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## Du micromètre à l'attomètre : une détermination optique de la taille du proton

François Nez

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# Du micromètre à l'attomètre : une détermination optique de la taille du proton

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



<http://muhy.web.psi.ch>

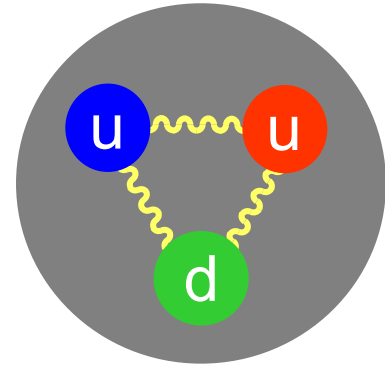
<http://www.lkb.ens.fr/-Metrologie-Quantique->



# Proton

## Structure

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



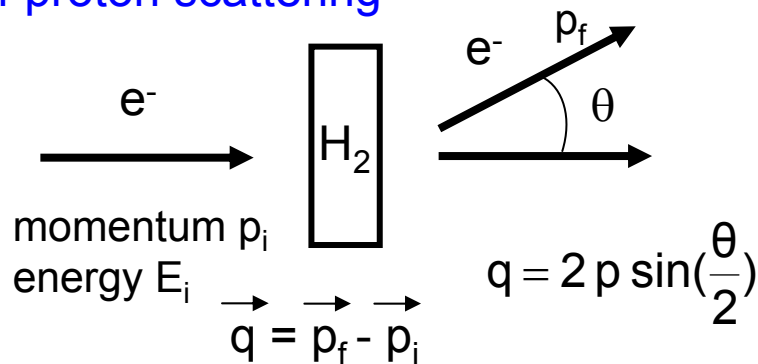
“proton size”  $\lambda_c = \frac{h}{m_p c} \approx 1.3 \text{ fm}$

Proton charge radius :  $r_p \sim 0.8 \text{ fm}$

$$r_p = \sqrt{\langle r^2 \rangle} \quad \langle r^2 \rangle = \frac{\int r^2 \rho(r) d^3r}{\int \rho(r) d^3r}$$

$\rho(r)$  : proton charge distribution

## Electron-proton scattering

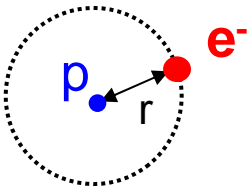


$$\frac{d\sigma}{d\Omega}(E_i, \theta) \approx \underbrace{\left[ \frac{d\sigma}{d\Omega}(E_i, \theta) \right]}_{\text{Rutherford}} G(q^2)$$

$$G(q^2) = \int d^3r e^{iqr} \frac{\rho(r)}{4\pi} \approx 1 - \frac{r_p^2}{6} q^2$$

$r_p$  deduced from extrapolation  $q \rightarrow 0$  with  $\rho(r)$  unknown...

# hydrogen spectroscopy

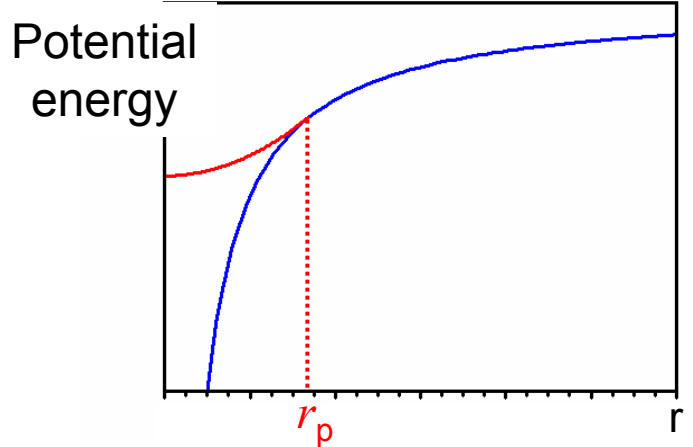


$$E(n,l,j) = \text{Dirac} + \text{recoil} + L(n,j)$$

$$hcR_\infty f(\alpha, m_e/m_p, n,l,j)$$

exact

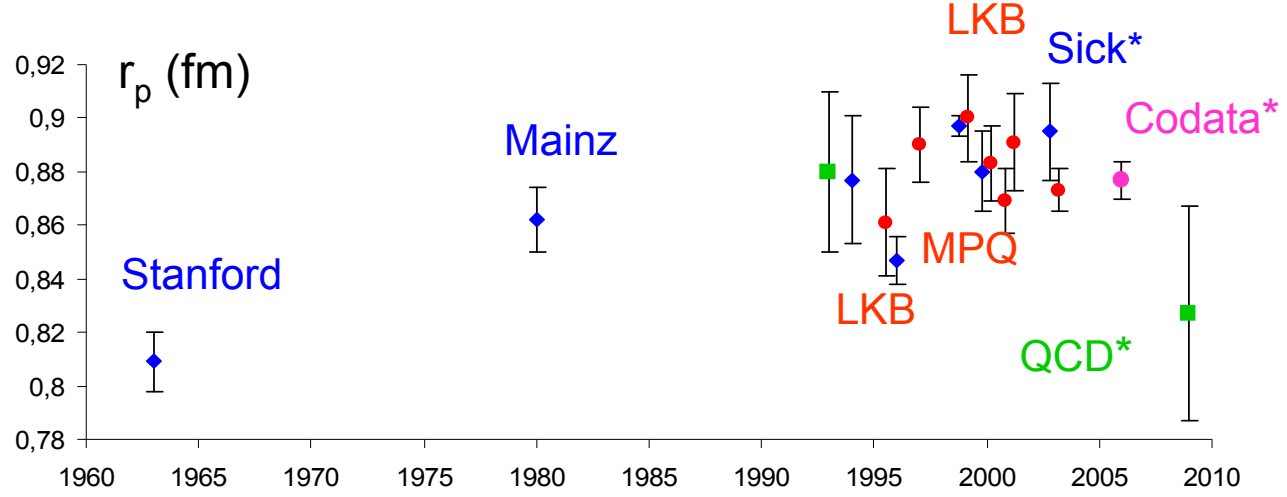
- QED corrections ( $1/n^3$ ) not well known
- relativistic recoil
- charge radius of the proton ( $1/n^3$ )



$$f_{1S-2S} = 2\,466\,061\,413\,187\,035 (10) \text{ Hz}$$

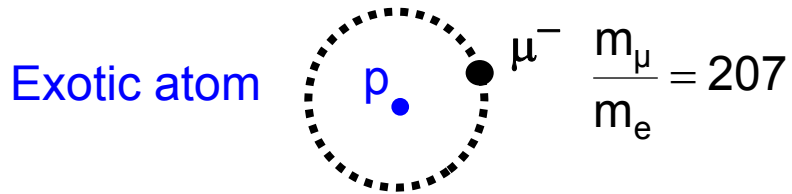
PRL 107 203001 (2011)

## Previous determinations of the "proton radius"



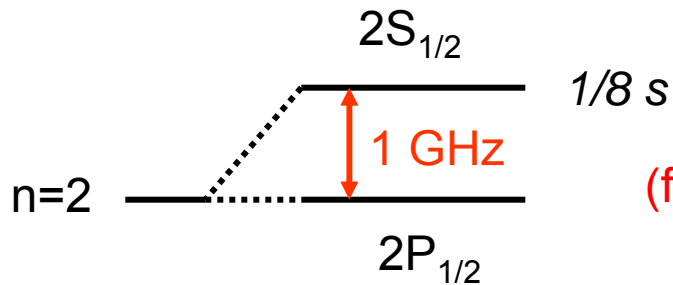
\* Hydrogen data(1S-2S and 2S-nS/nD) + QED re-evaluation : 0,8760 (78) fm  
 \* Electron scattering (all meas+re-analysis): 0,895 (18) fm  $f_{1S-2S} = 2\,466\,061\,413\,235\,502$  Hz  
 \* QCD (lattice cal.) : 0,827 (40) fm

# Muonic hydrogen spectroscopy



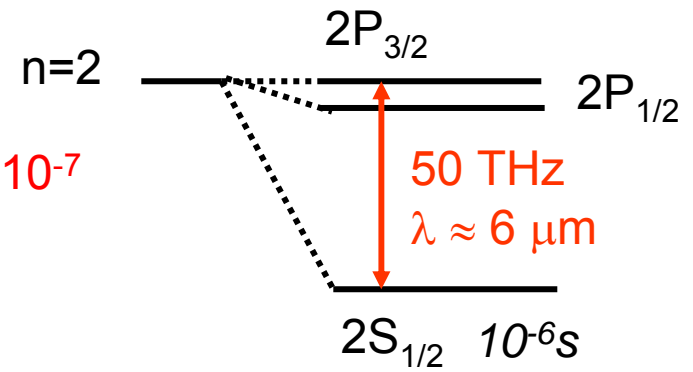
radius :  $\sim a_0/200$

electronic hydrogen : e-p



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

muonic hydrogen :  $\mu$ -p



Relative contribution  
due to  $r_p$  to 2S-2P

$$1.4 \times 10^{-4}$$

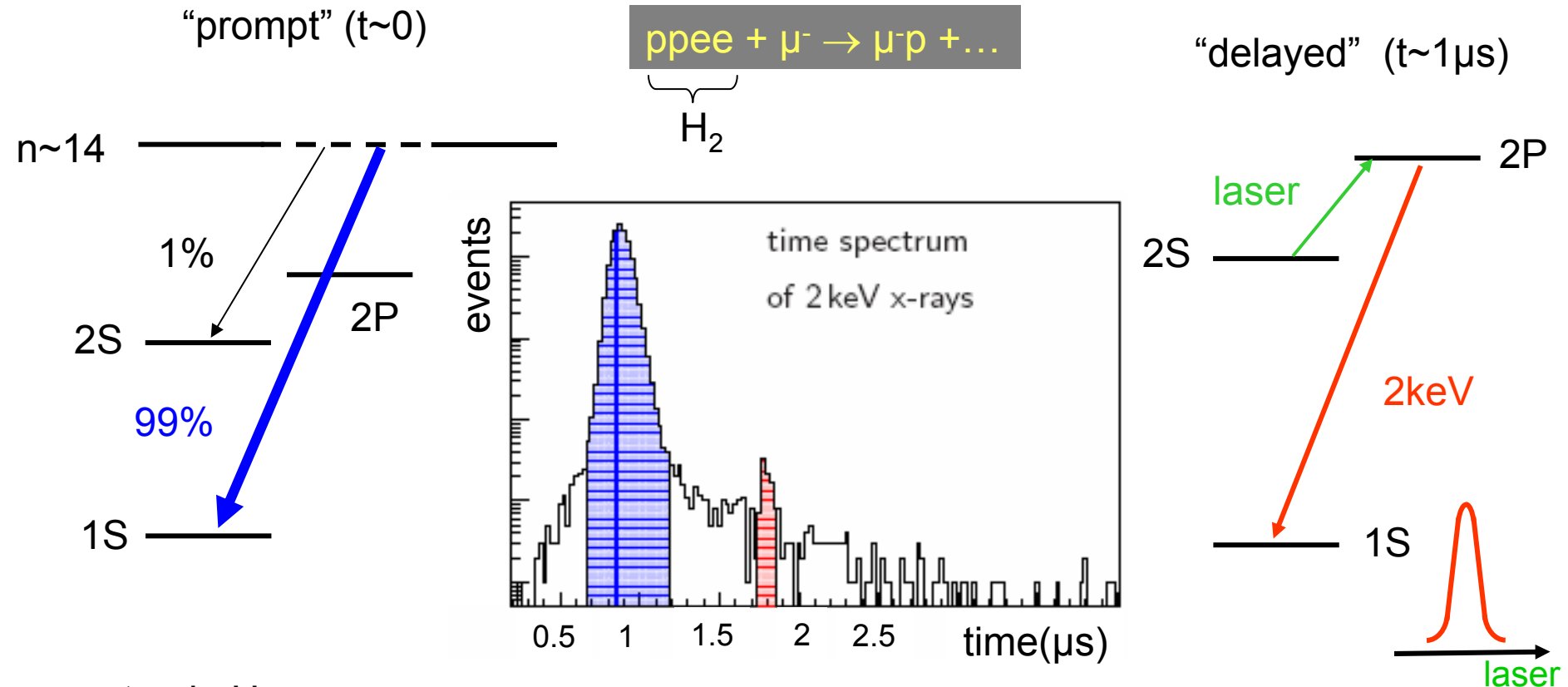
$$2 \times 10^{-2}$$

Predicted frequency of muonic hydrogen 2S-2P transition (2002)

$$\Delta E_{2S-2P} = 50.7702(12) - 1.2634 r_p^2 - 0.0084 r_p^3 = 49.8063 (149) \text{ THz}$$

$$\text{with } r_p = 0.8760(68) \text{ fm}$$

# Principle of the experiment



$\mu^-$  stop in  $\text{H}_2$  gas  
 $\Rightarrow \mu\text{p}^*$  atoms formed ( $n \sim 14$ )

99%: cascade to 1S emitting prompt  $\text{K}\alpha, \text{K}\beta, \dots$

1%: long lived 2S state ( $\tau \sim 1 \mu\text{s}$  at 1mbar)

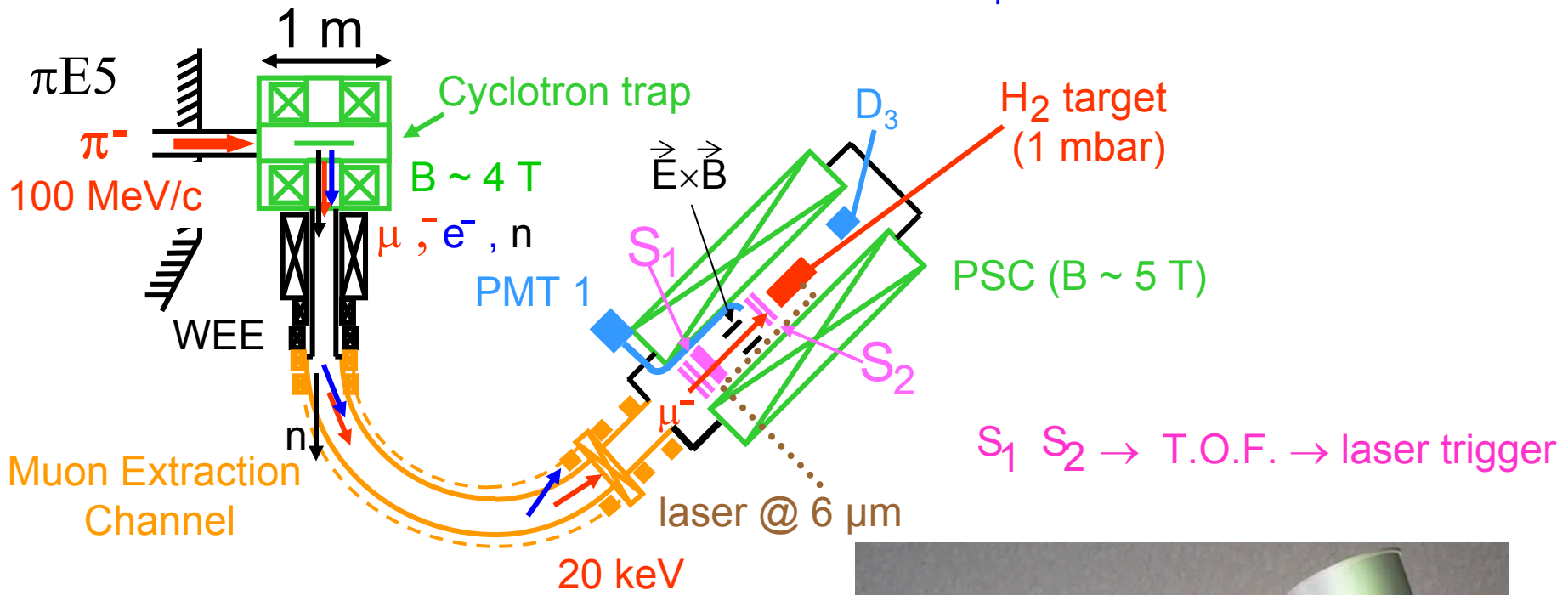
Fire laser ( $\lambda \sim 6 \mu\text{m}$ ,  $\Delta E \sim 0.2 \text{ eV}$ )  
 $\Rightarrow$  induce  $\mu\text{p}(2\text{S}-2\text{P})$

$\Rightarrow$  observe **delayed  $\text{K}\alpha$  x-rays**

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

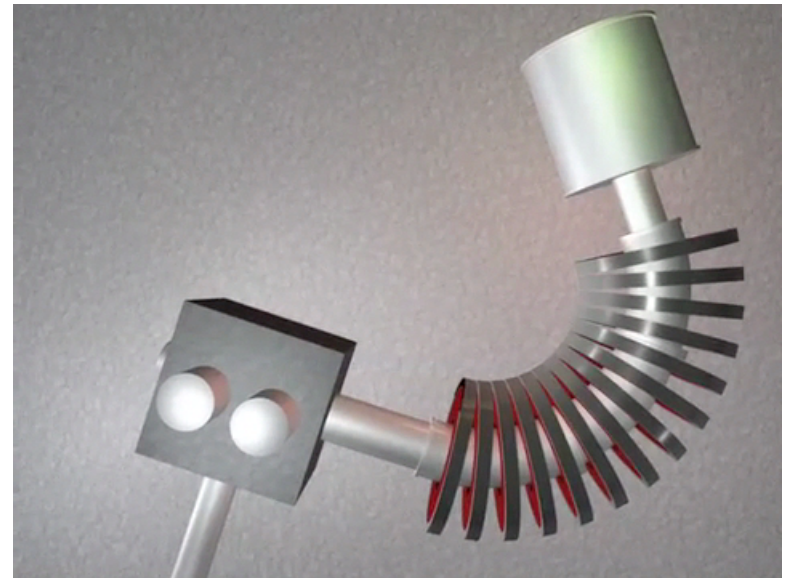
# Muonic hydrogen source

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



## muon life in CREMA experiment

- pion  $\pi^-$
- muon  $\mu^-$
- photon from scintillator



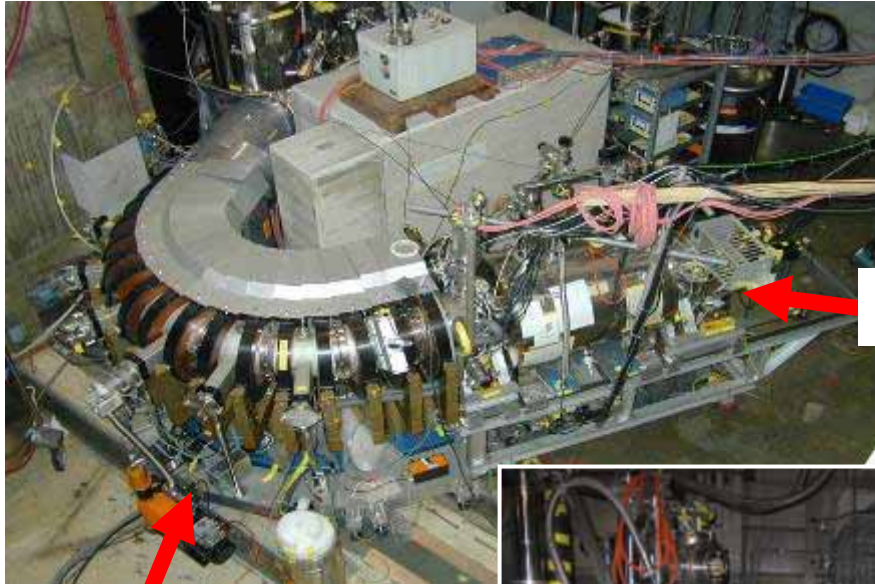
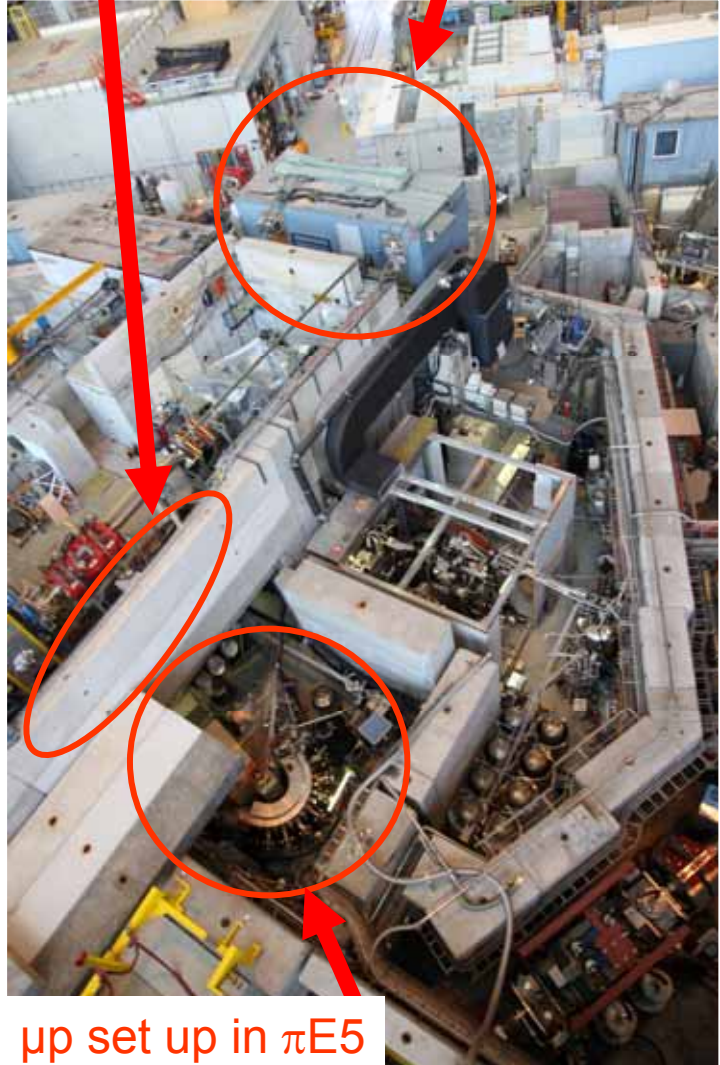


# muon beam apparatus



laser hut  
below  
concrete blocks

counting room

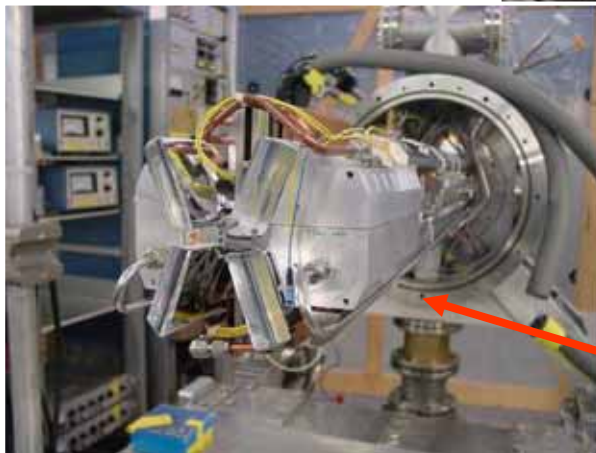


PSC solenoid,

Muon extraction  
channel



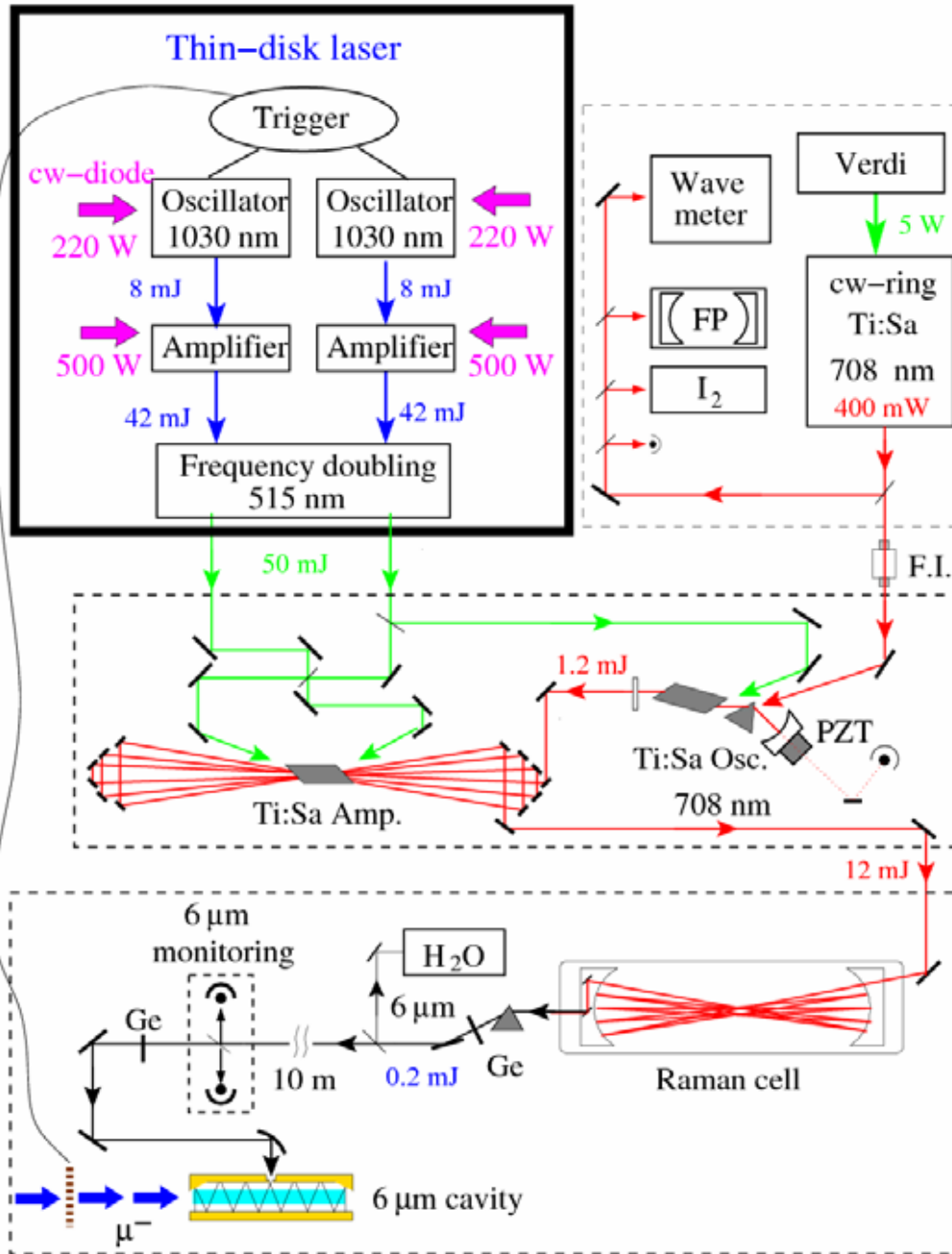
H2 target, laser cavity,  
detectors



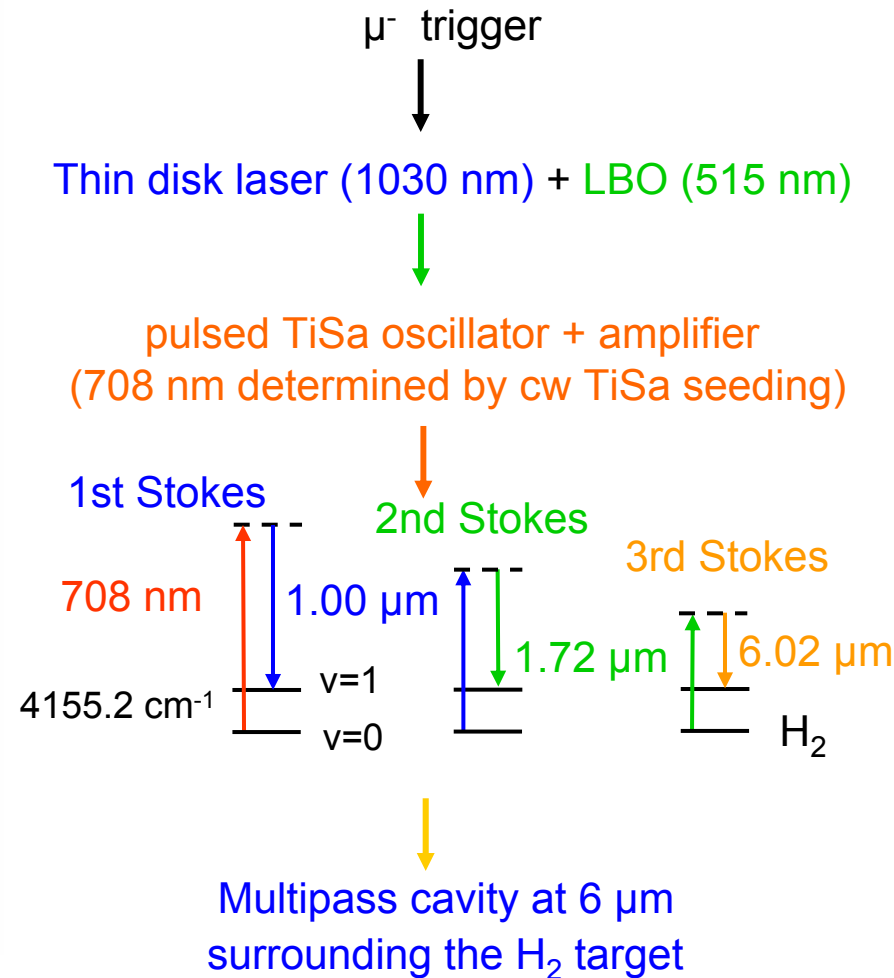
$\mu p$  set up in  $\pi E5$



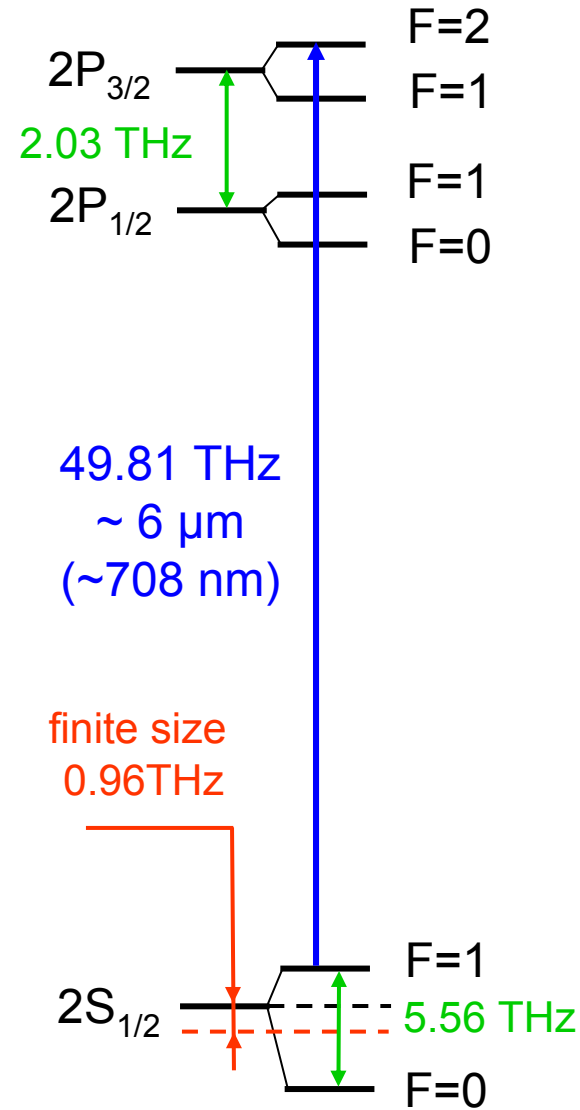
# Laser chain



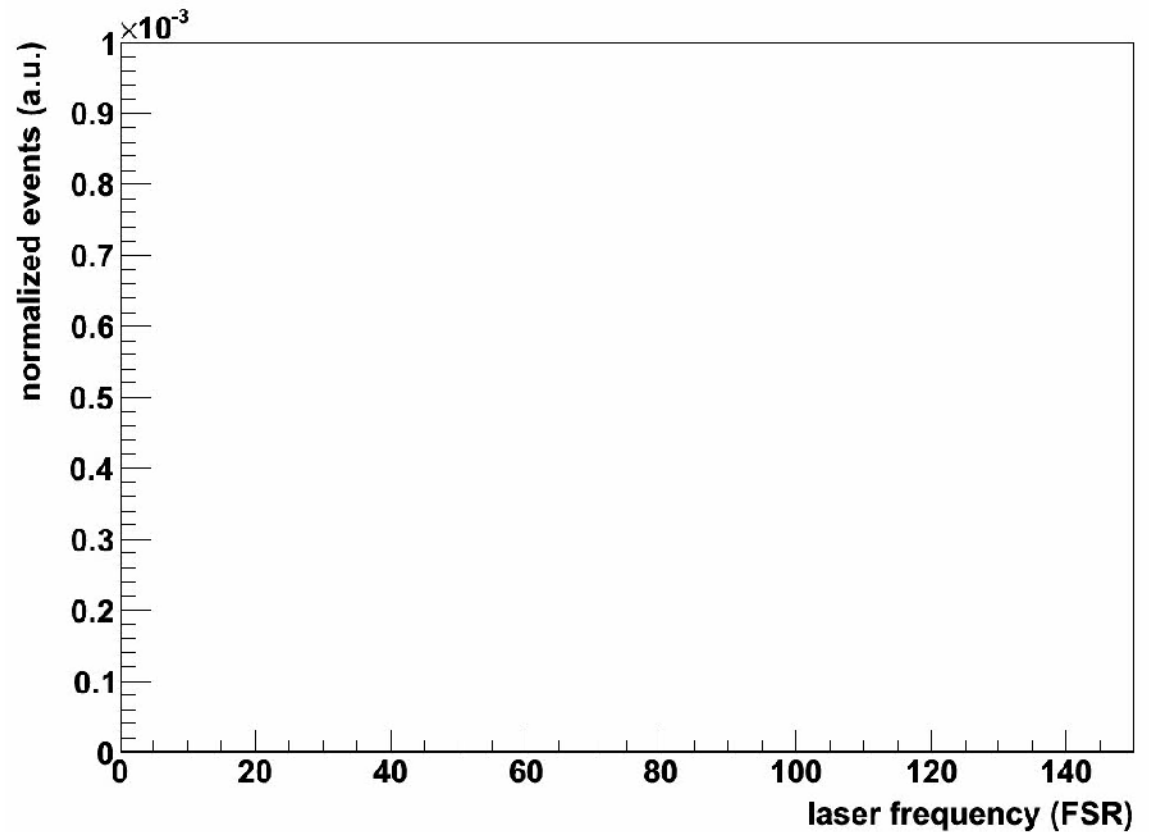
- Each single muon triggers the laser system (random trigger)
- 2S lifetime  $\sim 1 \mu\text{s}$   $\rightarrow$  **short laser delay (disk laser)**
- **6  $\mu\text{m}$  tunable** laser pulse (0.2 mJ)



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



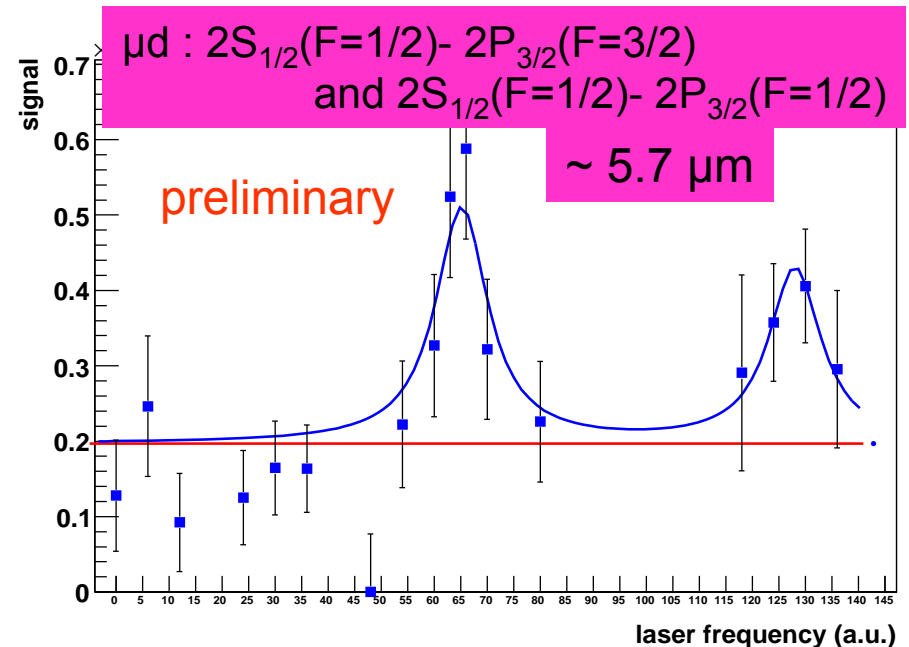
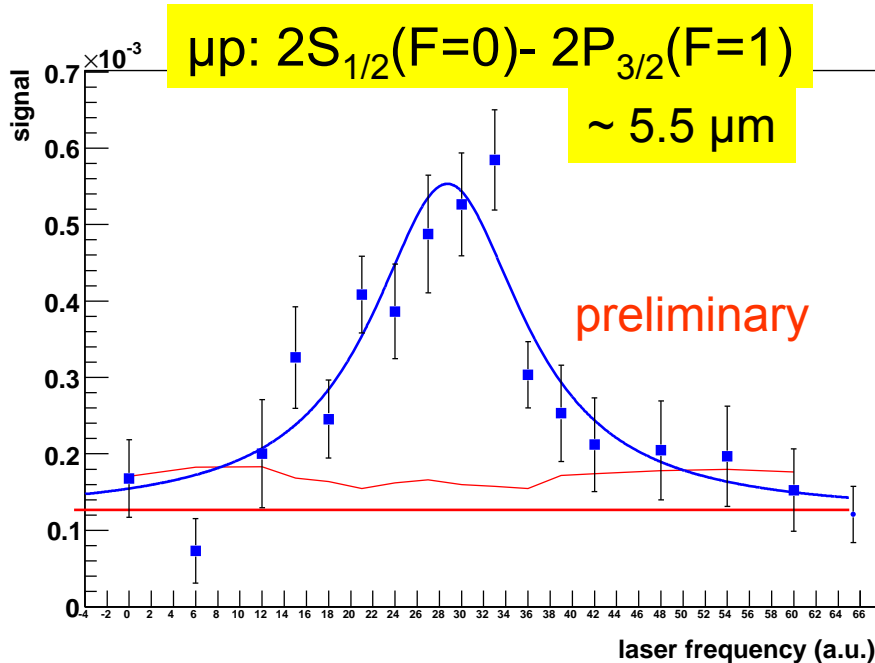
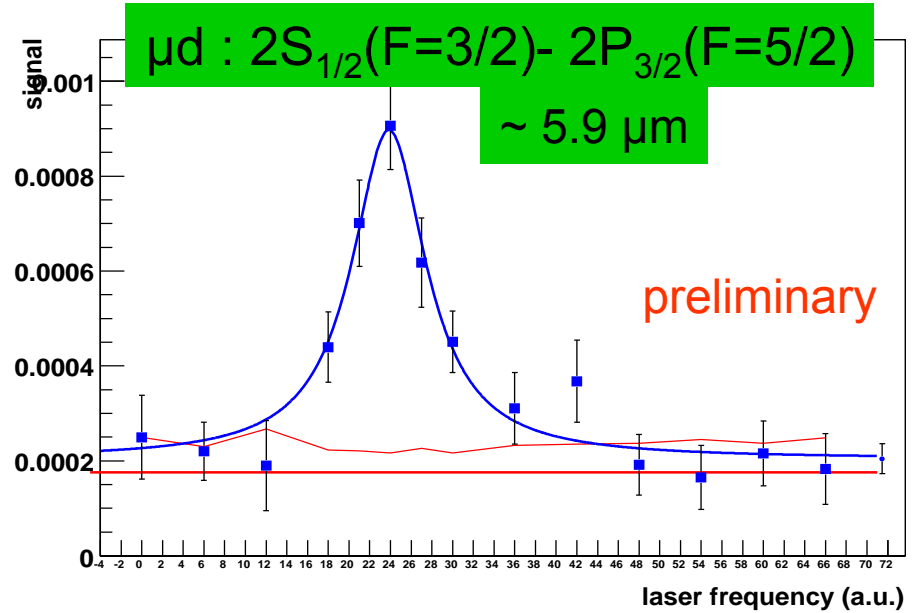
- 550 events measured
- 155 backgrounds
- 31 FP fringes
- 250 hours



→ proton charge radius ( $\sim 0.1\%$ )

# Other lines observed in $\mu p$ and $\mu d$ atoms

- **2<sup>nd</sup>  $\mu p$  line** : at the correct position  
hfs  $\rightarrow$  **Zeemach radius**
- **$\mu d$**  : not at the correct position with  
new rp and isotope shift  $\rightarrow$  **deuteron polarizability**
- **2<sup>nd</sup>  $\mu d$  line** : observation  $\rightarrow$  **check calculation**



# Comparison with other best determinations

$$\nu (\mu p : 2S_{1/2}(F=1) - 2P_{3/2}(F=2)) = 49\,881.88 \text{ (76) GHz}$$

$$\nu_{\text{theo}} = 50772.43 \text{ (118)} - 1263.69 r_p^2 + 8.39 r_p^3 \text{ GHz}$$

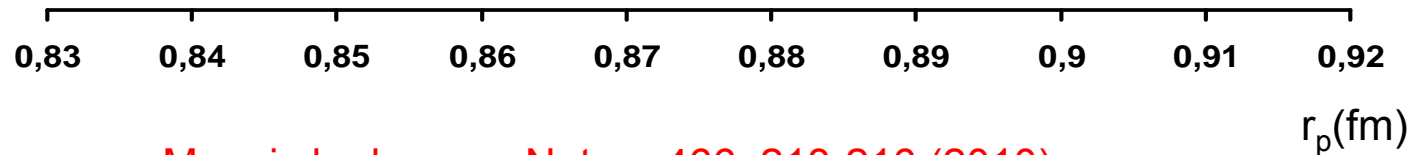
$$r_p = 0.84184 \text{ (36)(56) fm}$$

H/D spectroscopy + QED ● 0.8760 (78) fm

$\mu p (2S_{1/2} - 2P_{3/2}) + \text{QED}$  ● 0.84184 (68) fm

New electron-proton scattering ● 0.879 (8) fm

electron-proton scattering re-analysis ● 0,895 (18) fm



Muonic hydrogen : Nature 466, 213-216 (2010)

New elec-prot scattering : Phys Rev Lett 105, 242001 (2010)

$$f_{1S-2S} = 2\,466\,061\,413\,187\,035 \text{ (10) Hz} \quad \text{PRL 107 203001 (2011)}$$

$$f_{1S-2S} = 2\,466\,061\,413\,109\,090 \text{ Hz}$$



## New $r_p$ ( $\mu p$ ( $2S_{1/2}(F=1) - 2P_{3/2}(F=2)$ )) : outcomes

Muonic hydrogen Lamb shift theory ? checked

Hydrogen spectroscopy, Rydberg constant  $R_\infty$  ?

Codata 2006 “The experimental and theoretical H and D data remain highly consistent.”

First measurement of  $1S-3S$  (LKB) : 2 922 743 278 678(13) kHz. EPJ D **60** p.243 (2010)  
Prediction : 2 922 743 278 671.6(1.4) kHz PRL **95**, 163003 (2005)

“New physics” ?

“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.” PRL **106**, 153001 (2011)

Example of constrain : magnetic moment anomaly of the electron (Harvard)  $g-2 = f(\alpha/\pi)$

With recoil (LKB)  $v_r = \frac{\hbar k}{m(\text{Rb})}$   $\alpha^2 = \frac{2R_\infty}{c} \frac{m(\text{Rb})}{m_p} \frac{m_p}{m_e} \frac{h}{m(\text{Rb})}$  PRL **106**, 080801 (2011)

Polarizability of the proton ?

Model independent analysis of proton structure...: Phys Rev Lett 107, 160402 (2011)

$$\left. \begin{aligned} v(\mu p : 2S_{1/2}(F=1) - 2P_{3/2}(F=2)) &= 49\,881.88 \text{ (76) GHz} \\ v_{\text{theo}} &= 50772.43 \text{ (967)} - 1263.69 r_p^2 + 8.39 r_p^3 \text{ GHz} \end{aligned} \right\} r_p = 0.84184(36)(458) \text{ fm}$$

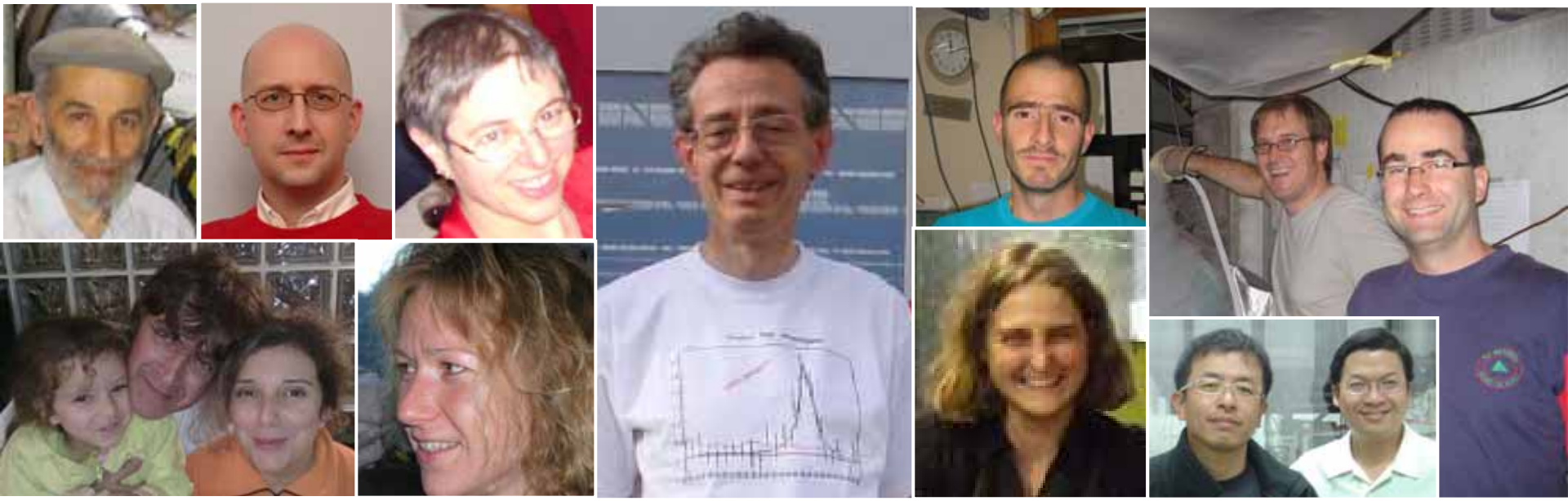
# Hydrogen spectroscopy, QED tests, ...

- Hydrogen Deuterium 2S-nS/nD spectroscopy at NPL,  
J.L. Flowers et al IEEE Trans. Instrum. Meas. 56, (2007) 331.
- $^{20}\text{Ne}^{9+}$  Rydberg states at NIST-Gaithersburg , U. D. Jentschura et al, PRL 100, 160404 (2008).
- Hydrogen 1S-2S at MPQ-Garching hydrogen cooled with magnetic field
- Hydrogen 1S-3S picosecond spectroscopy at MPQ-Garching E. Peters on going PhD
- Hydrogen 1S-3S cw-spectroscopy at LKB-Paris S.Galtier on going PhD
- $\text{He}^+$  spectroscopy femtosecond spectroscopy at MPQ-Garching  
M. Herrmann et al, PRA 79, 052505 2009.
- Muonic helium ( $\mu^4\text{He}^+$ ) spectroscopy at PSI-Villigen CREMA collaboration Proposal 2010.
- Electron-proton scattering MAMI/A1 collaboration at Mainz  
J. C. Bernauer et al., Can. J. Phys. 85, 419 (2007).
- QED test : a determination from recoil at LKB-Paris **Looking for PhD student**
- QED numerical calculation...
- QCD lattice calculation...





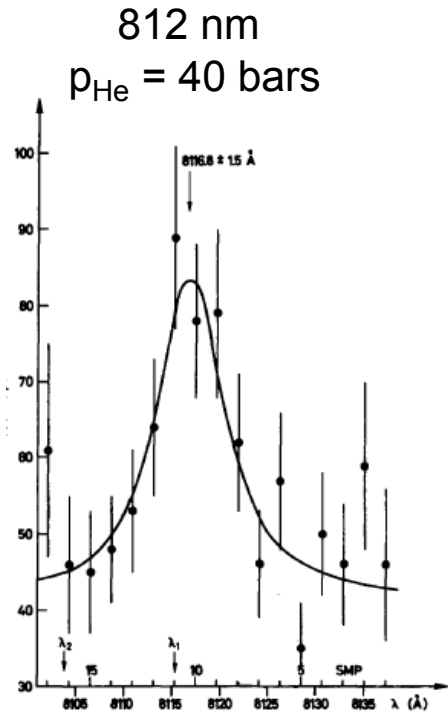
Proton Size Investigators thank you for your attention







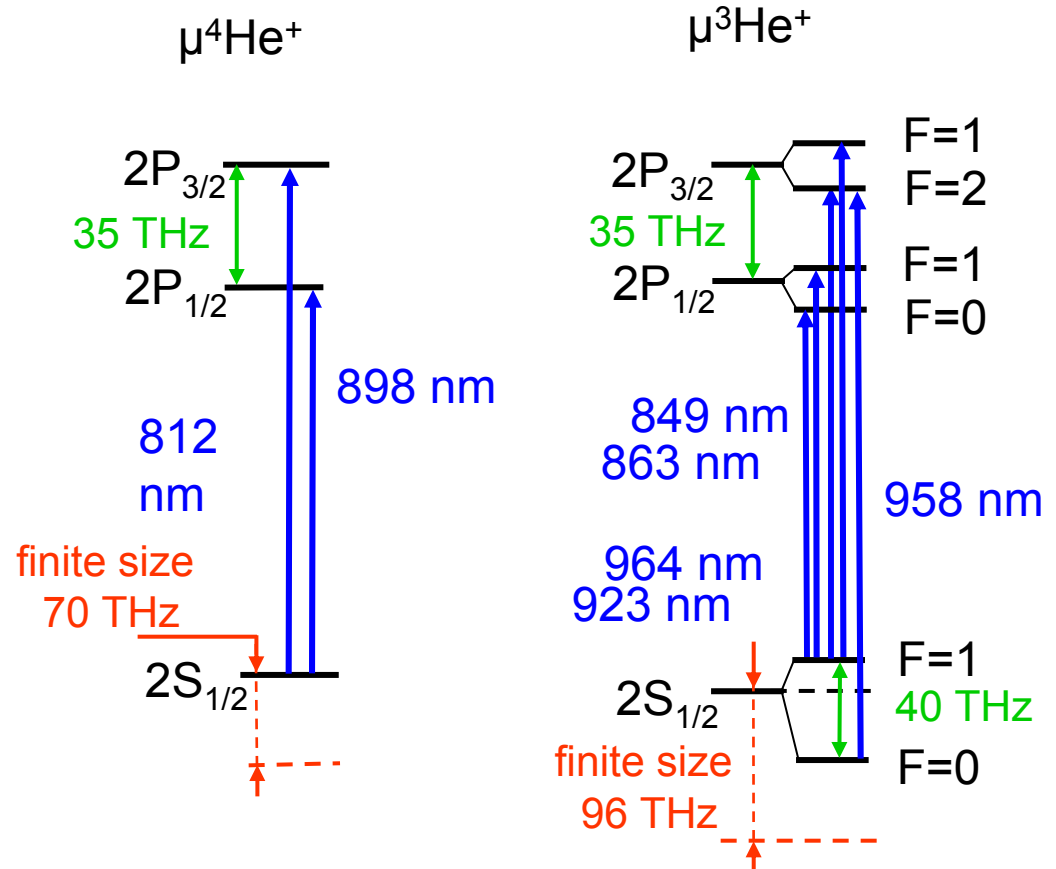
# Prospect : muonic helium spectroscopy at PSI



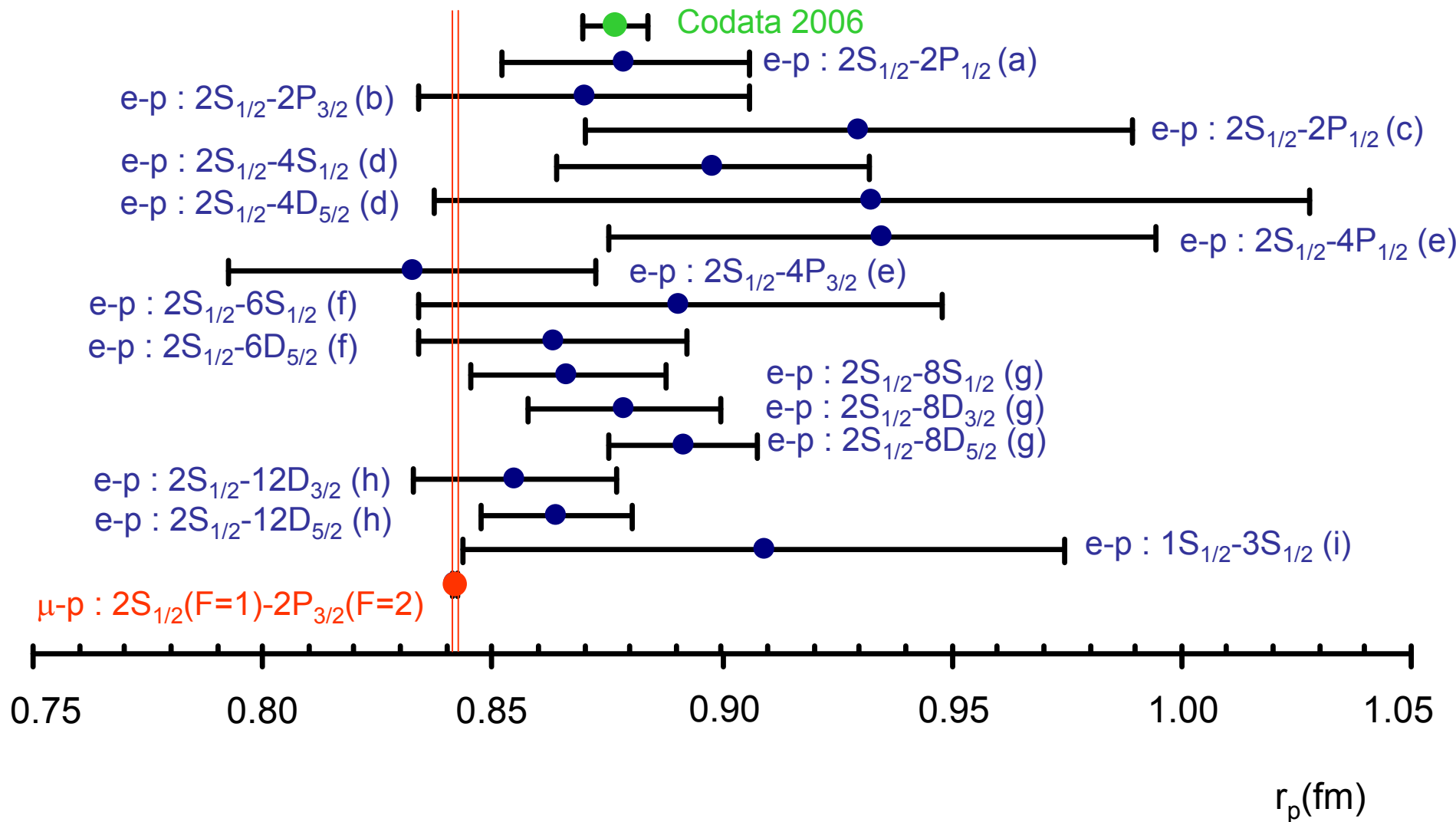
Nuclear Physics A278 (1977) p. 381

but signal never reproduced  
 (10 bars, 40 bars)

2011-2013 → muonic helium spectroscopy (4 mbar)



- $\mu\text{He}^+$  spectroscopy +  $\text{He}^+$  spectroscopy → QED test ( $Z\alpha$ )
- test of the spectroscopy of muonic system



# New $r_p$ ( $\mu p$ ( $2S_{1/2}(F=1) - 2P_{3/2}(F=2)$ )) : outcomes

“New physics”:

Constrains due to other high precision determination (S.Karshenboim PRL104, 220406 (2010), U.D. Jentschura, Annals of Physics (2010), V. Barger et al, arXiv:10113519V1, ...)

“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.” V.Barger et al (Nov 2010)

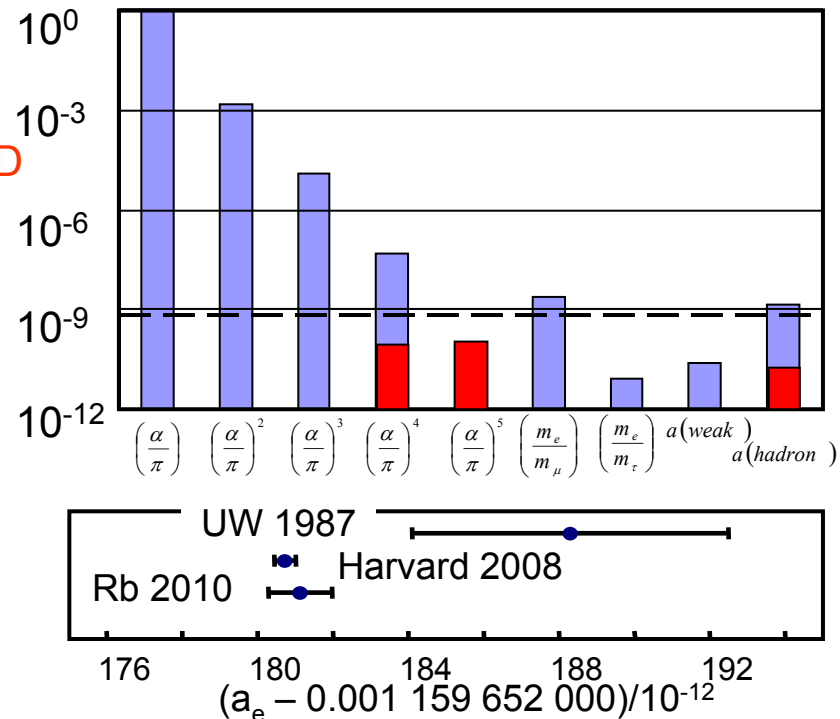
Example of constrain : magnetic moment anomaly of the electron (Gabielse, Kinoshita)

$$a_e = \frac{|\mu_e|}{\mu_B} - 1 = A_1 \left( \frac{\alpha}{\pi} \right) + \dots + A_5 \left( \frac{\alpha}{\pi} \right)^5 + a_e(\text{muon}) + a_e(\text{tau}) + a_e(\text{weak}) + a_e(\text{hadron})$$

With our new determination of  $\alpha$  : stringent test of QED

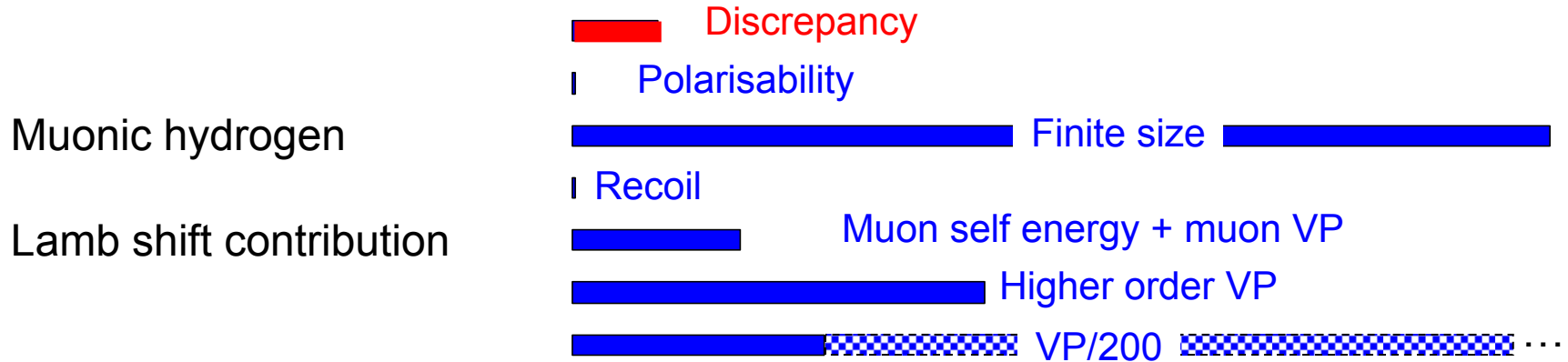
Recoil  $v_r = \frac{\hbar k}{m(\text{Rb})}$   $\alpha^2 = \frac{2R_\infty}{c} \frac{m(\text{Rb})}{m_p} \frac{m_p}{m_e} \frac{h}{m(\text{Rb})}$

Paris measurement of  $\alpha(\text{Rb-2010})$  ( $6.6 \times 10^{-10}$ )  
submitted to PRL (15 Dec 2010), arXiv 1012.3627v1





# Lamb shift - form factor – polarizability

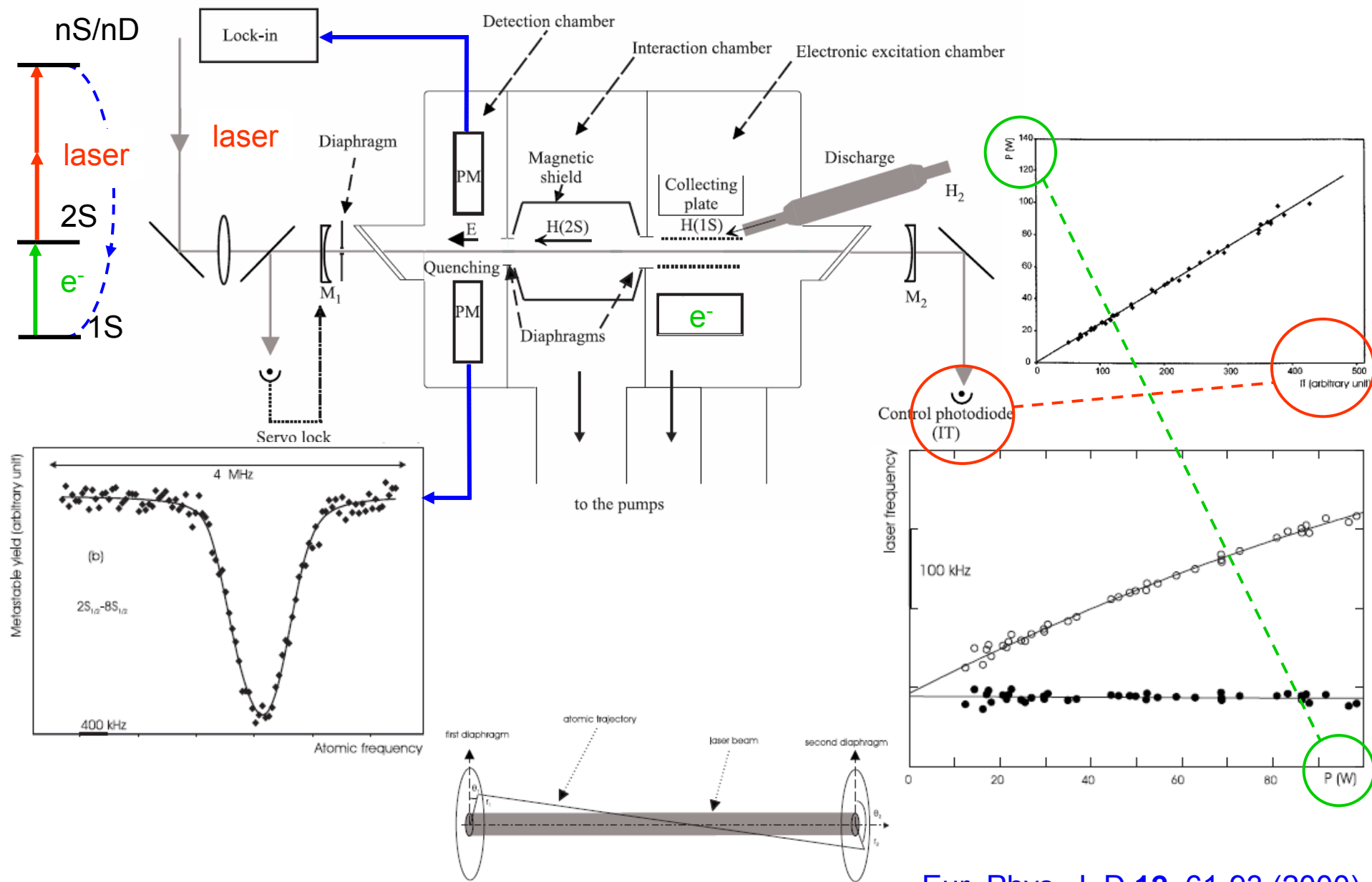


➤ Dipole form factor  $\rho(r) = e^{-\frac{r}{R}}$

➤ Gaussian form factor  $\rho(r) = e^{-\frac{r^2}{R^2}}$

	polarizability	form-factor
• 2S state electronic hydrogen (e-p)	8.7 Hz	
• 2S state electronic deuterium (e-d)	2.7 kHz	
• 2S state muonic hydrogen ( $\mu$ -p)	3.6 GHz	500 MHz
• 2S state muonic deuterium ( $\mu$ -d)	360 GHz	

# 2S-nS/nD hydrogen/deuterium spectroscopy

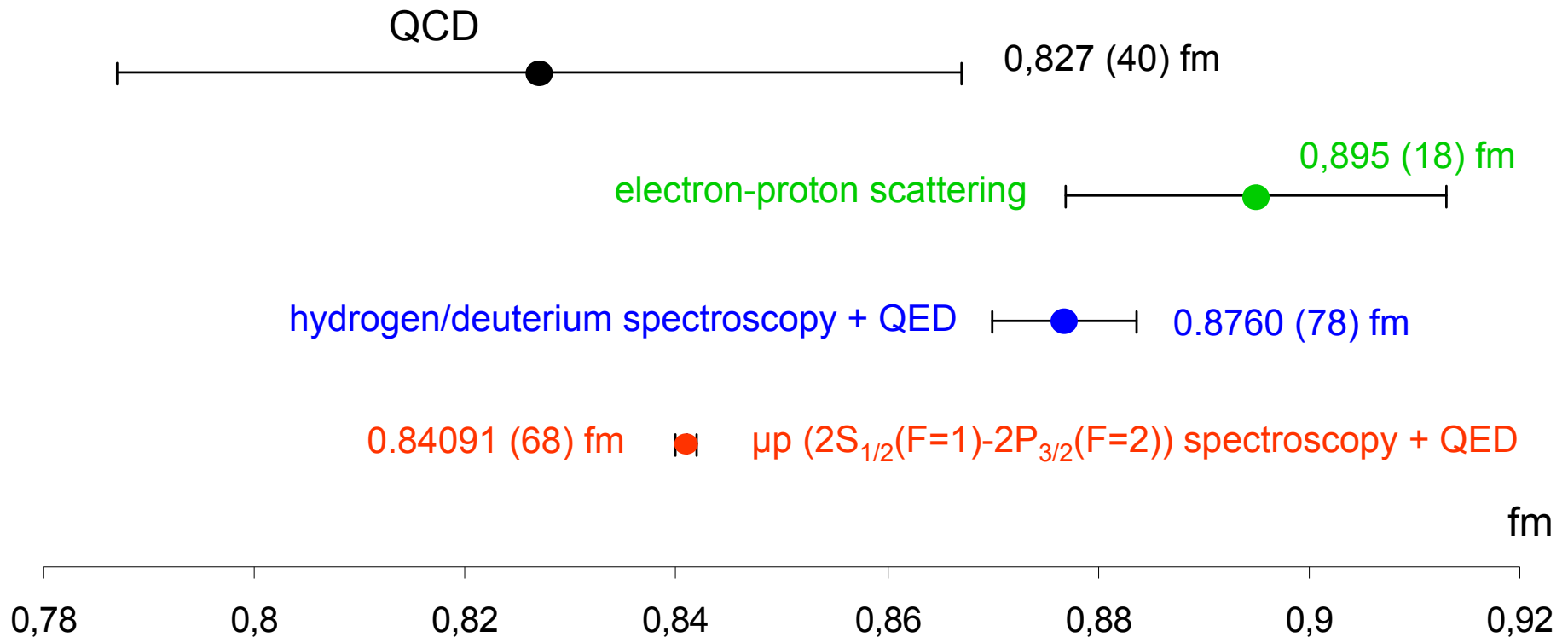


# Comparison with other best determinations

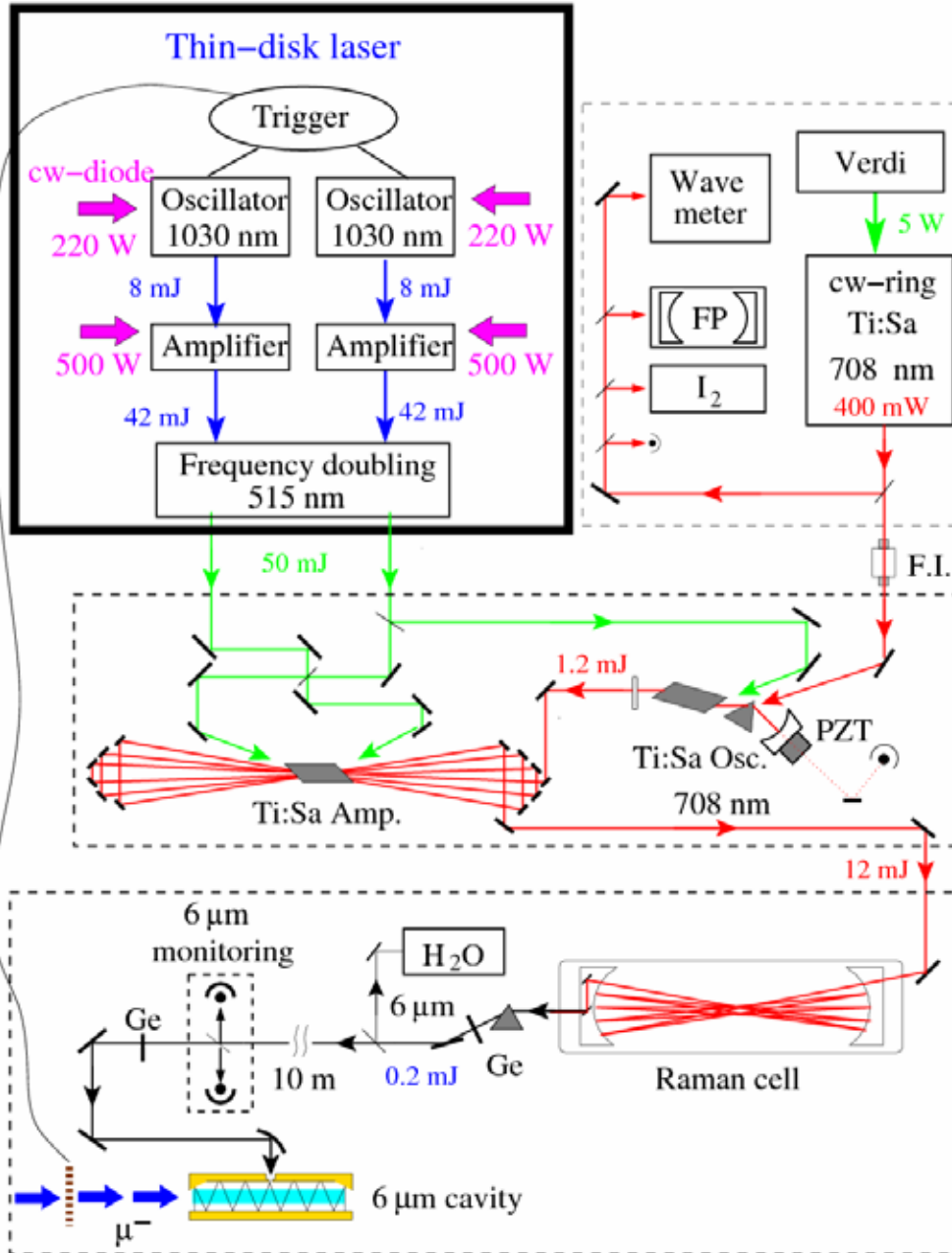
$$\nu (\mu p : 2S_{1/2}(F=1) - 2P_{3/2}(F=2)) = 49\,881.88 \text{ (76) GHz}$$

$$\nu_{\text{theo}} = 50772.43 \text{ (118)} - 1263.69 r_p^2 + 8.39 r_p^3 \text{ GHz}$$

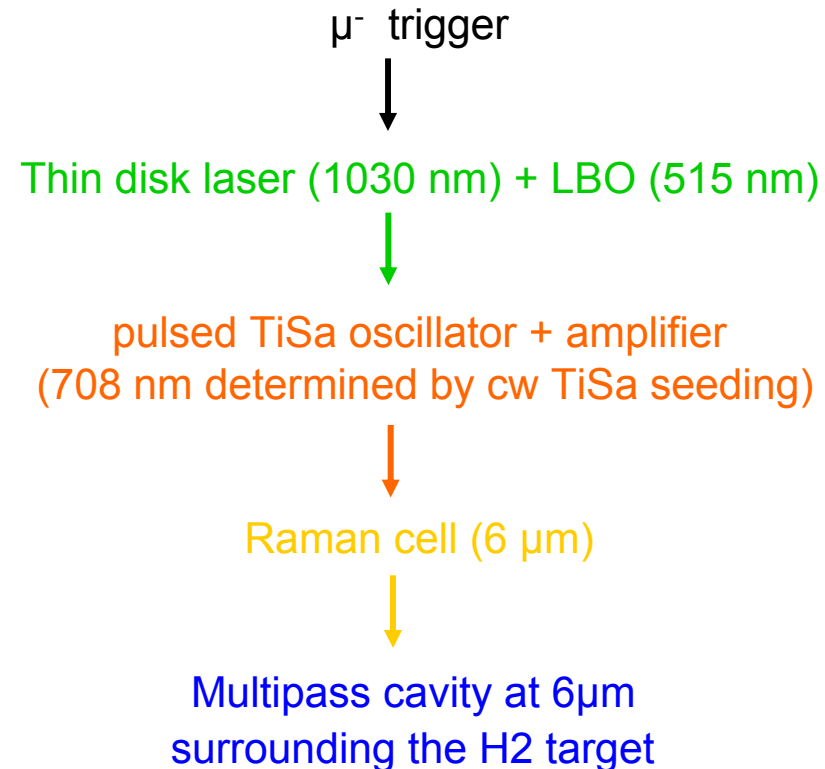
$$r_p = 0.84184 \text{ (36)(56) fm}$$



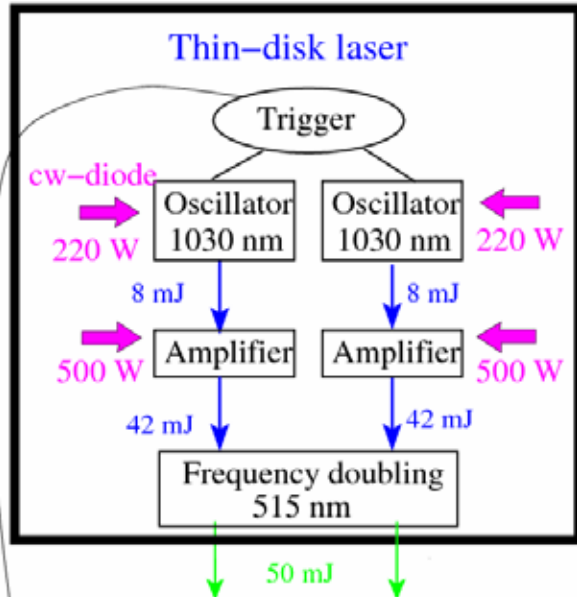
# Laser chain : principle



- Each single muon triggers the laser system (random trigger)
- 2S lifetime  $\sim 1\mu\text{s}$   $\rightarrow$  short laser delay
- 6  $\mu\text{m}$  tunable laser pulse (0.2mJ)

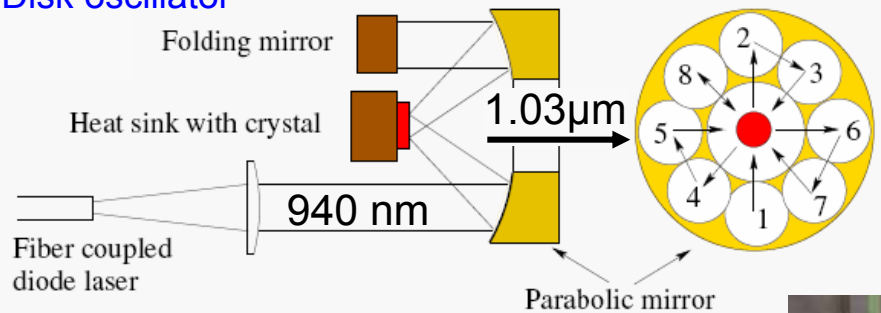


# Laser chain : thin-disk Yb:YAG laser

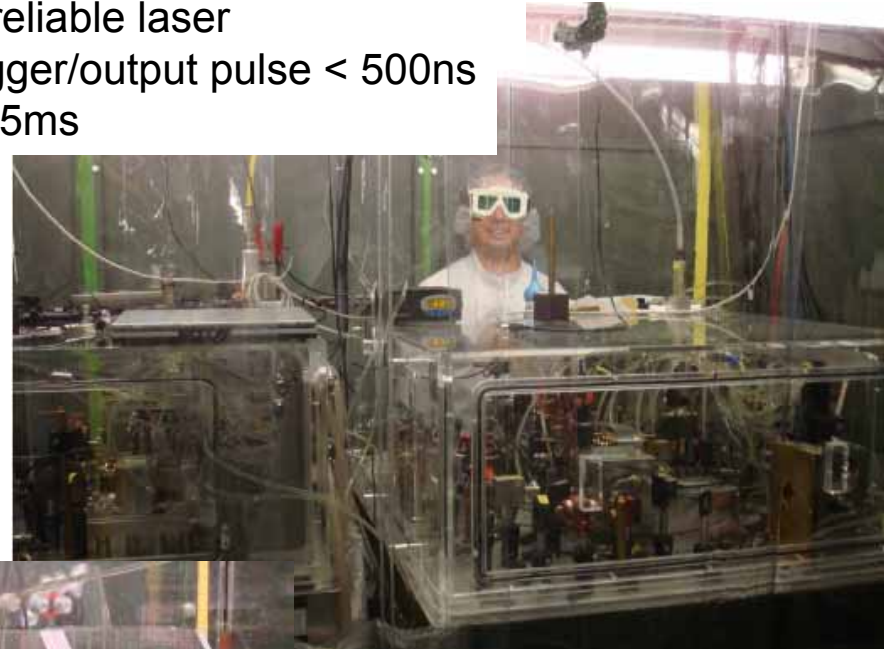
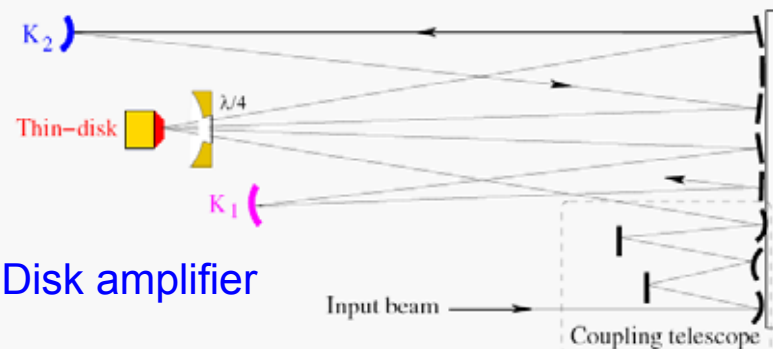


- Q-switch oscillator (cw prelasing mode → short delay between electronic trigger and opt. output (8mJ, xxx ns, delay 250ns)
  - 12 pass amplifier (20m propagation) (42mJ)
  - LBO frequency doubling 25mJ @ 515nm
- 
- 50 mJ @ 515 nm, reliable laser
  - delay electronic trigger/output pulse < 500ns
  - random trigger ≥ 1.5ms

## Disk oscillator



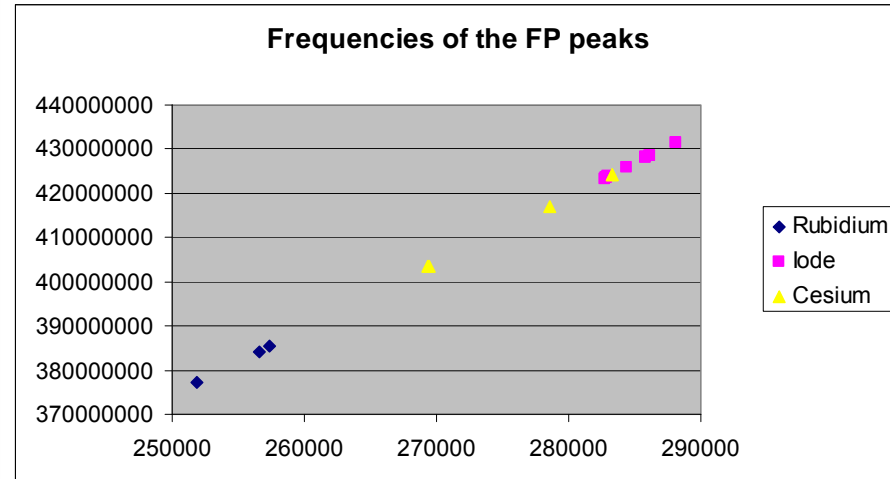
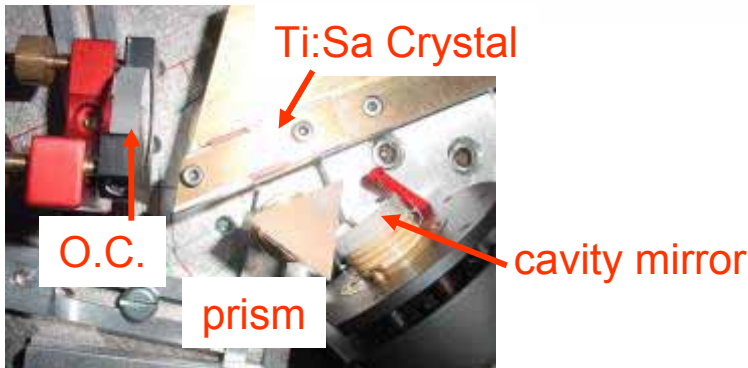
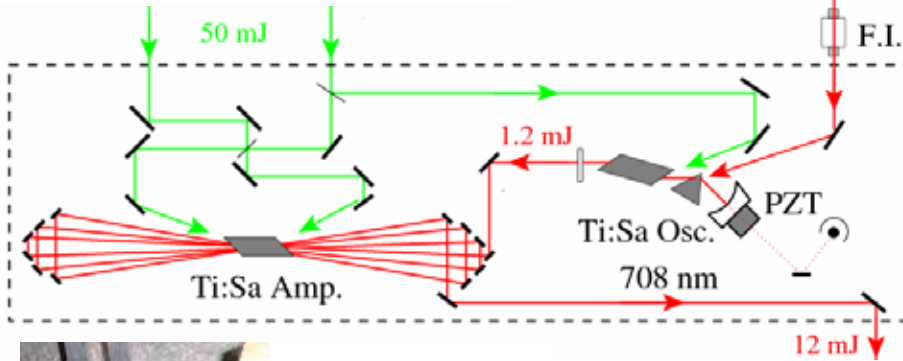
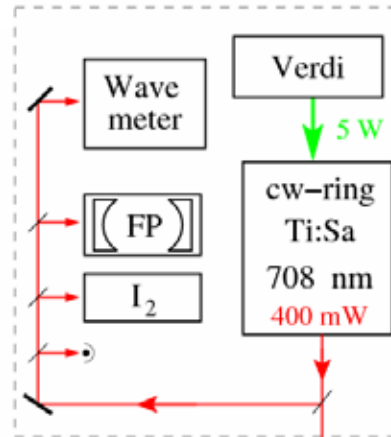
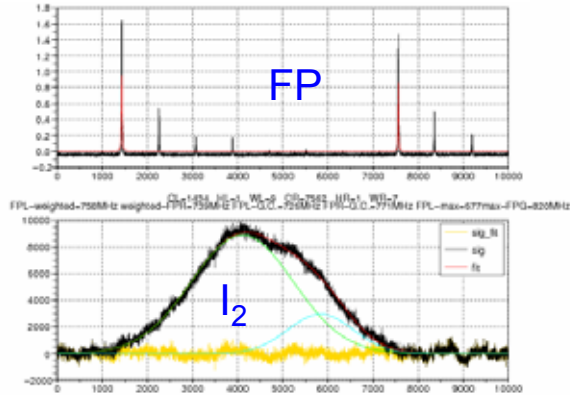
## Disk amplifier



A. Antognini et al,  
 IEEE J. of Q. Electronics  
 vol 45, n°8, 2009

# Laser chain : Ti:Sa

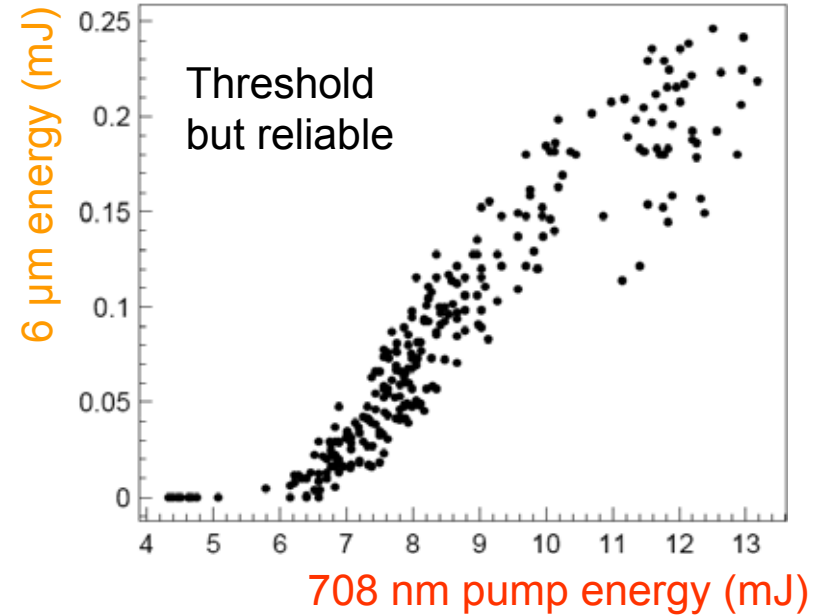
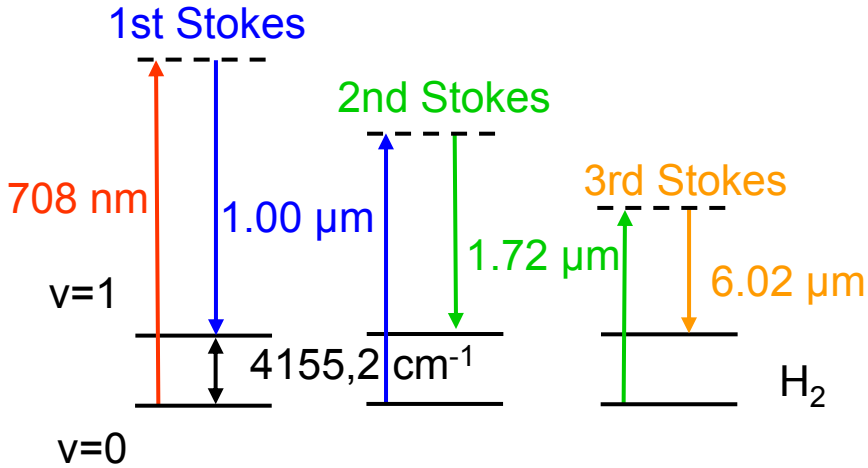
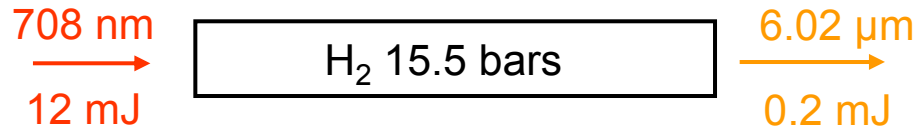
Calibration FP/ I<sub>2</sub>, Cs, Rb  
(700-794nm)



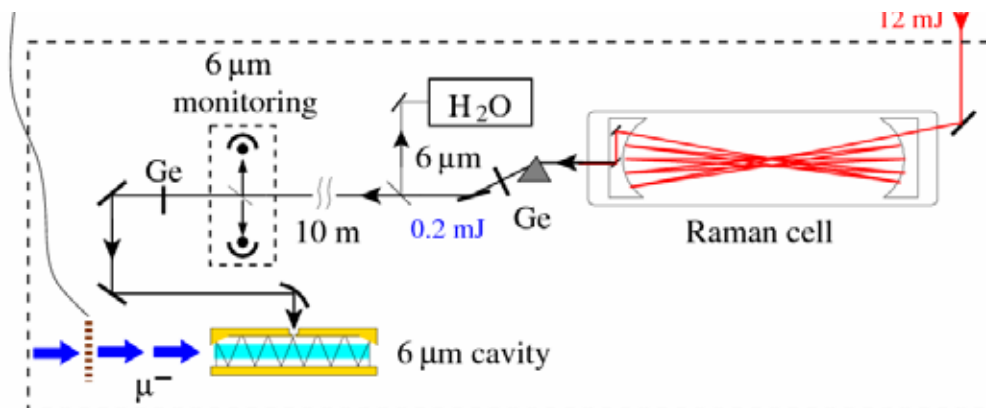
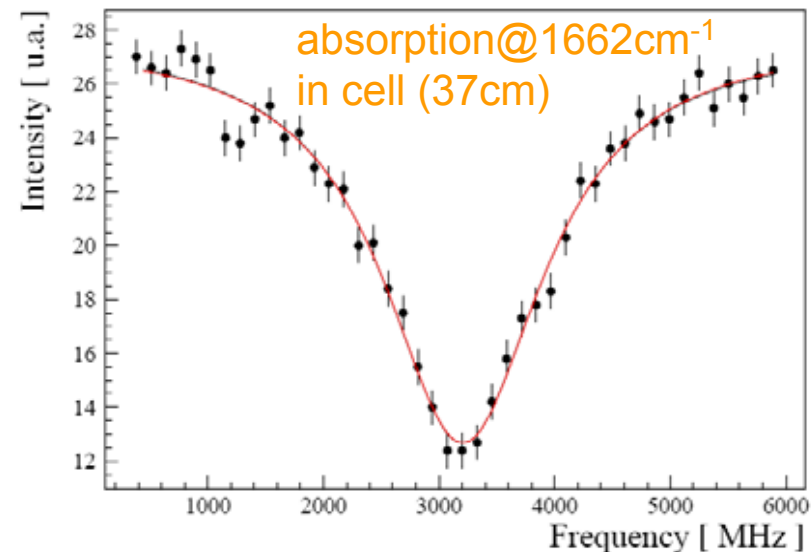
- home made Ti:Sa lasers
- cw-Ti:Sa frequency controlled with FP, atom, molecule (abs. freq. <50MHz)
- short length pulsed oscillator seeded with Cw-Ti:Sa (1.2 mJ, 6 ns, delay 50 ns,  $\Delta\nu = 200\text{MHz}$ )
- multipass amplifier  $\times 6$  (12 mJ, 5 ns)



# Laser chain : Raman cell

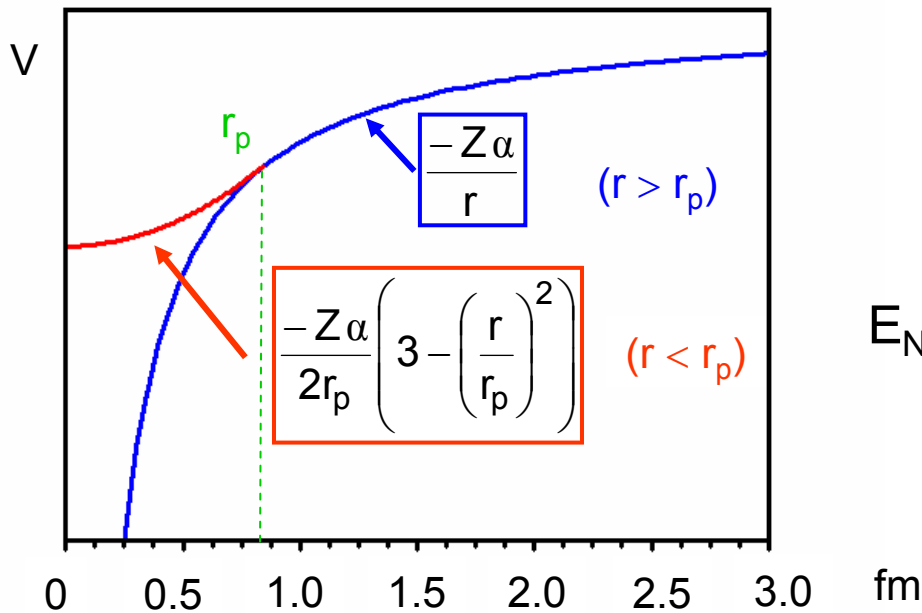


6 μm frequency calibration : H<sub>2</sub>O lines



# proton charge radius hydrogen spectroscopy

- hydrogen spectroscopy (1989, ..., 2008)
- muonic hydrogen spectroscopy (2009)



$$E_{\text{NS}} = \frac{2}{3} \left( \frac{\mu}{m_e} \right)^3 \frac{(Z\alpha)^2}{n^3} m_e c^2 \left( \frac{Z\alpha R_N}{\lambda_c} \right)^2 \delta_{10}$$

# Muonic hydrogen Lamb shift

Name	Reference	formula	value	Pachucki [1]	Borie [3]
NR One loop electron VP		$\frac{8\alpha(Z\alpha)^2}{5\pi n^3} Q_{nl}^{(1)} m_r$	205.00740	205.0074	
Relativistic one loop VP	[3]				205.0282
NR two-loop electron VP		$\frac{4\alpha(Z\alpha)^2}{\pi^2 n^3} Q_{nl}^{(2)} m_r$	1.50790	1.5079	1.5081
NR three-loop electron VP	[12]	$0.08353(1) \frac{\alpha^3(Z\alpha)^2}{\pi^3} m_r$	0.00530	check	
Polarization insertion in two coulomb lines	[4,1]	$0.01244 \frac{\alpha^2(Z\alpha)^2}{9\pi^2} m_r$	0.15090	0.1509	0.1510
Polarisation insertion in two and three coulomb lines	[12]	$0.036506(4) \frac{\alpha^3(Z\alpha)^2}{\pi^3} m_r$	0.00230		
Relativistic correction	[2,4,1,3]	$\alpha(Z\alpha)^4$	0.01690	0.0169	
Wichmann-Kroll	[13,14,3]	$\frac{4\alpha(Z\alpha)^4}{\pi n^3} Q_{nl}^{WK} m_r$	-0.00103		-0.00103
Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	[4,1]		-0.00500	0.0010	-0.006
Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$		$\left[1.09426 \left(-\frac{m}{8m_r} - 1\right) - 4 \times 2.21656\right] \times \frac{\alpha^2(Z\alpha)^4}{\pi^2 n^3} \left(\frac{m_r}{m}\right)^5 m$	-0.00150		
Mixed electron and muon loops	[15]	$\frac{64\alpha^2(Z\alpha)^2}{45\pi^2 n^3} \left(\frac{m_e}{m}\right)^2 Q_{nl}^{(3)} m_r$	0.00007		0.00007
Hadronic polarization $\alpha(Z\alpha)^4 m$	[16]	$-0.638(22) \frac{4\alpha(Z\alpha)^4}{15\pi^2 n^3} \left(\frac{m_r}{m}\right)^5 m \delta_{10}$	0.01080	0.0004	0.0113
Hadronic polarization $\alpha(Z\alpha)^5 m$			0.00005		0.0110
Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m$			-0.00002		
Recoil contribution	[17]	$\frac{(Z\alpha)^4 m^3}{2n^3 M^2} \left(\frac{1}{j+\frac{1}{2}} - \frac{1}{l+\frac{1}{2}}\right) (1 - \delta_{10})$	0.05750	0.0575	0.0575
Radiative corrections of order $\alpha^n(Z\alpha)^k m$	[11]	Tables 3.2, 3.3, 3.7, 3.8, 3.9	-0.66770	-0.6677	-0.66788
Recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m$	[11]	Table 4.1	-0.04470	-0.045	-0.04497
Radiative Recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m$	[11]	Table 5.1	-0.00960	-0.0099	-0.0096
Nuclear structure correction of order $(Z\alpha)^5$	[1]	$-\frac{0.095(18)}{n^3} \delta_{10} \text{ meV}$	0.01200		0.015
Light by light electron loop contribution			0.00135	0.00135	
Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m$		$-\frac{0.00152}{n^3} \delta_{10} \text{ meV}$	0.00019		
Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m$		$\frac{0.000092}{n^3} \delta_{10} \text{ meV}$	-0.00001		
Sum			206.04310	0.00275	206.0353
terms dependent on the nuclear radius from Ref. [11] (contributions in meV)					
Leading nuclear size contribution		$\frac{2(Z\alpha)^4 m_r^3}{5n^3} \langle r^2 \rangle \delta_{10}$	-5.1975	$\langle r_p^2 \rangle$	
Nuclear size correction of order $(Z\alpha)^5$	[4,1]	$-\frac{(Z\alpha)^5 m_r^4}{3n^3} \langle r^3 \rangle \delta_{10}$	0.0347	$\langle r_p^3 \rangle$	0.0347 $\langle r_p^3 \rangle$
Radiative corrections to nuclear finite size effect	[1]	$\alpha(Z\alpha)^4 m_r^3 \langle r_p^2 \rangle$	-0.0275	$\langle r_p^2 \rangle$	-0.0273 $\langle r_p^2 \rangle$
Nuclear size correction of order $(Z\alpha)^6 \langle r_p^2 \rangle$	[1]	$-\langle \ln \frac{Z\alpha}{2} \rangle \frac{2(Z\alpha)^6}{3n^3} m_r^3 \langle r_p^2 \rangle$		$\langle r_p^2 \rangle$	
Nuclear size correction of order $(Z\alpha)^6 \langle r_p^4 \rangle$	[1]	$\frac{2}{3} \frac{2(Z\alpha)^6}{5n^3} m_r^5 \langle r_p^4 \rangle$		$\langle r_p^4 \rangle$	
Total $\langle r^2 \rangle$ contribution			-5.225		

Form factor (dipole, Gaussian, ...)

d:4, G:1

Table 7. All known contributions from Eides et al.[11])

## Hydrogen spectroscopy

**Transition energy** :  $(E_n - E_p) = (E_n^{Dirac} - E_p^{Dirac}) + (E_n^{Recoil} - E_p^{recoil}) + (L_n - L_p)$

in which :  $E_{Dirac}$  and  $E_{Recoil}$  have an exact formulation prop. to  $R_\infty$   
 $L_n = F(\text{QED}, R_p)$  Lamb shift

✓ Q.E.D. = series expansion of  $\alpha$ ,  $Z\alpha$ ,  $\ln(Z\alpha)$  which depends on  $n$  as  $1/n^3$

$$\Delta E = \left(\frac{\alpha}{\pi}\right)^2 \frac{(Z\alpha)^4}{n^3} m_e c^2 \left[ B_{40} + (Z\alpha) B_{50} + (Z\alpha)^2 (L^3 B_{63} + L^2 B_{62} + L B_{61} + B_{60}) + \dots \right]$$

$$\approx \dots \left[ 0,54 - 0,16 + 5 \times 10^{-5} (-280 - 50 + 500 - 100) + \dots \right]$$

avec  $L = \ln[(Z\alpha)^{-2}]$

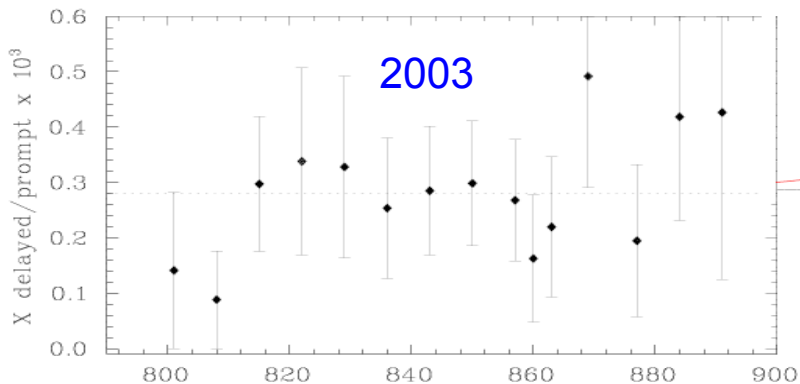
✓ Distribution charge radius contributions vary as  $1/n^3$

$$E_{NS} = \frac{2}{3} \left(\frac{\mu}{m_e}\right)^3 \frac{(Z\alpha)^2}{n^3} m_e c^2 \left(\frac{Z\alpha R_p}{\lambda_c}\right)^2 \delta_{l0}$$

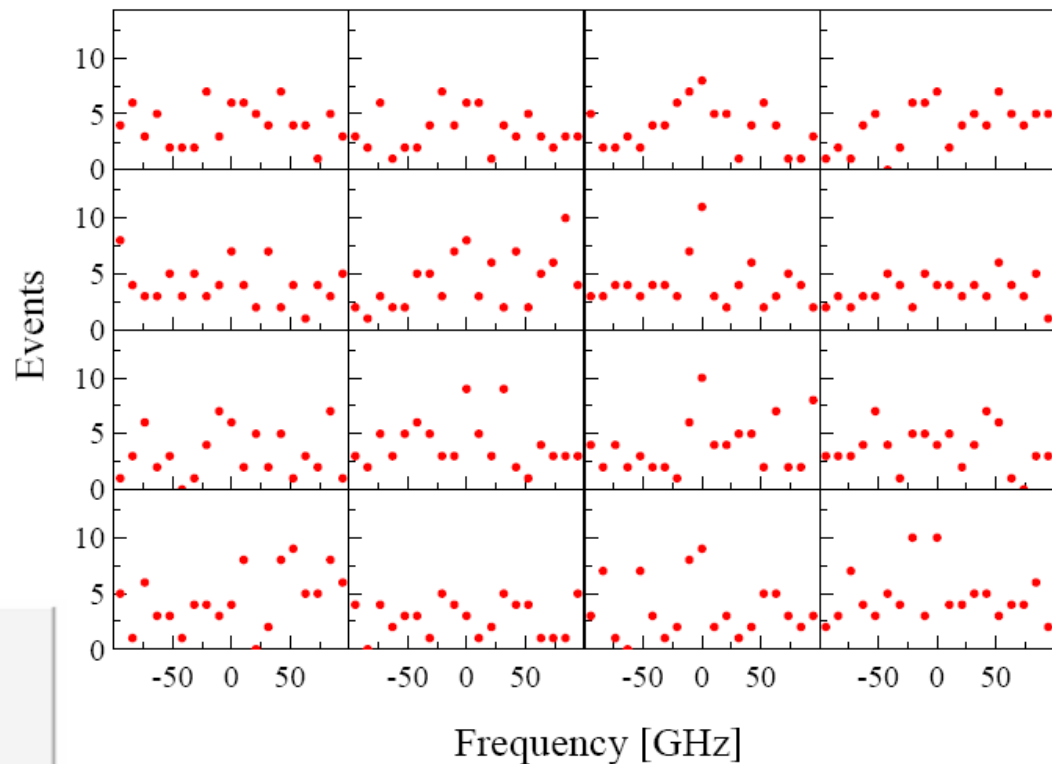
- Q.E.D. calculations are right ! : 2 experimental data  $\rightarrow R_\infty, R_p$
- are Q.E.D. calculations right ? : 3 experimental data  $\rightarrow R_\infty, R_p, \text{Q.E.D.}$

# Resonance searches (2002, 2003, 2007)

2002 : Run with all the components of the experiment at the same time (search for resonance 10 hours).

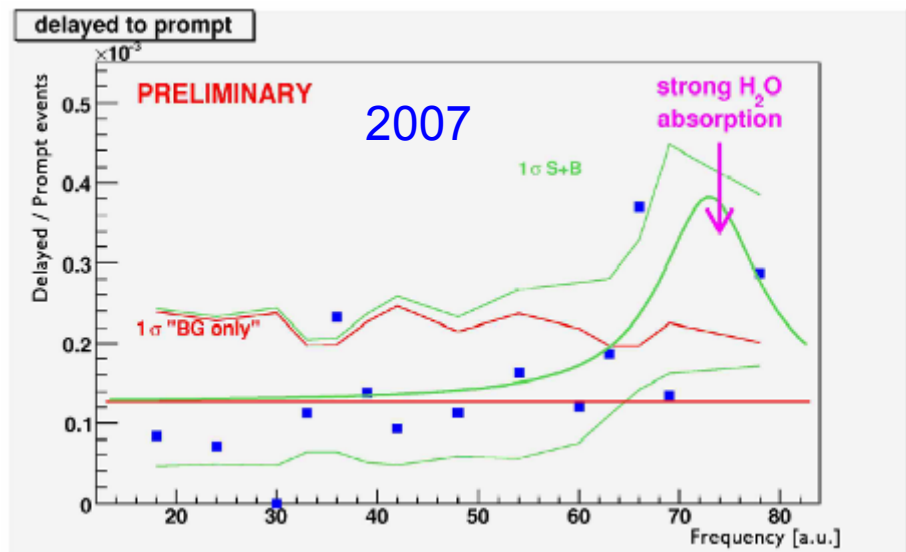


Simulation 2003 :

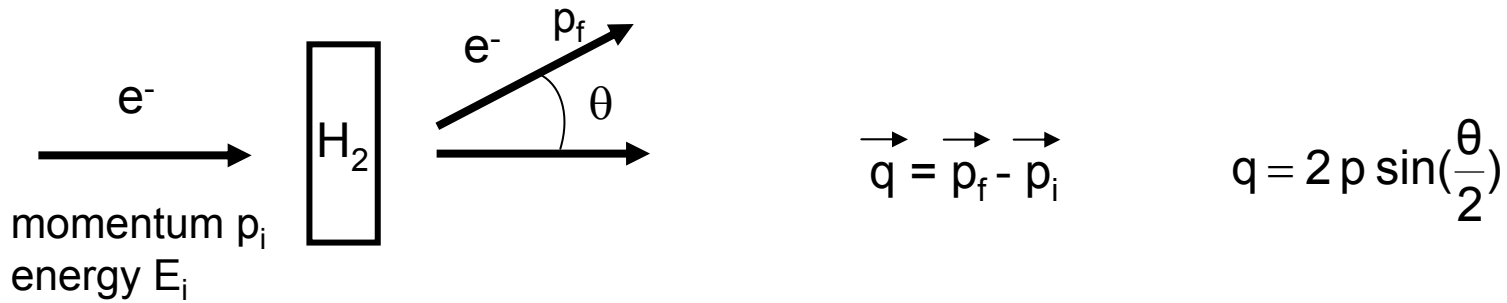


sig. 0.5 c/hour  
noise 0.5 c/hour

from A. Antognini Phd thesis



## electron-proton scattering



$$\frac{d\sigma}{d\Omega}(E_i, \theta) \approx \underbrace{\left[ \frac{d\sigma}{d\Omega}(E_i, \theta) \right]}_{\text{Rutherford}} G(q^2)$$

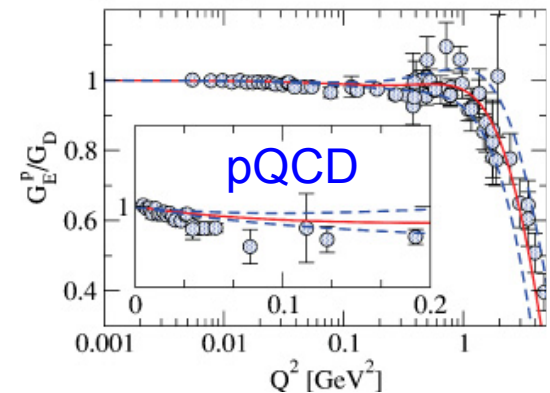
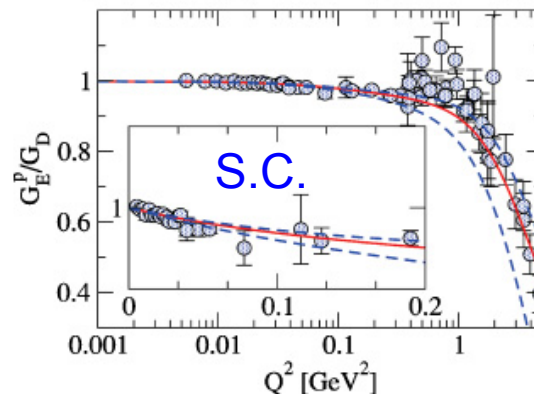
$$G(q^2) = \int d^3r e^{iqr} \frac{\rho(r)}{4\pi} \approx 1 - \frac{r_p^2}{6} q^2$$

Sick 2003 :

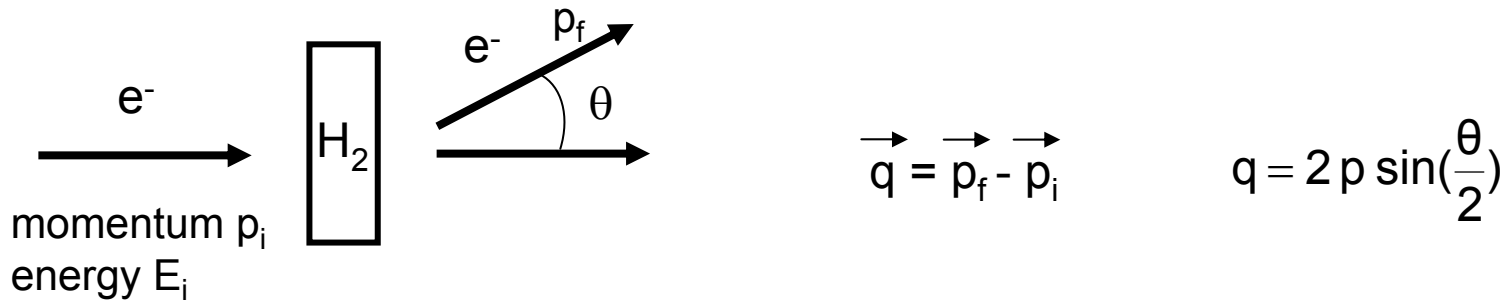
$$G_e(q) = \frac{1}{1 + \frac{q^2 b_1}{1 + \frac{q^2 b_2}{1 + \dots}}}$$

Belushkin et al 2007 :

$$G_D(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{m_D^2}\right)^2}$$

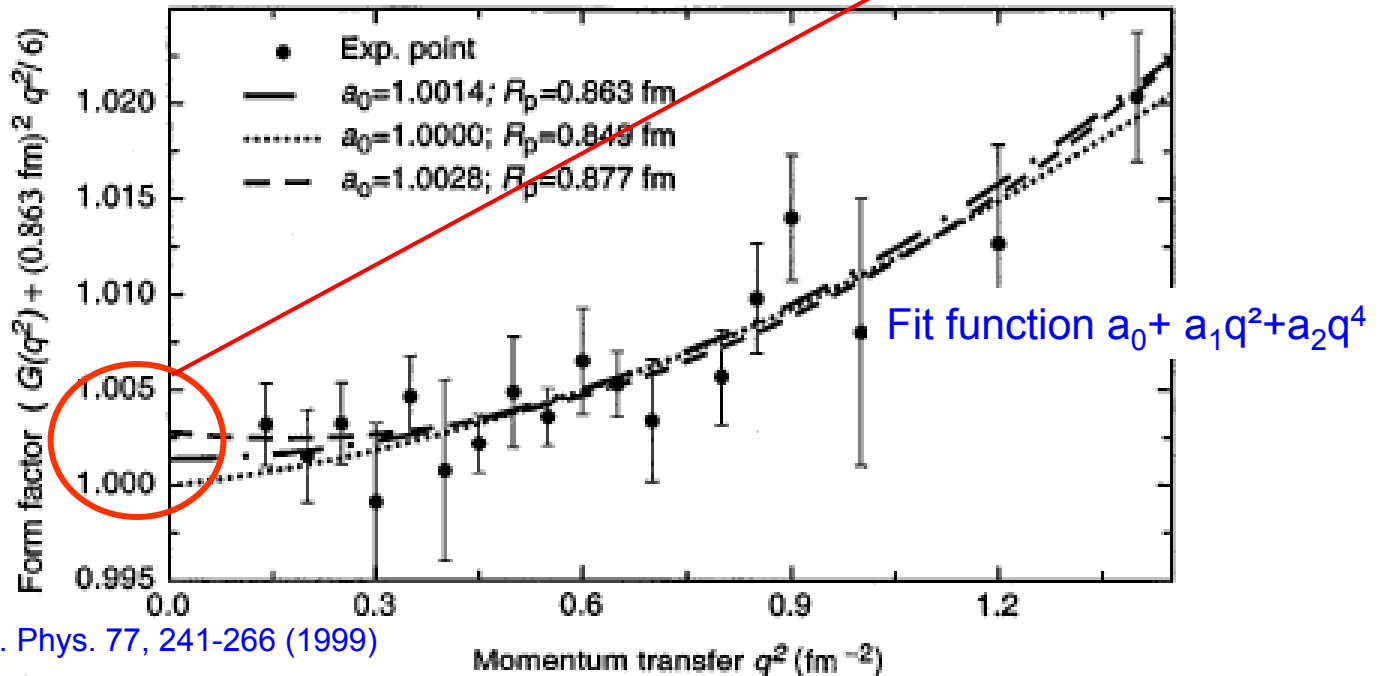


# electron-proton scattering



$$\frac{d\sigma}{d\Omega}(E_i, \theta) \approx \underbrace{\left[ \frac{d\sigma}{d\Omega}(E_i, \theta) \right]}_{\text{Rutherford}} G(q^2)$$

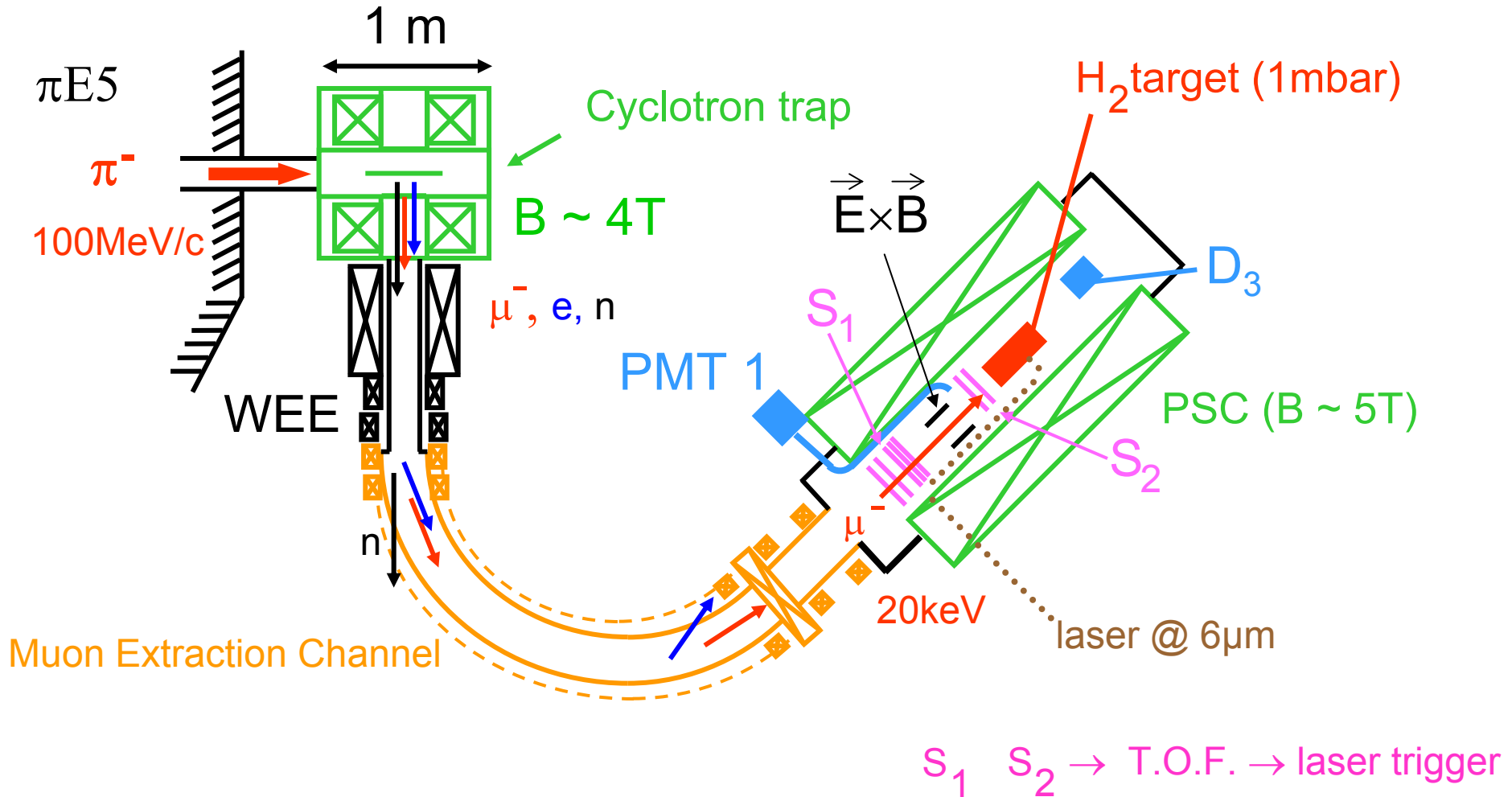
$$G(q^2) = \int d^3r e^{iqr} \frac{\rho(r)}{4\pi} \approx 1 - \frac{r_p^2}{6} q^2$$





# muonic hydrogen source

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

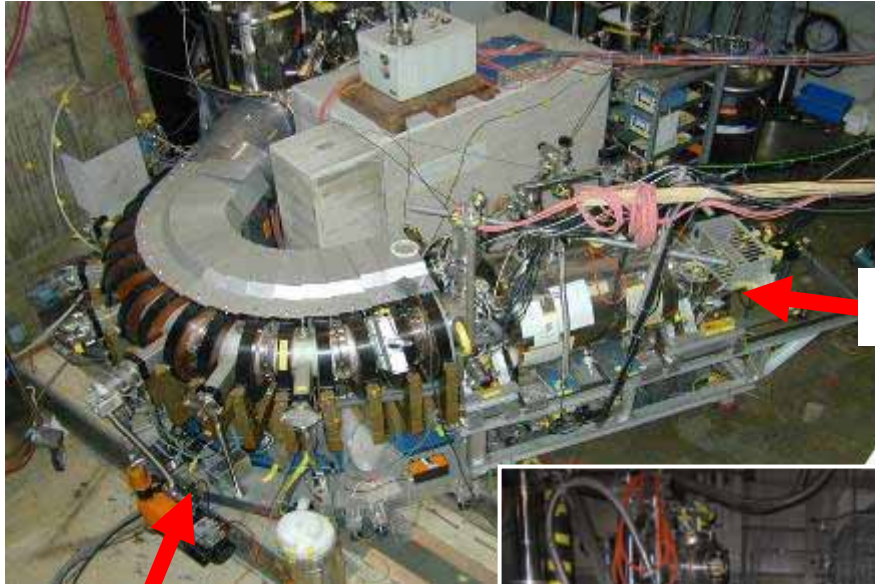
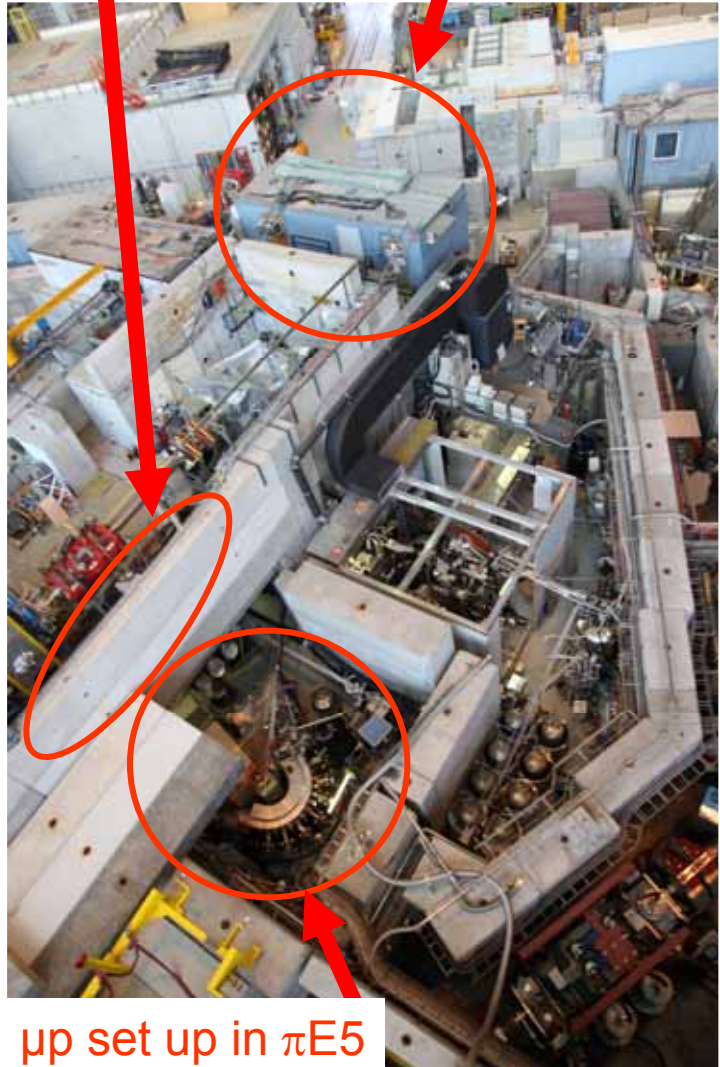


# muon beam apparatus



laser hut  
below  
concrete blocks

counting room

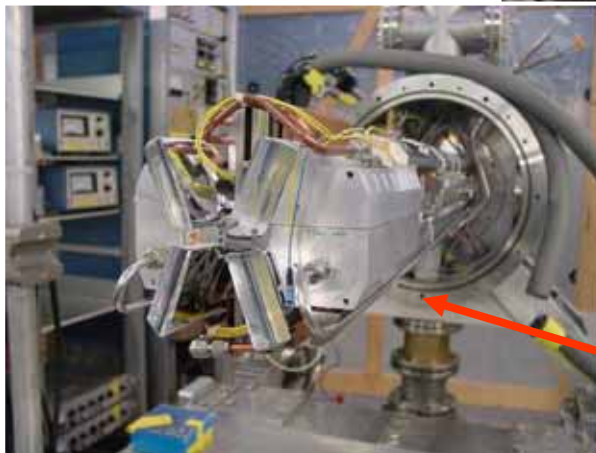


PSC solenoid,

Muon extraction  
channel

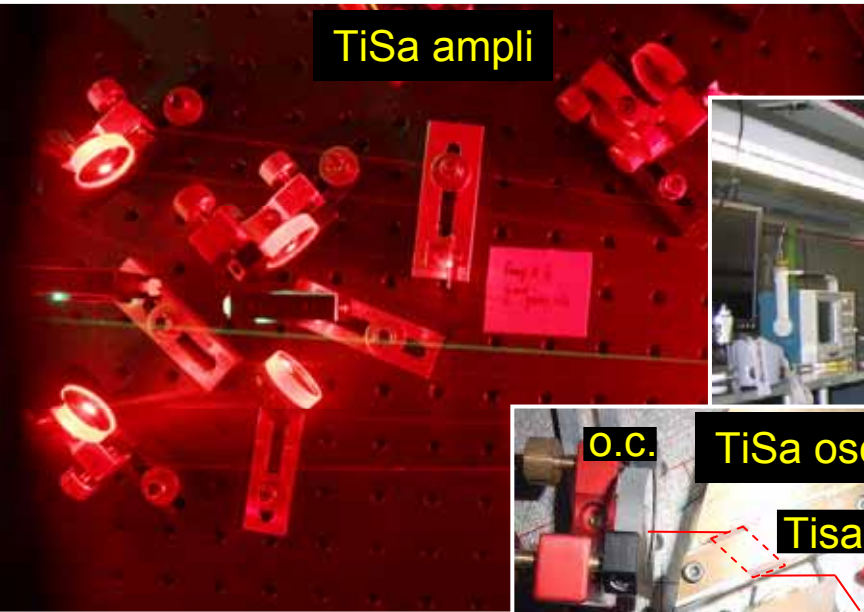


H2 target, laser cavity,  
detectors

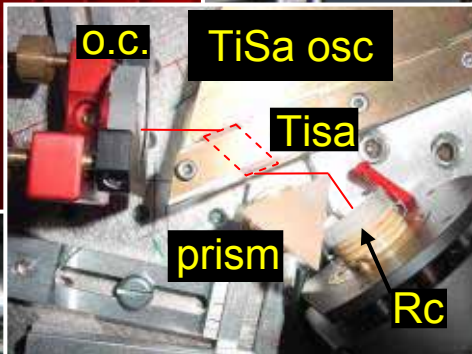
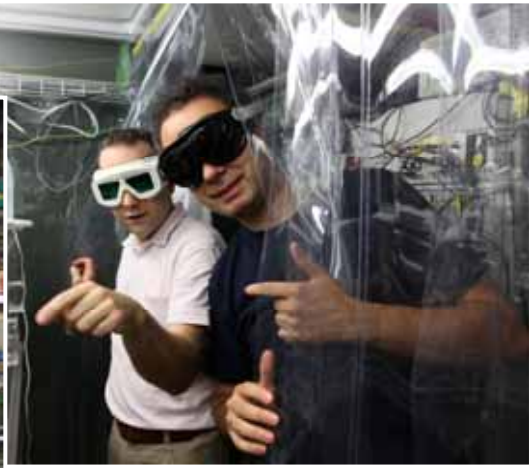




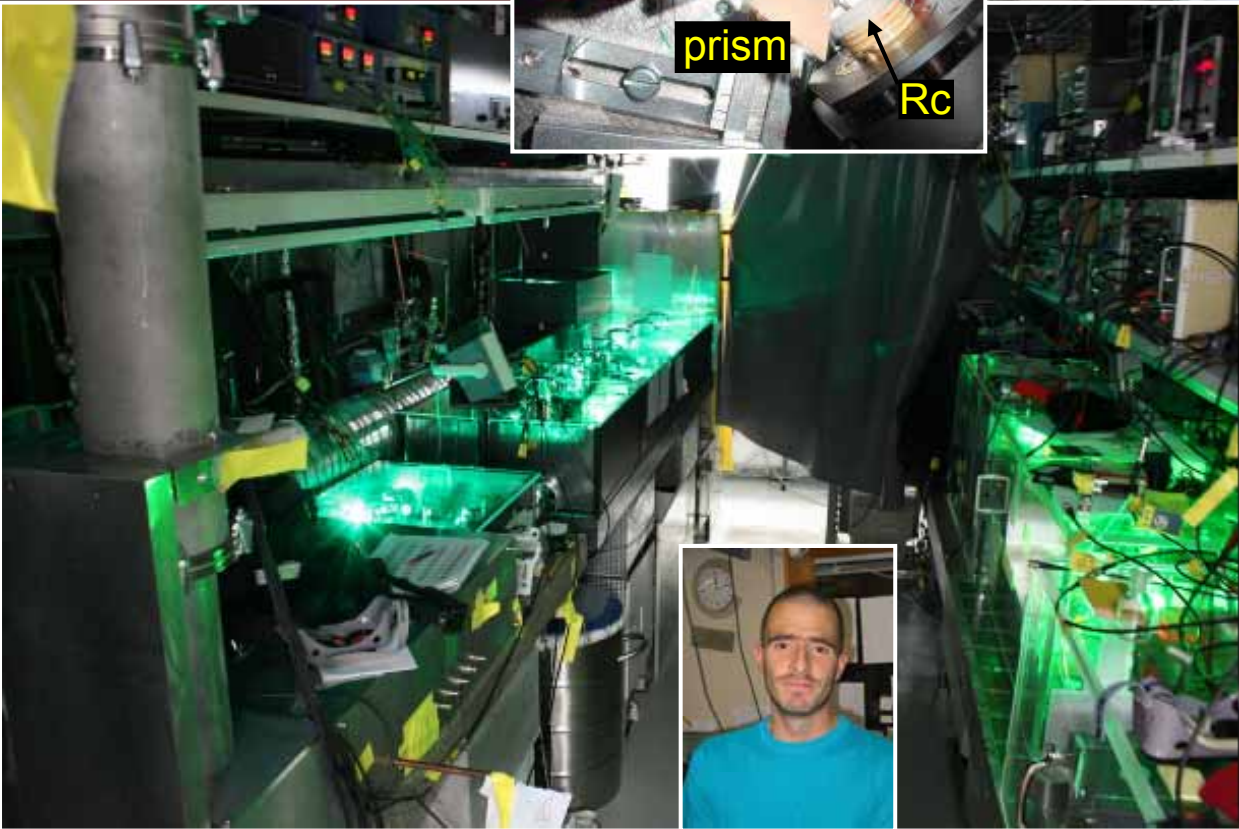
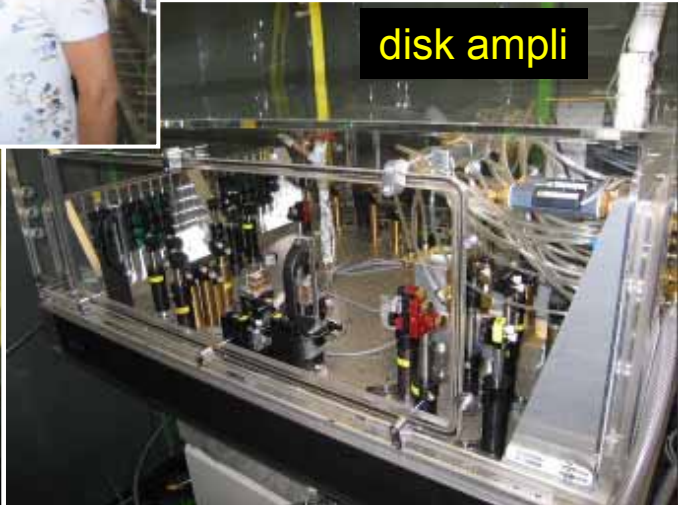
TiSa ampli



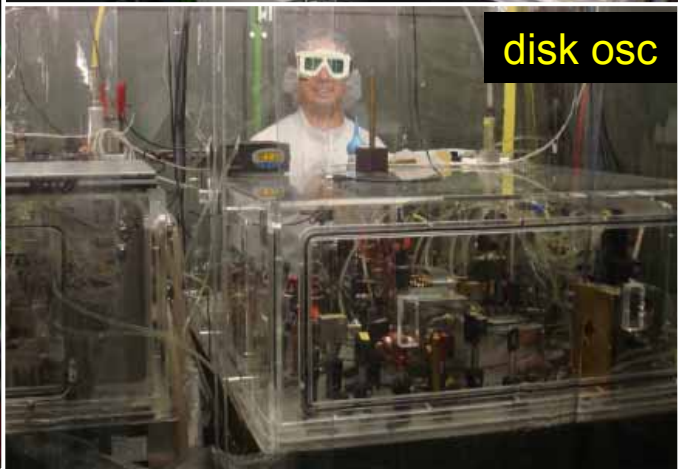
Laser hütte



disk ampli

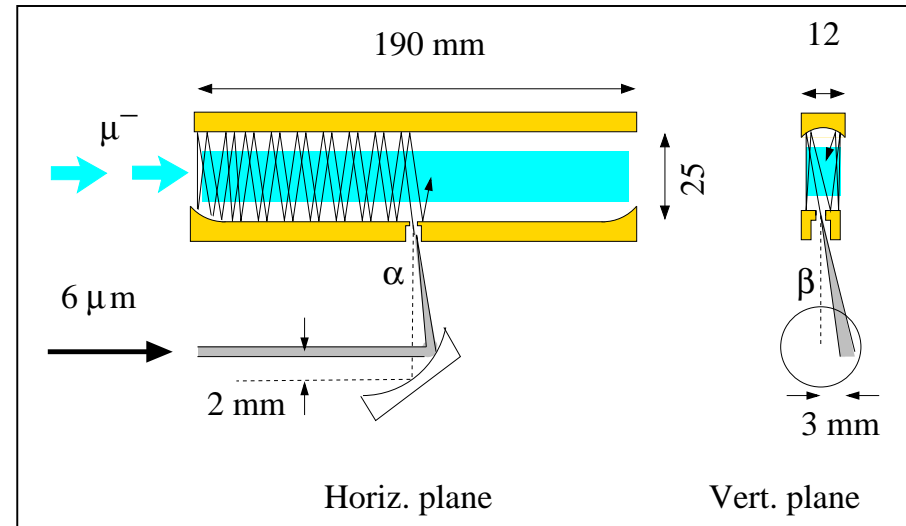
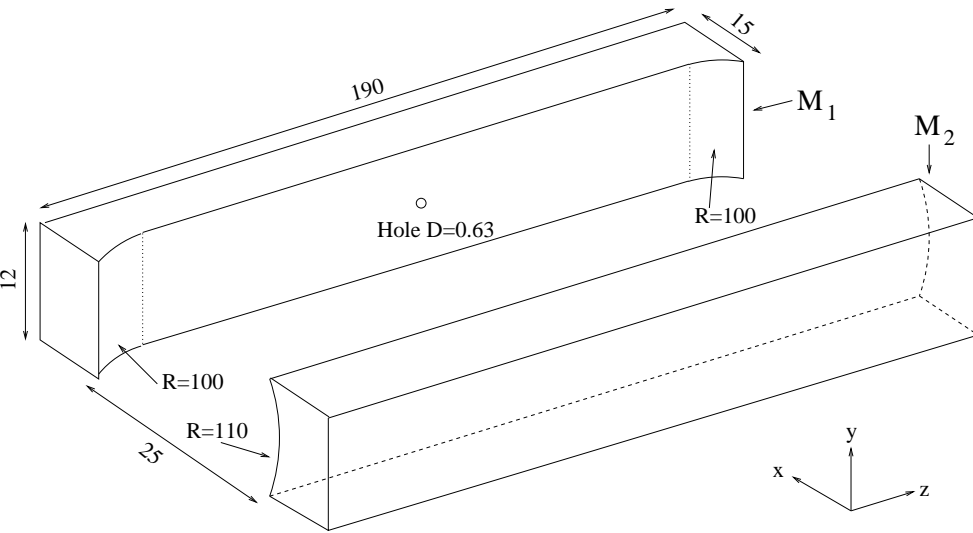


disk osc

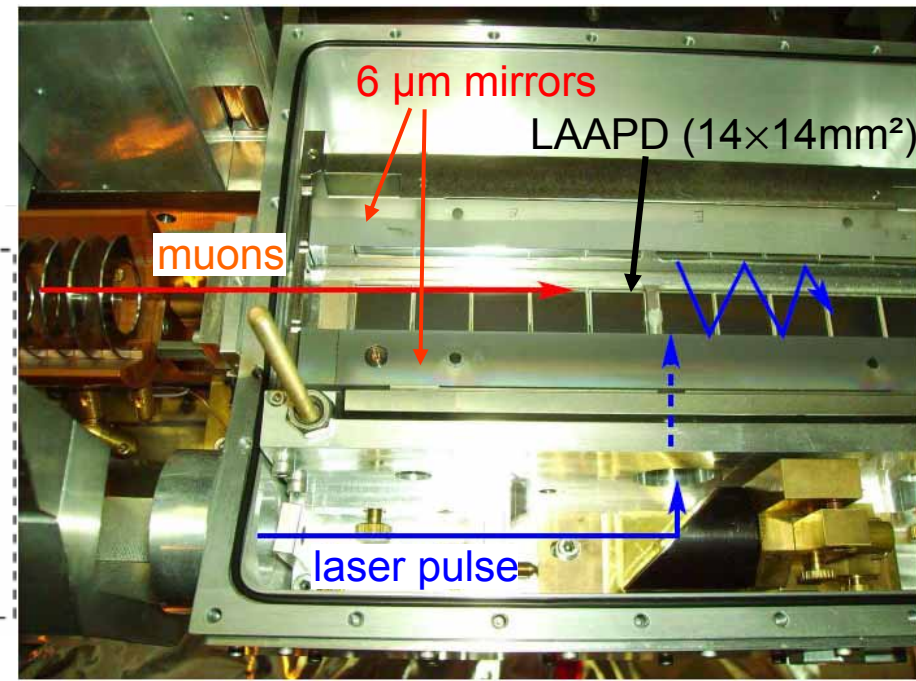
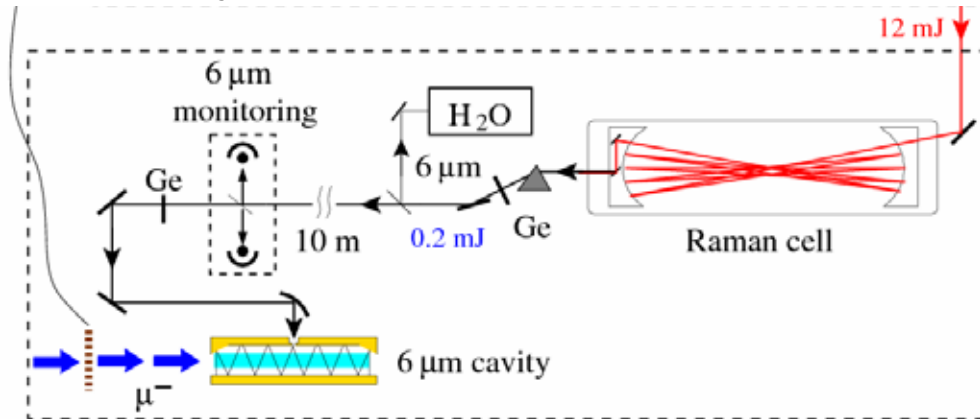


# Laser chain : multipass cavity

→ illuminate at 6  $\mu\text{m}$  all the muon stopping volume ( $5 \times 15 \times 190 \text{ mm}^3$ )



- coupling through a 0.63mm diameter hole
- $R=99.90\%$  at 6  $\mu\text{m}$
- 1000 reflections
- 0.15mJ injected → 2S-2P saturated



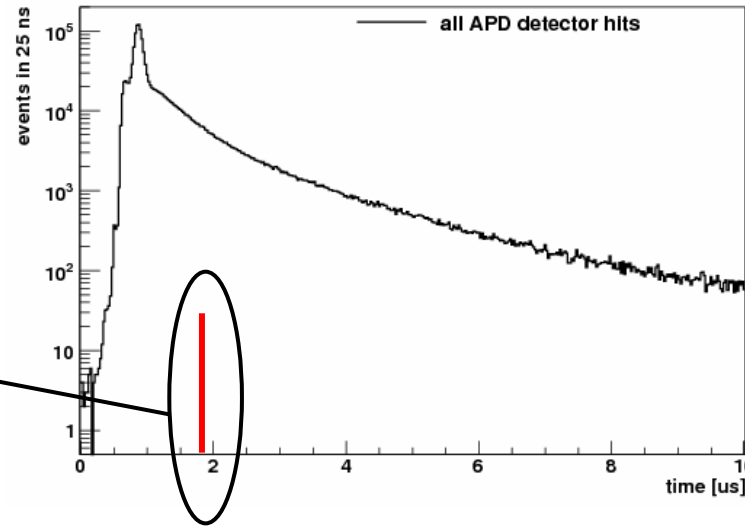


# X-rays analysis → event gate sorting → noise rejection

Example : FP 900 - 11 hrs meas.

1.56 million detector events

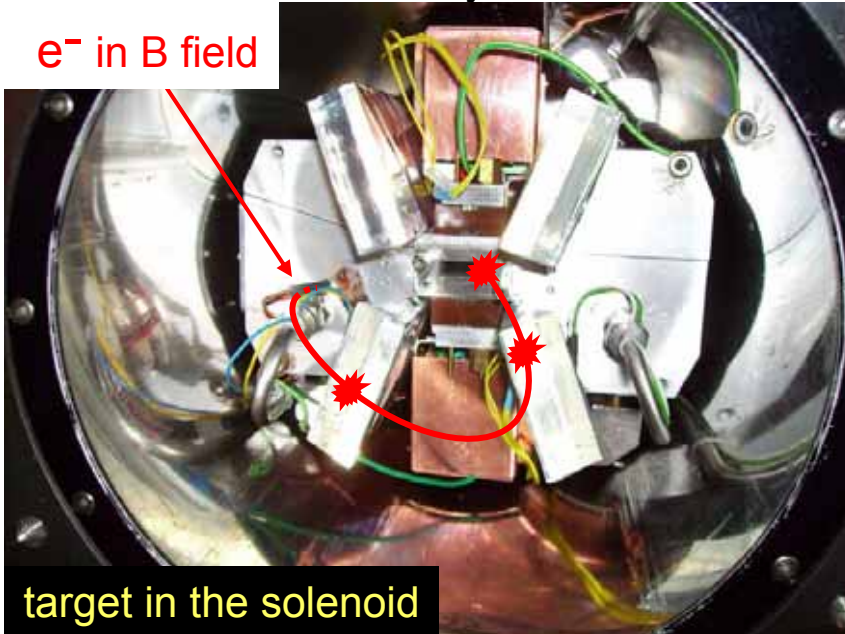
expected 2-3 laser induced events/hour !



## time signature in LAAPD

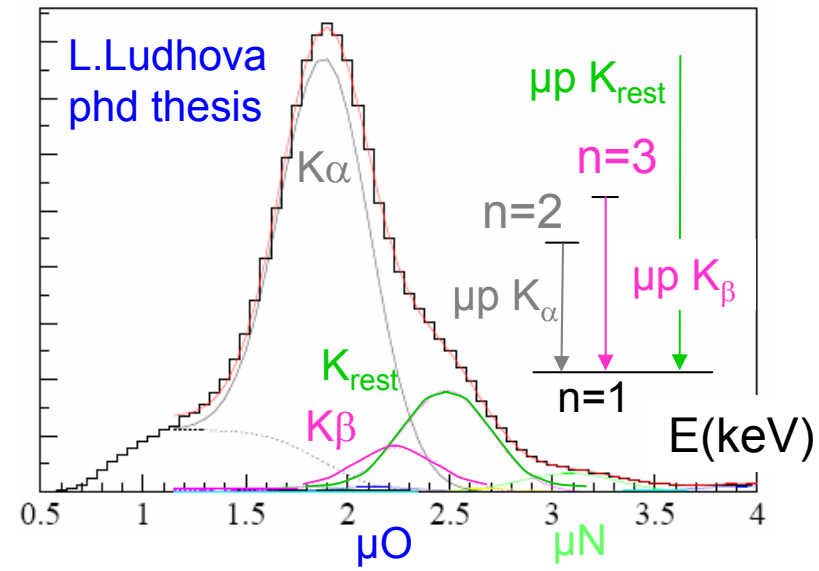
- photon  $< 10\text{keV}$  → 1 shot in the LAAPD
- $e^-$  in  $B = 5\text{T}$  → many counts in detectors

$e^-$  in B field



## energy signature in LAAPD

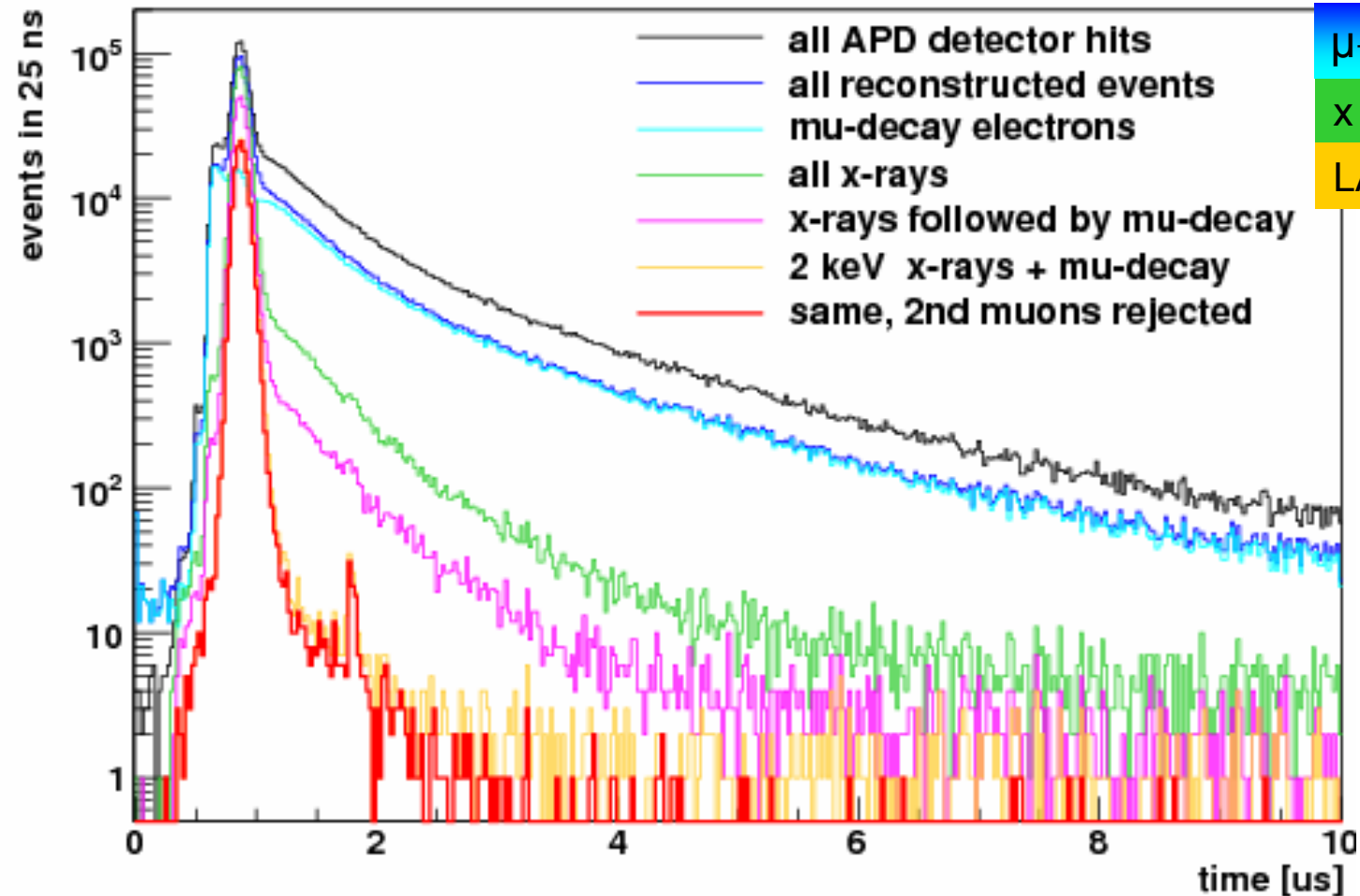
- $E > 8\text{keV}$  ⇔ electron
- $1\text{keV} < E < 8\text{keV}$  ⇔ X ray
- $E < 1\text{keV}$  ⇔ neutron



## X-rays analysis → noise rejection

Example : FP 900 - 11 hrs meas.

- 400  $\mu^-$ /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 !



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

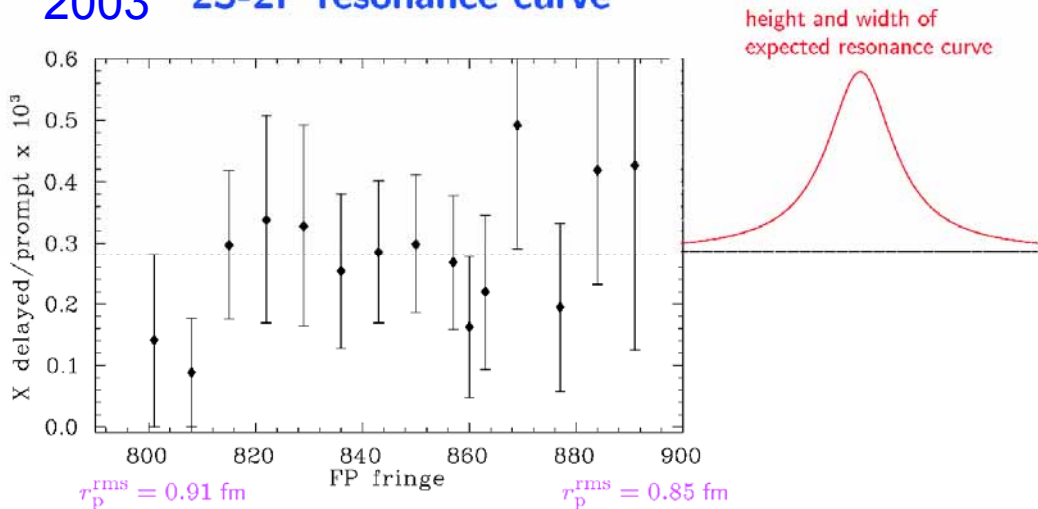
x rays multiplicity 1

LAAPD energy resolution

# Resonance searches (2002, 2003, 2007)

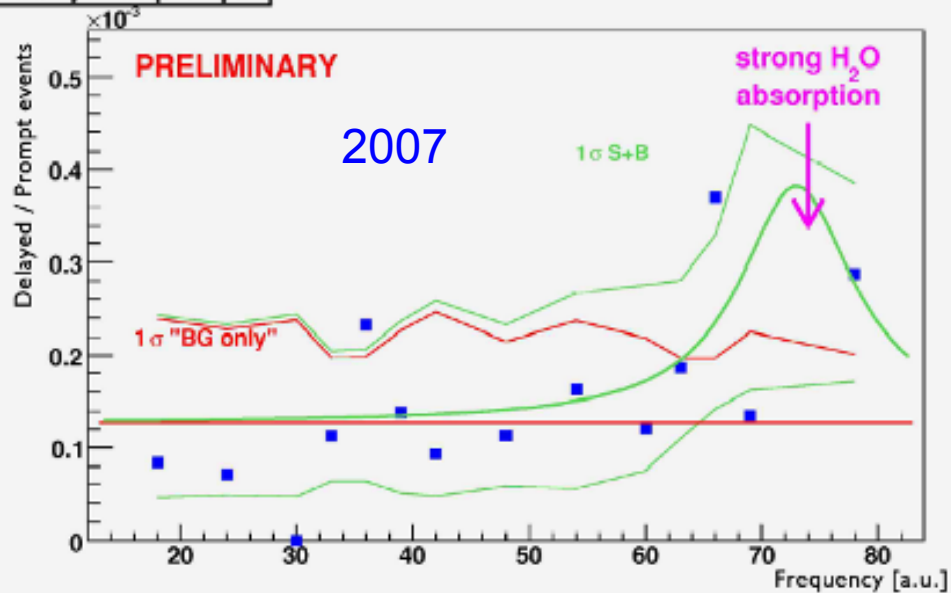
2002 : Run with all the parts at the same time (search for resonance 10 hrs).

## 2003 2S-2P resonance curve



2 “new” XeCl lasers

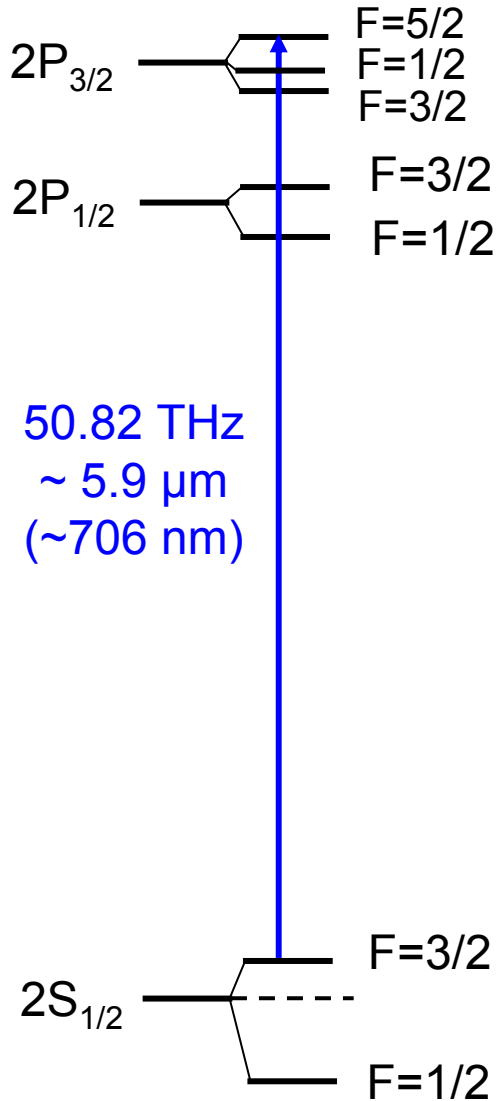
delayed to prompt



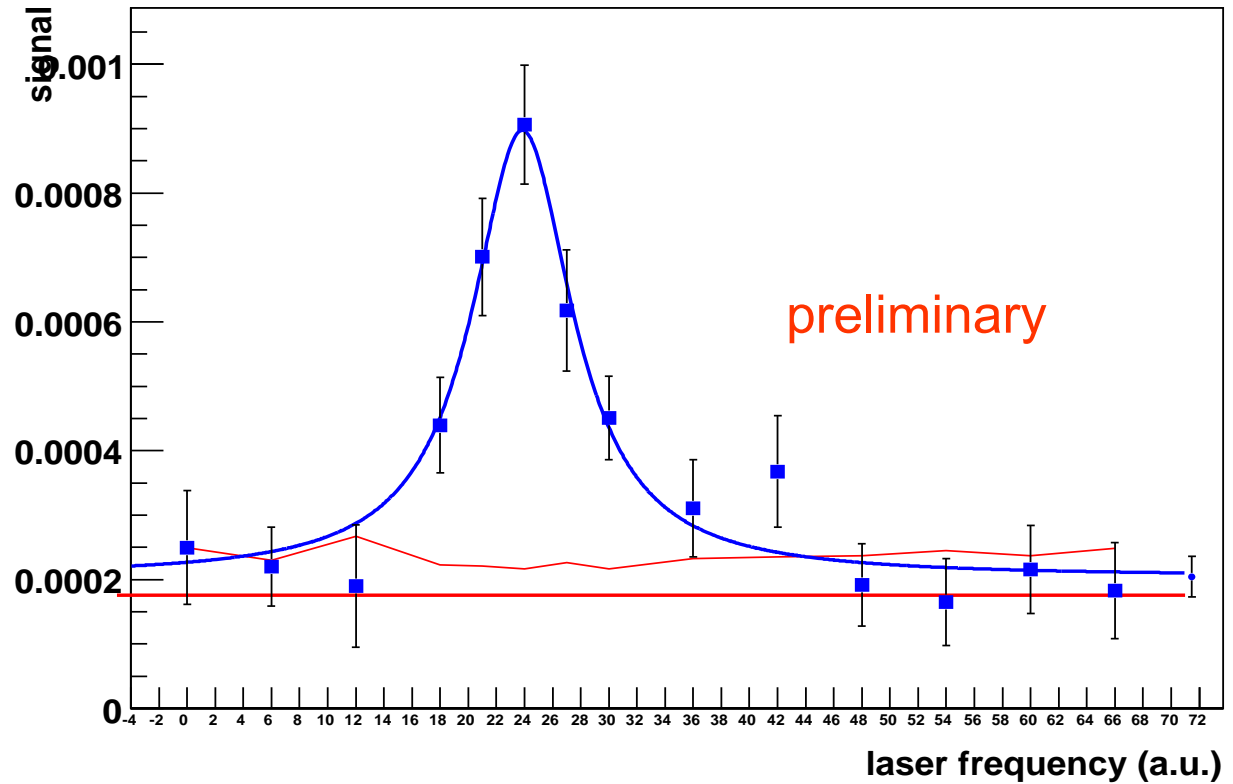
new disk laser



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

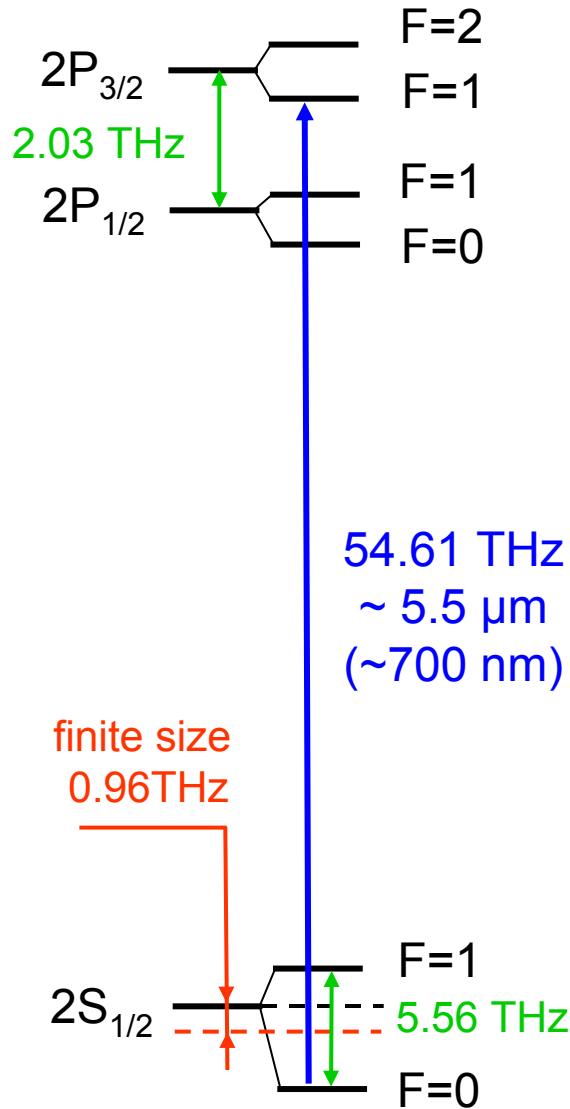


- on line signal, **preliminary**
- frequency position again off

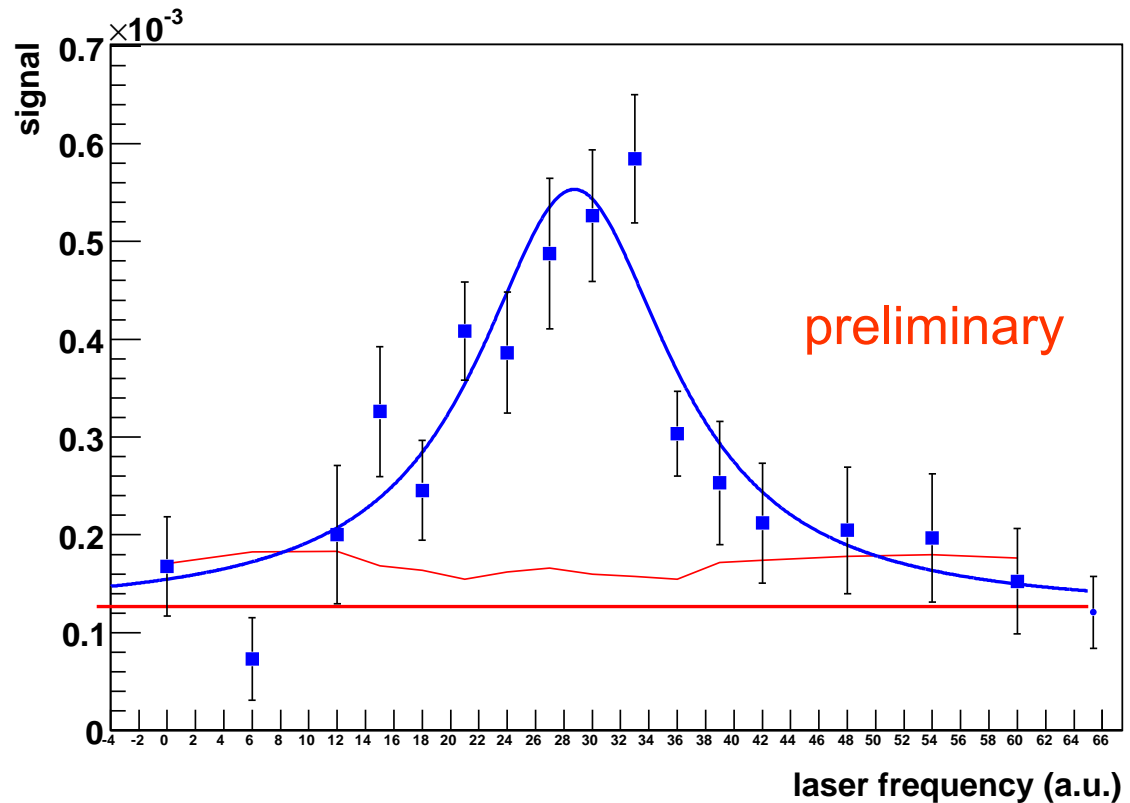


Not at the position estimated with new  $r_p$  and isotopic shift  $\rightarrow$  deuteron polarizability

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

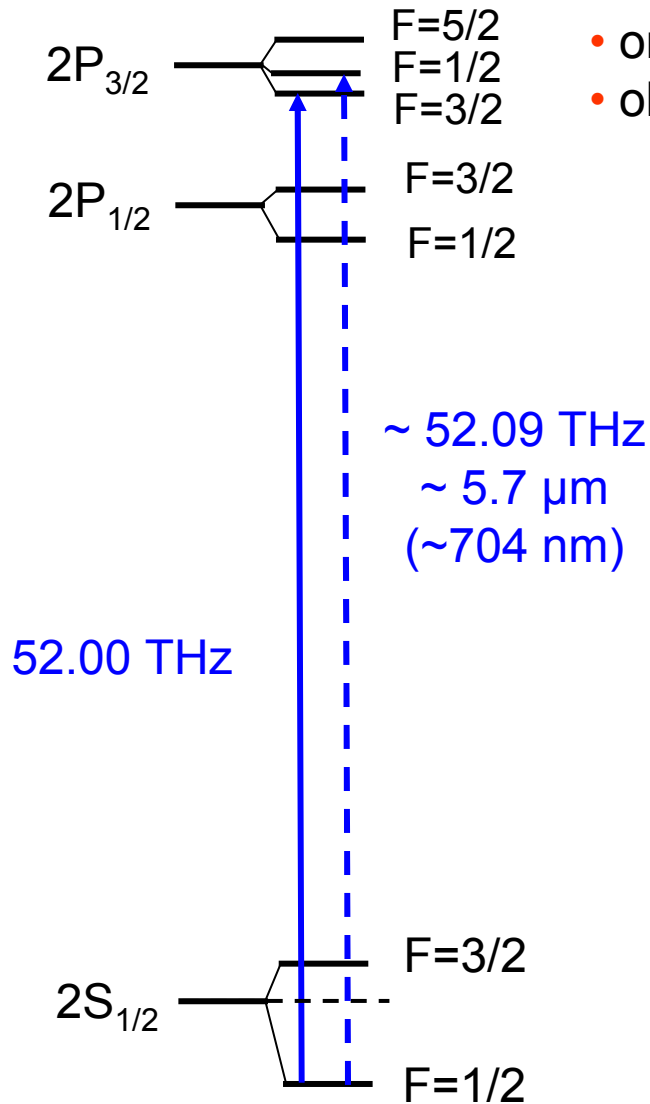


- measured position fits with our proton radius (**preliminary**)
- laser worked even better at  $5.5 \mu\text{m}$

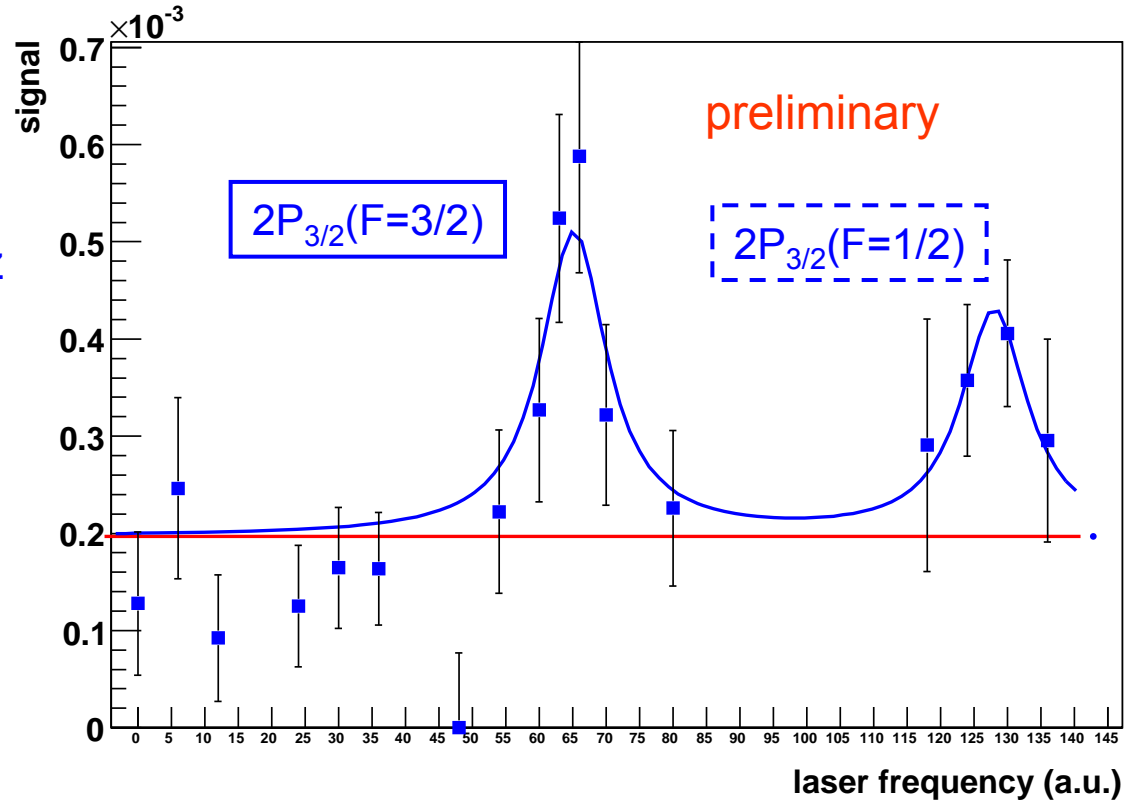


$\sim$  at the position deduced with new  $r_p \rightarrow$  hfs : Zeemach radius (few %)

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



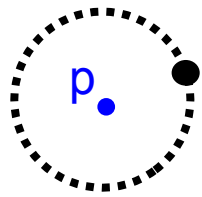
- on line signal, **preliminary**
- observation of 2 more lines in the last 2 days of beam line



“observation” → check calculation in  $\mu\text{d}$

# Muonic hydrogen spectroscopy

Exotic atom



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

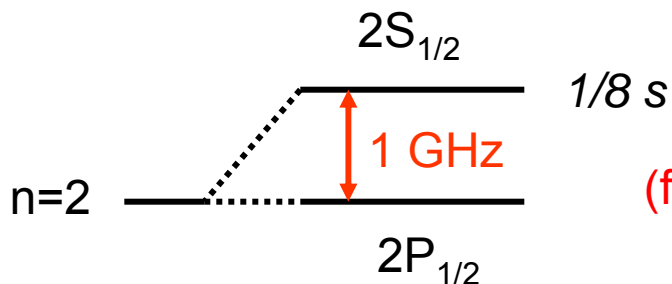
radius :  $\sim a_0/200$

$$E_{NS} = \frac{4}{3} \left( \frac{m_r}{m_e} \right)^3 \frac{R_{\infty} hc}{n^3} \left( \frac{r_p}{a_0} \right)^2 \delta_{10}$$

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

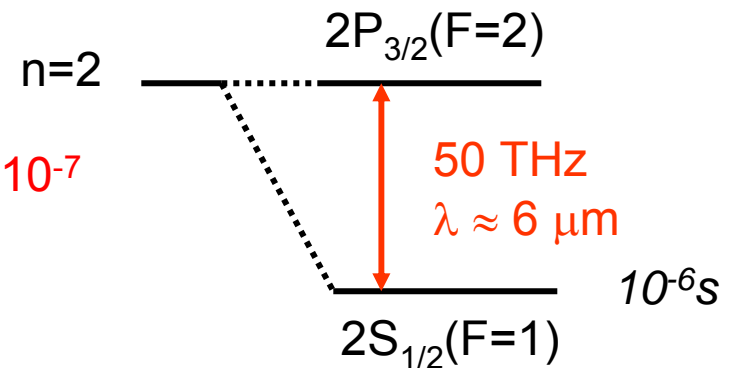
2S-2P	self-energy	vacuum pol.	$r_p$	total
e-p	1084.1 MHz	-26.9 MHz	0.146 MHz	1057.8 MHz
$\mu$ -p	0.17 THz	-50.94 THz	0.96 THz	-49,81 THz

electronic hydrogen : e-p



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

muonic hydrogen :  $\mu$ -p

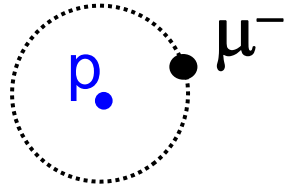


$$\Delta E_{2S-2P} = 50.7724(12) - 1.2637 r_p^2 - 0.0084 r_p^3 = 49.8083 (149) \text{ THz}$$

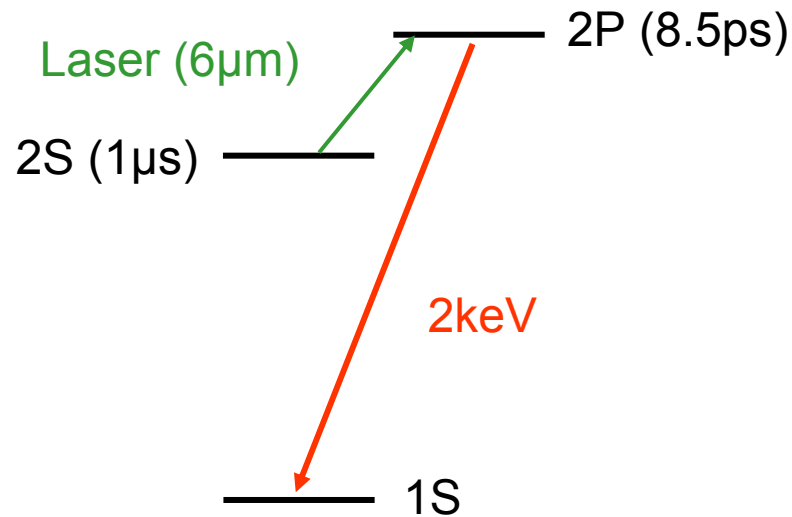
with  $r_p = 0.8760(68) \text{ fm}$

# muonic hydrogen 2S Lamb shift determination of the “proton radius”

Exotic atom



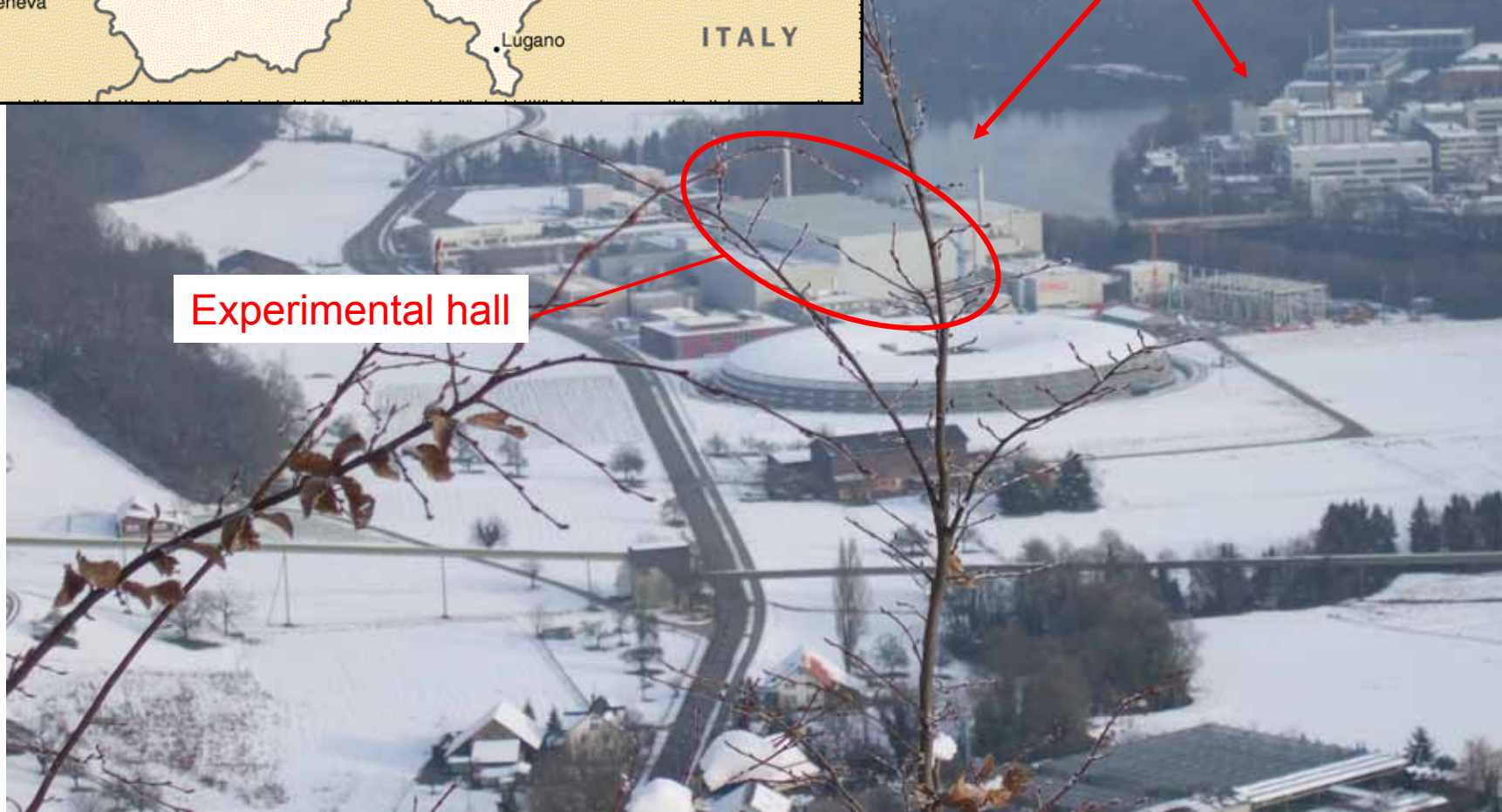
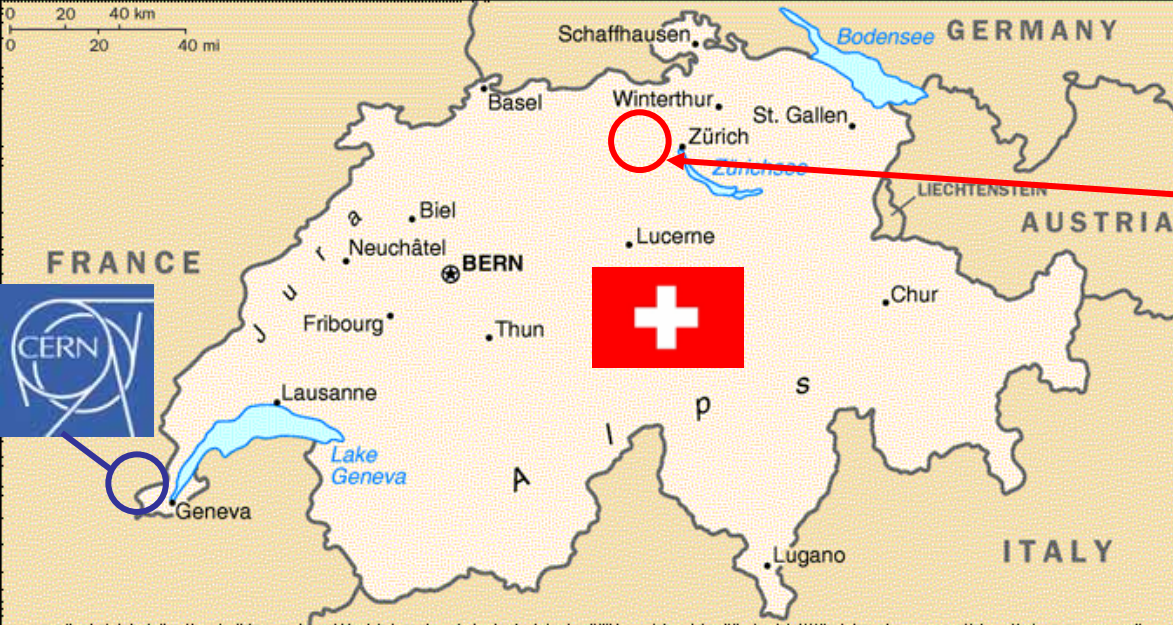
Experiment



Challenges

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

Aim : better determination of proton radius  $r_p$



# 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

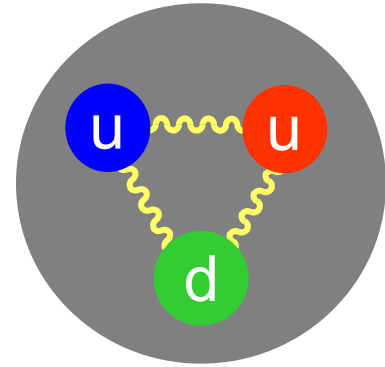
## 4. Future



# Proton

## Structure

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



Proton charge radius :  $r_p$

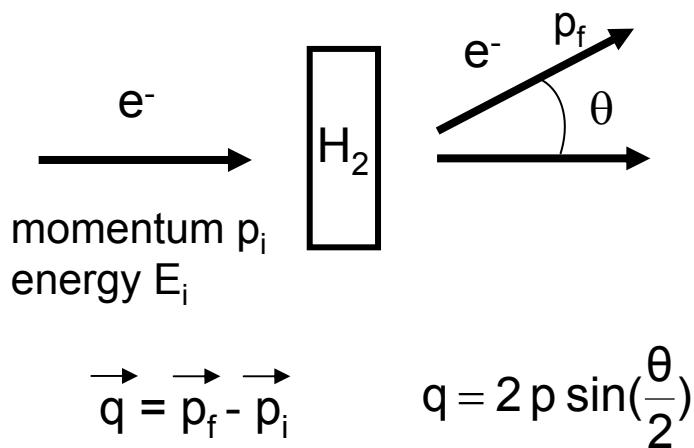
$$r_p = \sqrt{\langle r^2 \rangle} \quad \langle r^2 \rangle = \frac{\int r^2 \rho(r) d^3r}{\int \rho(r) d^3r}$$

$\rho(r)$  : proton charge distribution

## QCD Calculations

- proton mass (< 4%)
- $r_p$  (< 5%)

## Electron-proton scattering

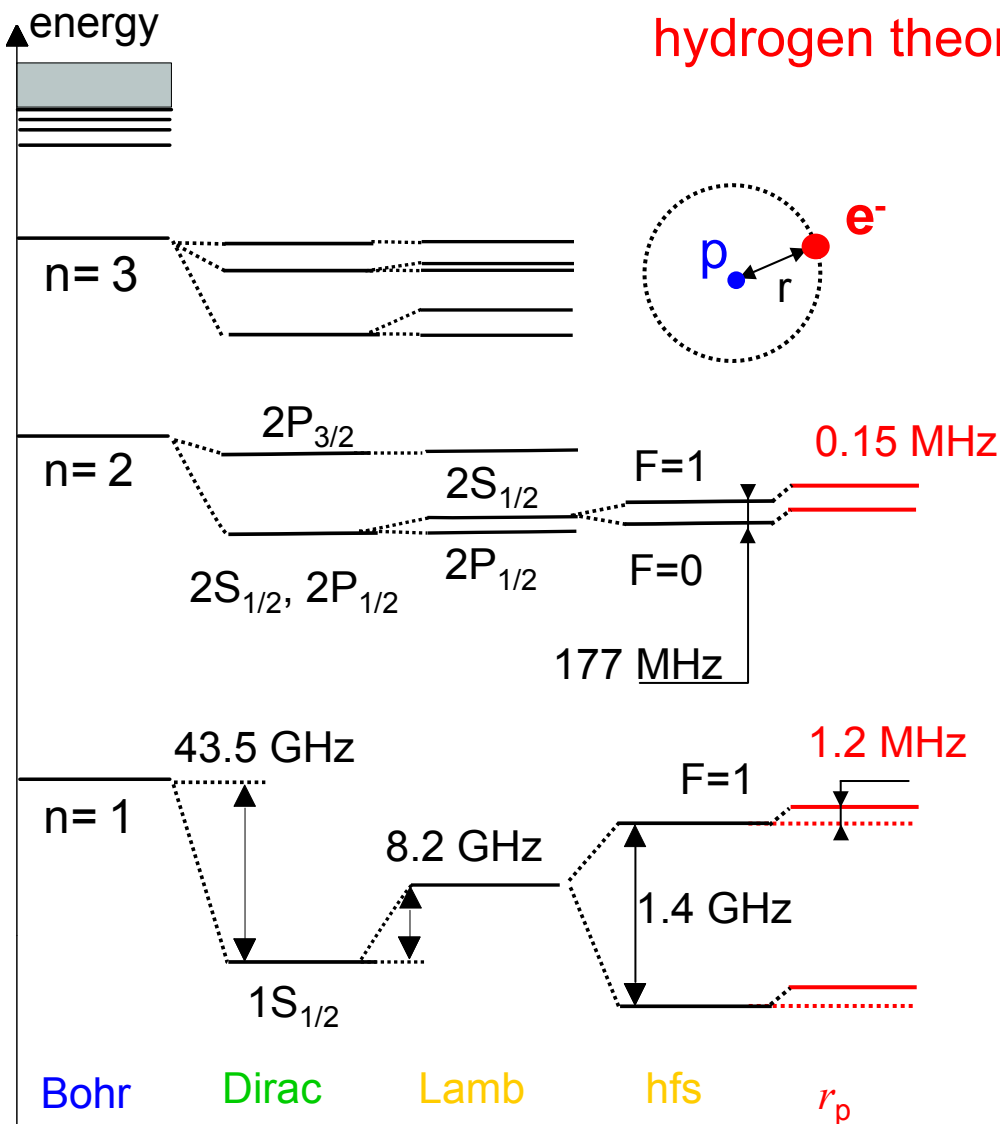


$$\frac{d\sigma}{d\Omega}(E_i, \theta) \approx \underbrace{\left[ \frac{d\sigma}{d\Omega}(E_i, \theta) \right]}_{\text{Rutherford}} G(q^2)$$

$$G(q^2) = \int d^3r e^{iqr} \frac{\rho(r)}{4\pi} \approx 1 - \frac{r_p^2}{6} q^2$$

Limiting factor

# hydrogen theory



$$E(n,l,j) = \underbrace{\text{Dirac} + \text{recoil}}_{\text{exact}} + \underbrace{L(n,j)}_{\text{not well known}}$$

$$hcR_\infty f(\alpha, m_e/m_p, n,l,j)$$

exact

not well known

- QED corrections ( $1/n^3$ )
- relativistic recoil
- charge radius of the proton ( $1/n^3$ )

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

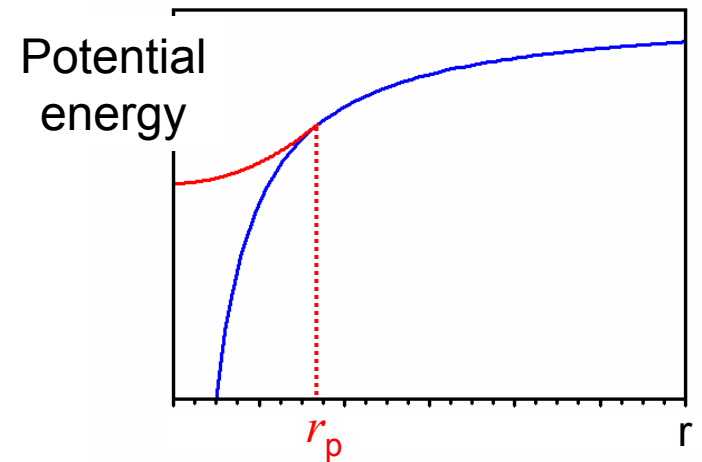
e<sup>-</sup> spin relativity

QED

proton spin

proton size

$$E(1S_{1/2}) = -3\,288\,086\,857\,127.6 \text{ (3.1) kHz.}$$



## hydrogen spectroscopy experiments

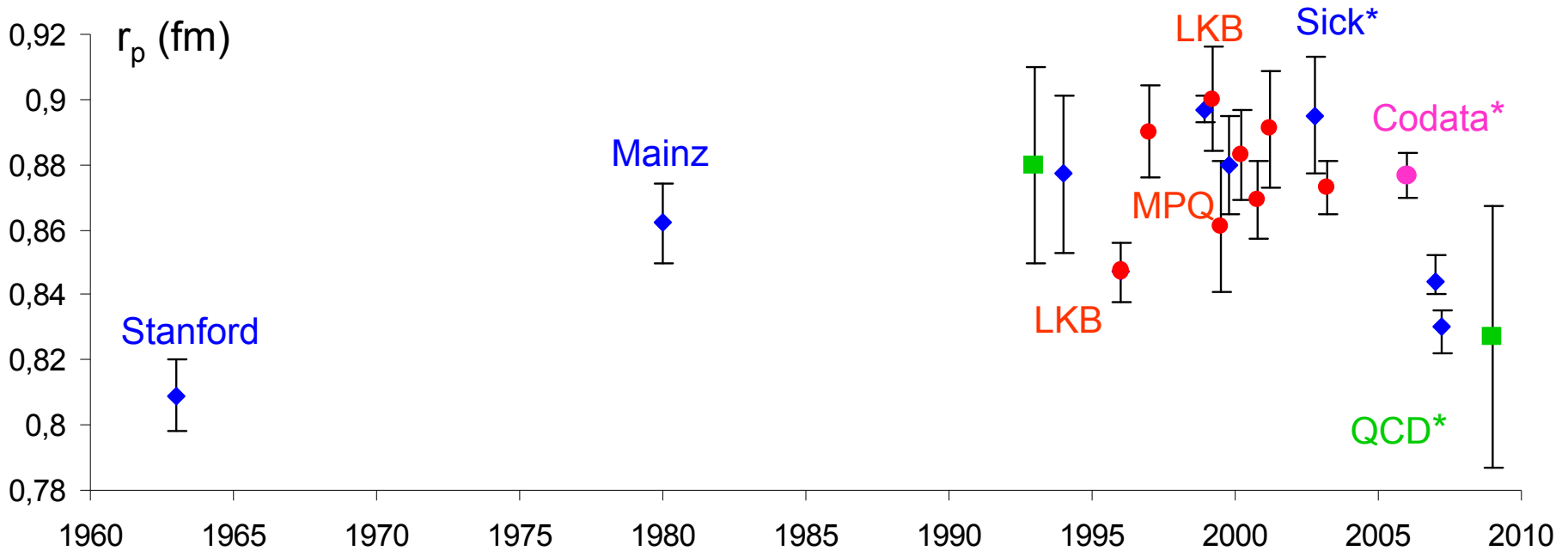
$$E(n,l,j) = hcR_\infty f(\alpha, m_e/m_p, n,l,j) + \text{recoil} + L(n,j,r_p) \approx \frac{R_\infty}{n^2} + L(n,r_p)$$

}	MPQ Garching	$\nu(1S - 2S) = (1 - \frac{1}{4})R_\infty + L(1S) - L(2S)$
	LKB Paris	$\nu(2S - 8S) = (\frac{1}{4} - \frac{1}{64})R_\infty + L(2S) - L(8S)$
	S. Karshenboim K. Pachucki	$L(1S) - 8L(2S) = \text{precisely calculated}$

Linear combinations  $\rightarrow R_\infty, L^{\text{exp}}(1S)$

$$L^{\text{exp}}(1S) = 8172.840 (19) \text{ kHz} + \text{QED} \rightarrow r_p (1\%)$$

## Previous determinations of the “proton radius”



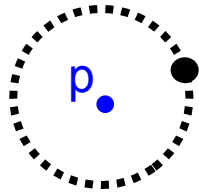
\* Hydrogen data(1S-2S and 2S-nS/nD) + QED re-evaluation : 0,8760 (78) fm

\* Electron scattering (all meas+re-analysis): 0,895 (18) fm

\* QCD (lattice cal.) : 0,827 (40) fm

# Muonic hydrogen spectroscopy

Exotic atom

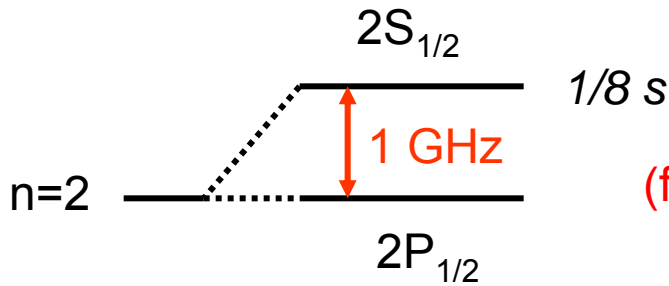


$$\frac{m_{\mu}}{m_e} = 207$$

radius :  $\sim a_0/200$

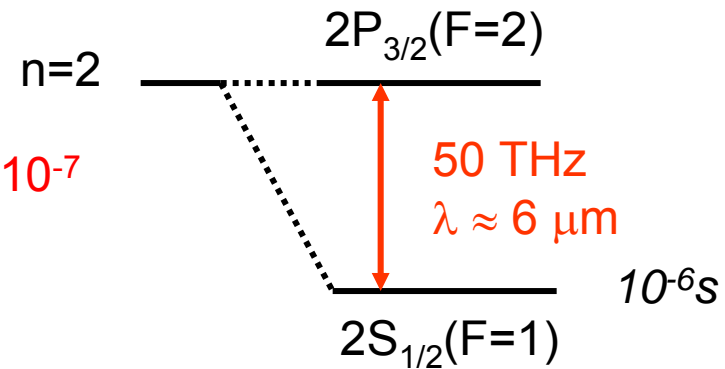
$$E_{NS} = \frac{4}{3} \left( \frac{m_r}{m_e} \right)^3 \frac{R_{\infty} hc}{n^3} \left( \frac{r_p}{a_0} \right)^2 \delta_{l0}$$

electronic hydrogen : e-p



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

muonic hydrogen :  $\mu$ -p



$$\Delta E_{2S-2P} = 50.7724(12) - 1.2637 r_p^2 - 0.0084 r_p^3 = 49.8083 (149) \text{ THz}$$

with  $r_p = 0.8760(68) \text{ fm}$

# Outline

## 1. Introduction

- proton properties
- experimental proton size determinations
- muonic hydrogen

## 2. Experiment

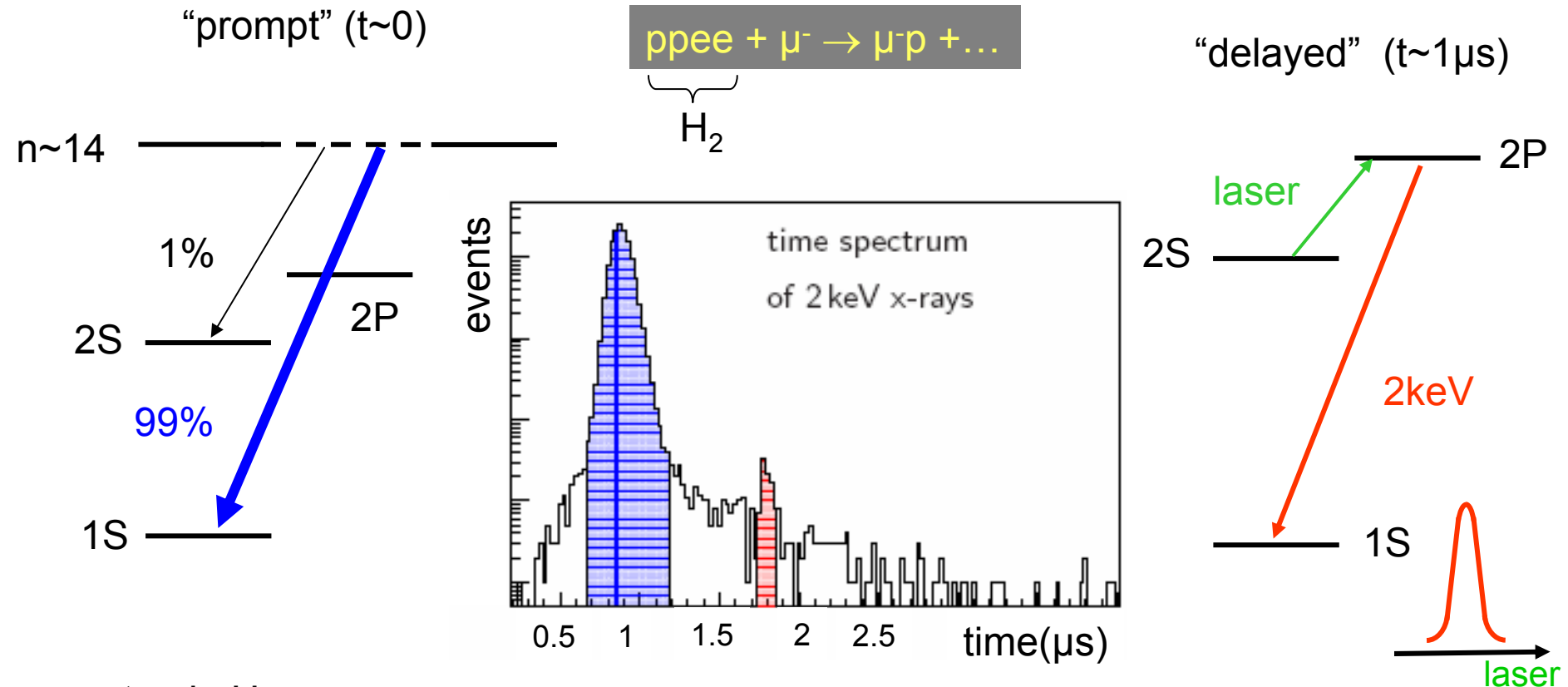
- muonic hydrogen source
- laser system
- analysis

## 3. Results

- signal
- proton radius from muonic hydrogen spectroscopy
- outcomes

## 4. Future

# Principle of the experiment



$\mu^-$  stop in  $\text{H}_2$  gas  
 $\Rightarrow \mu\text{p}^*$  atoms formed ( $n \sim 14$ )

99%: cascade to 1S emitting prompt  $\text{K}\alpha, \text{K}\beta, \dots$

1%: long lived 2S state ( $\tau \sim 1 \mu\text{s}$  at 1mbar)

Fire laser ( $\lambda \sim 6 \mu\text{m}$ ,  $\Delta E \sim 0.2 \text{eV}$ )  
 $\Rightarrow$  induce  $\mu\text{p}(2\text{S}-2\text{P})$

$\Rightarrow$  observe delayed  $\text{K}\alpha$  x-rays

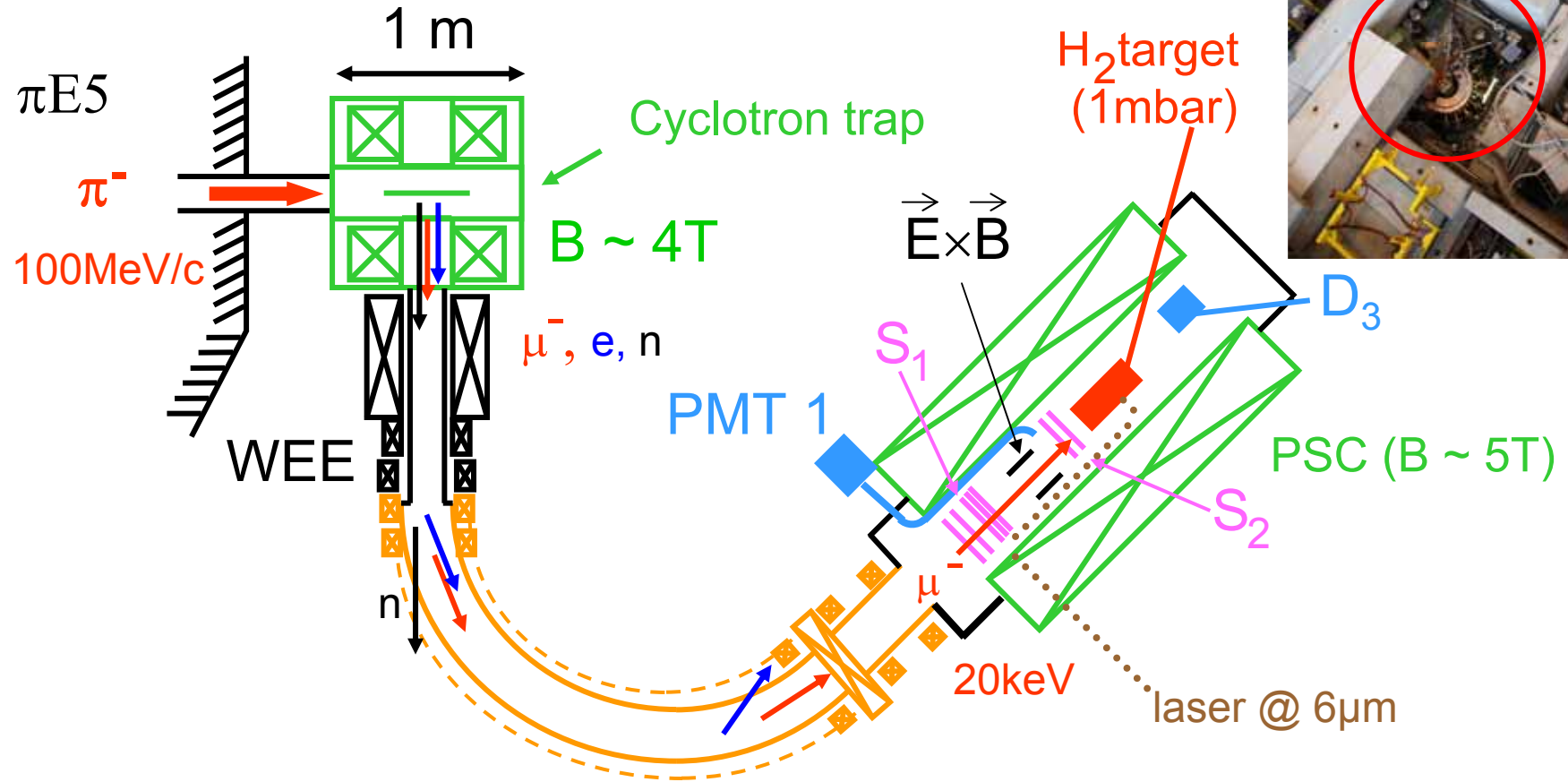
$\Rightarrow$  normalize  $\frac{\text{delayed } \text{K}\alpha}{\text{prompt } \text{K}\alpha}$  x-rays



# muonic hydrogen source

$p$  (500MeV, 2mA)  $\rightarrow$  carbon target  $\rightarrow$




$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (300 \mu\text{/s})$$



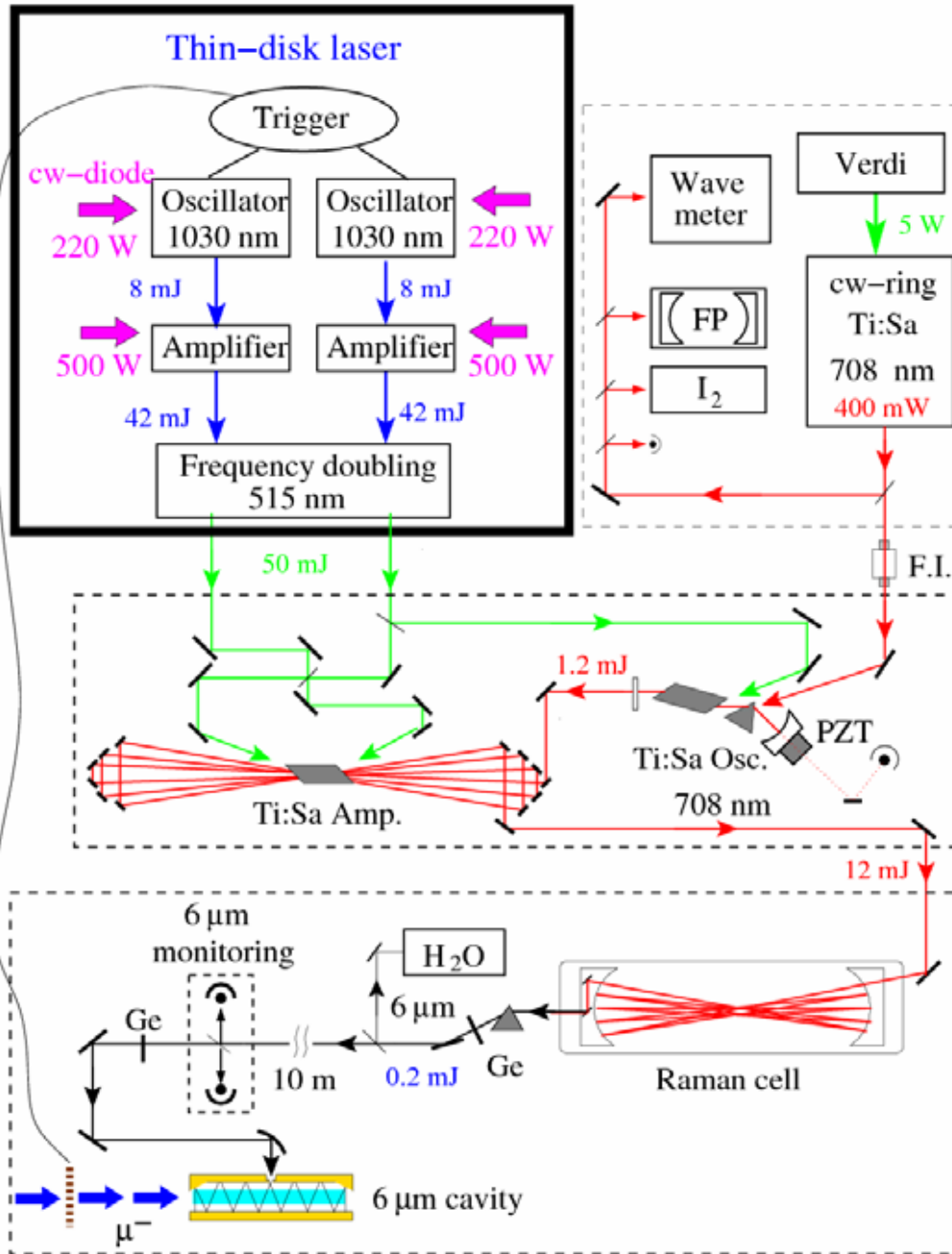
Muon Extraction Channel

$S_1 S_2 \rightarrow$  T.O.F.  $\rightarrow$  laser trigger

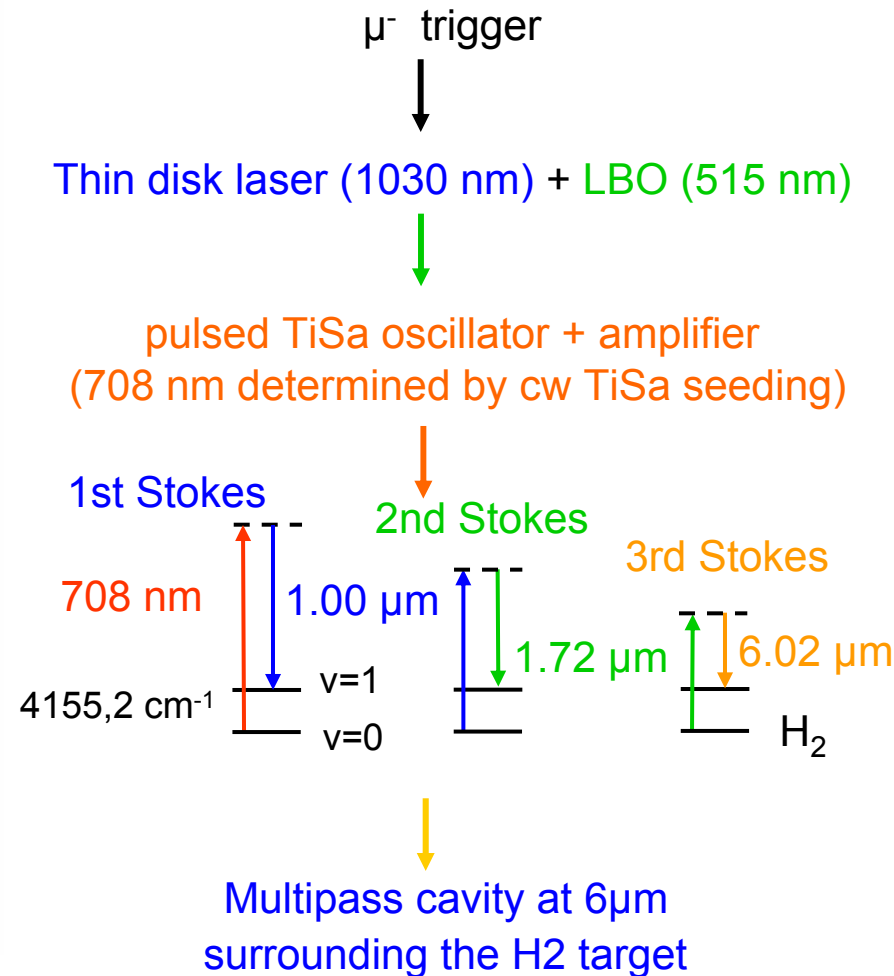
## muon life in CREMA experiment

-  pion  $\pi^-$
-  muon  $\mu^-$
-  photon from scintillator

# Laser chain



- Each single muon triggers the laser system (random trigger)
- 2S lifetime  $\sim 1\mu\text{s}$   $\rightarrow$  short laser delay (disk laser)
- 6  $\mu\text{m}$  tunable laser pulse (0.2mJ)



# X-rays analysis → noise rejection

Example : FP 900 - 11 hrs meas.

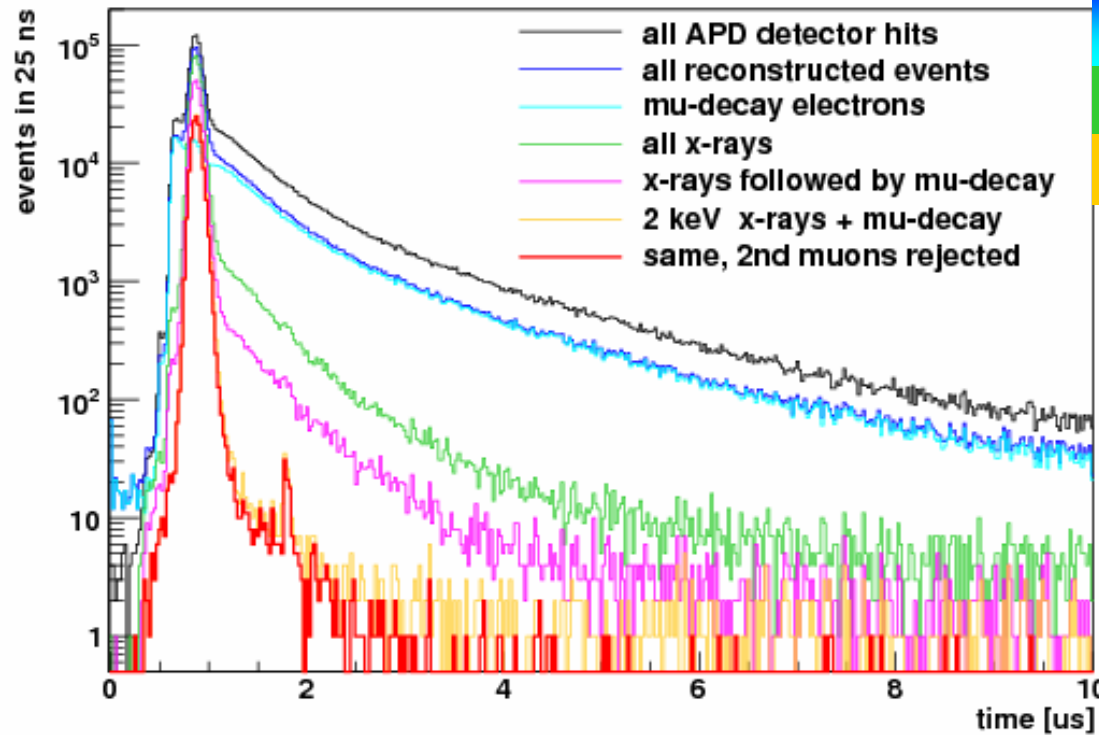
- 400  $\mu^-$ /s
- 240 laser shot/s
- 860 000 laser shot/hour
- 1.56 million detector clicks
- 19600 clicks in the laser region
- expected 2-3 laser induced events/hour !

## time signature in LAAPD

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

## energy signature in LAAPD

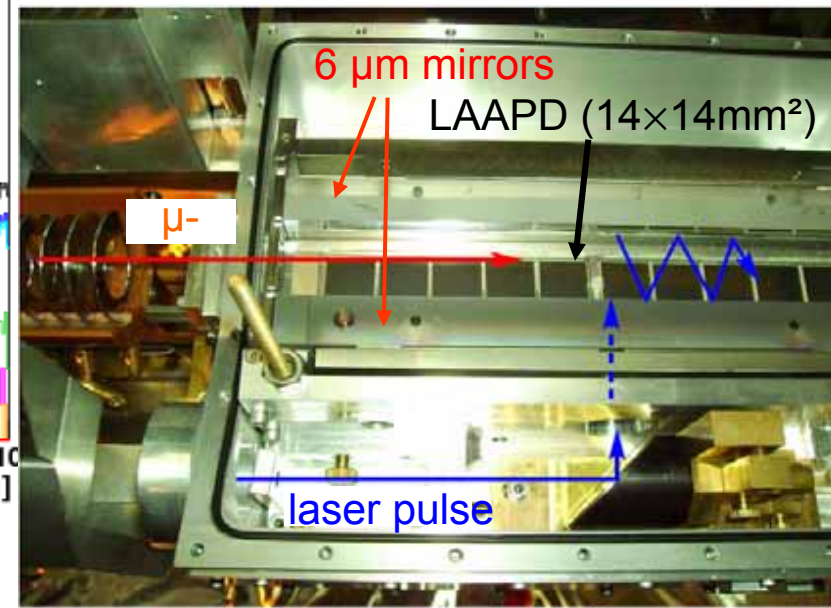
- $E > 8\text{keV} \Leftrightarrow$  electron
- $1\text{keV} < E < 8\text{keV} \Leftrightarrow$  X ray
- $E < 1\text{keV} \Leftrightarrow$  neutron



$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

x rays multiplicity 1

LAAPD energy resolution



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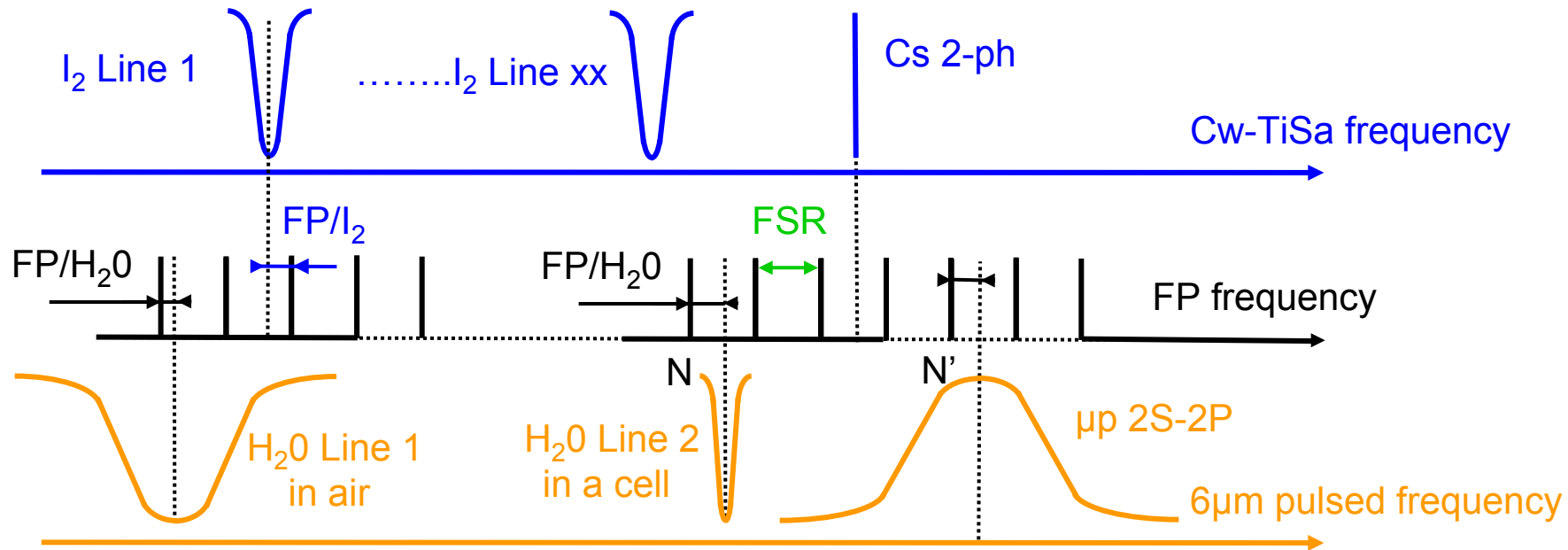
## 3. Results

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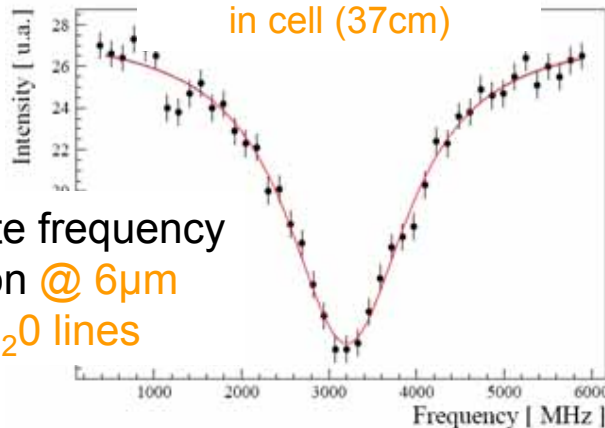
## 4. Future

# Laser chain : frequency calibration

FSR measured/controlled in cw with I<sub>2</sub> (1 ph abs), Cs (2 ph fluo), Rb (2 ph fluo), lines



absorption@1662cm<sup>-1</sup>  
in cell (37cm)



$$\nu(\mu\text{p}:2\text{S}-2\text{P}) = \nu(\text{H}_2\text{O Line 2}) + (N-N') \text{ FSR}$$

FP absolute frequency  
calibration @ 6µm  
with H<sub>2</sub>O lines

## $\mu\text{p } (2S_{1/2}(F=1)-2P_{3/2}(F=2))$ : uncertainty budget

### Statistics

- uncertainty on position (fit) 700 MHz ( $\sim 4\%$  of  $\Gamma_{\text{nat}}$ )

$$\Delta\nu_{\text{experimental}} = 20 (1) \text{ GHz} \quad (\Gamma_{\text{nat}} = 18.6 \text{ GHz})$$

### Sources :

- Laser frequency ( $\text{H}_2\text{O}$  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  $\mu\text{m}$  laser line width  $\sim 2$  GHz
- Doppler Broadening  $< 1$  GHz
- Collisional broadening 2.4 MHz

$$\nu (\mu\text{p} : 2S_{1/2}(F=1)- 2P_{3/2}(F=2)) = 49\,881.88 (76) \text{ GHz} \quad (1.6 \times 10^{-5})$$



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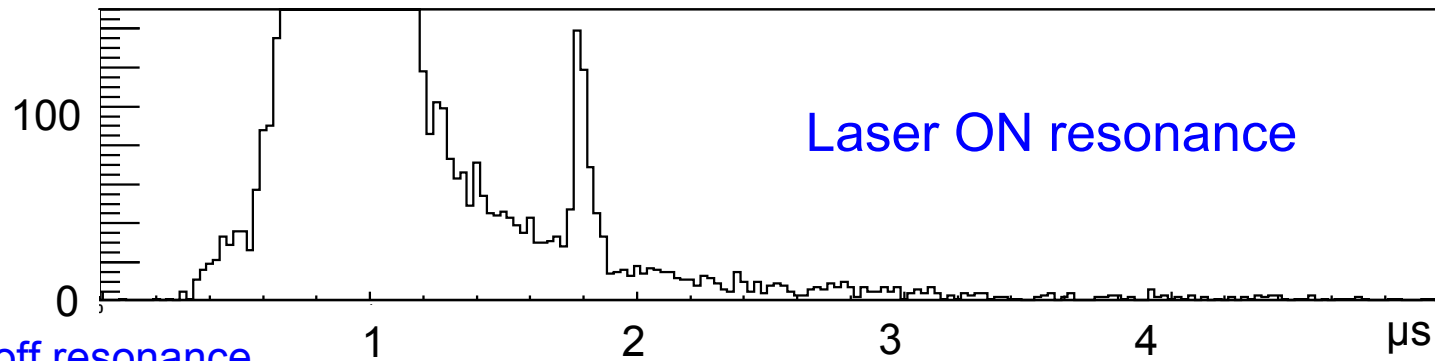
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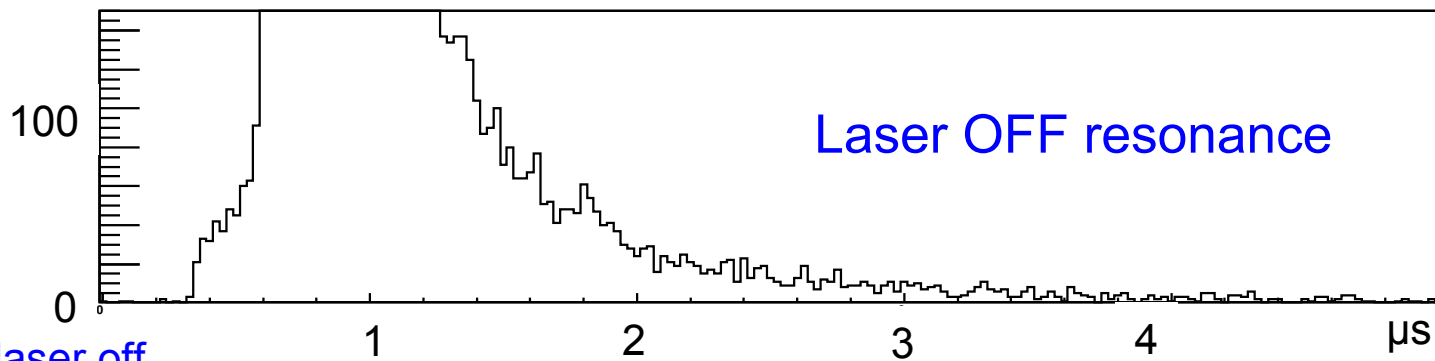
## 4. Future

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

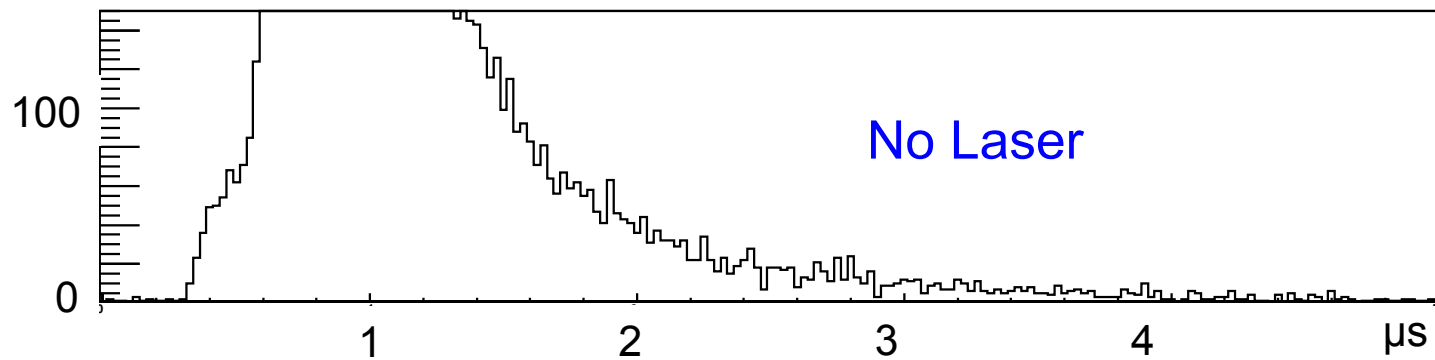
summed on resonance



summed off resonance



summed laser off



## New $r_p$ ( $\mu p$ ( $2S_{1/2}(F=1) - 2P_{5/2}(F=2)$ )) : outcomes

### Muonic hydrogen Lamb shift

- check on line consistency of all publications (P. Indelicato, E. O. Le Bigot, F. Kottmann)
- independent QED calculations (P.Indelicato, P.J.Mohr) (large contributions : OK)
- check others theoreticians (PSAS 2010...)

### Hydrogen spectroscopy, Rydberg constant $R_\infty$ :

$$\begin{array}{ll}
 H : \nu_{1S-2S} = \frac{3}{4} R_\infty + L(\text{QED}, r_p) & cR_\infty = 3\,289\,841\,960\,360.9 \text{ (21.9) kHz } (6.6 \times 10^{-12}) \\
 \uparrow \quad \quad \quad \uparrow & \\
 (34 \text{ Hz}) \quad u_r(R_\infty) : 2S-nS/nD \ (n=8,12) & cR_\infty = 3\,289\,841\,960\,250.9 \text{ (4.8) kHz } (1.5 \times 10^{-12}) \\
 & \quad \quad \quad (\sim 7 \text{ kHz}) \quad \quad \quad \text{but } \sim 5 \sigma \text{ shift } (3.3 \times 10^{-11})
 \end{array}$$

$$\begin{array}{l}
 \text{Without Paris } cR_\infty = 3\,289\,841\,960\,379.8 \text{ (48.0) kHz } (14.6 \times 10^{-12}) \\
 \text{(from CODATA98 Rev. Mod. Phys. 72, n°2, April 2000)}
 \end{array}$$

Codata 2006 “The experimental and theoretical H and D data remain highly consistent.”

First measurement of 1S-3S (LKB) : 2 922 743 278 678(13) kHz. EPJ D **60** p.243 (2010)  
 Prediction : 2 922 743 278 671.6(1.4) kHz PRL **95**, 163003 (2005)

### “New physics”:

*“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.”* PRL **106**, 153001 (2011)

Example of constrain : magnetic moment anomaly of the electron (Gabrielse, Kinoshita)  $g-2=f(\alpha/\pi)$

$$\begin{array}{ll}
 \text{With recoil (LKB)} & \nu_r = \frac{\hbar k}{m(\text{Rb})} \quad \alpha^2 = \frac{2R_\infty}{c} \frac{m(\text{Rb})}{m_p} \frac{m_p}{m_e} \frac{h}{m(\text{Rb})} \quad \text{PRL } \mathbf{106}, 080801 (2011)
 \end{array}$$

## Prospect : muonic helium spectroscopy at PSI

2013....→ muonic helium spectroscopy

- $\mu\text{He}^+$  spectroscopy +  $\text{He}^+$  spectroscopy → QED test ( $Z\alpha$ )
- test of the spectroscopy of muonic system

# Up date comparison

New electron-proton scattering : Phys Rev Lett 105, 242001 (2010)

Model independent analysis of proton structure...:Phys Rev Lett 107, 160402 (2011)

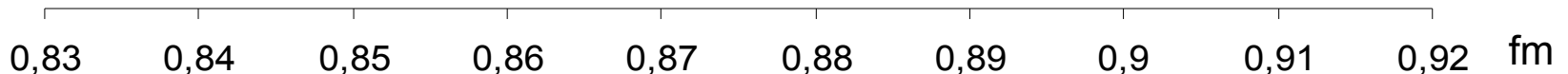
$$\nu (\mu\text{p} : 2S_{1/2}(F=1) - 2P_{3/2}(F=2)) = 49\,881.88 (76) \text{ GHz}$$
$$\nu_{\text{theo}} = 50772.43(967) - 1263.69 r_p^2 + 8.39 r_p^3 \text{ GHz}$$
$$r_p = 0.84184(36)(458) \text{ fm}$$

electron-proton scattering re-analysis |-----●-----| 0,895 (18) fm

H/D spectroscopy + QED |-----●-----| 0.8760 (78) fm

New electron-proton scattering |-----●-----| 0.879 (8) fm

|-----●-----|  $\mu\text{p} (2S_{1/2}(F=1) - 2P_{3/2}(F=2))$  spectroscopy + QED 0.8418 (46) fm

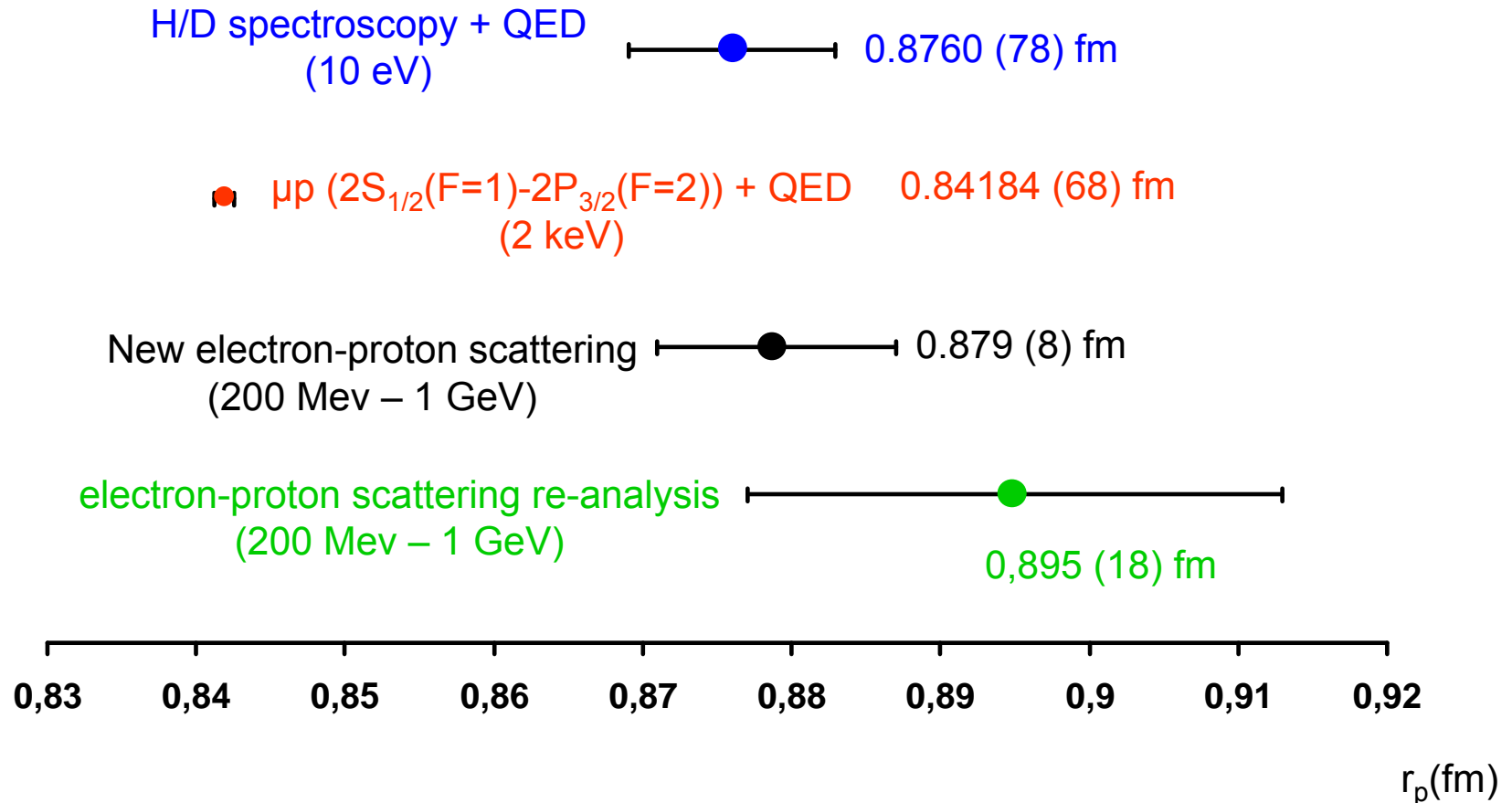


# Comparison with other best determinations

$$v_{\text{theo}} = f(R_{\infty}, \text{QED}, r_p) = 50772.43(1.18) - 1263.69 r_p^2 + 8.39 r_p^3 \text{ GHz}$$

$$v (\mu p : 2S_{1/2}(F=1) - 2P_{3/2}(F=2)) = 49\,881.88 (76) \text{ GHz}$$

$$\Rightarrow r_p = 0.84184(36)(56) \text{ fm}$$



New electron-proton scattering : Phys Rev Lett 105, 242001 (2010)

Muonic hydrogen : *Nature* 466, 213-216 (2010)