News from the proton

Lamb shift and hyperfine splitting in muonic hydrogen

Randolf Pohl

for the *CREMA* collaboration

Outline

- The problem:

  Proton rms charge radius r_p from muonic hydrogen $\mu\mathrm{p}$ is 4 % smaller than the values from elastic electron-proton scattering and hydrogen spectroscopy.

  That's 5σ ... 9.4σ.

  But the **μp** result is 10 times more accurate than any other measurement.

- Introduction:

  How large is the proton?

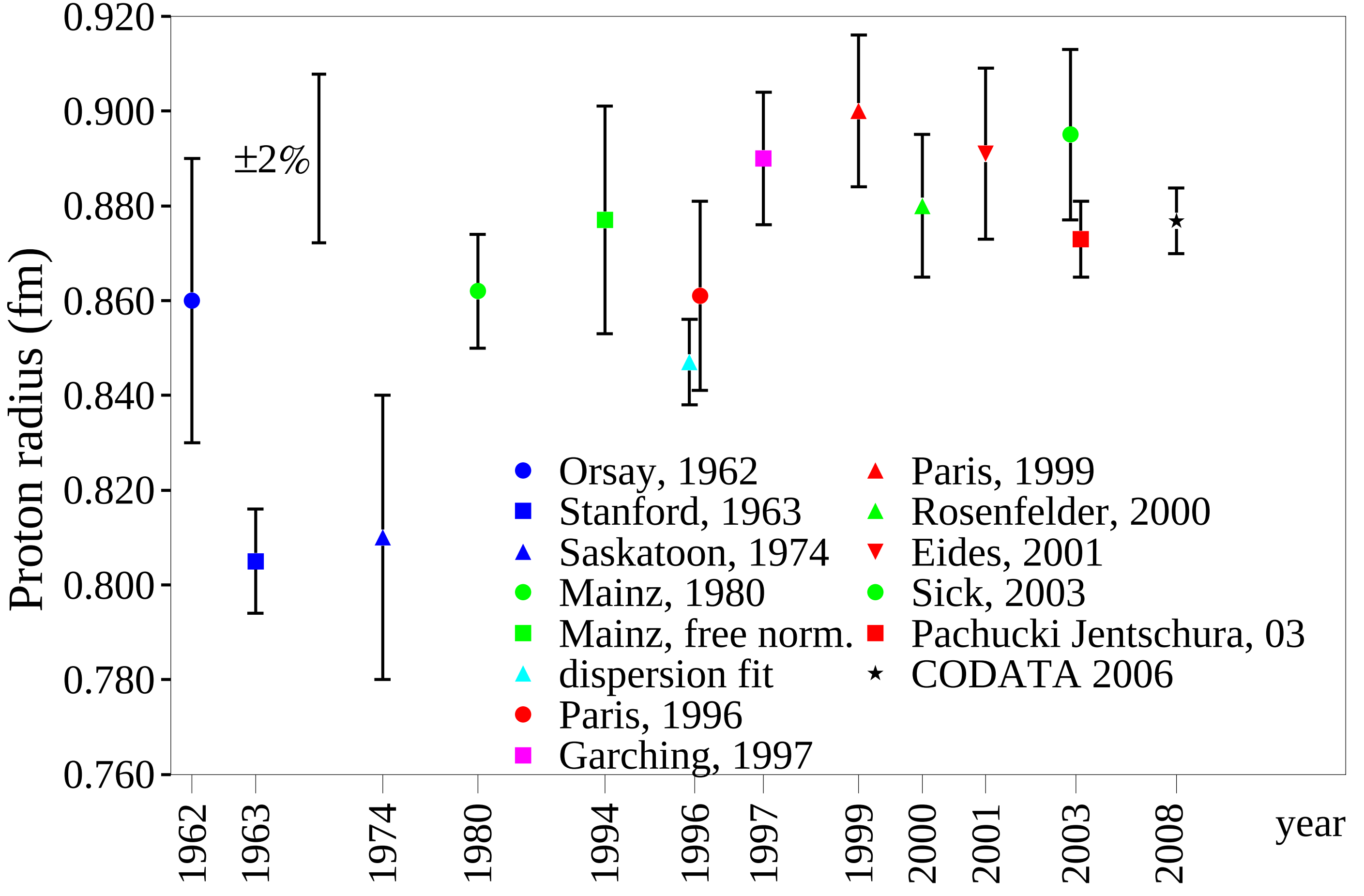
- Muonic hydrogen:

  Size does matter!

- Experiment:
  - Principle
  - Muon beam
  - Laser system
  - NEW ANALYSIS
  - NEW DATA
- Towards a solution of the "proton radius puzzle"

Proton radius vs. time

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



electron scattering

slope of G_E at $Q^2 = 0$

hydrogen spectr.

Lamb shift (S-states)

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

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

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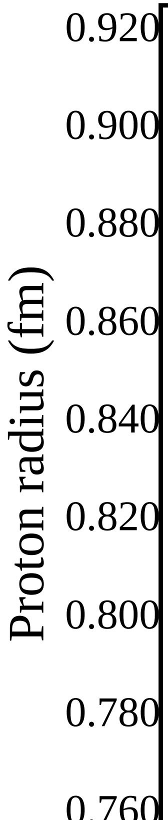
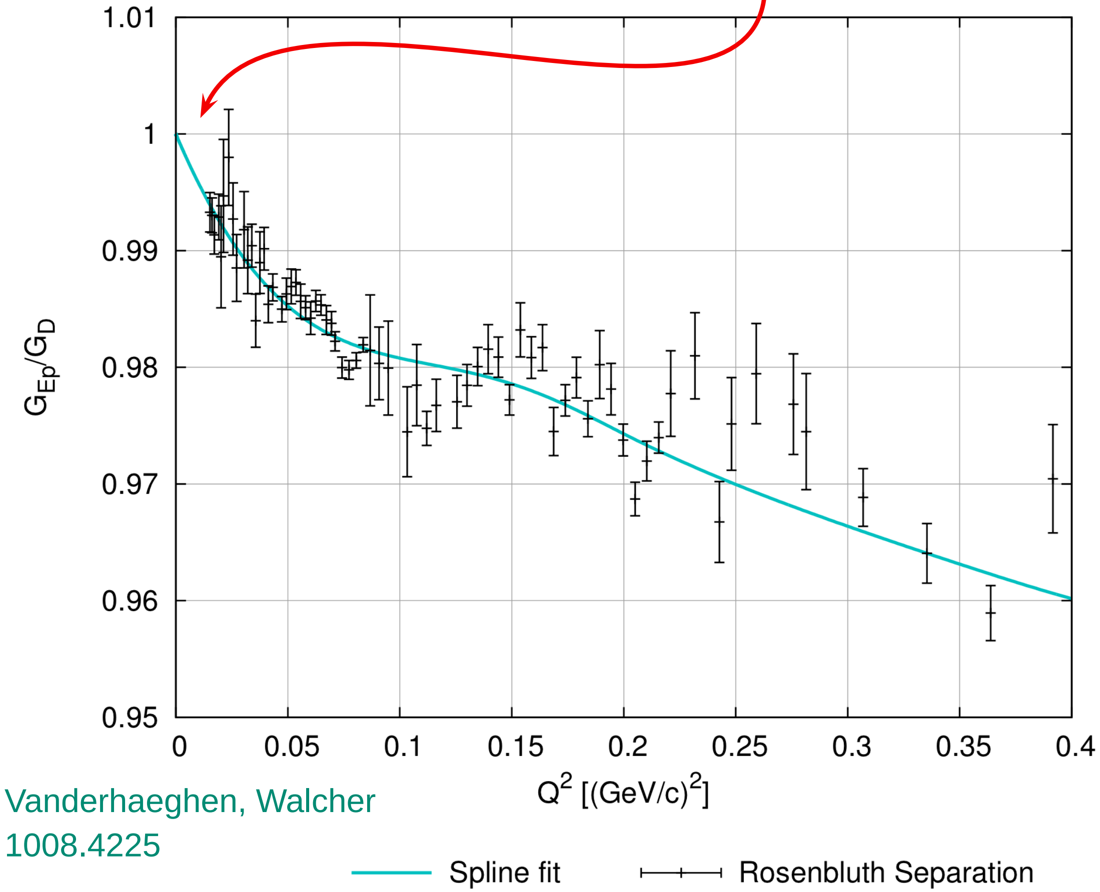


e-p

COD

Electron scattering:

$$\langle r_{\mathrm{p}}^2\rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \quad \Rightarrow \quad \text{slope of } G_E \text{ at } Q^2=0$$



Vanderhaeghen, Walcher
1008.4225

- electron scattering

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  Lamb shift (S-states)

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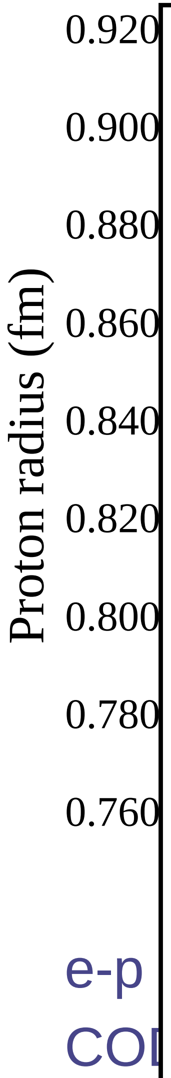
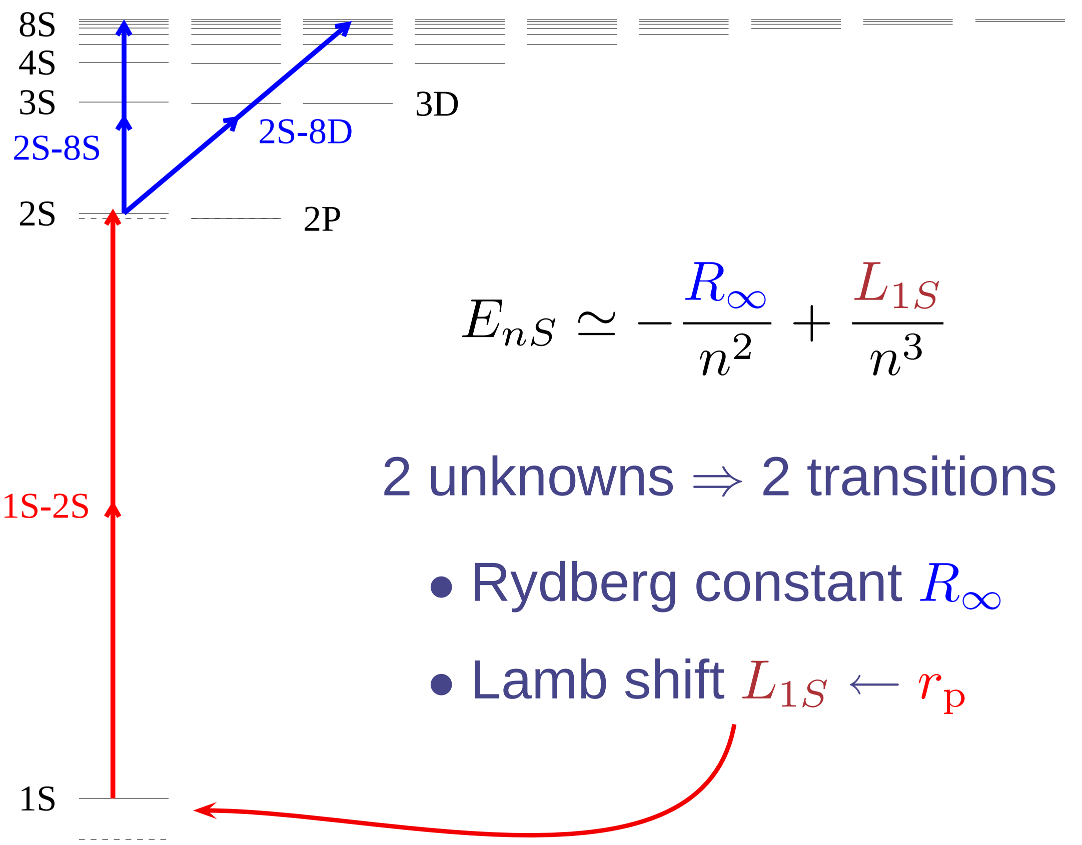


Hydrogen spectroscopy (Lamb shift):

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



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

2 unknowns ⇒ 2 transitions

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

- electron scattering
  slope of G_E at $Q^2 = 0$
- hydrogen spectr.
  Lamb shift (S-states)

Proton radius vs. time

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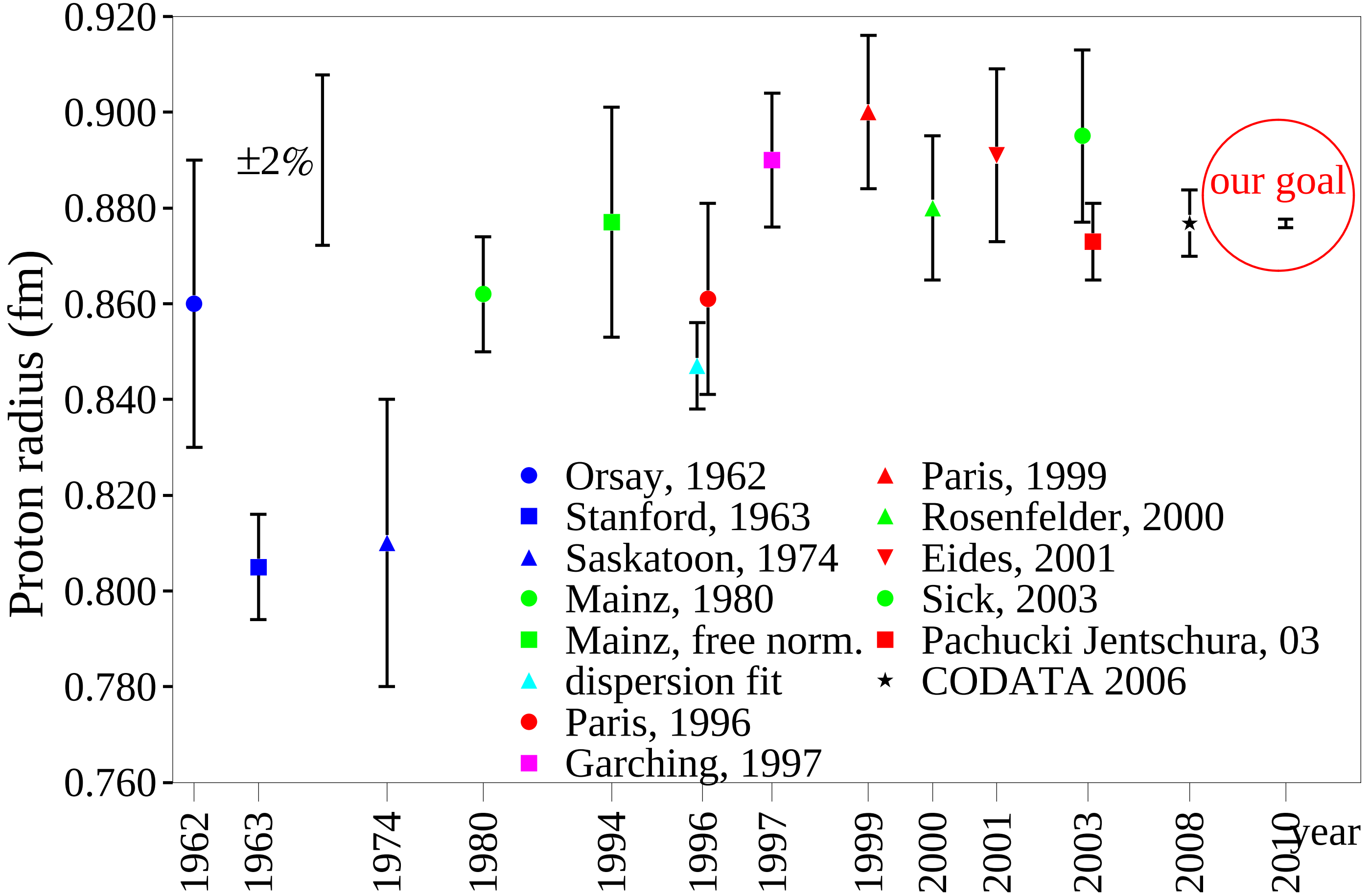

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e-p scattering: r_p = 0.895(18) fm $(u_r = 2\,\%)$

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

muonic hydrogen goal (1998): $u_r = 0.1\,\%$

20x improvement

(aim: 10x better QED test in H)

Proton charge radius and muonic hydrogen

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

$\Rightarrow$ Bohr: $\langle r^{\text{orbit}} \rangle \sim \dfrac{\hbar}{Z\alpha\, m_r\, c} n^2$

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

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

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

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

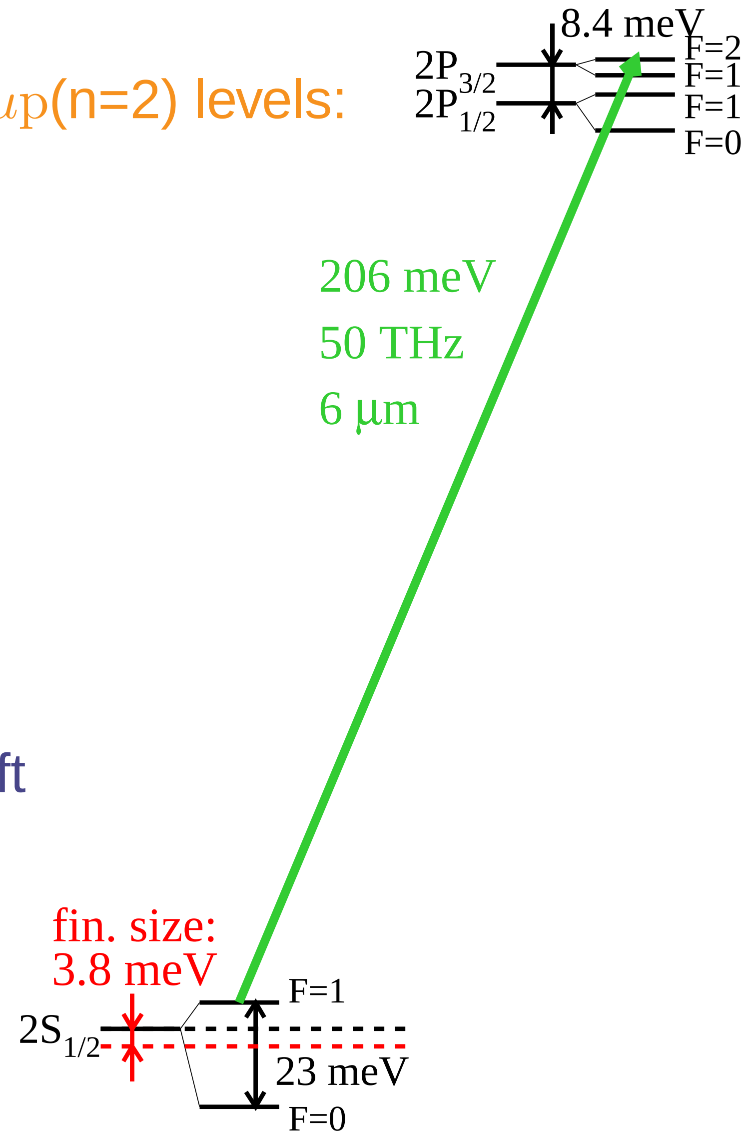
finite size contribution is 2% of the μp Lamb shift

measure ΔE(2S-2P) to 30 ppm = 1.5 GHz

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

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

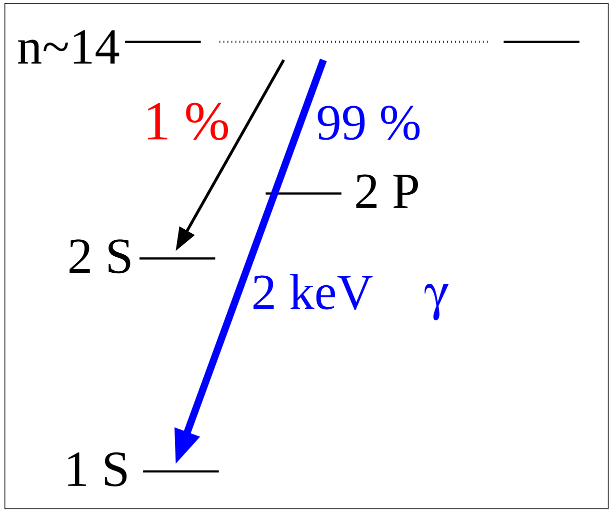
μp(n=2) levels:



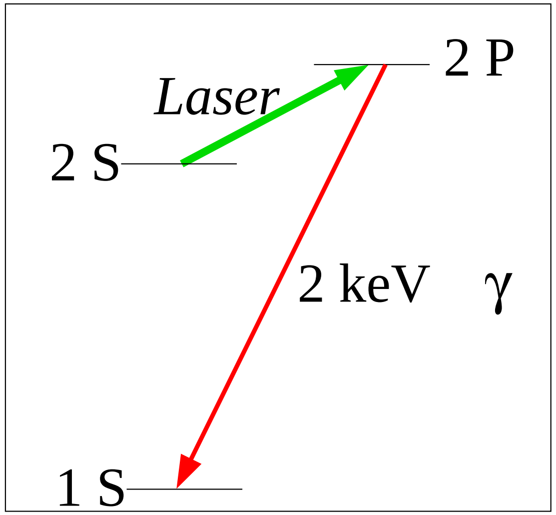
μp Lamb shift experiment: Principle

MPQ

"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 $\boxed{\tau_{2S} \approx 1\ \mu\text{s}}$ 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)

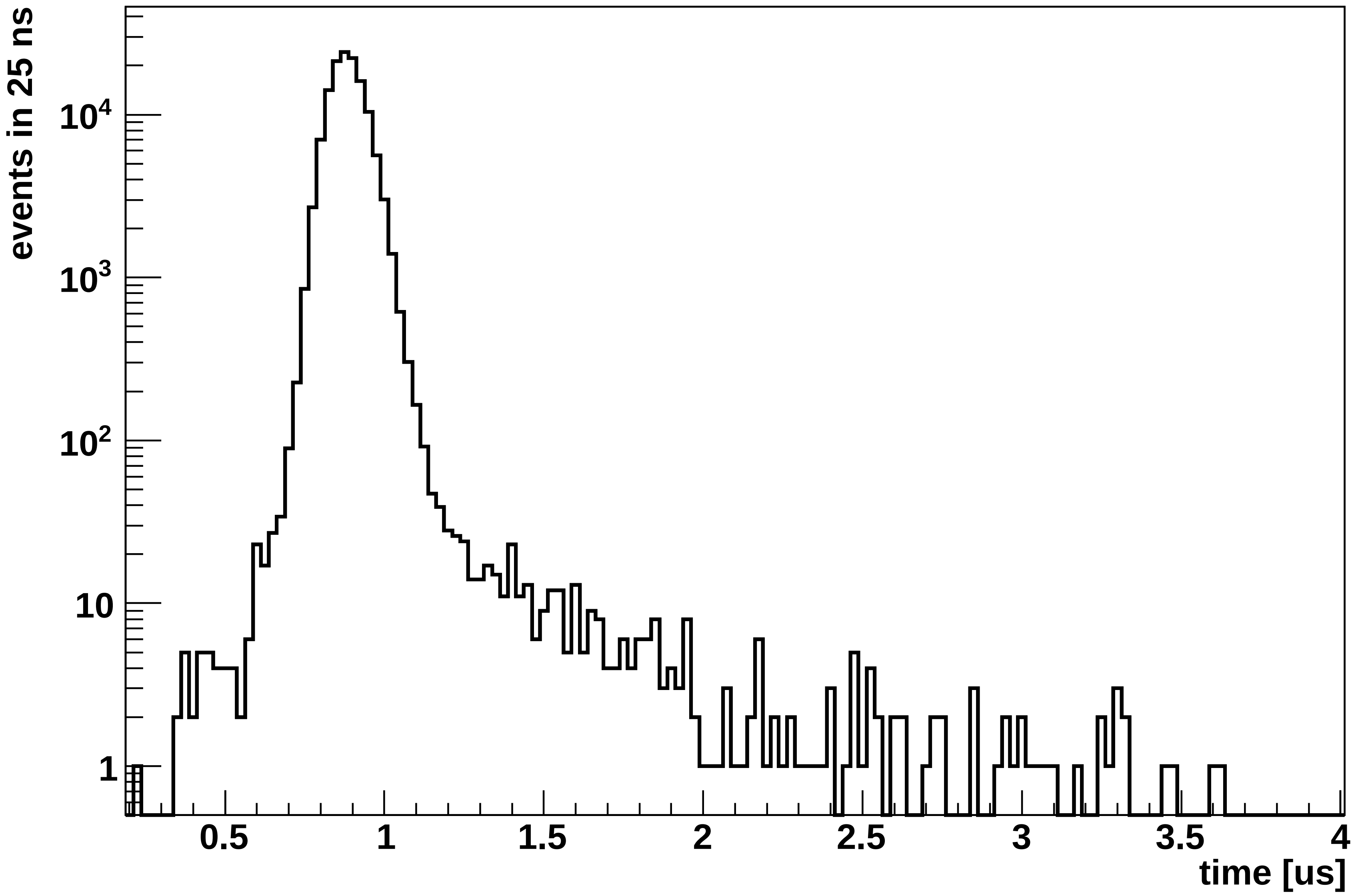
$\Rightarrow$ induce μp(2S) $\rightarrow$ μp(2P)

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

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

μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays   ($\sim$ 13 hours of data)



μp Lamb shift experiment: Principle

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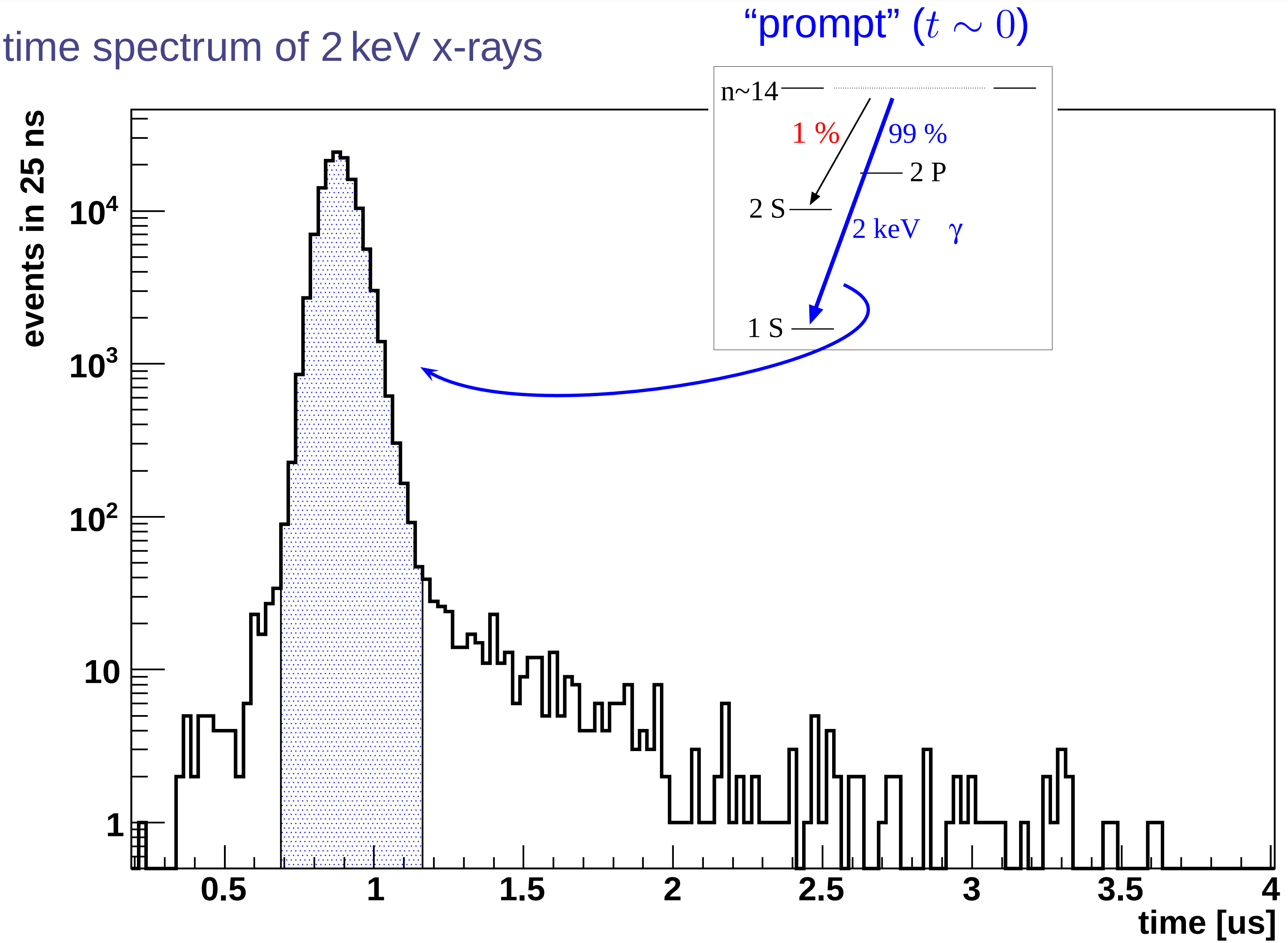

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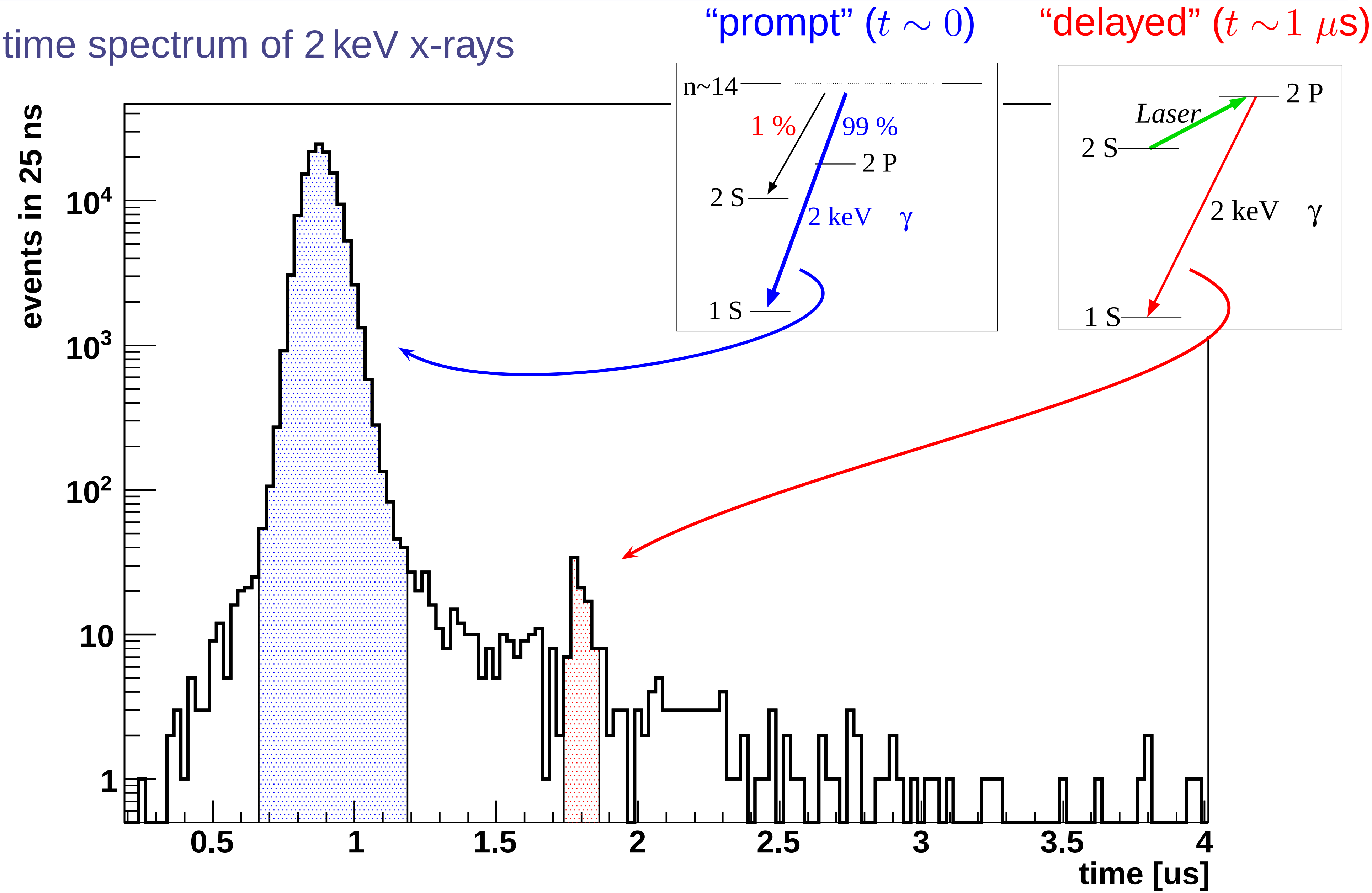

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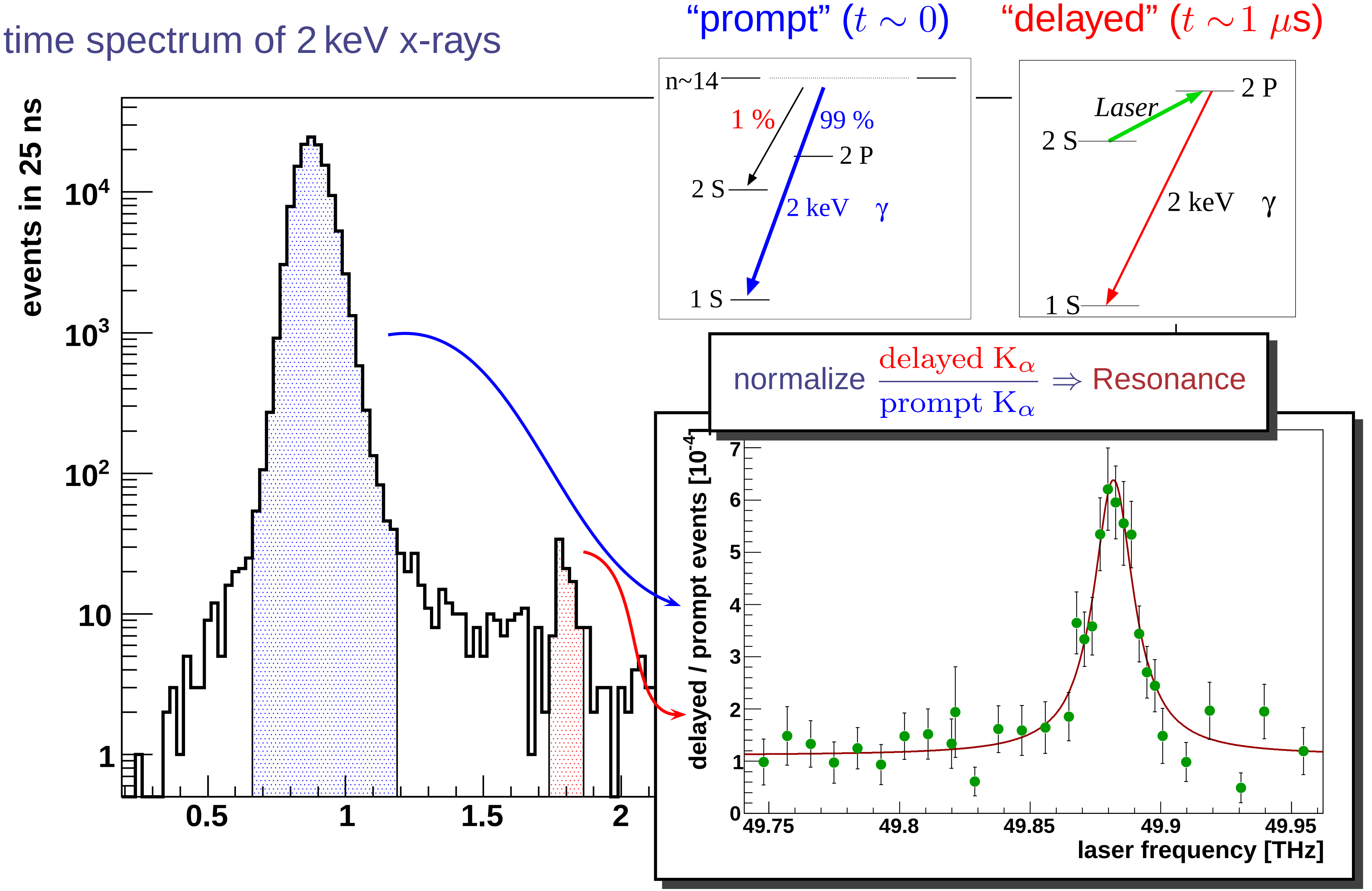
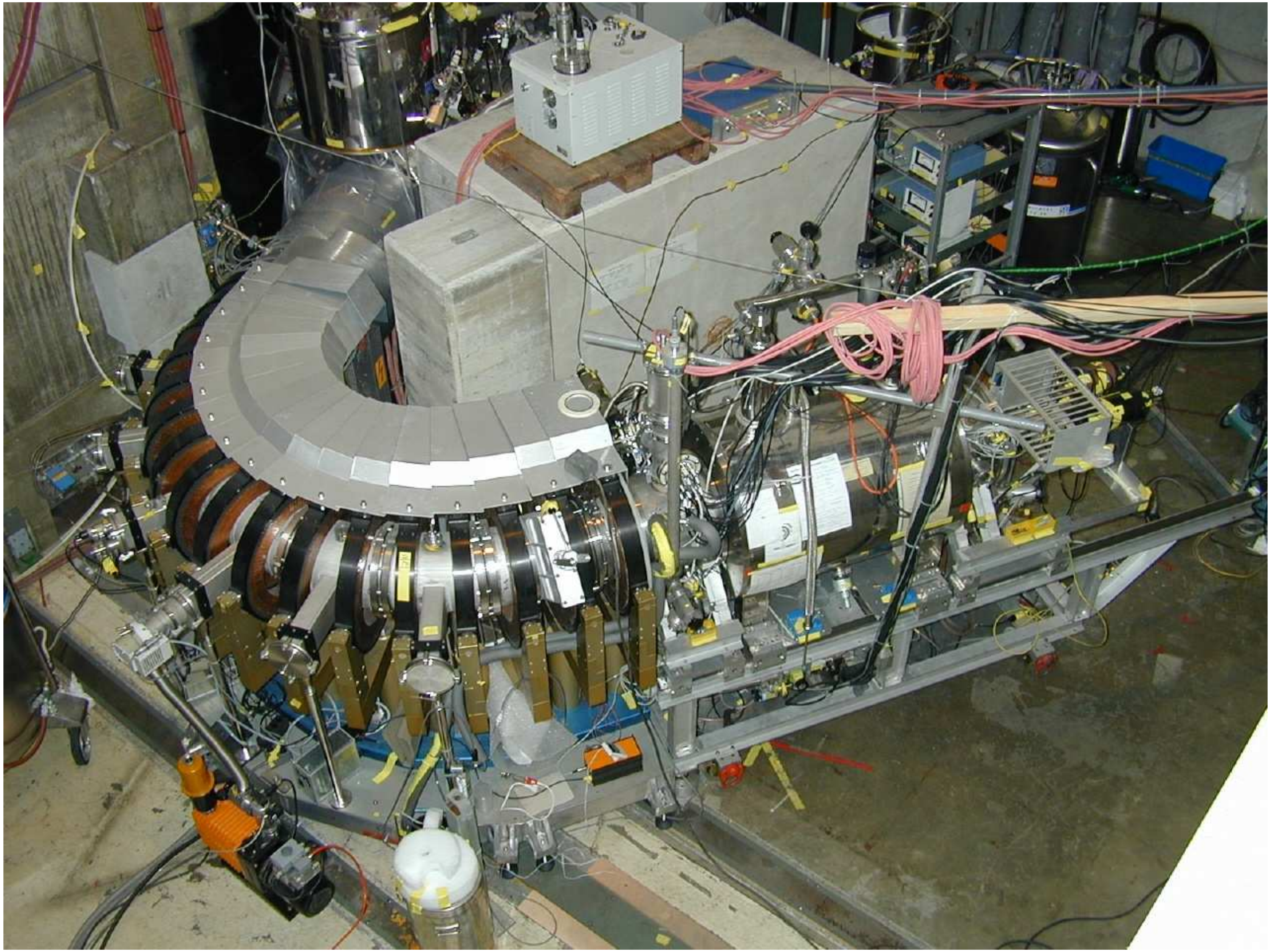
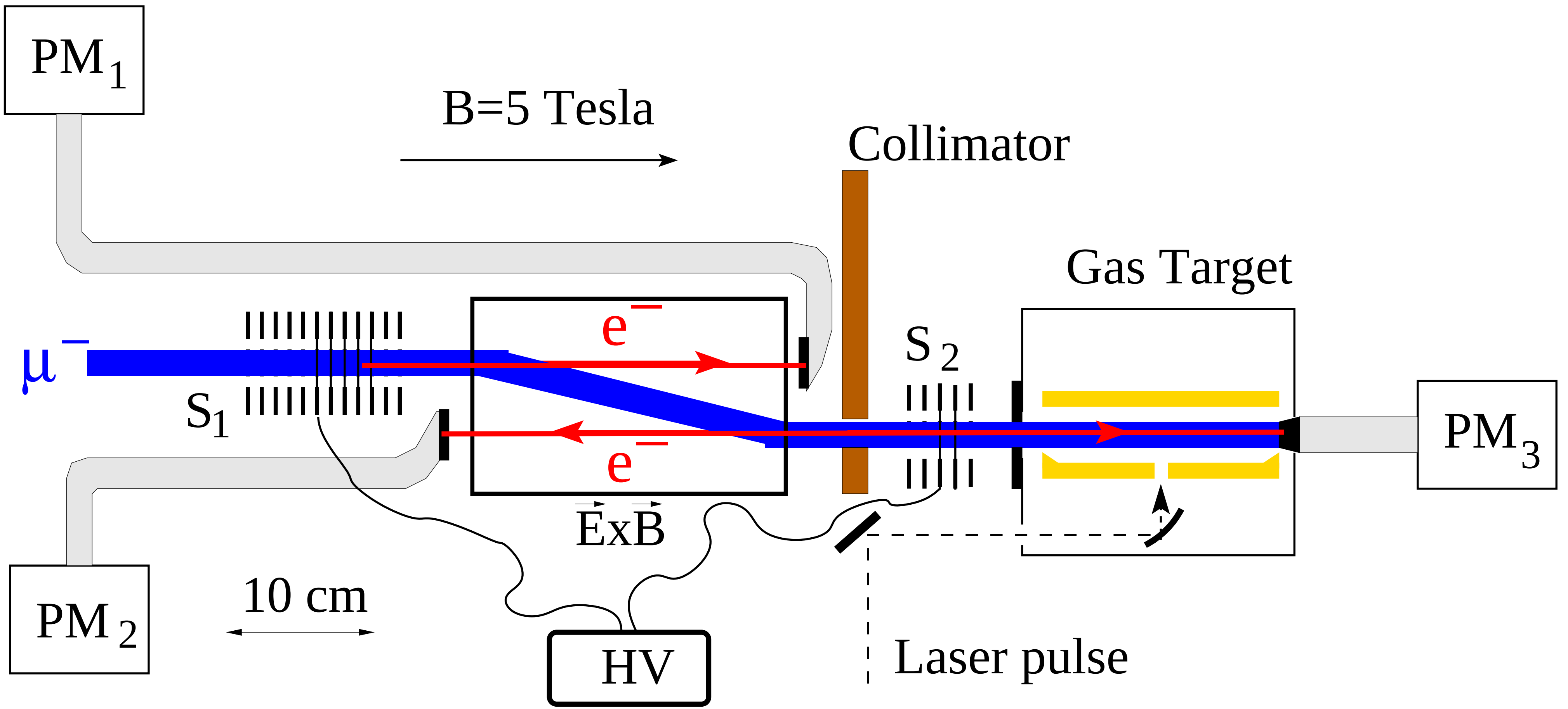


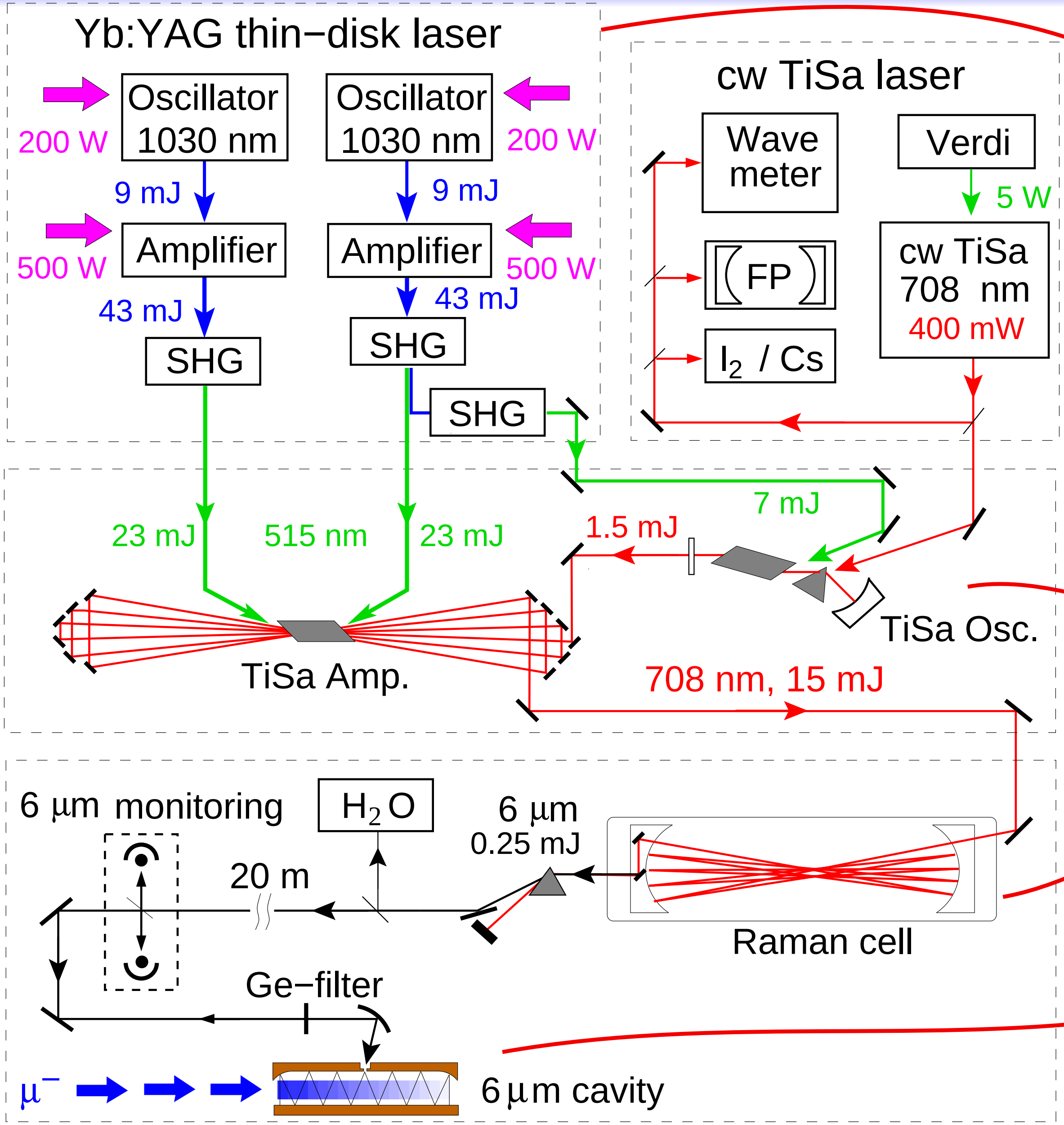
Muon beam line



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

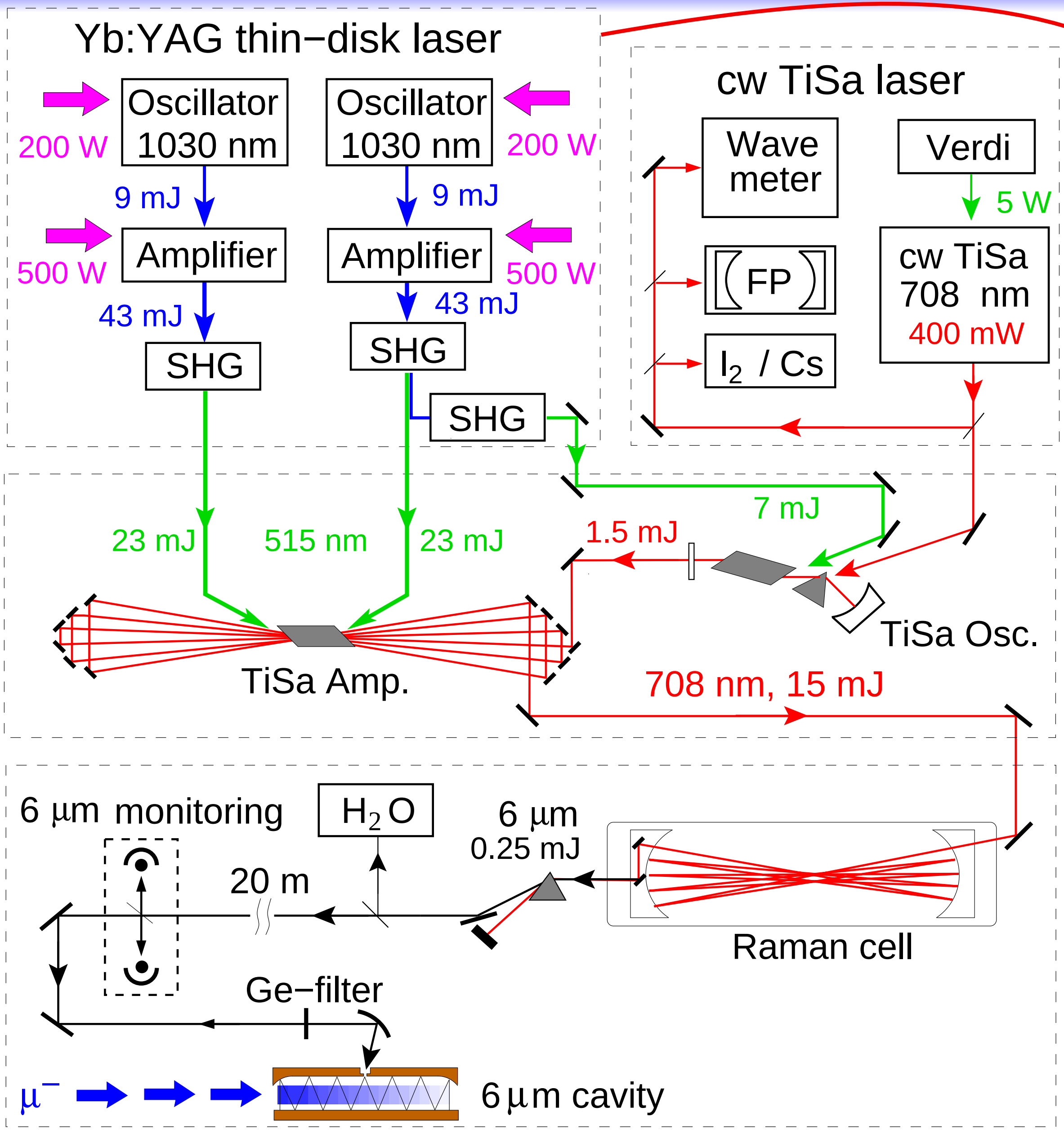
  multipass amplifier
- Raman cell

  3 Stokes: 708 nm $\longrightarrow$ 6 μm

  λ calibration @ 6 μm
- Target cavity

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

The laser system



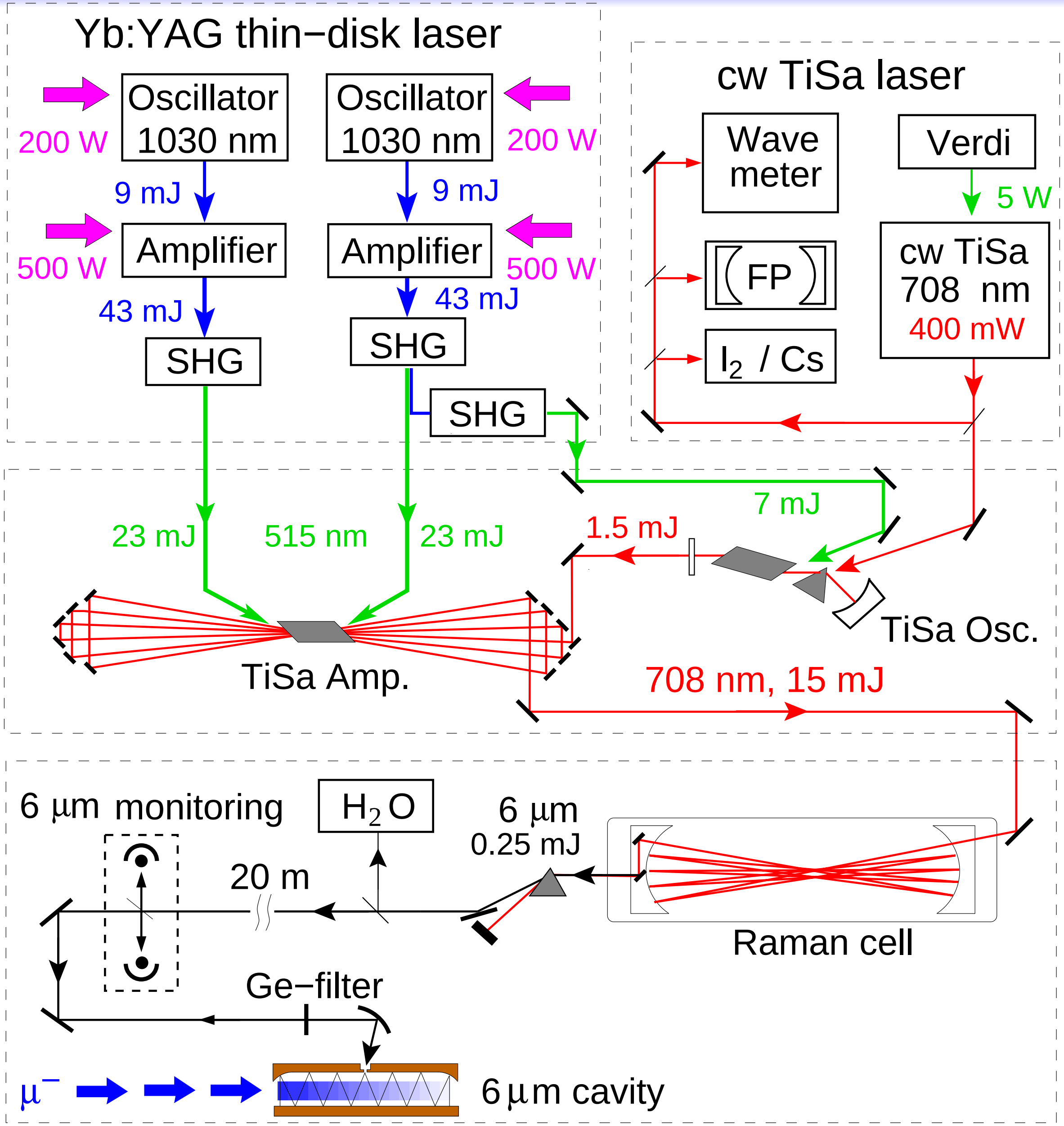
Thin-disk laser

- 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

$\nu_{\rm FP} = N \cdot FSR$

$FSR = 1497.344(6)$ MHz

$\nu^{\rm cw}_{\rm TiSa}$ absolutely known to 30 MHz

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

Seeded oscillator

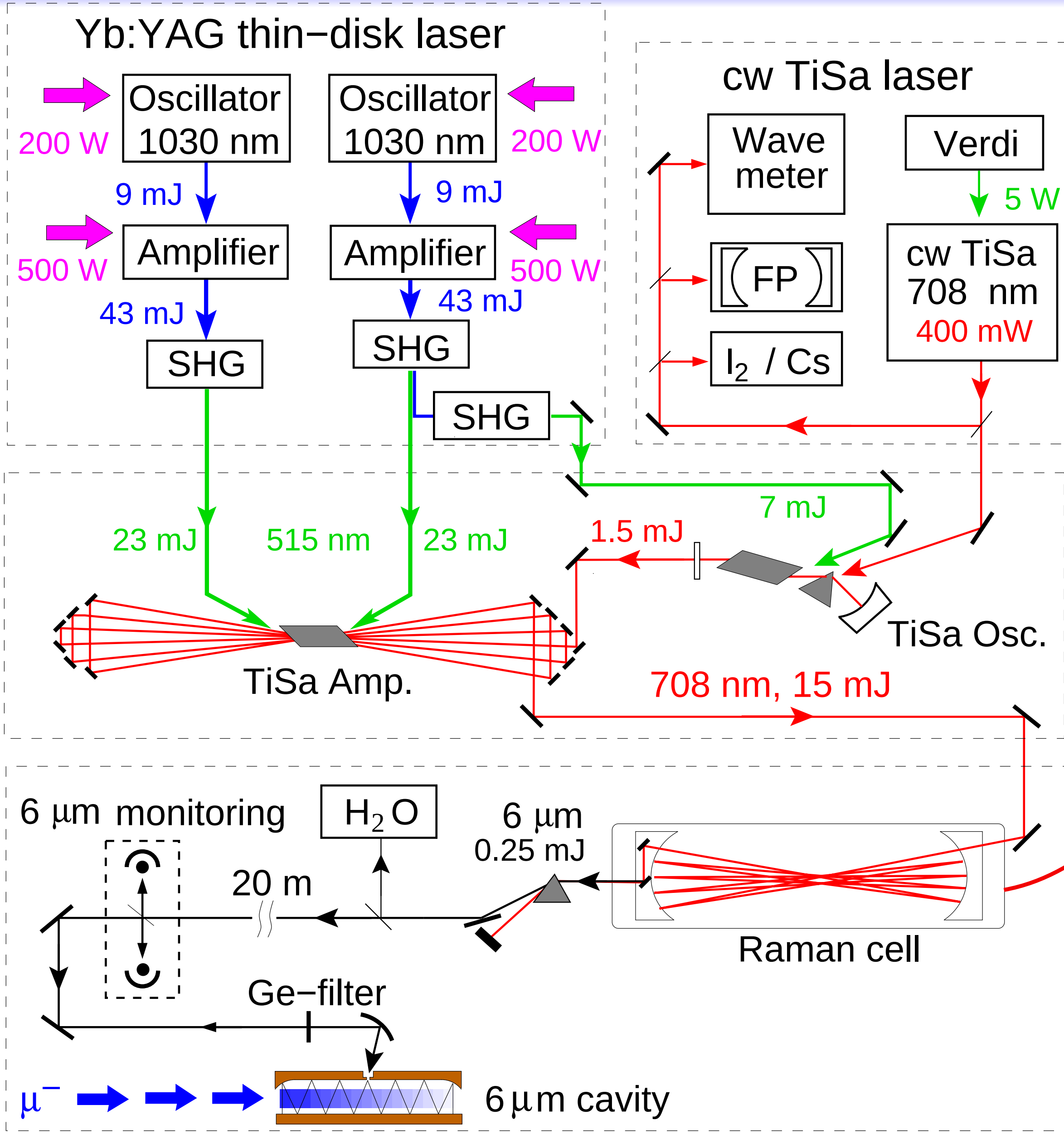
$\rightarrow \nu^{\rm pulsed}_{\rm TiSa} = \nu^{\rm cw}_{\rm TiSa}$

(frequency chirp ≤ 100 MHz)

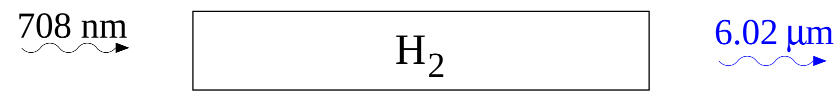
Multipass amplifier (2f- configuration)

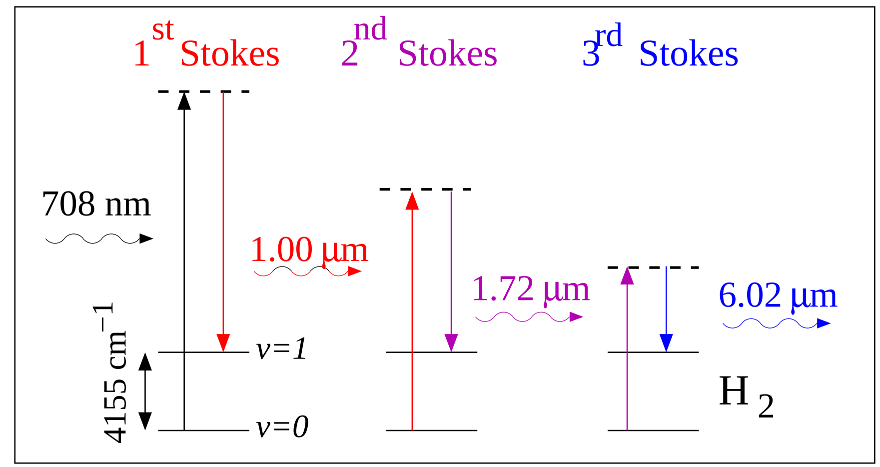
gain=10

The laser system



Raman cell:



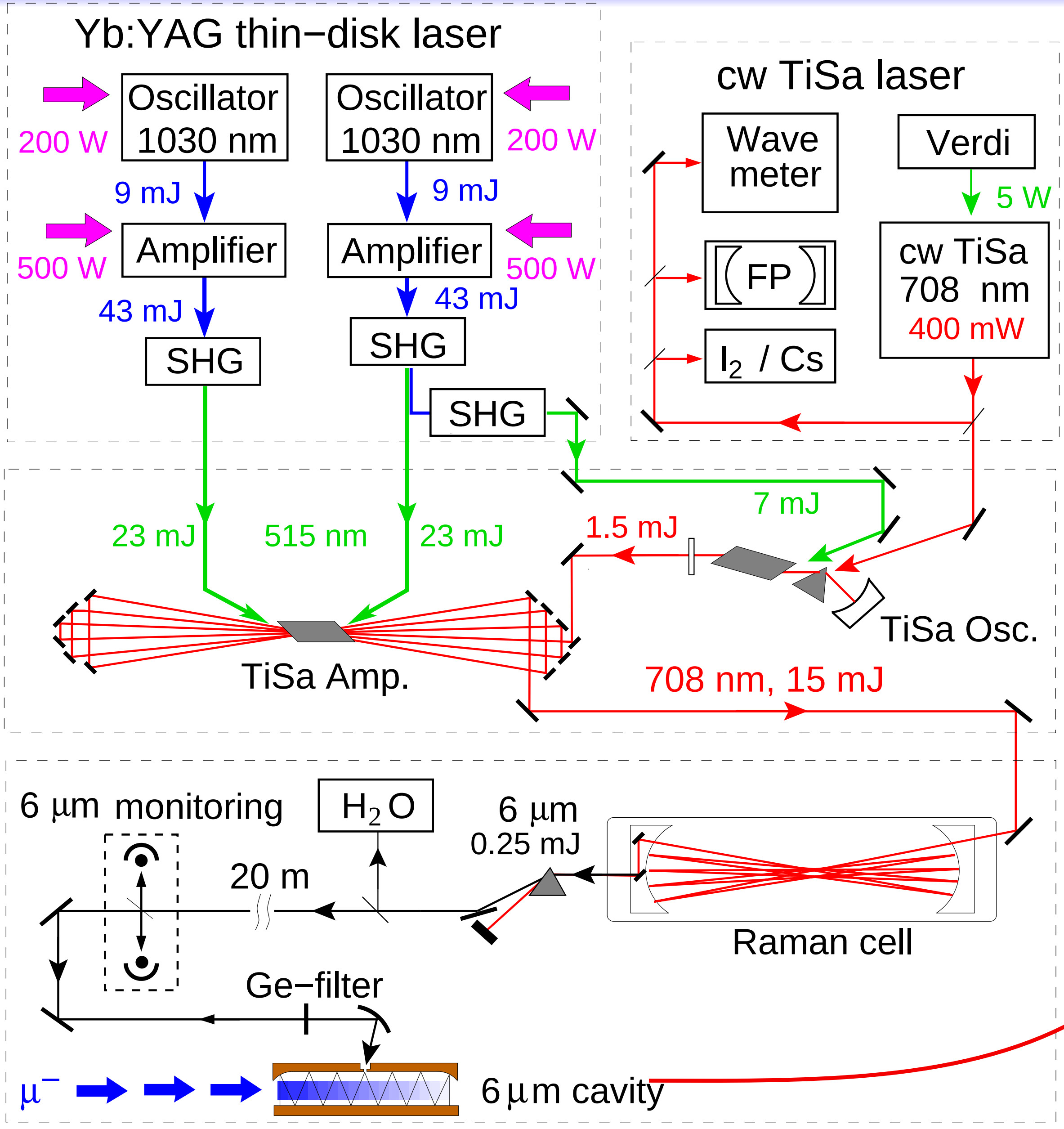


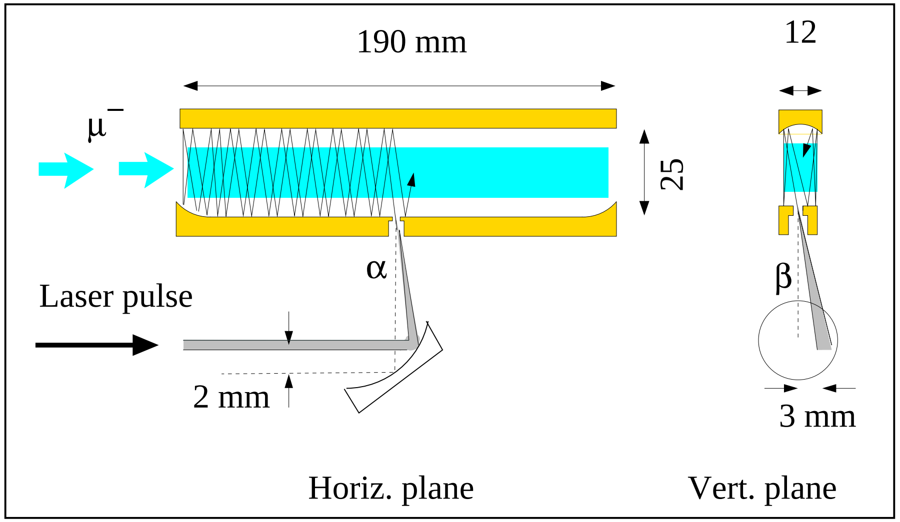
$$\nu^{6\mu m} = \nu^{708\mathrm{nm}} - 3\cdot\hbar\omega_{\mathrm{vib}}$$

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

P. Rabinowitz *et. al.*, IEEE J. QE **22**, 797 (1986)

The laser system





Design: insensitive to misalignment

Transverse illumination

Large volume

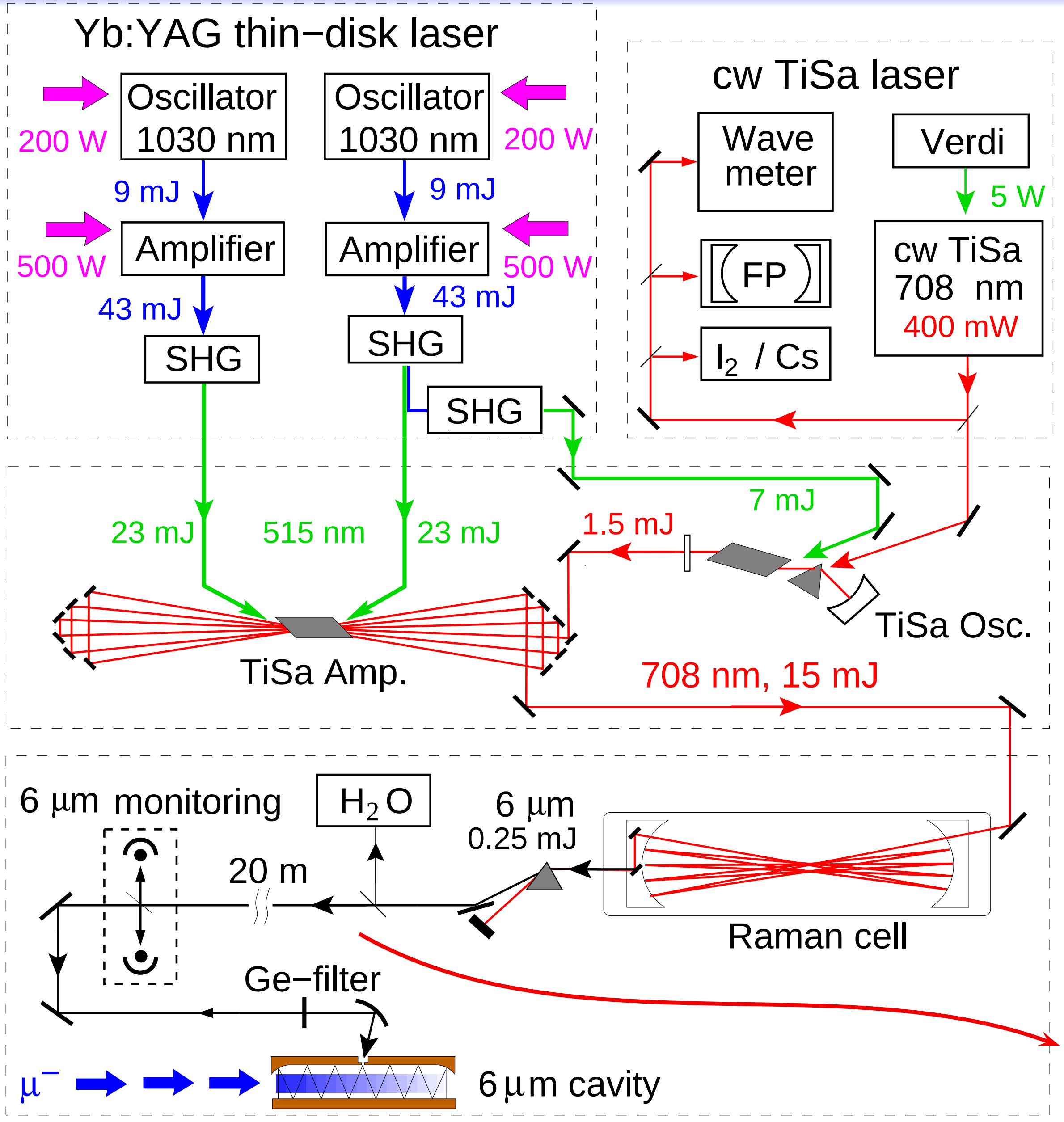
Dielectric coating with $R \geq 99.9\%$ (at 6 μm)

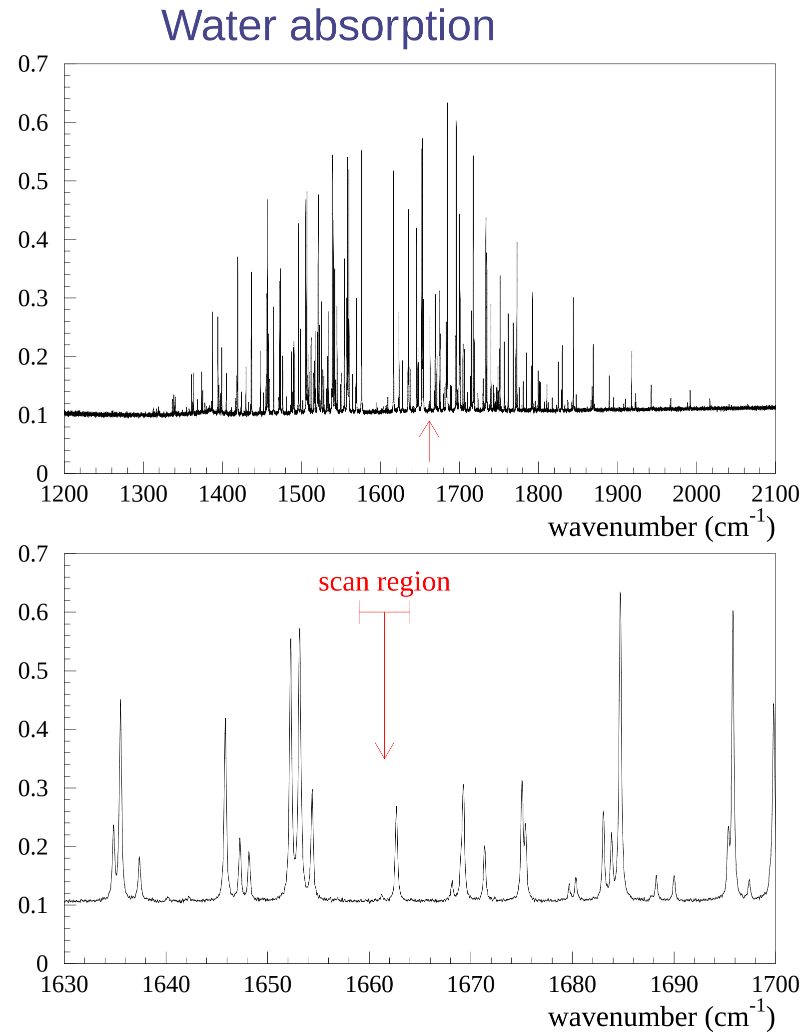
→ Light makes 1000 reflections

→ Light is confined for τ=50 ns

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

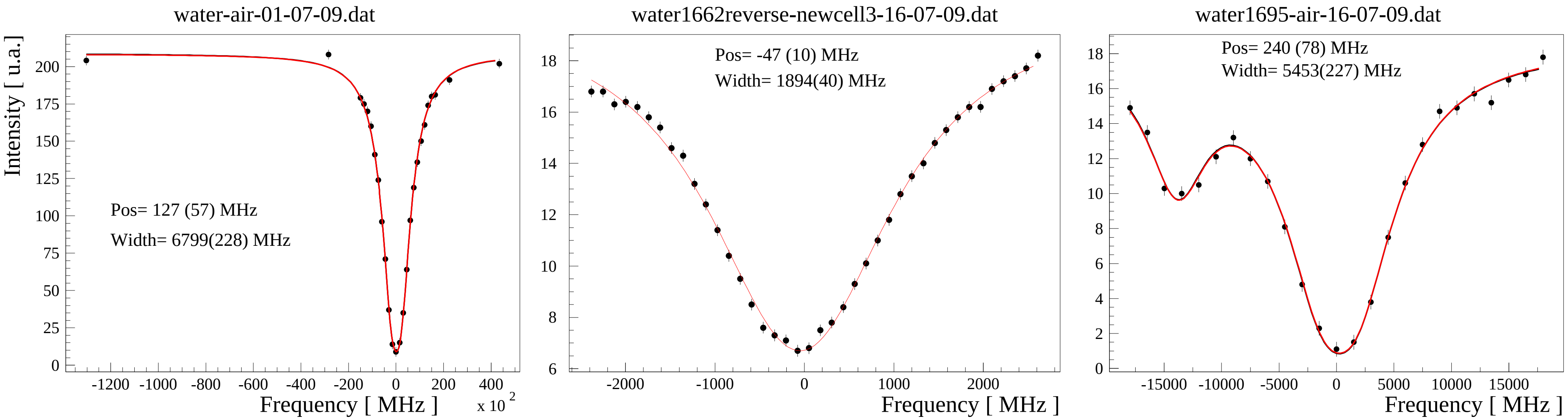
The laser system





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

6 μm wavelength calibration



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

  H_2O absorption lines known to a few MHz (HITRAN)

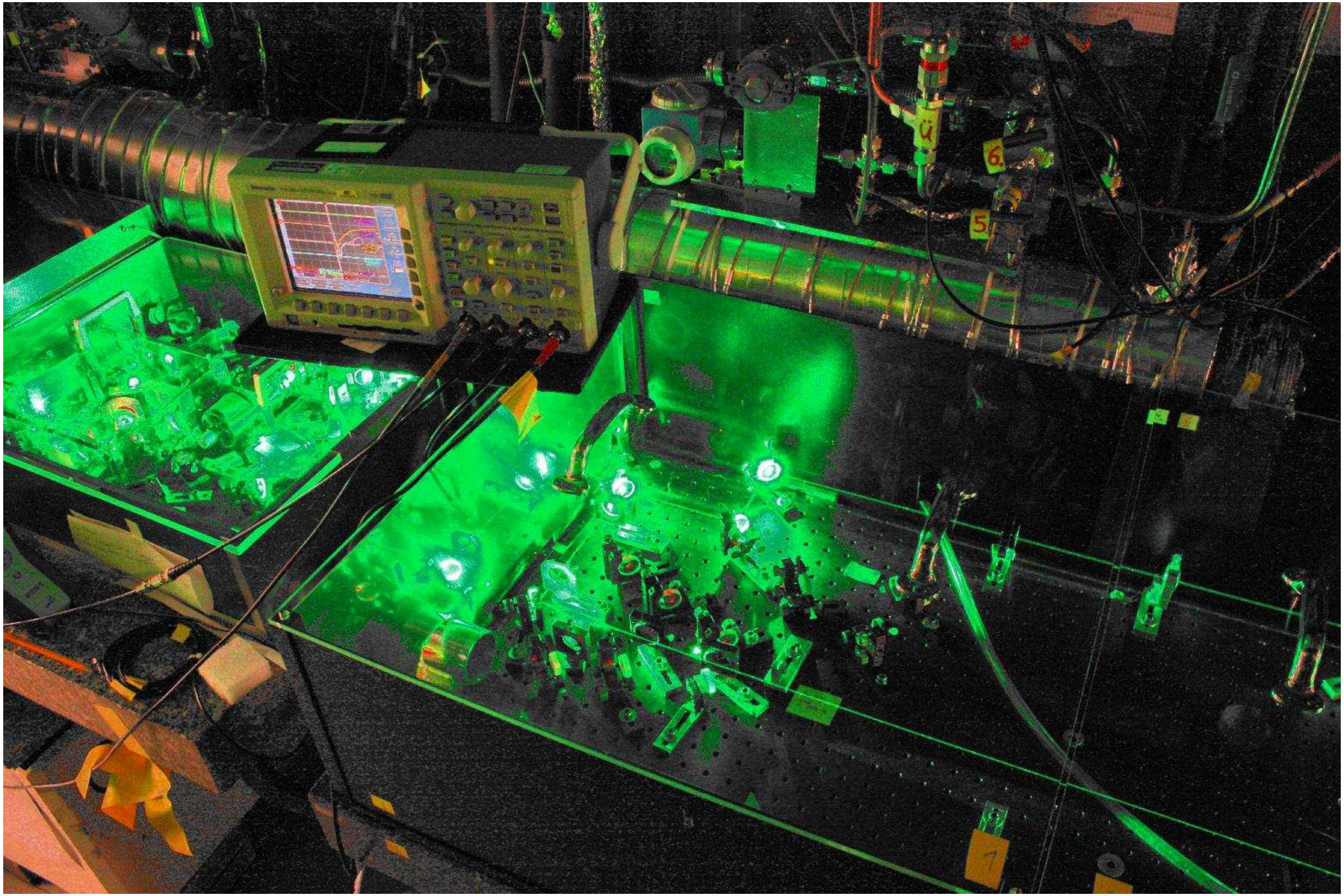
  $\Rightarrow$ $\delta\nu \approx 300$ MHz uncertainty (6 ppm of ΔE_{2S-2P}) due to our calibration accuracy

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

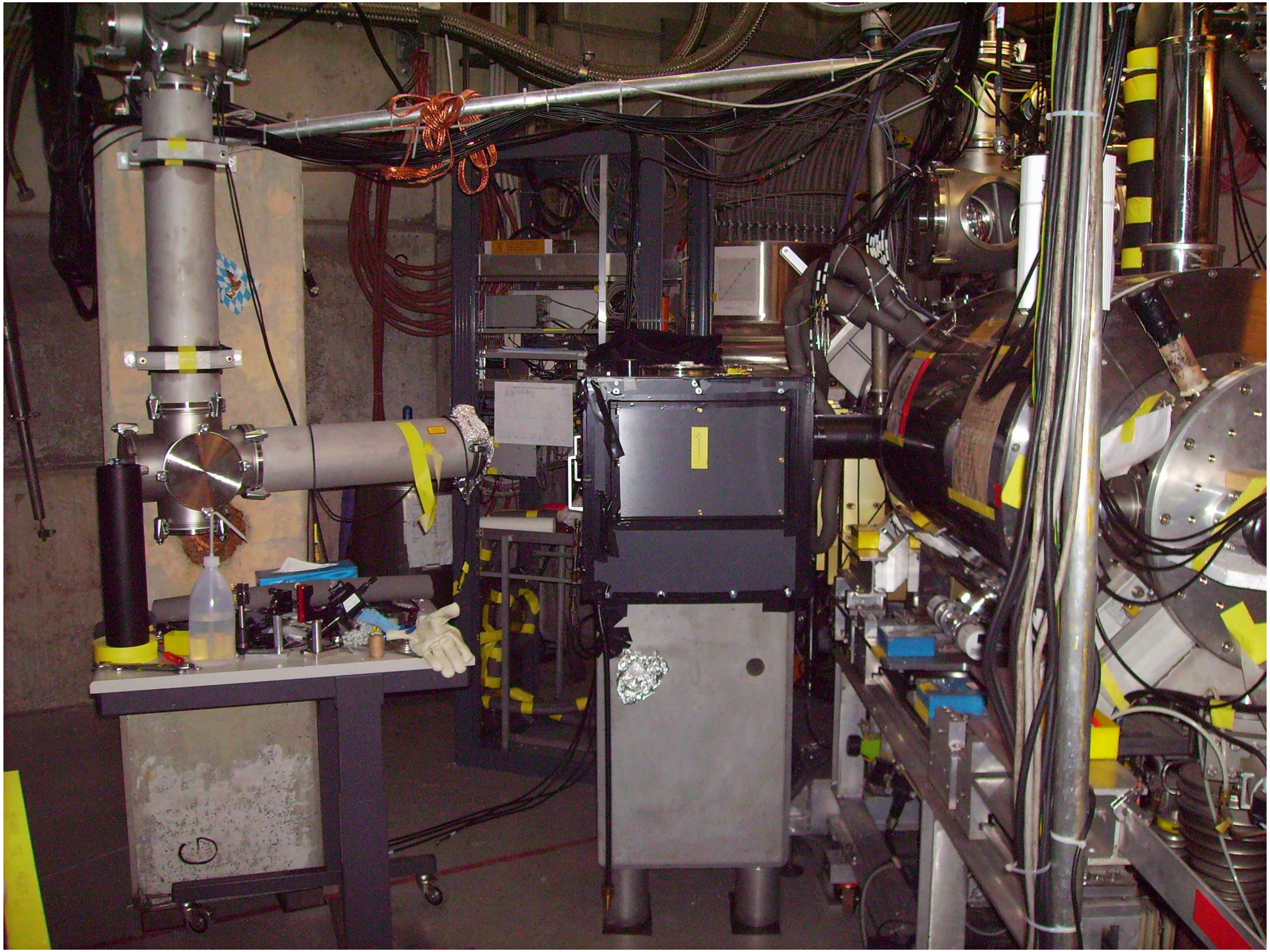
- Laser frequency detuning is measured in number of Fabry-Perot cavity fringes
  - grid spacing of our measurement: FSR(FP) = 1497.344(6) MHz
  - all measured resonances are within ± 70 FP fringes of a H_2O line

Laser hut

TiSa lasers



Laser beam tube



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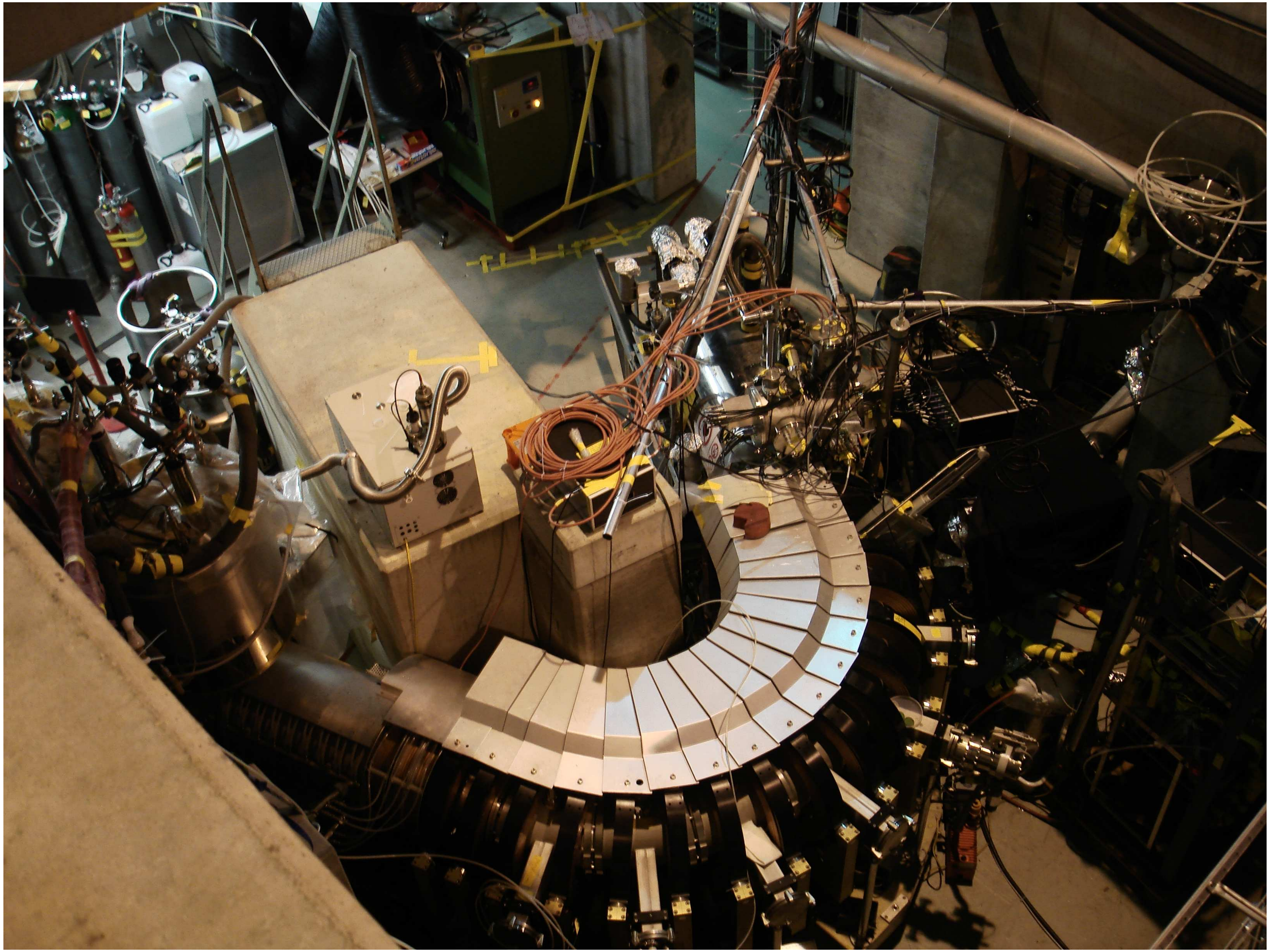
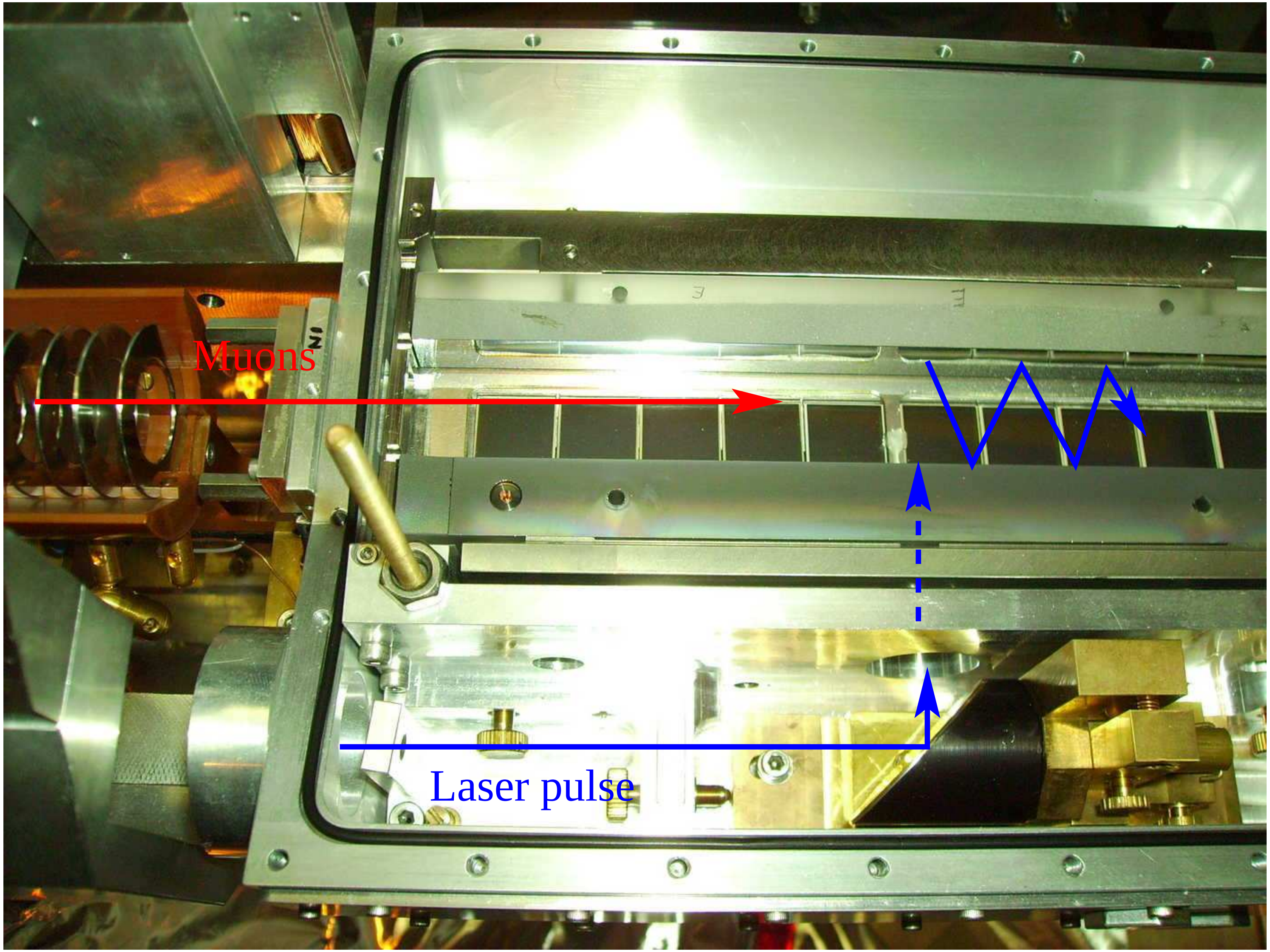


Target, cavity and detectors



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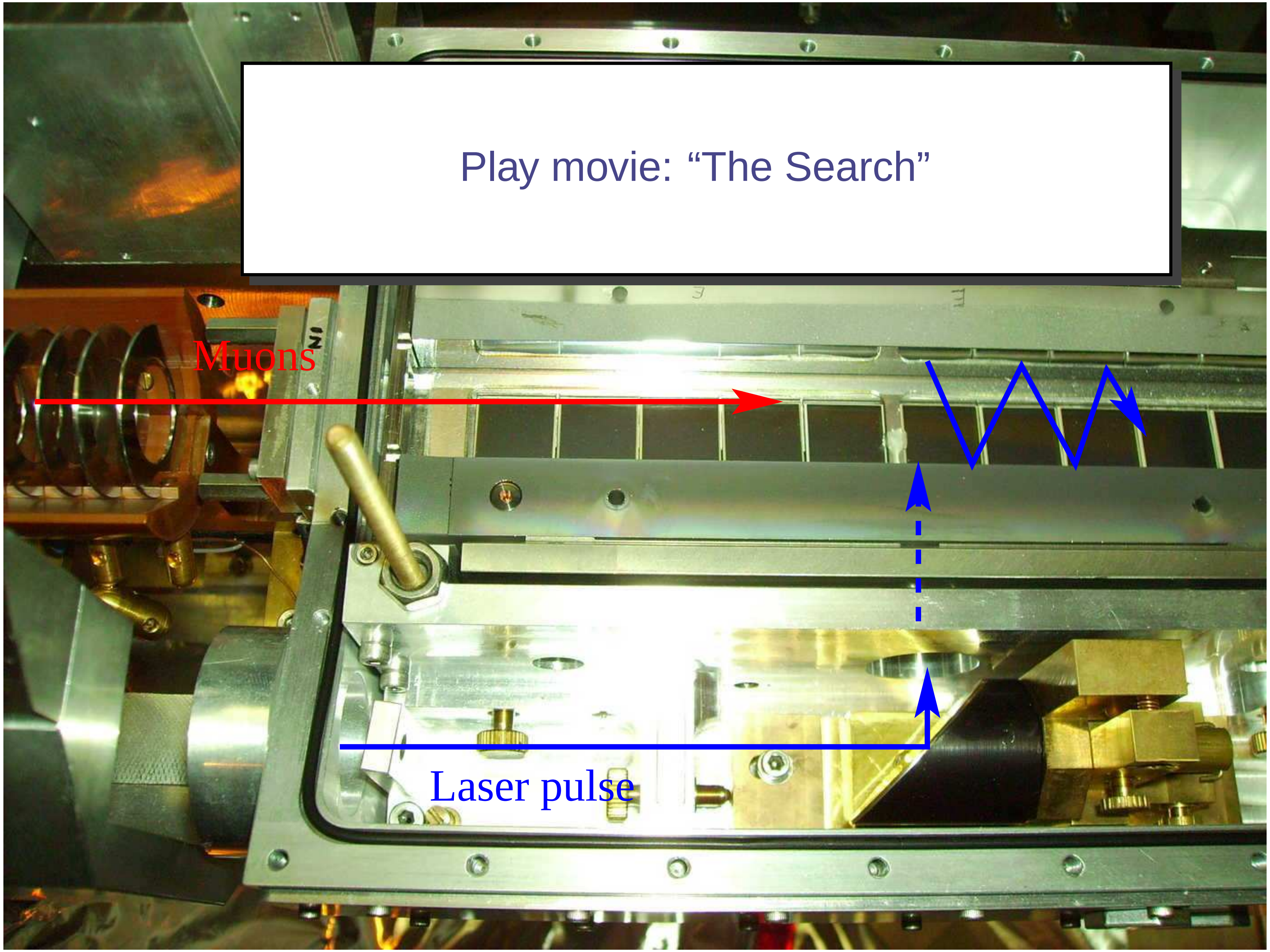
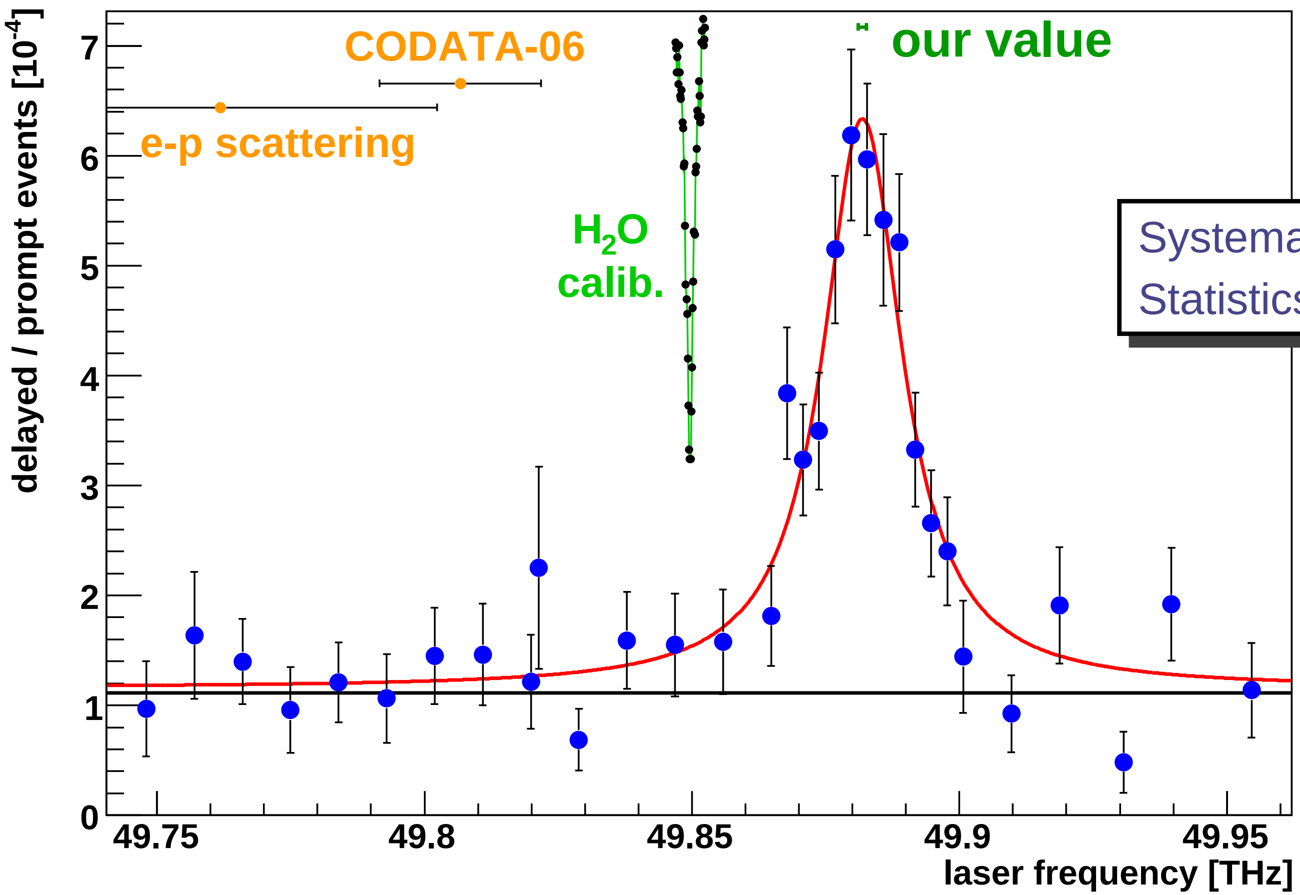


There are still surprises in physics.

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:
$5.0\,\sigma \;\leftrightarrow\; 75\text{ GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times 10^{-3}$

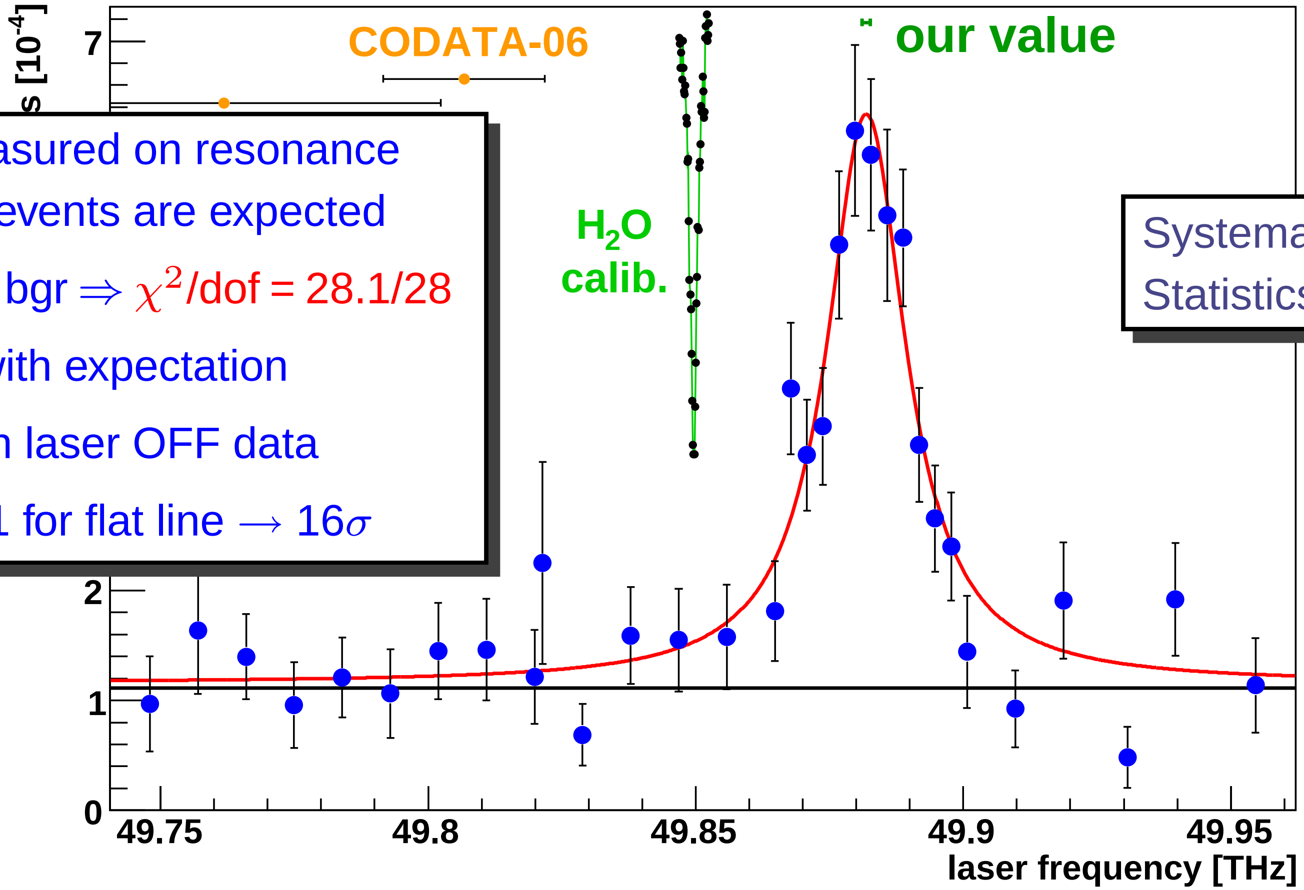
R. Pohl *et al.*, Nature 466, 213 (2010).

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 $\Rightarrow \chi^2$/dof = 28.1/28
width agrees with expectation
bgr agrees with laser OFF data
χ^2/dof = 283/31 for flat line $\rightarrow 16\sigma$



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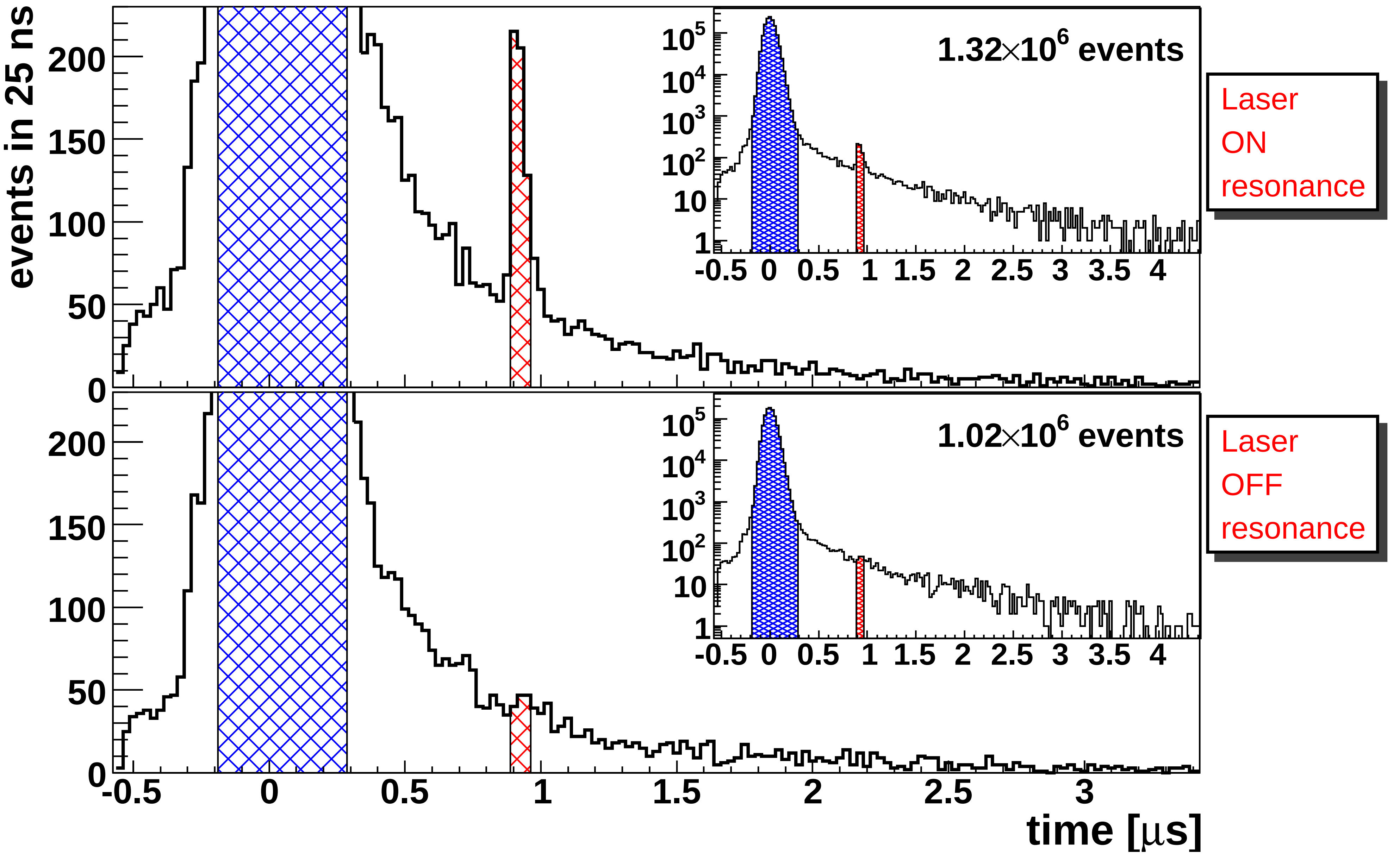
The time spectra



Uncertainty budget and sensitivity

- Statistics

Center position uncertainty ($\sim 4\%$ of Γ)	700 MHz

- Systematics

Laser frequency ($H_2$0 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

- Theory: proton polarizability — 1200 MHz

- Discrepancy with CODATA prediction — 75 300 MHz

Systematic effects are small since they scale like $\mathbf{1/m}$

Finite size effect scales like $\mathbf{m^3}$

Uncertainty budget and sensitivity

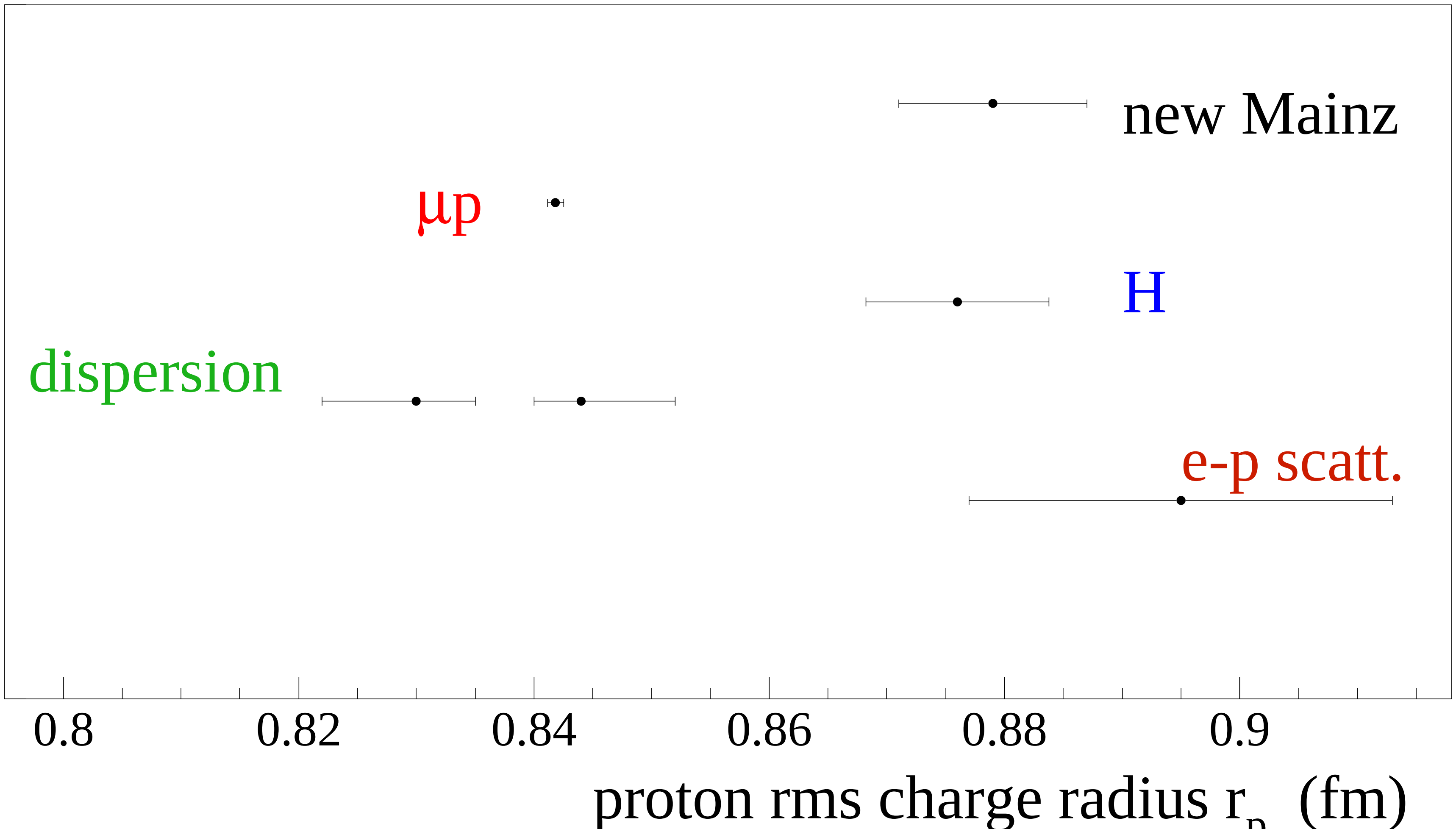
• Statistics		
Center position uncertainty ($\sim 4\%$ of Γ)	~~700~~ MHz	540 MHz
• Systematics		
Laser frequency ($H_2$0 calibration)	300 MHz	
AC and DC stark shift	< 1 MHz	
Zeeman shift (5 Tesla)	< 30 MHz	
Doppler shift	< 1 MHz	
Collisional shift	2 MHz	
• Total uncertainty of the line determination	~~760~~ MHz	620 MHz
• Theory: proton polarizability	1200 MHz	
• Discrepancy with CODATA prediction	75 300 MHz	

Systematic effects are small since they scale like $\mathbf{1/m}$

Finite size effect scales like $\mathbf{m^3}$

Proton radius 2010

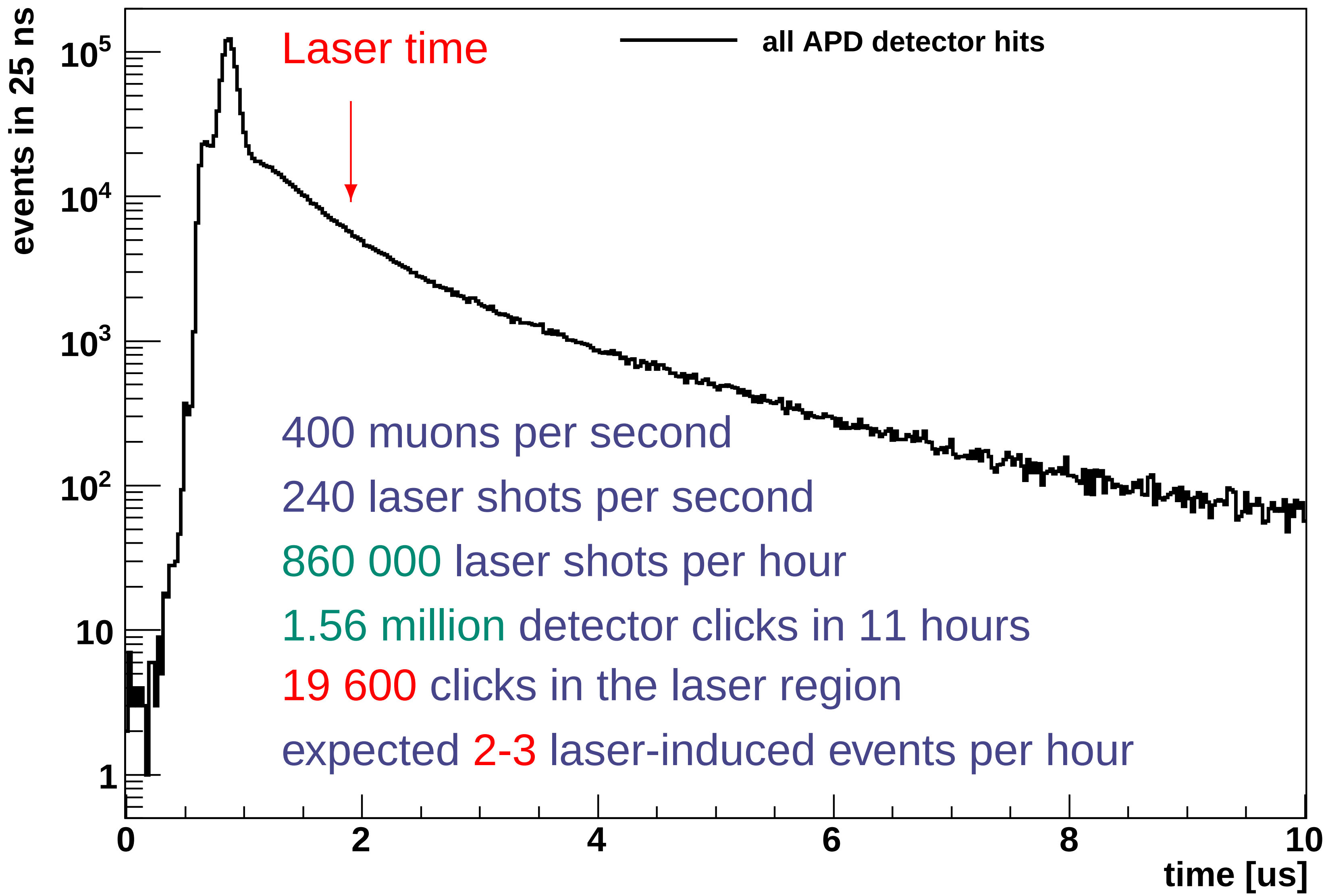
$$r_p = 0.84184\,(36)_{exp}(56)_{theo}\ \text{fm}$$



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

Data analysis

FP 900, 11 hours measurement



400 muons per second

240 laser shots per second

860 000 laser shots per hour

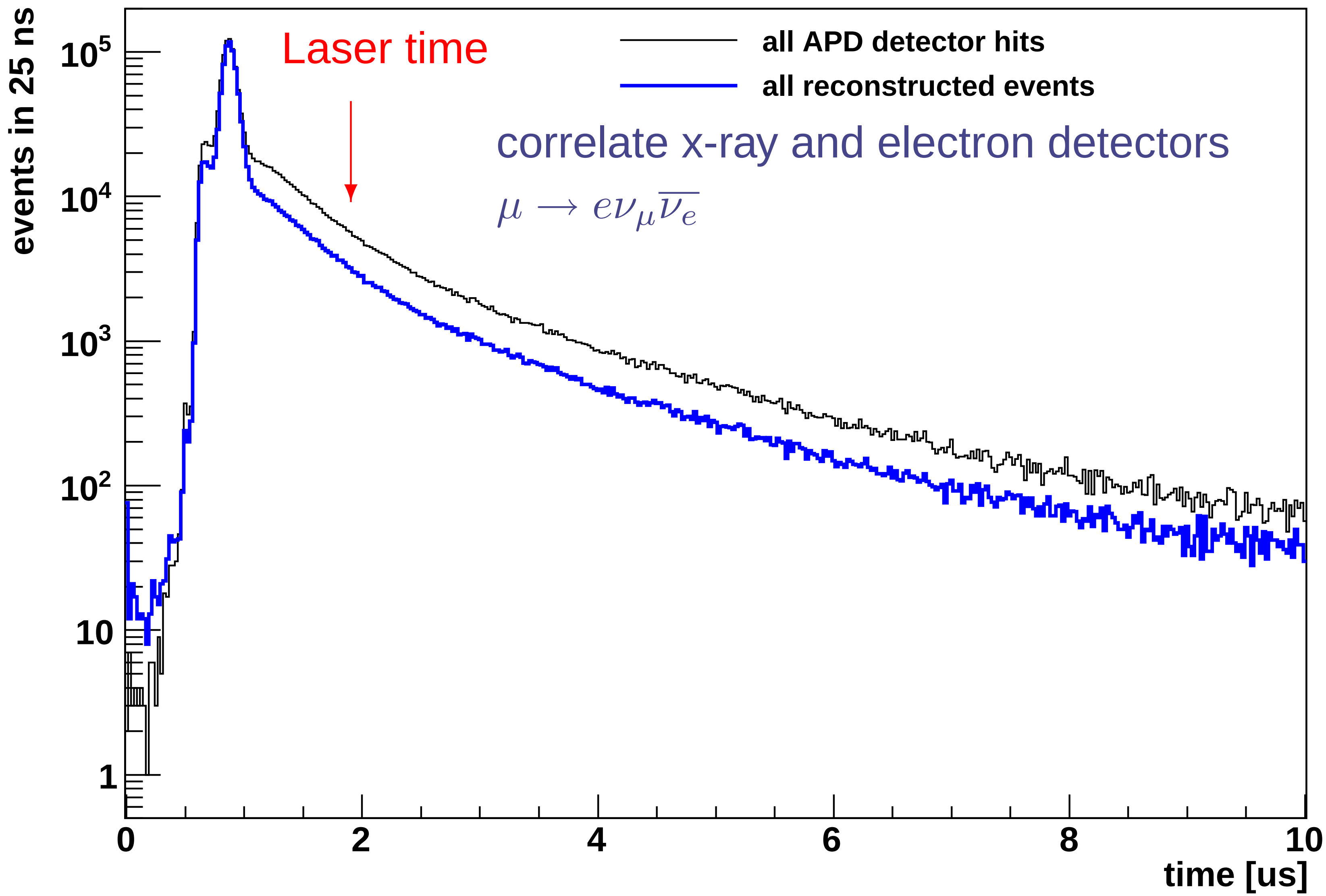
1.56 million detector clicks in 11 hours

19 600 clicks in the laser region

expected 2-3 laser-induced events per hour

Data analysis

FP 900, 11 hours measurement



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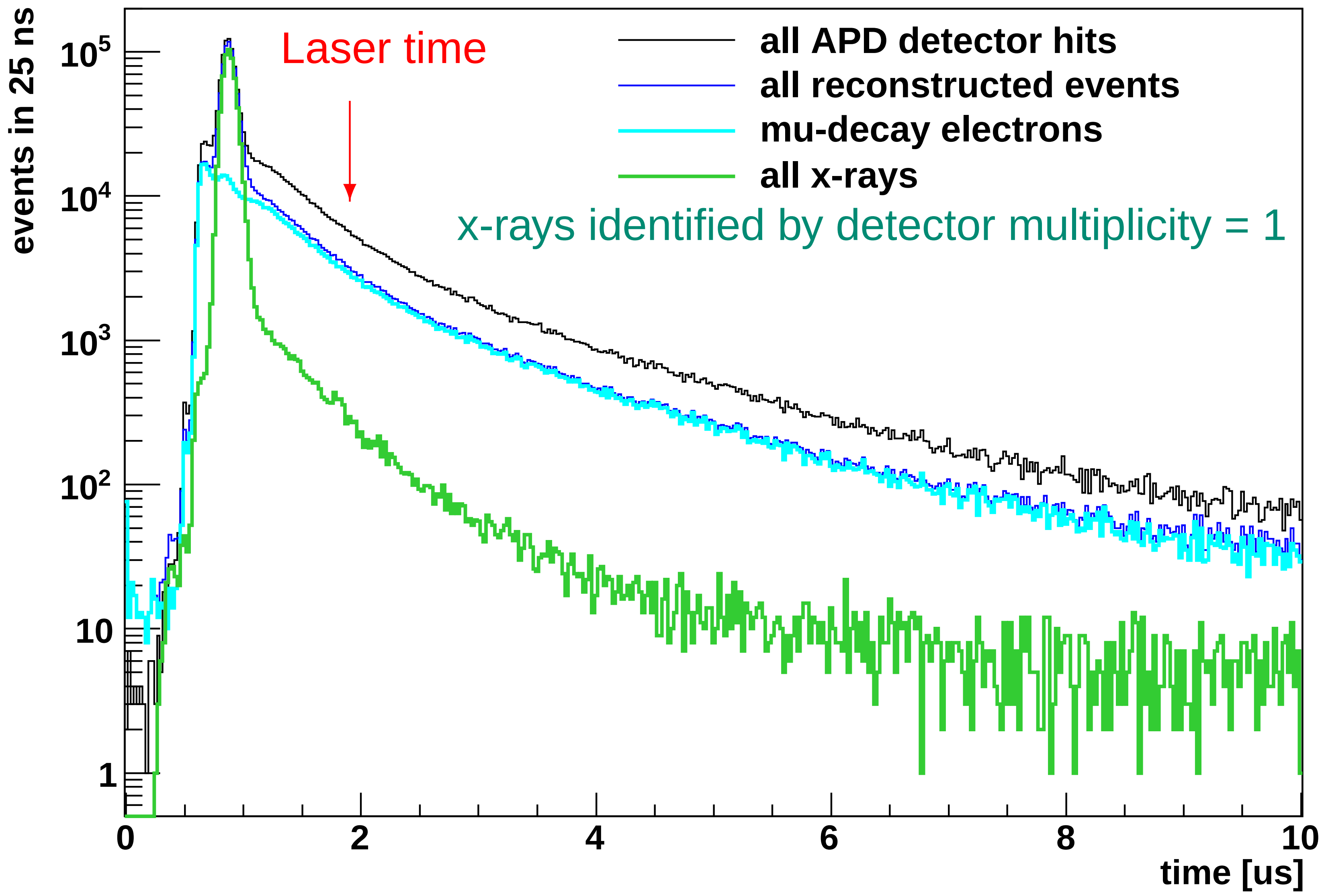

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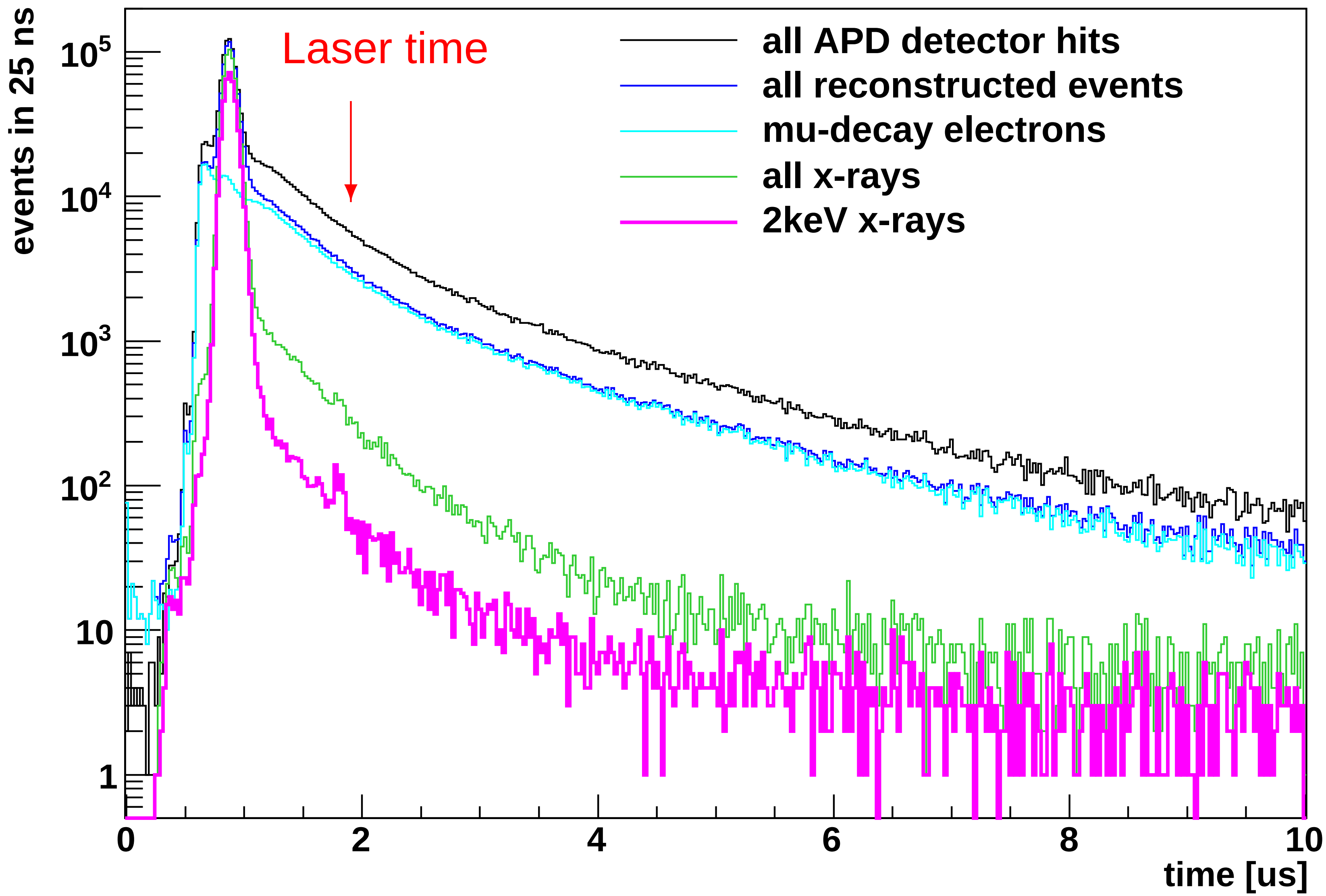

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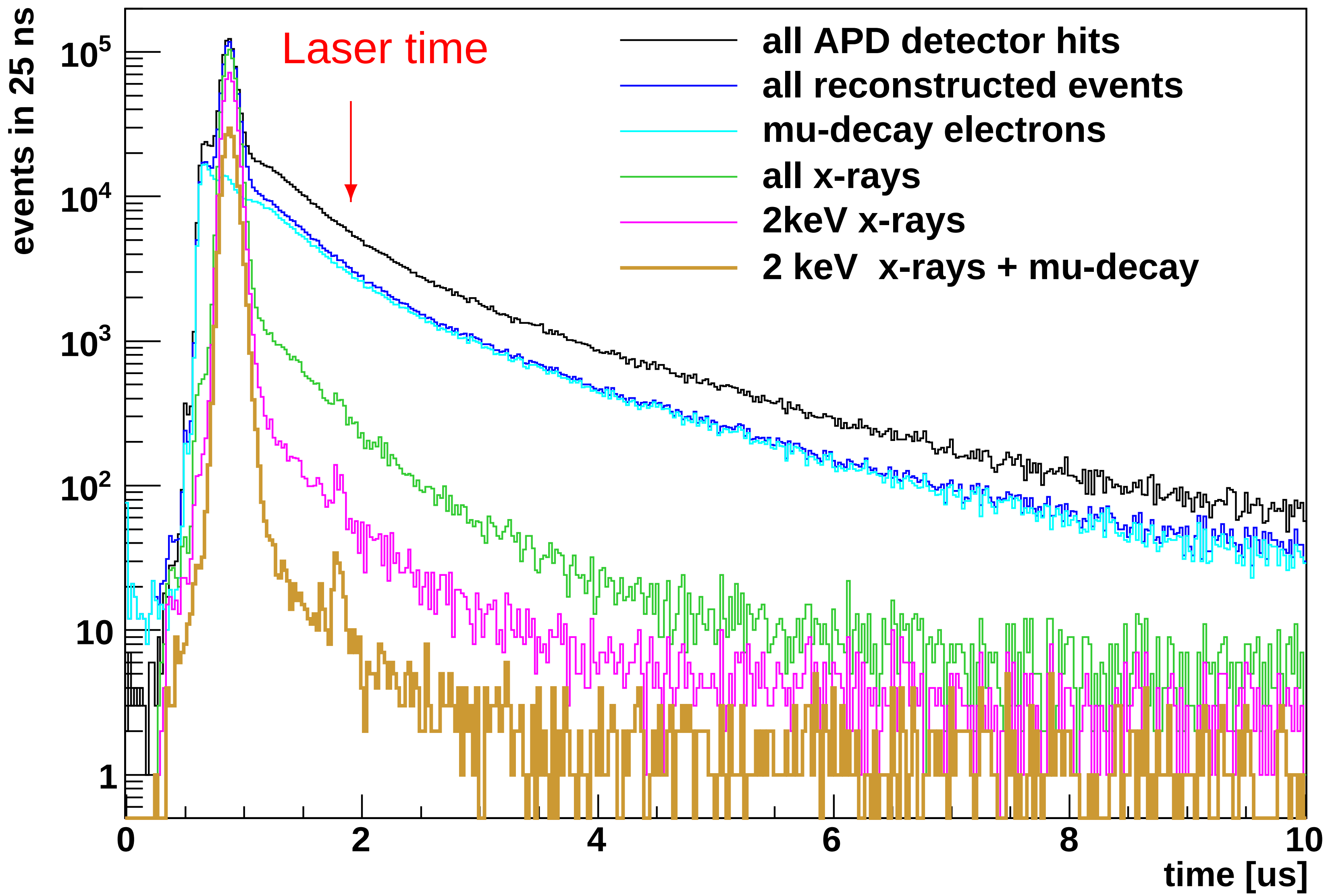
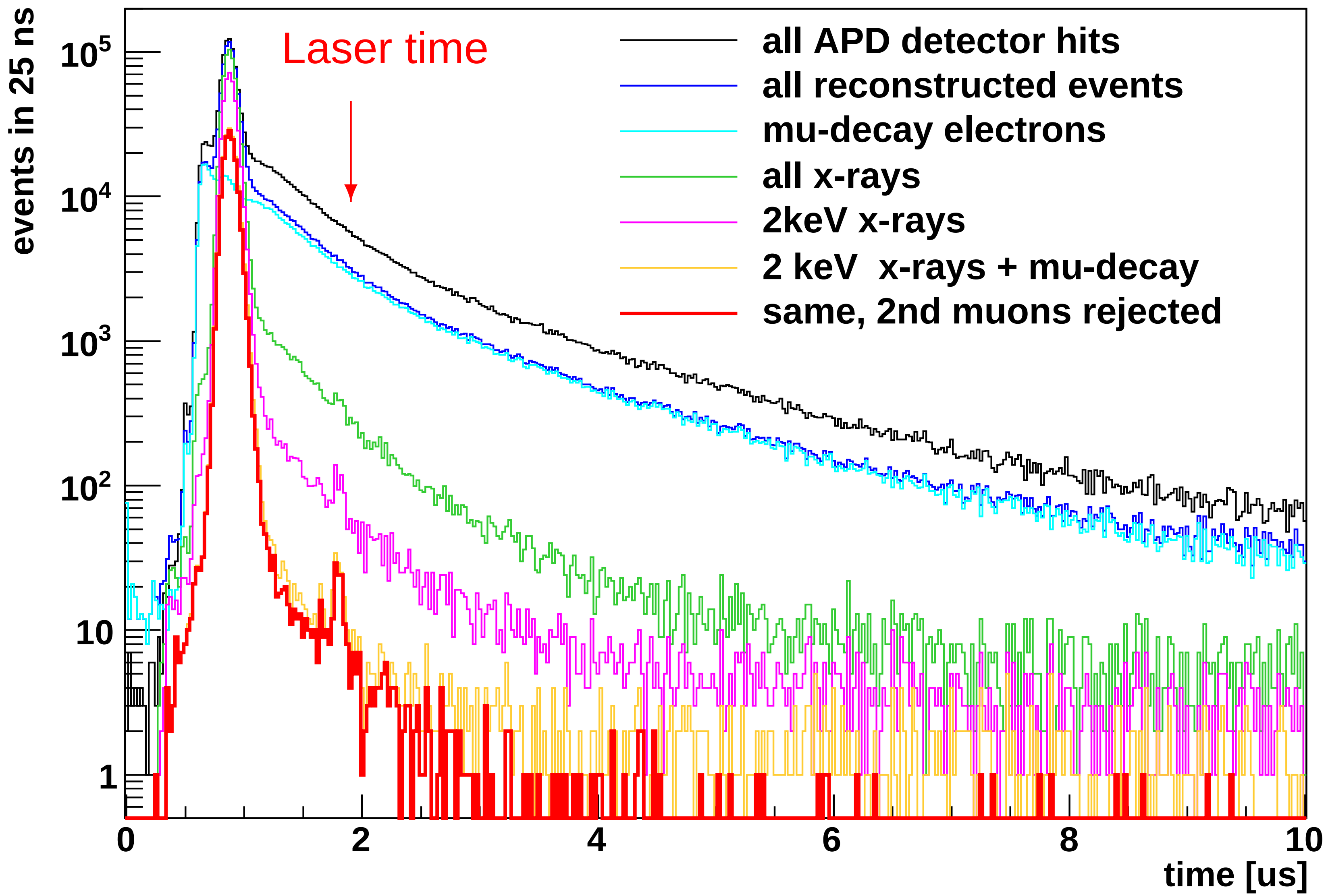


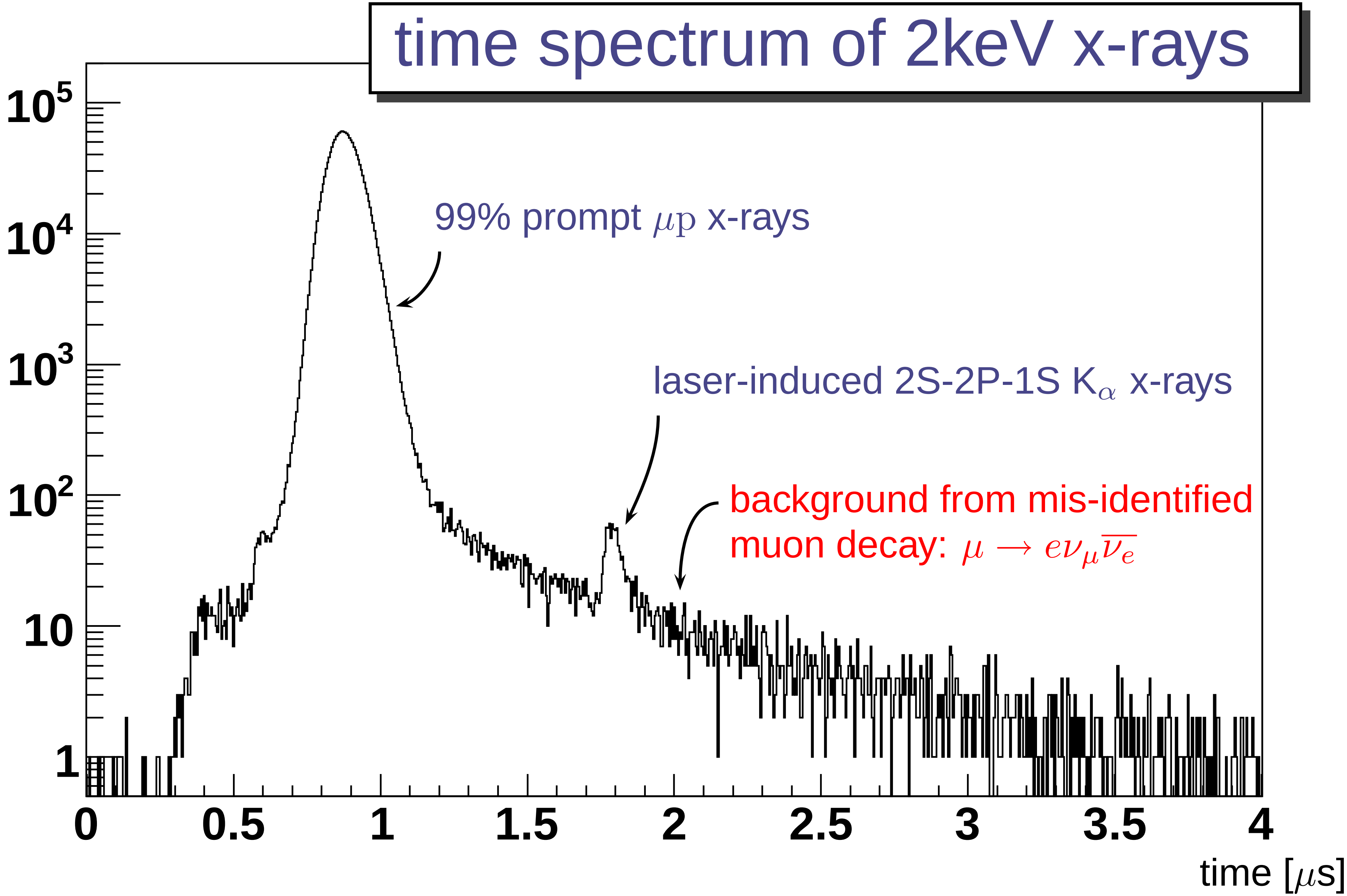
Data analysis

FP 900, 11 hours measurement

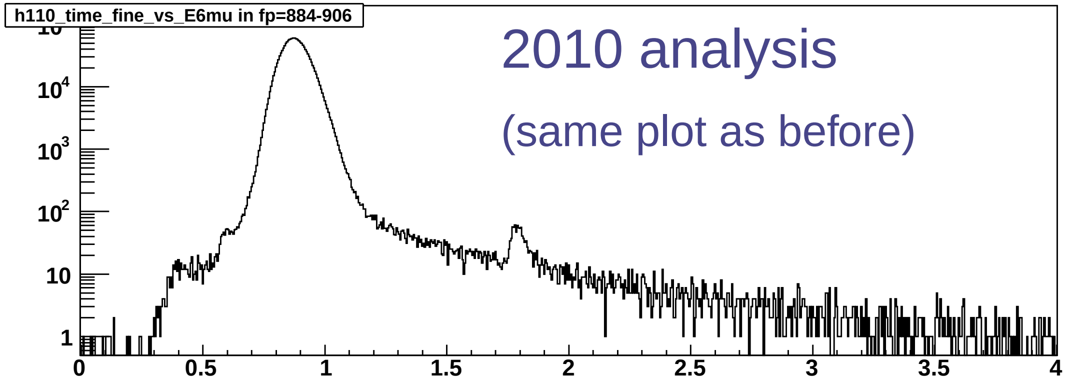
6 signal events per hour on resonance!
1 bgr. event/hour



Data analysis 2010



Data analysis 2011



golden event class:

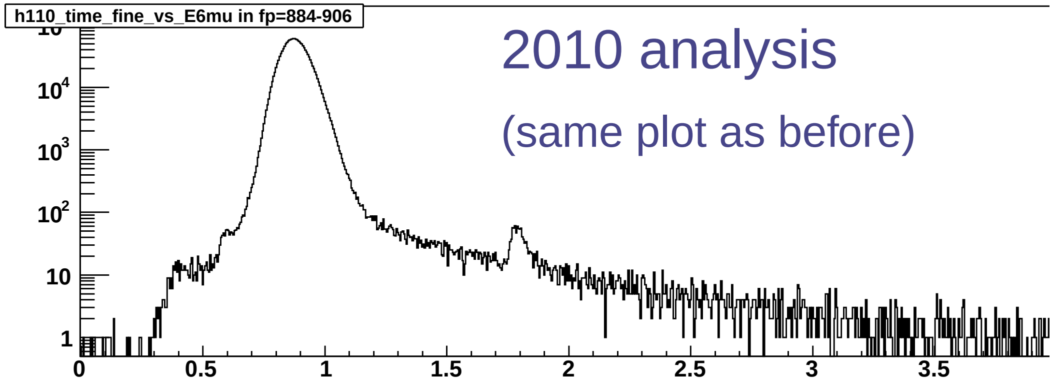
2 keV x-ray , followed by a μ-decay electron

e.g. [0.2 . . . 5.2] μs after the x-ray

several ways to detect μ decay electrons

statistics vs. quality

Divide above data into....



2010 analysis

(same plot as before)

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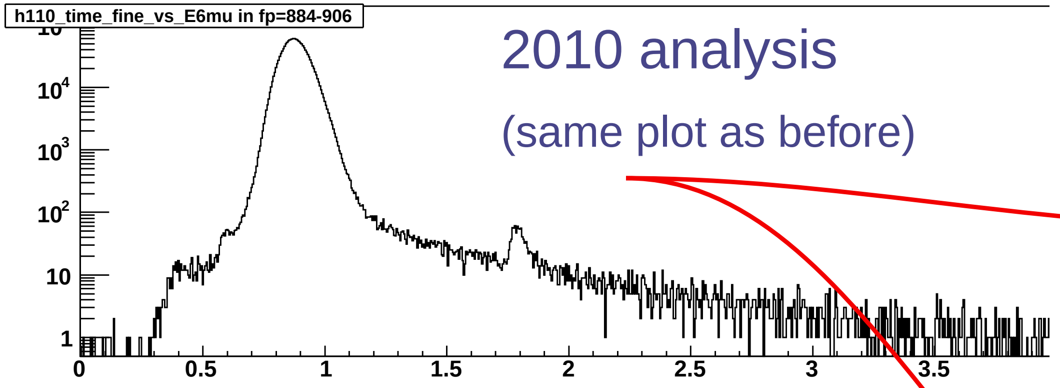

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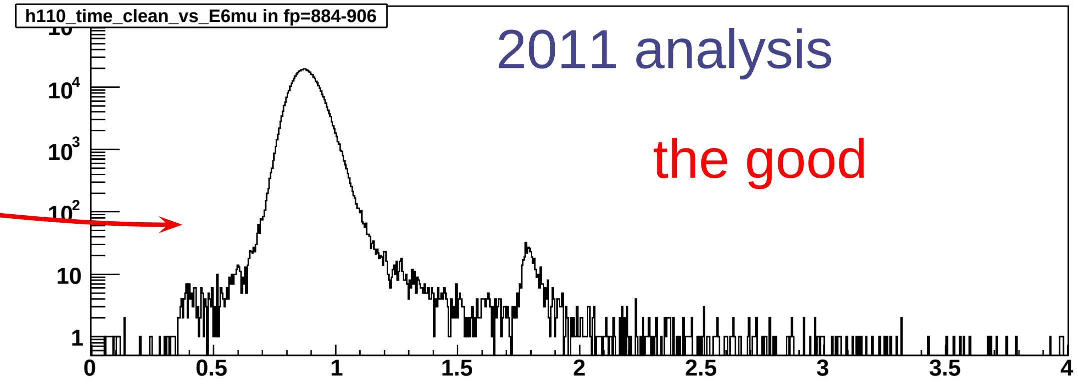
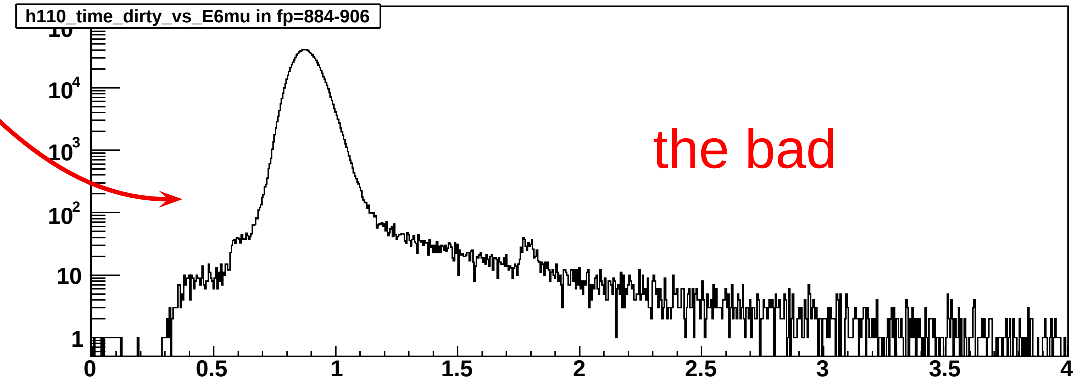


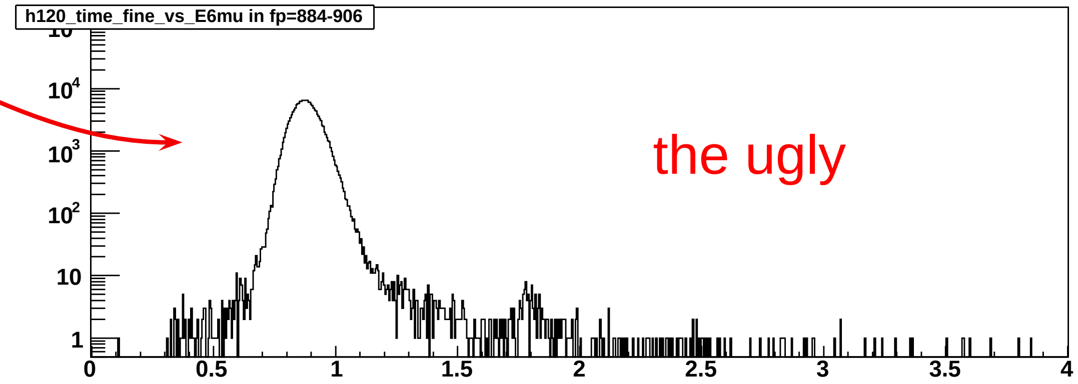
the good

split “2010 data” (Nature)



the bad

add previously discarded data

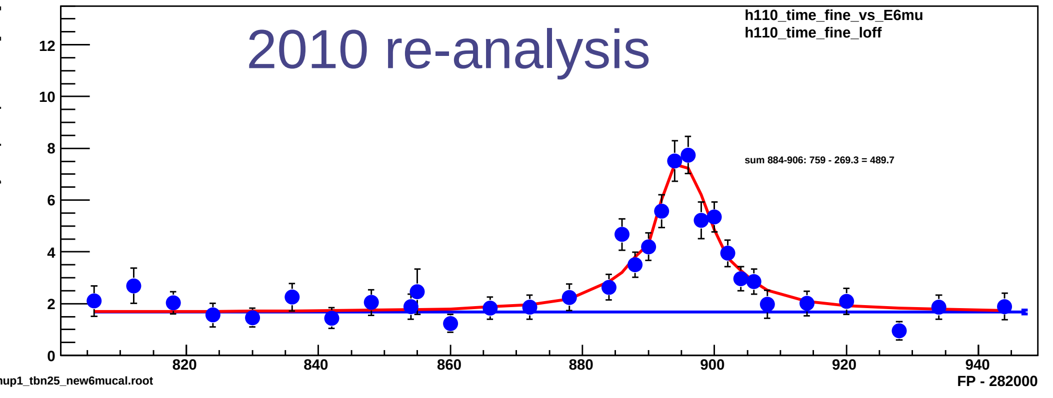


the ugly

fit 3 resonances simultaneously

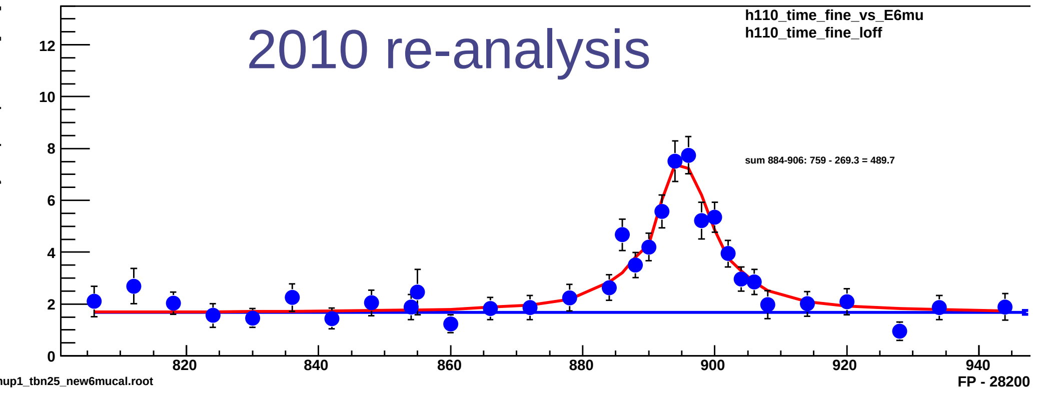
common position and width

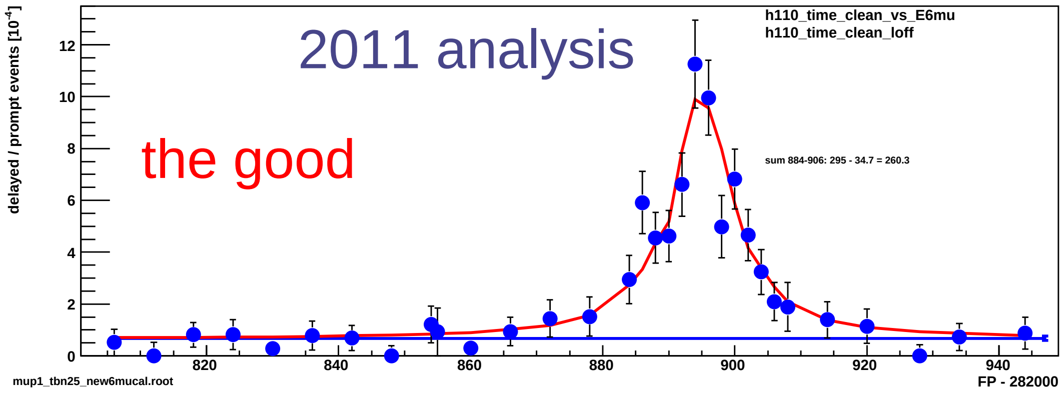
Data analysis 2011



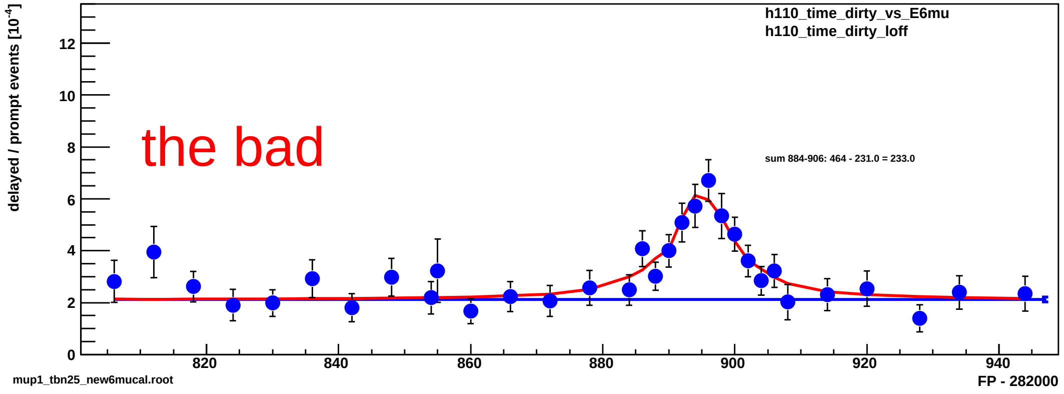
resonance plots

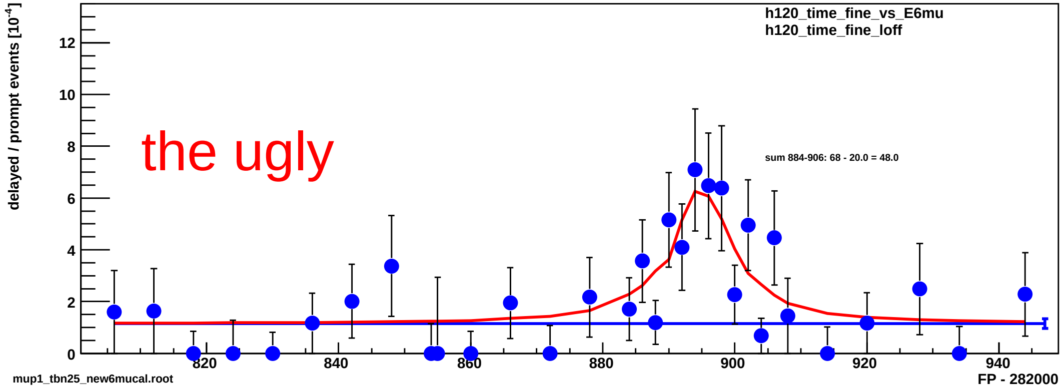
Data analysis 2011



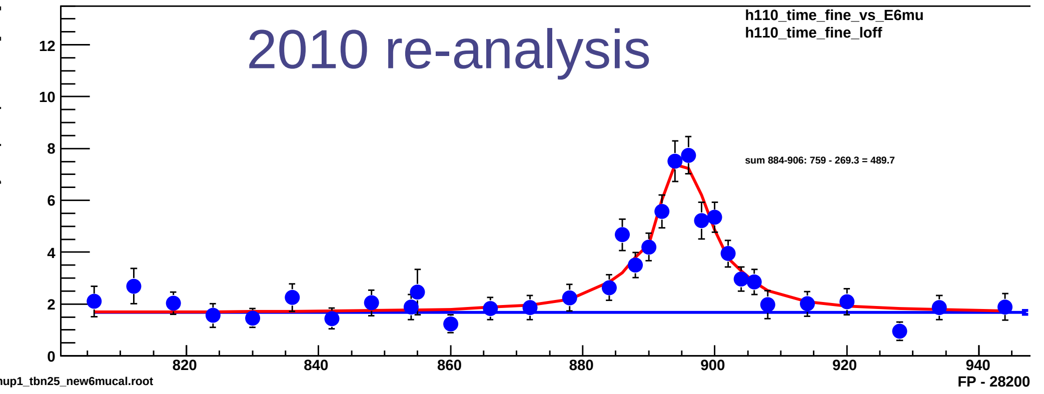


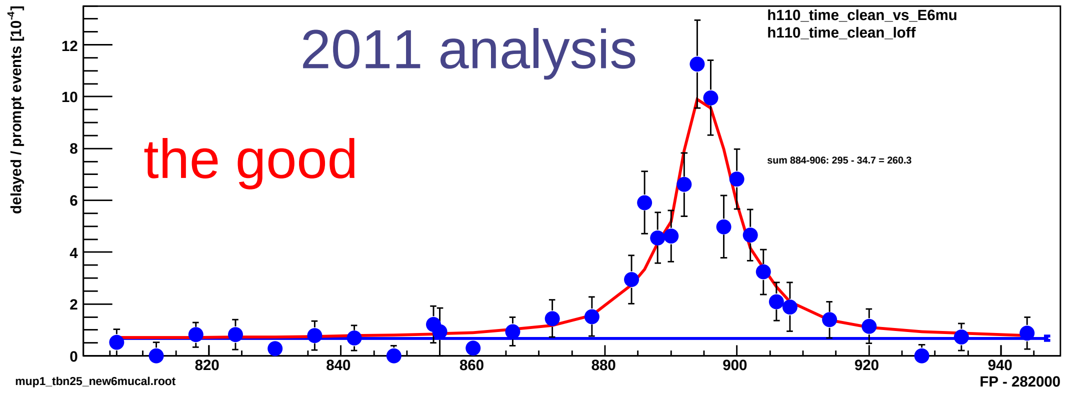
resonance plots

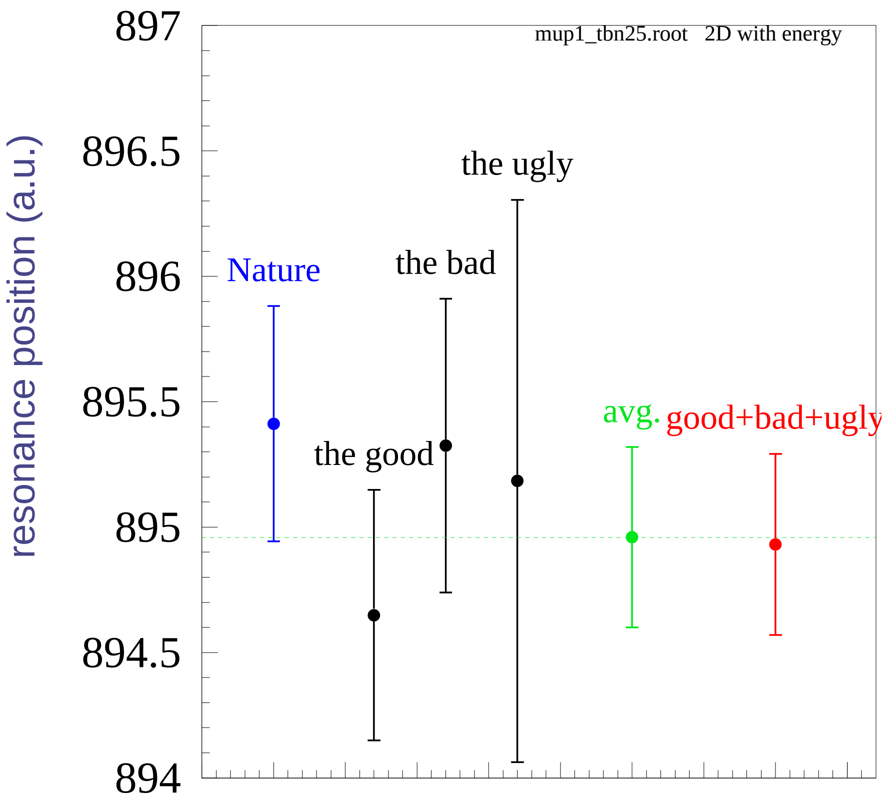


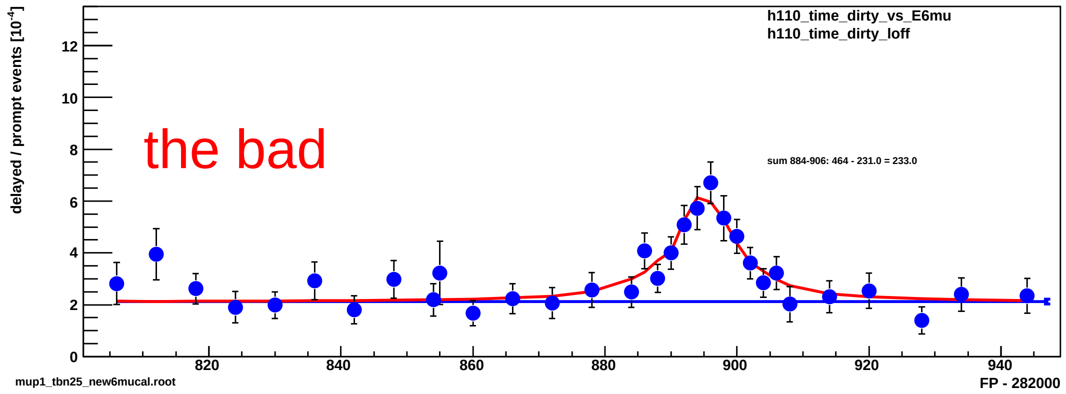


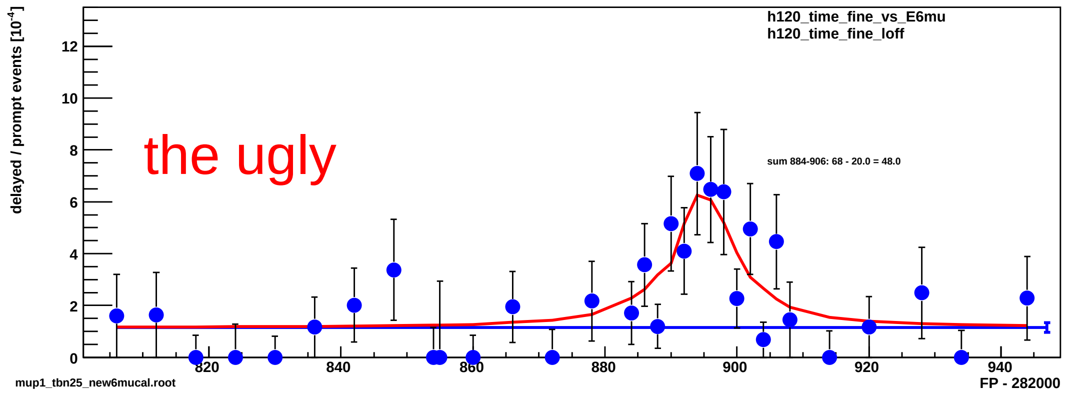
Data analysis 2011









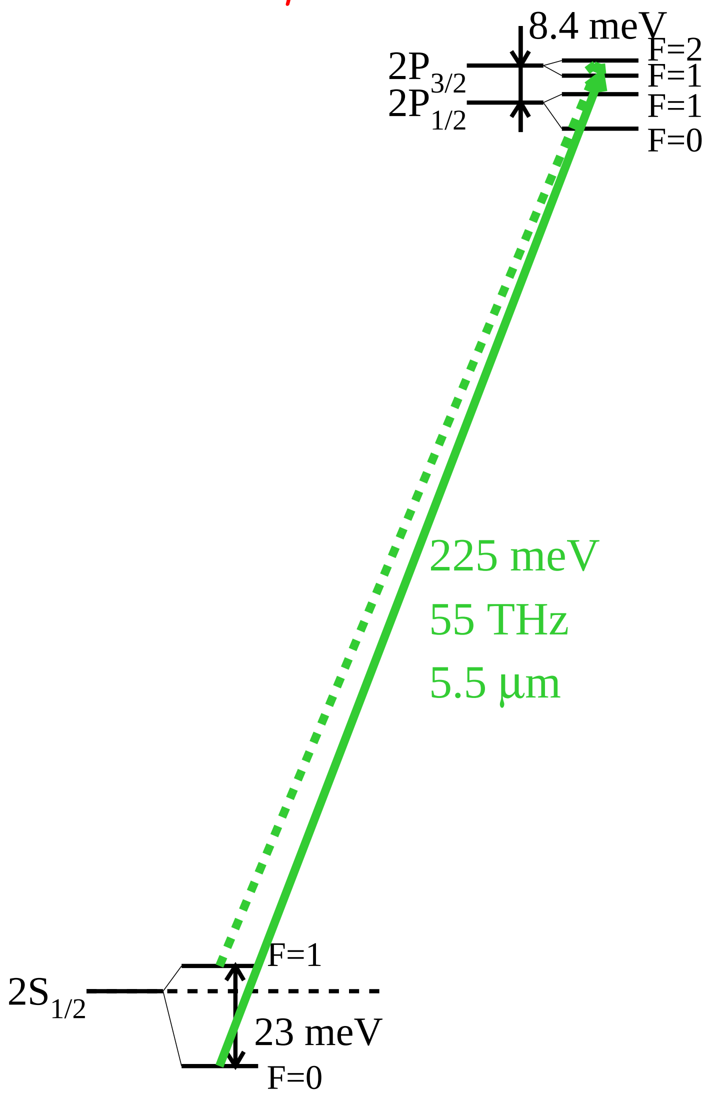


New data

2nd line in muonic hydrogen

μp ($2S_{1/2}$(F=0) $\rightarrow$ $2P_{3/2}$(F=1))

at $\lambda = 5.5\,\mu$m



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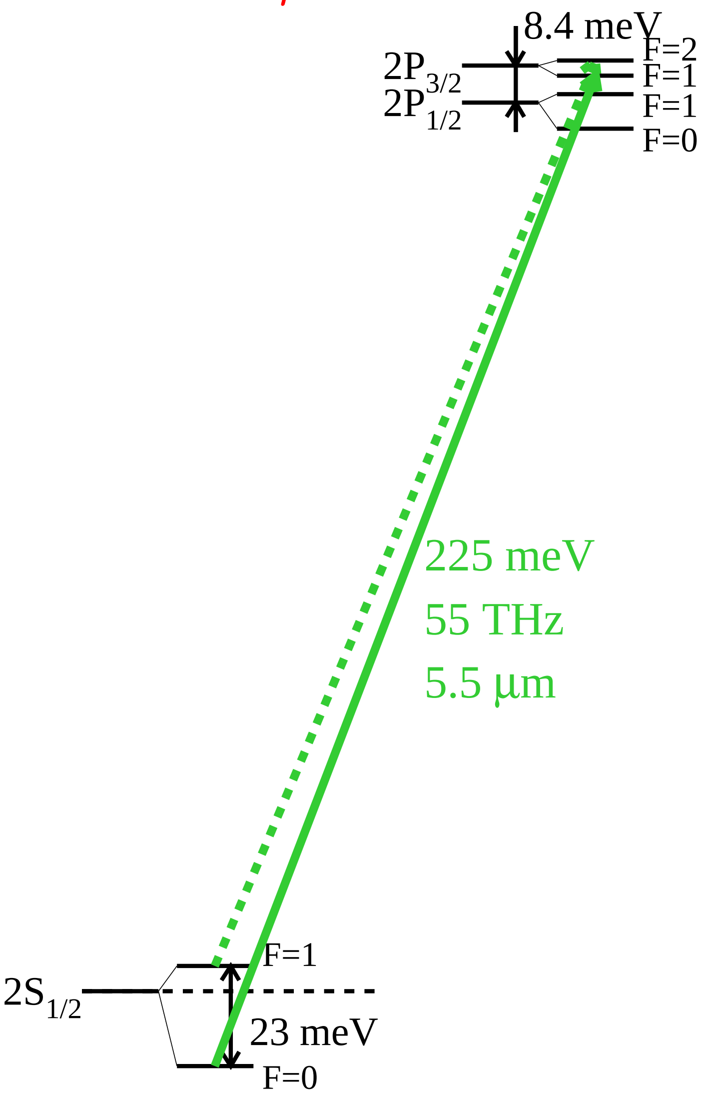

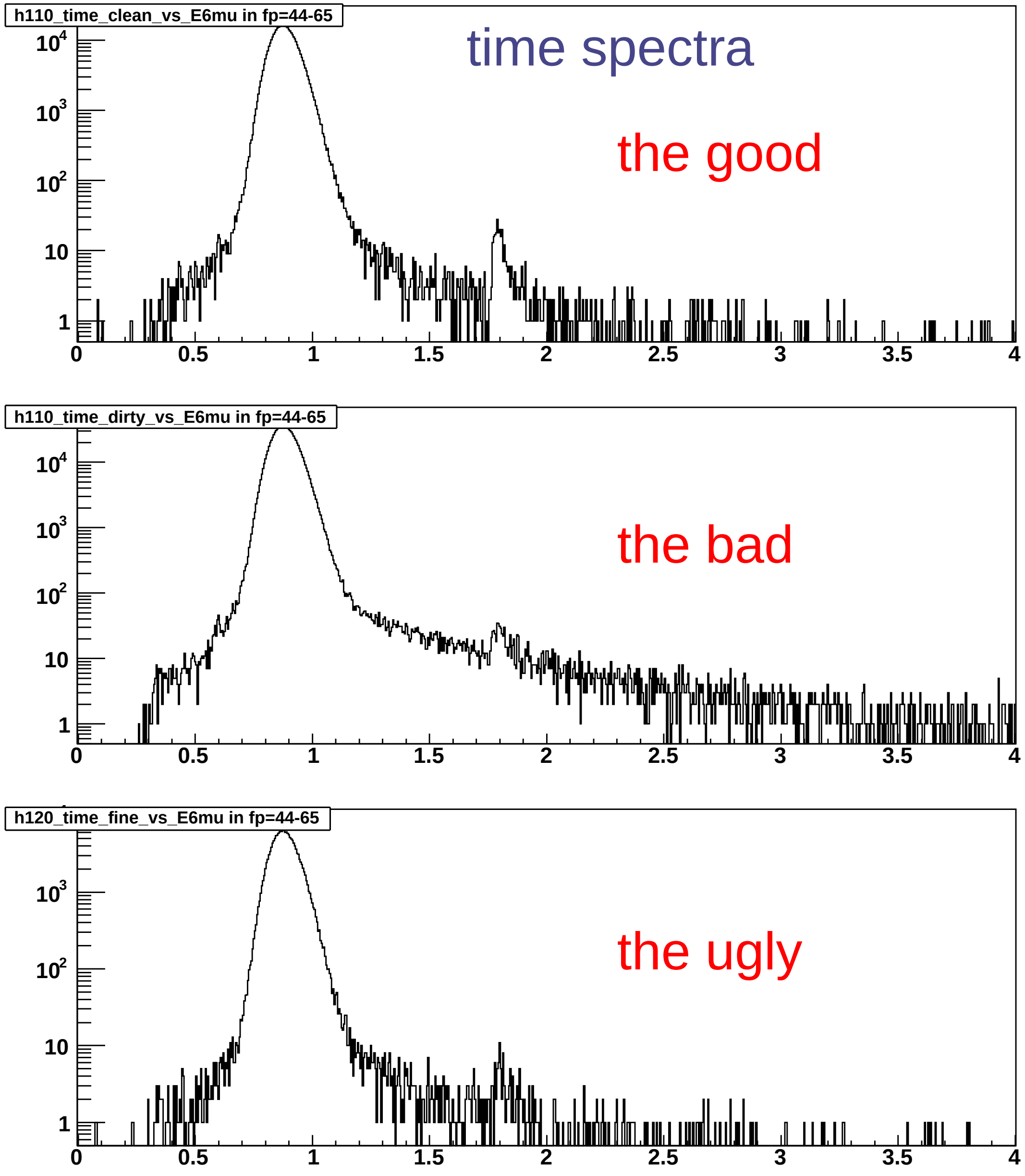

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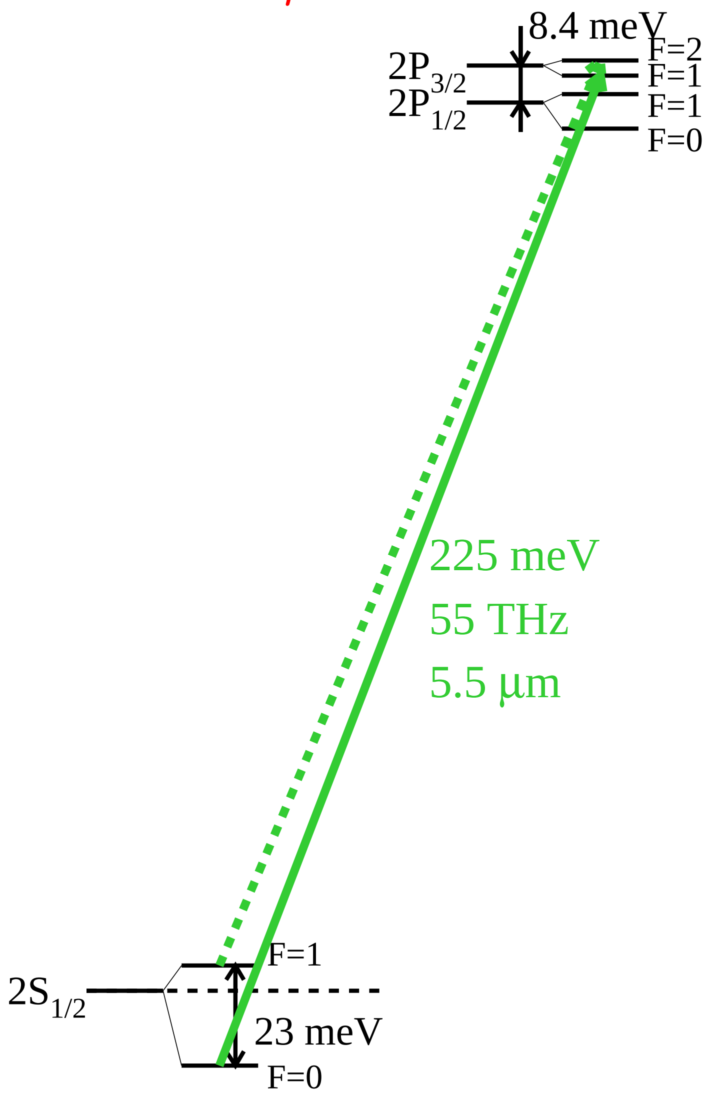

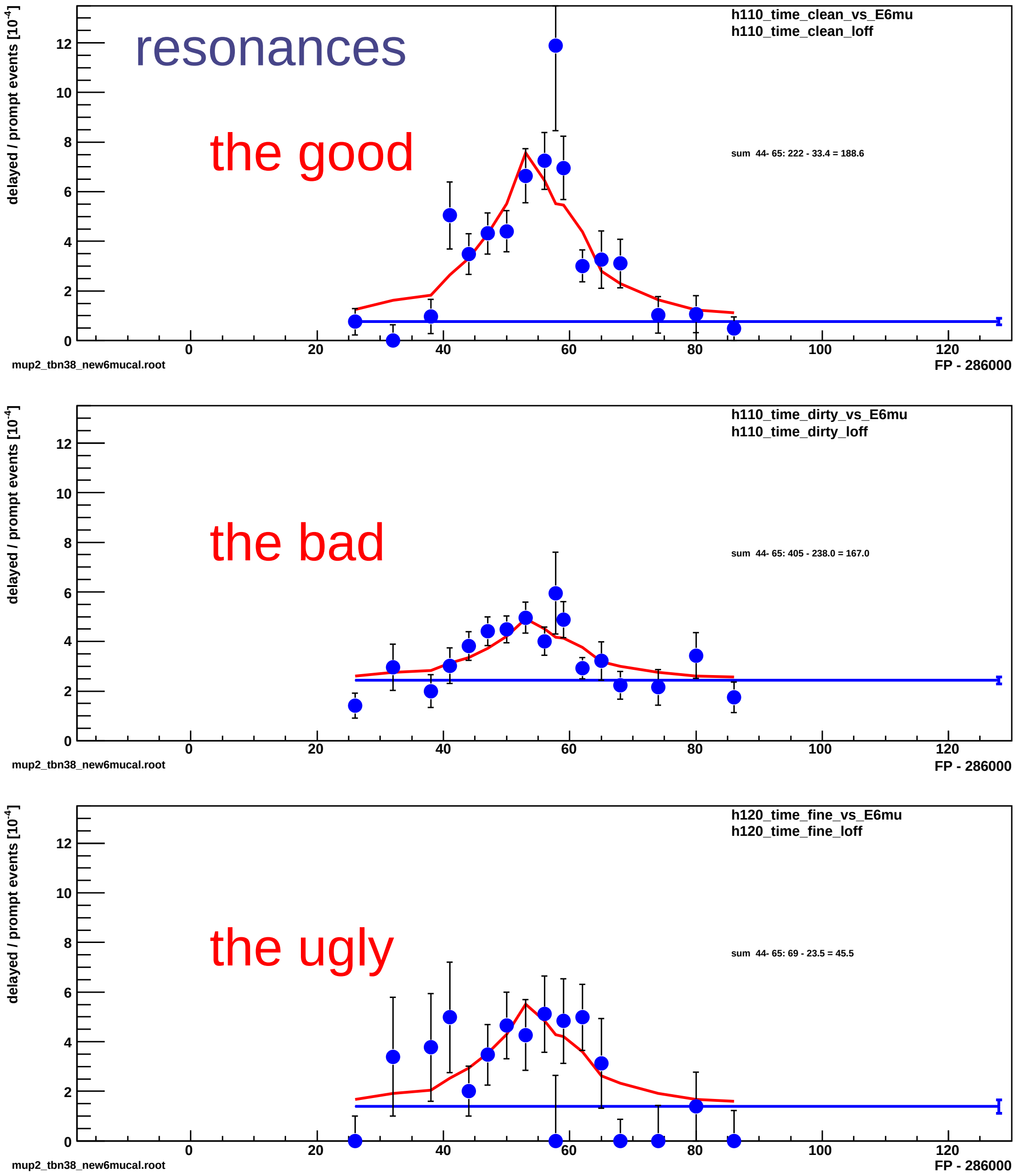

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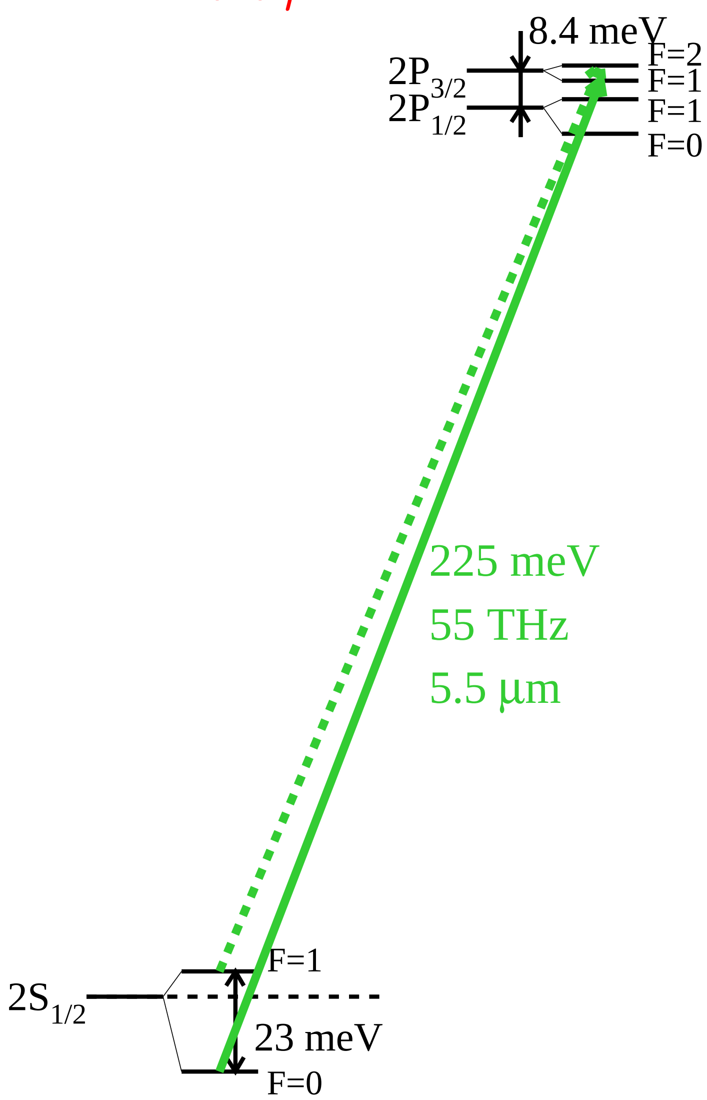

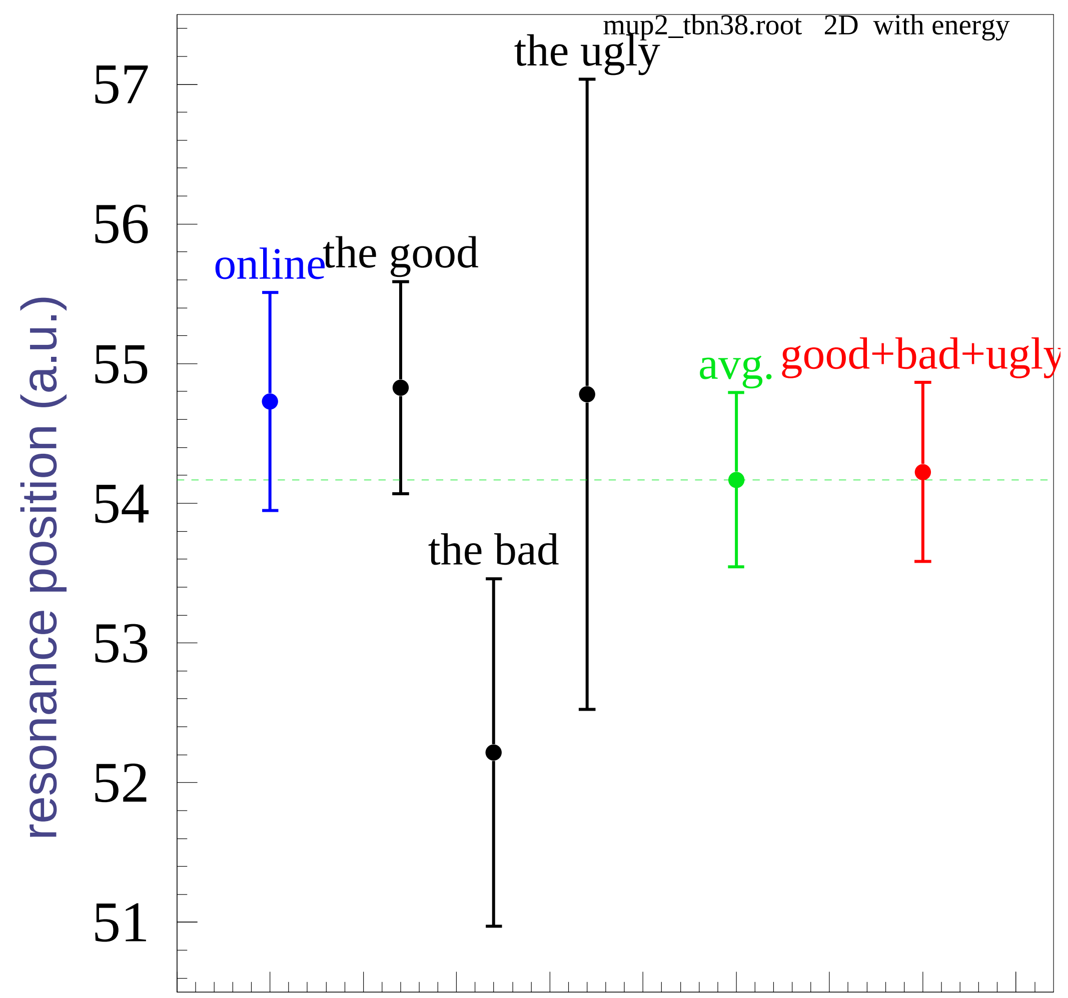

Results on muonic hydrogen

Transition frequencies:

$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2})$ = 49881.88(76) GHz R. Pohl *et al.*, Nature 466, 213 (2010)

49881.16(62) GHz PRELIMINARY 2011

$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1})$ = 54611.87(1.01) GHz PRELIMINARY 2011

Proton radius using 2010 theory

$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2})$: 0.84184(36)(56) fm R. Pohl *et al.*, Nature 466, 213 (2010)

0.84218(29)(56) fm PRELIMINARY 2011

$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1})$: 0.84252(48)(85) fm PRELIMINARY 2011

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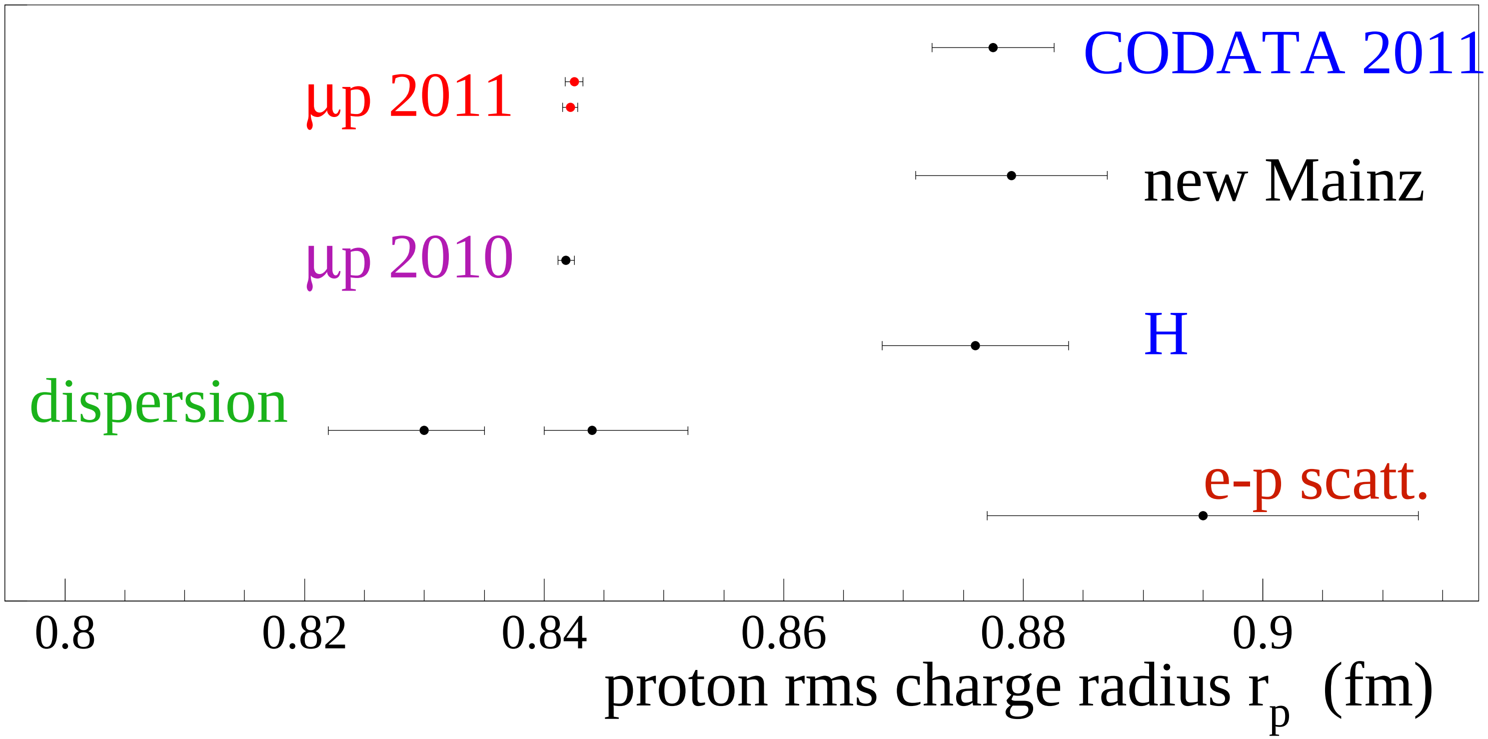

Proton radius puzzle

From the two transitions in muonic hydrogen we extract a PRELIMINARY value of the proton rms charge radius of

r_{p}=0.84284(58) fm $\quad (u_r = 6.8 \times 10^{-4})$

$$u_{\mathrm{exp}} = 3.0 \times 10^{-4}$$
$$u_{\mathrm{theo}} = 6.2 \times 10^{-4}$$

BUT:

CODATA 2006: $r_{\mathrm{p}} = (0.8768 \pm 0.0069)$ fm
Hydrogen: $r_{\mathrm{p}} = (0.876 \pm 0.008)$ fm
e-p scattering: $r_{\mathrm{p}} = (0.895 \pm 0.018)$ fm (Sick 2005)

r_{p} is 4% smaller

5.0σ from CODATA-2006
4.3σ from H
3.1σ from e-p scatt.

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Hydrogen: $r_p = (0.876 \pm 0.008)$ fm

e-p scattering: $r_p = (0.894 \pm 0.008)$ fm (Sick 2011)

$r_p = (0.879 \pm 0.008)$ fm (Mainz 2010)

$r_p = (0.875 \pm 0.010)$ fm (JLab Hall A 2011)

Proton radius puzzle

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$$u_{\text{theo}} = 6.2 \times 10^{-4}$$

BUT:

CODATA 2010: $r_p = (0.8775 \pm 0.0051)$ fm
CODATA 2006: $r_p = (0.8768 \pm 0.0069)$ fm
Hydrogen: $r_p = (0.876 \pm 0.008)$ fm
e-p scattering: $r_p = (0.894 \pm 0.008)$ fm (Sick 2011)
$r_p = (0.879 \pm 0.008)$ fm (Mainz 2010)
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r_p is 4% smaller

6.8σ from CODATA-2010
5.0σ from CODATA-2006
4.3σ from H
8.4σ from scatt.

What’s wrong ??

What's wrong ??

PRA **81**, 060501 (2010)	Karshenboim *et al.*: *"Nonrelativistic contributions of order $\alpha^5 m_\mu c^2$ to the Lamb shift in muonic ..." (1005.4879)*
JETP Lett. **92**, 8 (2010)	Karshenboim *et al.*: *"Contribution of light-by-light scattering to energy levels of light muonic atoms" (1005.4880)*
PRL **105**, 242001 (2010)	Bernauer *et al*: *"High-precision determination of the electric and magnetic form factors of the proton" (1007.5076)*
PRD **82**, 125020 (2010)	Jaeckel, Roy: *"Spectroscopy as a test of Coulomb's law" (1008.3536)*
PLB **693**, 555 (2010)	De Rujula: *"QED is not endangered by the proton's size" (1008.3861)*
Nucl.Phys.News **21**, 14 (2011)	Vanderhaeghen, Walcher: *"Long range structure of the nucleon" (1008.4225)*
Can. J. Phys. **89**, 109 (2011)	Jentschura: *"From first principles of QED to an application: hyperfine structure of P states of muonic hydrogen"*
PRC **83**, 012201(R) (2011)	Cloet, Miller: *"Third Zemach moment of the proton" (1008.4345)*
PRD **82**, 113005 (2010)	Hill, Paz: *"Model-independent extraction of the proton charge radius from electron scattering" (1008.4619)*
PLB **697**, 26 (2011)	De Rujula: *"QED confronts the proton's radius" (1010.3421)*
PLB **696**, 343 (2011)	Distler *et al*: *"The RMS radius of the proton and Zemach moments" (1011.1861)*
EPJD **61**, 7 (2011)	Jentschura: *"Proton radius, Darwin-Foldy term and radiative corrections" (1012.4029)*
PRL **106**, 153001 (2011)	Barger, Chiang, Keung, Marfatia: *"Proton size anomaly" (1011.3519)*
PRA **83**, 012507 (2011)	Yerokhin: *"Nuclear-size corrections to the Lamb shift of one-electron atoms" (1011.4272)*
PRD **83**, 101702(R) (2011)	Tucker-Smith, Yavin: *"Muonic hydrogen and MeV forces" (1011.4922)*
Ann. Phys. **326**, 500 (2011)	Jentschura: *"Lamb shift in muonic hydrogen I: Verification and update of theoretical predictions" (1011.5275)*
Ann. Phys. **326**, 516 (2011)	Jentschura: *"Lamb shift in muonic hydrogen II: Analysis of the discrepancy of theory and experiment" (1011.5453)*
Few-Body Syst. **50**, 367 (2011)	Sick: *"Troubles with the proton rms radius"*
PRD **83**, 035020 (2011)	Brax, Burrage: *"Atomic precision tests and light scalar couplings" (1010.5108)*
PRA **83**, 042509 (2011)	Carlson *et al.*: *"Proton-structure corrections to hyperfine splitting in muonic hydrogen" (1101.3239)*
PRL **106**, 193007 (2011)	Pachucki: *"Nuclear structure corrections in muonic deuterium" (1102.3296)*
PRL **107**, 011803 (2011)	Batell, McKeen, Pospelov: *"New parity-violating muonic forces and the proton charge radius" (1102.3296)*
PRA **84**, 012506 (2011)	Carroll *et al.*: *"Nonperturbative relativistic calculation of the muonic hydrogen spectrum" (1104.2971)*
PRA **84**, 012505 (2011)	Jentschura: *"Relativistic reduced-mass and recoil corrections to vacuum polarization in muonic hydrogen, ..." (1107.1737)*
PRA **84**, 020101(R) (2011)	Miller, Thomas, Carroll, Rafelski: *"Toward a resolution of the proton size puzzle" (1101.4073)*
PRA **84**, 020102(R) (2011)	Carlson, Vaderhaeghen: *"Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)*
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Summary

- μp laser experiment is correct
- theory in muonic hydrogen:
  - FS, HFS correct
  - QED correct on the level of the discrepancy
  - proton polarizability under discussion
- electron scattering: new data from Mainz and Jefferson lab
- no New Physics :-)

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Summary

- μp laser experiment is correct

except: U.D. Jentschura, Ann. Phys. **326**, 516:

e^- bound to μp(2S) with $r = a_0$ shifts resonance by 0.4 meV

- How should this bound state form?
  - "No" free electrons.
- Why should this bound state be stable?
  - Stark mixing !?!
  - Auger effect !!
  - Collisions: every 100 ns.
- Only 1 line observed: >80% formation rate in 1 state.
  - no peak at expected position
  - observed peak has expected width

What's wrong ??

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$\Rightarrow$ J.-Ph. Karr, L. Hilico

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Few-B

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PRA **84**, 020102(R) (2011) Carlson, Vaderhaeghen: *"Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)*

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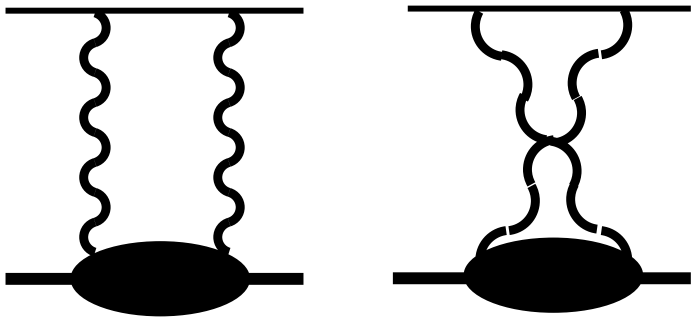
Discussions: Proton polarizability

proton polarizability aka. two-photon exchange



Seems to be the only contribution which *might* be able to solve the proton size puzzle by changing theory in $\mu\mathrm{p}$.

Keep in mind:

Discrepancy: 0.31 meV

Polarizability: 0.015(4) meV 20 times smaller!

Discussions: Proton polarizability

- PRA **83**, 042509 (2011) C.E. Carlson, V. Nazaryan, K. Griffioen:
  "Proton-structure corrections to hyperfine splitting in muonic hydrogen" (1101.3239)
  - The 2S HFS is confirmed with smaller uncertainty:
    22.8146(49) meV instead of the
    22.8148(78) meV we used.

Discussions: Proton polarizability

- PRA **84**, 020101(R) (2011) G.A. Miller *et al.*:
  "Toward a resolution of the proton size puzzle" (1101.4073)
  - New off-mass-shell effect $\sim \alpha \frac{m^4}{M^3}$ solves puzzle.
  - Others say: This is already included in standard treatment.
  - C.E. Carlson: calculation gives 50 times smaller value.
- PRA **84**, 020102(R) (2011) C.E. Carlson, M. Vanderhaeghen:
  "Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)
  - All off-shell effects are automatically included in standard treatment.
- PRL, **107**, 160402 (2011) R.J. Hill, G. Paz:
  "Model independent analysis of proton structure for hydrogenic bound states" (1103.4617)
  - forward Compton amplitude's $W_1(0, Q^2)$ is now well known
  - "Crazy" functional behaviour can give any correction.
  - No numbers given.

Discussions: Proton polarizability

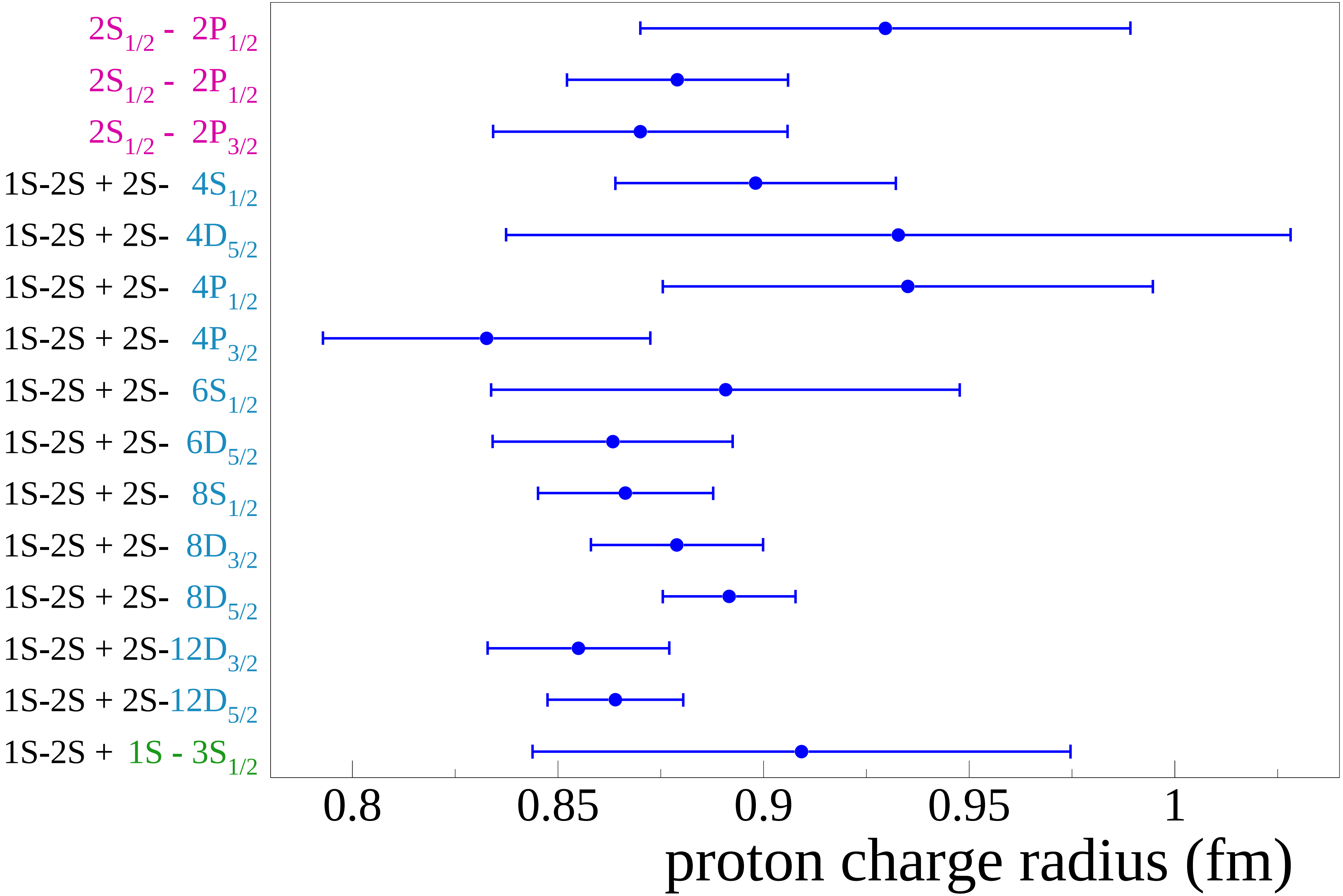
- Our value is based on 3 calculations
  - 0.017(4) meV: Rosenfelder, Phys. Lett. B 463, 317 (1999)
  - 0.012(2) meV: Pachucki, PRA 60, 3593 (1999)
  - 0.018 meV: Martynenko, Faustov, Phys. At. Nucl. 63, 845 (2000)
  - 0.015(4) meV: Borie, PRA 71, 032508 (2005)
- (0.31 meV is our discrepancy)
- No consensus about **validity** of the new claims
- Independent calculation of new effects give **50 times smaller** value.
- Lack of **numbers**

Don't know if this can solve the proton size puzzle.

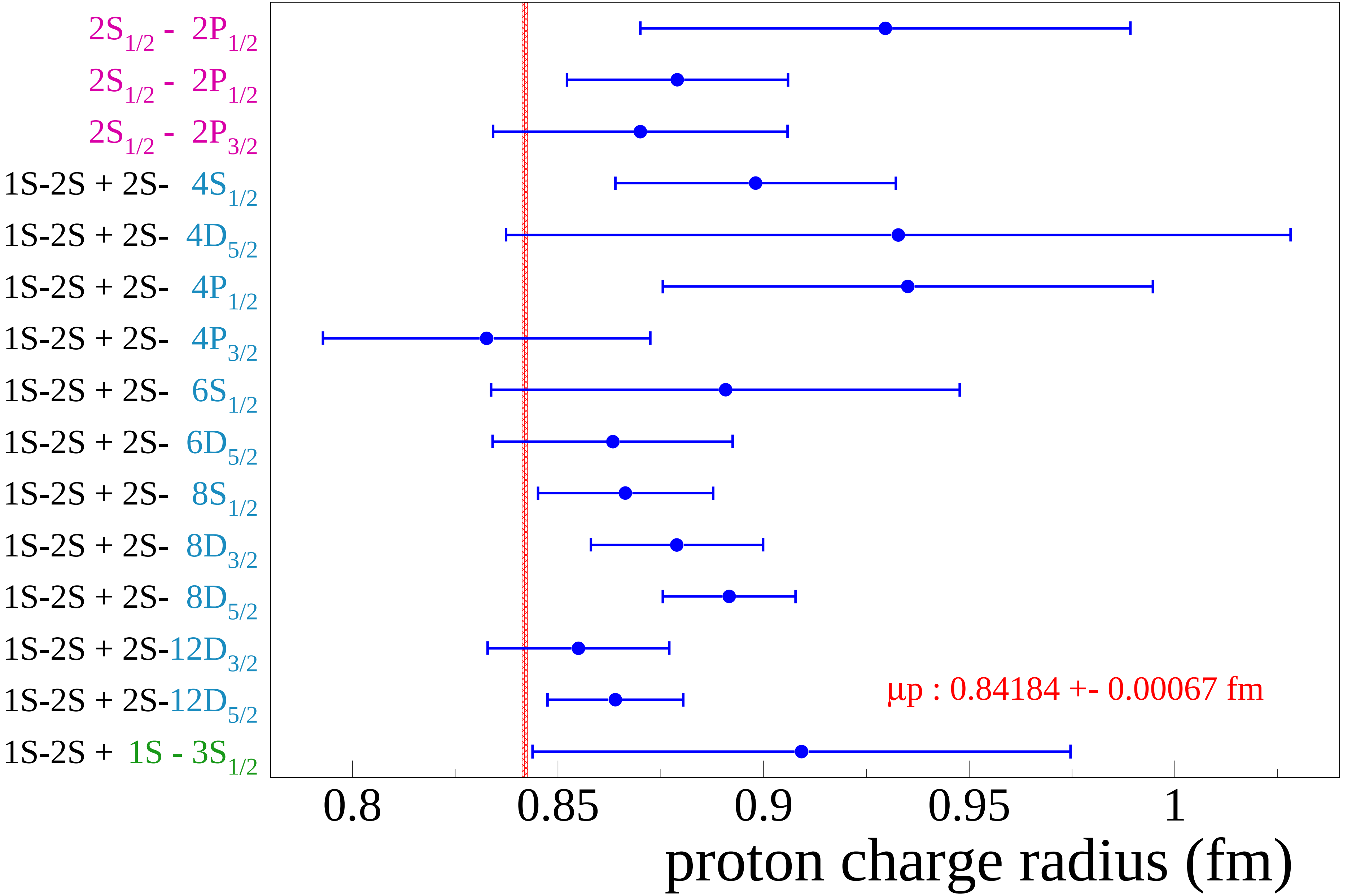
Numbers are needed which can be tested in experiments.

Are H spectroscopy and e-p scattering really "obviously correct"?

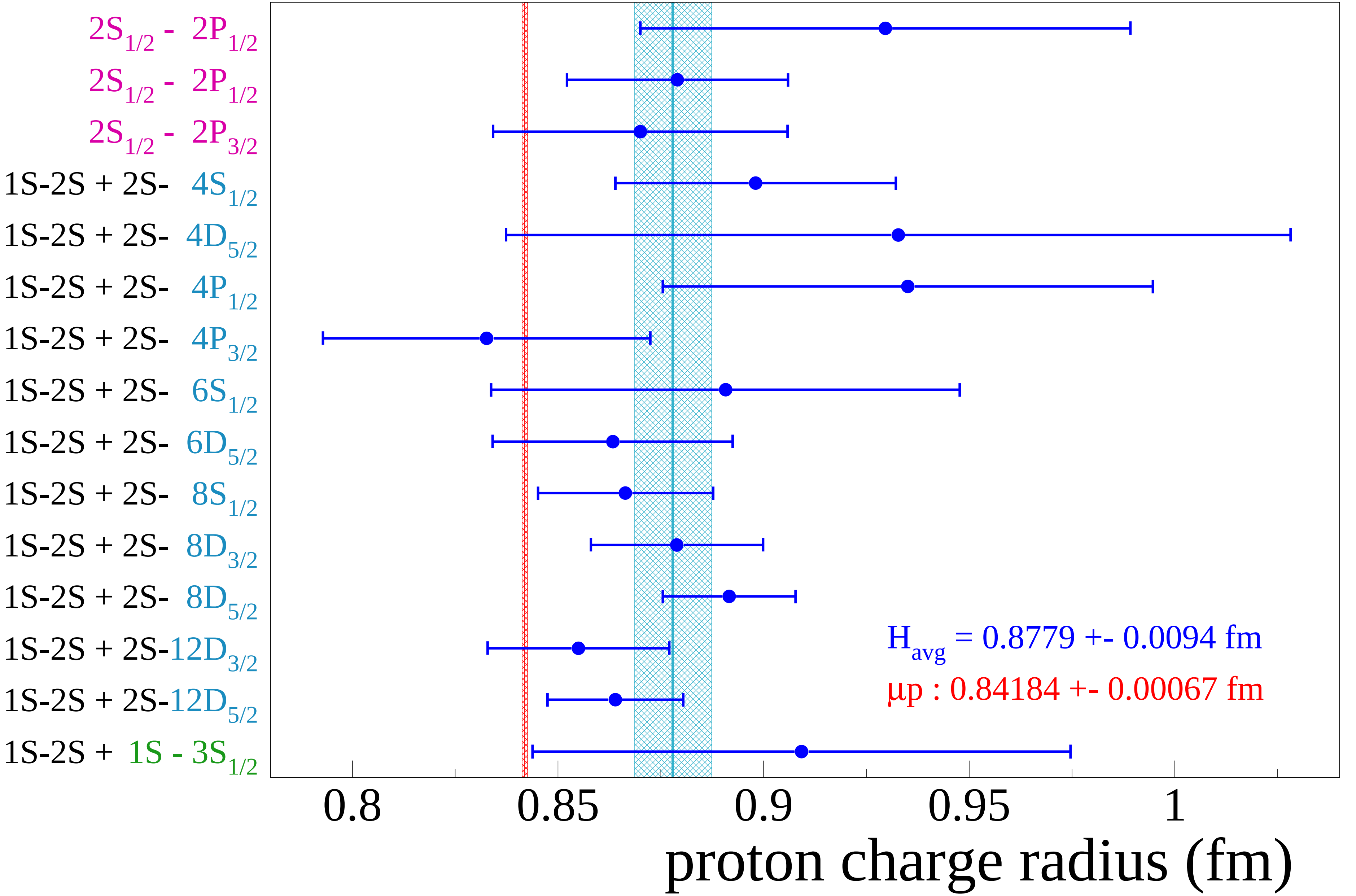
Hydrogen spectroscopy



Hydrogen spectroscopy



Hydrogen spectroscopy



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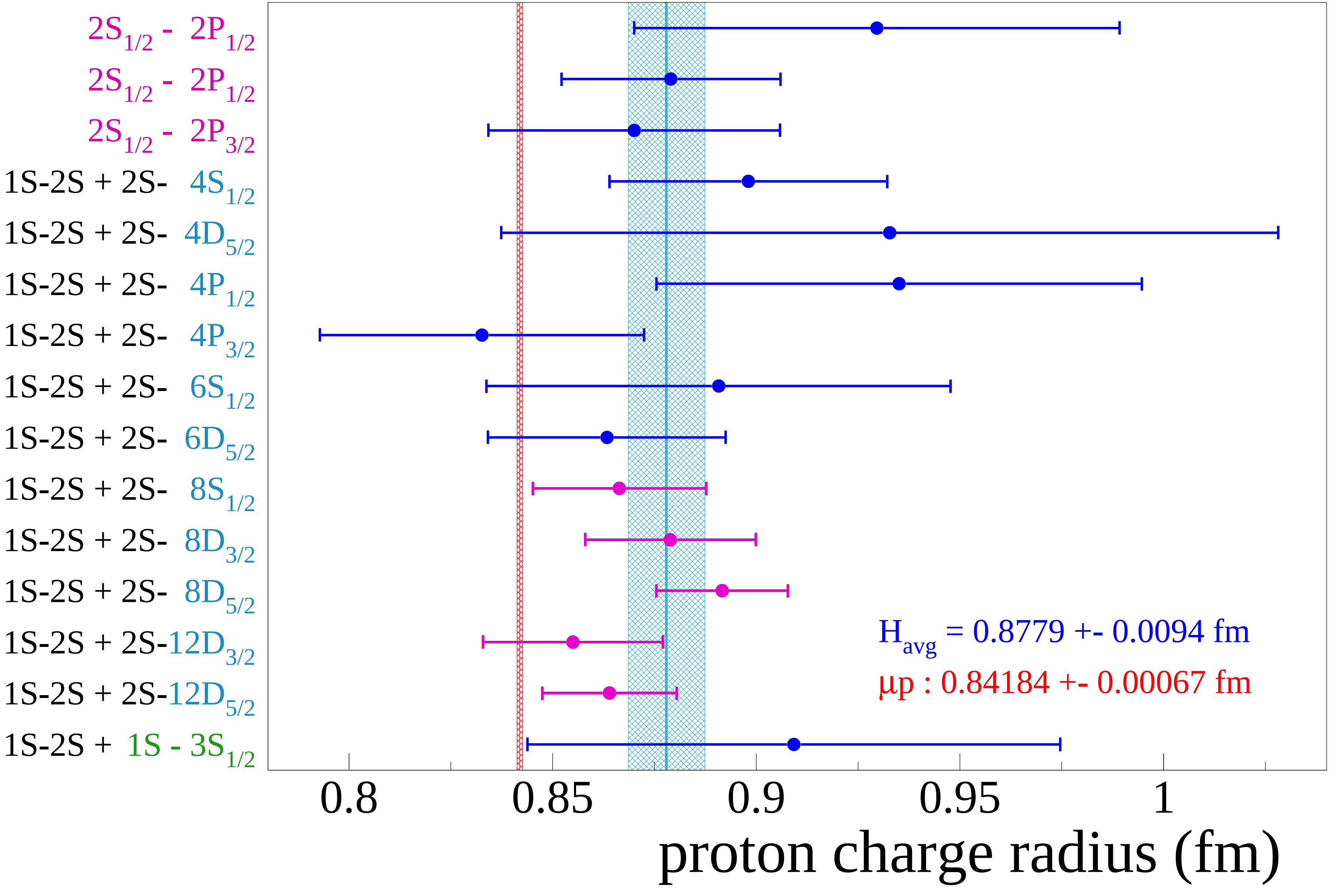

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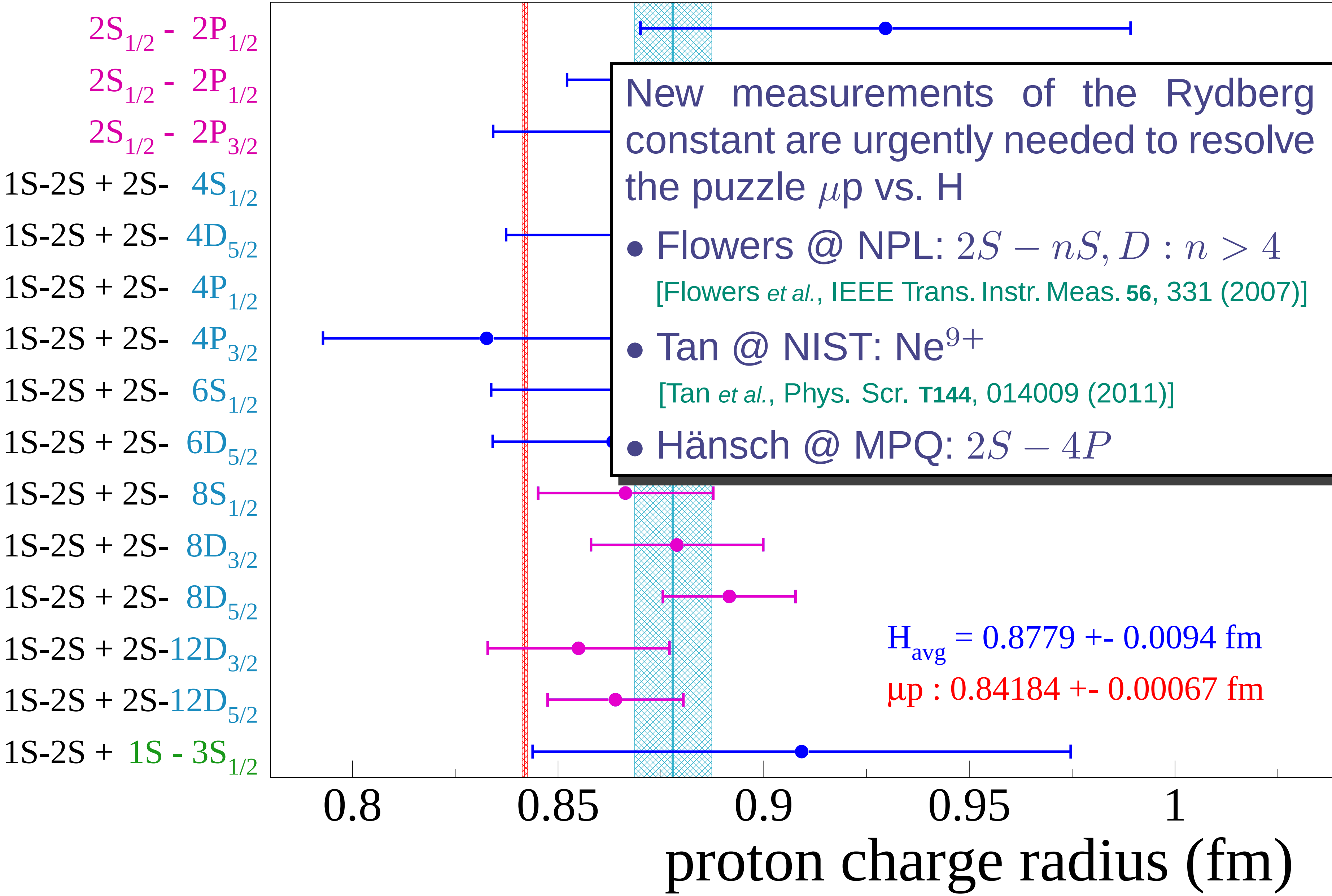


New measurements of the Rydberg constant are urgently needed to resolve the puzzle μp vs. H

- Flowers @ NPL: $2S - nS, D : n > 4$
  [Flowers *et al.*, IEEE Trans. Instr. Meas. **56**, 331 (2007)]
- Tan @ NIST: Ne^{9+}
  [Tan *et al.*, Phys. Scr. **T144**, 014009 (2011)]
- Hänsch @ MPQ: $2S - 4P$

r_p from electron scattering

PhD thesis J.C. Bernauer

- Rosenbluth cross section $\rightarrow$ Sachs form factor $\rightarrow r_\mathrm{p}$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{\varepsilon {G_E}^2 + \tau {G_M}^2}{\varepsilon(1+\tau)} \qquad \varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1} \quad ; \quad \tau = \frac{Q^2}{4m_p^2}$$

G_E and G_M are the Fourier transforms of the charge and magnetization distributions

$G_E(0) = 1$ (charge), and $G_M(0) = \mu_p$ (magnetic moment)

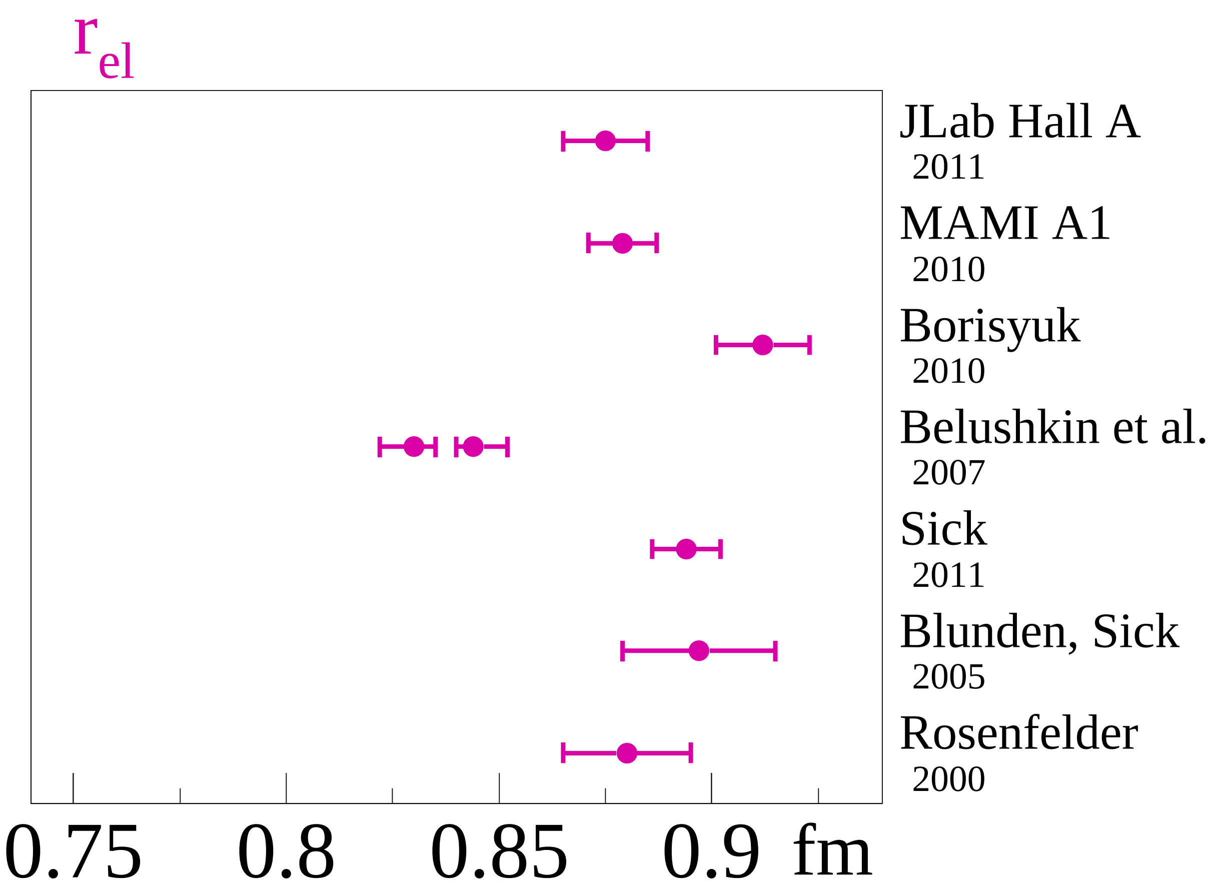
$$\langle r_\mathrm{p}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0} \quad \Rightarrow$$ rms charge radius = **slope of G_E at $Q^2 = 0$**

extrapolation to $Q^2 \rightarrow 0$ required

$$Q^2[\,(\mathrm{GeV/c})^2] = \begin{cases} 6 \cdot 10^{-7} & (\mu\mathrm{p}) \\ > 2 \cdot 10^{-2} & (\text{e-p scatt.}) \end{cases}$$

Note: You get **charge** and **magnetic** radius *simultaneously*.

Electron scattering



Rosenfelder , Phys Lett B 479, 381 (2000)
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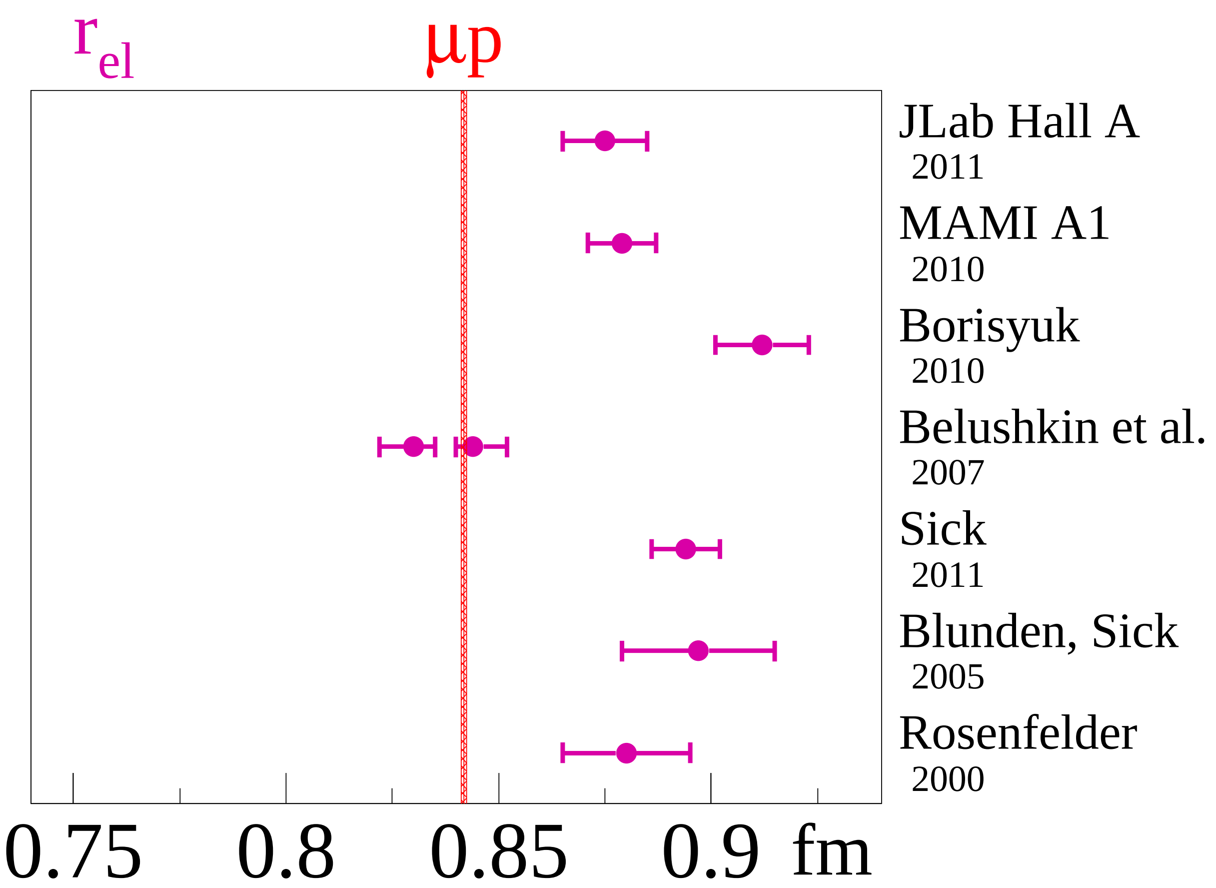
Electron scattering



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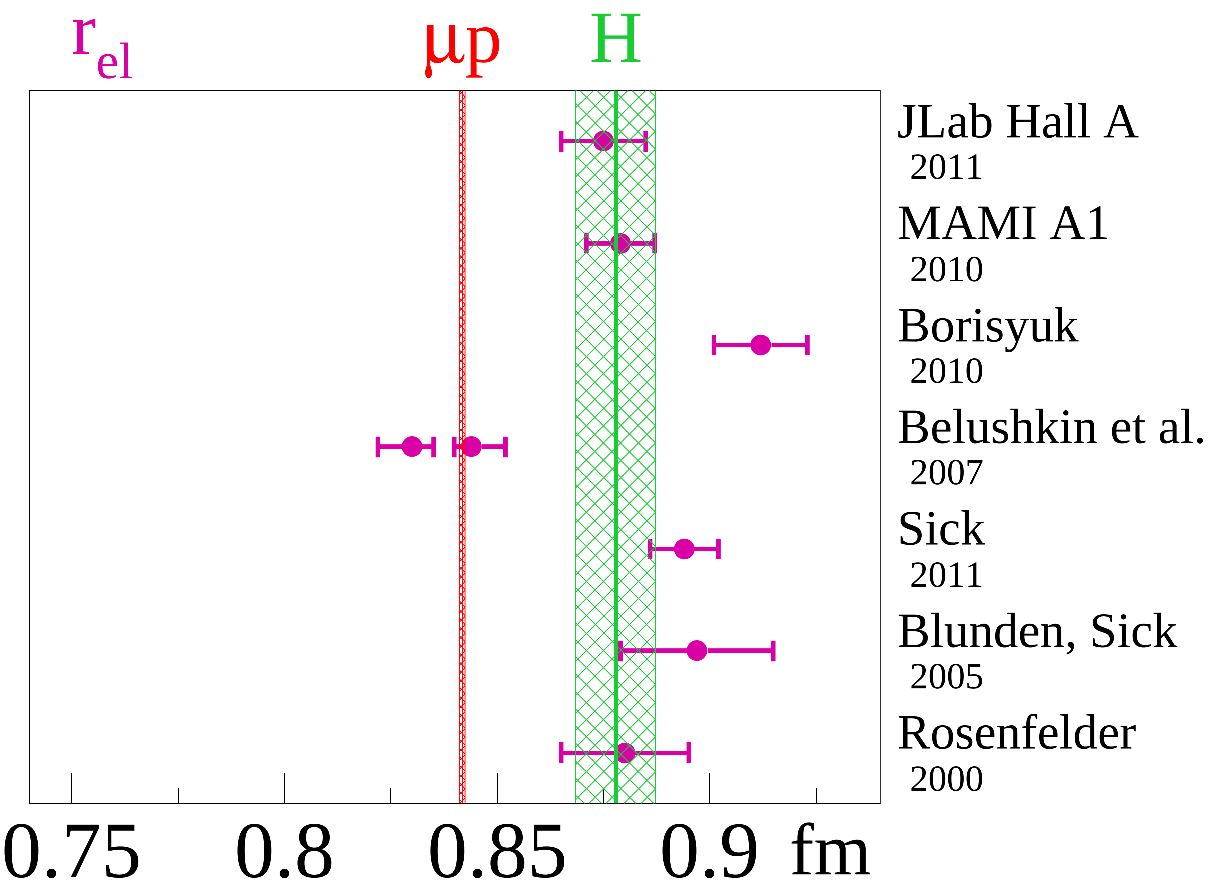

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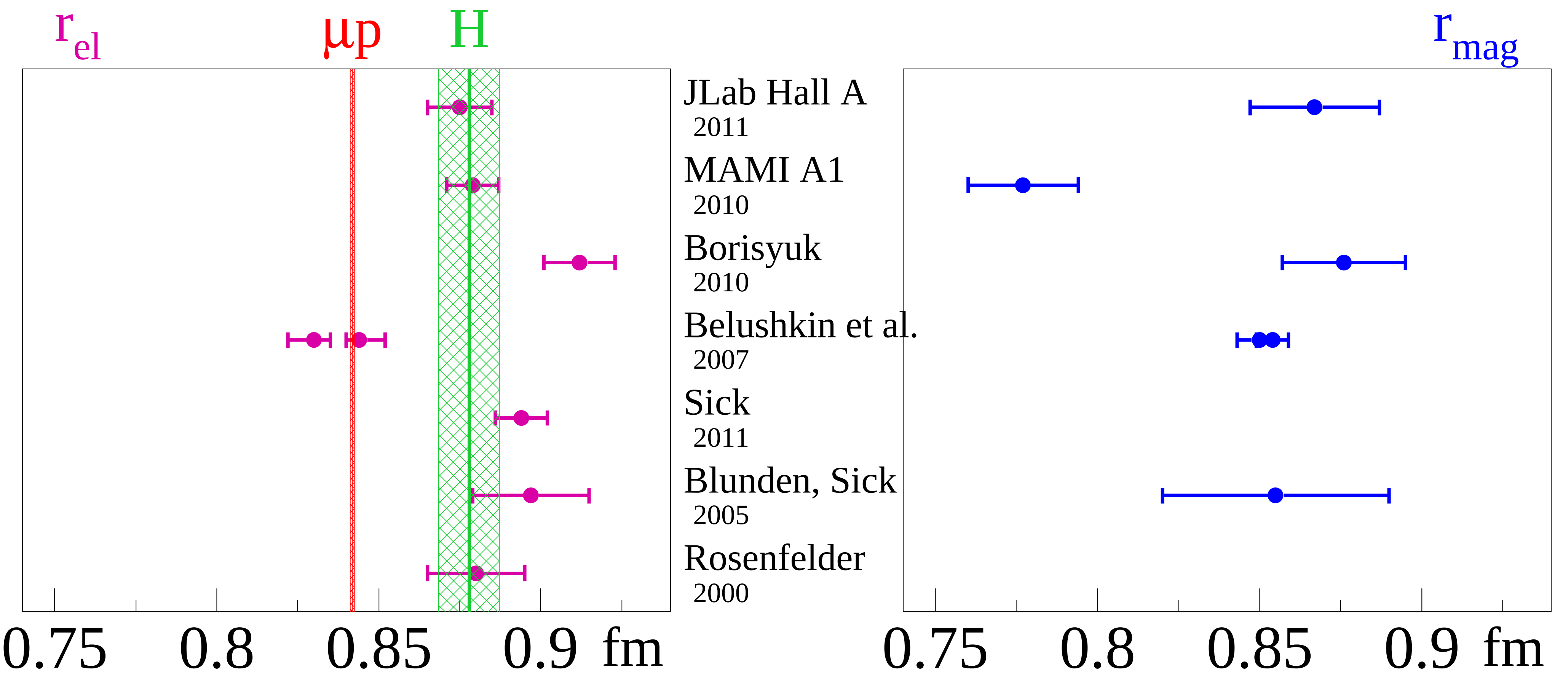

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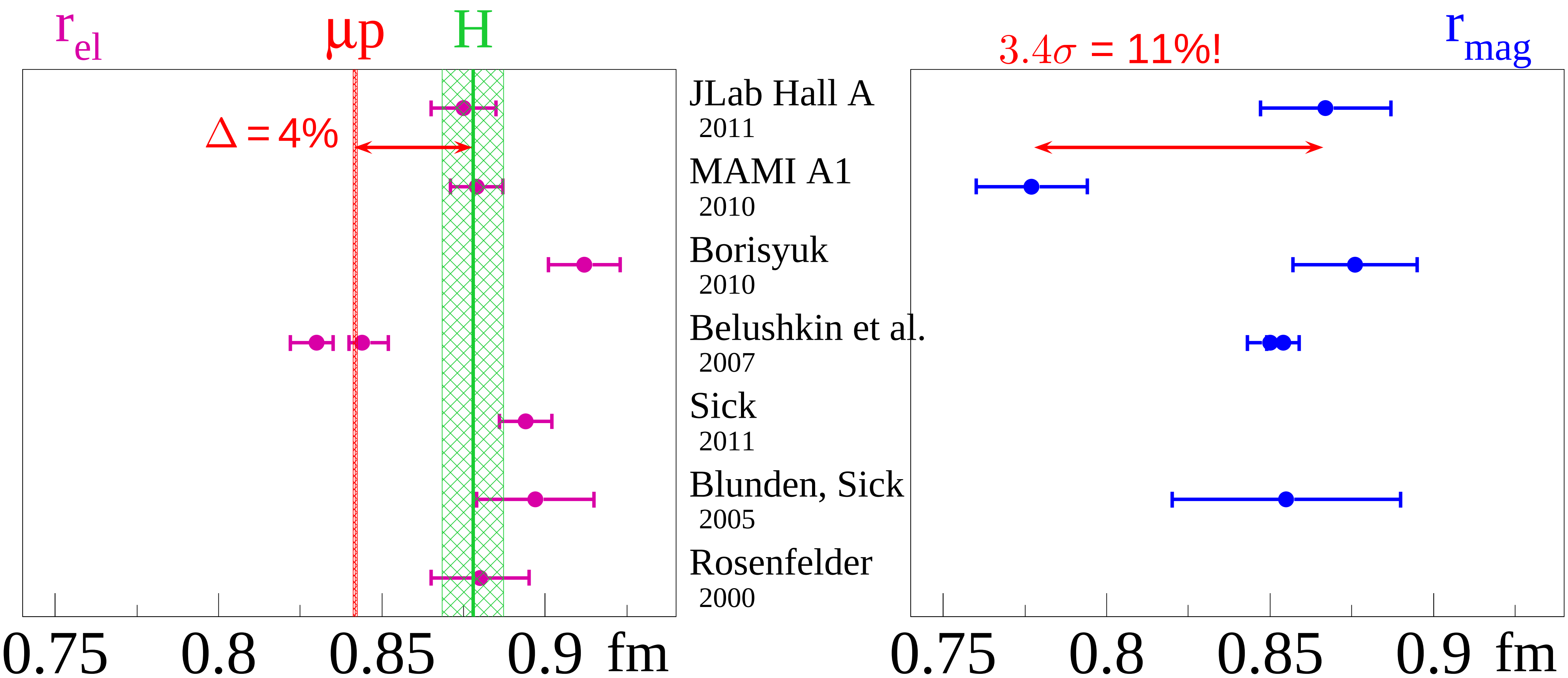

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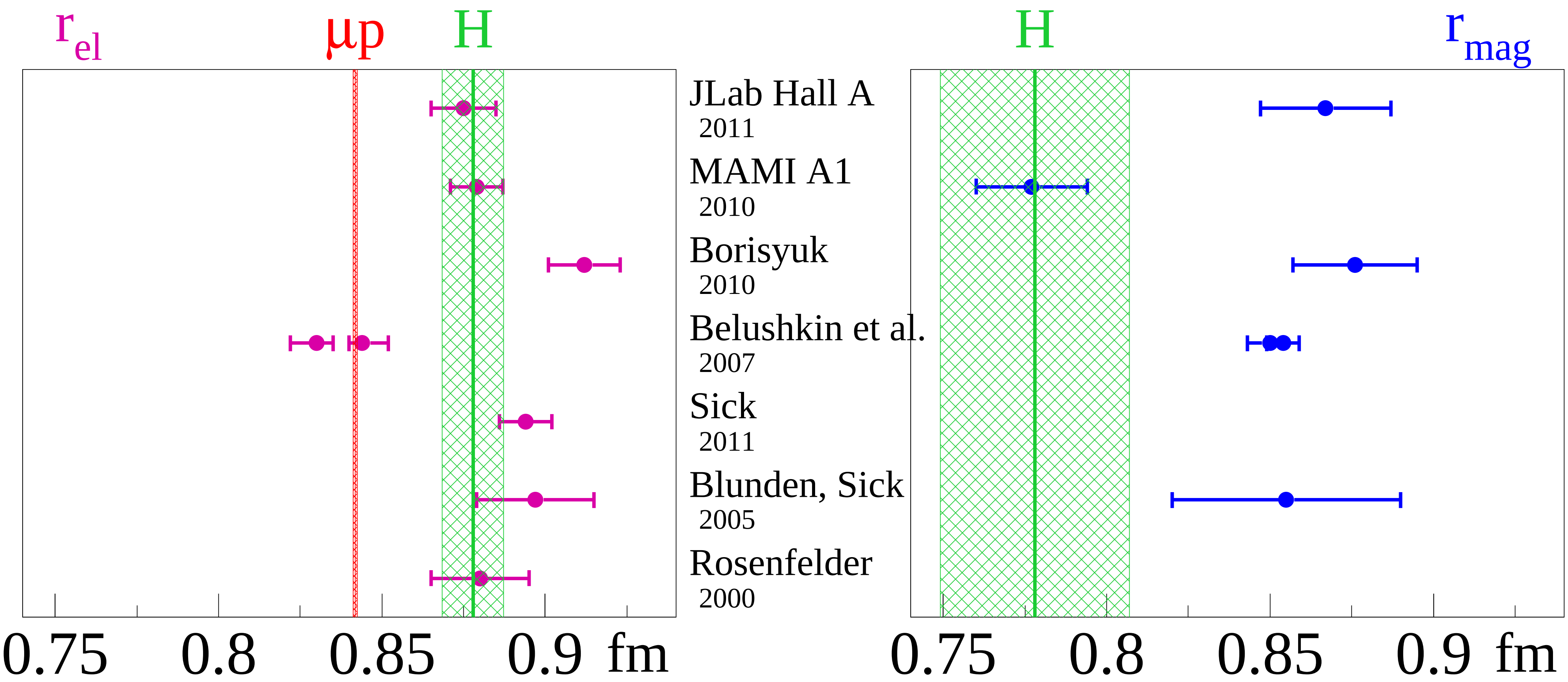

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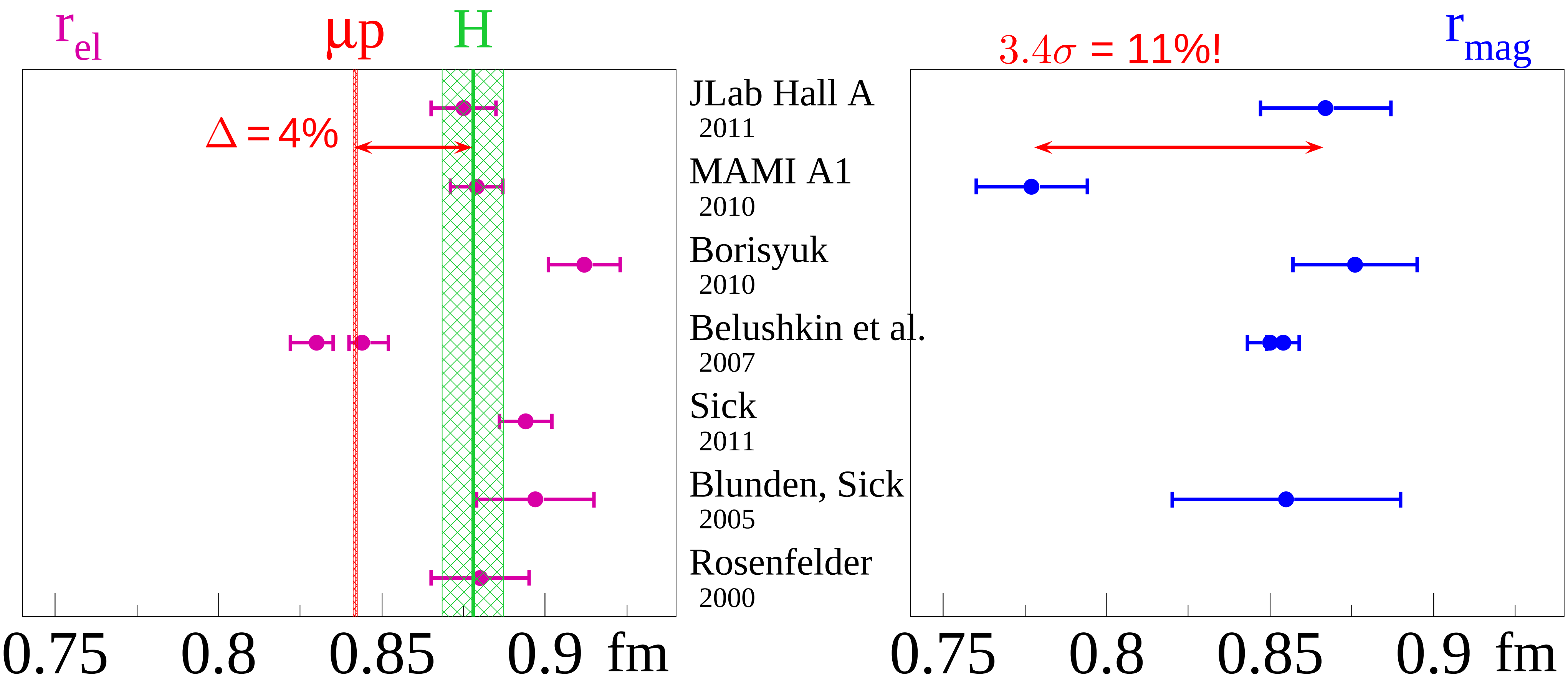
r_{mag}(H) Volotka et al., Eur Phys J D33, 23 (2005)

Electron scattering



e-p scattering claims 1% error bars for 40 years now $\Rightarrow$ limit reached?

Scatter of results suggests larger uncertainty.

r_p from electron scattering

PhD thesis J.C. Bernauer

- Rosenbluth cross section $\rightarrow$ Sachs form factor $\rightarrow r_\mathrm{p}$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{\varepsilon {G_E}^2 + \tau {G_M}^2}{\varepsilon(1+\tau)} \qquad \varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1} \quad ; \quad \tau = \frac{Q^2}{4m_p^2}$$

G_E and G_M are the Fourier transforms of the charge and magnetization distributions

$G_E(0) = 1$ (charge), and $G_M(0) = \mu_p$ (magnetic moment)

$$\langle r_\mathrm{p}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{\mathrm{Q}^2=0}$$

$\Rightarrow$ rms charge radius = **slope of G_E at $Q^2 = 0$**

extrapolation to $Q^2 \rightarrow 0$ required

$$Q^2[\,(\mathrm{GeV/c})^2] = \begin{cases} 6 \cdot 10^{-7} & (\mu\text{p}) \\ > 2 \cdot 10^{-2} & (\text{e-p scatt.}) \end{cases}$$

r_p from electron scattering

- Extrapolation non-trivial
  - Presence of "bump/dip" structure at lower Q^2 ?
  - Model assumption of the functional behavior of the form factor?
  - Normalization problems. Fitting with $G_E(Q^2 = 0) = 1 \rightarrow$ uncertainty underestimated.

r_p from new scattering data with 1% accuracy. Is that realistic?

r_p from electron scattering

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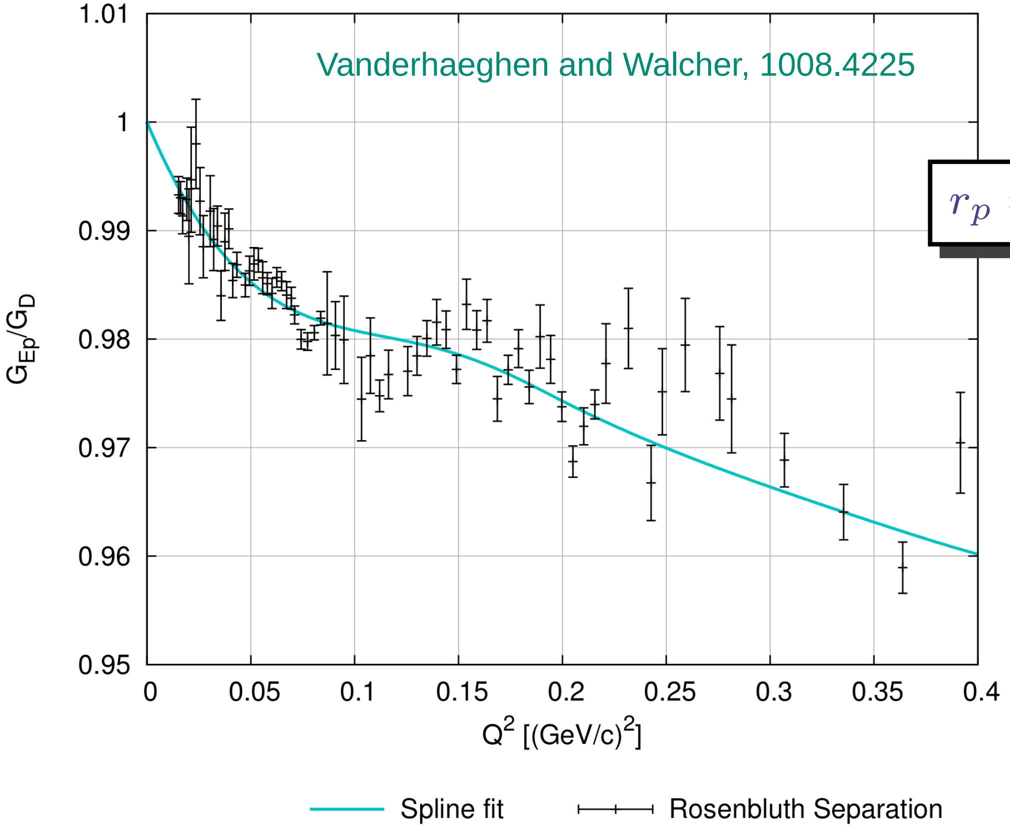
  - Presence of "bump/dip" structure at lower Q^2 ?
  - Model assumption of the functional behavior of the form factor?
  - Normalization problems. Fitting with $G_E(Q^2 = 0) = 1 \rightarrow$ uncertainty underestimated.

New Mainz data: G_E/G_{dipole} vs. $Q^2 \Leftarrow$ world's most accurate data at low Q^2



$$r_p = (0.879 \pm 0.005_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.005_{\text{model}})\ \text{fm}$$

Bernauer *et al.*, PRL **105**, 242001 (2010)

r_p from electron scattering

- Bernauer *et al.*, PRL **105**, 242001 (2010)

$$r_p = (0.879 \pm 0.005_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.005_{\mathrm{model}})\ \mathrm{fm}$$

- Bernauer, PhD thesis (2010)

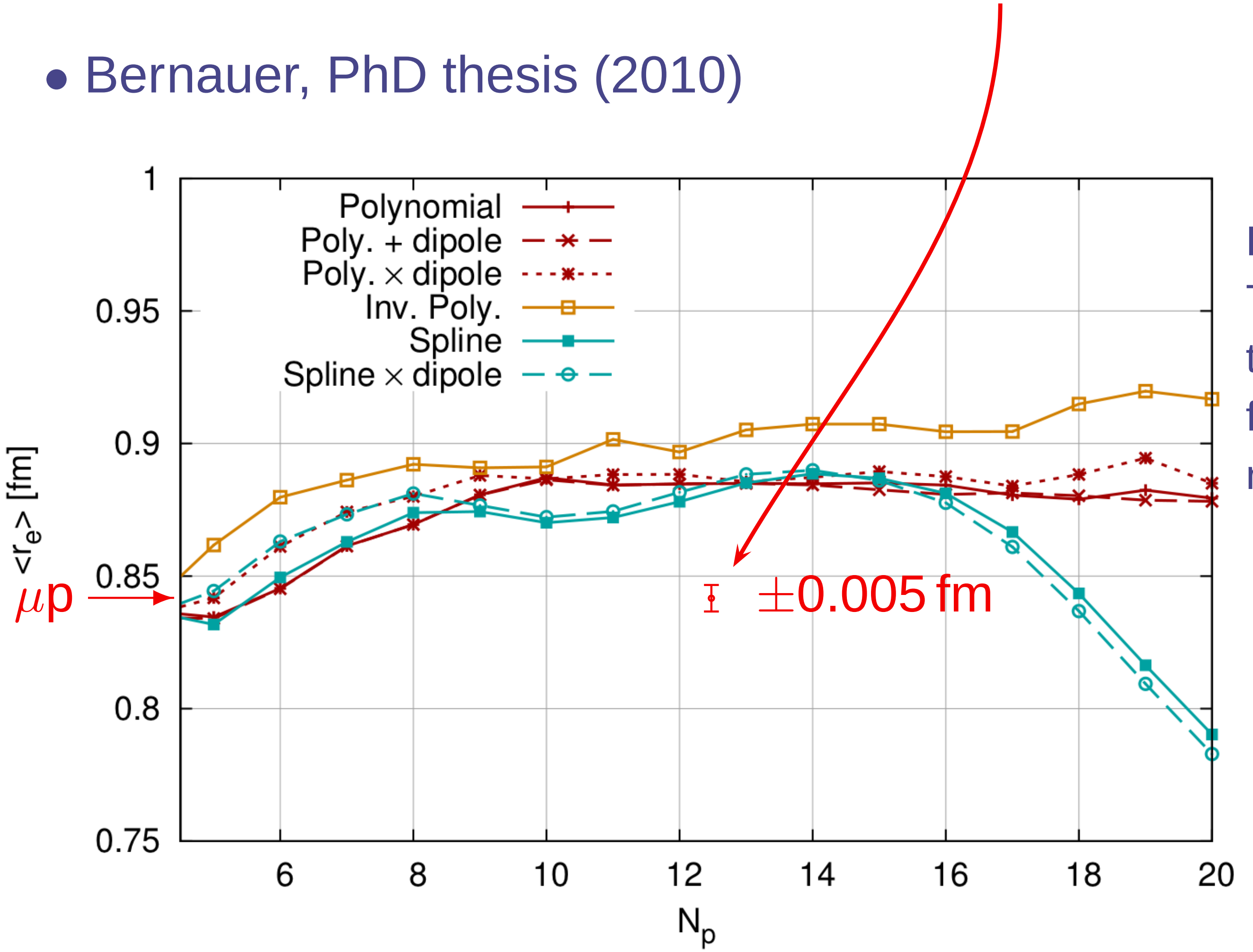


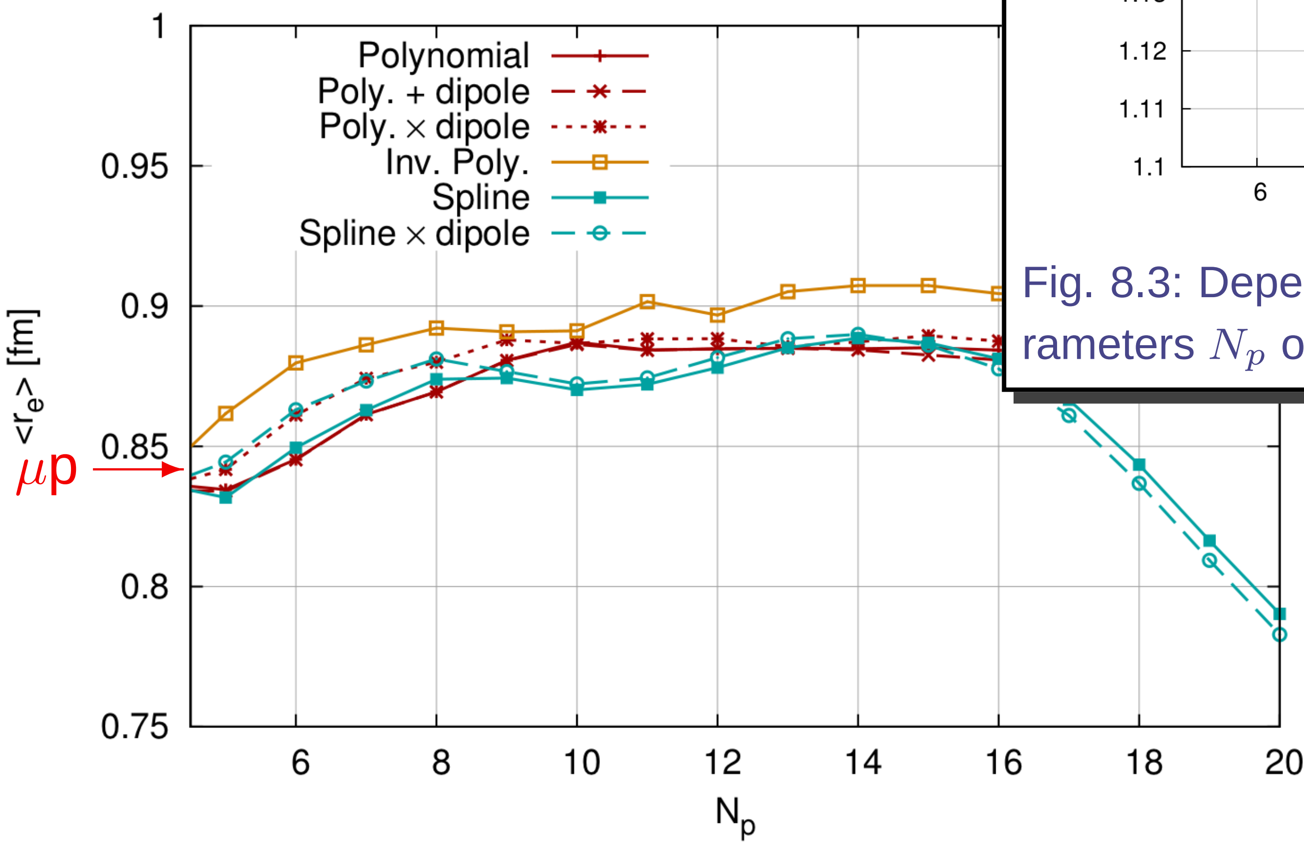
Fig. 9.21 (top):
The dependence of the extracted electric radius of the different flexible models on the number of parameters.

r_p from electron scattering

- Bernauer *et al.*, PRL **105**, 242001 (201

$r_p = (0.879 \pm 0.005_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm$

- Bernauer, PhD thesis (2010)



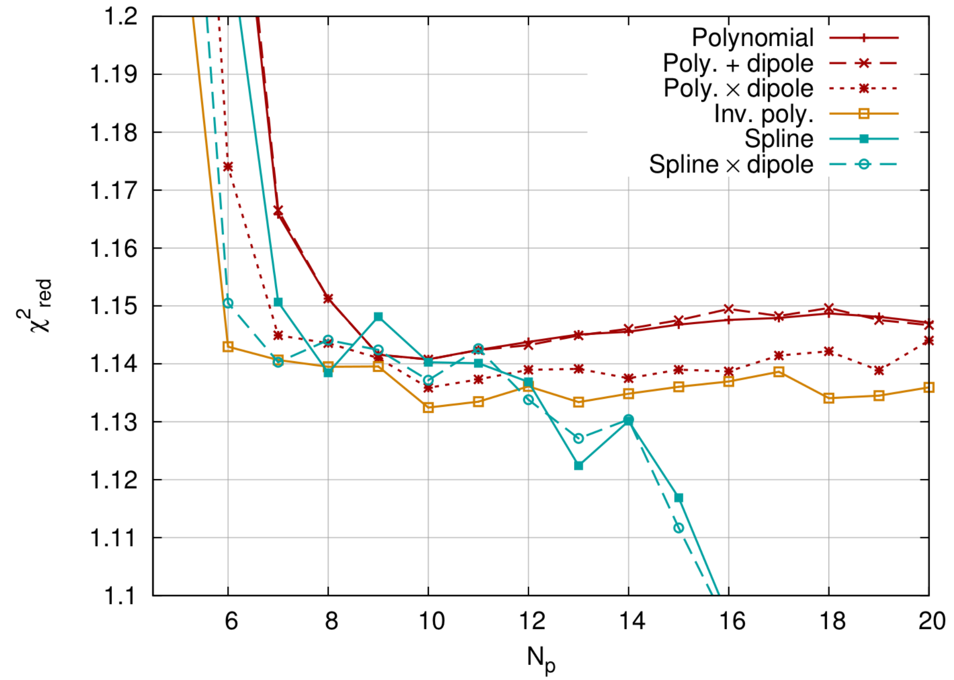


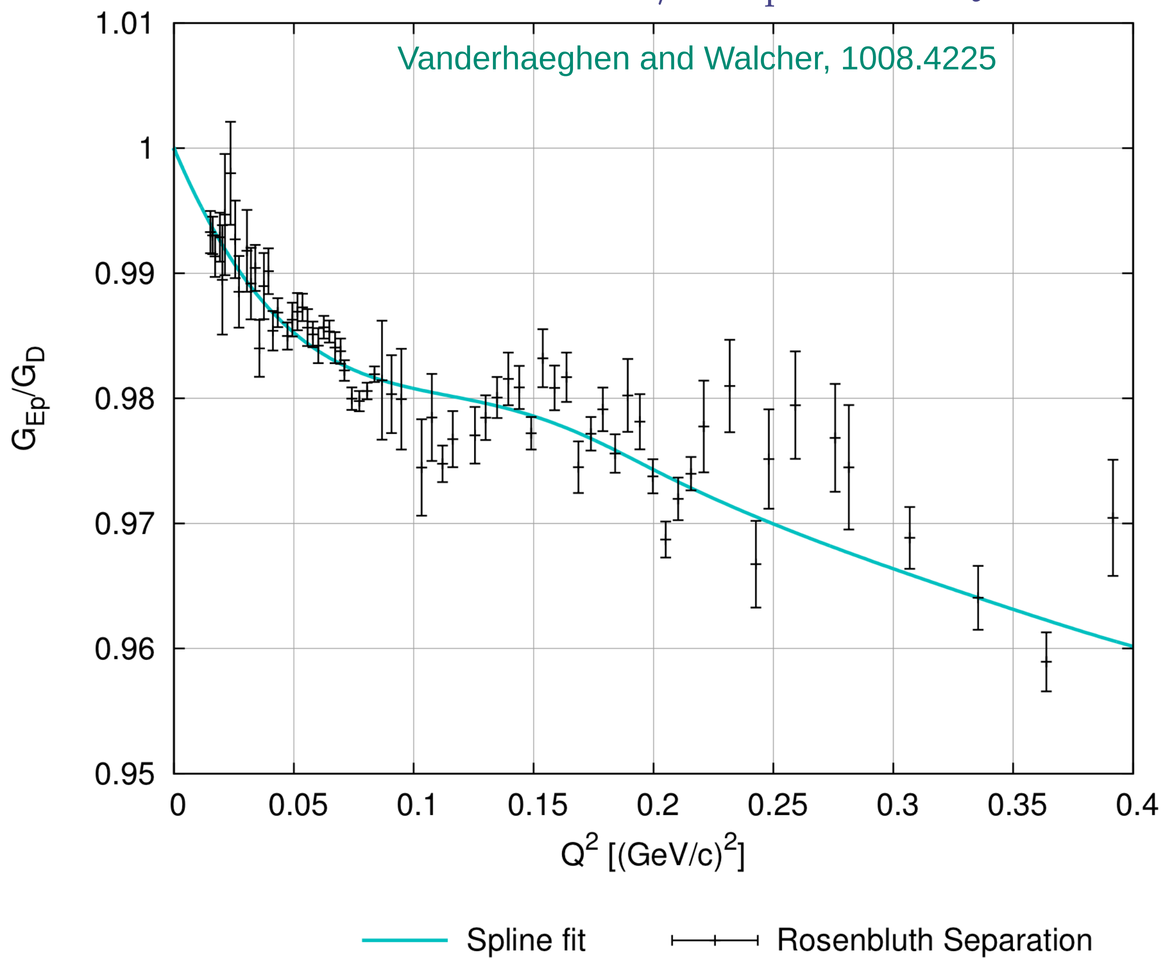
Fig. 8.3: Dependence of χ^2_{red} on the number of parameters N_p of the form factor parametrizations...

Mainz scattering data at lowest Q^2

$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$ $\Rightarrow$ rms charge radius = slope of G_E at $Q^2 = 0$

New Mainz data: G_E/G_{dipole} vs. Q^2

extrapolation to $Q^2 \to 0$ required



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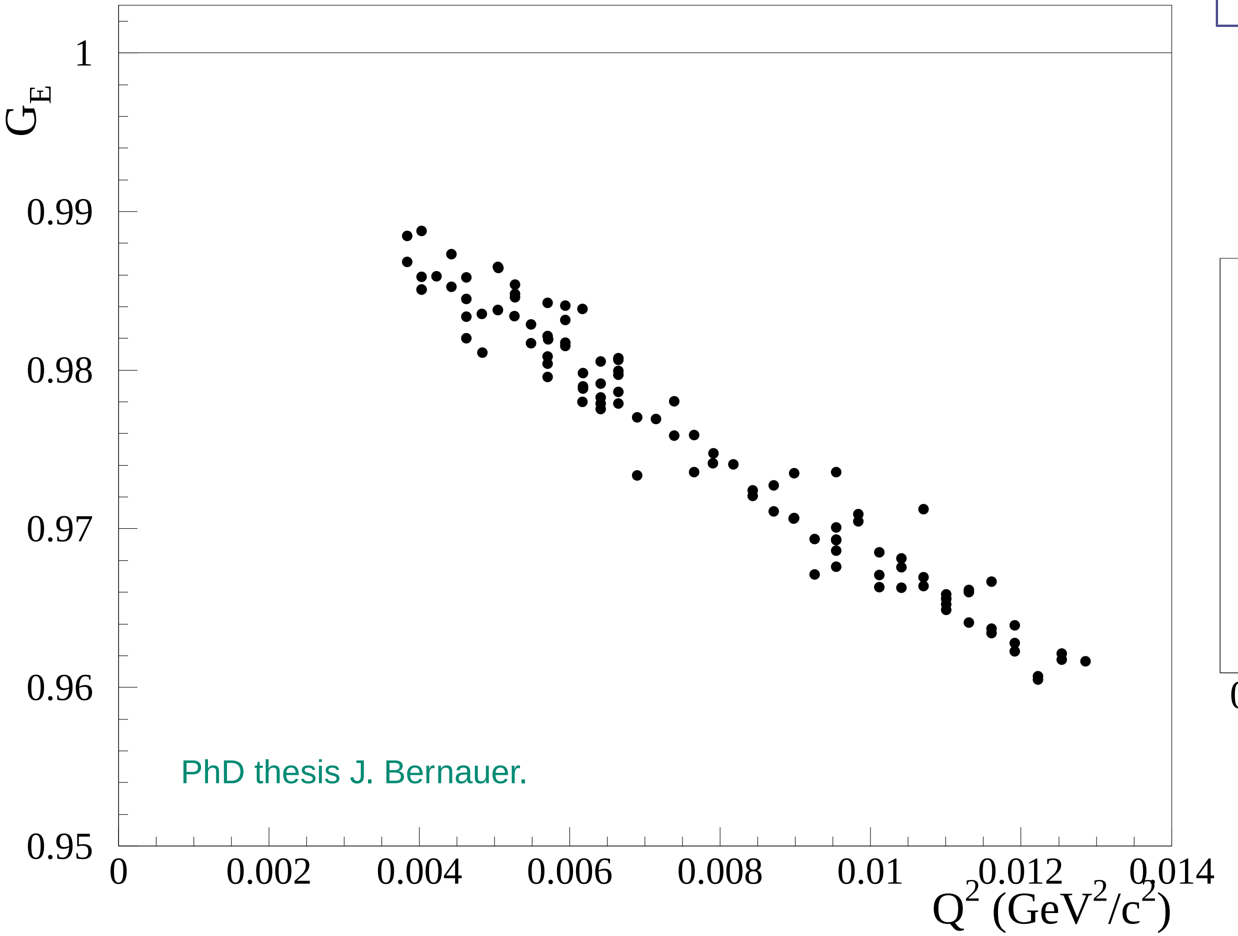
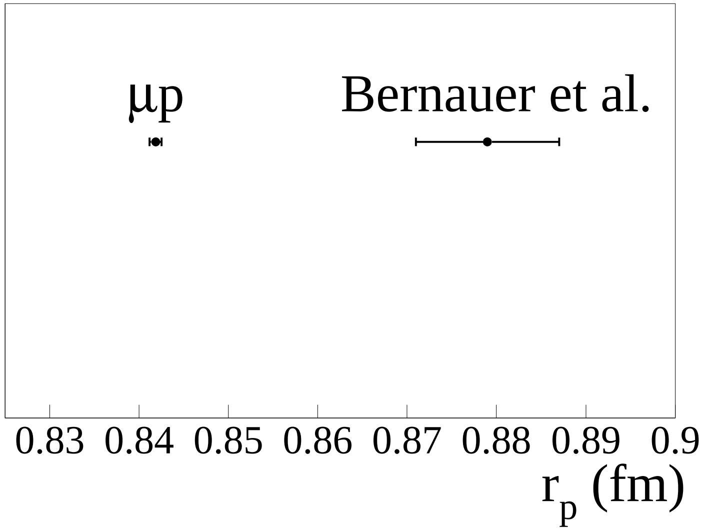
Lower half of 180MeV data



extrapolation to $Q^2 \rightarrow 0$ required

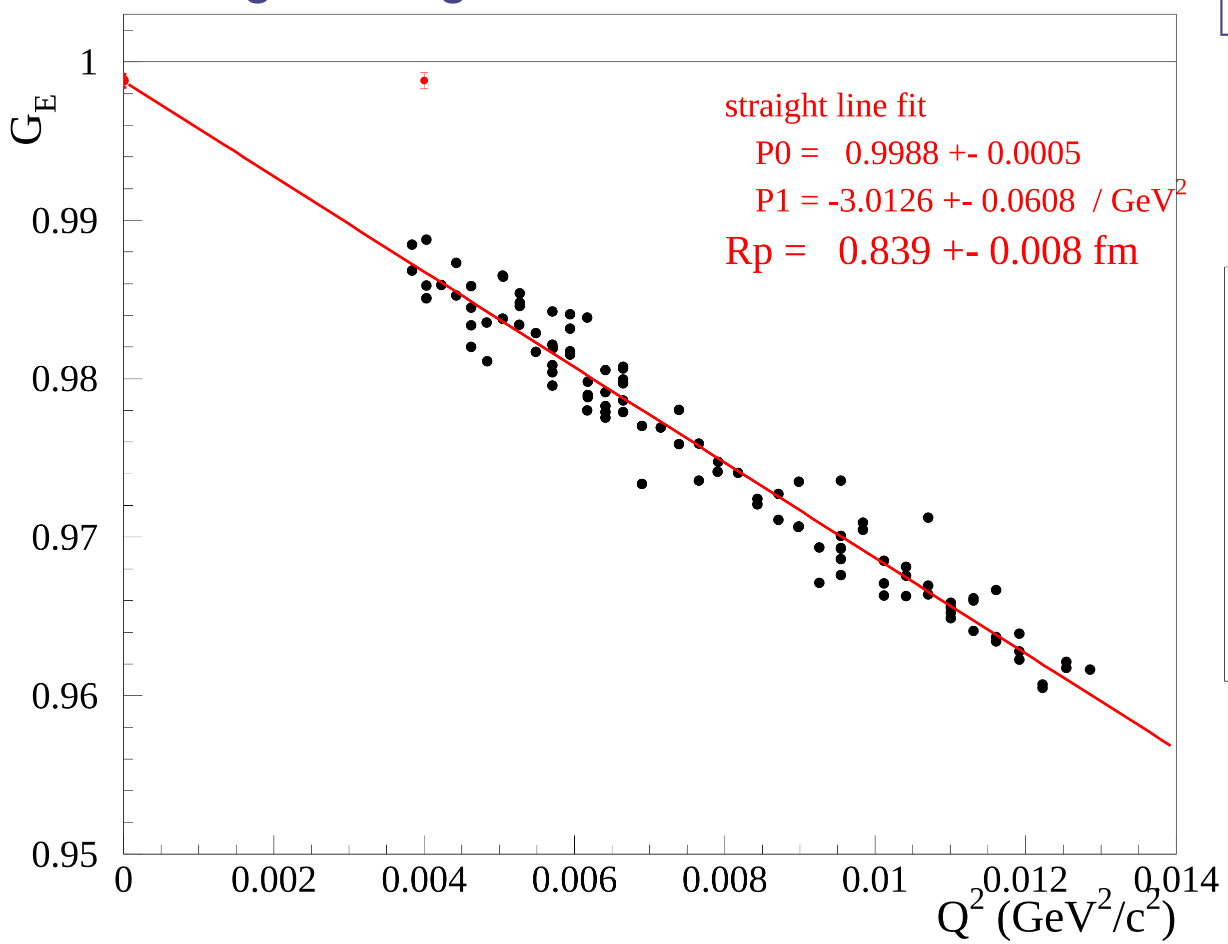


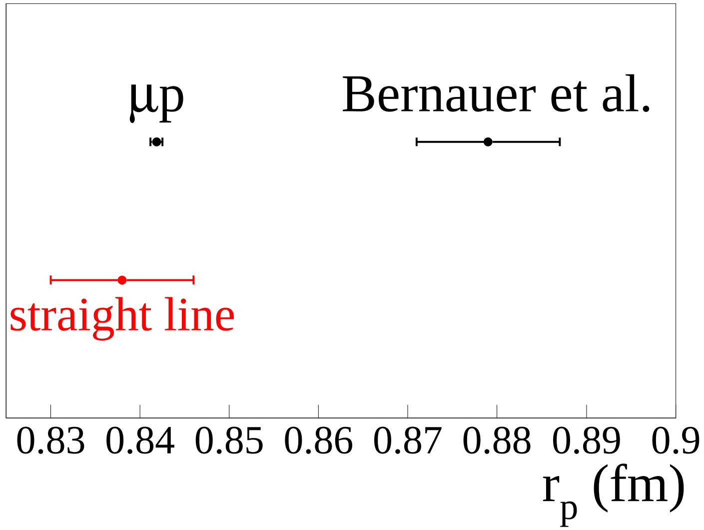
Mainz scattering data at lowest Q^2

$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \quad \Rightarrow \quad \text{rms charge radius = slope of } G_E \text{ at } Q^2 = 0$$

Fitting a straight line

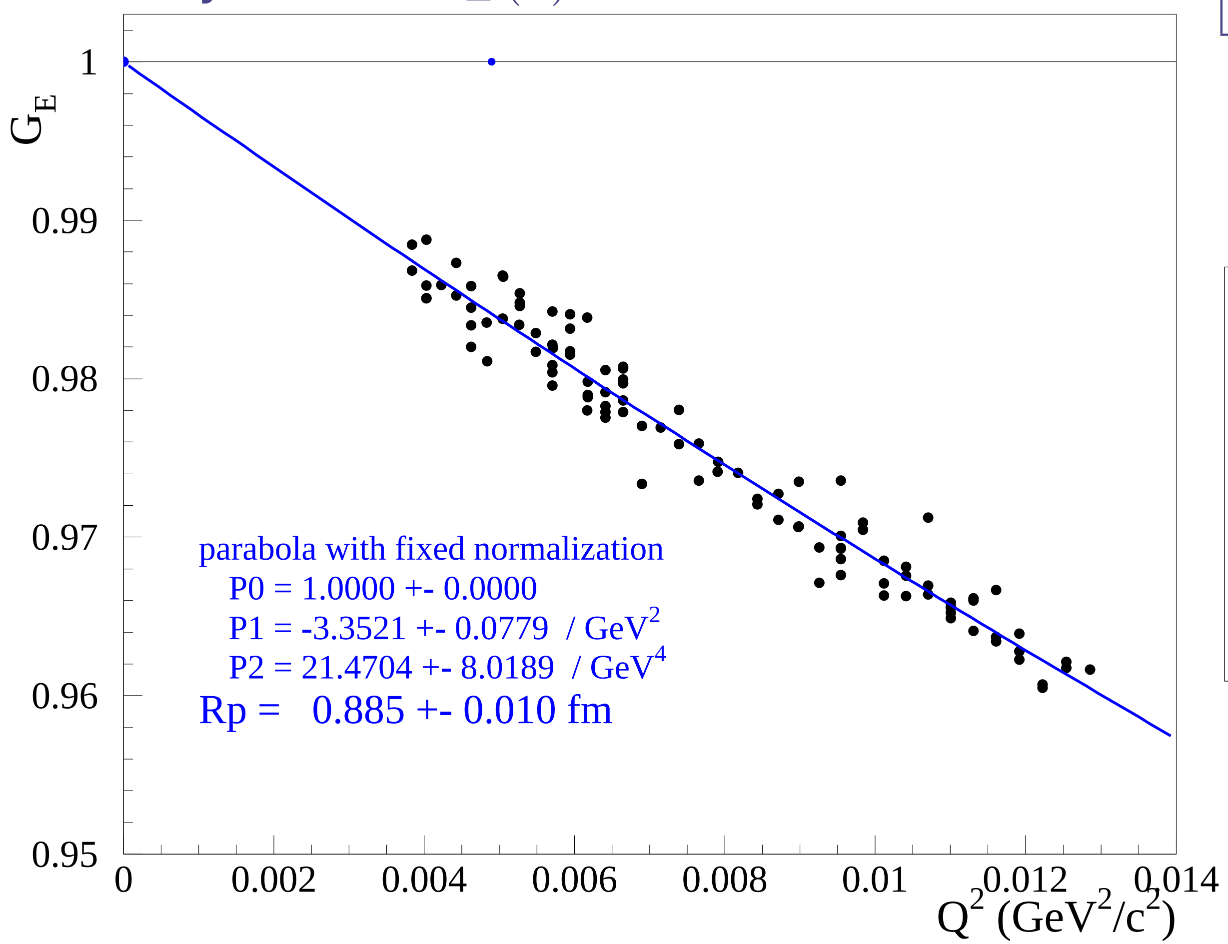
extrapolation to $Q^2 \to 0$ required





$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$ $\Rightarrow$ rms charge radius = slope of G_E at $Q^2 = 0$

Polynomial, $G_E(0) = 1$



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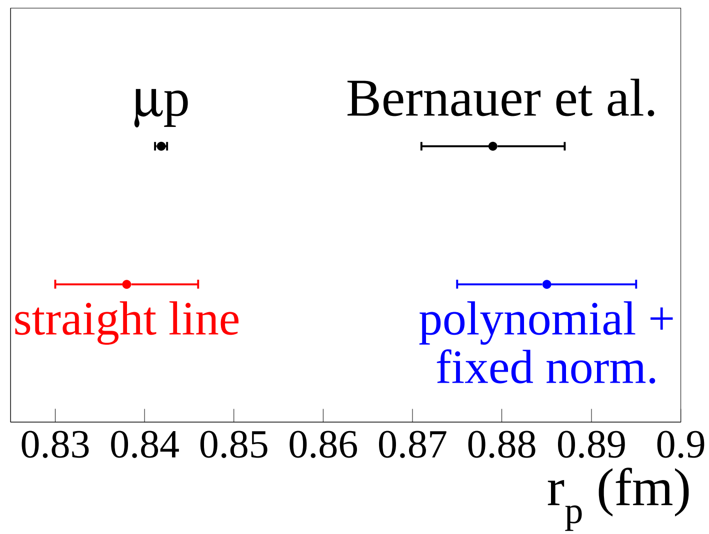
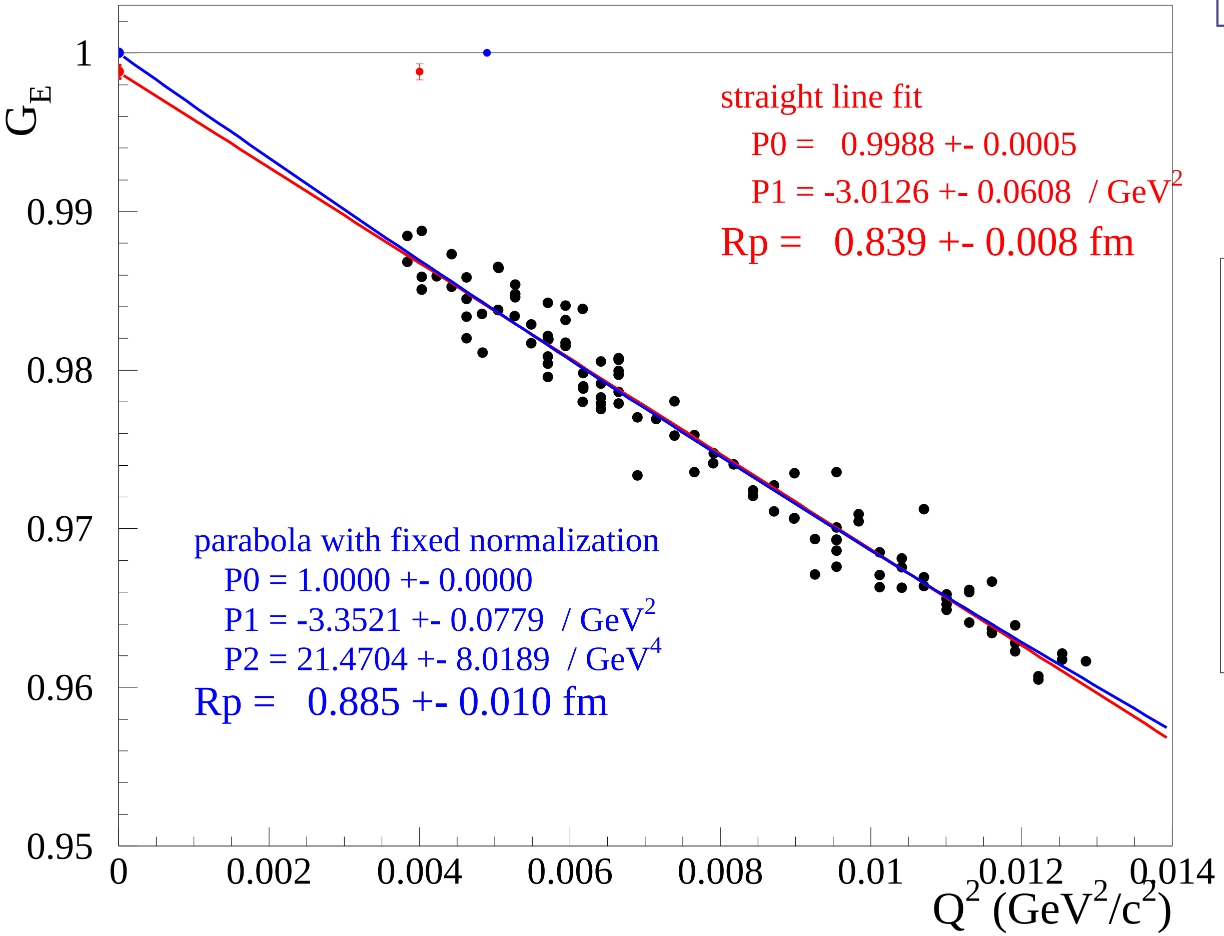


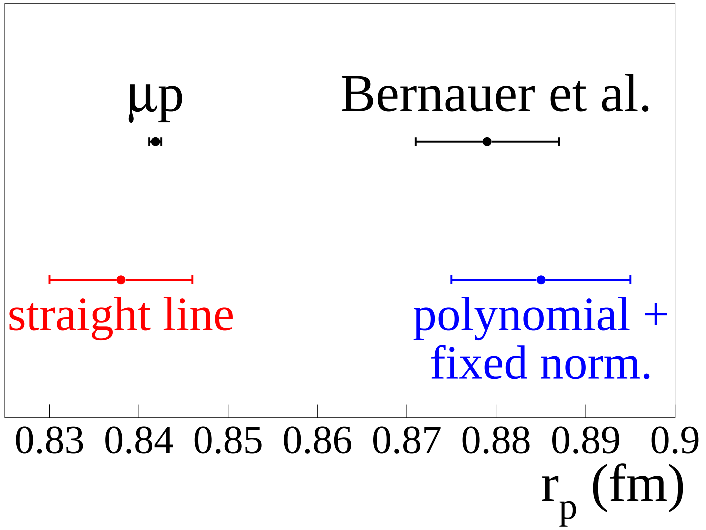
Mainz scattering data at lowest Q^2

$$\langle r_\mathrm{p}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0} \quad \Rightarrow \quad \text{rms charge radius} = \boxed{\text{slope of } G_E \text{ at } Q^2 = 0}$$

Extrapolation is subtle

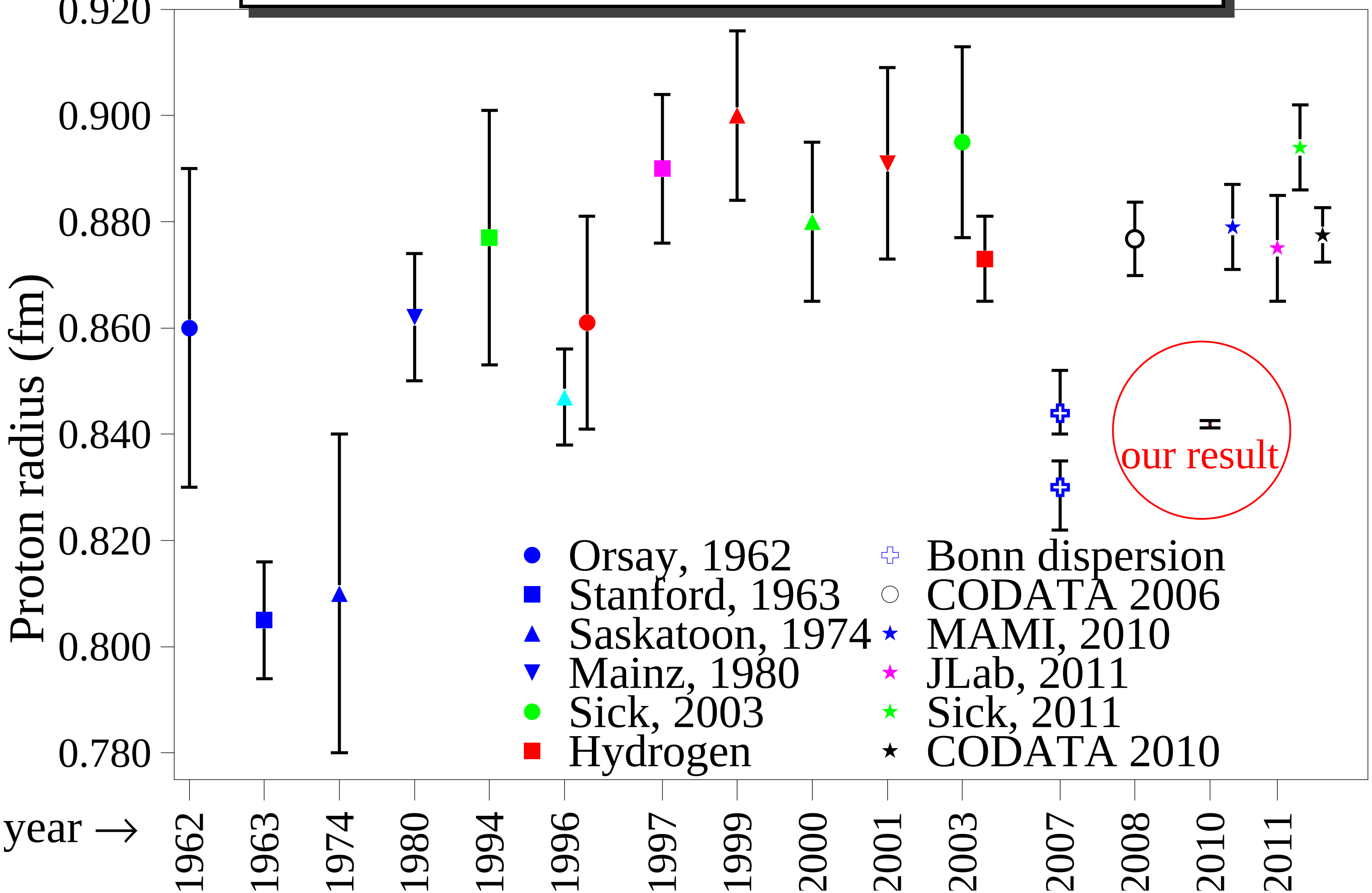
extrapolation to $Q^2 \to 0$ required





Proton radius 2011

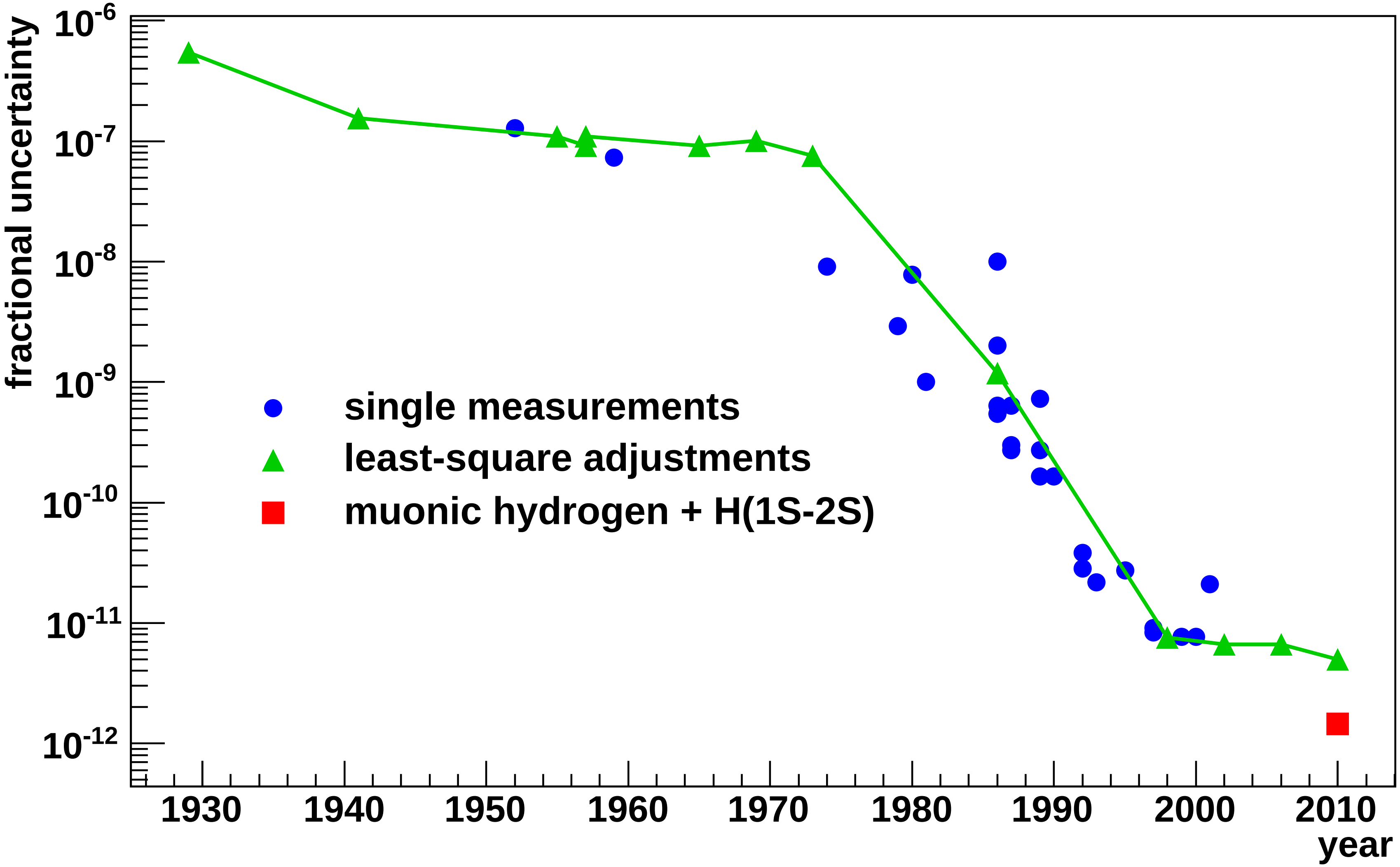
$r_p = 0.84184\,(36)_{exp}(56)_{theo}$ fm



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

Rydberg constant 2011

$$R_\infty = 10973731.568160(16)\,\mathrm{m}^{-1}$$ [1.5 parts in 10^{12}]



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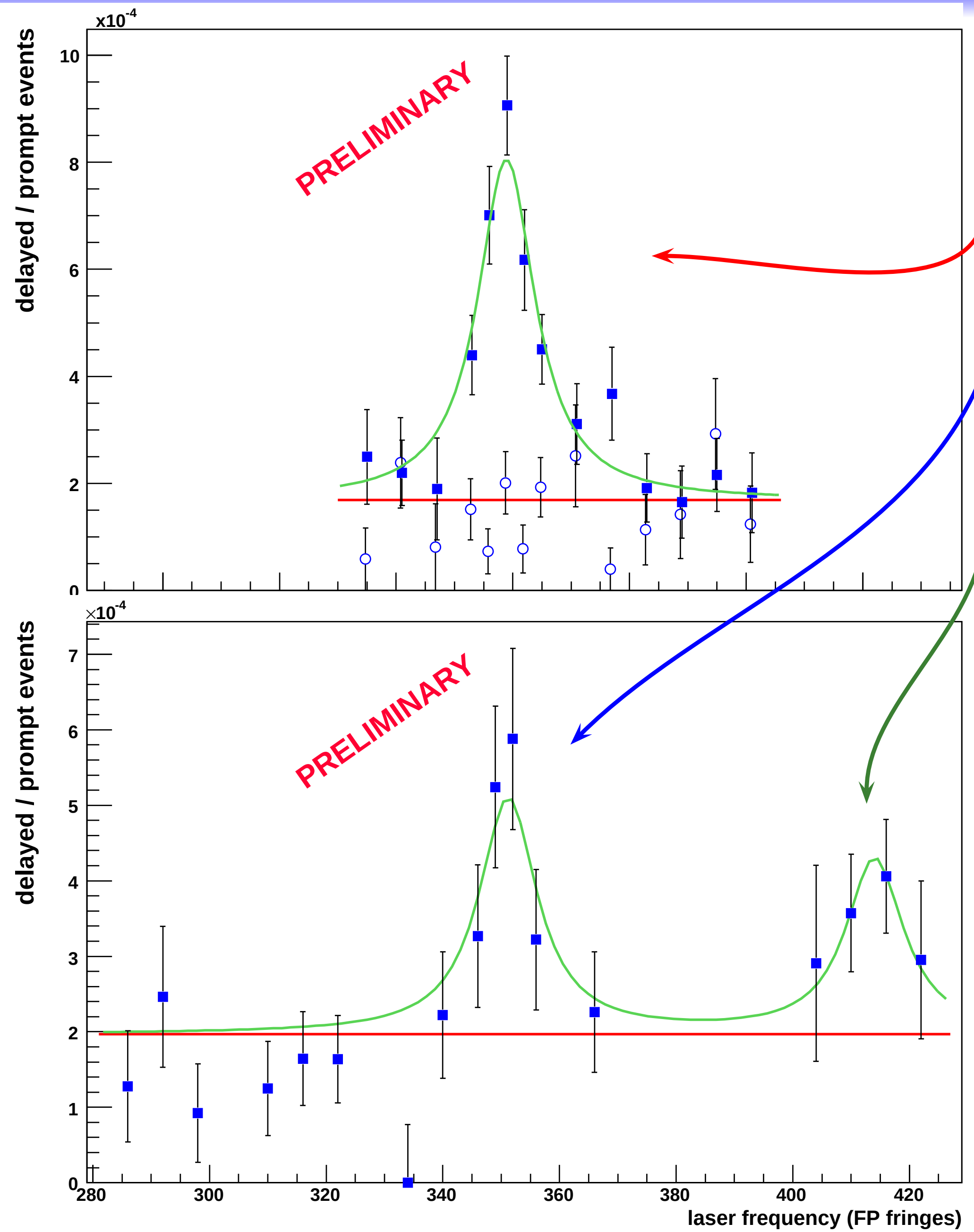
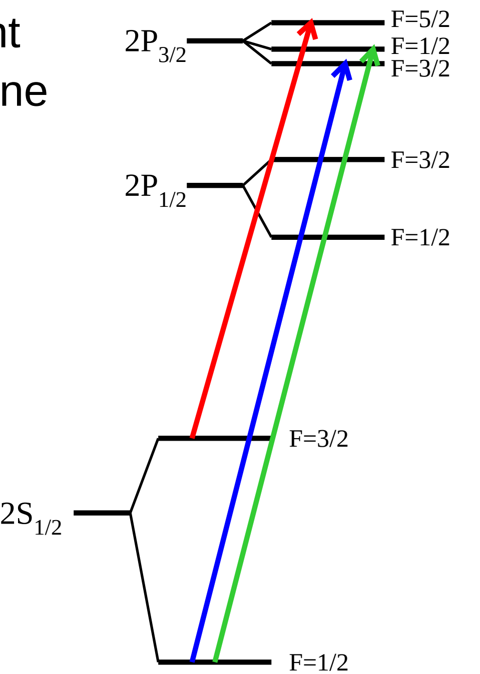
muonic deuterium

Muonic DEUTERIUM



2.5 resonances in muonic **deuterium**

- μd [$2S_{1/2}$(F=3/2) $\rightarrow$ $2P_{3/2}$(F=5/2)]
  20 ppm (stat., online)
- μd [$2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=3/2)]
  45 ppm (stat., online)
- μd [$2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=1/2)]
  70 ppm (stat., online)
  only 5σ significant
  identifies F=3/2 line



Summary

- muonic **hydrogen** $2S_{1/2}$(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})
  $r_p = 0.84284 \pm 0.00058$ fm is ~~5σ~~ 6.8σ away from CODATA-20~~06~~10

  The proton is 4% smaller, and the Rydberg constant R_∞ is ~~4.9~~ 6.6 sigma off

- muonic **hydrogen** $2S_{1/2}$(F=0) $\rightarrow$ $2P_{3/2}$(F=1) to 18 ppm (to be published)
  exactly at the position deduced with our new r_p
  $\rightarrow$ 2S hyperfine splitting to 220 ppm
  $\rightarrow$ Zemach radius to a few % (radius of the magnetic moment distribution)

- muonic **deuterium** $2S_{1/2}$(F=3/2) $\rightarrow$ $2P_{3/2}$(F=5/2) to 20 ppm (stat., online)
  Theory: missing QED and nuclear structure corrections
  $\rightarrow$ deuteron charge radius and polarizability

- muonic **deuterium** $2S_{1/2}$(F=1/2) $\rightarrow$ $2P_{3/2}$(F=3/2 and F=1/2)
  $\rightarrow$ HFS, check calculations in μd

http://muhy.web.psi.ch

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

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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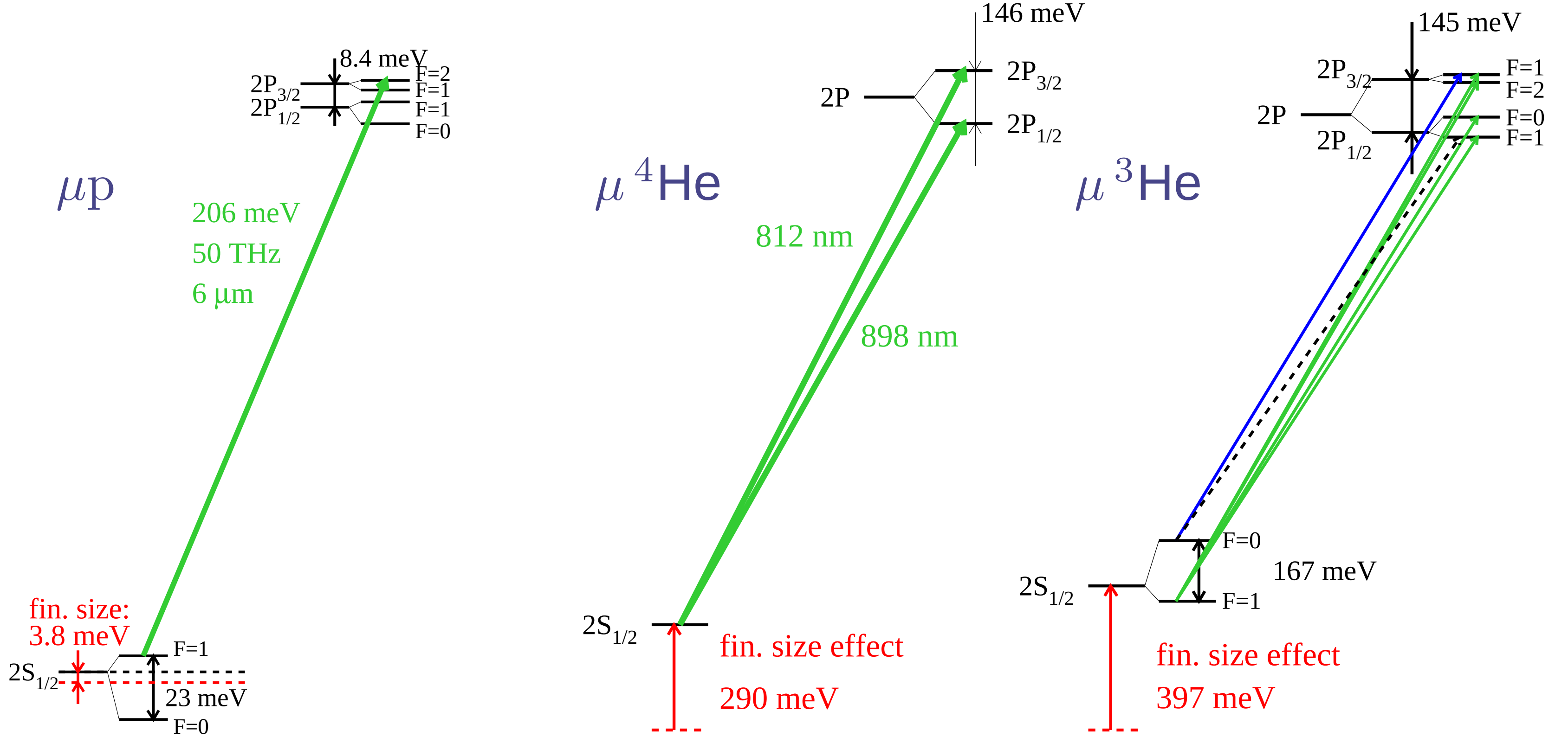

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  - absolute charge radii of helion, alpha
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  - QED test with He$^+$(1S-2S) [Udem @ MPQ, Eikema @ Amsterdam]

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- identical muon beam
- similar laser, no Raman cell ($\rightarrow$ 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!)

Outlook: Lamb shift in muonic helium

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  - abso
  - low-e ... , ^{4}He
  - QED ... na @ Amsterdam]
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ERC Starting Grant for RP, 2011

1st beam time expected for 2013.

Proton Size Investigators thank you for your attention

The $r_\mathrm{p}{}^3$ coefficient

$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1})$ = $209.9779(49) - 5.2262\, r_\mathrm{p}^2 + 0.0347\, r_\mathrm{p}^3$ [meV]

We've used the coefficient for a Dipole form factor given by Borie.

[PRA **71**, 032508 (2005)]

Dipole	$0.0347\ r_\mathrm{p}{}^3$	0.0207 meV
Gaussian	$0.0317\ r_\mathrm{p}{}^3$	0.0189 meV
difference		0.0018 meV
published uncertainty		0.0058 meV
discrepancy		0.31 meV

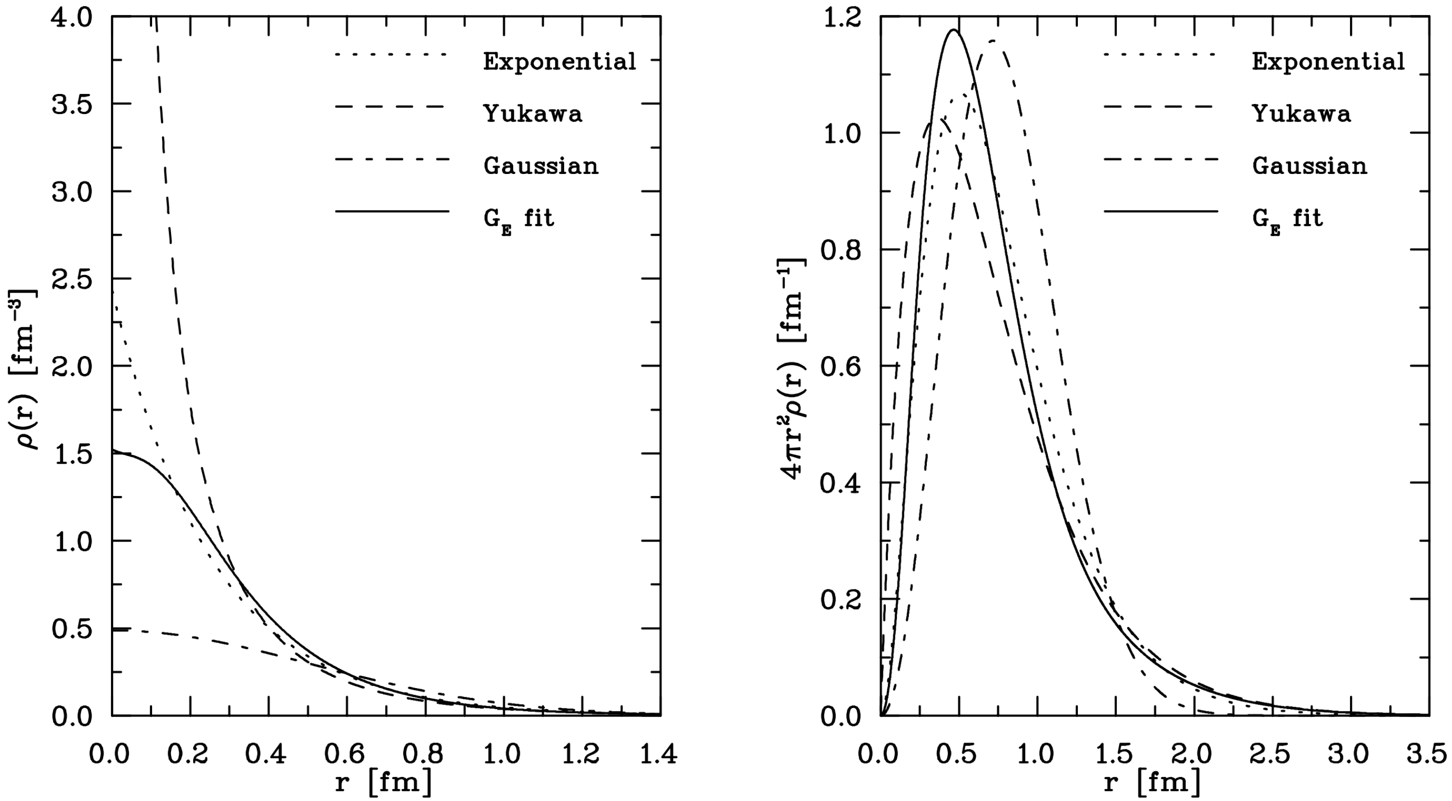
The $r_p{}^3$ coefficient

$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ [meV]}$$

more recently: Carroll, Thomas, Rafelski, Miller (1108.2541):

“Proton form-factor dependence of the finite-size correction to the Lamb shift in muonic hydrogen”

Various charge distributions: Exponential, Yukawa, Gaussian, G_E fit



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"Proton form-factor dependence of the finite-size correction to the Lamb shift in muonic hydrogen"

resulting $r_p{}^2$ and $r_p{}^3$ coefficients:

Name	$\rho(r)$	$a\ [\propto \langle r^2 \rangle]$	$b\ [\propto \langle r^2 \rangle^{3/2}]$
exponential	Ae^{-Br}	-5.2276	0.0351
Yukawa	Ae^{-Br}/r	-5.2275	0.0378
Gaussian	Ae^{-Br^2}	-5.2276	0.0323
Ref. [1]		-5.22495	0.0347
Ref. [3]		-5.22456	0.0346
Ref. [13]		-5.2249	0.0363

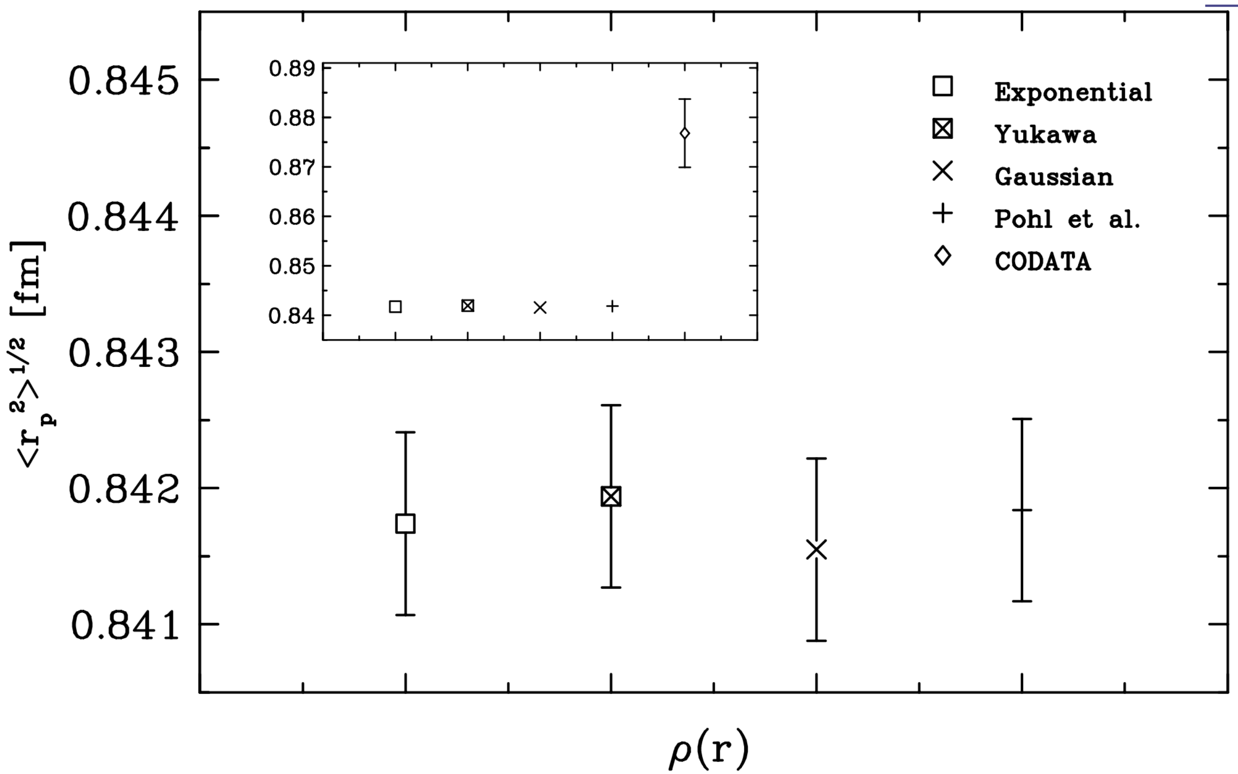
The $r_p{}^3$ coefficient

$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ [meV]}$$

more recently: Carroll, Thomas, Rafelski, Miller (1108.2541):

"Proton form-factor dependence of the finite-size correction to the Lamb shift in muonic hydrogen"

and the corresponding r_p values they extract



Name	$\rho(r)$	$\sqrt{\langle r_p^2 \rangle}$ [fm]
exponential	Ae^{-Br}	0.84174(67)
Yukawa	Ae^{-Br}/r	0.84194(67)
Gaussian	Ae^{-Br^2}	0.84155(67)
ours		0.84184(67)

$r_p{}^3$ coefficient increases our uncertainty by 11.6% to ± 0.00078 fm

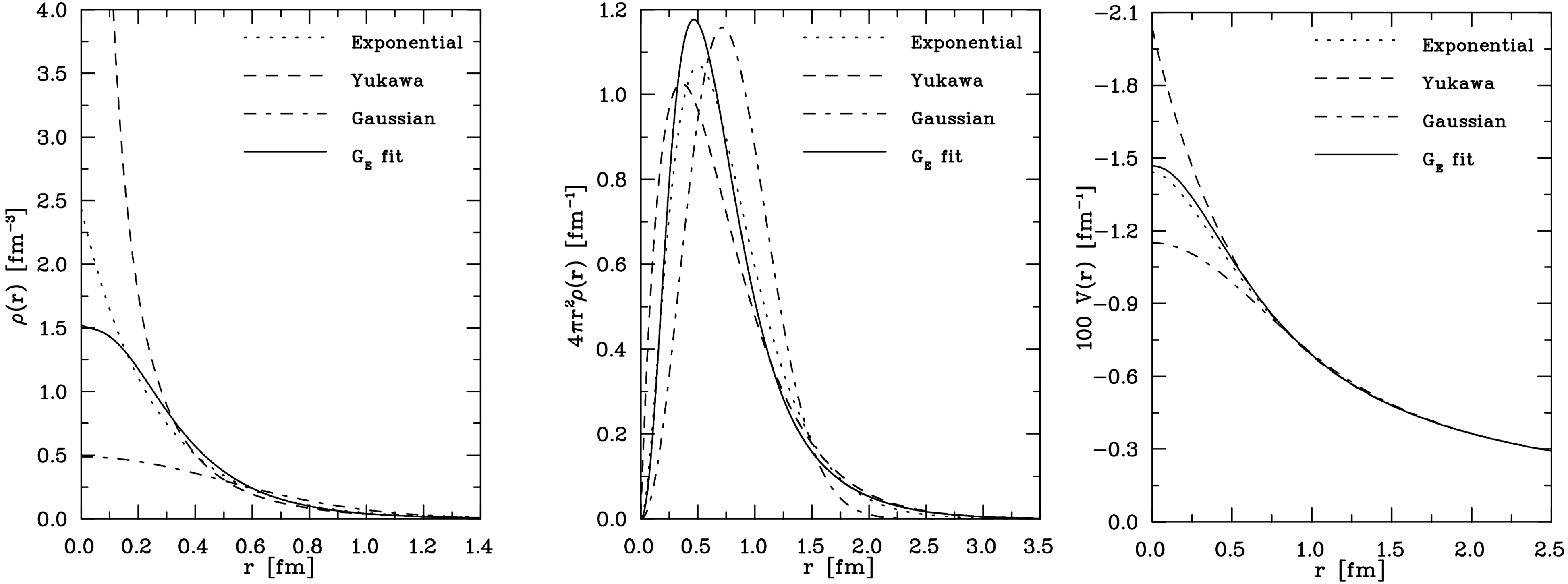
The $r_p{}^3$ coefficient

$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1})$ = $209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ [meV]

more recently: Carroll, Thomas, Rafelski, Miller (1108.2541):

"Proton form-factor dependence of the finite-size correction to the Lamb shift in muonic hydrogen"

Very different charge distributions give quite similar Coulomb potentials:



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

Contributions to the μp Lamb shift

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

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

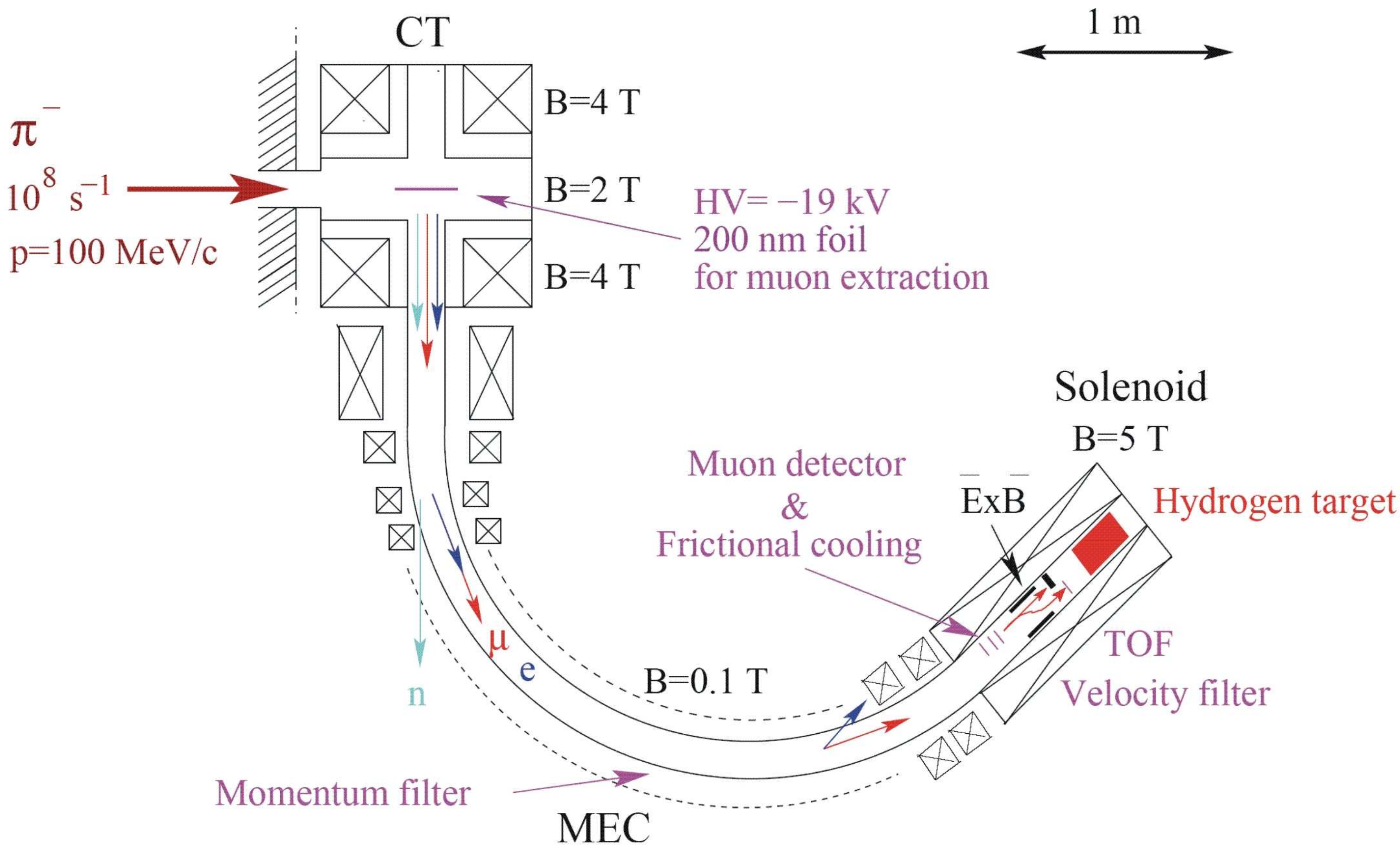
$2S$ Hyperfine structure: $\Delta E^{2S}_{HFS} = 22.8148\,(78)$ meV

using $R_Z = 1.022$ fm and scatter.

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

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

Muon beam line



What's wrong ??

PRA **81**, 060501 (2010)	Karshenboim *et al.*: *"Nonrelativistic contributions of order $\alpha^5 m_\mu c^2$ to the Lamb shift in muonic ..." (1005.4879)*
JETP Lett. **92**, 8 (2010)	Karshenboim *et al.*: *"Contribution of light-by-light scattering to energy levels of light muonic atoms" (1005.4880)*
PRL **105**, 242001 (2010)	Bernauer *et al*: *"High-precision determination of the electric and magnetic form factors of the proton" (1007.5076)*
PRD **82**, 125020 (2010)	Jaeckel, Roy: *"Spectroscopy as a test of Coulomb's law" (1008.3536)*
PLB **693**, 555 (2010)	De Rujula: *"QED is not endangered by the proton's size" (1008.3861)*
Nucl.Phys.News **21**, 14 (2011)	Vanderhaeghen, Walcher: *"Long range structure of the nucleon" (1008.4225)*
Can. J. Phys. **89**, 109 (2011)	Jentschura: *"From first principles of QED to an application: hyperfine structure of P states of muonic hydrogen"*
PRC **83**, 012201(R) (2011)	Cloet, Miller: *"Third Zemach moment of the proton" (1008.4345)*
PRD **82**, 113005 (2010)	Hill, Paz: *"Model-independent extraction of the proton charge radius from electron scattering" (1008.4619)*
PLB **697**, 26 (2011)	De Rujula: *"QED confronts the proton's radius" (1010.3421)*
PLB **696**, 343 (2011)	Distler *et al*: *"The RMS radius of the proton and Zemach moments" (1011.1861)*
EPJD **61**, 7 (2011)	Jentschura: *"Proton radius, Darwin-Foldy term and radiative corrections" (1012.4029)*
PRL **106**, 153001 (2011)	Barger, Chiang, Keung, Marfatia: *"Proton size anomaly" (1011.3519)*
PRA **83**, 012507 (2011)	Yerokhin: *"Nuclear-size corrections to the Lamb shift of one-electron atoms" (1011.4272)*
PRD **83**, 101702(R) (2011)	Tucker-Smith, Yavin: *"Muonic hydrogen and MeV forces" (1011.4922)*
Ann. Phys. **326**, 500 (2011)	Jentschura: *"Lamb shift in muonic hydrogen I: Verification and update of theoretical predictions" (1011.5275)*
Ann. Phys. **326**, 516 (2011)	Jentschura: *"Lamb shift in muonic hydrogen II: Analysis of the discrepancy of theory and experiment" (1011.5453)*
Few-Body Syst. **50**, 367 (2011)	Sick: *"Troubles with the proton rms radius"*
PRD **83**, 035020 (2011)	Brax, Burrage: *"Atomic precision tests and light scalar couplings" (1010.5108)*
PRA **83**, 042509 (2011)	Carlson *et al.*: *"Proton-structure corrections to hyperfine splitting in muonic hydrogen" (1101.3239)*
PRL **106**, 193007 (2011)	Pachucki: *"Nuclear structure corrections in muonic deuterium" (1102.3296)*
PRL **107**, 011803 (2011)	Batell, McKeen, Pospelov: *"New parity-violating muonic forces and the proton charge radius" (1102.3296)*
PRA **84**, 012506 (2011)	Carroll *et al.*: *"Nonperturbative relativistic calculation of the muonic hydrogen spectrum" (1104.2971)*
PRA **84**, 012505 (2011)	Jentschura: *"Relativistic reduced-mass and recoil corrections to vacuum polarization in muonic hydrogen, ..." (1107.1737)*
PRA **84**, 020101(R) (2011)	Miller, Thomas, Carroll, Rafelski: *"Toward a resolution of the proton size puzzle" (1101.4073)*
PRA **84**, 020102(R) (2011)	Carlson, Vaderhaeghen: *"Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)*

Discussions: 3rd Zemach moment

- PLB **693**, 555 De Rujula: *"QED is not endangered by the proton's size" (1008.3861)*

  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: μp, H, e-p

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

- PRC **83**, 012201 Cloet, Miller: *"Third Zemach moment of the proton" (1008.4345)*

  Such a large third Zemach moment is impossible.

  $\langle r_p^3 \rangle_{(2)}$ (De Rujula) = 36.6 ± 6.9 fm^3

  $\langle r_p^3 \rangle_{(2)}$ (Sick) = 2.71 ± 0.13 fm^3

- PLB **696**, 343 Distler *et al*: *"The RMS radius of the proton and Zemach moments"* (1011.1861)

  $\langle r_p^3 \rangle_{(2)}$ (Mainz 2010) = 2.85 ± 0.08 fm^3

Discussions: New Physics

- PRD **82**, 125020 Jaeckel, Roy: *"Spectroscopy as a test of Coulomb's law" (1008.3536)*

  hidden photons, minicharged particles $\rightarrow$ deviations from Coulomb's law.

  $\mu\mathrm{p}$ transition can NOT be explained this. (contradicts Lamb shift in H)

- PRL **106**, 153001 Barger *et al.*: *"Proton size anomaly" (1011.3519)*

  decay of Υ, J/ψ, π^0, η, neutron scattering, muon g-2, μ^{24}Mg, μ^{28}Si

  $\Rightarrow$ It's NOT a new flavor-conserving spin-0, 1 or 2 particle

- PRD **83**, 101702 Tucker-Smith, Yavin: *"Muonic hydrogen and MeV forces" (1011.4922)*

  MeV force carrier can explain discrepancies for r_p and (g-2)$_\mu$
  IF coupling to e, n is suppressed relative to coupling to μ, p
  prediction for μHe$^+$, $\mu^+\mu^-$

- PRL **107**, 011803 Batell *et al.*: *"New Parity-violating muonic forces" (1103.0721)*

  10...100 MeV heavy photon ("light Higgs") can explain r_p and (g-2)$_\mu$
  prediction for μHe$^+$, enhanced PNC in muonic systems

- 1109.6652, Barger *et al.*: *"Constraint on parity-violating muonic forces*

  No missing mass events observed in leptonic Kaon decay.
  $\Rightarrow$ no light Higgs.

Discussions: Theory updates

- EPJD **61**, 7 Jentschura: *"Proton radius, Darwin-Foldy term and radiative corrections"*
  - Darwin-Foldy term: Zitterbewegung of spin-1/2 nucleus
  - Atomic physics: Nuclear size is *without* DF term (point-like $\rightarrow$ r=0)
  - Nuclear physics: DF term somethimes pushed into nuclear size
  - CODATA: $\rightarrow$ consistent treatment

  $\Rightarrow$ proton charge radius = slope of electric Sachs G_E FF, w/o DF term
  - Radiative corrections are treated consistently.

- PRA **83**, 012507 Yerokhin: *"Nucl. size corr. to the Lamb shift of 1-e atoms"* (1011.4272)
  - Higher-order NS corr. to SE, VP increase LO result by 4.4%
  - shifts H(1S) state by ~ 800 Hz $\Leftrightarrow$ 110'000 Hz discrepancy

- Ann. Phys. **326**, 500 Jentschura: *"LS in μp 1: Theory verification + update"* (1011.5275)
  - μp theory ok, minor corrections $\rightarrow r_\mathrm{p}$ = 0.84169 (66) fm

- Ann. Phys. **326**, 516 Jentschura: *"LS in μp 2: Analysis of discrepancy"* (1011.5453)
  - no millicharged particles, no unstable neutral vector boson
  - e^- bound to μp(2S) ?!?!?!

NO!!!

Discussions: Theory updates

- EPJD **61**, 7 Jentschura: *"Proton radius, Darwin-Foldy term and radiative corrections"*

e^- bound to μp(2S) not likely:

- How should this bound state form?
  - "No" free electrons.
- Why should this bound state be stable?
  - Stark mixing !?!
  - Auger effect !!
  - Collisions: every 100 ns.
  - Only 1 line observed: >80% formation rate in 1 state.
    - no peak at expected position
    - observed peak has expected width

⇒ … n

- PR … 1.4272)
- Ar … 1011.5275)
- Ar … .5453)
  - no millicharged particles, no unstable neutral vector boson
  - e^- bound to μp(2S) ?!?!?!

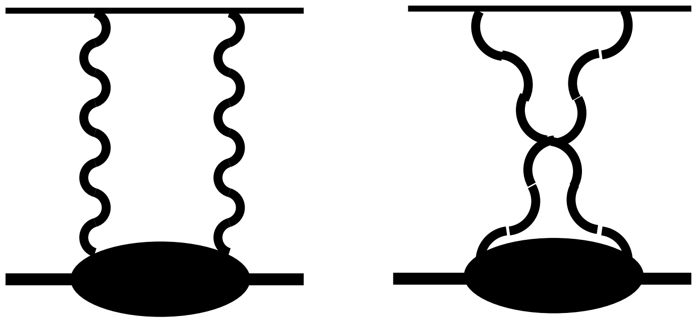
NO!!!

Discussions: Theory updates II

- PRA **84**, 012506 J.D. Carroll, A.W. Thomas, J. Rafelski, and G.A. Miller: *"Nonperturbative relativistic calculation of the muonic hydrogen spectrum"*, (1104.2971)
  - Theory in muonic hydrogen confirmed by fully numerical calculations.
  - Creative treatment of the 2S HFS won't fit with our measured 2nd transition in $\mu\mathrm{p}$
  - Other than that: Our r_p confirmed. $\surd$
- 1103.1772 Borie: *"Lamb shift in light muonic atoms - revisited"*
  - Recalculation of all 2S–2P energy differences for
    - muonic **hydrogen**
    - muonic **deuterium** (measured 2009)
    - muonic **helium-3** (CREMA 2014)
    - muonic **helium-4** (CREMA 2013)
  - Our r_p confirmed. $\surd$

Discussions: Proton polarizability

proton polarizability aka. two-photon exchange



Seems to be the only contribution which *might* be able to solve the proton size puzzle by changing theory in $\mu\mathrm{p}$.

Keep in mind:

Discrepancy:	0.31 meV	
Polarizability:	0.015(4) meV	20 times smaller!

Discussions: Proton polarizability

- PRA **83**, 042509 (2011) C.E. Carlson, V. Nazaryan, K. Griffioen:
  "Proton-structure corrections to hyperfine splitting in muonic hydrogen" (1101.3239)
  - The 2S HFS is confirmed with smaller uncertainty:
    22.8146(49) meV instead of the
    22.8148(78) meV we used.

Discussions: Proton polarizability

- PRA **84**, 020101(R) (2011) G.A. Miller *et al.*:
  "Toward a resolution of the proton size puzzle" (1101.4073)
  - New off-mass-shell effect $\sim \alpha \frac{m^4}{M^3}$ solves puzzle.
  - Others say: This is already included in standard treatment.
  - C.E. Carlson: calculation gives 50 times smaller value.
- PRA **84**, 020102(R) (2011) C.E. Carlson, M. Vanderhaeghen:
  "Higher-order proton structure corrections to the Lamb shift in muonic hydrogen" (1101.5965)
  - All off-shell effects are automatically included in standard treatment.
- PRL, **107**, 160402 (2011) R.J. Hill, G. Paz:
  "Model independent analysis of proton structure for hydrogenic bound states" (1103.4617)
  - forward Compton amplitude's $W_1(0, Q^2)$ is now well known
  - "Crazy" functional behaviour can give any correction.
  - No numbers given.

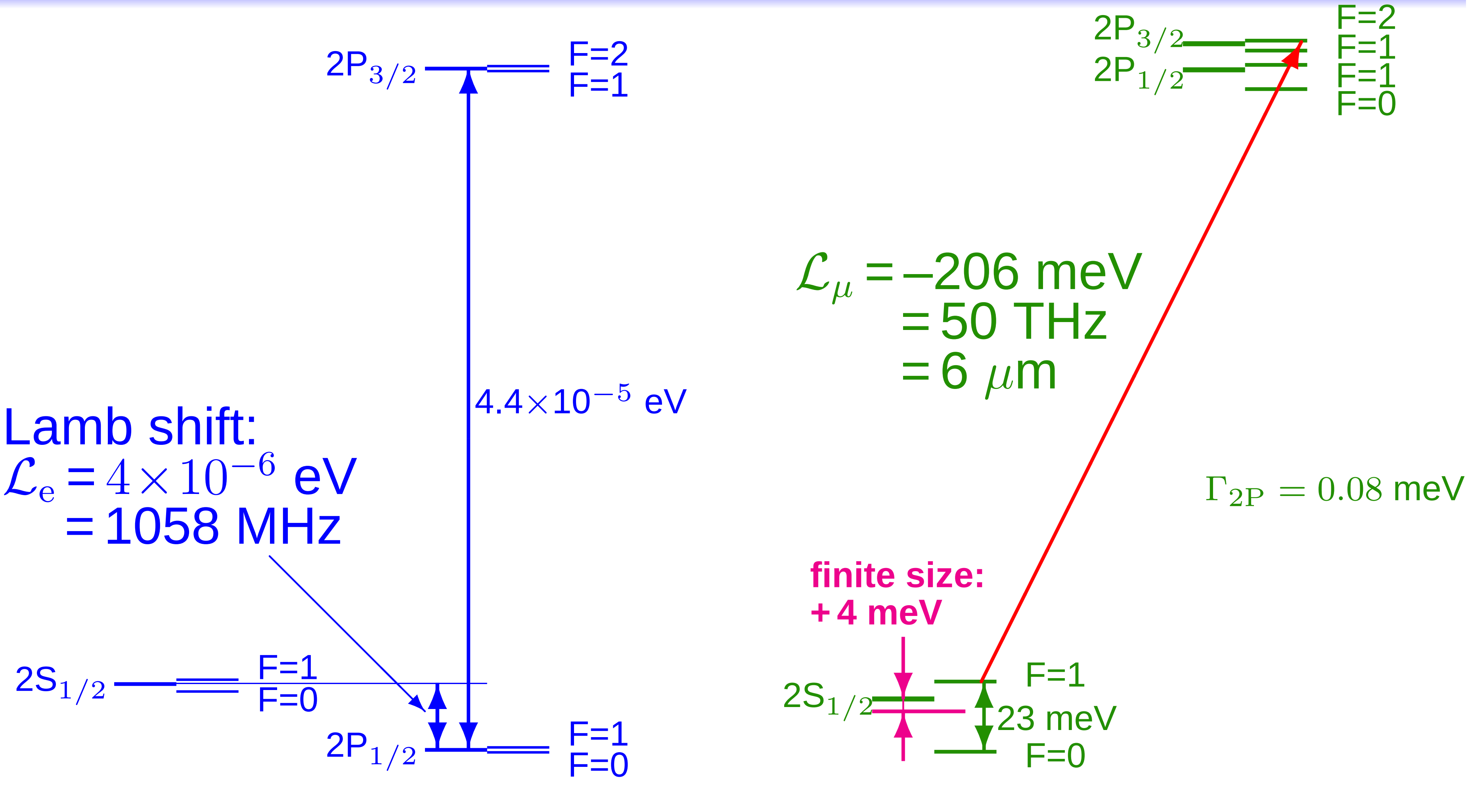
Discussions: Proton polarizability

- Our value is based on 3 calculations
  - 0.017(4) meV: Rosenfelder, Phys. Lett. B 463, 317 (1999)
  - 0.012(2) meV: Pachucki, PRA 60, 3593 (1999)
  - 0.018 meV: Martynenko, Faustov, Phys. At. Nucl. 63, 845 (2000)
  - 0.015(4) meV: Borie, PRA 71, 032508 (2005)
- (0.31 meV is our discrepancy)
- No consensus about **validity** of the new claims
- Independent calculation of new effects give **50 times smaller** value.
- Lack of **numbers**

Don't know if this can solve the proton size puzzle.

Numbers are needed which can be tested in experiments.

(n=2) - states of ep and μp



$a_o = 5 \times 10^{-11}$ m	$a_o^\mu = 3 \times 10^{-13}$ m
ΔE_{2P-1S} = 10 eV	ΔE_{2P-1S} = 1900 eV
self energy = +1086 MHz	self energy = + 0.6 meV
vac. pol. = – 27 MHz	vac. pol. = – 206 meV

Contributions to the μ^4He$^+$ Lamb shift

Contributions	ΔE (meV)
One-photon VP contribution, $\alpha(Z\alpha)^2$	1665.782
Two-loop VP contributions in first and second order PT, $\alpha^2(Z\alpha)^2$	15.188
Wichmann-Kroll correction	0.135
Three-loop VP in first and second order PT $\alpha^3(Z\alpha)^2$	0.138
Relativistic VP effects	-0.203
Hadronic VP	0.223
μ self-energy, μ VP, μ form factor corrections ($F_1'(0),\ F_2(0)$)	-11.243
Recoil corrections $(Z\alpha)^4$, $(Z\alpha)^5$, $(Z\alpha)^6$	-0.355
Radiative-recoil corrections	-0.040
Nuclear structure contribution of order $(Z\alpha)^4$: -105.322 $r_{\mathrm{He}}{}^2$	$-297.615\ (1.420)$
Nuclear structure contribution of order $(Z\alpha)^5$: 1.529 $r_{\mathrm{He}}{}^3$	$7.261\ (0.035)$
Nuclear structure and one- two-loop VP+ higher order nucl. structure	-2.357
Nuclear polarizability contribution	$3.100\ (0.600)$
Total splitting	1380.020 meV

μHe$^+$ Lamb shift, He nuclear radius

$$\Delta E(2P_{1/2} - 2S_{1/2}) = 1670.370(10)(600) - 105.322\, {r_{\rm He}}^2 + 1.529\, {r_{\rm He}}^3 \quad \text{meV}$$
$$= 1380.020(10)^{\rm th}(600)^{\rm pol}(1420)^{\text{fin. size}} \quad \text{meV}$$

for $r_{\rm He}$ = 1.681(4) fm (Sick, 2008)

- Measure the transition frequency to 50 ppm ($\Leftrightarrow \Gamma/20 \Leftrightarrow 20$ GHz)
  $\longrightarrow$ Determine $r_{\rm He}$ with $u_r = 1 \times 10^{-3}$ accuracy
  Limited by nuclear polarizability
  Polarizability was calculated in 1978 with $u_r = 20\%$
- Once He nuclear polarizability is calculated with $u_r = 5\%$
  $\longrightarrow$ Determine $r_{\rm He}$ with $u_r = 3 \times 10^{-4}$ accuracy (10 times better than now)

Transitions in μ^3He$^+$ and μ^4He$^+$

Isotope	Transition	ΔE [meV]	λ [nm]	Pop.(η)	Mat. el. [a_μ]	$f_{a,b}$	$F_{\rm sat}$ [J/cm^2]	event rate [h^{-1}]
$\mu\,^4\mathrm{He}^+$	$2S_{1/2} - 2P_{3/2}$	1526	812	1	6	8/12	1.1	48
$\mu\,^4\mathrm{He}^+$	$2S_{1/2} - 2P_{1/2}$	1380	898	1	3	4/12	2.2	48
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=0} - 2P_{1/2}^{F=1}$	1119	1108	1/4	3	1/12	2.1	—
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=0} - 2P_{3/2}^{F=1}$	1294	958	1/4	6	2/12	1.1	12
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=1} - 2P_{1/2}^{F=1}$	1286	964	3/4	2	2/12	3.2	22
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=1} - 2P_{1/2}^{F=0}$	1344	923	3/4	1	1/12	6.4	13
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$	1436	863	3/4	5	5/12	1.3	36
$\mu\,^3\mathrm{He}^+$	$2S_{1/2}^{F=1} - 2P_{3/2}^{F=1}$	1461	849	3/4	1	1/12	6.4	16

adapted from A.P. Martynenko, PRA **76**, 0125505 (2007), with
$r_{^4\mathrm{He}}$= 1.681(4) fm from I. Sick, PRC **77**, 041302, (2008).
$r_{^3\mathrm{He}}$= 1.971(4) fm using ^{3}He-^{4}He isotope shift from P. Mueller et al., PRL **99**, 252501 (2007).

μHe^+ Signal rates

Effect	μp 1 mbar	$\mu\,^4He^+$ 4 mbar	$\mu\,^4He^+$ / μp
Long lived $2S$-population	1.1%	2.2% *	2
$2S$ sub-level population	75%	100%	1.33
$2S$-lifetime (survival probability $= e^{-t_{Laser}/\tau_{2S}}$)	1 μs	1.7 μs *	1.65
Muon stop in gas (trigger quality Q)	40%	60%	1.5
Muonic $2S$ atoms not drifting out of laser volume	80%	100%	1.25
Laser transition probability (only 20% for some weak transitions in $\mu\,^3He^+$)	30%	30%	1
Laser repetition rate	500 s^{-1}	500 s^{-1}	1
Detection of Lyman alpha X-ray	70%	70%	1
Total event rate increase: for $\mu\,^4He^+$			8
Total event rate increase: for $\mu\,^3He^+$ strong transition and triplet population			6
Total event rate increase: for $\mu\,^3He^+$ singlet population			2

* v. Arb *et al.*, Phys. Lett. B **136**, 232 (1984)

μp rate = 6 events/h $\longrightarrow$ $\mu\,^4He^+$ rate = 48 events/h

μHe$^+$ Statistics and Systematics

	$\mu\,^4$He$^+$	$\mu\,^3$He$^+$ (max)	$\mu\,^3$He$^+$ (min)	μp (max)
Event rate on resonance:	48 ev/h	36 ev/h	12 ev/h	6 ev/h
Background rate:	2.5 ev/h for all μ He$^+$			1 ev/h

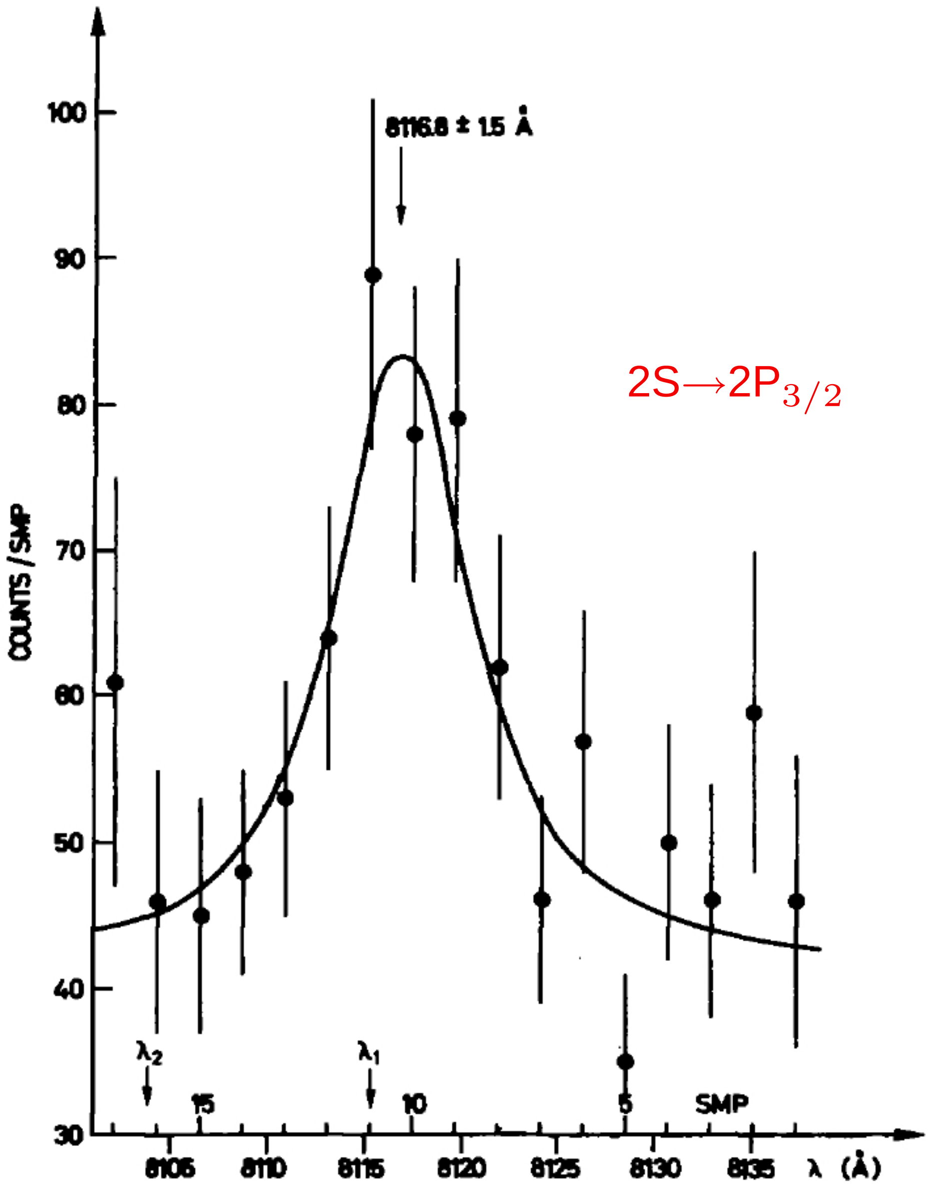
- We want to measure the transition with 50 ppm accuracy.

  This corresponds to $\Gamma/20$ = 20 GHz.
  - 500 events are sufficient $\Longleftrightarrow$ 1500 events on resonance
  - laser wavelength calibration: uncritical

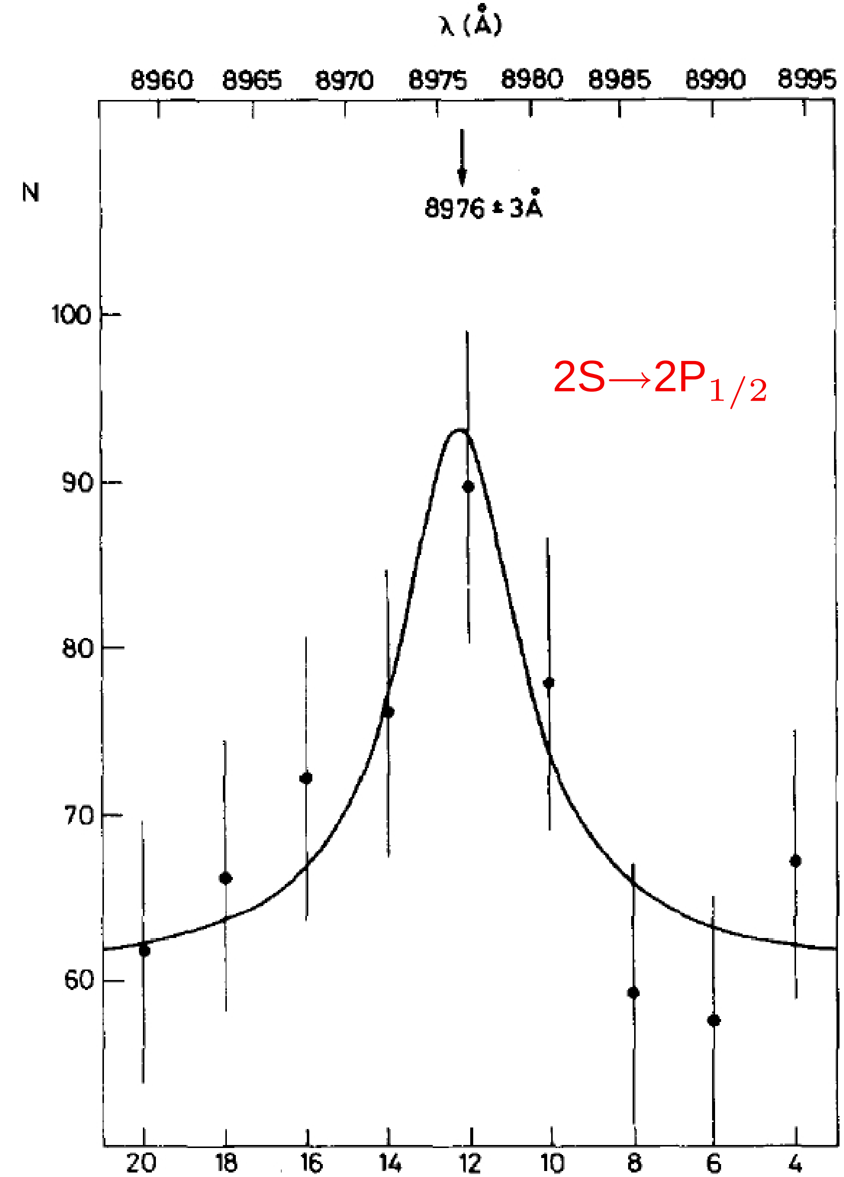
    (we have determined the μp transition freq. to $<$ 1 GHz)
- Systematics: will be < 5 GHz
  - AC/DC-Stark shift, Zeeman shift are all uncritical
  - Pressure shift, Doppler shift < 50 MHz.
  - Laser energy asymmetry left/right of centroid:

    $\rightarrow$ Need to measure the average laser energy with 3% accuracy

Old μHe^{+} resonances



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



Carboni et al, Phys. Lett. 73B, 229 (1978)