Laboratoire Kastler Brossel
Physique quantique et applications

The proton size, current status and perspectives

Paul Indelicato for the CREMA collaboration

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

Laboratoire Kastler Brossel – Physique quantique et applications
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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-

LKB

Outline

1. Introduction

- proton properties
- experimental proton size determinations
- muonic hydrogen

2. Experiment

- muonic hydrogen source
- laser system
- analysis

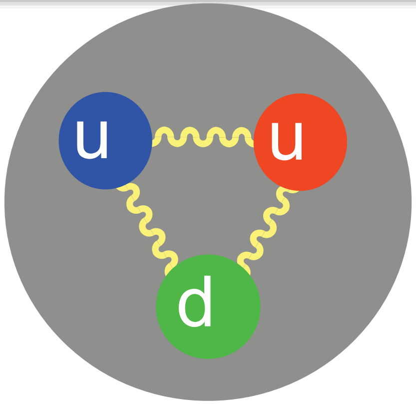
3. Results

- signal
- proton radius from muonic hydrogen spectroscopy

4. Perspectives

Proton

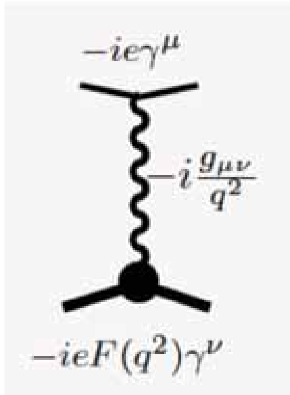
2 quarks up (2/3 e) + 1 quark down (-1/3 e) + strong interaction (gluons)



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

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

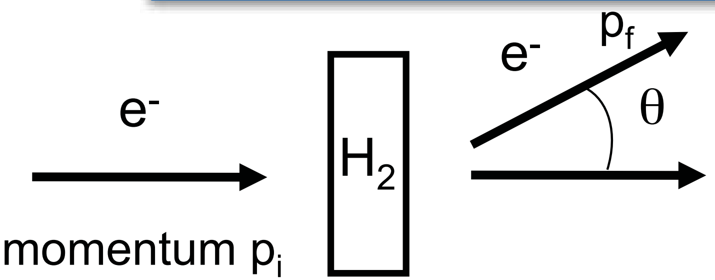
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2).$$

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

Measure the moments of the charge distribution:

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

Electron-proton elastic scattering



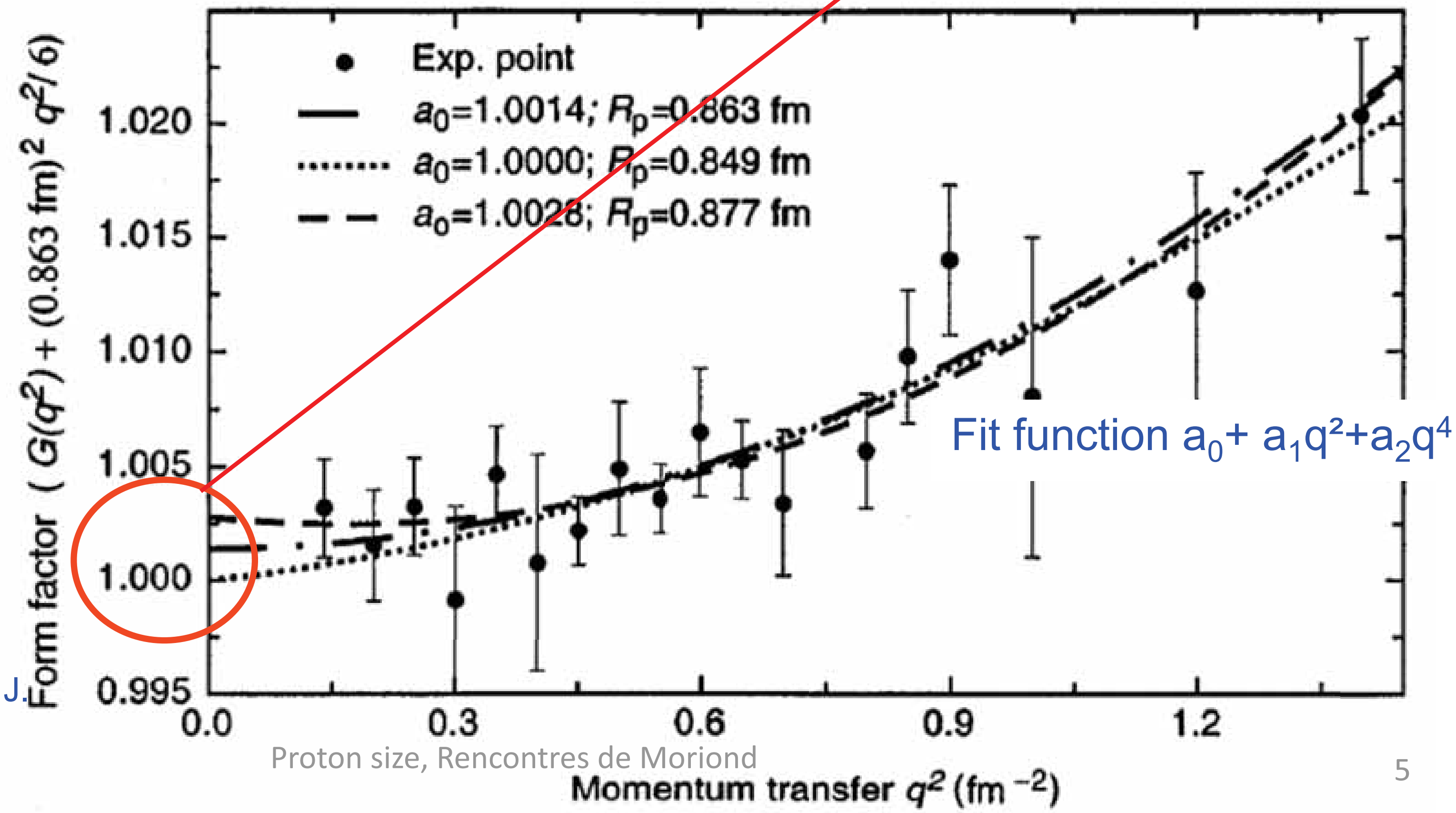
momentum p_i
energy E_i

$$\vec{q} = \vec{p}_f - \vec{p}_i \qquad q = 2p_f \sin\left(\frac{\theta}{2}\right)$$

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

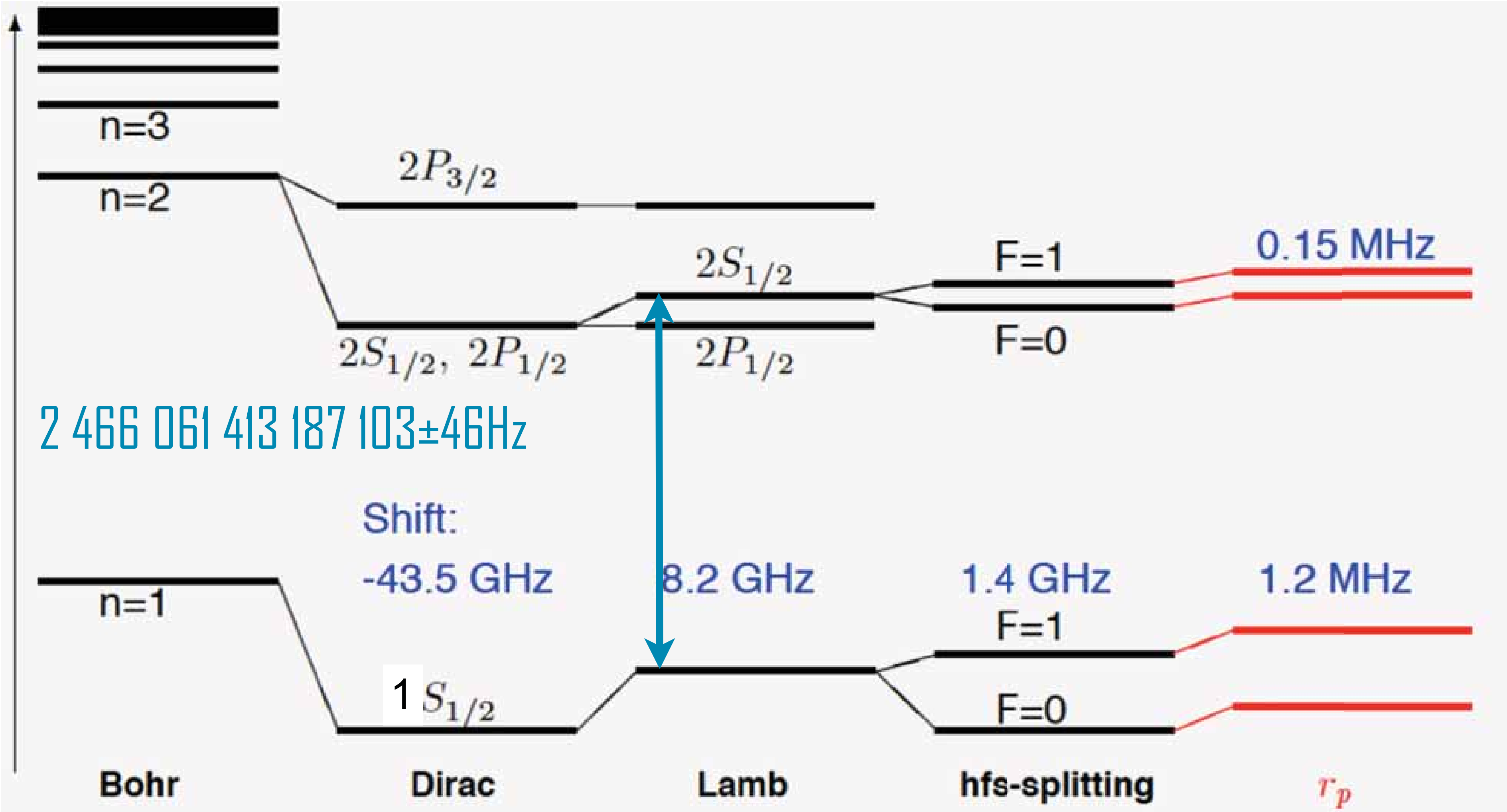
$$G_N(q^2) = \frac{1}{\left(1 + \frac{R^2 q^2}{12}\right)^2} \approx 1 - \frac{R^2}{6} q^2 + \frac{R^4}{48} q^4 + \cdots$$

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

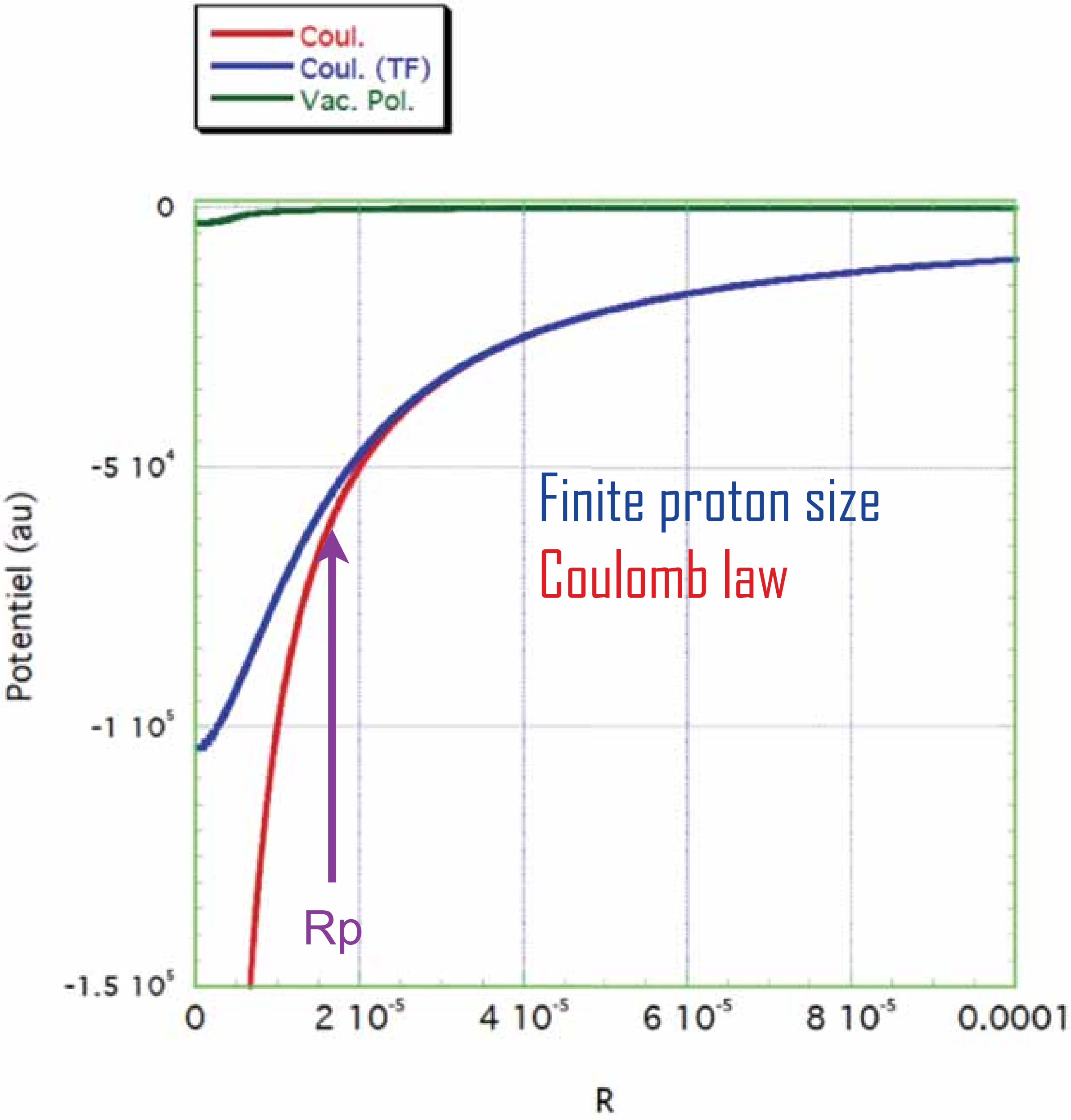


see S. Karshenboim in Can. J. Phys. 77, 241-266 (1999) and refs therein

Hydrogen


n=3
n=2
$2P_{3/2}$
$2S_{1/2}$
F=1
0.15 MHz
$2S_{1/2}, 2P_{1/2}$
$2P_{1/2}$
F=0
2 466 061 413 187 103±46Hz
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

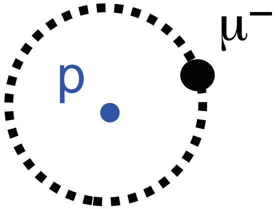
Proton size effect and VP potential



Muonic hydrogen spectroscopy

ΛLKB

Exotic atom



$\frac{m_\mu}{m_e} = 207$

radius : ~ $a_0/200$

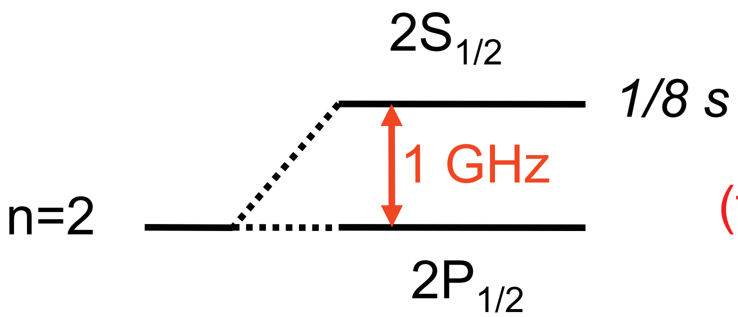
$$\mathcal{E}_{NS} = \frac{2}{3}\left(\frac{m_r}{m_e}\right)^3 \frac{(Z\alpha)^2}{n^3} m_e c^2 \left(\frac{Z\alpha R_N}{\lambda_C}\right)^2$$

Lamb shift = self-energy + vacuum polarization + proton radius

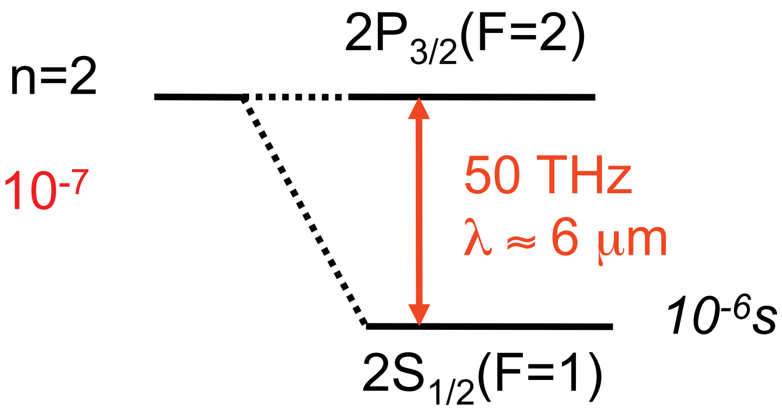
2S-2P	self-energy	vacuum pol.	r_p	total
e-p	1084.1 MHz	-26.9 MHz	0.146 MHz	1057.8 MHz
μ-p	0.17 THz	-50.94 THz	0.96 THz	-49,81THz

electronic hydrogen : e-p

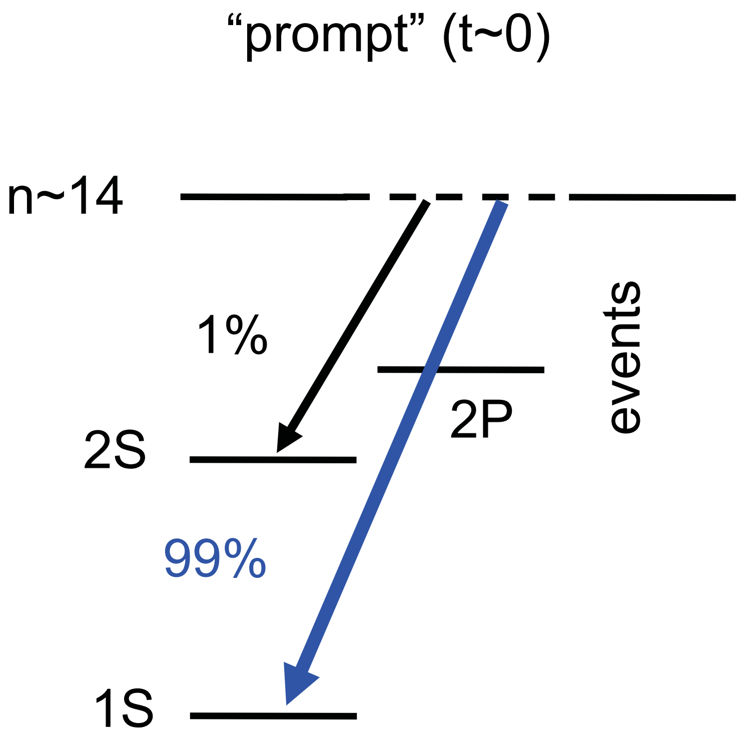
muonic hydrogen : μ-p

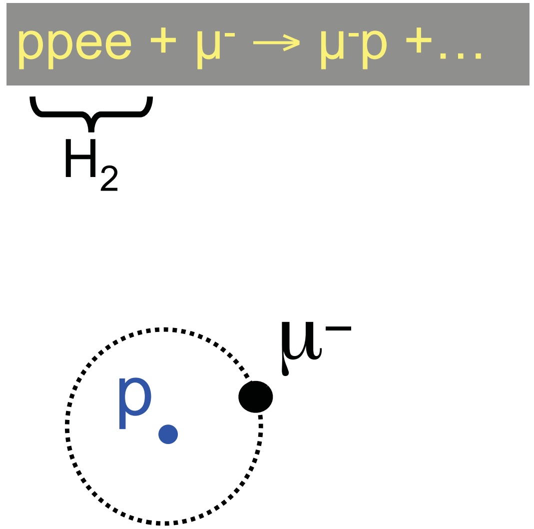


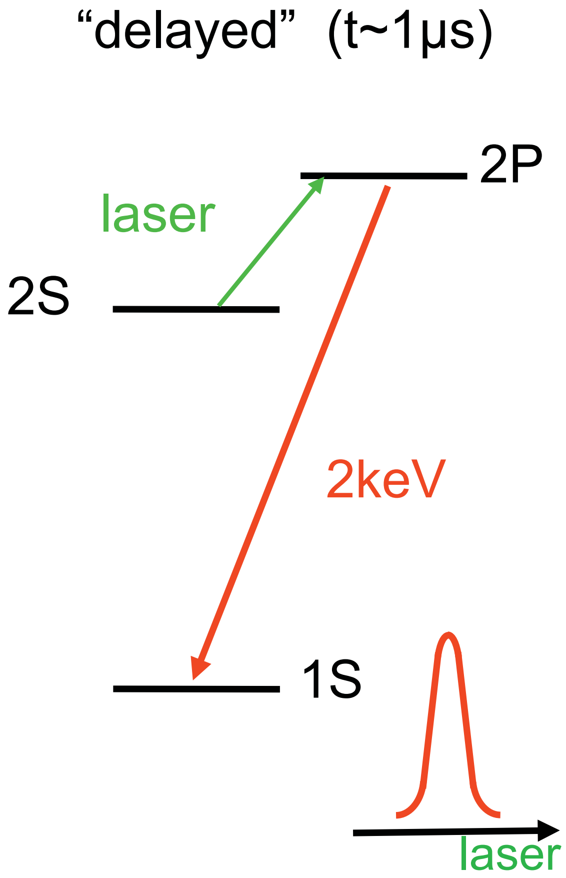
$(f_{\mu p}/f_{ep}) \propto 1/(200)^3 \approx 10^{-7}$



Principle of the experiment







μ^- stop in H_2 gas

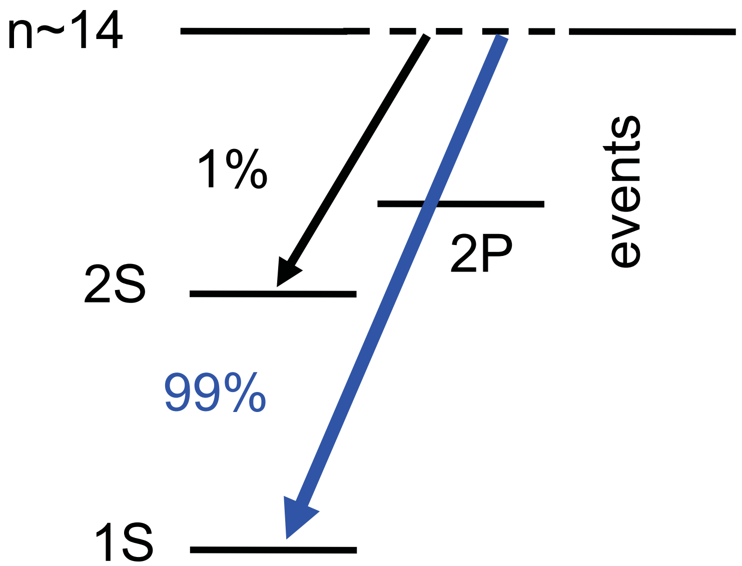
⇒ μp* atoms formed (n~14)

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

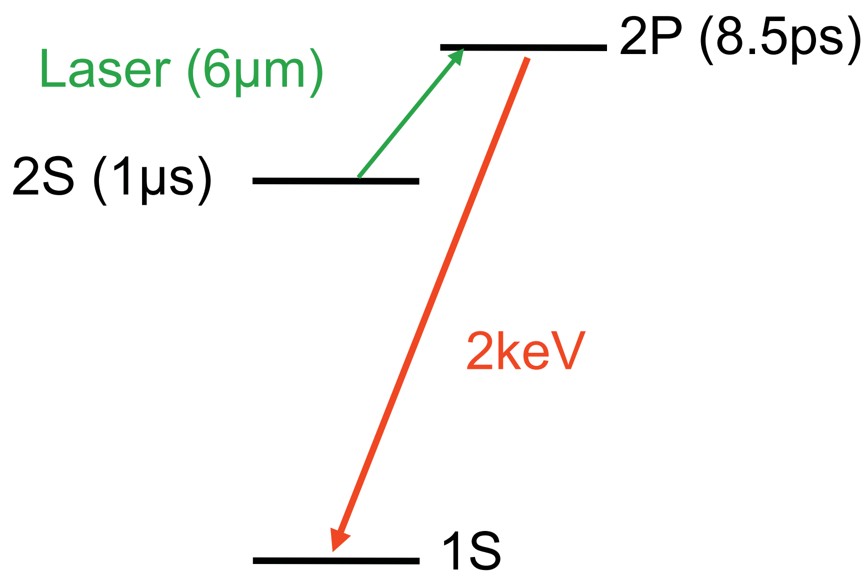
1%: long lived 2S state (τ ~ 1μs at 1mbar)

Principle of the experiment

"prompt" (t~0)



"delayed" (t~1μs)



Challenges

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

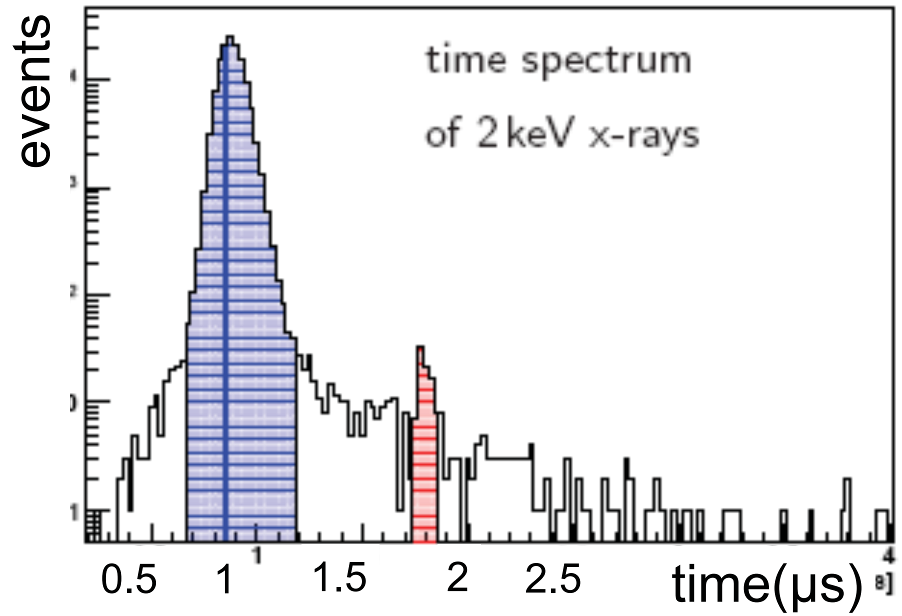
Fire laser (λ~6μm, ΔE~0.2eV)

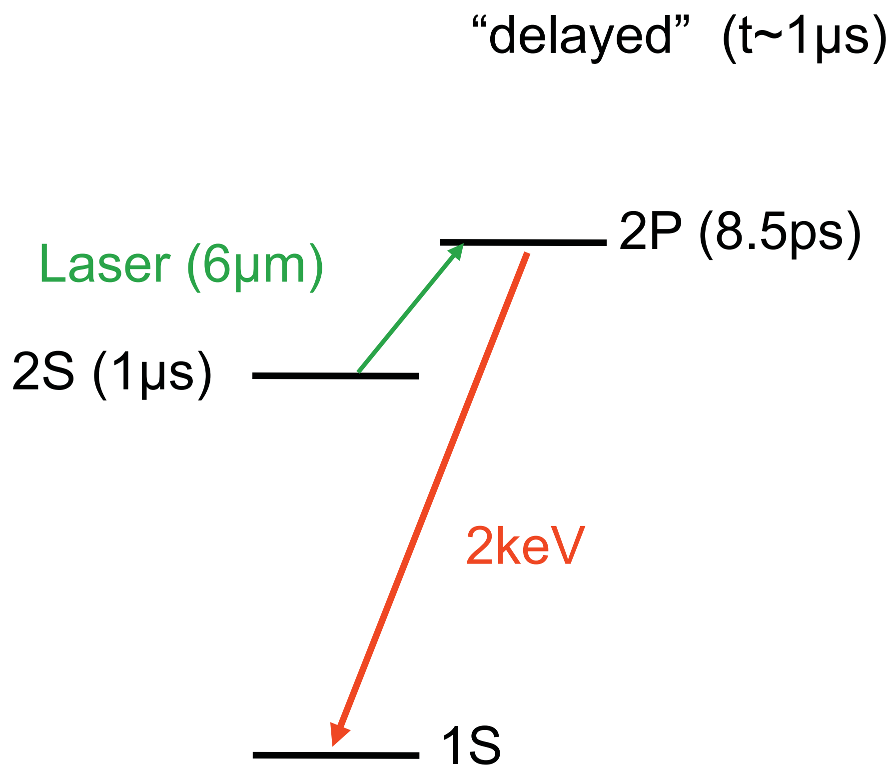
⇒ induce μp(2S-2P)

⇒ observe delayed Kα x-rays

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

Principle of the experiment





Challenges

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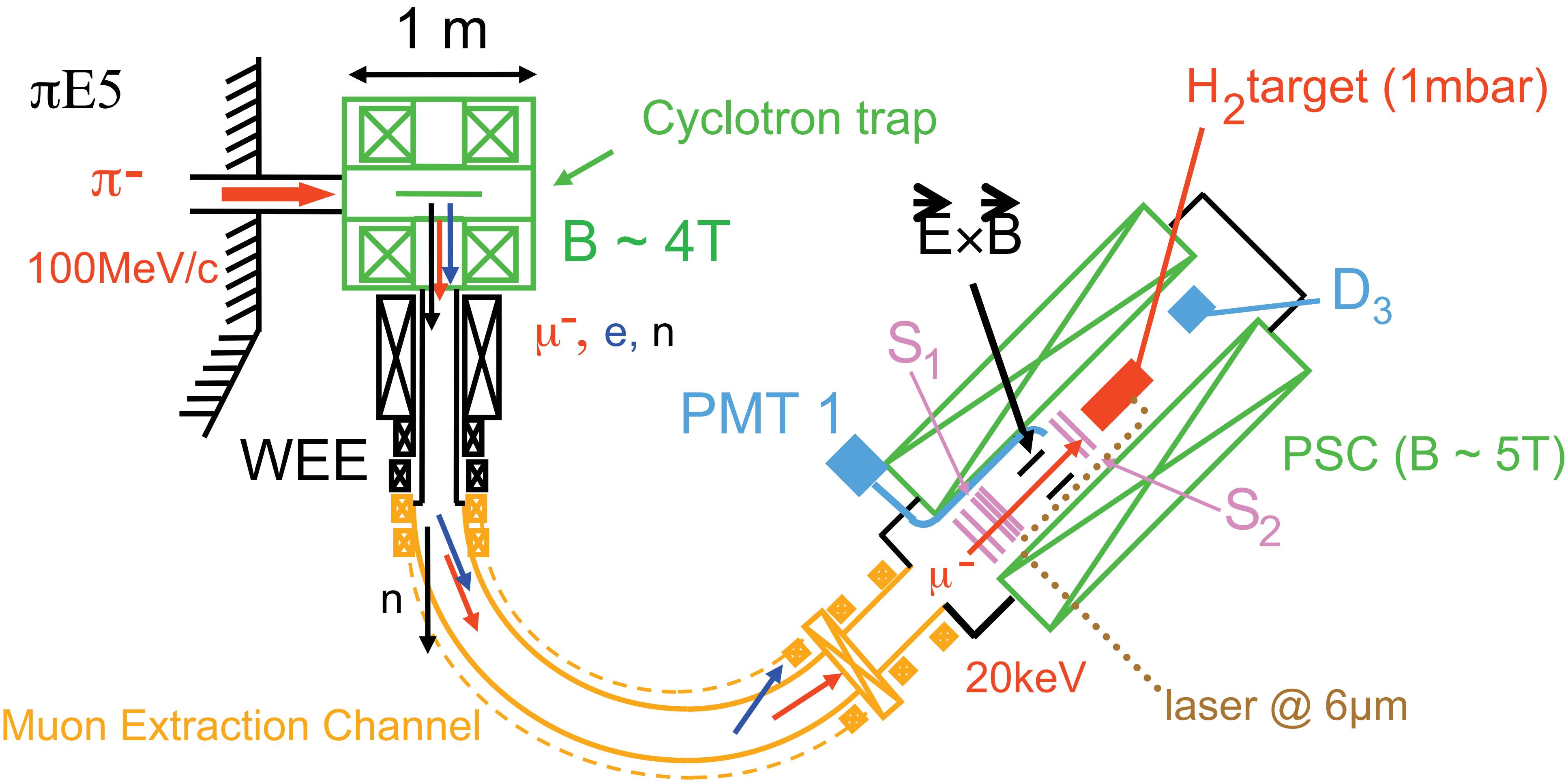
muonic hydrogen source

p (500Mev, 2mA) → carbon target → $\pi^- \rightarrow \mu^- + \overline{\nu}_{\mu^-}$ (300 μ^-/s)

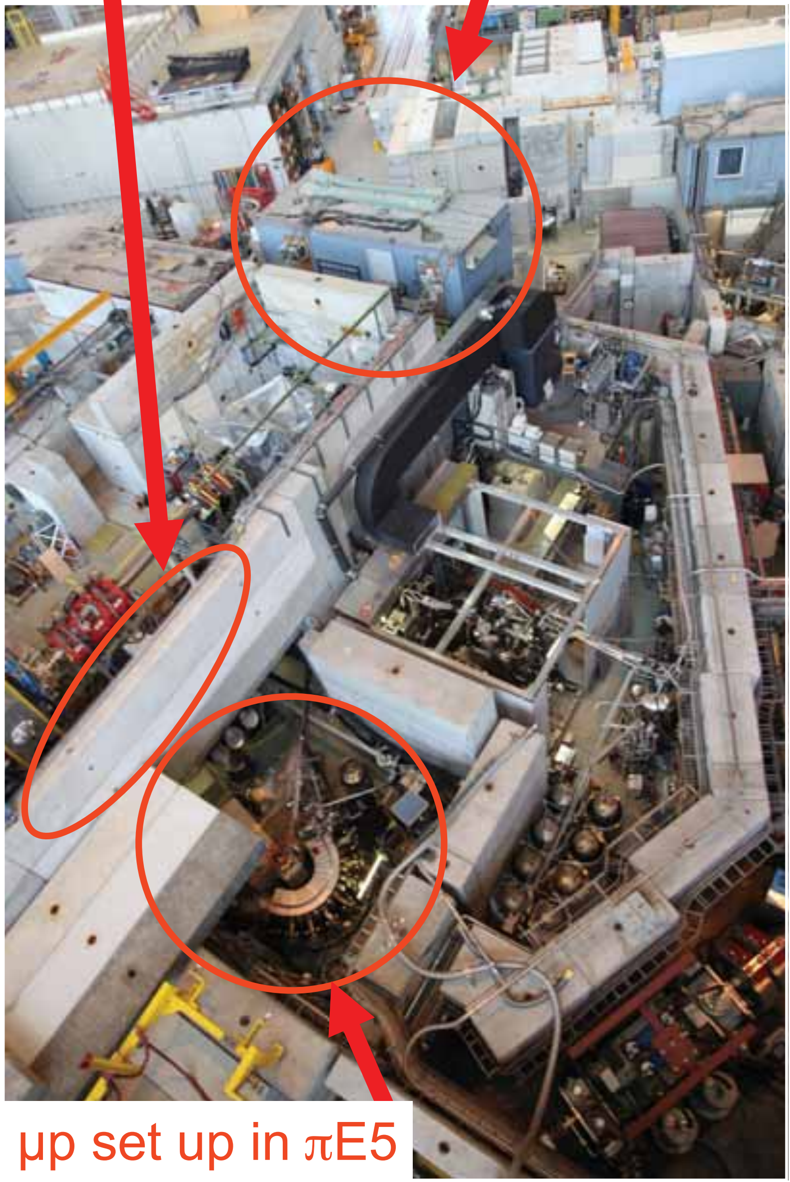


S_1 S_2 → T.O.F. → laser trigger

muon beam apparatus

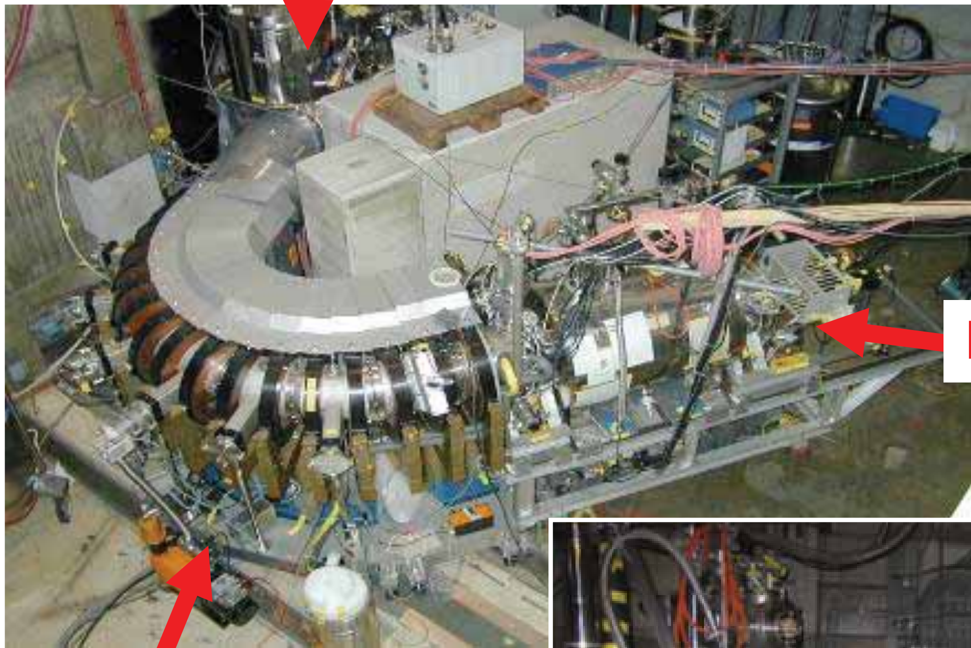
laser hut
below
concrete blocks

counting room



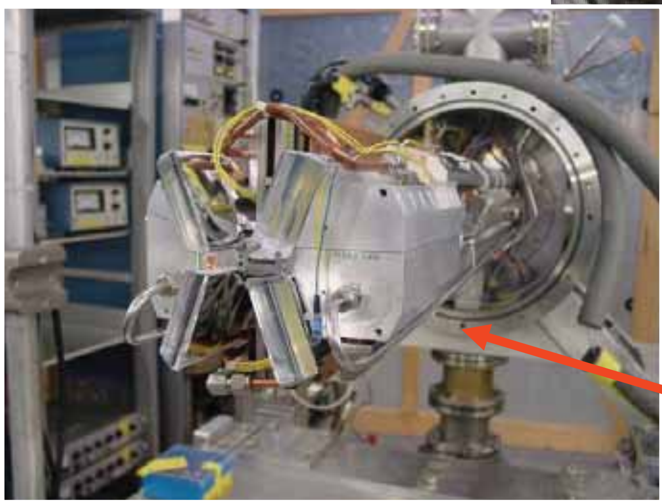
μp set up in πE5

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



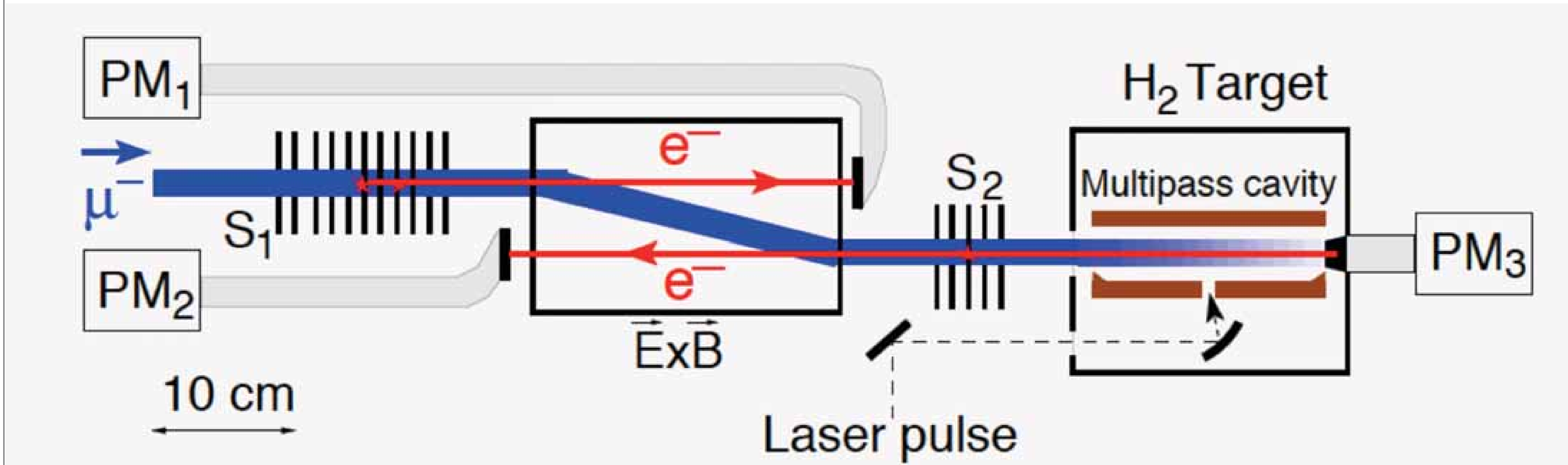
PSC solenoid,

Muon extraction
channel



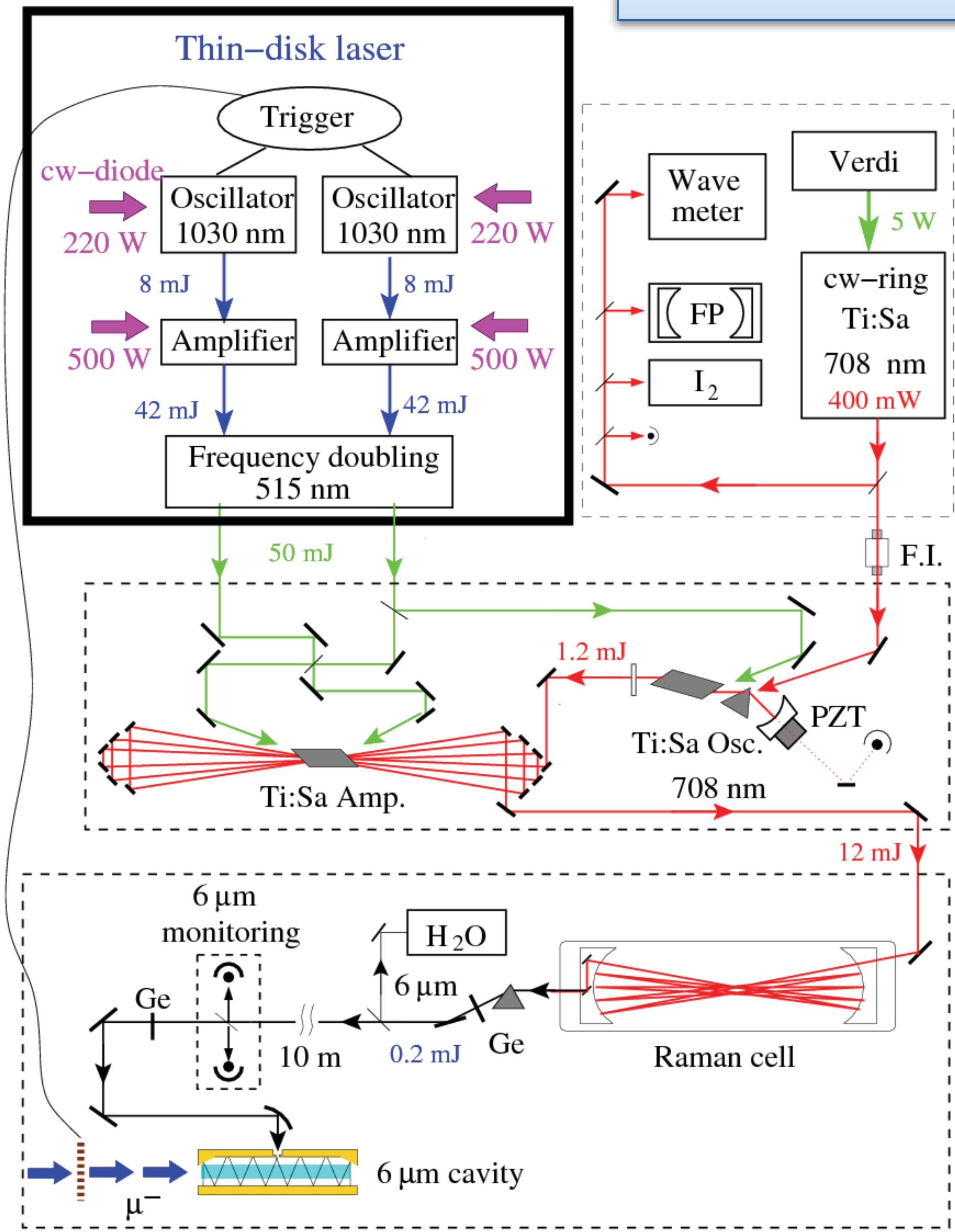
H2 target, laser cavity,
detectors

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

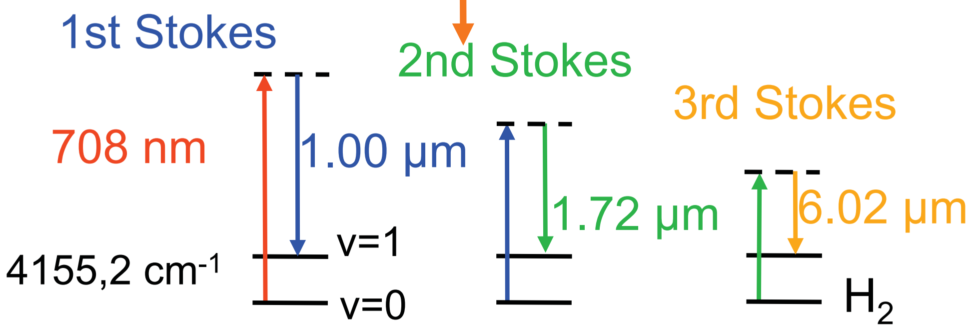
↓

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

↓

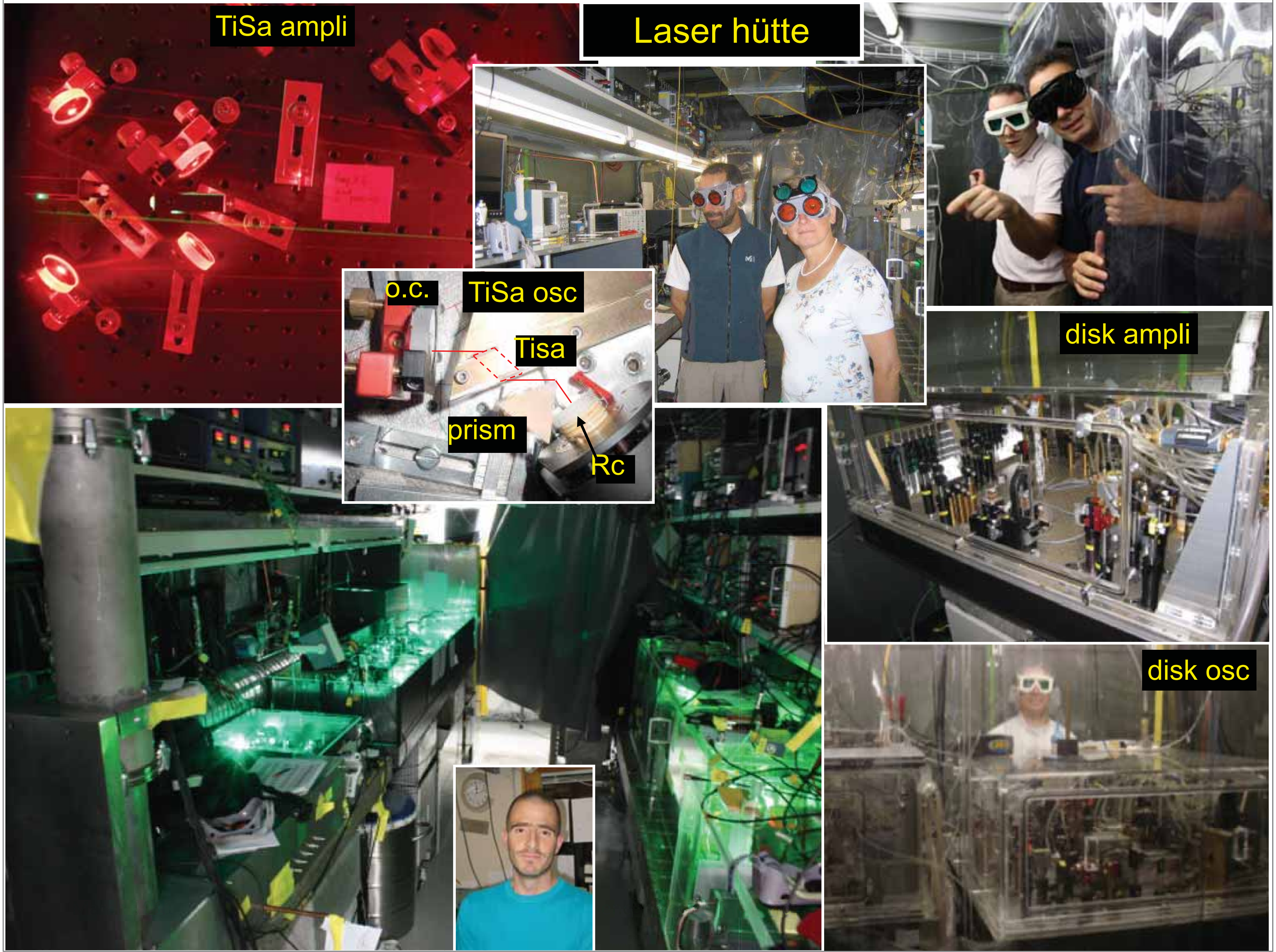
pulsed TiSa oscillator + amplifier
(708 nm determined by cw TiSa seeding)

↓



↓

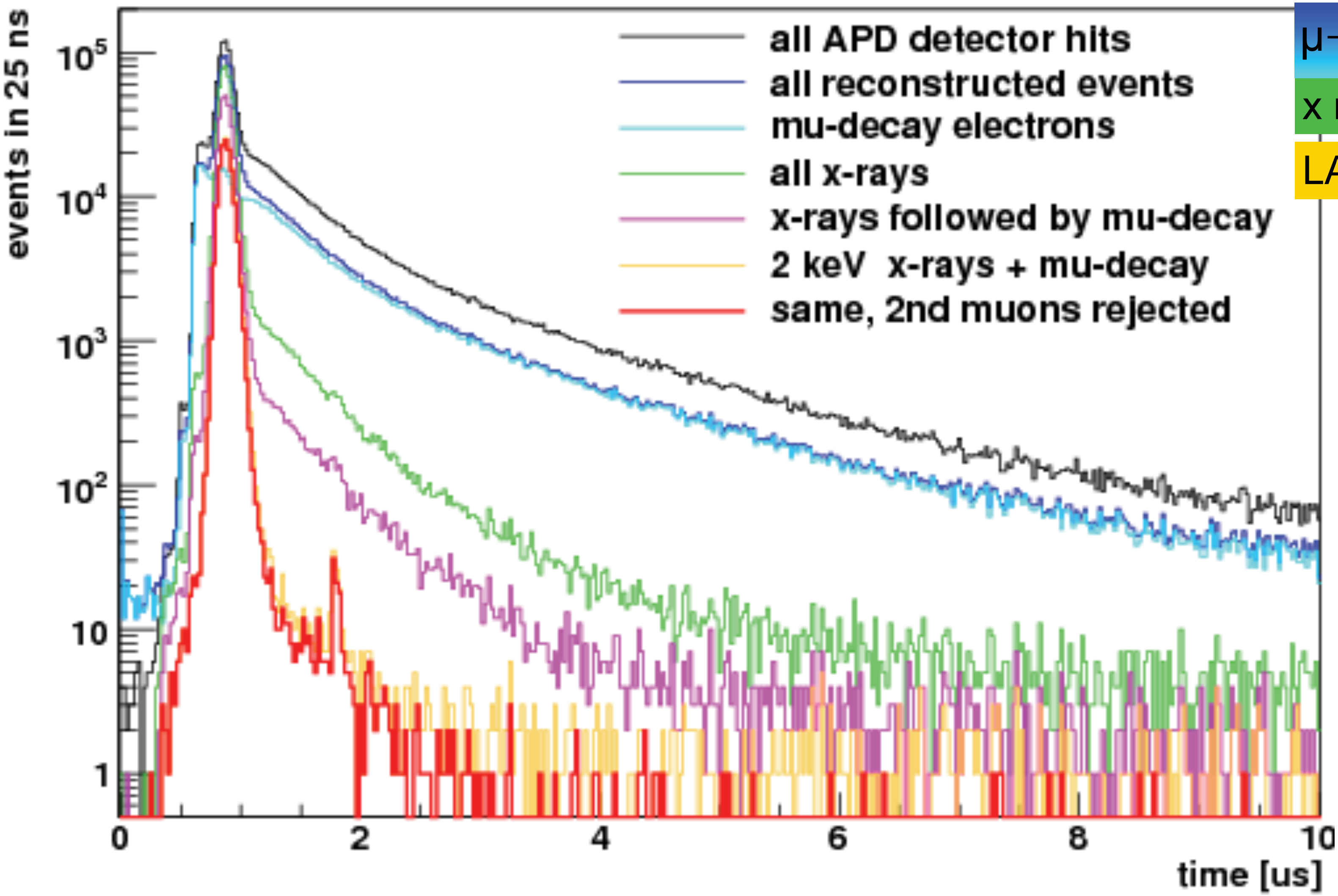
Multipass cavity at 6μm
surrounding the H2 target


Laser hütte
TiSa ampli
o.c.
TiSa osc
Tisa
prism
Rc
disk ampli
disk osc

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 !

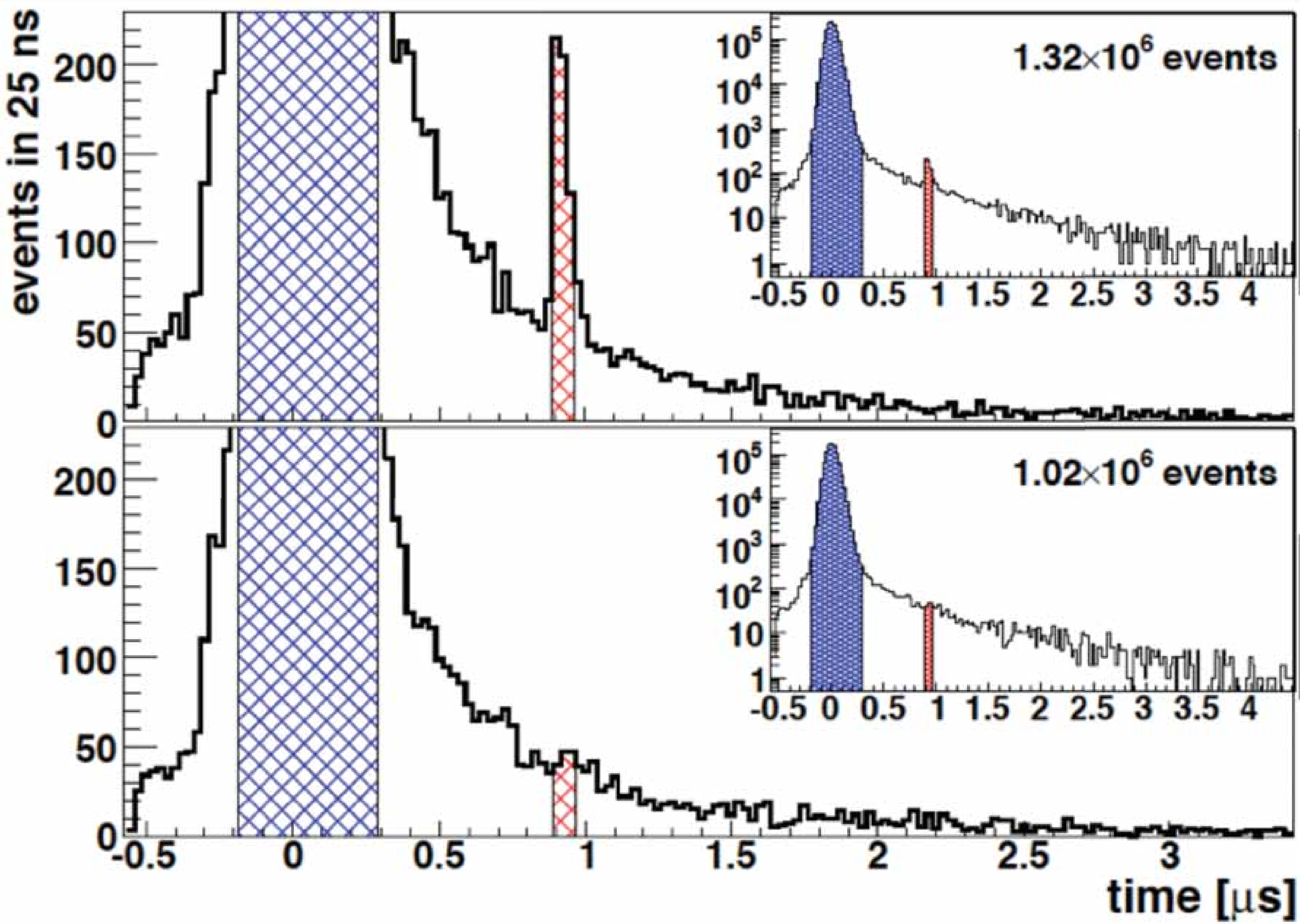


$\mu \to e\, \nu_\mu\, \bar{\nu}_e$

x rays multiplicity 1

LAAPD energy resolution

Time spectra

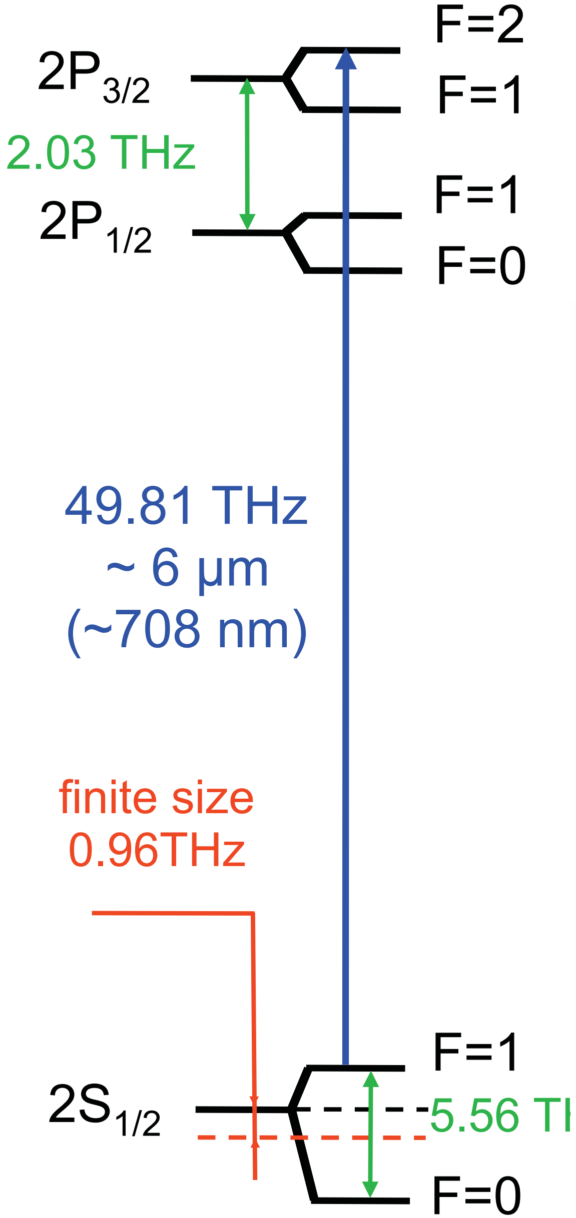


Laser ON resonance

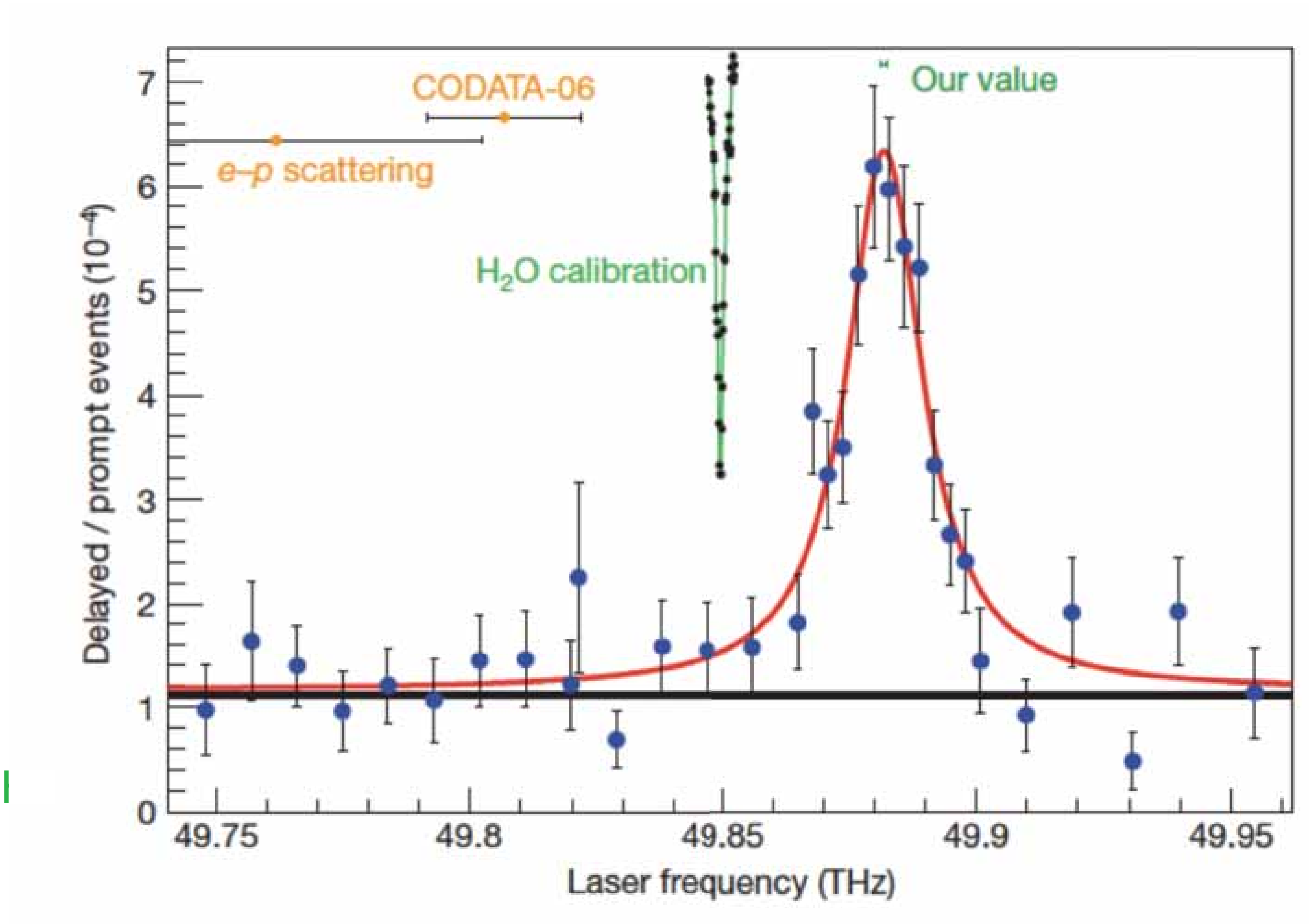
Laser OFF resonance

Same if laser on resonance but blocked

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



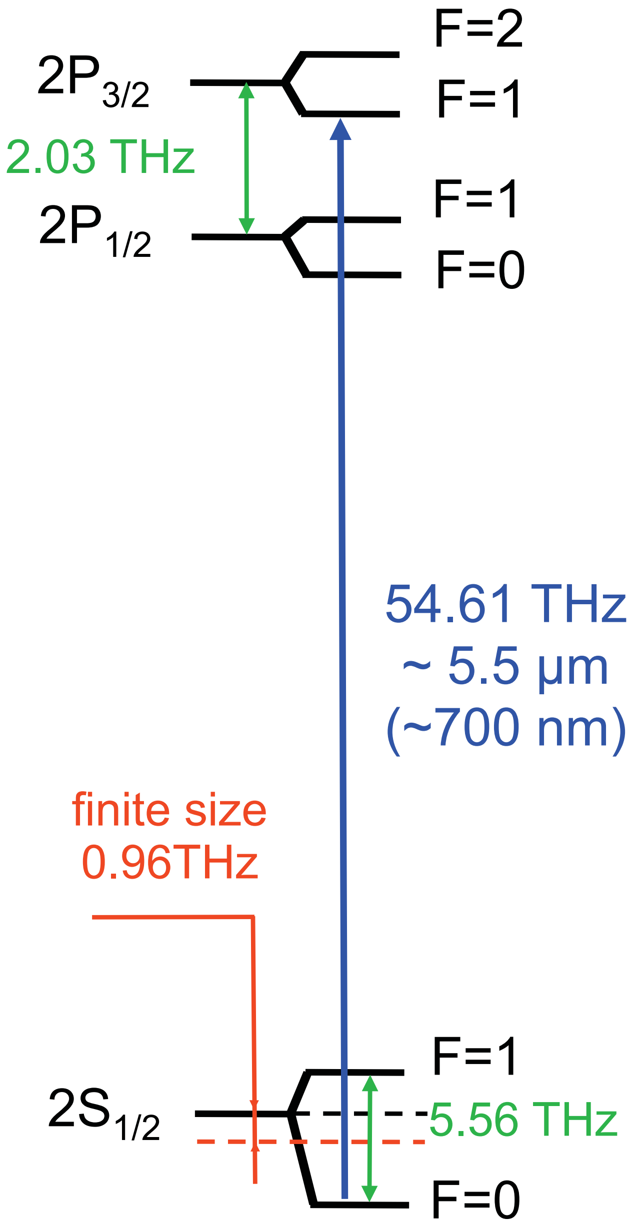
- 550 events measured
- 155 backgrounds
- 31 FP fringes
- 250 hours



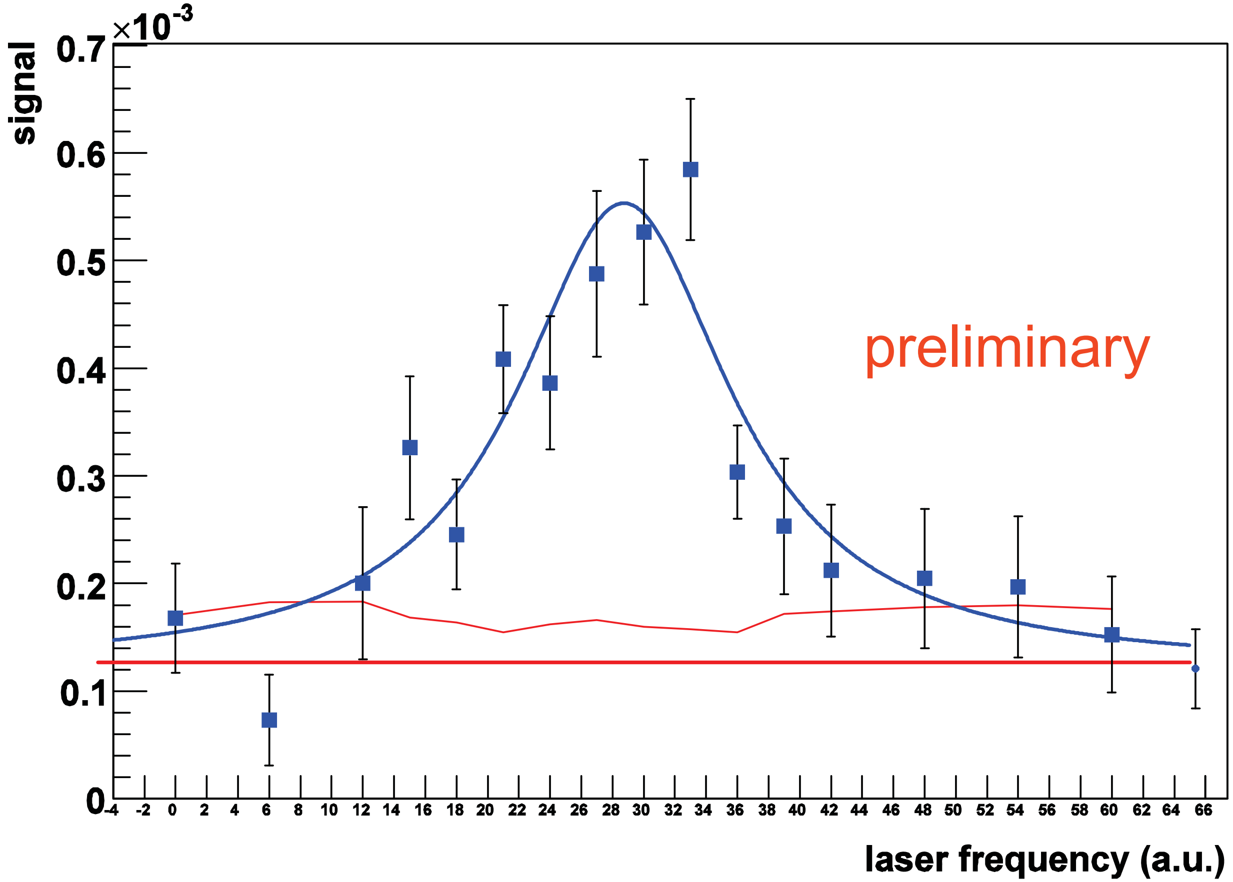
R. Pohl, A. Antognini, F. Nez, et al., Nature 466, 213 (2010).

→ proton charge radius (~0.1%)

muonic hydrogen: $2S_{1/2}(F=0)$- $2P_{3/2}(F=1)$

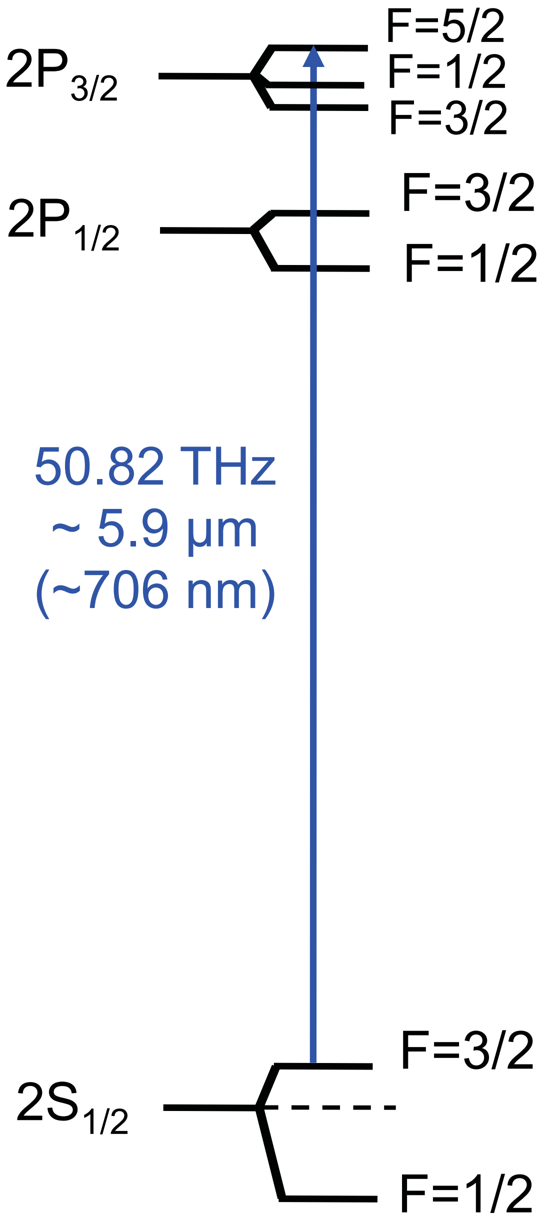


- measured position fits with our proton radius (preliminary)
- laser worked even better at 5.5 µm

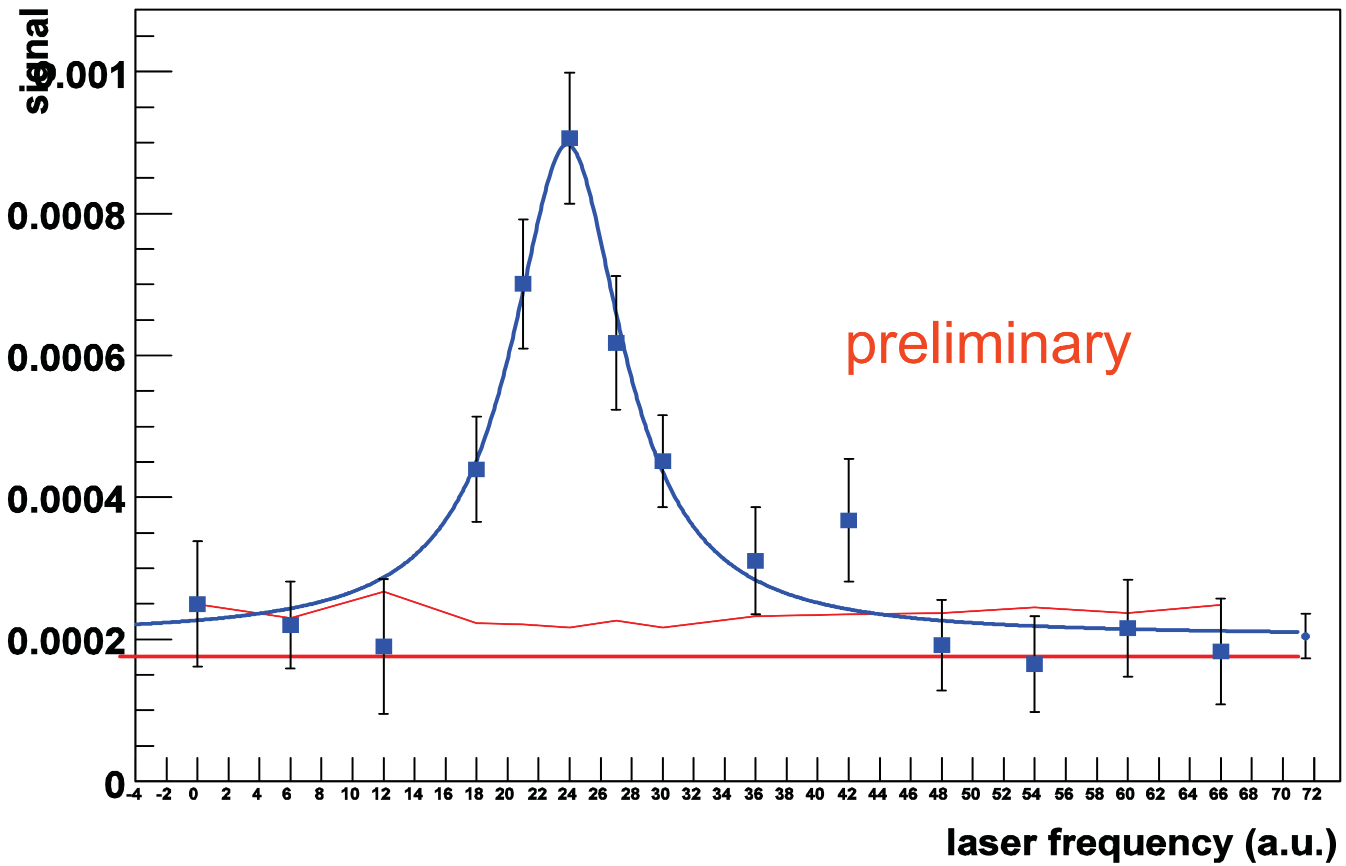


~ at the position deduced with new r_p → hfs : Zeemach radius (few %)

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



- on line signal, preliminary
- frequency position again off



Not at the position estimated with new r_p and isotopic shift → deuteron polarizability

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

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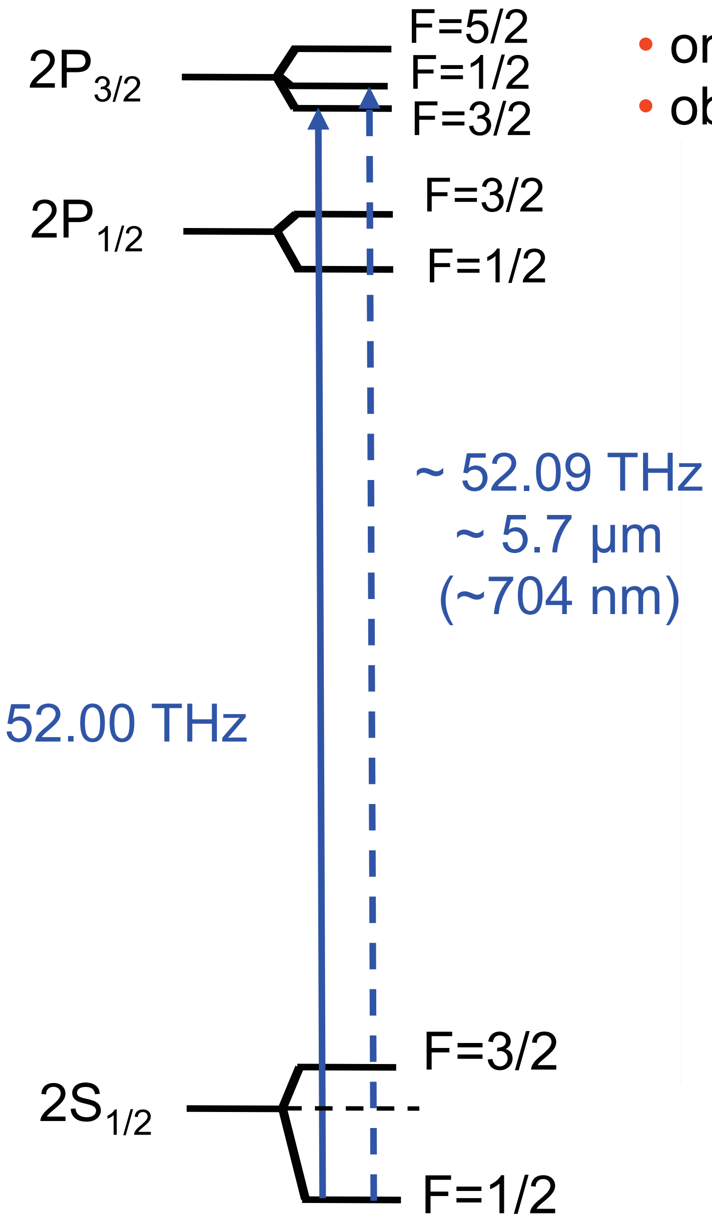
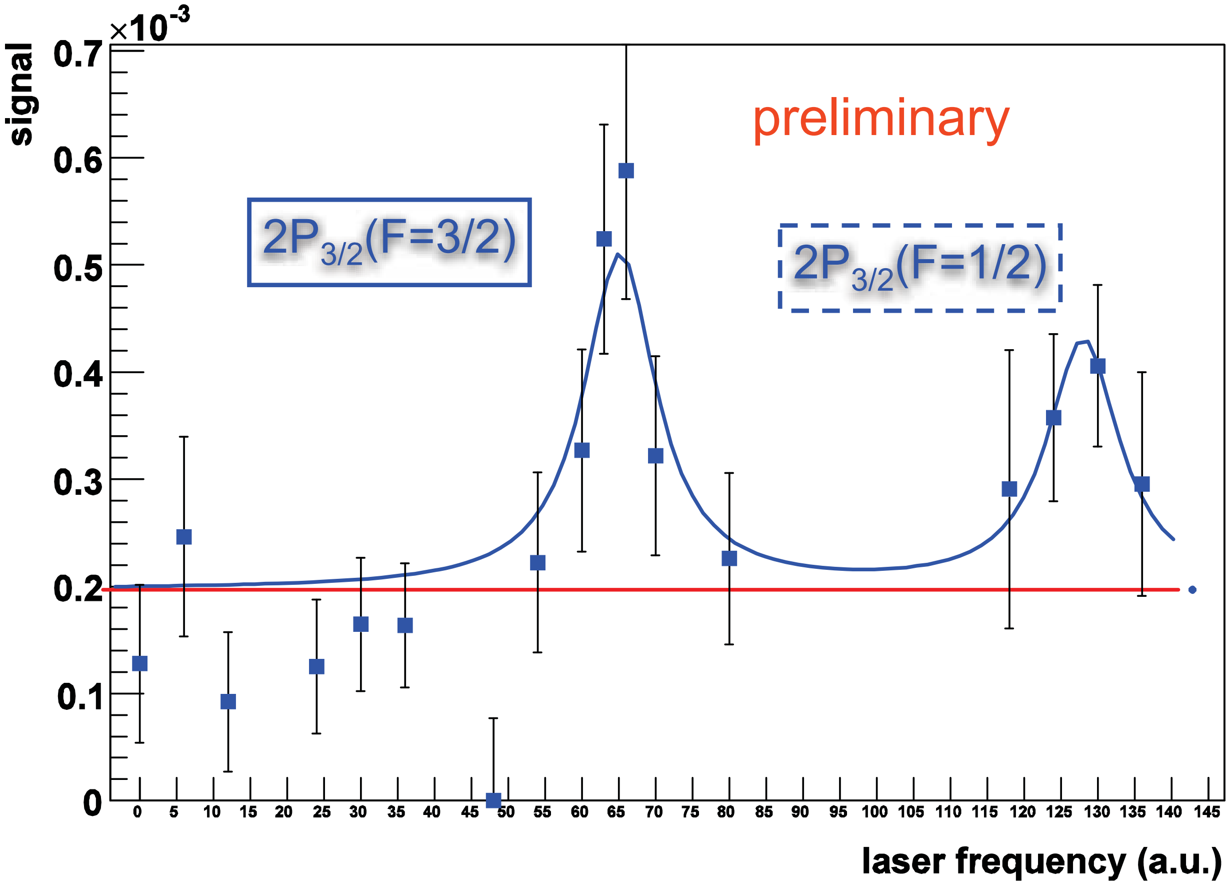
- on line signal, preliminary
- observation of 2 more lines in the last 2 days of beam line

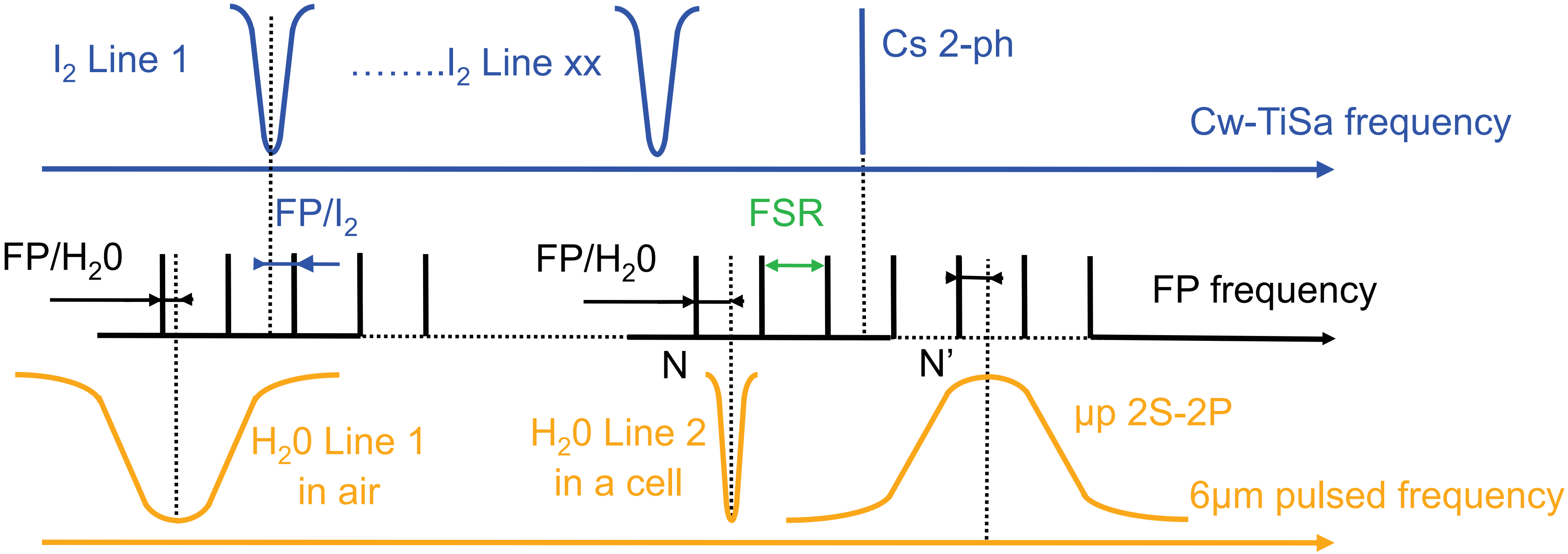




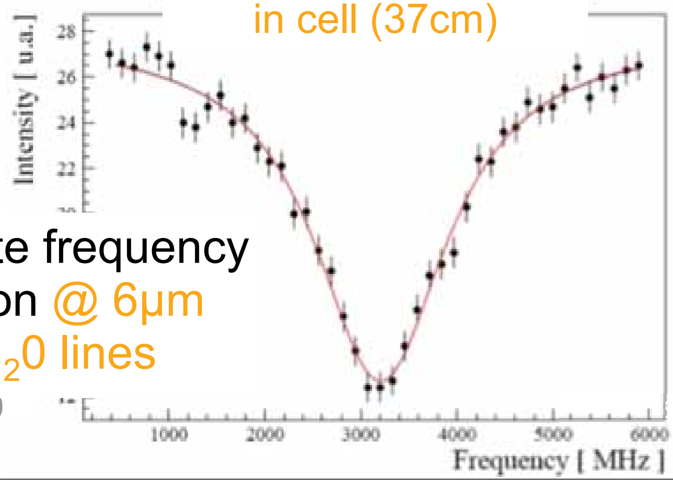
"observation" → check calculation in µd

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

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

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

Statistics

- uncertainty on position (fit) 700 MHz (~ 4 % of Γ_{nat})

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

Sources :

- Laser frequency (H_20 calibration) 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 762 MHz

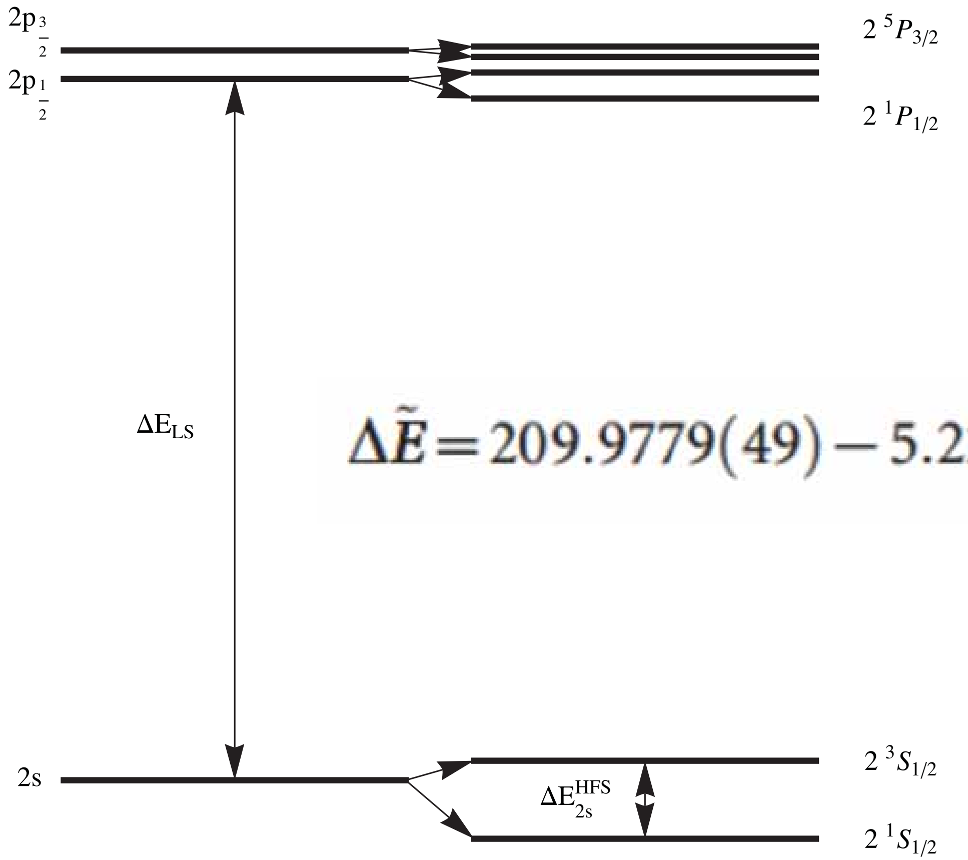
Broadening :

- 6 μm laser line width ~ 2 GHz
- Doppler Broadening < 1 GHz

ν (μp : $2S_{1/2}(F=1)- 2P_{3/2}(F=2)$) = 49 881.88 (76) GHz ($1.6 \times 10^{-5}$)

Proton charge Radius from muonic hydrogen

We need QED including Hyperfine structure



$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV}$$

Fig. 19. The energy structure of the $n = 2$ level in muonic hydrogen. The drawing is to scale. Details of the $2p$ level structure are presented in Fig. 20.

Proton charge Radius from muonic hydrogen

We need QED including Hyperfine structure

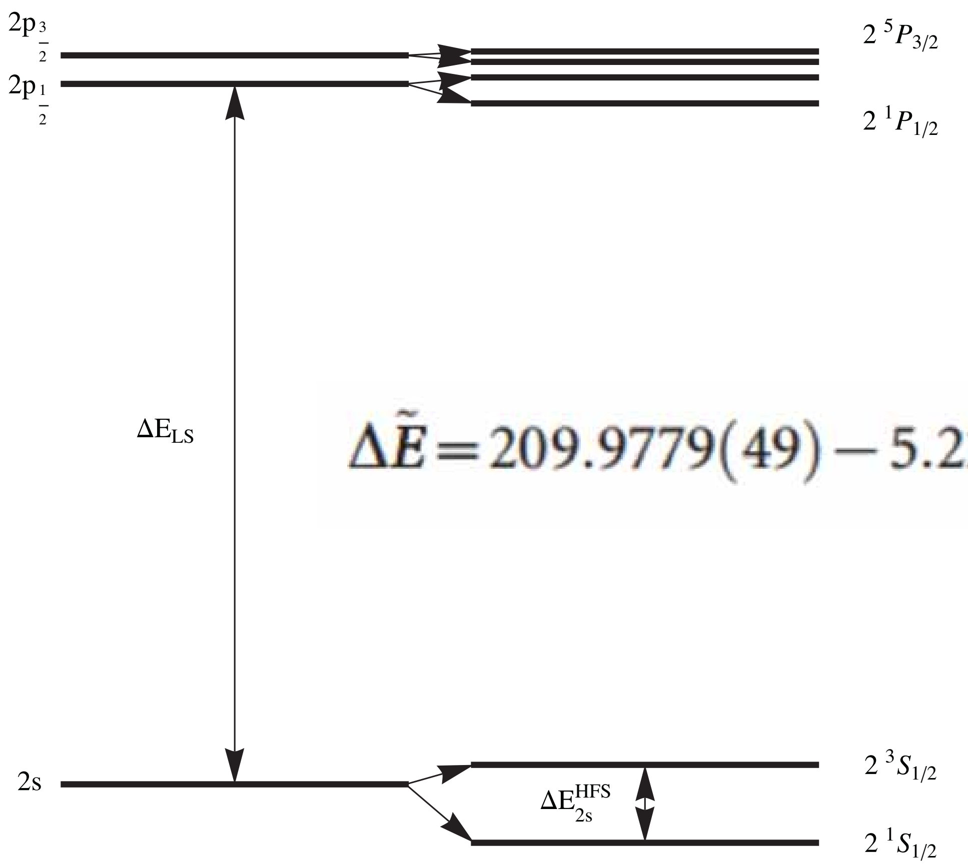
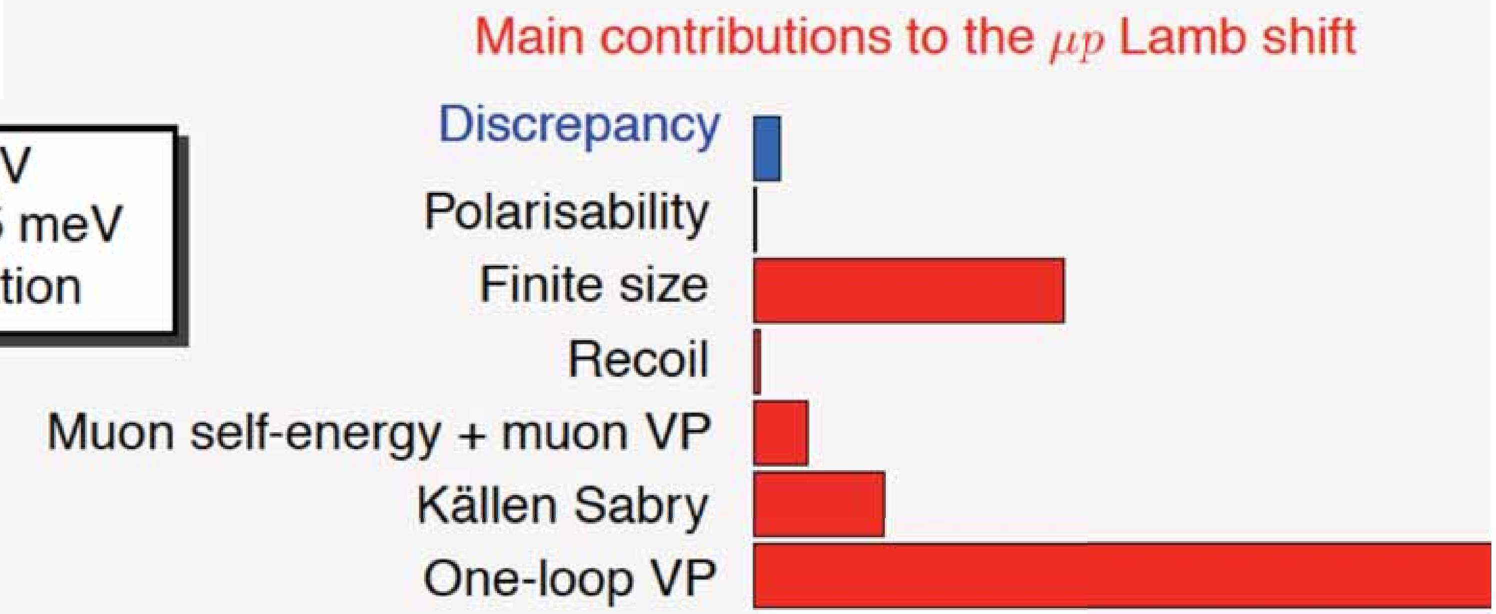


Fig. 19. The energy structure of the *n* = 2 level in muonic hydrogen. The drawing is to scale. Details of the 2*p* level structure are presented in Fig. 20.

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV}$$

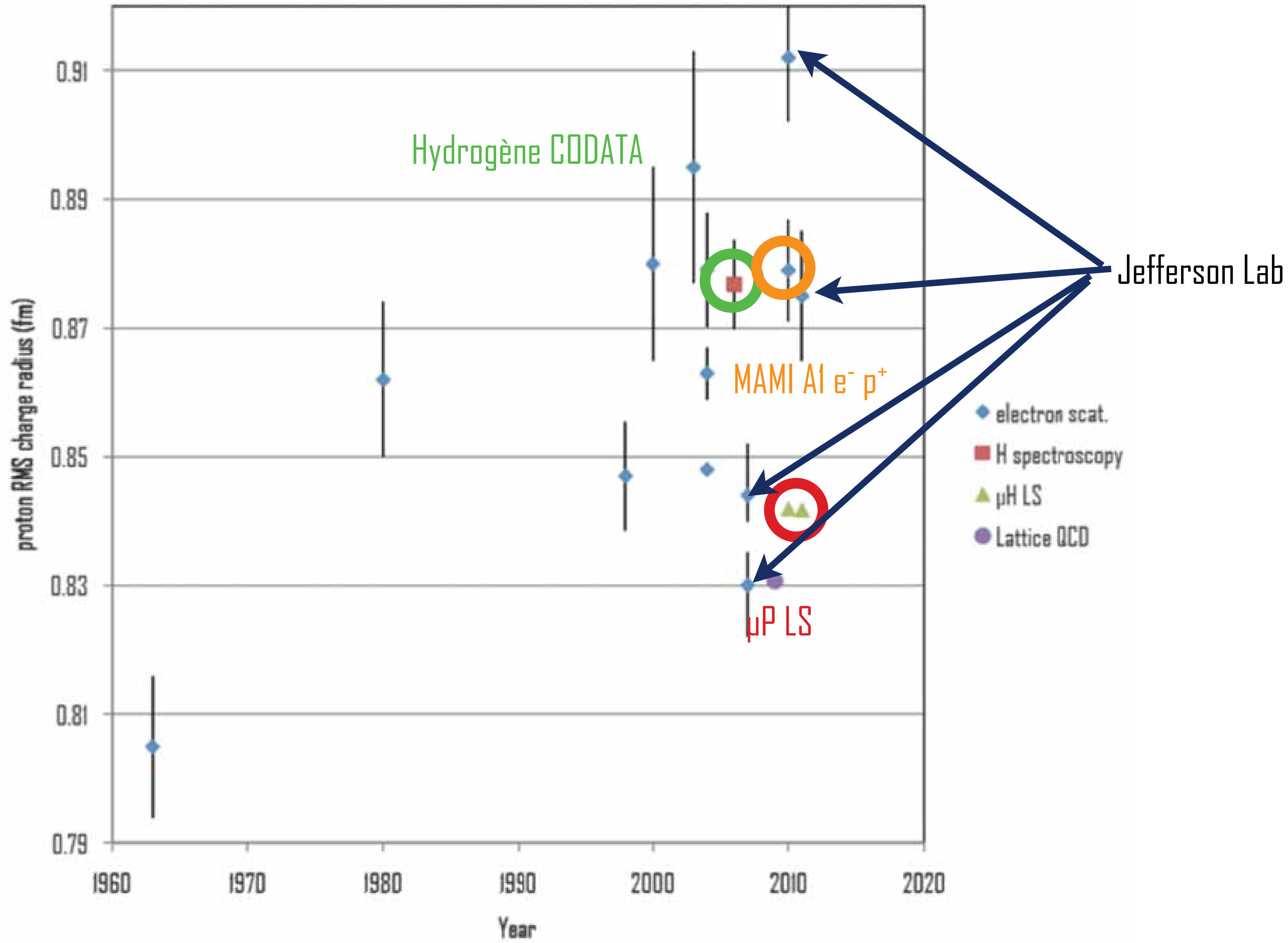
0.84184(67) fm 5.06 σ

µP theory



Discrepancy=0.31 meV
Th. uncertainty=0.005 meV
$\Longrightarrow 60\delta(\text{theory})$ deviation

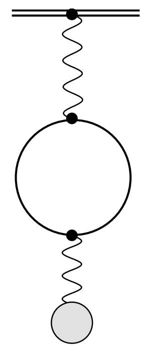
Proton size results summary



Finite nuclear size effect by direct numerical solution of Dirac Equation

Direct numerical solution of Dirac equation, numerical grid, 10000 points, ~4000 inside the proton

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



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

$$\chi_n(x)=\int_1^\infty dz e^{-xz}\frac{1}{z^n}\left(\frac{1}{z}+\frac{1}{2z^3}\right)\sqrt{z^2-1}.$$

$$\begin{aligned}V_{11}(r) &= -\frac{2\alpha(Z\alpha)}{12\pi}\frac{1}{r}\int_0^\infty dr'\,r'\rho(r')\\ &\times\left[\chi_2\left(\frac{2}{\lambda_e}\mid r-r'\mid\right)-\chi_2\left(\frac{2}{\lambda_e}\mid r+r'\mid\right)\right].\end{aligned}$$

Analytical expression for the evaluation of vacuum-polarization potentials in muonic atoms, S. Klarsfeld. Physics Letters 66B, 86-88 (1977).

Charge radius dependence Coul.+VP

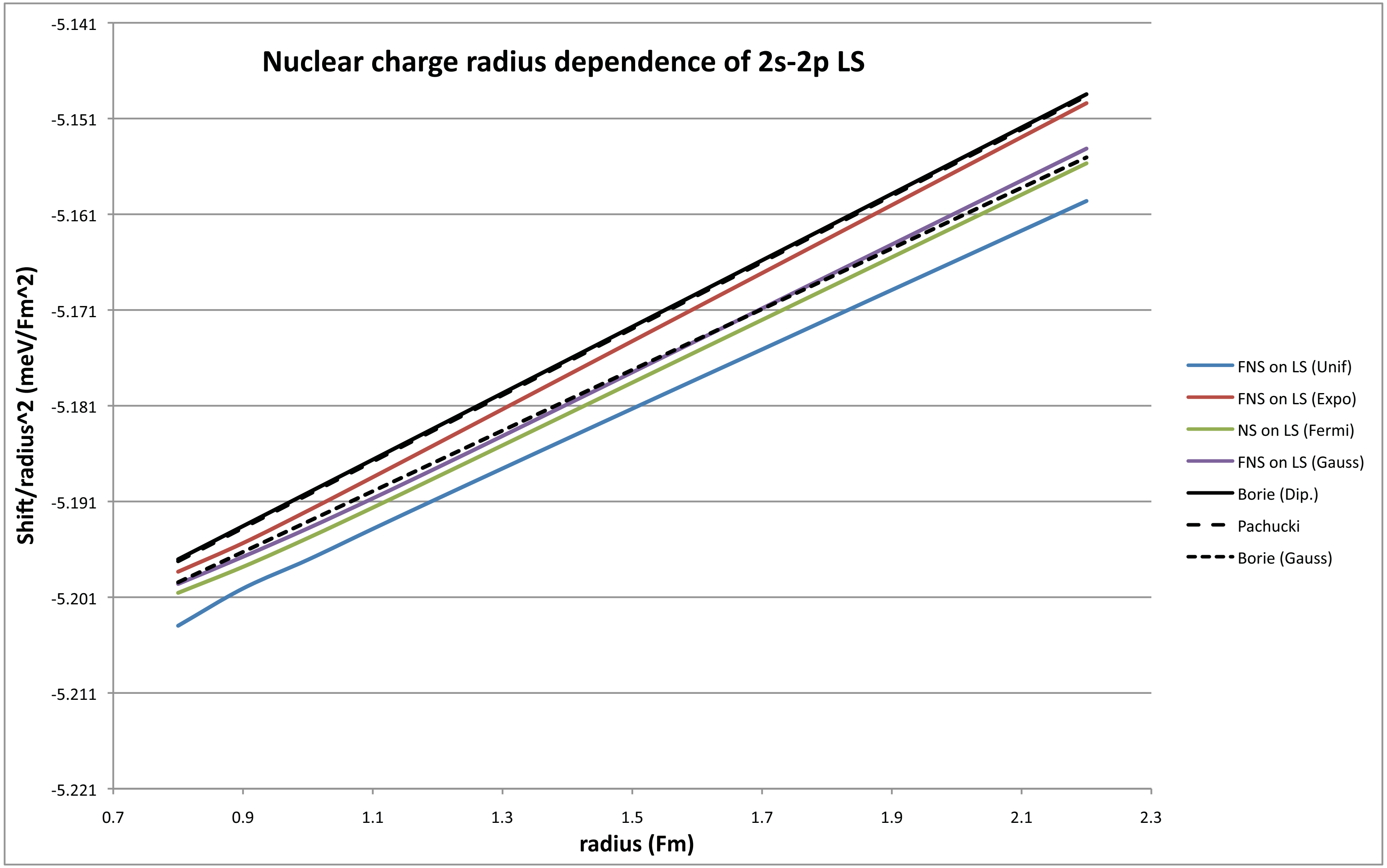


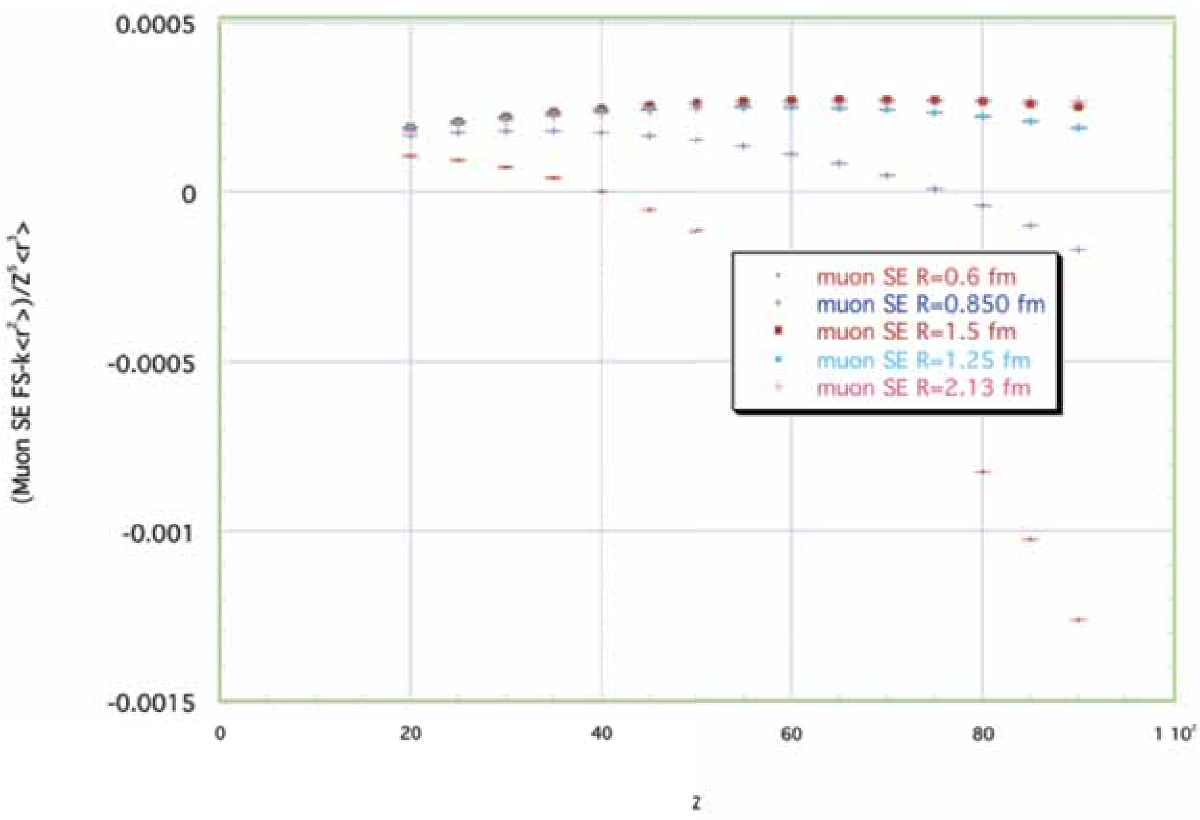
Fig. 3. Dependence of $\frac{\Delta E_{\mathrm{V11FN}}}{R^2}$ as a function of R in meV/fm^2 for different charge distribution models.

Finite size correction on muon self-energy

All-orders calculations

$$E_{SE-NS} = \left(4\ln 2 - \frac{23}{4}\right)\alpha(Z\alpha)\mathcal{E}_{NS}$$

$$\mathcal{E}_{NS} = \frac{2}{3}\left(\frac{\mu_r}{m_\mu}\right)^3 \frac{(Z\alpha)^2}{n^3} m_\mu \left(\frac{Z\alpha < r >}{\lambda\!\!\!^{-}_C}\right)^2$$



$$E_{SE-NS} = -0.000824 < r^2 >$$

(All-orders calculations-$E_{SE\text{-}NS}$<r^2>)/Z^5 <r^3>
1.8±1 x 10^{-5}

Proton charge Radius from muonic hydrogen

$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV}$$

0.84184(67) fm 5.06 σ

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

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$$209.9759 - 5.228880\,R^2 + 0.03573760\,R^3 - 0.00004500000\,R^4$$

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P. Indelicato, P. Mohr, in preparation

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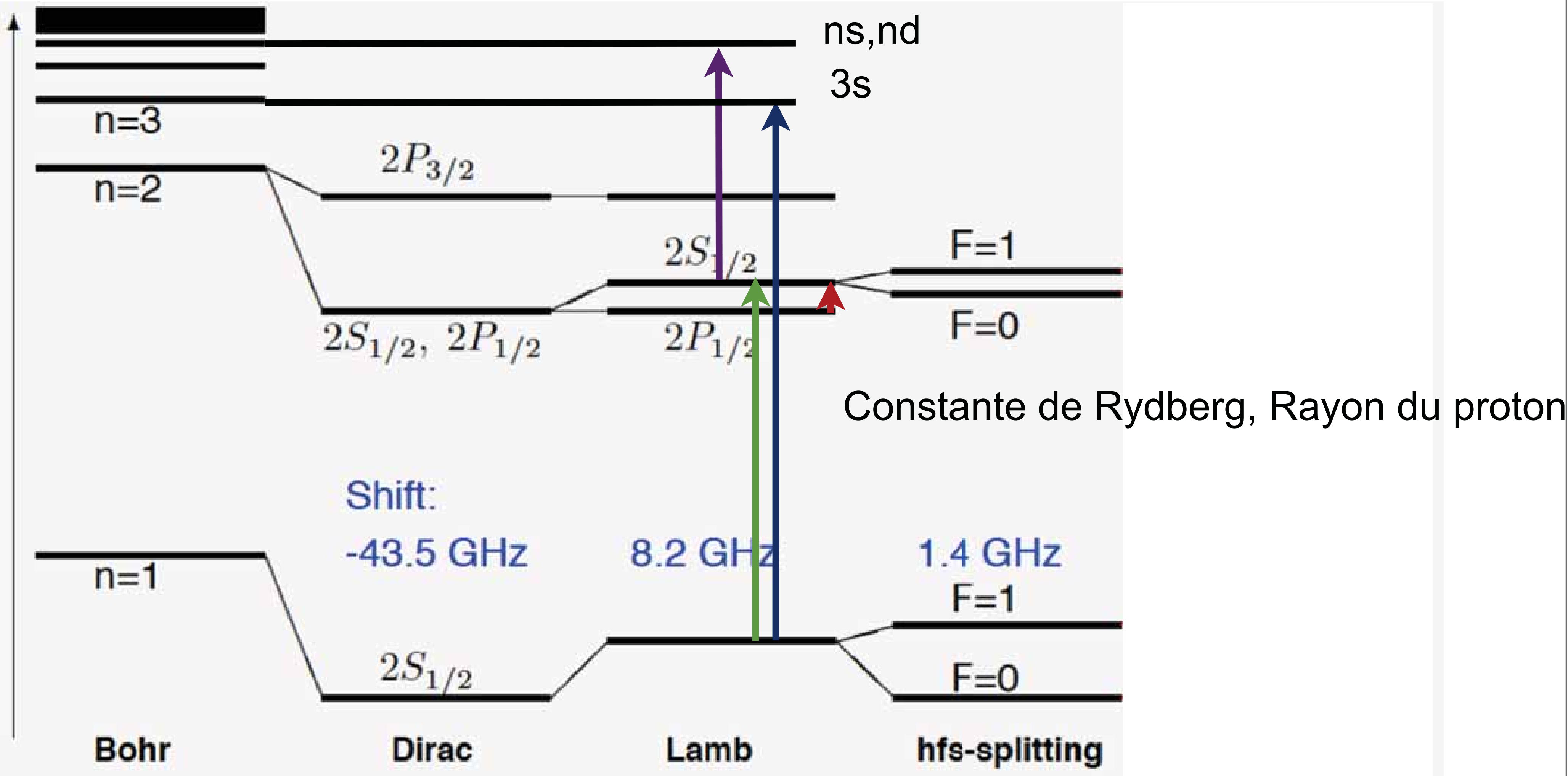
The coefficient of r_p^3 is model dependent, using dipole model (more on next talk)

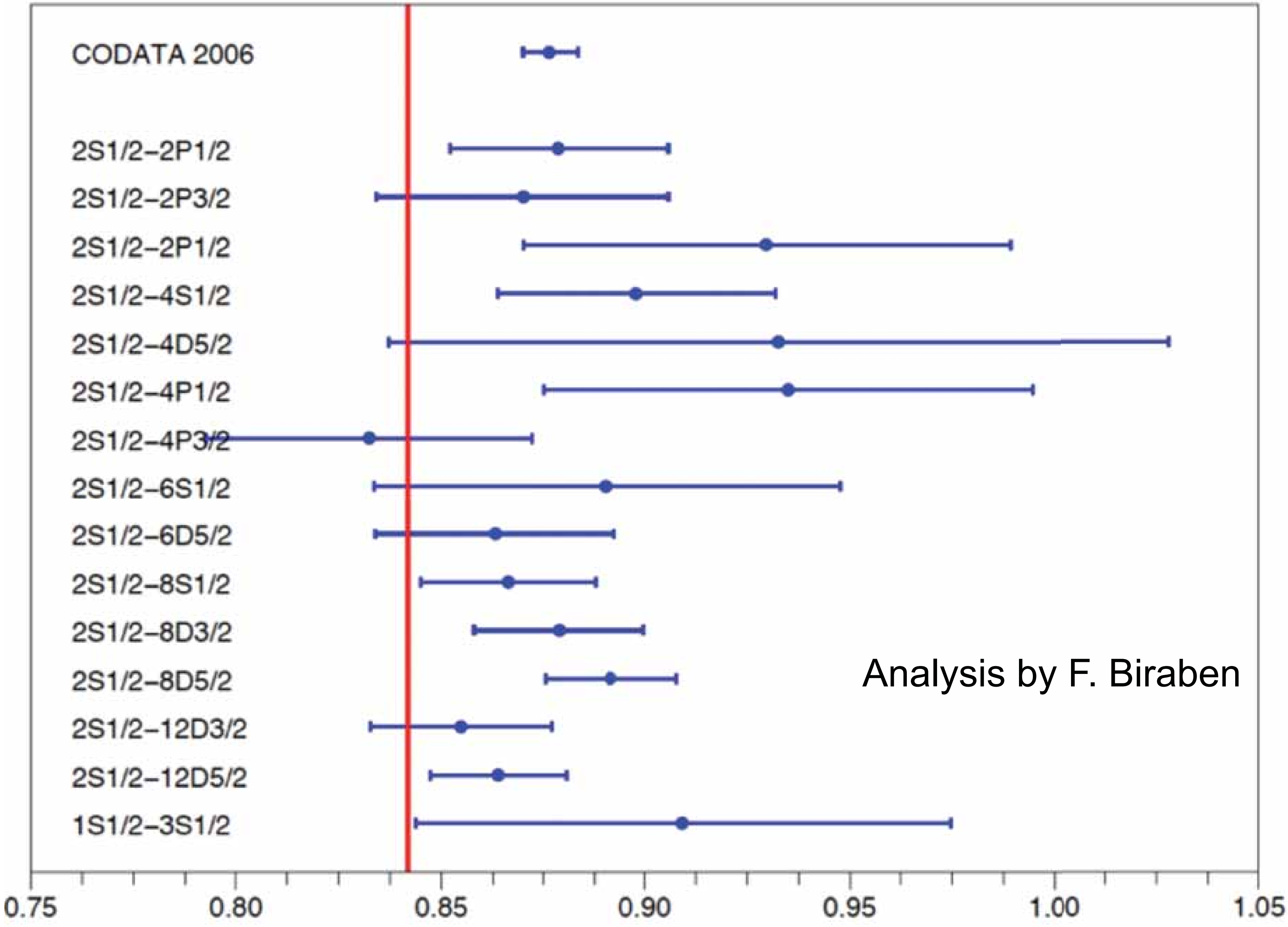
Possible origin for the discrepancy

- Electron-proton elastic scattering data analysis:
  - very probable (next talk)
- Under-estimated systematic errors in some hydrogen measurements:
  - possible, but many different experiments (microwave, 1s-3s, 2s-ns and 2s-nd)
- New physics:
  - Predictions are always difficult, in particular about the Future [N. Bohr]

Hydrogen


ns,nd
3s
n=3
n=2
$2P_{3/2}$
$2S_{1/2}$
F=1
F=0
$2S_{1/2}$, $2P_{1/2}$
$2P_{1/2}$
Constante de Rydberg, Rayon du proton
Shift:
-43.5 GHz
8.2 GHz
1.4 GHz
F=1
n=1
$2S_{1/2}$
F=0
Bohr
Dirac
Lamb
hfs-splitting

Hydrogène


CODATA 2006
2S1/2–2P1/2
2S1/2–2P3/2
2S1/2–2P1/2
2S1/2–4S1/2
2S1/2–4D5/2
2S1/2–4P1/2
2S1/2–4P3/2
2S1/2–6S1/2
2S1/2–6D5/2
2S1/2–8S1/2
2S1/2–8D3/2
2S1/2–8D5/2
2S1/2–12D3/2
2S1/2–12D5/2
1S1/2–3S1/2
Analysis by F. Biraben
0.75
0.80
0.85
0.90
0.95
1.00
1.05

Hydrogène

- Hydrogen mean value: 0.8752(71) fm: 4.8 σ
- CODATA: 0.8768(69) fm (uses scattering data): 5.1 σ

LKB

From where else could it come from?

- A muon edm? If $d_\mu = 2 \times 10^{-19}$ e·cm would shifts the energy level < 200 MHz
- Charge equality between e^- and μ^- generation? Checked to $u_r = 10^{-8}$ (from $\mu^+ e^-$)

- Deviation from Coulomb's law: probe of hidden sector
  - Test of Coulomb law via spectroscopy is very clean and model independent probe of new particles
    It is independent on stability and decay channel.

$$V(r) = -\frac{Z\alpha}{r}(1 + \alpha' e^{-mr}) \quad \text{or} \quad V(r) = -\frac{Z\alpha}{r}(1 + \alpha''(\mathbf{s_1} \cdot \mathbf{s_2}) e^{-mr})$$

  - From simple atoms there are constraints on light bosons with ultra-weak coupling:
    $m \in [1\mathrm{eV}, \mathrm{MeV}]$ and $\alpha' < 10^{-13}$, $\alpha'' < 10^{-17}$ [PRL 104,220406 (2010), arXiv:1008.3536v2]

- Minicharge particles? [Jaeckel and Roy (2010), Jentschura(2010)]
  Vacuum polarization with pair production of light fermions with $q = \varepsilon e$ and masses $m_\varepsilon < m_e$

No parameter found explaining r_p puzzle without contradicting, simple atoms spectroscopy, $g_{e/\mu} - 2$, α...

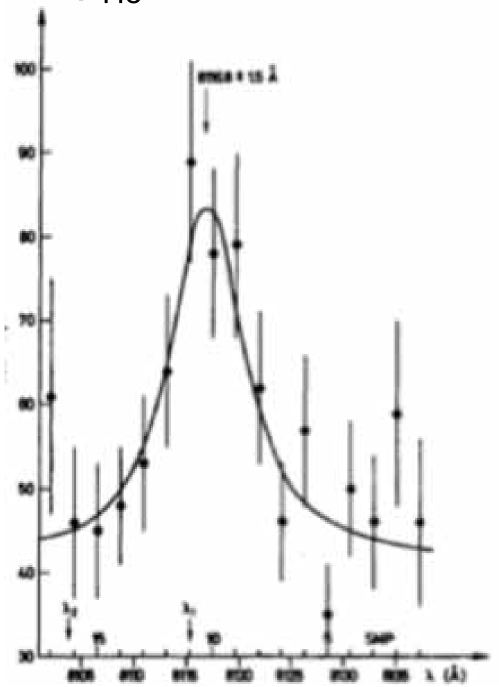
Conclusions

- We have performed a 15 ppm measurement of the Lamb-shift in muonic hydrogen
- The deduced proton radius using a Dipole model is 5 standard deviations away from the hydrogen and electron-proton elastic scattering data
- Better modeling of the proton form-factor required to confirm or reduce the disagreement
- Experiment checked with 2nd µH line and 3 µD lines
- Muonic He in 2013 (check of theory, different laser wavelength-in the red)

Proton Size Investigators thank you for your attention

Prospect : muonic helium spectroscopy at PSI

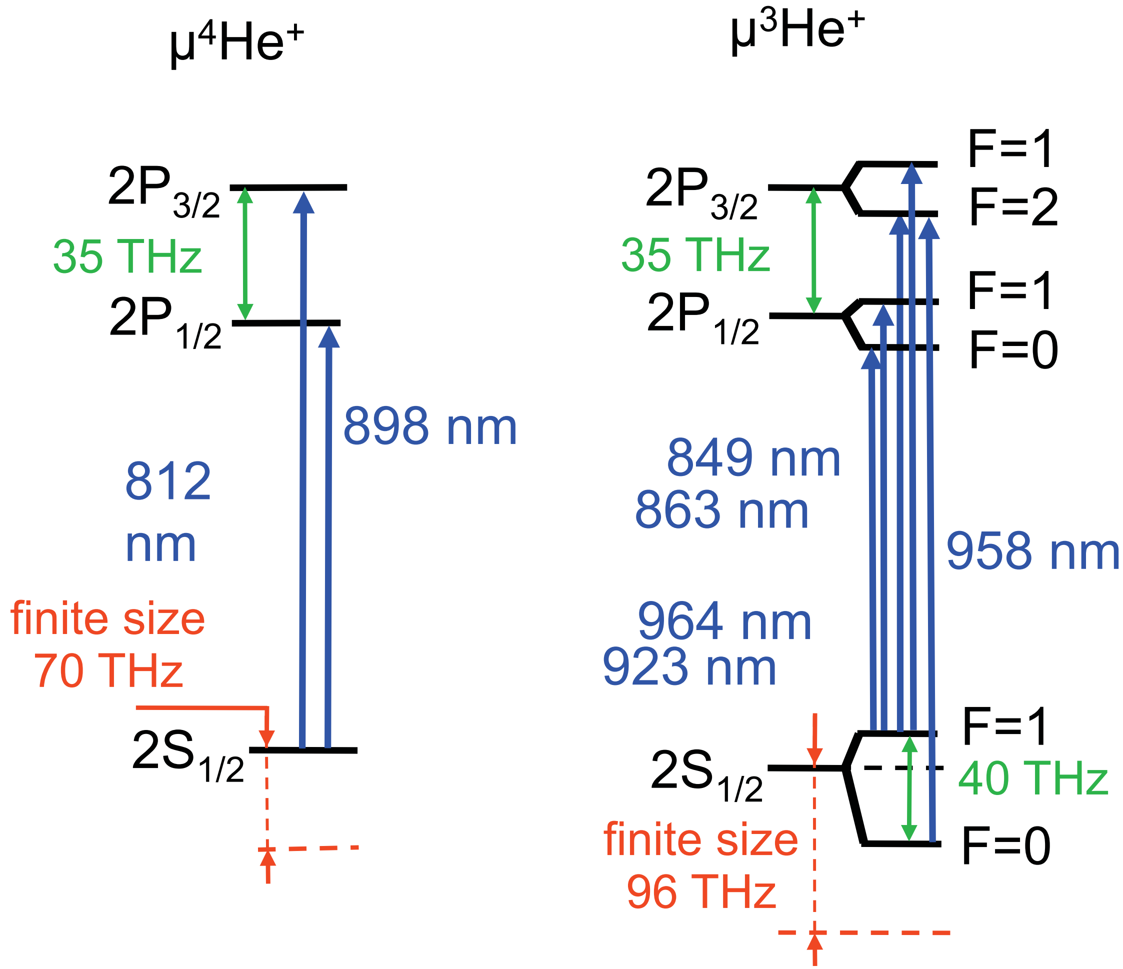
812 nm
p_{He} = 40 bars



Nuclear Physics A278 (1977) p. 381

but signal never reproduced (10 bars, 40 bars)

2011-2013→ muonic helium spectroscopy (4 mbar)



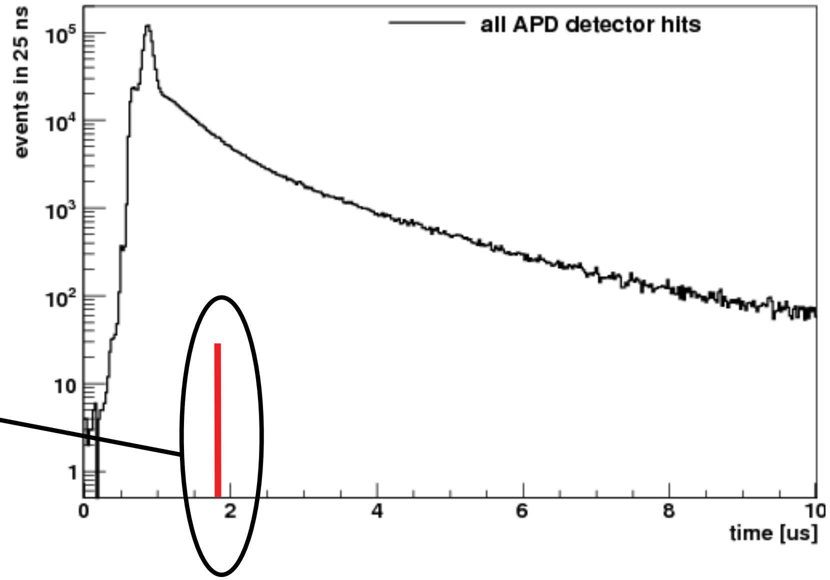
- μHe^+ spectroscopy + He^+ spectroscopy → QED test ($Z\alpha$)
- improve He spectroscopy

X-rays analysis → event gate sorting → noise rejection

Example : FP 900 - 11 hrs meas.

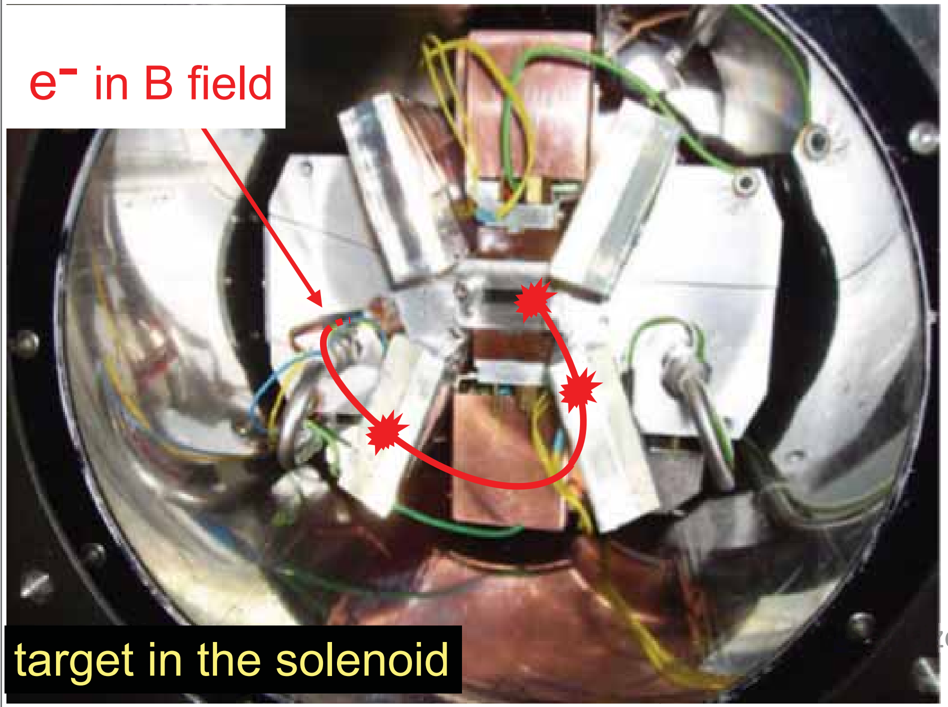
1.56 million detector events

expected 2-3 laser induced events/hour !



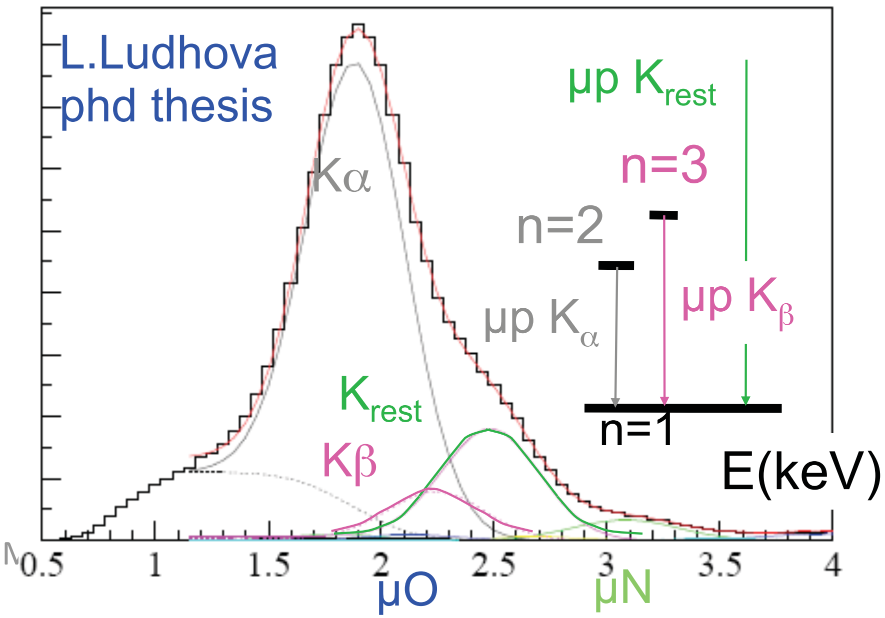
time signature in LAAPD

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



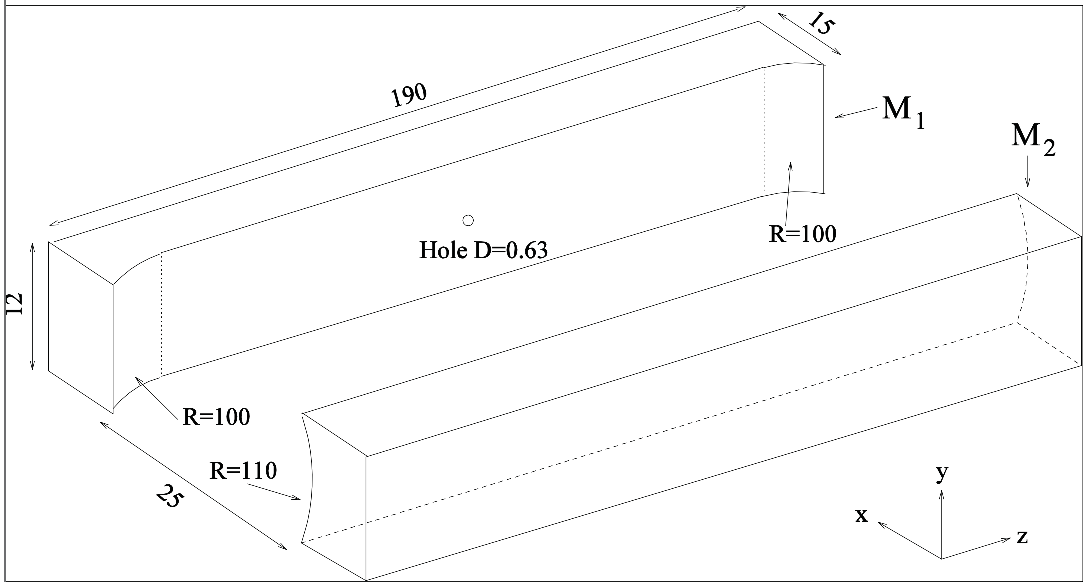
energy signature in LAAPD

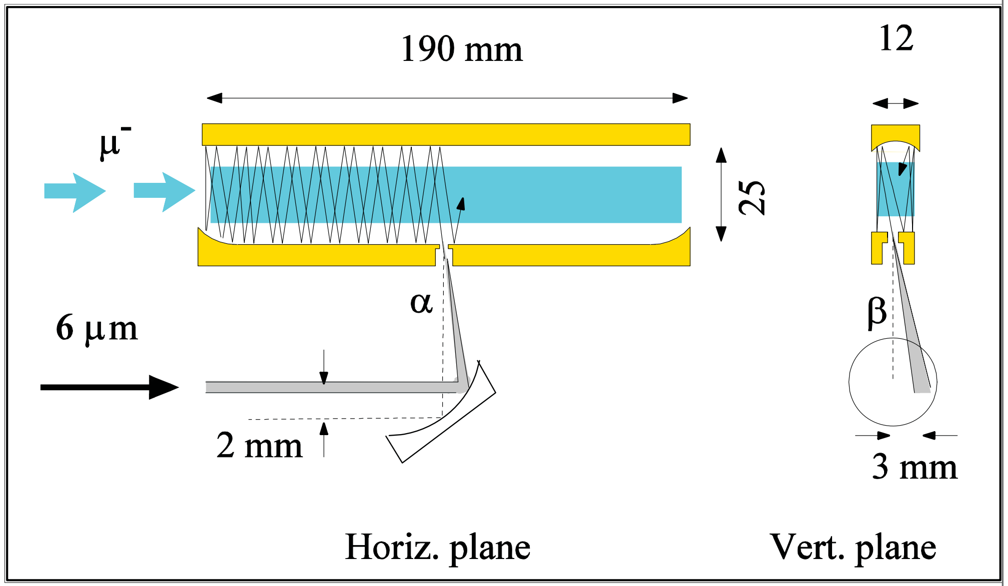
- E > 8keV ⇔ electron
- 1keV < E < 8keV ⇔ X ray
- E<1keV ⇔ neutron



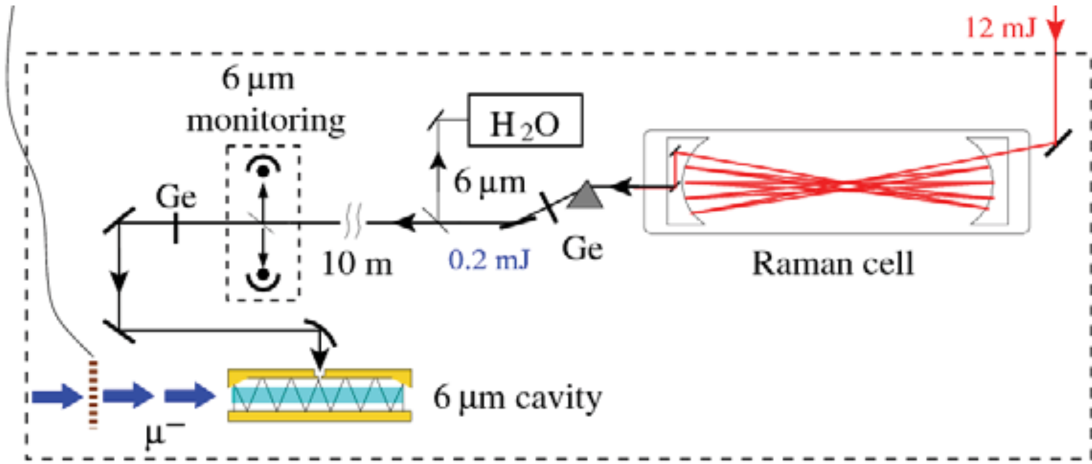
Laser chain : multipass cavity

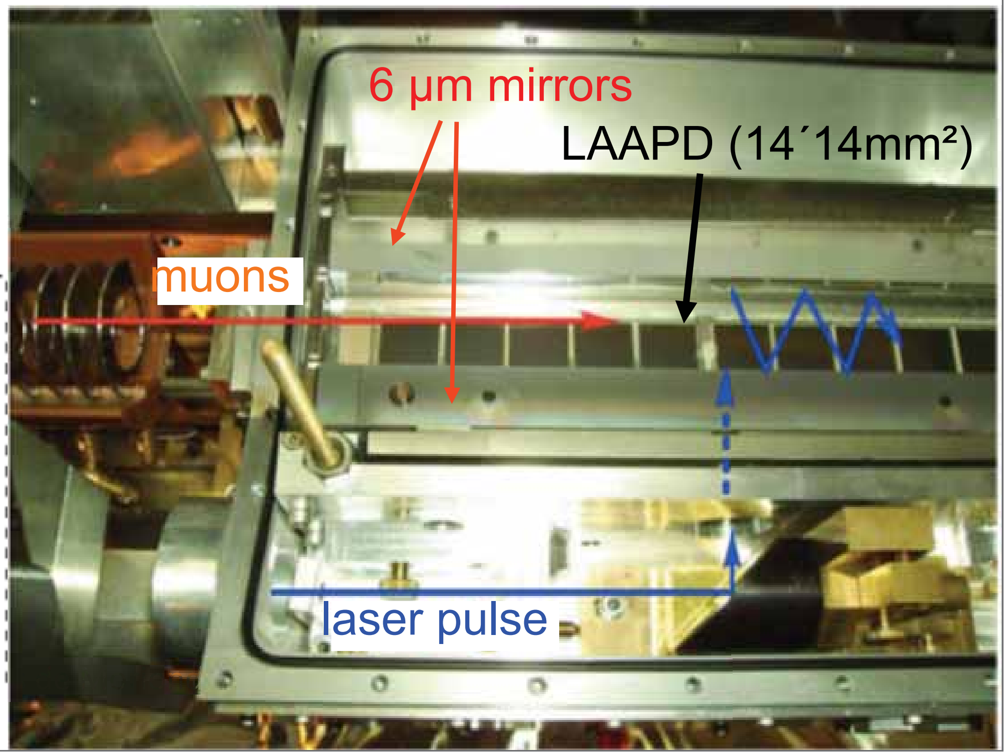
→ illuminate at 6 μm all the muon stopping volume (5´15´190 mm^3)



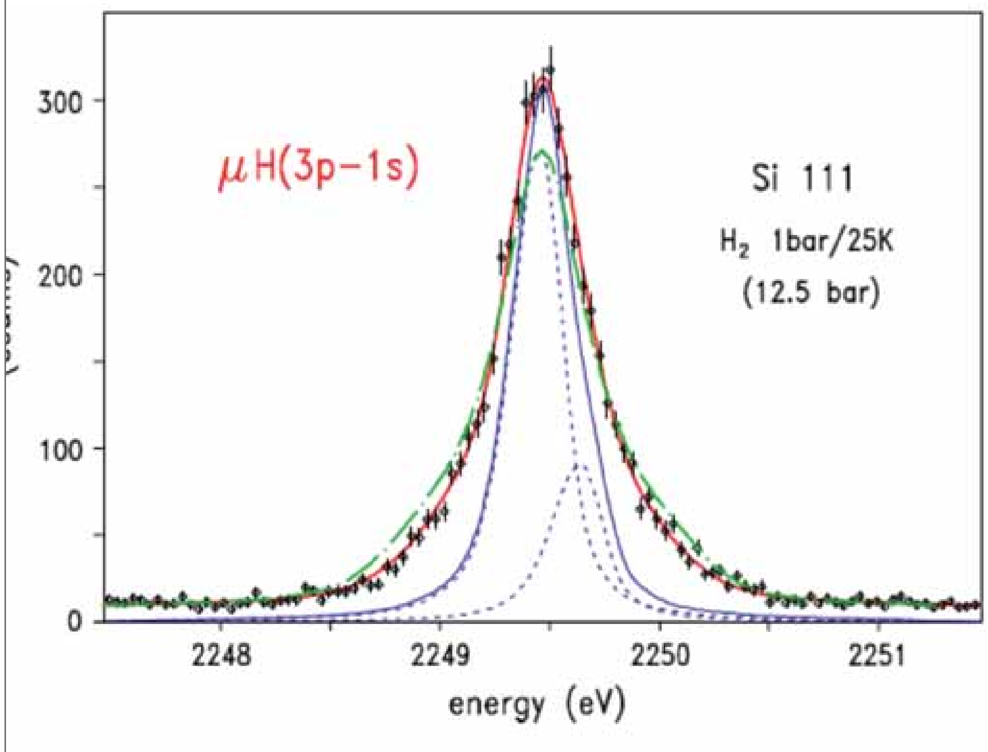


- coupling through a 0.63mm diameter hole
- R=99.90% at 6 μm
- 1000 reflections
- 0.15mJ injected → 2S-2P saturated

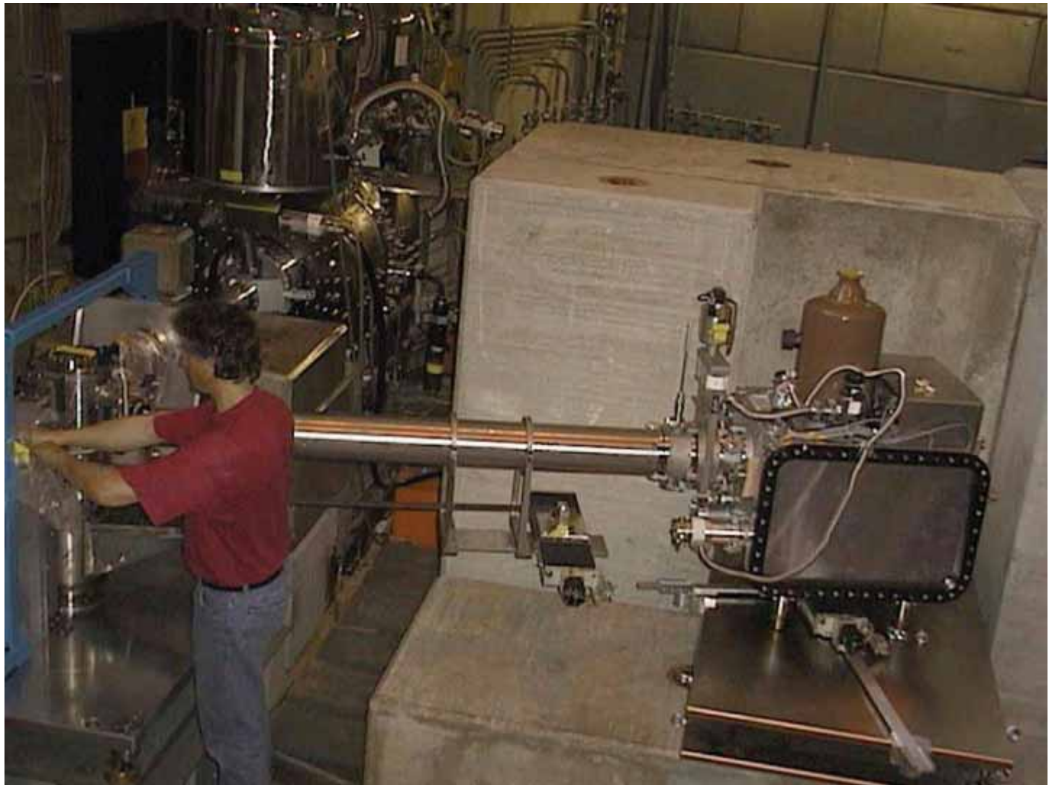




Muonic Hydrogens X-ray spectroscopy



Line Shape of the mu H(3p-1s) Hyperfine Transitions, D.S. Covita, D.F. Anagnostopoulos, H. Gorke, D. Gotta, A. Gruber, A. Hirtl, T. Ishiwatari, P. Indelicato, E.-O.L. Bigot, M. Nekipelov, J.M.F.d. Santos, P. Schmid, L.M. Simons, M. Trassinelli, J.F.C.A. Veloso and J. Zmeskal. Phys. Rev. Lett. 102, 023401 (2009).



Summary of radii

Ref.	proton charge radius (fm)		
Hand et al. [1]	0.805	±	0.011
Simon et a/ [2]	0.862	±	0.012
Mergel et al. [11]	0.847	±	0.008
Rosenfelder [12]	0.880	±	0.015
Sick 2003 [13]	0.895	±	0.018
Angeli [14]	0.8791	±	0.0088
Kelly [15]	0.863	±	0.004
Hammer et al. [16]	0.848		
CODATA 06 [10]	0.8768	±	0.0069
Arington et al. [17]	0.850		
Belushkin et al. [18] SC approach	0.844	$^{-0.004}_{+0.008}$	
Belushkin et al. [18]pQCD app.	0.830	$^{-0.008}_{+0.005}$	
Wang (ChPt, 2009) [19]	0.828		
Pohl et al. [20]	0.84184	±	0.00067
Bernauer et al (2010)	0.879	±	0.008

Table 1. Proton charge radii. For the result corresponding to Ref. [17] see the analysis in Sec.2.1

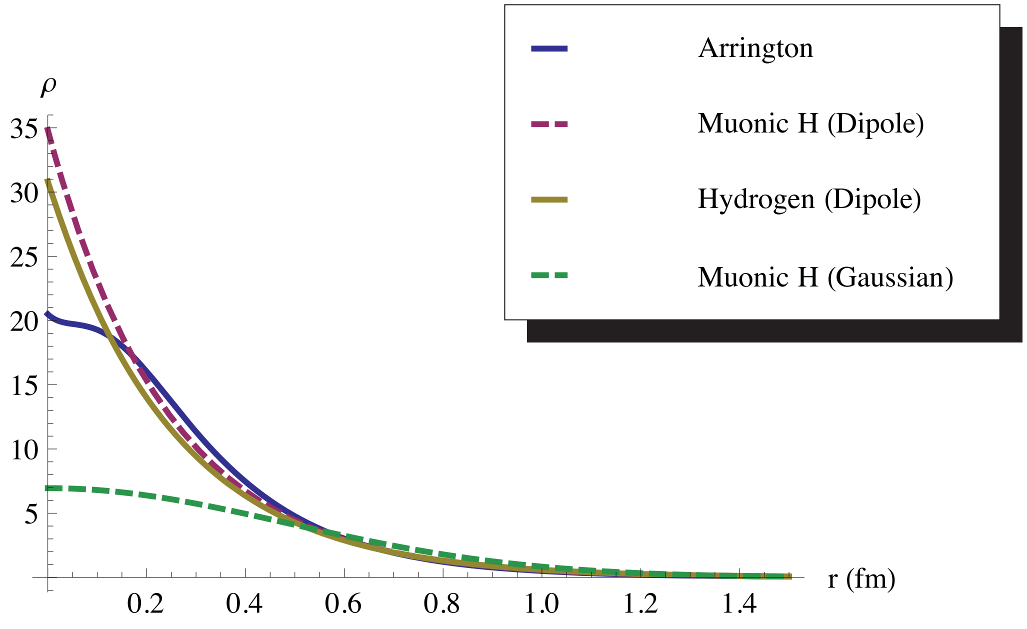
Analyse fondée sur des modèles physiques

	SC approach	Explicit pQCD app.	Ref. [23]	Recent determ.
r_E^p (fm)	0.844 (0.840 ... 0.852)	0.830 (0.822 ... 0.835)	0.848	0.886(15) [72–74]
r_M^p (fm)	0.854 (0.849 ... 0.859)	0.850 (0.843 ... 0.852)	0.857	0.855(35) [73,75]
$(r_E^n)^2$ (fm^2)	−0.117 (−0.11 ... −0.128)	−0.119 (−0.108 ... − 0.13)	−0.12	−0.115(4) [52]
r_M^n (fm)	0.862 (0.854 ... 0.871)	0.863 (0.859 ... 0.871)	0.879	0.873(11) [76]

Resonance	Mass (GeV)	a_1 (GeV^2)	a_2 (GeV^2)	Γ (GeV)
ω	0.782	0.755960	0.370592	–
ϕ	1.019	−0.776537	−2.913229	–
s_1	1.124860	0.902379	2.484859	–
s_2	2.019536	0.022798	−0.130622	5.158635
v_1	1.062128	−0.127290	−2.162533	–
v_2	1.300946	−1.243412	3.704233	–
v_3	1.493630	4.191380	−7.091021	–
v_4	1.668522	−3.176013	3.723858	–
v_5	2.915451	0.048987	0.075965	19.088297

Dispersion analysis of the nucleon form factors including meson continua, M.A. Belushkin, H.W. Hammer and U.-G. Meißner. Phys. Rev. C **75,** 035202 (2007).

Comparison of charge densities



[1] QED is not endangered by the proton's size, A. De Rújula. Physics Letters B 693, 555-558 (2010).

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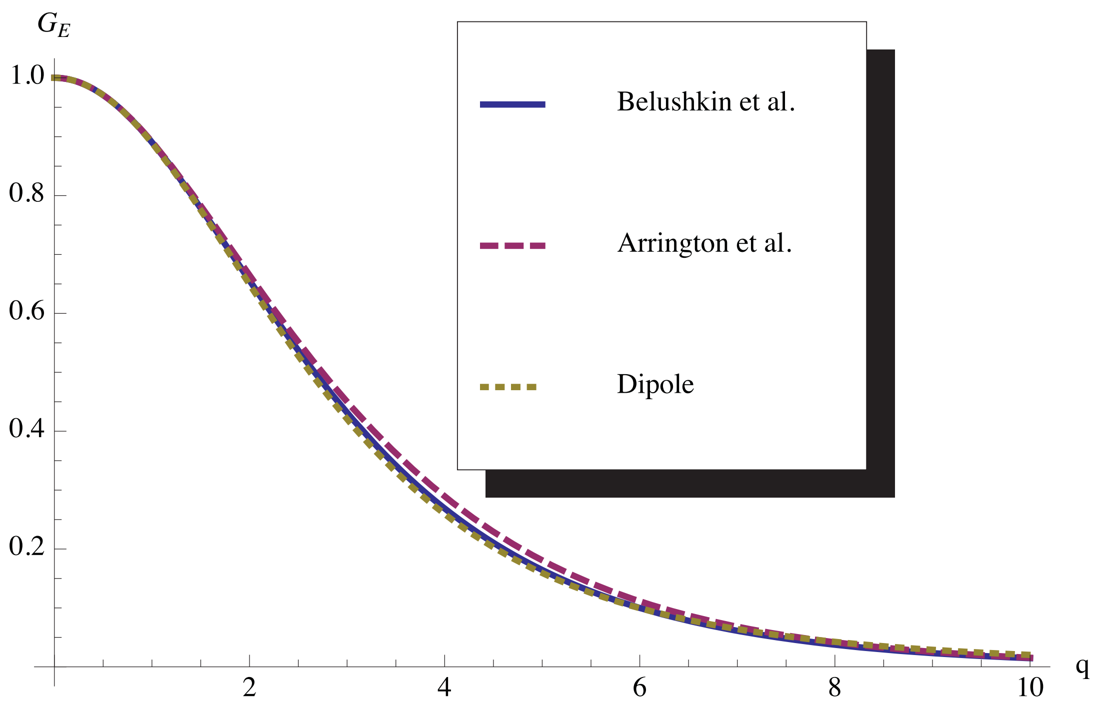

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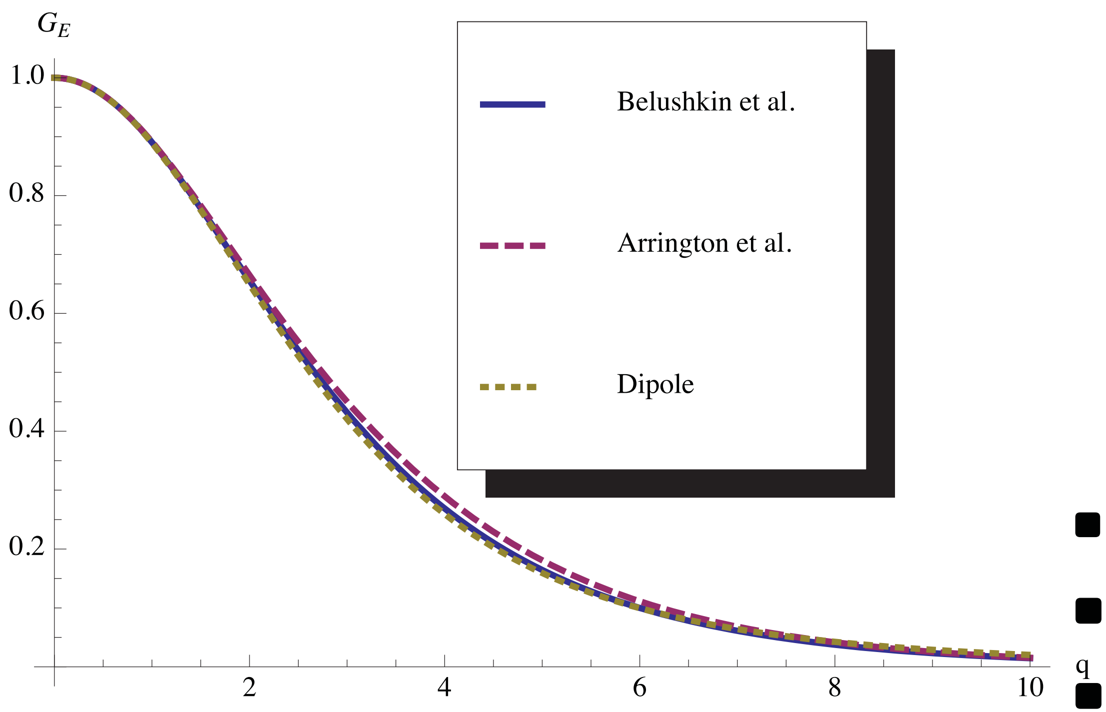


- $\langle r^3 \rangle_{(2)} = 3.789 \ \langle r^2 \rangle^{3/2}$ Dipole
- $\langle r^3 \rangle_{(2)} = 1.960 \ \langle r^2 \rangle^{3/2}$ Gauss
- $\langle r^3 \rangle_{(2)} = 3.983 \ \langle r^2 \rangle^{3/2}$ Arrington et al.

- $\langle r^3 \rangle_{(2)} = 36.6 \pm 7.3 = 43 \ \langle r^2 \rangle^{3/2}$ De Rùjula ?!

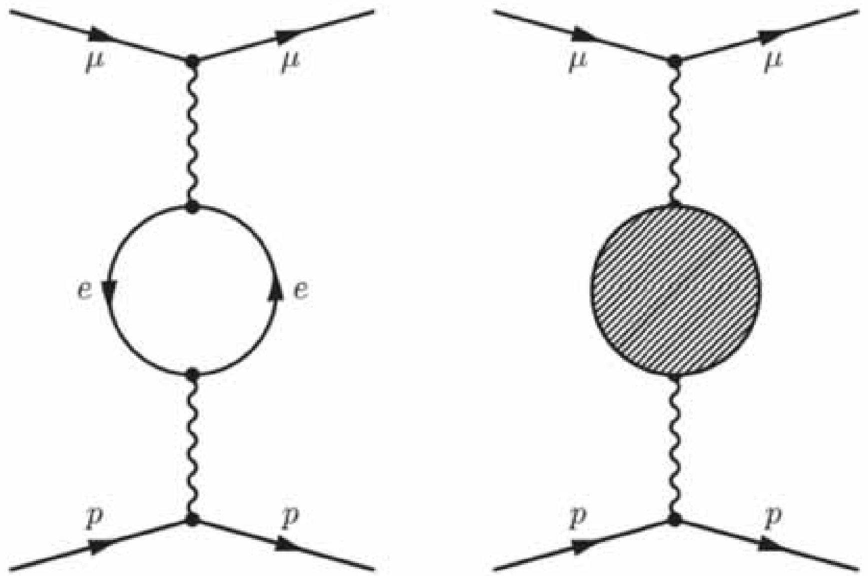
[1] QED is not endangered by the proton's size, A. De Rújula. Physics Letters B 693, 555-558 (2010).

Particules millichargées

- Extensions de type Stuekelberg du Modèle Standard, compatible avec les données du LEP [1]
- Charge εe $\varepsilon \ll 1$, candidats pour la matière noire
- Si dans la gamme de masse $m_e \leq m_M \leq m_\mu$ (sensibilité maximale) on prend la particule milichargée (la charge s'élimine) qui assure l'accord hydrogène-hydrogène muonique, alors on a un g-2 dans le muon qui est à 85 écarts standards de l'expérience [2]
- Si on prend $\varepsilon=0.0179$ et $m_M=0.221\ m_e$ on a un bon accord, mais dans ce cas la constante de structure fine

[1] D. Feldman, Z. Liu, and P. Nath, Physical Review D **75**, 115001 (2007).
[2] U. D. Jentschura, Annals of Physics **326**, 516 (2011).
[3] J. Jaeckel and S. Roy, Physical Review D **82**, 125020 (2010).

Bosons de jauge instables



$$\delta\rho(t) = \frac{1}{30}\Theta(t - 20m_e^2)\Theta(24m_e^2 - t).$$

- $m_e \leq m_V \leq m_\mu$ avec le choix précédent de ρ, on réduit à 2.5σ la différence sur l'hydrogène muonique et sur le moment magnétique anormal du muon
- Le moment magnétique anormal de l'électron ne change pas
- Mais le rayon du proton dans l'hydrogène bouge à 0.904

U. D. Jentschura, Annals of Physics **326**, 516 (2011).

Photons du «secteur caché»

- Tests de la loi de Coulomb à courtes distances pour des «photon cachés» supplémentaires de masse $m_{\gamma'}$
- Tests ~ke r l'hydrogène muonique

$$V(r) = -\frac{Z\alpha}{r}(1 + e^{-m_{\gamma'} r}\chi^2),$$

$$\Delta r_p^2 = -6\chi^2 \frac{a_o^4 m_{\gamma'}^2}{(1 + a_o m_{\gamma'})^4},$$

- Mais l'effet croît avec a_0 et donc est plus grand pour H que

J. Jaeckel and S. Roy, Physical Review D **82**, 125020 (2010)