Laboratoire Kastler Brossel
Physique quantique et applications

The proton charge radius unsolved puzzle

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LKB

CREMA: Muonic Hydrogen Collaboration

F.D Amaro, A. Antognini, F.Biraben, J.M.R. Cardoso, D.S. Covita, A. Dax, S. Dhawan,
L.M.P. Fernandes, A. Giesen, T. Graf, T.W. Hänsch, P. Indelicato, L.Julien, C.-Y. Kao,
P.E. Knowles, F. Kottmann, J.A.M. Lopes, E. Le Bigot, Y.-W. Liu, L. Ludhova,
C.M.B. Monteiro, F. Mulhauser, T. Nebel, F. Nez, R. Pohl, P. Rabinowitz,
J.M.F. dos Santos, L.A. Schaller, K. Schuhmann, C. Schwob, D. Taqqu, J.F.C.A. Veloso

EMMI

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PRINCETON UNIVERSITY

universidade de aveiro

DEPARTMENT OF PHYSICS
National Tsing Hua University

http://muhy.web.psi.ch http://www.lkb.ens.fr/-Metrology-of-simple-sistems-and-

- Description of the experiment
- spectra for μp
- specta for μd
- Theory
- Results for radii of p and d
- explanations

8 juillet 2010

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There's more to come

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The battle for survival

SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent

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The size of the proton, R. Pohl, A. Antognini, F. Nez *et al.* Nature **466,** 213-216 (2010).

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The size of the proton, R. Pohl, A. Antognini, F. Nez *et al.* Nature **466,** 213-216 (2010).

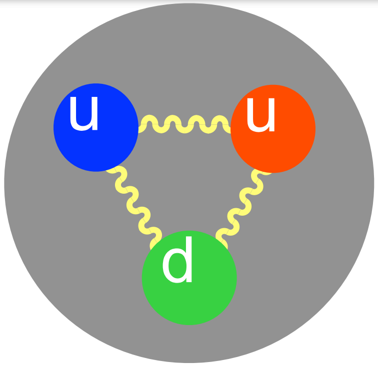
Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen, A. Antognini, F. Nez, K. Schuhmann *et al.* Science **339,** 417-420 (2013).

Form factor

A rapid definition

Proton form factor

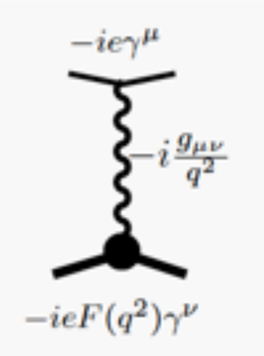
2 quarks up (2/3 e) + 1 quark down (-1/3 e) + strong interaction (gluons)



Vertex EM interaction: Dirac and Pauli Form factors
(S, P: spin and 4-momentum of nucleon, f: quark flavor)

$$\langle P', S'|V^{\mu}_{(f)}|P, S\rangle = \bar{U}(P', S')\Big[\gamma^{\mu} F_1^{(f)}(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M_N}F_2^{(f)}(Q^2)\Big]U(P, S),$$

$$V^{\mu}_{(f)} = \bar{\psi}_{(f)}\gamma^{\mu}\psi_{(f)},$$



Physical charge density are derived from the Sachs Form factors

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{(2M_N)^2}F_2(Q^2),$$

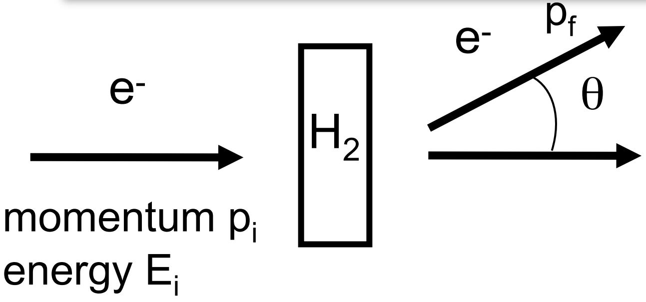
$$G_N(q^2) = \int d\boldsymbol{r}e^{-i\boldsymbol{q}\cdot\boldsymbol{r}}\frac{\rho_N(\boldsymbol{r})}{4\pi},$$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2).$$

Measure the moments of the charge distribution:

$$< r^n >= \int_0^{\infty} r^{2+n}\rho(r)dr,$$

Electron-proton scattering



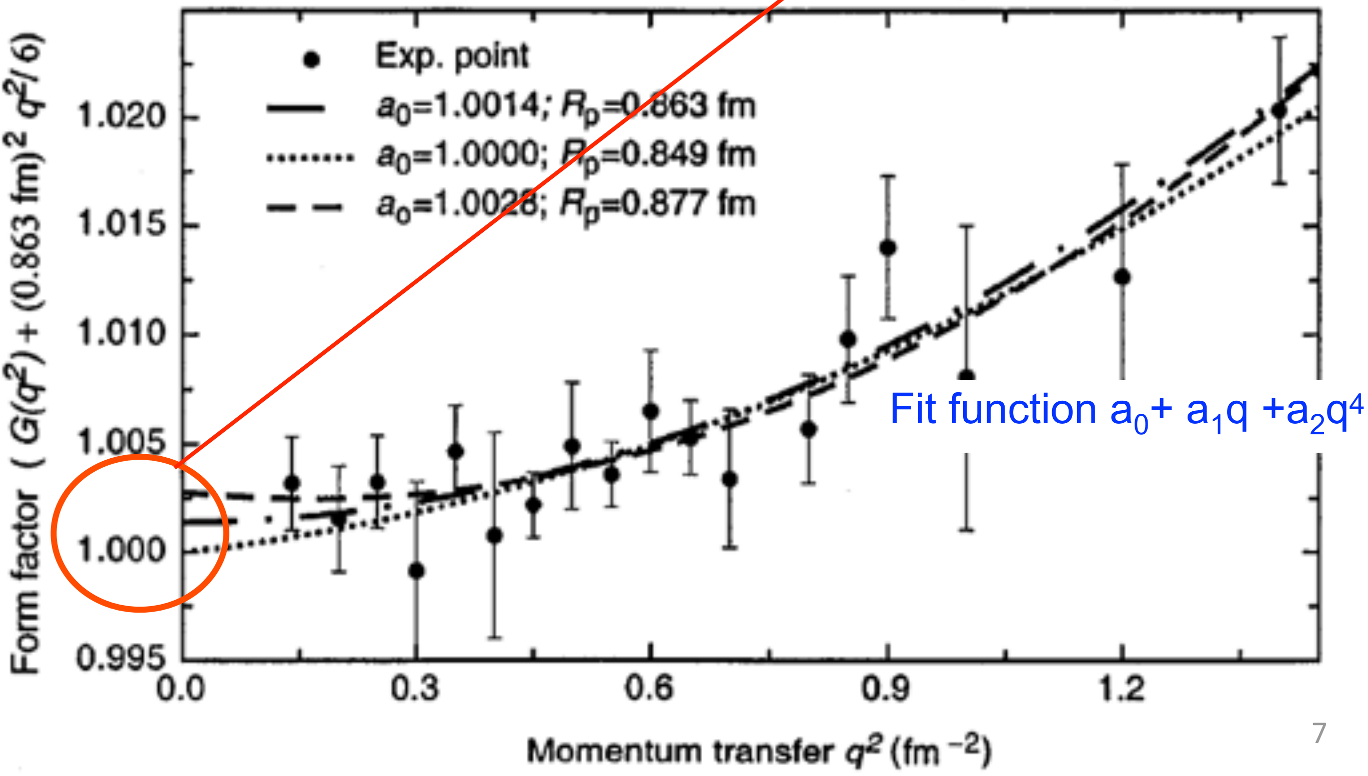
$$q = 2p_f \sin\left(\frac{\theta}{2}\right)$$

$$\vec{q} = \vec{p}_f - \vec{p}_i$$

$$G_N(q^2) = \frac{1}{\left(1 + \frac{R^2 q^2}{12}\right)^2} \approx 1 - \frac{R^2}{6} q^2 + \frac{R^4}{48} q^4 + \cdots$$

$$\frac{d\sigma(E_i,\theta)}{d\omega} = \frac{d\sigma_{\mathrm{Rut.}}(E_i,\theta)}{d\omega} G_E(q^2)$$

$$G_N(q^2) = e^{-\frac{1}{6}R^2 q^2} \approx 1 - \frac{R^2}{6} q^2 + \frac{R^4}{72} q^4 + \cdots$$



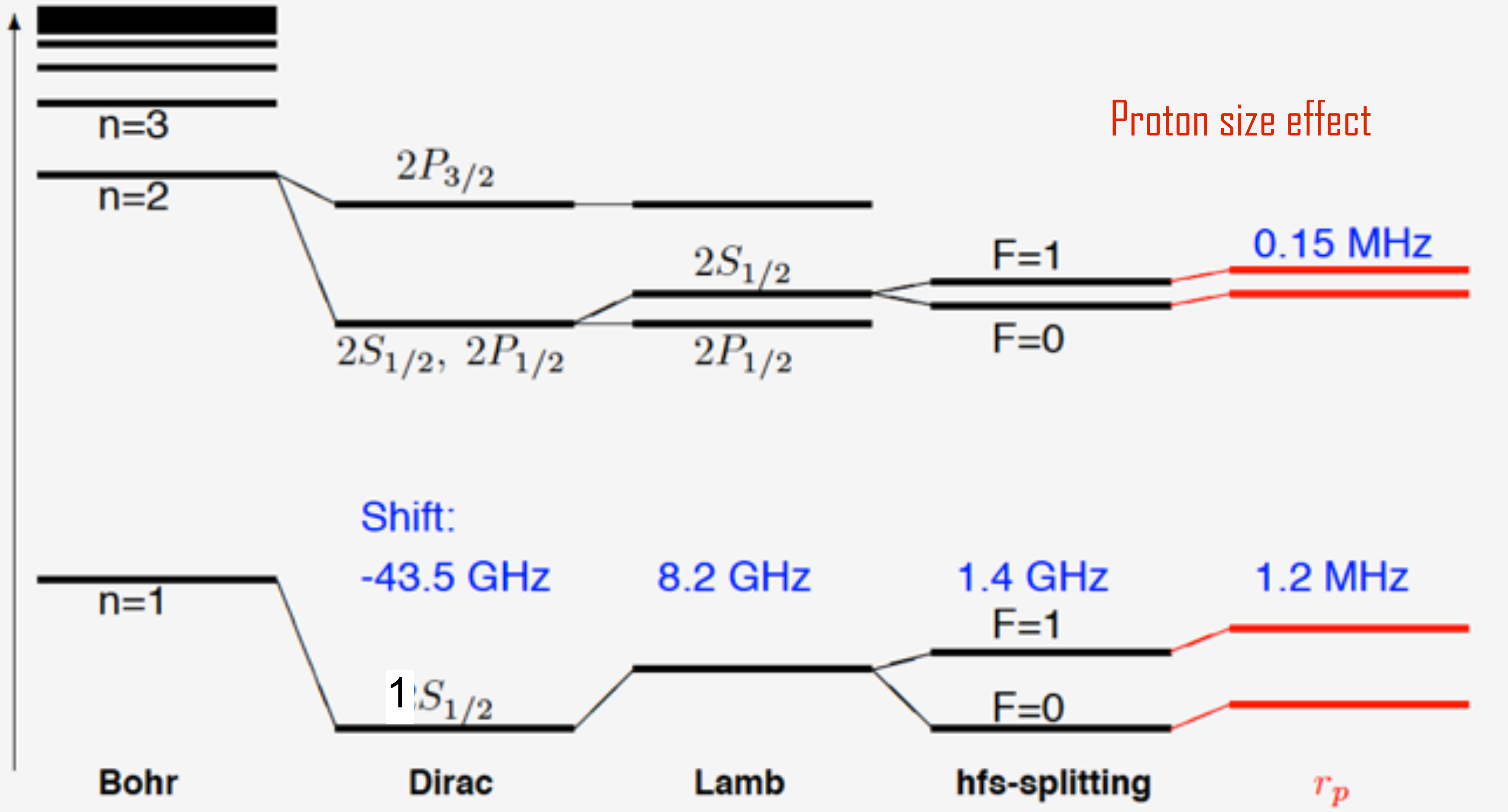
Fit function $a_0 + a_1 q + a_2 q^4$

see S. Karshenboim in Can. J. Phys. 77, 241-266 (1999) and refs therein

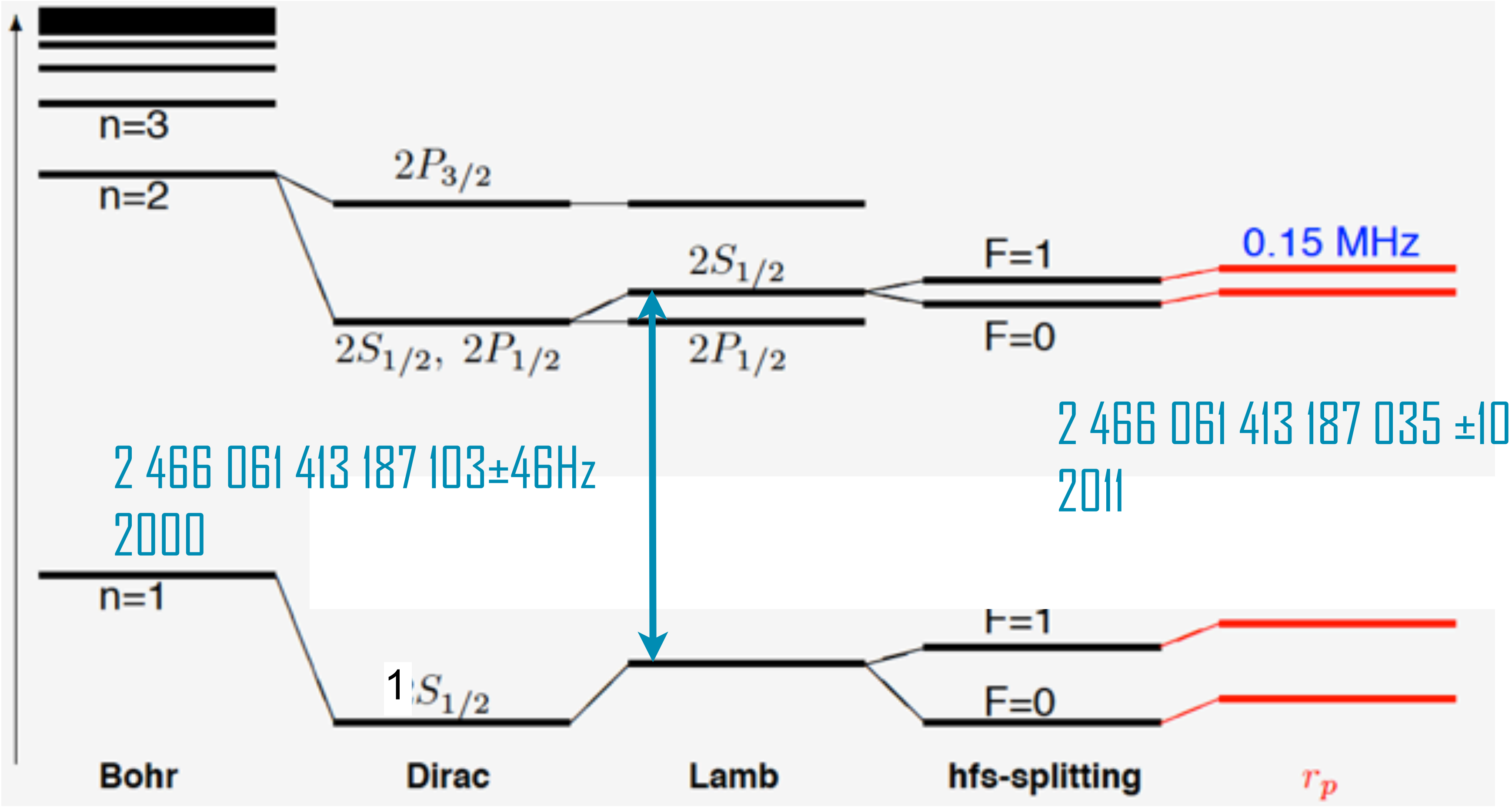
Metrology in hydrogen

Highest precision experiments

Hydrogen


Proton size effect
n=3
n=2
$2P_{3/2}$
$2S_{1/2}$
F=1
0.15 MHz
F=0
$2S_{1/2},\ 2P_{1/2}$
$2P_{1/2}$
Shift:
-43.5 GHz
8.2 GHz
1.4 GHz
1.2 MHz
n=1
F=1
$1S_{1/2}$
F=0
Bohr
Dirac
Lamb
hfs-splitting
r_p

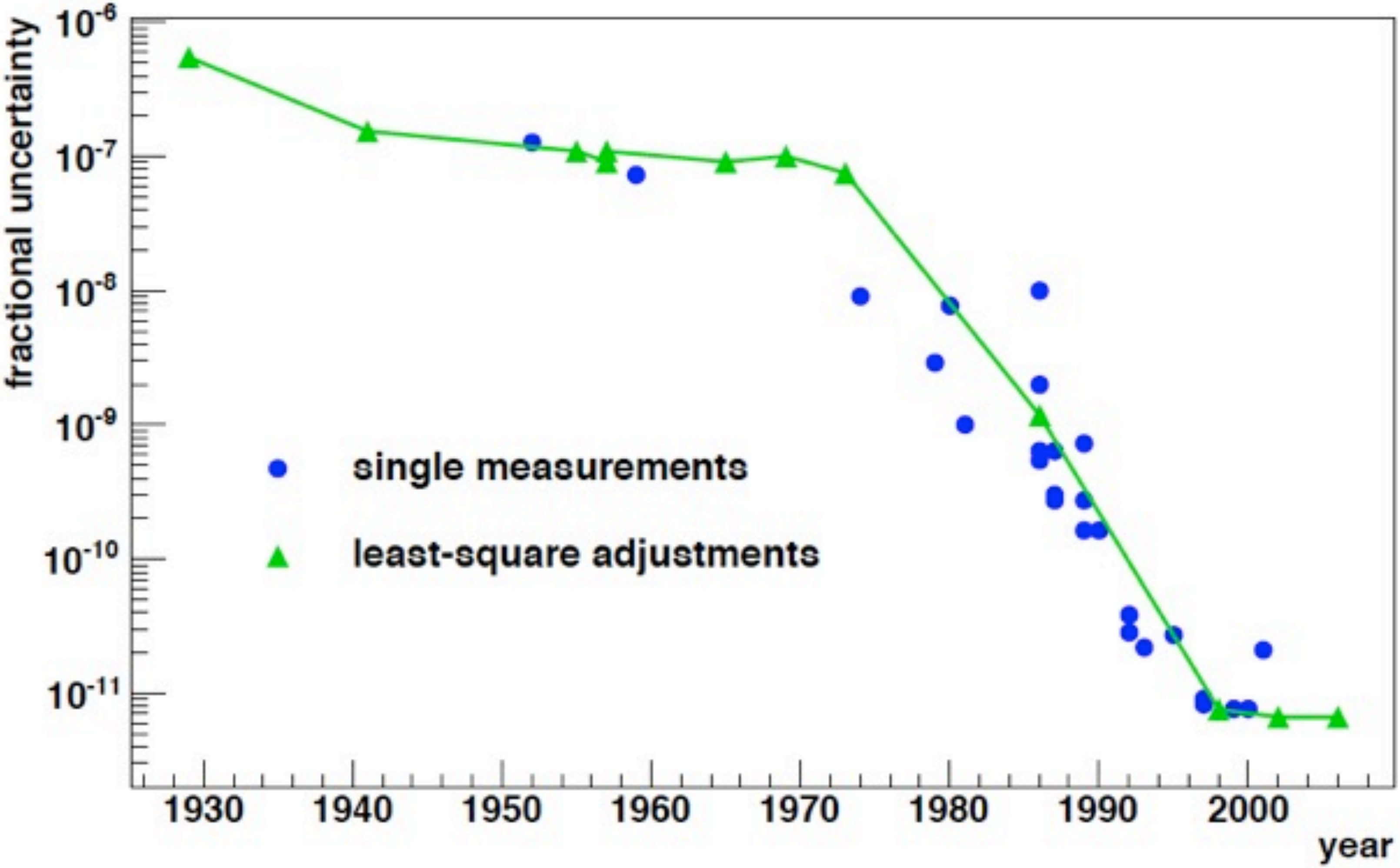
Hydrogen



2 466 061 413 187 103±46Hz
2000

2 466 061 413 187 035 ±10 Hz
2011

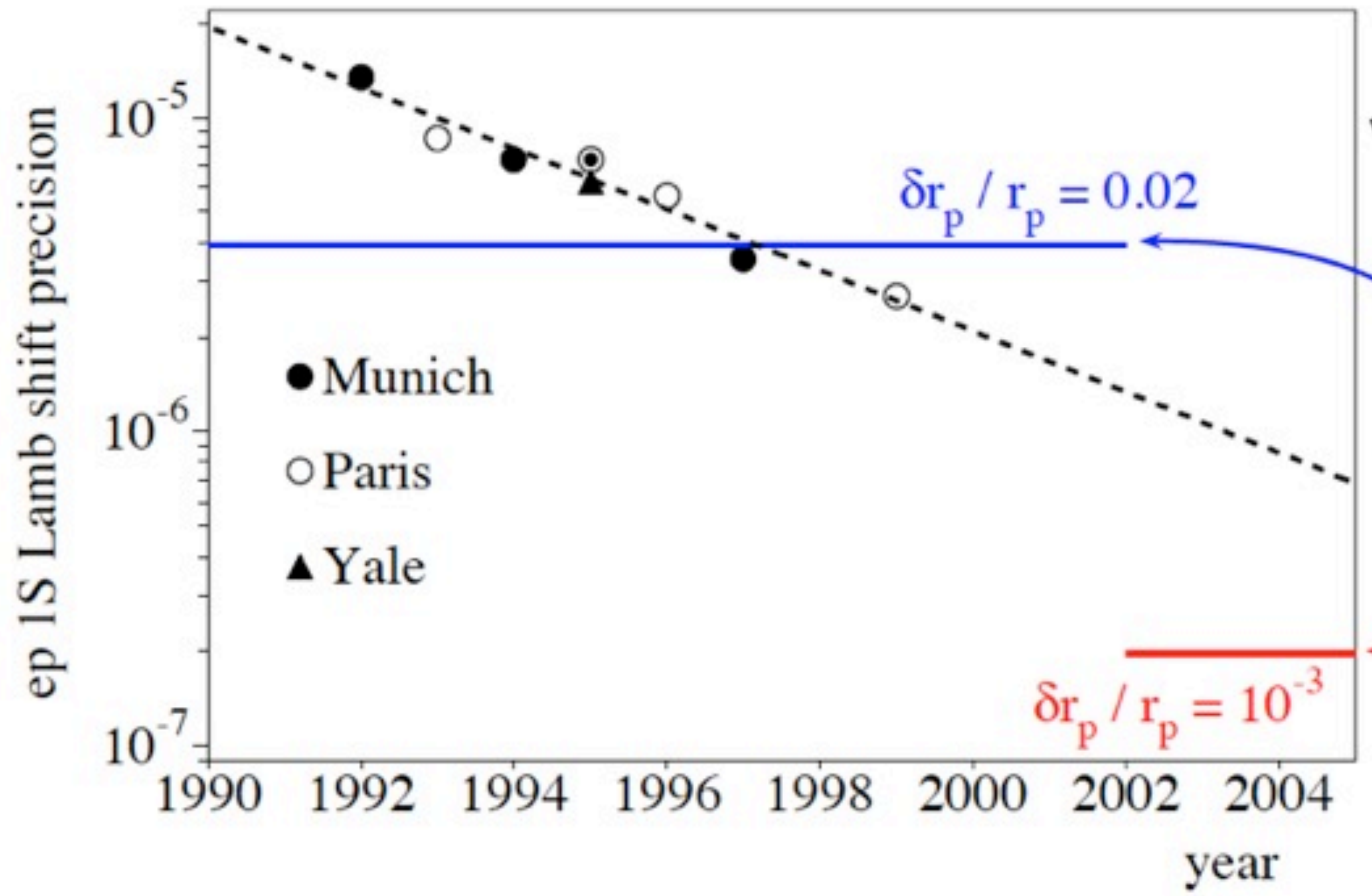
Rydberg constant



2006: R_∞ = 10 973 731.568 525 ± 0.000 073m^{-1} (ur = 6.6 x 10^{-12}) is the most accurately determined fundamental constant.

Why re-measure the proton charge radius?

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



slide from 1999

until "now"

accuracy of QED calculations

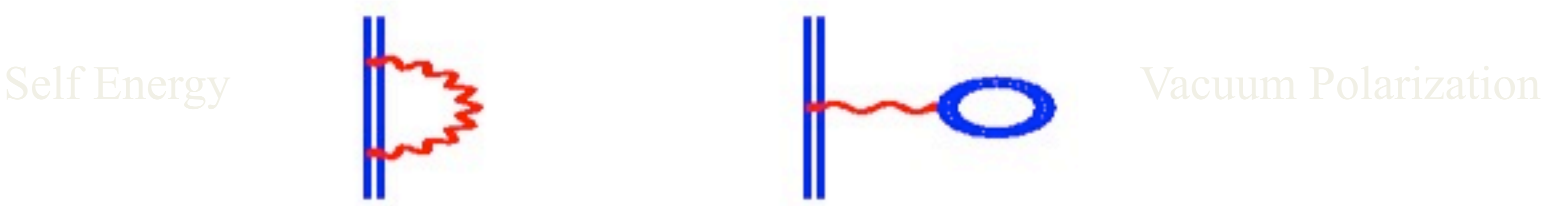
future?

QED-test is limited by the uncertainty of the proton rms charge radius.

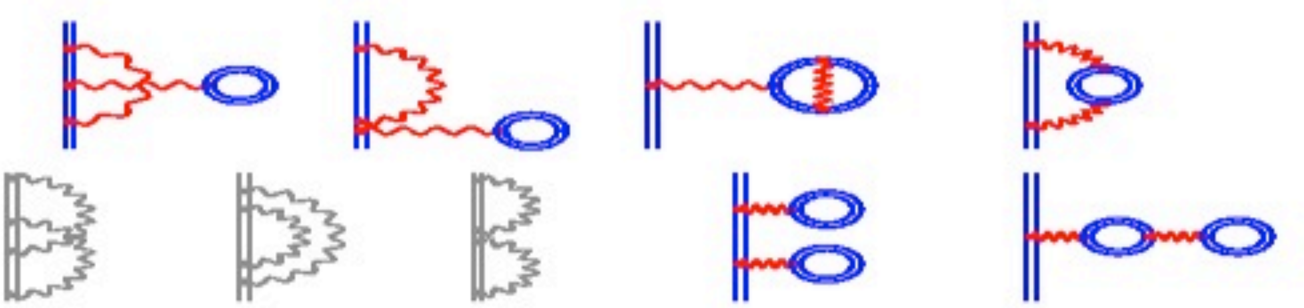
Hydrogen

QED corrections

QED at order α and α^2



H-like "One Photon" order α

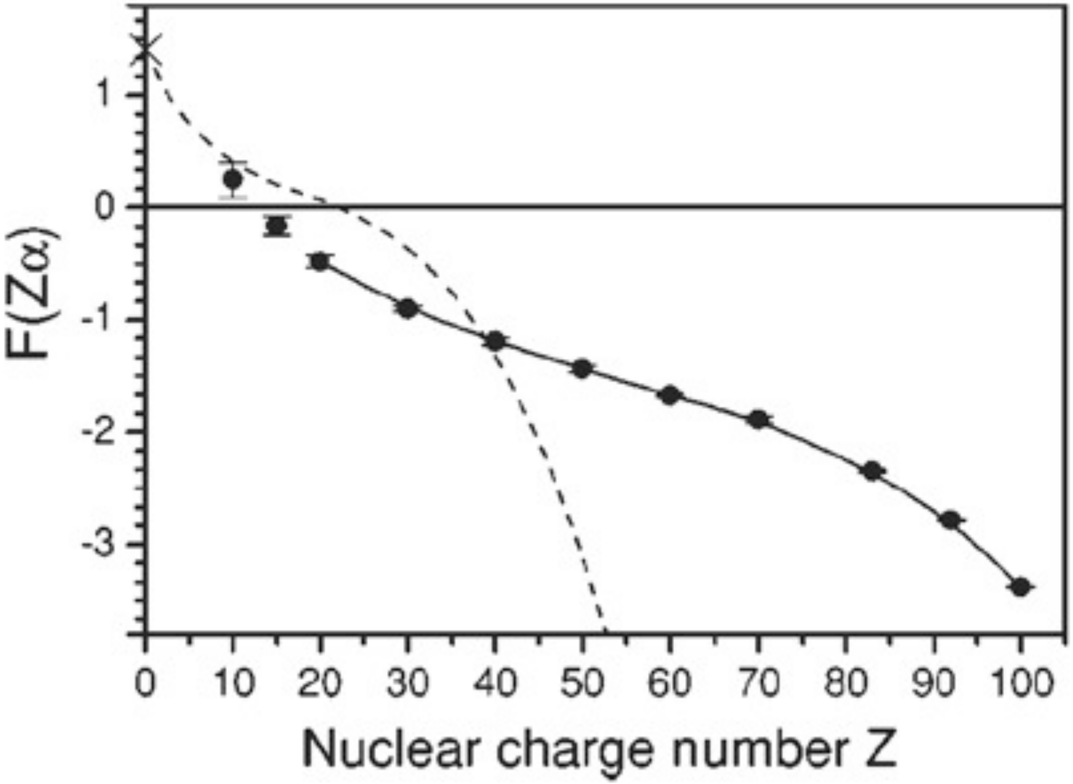


H-like "Two Photon" order α^2

Z α expansion; replace exact Coulomb propagator by expansion in number of interactions with the nucleus

Two-loop self-energy (1s)

$$\Delta E = m\left(\frac{\alpha}{\pi}\right)^2 \frac{(Z\alpha)^4}{n^3} F(Z\alpha)$$



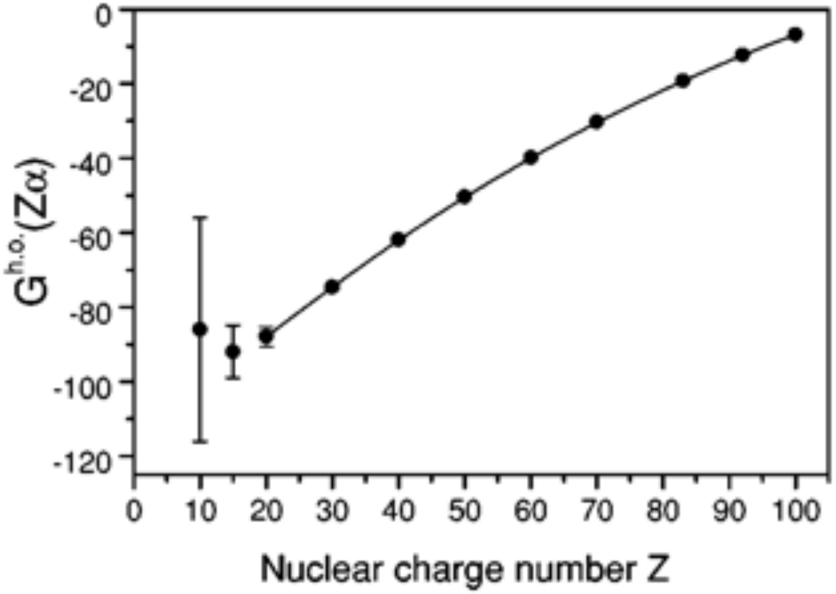
V. A. Yerokhin, P. Indelicato, and V. M. Shabaev, Phys. rev. A 71, 040101(R) (2005).

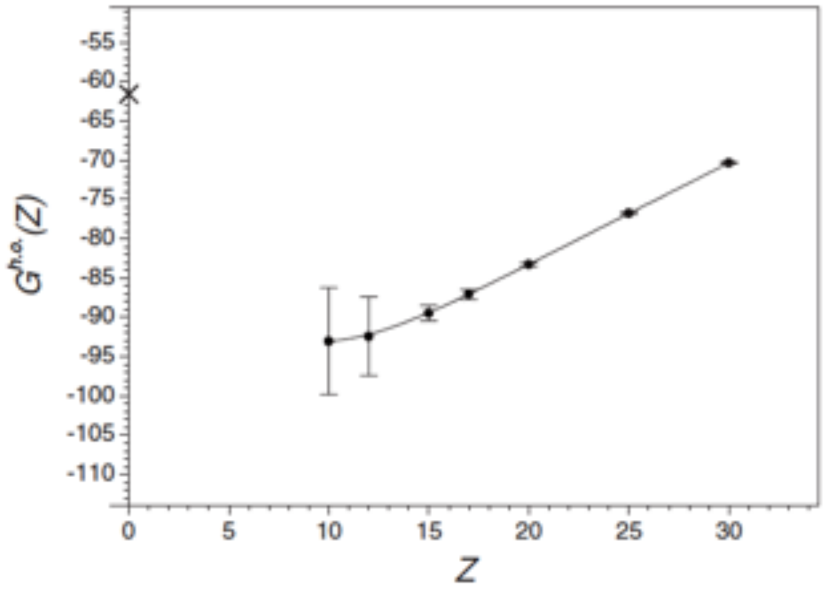
Two-loop self-energy (1s)

V. A. Yerokhin, P. Indelicato, and V. M. Shabaev, Phys. rev. A 71, 040101(R) (2005).

$$\Delta E_{\mathrm{SESE}} = m\left(\frac{\alpha}{\pi}\right)^2 (Z\alpha)^4\{B_{40} + (Z\alpha)B_{50} + (Z\alpha)^2$$

$$\times[L^3 B_{63} + L^2 B_{62} + L B_{61} + G^{\mathrm{h.o.}}_{\mathrm{SESE}}(Z)]\},$$





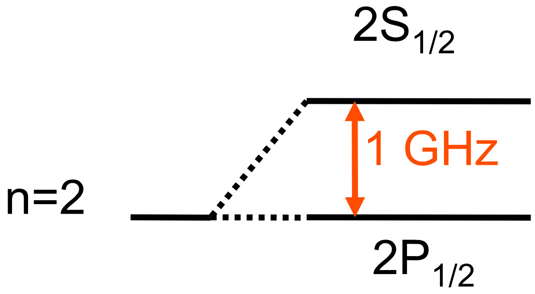
V. A. Yerokhin, Physical Review A 80, 040501 (2009)

Using muonic hydrogen

The exotic way...

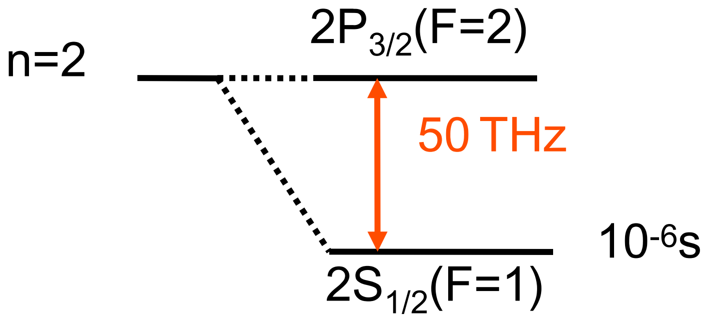
Lamb shift

Self-energy:
The heavier the particle, the smaller (in relative term) it is



Hydrogen (electron)
Effect of R: 6×10^{-11}

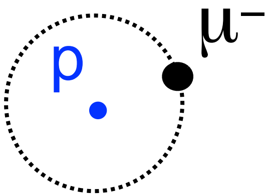
Vacuum Polarization:
The closer the particle is, the stronger it is



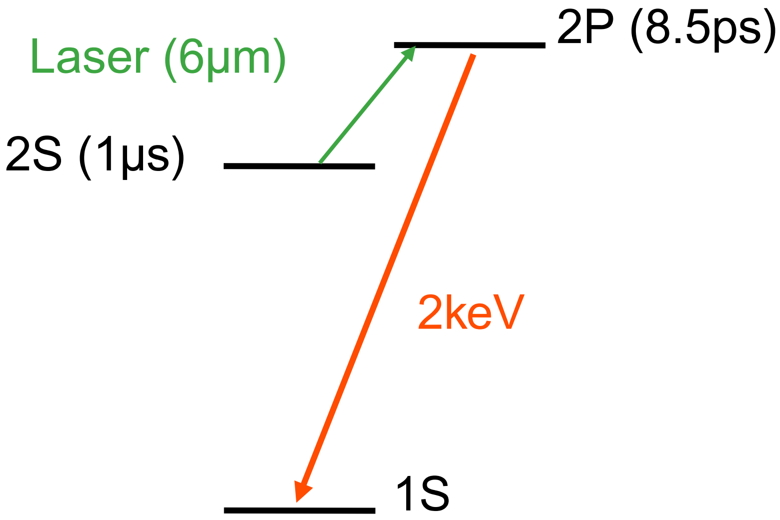
Muonic Hydrogen
(muon 207 times heavier than the electron)
Effect of R: 1.7%

muonic hydrogen 2S Lamb shift
determination of the "proton radius"

Exotic atom



Experiment



Challenges

- production of muonic hydrogen in 2S
- powerful triggerable 6μm laser
- small signal analysis

Aim : better determination of proton radius r_p

The muonic hydrogen experiment

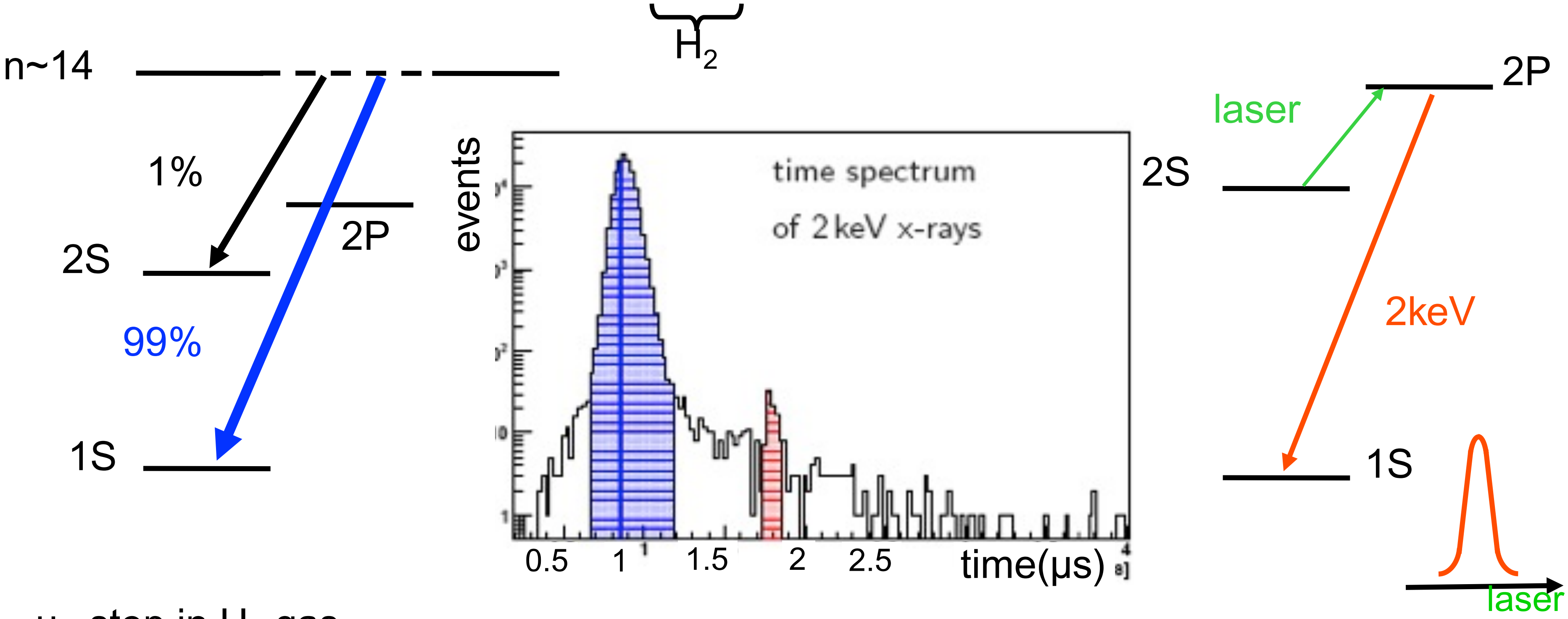
Getting up close and personal with the proton!

Principle of the experiment

“prompt” (t~0)

$ppee + \mu^- \rightarrow \mu^- p + \ldots$

“delayed” (t~1μs)



μ^- stop in H_2 gas

⇒ μp* atoms formed (n~14)

99%: cascade to 1S emitting
prompt Kα,Kβ,…

1%: long lived 2S state (τ ~ 1μs at 1mbar)

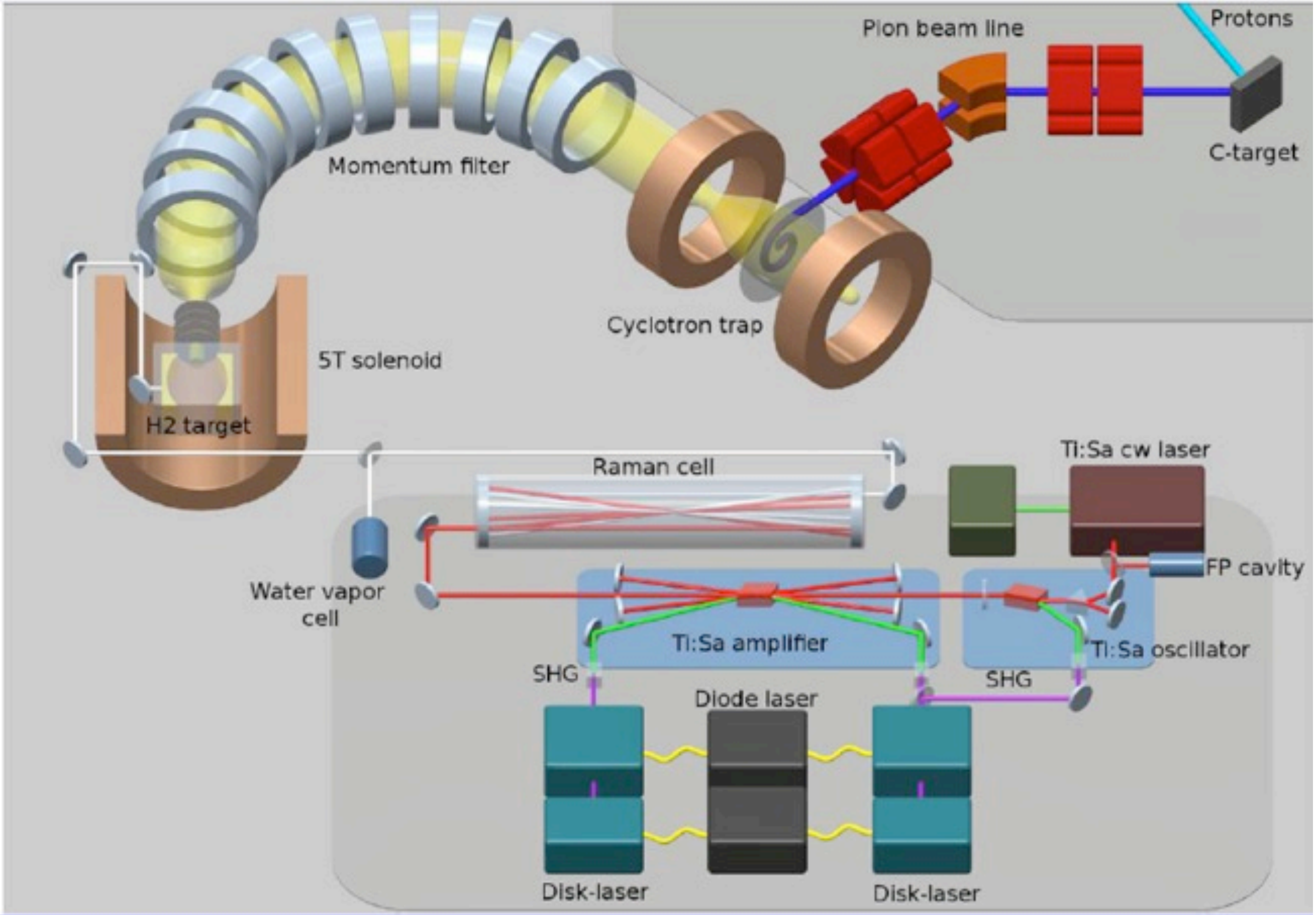
Fire laser (λ~6μm, ΔE~0.2eV)

⇒ induce μp(2S-2P)

⇒ observe delayed Kα x-rays

⇒ normalize $\frac{\text{delayed K}\alpha}{\text{prompt K}\alpha}$ x-rays

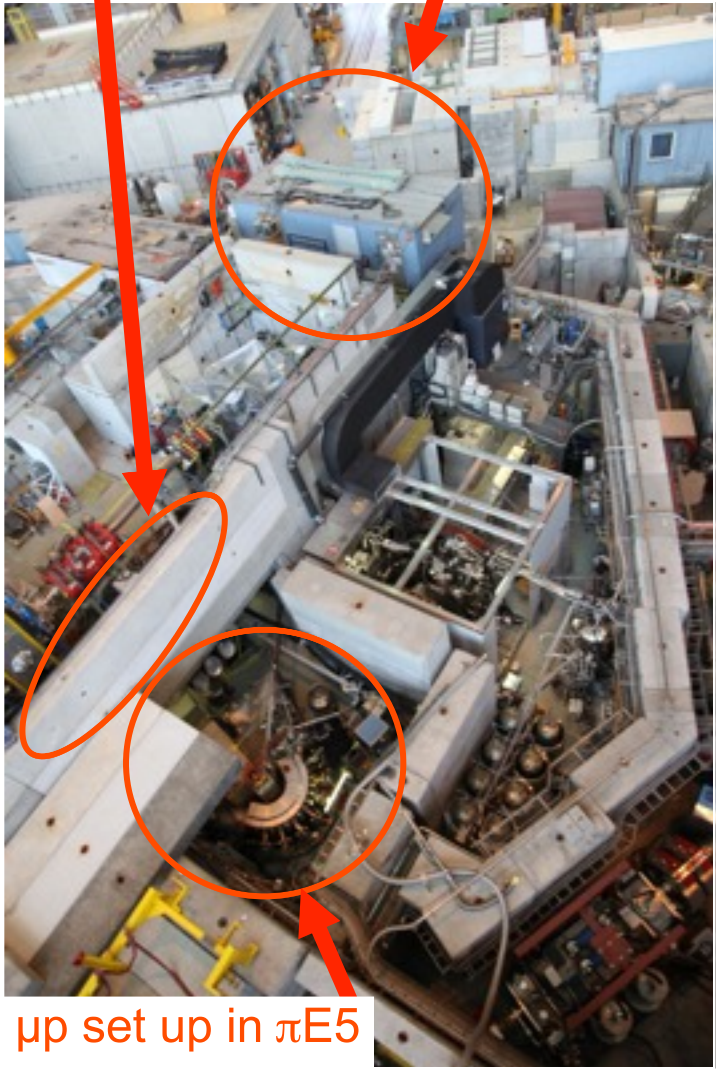
Experimental set-up



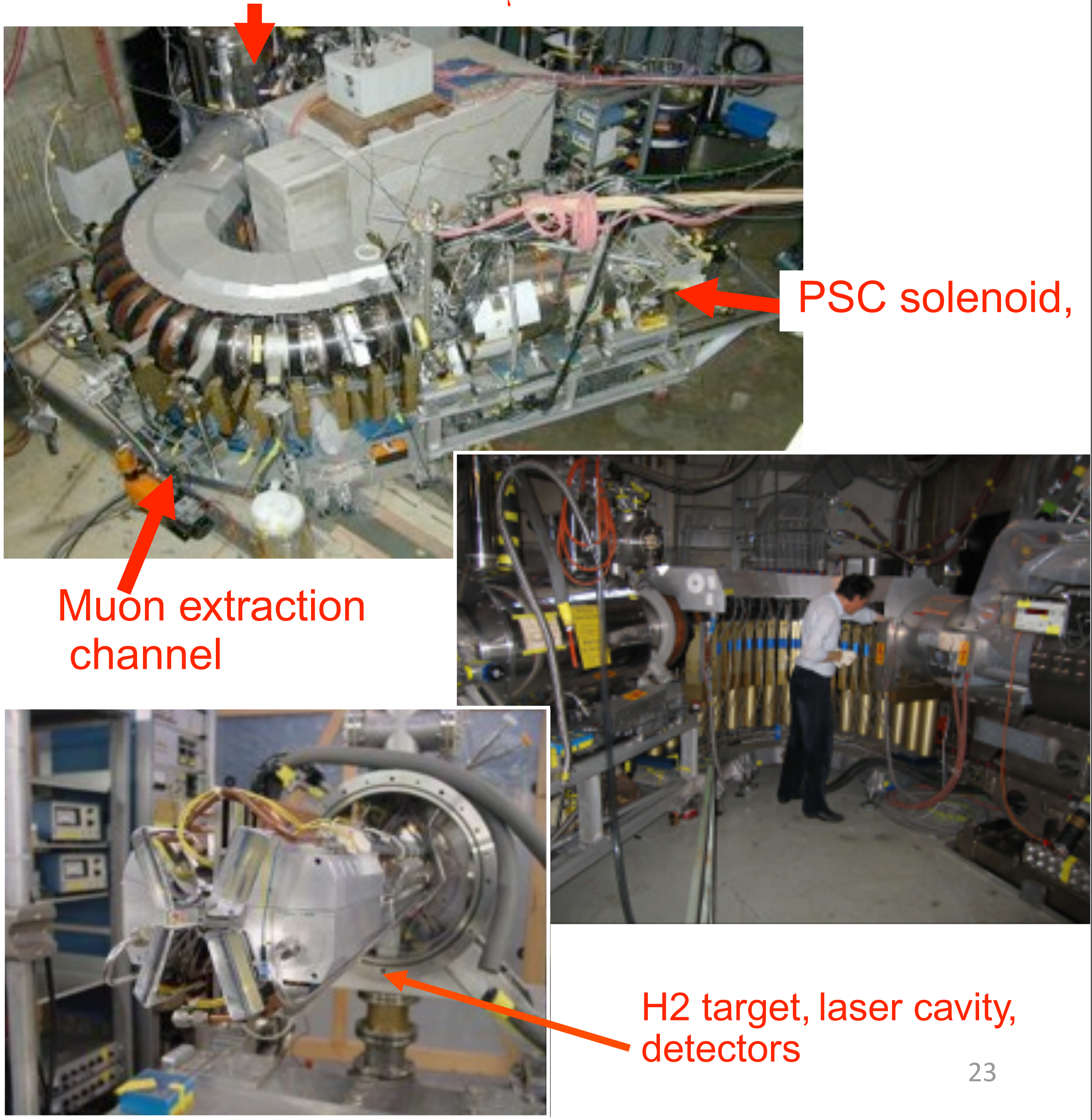
muon beam apparatus

laser hut
below
concrete blocks

counting room



μp set up in πE5



$\pi^- \rightarrow \mu^- + \nu_\mu$

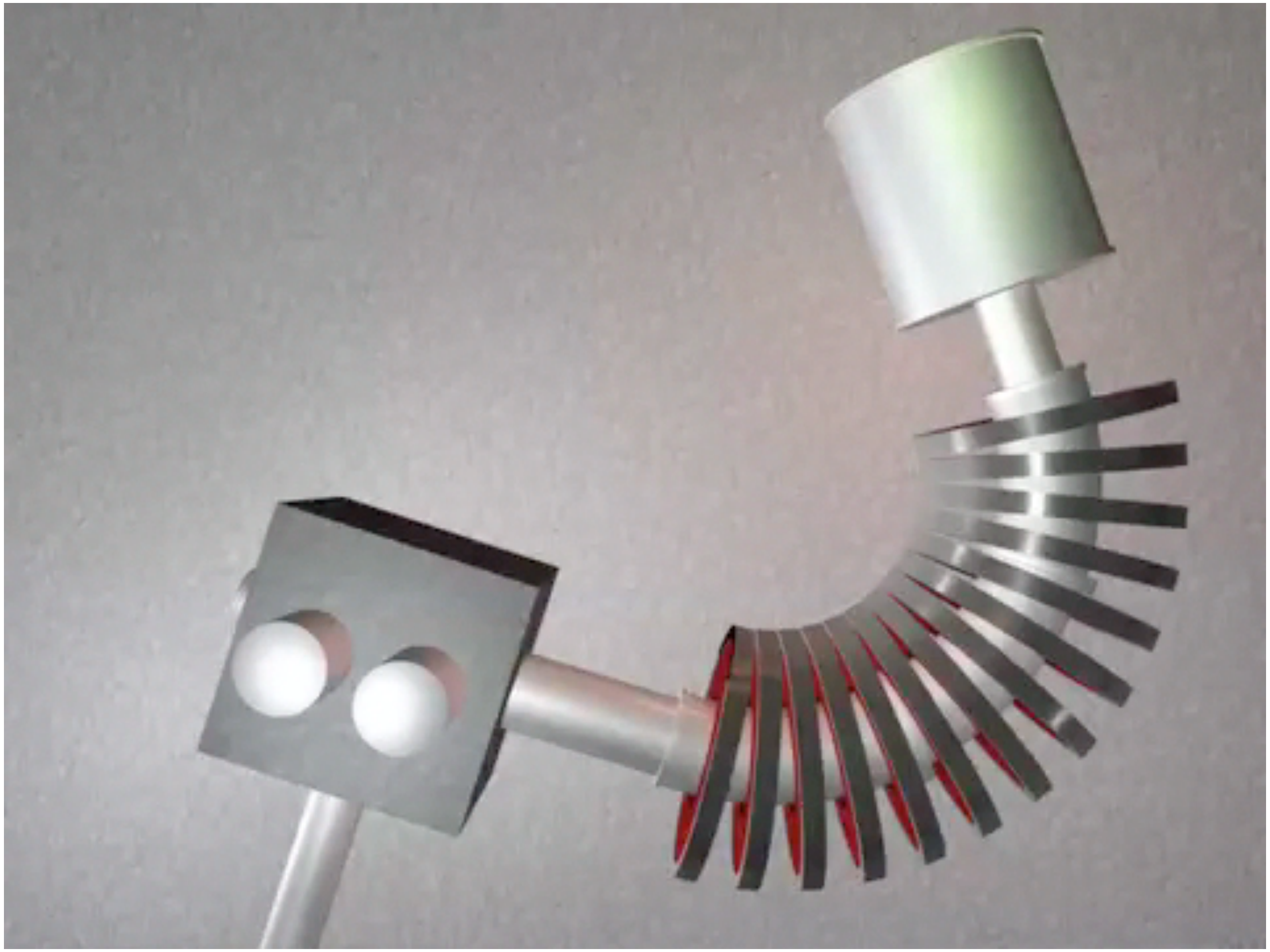
PSC solenoid,

Muon extraction
channel

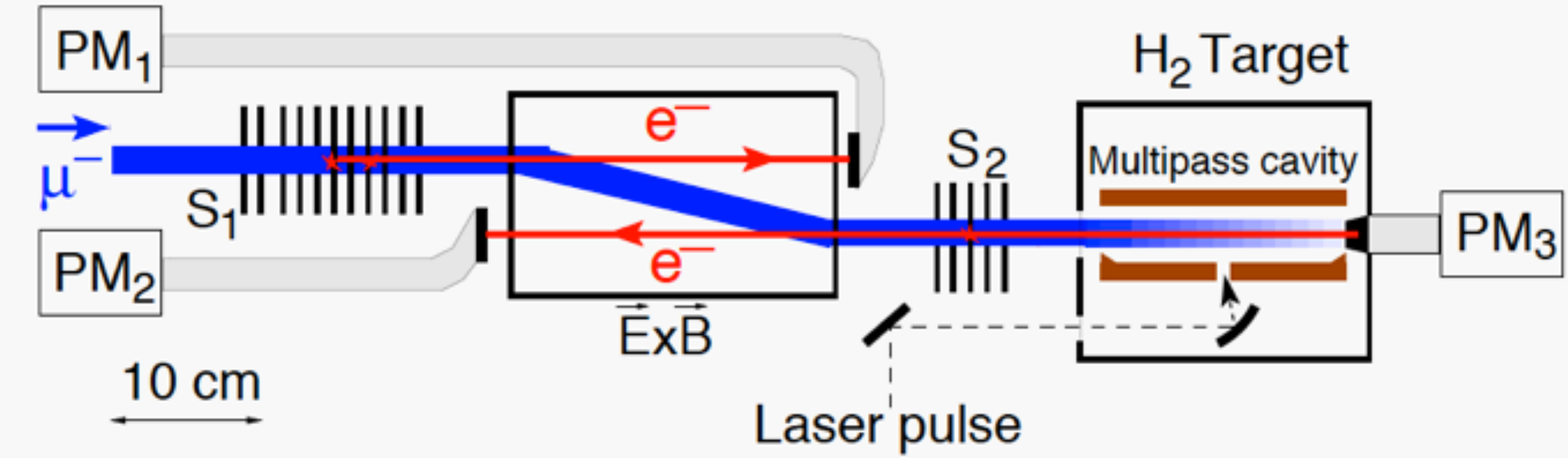
H2 target, laser cavity,
detectors

A muon’s Odyssey

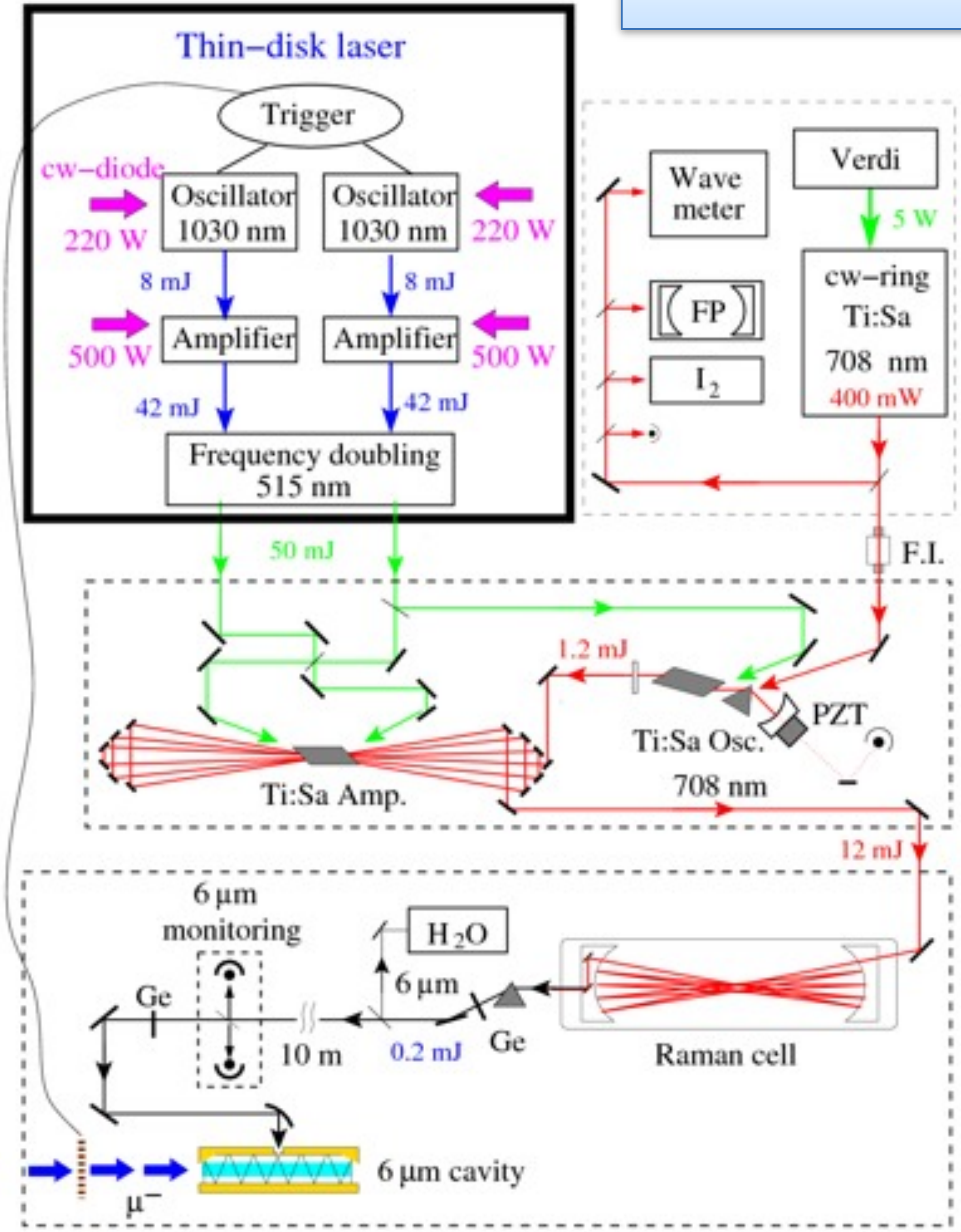
A muon’s Odyssey



The laser trigger signal



Laser chain



- Each single muon triggers the laser system (random trigger)
- 2S lifetime ~1μs → short laser delay (disk laser)
- 6 μm tunable laser pulse (0.2mJ)

μ⁻ trigger

↓

Thin disk laser (1030 nm) + LBO (515 nm)

↓

pulsed TiSa oscillator + amplifier
(708 nm determined by cw TiSa seeding)

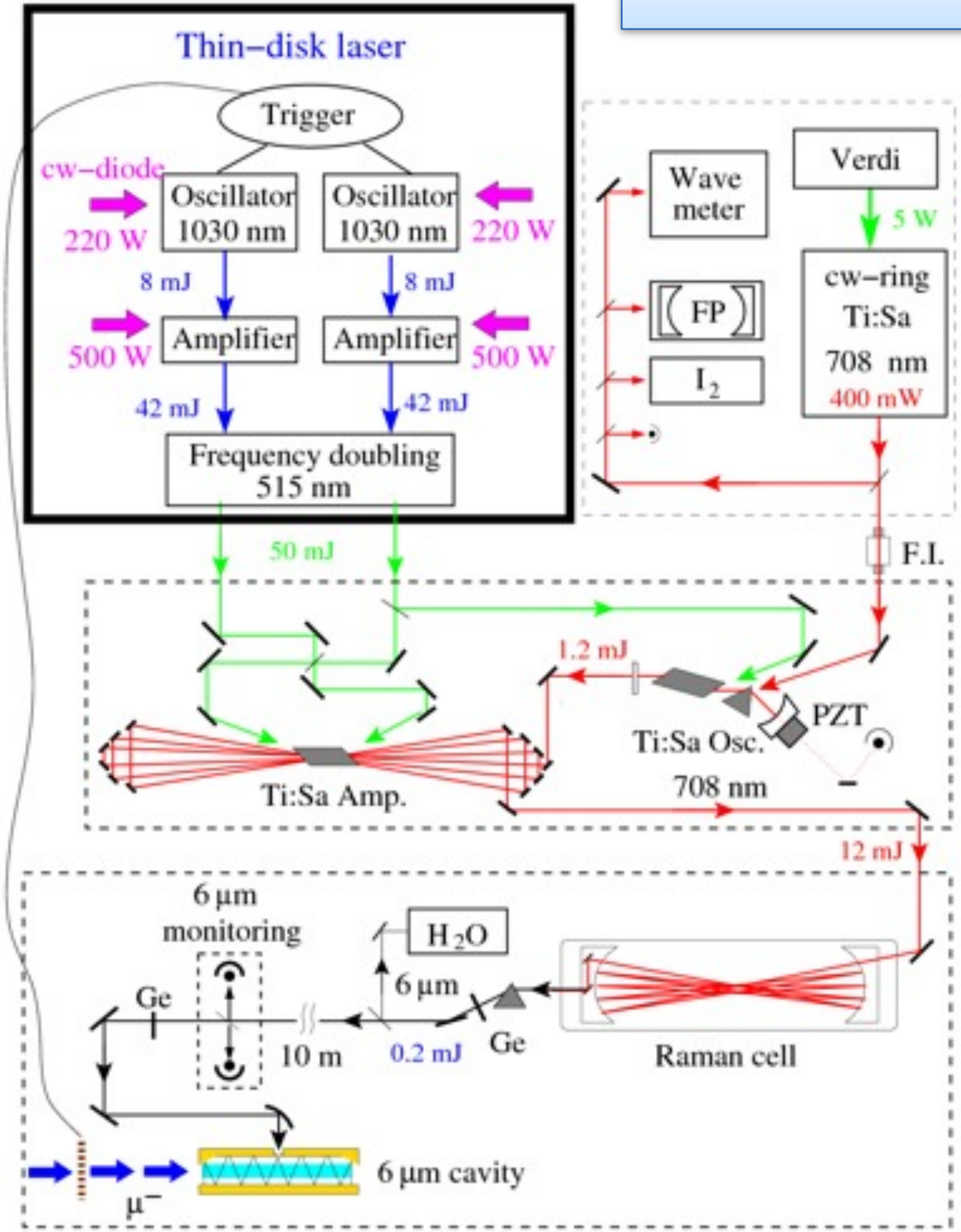
↓

Raman cell 6.02 μm

↓

Multipass cavity at 6μm
surrounding the H2 target

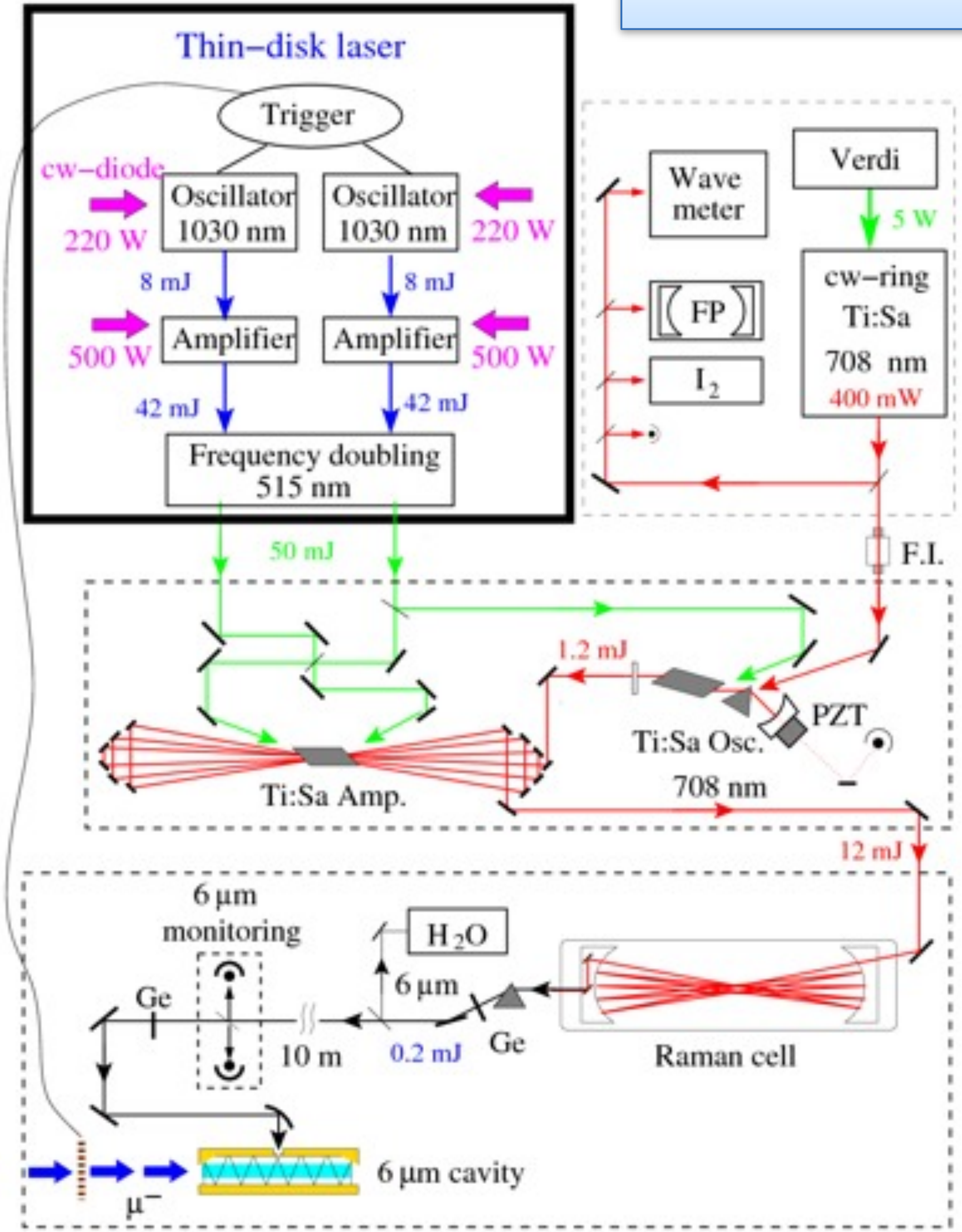
Laser chain



Thin disk laser

- Large pulse energy: 85 (160) mJ
- Short trigger-to-pulse delay: ≤ 400 ns
- Random trigger
- Pulse-to-pulse delays down to 2 ms (rep. rate ≥ 500 Hz)

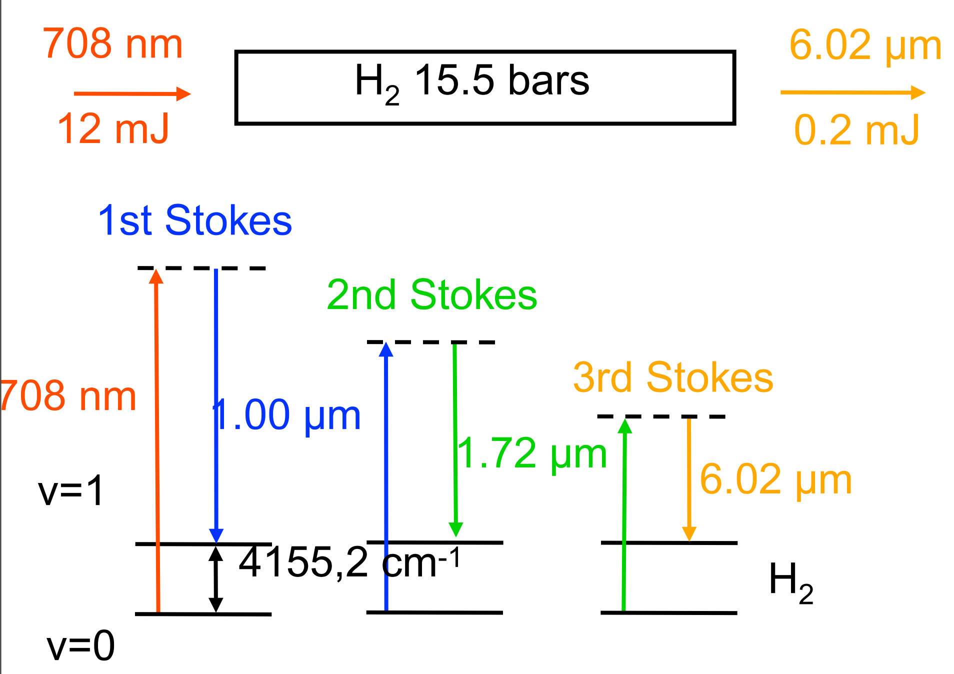
Laser chain



MOPA TiSa laser

- cw laser, frequency stabilized
  - referenced to a stable FP cavity
  - FP cavity calibrated with I2, Rb, Cs lines
  - FP = N . FSR (free spectral range)
  - FSR = 1497.344(6) MHz
- cw TiSa frequency absolutely known to 30 MHz
- Γ_{2P-2S} = 18.6 GHz
- Seeded oscillator
- TiSa = cw → pulsed TiSa (frequency chirp ≤ 100 MHz)
- Multipass amplifier (2f- configuration)
  - gain=10

Laser chain : Raman cell



708 nm

12 mJ

H_2 15.5 bars

6.02 µm

0.2 mJ

1st Stokes

2nd Stokes

3rd Stokes

708 nm

1.00 µm

1.72 µm

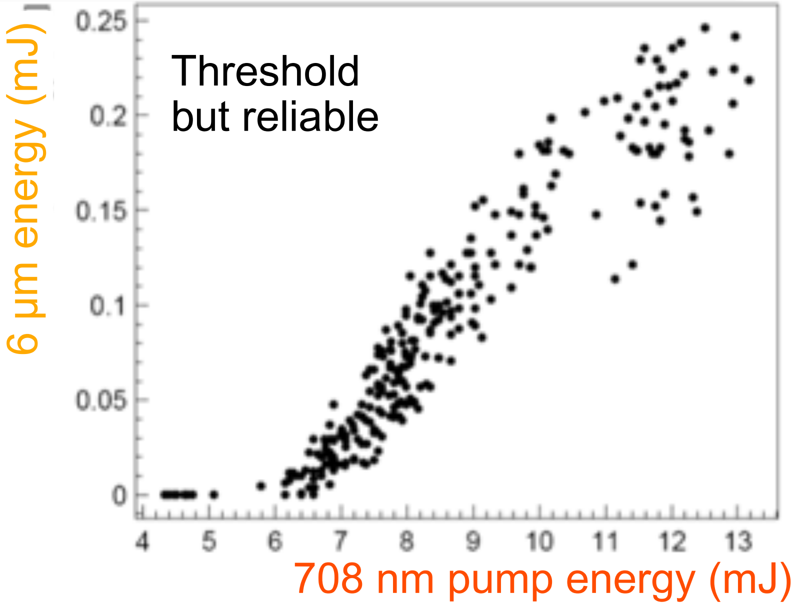
6.02 µm

v=1

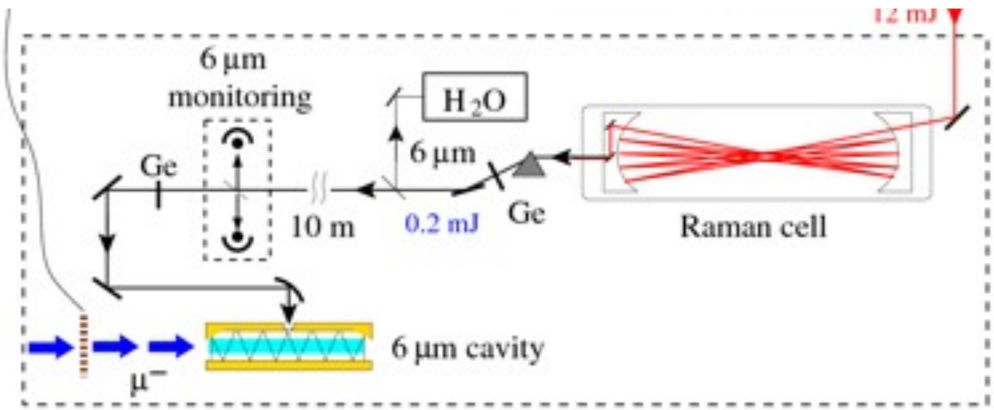
4155,2 cm^{-1}

v=0

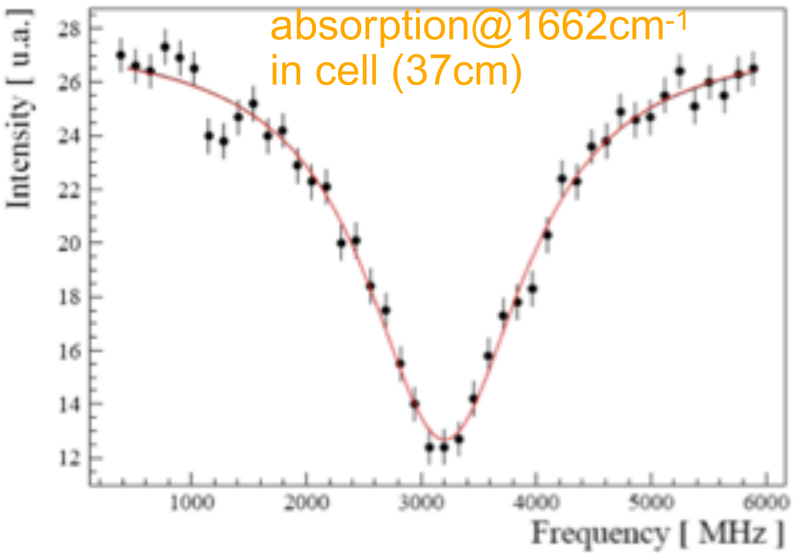
H_2



Threshold
but reliable

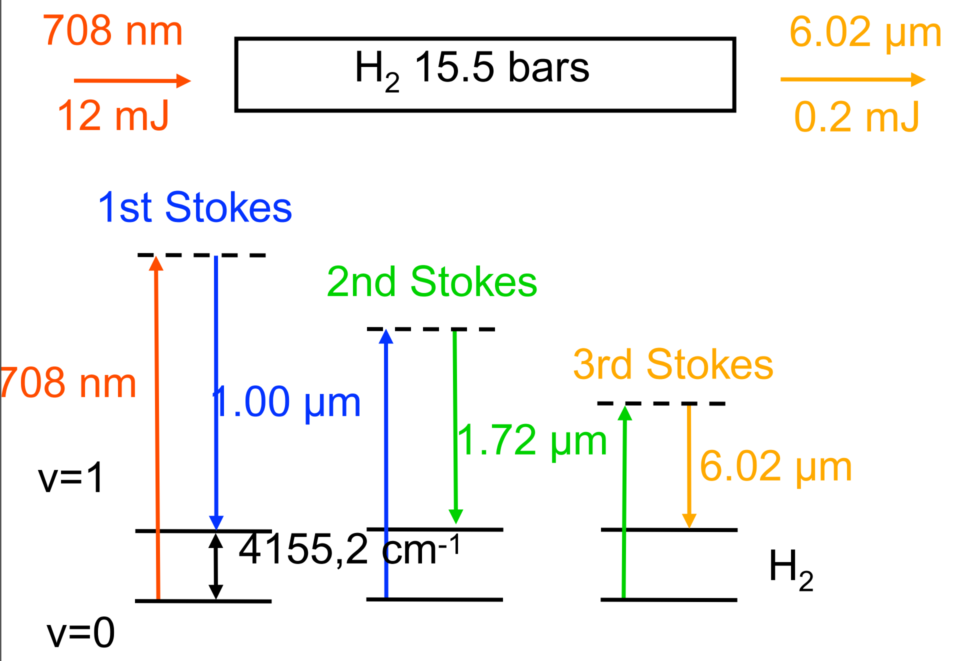


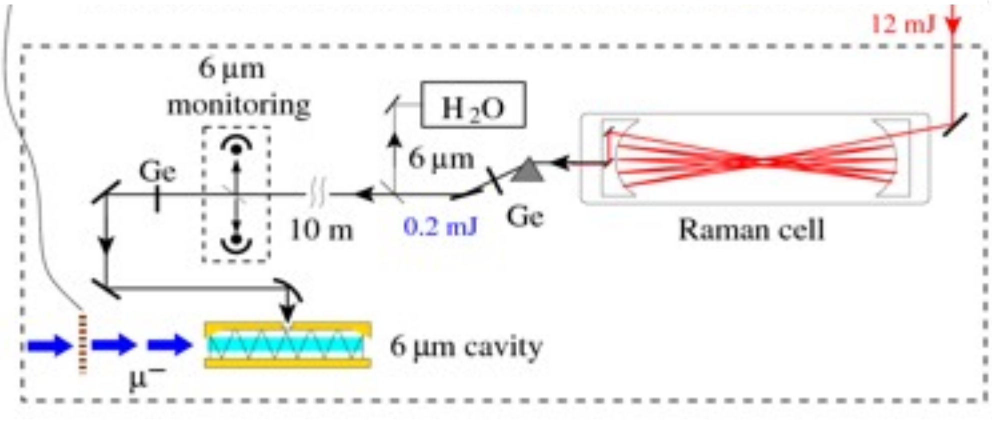
6 µm frequency calibration : H_20 lines

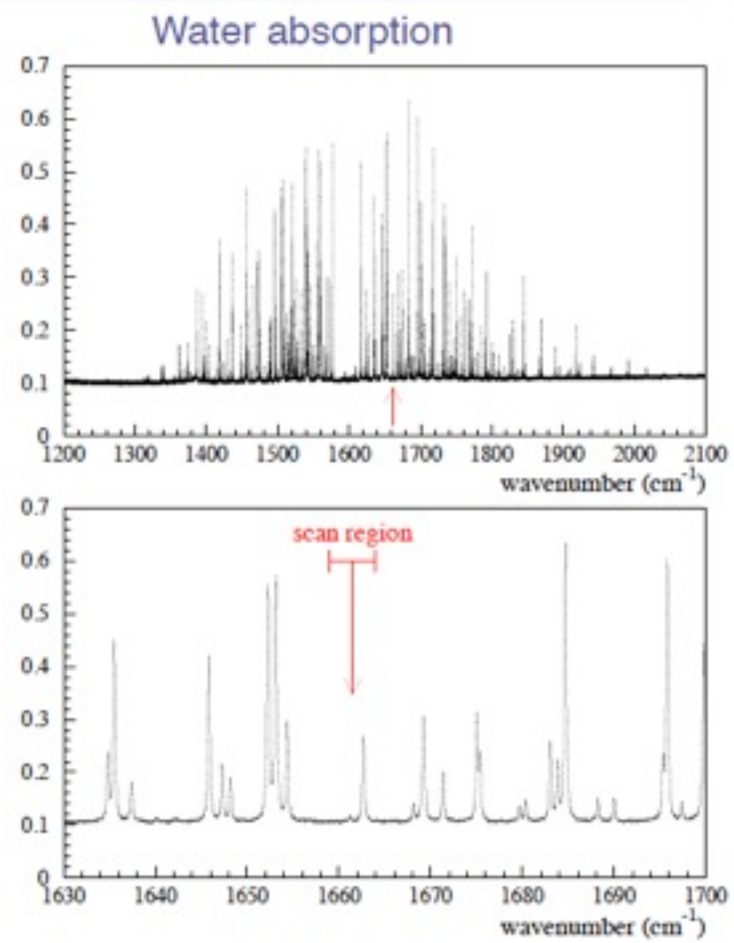


absorption@1662cm^{-1}
in cell (37cm)

Laser chain : Raman cell



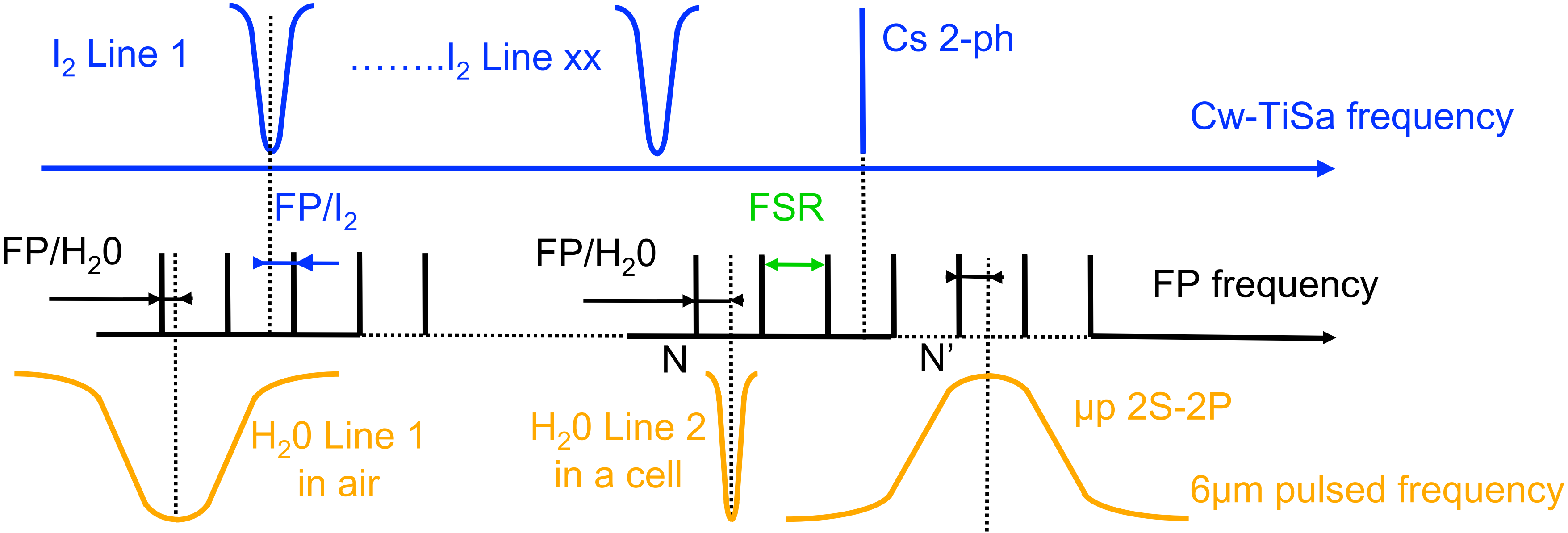




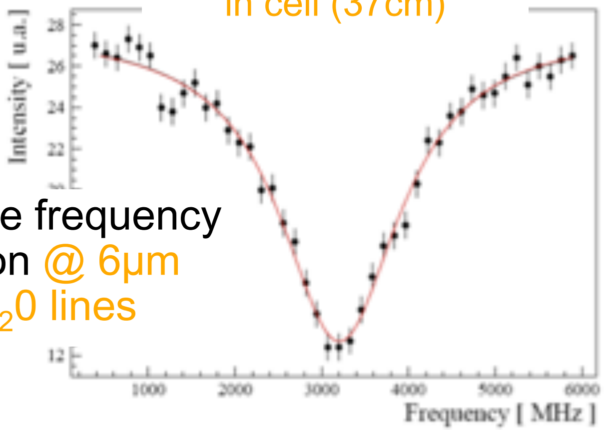
- Vacuum tube for 6µm laser beam transport
- Direct frequency calibration at 6µm
- Well known lines

Laser chain : frequency calibration

FSR measured/controlled in cw with I_2 (1 ph abs), Cs (2 ph fluo), Rb (2 ph fluo), lines



absorption@1662cm-1
in cell (37cm)

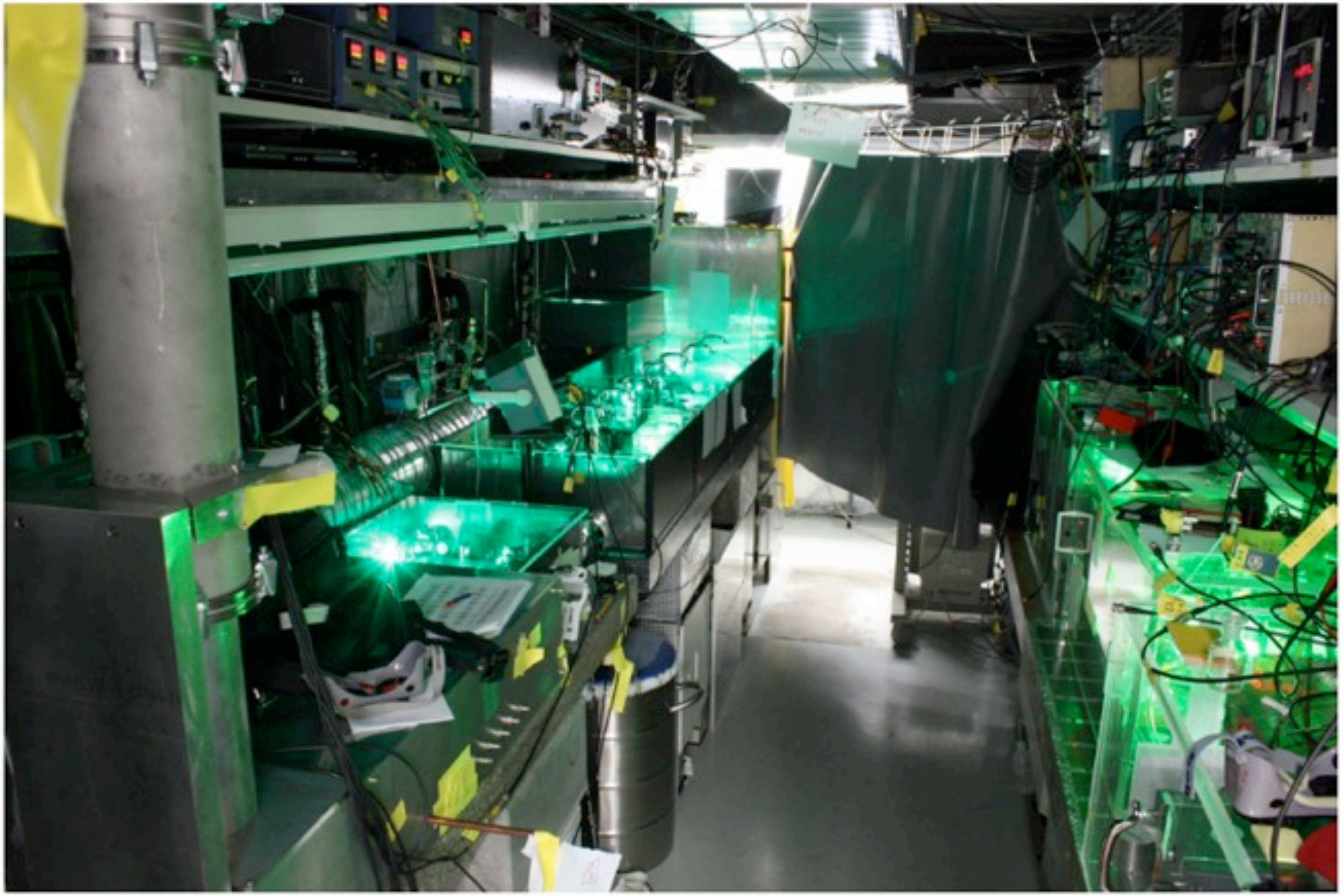


FP absolute frequency calibration @ 6µm with H_20 lines

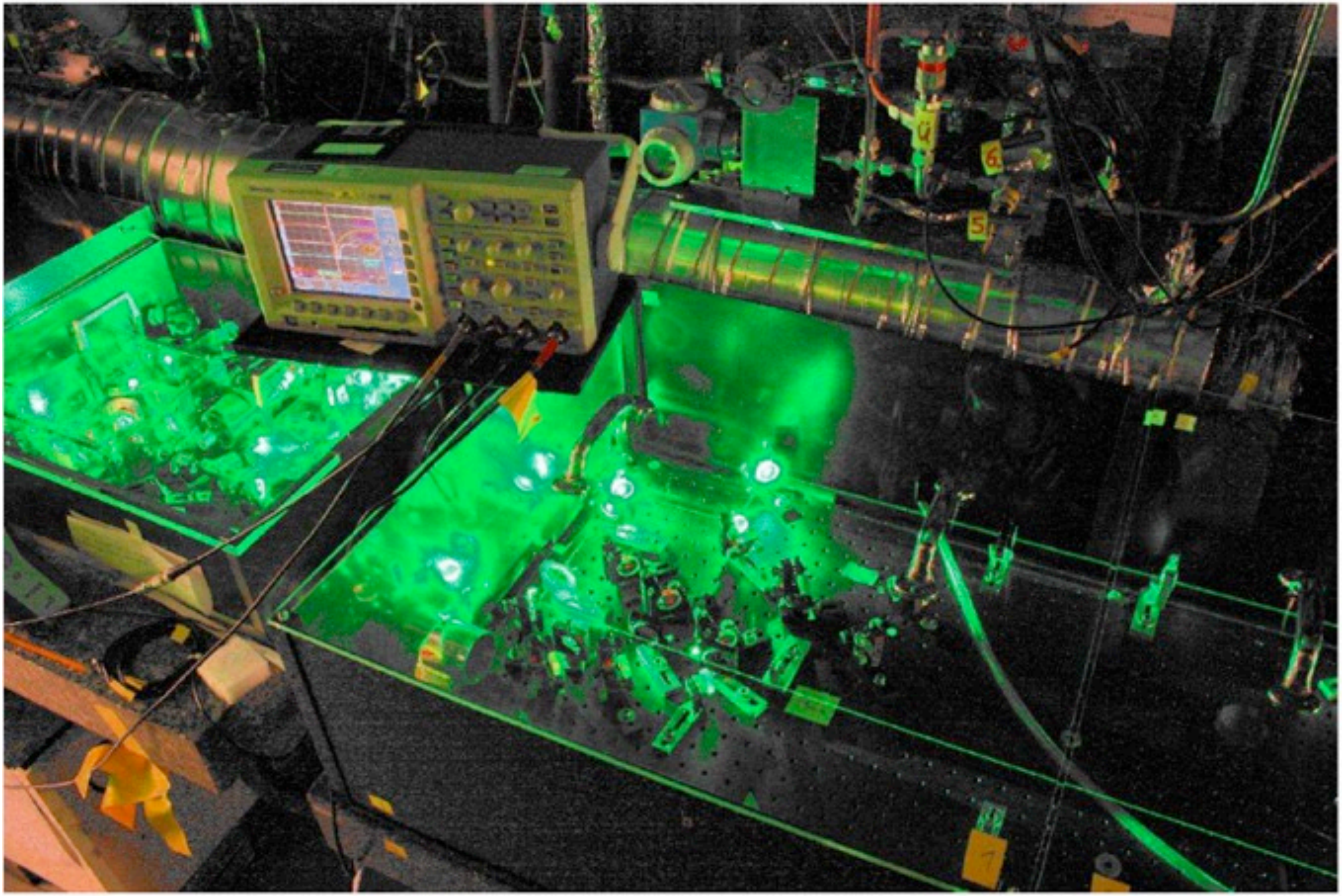
Mainz MI-

$$\nu(\mu p{:}2S\text{-}2P) = \nu(H_20 \text{ Line } 2\,) + (N\text{-}N')\ \mathrm{FSR}$$

The laser hut

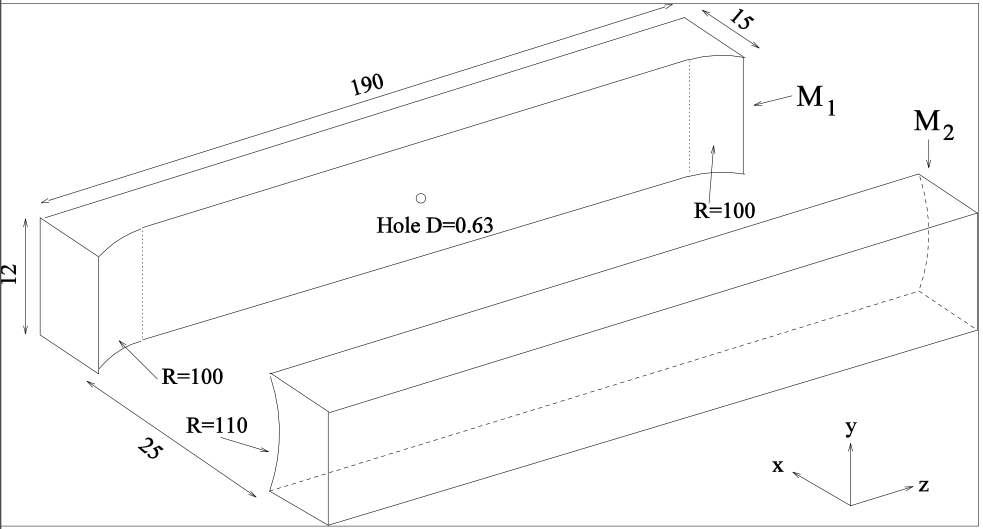


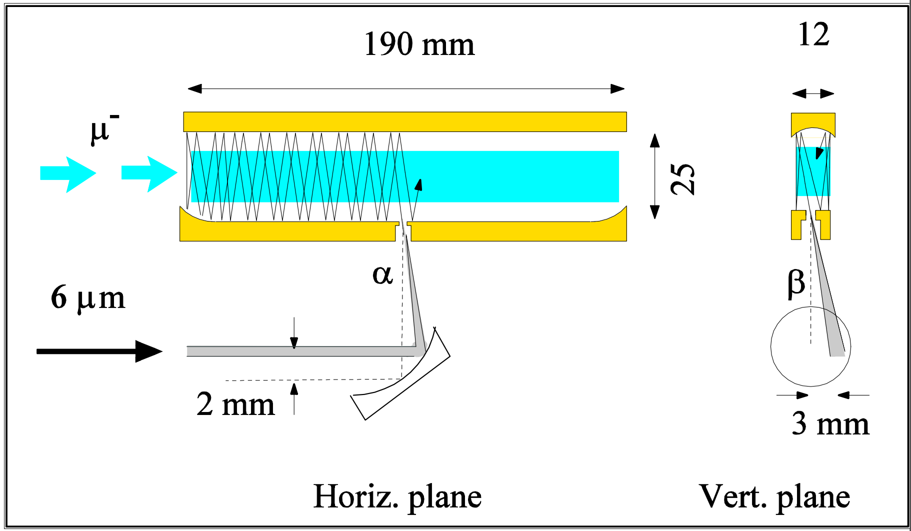
Ti:Sa and raman cell



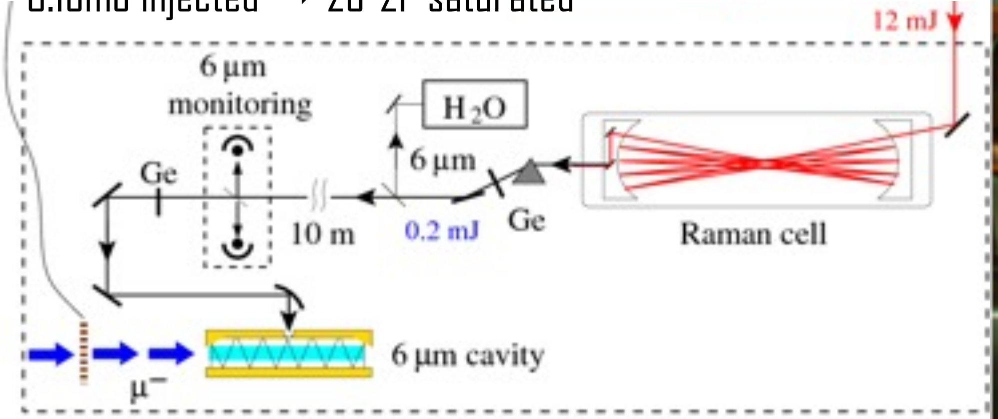
Laser chain : multipass cavity

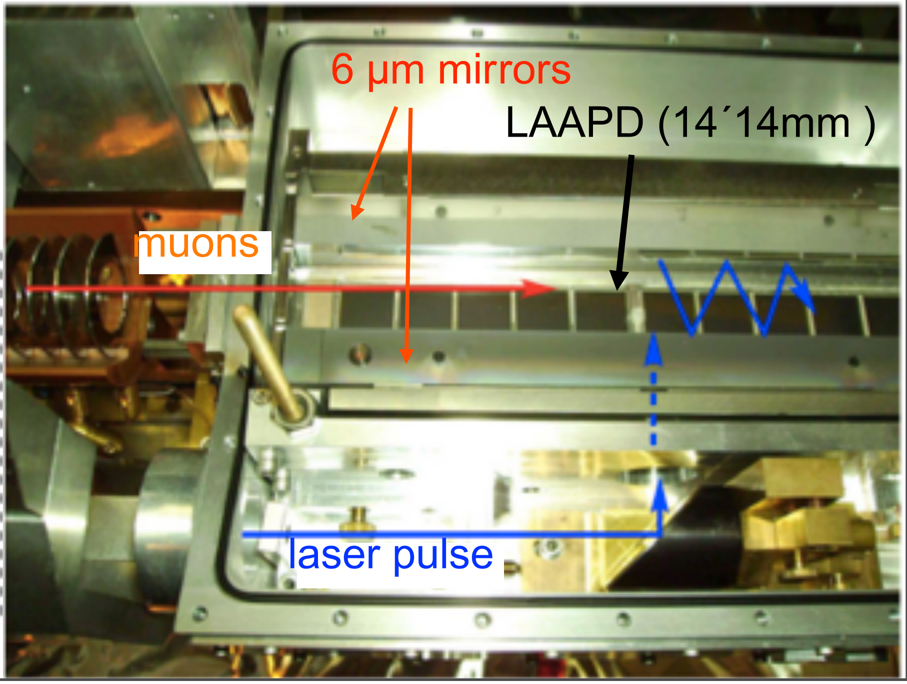
→ illuminate at 6 μm all the muon stopping volume (5×15×190 mm^3)





- coupling through a 0.63mm diameter hole
- R=99.90% at 6 μm
- 1000 reflections
- 0.15mJ injected → 2S-2P saturated



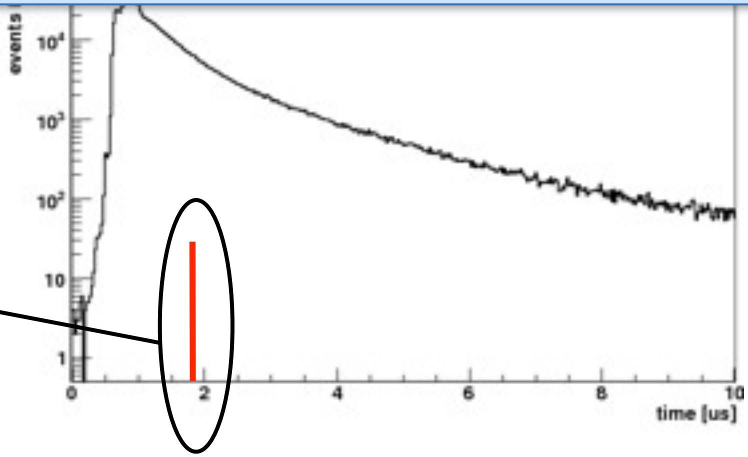


X-rays analysis → event gate sorting → noise rejection

Example : FP 900 - 11 hrs meas.

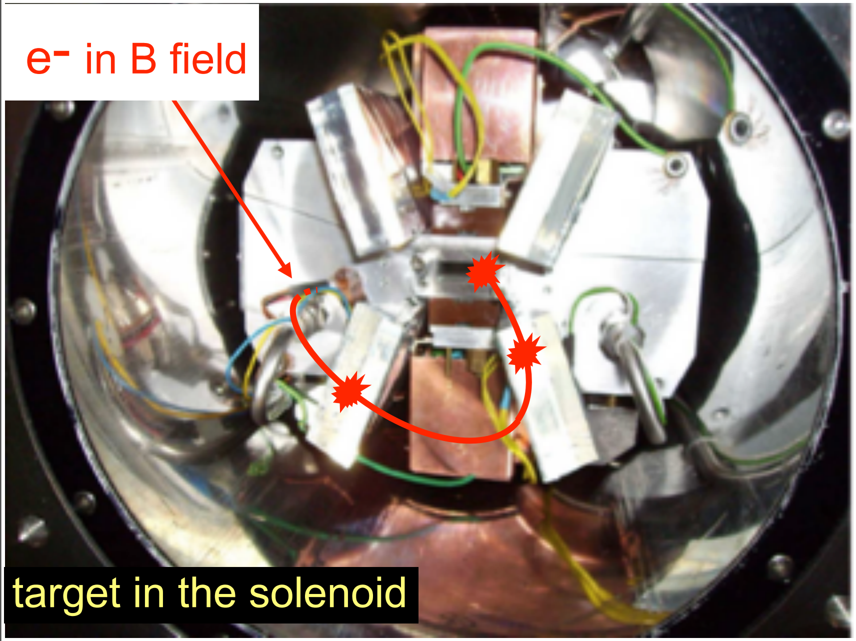
1.56 million detector events

expected 2-3 laser induced events/hour !



time signature in LAAPD

- photon < 10keV → 1 shot in the LAAPD
- e^- in B = 5T → many counts in detectors

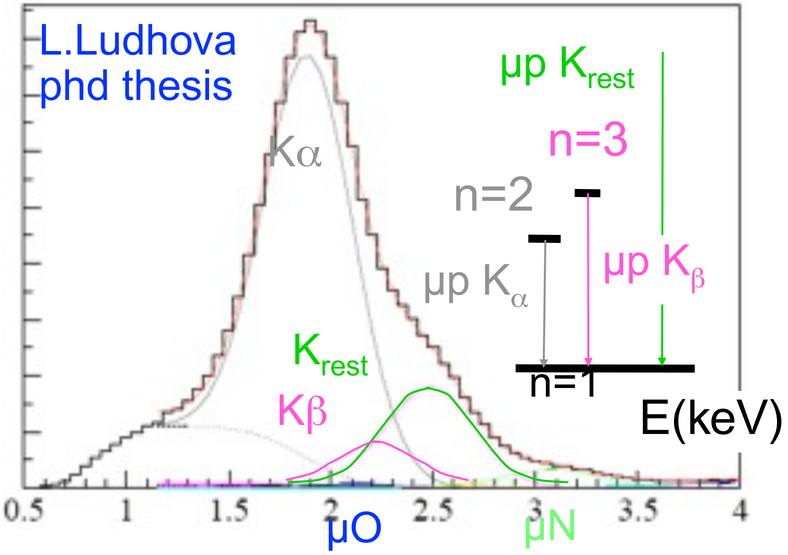


e^- in B field

target in the solenoid

energy signature in LAAPD

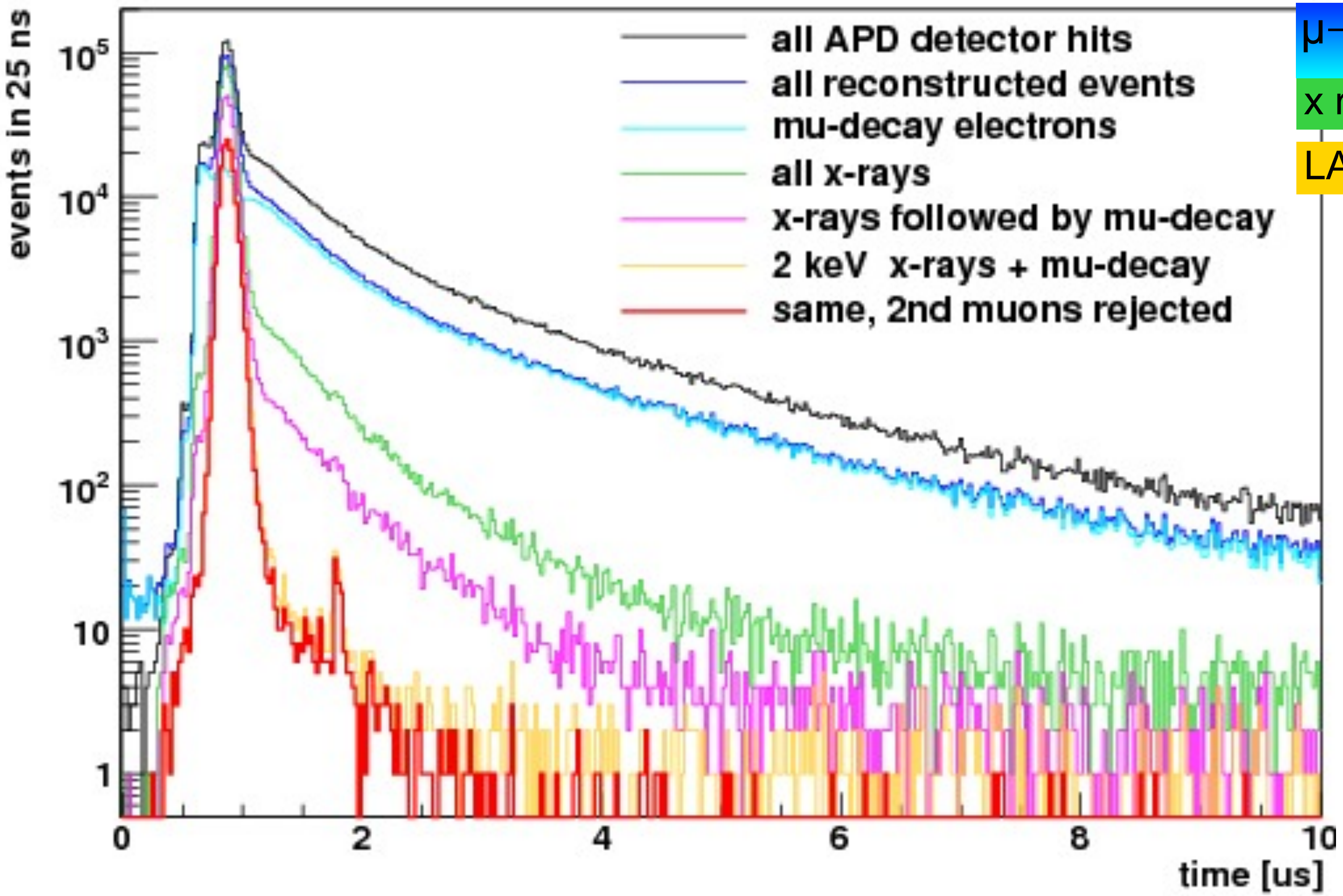
- E > 8keV ⇔ electron
- 1keV < E < 8keV ⇔ X ray
- E<1keV ⇔ neutron


L.Ludhova phd thesis

X-rays analysis → noise rejection

Example : FP 900 - 11 hrs meas.

- 400 μ^-/s
- 240 laser shot/s
- 860 000 laser shot/hour
- 1.56 million detector clicks
- 19600 clicks in the laser region
- expected 2-3 laser induced events/hour !

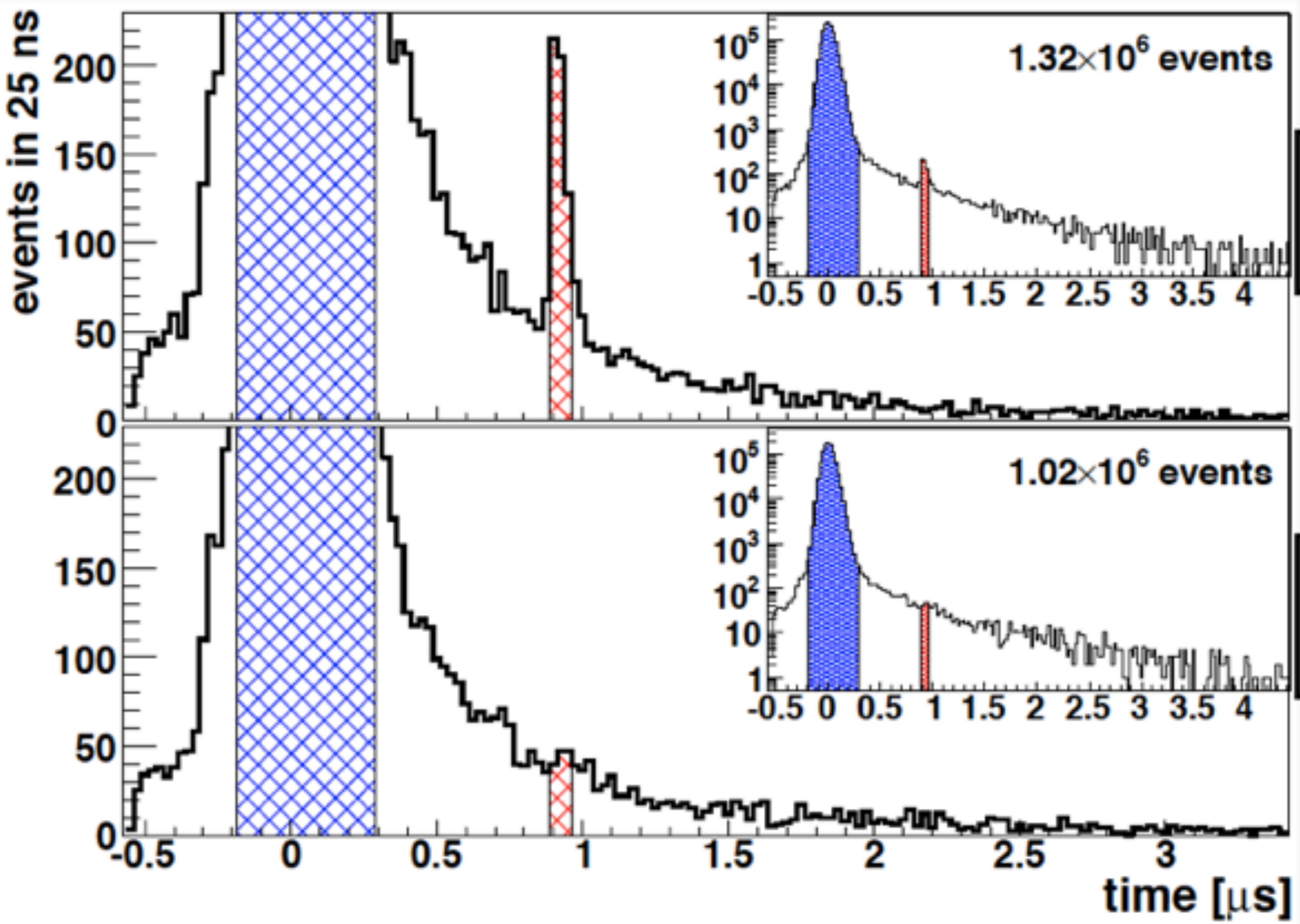


$\mu \to e\ \nu_\mu \bar{\nu}_e$

x rays multiplicity 1

LAAPD energy resolution

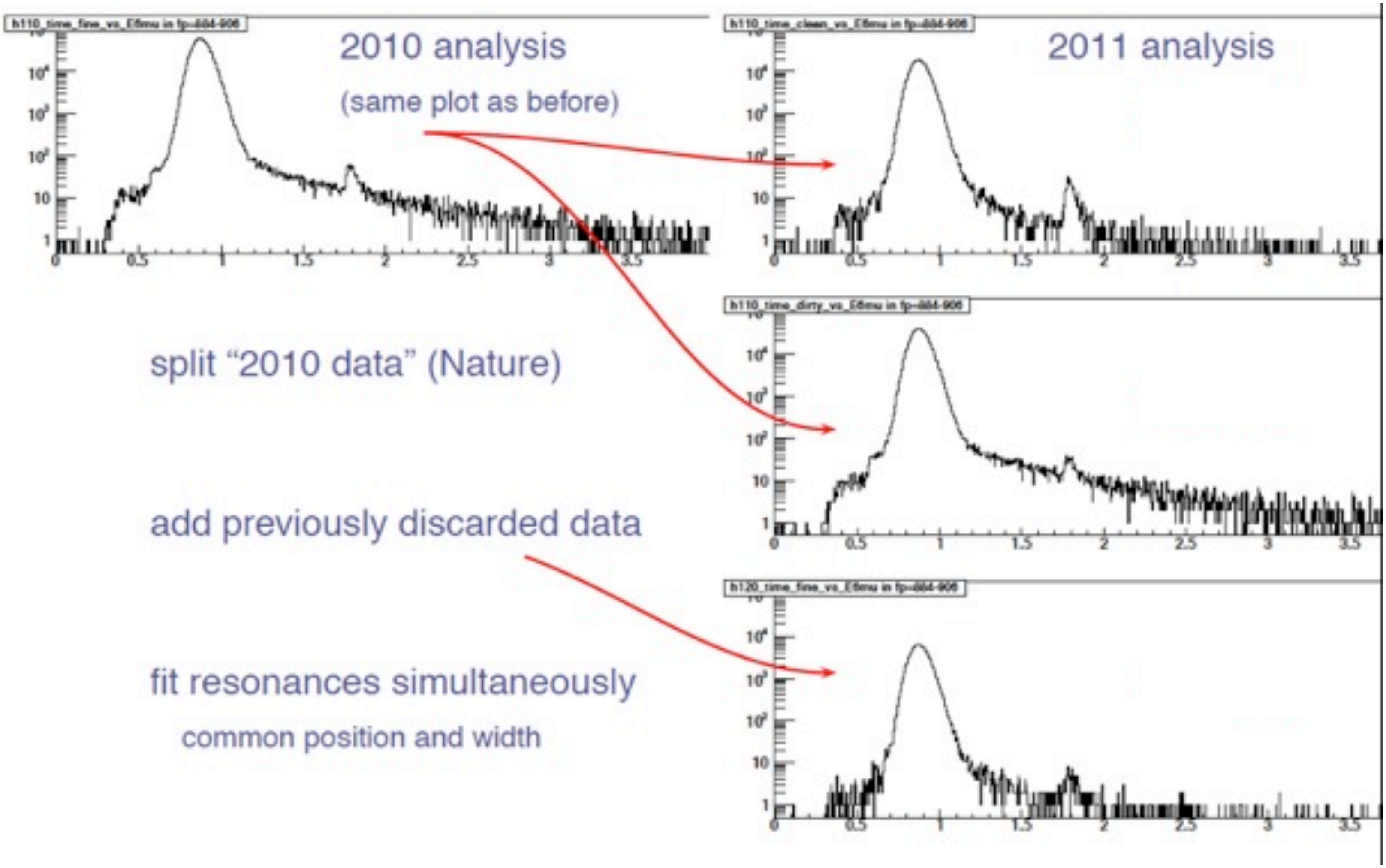
Time spectra



Laser
ON
resonance

Laser
OFF
resonance

New analysis: tacking into account more events



2010 analysis

(same plot as before)

2011 analysis

split “2010 data” (Nature)

add previously discarded data

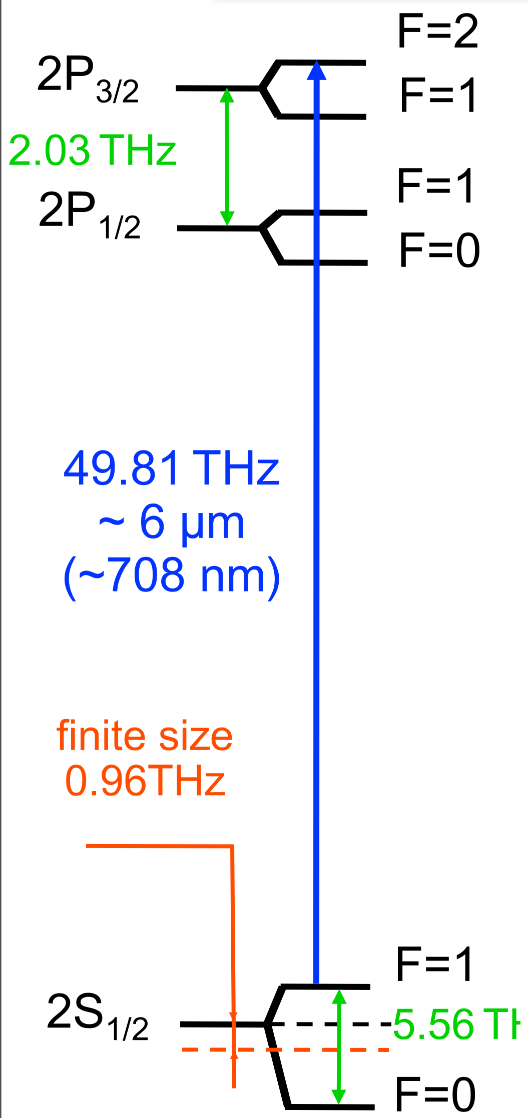
fit resonances simultaneously

common position and width

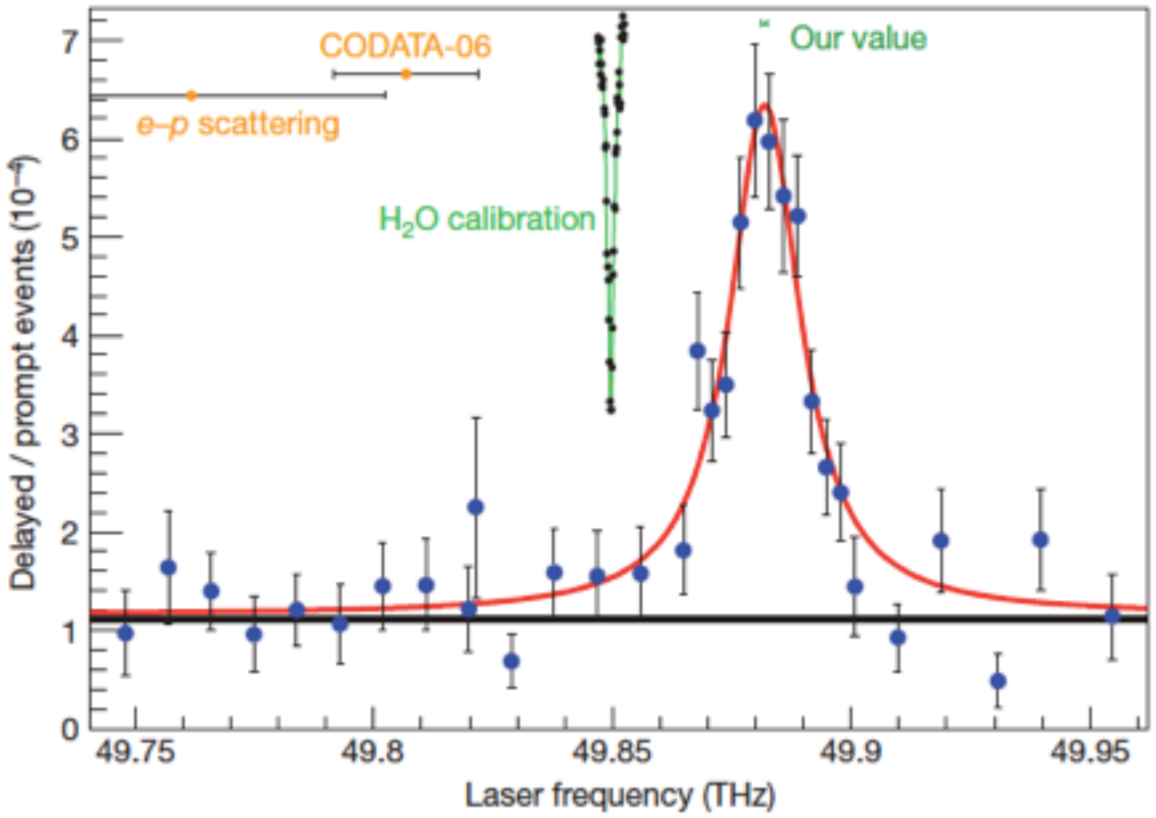
1.9 keV Ka x-ray must followed by the detection of an MeV-energy electron, but there are several detectors

Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen, A. Antognini, F. Nez, K. Schuhmann *et al.* Science **339,** 417-420 (2013).

muonic hydrogen : ${}^2S_{1/2}(F=1)$ - ${}^2P_{3/2}(F=2)$



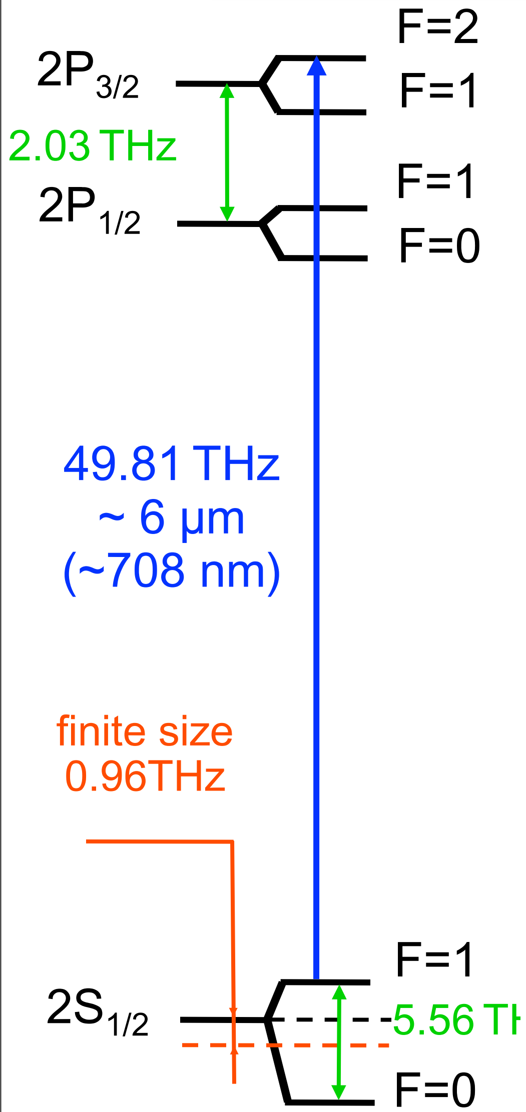
- 550 events measured
- 155 backgrounds
- 31 FP fringes
- 250 hours

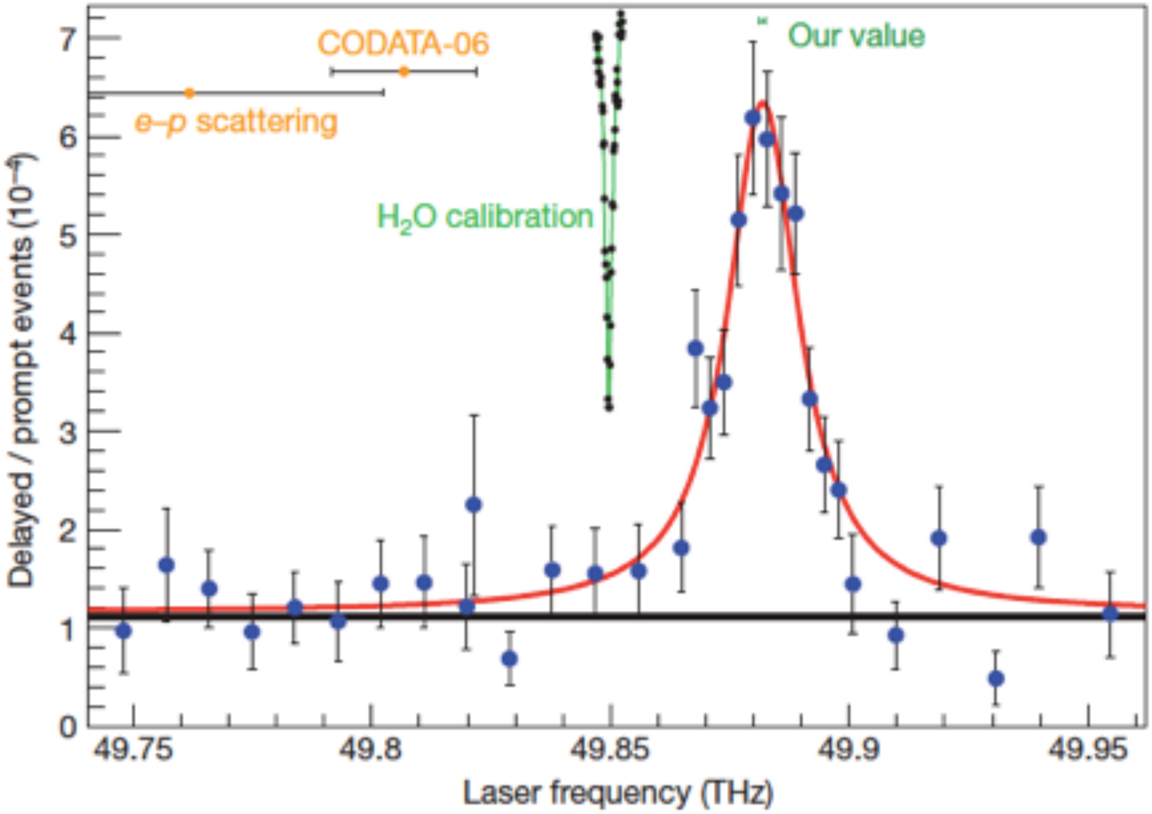


R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

→ proton charge radius (~0.1%)

muonic hydrogen : $^2S_{1/2}(F=1)$ - $^2P_{3/2}(F=2)$





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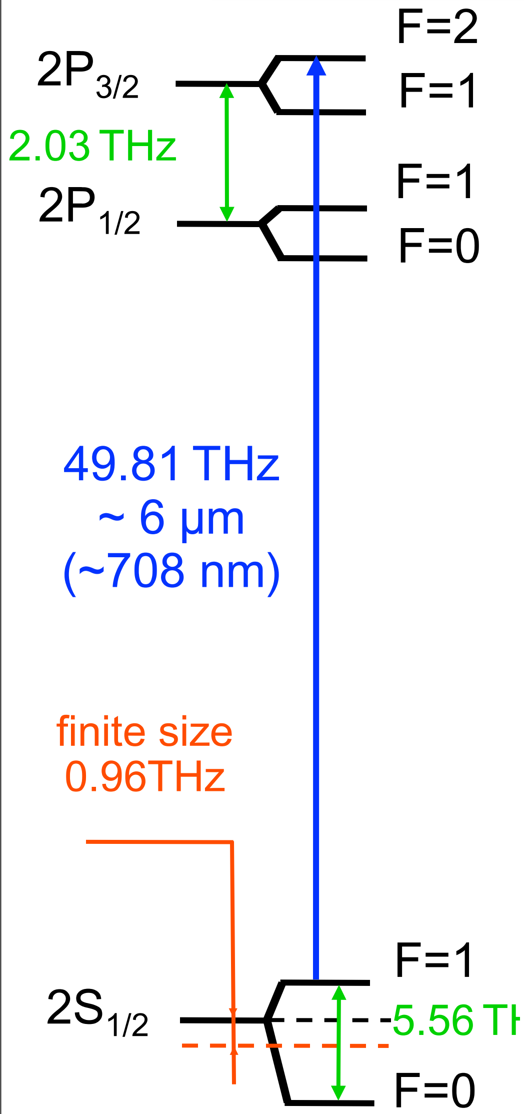
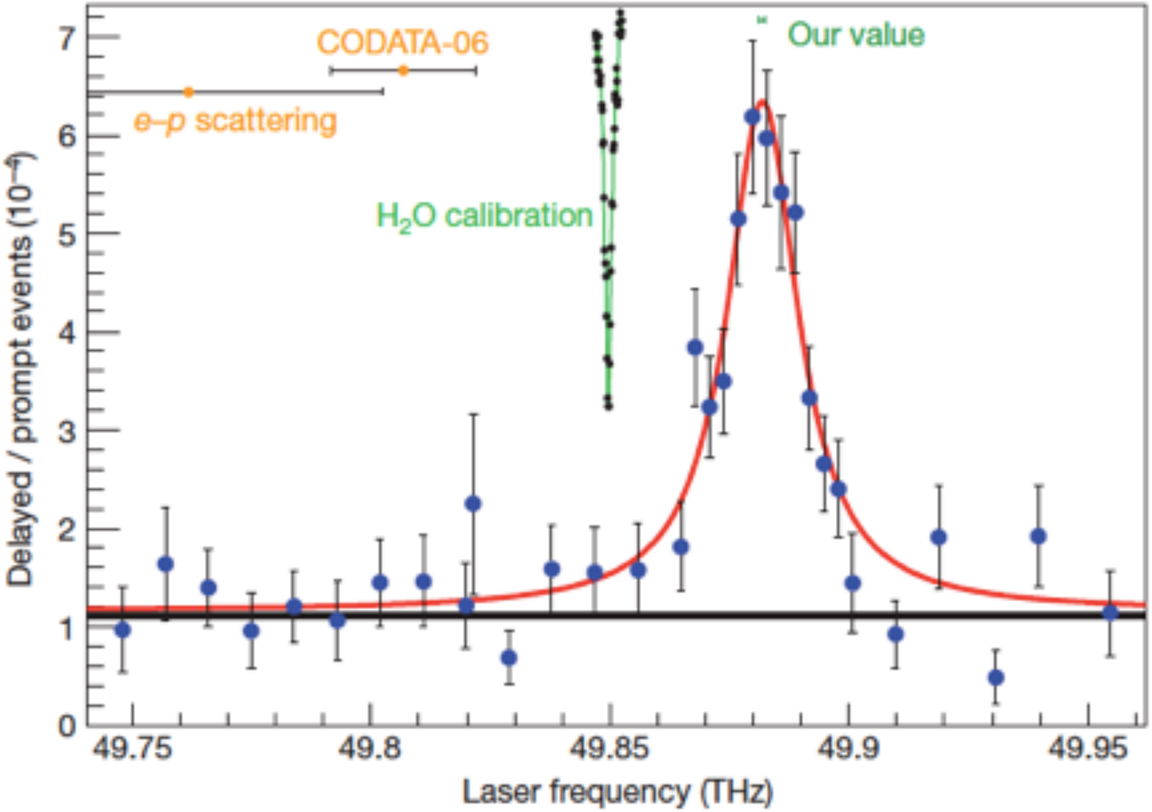


49.81 THz
~ 6 µm
(~708 nm)

finite size
0.96THz

Discrepancy CODATA
2010: 7σ (75 GHz)



R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

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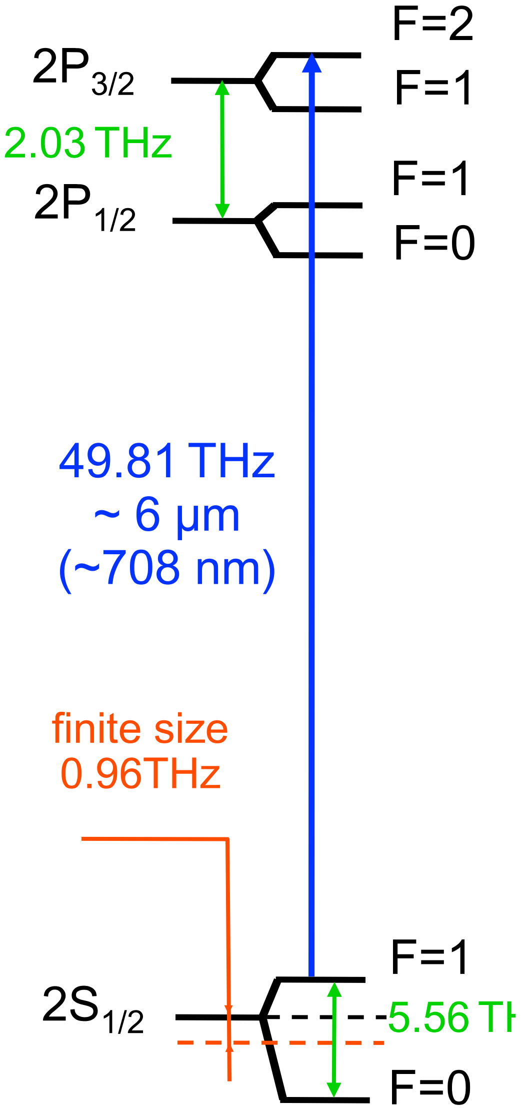

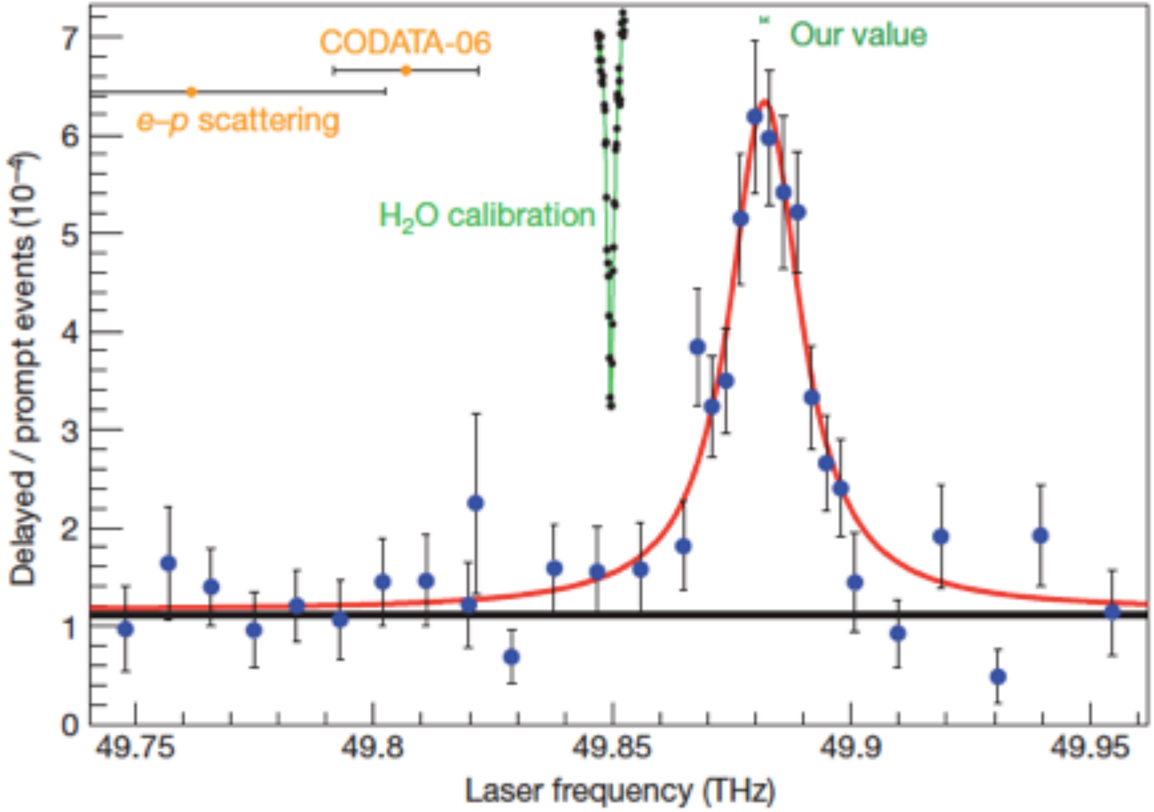

R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

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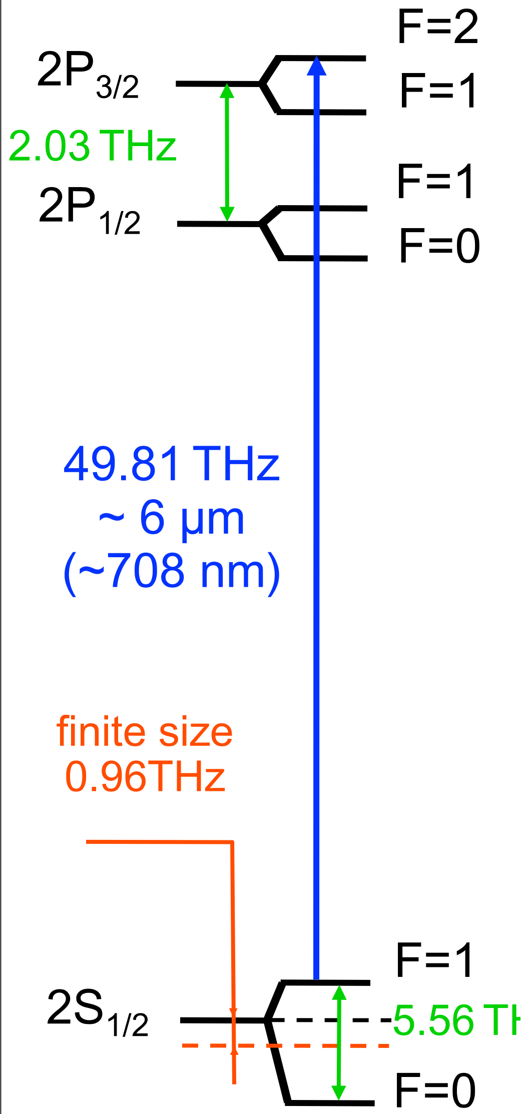
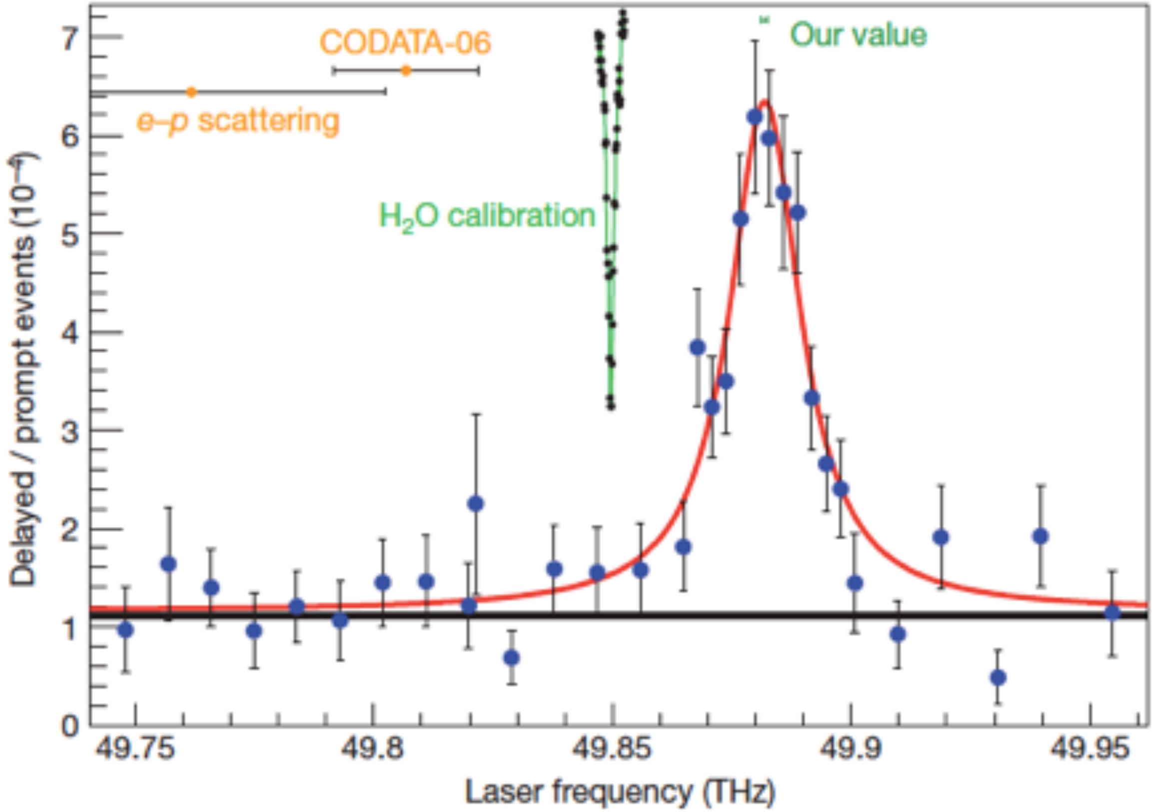


Water-line/laser
wavelength:
300 MHz uncertainty



R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

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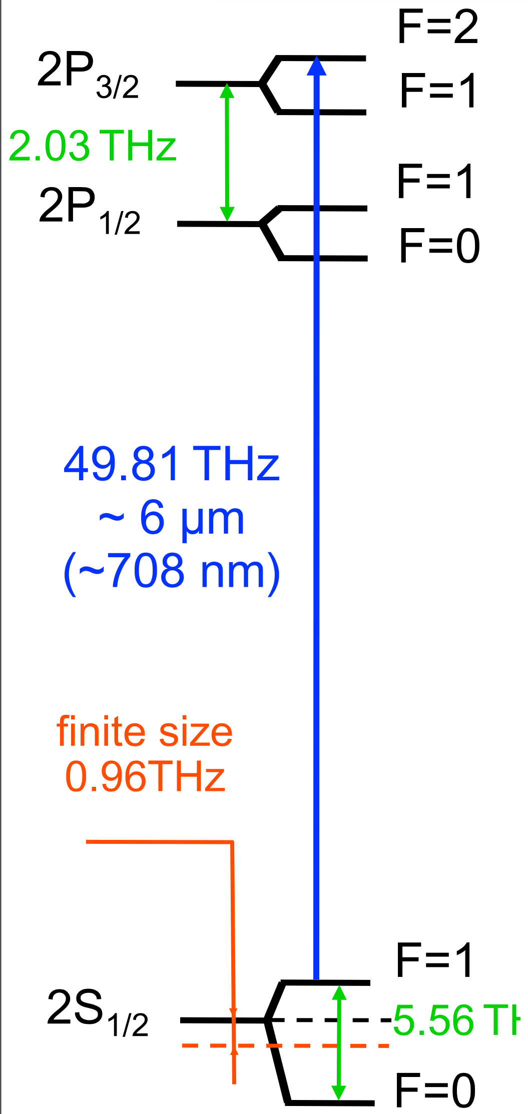

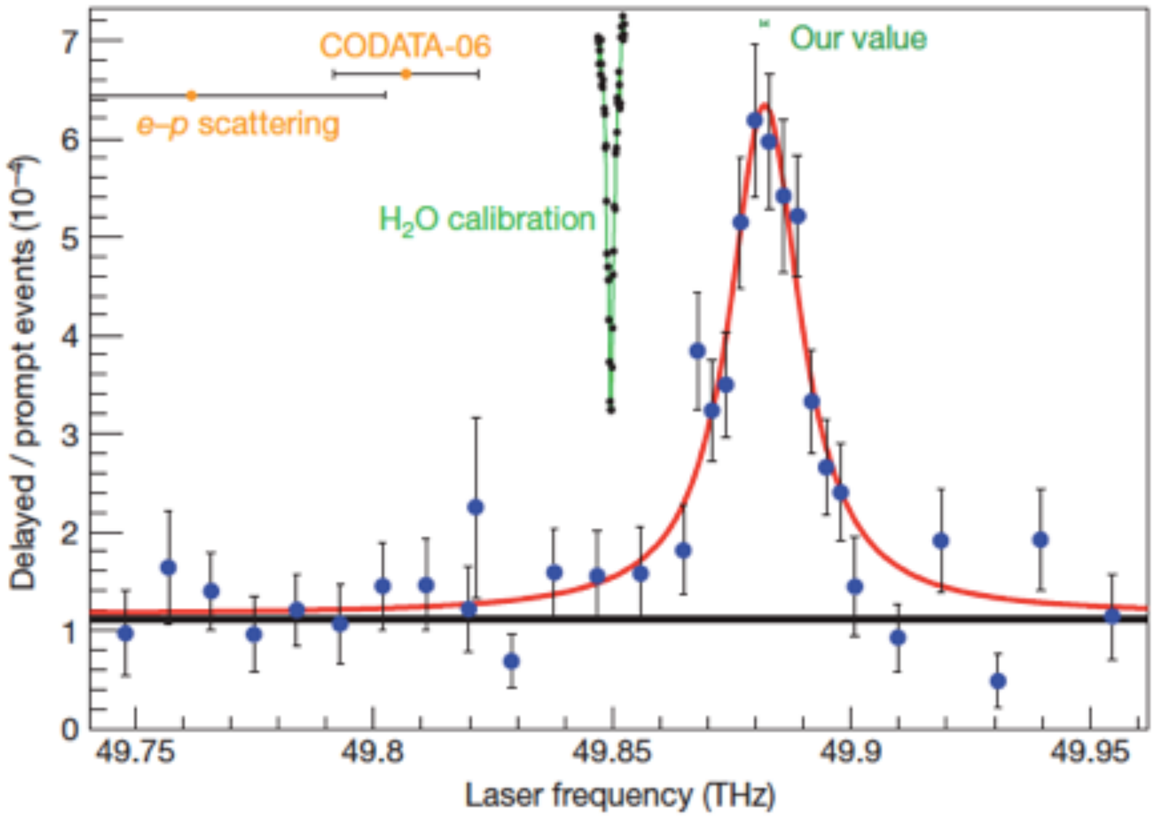

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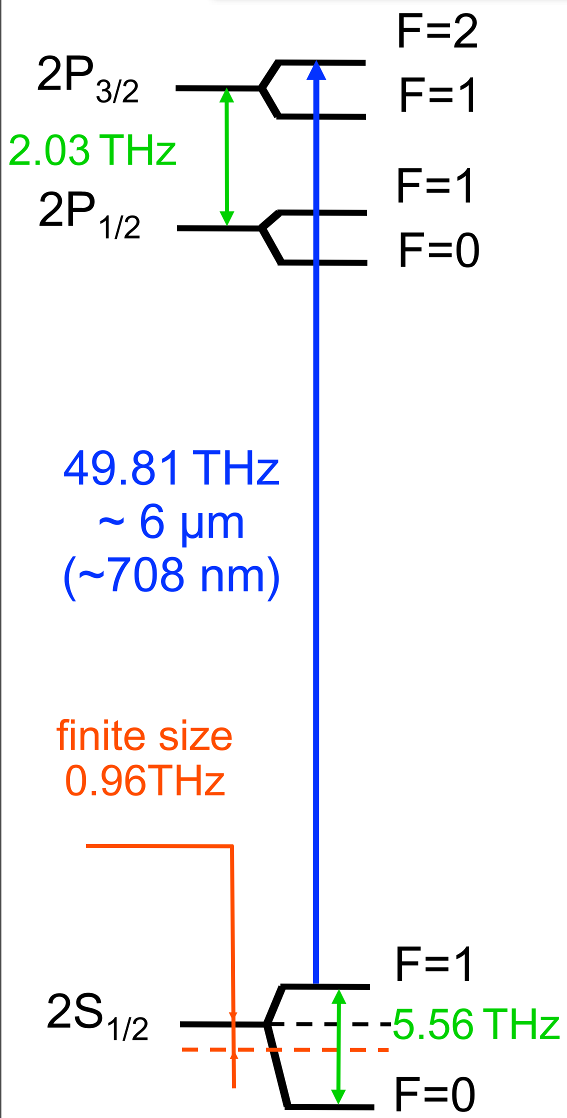

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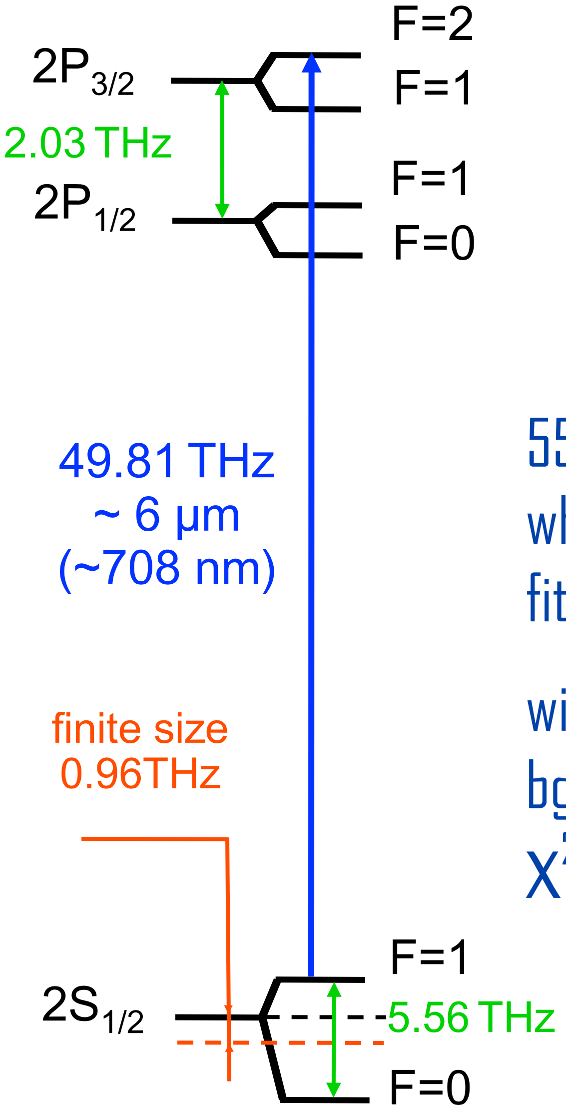


550 events measured on resonance
where 155 bgr events are expected
fit Lorentz + flat bgr ⇒ χ^2/dof = 28.1/28

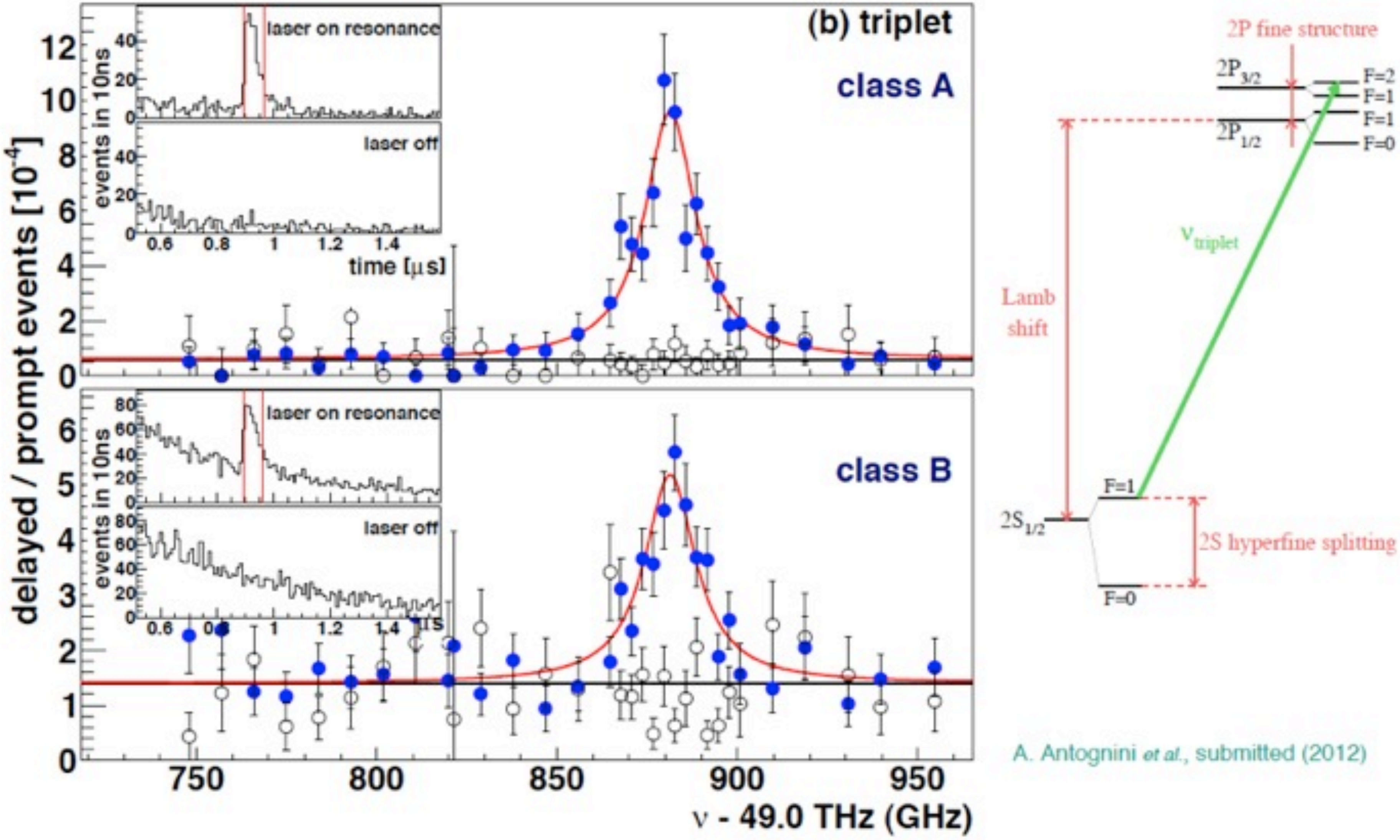
width agrees with expectation
bgr agrees with laser OFF data
χ^2/dof = 283/31 for flat line → 16σ

R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

→ proton charge radius (~0.1%)

Reanalysis 2012

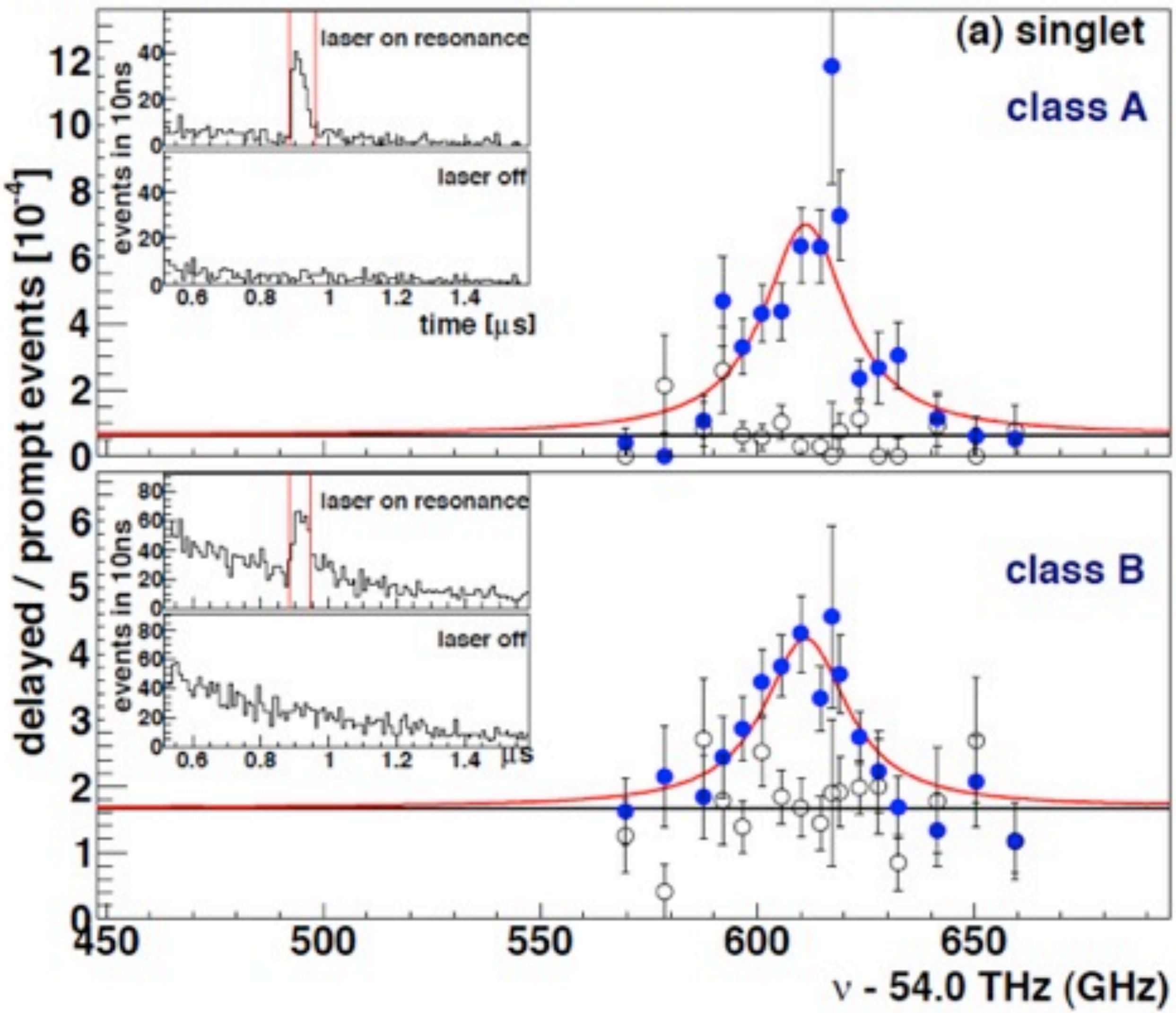
μp ($2S_{1/2}$(F=1) $\rightarrow$ $2P_{3/2}$(F=2)) at $\lambda = 6.0\,\mu$m

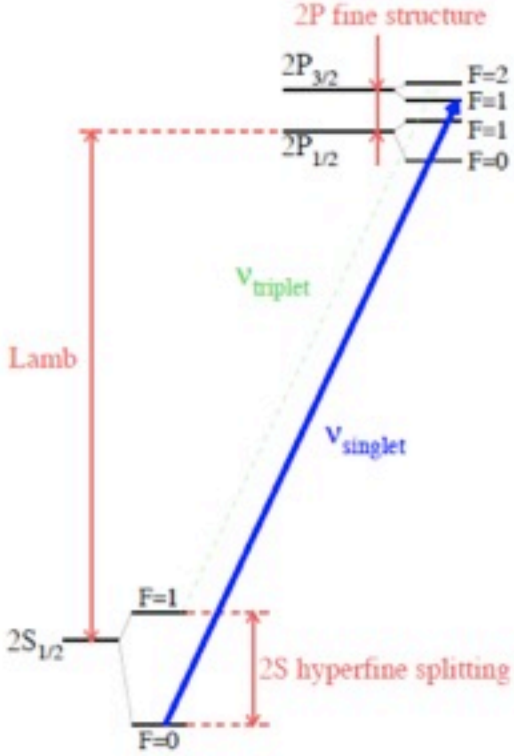


A. Antognini *et al.*, submitted (2012)

New resonance 2012

μp ($2S_{1/2}$(F=0) $\rightarrow$ $2P_{3/2}$(F=1)) at $\lambda = 5.5\,\mu$m





A. Antognini *et al.*, submitted (2012)

µP : $^2S_{1/2}(F=1)$ - $^2P_{3/2}(F=2)$ uncertainty budget

Statistics

• uncertainty on position (fit)	541 MHz (~ 3 % of Γ_{nat})

$\Delta\nu_{experimental}$= 20 (1) GHz (Γ_{nat} = 18.6 GHz)

Sources :

• Laser frequency (H$_2$0 calibration, lines known to ~1 MHz)	300 MHz
• AC and DC stark shift	< 1 MHz
• Zeeman shift (5 Telsa)	< 30 MHz
• Doppler shift	< 1 MHz
• Collisional shift	2 MHz
TOTAL UNCERTAINTY ON FREQUENCY	618 MHz

Broadening :

• 6 µm laser line width	~ 2 GHz
• Doppler Broadening	< 1 GHz
• Collisional broadening	2.4 MHz

Updated: ν (µp : $2S_{1/2}(F=1)$- $2P_{3/2}(F=2)$) <1σ (12.5 ppm)

Nature: ν (µp : $2S_{1/2}(F=1)$- $2P_{3/2}(F=2)$) = 49 881.88 (76) GHz (16 ppm)

μP : $^2S_{1/2}$(F=0) - $^2P_{3/2}$(F=1) uncertainty budget

Statistics

uncertainty on position (fit)	960 MHz

Sources :

Laser frequency ($H_2$0 calibration)	300 MHz
AC and DC stark shift	< 1 MHz
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TOTAL UNCERTAINTY ON FREQUENCY	1006 MHz

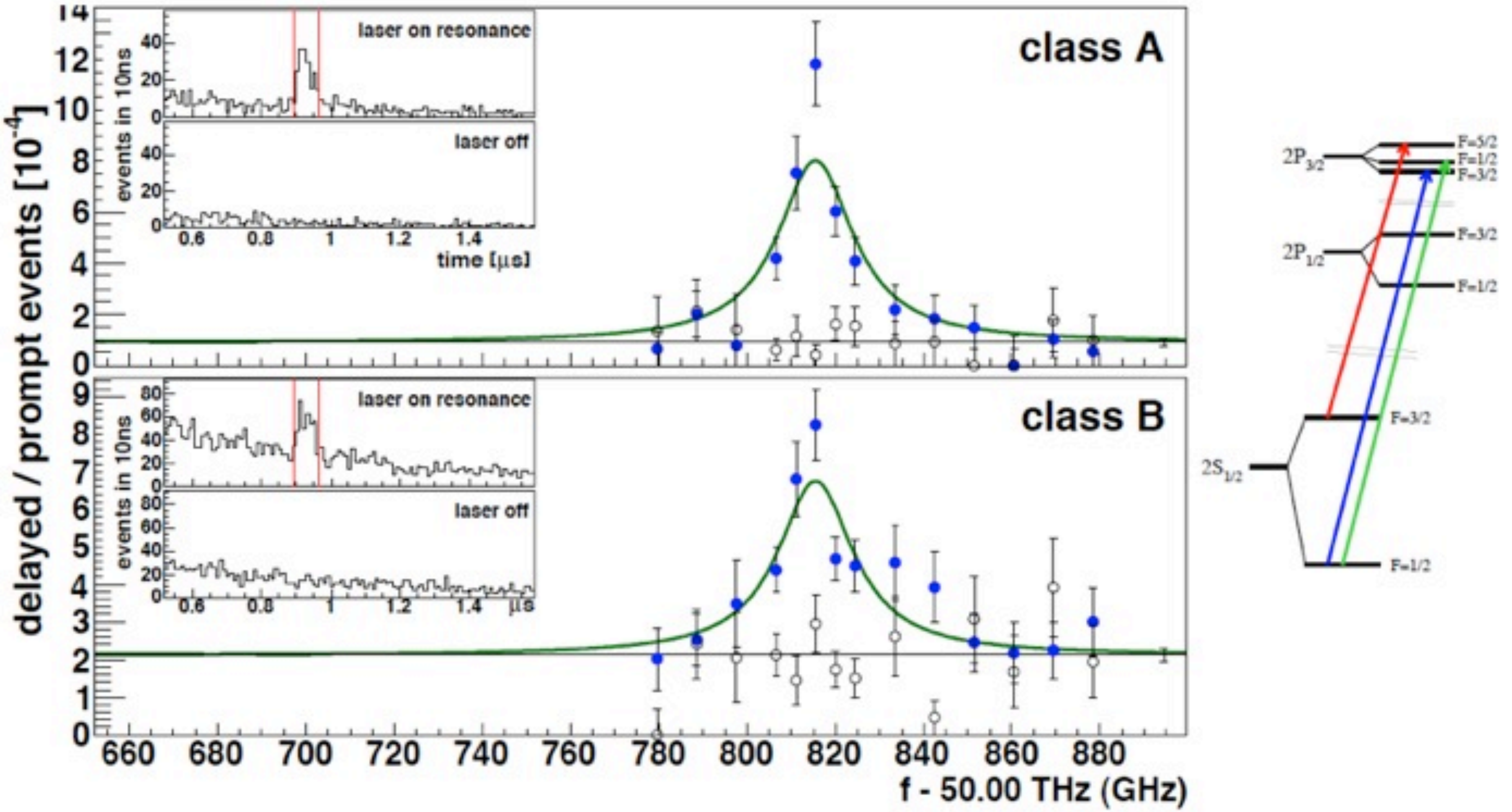
Broadening :

6 μm laser line width	~ 2 GHz
Doppler Broadening	< 1 GHz
Collisional broadening	2.4 MHz

ν (μp : $2S_{1/2}$(F=0)- $2P_{3/2}$(F=1)) good agreement with the other (18.5ppm)

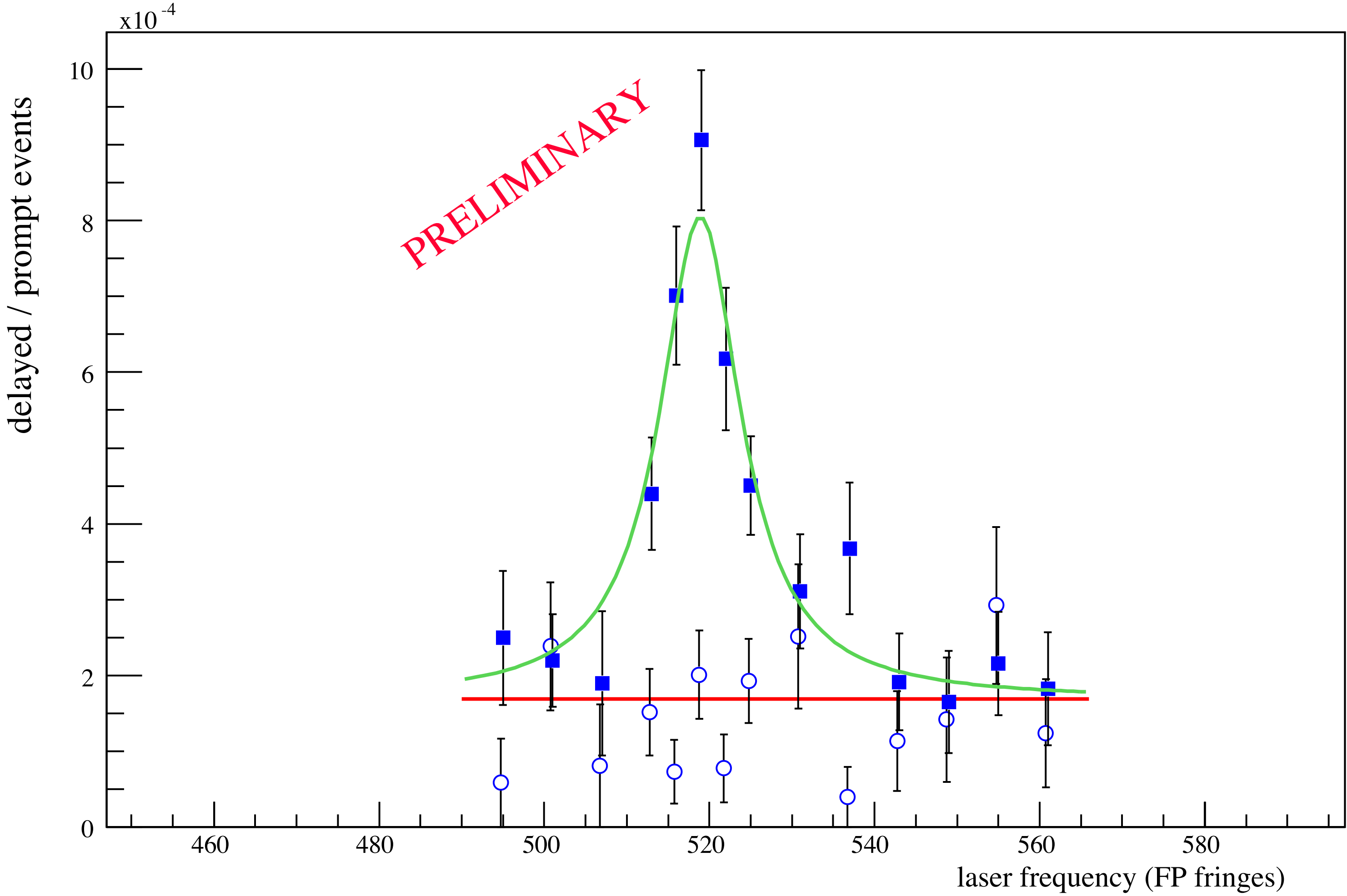
muonic deuterium : $^2S_{1/2}$(F=3/2) - $^2P_{3/2}$(F=5/2)

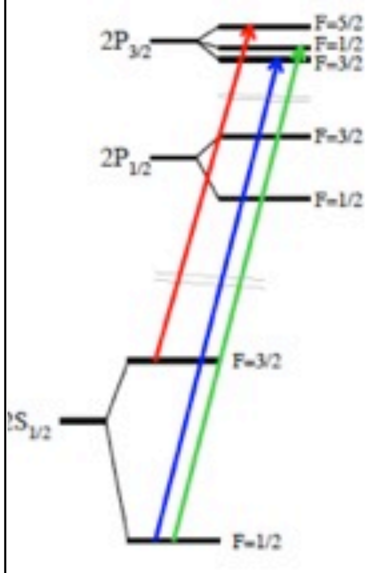
μd ($2S_{1/2}$(F=3/2) → $2P_{3/2}$(F=5/2)) 50815.491±0.815GHz still preliminary



muonic deuterium : $^2S_{1/2}(F=3/2)$ - $^2P_{3/2}(F=5/2)$

$\mu d\ (2S_{1/2}(F{=}3/2) \rightarrow 2P_{3/2}(F{=}5/2))$ 50815.491±0.815GHz still preliminary

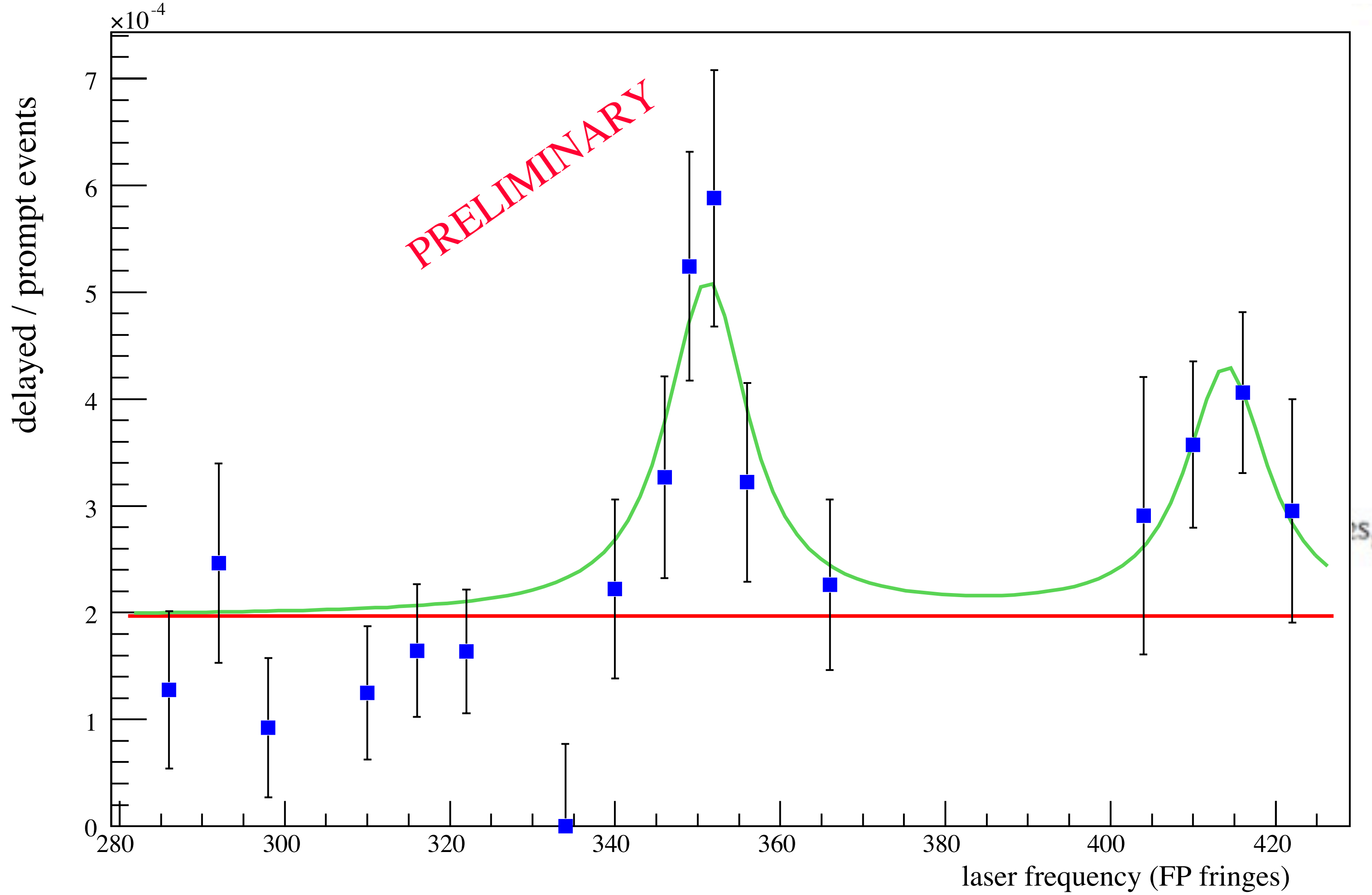


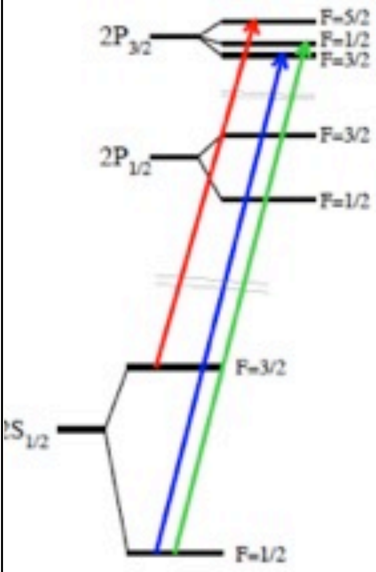


muonic deuterium : $^2S_{1/2}(F=1/2)$- $^2P_{3/2}(F=3/2)$ and $^2S_{1/2}(F=1/2)$- $^2P_{3/2}(F=1/2)$

$\mu d\ (2S_{1/2}(F=1/2) \rightarrow 2P_{3/2}(F=3/2))$: 52061.0±1.6GHz preliminary

$\mu d\ (2S_{1/2}(F=1/2) \rightarrow 2P_{3/2}(F=1/2))$: 52154.4±3.0GHz preliminary

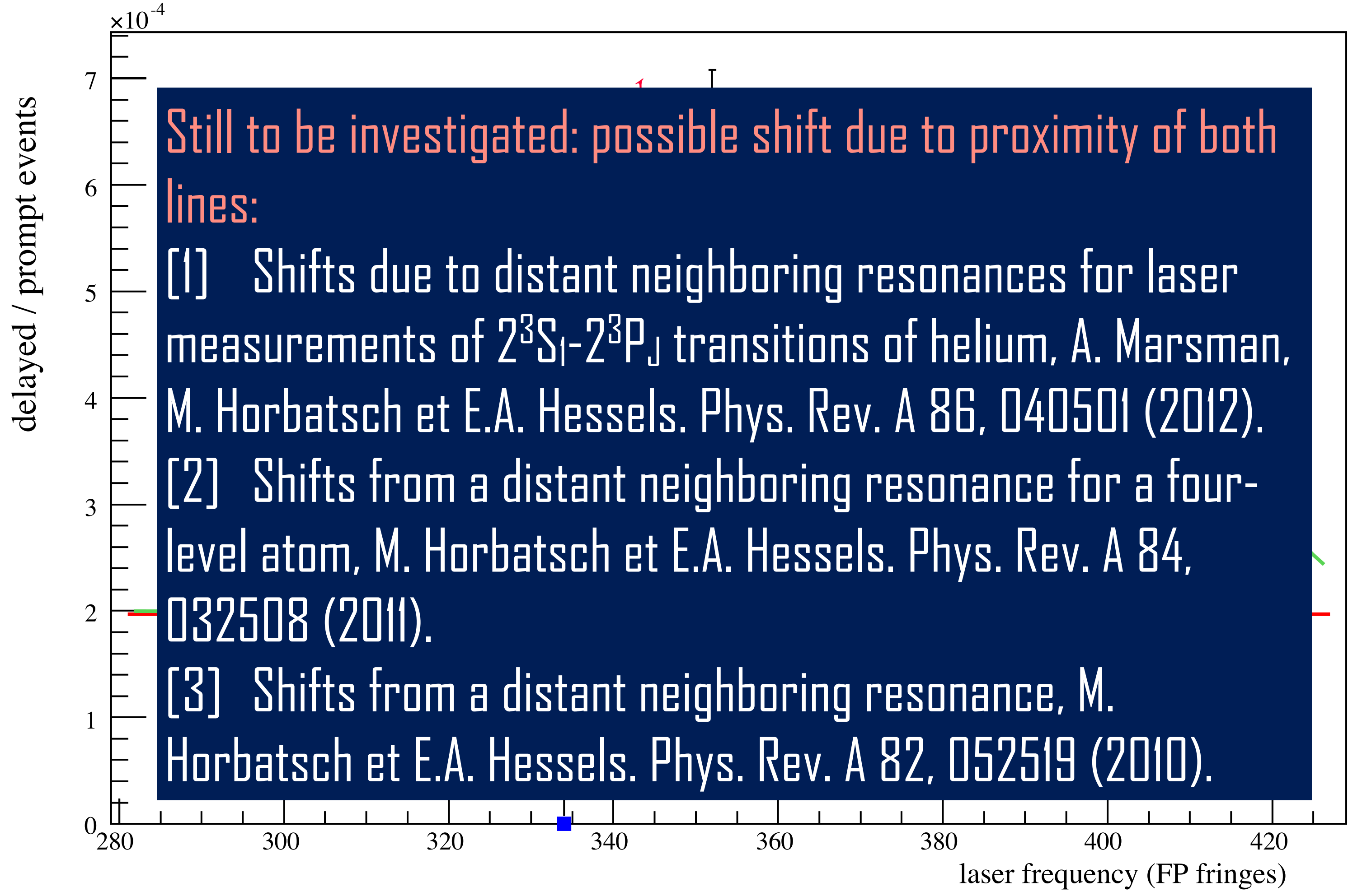




muonic deuterium : $^2S_{1/2}(F=1/2)$- $^2P_{3/2}(F=3/2)$ and $^2S_{1/2}(F=1/2)$- $^2P_{3/2}(F=1/2)$

$\mu d\ (2S_{1/2}(F=1/2) \rightarrow 2P_{3/2}(F=3/2))$: 52061.0±1.6GHz preliminary

$\mu d\ (2S_{1/2}(F=1/2) \rightarrow 2P_{3/2}(F=1/2))$: 52154.4±3.0GHz preliminary

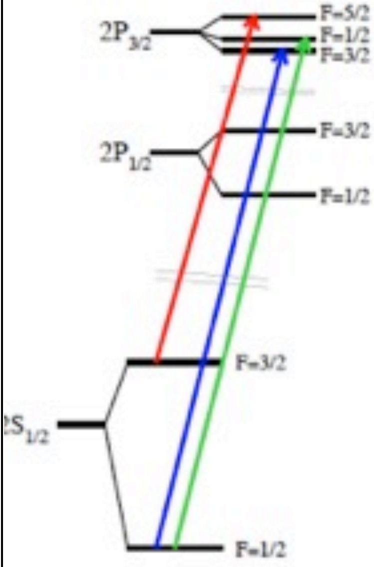


Still to be investigated: possible shift due to proximity of both lines:

[1] Shifts due to distant neighboring resonances for laser measurements of 2^3S_1-2^3P_J transitions of helium, A. Marsman, M. Horbatsch et E.A. Hessels. Phys. Rev. A 86, 040501 (2012).

[2] Shifts from a distant neighboring resonance for a four-level atom, M. Horbatsch et E.A. Hessels. Phys. Rev. A 84, 032508 (2011).

[3] Shifts from a distant neighboring resonance, M. Horbatsch et E.A. Hessels. Phys. Rev. A 82, 052519 (2010).



Extraction of the radii

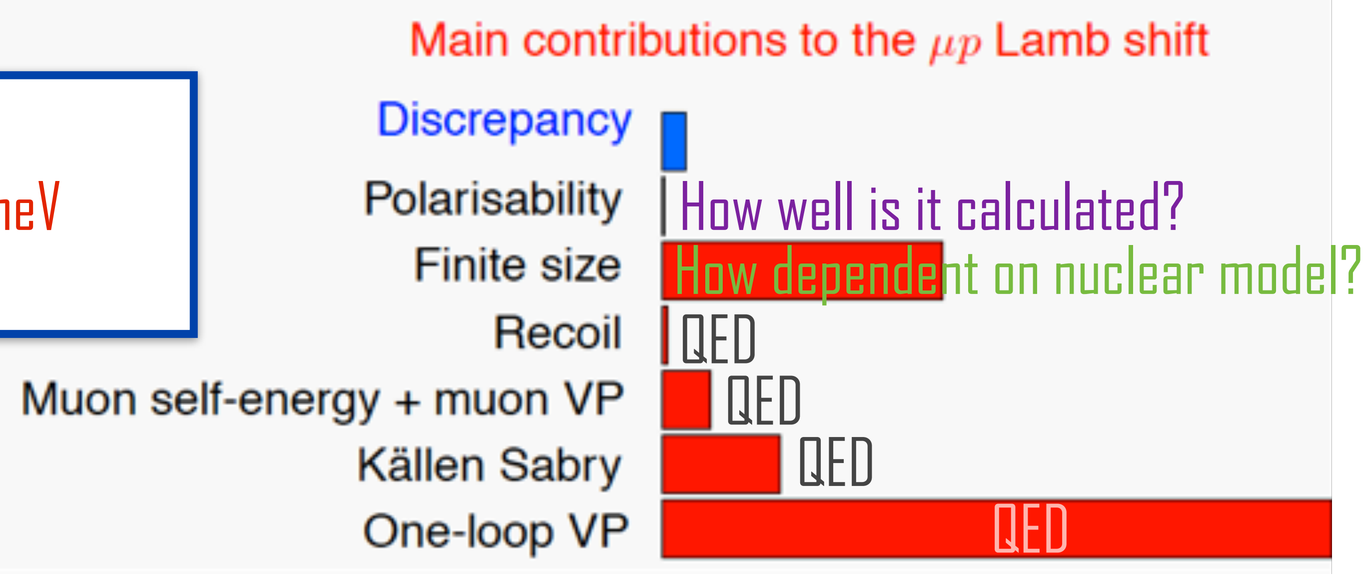
Charge, magnetic and Zemach's radii

New results

- 2010 CODATA value uses improved theory for hydrogen and Mainz electron-proton scattering is now at 6.9σ mostly by a reduction of σ:
  - 0.8775 (59) fm 2010
  - 0.8768 (69) fm 2006
- We have analyzed in details the second transition that was observed, using an improved algorithm that correct for the variation of the laser pulse energy from shot to shot
- We take into account more events
- We have reanalyzed the first observed line using the improved method
- This lead to a slightly reduced error bar for the first transition, an accurate value of a second transition which allows to
  - Get a measurement of the magnetic moment distribution mean radius
  - An improved charge radius

µP theory

Discrepancy: 0.31 meV
Th. Uncertainty 0.0025 meV
That's 120 times smaller!



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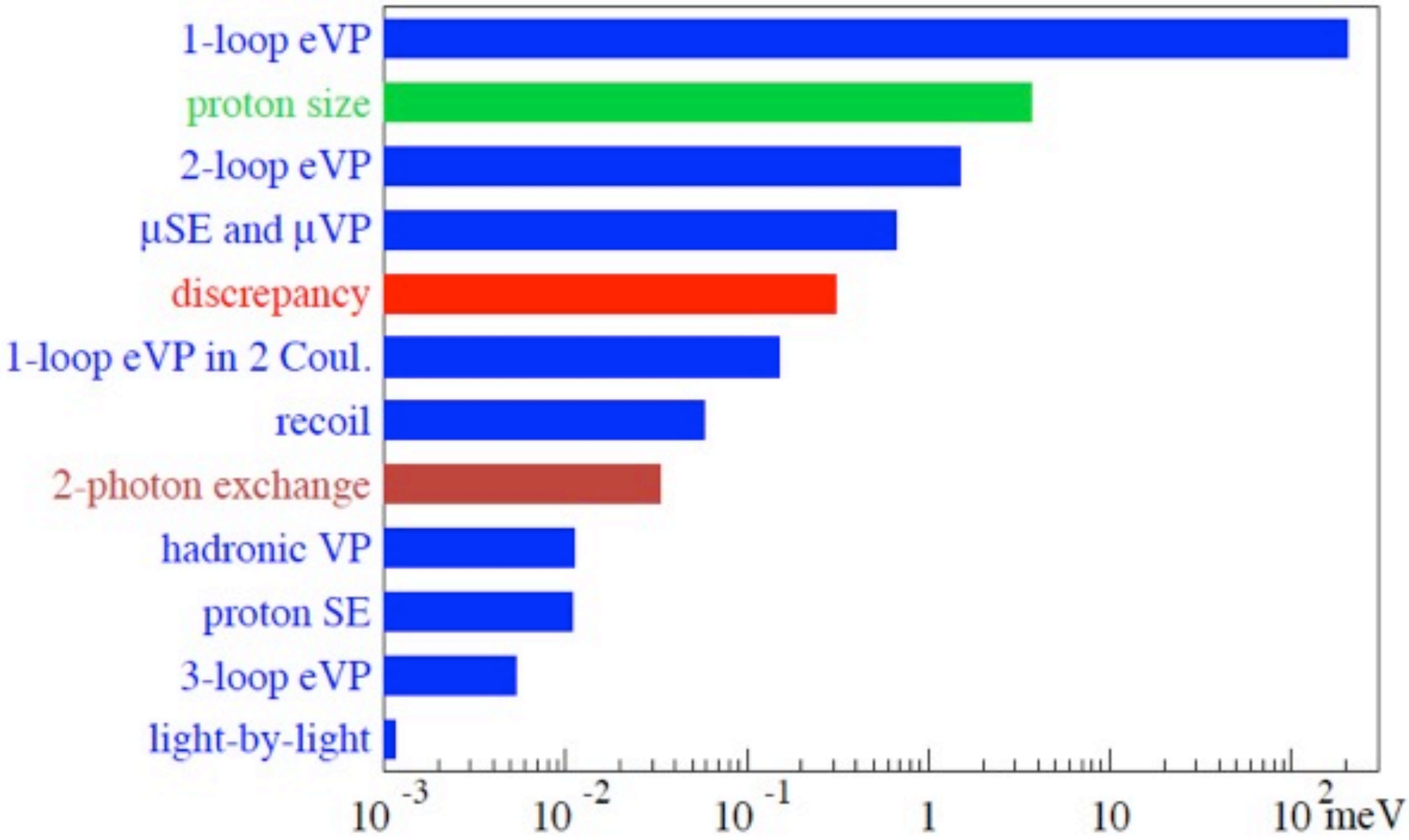
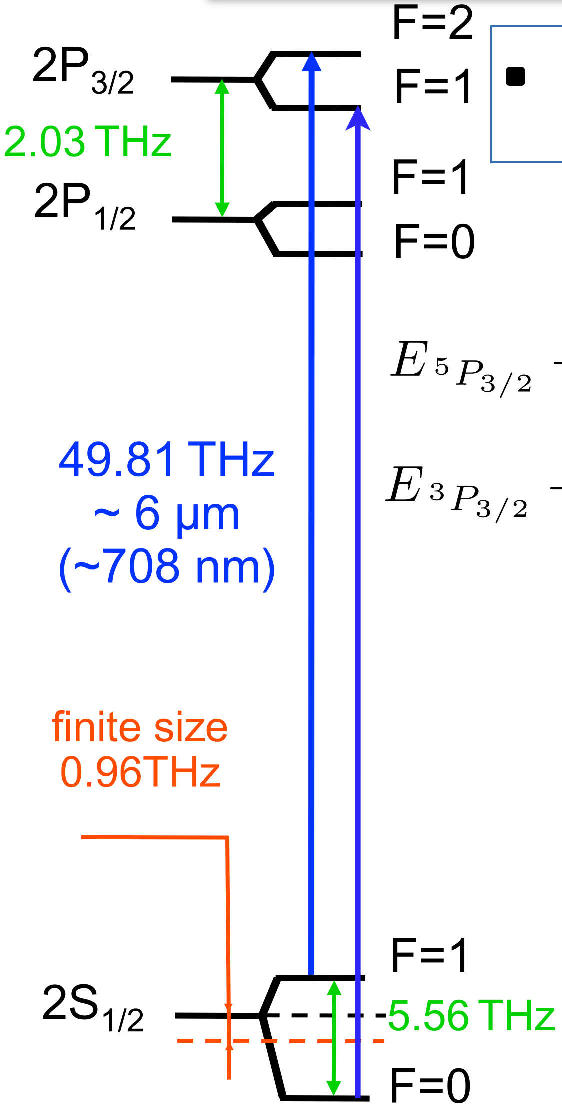


QED and Hyperfine energy



- The two measured lines obey to:

$$E_{^5P_{3/2}} - E_{^3S_{1/2}} = \Delta E_{\mathrm{LS}} + \Delta E_{\mathrm{FS}} + \tfrac{3}{8}\Delta E_{\mathrm{HFS}}(2p_{3/2}) - \tfrac{1}{4}\Delta E_{\mathrm{HFS}}(2s)$$

$$E_{^3P_{3/2}} - E_{^1S_{1/2}} = \Delta E_{\mathrm{LS}} + \Delta E_{\mathrm{FS}} - \tfrac{5}{8}\Delta E_{\mathrm{HFS}}(2p_{3/2}) + \tfrac{3}{4}\Delta E_{\mathrm{HFS}}(2s)$$

Lamb shift

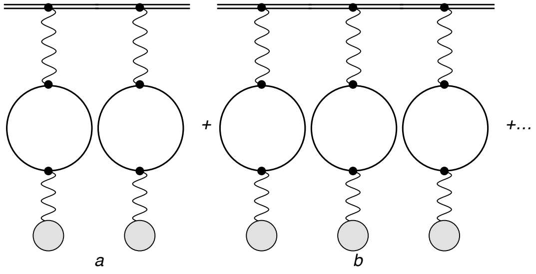
Fine structure

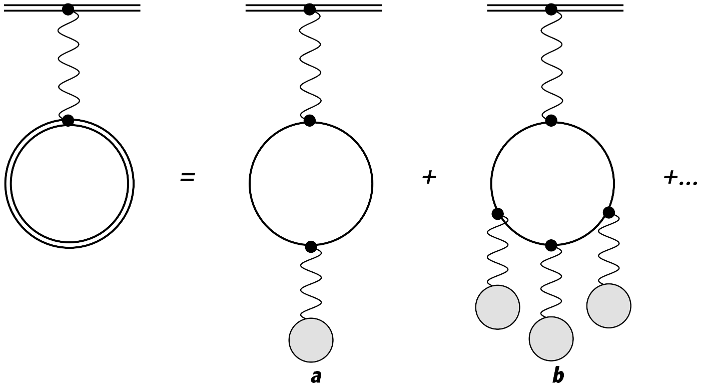
2p Hyperfine structure

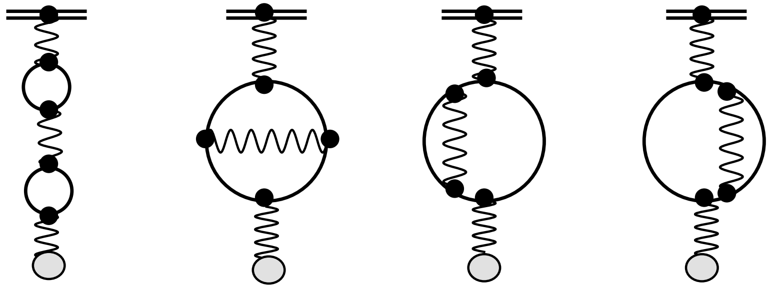
2s hyperfine structure

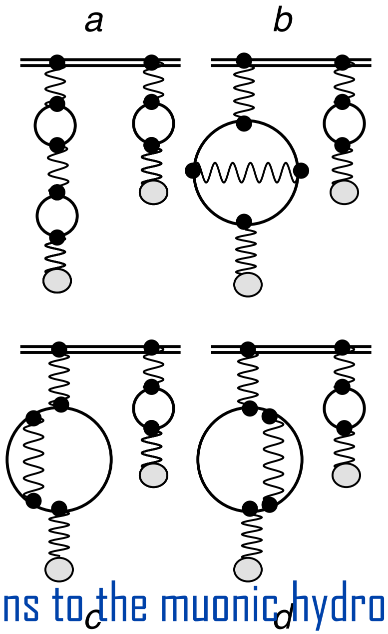
Contributions included to all-order

All-order: the charge distribution is included exactly in the wavefunction and in the operator, when relevant. Higher order Vacuum Polarization contribution included by numerical solution of the Dirac equation



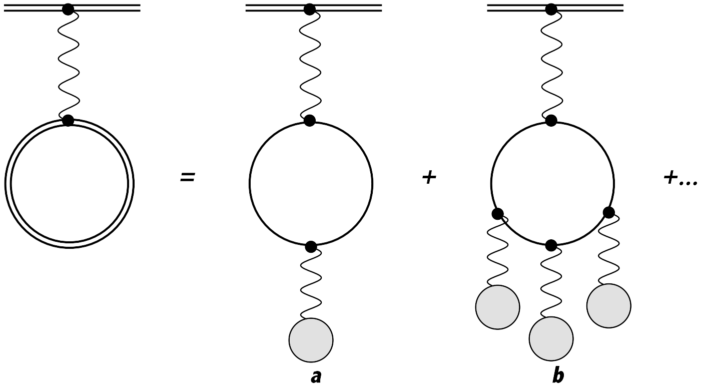


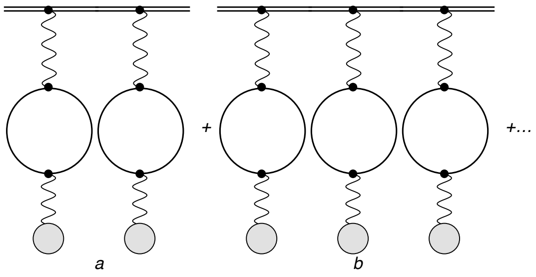


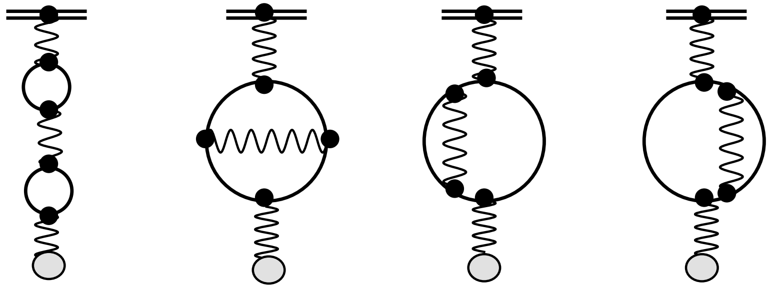


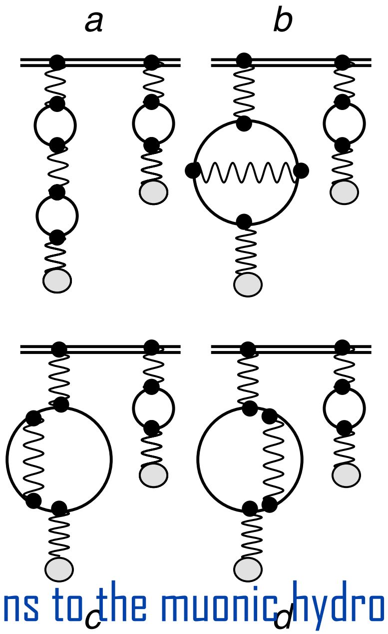
Nonperturbative evaluation of some QED contributions to the muonic hydrogen n=2 Lamb shift and hyperfine structure, P. Indelicato. Phys. Rev. A 87, 022501 (2013).

Contributions included to all-order









Nonperturbative evaluation of some QED contributions to the muonic hydrogen n=2 Lamb shift and hyperfine structure, P. Indelicato. Phys. Rev. A 87, 022501 (2013).

Remark: scale of QED corrections

$$\left(c\boldsymbol{\alpha}\cdot\boldsymbol{p}+\beta\mu_{\mathrm{r}}c^2+V_{\mathrm{Nuc}}(\boldsymbol{r})\right)\Phi_{n\kappa\mu}(\boldsymbol{r})=\mathcal{E}_{n\kappa\mu}\Phi_{n\kappa\mu}(\boldsymbol{r}),$$

$$\begin{aligned}V_{11}^{pn}(r) &= -\frac{\alpha(Z\alpha)}{3\pi}\int_1^\infty dz\,\sqrt{z^2-1}\left(\frac{2}{z^2}+\frac{1}{z^4}\right)\frac{e^{-2m_e rz}}{r}\\ &= -\frac{2\alpha(Z\alpha)}{3\pi}\frac{1}{r}\chi_1\left(\frac{2}{\boxed{\lambda_e}}r\right)\end{aligned}$$

Bohr radius/particle mass:

Electron Compton wavelength/2π=440 R

n=1 in hydrogen: $a_0=137\lambda_e$=60340 R

n=2 in muonic H: $a=2.65\lambda_e$

n=1 in h-like (Z=52) : $a=2.65\lambda_e$

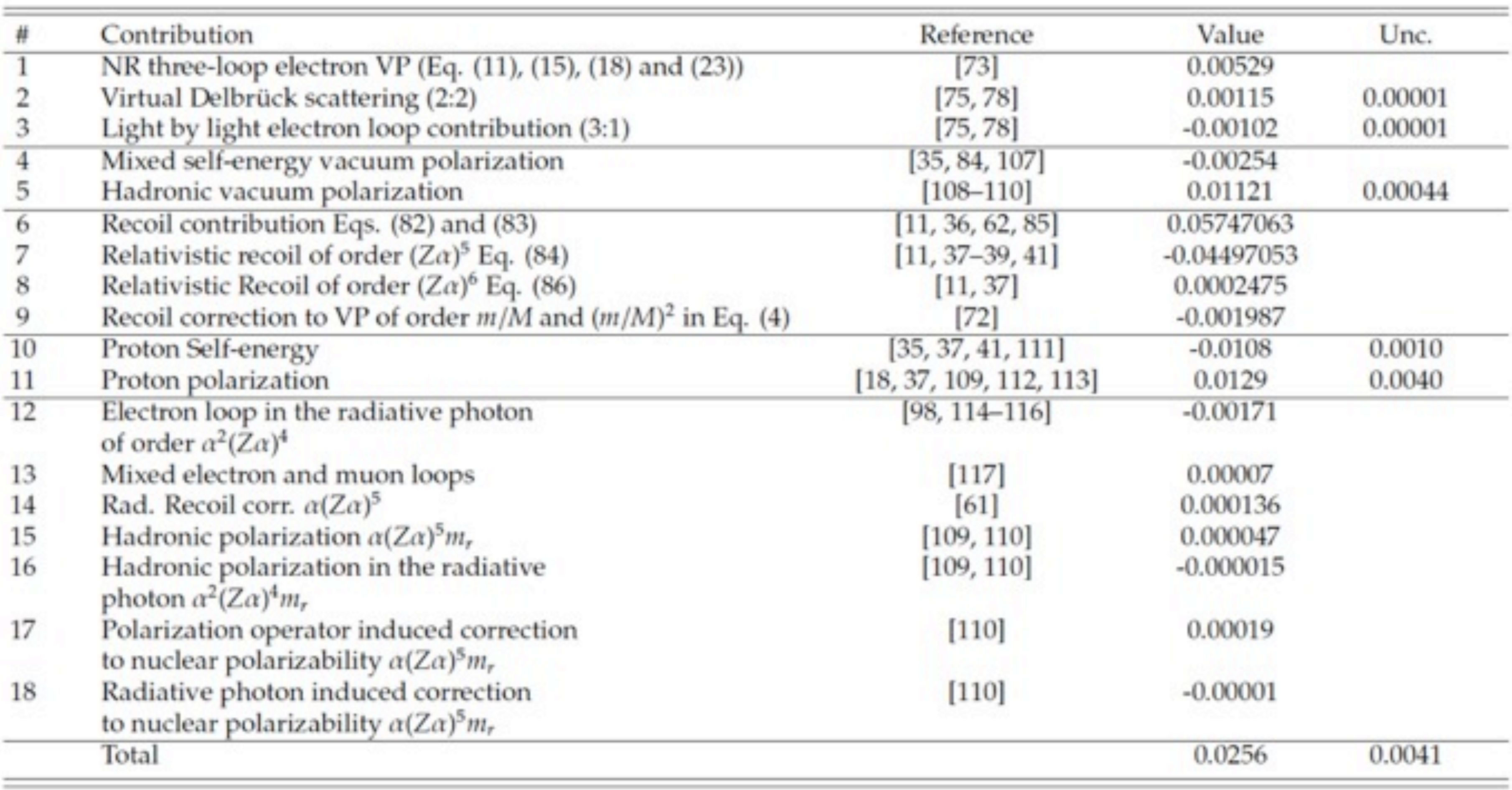
Extraction of the size dependence

- Fit to the Coulomb+Vacuum polarization contribution to 2s-2p$_{1/2}$ separation, plus higher order corrections using Friar functional form

$$
\begin{aligned}
E^{\mathrm{Tot,fs}}_{2p_{1/2}} - E^{\mathrm{Tot,fs}}_{2s_{1/2}}(R) = {} & 206.046613695 - 5.226988678R^2 \\
& + 0.03532068001R^3 \\
& + 0.00006692700063R^4 \\
& + 0.0002962967640R^2 \log(R) \\
& - 0.0004751147090R^4 \log(R)\ \mathrm{meV}.
\end{aligned}
$$

Nonperturbative evaluation of some QED contributions to the muonic hydrogen n=2 Lamb shift and hyperfine structure, P. Indelicato. Phys. Rev. A 87, 022501 (2013).

Other contributions for µP



#	Contribution	Reference	Value	Unc.
1	NR three-loop electron VP (Eq. (11), (15), (18) and (23))	[73]	0.00529	
2	Virtual Delbrück scattering (2:2)	[75, 78]	0.00115	0.00001
3	Light by light electron loop contribution (3:1)	[75, 78]	-0.00102	0.00001
4	Mixed self-energy vacuum polarization	[35, 84, 107]	-0.00254	
5	Hadronic vacuum polarization	[108–110]	0.01121	0.00044
6	Recoil contribution Eqs. (82) and (83)	[11, 36, 62, 85]	0.05747063	
7	Relativistic recoil of order $(Z\alpha)^5$ Eq. (84)	[11, 37–39, 41]	-0.04497053	
8	Relativistic Recoil of order $(Z\alpha)^6$ Eq. (86)	[11, 37]	0.0002475	
9	Recoil correction to VP of order m/M and $(m/M)^2$ in Eq. (4)	[72]	-0.001987	
10	Proton Self-energy	[35, 37, 41, 111]	-0.0108	0.0010
11	Proton polarization	[18, 37, 109, 112, 113]	0.0129	0.0040
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	[98, 114–116]	-0.00171	
13	Mixed electron and muon loops	[117]	0.00007	
14	Rad. Recoil corr. $\alpha(Z\alpha)^5$	[61]	0.000136	
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	[109, 110]	0.000047	
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	[109, 110]	-0.000015	
17	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[110]	0.00019	
18	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	[110]	-0.00001	
	Total		0.0256	0.0041

Laboratoire Kastler Brossel
Physique quantique et applications

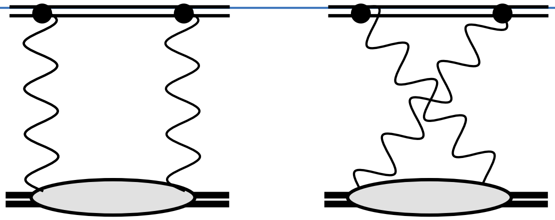
The role of the nuclear model

Dependence on the charge distribution

Nuclear Models and experiment

- Using the electronic density from Arrington et al. I get
  - Rp = 0.85035 fm Rm = 0.831 fm Rz = 1.0466 fm
- Dirac + Uehling vacuum polarization with this density:
  - E=201.2789 meV
- Dirac + Uehling vacuum polarization with same radius and other models
  - Gauss: E=201.2680 (-0.0109) meV
  - Dipole: E=201.2700 (-0.0089) meV
  - Uniform: E=201.2669 (-0.0120) meV
  - Fermi: E=201.2686 (-0.0102)
- Solving E_{Dipole}(R)=201.2789 meV gives:
  - R=0.84934 (-0.00101) fm

Proton polarization



- Several calculations
  - Rosenfelder (1999)

$$\Delta E_{2s}^{\mathrm{p.pol}} = -\frac{136 \pm 30}{n^3}\,\mu\mathrm{eV} = -0.017 \pm 0.004\,\mathrm{meV}.$$

  - Pachucki (1999) $\Delta E_{2s}^{\mathrm{p.pol}} = -0.012 \pm 0.002\,\mathrm{meV},$
  - Martynenko (2006)

$$\begin{aligned}\Delta E_{2s}^{\mathrm{p.pol}} &= \Delta E^{\mathrm{subt.}} + \Delta E^{\mathrm{inel.}}\\ &= 0.0023 - 0.01613\,\mathrm{meV}\\ &= -0.0138(29)\,\mathrm{meV},\end{aligned}$$

  - Carlson and Vanderhaeghen (2011)

$$\begin{aligned}\Delta E_{2s}^{\mathrm{p.pol}} &= \Delta E^{\mathrm{subt.}} + \Delta E^{\mathrm{inel.}} + \Delta E^{\mathrm{el.}}\\ &= 0.0053(19) - 0.0127(5) - 0.0295(13)\,\mathrm{meV}\\ &= -0.0074(20) - 0.0295(13)\,\mathrm{meV}.\end{aligned}$$

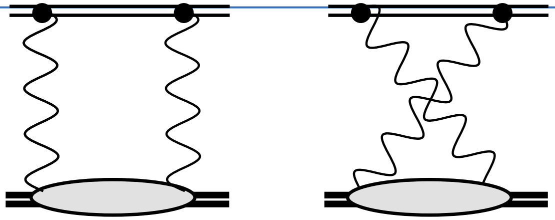
  - Hill and Paz (2011+DPF 2011)

$$\begin{aligned}\Delta E_{2s}^{\mathrm{p.pol}} &= \Delta E^{\mathrm{subt.}} + \Delta E^{\mathrm{inel.}}\\ &= \left[\delta E^{W_1(0,Q^2)} + \delta E^{\mathrm{proton\ pole}}\right] + \delta E^{\mathrm{continuum}}\\ &= \left[\delta E^{W_1(0,Q^2)} + 0016\right] - 0.0127(5)\,\mathrm{meV},\end{aligned}$$

Could be wrong by 0.04 meV →

Proton polarization

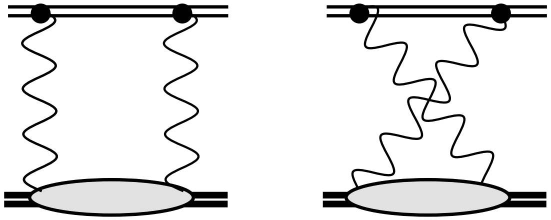
- Several calculations

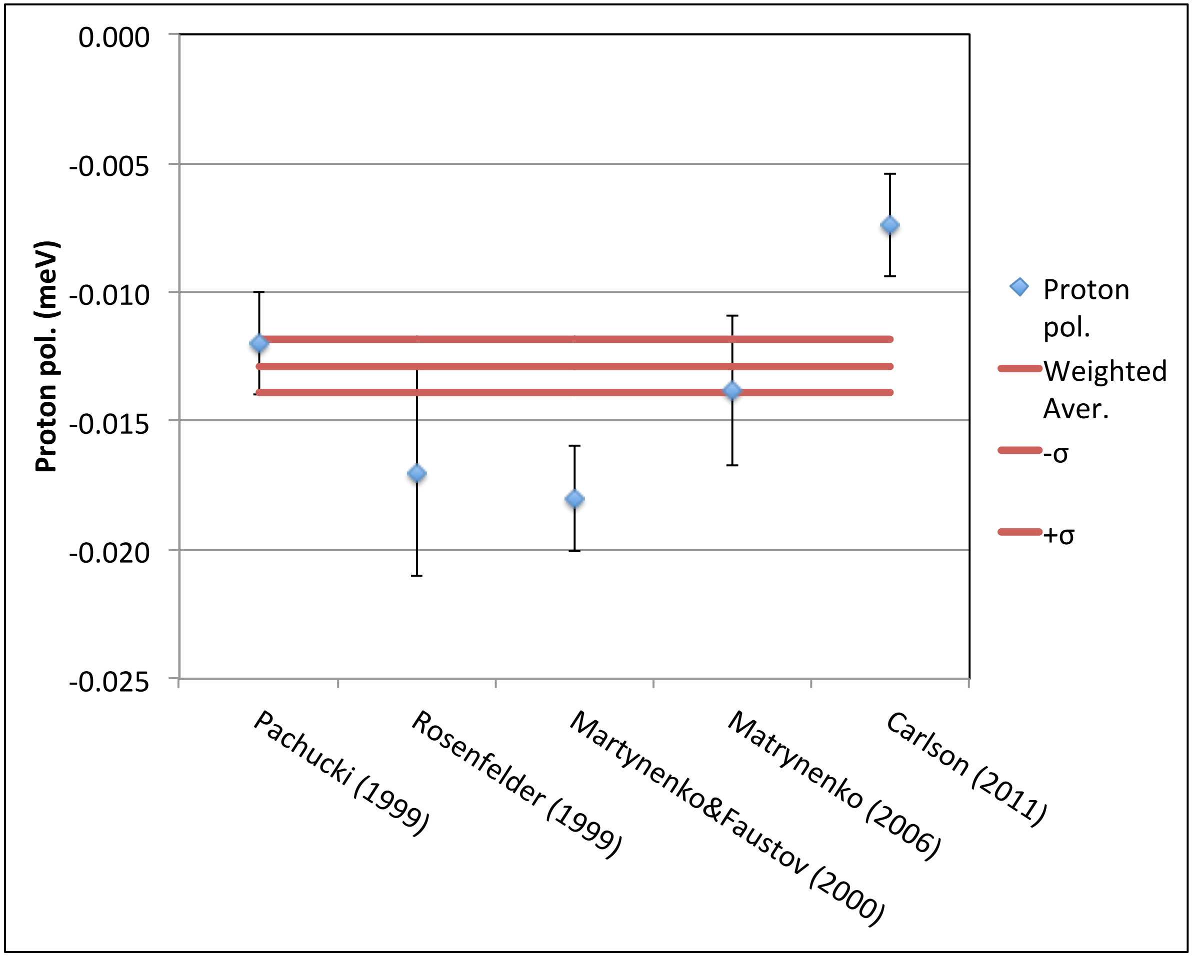


  - Proton polarisability contribution to the Lamb shift in muonic hydrogen at fourth order in chiral perturbation theory, M.C. Birse et J.A. McGovern. Eur. Phys. J. A 48, 1-9 (2012).

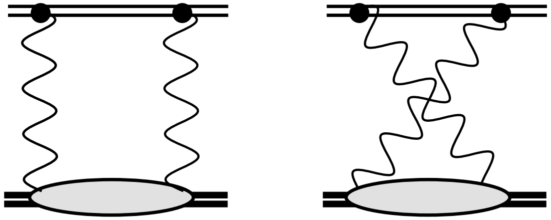
We calculate the amplitude T1 for forward doubly virtual Compton scattering in heavy-baryon chiral perturbation theory, to fourth order in the chiral expansion and with the leading contribution of the γNΔ form factor. This provides a model-independent expression for the amplitude in the low-momentum region, which is the dominant one for its contribution to the Lamb shift. It allows us to significantly reduce the theoretical uncertainty in the proton polarisability contributions to the Lamb shift in muonic hydrogen. We also stress the importance of consistency between the definitions of the Born and structure parts of the amplitude. Our result leaves no room for any effect large enough to explain the discrepancy between proton charge radii as determined from muonic and normal hydrogen.

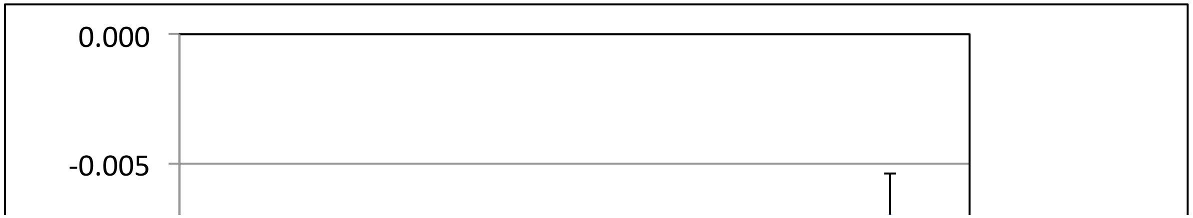
Proton polarization





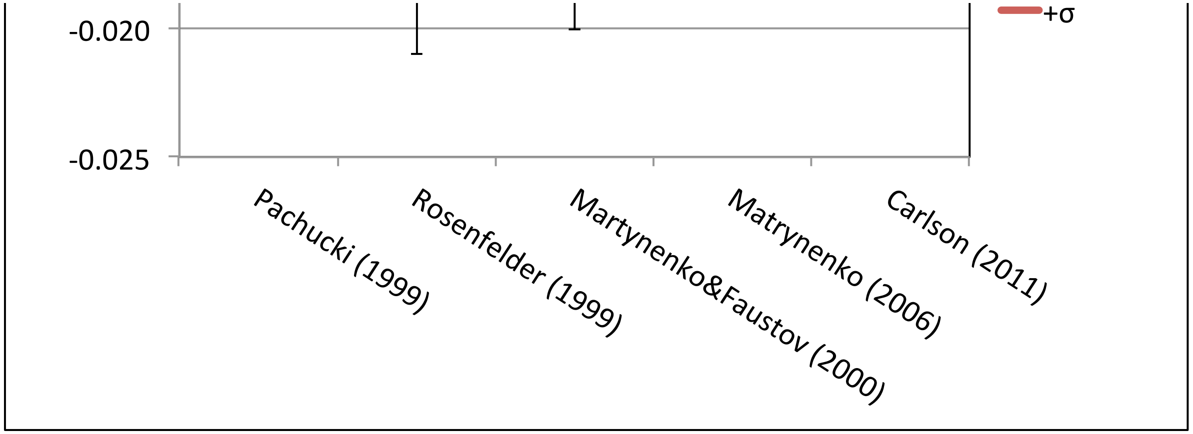
Proton polarization



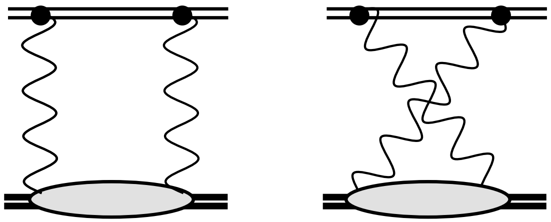


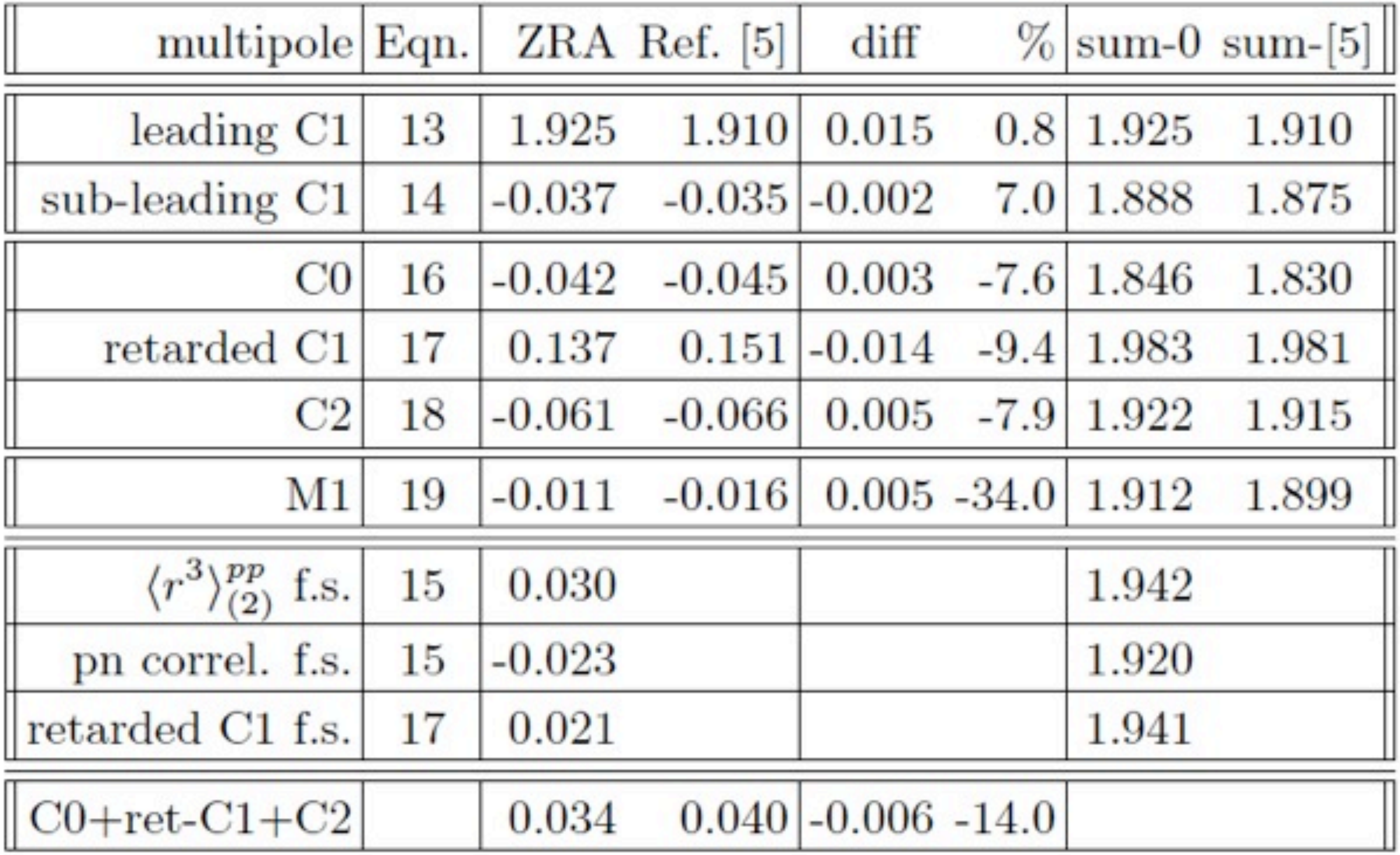
No radial excitations in low energy QCD. I. Diquarks and classification of mesons, T. Friedmann. The European Physical Journal C 73, 2298 (2013)

No radial excitations in low energy QCD. II. The shrinking radius of hadrons, T. Friedmann. The European Physical Journal C 73, 2299 (2013).



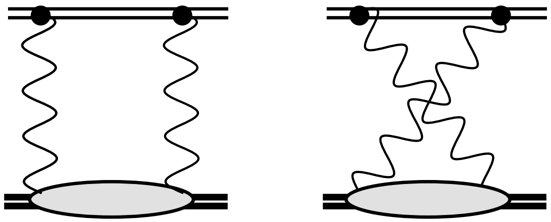
Deuteron polarization (Friar, Pachucki)





multipole	Eqn.	ZRA	Ref. [5]	diff	%	sum-0	sum-[5]
leading C1	13	1.925	1.910	0.015	0.8	1.925	1.910
sub-leading C1	14	-0.037	-0.035	-0.002	7.0	1.888	1.875
C0	16	-0.042	-0.045	0.003	-7.6	1.846	1.830
retarded C1	17	0.137	0.151	-0.014	-9.4	1.983	1.981
C2	18	-0.061	-0.066	0.005	-7.9	1.922	1.915
M1	19	-0.011	-0.016	0.005	-34.0	1.912	1.899
$\langle r^3 \rangle^{pp}_{(2)}$ f.s.	15	0.030				1.942	
pn correl. f.s.	15	-0.023				1.920	
retarded C1 f.s.	17	0.021				1.941	
C0+ret-C1+C2		0.034	0.040	-0.006	-14.0		

Deuteron polarization



Chen Ji, Nir Nevo Dinur, Sonia Bacca, Nir Barnea (arXiv:1307.6577)

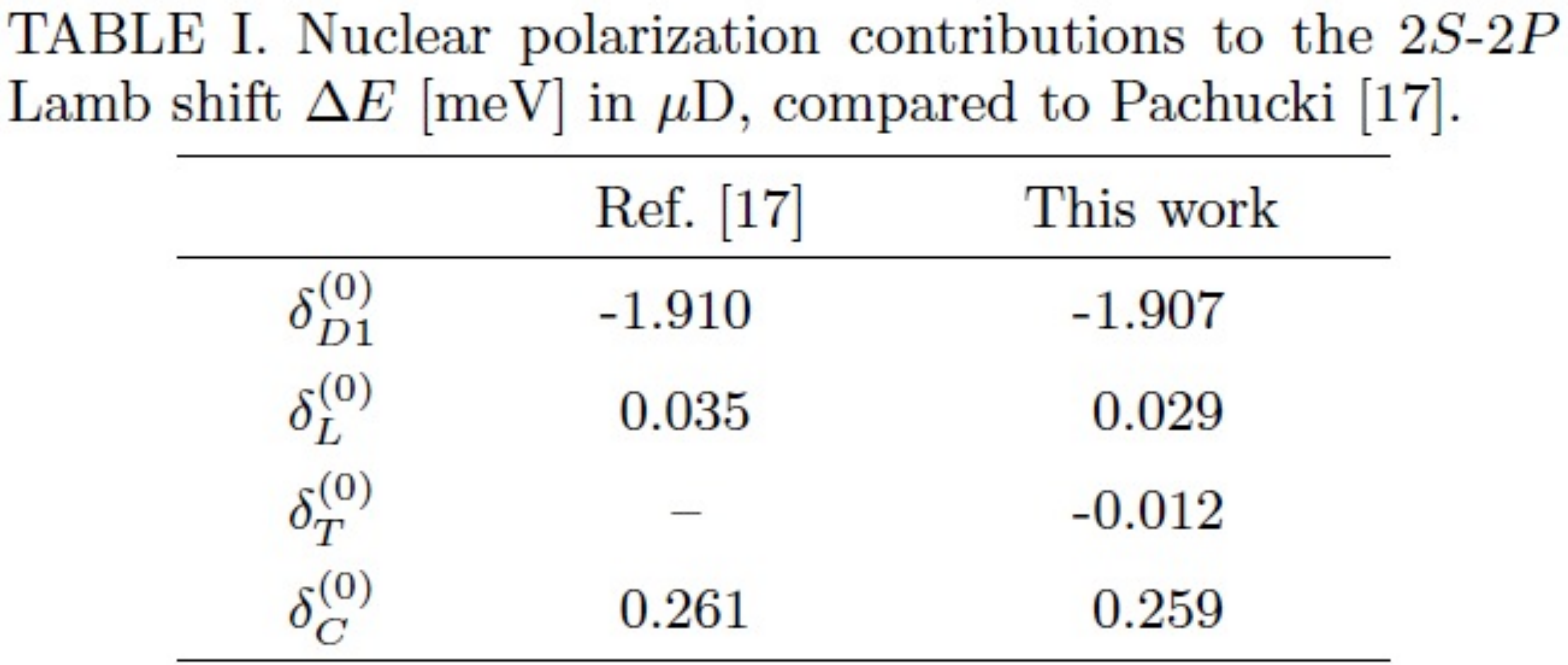


TABLE I. Nuclear polarization contributions to the $2S$-$2P$ Lamb shift ΔE [meV] in μD, compared to Pachucki [17].

	Ref. [17]	This work
$\delta_{D1}^{(0)}$	-1.910	-1.907
$\delta_{L}^{(0)}$	0.035	0.029
$\delta_{T}^{(0)}$	–	-0.012
$\delta_{C}^{(0)}$	0.261	0.259

LKB

Hyperfine structure

Beyond Zemach

Hyperfine structure

$$\Delta E^{HFS}_{\mathrm{M1}} = A\frac{g\alpha}{2M_p}\int_0^\infty dr\frac{P_1(r)Q_2(r)+P_2(r)Q_1(r)}{r^2},$$

$$\begin{aligned}\Delta E^{BW} = -A\frac{g\alpha}{2M_p}\int_0^\infty & dr_n r_n^2 \mu(r_n)\\ \times\int_0^{r_n} & dr\frac{P_1(r)Q_2(r)+P_2(r)Q_1(r)}{r^2},\end{aligned}$$

$$\begin{aligned}\Delta E^{\mathrm{Z}}_{\mathrm{HFS}} &= -\frac{2}{3}\left\langle \boldsymbol{S}_p\cdot\boldsymbol{S}_\mu\right\rangle\left|\phi_{\mathrm{C}}(0)\right|^2\\ &\quad\times\left(1-2\alpha m_\mu\int\rho(\boldsymbol{u})\mid\boldsymbol{u}-\boldsymbol{r}\mid\mu(\boldsymbol{r})d\boldsymbol{u}d\boldsymbol{r}\right),\\ &= E_{\mathrm{F}}\left(1-2\alpha m_\mu\int\rho(\boldsymbol{u})\mid\boldsymbol{u}-\boldsymbol{r}\mid\mu(\boldsymbol{r})d\boldsymbol{u}d\boldsymbol{r}\right),\end{aligned}$$

$$\Delta E^{\mathrm{Z}}_{\mathrm{HFS}} = E_{\mathrm{F}}\left(1-2\alpha m_\mu\left\langle r_{\mathrm{Z}}\right\rangle\right),$$

Hyperfine structure

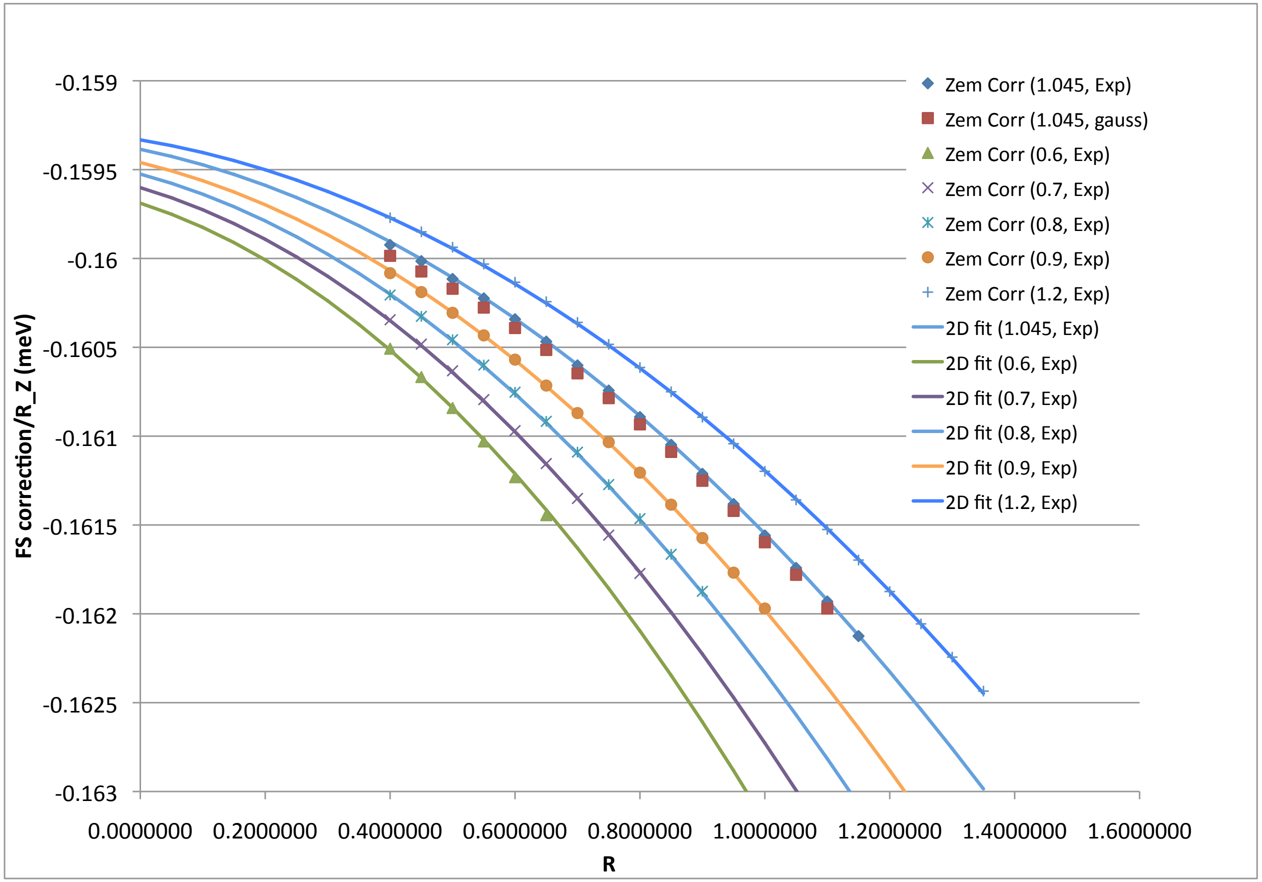
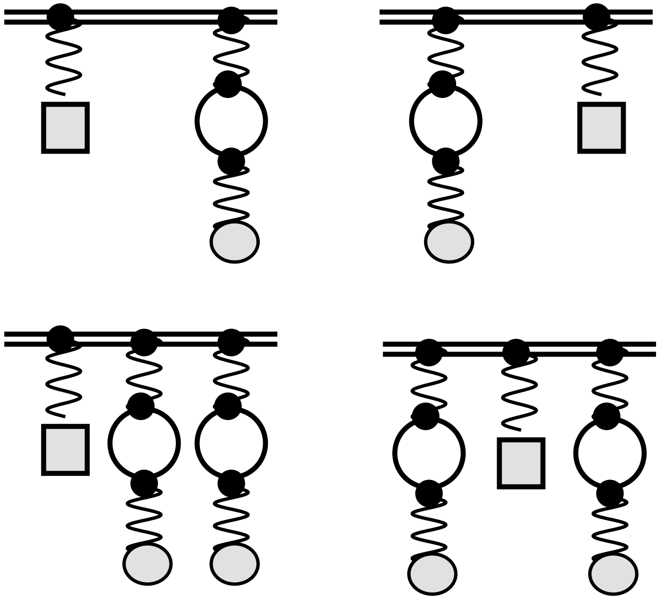


Fig. 10. Finite charge and magnetic moment distribution energy shift for the 2*s* state as a function of the charge *R* and Zemach radius R_Z for the Gaussian ($R_Z = 1.045$fm) and exponential model, divided by R_Z. The lines correspond to the function in Eq. (90).

Hyperfine structure FS corrections

$$\begin{aligned}E^{2s}_{\mathrm{HFS}}(R_Z,R) = {} & 22.807995 \\ & - 0.0022324349R^2 + 0.00072910794R^3 \\ & - 0.000065912957R^4 \boxed{- 0.16034434R_Z} \\ & - 0.00057179529RR_Z \\ & - 0.00069518048R^2R_Z \\ & - 0.00018463878R^3R_Z \\ & + 0.0010566454R_Z^2 \\ & + 0.00096830453RR_Z^2 \\ & + 0.00037883473R^2R_Z^2 \\ & - 0.00048210961R_Z^3 \\ & - 0.00041573690RR_Z^3 \\ & + 0.00018238754R_Z^4 \text{ meV.}\end{aligned}$$

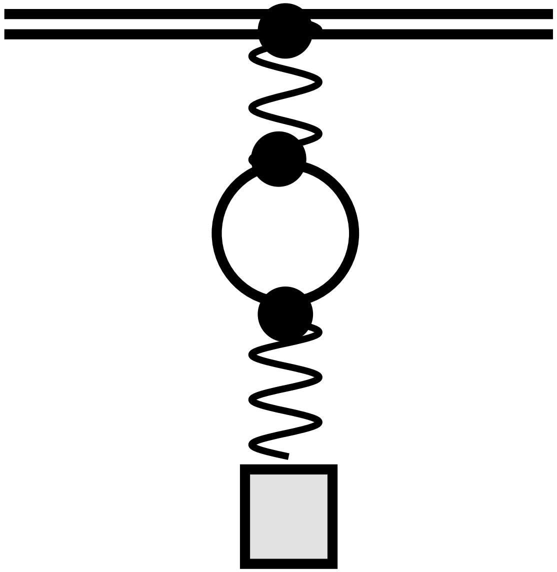
$$\begin{aligned}E^{2s,VP}_{\mathrm{HFS}}(R_Z,R) = {} & 0.074369030 + 0.000074236132R^2 \\ & + 0.00013277334R^3 - 8.0987285 \times 10^{-6}R^4 \\ & - 0.0017880269R_Z - 0.00017204505RR_Z \\ & - 0.00037499458R^2R_Z \\ & - 0.000070355379R^3R_Z \\ & - 0.00022093411R_Z^2 + 0.00035038656RR_Z^2 \\ & + 0.00020554316R^2R_Z^2 + 0.00025100642R_Z^3 \\ & - 0.00017200435RR_Z^3 \\ & - 0.000061266973R_Z^4 \text{ meV.}\end{aligned}$$



Full calculation beyond Zemach

Nonperturbative evaluation of some QED contributions to the muonic hydrogen n=2 Lamb shift and hyperfine structure, P. Indelicato. Phys. Rev. A **87,** 022501 (2013).

Hyperfine structure FS corrections



Would need to be evaluated as well

Results HFS

	#	Ref. [40]	Ref. [70]	This work
Fermi energy	1	22.8054	22.8054	
Dirac Energy (includes Breit corr.)	2			22.807995
Vacuum polarization corrections of orders α^5, α^6 in 2nd-order perturbation theory ϵ_{VP1}	3	0.0746	0.07443	
All-order VP contribution to HFS, with finite magnetisation distribution	4			0.07244
finite extent of magnetisation density correction to the above	5		−0.00114	
Proton structure corr. of order α^5	6	−0.1518	−0.17108	−0.17173
Proton structure corrections of order α^6	7	−0.0017		
Electron vacuum polarization contribution+ proton structure corrections of order α^6	8	−0.0026		
contribution of 1γ interaction of order α^6	9	0.0003	0.00037	0.00037
$\epsilon_{VP}2E_F$ (neglected in Ref. [40])	10		0.00056	0.00056
muon loop VP (part corresponding to ϵ_{VP2} neglected in Ref. [40])	11		0.00091	0.00091
Hadronic Vac. Pol.	12	0.0005	0.0006	0.0006
Vertex (order α^5)	13		−0.00311	−0.00311
Vertex (order α^6) (only part with powers of $\ln(\alpha)$ - see Ref. [103])	14		−0.00017	−0.00017
Breit	15	0.0026	0.00258	
Muon anomalous magnetic moment correction of order α^5, α^6	16	0.0266	0.02659	0.02659
Relativistic and radiative recoil corrections with proton anomalous magnetic moment of order α^6	17	0.0018		
One-loop electron vacuum polarization contribution of 1γ interaction of orders α^5, α^6 (ϵ_{VP2})	18	0.0482	0.04818	0.04818
finite extent of magnetisation density correction to the above	19		−0.00114	−0.00114
One-loop muon vacuum polarization contribution of 1γ interaction of order α^6	20	0.0004	0.00037	0.00037
Muon self energy+proton structure correction of order α^6	21	0.001		0.001
Vertex corrections+proton structure corrections of order α^6	22	−0.0018		−0.0018
"Jellyfish" diagram correction+ proton structure corrections of order α^6	23	0.0005		0.0005
Recoil correction Ref. [104]	24		0.02123	0.02123
Proton polarizability contribution of order α^5	25	0.0105		
Proton polarizability Ref. [104]	26		0.00801	0.00801
Weak interaction contribution	27	0.0003	0.00027	0.00027
Total		22.8148	22.8129	22.8111

Results

- Using the second line measured during the experiment we can improve the charge radius and get a value for the Zemach's radius.

$$\begin{aligned}E^{F=2}_{2p_{3/2}} - E^{F=1}_{2s_{1/2}}(R_Z, R) = {} & 209.92451 - 5.2265012R^2 \\ & + 0.035105381R^3 \\ & + 0.000085386880R^4 \\ & + 1.5472388 \times 10^{-8}R^5 \\ & - 2.1359270 \times 10^{-9}R^6 \\ & + 0.040533092Rz \\ & + 0.00018596008RRz \\ & + 0.00026754376R^2Rz \\ & + 0.000063748539R^3Rz \\ & - 0.00020892783Rz^2 \\ & - 0.00032967277RRz^2 \\ & - 0.00014609447R^2Rz^2 \\ & + 0.000057775798Rz^3 \\ & + 0.00014693531RRz^3 \\ & - 0.000030280142Rz^4 \\ & + 0.00029629676R^2\log(R) \\ & - 0.000047511471R^4\log(R) \\ & \text{meV.}\end{aligned}$$

$$\begin{aligned}E^{F=1}_{2p_{3/2}} - E^{F=0}_{2s_{1/2}}(R_Z, R) = {} & 229.66172 - 5.2286594R^2 \\ & + 0.035967212R^3 \\ & + 0.000011416693R^4 \\ & - 0.12159928R_Z - 0.00055788025RR_Z \\ & - 0.00080263129R^2R_Z \\ & - 0.00019124562R^3R_Z \\ & + 0.00062678350R_Z^2 \\ & + 0.00098901832RR_Z^2 \\ & + 0.00043828342R^2R_Z^2 \\ & - 0.00017332740R_Z^3 \\ & - 0.00044080593RR_Z^3 \\ & + 0.000090840426R_Z^4 \\ & + 0.00029629676R^2\log(R) \\ & - 0.000047511471R^4\log(R) \\ & \text{meV.}\end{aligned}$$

Simultaneous solution of these two equations with the two line energies

Rc = 0.84100(63) fm and Rz=1.086(40) fm

Assuming a dipole model, this gives Rm: 0.879(50) fm

Mainz results: Rc = 0.879 fm, Rm = 0.777 fm and Rz = 1.047 fm

Extracting the magnetic radius

- We can extract the magnetic radius by using the dipole model to be consistent withe the calculations.

$$R_{\mathrm{Z}}^{\mathrm{Exp.}} = \frac{3R^4 + 9R^3R_{\mathrm{M}} + 11R^2R_{\mathrm{M}}^2 + 9RR_{\mathrm{M}}^3 + 3R_{\mathrm{M}}^4}{2\sqrt{3}(R + R_{\mathrm{M}})^3}$$

Simultaneous solution of the two equations with the two line energies
Rc = 0.84100(63) fm and Rz=1.086(40) fm
Assuming a dipole model, this gives Rm: 0.879(50) fm
Mainz results: Rc = 0.879 fm, Rm = 0.777 fm and Rz = 1.047 fm

A magnetic radius larger than the charge radius leads to large discrepancies when applied to electron proton scattering data

Summary of results: charge radius

$$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2}) \quad = \quad 49881.88(76)\,\text{GHz}$$

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

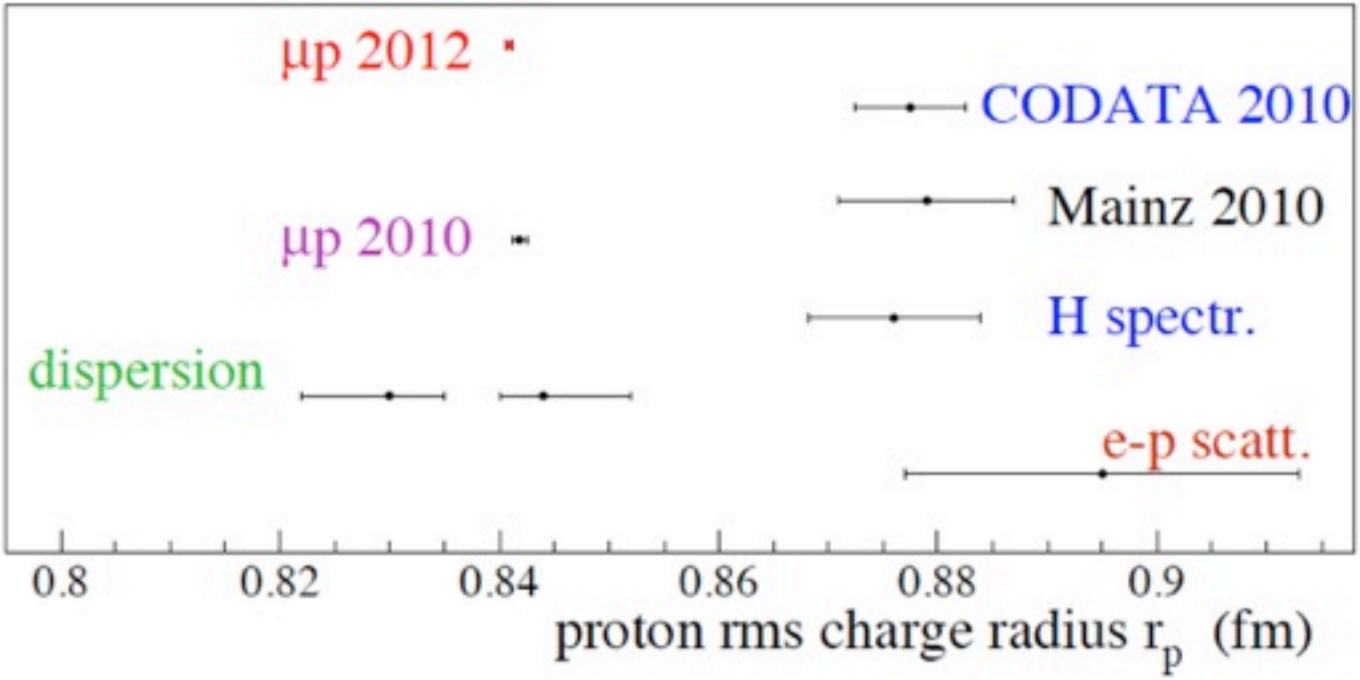
$$49881.35(64)\,\text{GHz}$$

$$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1}) \quad = \quad 54611.16(1.04)\,\text{GHz}$$

A. Antognini, F. Nez, K. Schuhmann, et al., Science **339**, 417 (2013).

Proton charge radius: $r_p = 0.84089\,(26)_{\text{exp}}\,(29)_{\text{th}} = 0.84089\,(39)$ fm

μp theory: A. Antognini, F. Kottmann, F. Biraben, et al., Annals of Physics **331**, 127 (2013).



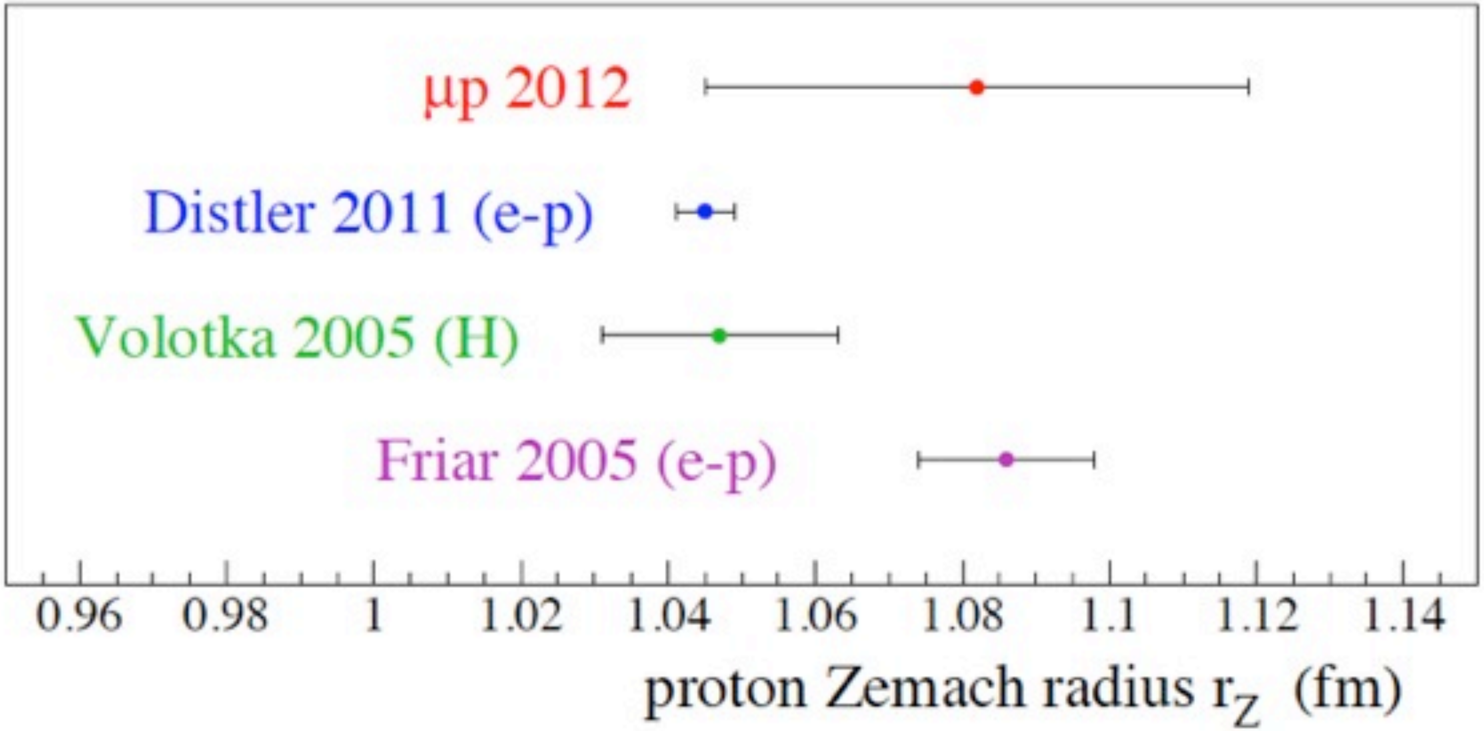
Summary of results: Zemach radius

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

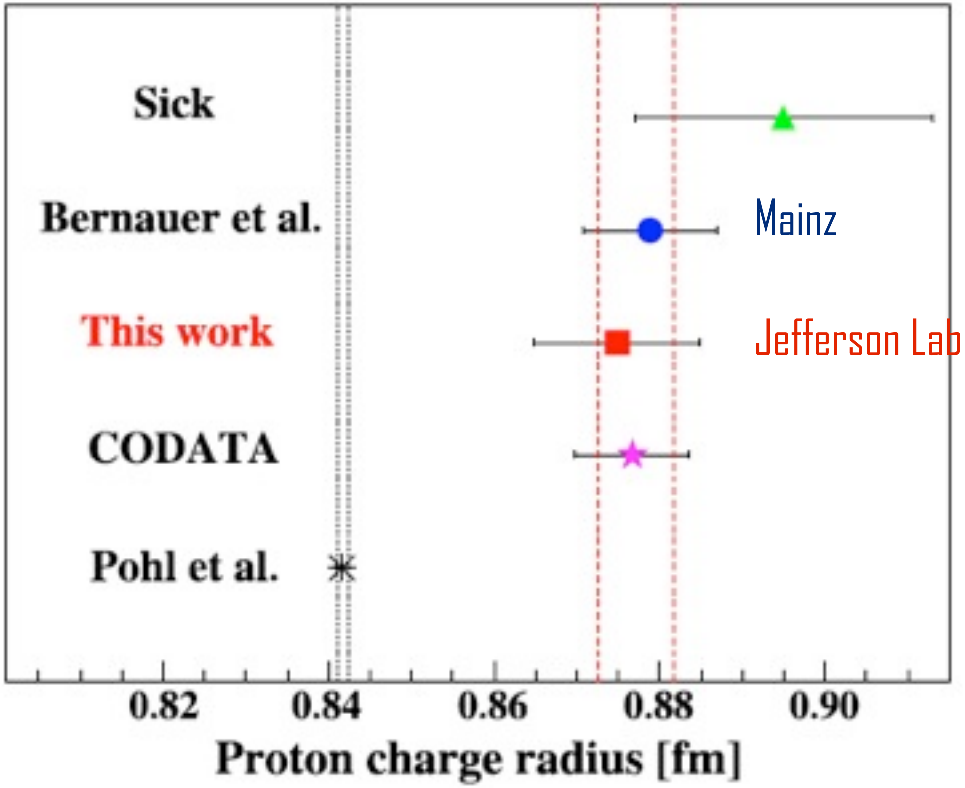
gives a proton Zemach radius $r_Z = \int \mathrm{d}^3r \int \mathrm{d}^3r' \, r \, \rho_E(r)\rho_M(r-r')$

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

μp theory: A. Antognini, F. Kottmann, F. Biraben, et al., Annals of Physics **331**, 127 (2013).

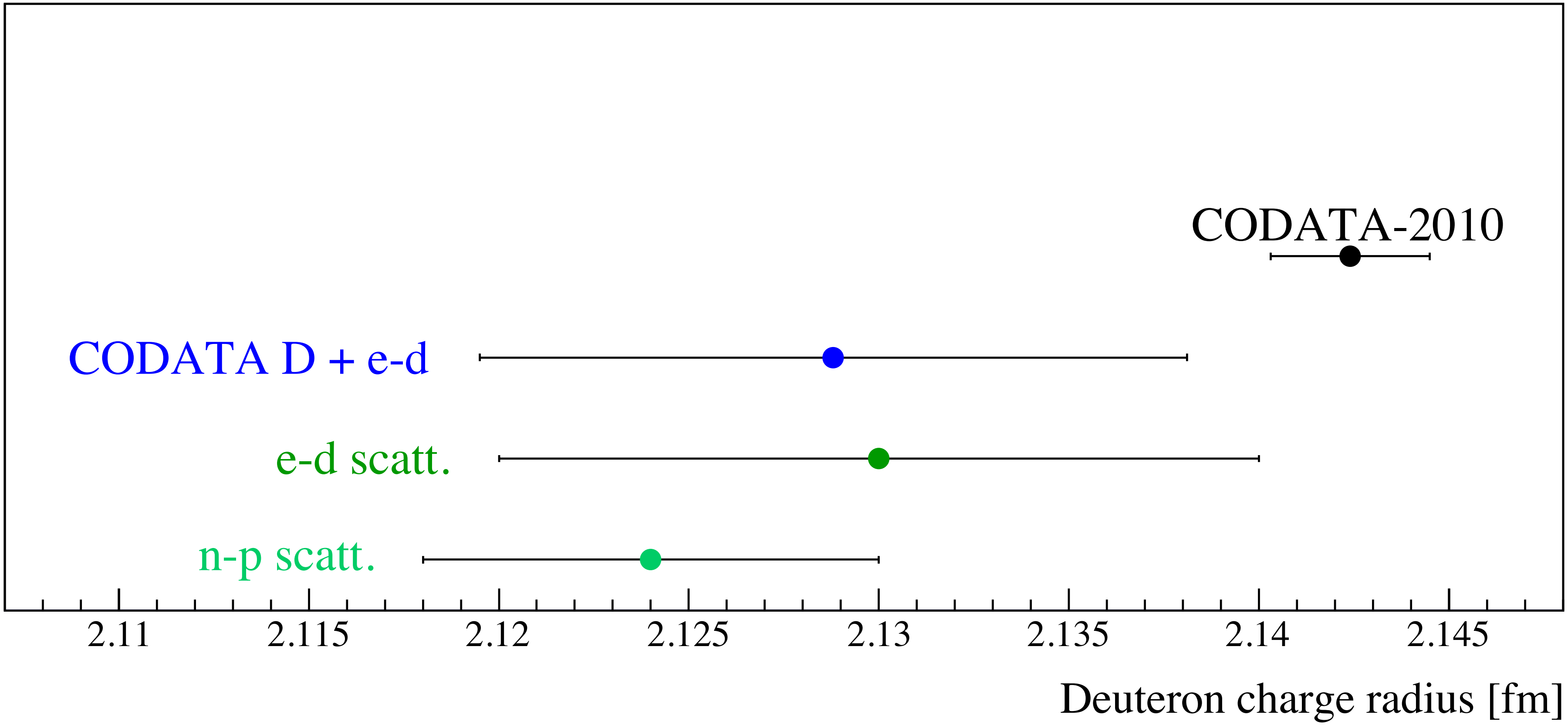


Summary of present status

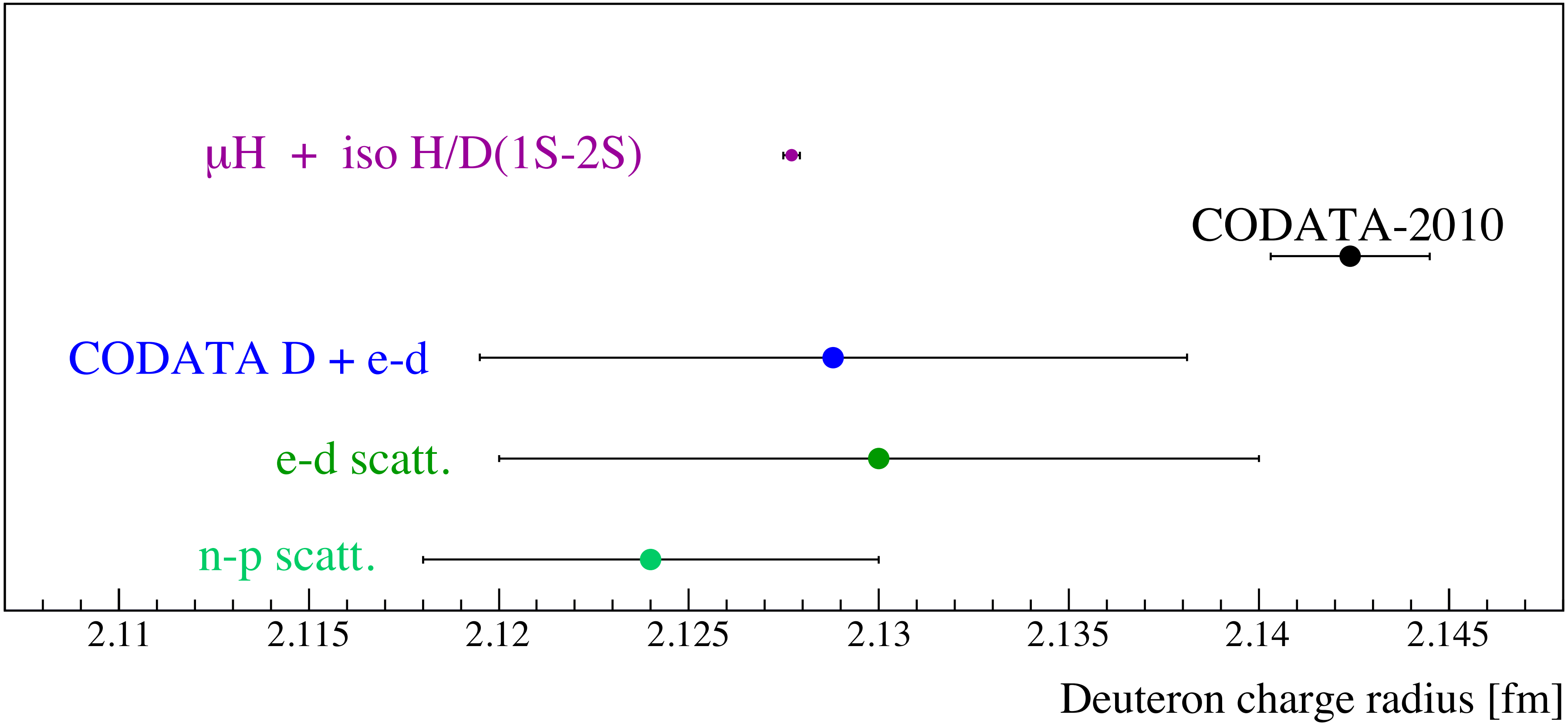


High-precision measurement of the proton elastic form factor ratio at low, X. Zhan, et al Physics Letters B **705,** 59-64 (2011).

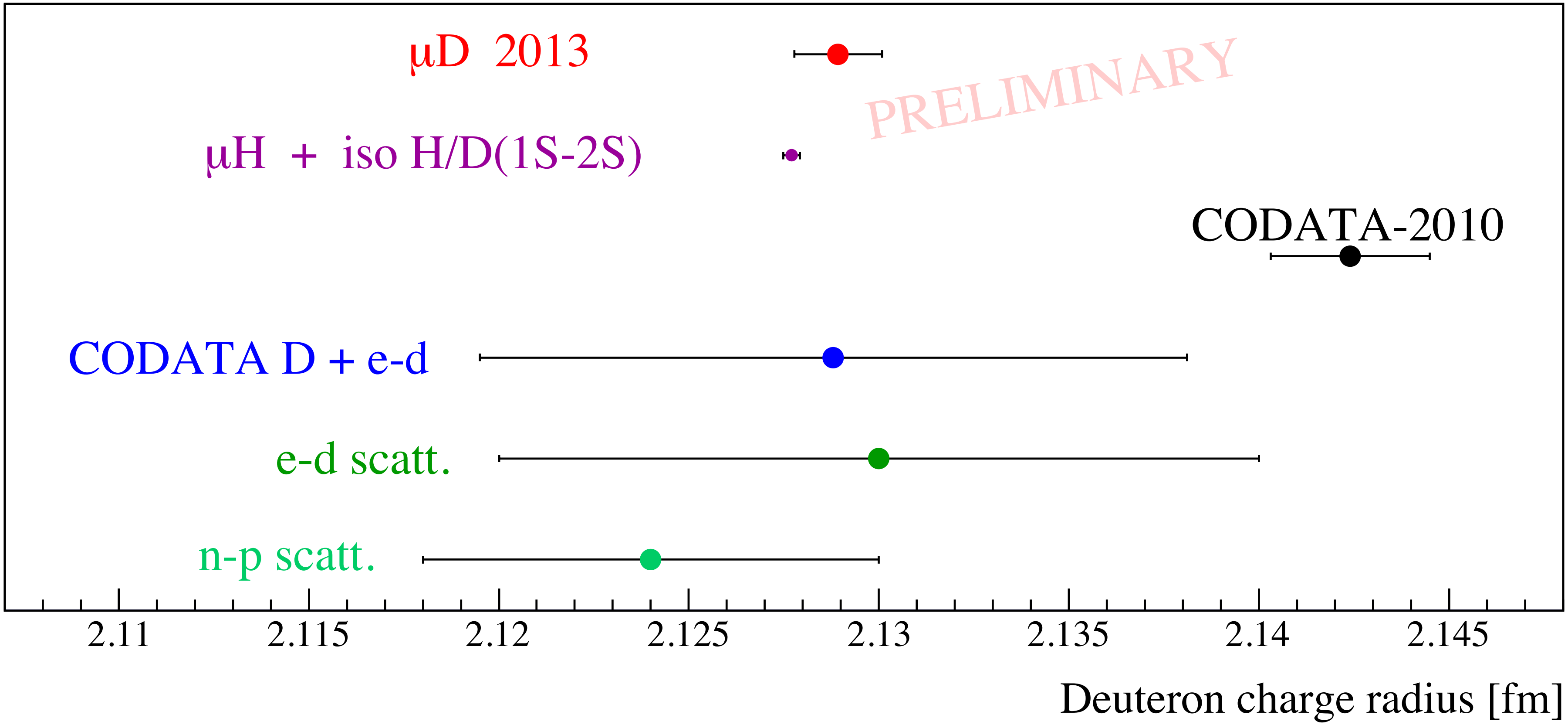
New 2013: deuterium charge radius



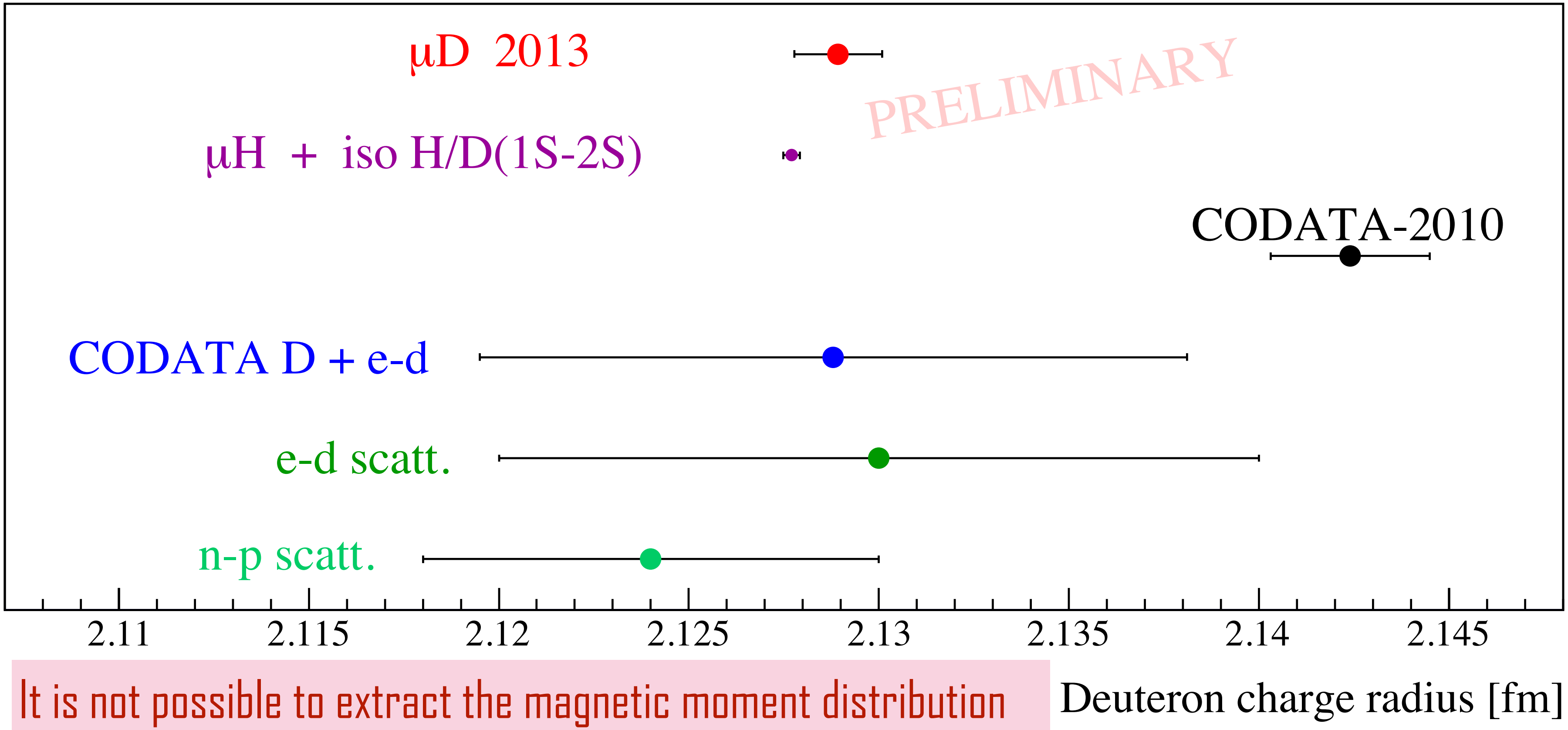
New 2013: deuterium charge radius



New 2013: deuterium charge radius



New 2013: deuterium charge radius

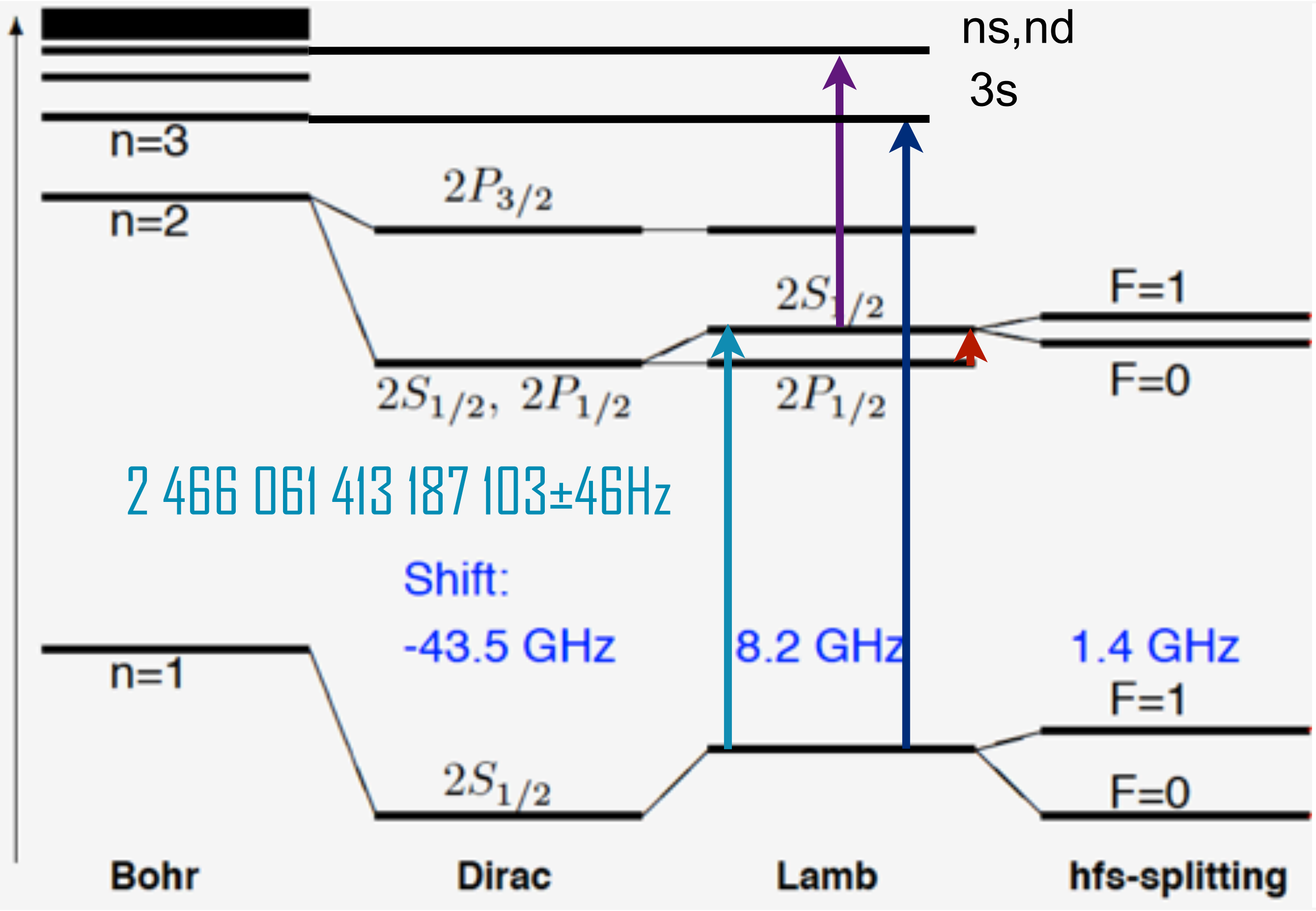


It is not possible to extract the magnetic moment distribution radius: uncalculated μD 2S hyperfine structure polarization correction.

Other measurements

How to get the radius from hydrogen and electron-proton scattering

Hydrogen spectroscopy



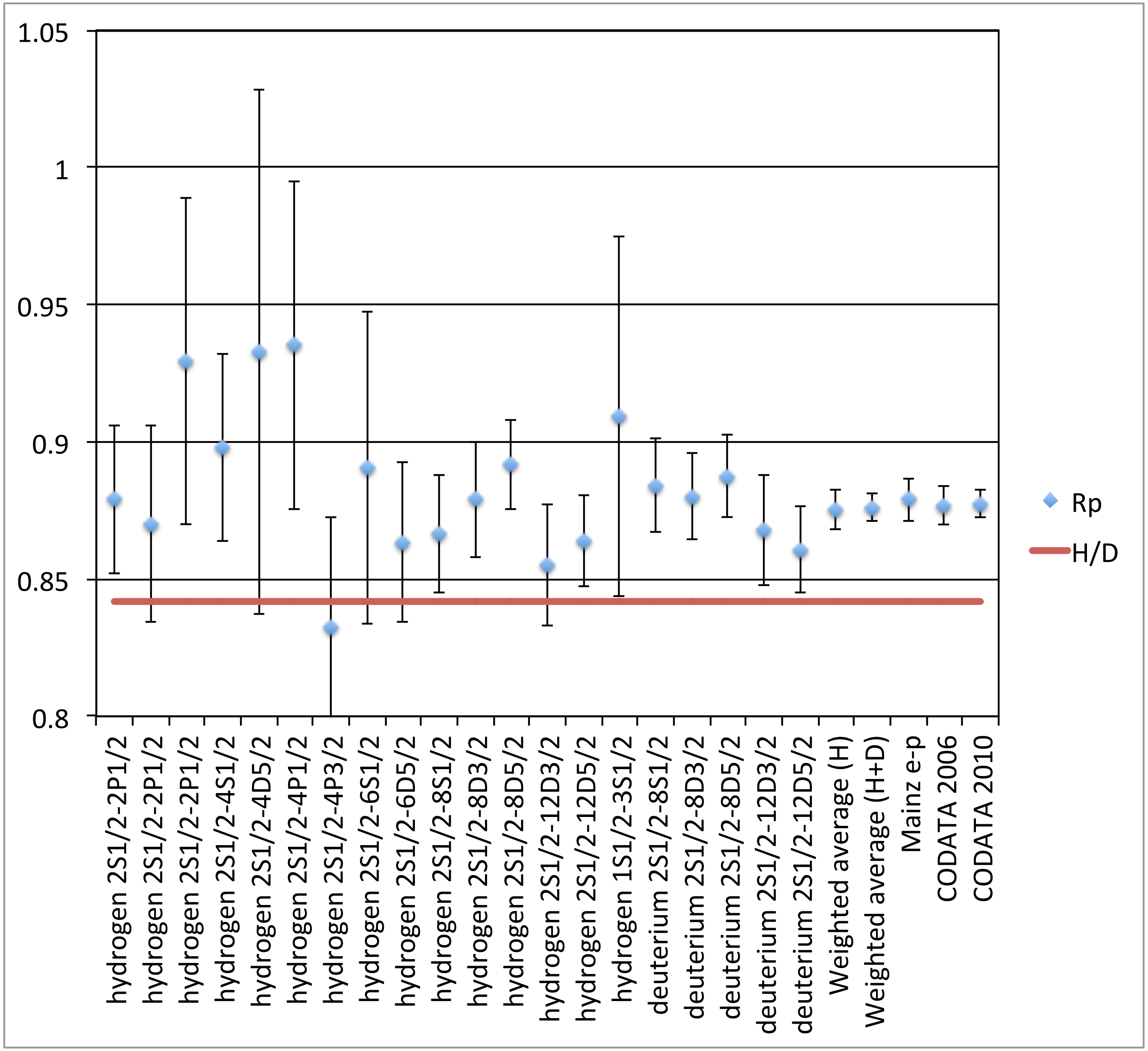
Two lines needed:

Rydberg constant

Proton radius

Hydrogen+Deuterium

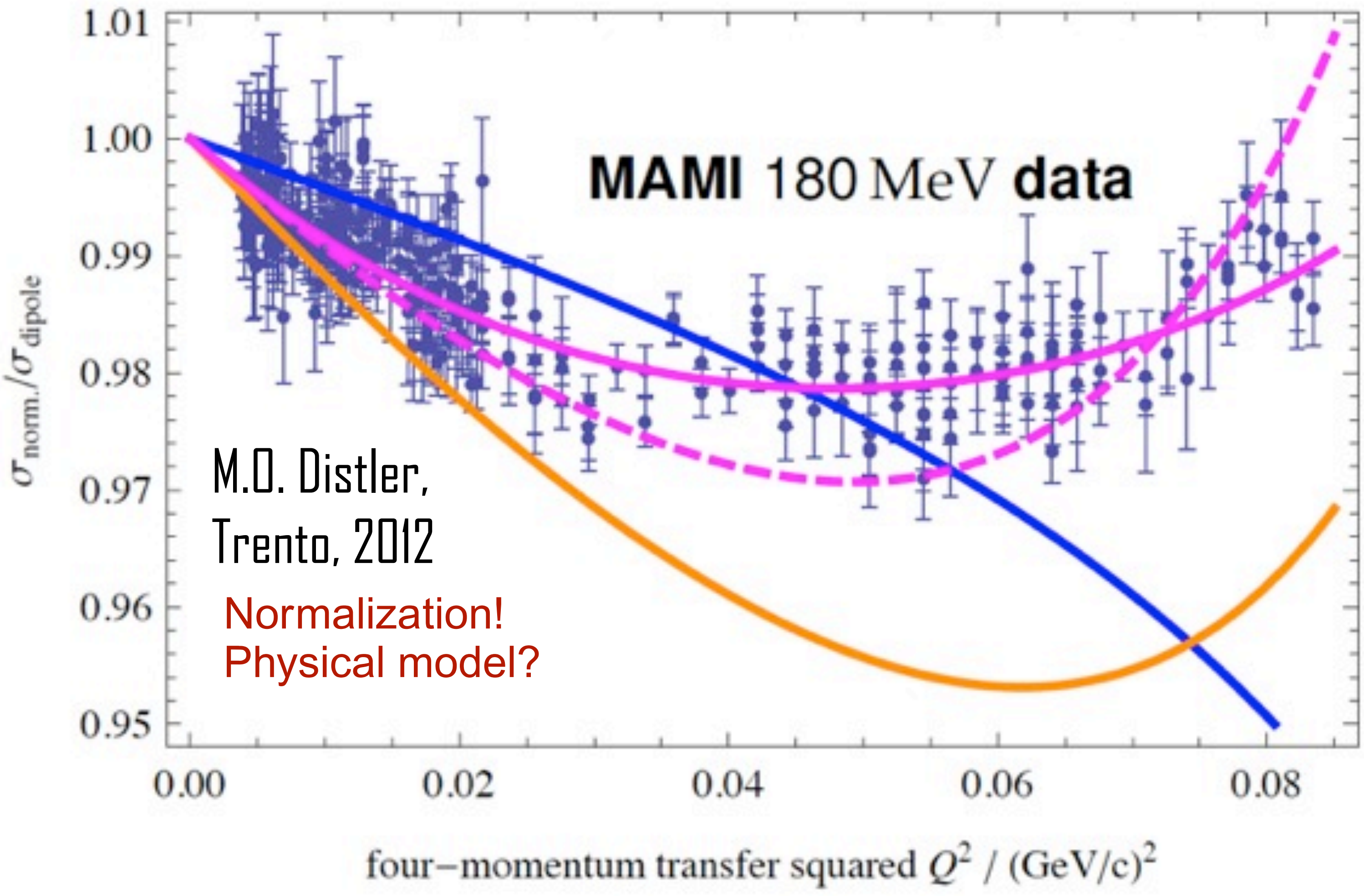
Analysis by F. Biraben



Hydrogen+Deuterium

- Needed: new measurements with independent systematic errors and get an independent Rydberg constant value:
  - 2S-4P in H (Garching)
  - 2S-nS,D in H (J. Flowers, NPL)
  - 1S-3S (Garching, Paris)
  - transitions between Rydberg states of heavy H-like ion (NIST)
  - 1S-2S and 1S hfs in μe (A. Antognini, PSI)

Electron-Proton scattering



M.O. Distler,
Trento, 2012

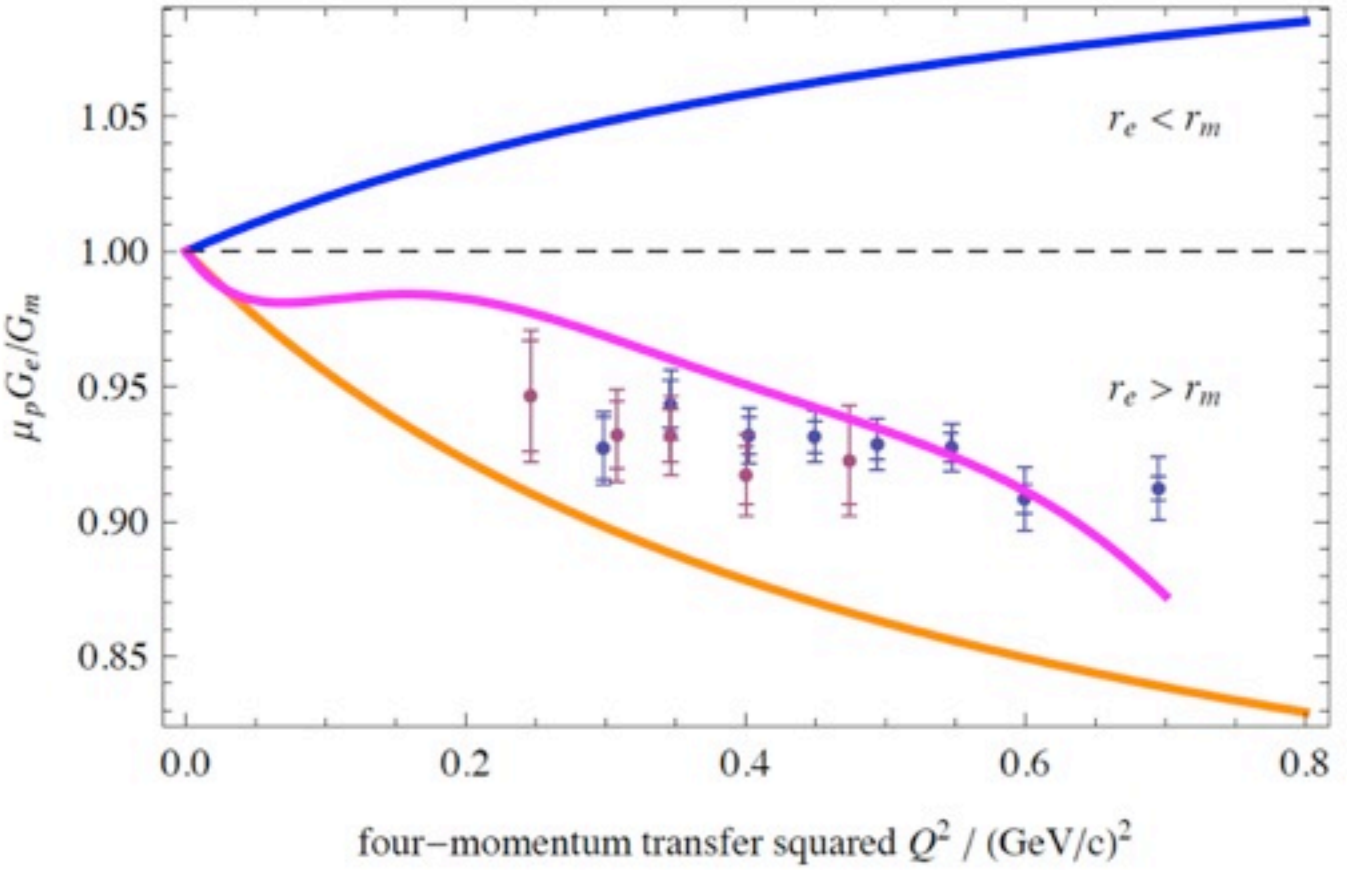
Normalization!
Physical model?

$r_e = 0.84$ fm, $r_m = 0.87$ fm

$r_e = 0.90$ fm, $r_m = 0.82$ fm

Bernauer fit (solid) and
$r_e = 0.88$ fm, $r_m = 0.78$ fm

Electron-Proton scattering



$r_\mathrm{e} = 0.84\,\mathrm{fm},\ r_\mathrm{m} = 0.87\,\mathrm{fm}$ Bernauer fit

$r_\mathrm{e} = 0.90\,\mathrm{fm},\ r_\mathrm{m} = 0.82\,\mathrm{fm}$

M.O. Distler, Trento, 2012

Possible origin of the discrepancy

Systematic errors or new physics?

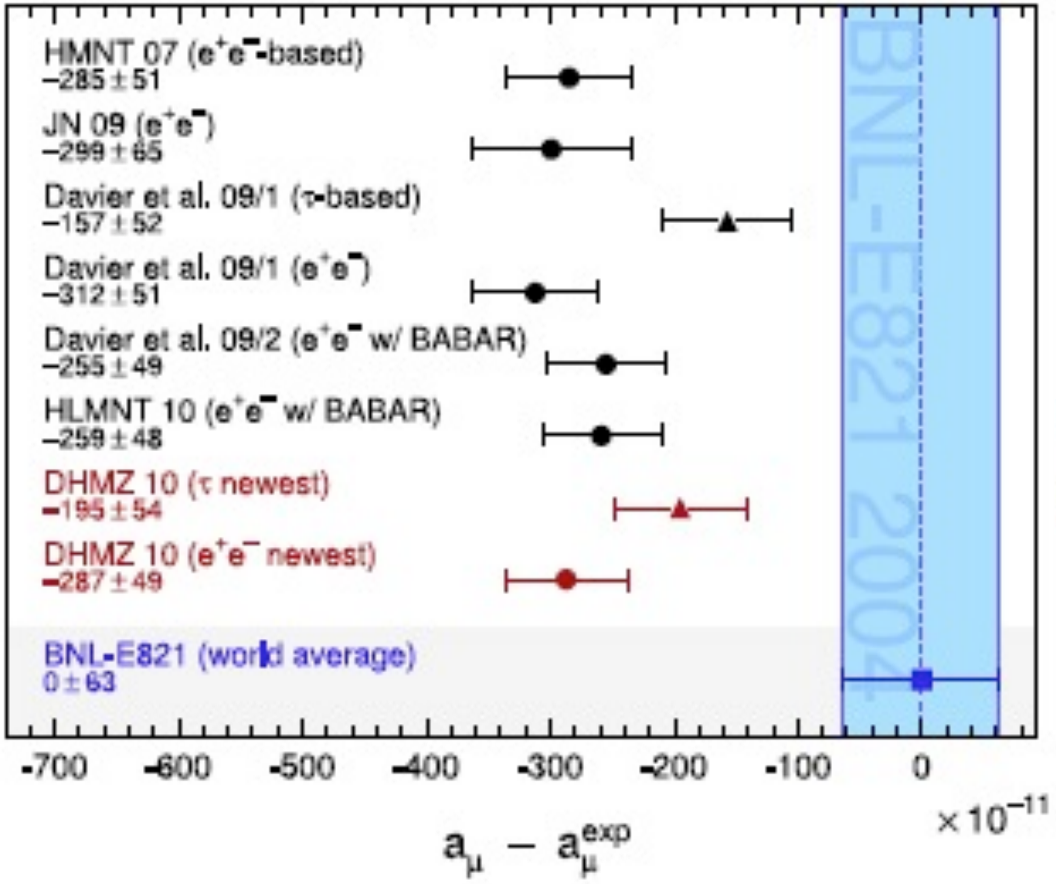
Possible sources of discrepancy (µP)

- Frequency shift: unlikely - several redundant measurements at 708 nm (Fabry-Perot, two-photon transition in Rb) and 6µm (water lines)
- µ e$^-$ p molecules or p p µ molecules. Not possible - Why Three-Body Physics Does Not Solve the Proton-Radius Puzzle, J.-P. Karr and L. Hilico. Phys. Rev. Lett. 109, 103401 (2012).
- Experimental problems, e.g., a small air leak in the hydrogen target: we see characteristic µN and µO x-rays
  - Less than 1% of all created µP atoms see any N_2 molecules
  - Less than 0.1% of all µP in 2S state see any N_2 molecule during laser time
- µP theory: many checks, no effect seems large enough to explain a 0.3 meV energy shift, probably not even proton polarization (30 times too small)

Possible origin for the discrepancy

- Electron-proton elastic scattering data analysis
- Under-estimated systematic errors in some hydrogen measurements
  - possible, but many different kind of experiments (microwave, 1s-3s, 2s-ns and 2s-nd)
- Proton structure
- New physics
  - Constraints:
    - g-2 of the muon (3σ),
    - g-2 of the electron (Harvard)+fine structure constant from atomic recoil (LKB)
    - Hydrogen
    - Precision highly charged ions experiments at GSI (if long range interaction)
    - ...

Unsolved problems in the muon corner...



Example: muon g-2, discrepancy not solved after improved QED calculation

For electrons:

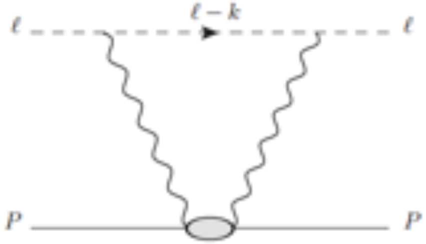
$$\alpha^{-1}(a_e) = 137.0359991727(68)(46)(19)(331)$$

$$\alpha^{-1} = 137.035\,999\,037\,(91)$$

Reevaluation of the hadronic contributions to the muon g-2 and to $\alpha (M^{2}_{Z})$", M. Davier, A. Hoecker, B. Malaescu and Z. Zhang. The European Physical Journal C - Particles and Fields **71,** 1-13 (2011).
Tenth-Order QED Contribution to the Electron g-2 and an Improved Value of the Fine Structure Constant, T. Aoyama, M. Hayakawa, T. Kinoshita and M. Nio. Phys. Rev. Lett. **109,** 111807 (2012).
Complete Tenth-Order QED Contribution to the Muon g-2, T. Aoyama, M. Hayakawa, T. Kinoshita and M. Nio. Phys. Rev. Lett. **109,** 111808 (2012).

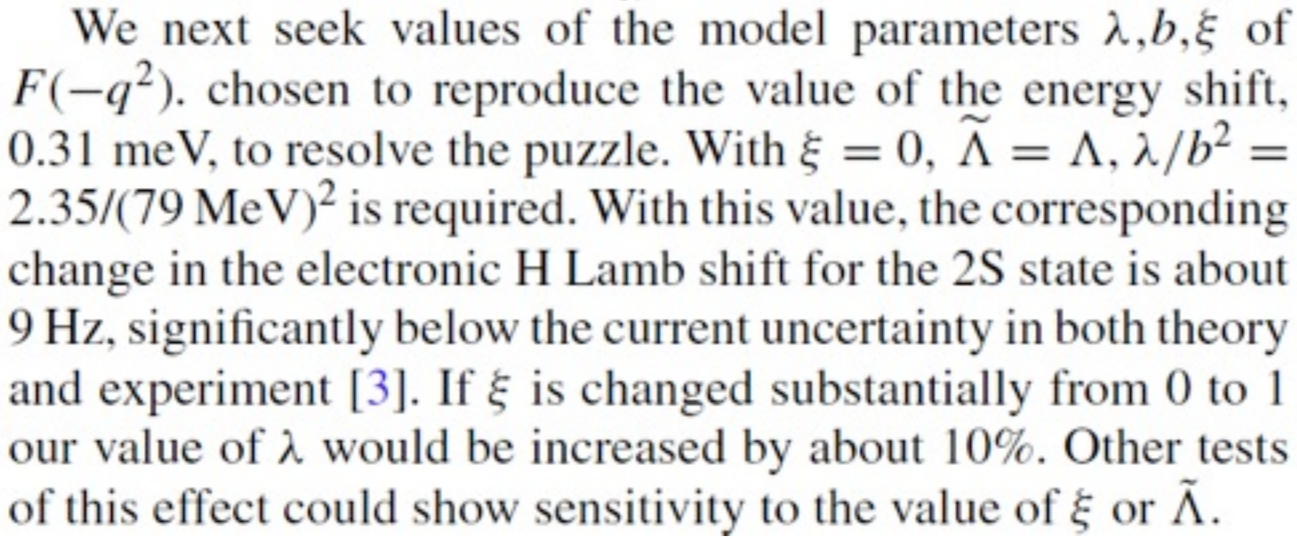
A new polarization term ?

Toward a resolution of the proton size puzzle, G.A. Miller, A.W. Thomas, J.D. Carroll and J. Rafelski. Phys. Rev. A 84, 020101 (2011).



0.31 meV for μH and 9Hz for hydrogen
(with model dependent parametrization)

FIG. 1: Direct two-photon exchange graph corresponding to the hitherto neglected term. The dashed line denotes the lepton; the solid line, the n
and the ellipse the off-shell


We next seek values of the model parameters λ, b, ξ of $F(-q^2)$. chosen to reproduce the value of the energy shift, 0.31 meV, to resolve the puzzle. With $\xi = 0$, $\widetilde{\Lambda} = \Lambda$, $\lambda/b^2 = 2.35/(79\ \mathrm{MeV})^2$ is required. With this value, the corresponding change in the electronic H Lamb shift for the 2S state is about 9 Hz, significantly below the current uncertainty in both theory and experiment [3]. If ξ is changed substantially from 0 to 1 our value of λ would be increased by about 10%. Other tests of this effect could show sensitivity to the value of ξ or $\tilde{\Lambda}$.

No other work supports such a large effect

Where could it come from?

- Proton Size Anomaly, V. Barger, C.-W. Chiang, W.-Y. Keung et al. Phys. Rev. Lett. 106, 153001 (2011):

  A measurement of the Lamb shift in muonic hydrogen yields a charge radius of the proton that is smaller than the CODATA value by about 5 standard deviations. We explore the possibility that new scalar, pseudoscalar, vector, and tensor flavor-conserving nonuniversal interactions may be responsible for the discrepancy. We consider exotic particles that, among leptons, couple preferentially to muons and mediate an attractive nucleon-muon interaction. We find that the many constraints from low energy data disfavor new spin-0, spin-1, and spin-2 particles as an explanation.

- Lamb shift in muonic hydrogen--II. Analysis of the discrepancy of theory and experiment, U.D. Jentschura. Annals of Physics 326, 516-533 (2011).

  No unstable vector boson, no millicharged particles,

Where could it come from?

- New physics and the proton radius problem, C.E. Carlson and B.C. Rislow. Physical Review D 86, 035013 (2012):
  - Particles that couple to muons and hadrons but not electrons
  - For the scalar-pseudoscalar model, masses between 100 to 200 MeV are not allowed.
  - For the vector model, masses below about 200 MeV are not allowed. The strength of the couplings for both models approach that of electrodynamics for particle masses of about 2 GeV.
  - New physics with fine-tuned couplings may be entertained as a possible explanation for the Lamb shift discrepancy.
- New Parity-Violating Muonic Forces and the Proton Charge Radius, B. Batell, D. McKeen and M. Pospelov. Phys. Rev. Lett. 107, 011803 (2011).
  - We identify a class of models with gauged right-handed muon number, which contains new vector and scalar force carriers at the100 MeV scale or lighter, that is consistent with observations.
  - Such forces would lead to an enhancement by several orders-of-magnitude of the parity-violating asymmetries in the scattering of low-energy muons on nuclei.

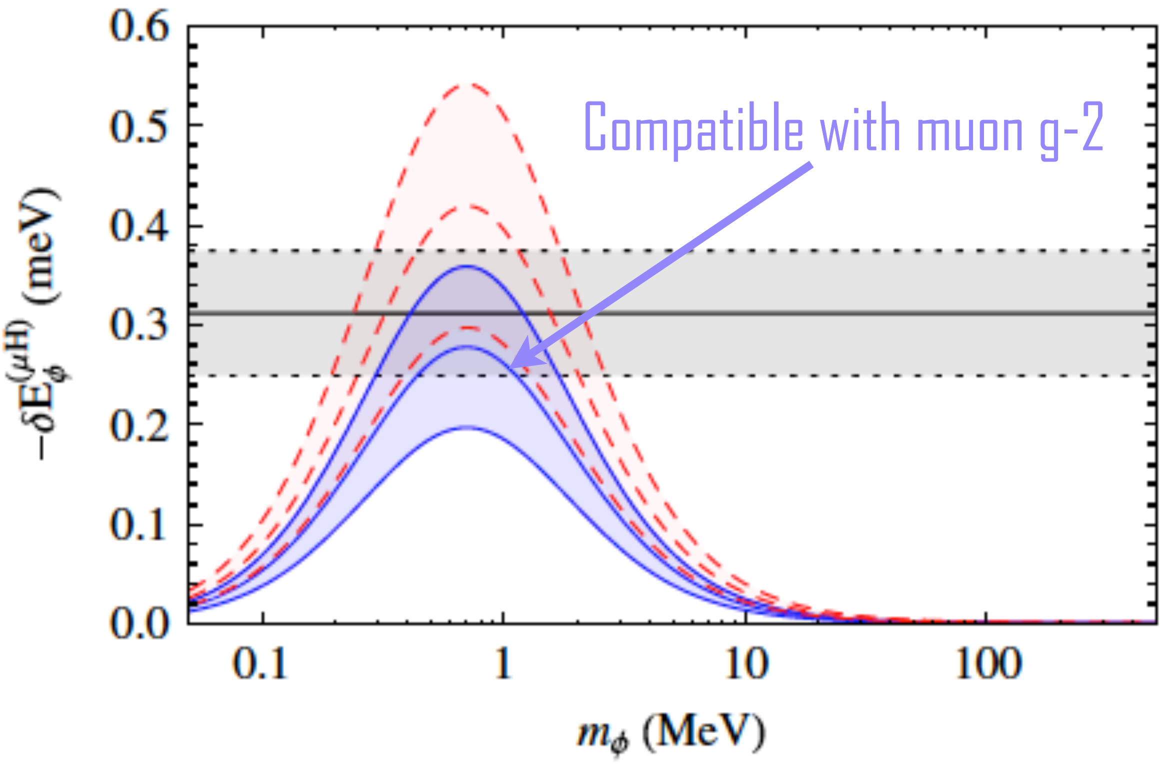
Where could it come from?

Muonic hydrogen and MeV forces, D. Tucker-Smith et I. Yavin. Physical Review D 83, 101702 (2011).

We explore the possibility that a new interaction between muons and protons is responsible for the discrepancy between the CODATA value of the proton-radius and the value deduced from the measurement of the Lamb shift in muonic hydrogen. We show that a new force carrier with roughly MeV-mass can account for the observed energy-shift as well as the discrepancy in the muon anomalous magnetic moment. However, measurements in other systems constrain the couplings to electrons and neutrons to be suppressed relative to the couplings to muons and protons, which seems challenging from a theoretical point of view. One can nevertheless make predictions for energy shifts in muonic deuterium, muonic helium, and true muonium under the assumption that the new particle couples dominantly to muons and protons.

Where could it come from?

Muonic hydrogen and MeV forces, D. Tucker-Smith et I. Yavin. Physical Review D 83, 101702 (2011).



Compatible with muon g-2

$$\delta E_{\phi}^{(\mu D)} = -0.3 \pm 0.1 \text{ meV}.$$

Where could it come from?

Nonidentical protons, T. Mart et A. Sulaksono. Phys. Rev. C 87, 025807 (2013).

We have calculated the proton charge radius by assuming that the real proton radius is not unique and the radii are randomly distributed in a certain range. This is performed by averaging the elastic electron-proton differential cross section over the form factor cutoff. By using a dipole form factor and fitting the middle value of the cutoff to the low-Q2 Mainz data, we found the lowest χ2/N for a cutoff = 0.8203 ± 0.0003 GeV, which corresponds to a proton charge radius r_E= 0.8333± 0.0004 fm. The result is compatible with the recent precision measurement of the Lamb shift in muonic hydrogen as well as recent calculations using more sophisticated techniques. Our result indicates that the relative variation of the form factor cutoff should be around 21.5%. Based on this result we have investigated effects of the nucleon radius variation on the symmetric nuclear matter (SNM) and the neutron star matter (NSM) by considering the excluded volume effect in our calculation. The mass-radius relation of a neutron star is found to be sensitive to this variation. The nucleon effective mass in the SNM and the equation of state of both the SNM and the NSM exhibit a similar sensitivity.

Where could it come from?

No radial excitations in low energy QCD. II. The shrinking radius of hadrons, T. Friedmann. The European Physical Journal C 73, 2299 (2013).

We discuss the implications of our prior results obtained in our companion paper (Eur. Phys. J. C (2013)). Inescapably, they lead to three laws governing the size of hadrons, including in particular protons and neutrons that make up the bulk of ordinary matter: (a) there are no radial excitations in low-energy QCD; (b) the size of a hadron is largest in its ground state; (c) the hadron's size shrinks when its orbital excitation increases. The second and third laws follow from the first law. It follows that the path from confinement to asymptotic freedom is a Regge trajectory. It also follows that the top quark is a free, albeit short-lived, quark.

Note added Nine months after this paper was originally posted to arXiv [32, 33], an experiment studying muonic hydrogen [34], repeated more recently [35], observed a smaller size of the proton than previously expected, consistent with our predictions. It is possible that this is a manifestation of our three laws, and may be a QCD, rather than QED, effect.

Where could it come from?

- PROTON RADIUS PUZZLE AND LARGE EXTRA DIMENSIONS, L.B. Wang et W.T. Ni. Modern Physics Letters A 28, 1350094 (2013).

We propose a theoretical scenario to solve the proton radius puzzle which recently arises from the muonic hydrogen experiment. In this framework, 4 + n dimensional theory is incorporated with modified gravity. The extra gravitational interaction between the proton and muon at very short range provides an energy shift which accounts for the discrepancy between spectroscopic results from muonic and electronic hydrogen experiments. Assuming the modified gravity is a small perturbation to the existing electromagnetic interaction, we find the puzzle can be solved with stringent constraint on the range of the new force. Our result not only provides a possible solution to the proton radius puzzle but also suggest a direction to test new physics at very small length scale.

Where could it come from?

Can Large Extra Dimensions Solve the Proton Radius Puzzle?
Zhigang Li, Xuelei Chen (http://arxiv.org/abs/1303.5146v1)

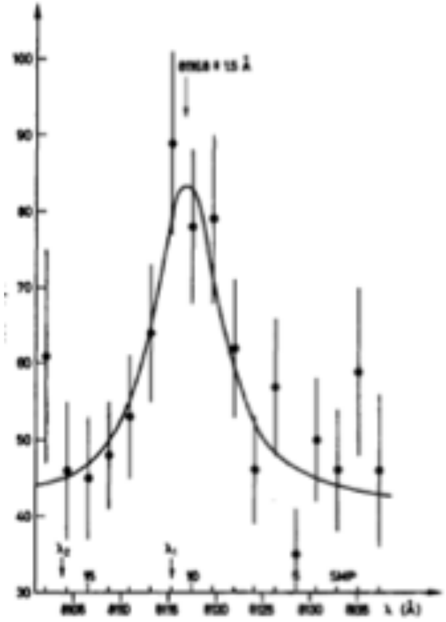
The proton charge radius extracted from the recent muonic hydrogen spectroscopy [Antognini et al. 2013; Pohl et al. 2010] differs from the CODATA 2010 recommended value [Mohr et al. 2012] by more than 4%. This discrepancy, dubbed as the "Proton Radius Puzzle", is a big challenge to the Standard Model of particle physics, and has triggered a number of works on the quantum electrodynamic calculations recently. The proton radius puzzle may indicate the presence of an extra correction which enlarges the 2S-2P energy gap in muonic hydrogen. Here we explore the possibility of large extra dimensions which could modify the Newtonian gravity at small scales and lower the 2S state energy while leaving the 2P state nearly unchanged. We find that such effect could be produced by four or more large extra dimensions which are allowed by the current constraints from low energy physics.

What’s next

Muonic Helium: experiment set up October 8th, 2013

Muonic He spectroscopy

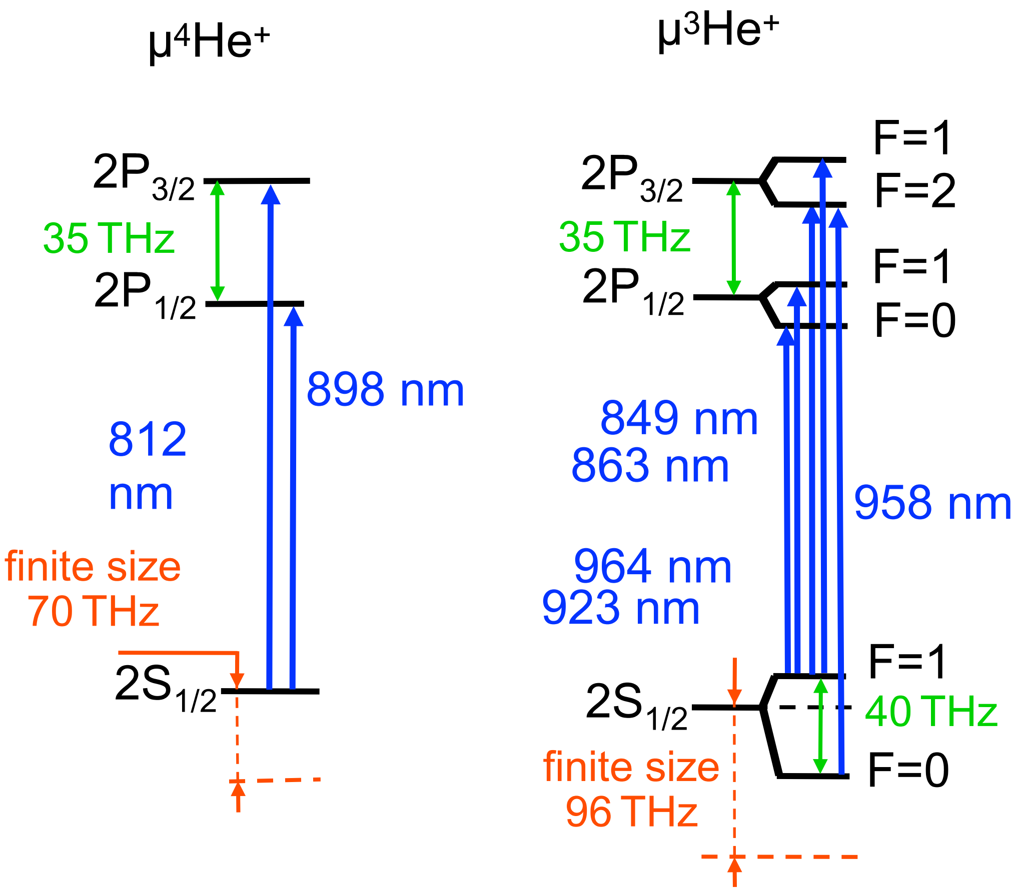
812 nm
p_{He} = 40 bars



Nuclear Physics A278 (1977) p. 381

but signal never
reproduced
(10 bars, 40 bars)

2011-2013→ muonic helium spectroscopy (4 mbar)



μ^4He^+

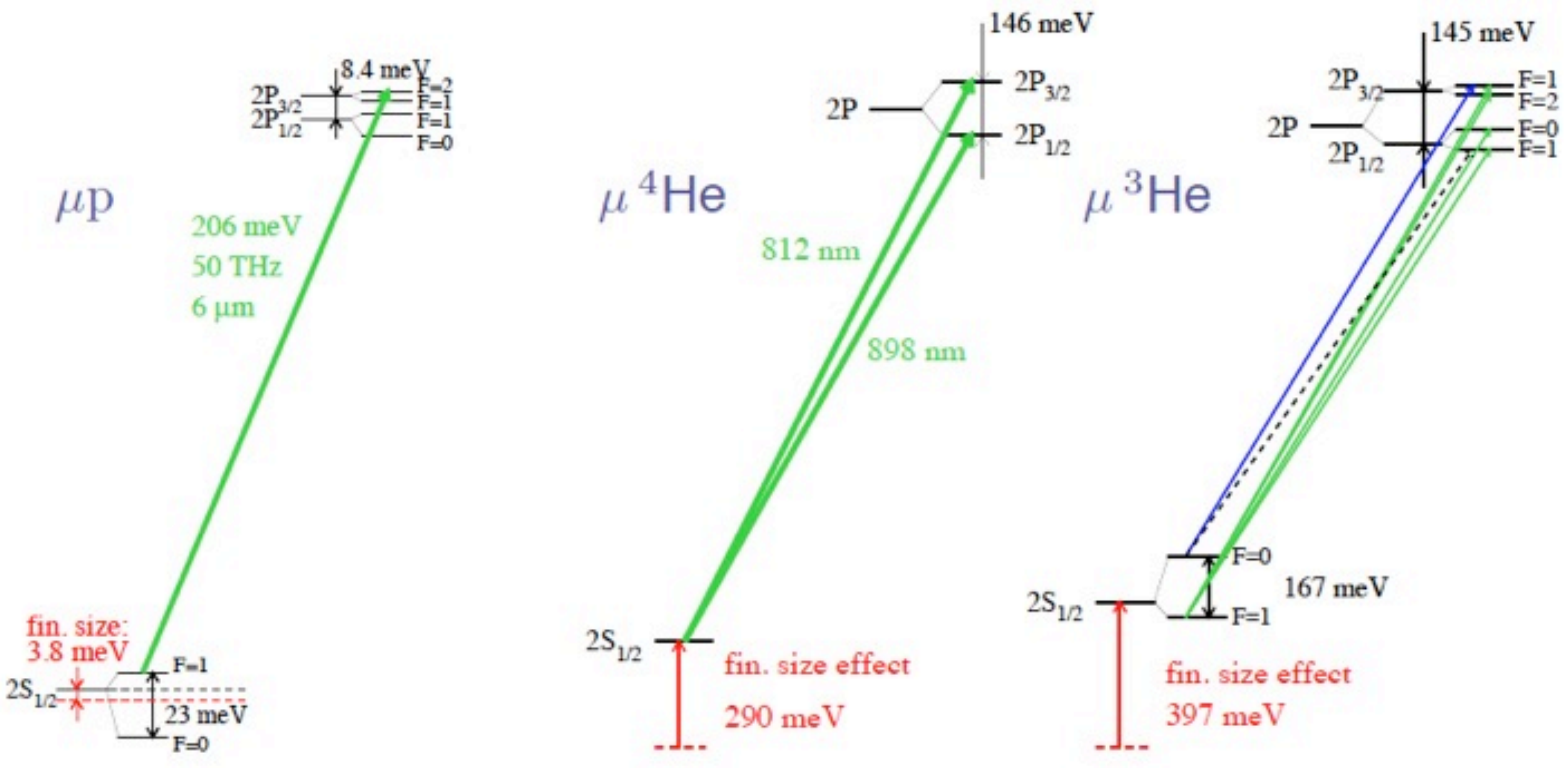
$2P_{3/2}$
35 THz
$2P_{1/2}$
898 nm
812
nm
finite size
70 THz
$2S_{1/2}$

μ^3He^+

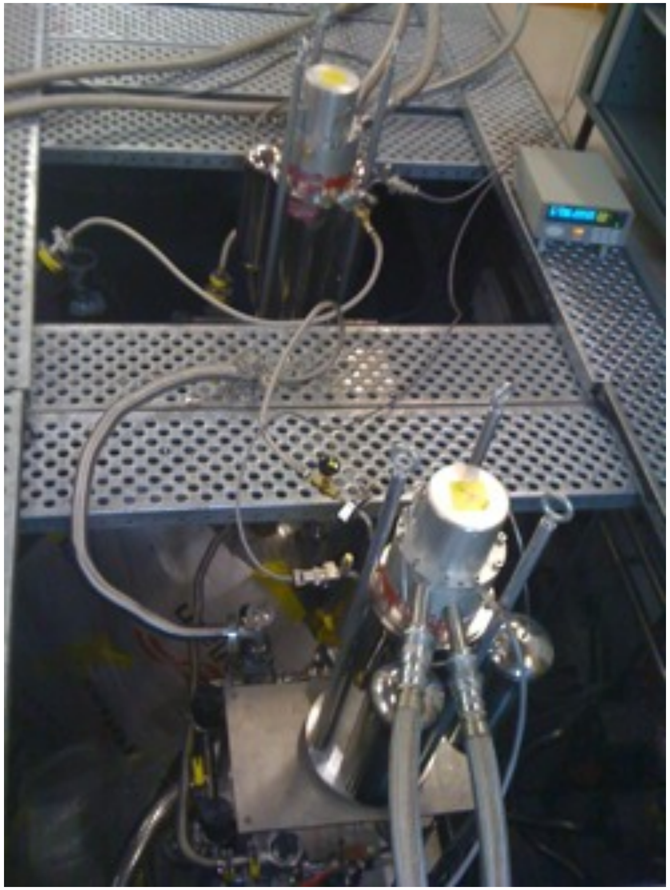
$2P_{3/2}$
F=1
F=2
35 THz
$2P_{1/2}$
F=1
F=0
849 nm
863 nm
958 nm
964 nm
923 nm
$2S_{1/2}$
F=1
40 THz
F=0
finite size
96 THz

- μHe^+ spectroscopy + He^+ spectroscopy → QED test ($Z\alpha$)
- improve He spectroscopy

Muonic He spectroscopy



Improve statistics...



Moving in on October 3rd
beam time until December 19th

16% more from the beam time: reliquefying He
Better disk laser
Much more intensity (no Raman shift)

Conclusions

- We have performed a 12.5 ppm measurement of the Lamb-shift in muonic hydrogen
- The deduced proton radius using a Dipole model is 6.9 standard deviations away from the hydrogen and electron-proton elastic scattering data
- Better modeling of the proton form-factor and polarization required to confirm or reduce the disagreement
- Experiment confirmed with 2nd μH line
- 3 μD lines observed and being analyzed
- No explanation of the discrepancy yet, but possibilities
  - QCD
  - Problems with hydrogen experiments
  - New physics
- Muonic He in 2013 (check of theory, different laser wavelength-in the red) predictions of measurable effects from new physics!!

CREMA 2011