The size of the proton

from the Lamb shift in muonic hydrogen

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THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

OIL SPILLS
There's worse to come

BIODIVERSITY
The need to cost the Earth

EARLY EUROPEANS
A northern outpost

SHRINKING THE PROTON
New value from exotic atom trims radius by five percent

for the *CREMA* collaboration

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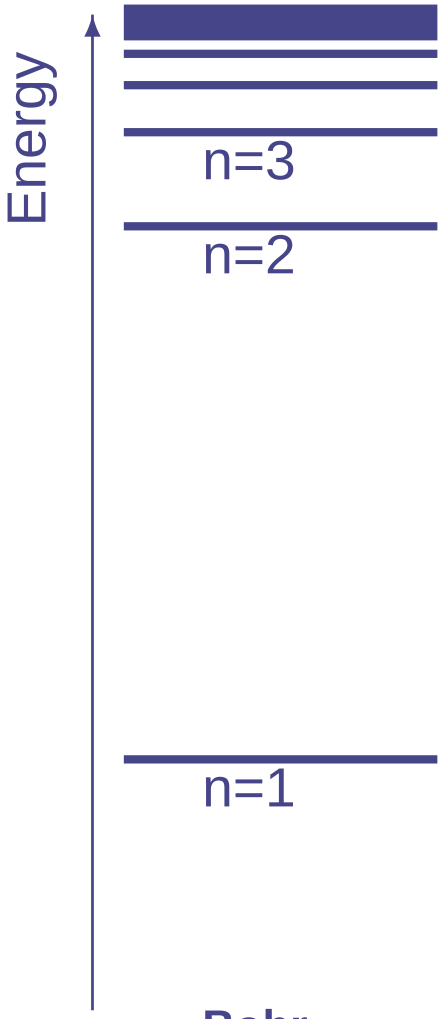
Outline

- Introduction:
  Hydrogen, fundamental constants, QED tests and all that.
  How large is the proton?
- Muonic hydrogen:
  (Finite) size does matter!
- Experiment
  - Principle
  - Muon beam
  - Laser system
  - Data
- Results
  - muonic hydrogen #1 $\longrightarrow$ proton charge radius
  - muonic hydrogen #2 $\longrightarrow$ proton's Zemach (magnetic) radius
  - muonic deuterium #1 $\longrightarrow$ deuteron charge radius, polarizability
  - muonic deuterium #2 + #3 $\longrightarrow$ theory work ahead!

Hydrogen energy levels

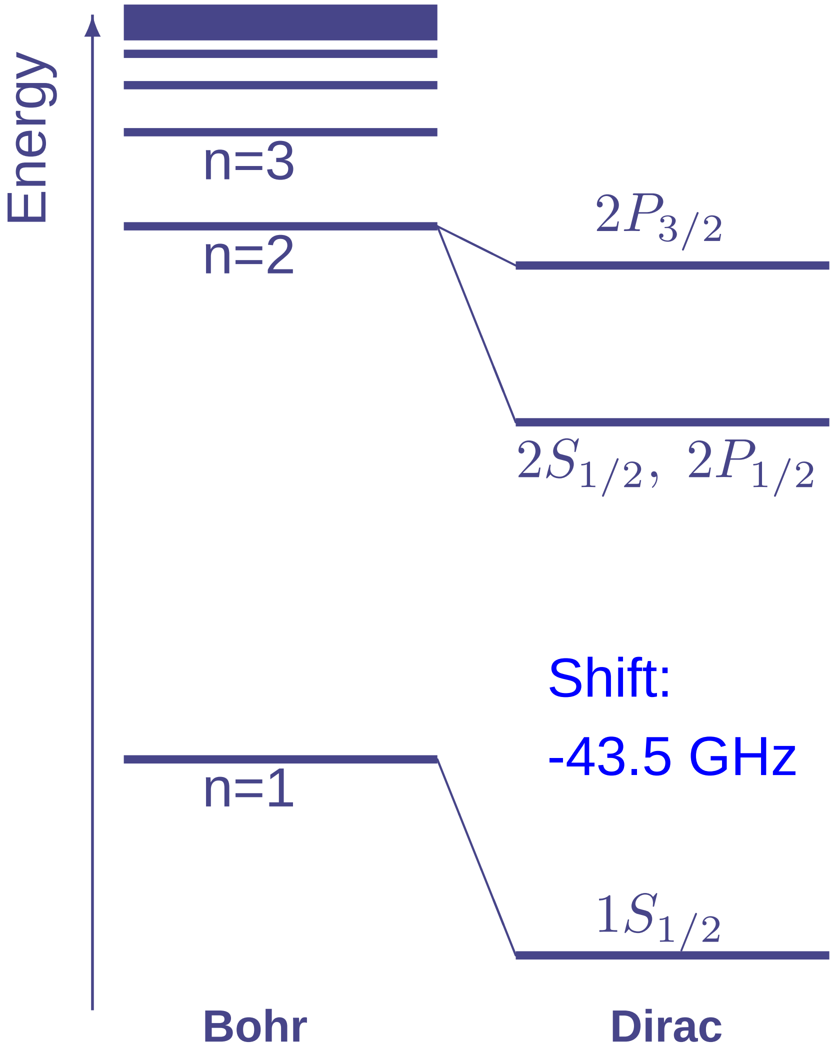


Bohr

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

$$V \sim 1/r$$

Hydrogen energy levels



Shift:

-43.5 GHz

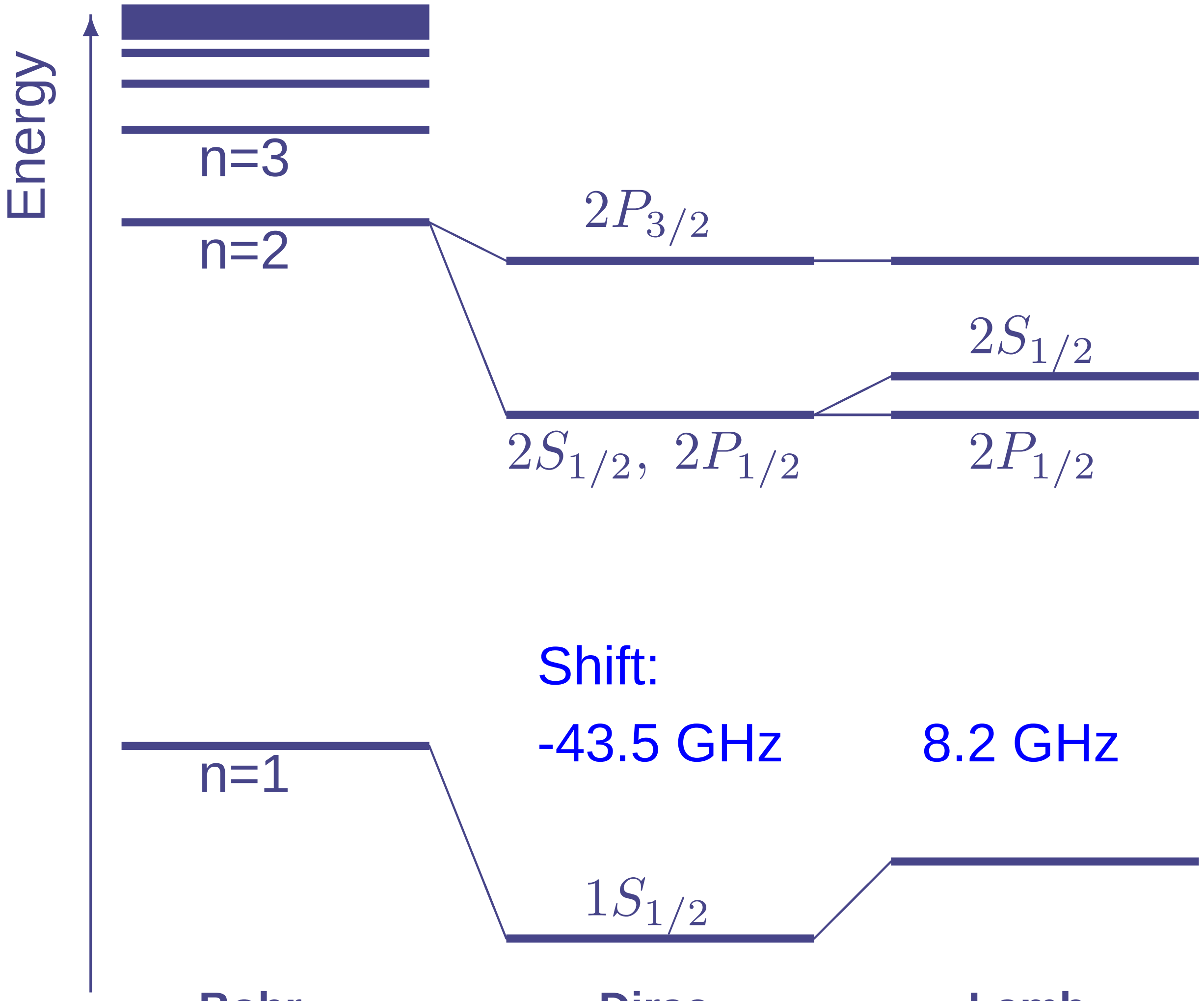
$E = R_\infty / n^2$

$V \sim 1/r$

e^- spin

relativity

Hydrogen energy levels

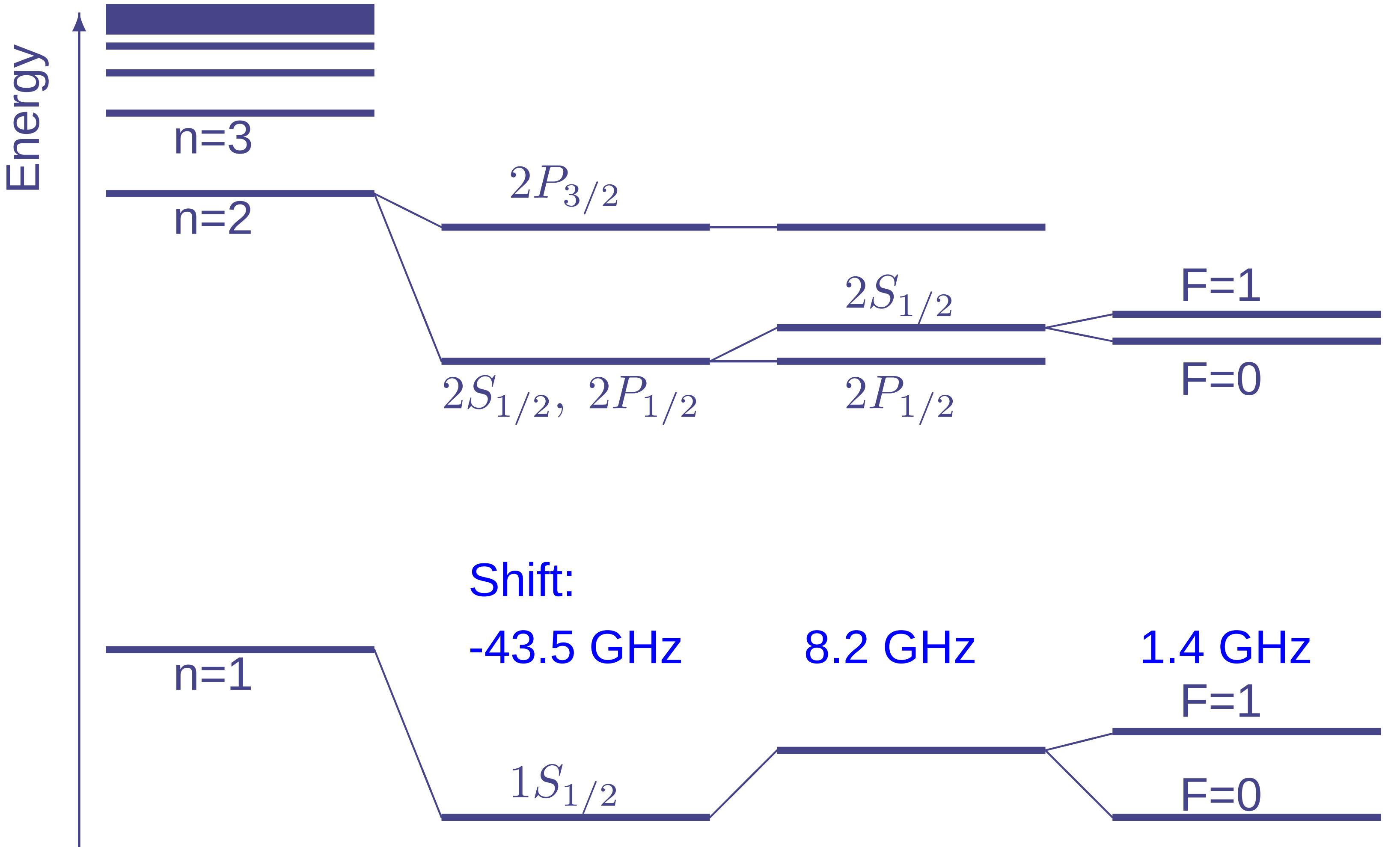


Shift:

-43.5 GHz 8.2 GHz

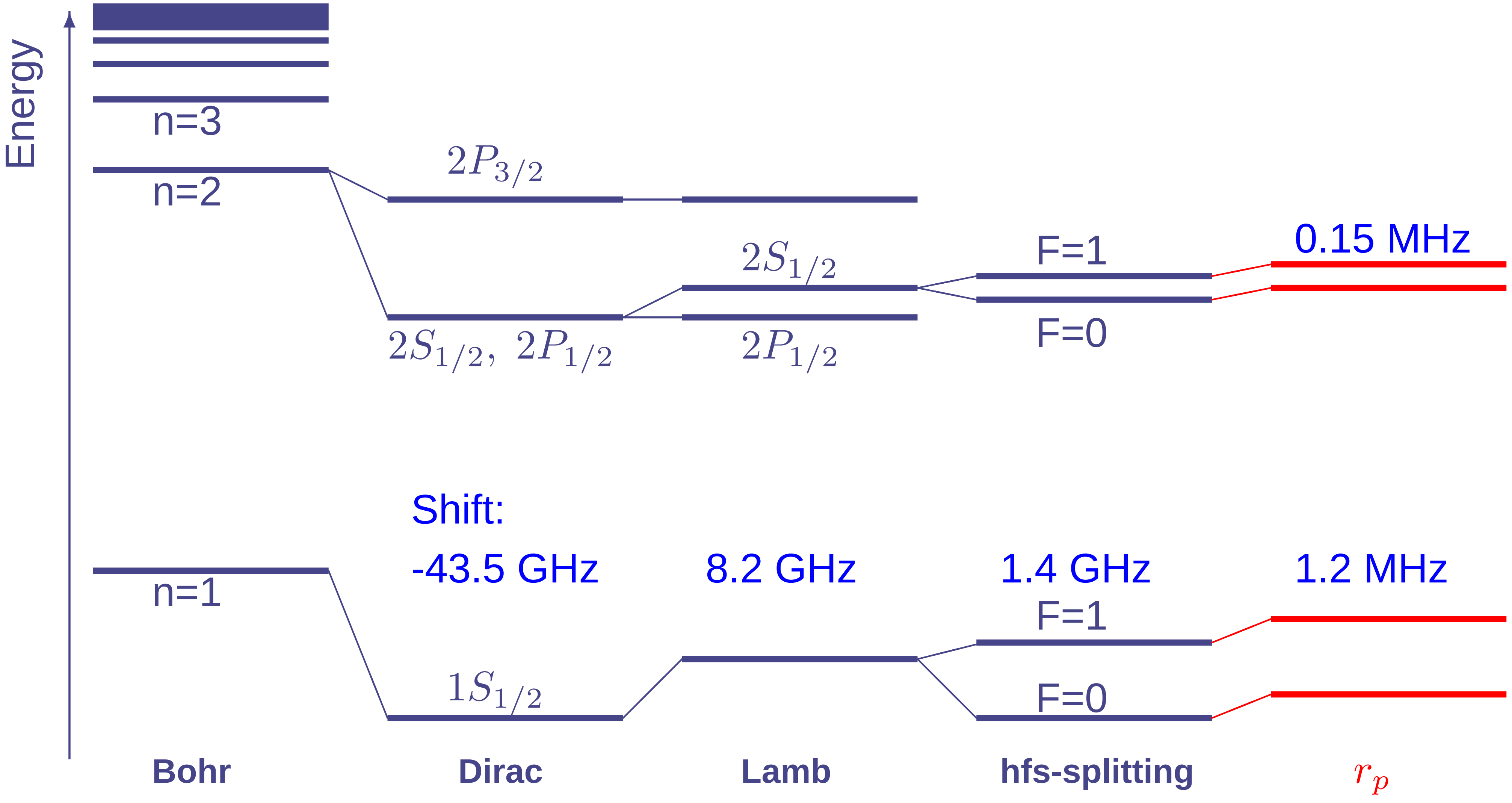
Bohr	Dirac	Lamb
$E = R_\infty / n^2$ $V \sim 1/r$	e$^-$ spin relativity	QED

Hydrogen energy levels



Bohr	**Dirac**	**Lamb**	**hfs-splitting**
$E = R_\infty / n^2$ $V \sim 1/r$	e^- spin relativity	QED	proton-spin $H^{\mathrm{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$

Hydrogen energy levels



Energy

n=3

n=2

n=1

$2P_{3/2}$

$2S_{1/2},\ 2P_{1/2}$

$1S_{1/2}$

$2S_{1/2}$

$2P_{1/2}$

F=1

F=0

F=1

F=0

0.15 MHz

Shift:

-43.5 GHz

8.2 GHz

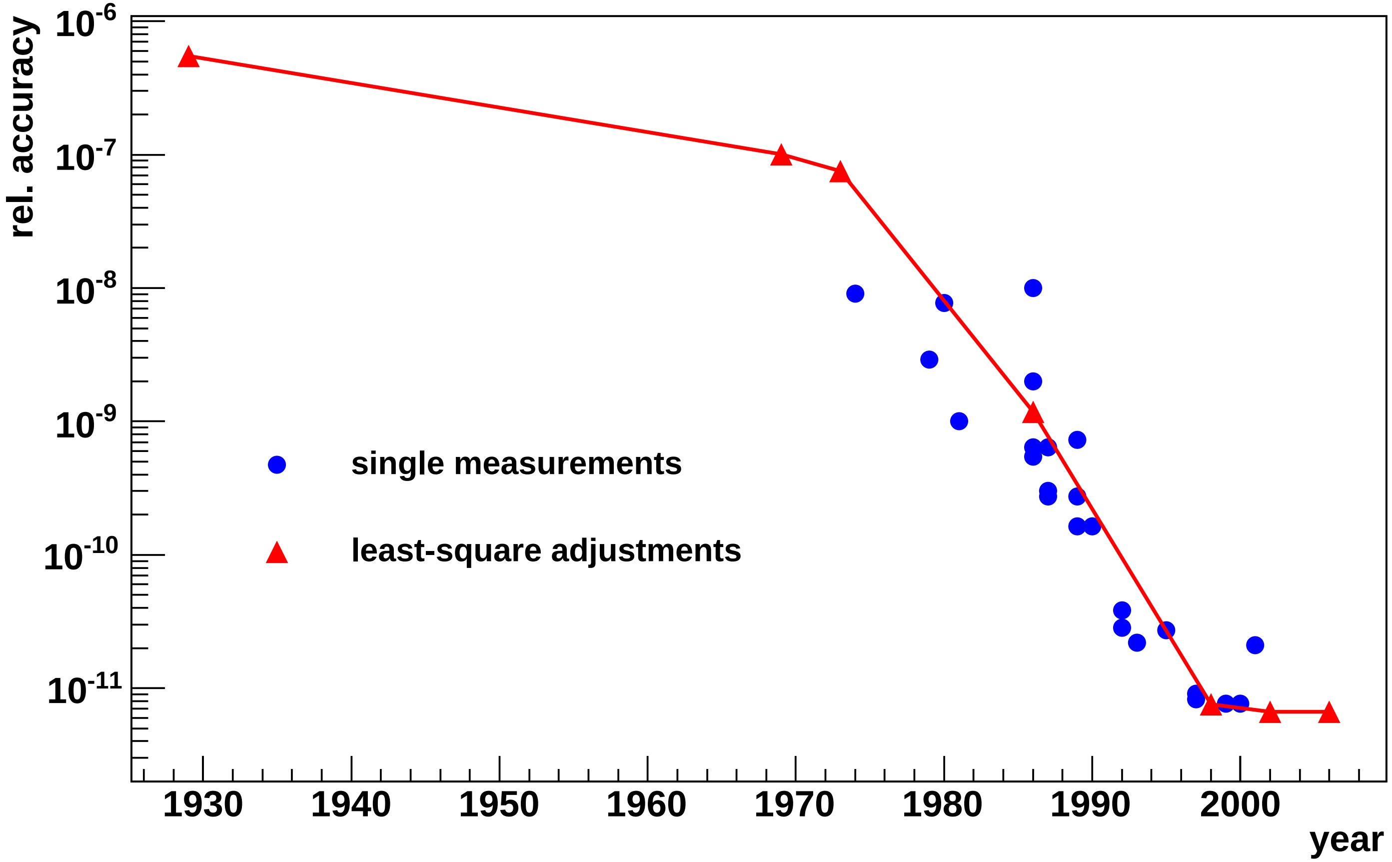
1.4 GHz

1.2 MHz

Bohr	**Dirac**	**Lamb**	**hfs-splitting**	r_p
$E = R_\infty / n^2$	e$^-$ spin	QED	proton-spin	proton size
$V \sim 1/r$	relativity		$H^{\text{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$	$V \not\sim 1/r$

Increasing accuracy !!!

The Rydberg constant:

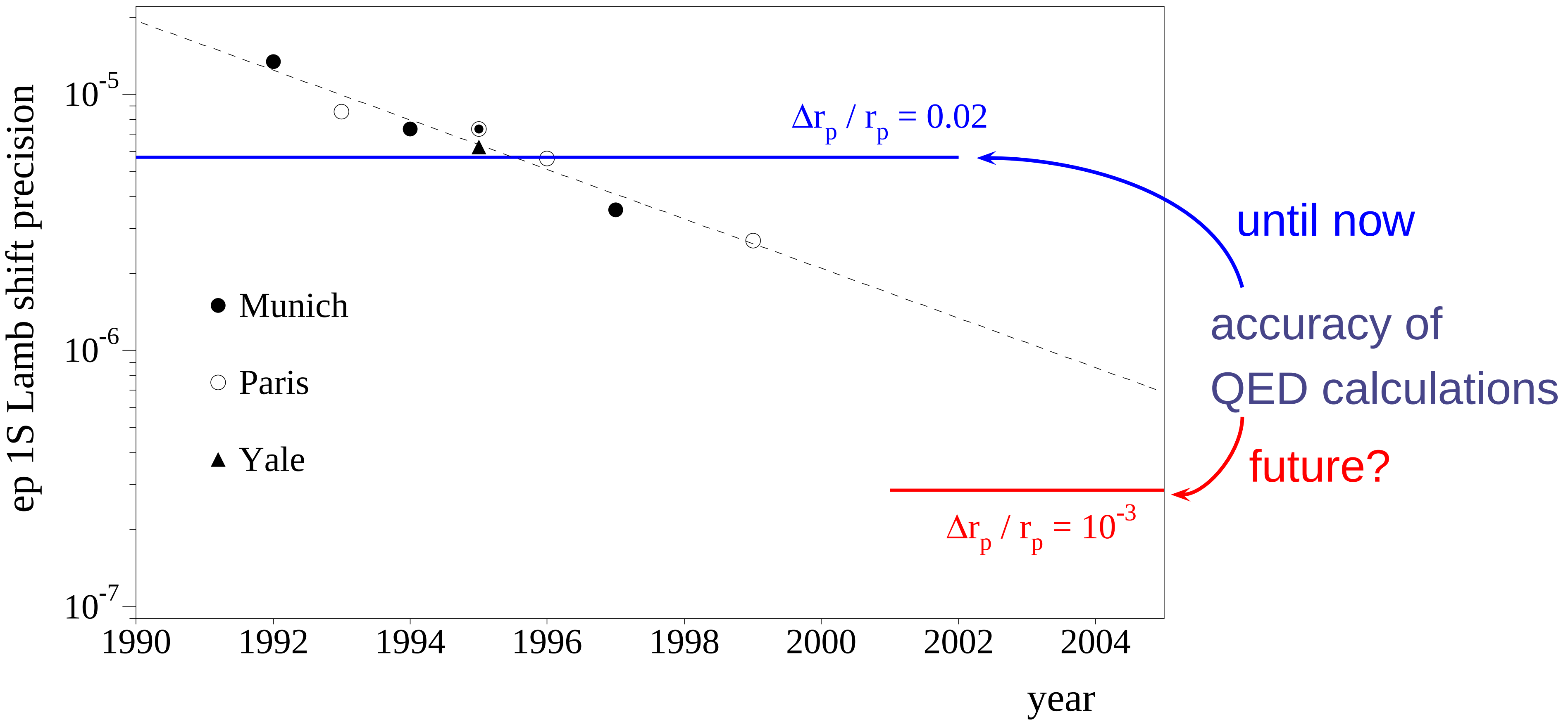


2006: R_∞ = $10\,973\,731.568\,525 \pm 0.000\,073\,\mathrm{m}^{-1}$ $(u_r = 6.6 \cdot 10^{-12})$

is the most accurately determined fundamental constant.

Increasing accuracy ?!

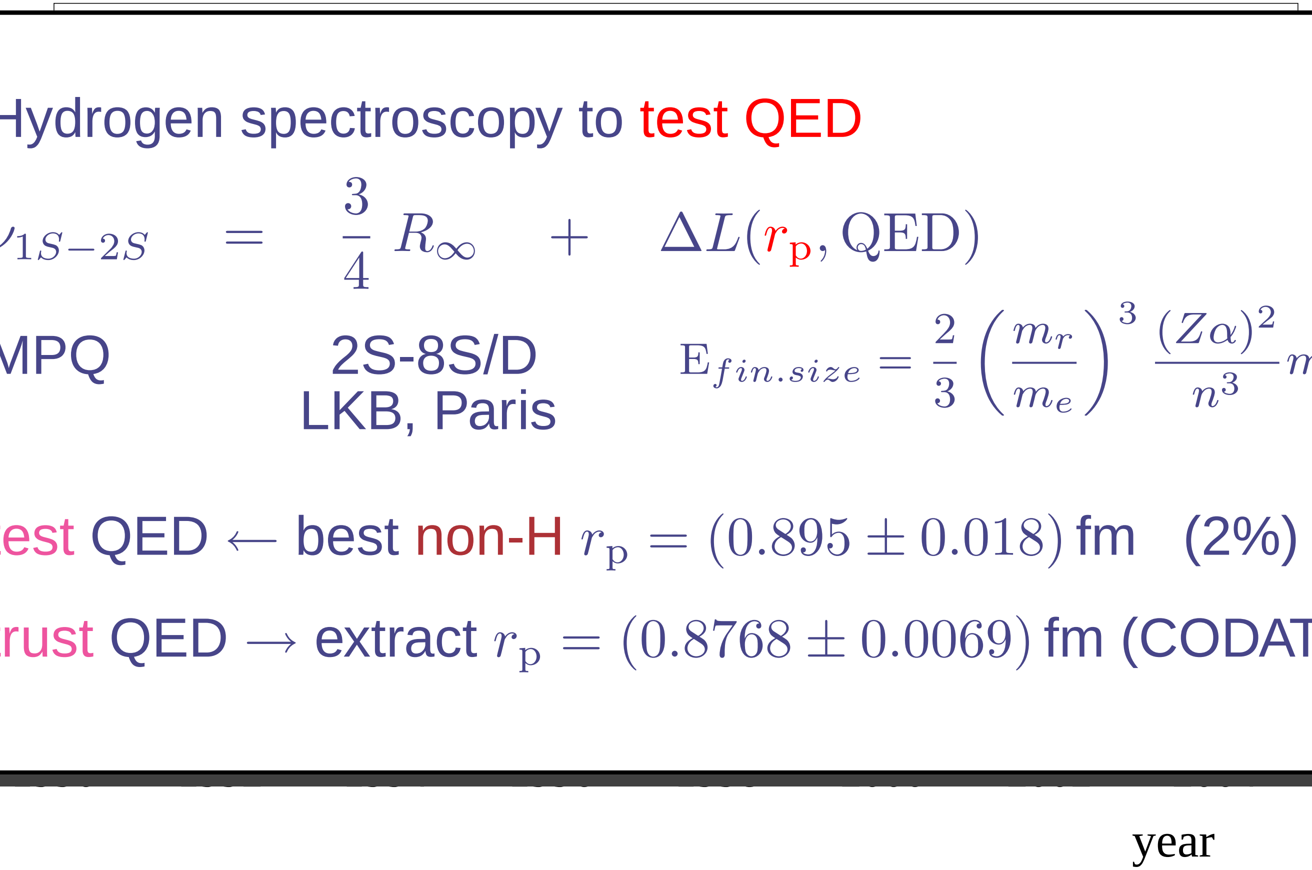
Test of bound-state QED (Lamb shift) in Hydrogen:



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

Increasing accuracy ?!

Test of bound-state QED (Lamb shift) in Hydrogen:



- Hydrogen spectroscopy to test QED

$$\nu_{1S-2S} \quad = \quad \frac{3}{4} R_\infty \quad + \quad \Delta L(r_\mathrm{p}, \mathrm{QED})$$

MPQ — 2S-8S/D LKB, Paris

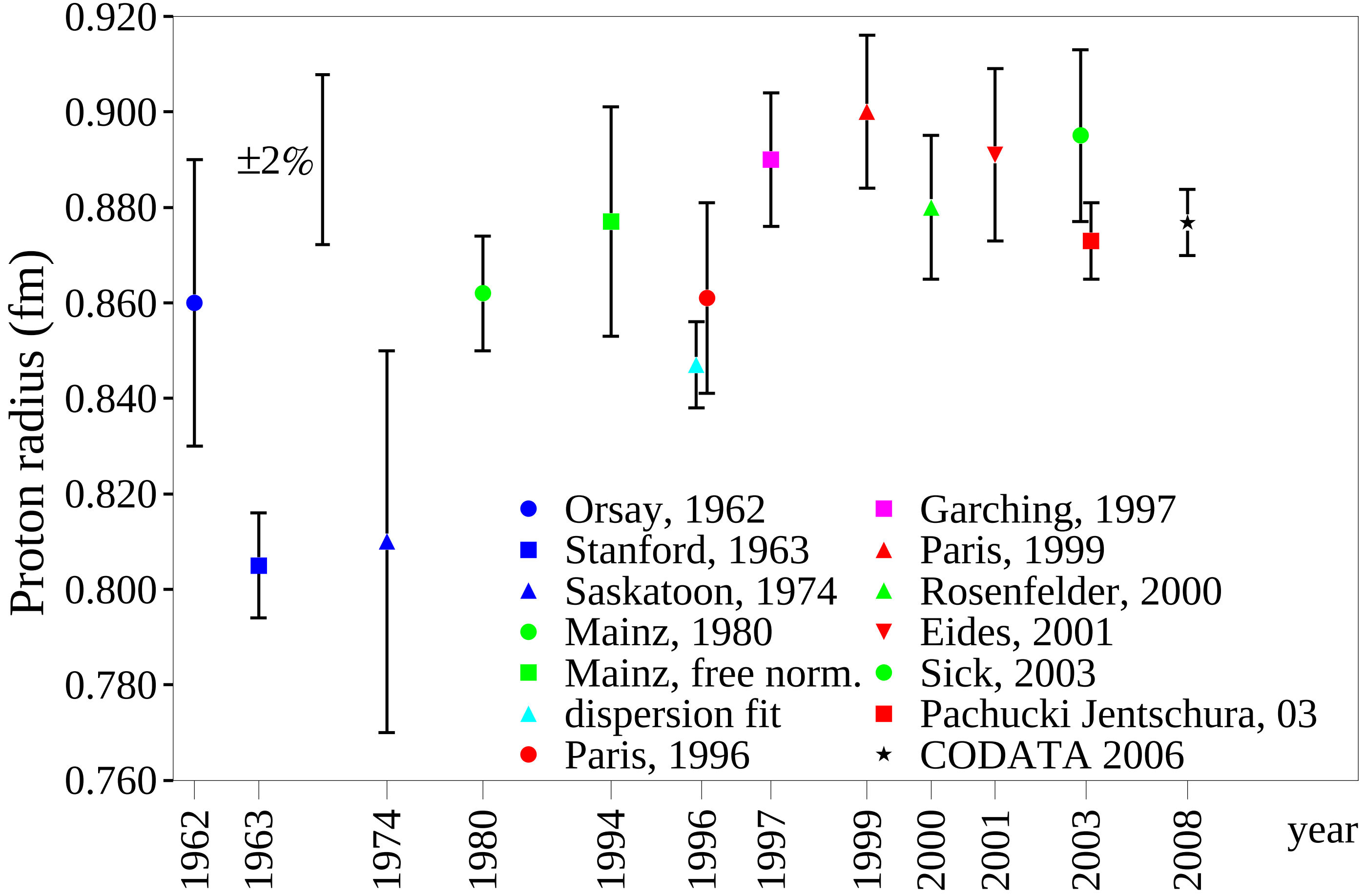
$$\mathrm{E}_{fin.size} = \frac{2}{3}\left(\frac{m_r}{m_e}\right)^3 \frac{(Z\alpha)^2}{n^3} m_e c^2 \left(\frac{2\pi Z\alpha\, r_\mathrm{p}}{\lambda_C}\right)^2$$

- test QED ← best non-H $r_\mathrm{p} = (0.895 \pm 0.018)$ fm (2%) ← e-p scattering
- trust QED → extract $r_\mathrm{p} = (0.8768 \pm 0.0069)$ fm (CODATA)

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

Increasing accuracy ???

The proton rms charge radius is not the most accurate quantity in the universe.

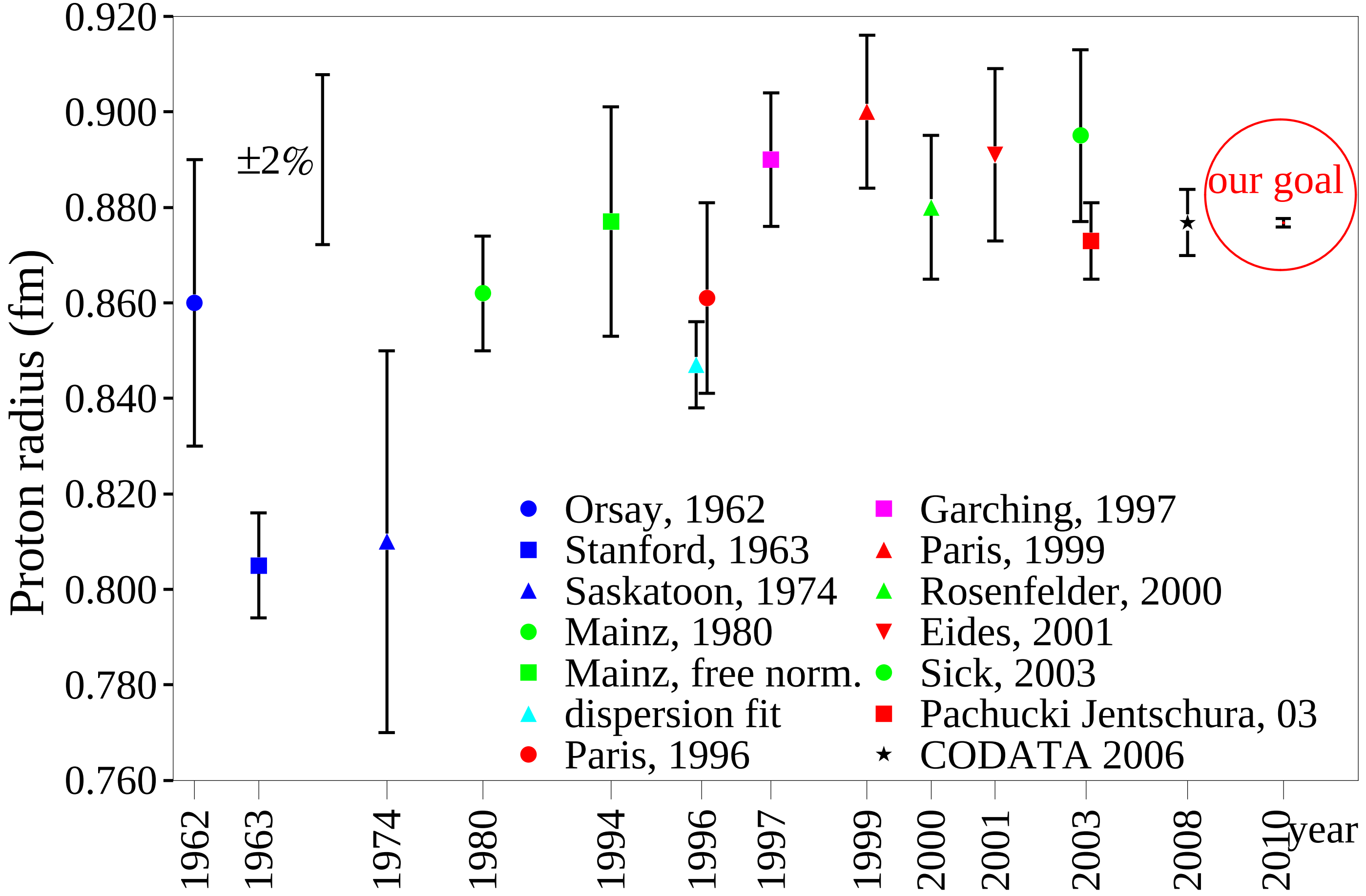


e-p scattering: r_p = 0.895(18) fm $(u_r = 2\,\%)$

CODATA: r_p = 0.8768(69) fm $(u_r = 0.8\,\%)$

Increasing accuracy ???

The proton rms charge radius is not the most accurate quantity in the universe.



e-p scattering: r_{p} = 0.895(18) fm $(u_r = 2\,\%)$

CODATA: r_{p} = 0.8768(69) fm $(u_r = 0.8\,\%)$

muonic hydrogen goal: $u_r = 0.1\,\%$

20x improvement

Proton charge radius and muonic hydrogen

muonic hydrogen = μ^- p   mass m_μ = 207 m_e

$$\Delta E_{\text{finite size}}(nl) \sim r_{\text{p}}^2 \, |\Psi(r=0)|^2$$

$$\langle r^{\text{orbit}} \rangle \sim \frac{\hbar}{Z\alpha m_r c} n^2$$

$$\Delta E_{\text{finite size}}(nl) = \frac{2(Z\alpha)^4 c^4}{3\hbar^2 n^3} m_r^3 r_{\text{p}}^2 \delta_{l0}$$

Lamb shift in μp: $\Delta E(2P_{3/2}^{\text{F}=2} - 2S_{1/2}^{\text{F}=1})$ =

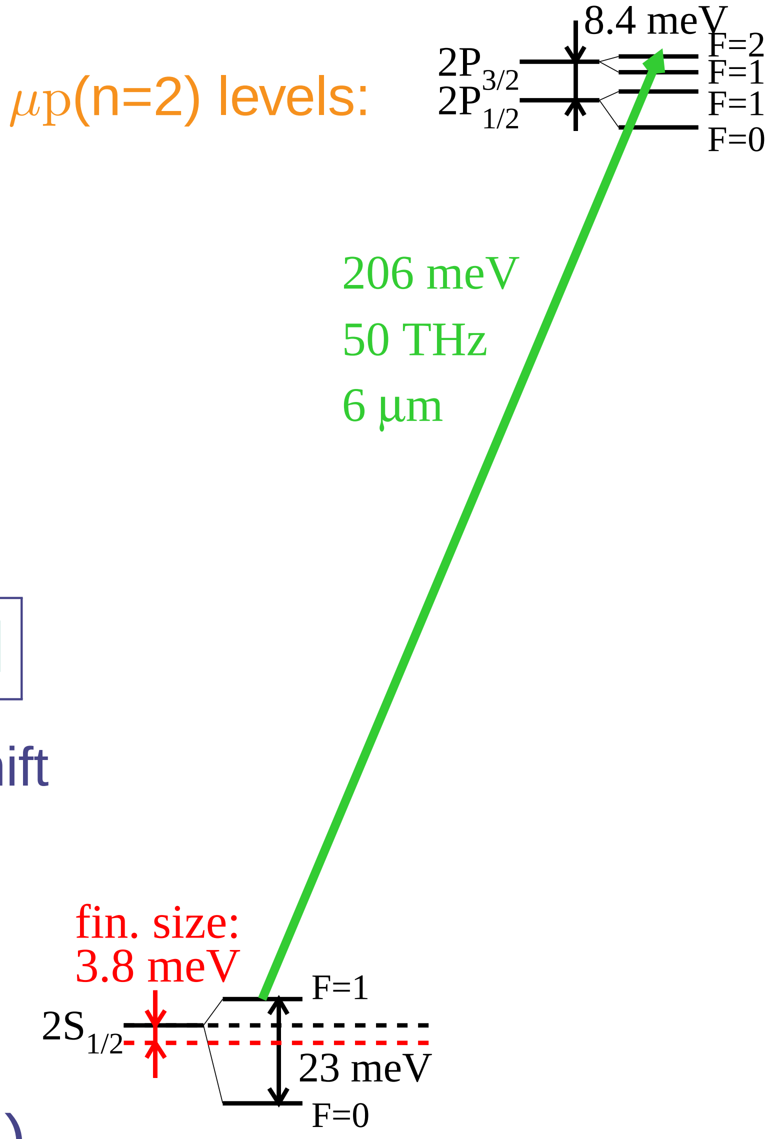
$$\boxed{209.9779(49) - 5.2262\, r_{\text{p}}^2 + 0.0347\, r_{\text{p}}^3 \ \ \text{[meV]}}$$

finite size contribution is 2% of the μp Lamb shift

measure ΔE(2S-2P) to 30 ppm = 1.5 GHz

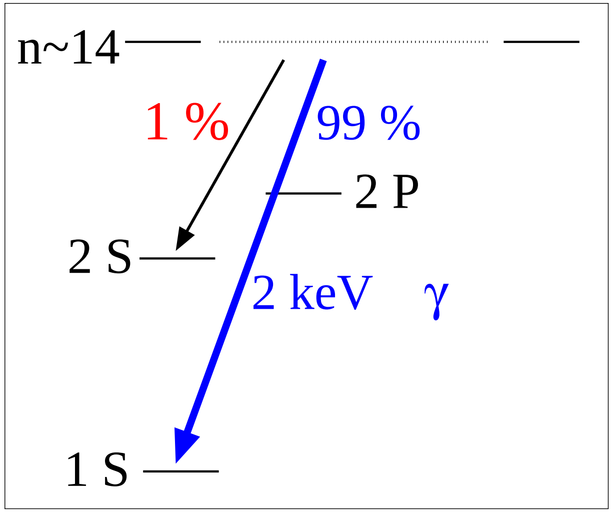
$$\boxed{\Rightarrow r_{\text{p}} \text{ to } 10^{-3}}$$

$$\Gamma_{2P} \; = \; 18.6 \text{ GHz} \qquad (\Gamma_{\text{rad.}})$$

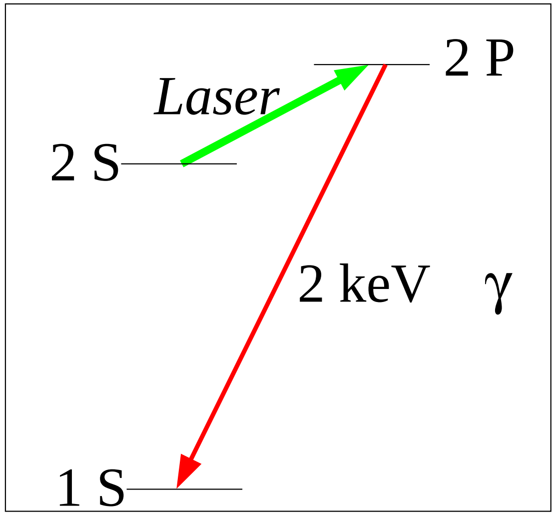


μp Lamb shift experiment: Principle

"prompt" ($t \sim 0$)



"delayed" ($t \sim 1\ \mu$s)



μ^- stop in H_2 gas
$\Rightarrow$ μp* atoms formed ($n \sim 14$)

99%: cascade to μp(1S),
emitting prompt K$_\alpha$, K$_\beta$ ...

1%: long-lived μp(2S) atoms
lifetime $\boxed{\tau_{2S} \approx 1\ \mu\mathrm{s}}$ at 1 mbar H$_2$

R. Pohl *et. al.*, Phys. Rev. Lett. 97, 193402 (2006).

fire laser ($\lambda \approx 6\ \mu$m, $\Delta E \approx 0.2$ eV)

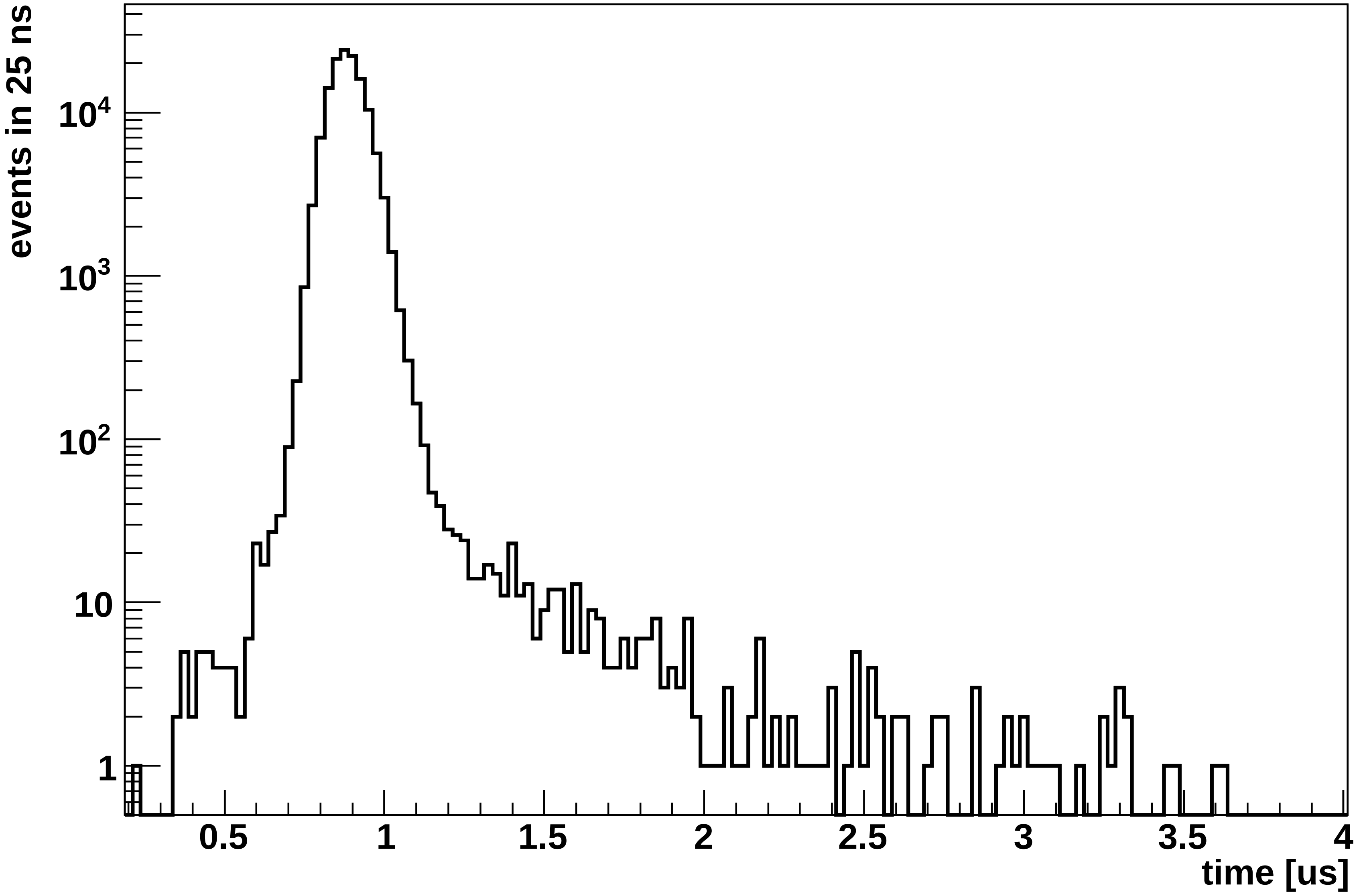
$\Rightarrow$ induce μp(2S) $\rightarrow$ μp(2P)

$\Rightarrow$ observe delayed K$_\alpha$ x-rays

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

μp Lamb shift experiment: Principle

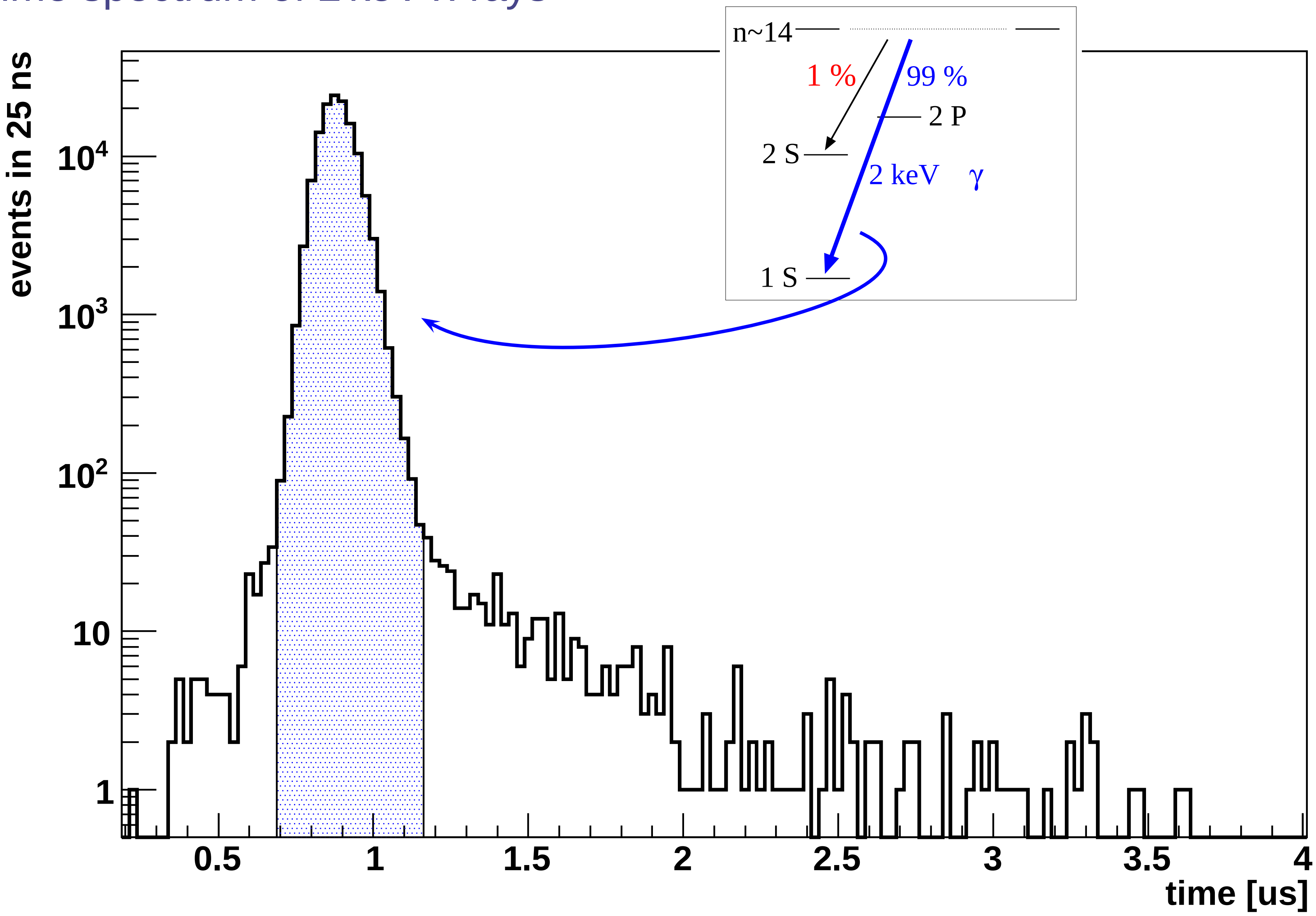
time spectrum of 2 keV x-rays (∼ 13 hours of data)



μp Lamb shift experiment: Principle

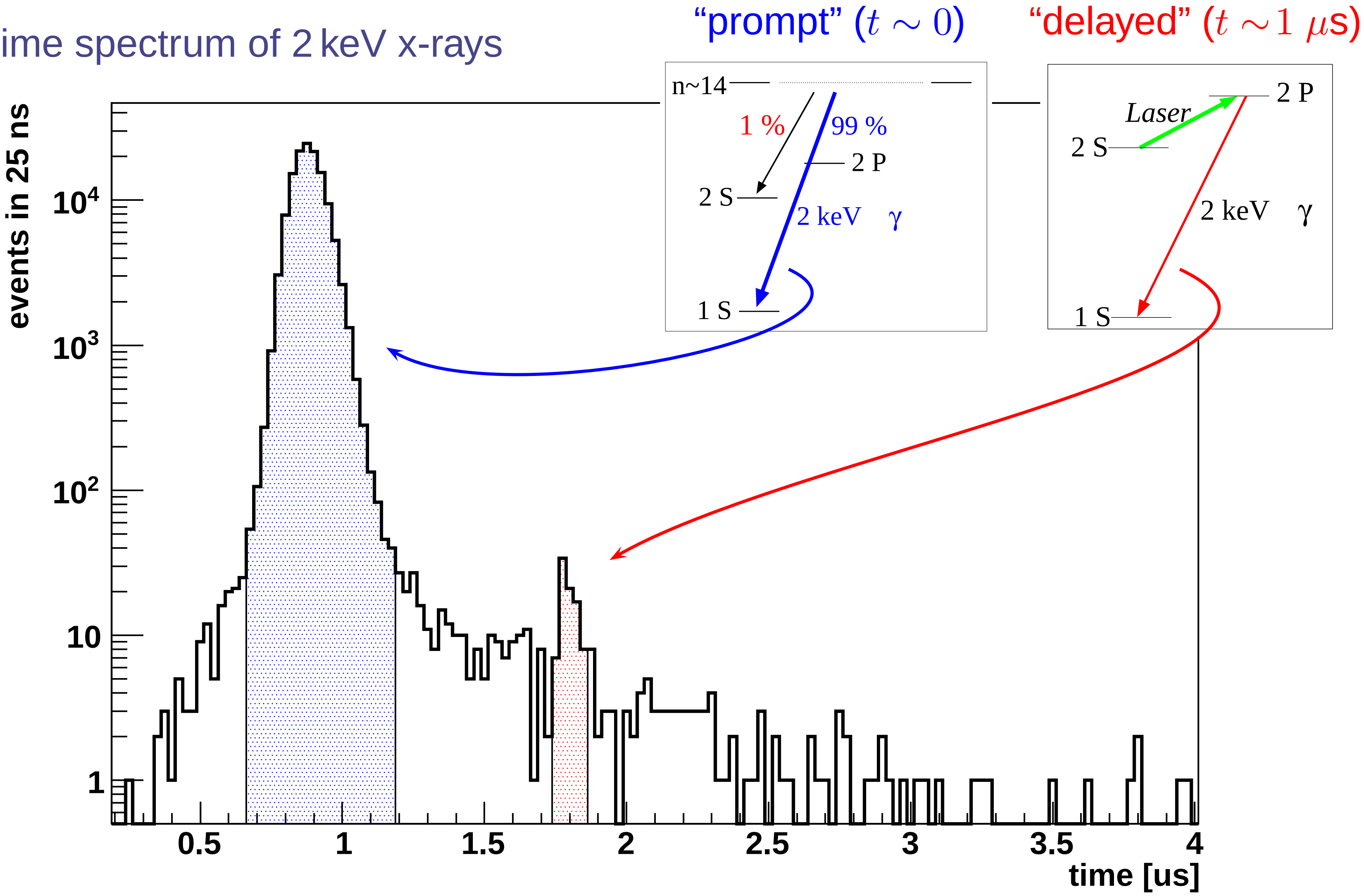
time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)



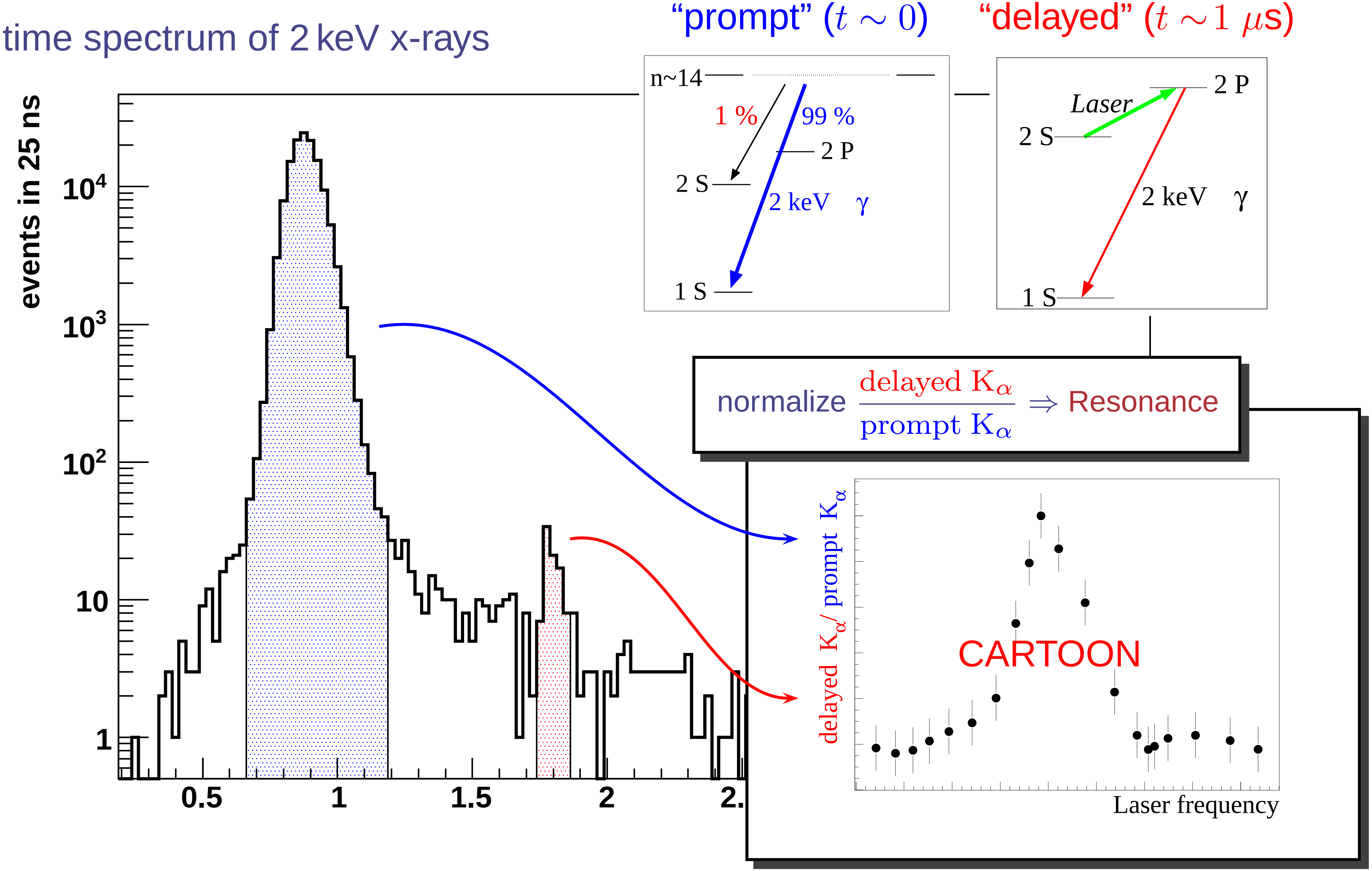
μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays



μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

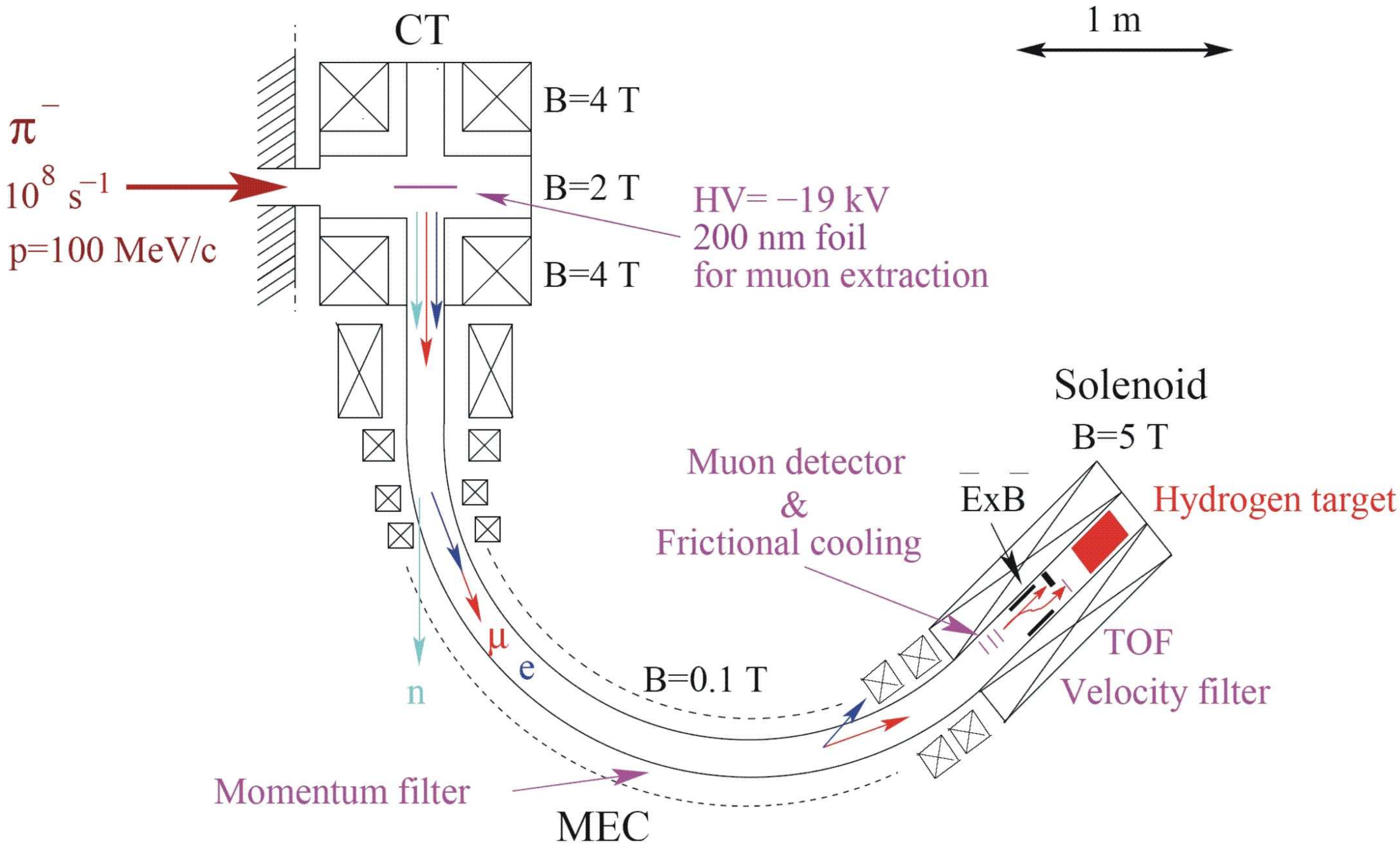


normalize $\dfrac{\text{delayed } K_\alpha}{\text{prompt } K_\alpha} \Rightarrow$ Resonance

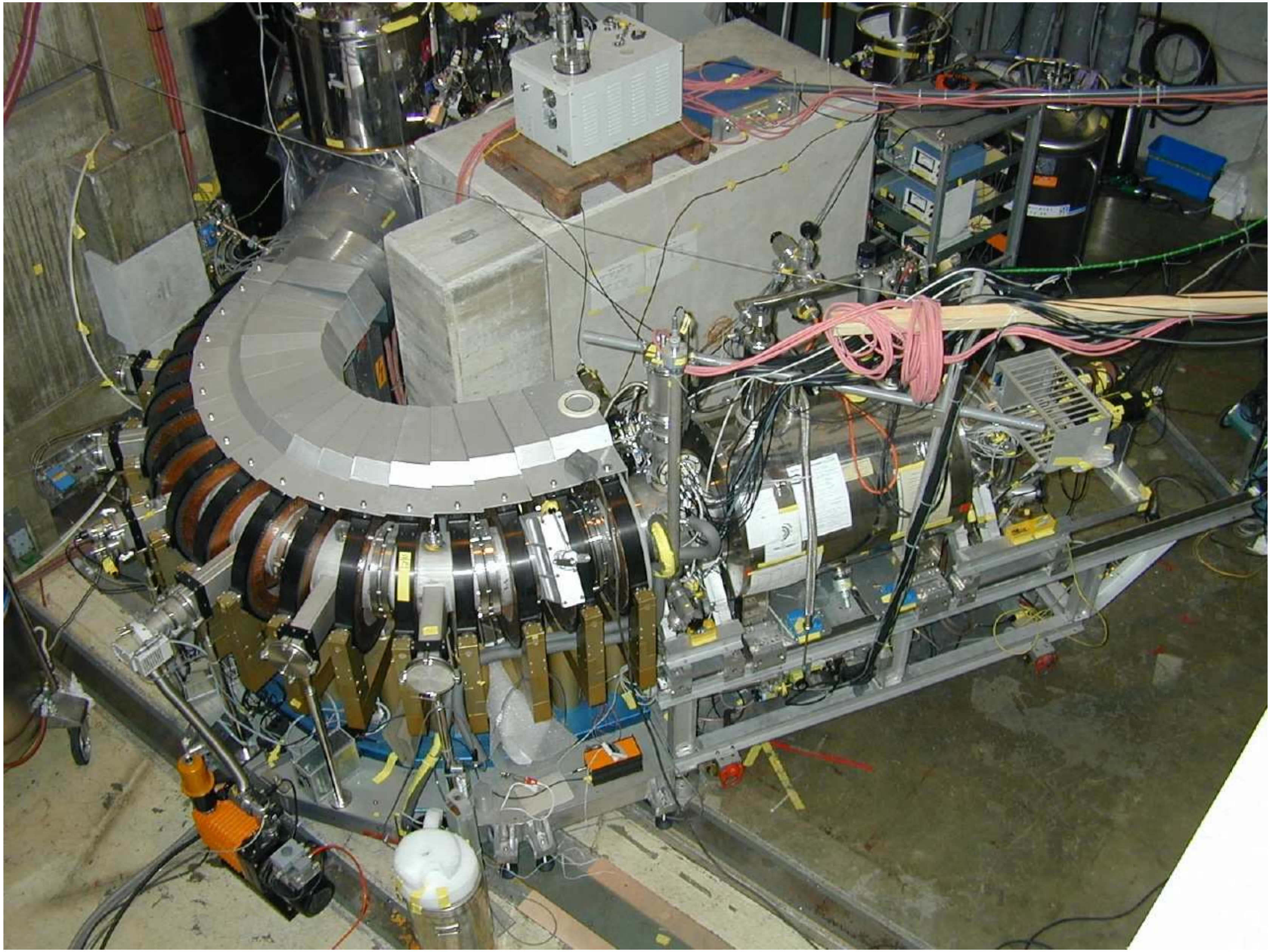
Experimental Hall at PSI

πE5 area at PSI

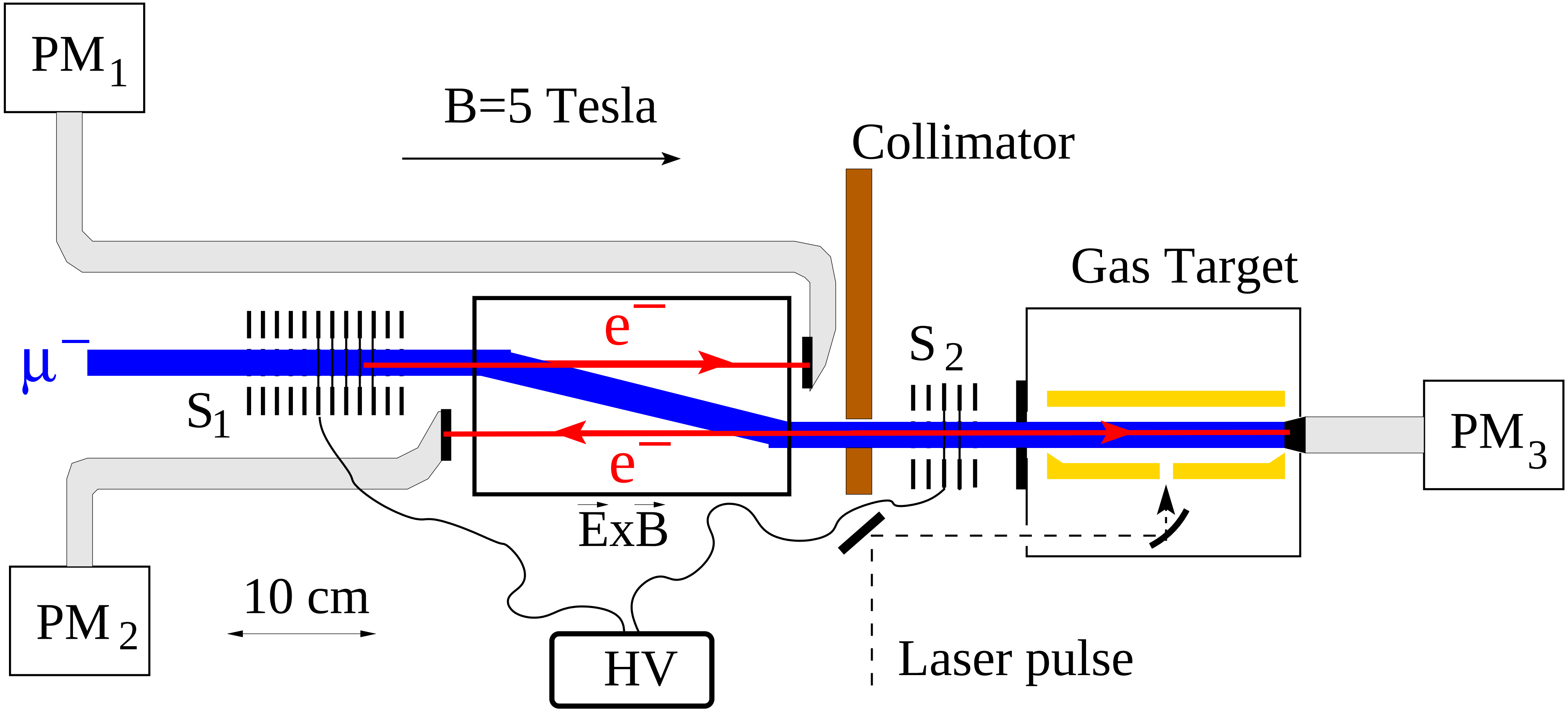
Muon beam line



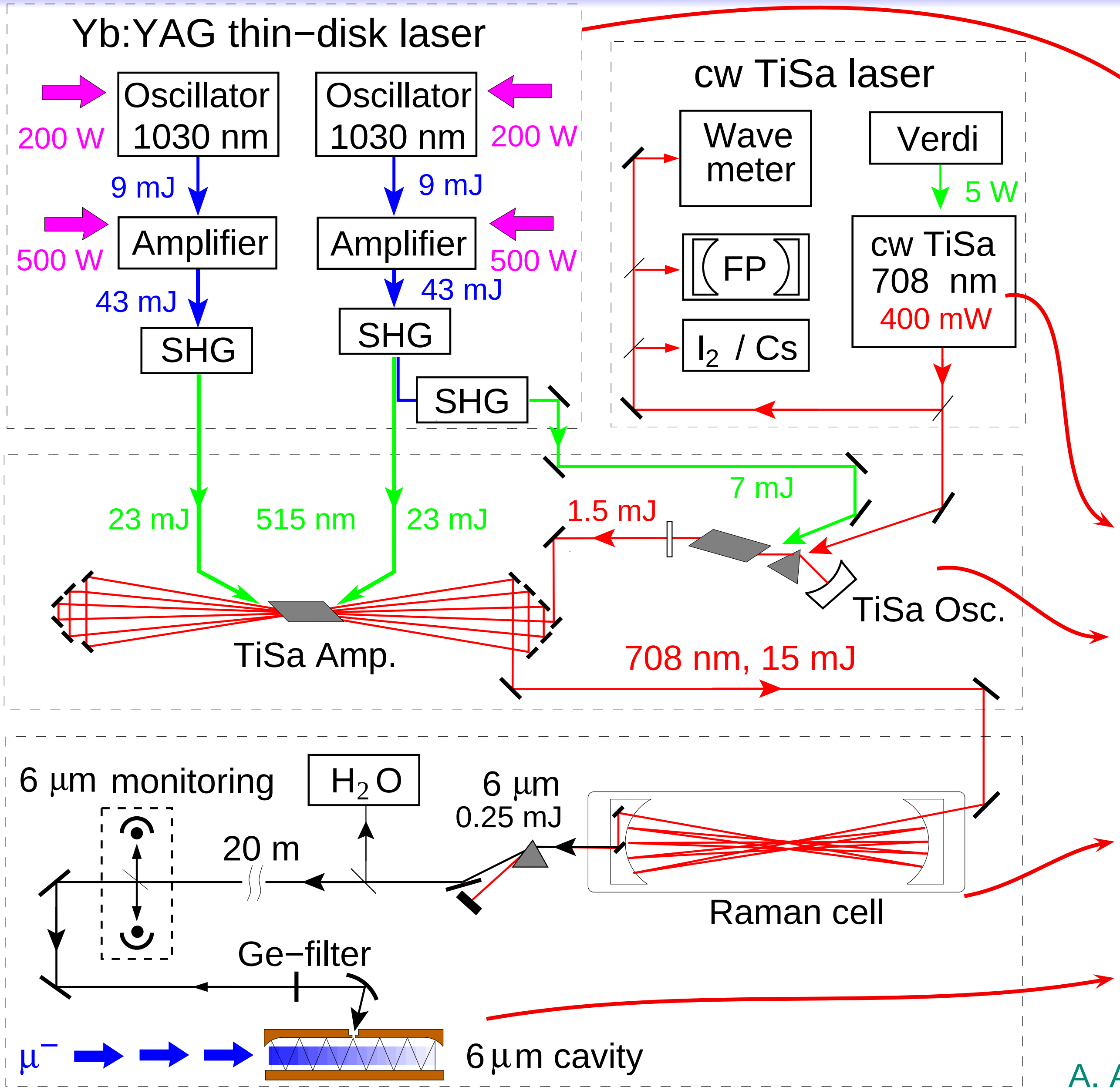
Muon beam line



Muon beam: inside 5 T solenoid



The laser system

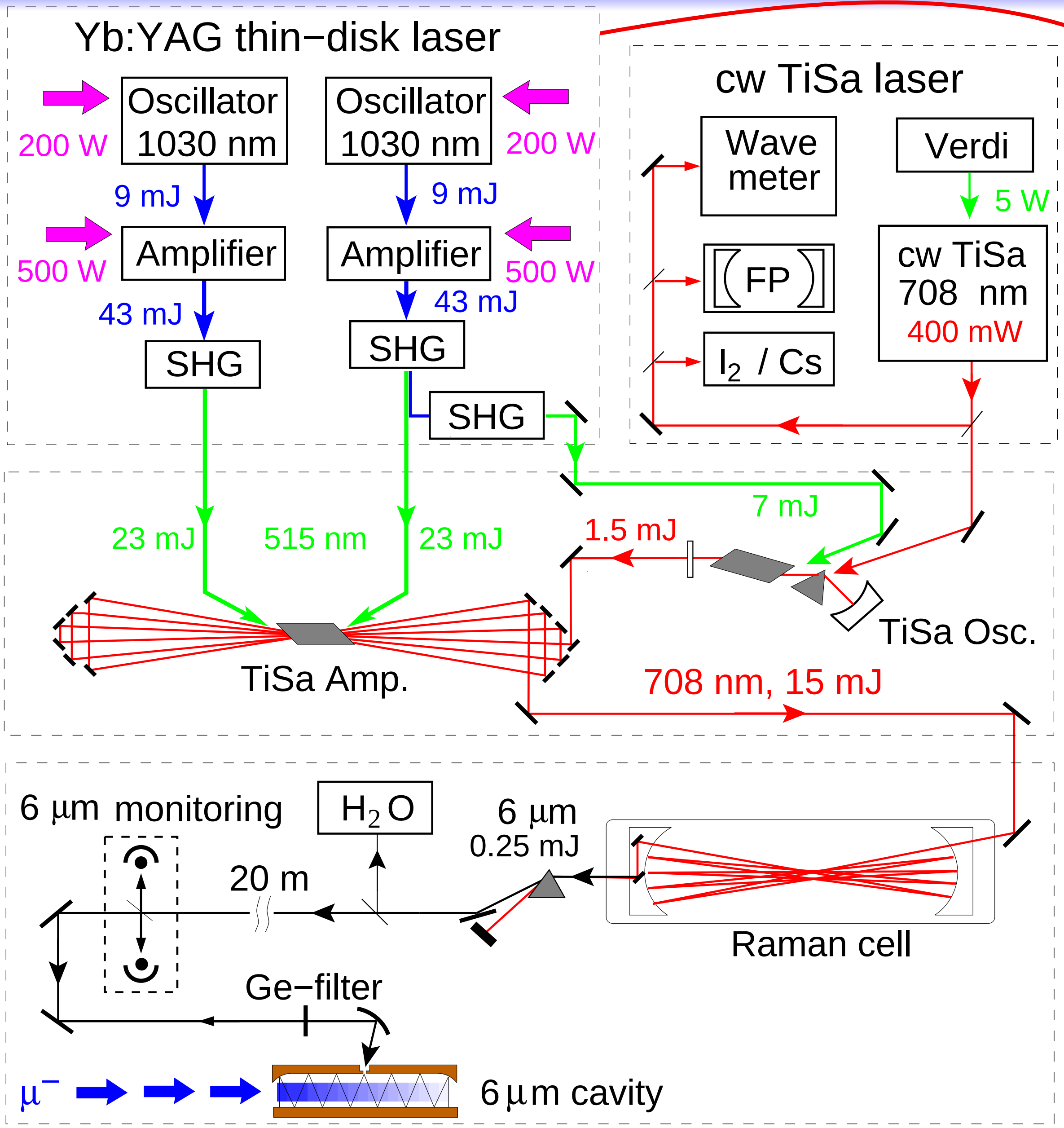


Main components:

- Thin-disk laser
  - fast response to detected μ^-
- Frequency doubling
- TiSa laser:
  - frequency stabilized cw laser
  - injection seeded oscillator
  - multipass amplifier
- Raman cell
  - 3 Stokes: 708 nm → 6 μm
  - λ calibration @ 6 μm
- Target cavity

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

The laser system



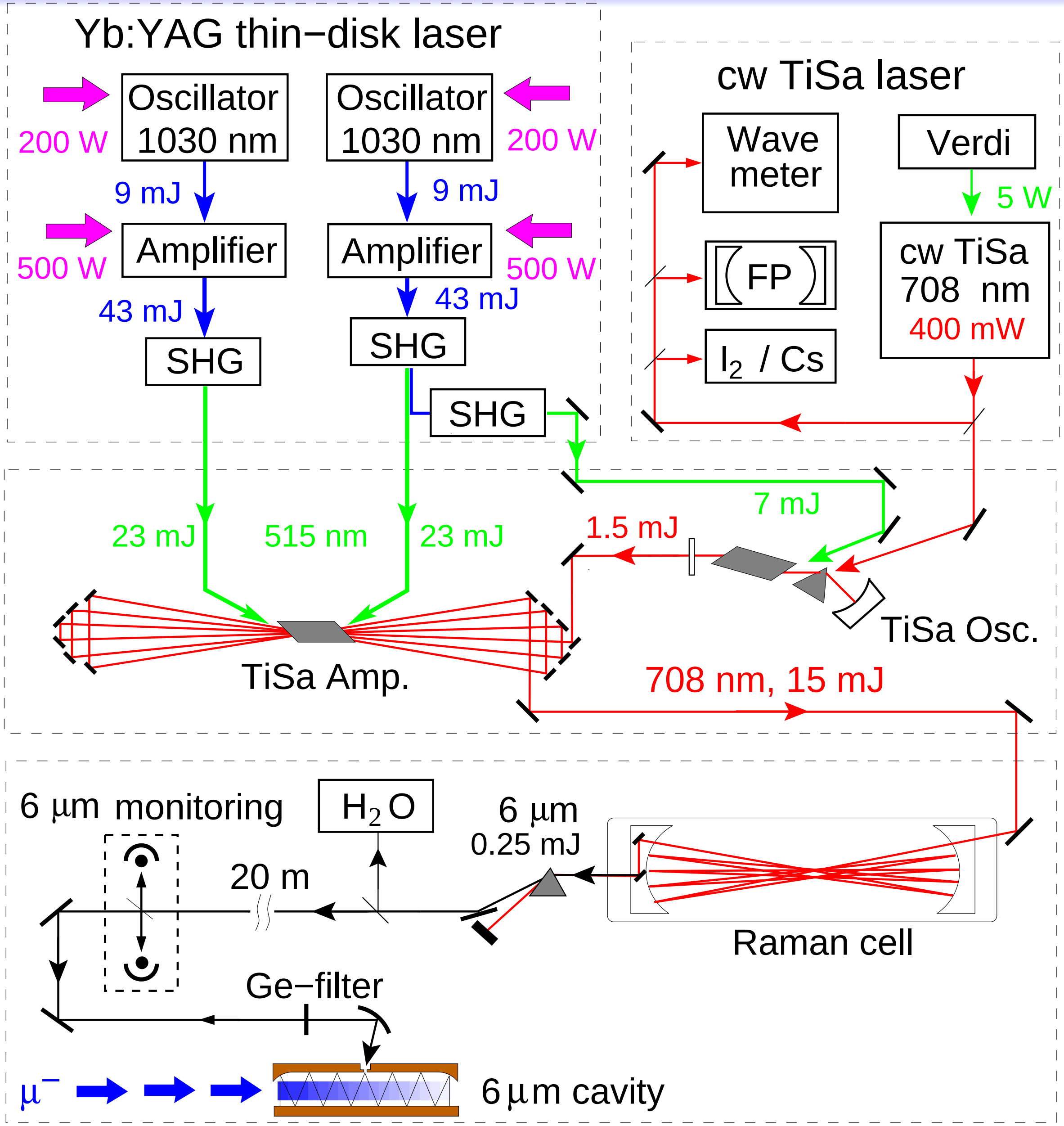
Thin-disk laser

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

- Each single μ^- triggers the laser system
- $2S$ lifetime $\approx 1\ \mu$s $\rightarrow$ short laser delay

A. Antognini *et. al.*,
IEEE J. Quant. Electr. 45, 993 (2009).

The laser system



MOPA TiSa laser:

Cw frequency stabilized laser

- referenced to a stable FP cavity
- FP cavity calibrated with I_2, Rb, Cs lines

$\nu_{\mathrm{FP}} = N \cdot FRS$

$FRS = 1497.344(6)$ MHz, $N \approx 2 \times 10^5$.

$\nu^{\mathrm{cw}}_{\mathrm{TiSa}}$ absolutely known with $\sigma = 30$ MHz

$\Gamma_{\mathrm{2P-2S}} = 18.6$ GHz

Seeded oscillator

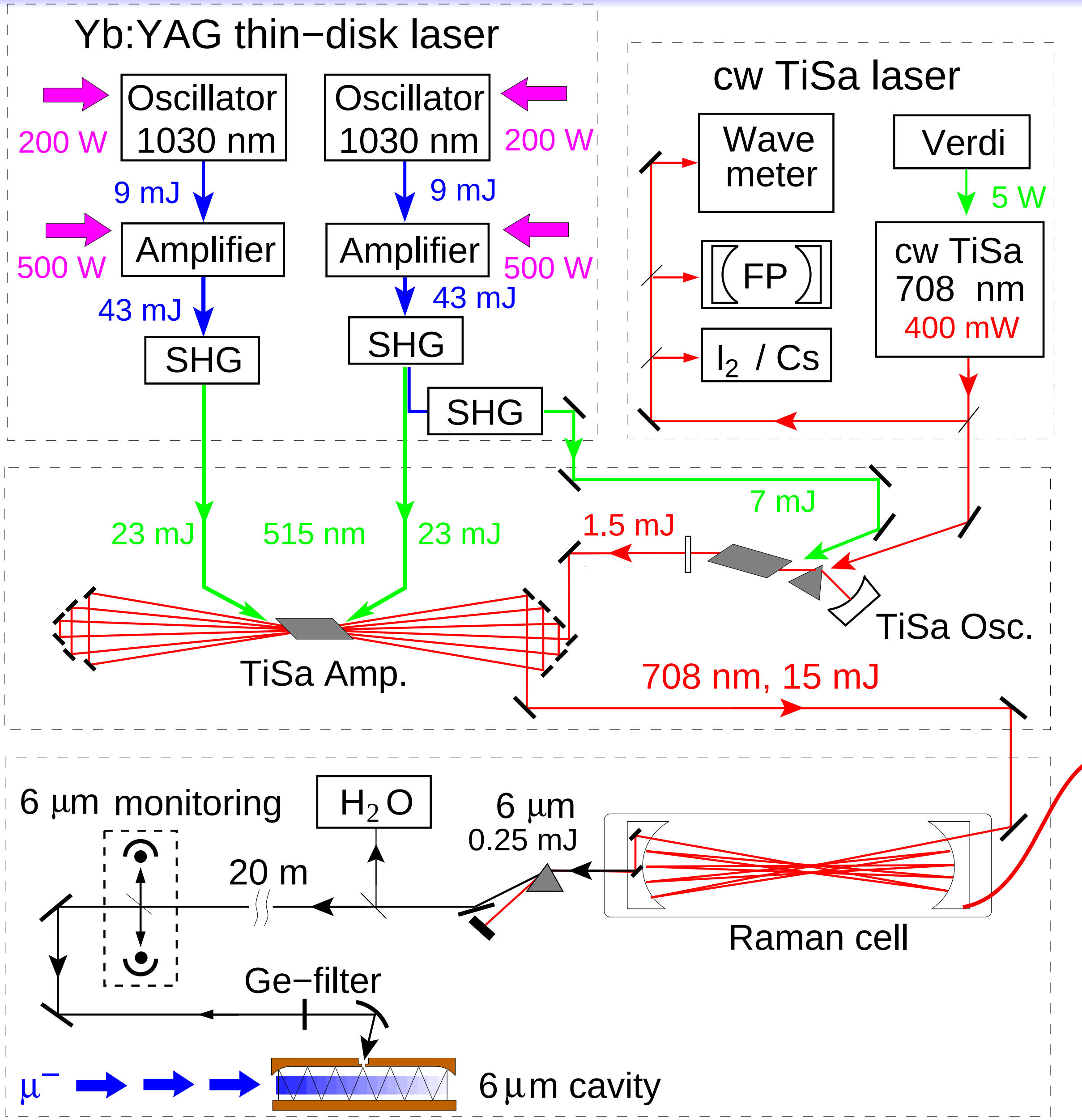
$\rightarrow \nu^{\mathrm{pulsed}}_{\mathrm{TiSa}} = \nu^{\mathrm{cw}}_{\mathrm{TiSa}}$

(frequency chirp ≤ 100 MHz)

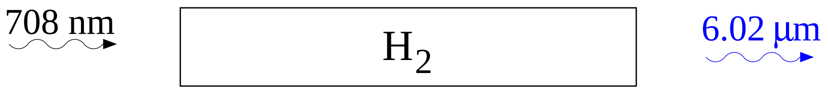
Multipass amplifier (2f- configuration)

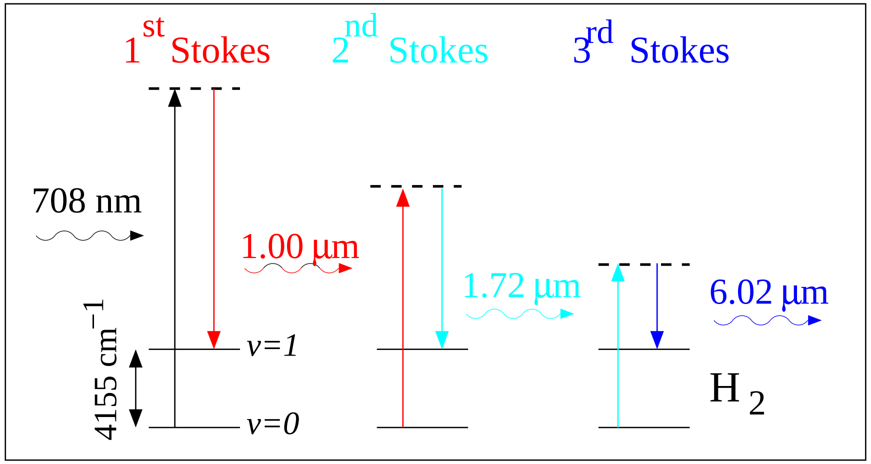
gain=10

The laser system



Raman cell:



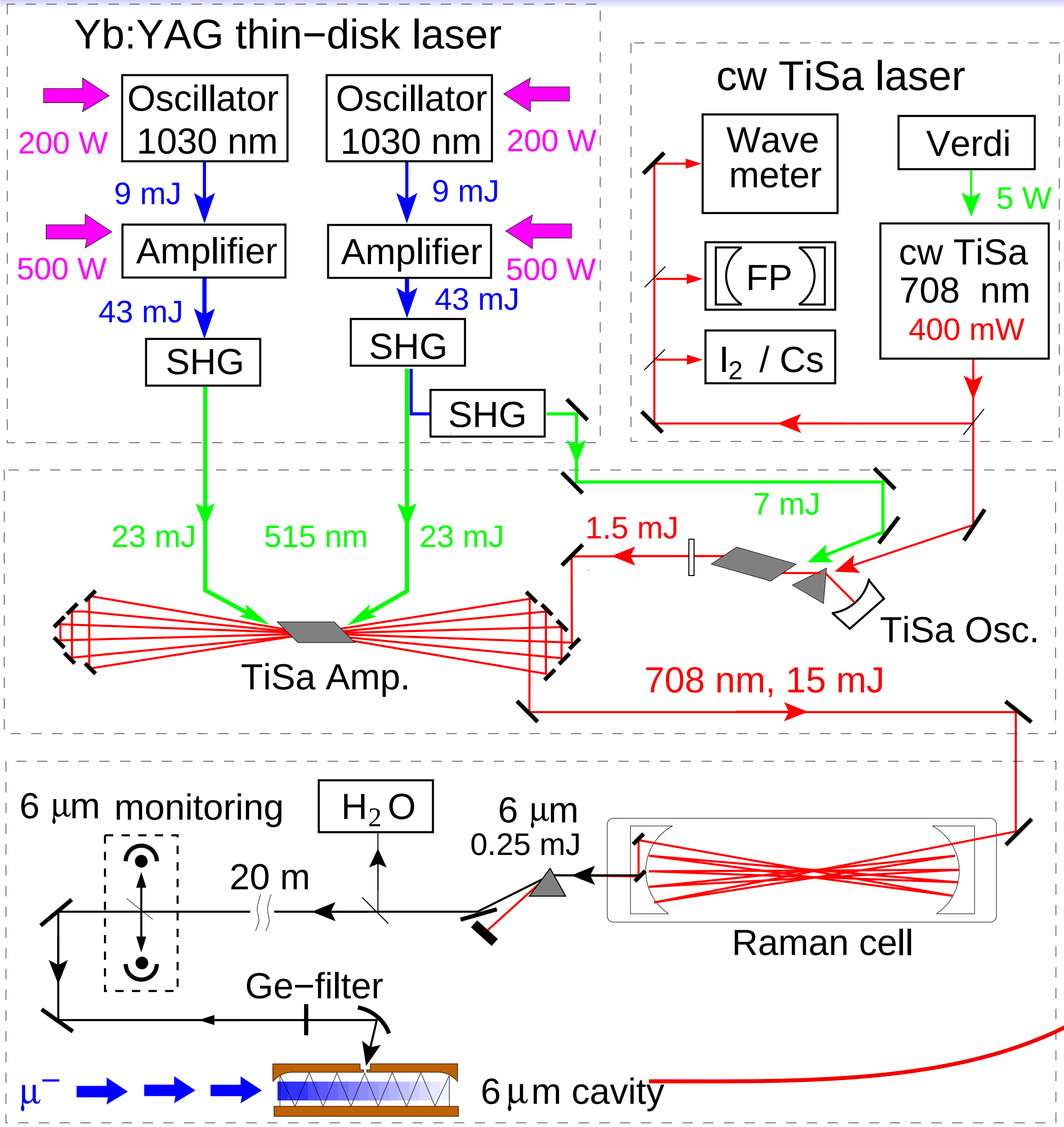


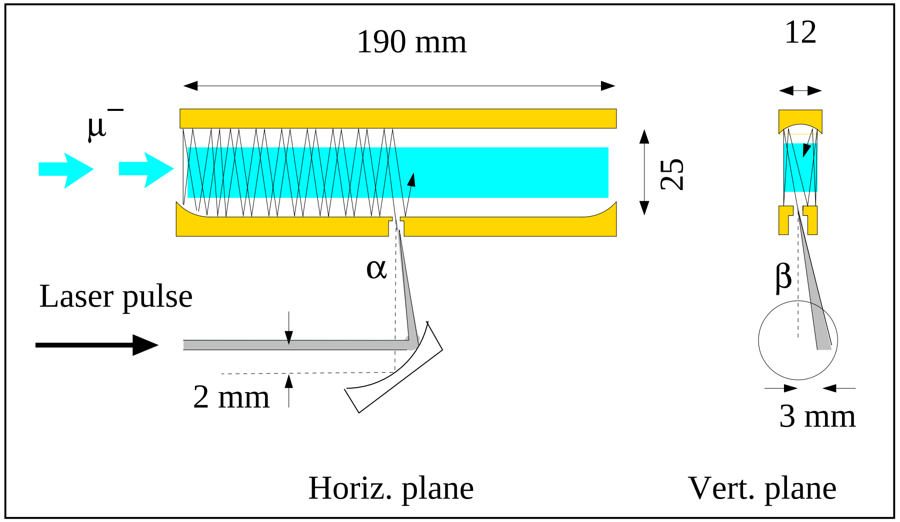
$$\boxed{\nu^{6\mu m} = \nu^{708\mathrm{nm}} - 3 \cdot \hbar\omega_{\mathrm{vib}}}$$

tunable

$\omega_{\mathrm{vib}}(p, T) =$ const

The laser system





Design: insensitive to misalignment

Transverse illumination

Large volume

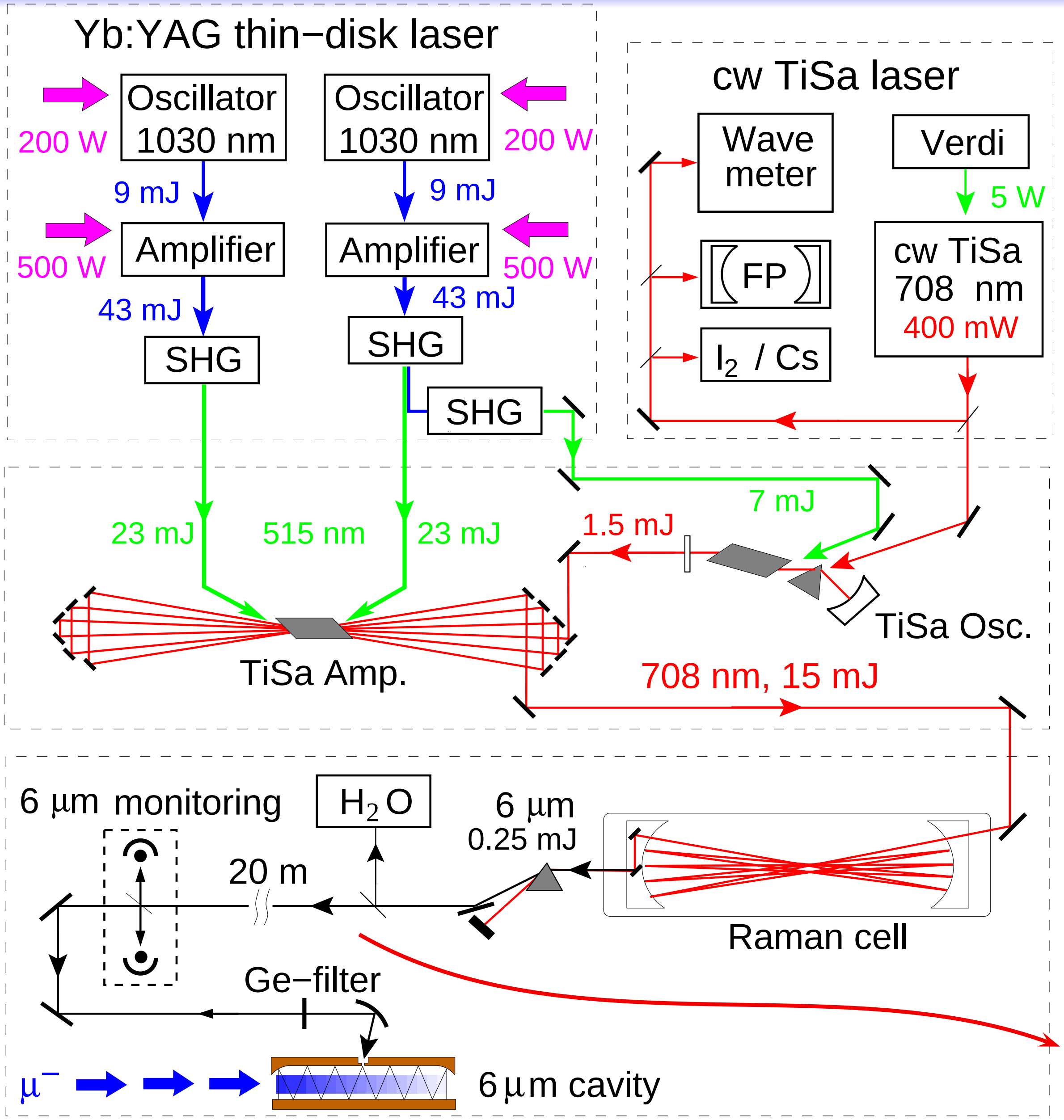
Dielectric coating with $R \geq 99.9\%$ (at 6 μm)

→ Light makes 1000 reflections

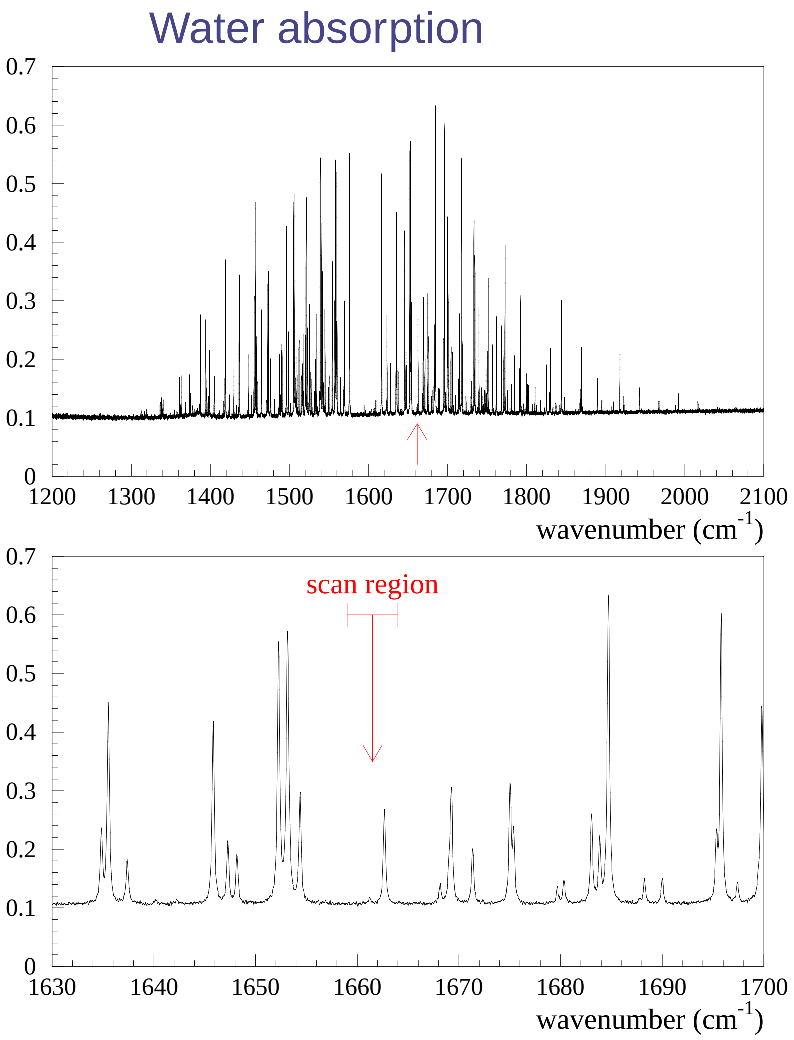
→ Light is confined for τ=50 ns

→ 0.15 mJ saturates the $2S-2P$ transition

The laser system

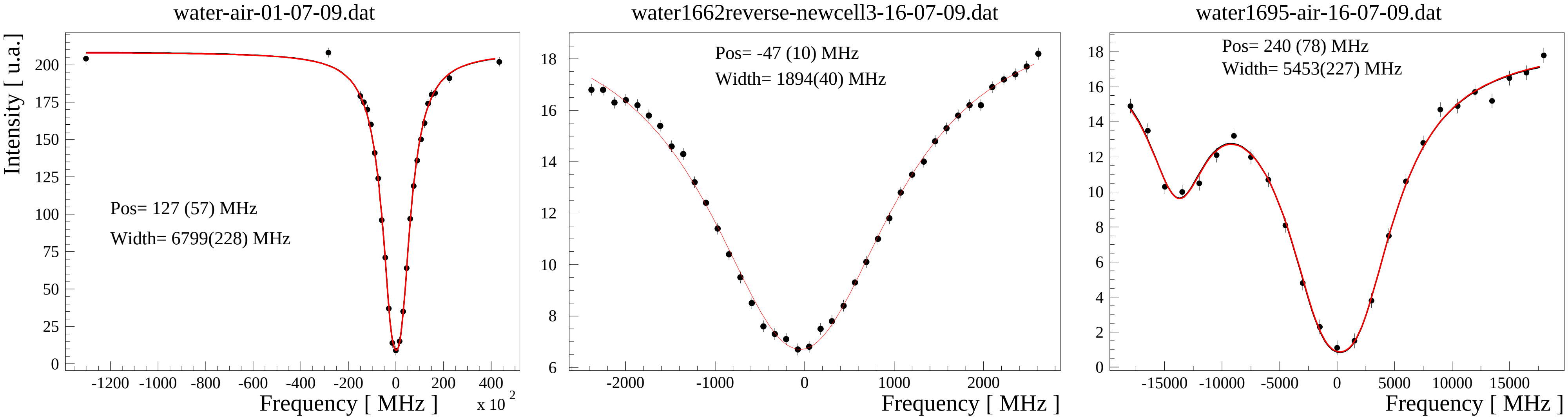


Water absorption



- Vacuum tube for 6 μm beam transport.
- Direct frequency calibration at 6 μm.

6 μm wavelength calibration


water-air-01-07-09.dat

water1662reverse-newcell3-16-07-09.dat

water1695-air-16-07-09.dat

- $6\ \mu$m light calibration: H_2O vapor absoprtion measurement in air / cell

  H_2O absorption lines known to a few MHz (HITRAN)

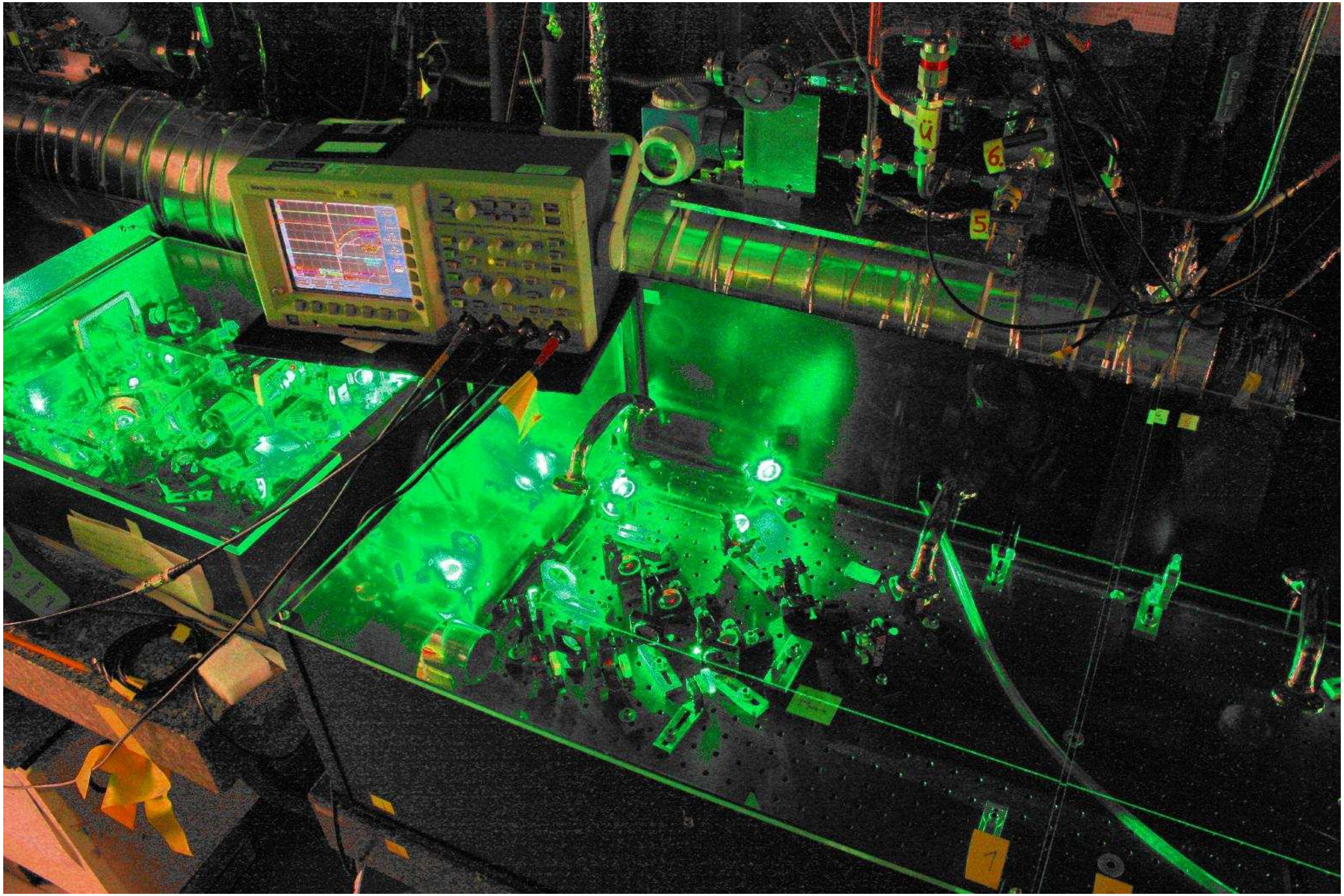
  $\Rightarrow$ $\boxed{\delta\nu \approx 300\text{ MHz uncertainty}}$ (6 ppm of ΔE_{2S-2P}) due to our calibration accuracy

  over the whole wavelength range λ = 5.5 ... 6.1 μm

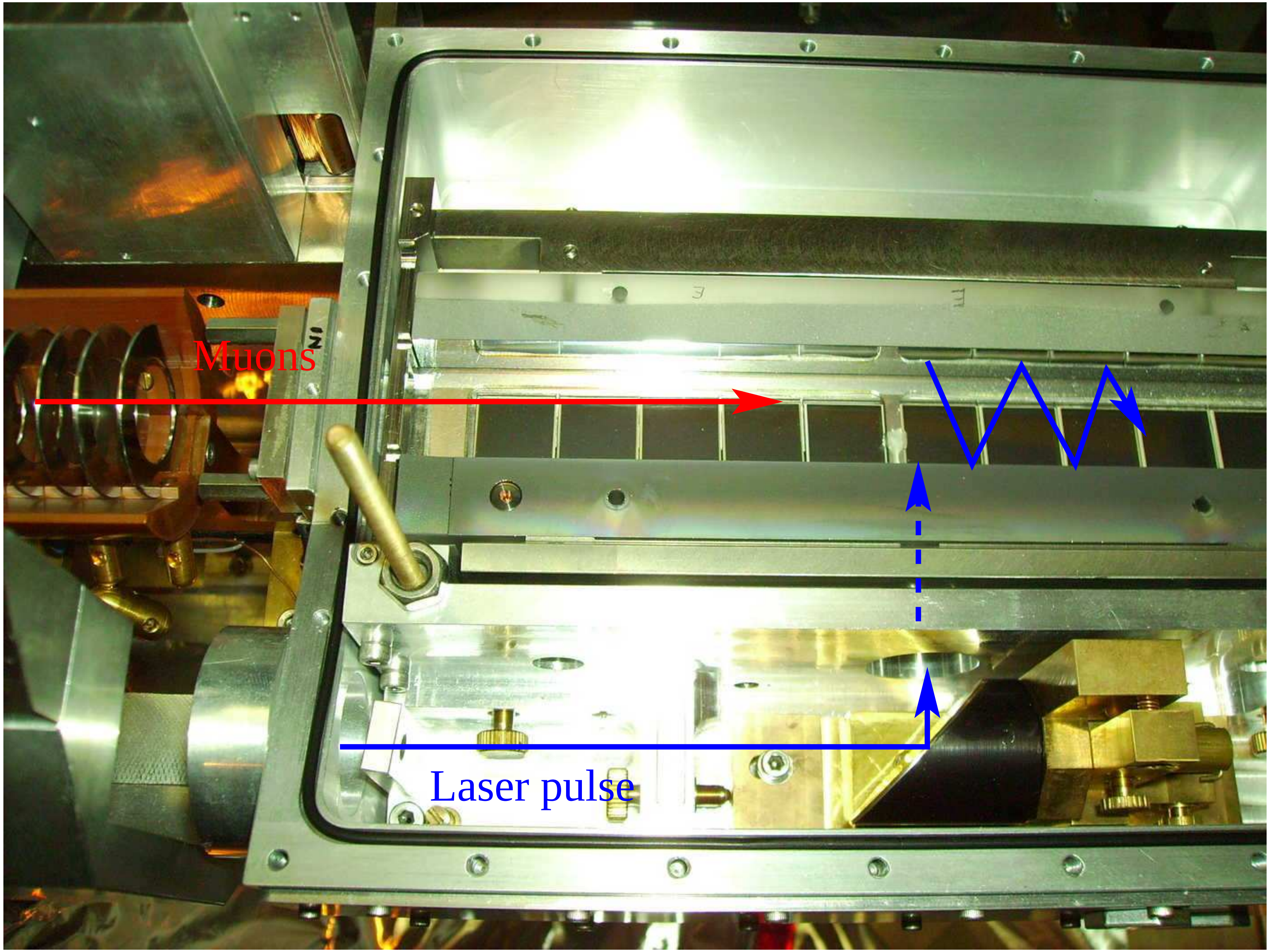
- Laser frequency detuning is measured in number of Fabry-Perot cavity fringes
  - grid spacing of our measurement: FSR(FP) = 1497.344(6) MHz
  - all measured resonances are within ± 70 FP fringes of a H_2O line

Laser hut

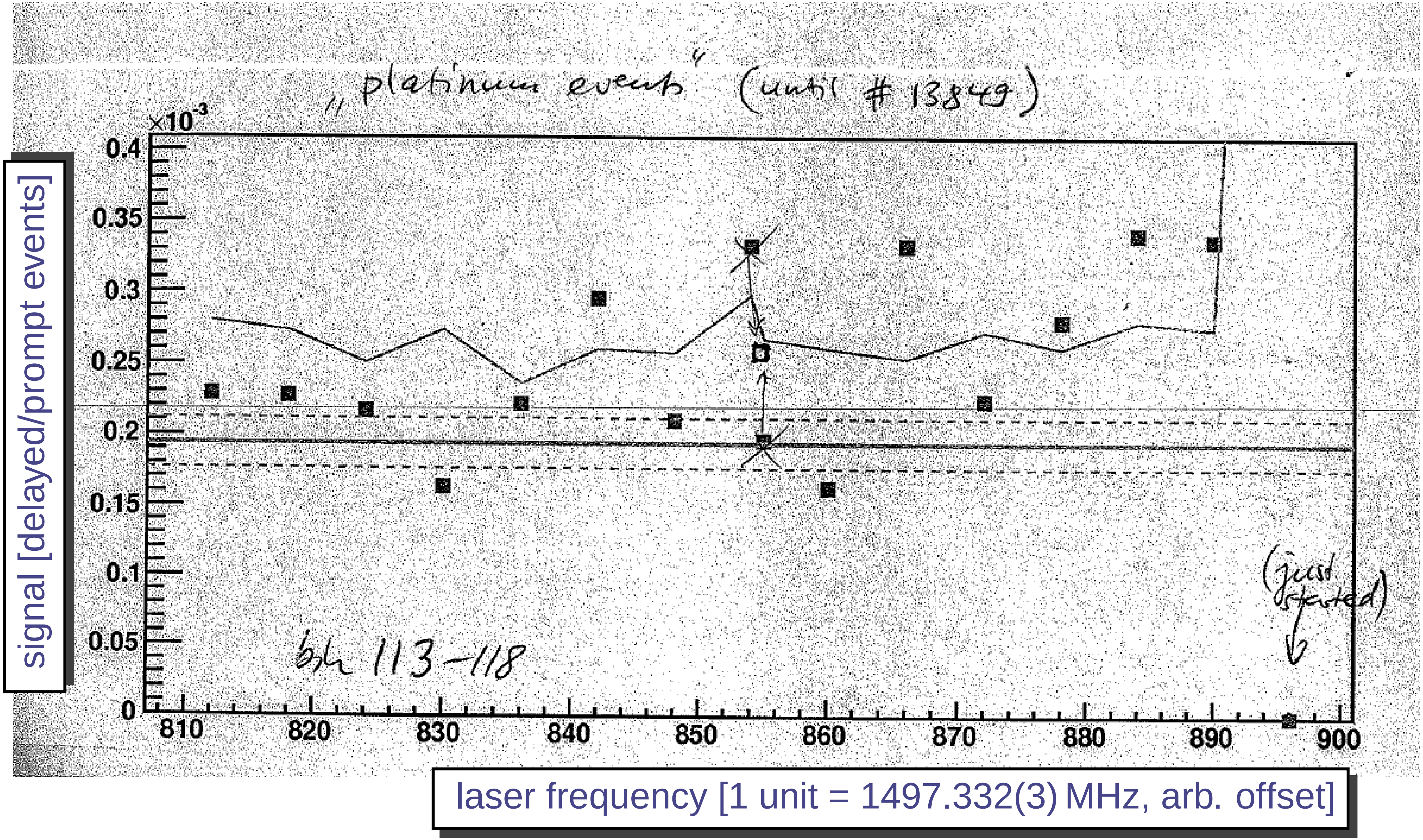
TiSa lasers



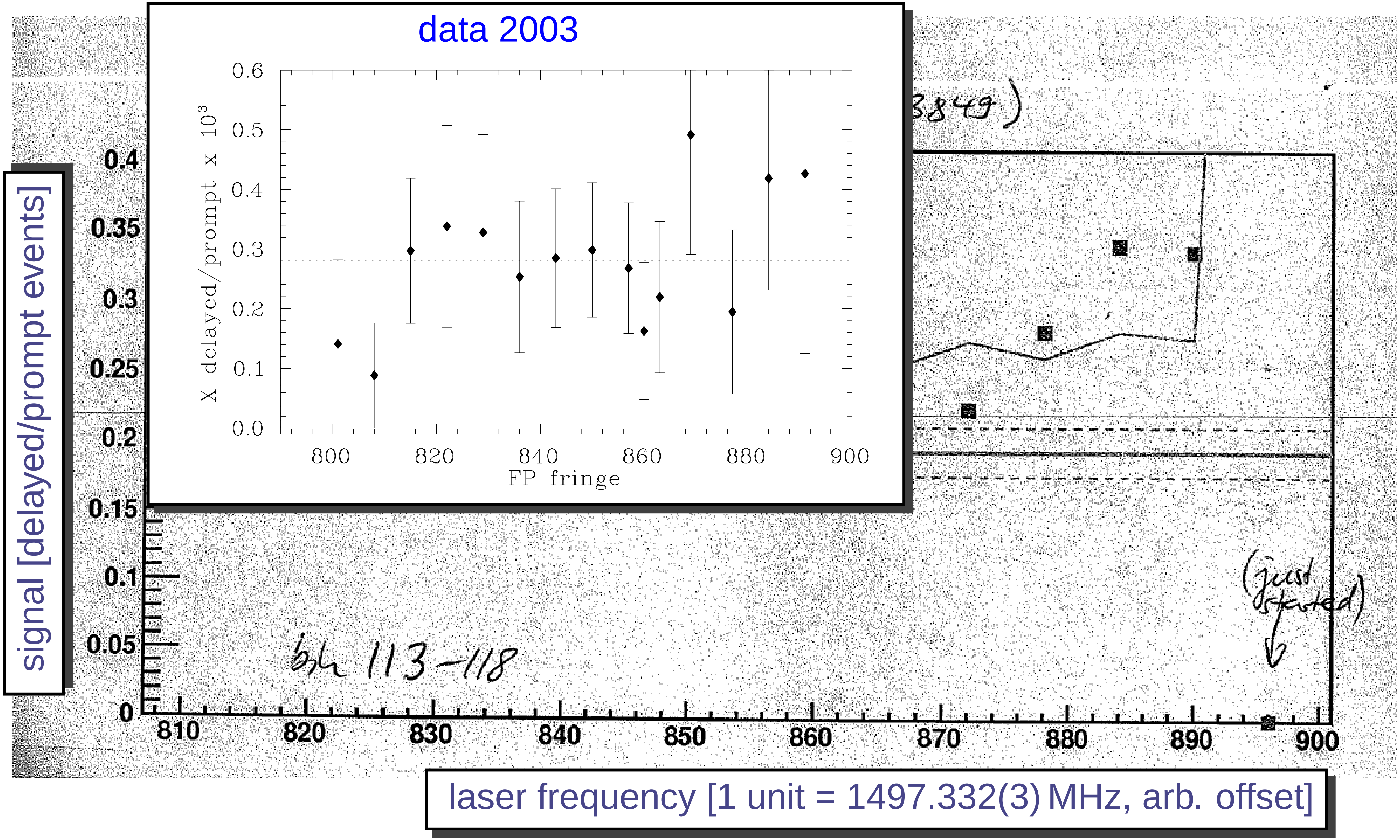
Target, cavity and detectors



The situation June 28, 2009, 18:00



The situation June 28, 2009, 18:00



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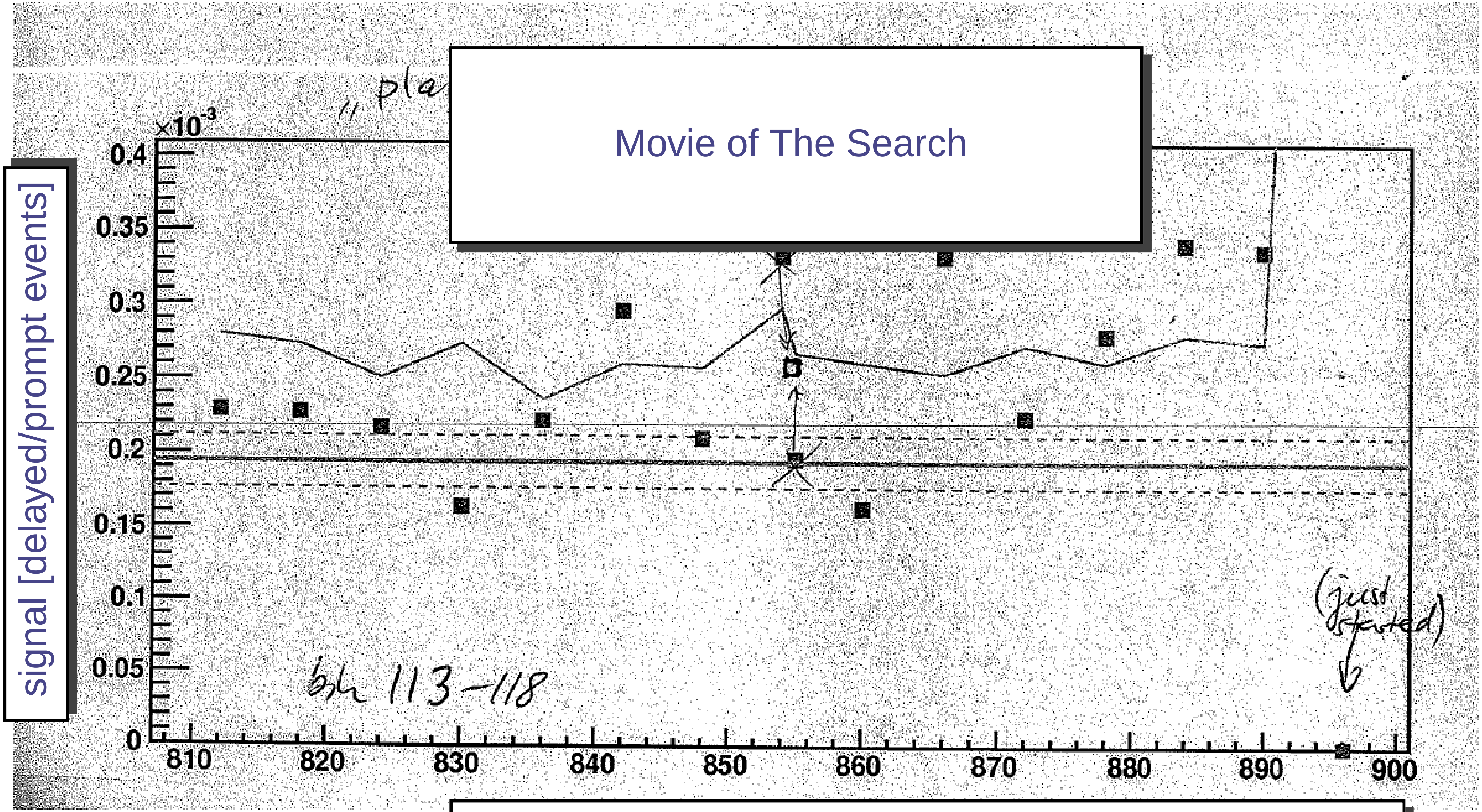
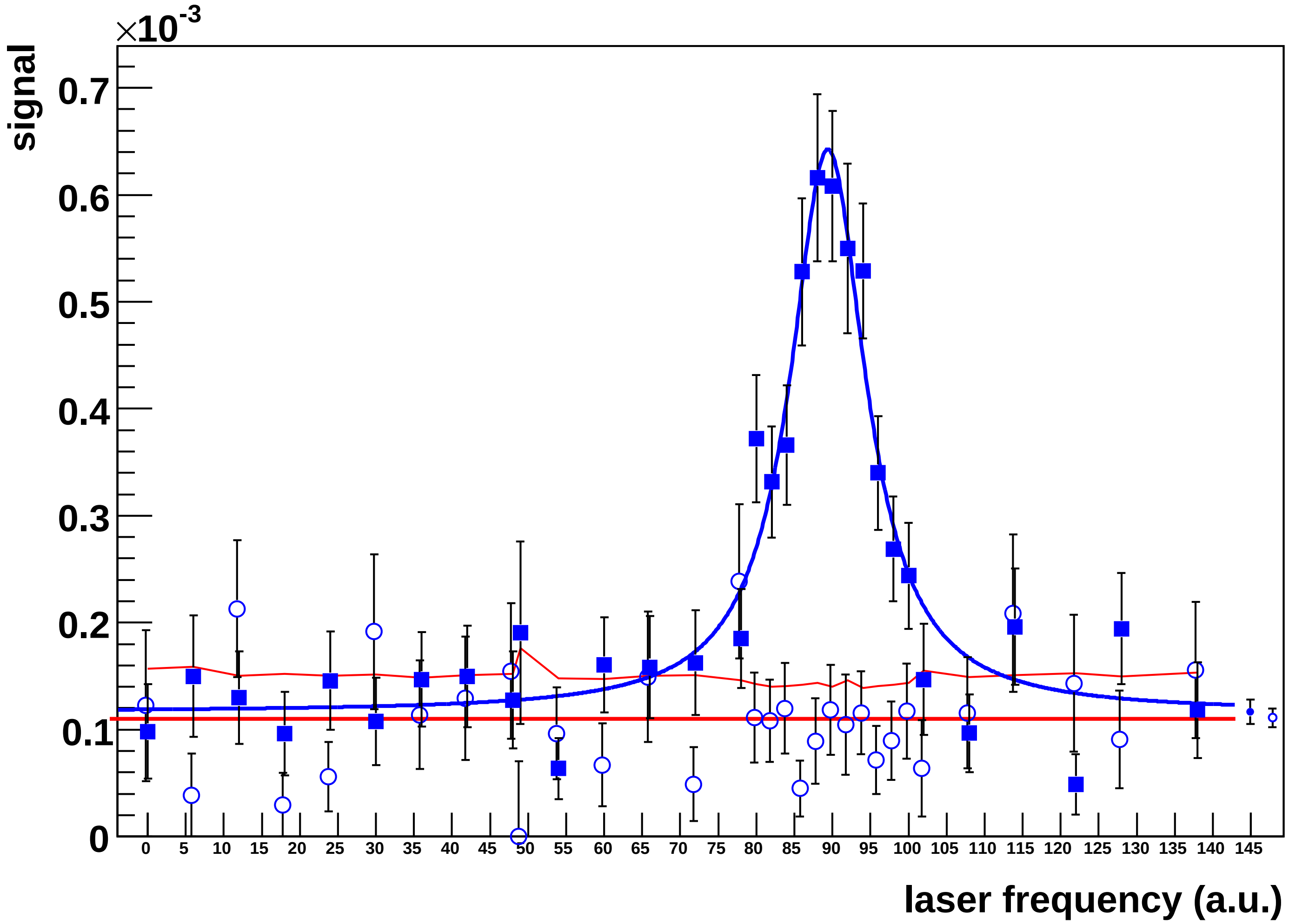


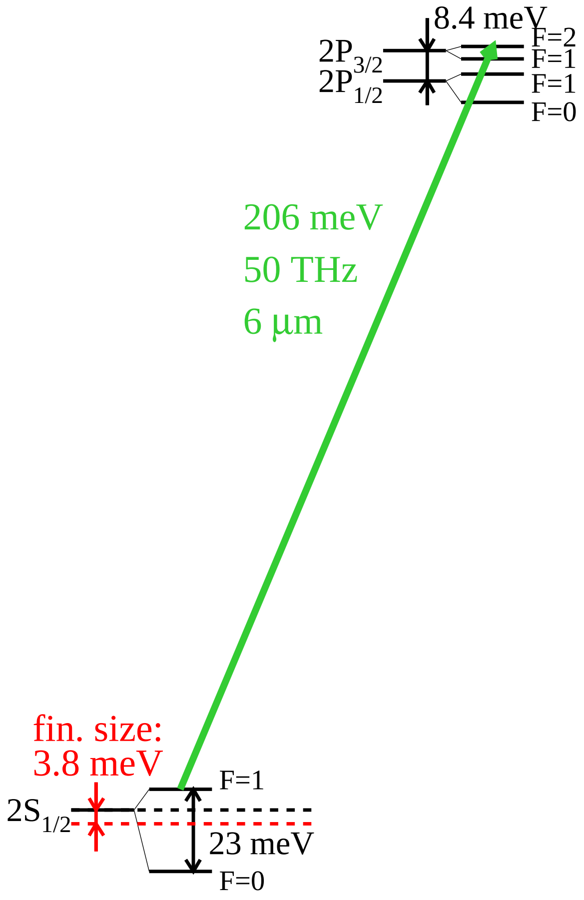
Movie of The Search

signal [delayed/prompt events]

laser frequency [1 unit = 1497.332(3) MHz, arb. offset]

μp ($2S_{1/2}$(F=1) $\rightarrow$ $2P_{3/2}$(F=2))

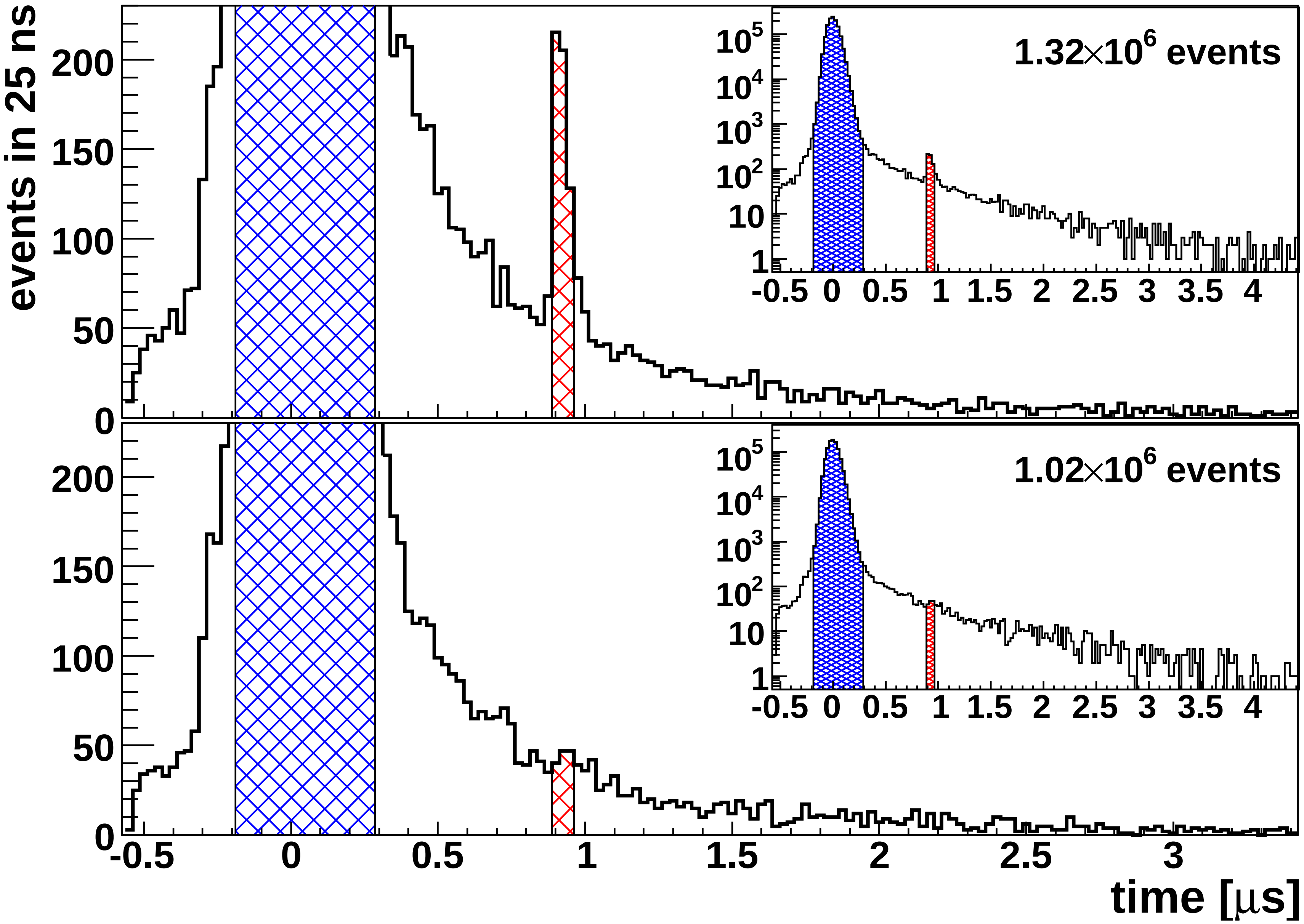




stat.: 700 MHz (14 ppm)

but 75 GHz away from prediction ($\Gamma = 18.6$ GHz)

The time spectra



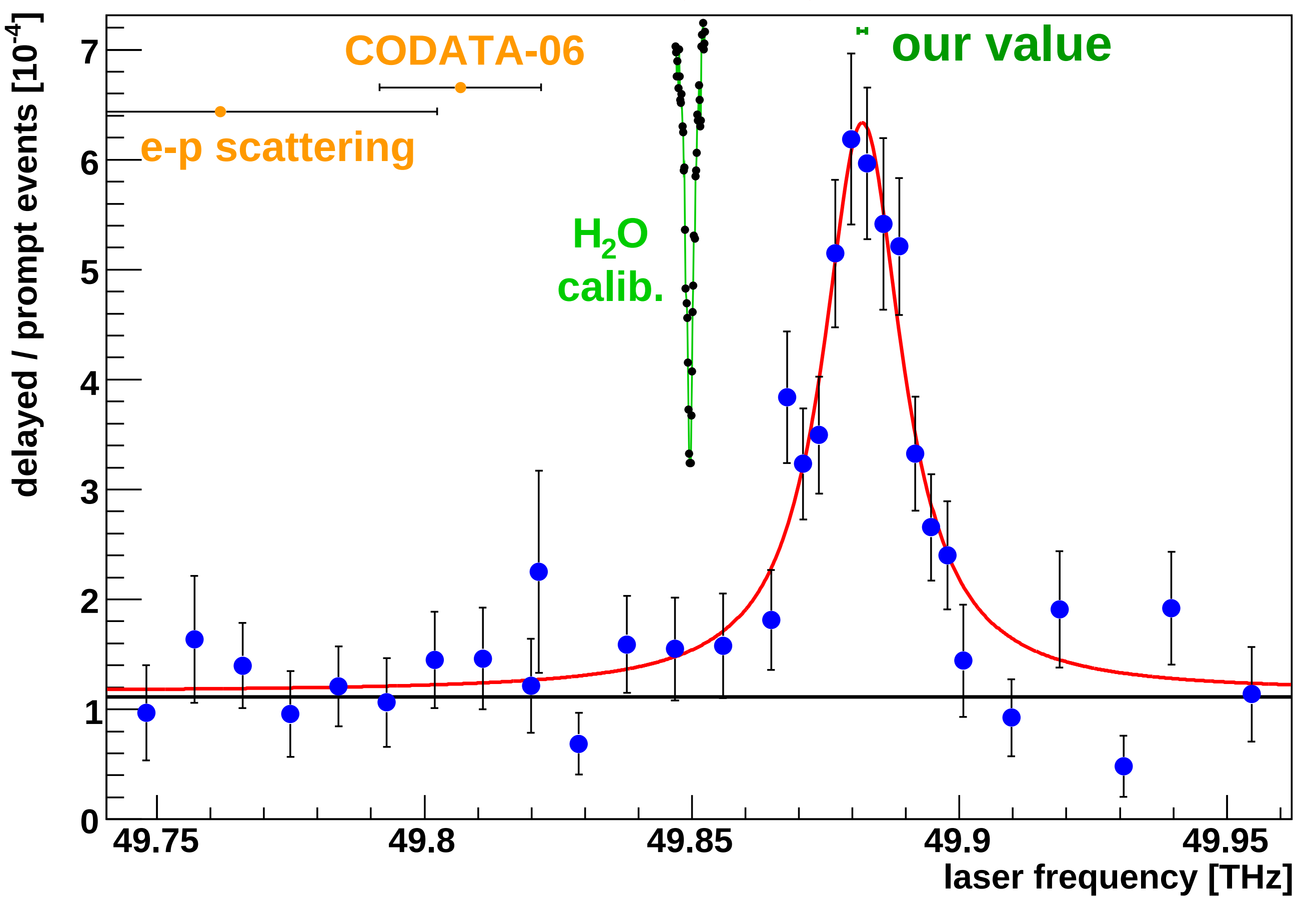
Laser
ON
resonance

Laser
OFF
resonance

The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

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



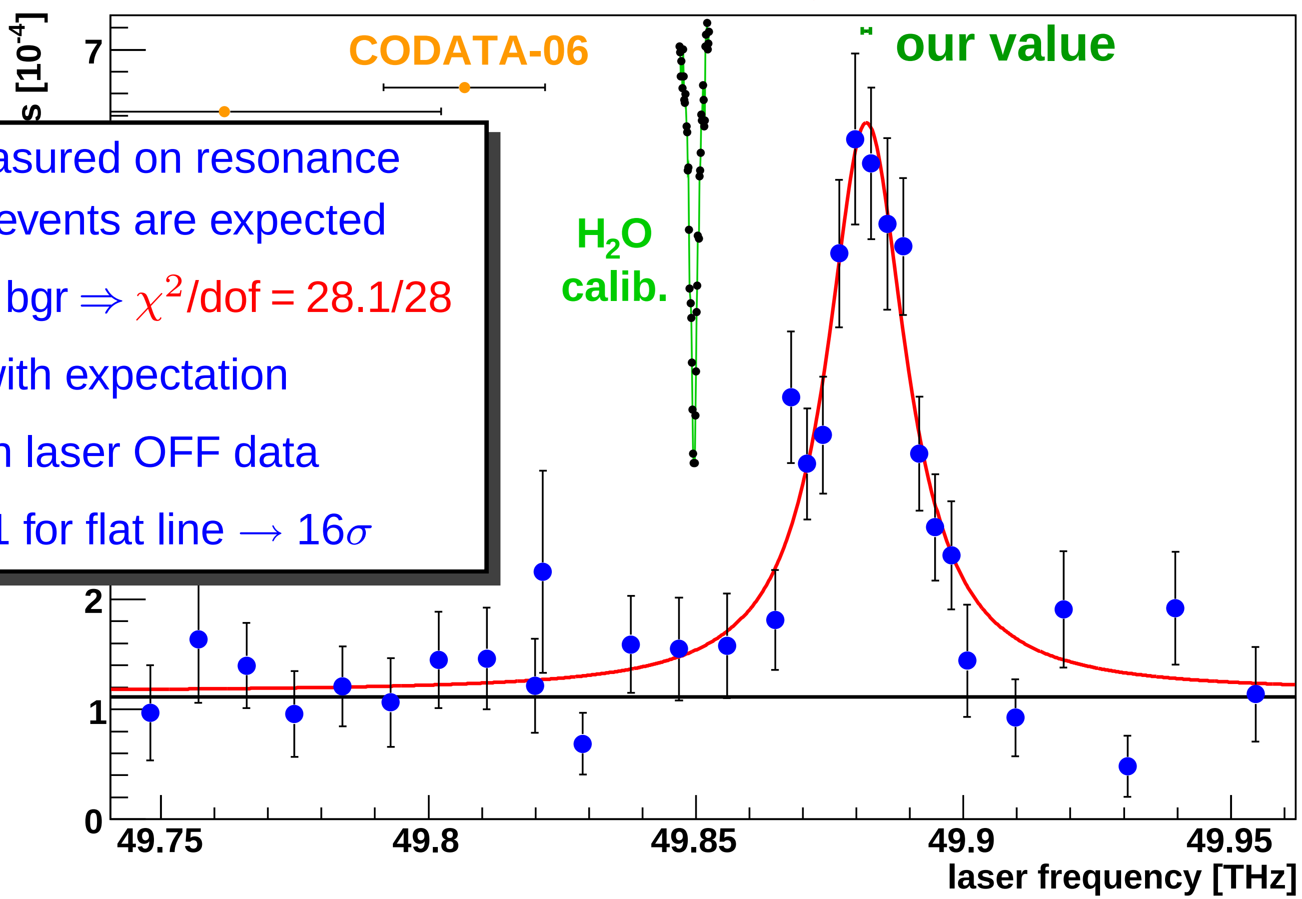
Systematics: 300 MHz
Statistics: 700 MHz

Discrepancy:
$5.0\,\sigma \;\leftrightarrow\; 75\text{ GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$

The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

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



550 events measured on resonance
where 155 bgr events are expected

fit Lorentz + flat bgr $\Rightarrow$ χ^2/dof = 28.1/28

width agrees with expectation

bgr agrees with laser OFF data

χ^2/dof = 283/31 for flat line $\rightarrow$ 16σ

Systematics: 300 MHz
Statistics: 700 MHz

Discrepancy:

$5.0\,\sigma \;\leftrightarrow\; 75\text{ GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$

Uncertainty budget and sensitivity

Statistics	
Center position uncertainty ($\sim 4\%$ of Γ)	700 MHz
Systematics	
Laser frequency (H_20 calibration)	300 MHz
AC and DC stark shift	< 1 MHz
Zeeman shift (5 Tesla)	< 30 MHz
Doppler shift	< 1 MHz
Collisional shift	2 MHz
Total uncertainty of the line determination	760 MHz
Discrepancy with prediction	75 300 MHz

Systematic effects are small since they scale like $1/m$

Finite size effect scales like m^3

Proton radius

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

$$\left.\begin{array}{l}\widetilde{L}^{\text{exp.}} = 206.2949(32)\ \text{meV} \\ \widetilde{L}^{\text{th.}} = 209.9779(49) - 5.2262\, r_{\text{p}}^2 + 0.0347\, r_{\text{p}}^3\ \text{meV}\end{array}\right\} \Rightarrow \boxed{r_{\text{p}}=0.84184(36)(56)\ \text{fm}}$$

$$u_{\text{exp}} = 4.3 \times 10^{-4}$$

$$u_{\text{theo}} = 6.7 \times 10^{-4}$$

$$\boxed{r_{\text{p}}=0.84184(67)\ \text{fm} \qquad (u_r = 8 \times 10^{-4})}$$

CODATA 2006: $r_{\text{p}} = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_{\text{p}} = (0.895 \pm 0.018)$ fm

3.1σ from e-p scatt.
5.0σ from CODATA
r_{p} is 4% smaller

What may be wrong?

$$\boxed{\widetilde{L}^{\text{theo.}}_{\mu p}\left(r_{\text{p}}^{\text{CODATA}}\right) - \widetilde{L}^{\text{exp.}}_{\mu p} = \begin{cases} 75\ \text{GHz} \\ .31\ \text{meV} \\ 0.15\ \% \end{cases}}$$

μp theory wrong?

μp experiment wrong?

H theory wrong?
H experiments wrong? → R_∞ wrong?

What may be wrong?

$$\widetilde{L}^{\text{theo.}}_{\mu p}(r_{\text{p}}^{\text{CODATA}}) - \widetilde{L}^{\text{exp.}}_{\mu p} = \begin{cases} 75\ \text{GHz} \\ .31\ \text{meV} \\ 0.15\ \% \end{cases}$$

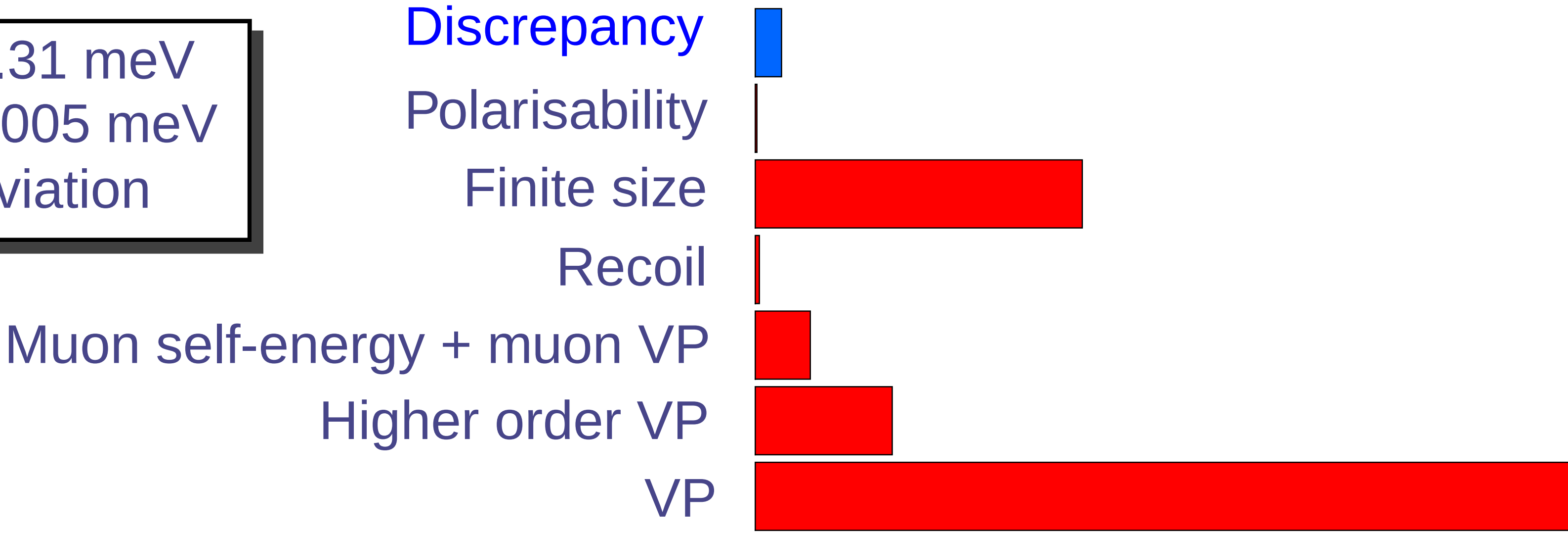
μp theory wrong?

μp experiment wrong?

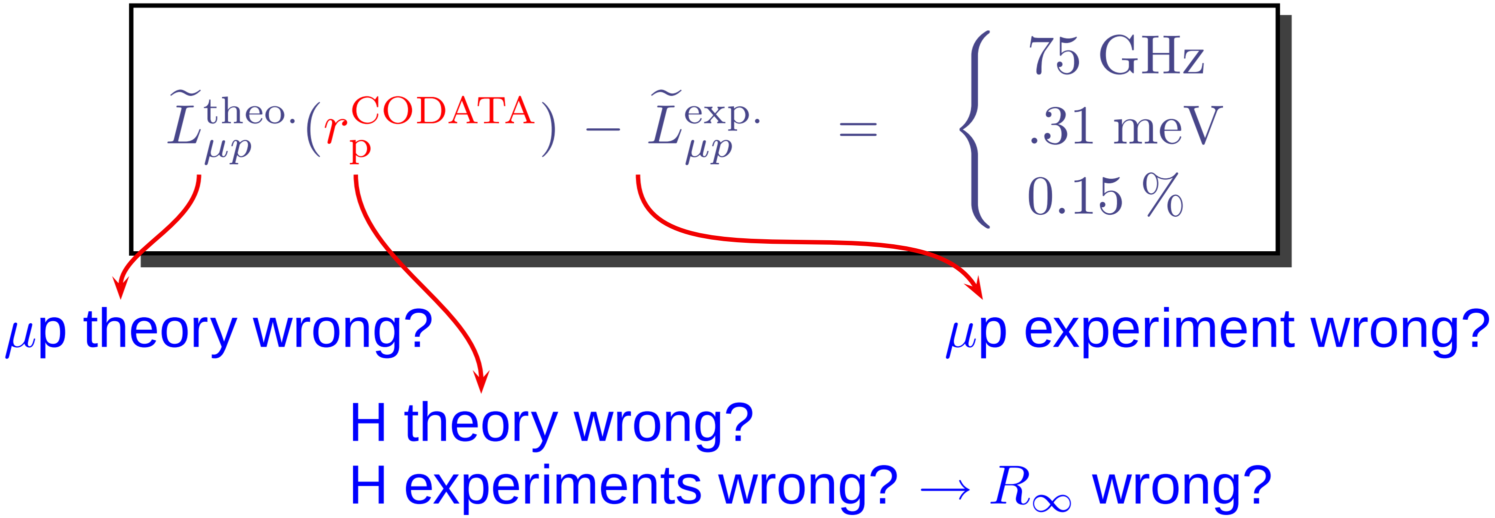
H theory wrong?
H experiments wrong? → R_∞ wrong?

μp theory wrong?

Discrepancy = 0.31 meV
Theory uncert. = 0.005 meV
$\Longrightarrow$ $64\delta(\text{theory})$ deviation



What may be wrong?



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μp theory wrong?

μp experiment wrong?

H theory wrong?
H experiments wrong? $\rightarrow$ R_∞ wrong?

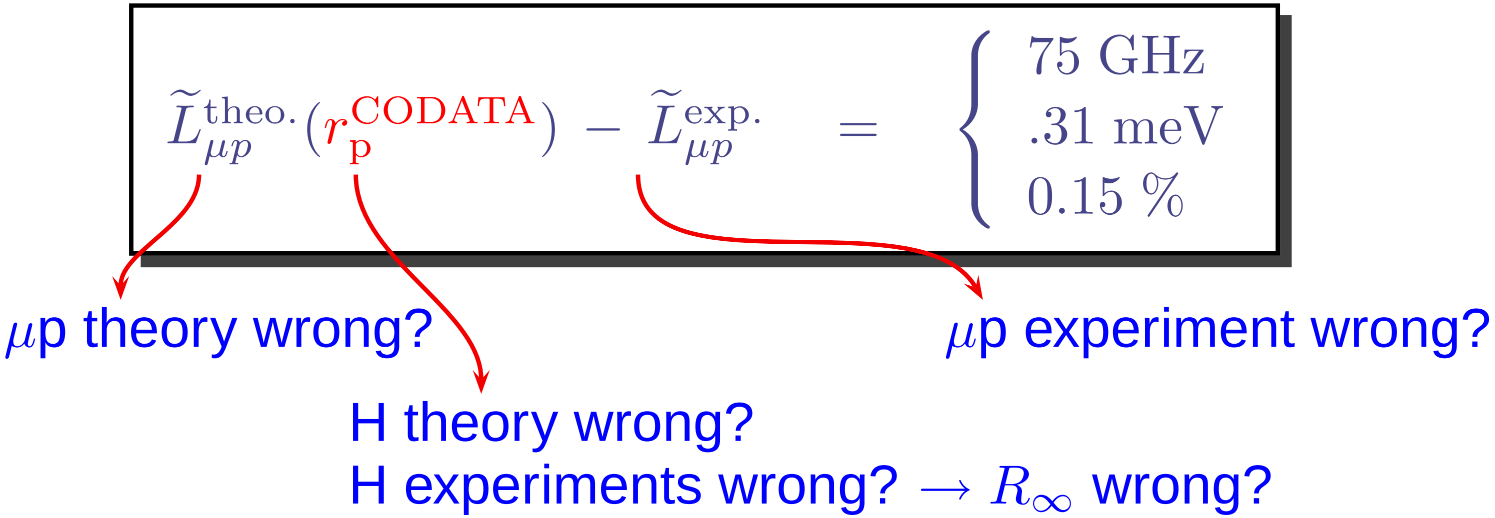
μp experiment wrong?

Frequency mistake by 75 GHz ($\Leftrightarrow 0.15\%$)?

That is 100 σ ! σ_{tot} = 760 MHz, [700 MHz$_{\text{stat}}$, 300 MHz$_{\text{syst}}$]

2$^{\text{nd}}$ line in μp agrees with this 1$^{\text{st}}$ line! ($\rightarrow$ next slides)

What may be wrong?



$$\widetilde{L}^{\mathrm{theo.}}_{\mu p}(r_{\mathrm{p}}^{\mathrm{CODATA}}) - \widetilde{L}^{\mathrm{exp.}}_{\mu p} = \begin{cases} 75\ \mathrm{GHz} \\ .31\ \mathrm{meV} \\ 0.15\ \% \end{cases}$$

μp theory wrong?

μp experiment wrong?

H theory wrong?
H experiments wrong? → R_∞ wrong?

H experiments wrong?

What may be wrong?

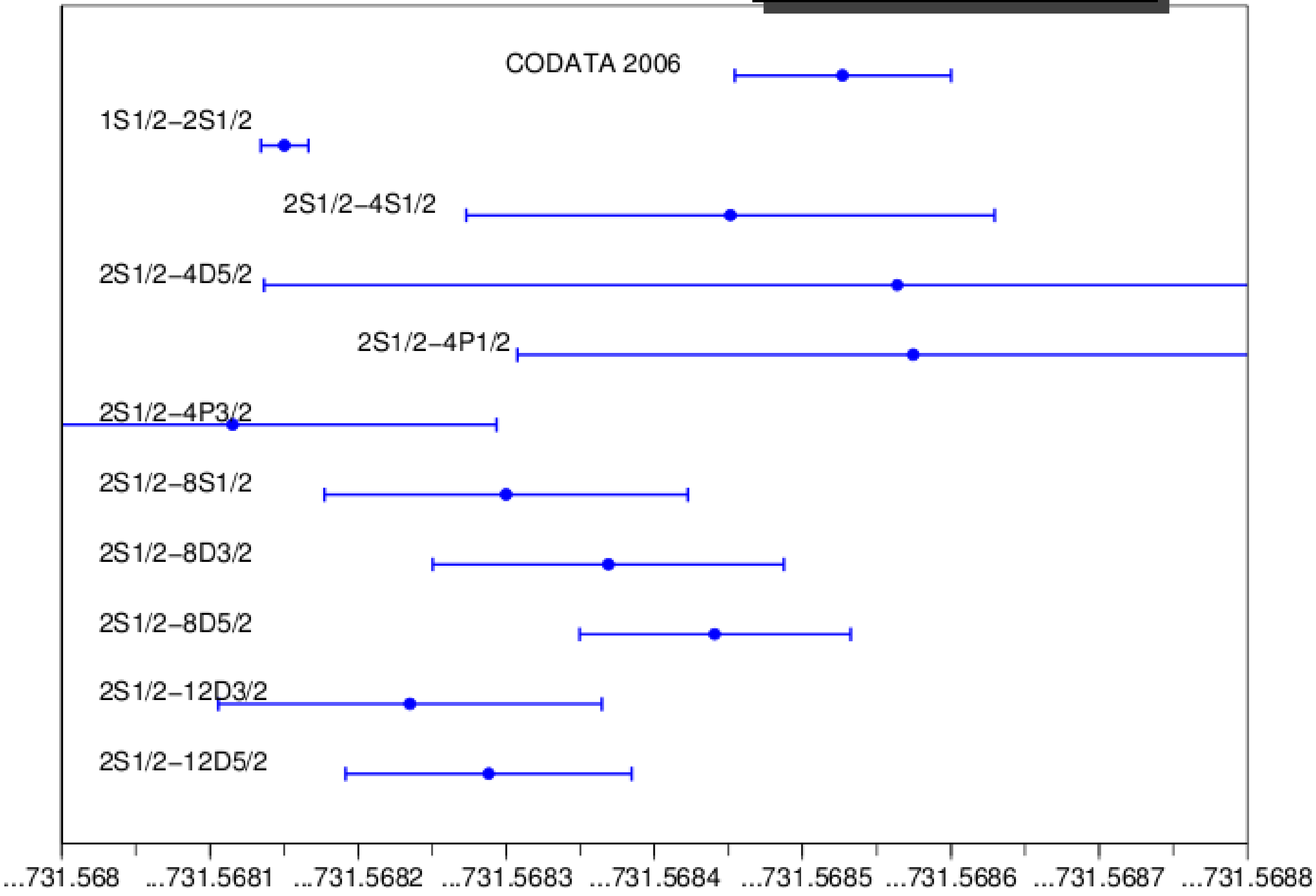
$$\widetilde{L}^{\text{theo.}}_{\mu p}(r_{\text{p}}^{\text{CODATA}}) - \widetilde{L}^{\text{exp.}} = \left\{ \begin{array}{l} 75\ \text{GHz} \\ .31\ \text{meV} \end{array} \right.$$

μp theory wrong?

H theory w
H experim

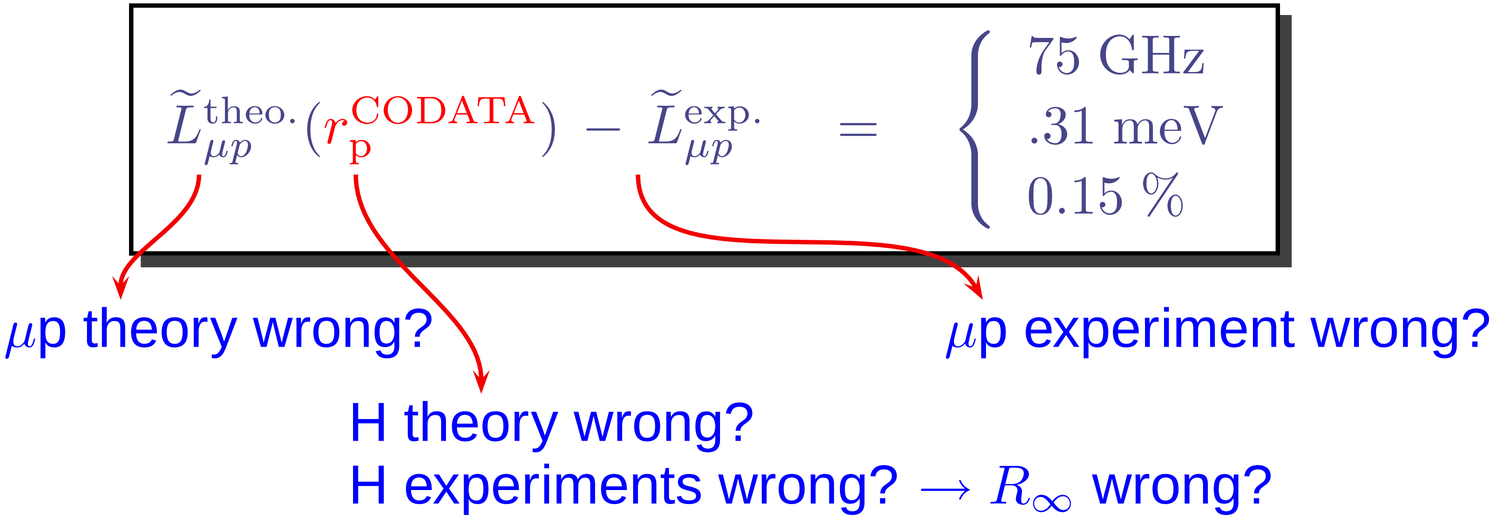
H experiments wrong?

R_∞ with our r_p



F. Biraben, spring 2010

What may be wrong?



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μp theory wrong?

μp experiment wrong?

H theory wrong?

H experiments wrong? $\rightarrow R_\infty$ wrong?

H experiments wrong?

H(1S-2S): 60 kHz $\rightarrow$ 1700σ

all H(2S-$n\ell$) where $n\ell$= $2P$, $4, 6, 8S/D$, $12D$

in the same direction by 1...3σ

What may be wrong?

$$\widetilde{L}^{\text{theo.}}_{\mu p}\left(r_{\text{p}}^{\text{CODATA}}\right) - \widetilde{L}^{\text{exp.}}_{\mu p} = \begin{cases} 75\ \text{GHz} \\ .31\ \text{meV} \\ 0.15\ \% \end{cases}$$

μp theory wrong?

μp experiment wrong?

H theory wrong?
H experiments wrong? → R_∞ wrong?

H theory wrong!

New Physics! :-)

And what about e-p scattering ?!?!?

Discussions...

1005.4879 Karshenboim et al: previously missing QED term.

1005.4880 Karshenboim et al: previously missing QED term.

1007.1419 Krutov, Martynenko: Ground-state HFS of $e\,\mu\,{}^3$He

1007.5076 Bernauer et al: New Mainz electron scattering value

1008.3536 Jaeckel, Roy: *“Spectroscopy as a test of Coulomb’s law”*

1008.3861 De Rujula: *“QED is not endangered by the proton’s size”*

1008.4225 Vanderhaegen, Walcher: *“Long range structure of the nucleon”*

1008.4345 Cloet, Miller: *“Third Zemach moment of the proton”*

1008.4384 Garcia et al: *“Hyperfine splitting in hydrogen with form factors”*

1008.4546 De Rujula: *“Comment on Third Zemach moment of the proton”*

1008.4619 Hill, Paz: *“Model independent extraction of the proton charge radius from electron scattering”*

Discussions...

1005.48

1005.48

1007.14

1007.50

1008.35

1008.38

1008.4225 Vanderhaeghen, Walcher: *"Long range structure of the nucleon"*

1008.3536 Jaeckel, Roy: *"Spectroscopy as a test of Coulomb's law"*

extra hidden photons, minicharged particles
cause deviations from Coulomb's law.

μp transition can NOT be explained this.

(contradicts Lamb shift measurements in ordinary hydrogen)

1008.4345 Cloet, Miller: *"Third Zemach moment of the proton"*

1008.4384 Garcia et al: *"Hyperfine splitting in hydrogen with form factors"*

1008.4546 De Rujula: *"Comment on Third Zemach moment of the proton"*

1008.4619 Hill, Paz: *"Model independent extraction of the proton charge radius from electron scattering"*

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1005.48

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1008.35

1008.38

1008.42

1008.43

1008.43

1008.45

1008.4619 Hill, Paz: *"Model independent extraction of the proton charge radius from electron scattering"*

1008.3861 De Rujula: *"QED is not endangered by the proton's size"*
(Phys. Lett. B, in press)

A large third Zemach moment

$$\langle r_p^3\rangle_{(2)} = \int d^3r_1\, d^3r_2\, \rho(r1)\, \rho(r_2)\, |\boldsymbol{r}_1 - \boldsymbol{r}_2|^3$$

of the proton can explain all three measurements: $\mu\mathrm{p}$, H, e-p

$\rho(r)$ is not a simple Dipole, but has "core" and "tail"

Sick's CF fit to e-p data has χ^2/dof = 1.65 for dof = 310
$\Longrightarrow p = 3.9 \times 10^{-12}$

"This casts doubt even on the corresponding extracted value of the mean square radius ..."

Discussions...

1008.4345 Cloet, Miller: *“Third Zemach moment of the proton”*
(is a comment on De Rujula)

Such a large third Zemach moment is impossible.

$$\langle r_p^3 \rangle_{(2)}(\mathrm{DeRujula}) = 36.6 \pm 6.9\,\mathrm{fm}^3$$
$$\langle r_p^3 \rangle_{(2)}(\mathrm{Sick}) \;=\; 2.71 \pm 0.13\,\mathrm{fm}^3$$

1005.48

1005.48

1007.14

1007.50

1008.35

1008.38

1008.4225 Vanderhaegen, Walcher: *“Long range structure of the nucleon”*

1008.4345 Cloet, Miller: *“Third Zemach moment of the proton”*

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Discussions...

1005.4879 Karshenboim et al: previously missing QED term

1008.4619 Hill, Paz: *"Model independent extraction of the proton charge radius from electron scattering"*

- so-called "model-independent" fits are in fact model-dependent
- uncertainties may have been underestimated

1008.4225 Vanderhaegen, Walcher: *"Long range structure of the nucleon"*

1008.4345 Cloet, Miller: *"Third Zemach moment of the proton"*

1008.4384 Garcia et al: *"Hyperfine splitting in hydrogen with form factors"*

1008.4546 De Rujula: *"Comment on Third Zemach moment of the proton"*

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Discussions...

1005.4879 Karshenboim et al: previously missing QED term

1008.4619 Hill, Paz: *“Model independent extraction of the proton charge radius from electron scattering”*

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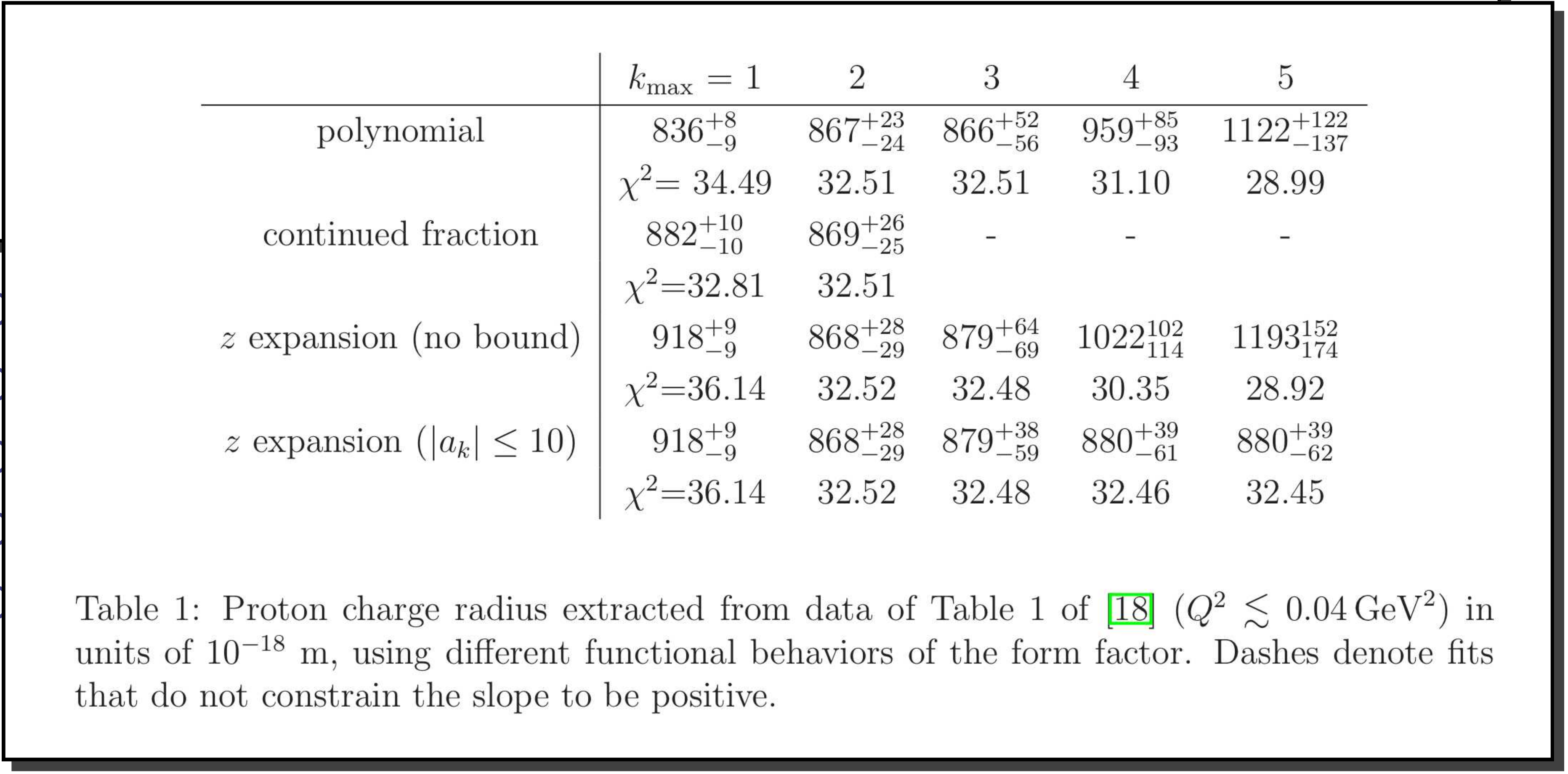


	$k_{\max}=1$	2	3	4	5
polynomial	836^{+8}_{-9}	867^{+23}_{-24}	866^{+52}_{-56}	959^{+85}_{-93}	1122^{+122}_{-137}
	$\chi^2 = 34.49$	32.51	32.51	31.10	28.99
continued fraction	882^{+10}_{-10}	869^{+26}_{-25}	-	-	-
	$\chi^2 = 32.81$	32.51			
z expansion (no bound)	918^{+9}_{-9}	868^{+28}_{-29}	879^{+64}_{-69}	1022^{102}_{114}	1193^{152}_{174}
	$\chi^2 = 36.14$	32.52	32.48	30.35	28.92
z expansion ($\lvert a_k \rvert \leq 10$)	918^{+9}_{-9}	868^{+28}_{-29}	879^{+38}_{-59}	880^{+39}_{-61}	880^{+39}_{-62}
	$\chi^2 = 36.14$	32.52	32.48	32.46	32.45

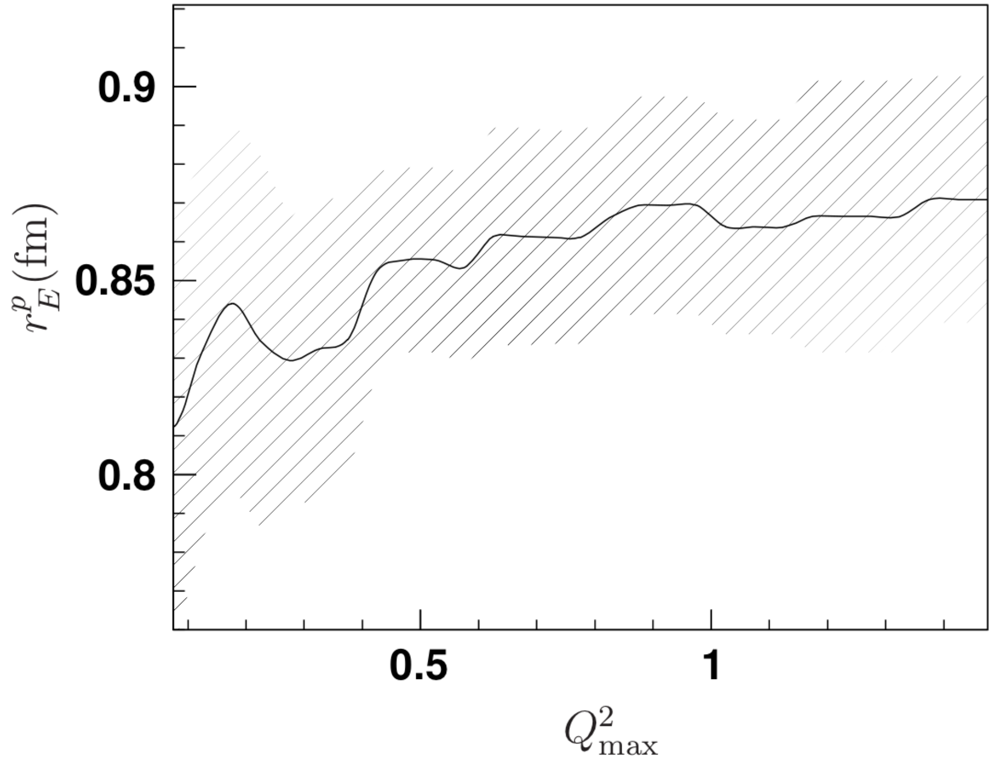
Table 1: Proton charge radius extracted from data of Table 1 of [18] ($Q^2 \lesssim 0.04\,\mathrm{GeV}^2$) in units of 10^{-18} m, using different functional behaviors of the form factor. Dashes denote fits that do not constrain the slope to be positive.

Discussions...

1005.4879 Karshenboim et al: previously missing QED term

1008.4619 Hill, Paz: *“Model independent extraction of the proton charge radius from electron scattering”*

Variation of the fitted proton charge radius as a function of maximum Q^2



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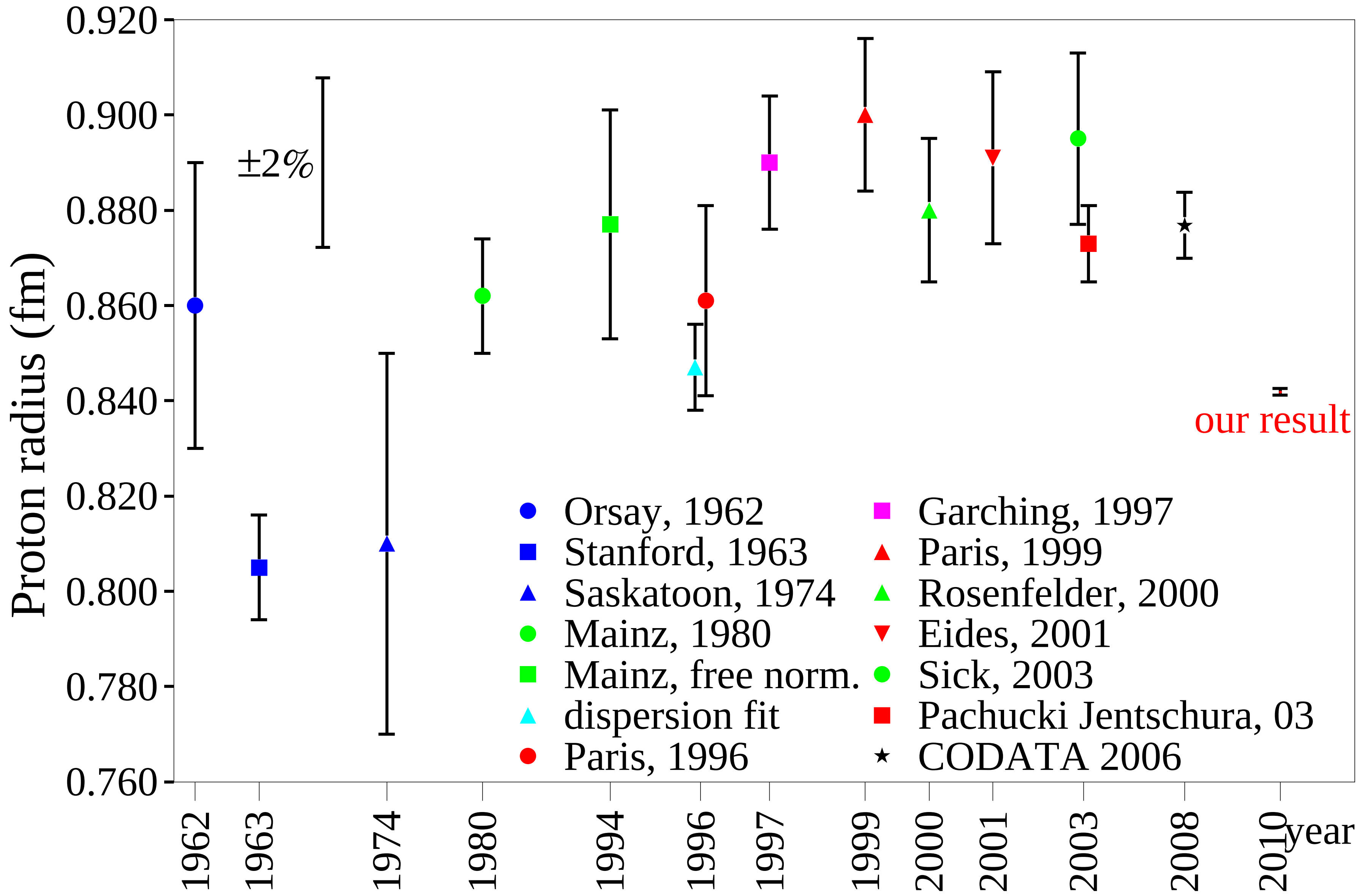
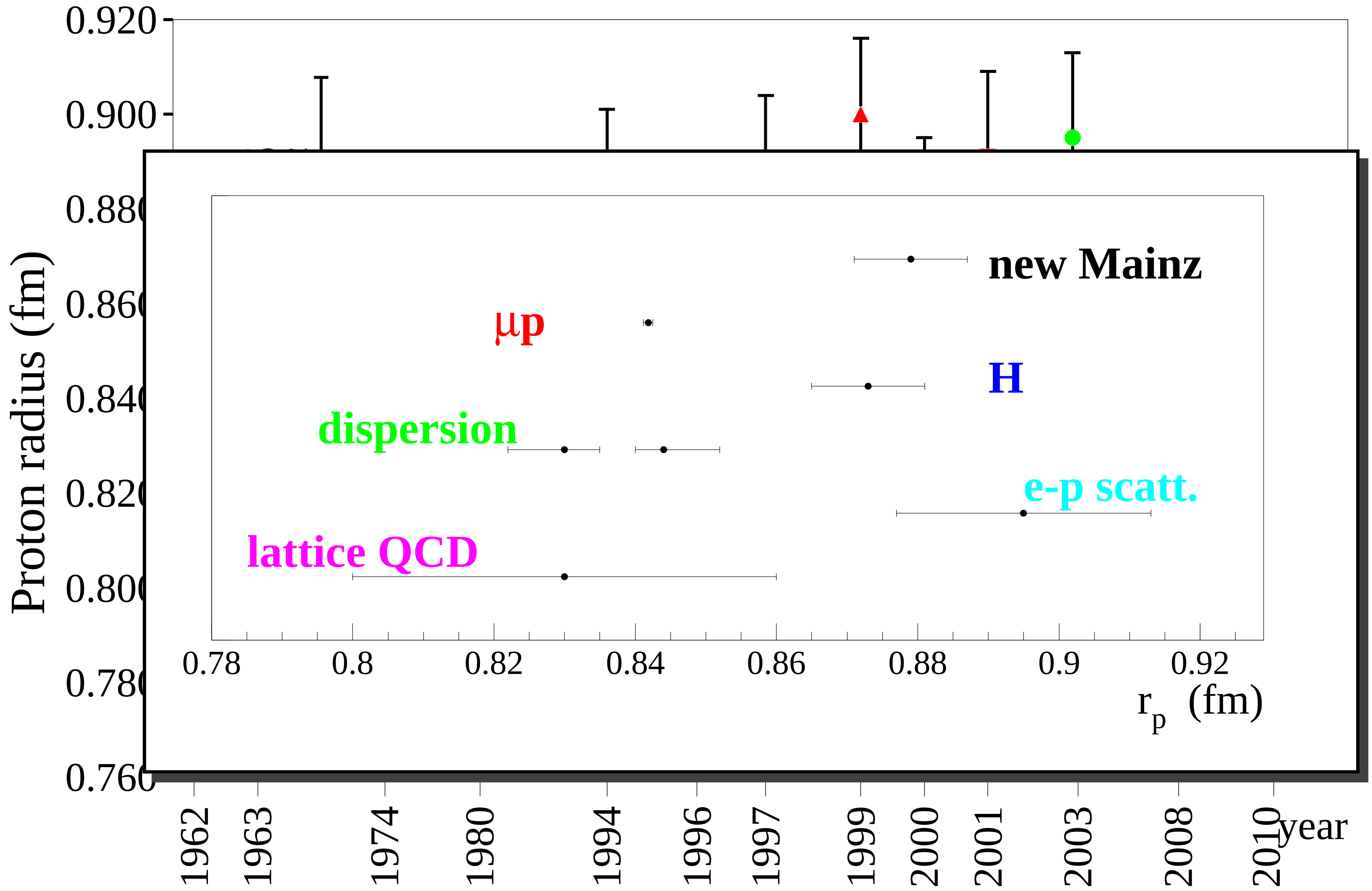
s from

New r_p and R_∞



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

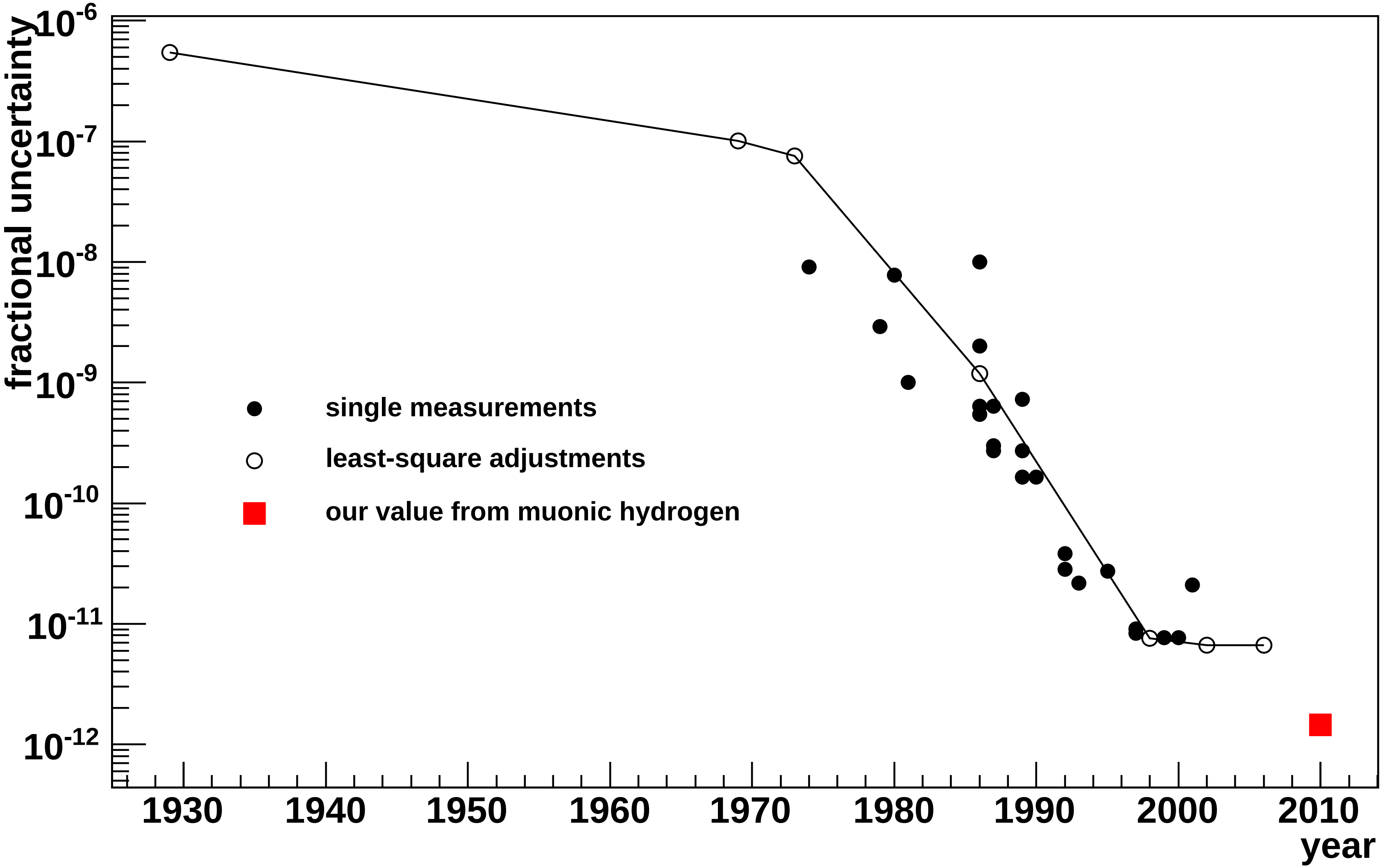
New r_p and R_∞



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

New r_p and R_∞

accuracy of the Rydberg constant

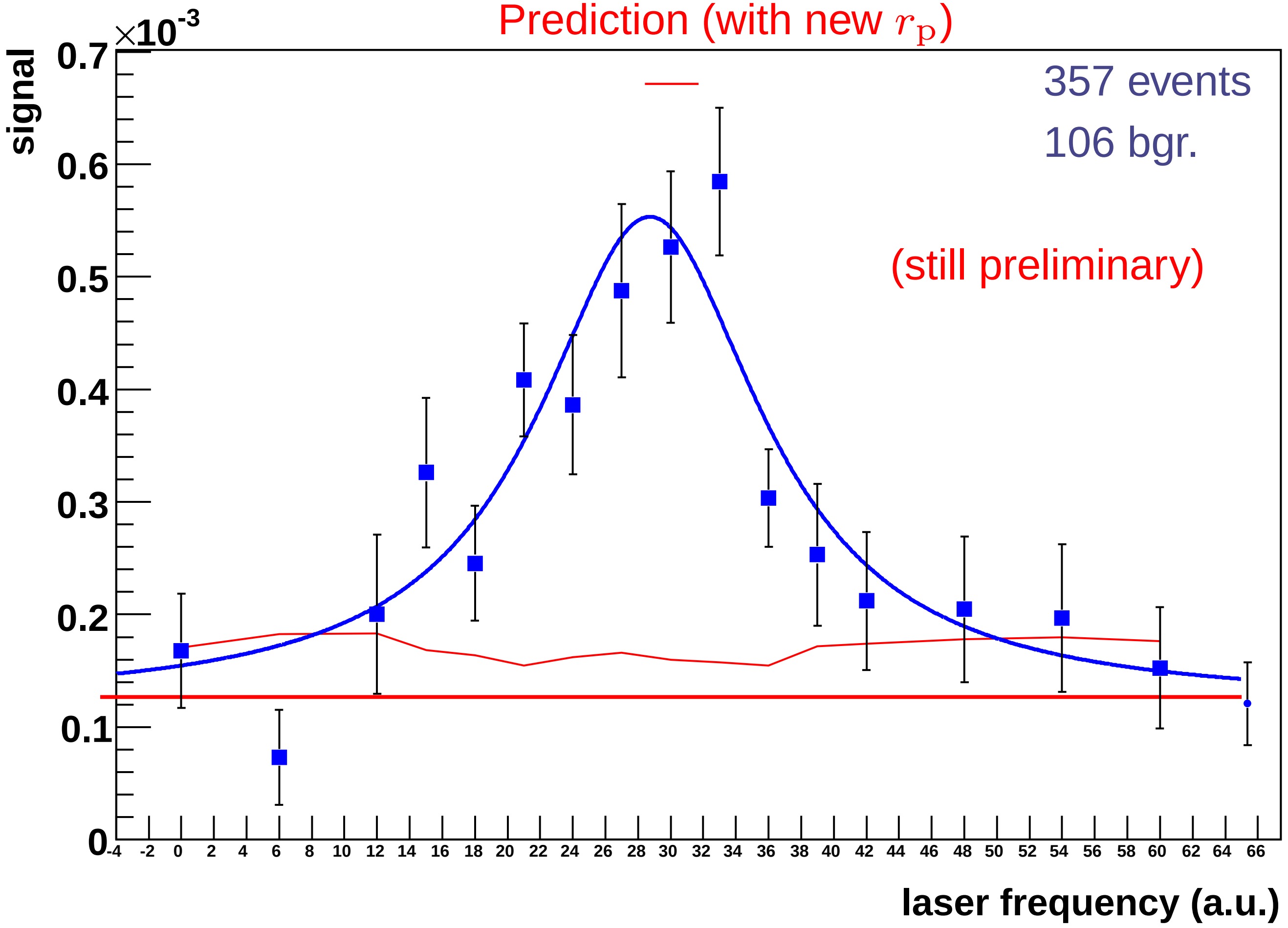


R. Pohl *et al.*, Nature 466, 213 (2010).

More measurements

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

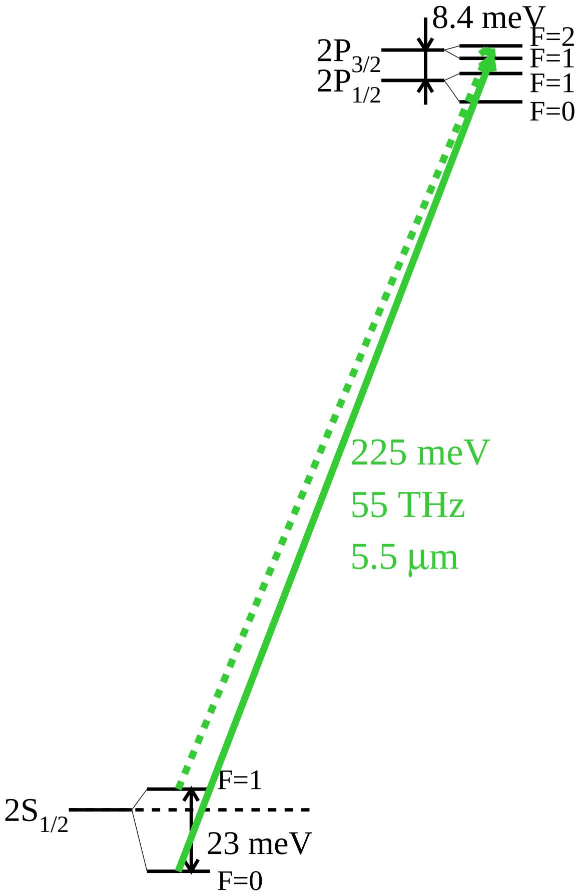
Prediction (with new r_p)



357 events

106 bgr.

(still preliminary)

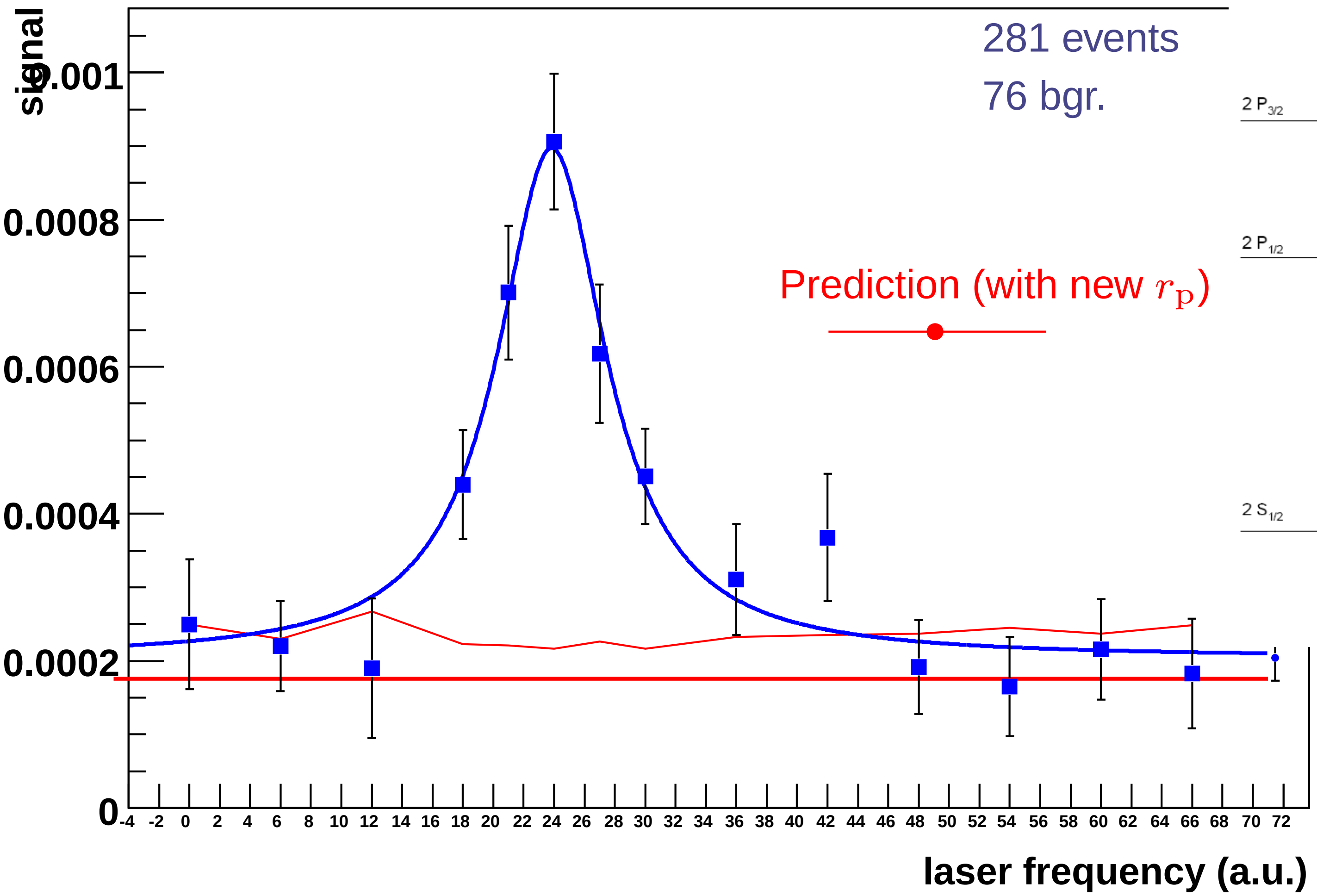


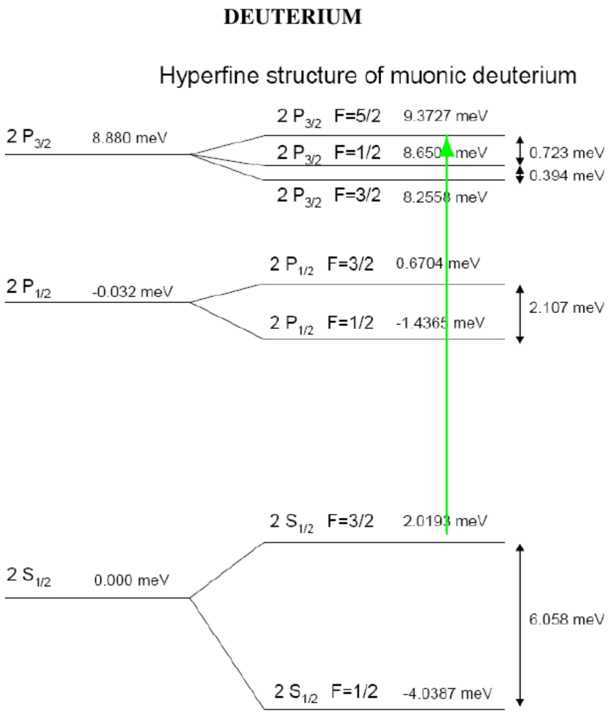
- $\sigma_\mathrm{position} = 1.1$ GHz $\Longleftrightarrow$ 25 ppm ($\Gamma = 18.6$ GHz)
- Position fits perfectly with theory using new r_p

Extract HFS and r_Zemach

μ**d** ($2S_{1/2}$**(F=3/2)** $\rightarrow$ $2P_{3/2}$**(F=5/2)**)

(still preliminary)

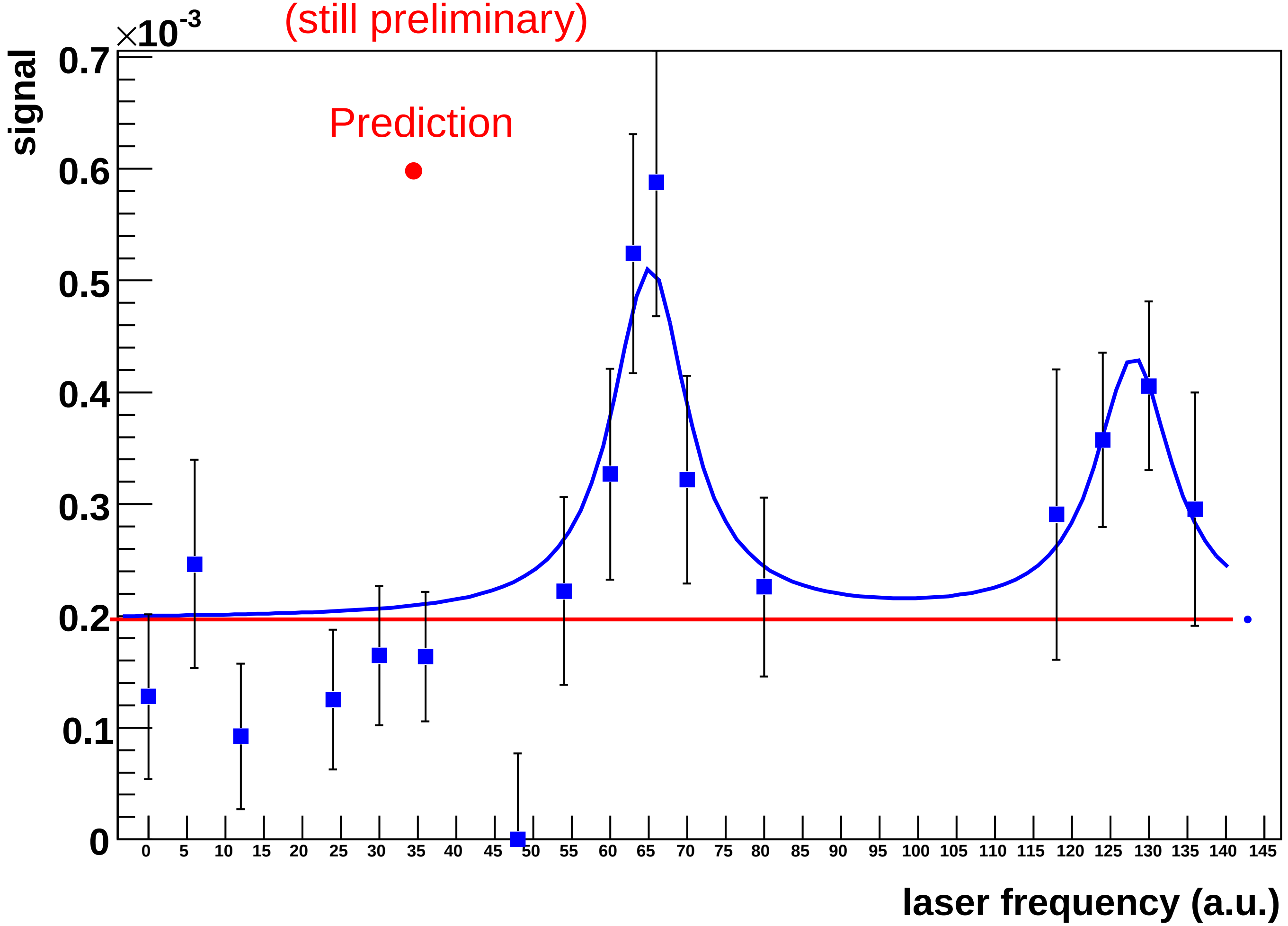


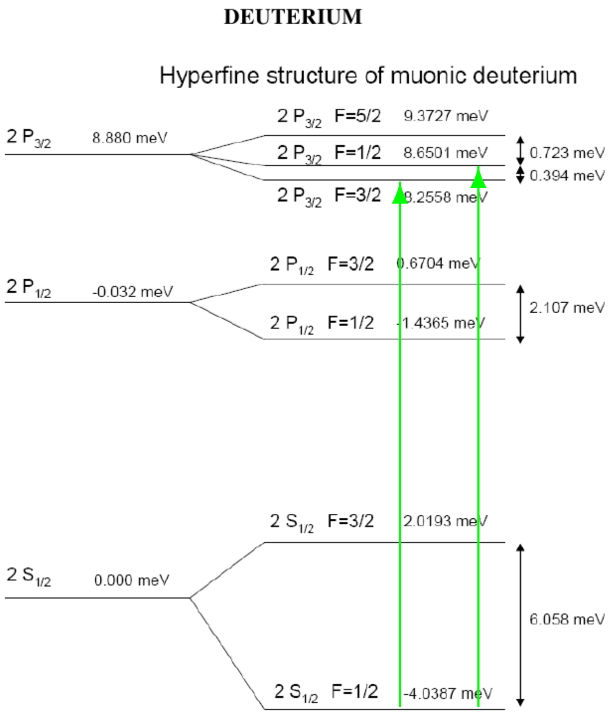


- $\sigma_\text{position} = 880$ MHz $\Longleftrightarrow$ 17 ppm ($\Gamma = 18.6$ GHz)
- Position does not fit with prediction: 3.5σ deviation

Extract r_d and d. pol.

μd ($2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=3/2 and 1/2))





- $\sigma_{\text{position}} = 2.2$ GHz $\Longleftrightarrow$ 43 ppm   ($\Gamma = 18.6$ GHz)
- Relative pos. fit to each others but not with the first μd line
- Background well known from previous μd line

Summary

- measured μp ($2S_{1/2}$(F=1) $\rightarrow$ $2P_{3/2}$(F=2)) to 15 ppm (stat.+syst.)
  $\rightarrow$ r_p to 8×10^{-4} (experimental precision 4×10^{-4})
  $r_p = 0.84184 \pm 0.00067$ fm is 5σ away from CODATA-2006

  The proton is 4% smaller, and the Rydberg constant R_∞ is 4.9 sigma off

- measured μp ($2S_{1/2}$(F=0) $\rightarrow$ $2P_{3/2}$(F=1)) to 25 ppm (stat., online)
  exactly at the position deduced with our new r_p
  $\rightarrow$ Zemach radius to a few % (radius of the magnetic moment distribution)

- measured μd ($2S_{1/2}$(F=3/2) $\rightarrow$ $2P_{3/2}$(F=5/2)) to 20 ppm (stat., online)
  not exactly where we expected it from r_p and H-D isotope shift
  $\rightarrow$ deuteron polarizability

- measured μd ($2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=3/2))
  observed μd ($2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=1/2))
  $\rightarrow$ check calculations in μd

http://muhy.web.psi.ch

Yeah!

Outlook: Lamb shift in muonic helium

- CREMA collaboration: Charge Radius Experiment with Muonic Atoms
- Exp. R10-01 approved at PSI in Feb. 2010
- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He
- $\Rightarrow$ alpha particle and helion charge radius to 3×10^{-4} (0.0005 fm)

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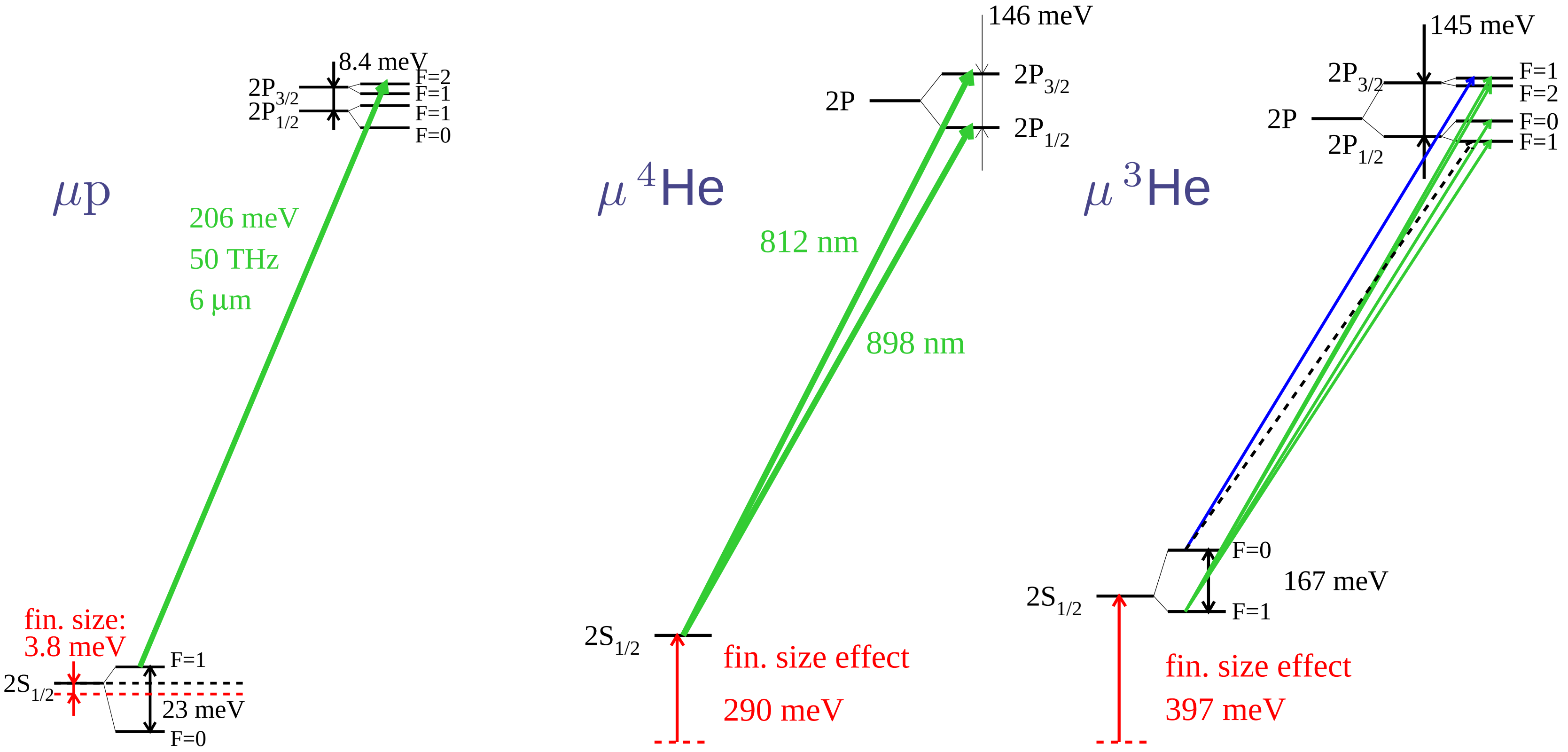

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- aims:
  - help to solve the proton size puzzle
  - absolute charge radii of helion, alpha
  - low-energy effective nuclear models: ^{1}H, ^{2}D, ^{3}He, ^{4}He
  - better bound-state QED test together with He$^+$(1S-2S) [Udem @ MPQ]

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  - low-energy effective nuclear models: ^{1}H, ^{2}D, ^{3}He, ^{4}He
  - better bound-state QED test together with He$^+$(1S-2S) [Udem @ MPQ]
- identical muon beam
- similar laser, no Raman cell ($\longrightarrow$ more pulse energy)
- similar, maybe better x-ray detectors (8.2 keV)
- event rate: 16-48 events per hour (not 6 per hour, μp)
- line with 300 GHz (1 nm!)

μp Lamb shift collaboration in 2009

F. KOTTMANN	ETH Zürich, Switzerland
A. ANTOGNINI, T.W. HÄNSCH, T. NEBEL, R. POHL	MPQ, Garching, Germany
D. TAQQU	PSI, Switzerland
E.-O. Le BIGOT, F. BIRABEN, P. INDELICATO, L. JULIEN, F. NEZ	Laboratoire Kastler Brossel, Paris, France
F.D. AMARO, J.M.R. CARDOSO, D.S. COVITA, L.M.P. FERNANDES, J.A.M. LOPEZ, C.M.B. MONTEIRO, J.M.F. DOS SANTOS, J.F.C.A. VELOSO	Department of Physics, Coimbra, Portugal
A. GIESEN, K. SCHUHMANN	Dausinger + Giesen, Stuttgart, Germany
T. GRAF	Institut für Strahlwerkzeuge, Stuttgart, Germany
C.-Y. KAO, Y.-W. LIU	National Tsing Hua University, Hsinchu, Taiwan
P. RABINOWITZ	Department of Chemistry, Princeton, USA
A. DAX, P. KNOWLES, L. LUDHOVA, F. MULHAUSER, L. SCHALLER	former members, spent holidays at run 2009

MPQ

Laboratoire Kastler Brossel
Physique quantique et applications

· U C ·
Universidade de Coimbra

PAUL SCHERRER INSTITUT
PSI

University of Stuttgart
Germany

Proton Size Investigators thank you for your attention

Contributions to the μp Lamb shift

#	Contribution	Value	Unc.
3	Relativistic one loop VP	205.0282	
4	NR two-loop electron VP	1.5081	
5	Polarization insertion in two Coulomb lines	0.1509	
6	NR three-loop electron VP	0.00529	
7	Polarisation insertion in two and three Coulomb lines (corrected)	0.00223	
8	Three-loop VP (total, uncorrected)		
9	Wichmann-Kroll	-0.00103	
10	Light by light electron loop ((Virtual Delbrück)	0.00135	0.00135
11	Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	-0.00500	0.0010
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	-0.00150	
13	Mixed electron and muon loops	0.00007	
14	Hadronic polarization $\alpha(Z\alpha)^4 m_r$	0.01077	0.00038
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	0.000047	
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	-0.000015	
17	Recoil contribution	0.05750	
18	Recoil finite size	0.01300	0.001
19	Recoil correction to VP	-0.00410	
20	Radiative corrections of order $\alpha^n(Z\alpha)^k m_r$	-0.66770	
21	Muon Lamb shift 4th order	-0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m}{M} m_r$	-0.04497	
23	Recoil of order α^6	0.00030	
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m_r$	-0.00960	
25	Nuclear structure correction of order $(Z\alpha)^5$ (Proton polarizability)	0.015	0.004
26	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	0.00019	
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	-0.00001	
	Sum	206.0573	0.0045

P. Indelicato, 2010

Contributions to the μp Lamb shift

Contribution	our selection		Pachucki	Borie
Leading nuclear size contribution	-5.19745	$< r_{\mathrm{p}}^2 >$	-5.1974	-5.1971
Radiative corrections to nuclear finite size effect	-0.0275	$< r_{\mathrm{p}}^2 >$	-0.0282	-0.0273
Nuclear size correction of order $(Z\alpha)^6 < r_{\mathrm{p}}^2 >$	-0.001243	$< r_{\mathrm{p}}^2 >$		
Total $< r_{\mathrm{p}}^2 >$ contribution	-5.22619	$< r_{\mathrm{p}}^2 >$	-5.2256	-5.2244
Nuclear size correction of order $(Z\alpha)^5$	0.0347	$< r_{\mathrm{p}}^3 >$	0.0363	0.0347
Nuclear size correction of order $(Z\alpha)^6 < r_{\mathrm{p}}^4 >$	-0.000043	$< r_{\mathrm{p}}^2 >^2$		

P. Indelicato, 2010

Contributions to the μp Lamb shift

Lamb shift: $\Delta E_{LS} = 206.0573(45) - 5.2262\, r_{\rm p}^2 + 0.0347\, r_{\rm p}^3$ meV

$u = 0.0045$ meV dominated by proton polarizability

$2S$ Hyperfine structure: $\Delta E_{HFS}^{2S} = 22.8148\,(78)$ meV

using $R_Z = 1.022$ fm and scatter.

Fine structure: $\Delta E_{FS} = 8.352082$ meV

$2P_{3/2}$ Hyperfine structure: $\Delta E_{HFS}^{2P_{3/2}} = 3.392588$ meV