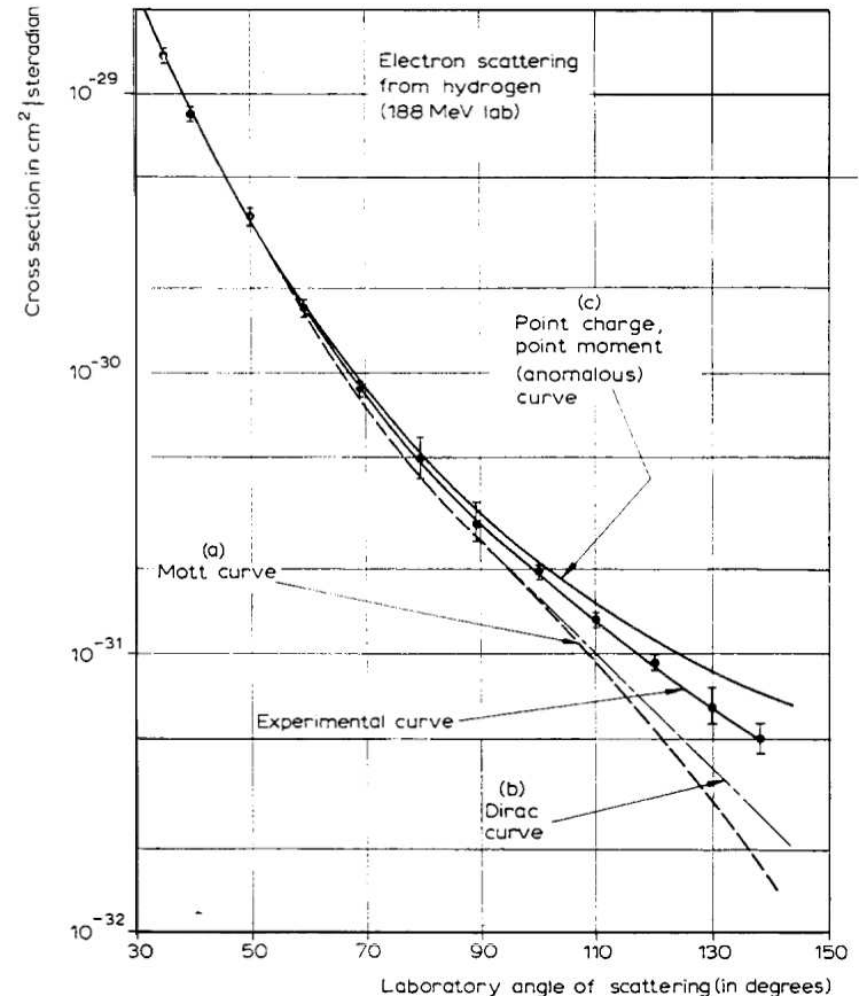
Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).

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"Proton has a
diameter of 0.7×10^{-13} cm"



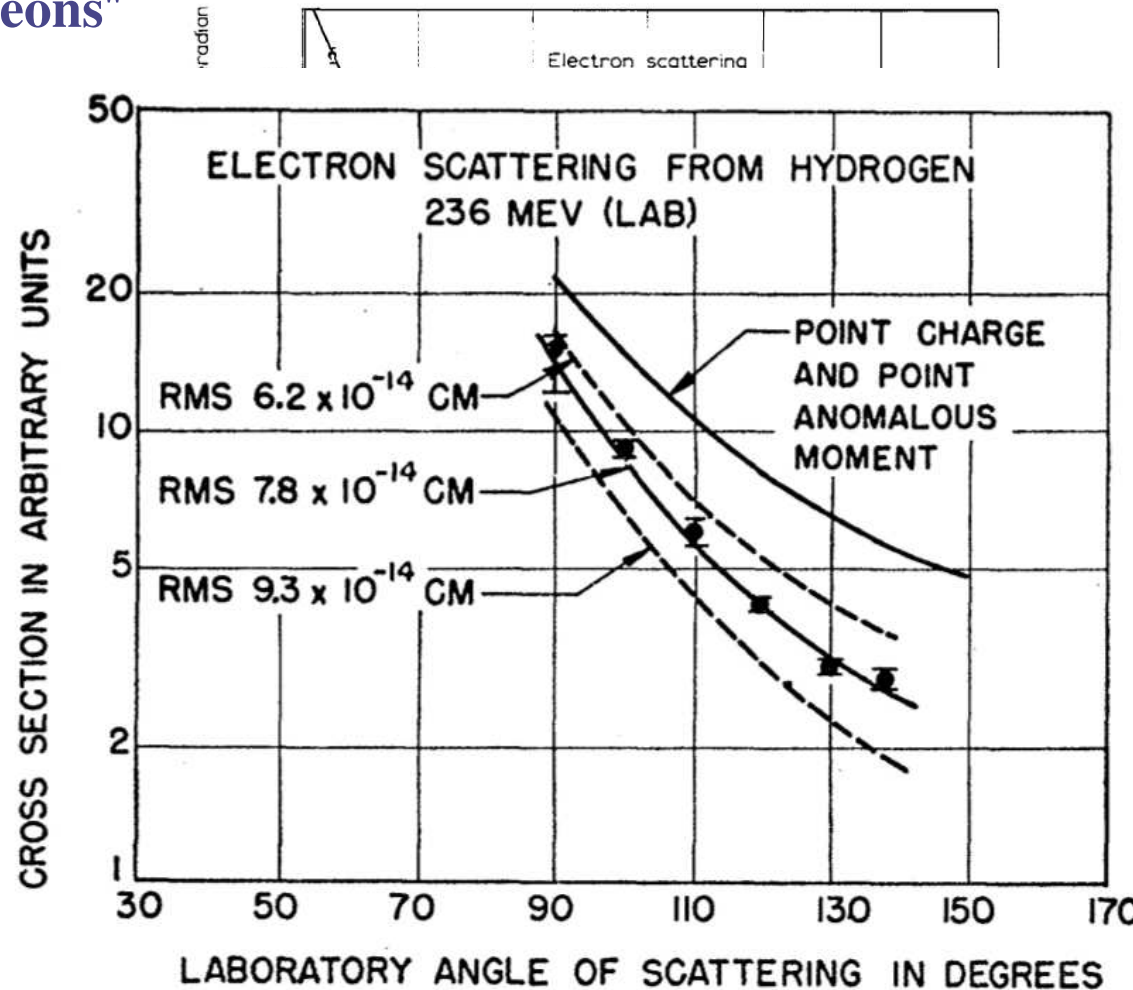
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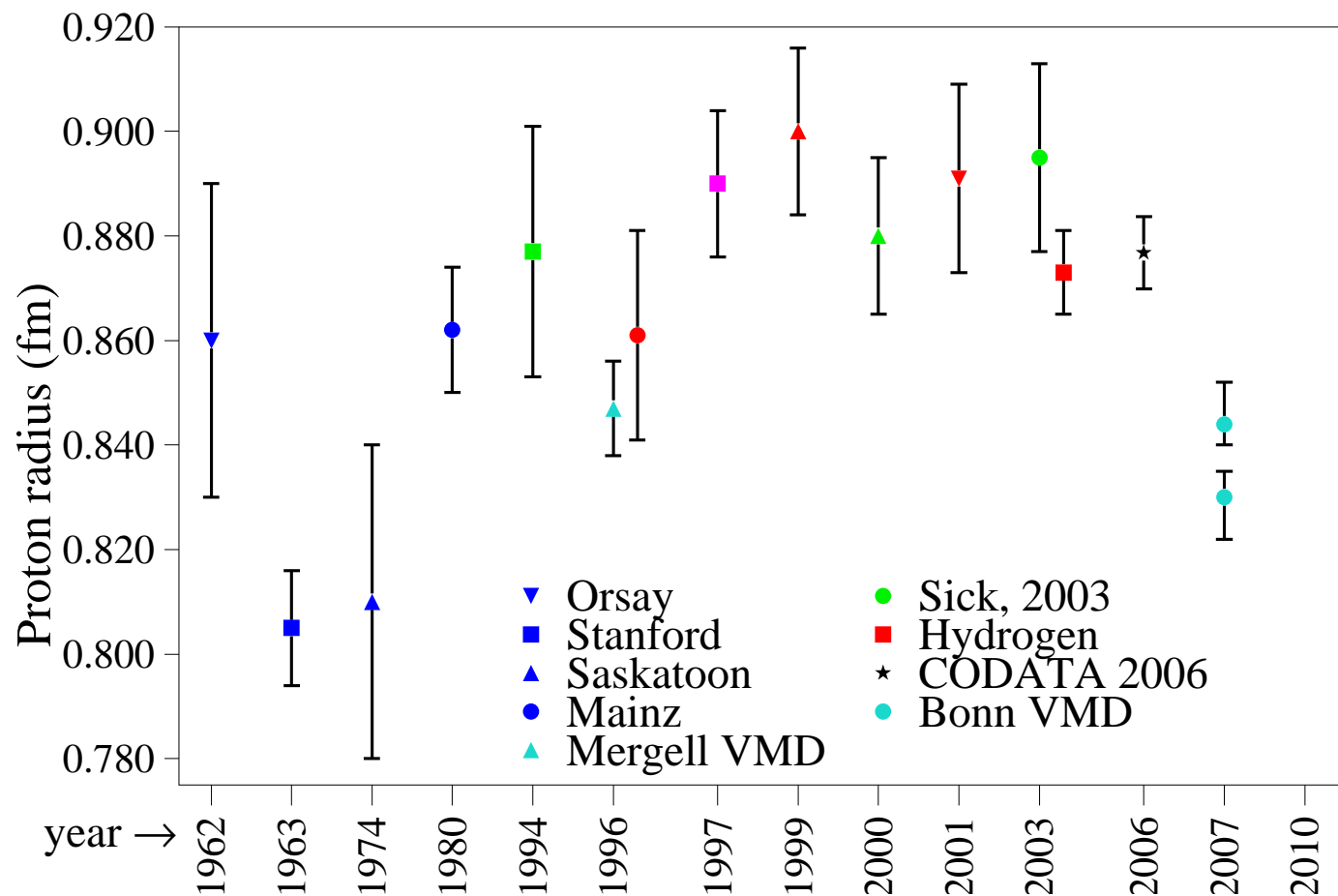
"The best fit lies near
diameter of 0.78×10^{-13} cm"



Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

Proton radius vs. time

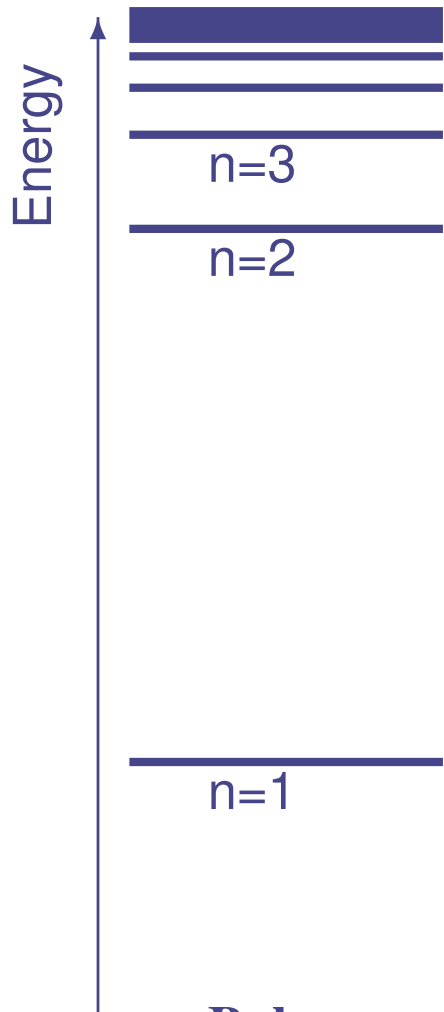
The **proton rms charge radius** over the last 50 years.



- 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 ($u_r = 0.9\%$)

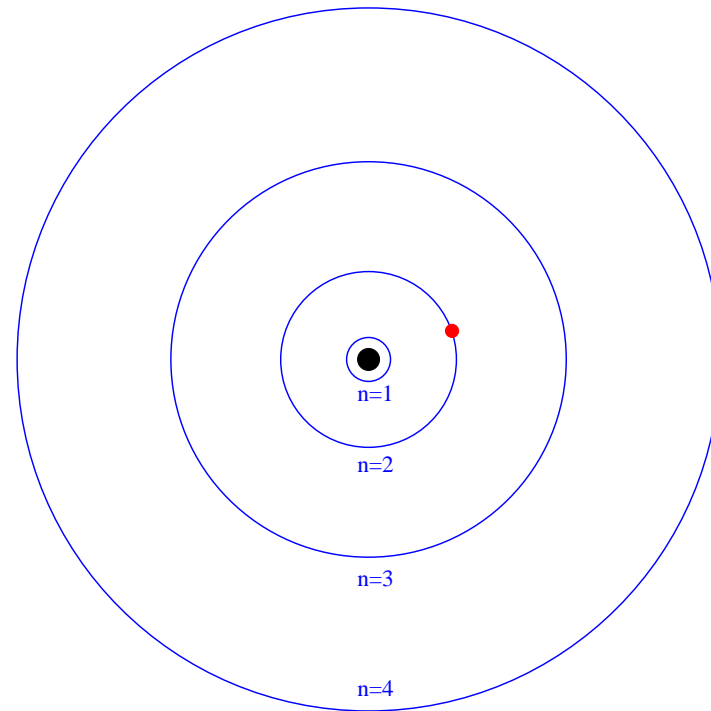


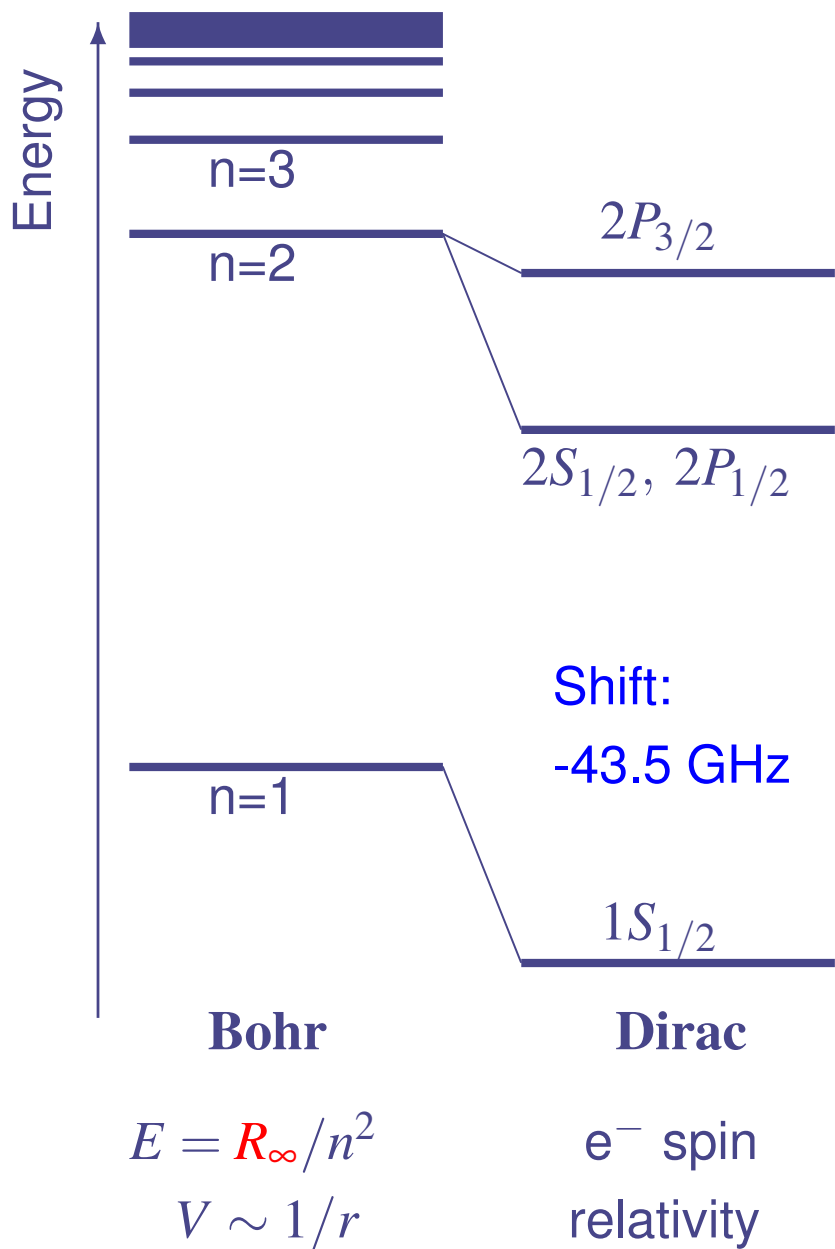
Bohr

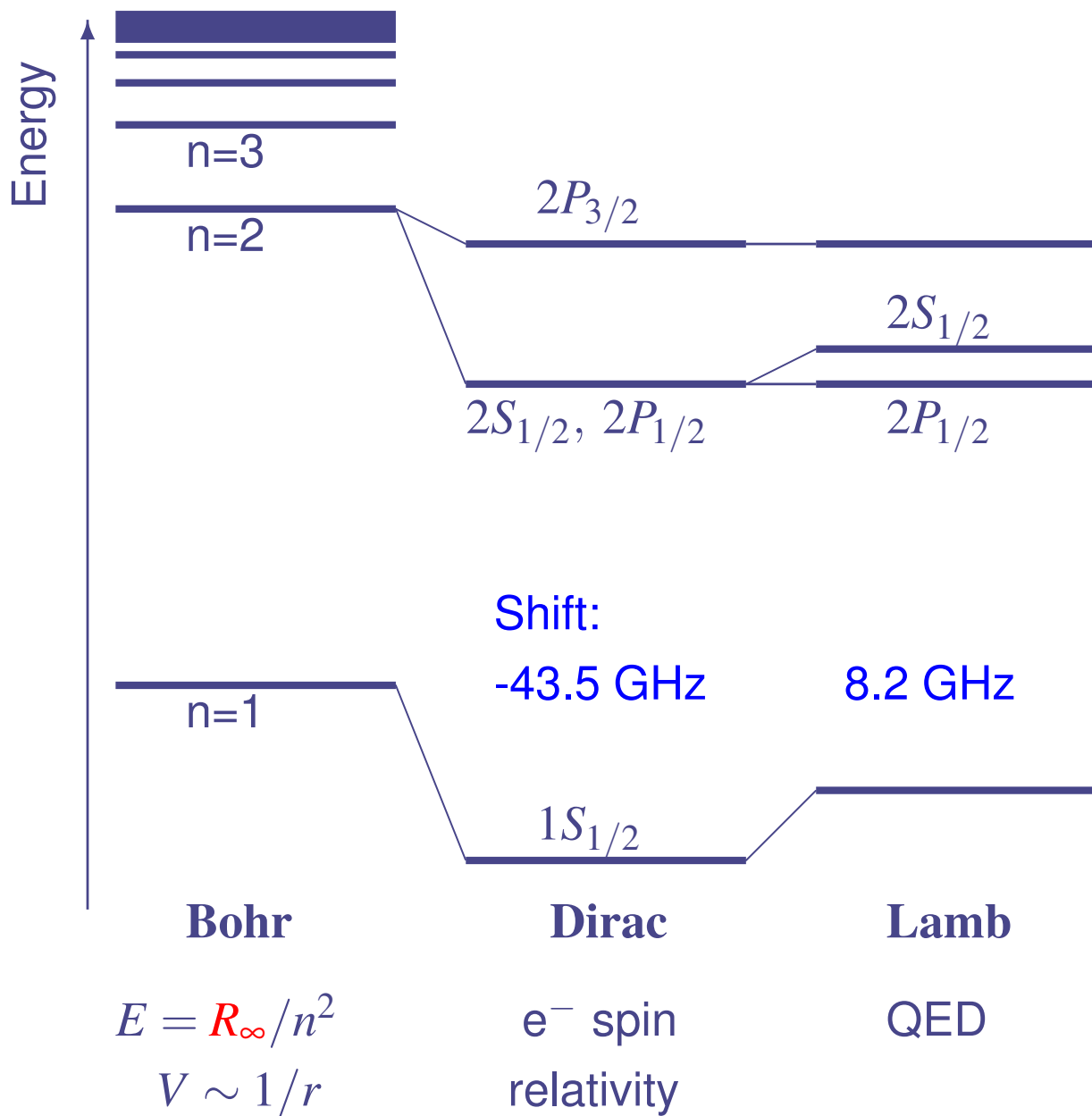
$$E = R_{\infty}/n^2$$

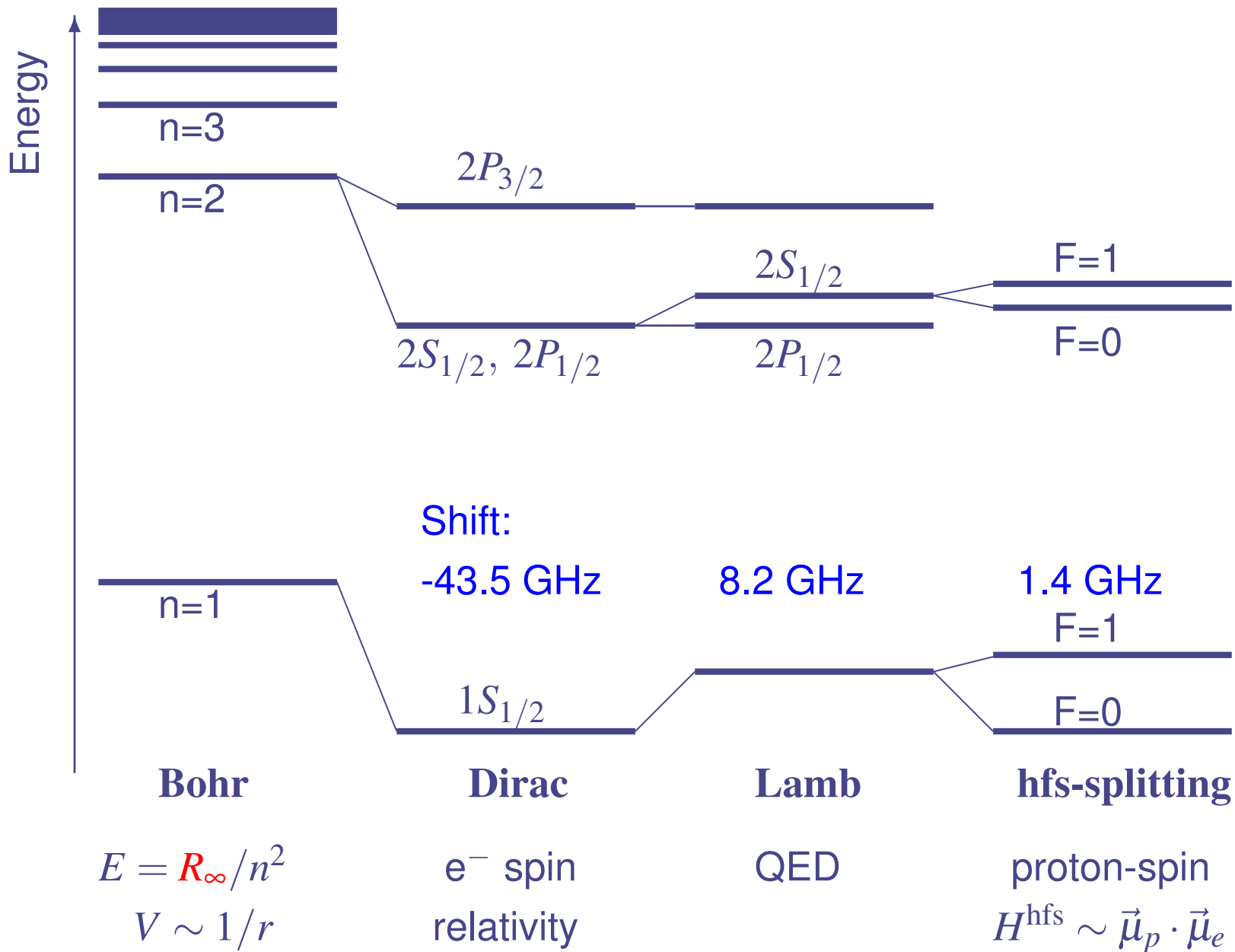
$$V \sim 1/r$$

Bohr model of the hydrogen atom

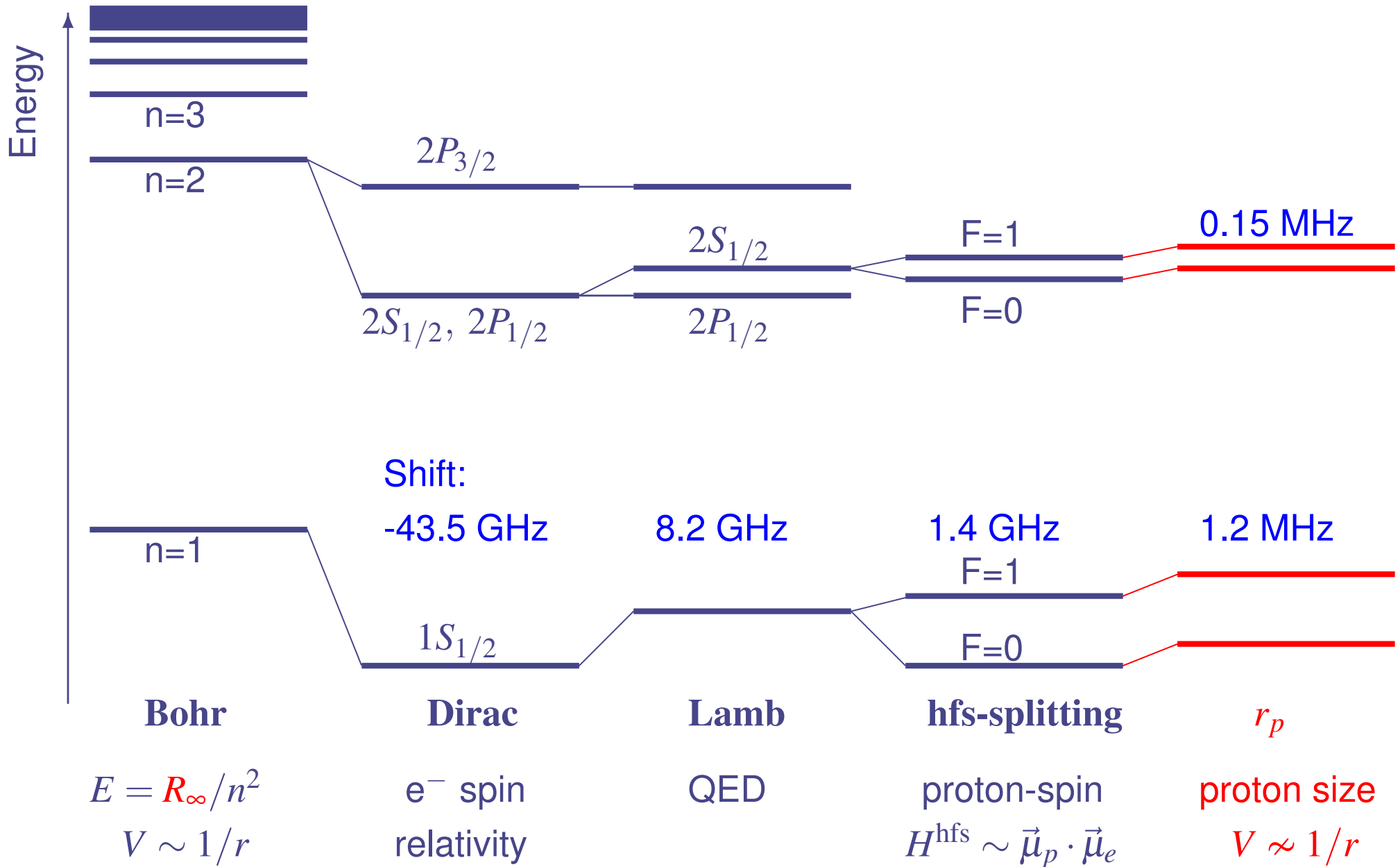






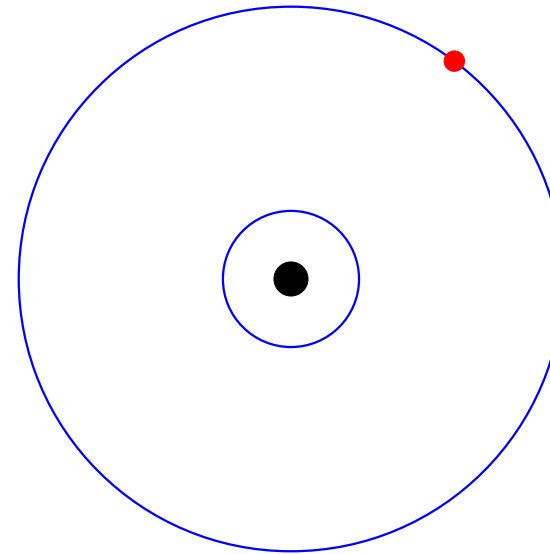


Hydrogen



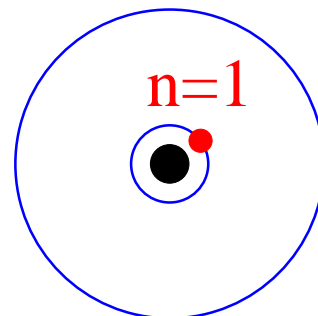
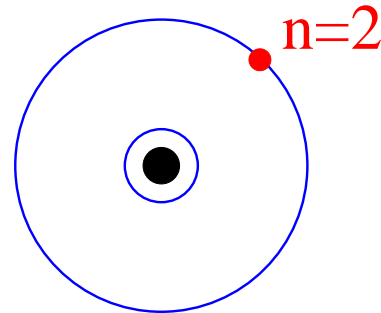
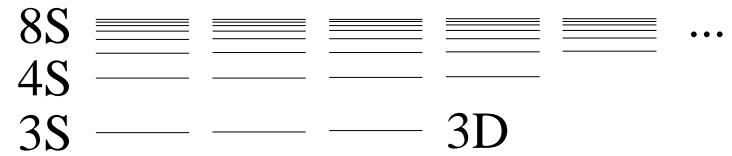
Bohr model of the atom

- Electrons orbit the nucleus
“Planetary system”
- Hydrogen: 1 electron + 1 proton



Spectrum of atomic hydrogen

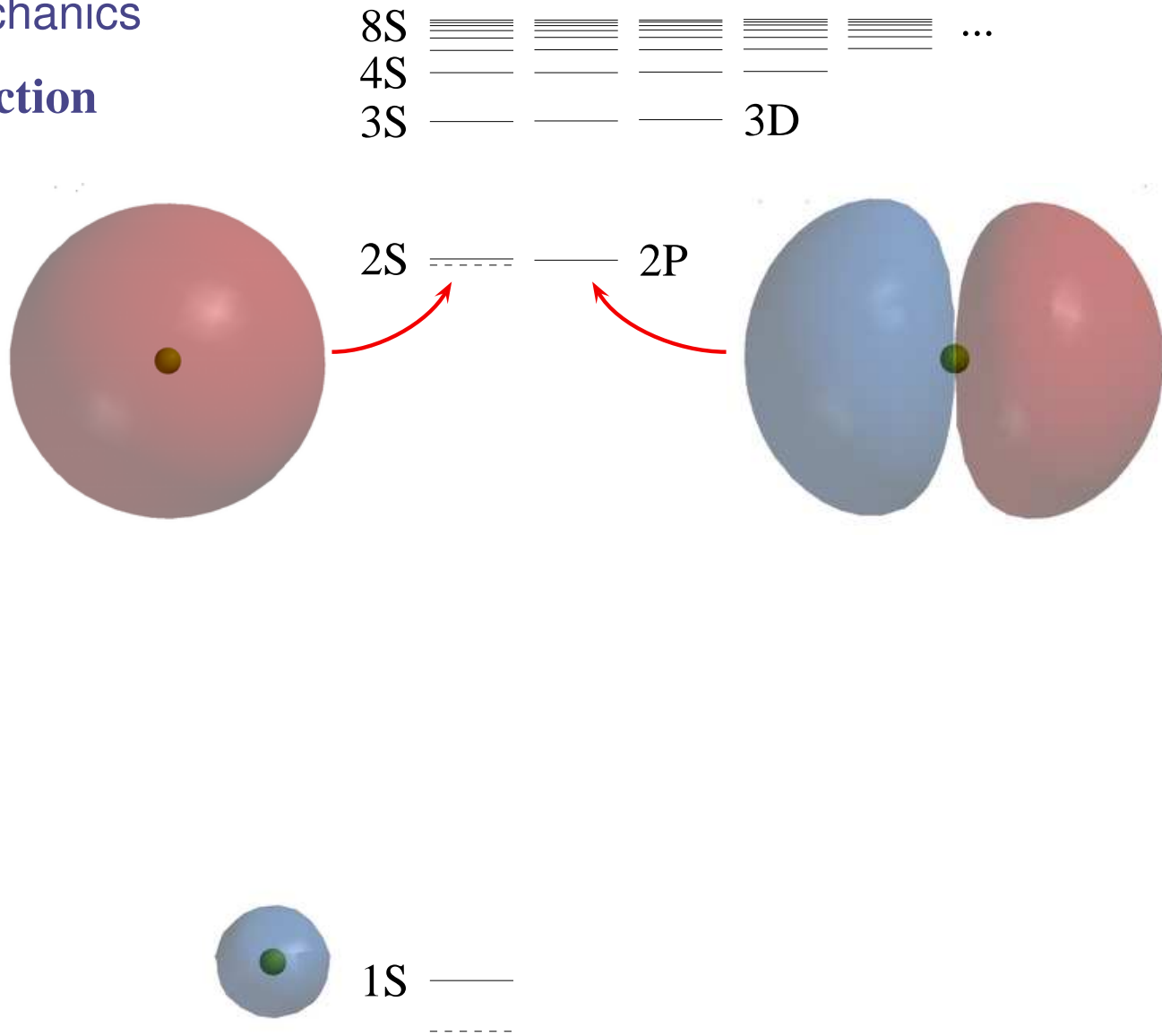
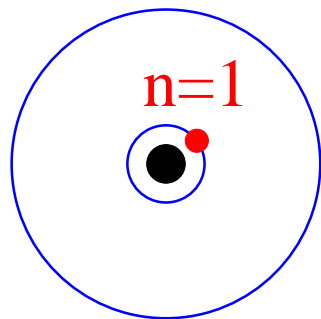
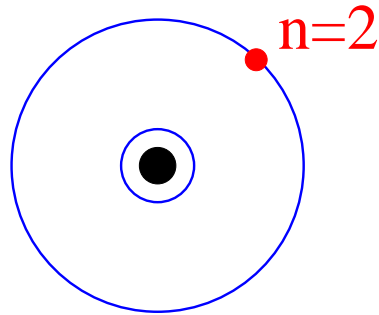
Bohr model \rightarrow quantum mechanics



Atomic physics

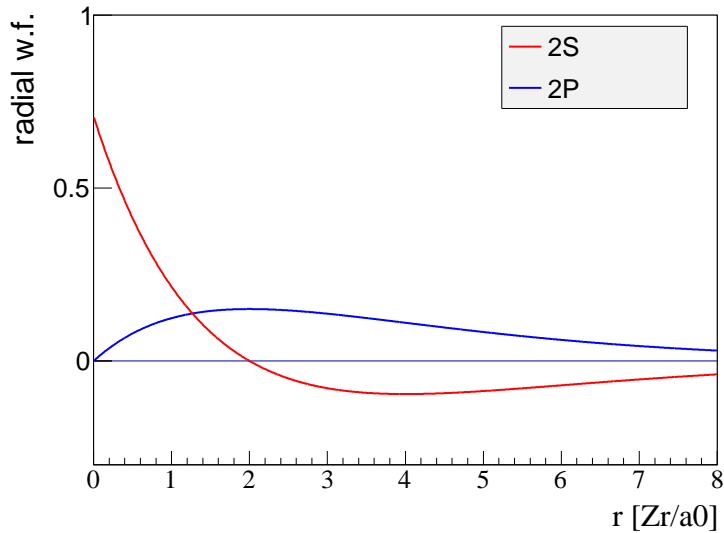
Bohr model → quantum mechanics

planetary orbits → **wave function**



Orbital pictures from Wikipedia

Wave functions of S and P states:



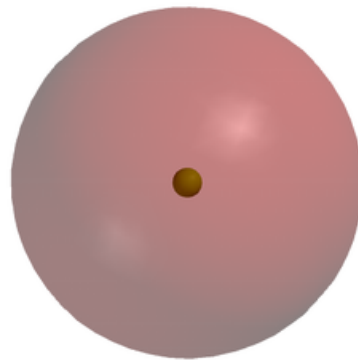
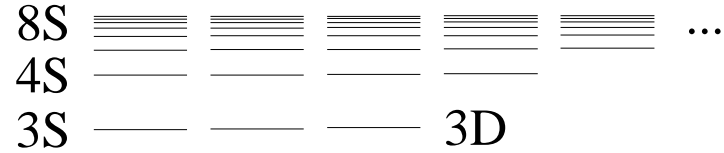
S states: max. at $r=0$

Electron sometimes **inside** the proton.

S states are shifted.

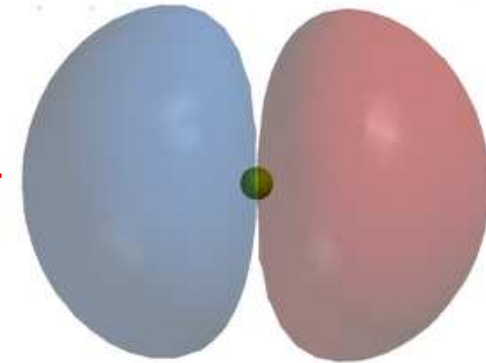
Shift is proportional to the

size of the proton



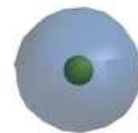
2S

2P



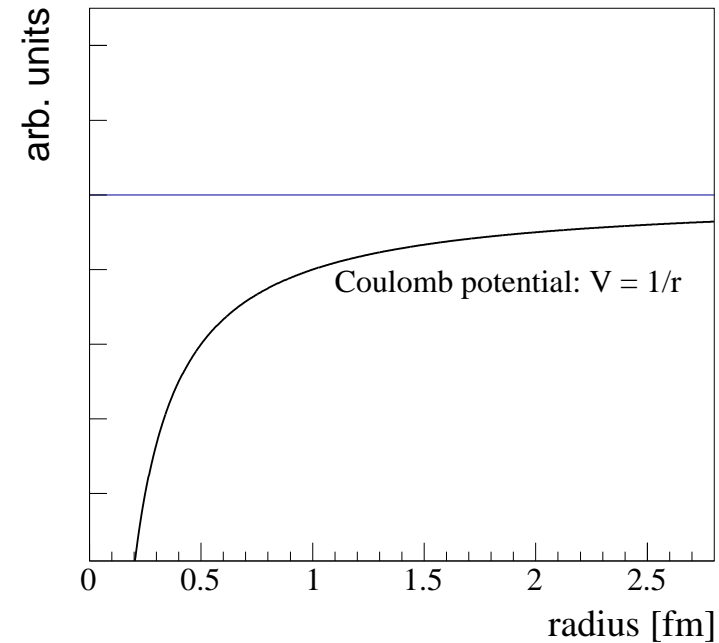
P states: zero at $r=0$

Electron is **not** inside the proton.



1S

Orbital pictures from Wikipedia



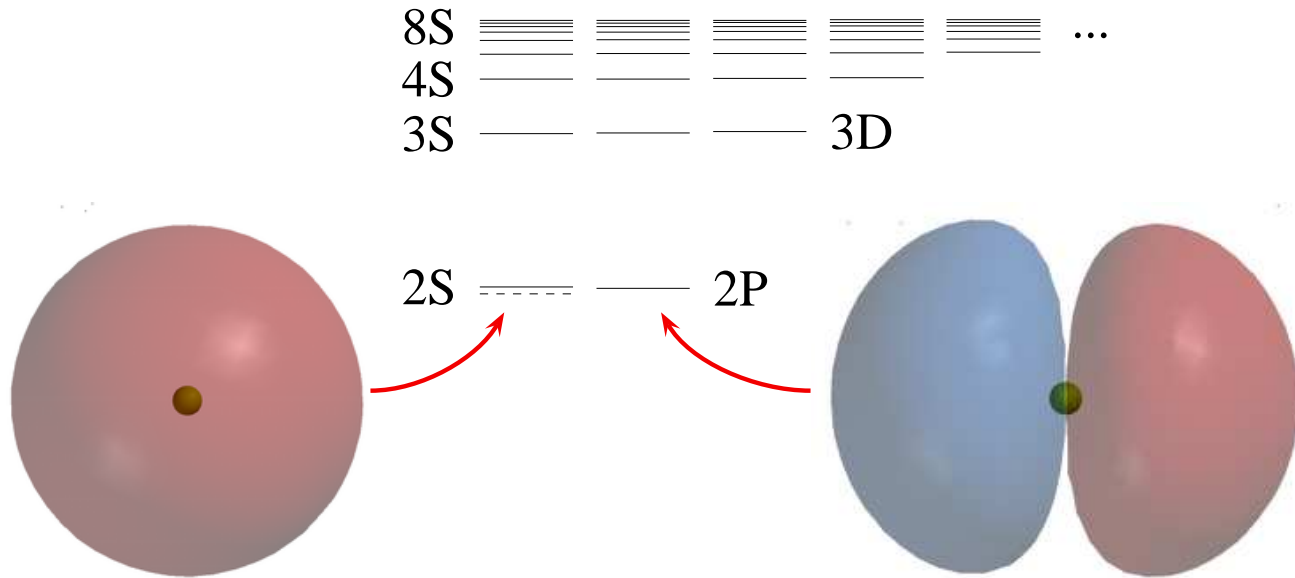
S states: max. at $r=0$

Electron sometimes **inside** the proton.

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Shift is proportional to the

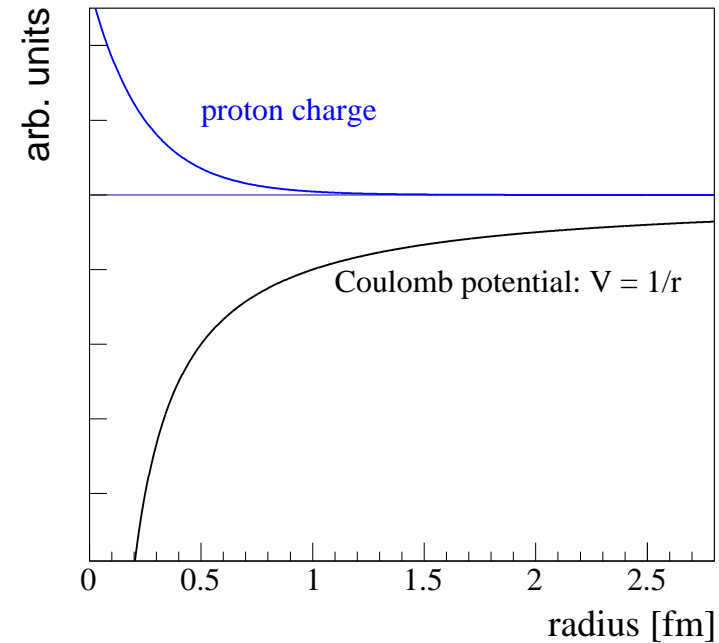
size of the proton



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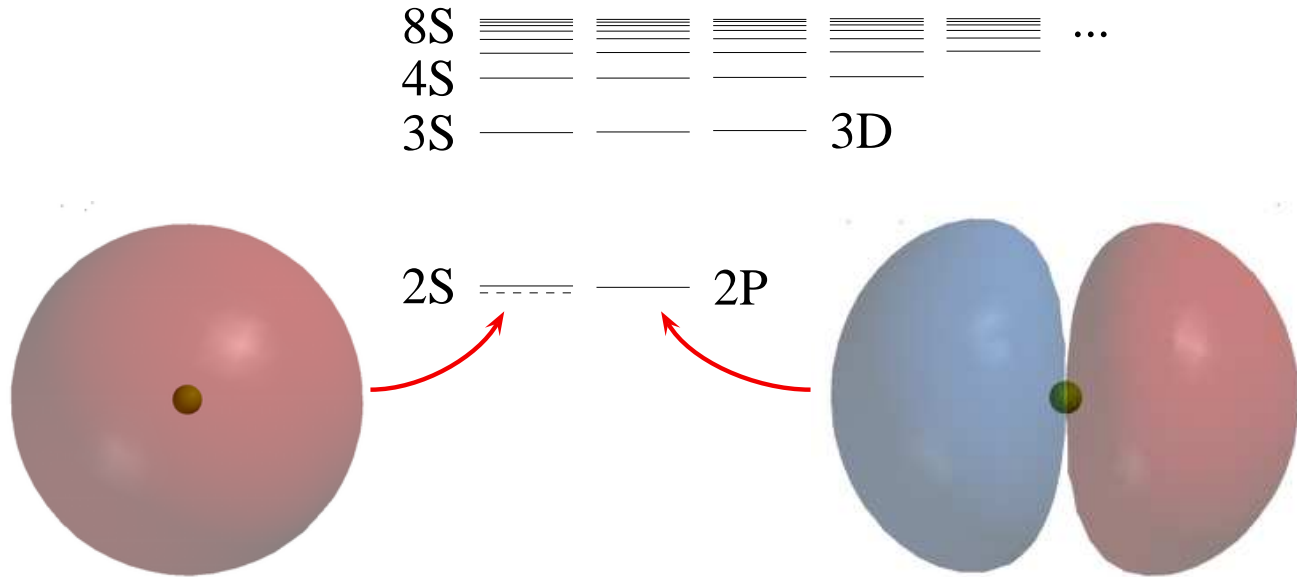
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Electron sometimes **inside** the proton.

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Shift is proportional to the

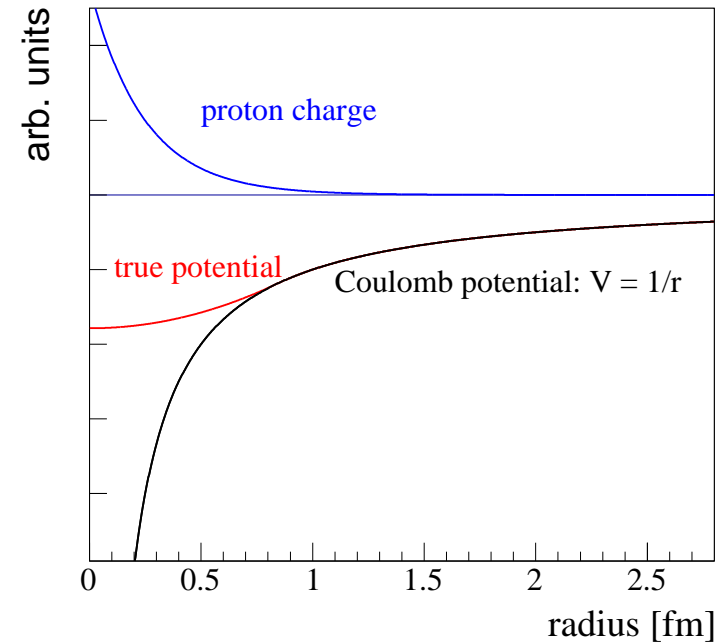
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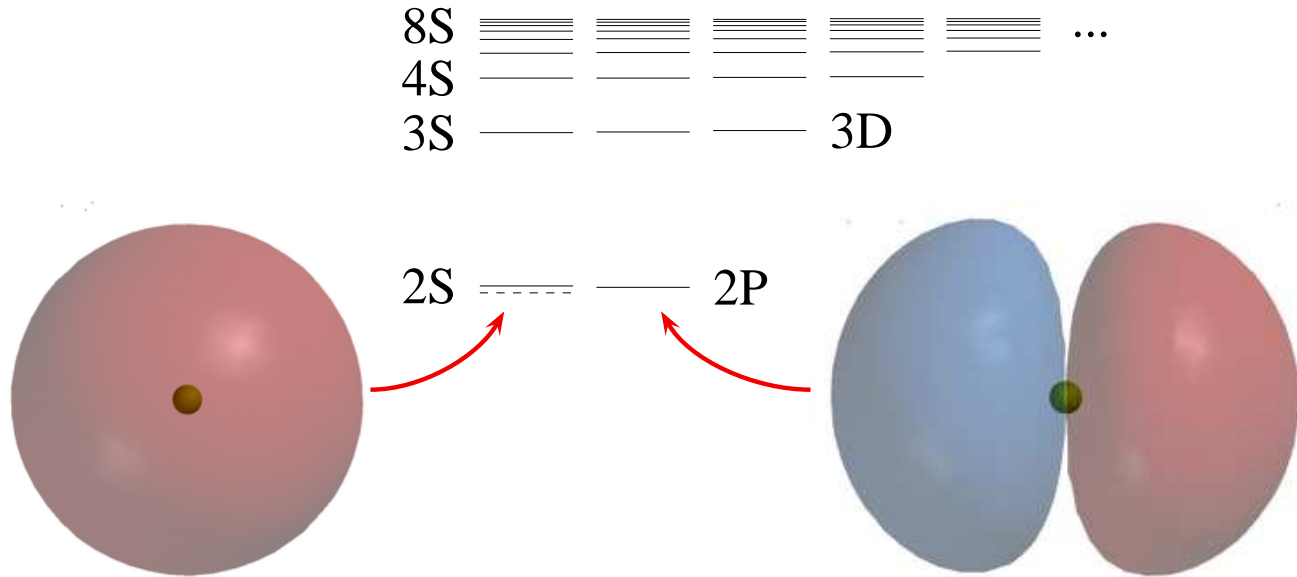
S states: max. at $r=0$

Electron sometimes **inside** the proton.

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Shift is proportional to the

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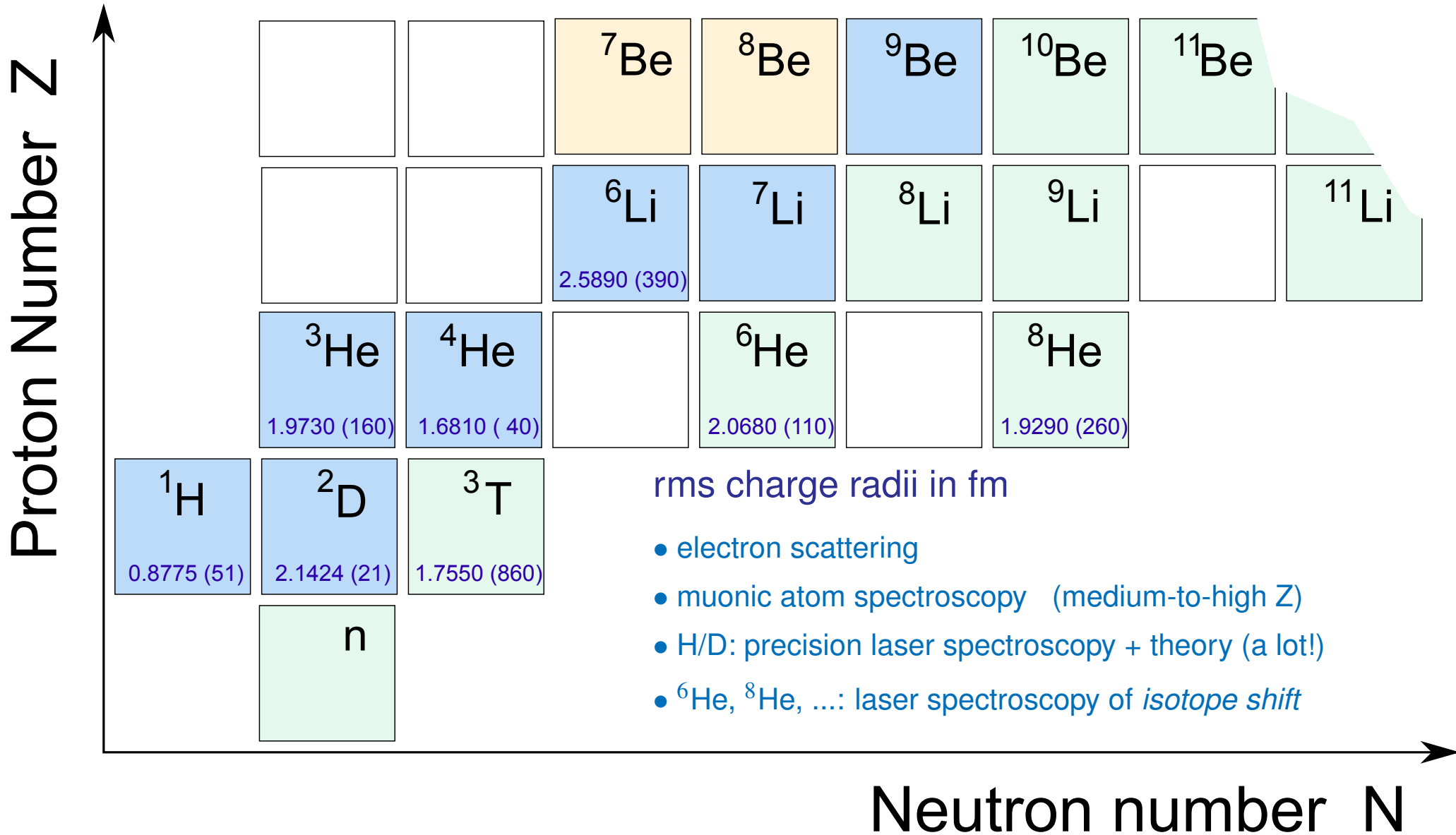


P states: zero at $r=0$

Electron is **not** inside the proton.



Charge radii of light nuclei



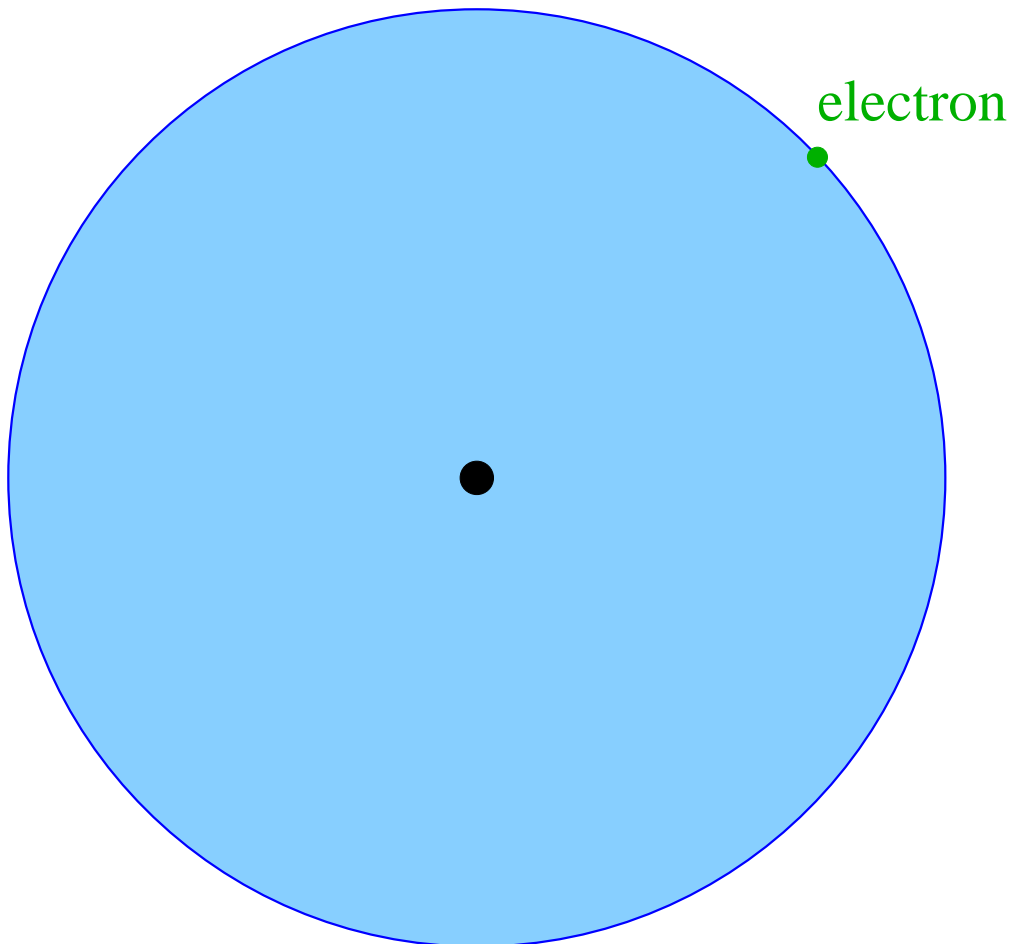
Muonic hydrogen

Regular hydrogen:

electron e^- + proton p

Muonic hydrogen:

muon μ^- + proton p



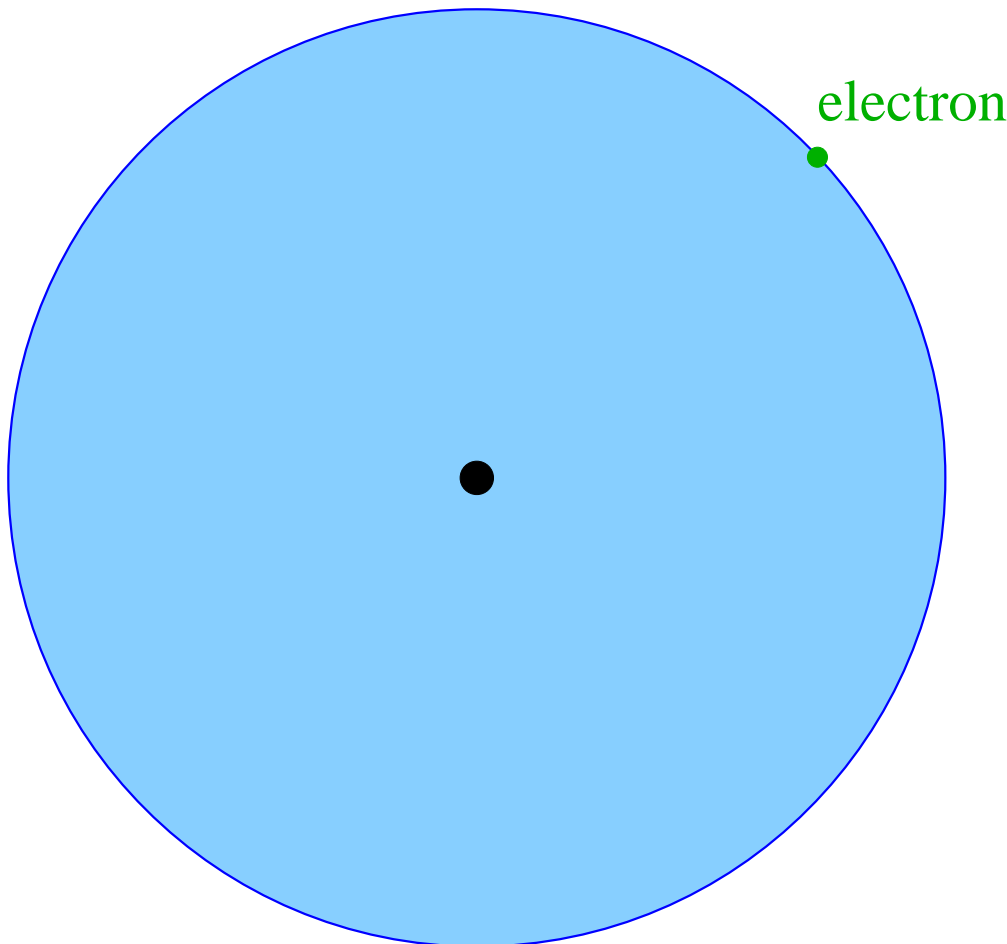
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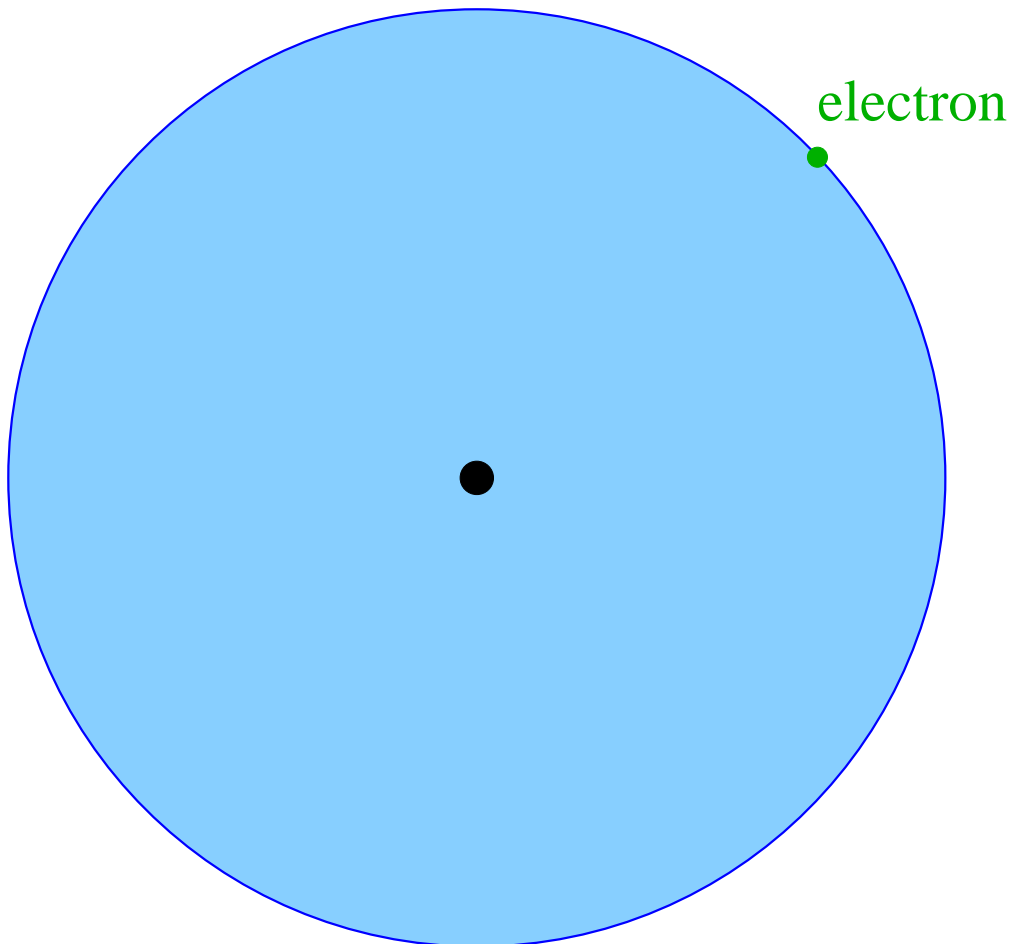


	mass → ≈2.3 MeV/c ² charge → 2/3 spin → 1/2	mass → ≈1.275 GeV/c ² charge → 2/3 spin → 1/2	mass → ≈173.07 GeV/c ² charge → 2/3 spin → 1/2	0 0 1	mass → ≈126 GeV/c ² 0 0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	mass → ≈4.8 MeV/c ² charge → -1/3 spin → 1/2	mass → ≈95 MeV/c ² charge → -1/3 spin → 1/2	mass → ≈4.18 GeV/c ² charge → -1/3 spin → 1/2	0 0 1	0 0 1
	d down	s strange	b bottom	γ photon	
	mass → 0.511 MeV/c ² charge → -1 spin → 1/2	mass → 105.7 MeV/c ² charge → -1 spin → 1/2	mass → 1.777 GeV/c ² charge → -1 spin → 1/2	0 0 1	mass → 81.2 GeV/c ² 0 1
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	mass → <2.2 eV/c ² charge → 0 spin → 1/2	mass → <0.17 MeV/c ² charge → 0 spin → 1/2	mass → <15.5 MeV/c ² charge → 0 spin → 1/2	±1 1	mass → 80.4 GeV/c ² ±1 1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	

from Wikipedia

Regular hydrogen:

electron e^- + proton p



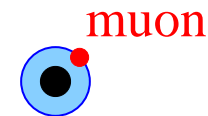
Muonic hydrogen:

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]:

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

Proton size effect is 2% of the μp Lamb shift

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

Experiment:

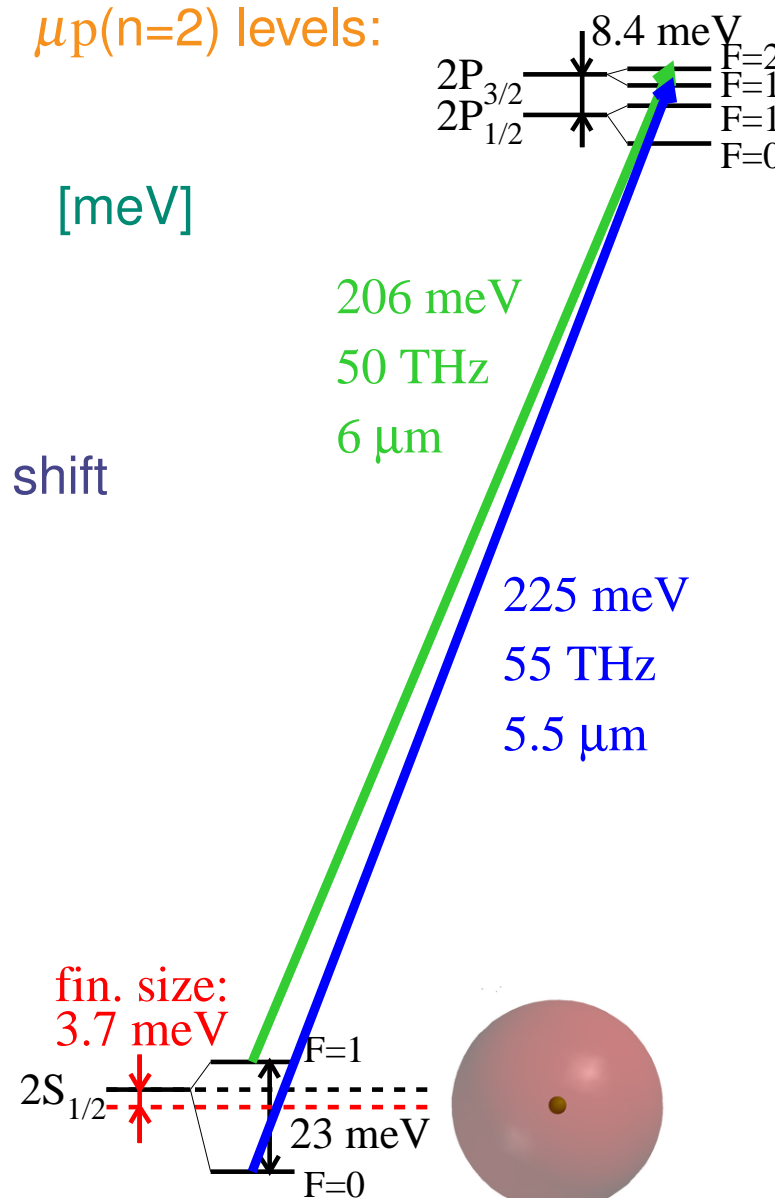
R. Pohl *et al.*, Nature 466, 213 (2010).

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

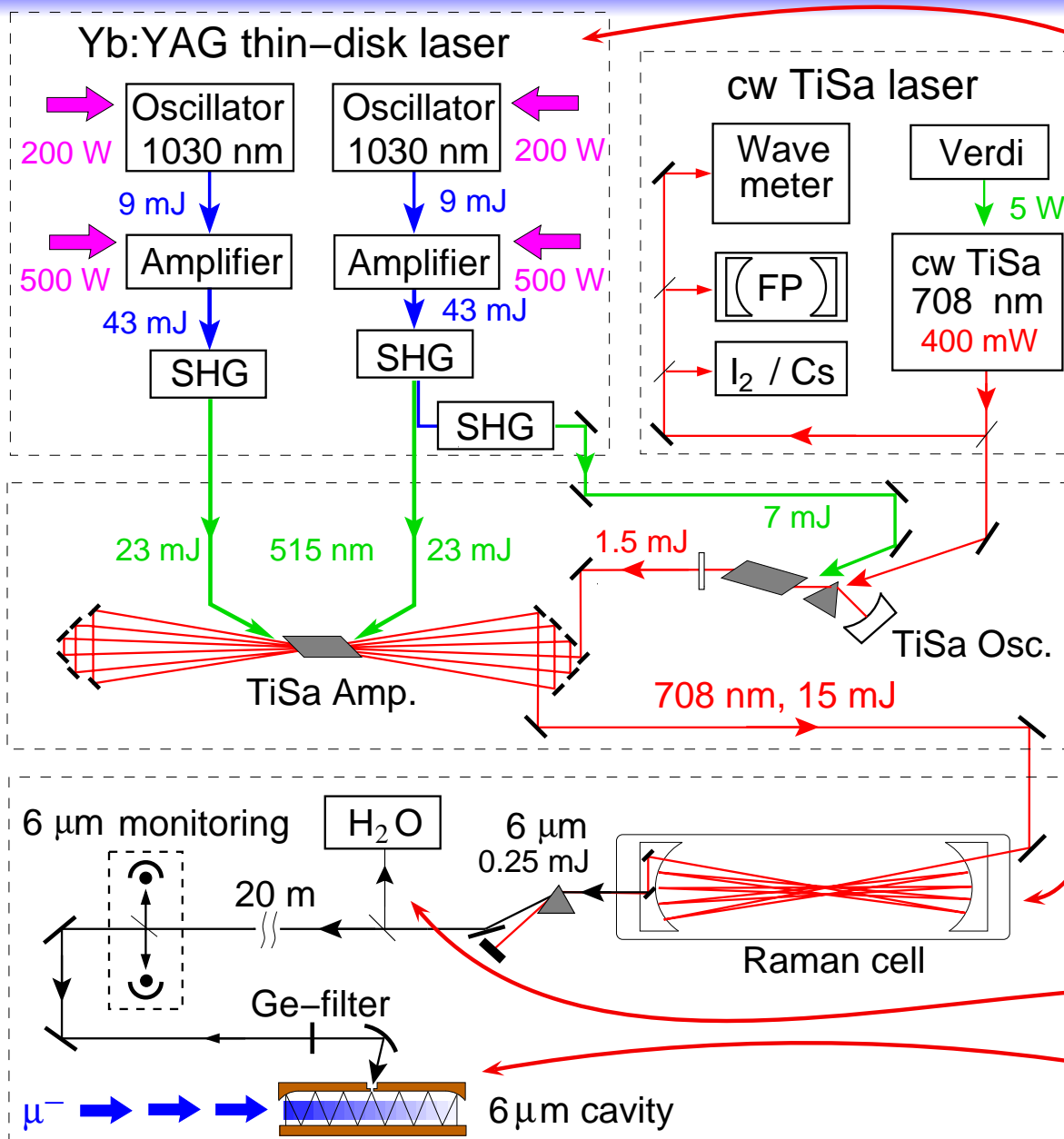
Theory summary:

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

$\mu p(n=2)$ levels:



The laser system

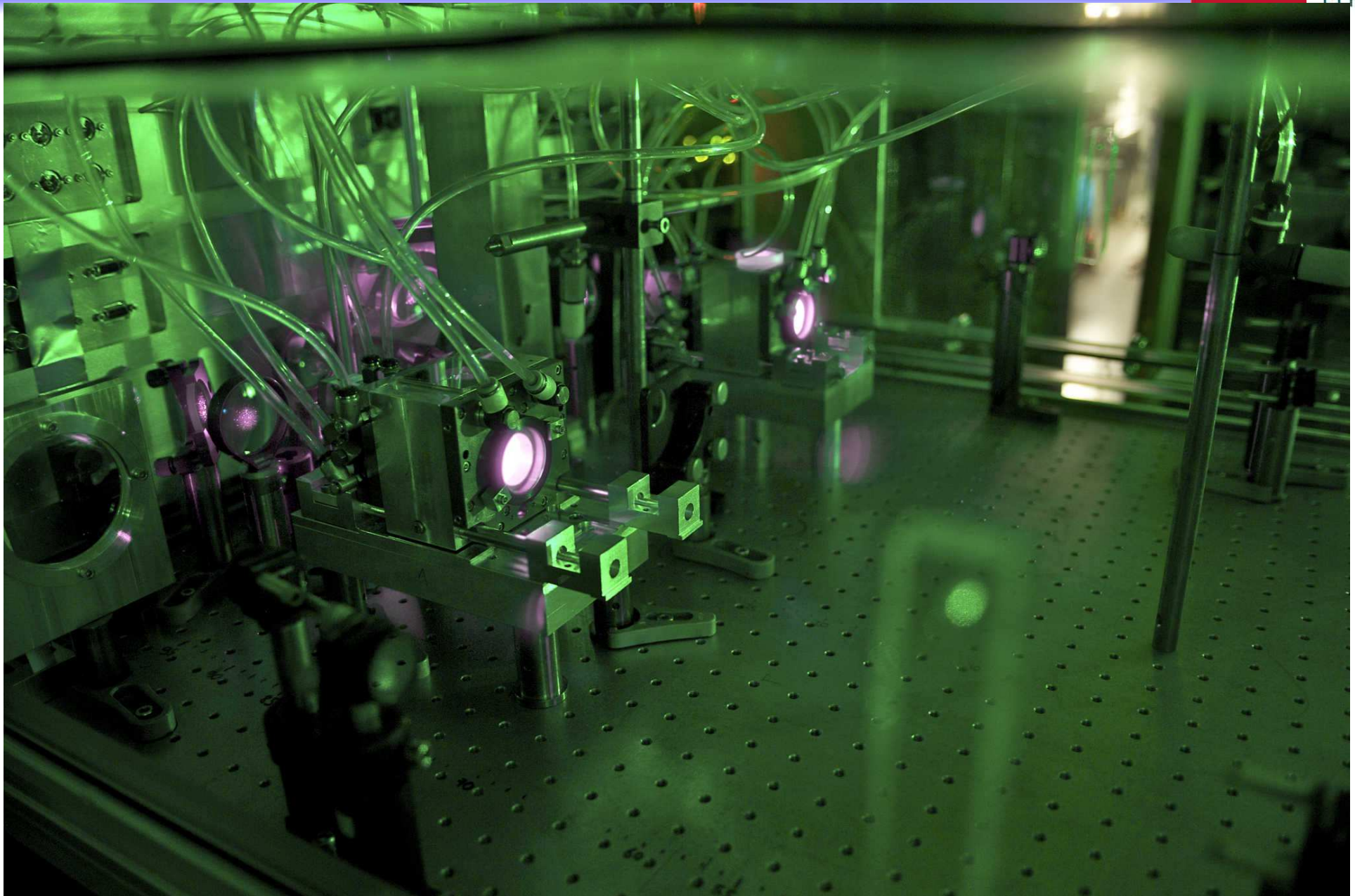


Main components:

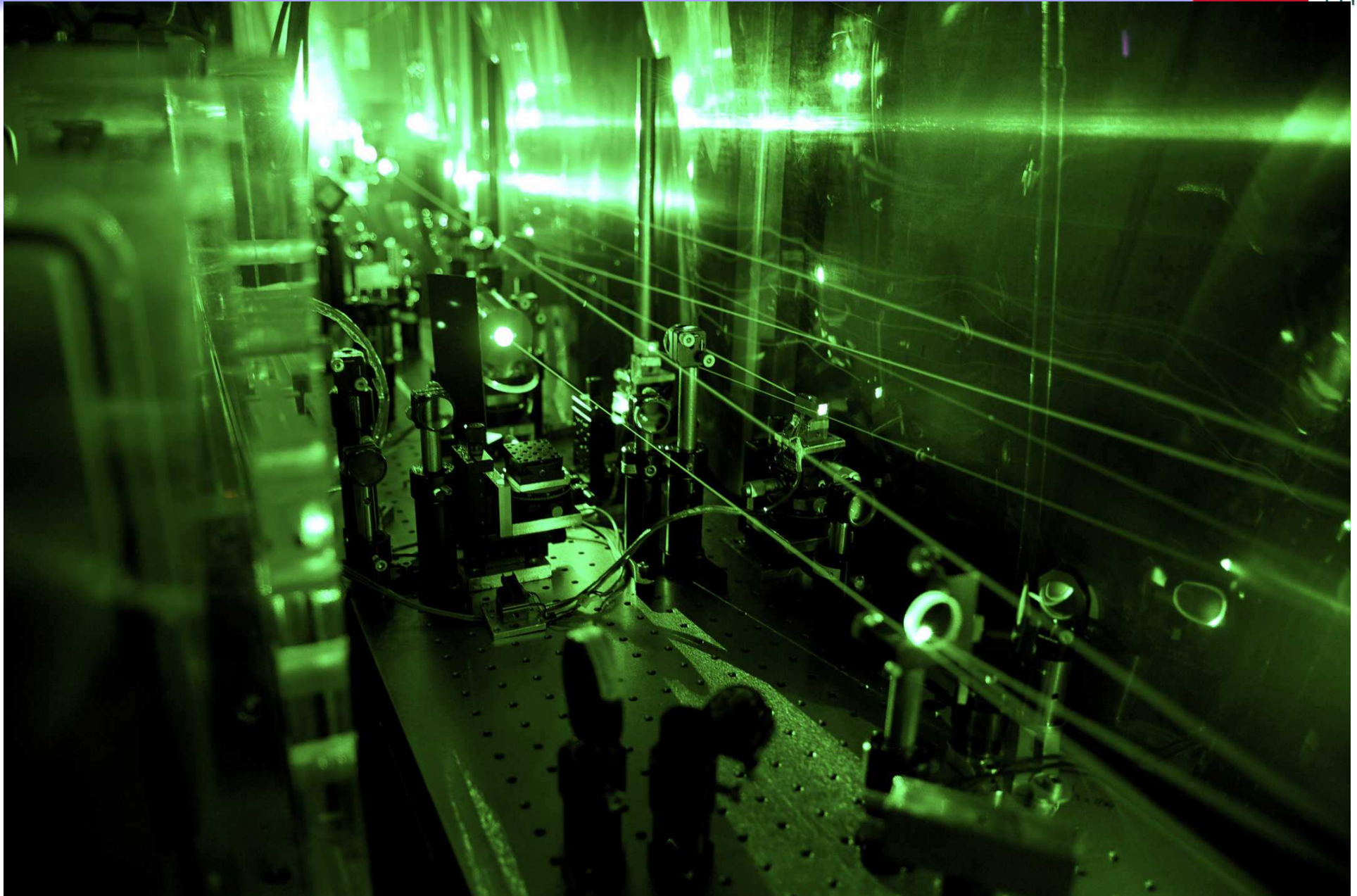
- Thin-disk laser
 - fast response to detected μ^-
- Frequency doubling
- TiSa laser:
 - frequency stabilized cw laser
 - injection seeded oscillator
 - multipass amplifier
- Raman cell
 - 3 Stokes: 708 nm \rightarrow 6 μ m
- λ calibration
 - (1) wavemeter + known Raman shift
 - (2) H₂O spectr. at 6 μ m
- Target cavity

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

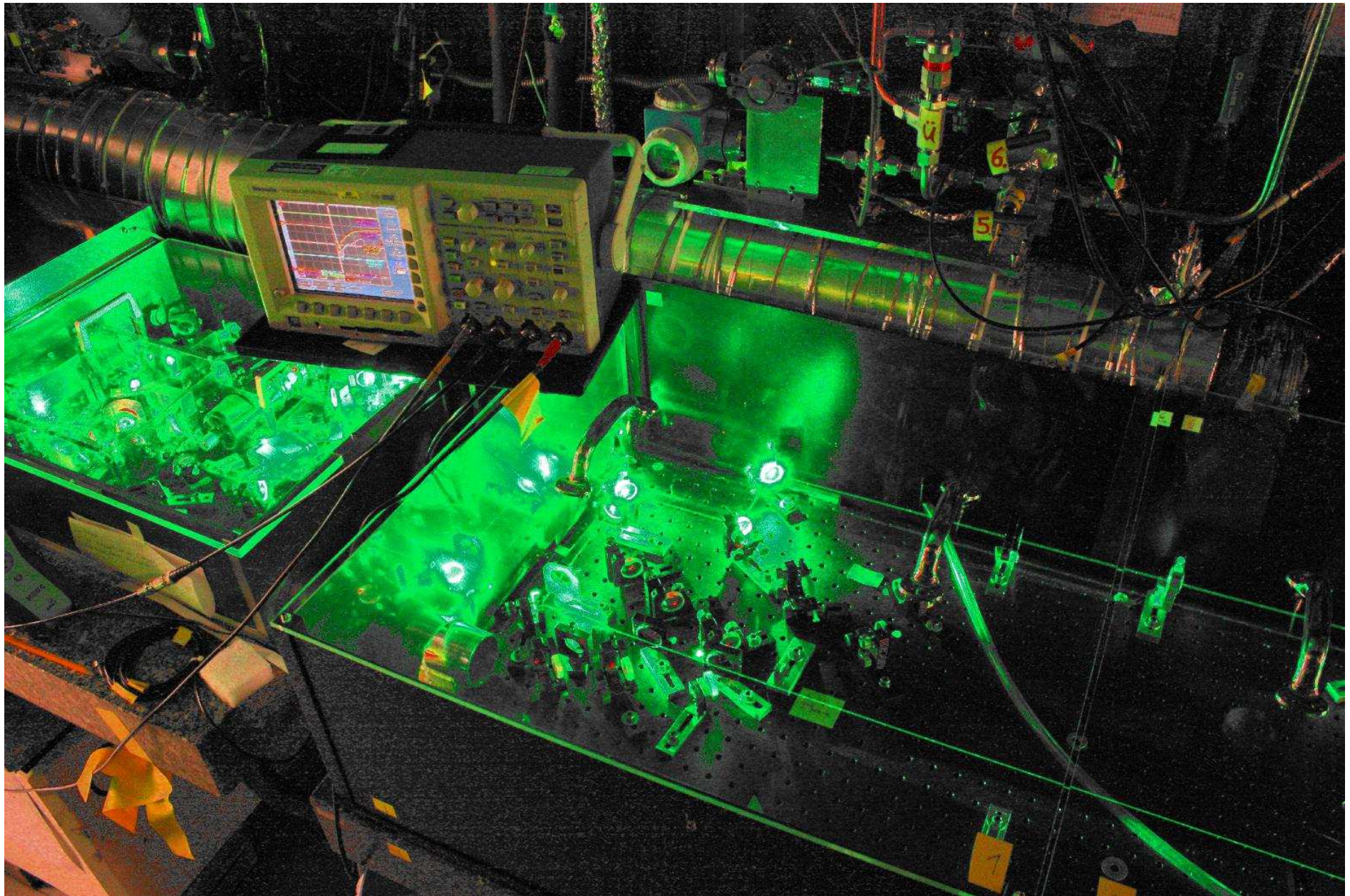
Disk amplifier laser heads



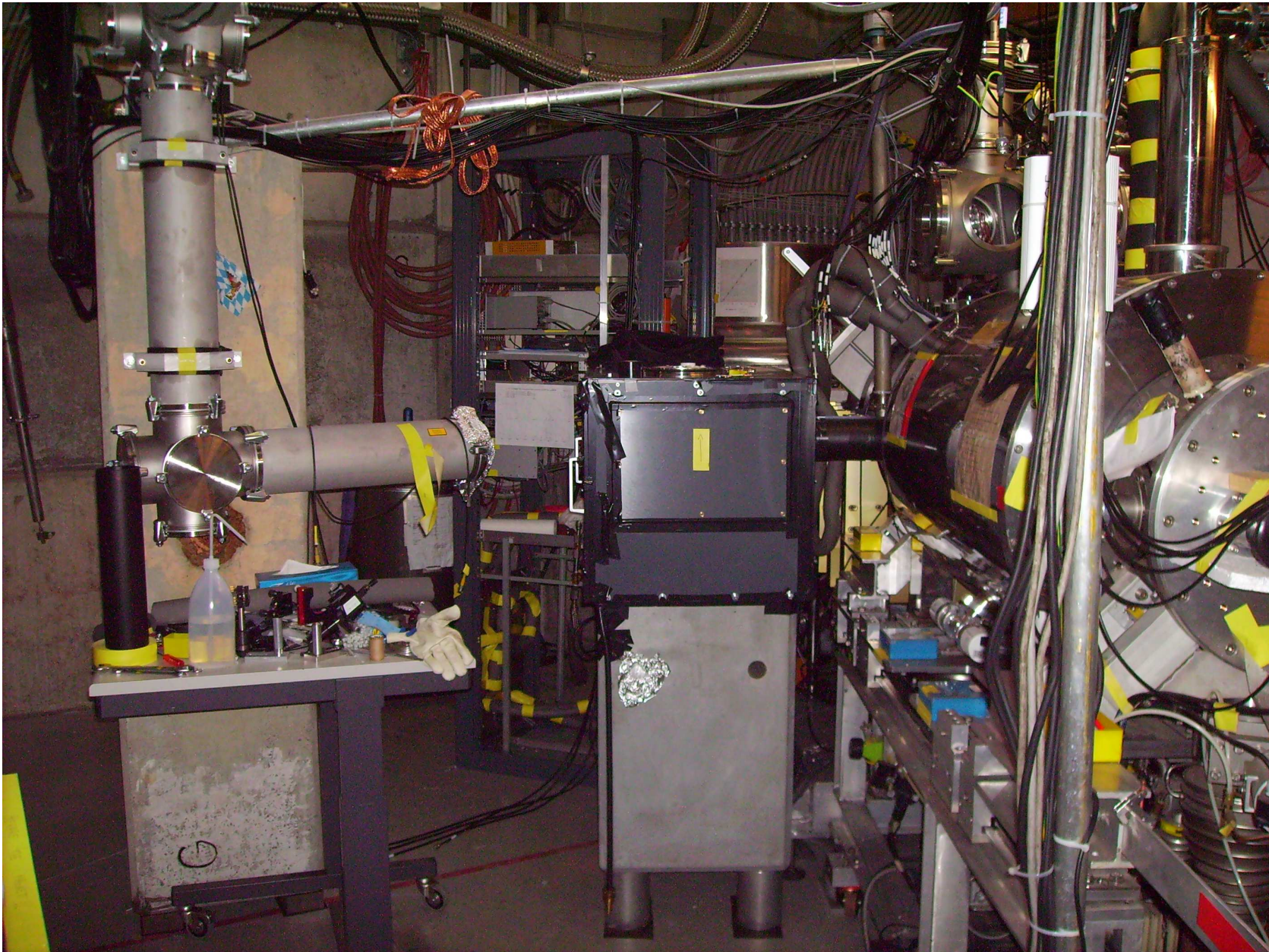
Disk laser doubling stages



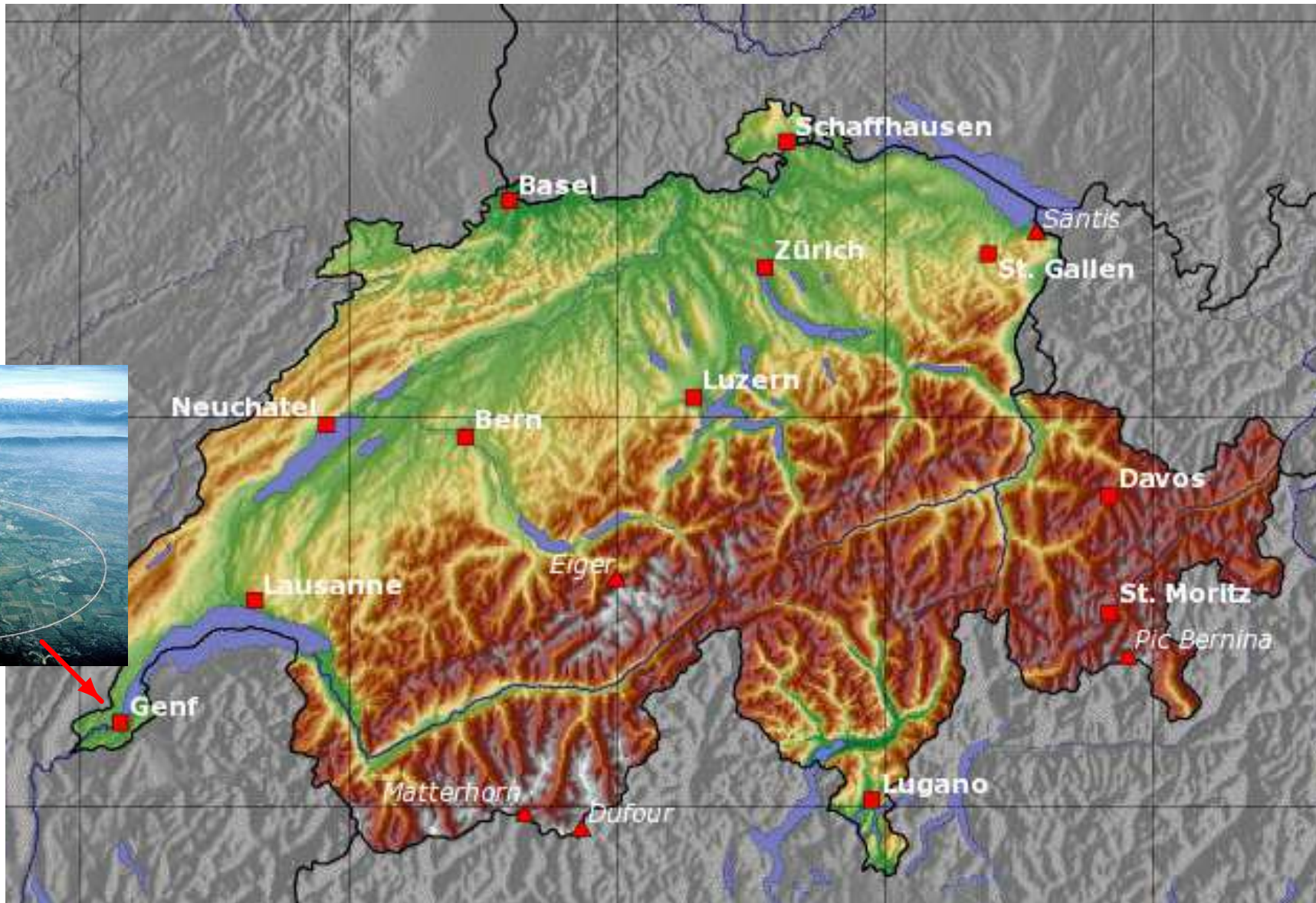
TiSa lasers and Raman cell



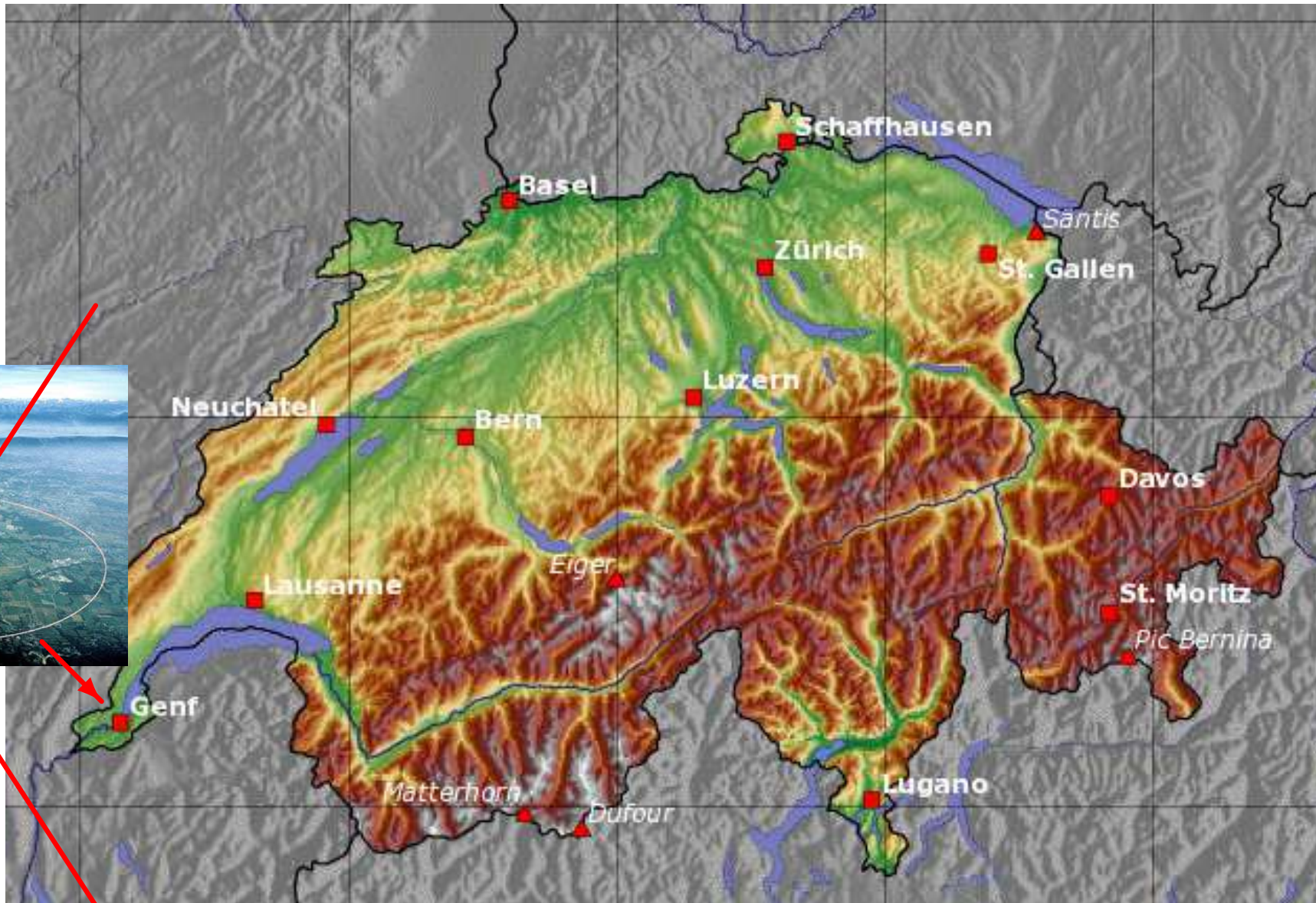
Laser beam tube



Swiss muons



Swiss muons

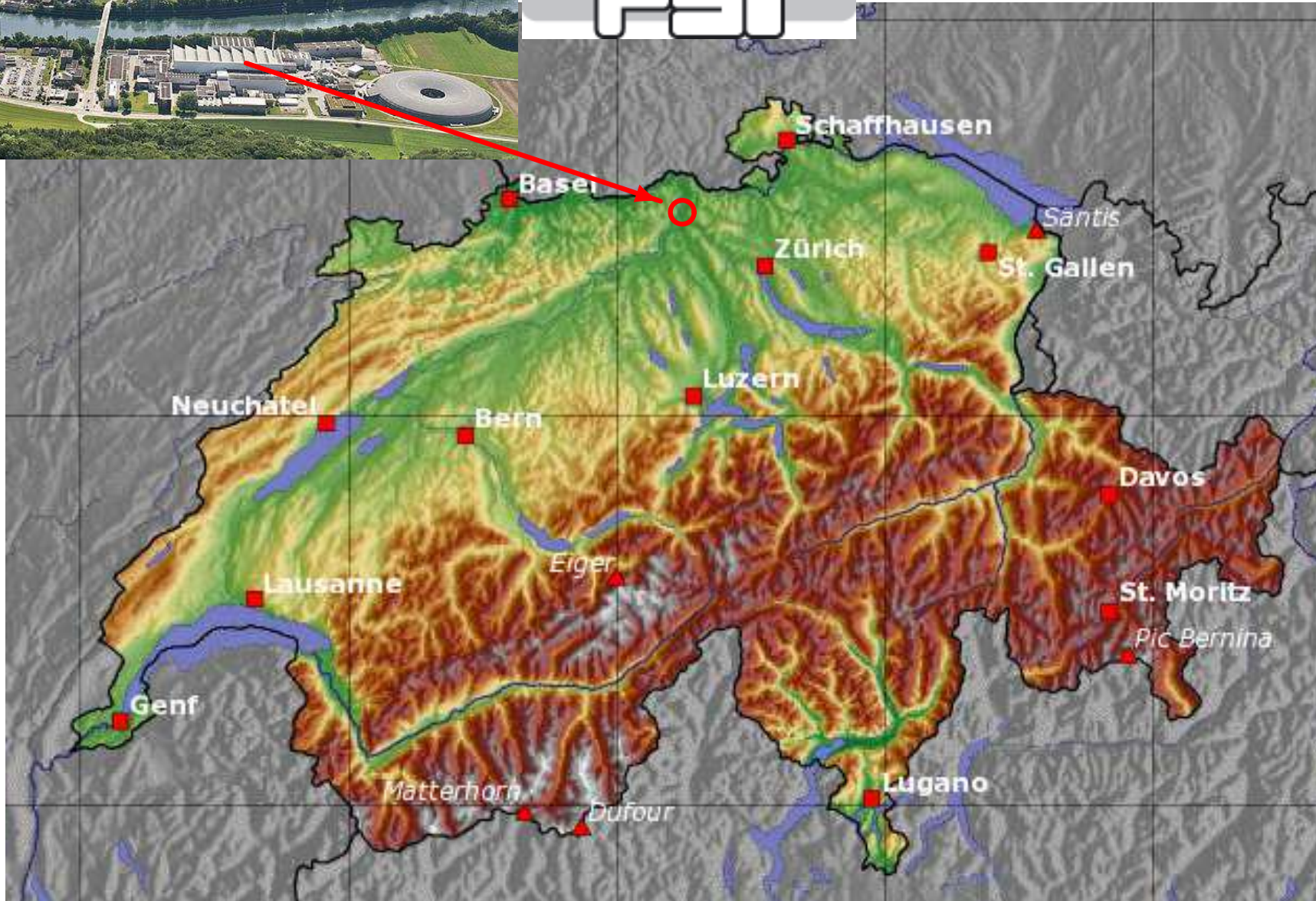


Swiss muons

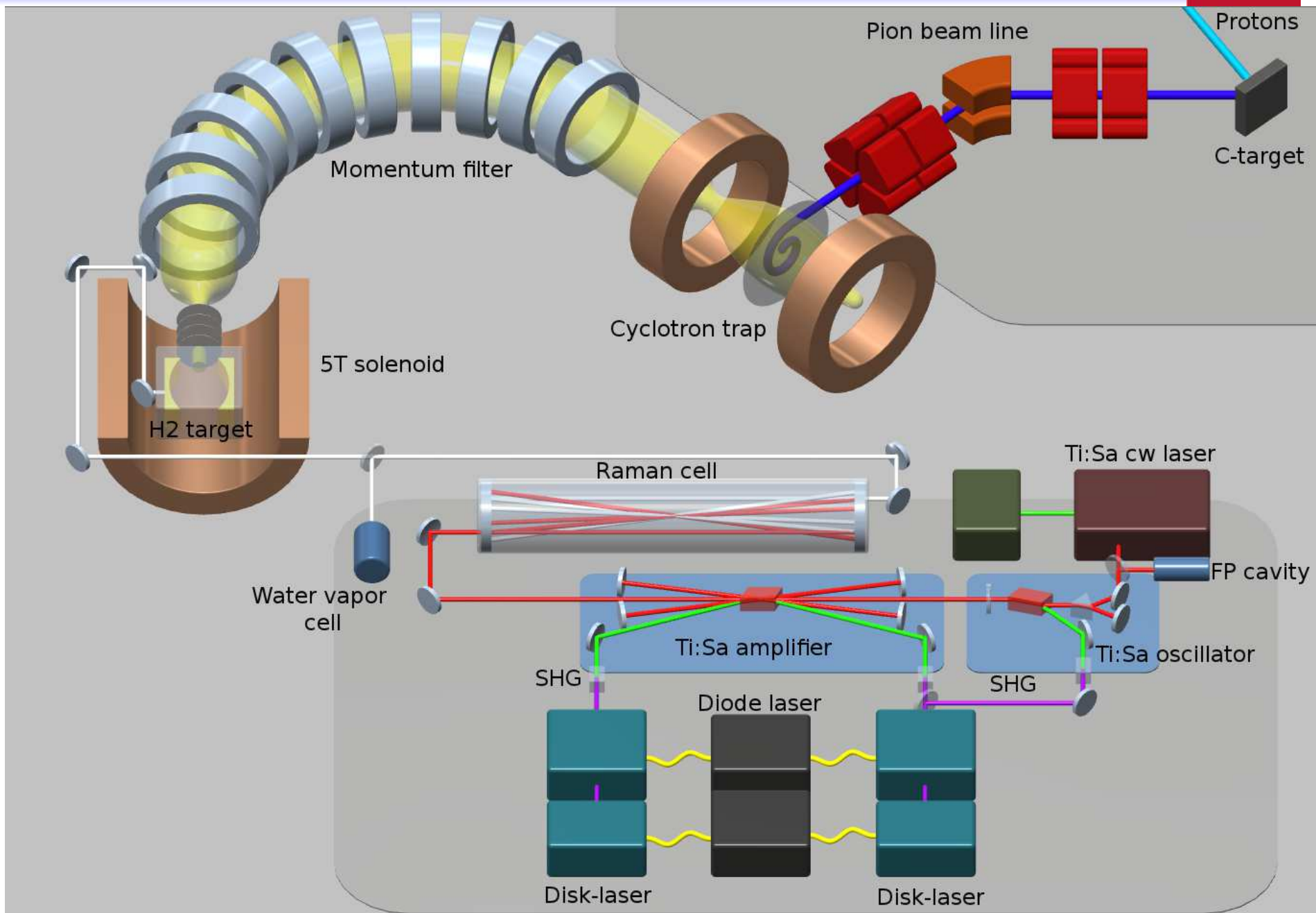


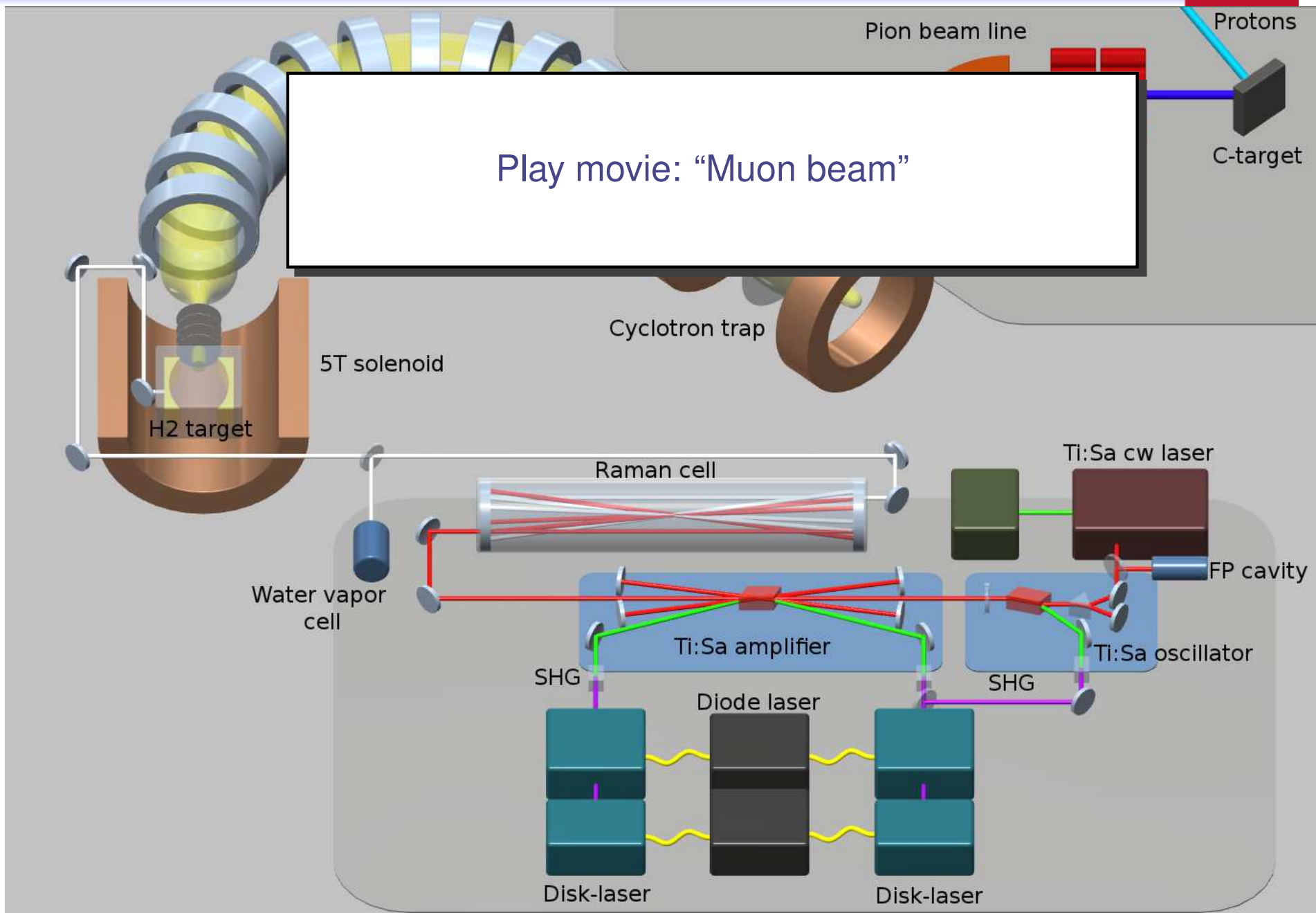
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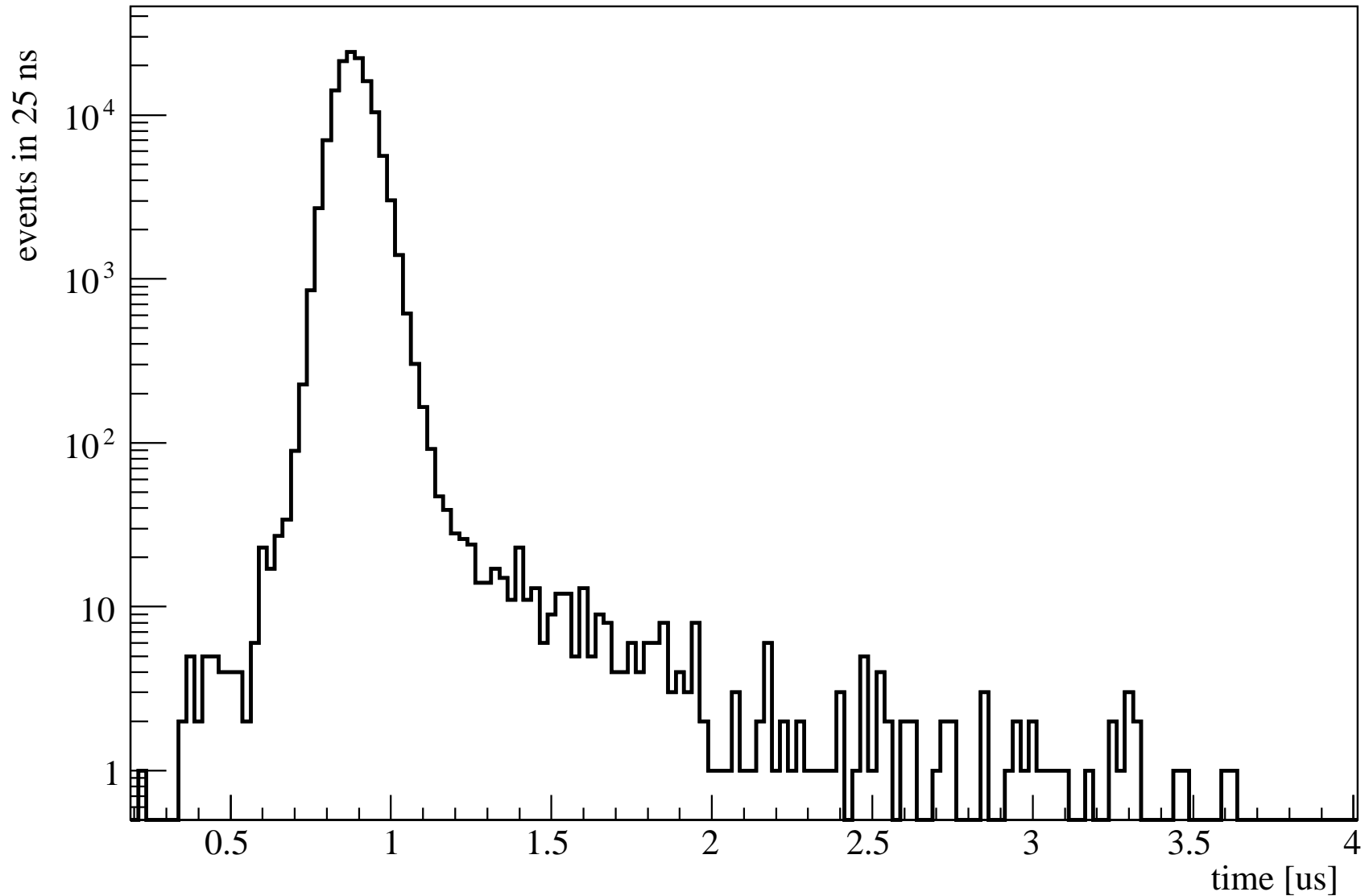
Setup





μp Lamb shift experiment: Principle

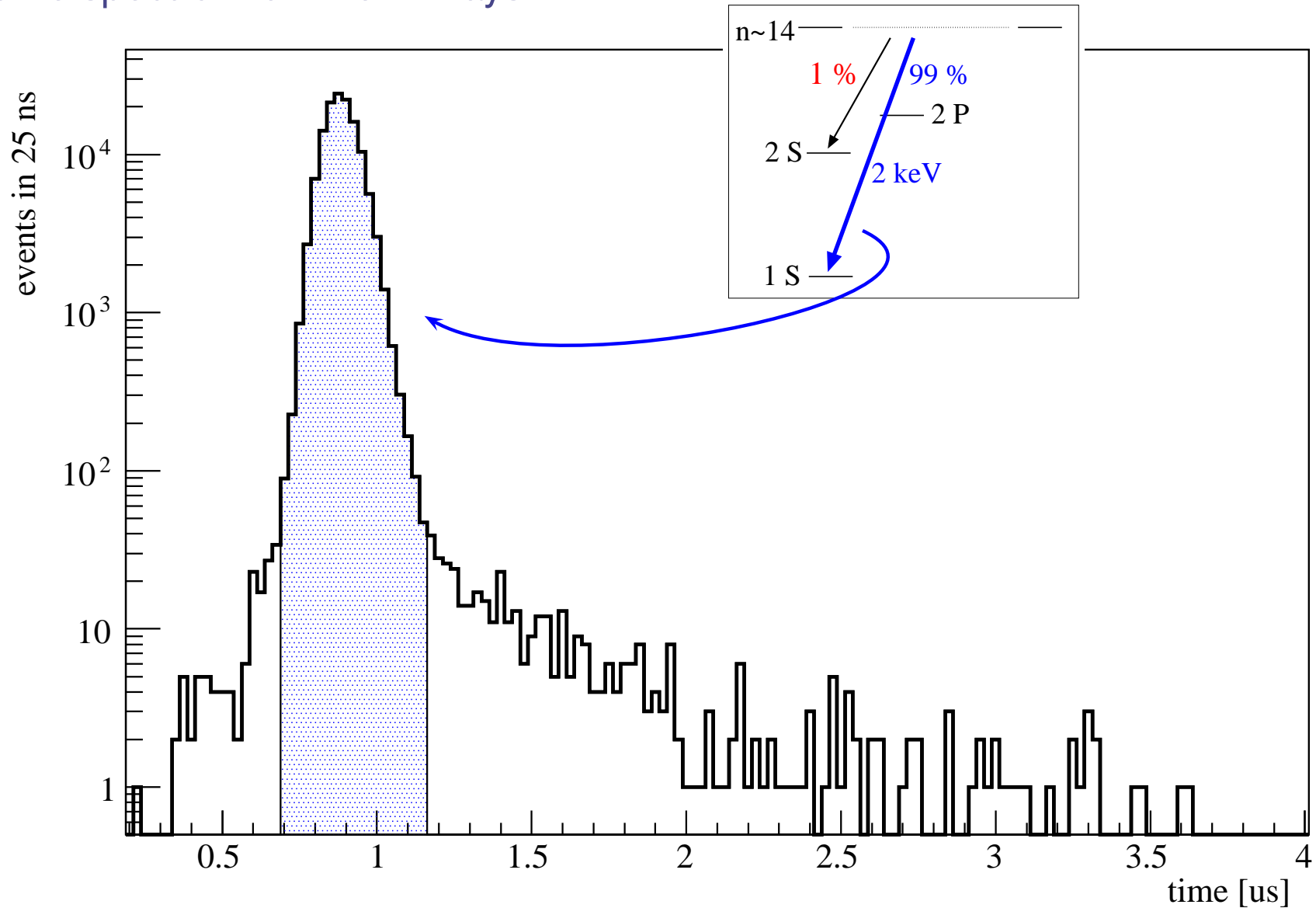
time spectrum of 2 keV x-rays (~ 13 hours of data @ 1 laser wavelength)



μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

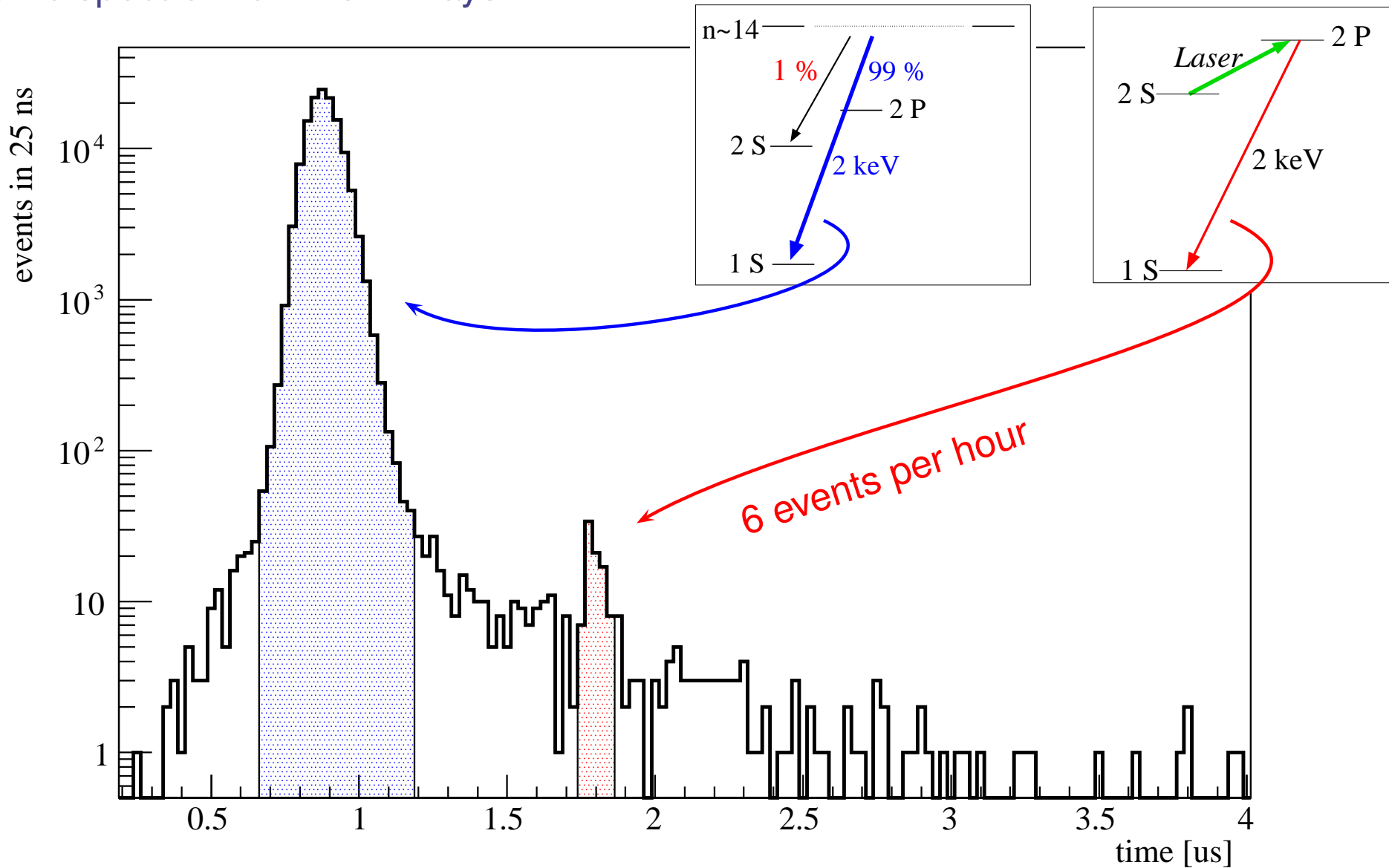


μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

“delayed” ($t \sim 1 \mu s$)

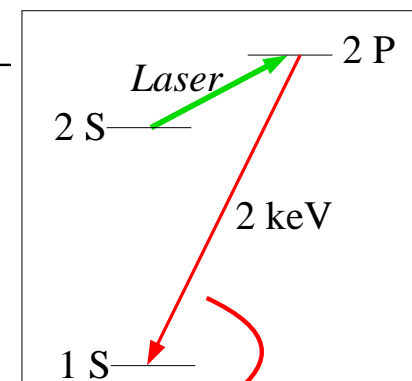
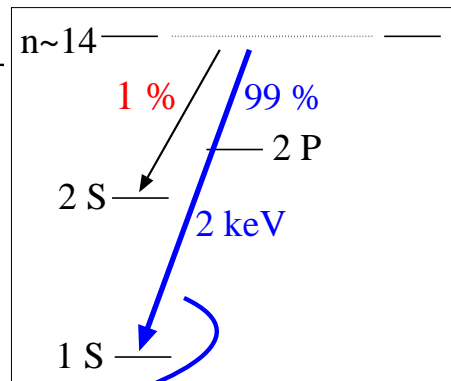
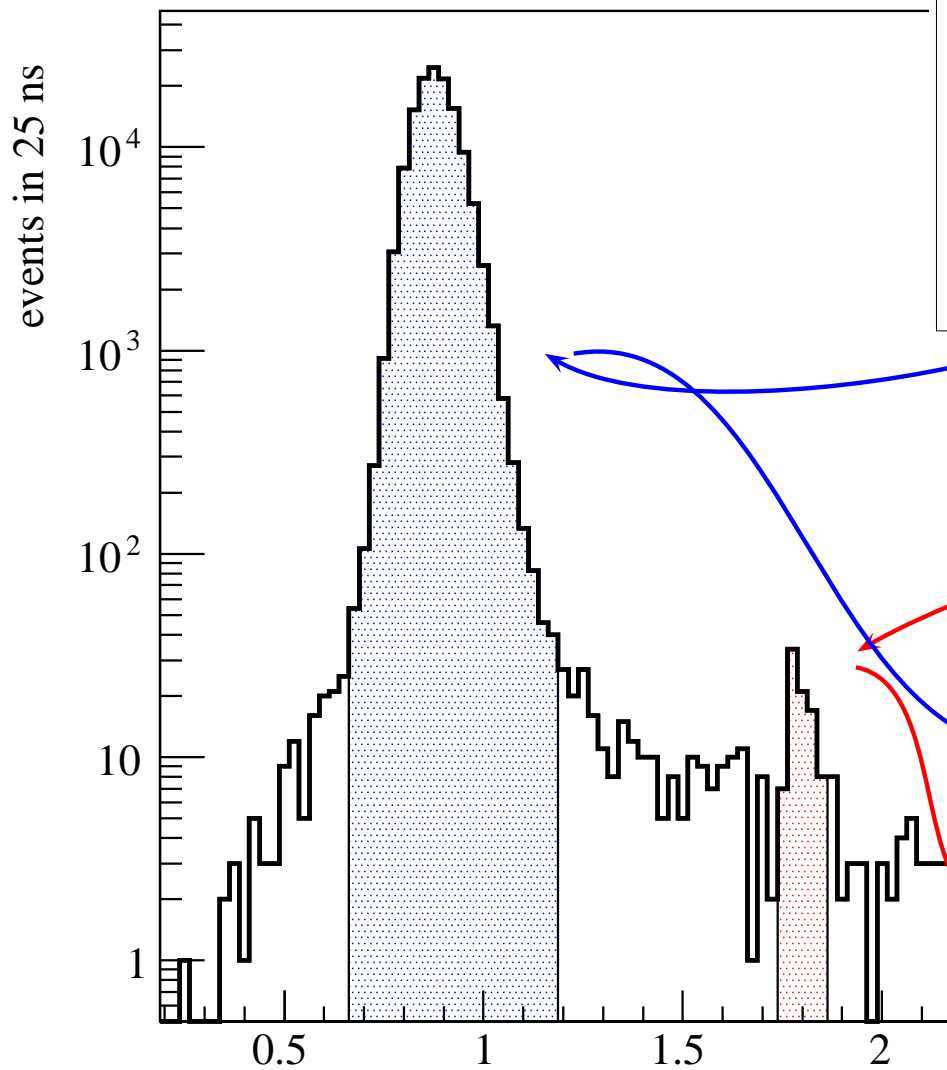


μp Lamb shift experiment: Principle

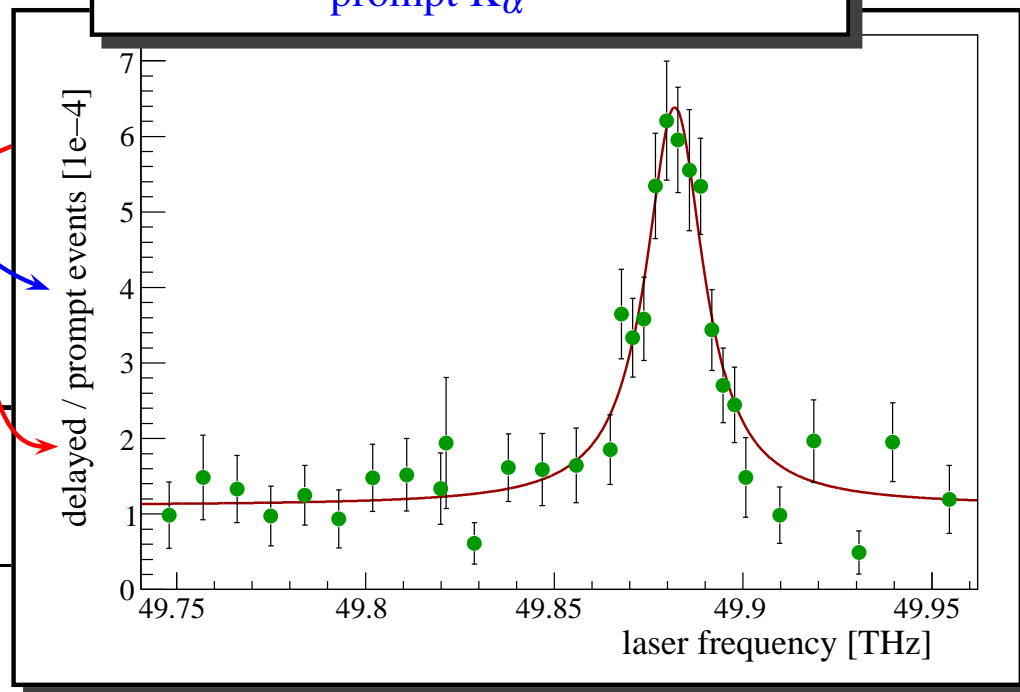
time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

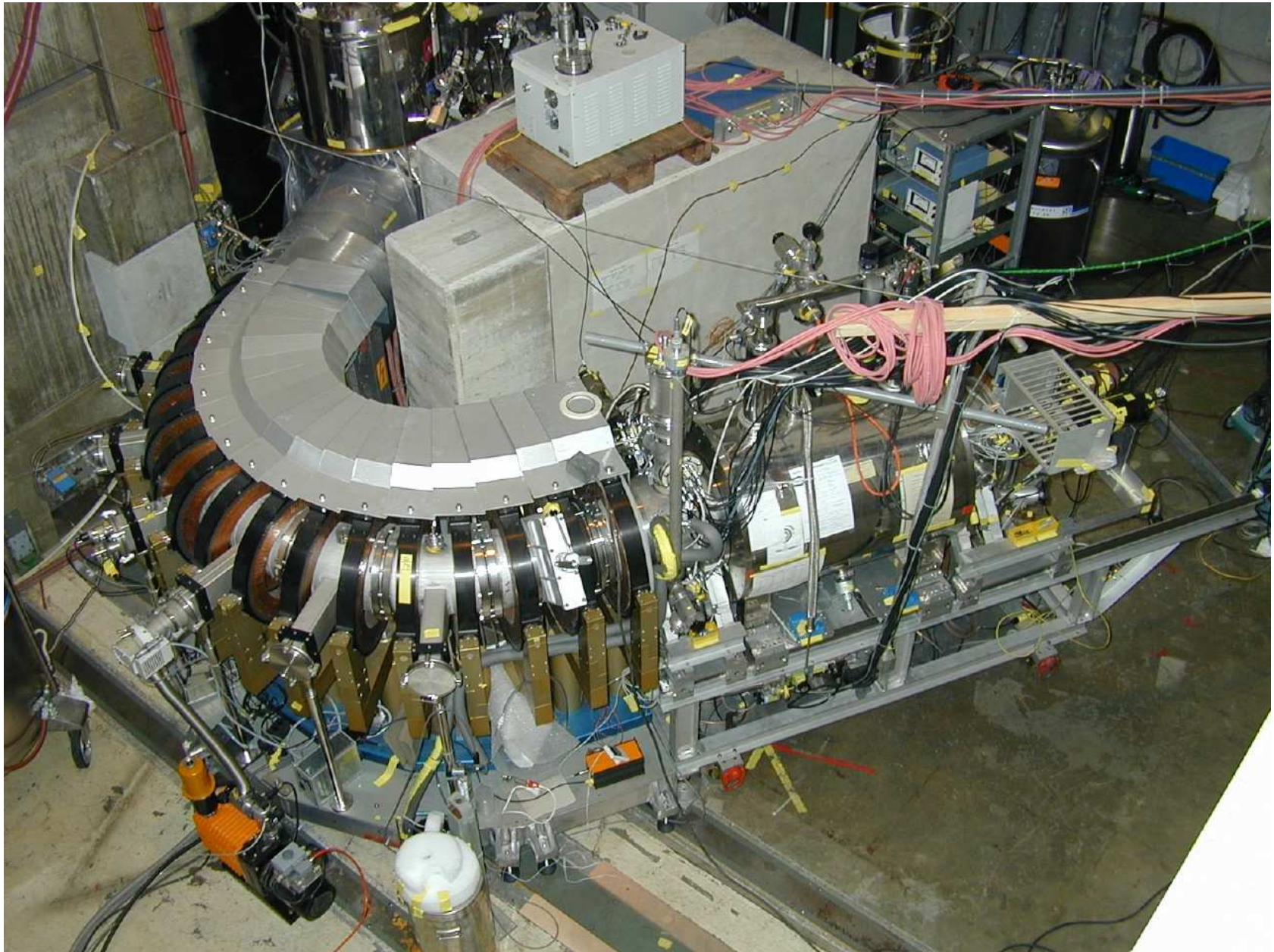
“delayed” ($t \sim 1 \mu\text{s}$)



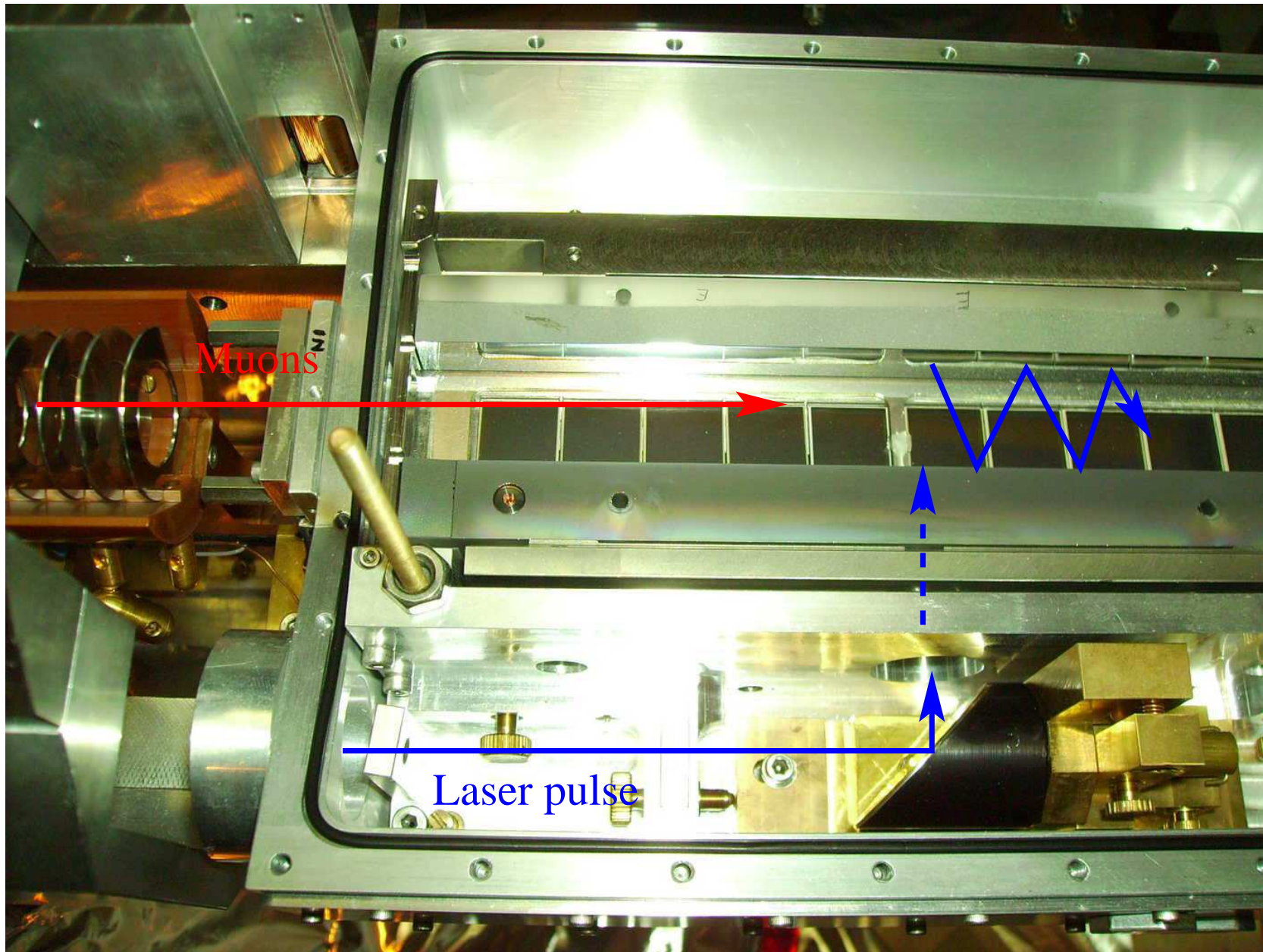
normalize $\frac{\text{delayed } K_{\alpha}}{\text{prompt } K_{\alpha}} \Rightarrow \text{Resonance}$



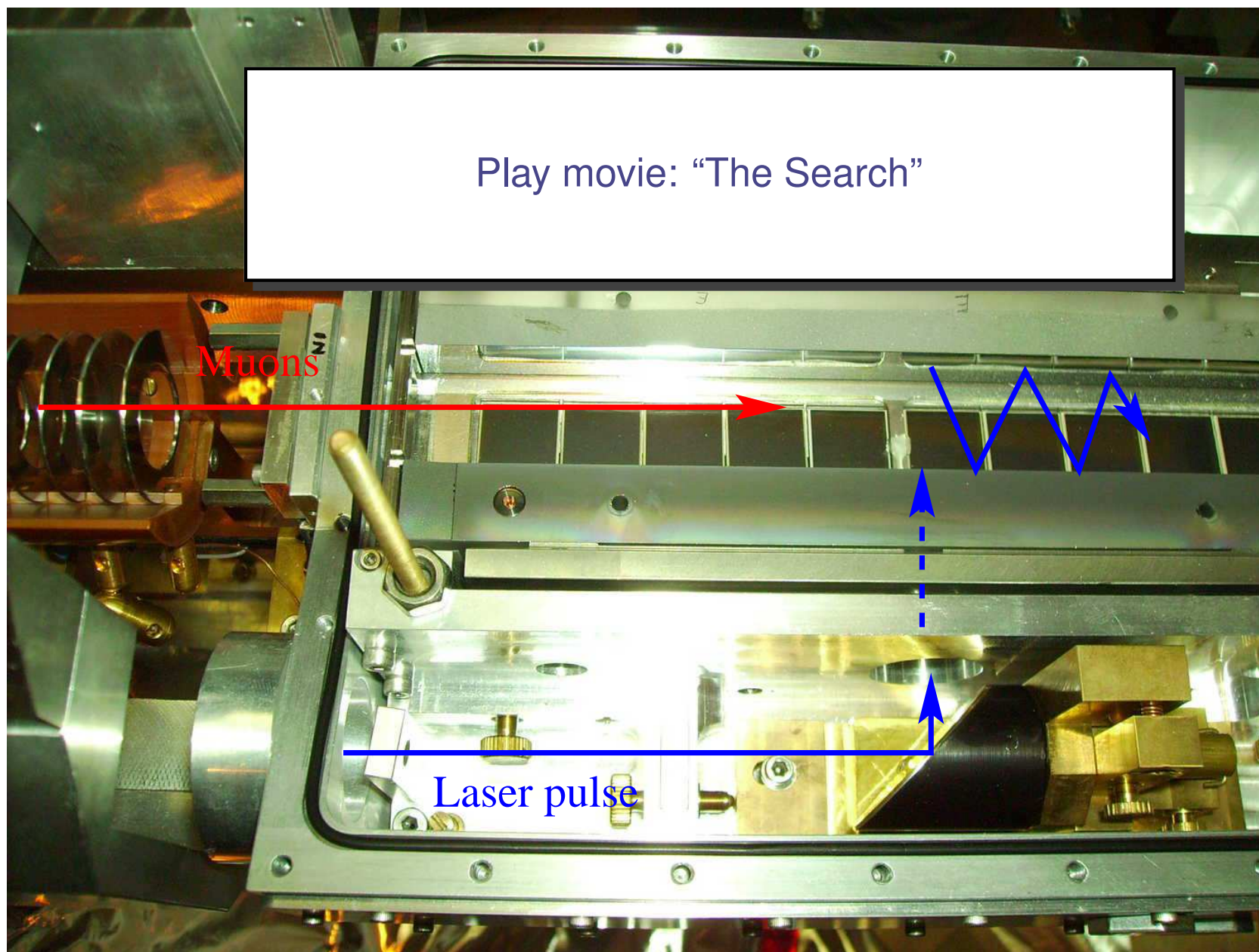
Muon beam line



Target, cavity and detectors



Target, cavity and detectors



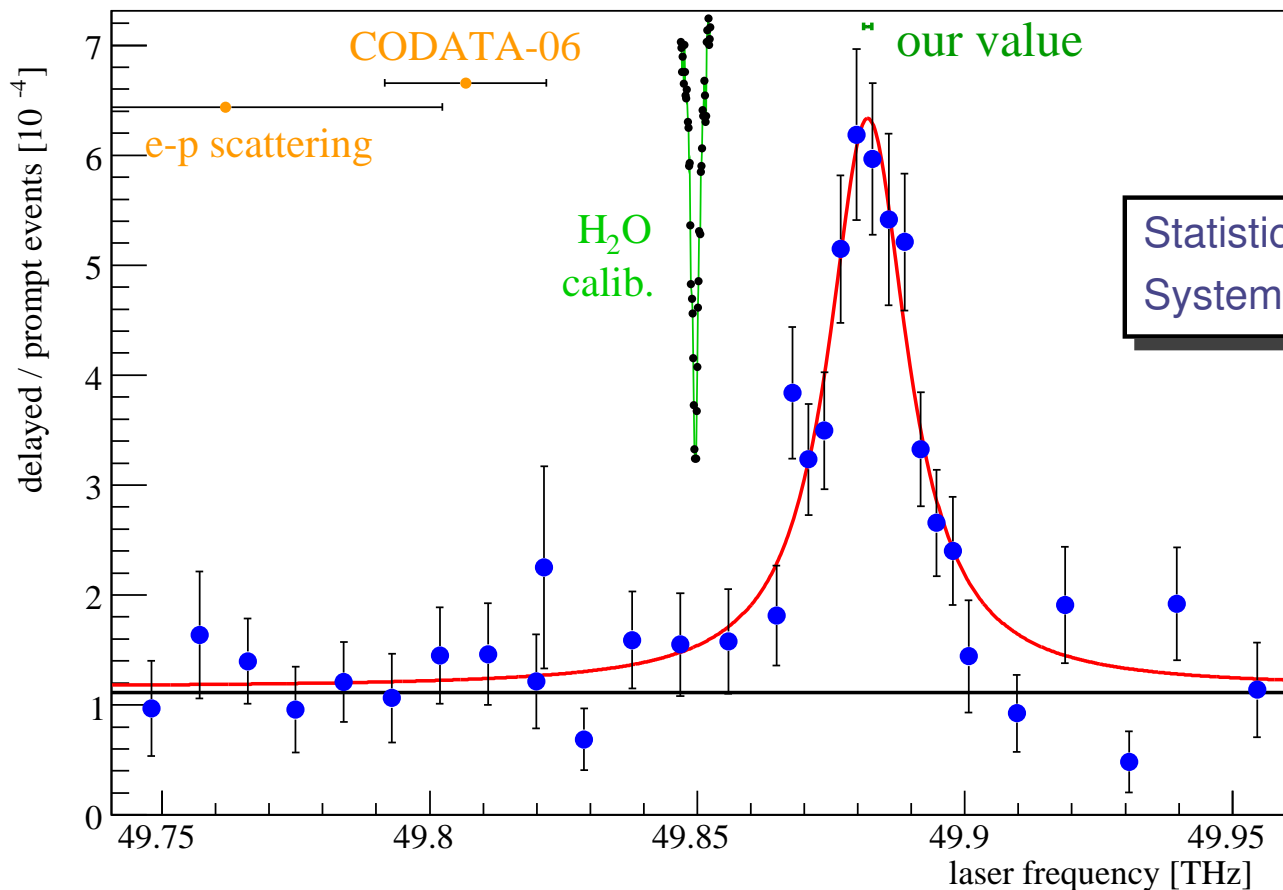
Yeah!



The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

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



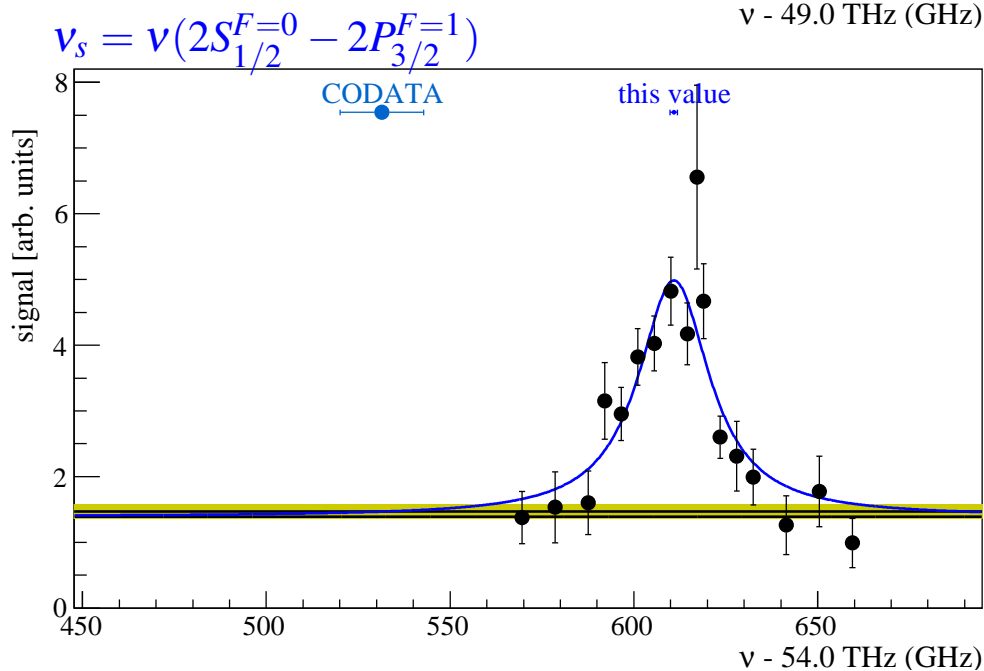
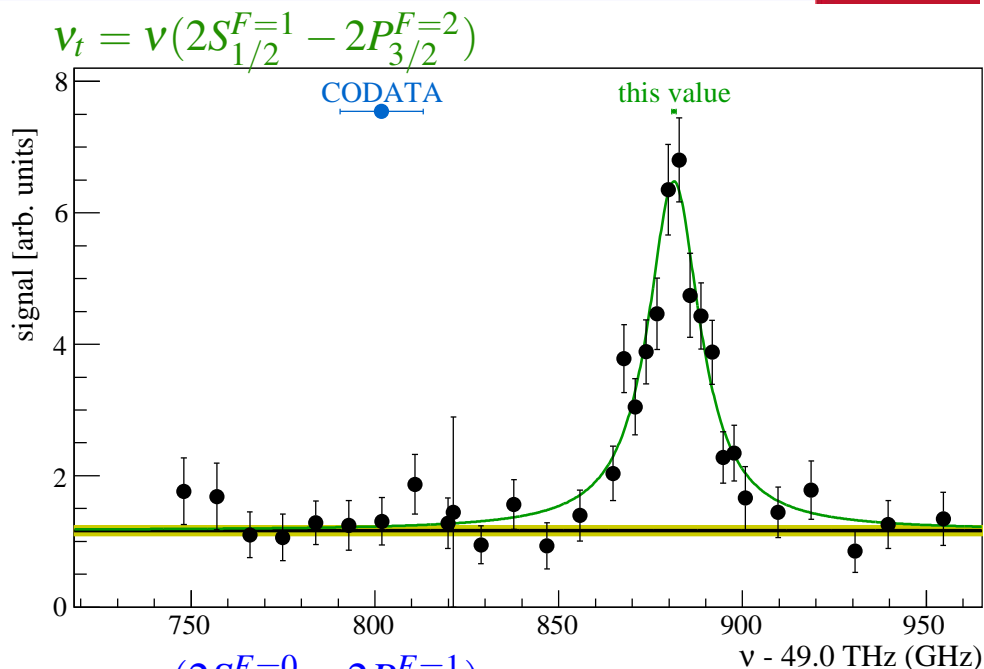
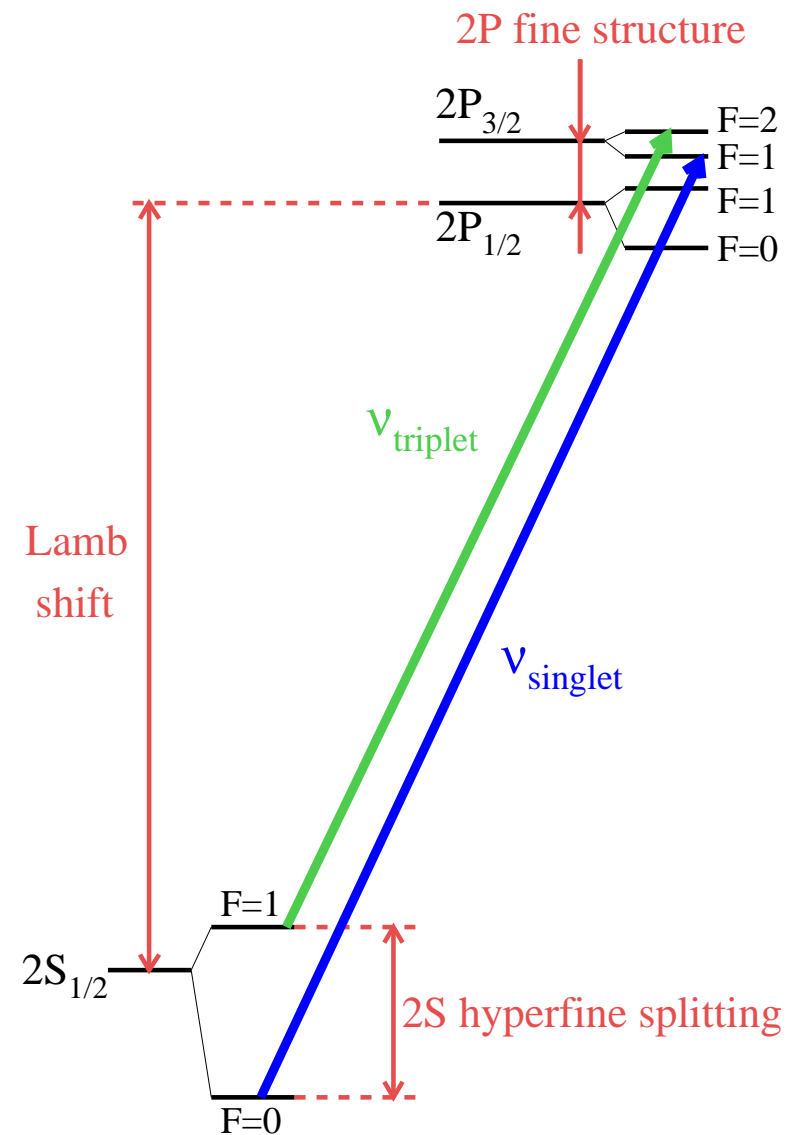
Discrepancy:

$$5.0\sigma \leftrightarrow 80 \text{ GHz} \leftrightarrow \delta\nu/\nu = 1.5 \times 10^{-3}$$

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

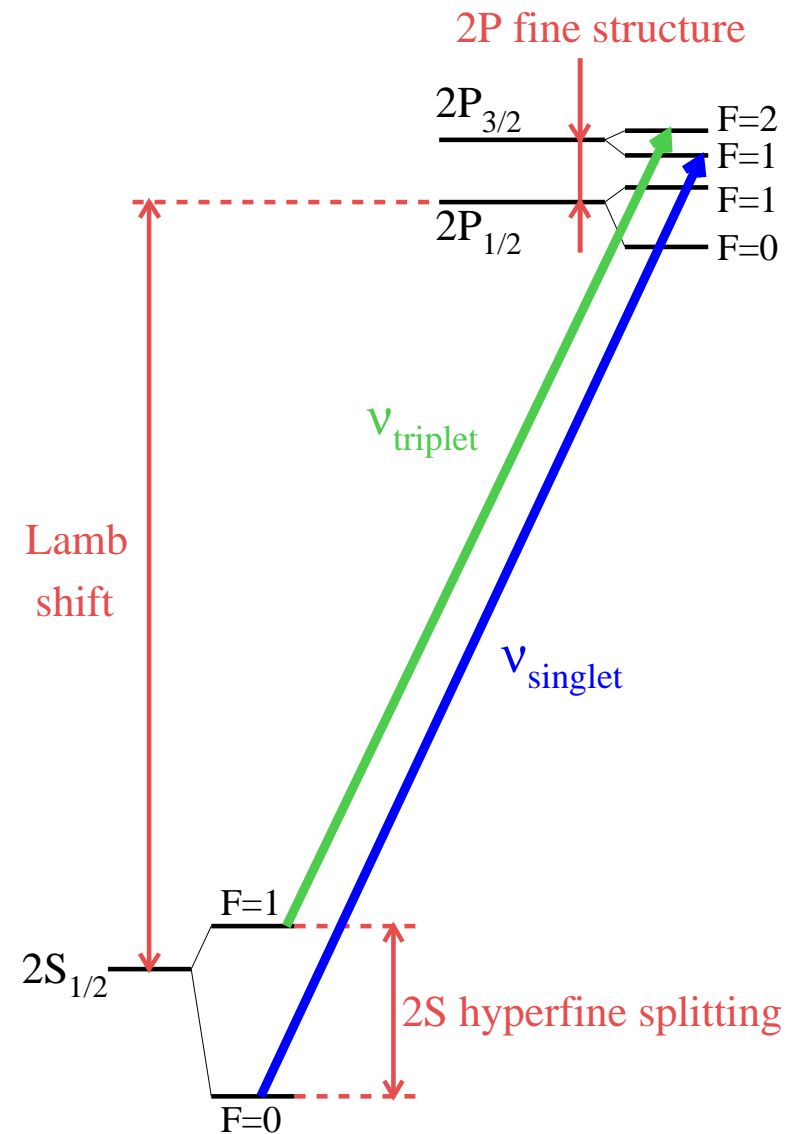
A. Antognini, RP *et al.*, Science 339, 417 (2013).

Muonic hydrogen results



Exp.: R. Pohl *et al.*, Nature 466, 213 (2010).
 A. Antognini, RP *et al.*, Science 339, 417 (2013).
 Theo: A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

Muonic hydrogen results



- two transitions measured

$$\nu_t = 49881.35(65) \text{ GHz}$$

$$\nu_s = 54611.16(1.05) \text{ GHz}$$

- Lamb shift \Rightarrow charge radius

$$\Delta E_{\text{LS}} = 206.0668(25) - 5.2275(10) r_E^2 \text{ [meV, fm]}$$

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

$$r_E = 0.84087(26)_{\text{exp}}(29)_{\text{th}} \text{ fm} = 0.84087(39) \text{ fm}$$

10x more precise than CODATA-2010

4% smaller (7σ)

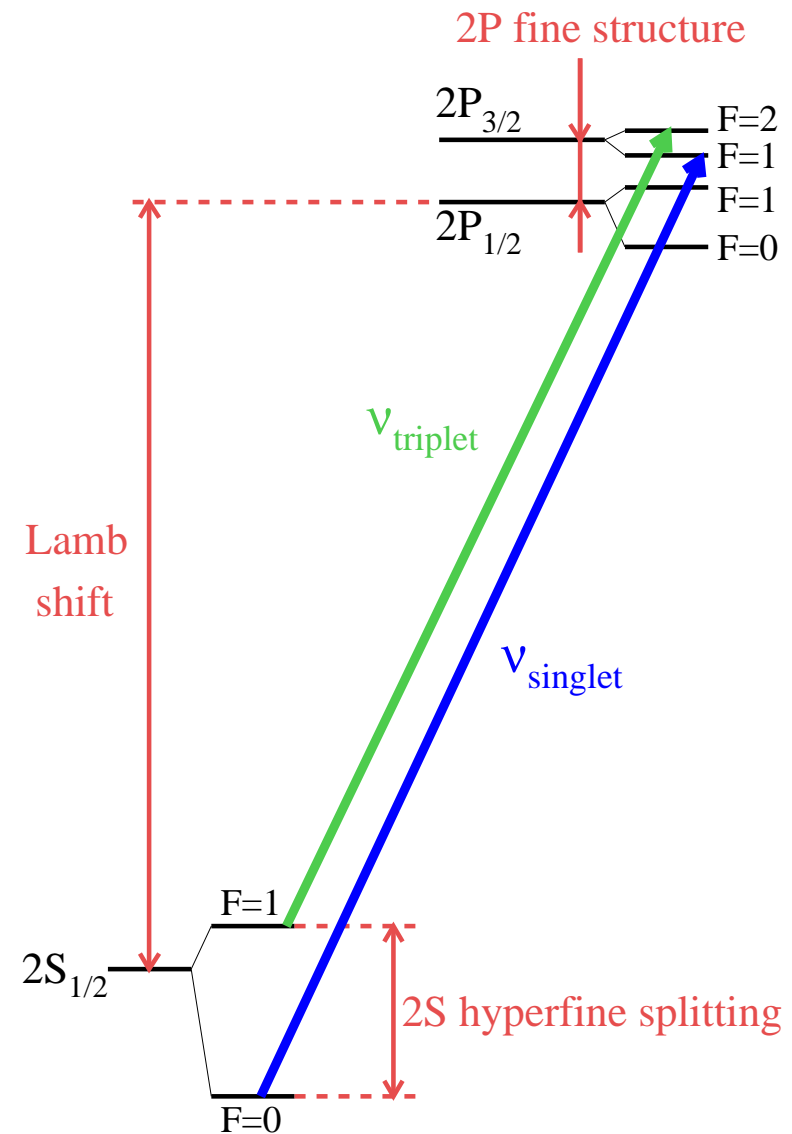
proton radius puzzle

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

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

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

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- 2S-HFS \Rightarrow Zemach radius

$$\Delta E_{\text{HFS}} = 22.9843(30) - 0.1621(10) r_Z \text{ [meV, fm]}$$

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

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

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

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

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

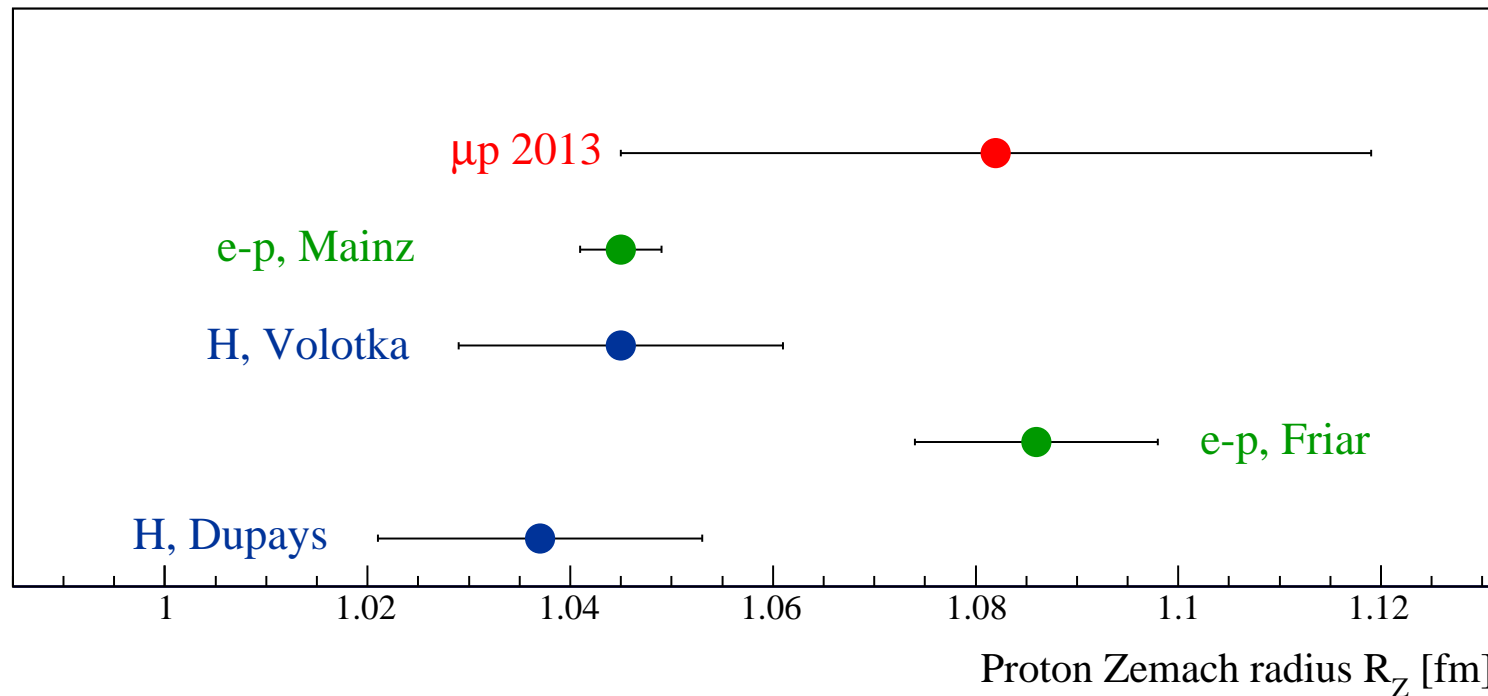
2S hyperfine splitting in μp is: $\Delta E_{\text{HFS}} = 22.9843(30) - 0.1621(10) r_Z$ [fm] meV

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

We measured

$$\Delta E_{\text{HFS}} = 22.8089(51) \text{ meV}$$

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



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

Proton Zemach radius

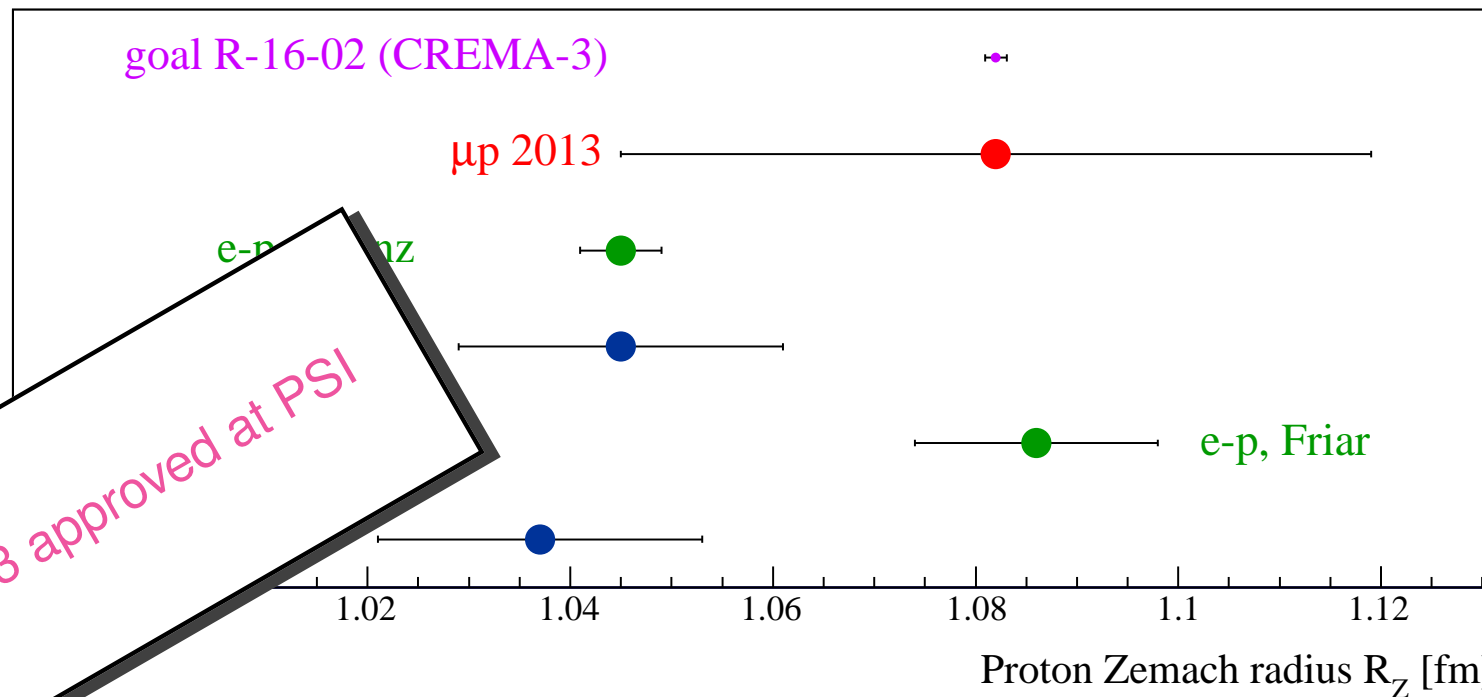
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We measured

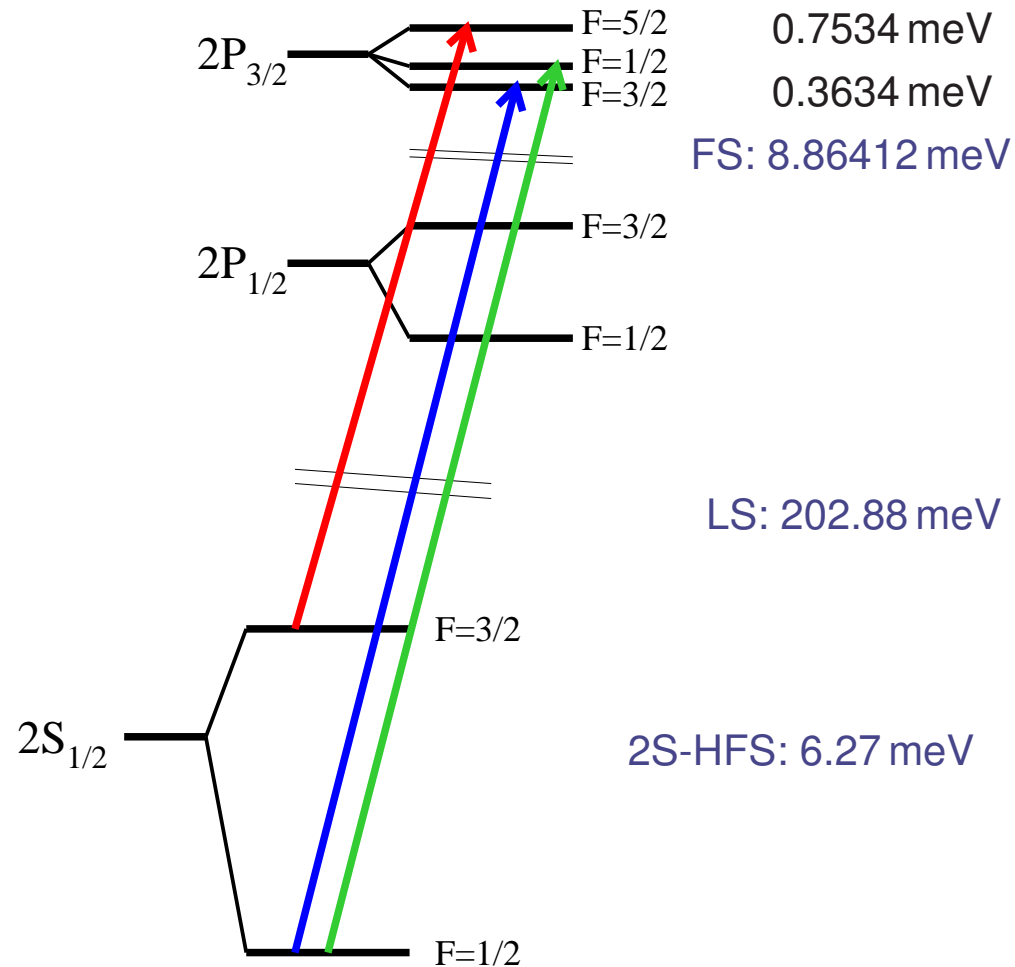
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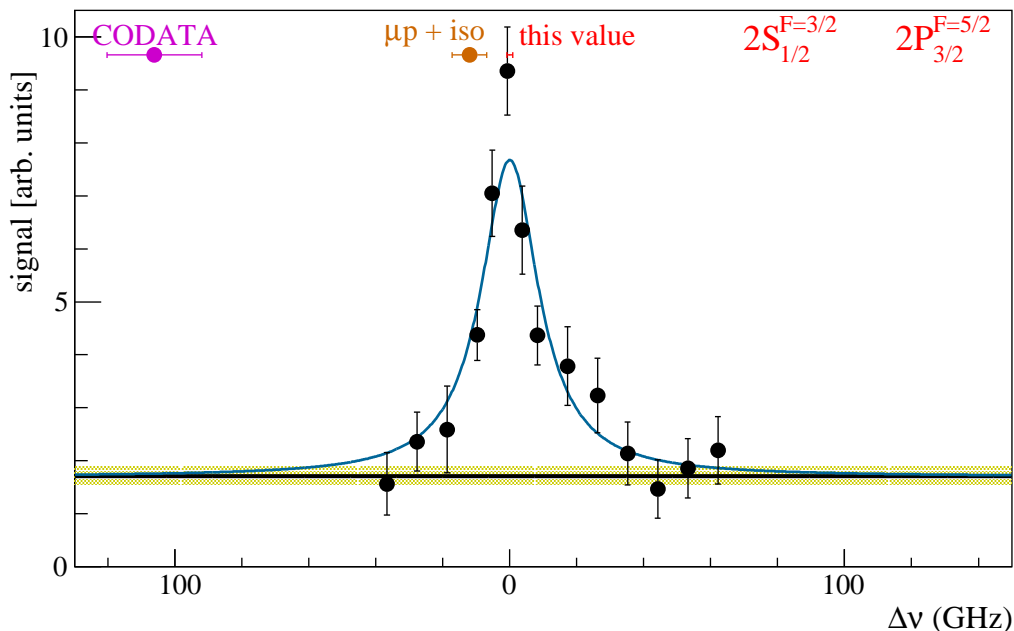


A. Antognini, RP *et al.*, Science 339, 417 (2013)

Muonic deuterium



Muonic DEUTERIUM

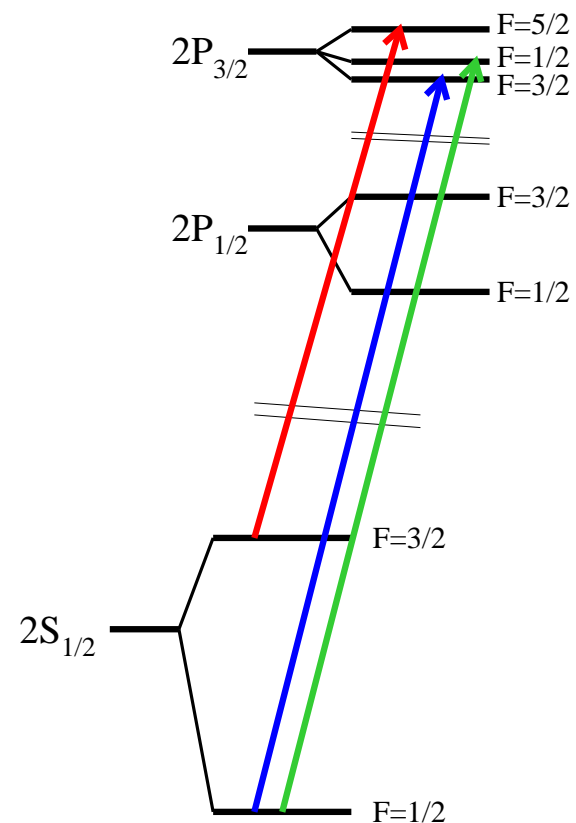
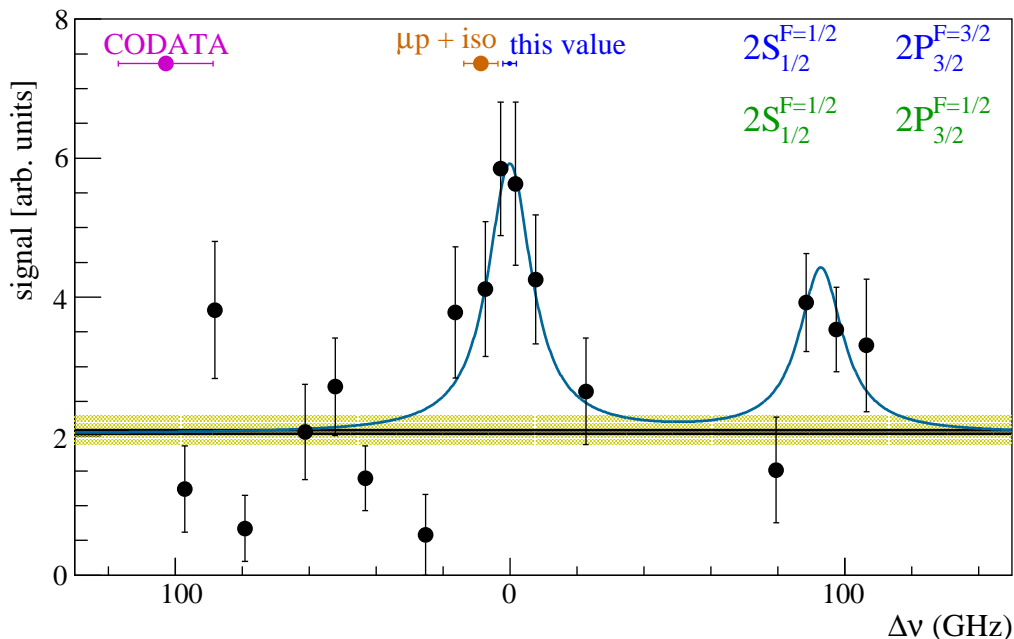


Experiment:

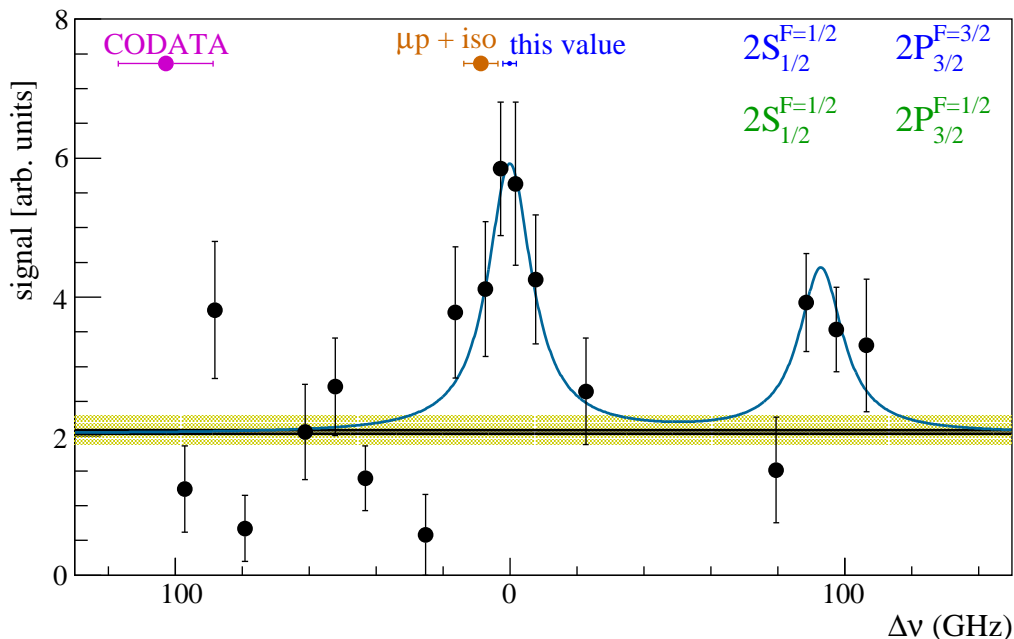
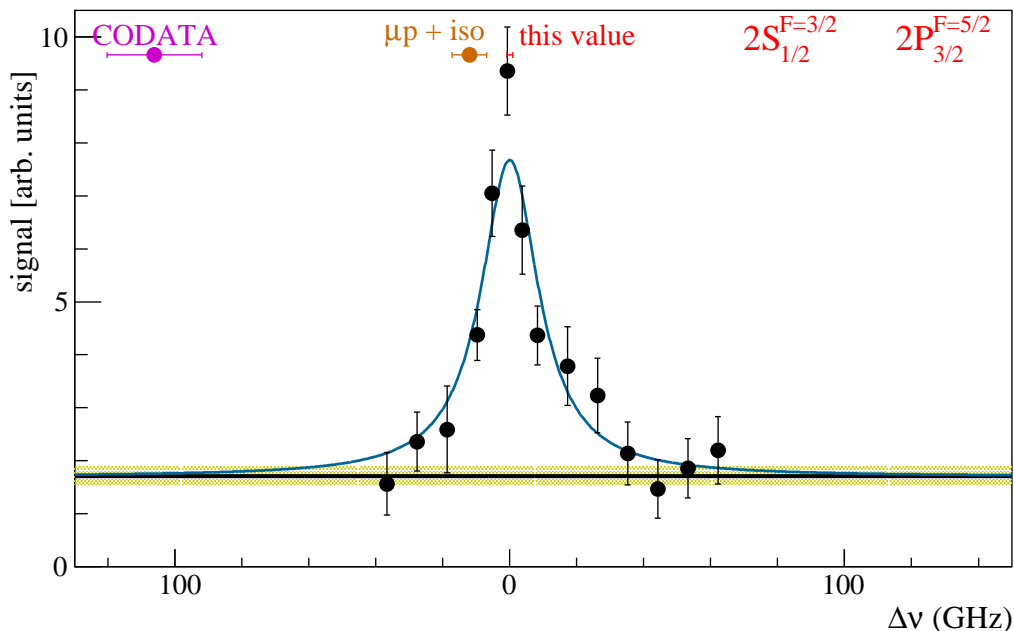
RP *et al.* (CREMA), Science 353, 417 (2016).

$$\Delta E_{LS}^{\text{exp}} = 202.8785 (31)_{\text{stat}} (14)_{\text{syst}} \text{ meV}$$

$$\Rightarrow r_d = 2.12562(13)_{\text{exp}} (77)_{\text{theo}} \text{ fm}$$



Muonic DEUTERIUM



Experiment:

RP *et al.* (CREMA), *Science* **353**, 417 (2016).

$$\Delta E_{LS}^{\text{exp}} = 202.8785 (31)_{\text{stat}} (14)_{\text{syst}} \text{ meV}$$

$$\Rightarrow r_d = 2.12562(13)_{\text{exp}}(77)_{\text{theo}} \text{ fm}$$

Theory:

$$\begin{aligned} \Delta E_{LS}^{\text{theo}} = & 228.7766(10) \text{ meV (QED)} \\ & + 1.7096(200) \text{ meV (TPE)} \\ & - 6.1103(3) r_d^2 \text{ meV/fm}^2, \end{aligned}$$

Krauth, RP *et al.*, *Ann. Phys.* **366**, 168 (2016)

[arXiv 1506.01298]

based on papers and communication from

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.*

THANK YOU!

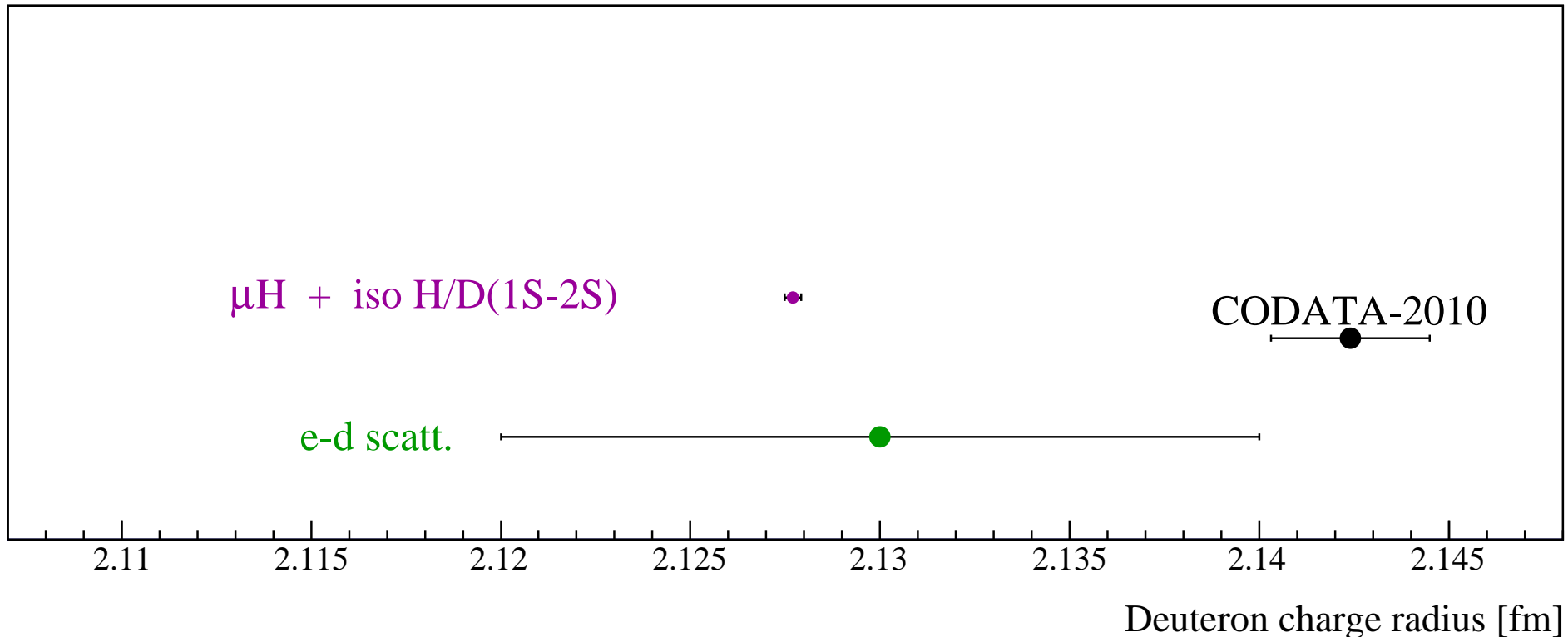
Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65) \text{ fm}^2$

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

CODATA 2010 $r_d = 2.14240(210) \text{ fm}$

r_p from μH gives $r_d = 2.12771(22) \text{ fm} \leftarrow 7\sigma$ from r_p



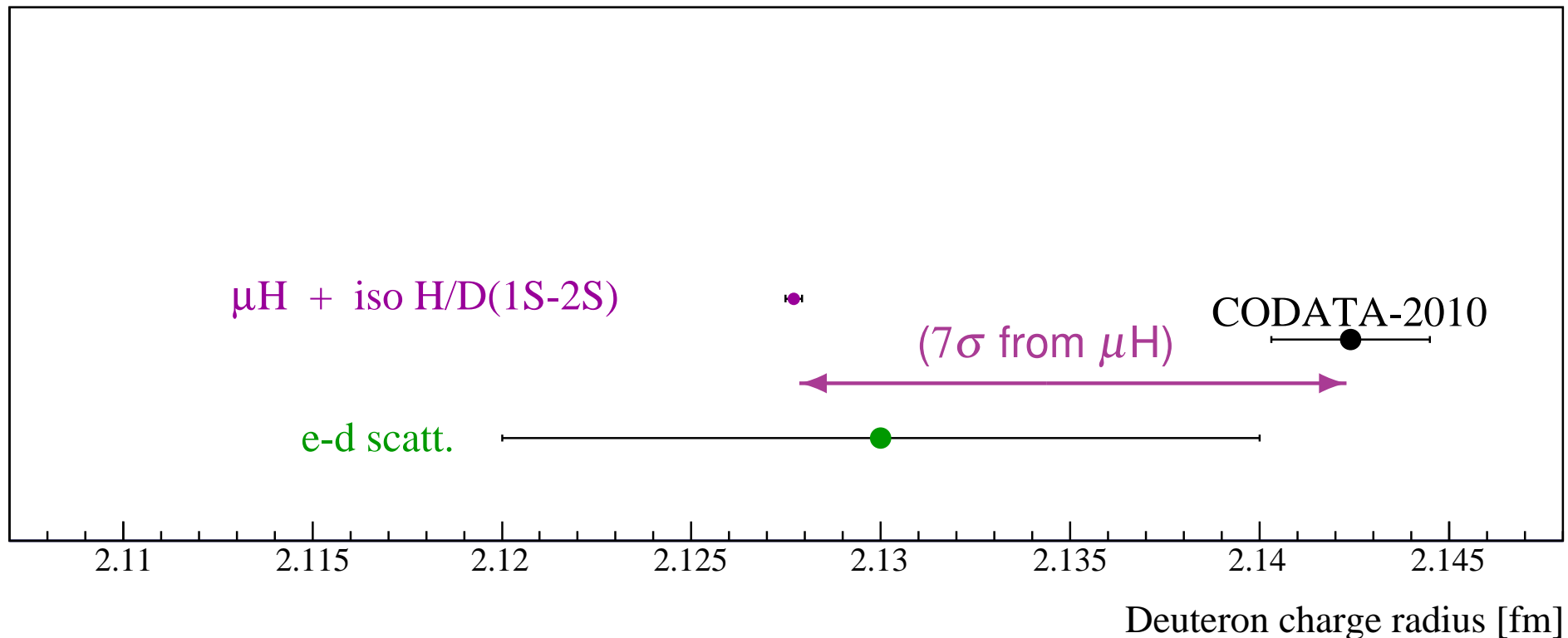
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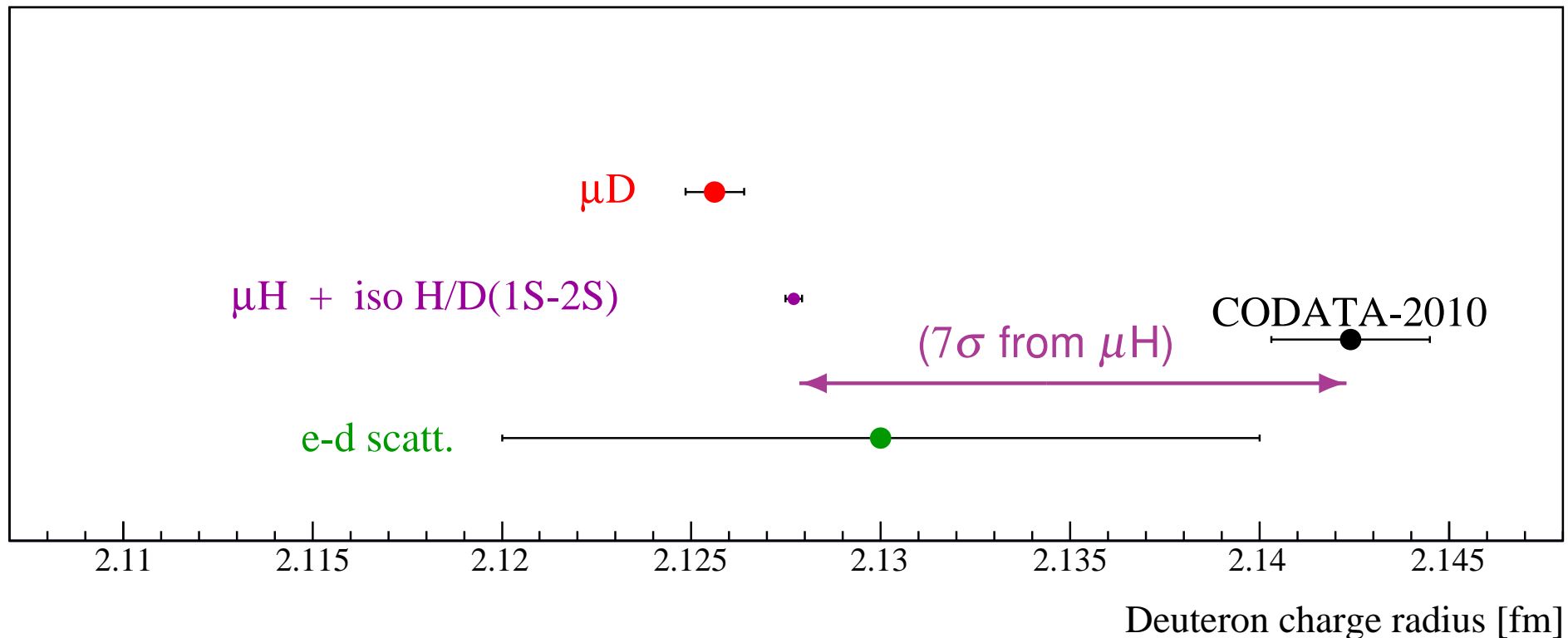
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Muonic DEUTERIUM $r_d = 2.12562(13)_{\text{exp}} (77)_{\text{theo}} \text{ fm}$ RP *et al.*, Science **353**, 417 (2016)



Deuteron charge radius

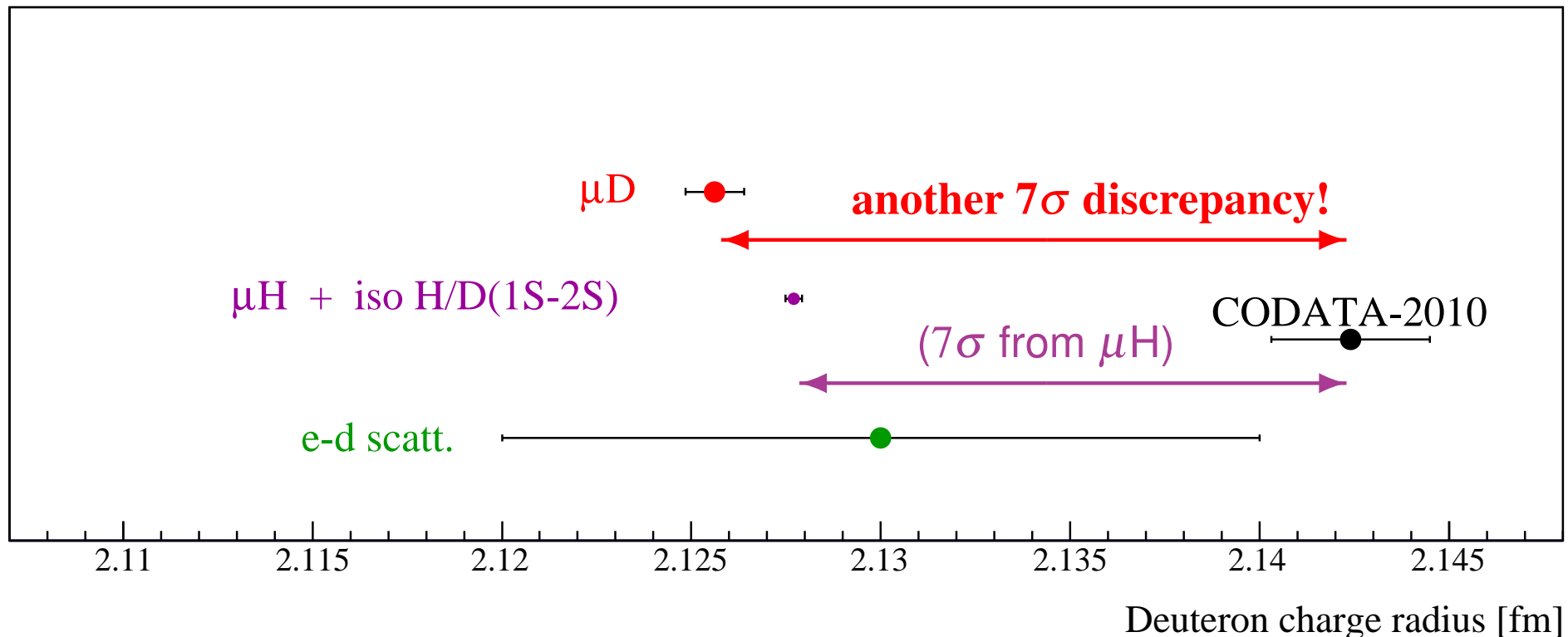
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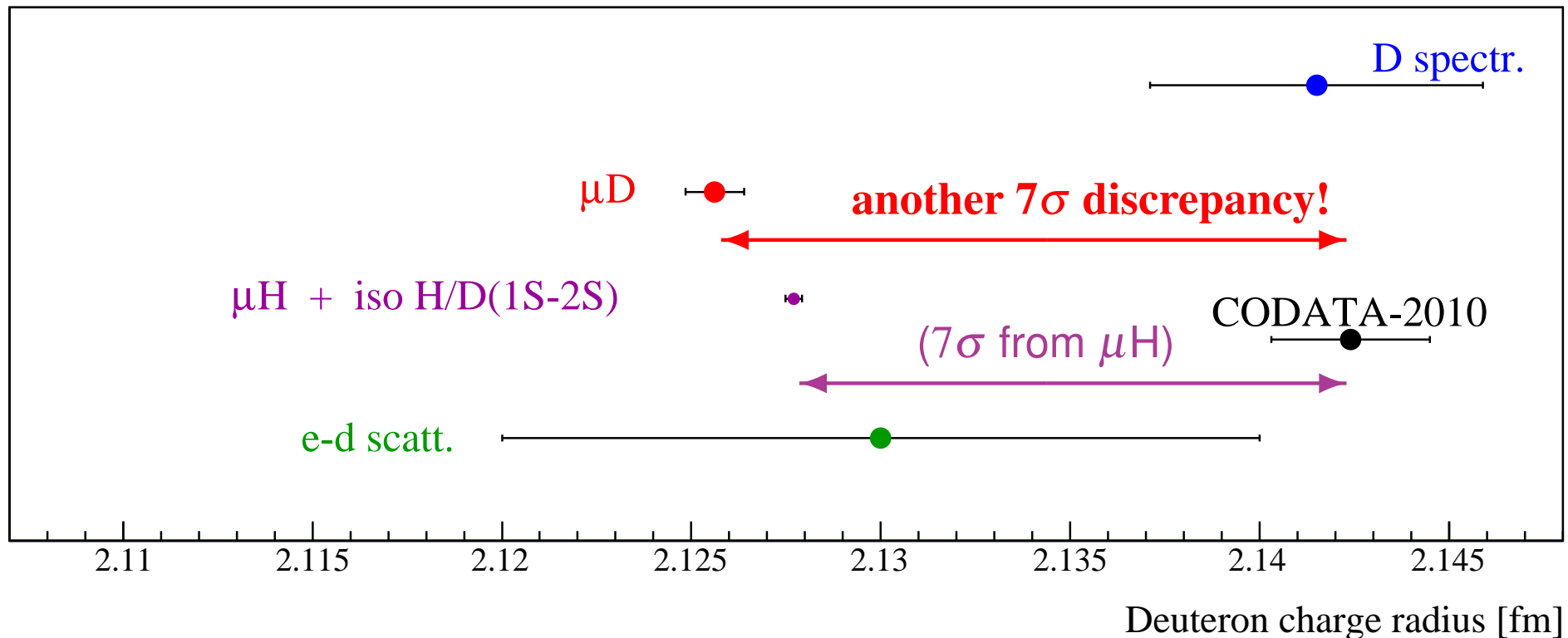
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Muonic DEUTERIUM $r_d = 2.12562(13)_{\text{exp}} (77)_{\text{theo}} \text{ fm}$ RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450) \text{ fm}$ RP *et al.* arXiv 1607.03165



Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65) \text{ fm}^2$

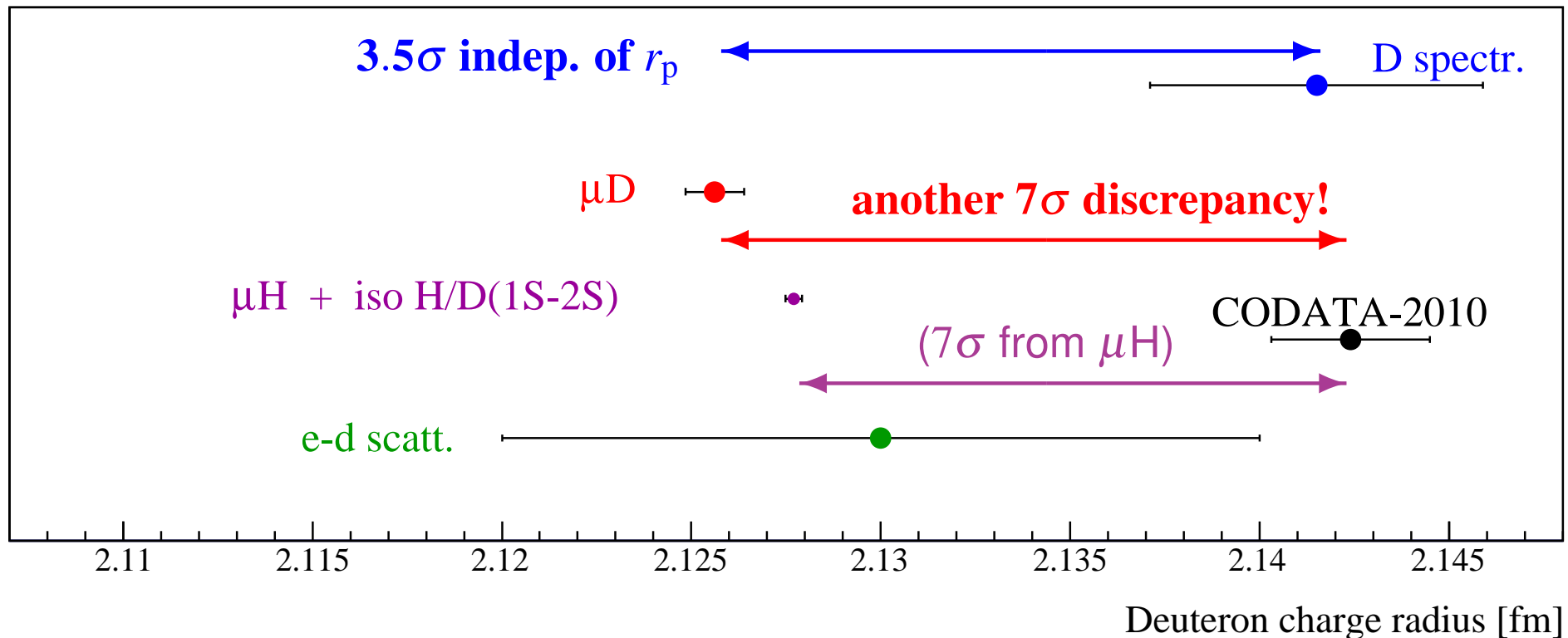
C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

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Muonic DEUTERIUM $r_d = 2.12562(13)_{\text{exp}} (77)_{\text{theo}} \text{ fm}$ RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450) \text{ fm} \leftarrow 3.5\sigma$ RP *et al.* arXiv 1607.03165



Lamb shift in muonic deuterium:

$$\Delta E_{\text{LS}}^{\text{theo}} = 228.7766(10) \text{ meV} + \Delta E^{\text{TPE}} - 6.1103(3) r_d^2 \text{ meV/fm}^2$$

with deuteron polarizability (TPE) $\Delta E^{\text{TPE}}(\text{theo}) = 1.7096(200) \text{ meV}$

J.J. Krauth *et al.*, *Ann. Phys.* **366**, 168 (2016) [1506.01298]

compilation of original results from:

Borie, Martynenko *et al.*, Karshenboim *et al.*, Jentschura, Bacca, Barnea, Nevo Dinur *et al.*, Pachucki *et al.*, Friar, Carlson, Gorchtein, Vanderhaeghen, and others

$$r_d(\mu\text{d}) = 2.12562(13)_{\text{exp}}(77)_{\text{theo}} \text{ fm} \quad (\text{preliminary})$$

$$r_d(\mu\text{p} + \text{iso}) = 2.12771(22) \text{ fm} \quad \text{from } r_p(\mu\text{p}) \text{ and H/D(1S-2S)} \quad 2.6\sigma$$

$$r_d(\text{CODATA}) = 2.14240(210) \text{ fm} \quad 7.5\sigma$$

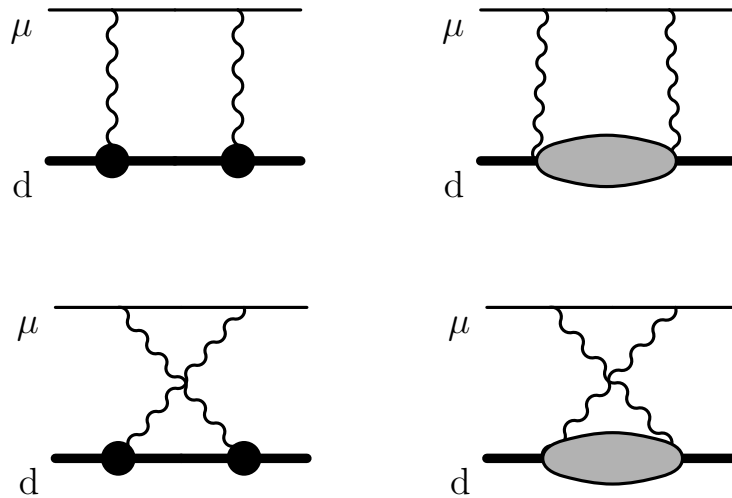
Disprepancy to $\Delta E_{\text{LS}}(r_d(\text{CODATA})) = 0.438(59) \text{ meV}$

(“proton radius puzzle” (μp discrepancy) = 0.329(47) meV)

$$r_d = 2.12562(13)_{\text{exp}}(77)_{\text{theo}} \text{ fm,}$$

$$\text{using } \Delta E_{\text{TPE}}^{\text{theo}} = 1.7096(200) \text{ meV}$$

limited by **deuteron structure** (TPE) contributions to the μd LS



Cancellation between elastic “Friar” (a.k.a. 3rd Zemach) terms and part of inelastic “polarizability” contributions.

Nucleon structure adds relevant contributions (and uncertainty).

Friar & Payne, PRA 56, 5173 (1997) ; Pachucki, PRL 106, 193007 (2011) ; Friar, PRC 88, 034003 (2013) ;
Hernandez *et al.*, PLB 736, 344 (2014) ; Pachucki & Wienczek, PRA 91, 040503(R) (2015) ;
Carlson, Gorchtein, Vanderhaeghen, PRA 89, 022504 (2014) ; Birse & McGovern *et al.*

J.J. Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Theory in μd : TPE

Table 3: Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV.

Item	Contribution	Pachucki [55]		Friar [60]		Hernandez <i>et al.</i> [58]		Pach.& Wienczek [65]		Carlson <i>et al.</i> [64]	Our choice			
		AV18		ZRA		AV18	N ³ LO †	AV18		data	value	source		
	Source	1		2		3	4	5		6				
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta_{D1}^{(0)}$	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	$\delta_L^{(0)}$	-0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta_T^{(0)}$						
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	$\delta_C^{(0)}$	-0.261			-0.2625 ± 0.0015	3-5	
p7	El. monopole excitation	-0.045	$\delta_{Q0} E$	-0.042	C0	-0.042	-0.041	$\delta_{R2}^{(2)}$	-0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta_{D1D3}^{(2)}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	-0.066	$\delta_{Q2} E$	-0.061	C2	-0.061	-0.061	$\delta_Q^{(2)}$	-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 \diamond	$\delta_M E$	-0.011	M1	-0.008	-0.007	$\delta_M^{(0)}$	-0.008	$\delta_M E$		-0.0090 ± 0.0020	2-5	
SUM_1	Total nuclear (corrected)	1.646		1.648		1.656	1.676		1.655			1.6615 ± 0.0103		
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 \diamond	0.021 \diamond	$\delta_{NS}^{(2)}$	0.020	$\delta_{FS} E$				
p12	n p charge correlation			-0.023	pn correl. f.s.	-0.017	-0.017	$\delta_{np}^{(1)}$	-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	$\langle r^{-3} \rangle_{(2)}^{pp}$	} 0.027(2)		δ_{pol}^N [64]	} 0.043(3) $\delta_P E$	} 0.016(8) $\delta_N E$	} 0.028(2) ΔE^{hadr}	} 0.0280 ± 0.0020	Eq.(13)	
p14	Proton inelastic polarizab.													
p15	Neutron inelastic polarizab.													
p16	Proton & neutron subtraction term													
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			-0.0098 ± 0.0098	Eq.(15)	
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)			0.0471 ± 0.0101		
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)			
	Sum, corrected			1.697(19)		1.714(20)			1.707(20)		1.748(740)		1.7096 ± 0.0147	

$$\Delta E^{\text{TPE}}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

$$\Delta E^{\text{TPE}}(\text{exp}) = 1.7638 \pm 0.0068 \text{ meV}$$

J.J. Krauth *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Experimental TPE in μd

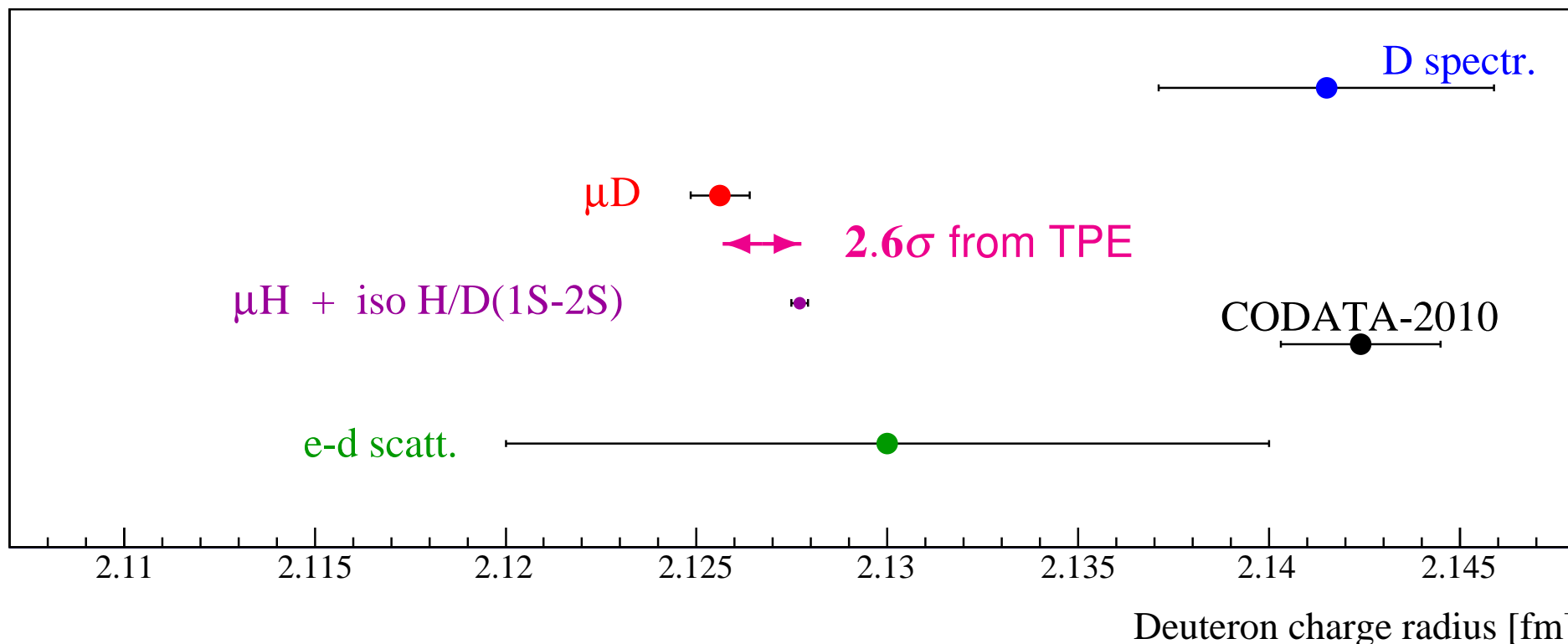
$$\Delta E^{\text{TPE}}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

$$\Delta E^{\text{TPE}}(\text{exp}) = 1.7638 \pm 0.0068 \text{ meV} \quad 2.6\sigma, \quad 3x \text{ more accurate}$$

$$\Delta E_{\text{LS}} = 228.7766(10) \text{ meV (QED)} + \Delta E^{\text{TPE}} - 6.1103(3) r_d^2 \text{ meV/fm}^2,$$

- $\Delta E_{\text{LS}}^{\text{exp}} = 202.8785(31)_{\text{stat}}(14)_{\text{syst}} \text{ meV}$ from μD exp.

- $r_d = 2.12771(22) \text{ fm}$ from $r_d^2 - r_p^2 = 3.82007(65) \text{ fm}^2$ [H/D(1S-2S) isotope shift]
using $r_p(\mu\text{H}) = 0.84087(39) \text{ fm}$



Experimental TPE in μd

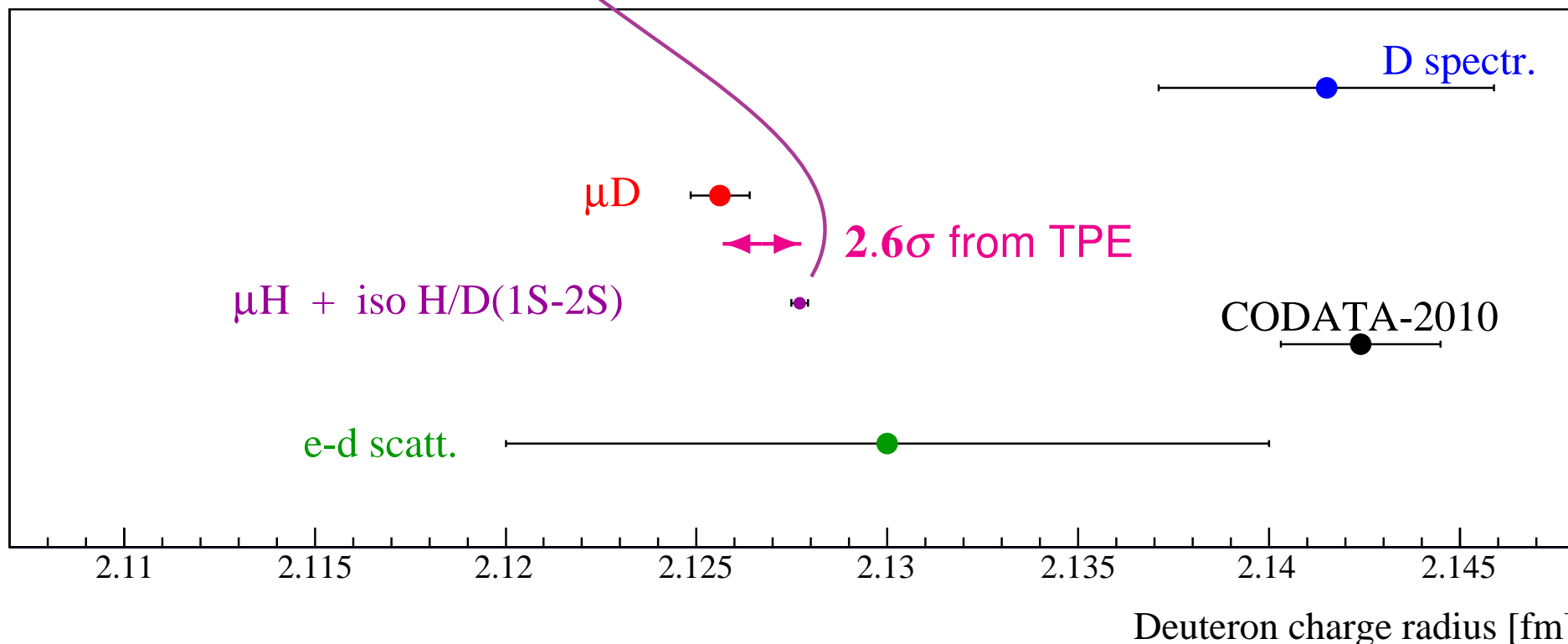
$$\Delta E^{\text{TPE}}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

$$\Delta E^{\text{TPE}}(\text{exp}) = 1.7638 \pm 0.0068 \text{ meV} \quad 2.6\sigma, \quad 3x \text{ more accurate}$$

$$\Delta E_{\text{LS}} = 228.7766(10) \text{ meV (QED)} + \Delta E^{\text{TPE}} - 6.1103(3) r_d^2 \text{ meV/fm}^2,$$

- $\Delta E_{\text{LS}}^{\text{exp}} = 202.8785(31)_{\text{stat}}(14)_{\text{syst}} \text{ meV}$ from μD exp.

- $r_d = 2.12771(22) \text{ fm}$ from $r_d^2 - r_p^2 = 3.82007(65) \text{ fm}^2$ [H/D(1S-2S) isotope shift] using $r_p(\mu\text{H}) = 0.84087(39) \text{ fm}$



Conclusions μp and μd

Putting BSM scenarios aside,

● Muonic hydrogen gives:

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

$$R_\infty = 3.2898419602495(10)^{\text{radius}}(25)^{\text{QED}} \times 10^{15} \text{ Hz}/c$$

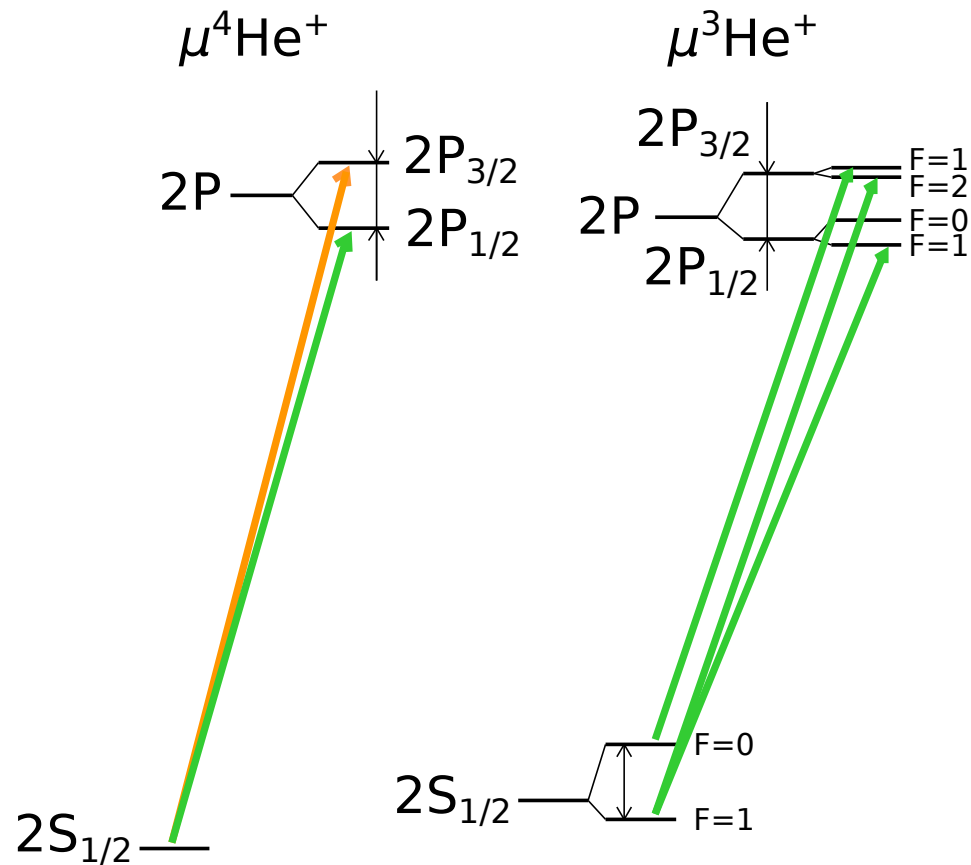
- Deuteron charge radius: $r_d = 2.12771(22)$ fm using H/D(1S-2S)
- r_p is $\sim 7\sigma$ smaller than CODATA-2010
4.0 σ smaller than r_p (H spectroscopy)

● Muonic deuterium gives:

- r_d is 7.5 σ smaller than CODATA-2010 (99% correlated with r_p !)
3.5 σ smaller than r_d (D spectroscopy)
- TPE contribution to Lamb shift: $\Delta E_{\text{LS}}^{\text{TPE}}(\text{exp}) = 1.7638(68)$ meV
2.6 σ larger, but 3x more accurate than theory 1.7096(200) meV
- TPE contribution to 2S-HFS: $\Delta E_{\text{HFS}}^{\text{TPE}}(\text{exp}) = 0.2178(74)$ meV
in good agreement with theor. estimate 0.2226(49) meV

Pohl *et al.*, Nature 466, 213 (2010).
Antognini *et al.*, Science 339, 417 (2013).
Pohl *et al.*, Science 353, 669 (2016).
Antognini *et al.*, Ann. Phys. 331, 127 (2013).
Krauth *et al.*, Ann. Phys. 366, 168 (2016).
Pohl *et al.*, Metrologia (accepted 2016).

Muonic helium ions



Lamb shift in muonic helium



- Goal: Measure $\Delta E(2S-2P)$ in $\mu^4\text{He}$, $\mu^3\text{He}$ to ~ 50 ppm
- \Rightarrow alpha particle and helion charge radius to 3×10^{-4} (± 0.0005 fm),

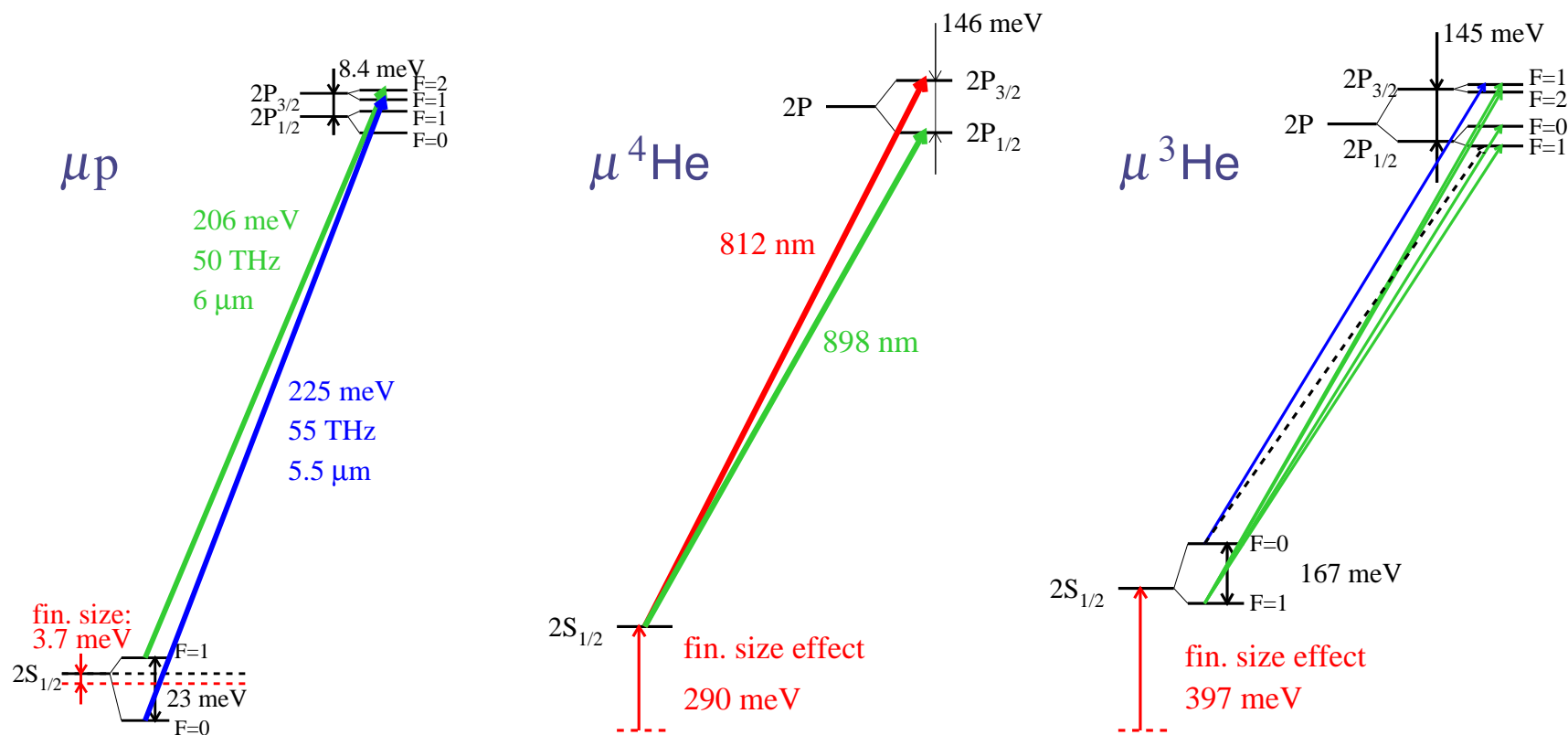
This is **10 times better** than from electron scattering.

- Solve discrepancy in ^3He - ^4He isotope shift.

Lamb shift in muonic helium

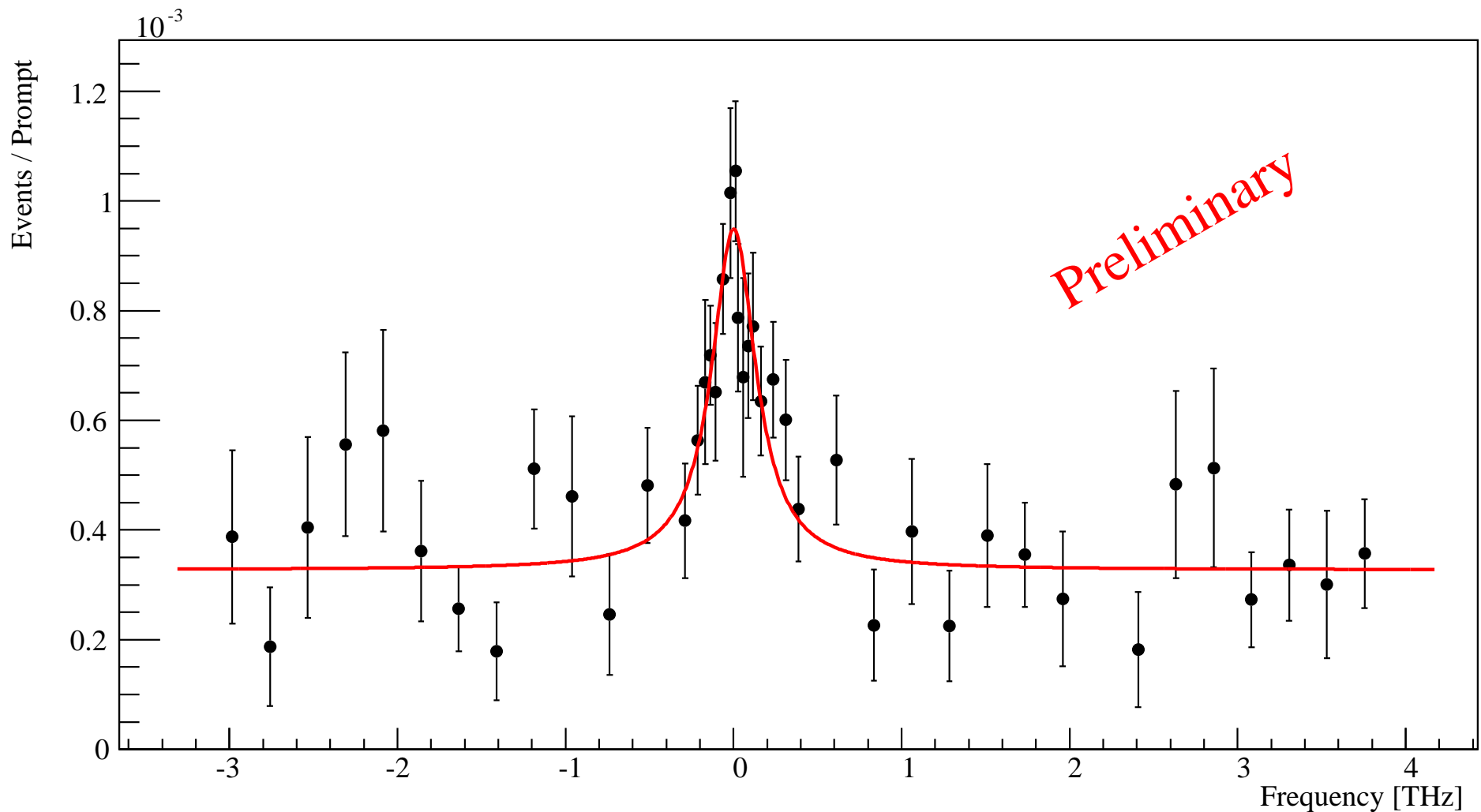


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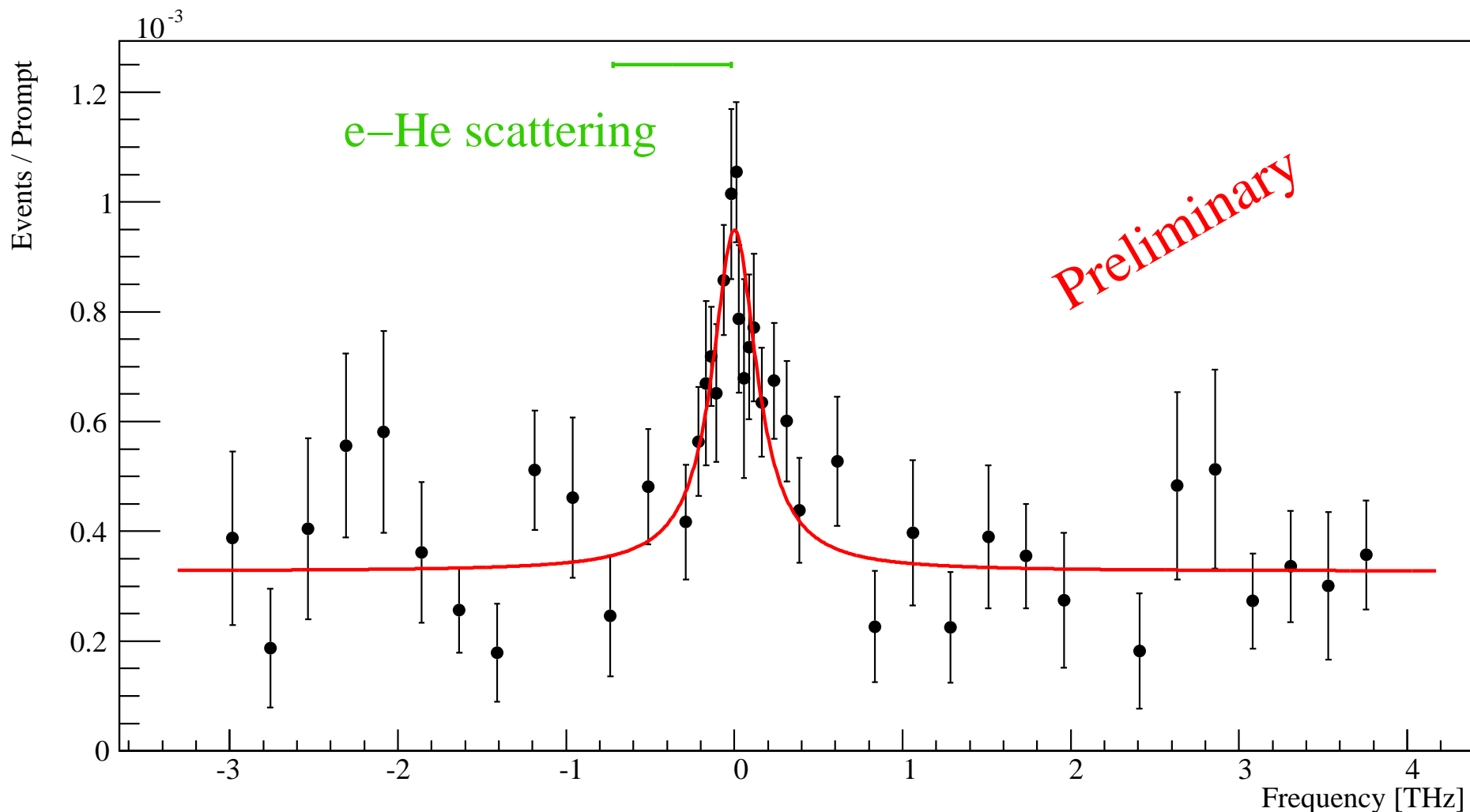
1st resonance in muonic He-4

$\mu^4\text{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength



1st resonance in muonic He-4

$\mu^4\text{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength

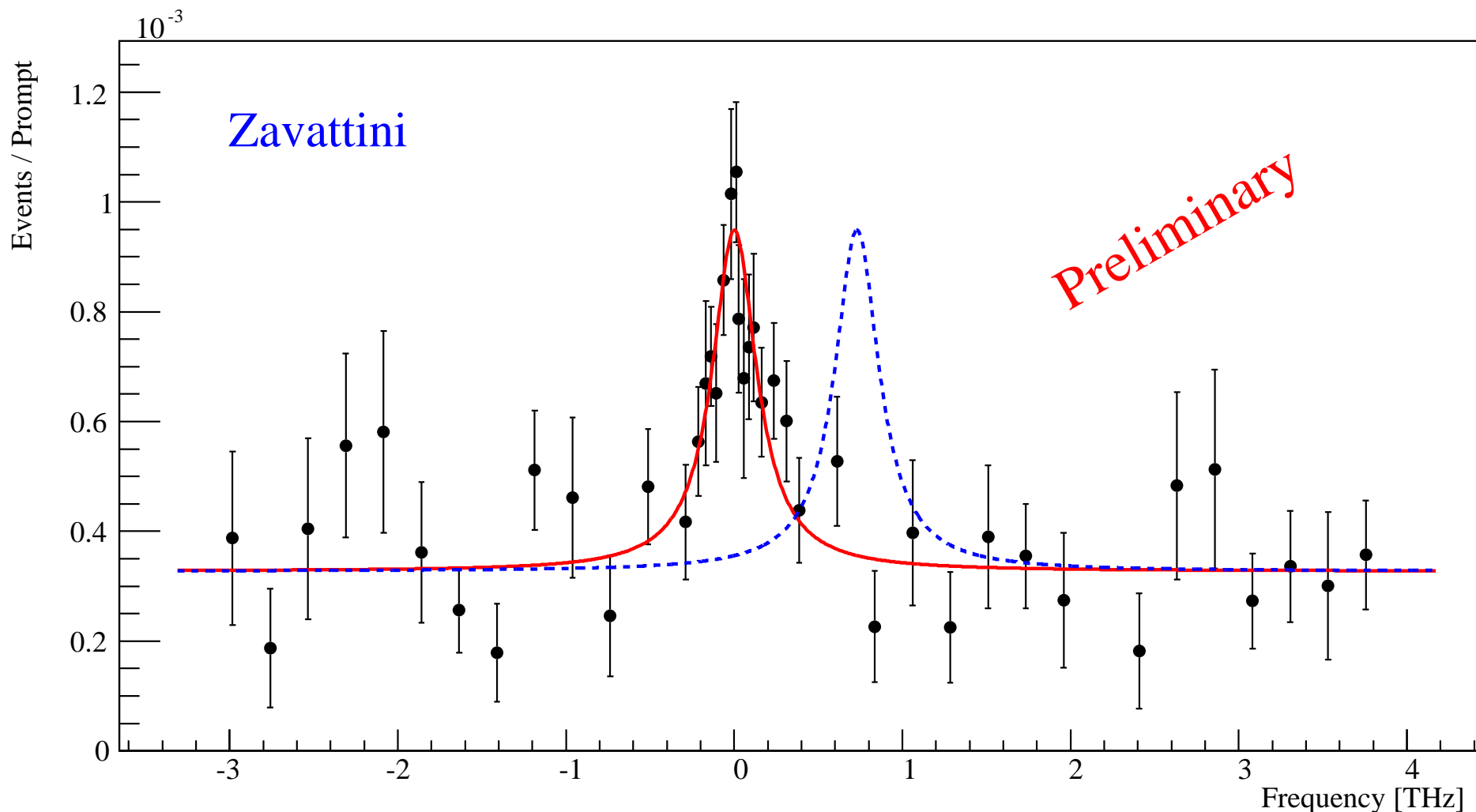


Sick, PRD 77, 040302(R) (2008)

Borie, Ann. Phys. 327, 733 (2012)

1st resonance in muonic He-4

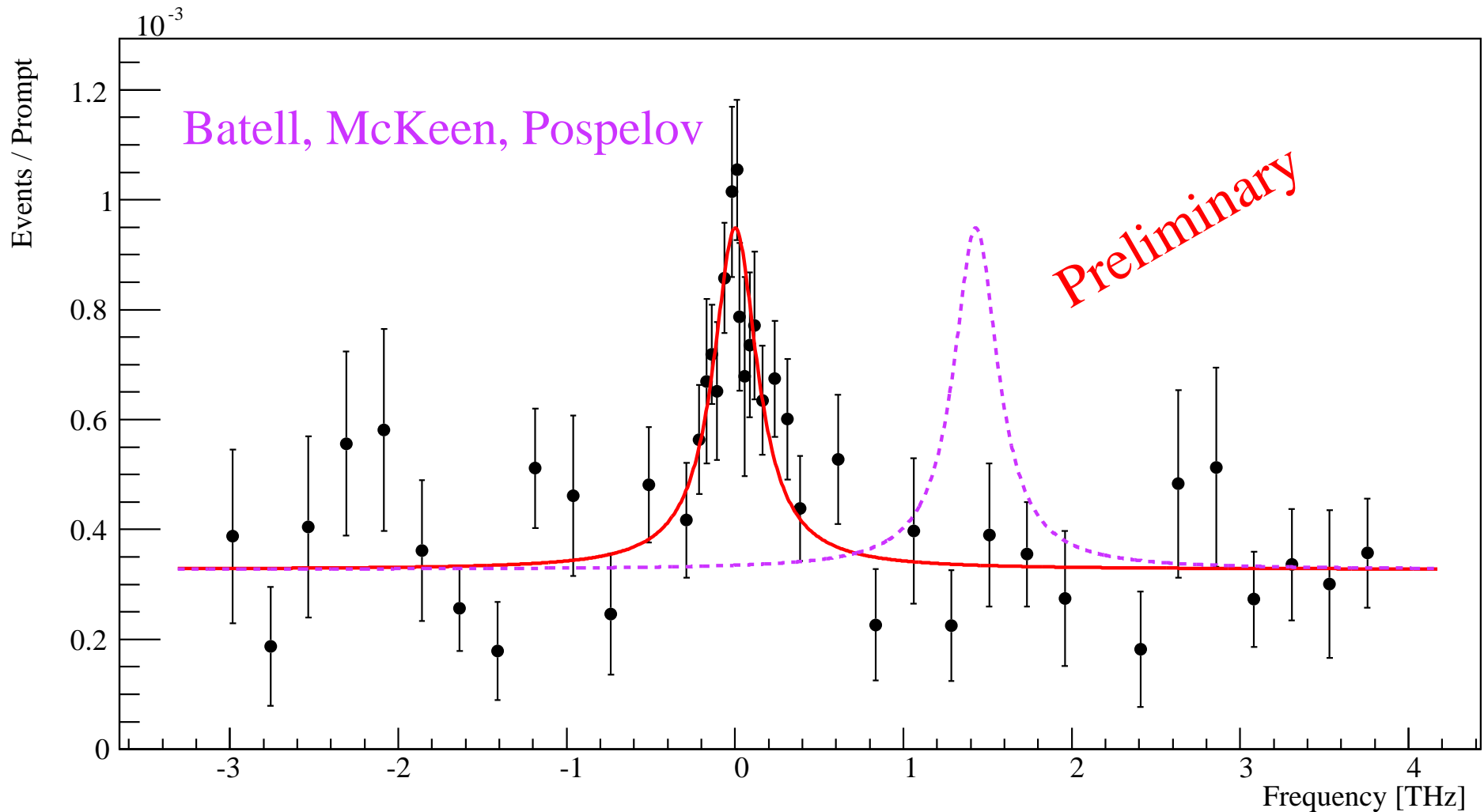
$\mu^4\text{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength



Carboni et al, Nucl. Phys. A273, 381 (1977)

1st resonance in muonic He-4

$\mu^4\text{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength



Batell, McKeen, Pospelov, PRL 107, 011803 (2011)

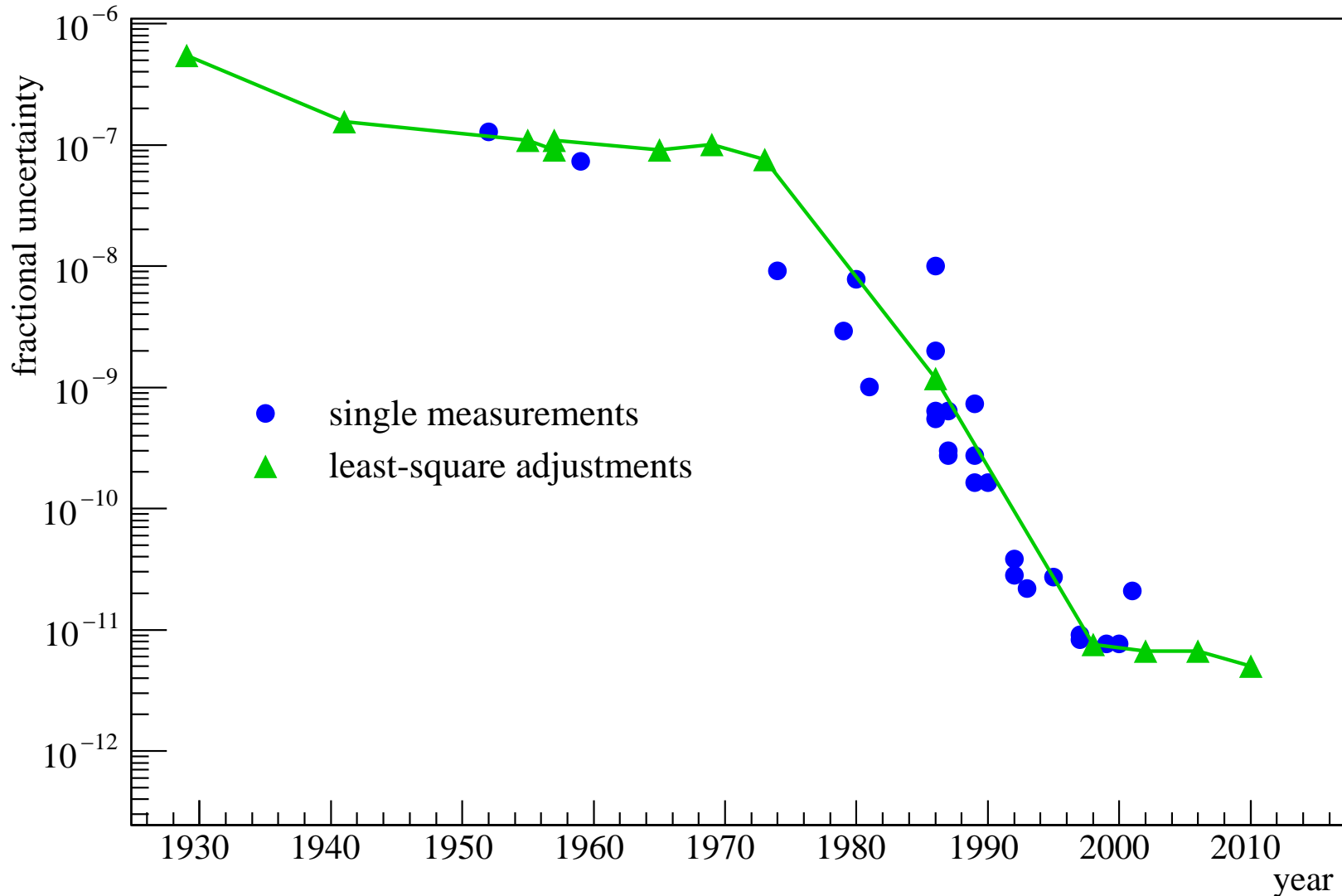
- Muonic **hydrogen** gives:
 - Proton charge radius: $r_p = 0.84087(39)$ fm
 7σ away from electronic average (CODATA: H, e-p scatt.)
 - Deuteron charge radius: $r_d = 2.12771(22)$ fm from $\mu\text{H} + \text{H/D}(1\text{S}-2\text{S})$
- Muonic **deuterium**:
 - Deuteron charge radius: $r_d = 2.12562(13)_{\text{exp}}(77)_{\text{theo}}$ fm
consistent with muonic proton radius, but
again 7σ away from CODATA: $2.14240(210)$ fm
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- Could **ALL** be solved if the **Rydberg constant** [and hence the (electronic) proton radius] was wrong.
Plus $\sim 2.6\sigma$ change in deuteron polarizability.
Plus: accept dispersion fits of e-p scattering
- Or: BSM physics, e.g. Tucker-Smith & Yavin (2011)

(Electronic) hydrogen.

Rydberg constant

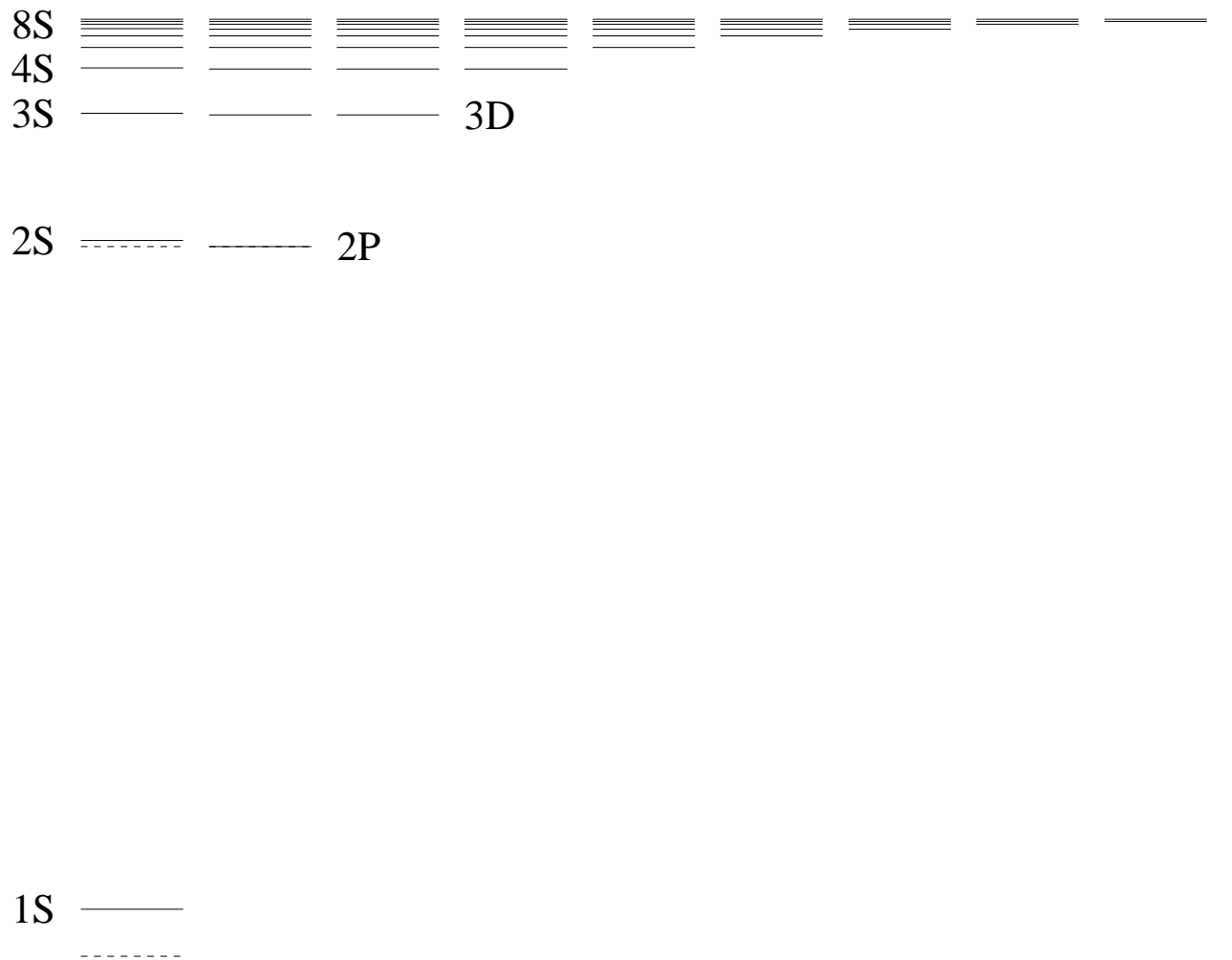
$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$



Hydrogen spectroscopy

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

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



Hydrogen spectroscopy (Lamb shift):

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



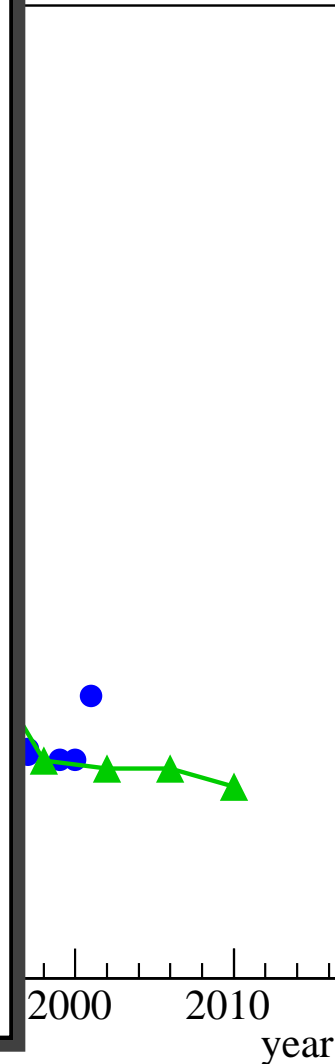
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns \Rightarrow 2 transitions

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

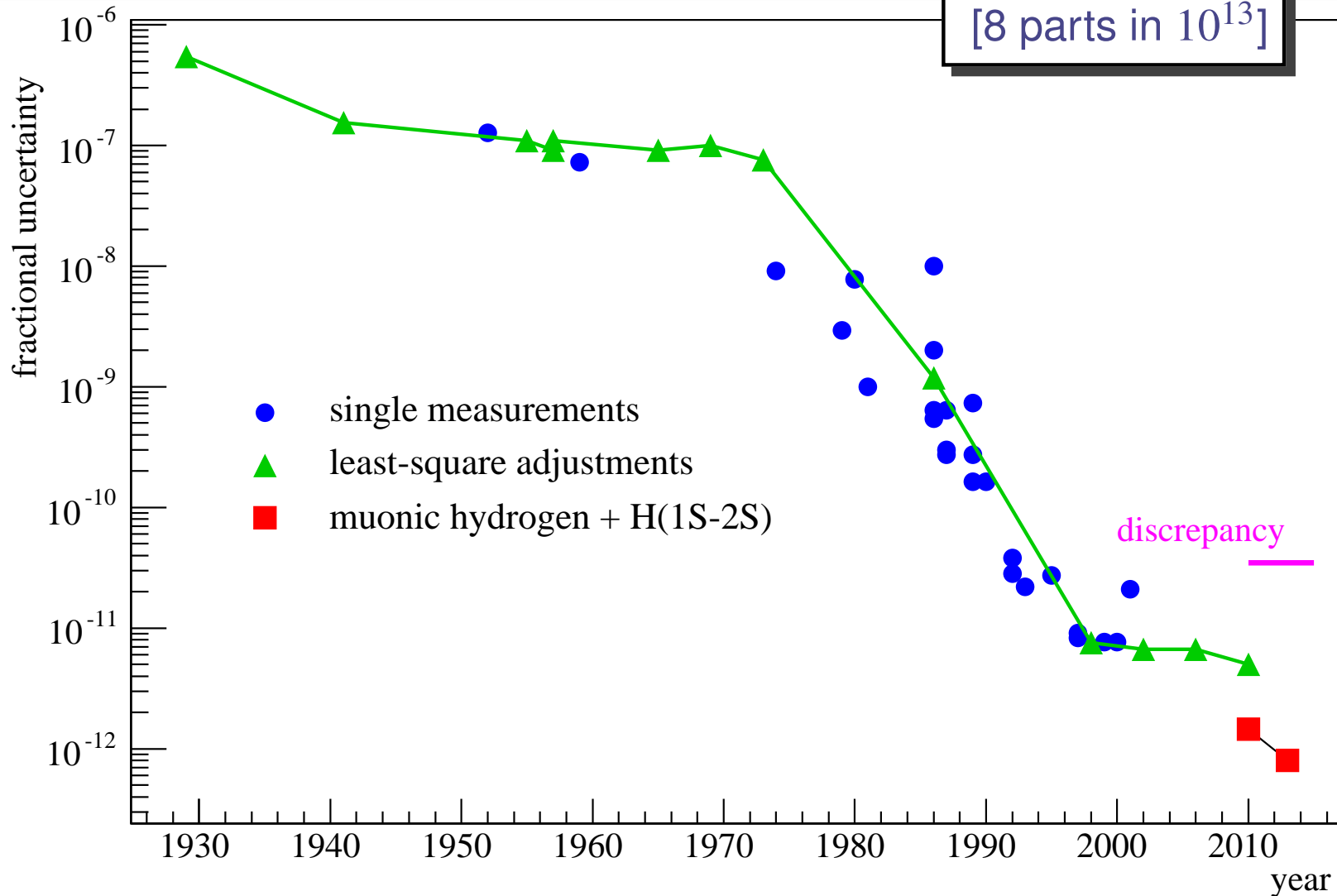
1S-2S

1S



Rydberg constant

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



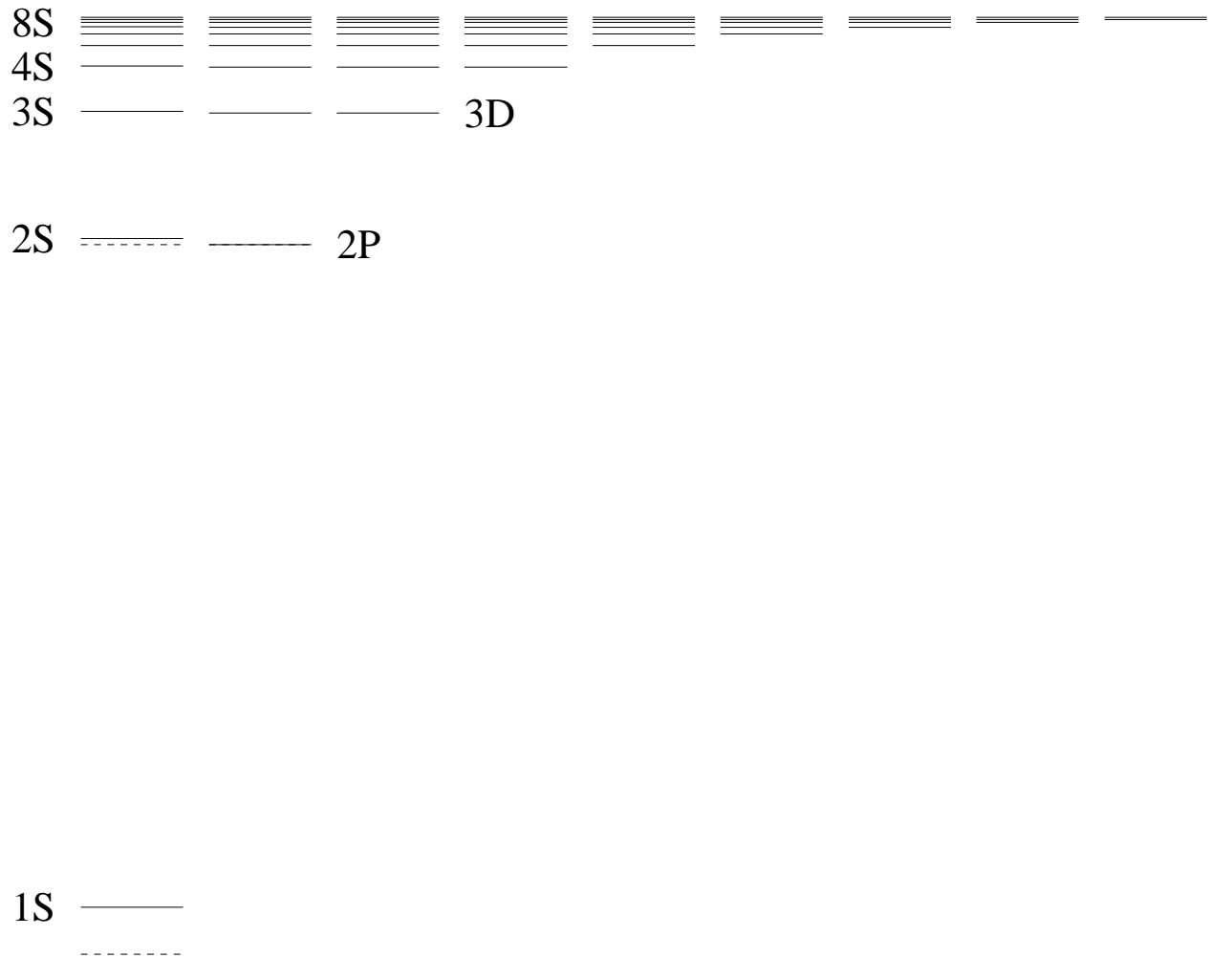
H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011).

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

Hydrogen spectroscopy

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

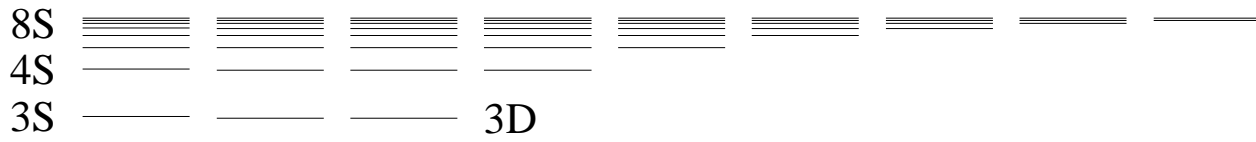
$$L_{nS} \approx \frac{L_{1S}}{n^3}$$



Hydrogen spectroscopy

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

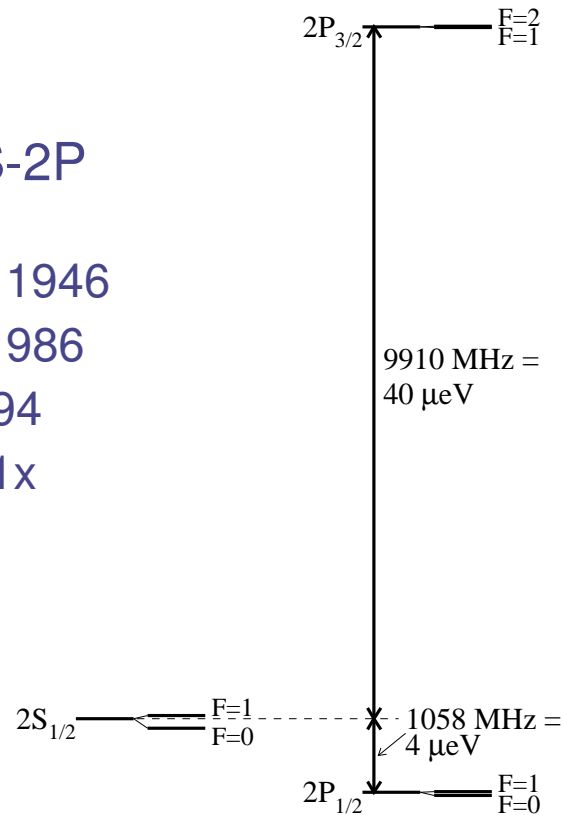
$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$



2S-2P

classical Lamb shift: 2S-2P

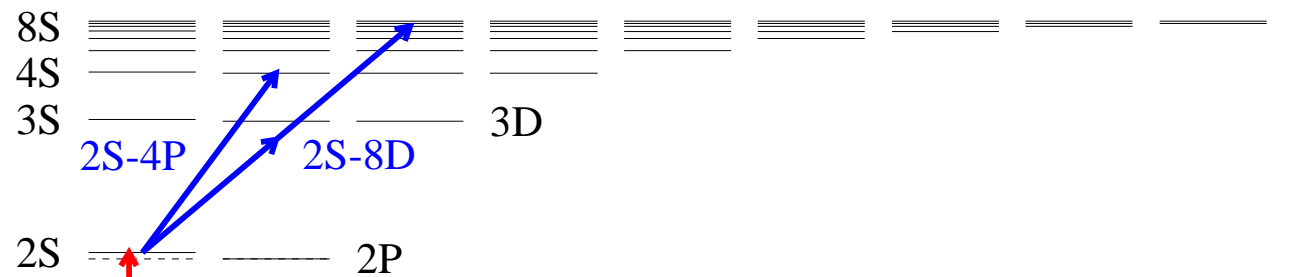
- Lamb, Retherford 1946
- Lundeen, Pipkin 1986
- Hagley, Pipkin 1994
- Hessels *et al.*, 201x



Hydrogen spectroscopy

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

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



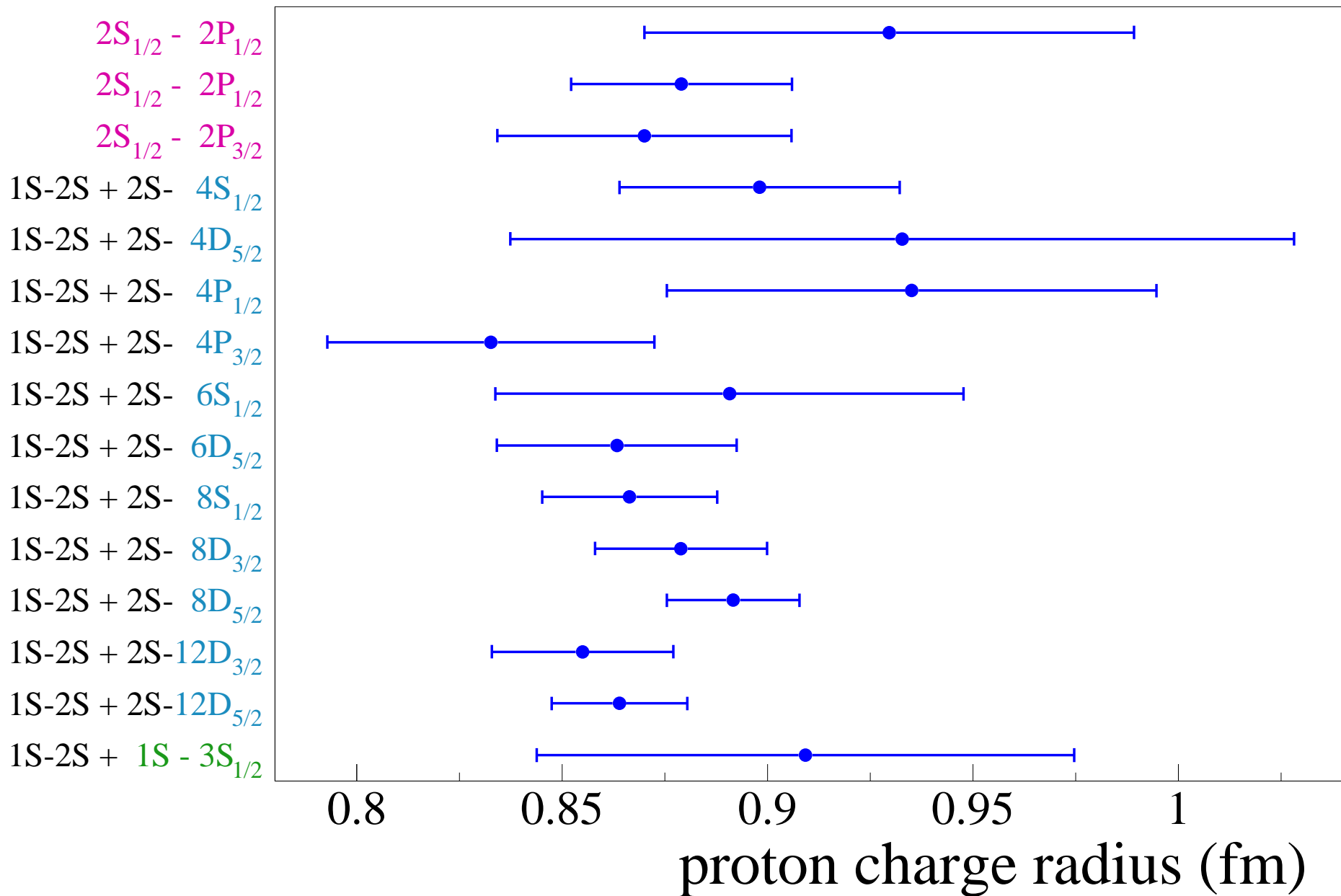
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns \Rightarrow 2 transitions

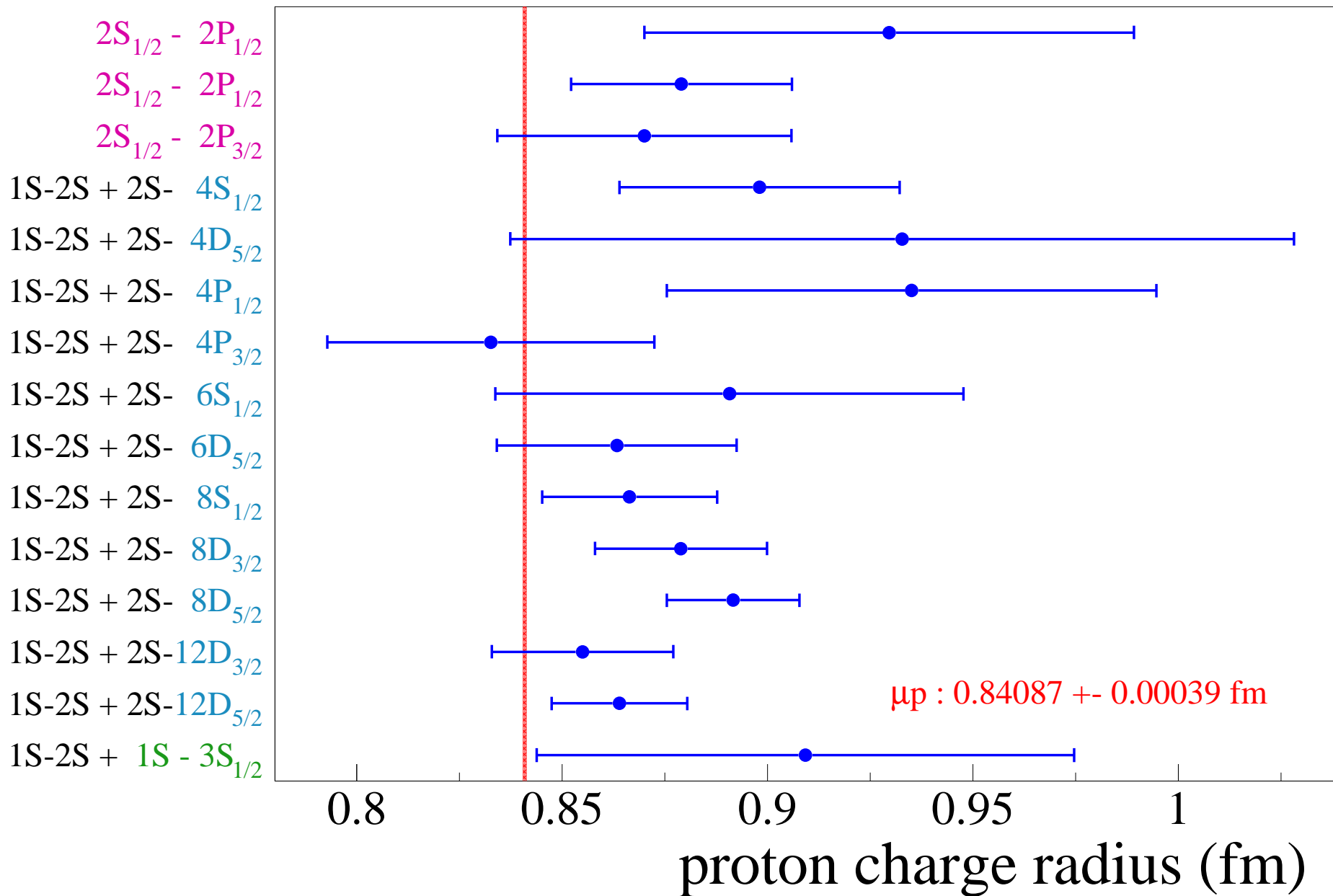
- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$



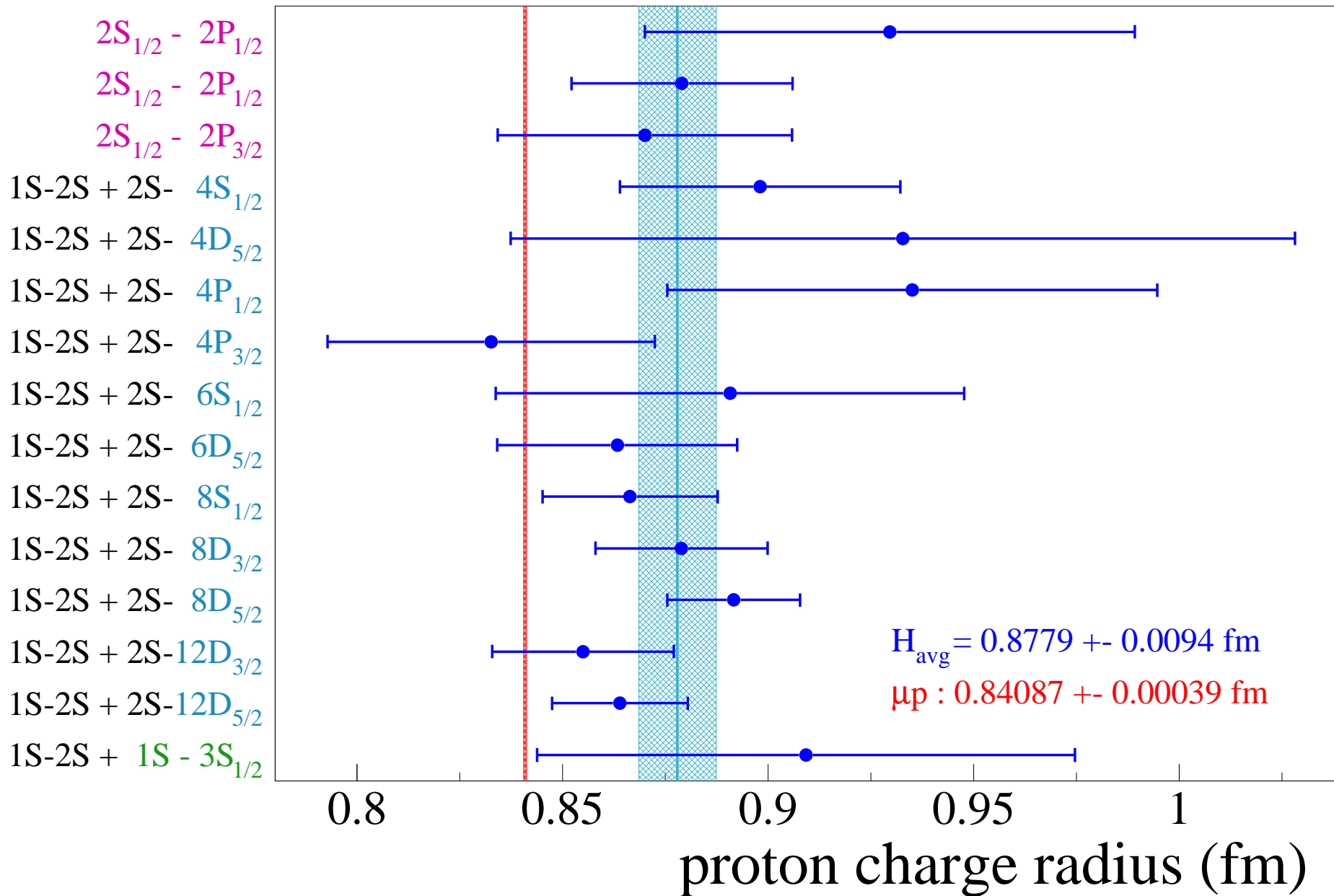
Hydrogen spectroscopy



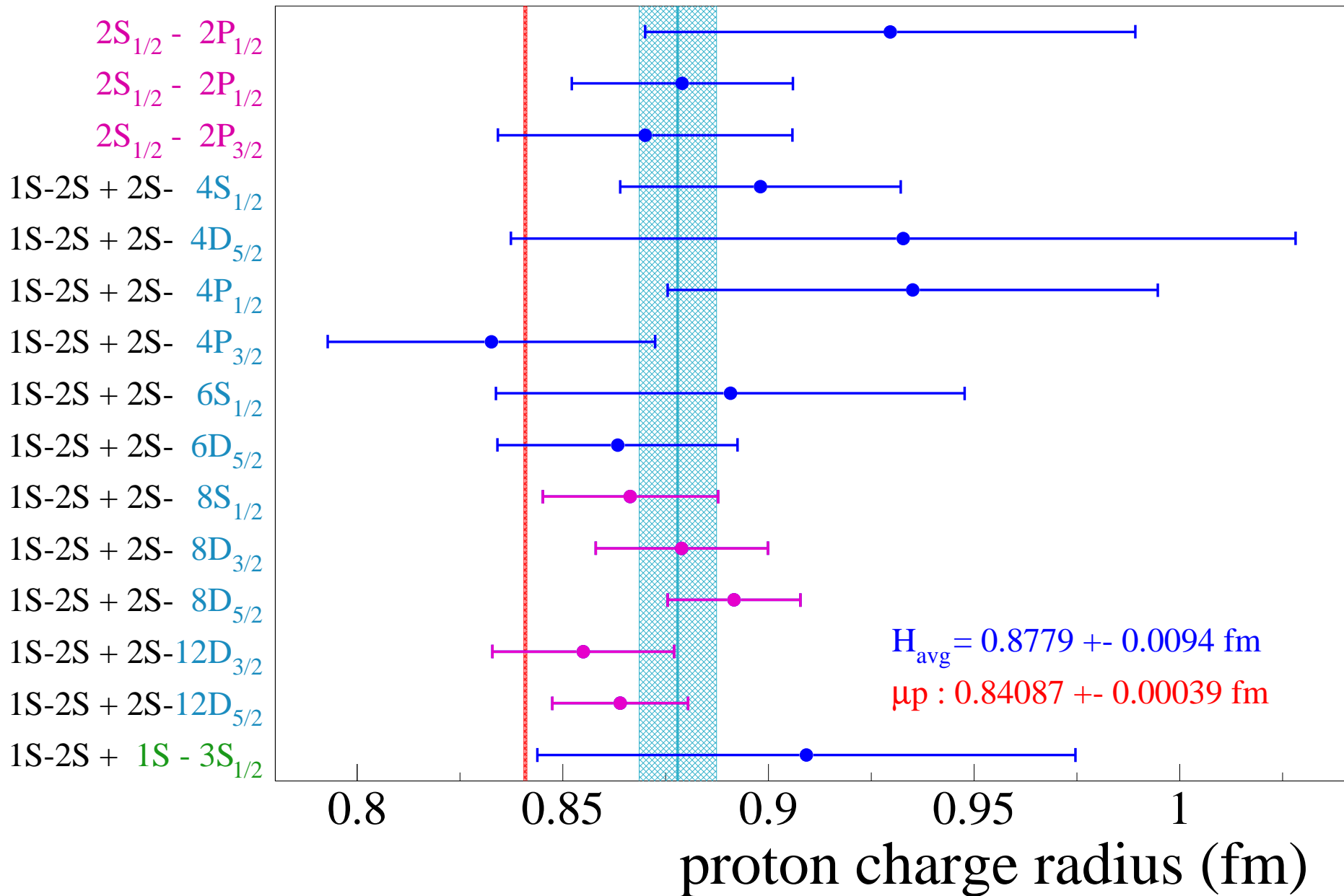
Hydrogen spectroscopy



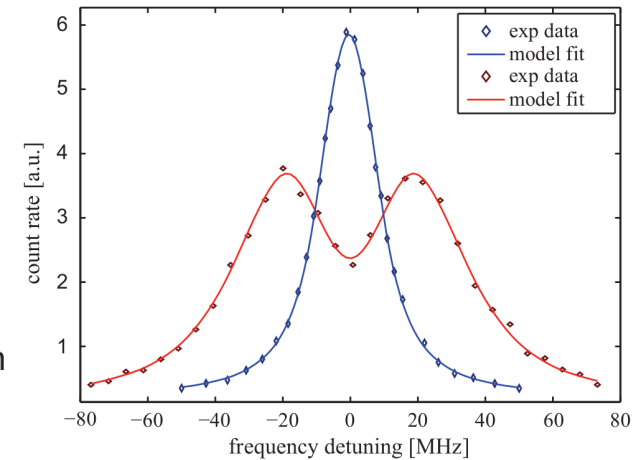
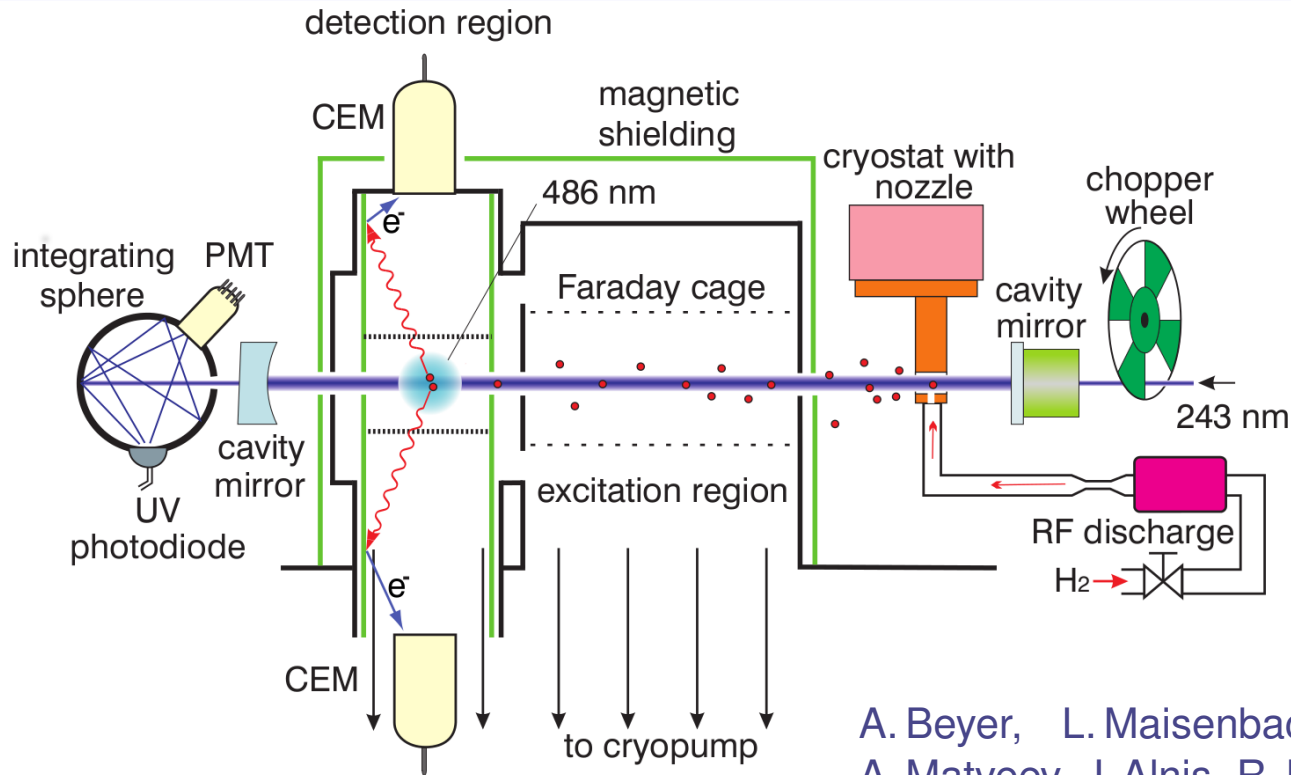
Hydrogen spectroscopy



Hydrogen spectroscopy



Rydberg constant from hydrogen



2S – 4P resonance at
 $88 \pm 0.5^\circ$ and $90 \pm 0.08^\circ$

A. Beyer, L. Maisenbacher, K. Khabarova, C.G. Parthey, A. Matveev, J. Alnis, R. Pohl, 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 order Doppler vs. ac-Stark shift
- ~ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic H beam, optical excitation to 2S**

A. Beyer, RP *et al.*, Ann. d. Phys. **525**, 671 (2013)

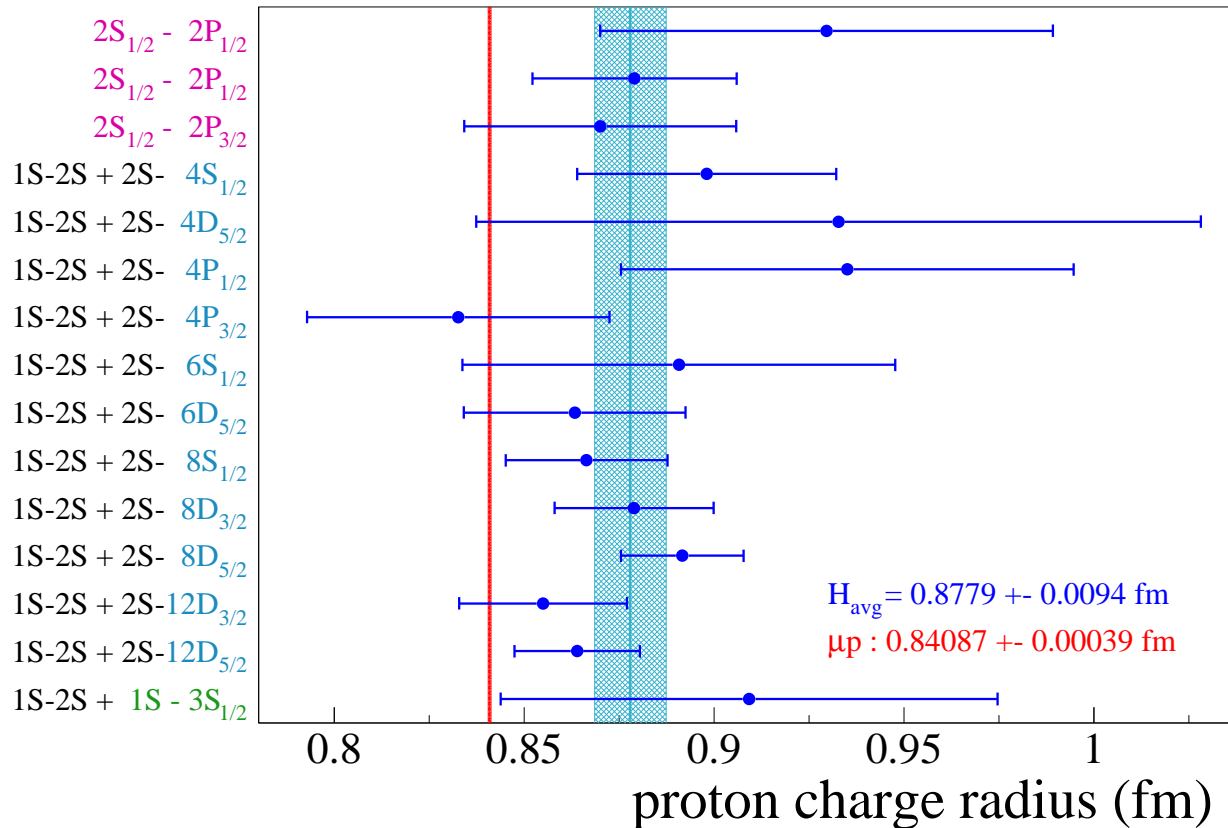
New hydrogen $2S \rightarrow 4P$ at MPQ!

Proton is small in regular hydrogen, too!

Proton radius puzzle is NOT “solved”.

Our main systematics do NOT affect the previous measurements.

—●— PRELIMINARY!



$2S \rightarrow 4P_{1/2}$ and $4P_{3/2}$

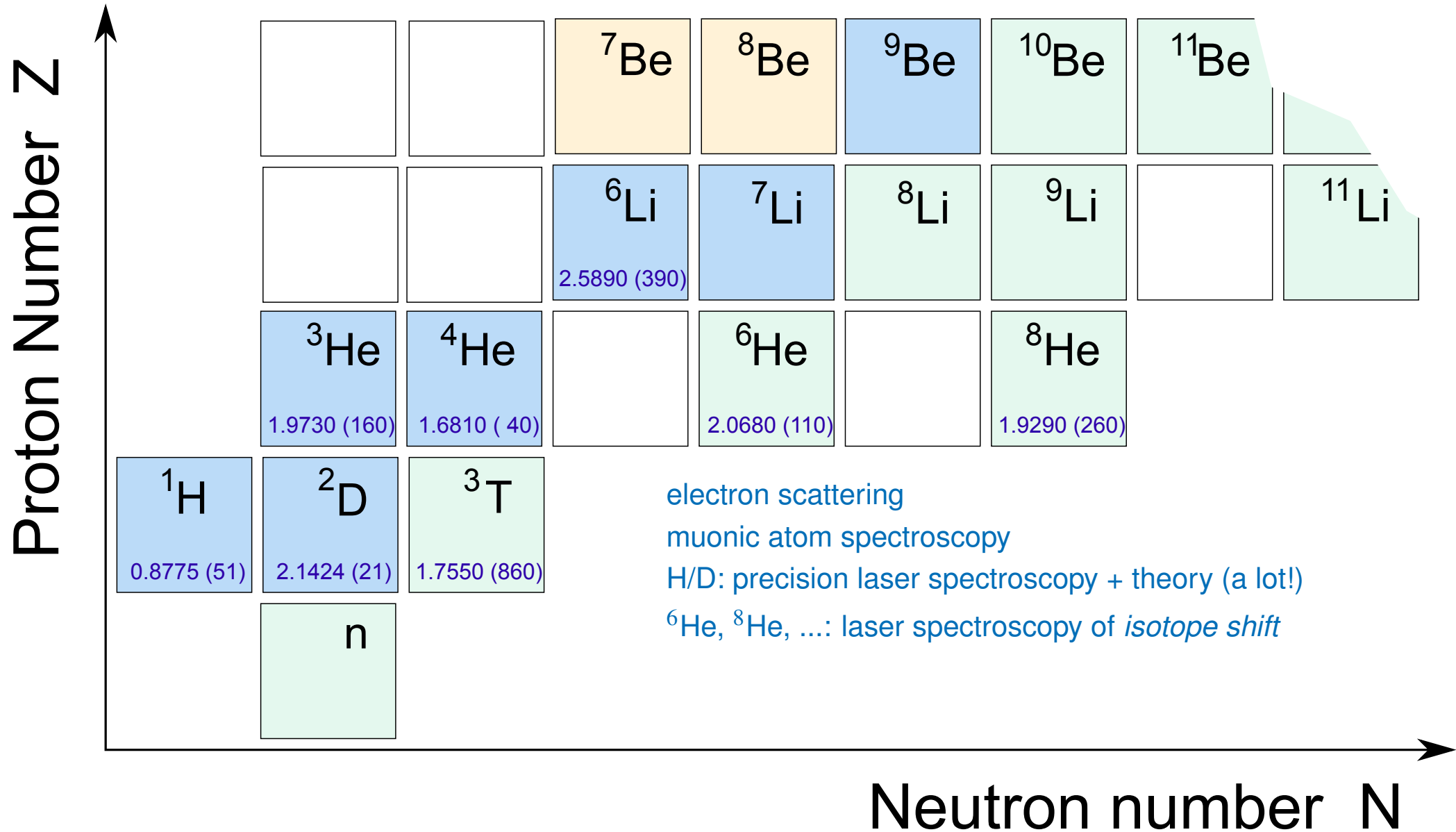
cold H(2S) beam

optically excited ($1S \rightarrow 2S$)

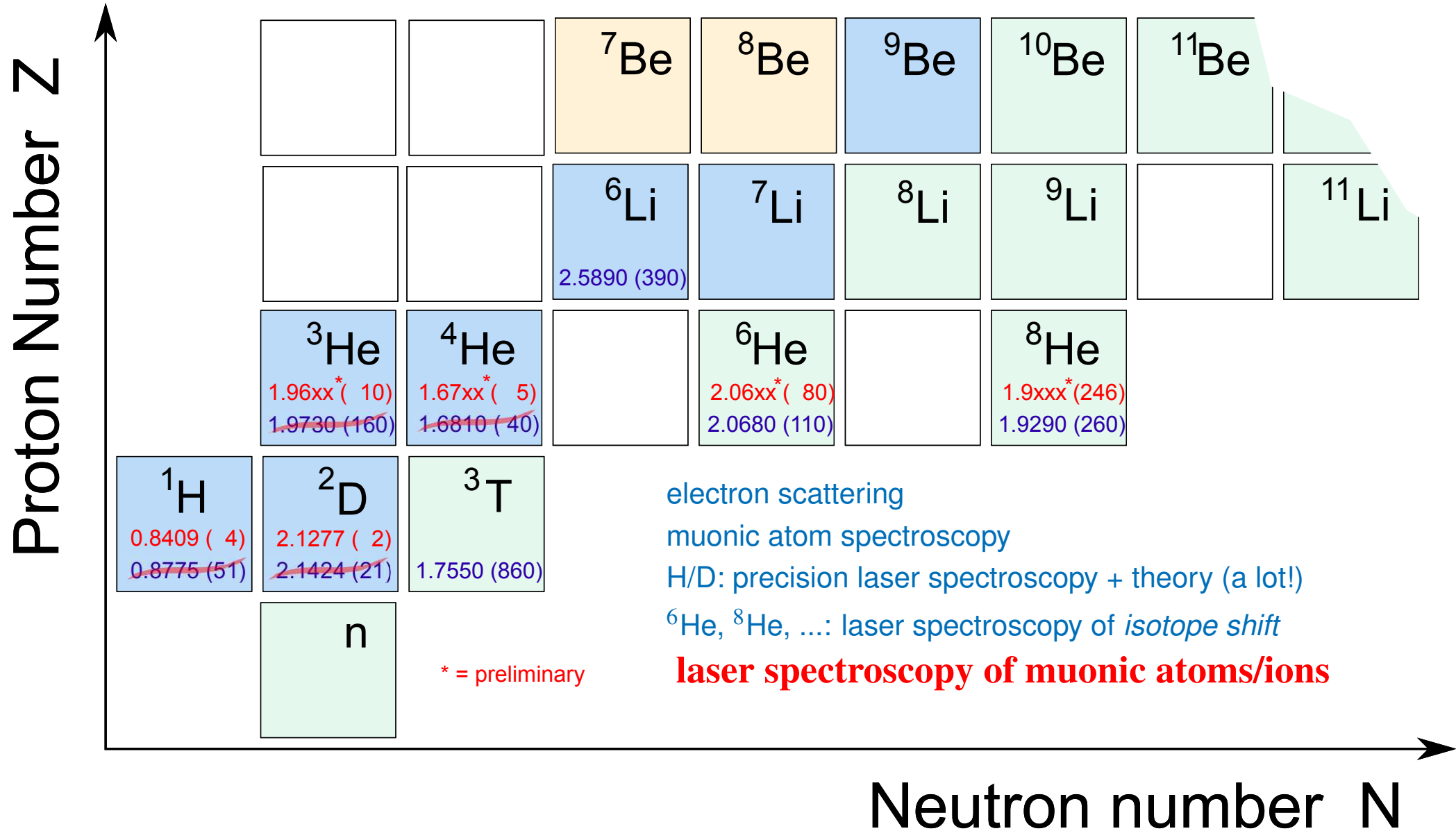
$\Delta\nu \sim 2 \text{ kHz} \equiv \Gamma/10'000$!!!

Beyer, Maisenbacher, Matveev, RP,
Khabarova, Grinin, Lamour, Yost,
Hänsch, Kolachevsky, Udem,
submitted (2016)

The nuclear chart

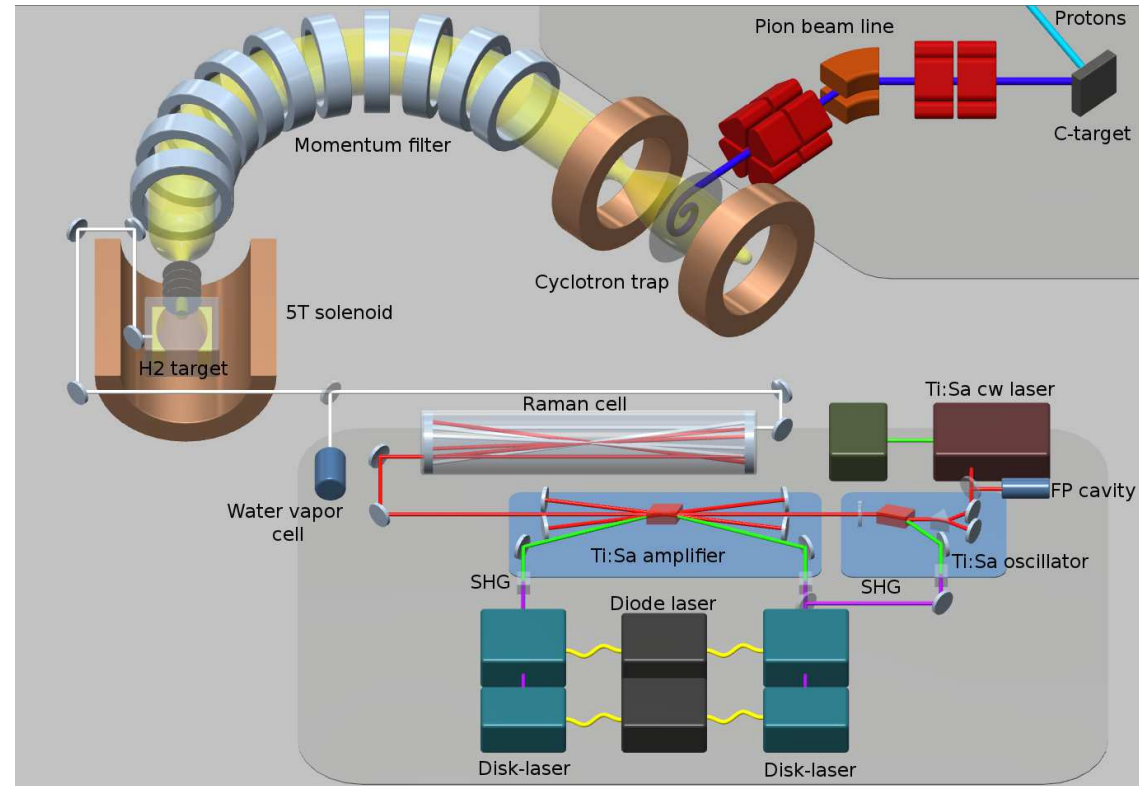


The nuclear chart - new charge radii



- Results from muonic hydrogen and deuterium:
 - Proton charge radius: $r_p = 0.84087(39)$ fm
 - Proton Zemach radius: $R_Z = 1.082(37)$ fm
 - Rydberg constant: $R_\infty = 3.2898419602495(10)r_p(25)^{\text{QED}} \times 10^{15}$ Hz/c
 - Deuteron charge radius: $r_d = 2.12771(22)$ fm from $\mu\text{H} + \text{H/D}(1\text{S}-2\text{S})$
 - The “Proton radius puzzle”
- muonic helium-3 and -4: charge radius 10x more precise. No big discrepancy
- H(2S-4P) gives revised Rydberg \Rightarrow small r_p **PRELIMINARY**
- New projects:
 - 1S-HFS in muonic hydrogen / ^3He \Leftarrow PSI, J-PARC, RIKEN-RAL, ...
 - LS in muonic Li, Be, B, T, ...; muonic high-Z, ...
 - 1S-2S and 2S- $n\ell$ in Hydrogen/Deuterium/Tritium, He^+
 - He, H_2 , HD^+ , ...
 - Positronium $\equiv e^+e^-$, Muonium $\equiv \mu^+e^-$
 - Electron scattering: H at lower Q^2 , D, He
 - Muon scattering: MUSE @ PSI
 - ...

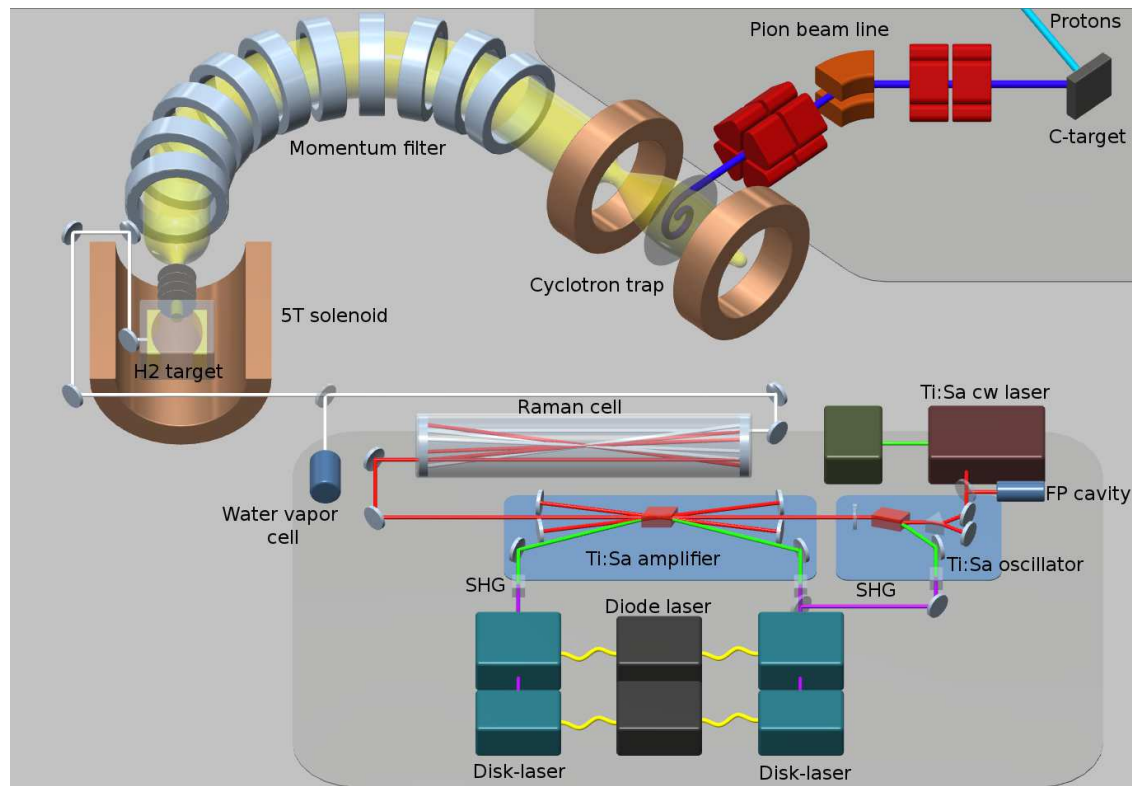
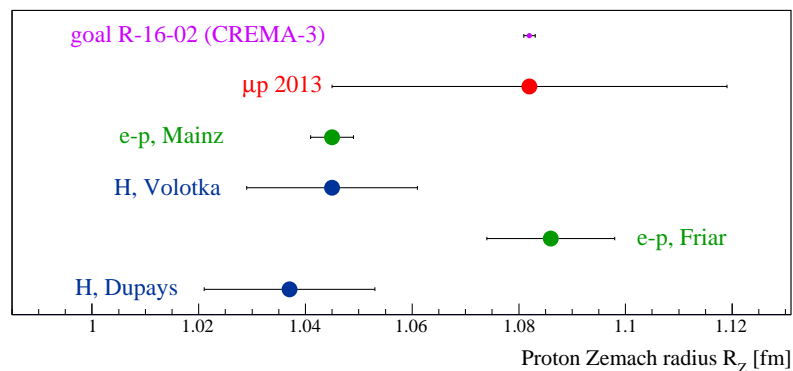
The world's most intense beam for low-energy μ^-



The world's most intense beam for low-energy μ^-

1S-HFS in μp , $\mu^3\text{He}$

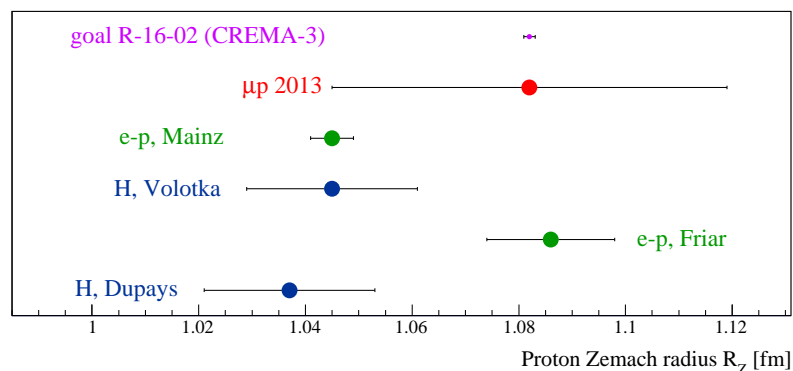
→ Zemach (magnetic) radius



The world's most intense beam for low-energy μ^-

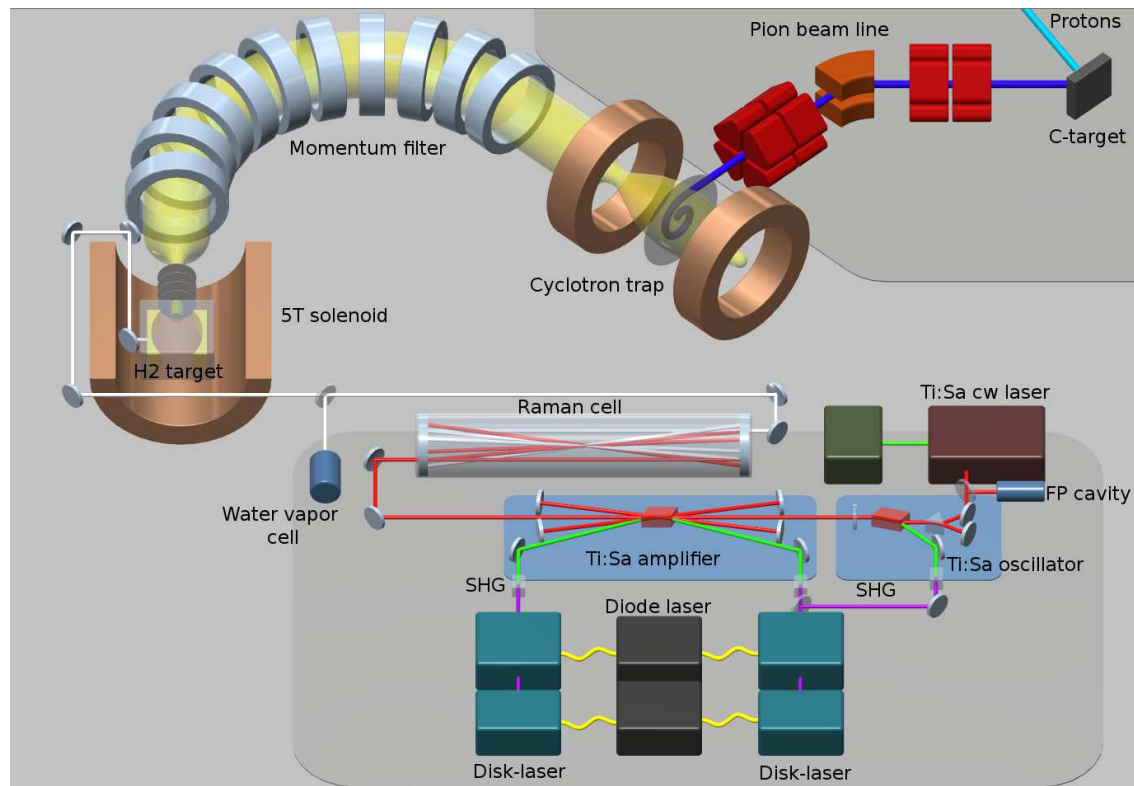
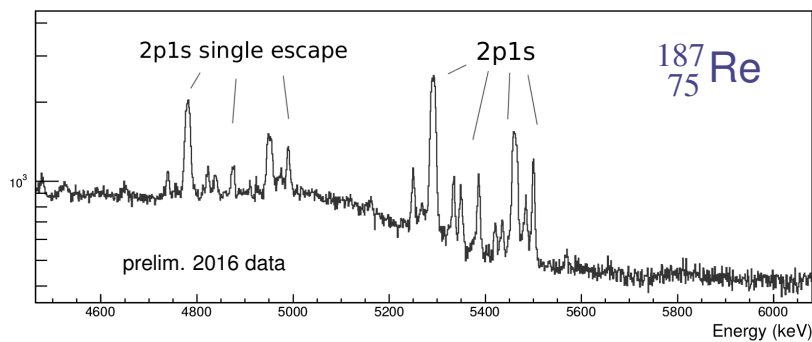
1S-HFS in μp , $\mu^3\text{He}$

→ Zemach (magnetic) radius



stop in μg of (radioactive) material

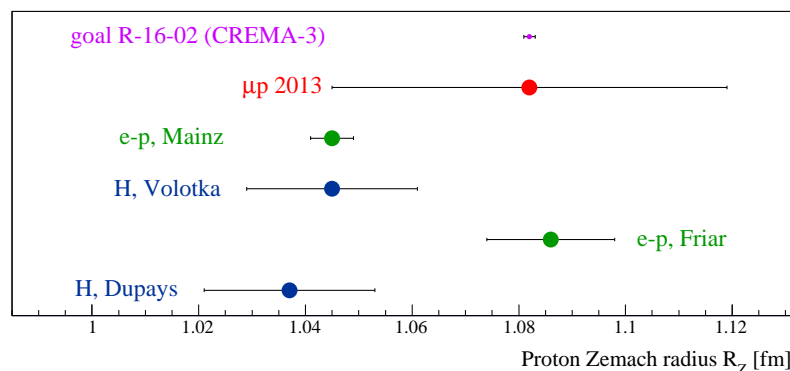
→ charge radii of higher Z



The world's most intense beam for low-energy μ^-

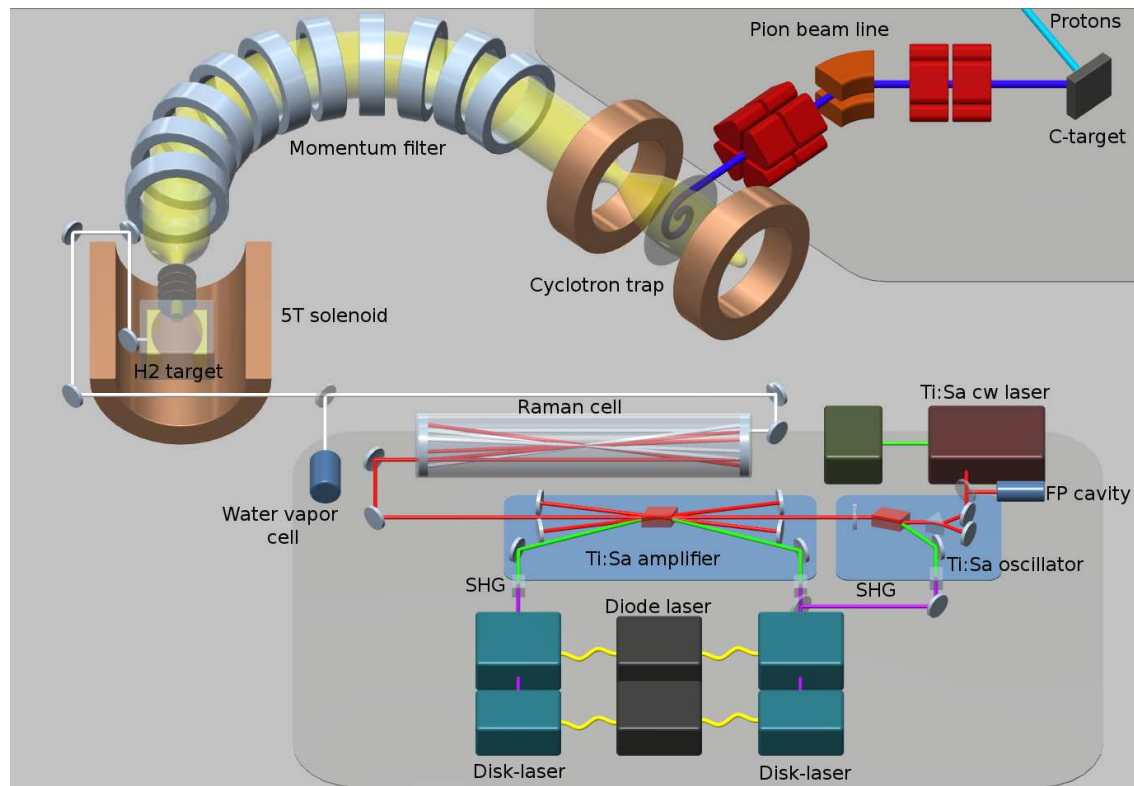
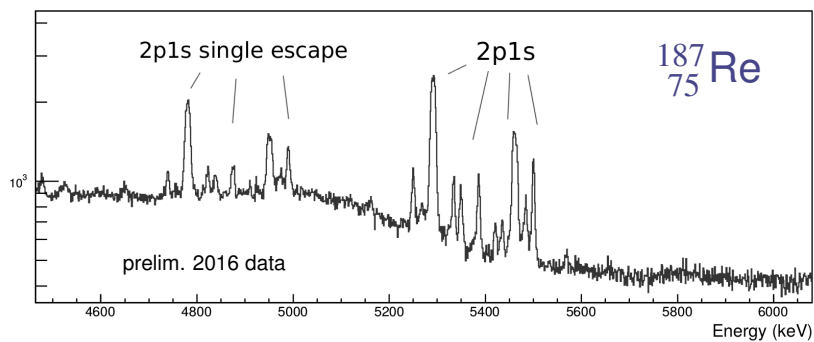
1S-HFS in μp , $\mu^3\text{He}$

→ Zemach (magnetic) radius



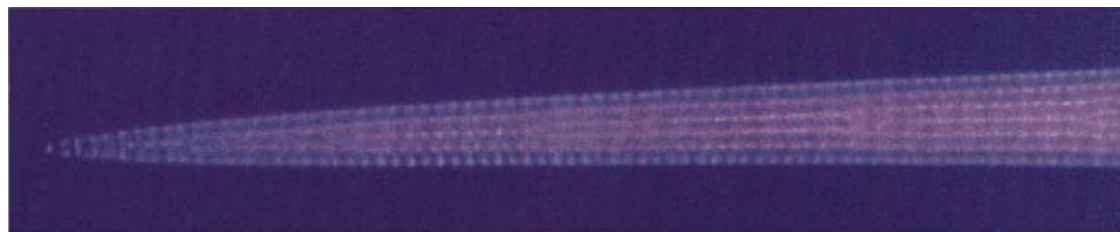
stop in μg of (radioactive) material

→ charge radii of higher Z



stop μ^- in Penning trap

→ charge radii of Li, Be, B, T



CREMA in 2009...



Proton Size Investigators thank you for your attention



... and 2014



According to **Forbes** (Jul. 2012), the Higgs discovery cost

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Cost increase for Higgs discovery: 1.06 billion USD.

My apologies.

:-)