Lamb shift in muonic hydrogen

Bound-state QED

&

proton radius

puzzle

A. Antognini

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ETH, Zurich, Switzerland

Collaboration

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The role of hydrogen in history of physics

Spectroscopy Fraunhofer, Amstrong, Balmer, Rydberg (1800-1900)

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$\bar{\mathrm{H}}$, $\bar{p}$He, e^+e^-, μ^+e^-, πp ...		CPT, QED test, const., scattering lengths...

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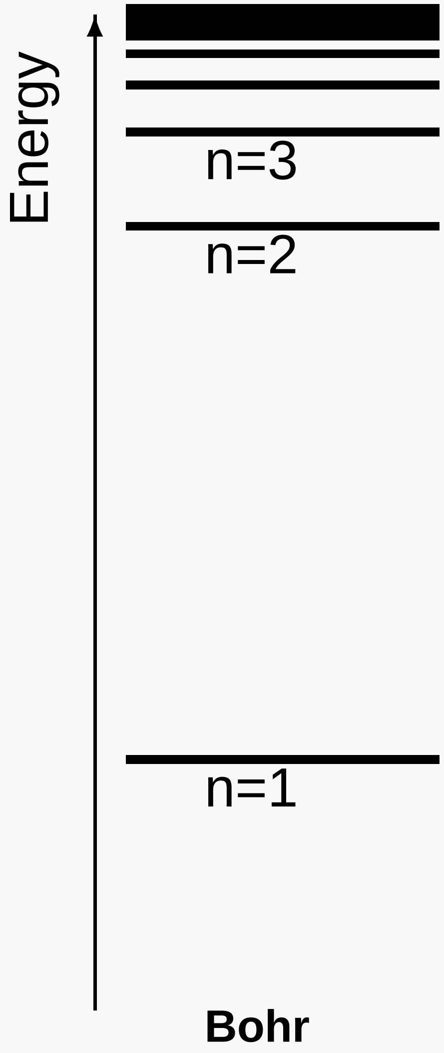
$\bar{\mathrm{H}}$, $\bar{p}$He, e^+e^-, μ^+e^-, πp ...		CPT, QED test, const., scattering lengths...
p and d radii	Lamb shift in μp, μd	QED test, R_∞, lattice QCD/few-nucleon th. 5σ deviation, New effects?

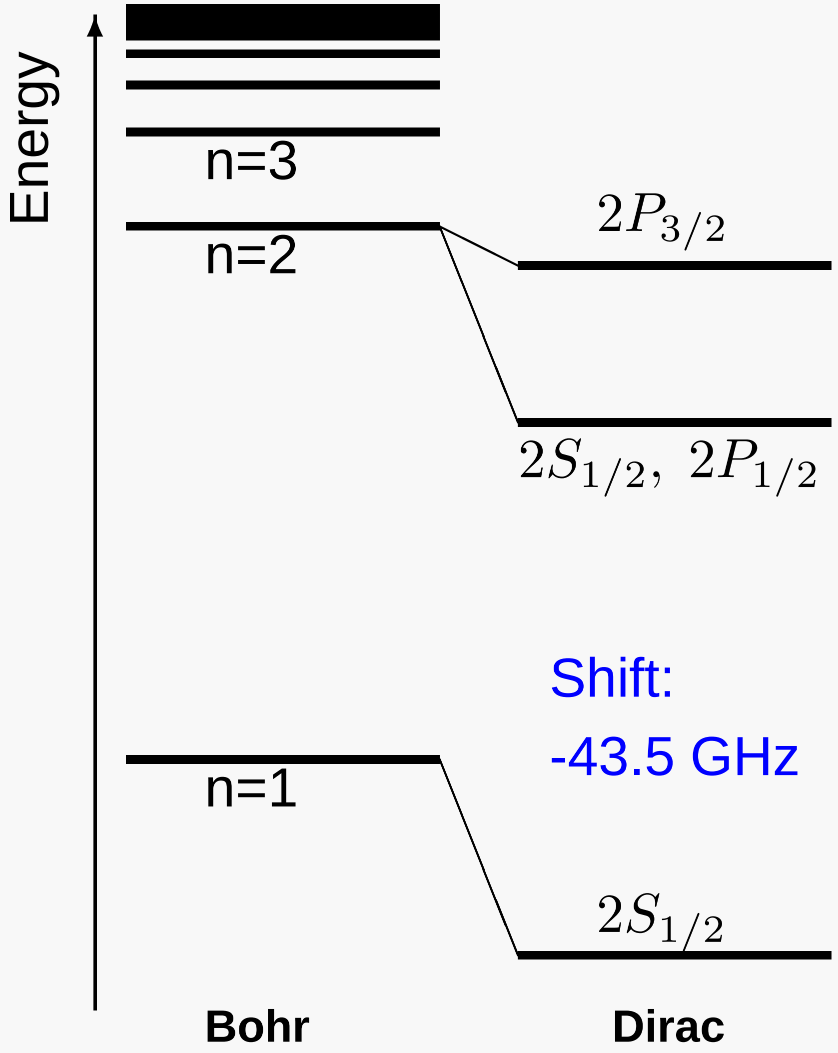
Hydrogen energy levels



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

$$V \sim 1/r$$

Hydrogen energy levels



$E = R_\infty / n^2$

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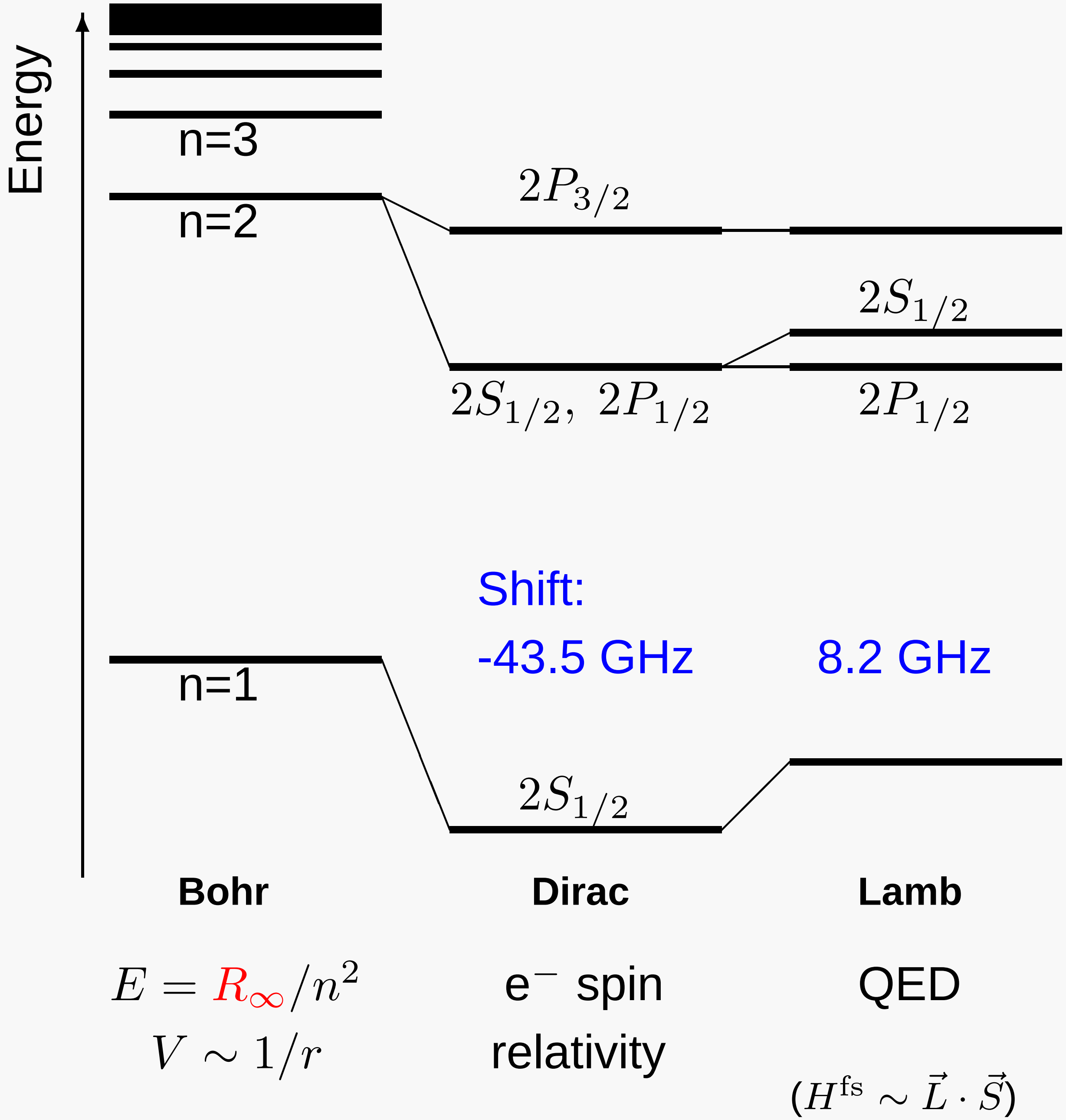
e^- spin

relativity

Hydrogen energy levels



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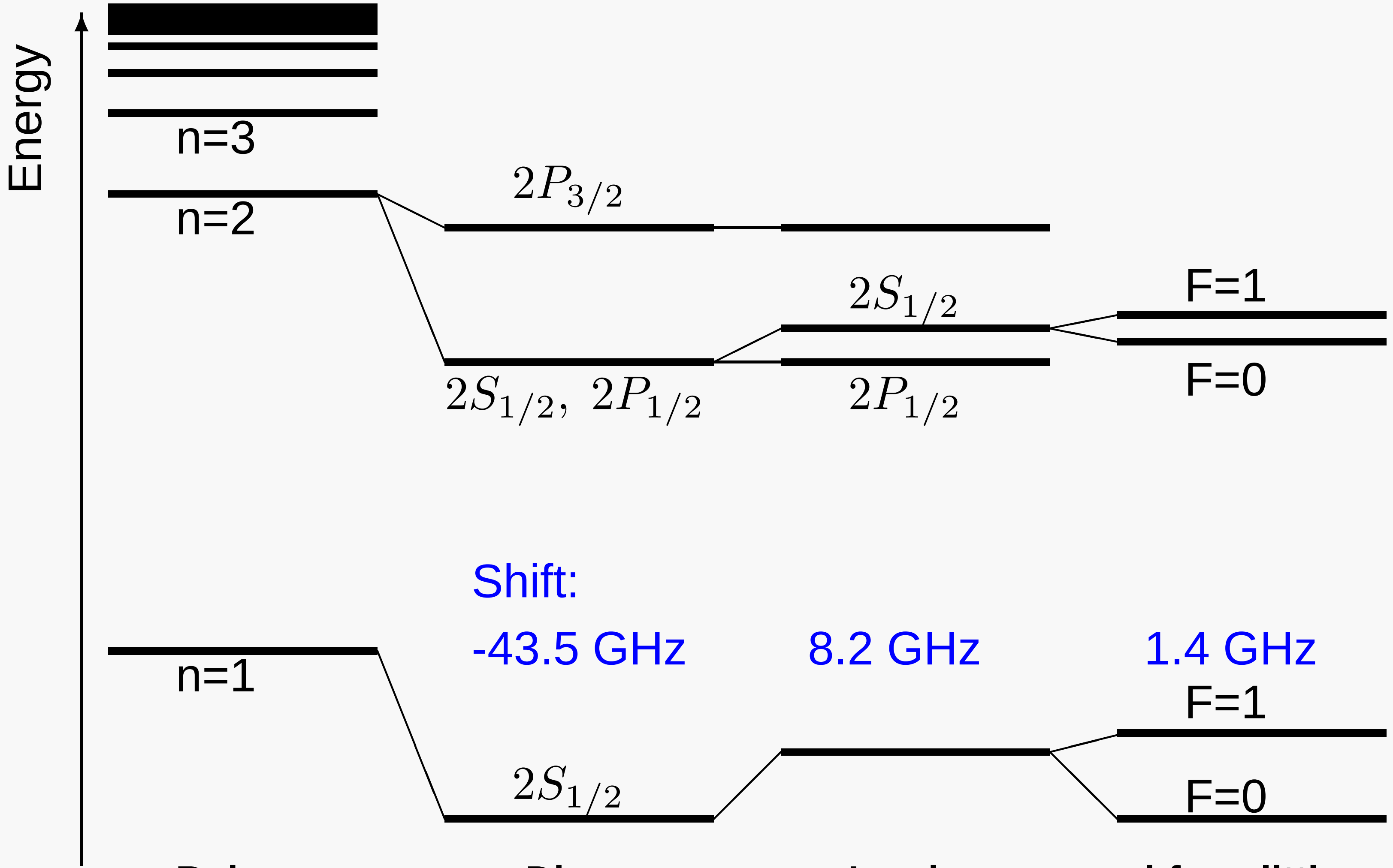
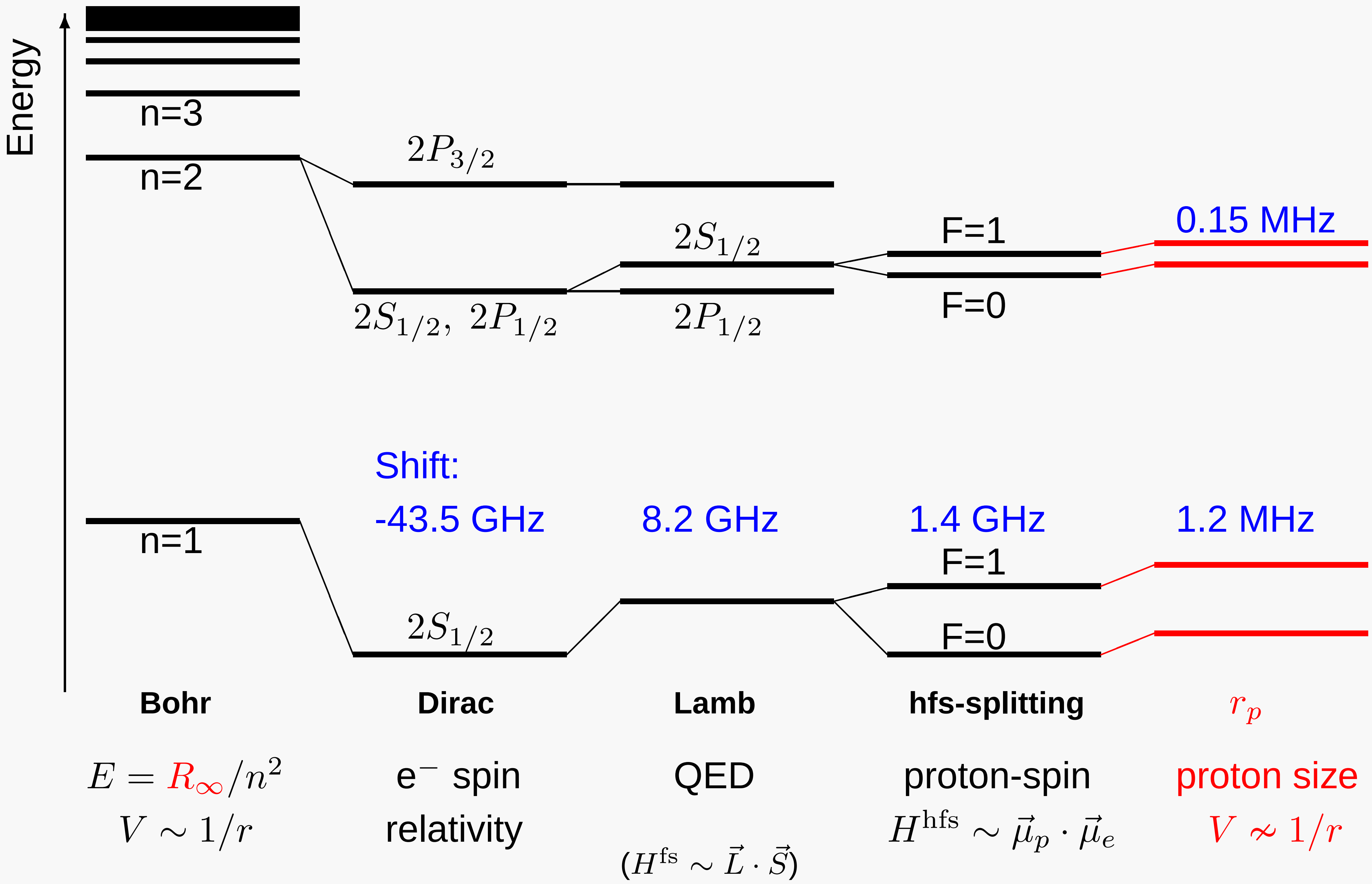


Bohr	**Dirac**	**Lamb**	**hfs-splitting**
$E = R_\infty / n^2$	e^- spin	QED	proton-spin
$V \sim 1/r$	relativity	$(H^{\rm fs} \sim \vec{L} \cdot \vec{S})$	$H^{\rm hfs} \sim \vec{\mu}_p \cdot \vec{\mu}_e$

Hydrogen energy levels



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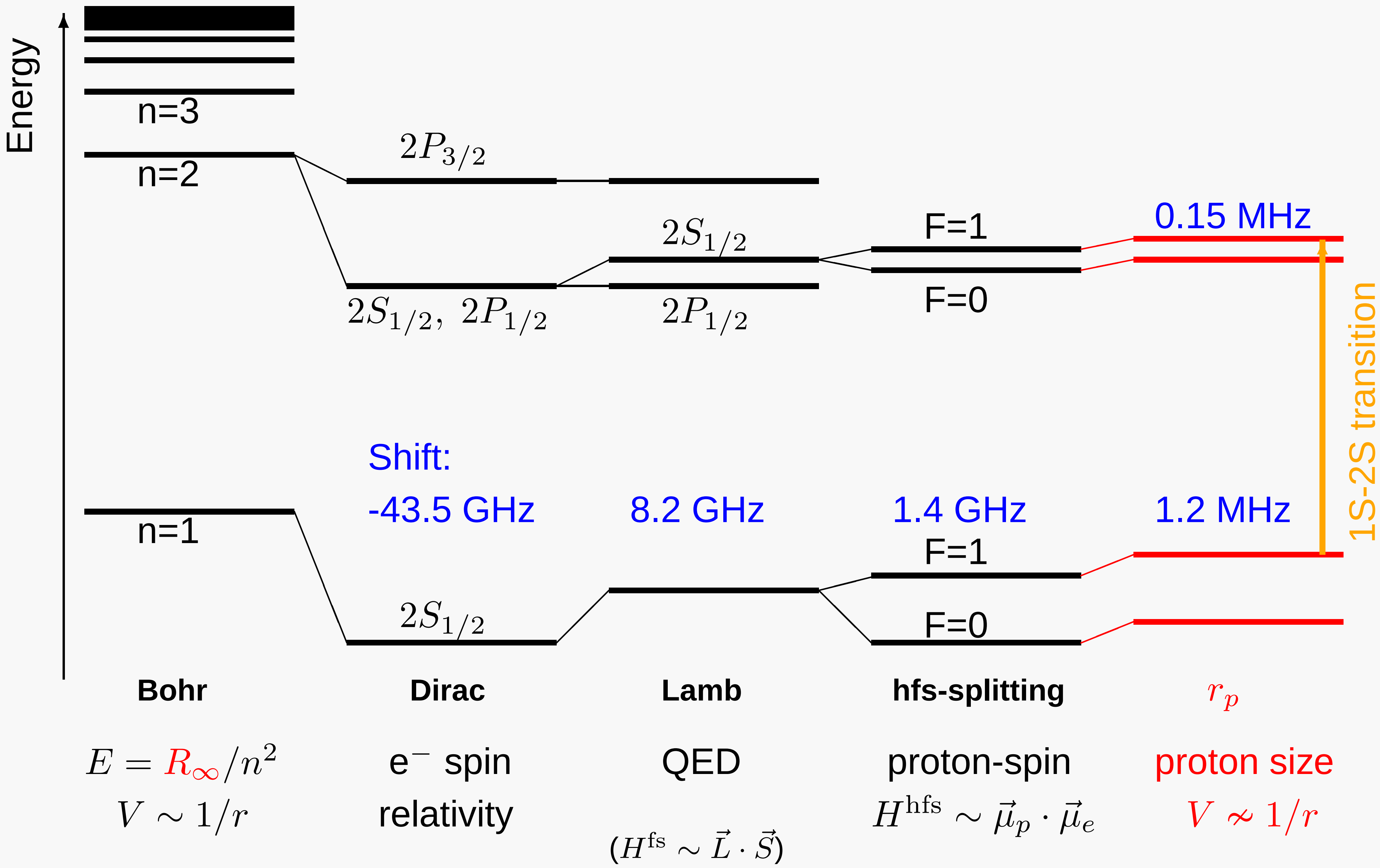
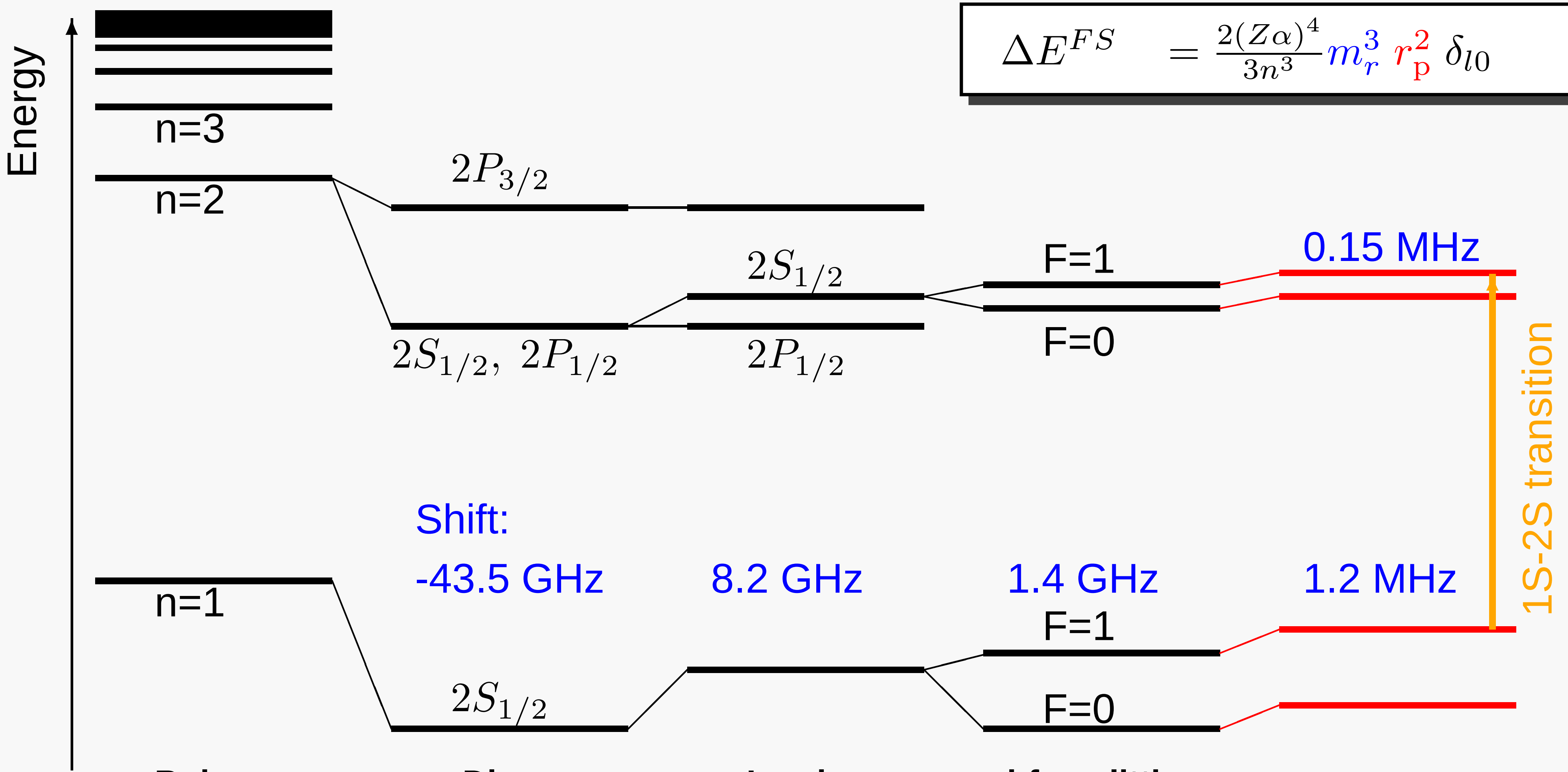


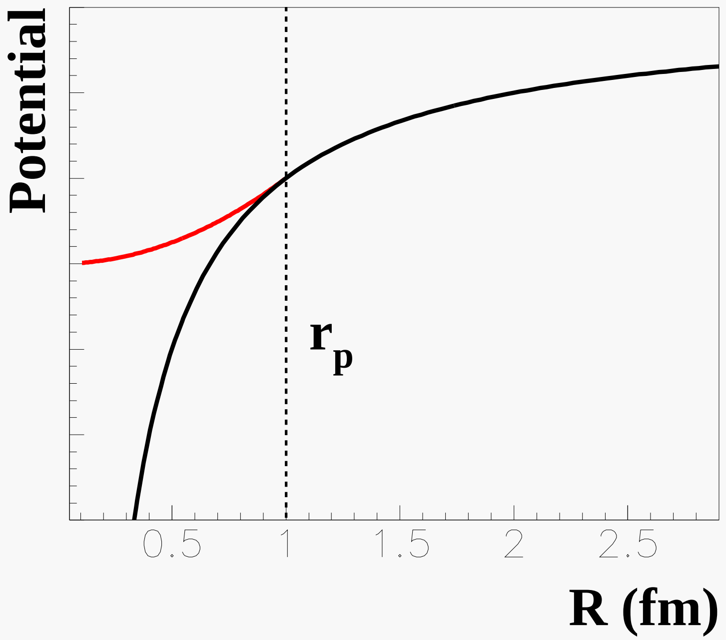
Hydrogen energy levels

$$\Delta E^{FS} = \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, r_p^2 \, \delta_{l0}$$



Bohr	Dirac	Lamb	hfs-splitting	r_p
$E = R_\infty / n^2$	e^- spin	QED	proton-spin	proton size
$V \sim 1/r$	relativity	$(H^{\mathrm{fs}} \sim \vec{L} \cdot \vec{S})$	$H^{\mathrm{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$	$V \nsim 1/r$

The leading proton finite size contribution



Maxwell equation: $\nabla E = 4\pi\rho$

$$V = \begin{cases} -\frac{Z\alpha}{2r_\mathrm{p}}\left(3 - (\frac{r}{r_\mathrm{p}})^2\right) & (r < r_\mathrm{p}) \\ -\frac{Z\alpha}{r} & (r > r_\mathrm{p}) \end{cases}$$

$$\Delta V = \begin{cases} -\frac{Ze^2}{2r_\mathrm{p}}\left(3 - (\frac{r}{r_\mathrm{p}})^2 - \frac{2r_\mathrm{p}}{r}\right) \\ 0 \end{cases}$$

$$\Delta E^{FS} = \langle\bar{\Psi}|\Delta V|\Psi\rangle$$

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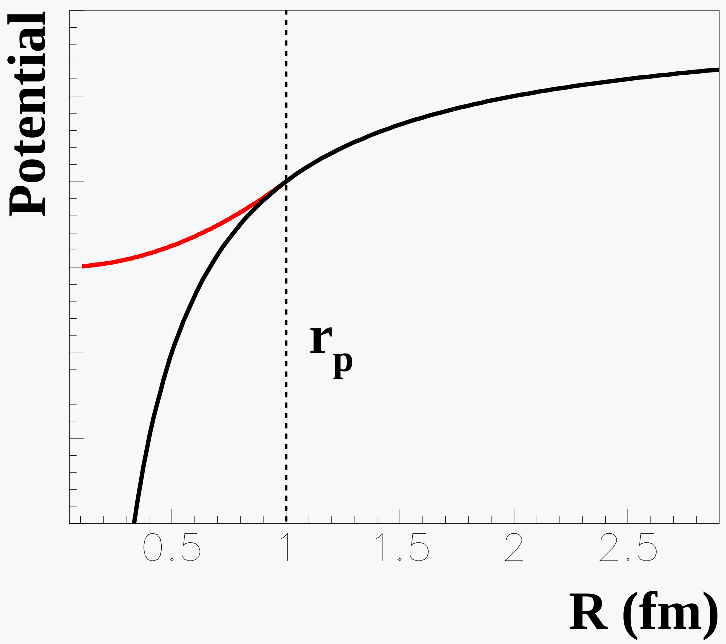

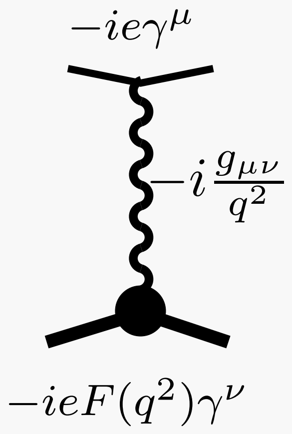

$$\frac{1}{q^2} \longrightarrow \frac{F(q^2)}{q^2}$$

$$r_{\mathrm{p}}^2 \equiv \int d^3r\,\rho(\mathbf{r})r^2$$

$$F(\mathbf{q^2}) = \int d^3r\,\rho(\mathbf{r})e^{-i\mathbf{q}\cdot\mathbf{r}} \simeq Z(1 - \frac{\mathbf{q^2}}{6}r_{\mathrm{p}}^2 + \cdots)$$

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$$\Delta E^{FS} = \langle\bar{\Psi}|\Delta V|\Psi\rangle$$

$$\Delta V(r) = V(r) - \left(-\frac{Z\alpha}{r}\right)$$

$$\Delta V(\mathbf{q}) = \frac{4\pi Z\alpha}{\mathbf{q}^2}\,(1 - F(\mathbf{q})) \simeq \frac{2\pi(Z\alpha)}{3}r_{\mathrm{p}}^2$$

$$\Delta V(r) = \frac{2\pi(Z\alpha)}{3}\,r_{\mathrm{p}}^2\,\delta(r)$$

$$\begin{aligned} \Delta E^{FS} &= \frac{2\pi(Z\alpha)}{3}\,r_{\mathrm{p}}^2\,|\Psi_n(0)|^2 \\ &= \frac{2(Z\alpha)^4}{3n^3}m_r^3\,r_{\mathrm{p}}^2\,\delta_{l0} \end{aligned}$$

Proton charge radius determinations

- Electron-proton scattering (1963, ... 2010)

  $\rightarrow r_{\mathrm{p}}$ with $u_r = 1\%$

Proton charge radius determinations

- Hydrogen spectroscopy (1989, . . .)
  - very precise measurements: $d\nu/\nu = 1 \times 10^{-14}$ (1S-2S)
  - interpretation of the measurements need r_p

  - conversely assuming correctness of bound-state QED $\longrightarrow r_\mathrm{p}$
  - however finite size effect small ($u_r \sim 10^{-10}$) $\longrightarrow r_\mathrm{p}$ with $u_r = 1\%$

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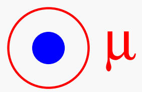
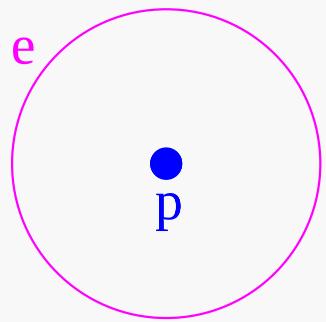
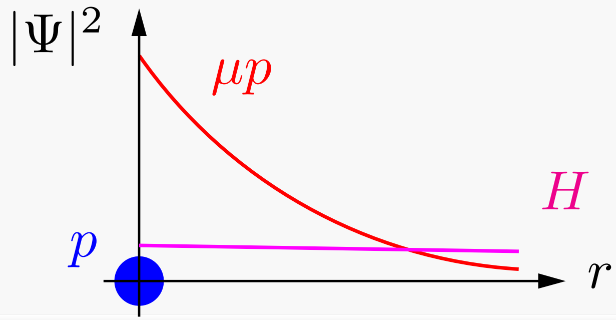
- Muonic hydrogen spectroscopy (2009 . . .)

  $m_\mu/m_e \approx 200 \rightarrow \mu^-$ “orbit” is 200 times smaller than e$^-$ “orbit”

  $\rightarrow$ large finite size effect $\rightarrow r_{\mathrm{p}}$ with $u_r = 0.1\%$

Muonic hydrogen 

Hydrogen 



$$\frac{|\Psi_\mu(0)|^2}{|\Psi_e(0)|^2} = \left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$$

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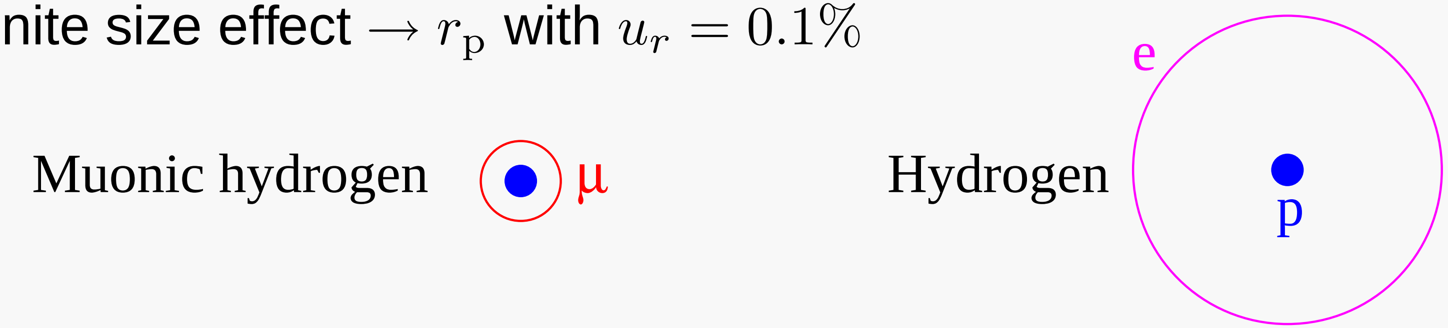


$$r_\mathrm{p}^2 = \int d^3r\, \rho(r) r^2 \qquad \longrightarrow \qquad r_\mathrm{p} \text{ is the rms charge radius}$$

Aim of the experiment

- Measure the $2S-2P$ energy difference (Lamb shift) in μp

  $\Delta E(2S-2P) = 209.978(5) - 5.226\, r_p^2 + 0.0347\, r_p^3$ meV

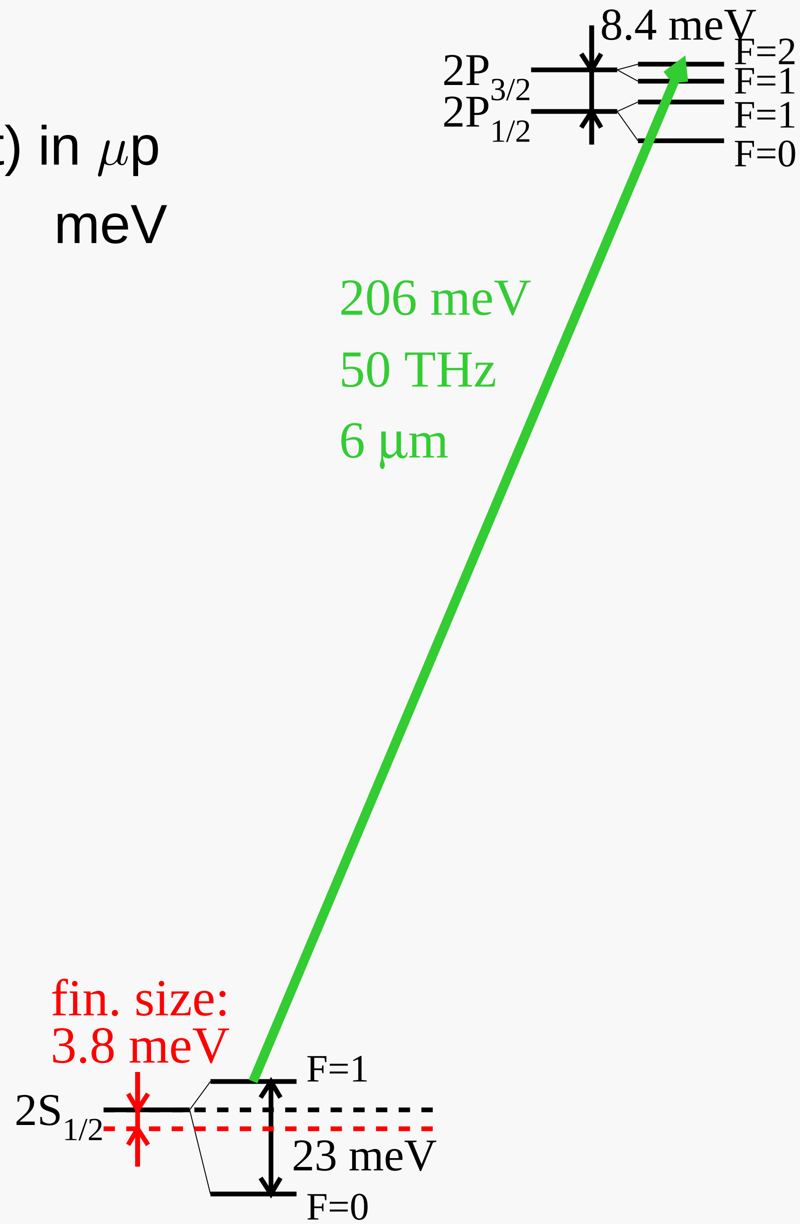
  with 30 ppm precision.

- Extract r_p with $u_r \approx 10^{-3}$ (rel. accuracy)

  → bound-state QED test in hydrogen
  to a level of $u_r \approx 3 \times 10^{-7}$ ($10\times$ better)

  → improve Rydberg constant ($R_\infty = mc\alpha^2/2h$)
  to a level of $u_r \approx 1 \times 10^{-12}$ ($6\times$ better)

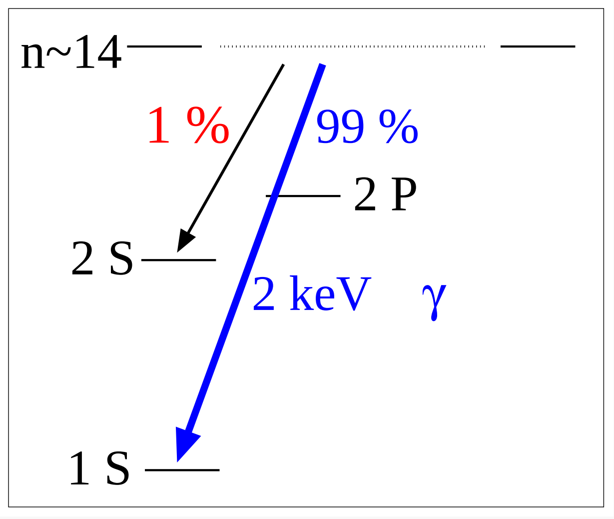
  → benchmark for lattice QCD calculations
  → confront with electron scattering results



Principle of the experiment

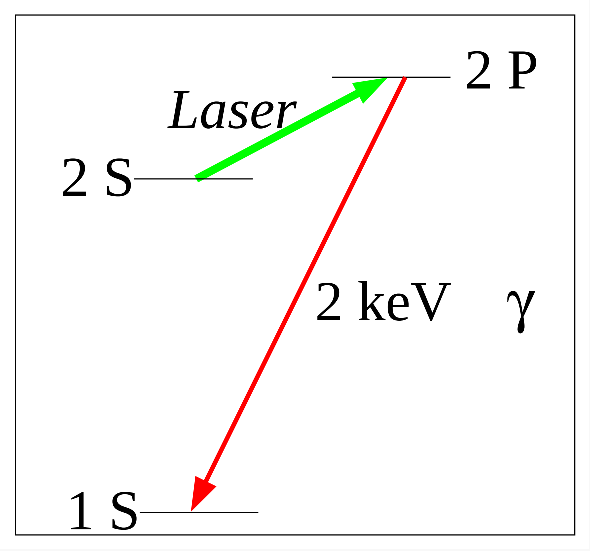
- μ^- are produced with the PSI accelerator (p$\rightarrow \pi^- \rightarrow \mu^-$)
- μ^- stop in a 1 mbar hydrogen target whereby muonic hydrogen is formed
- Before stopping, the μ^- trigger the laser system
- The laser pulse excites the $2S - 2P$ transition
- 2 keV X-ray are detected as a signature of the laser-induced transition

μp formation



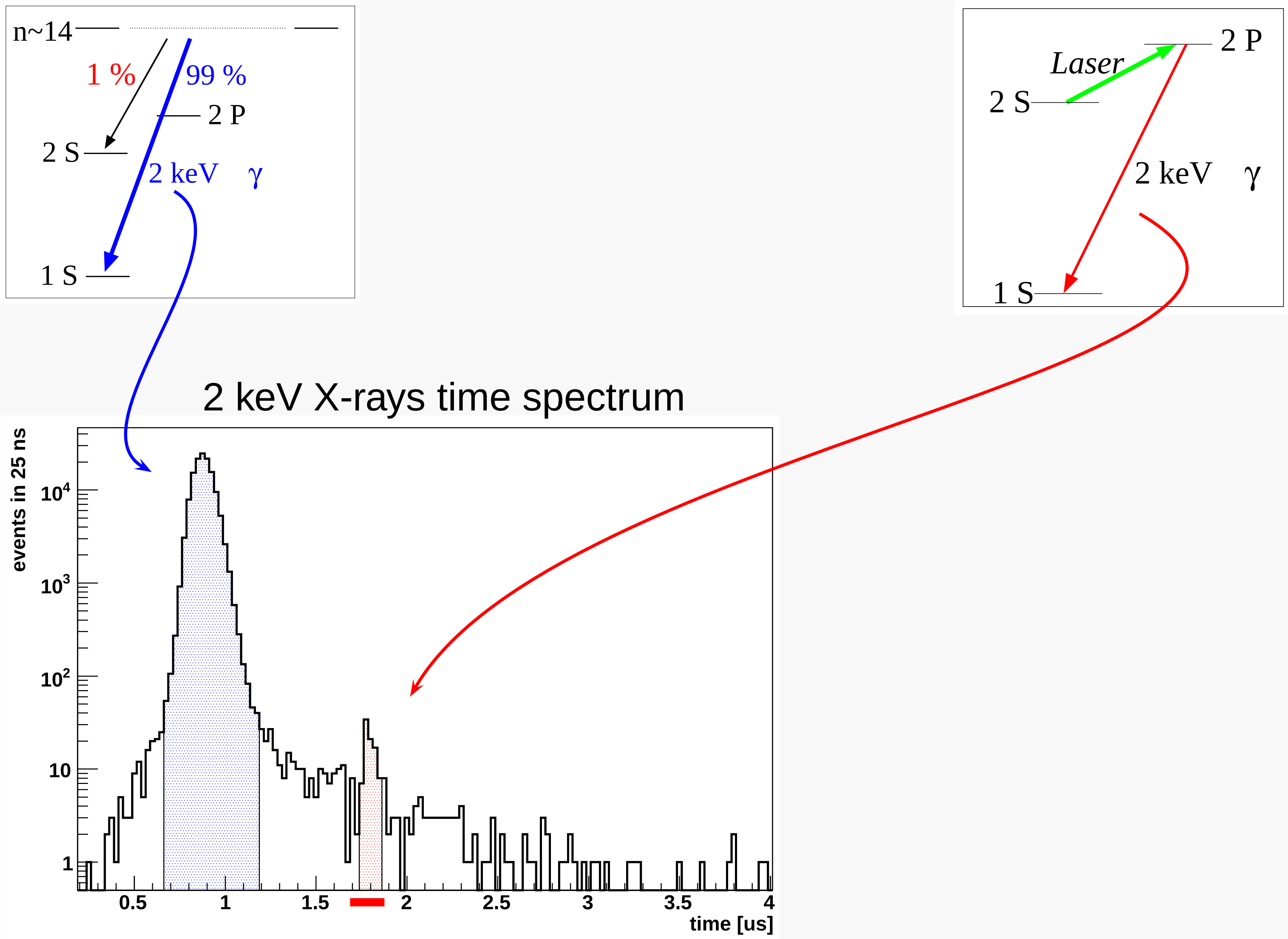
1%: long-lived μp($2S$)
with 1 μs lifetime (@ 1 mbar)

μp spectroscopy



Laser at $\lambda \approx 6\ \mu$m
Signature: 2 keV X-ray

Principle of the experiment



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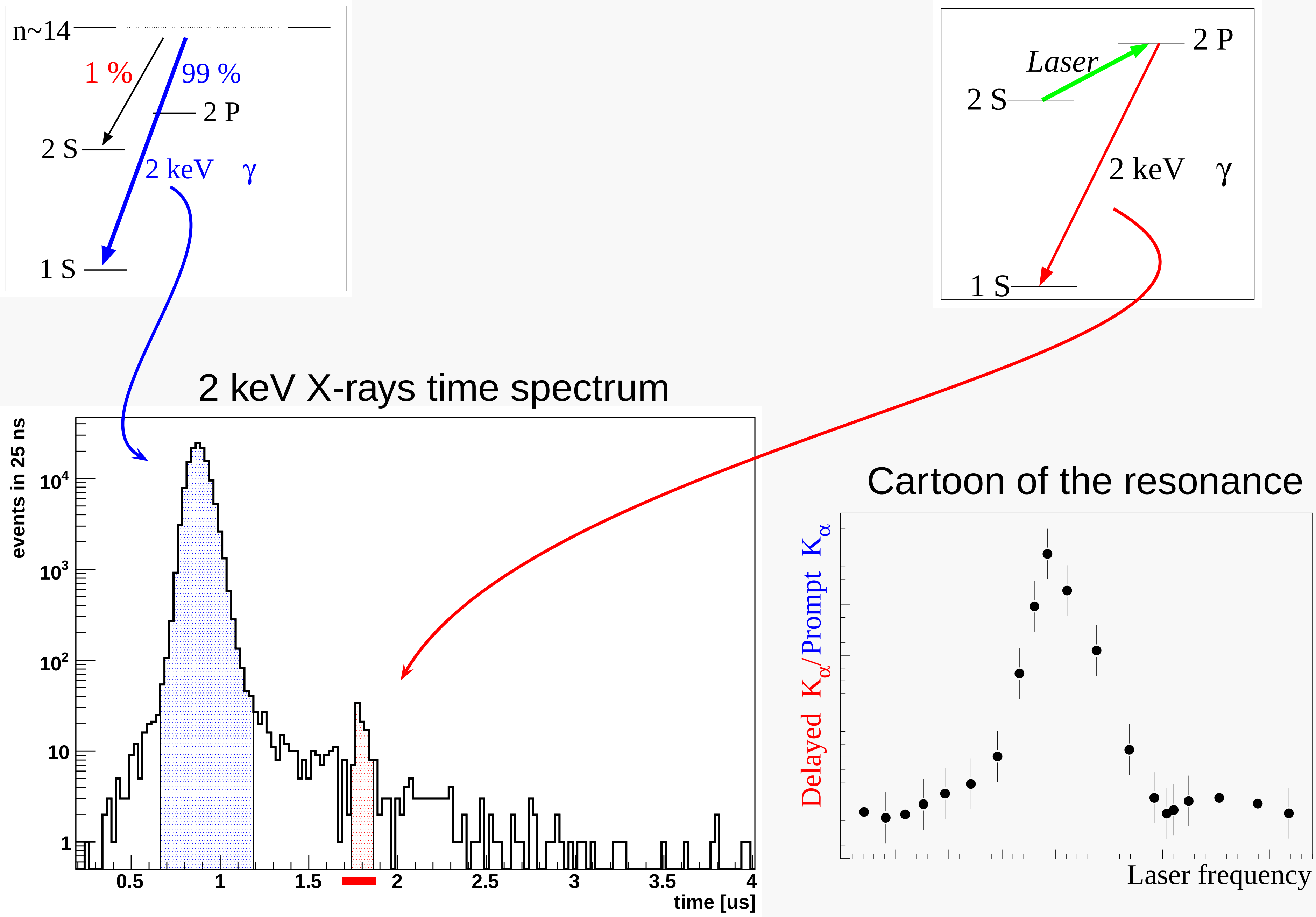
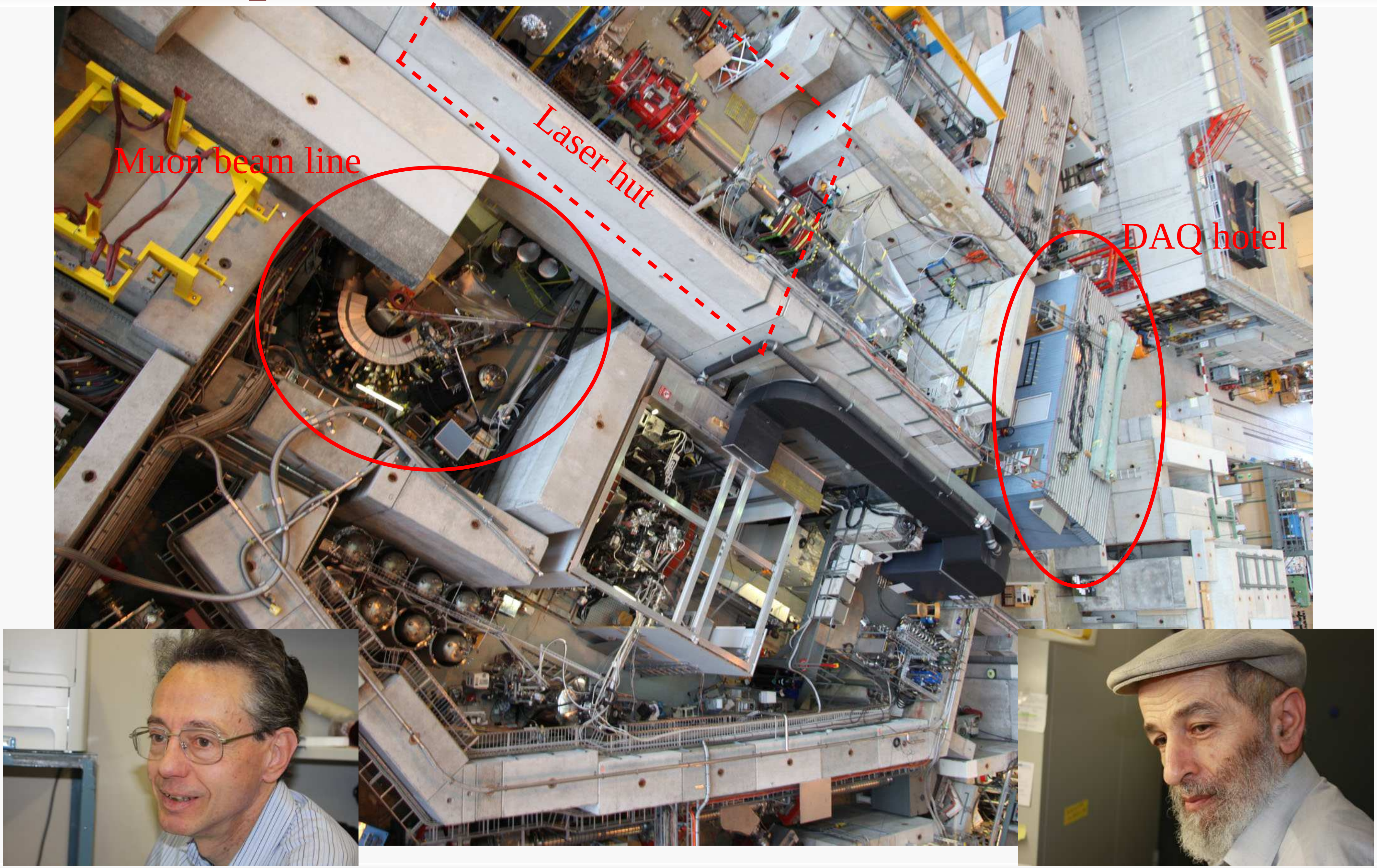


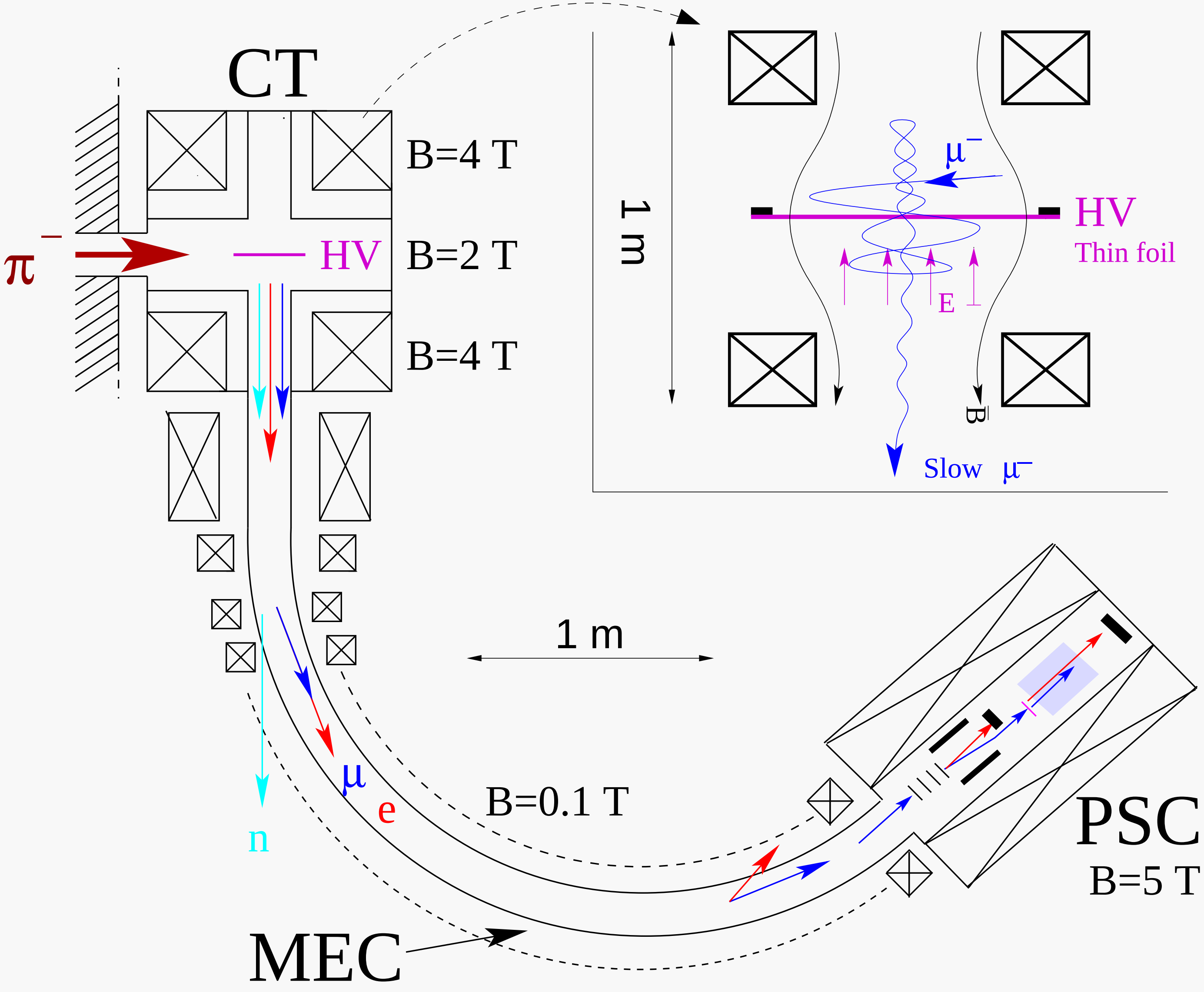
Apparatus

- Low energy muon beam line at PSI
- Laser system
- Detectors and DAQ

The experimental hall at PSI



5 keV energy muon beam line



- Production of 20-50 keV μ^-
  - 10^8 π^- injected in CT
  - π^- decay in MeV μ^-
  - μ^- decel. to 20-50 keV by crossing the foil
- Extraction of μ^- from CT

$$\frac{T_\parallel(0)}{T_\perp(0)} < \left(\frac{B_{\max}}{B_0} - 1\right) - \frac{qV}{T_\perp(0)}$$

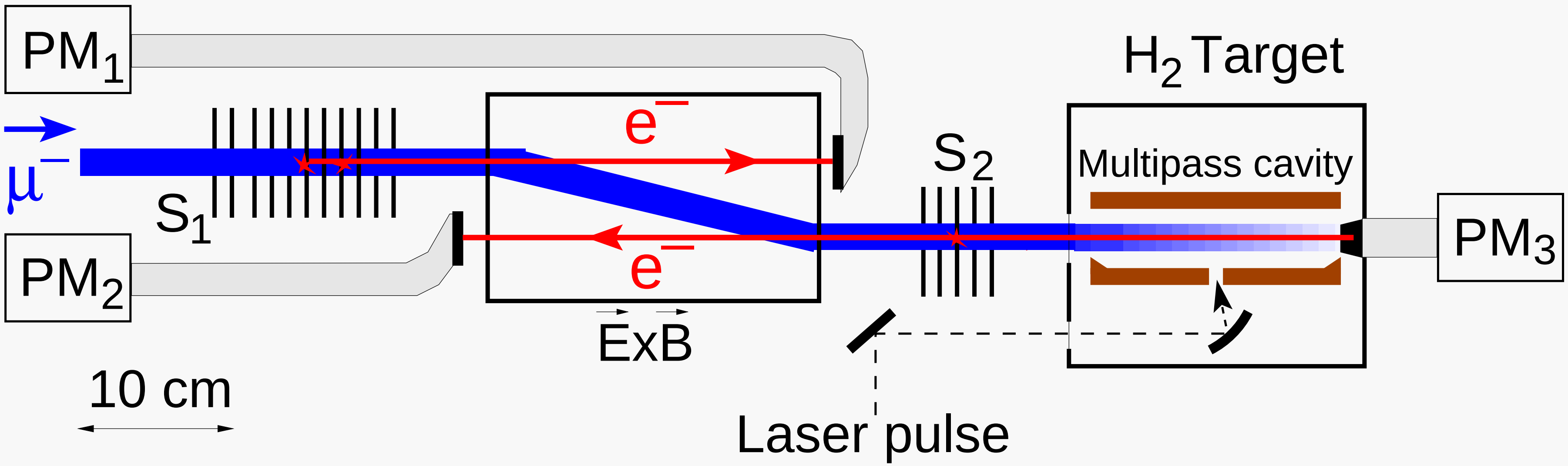
- Momentum selection
  - toroidal magnetic field $\rightarrow$ vertical drift
  - eliminate e^- and n bg
- μ^- detection
- μp formation and laser exp.

Inside the 5 Tesla solenoid

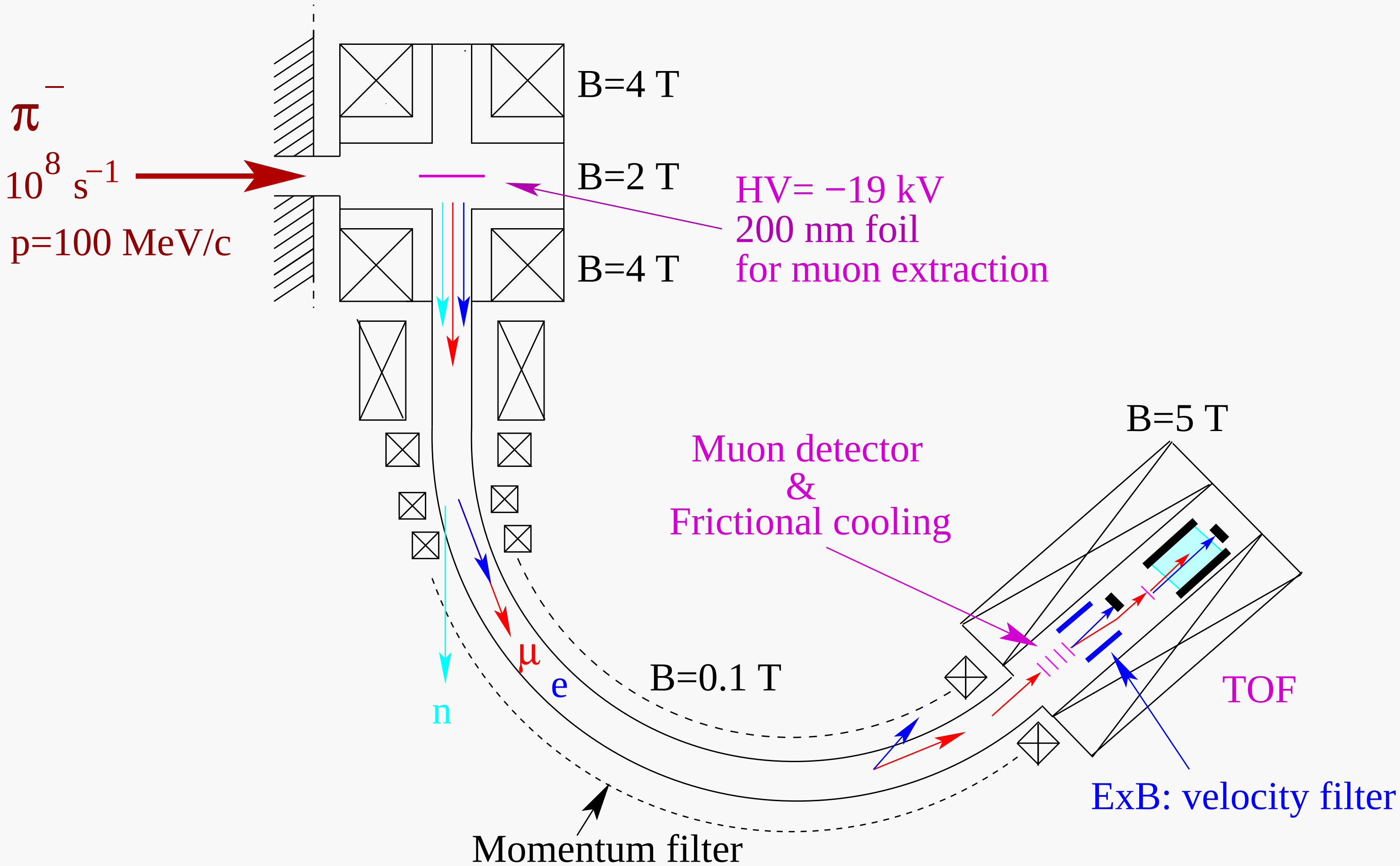
5 keV μ^-, 400 s^{-1} with stop vol. in 1 hPa H_2 gas of $5 \times 15 \times 190$ mm^3

- Stacks of C foils are used as non-destructive muon detector
  - μ^- loses few keV energy per foil
  - secondary electrons are emitted
  - ExB velocity dependent drift

- Laser is triggered by the electrons signals from the C stacks (coincidence with TOF)
- μ^- enter in 1 hPa hydrogen wherby μp is formed

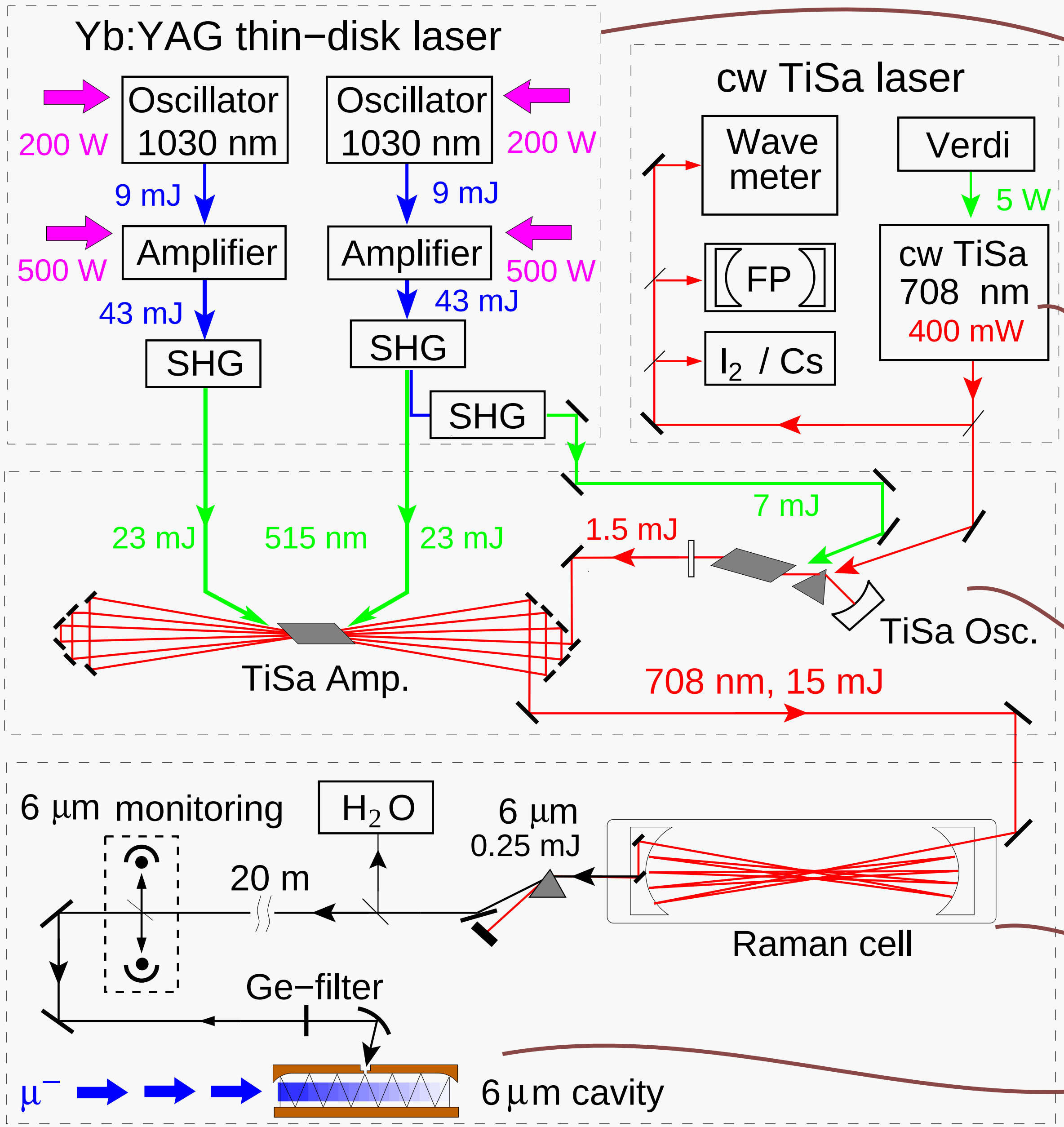


Animation of the experiment



(T.W. Hänsch)

The laser system

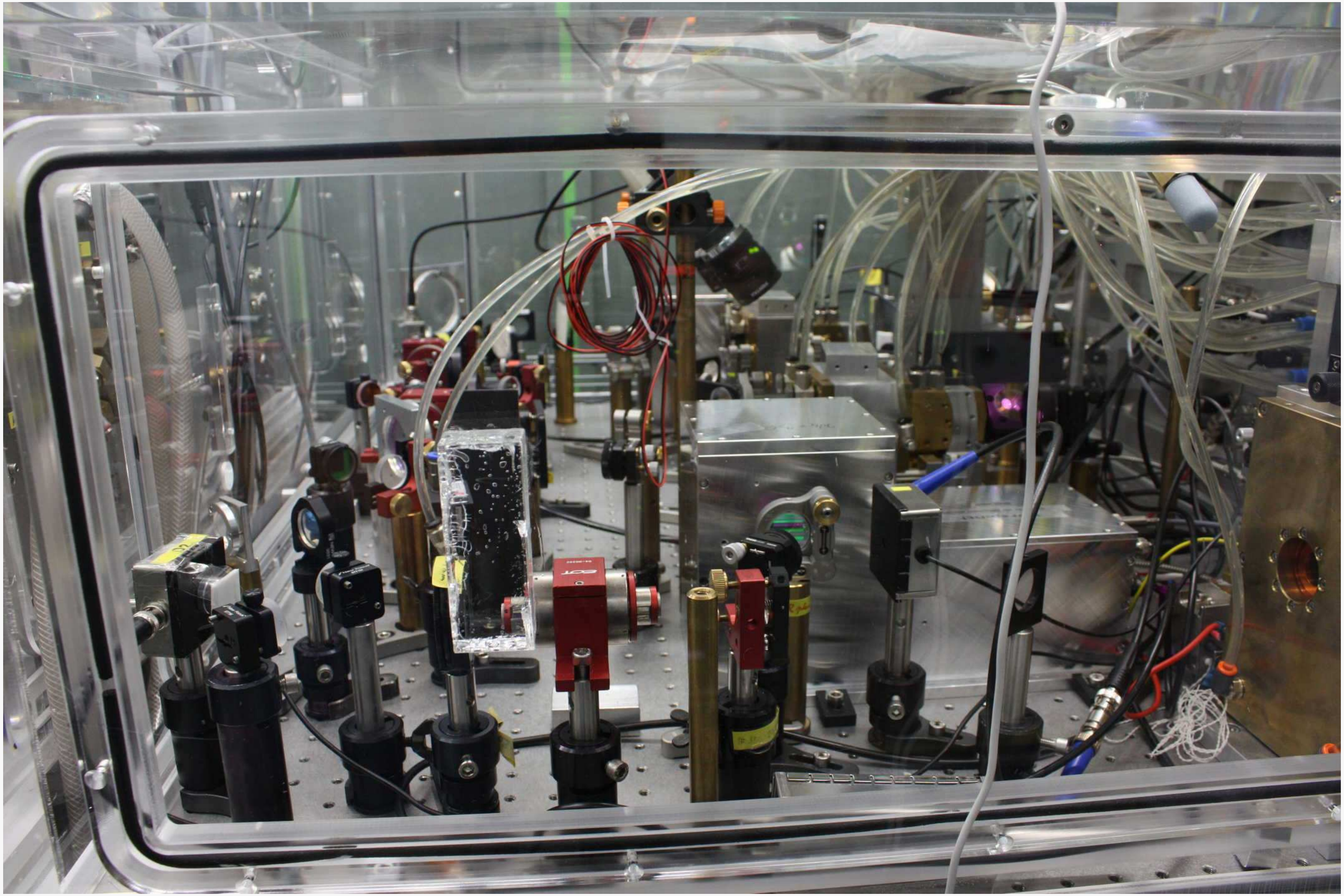


Main components:

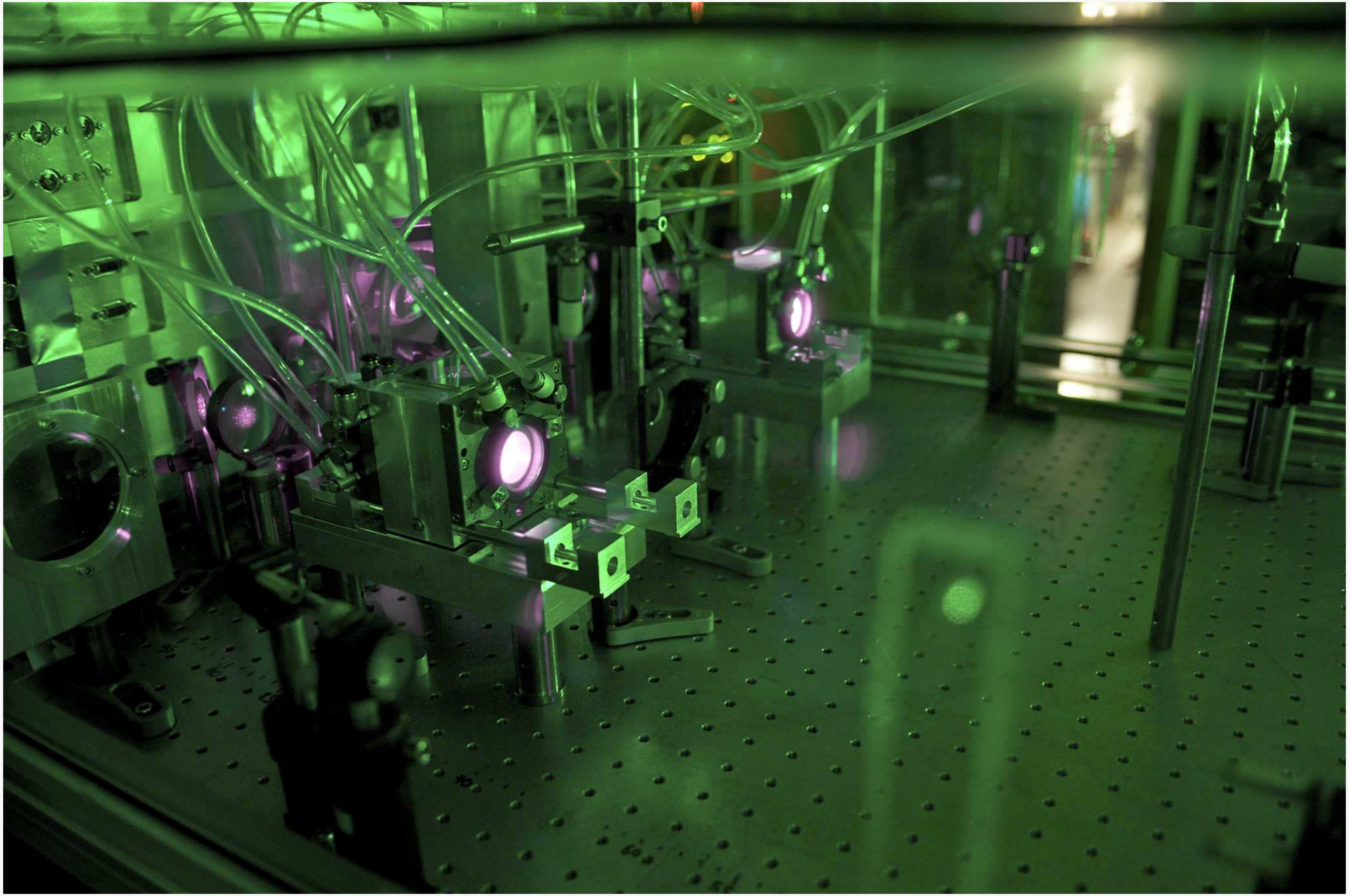
- Thin-disk laser
- Frequency doubling
- TiSa laser:
  - cw frequency stabilized laser
  - injected seeded oscillator
  - multipass amplifier
- Raman cell
- Target cavity

Impressions from the laser hut

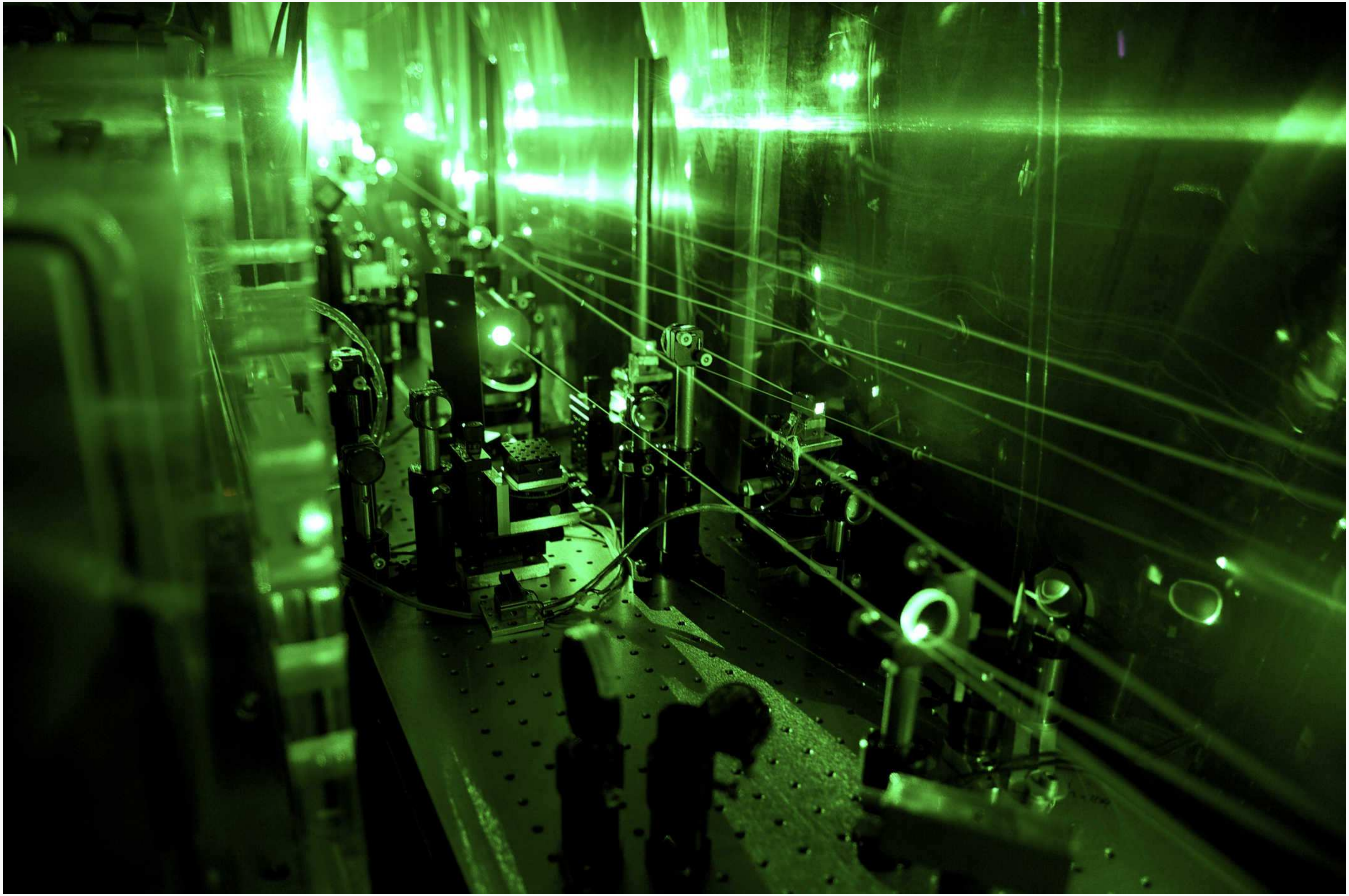
Disk laser oscillators



Disk amplifier laser heads

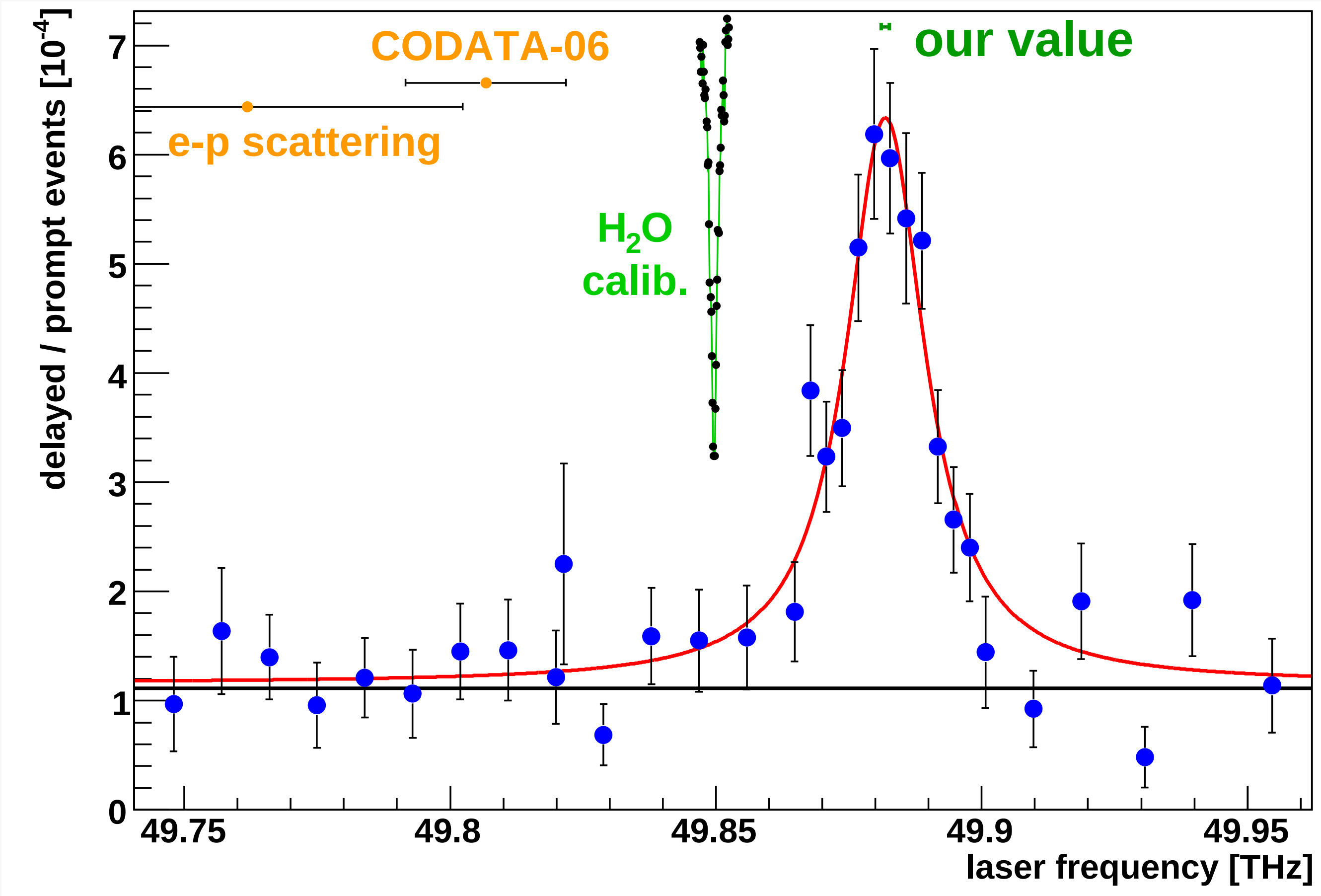


Disk laser doubling stages



Measurements

The resonance: discrepancy, sys., stat.



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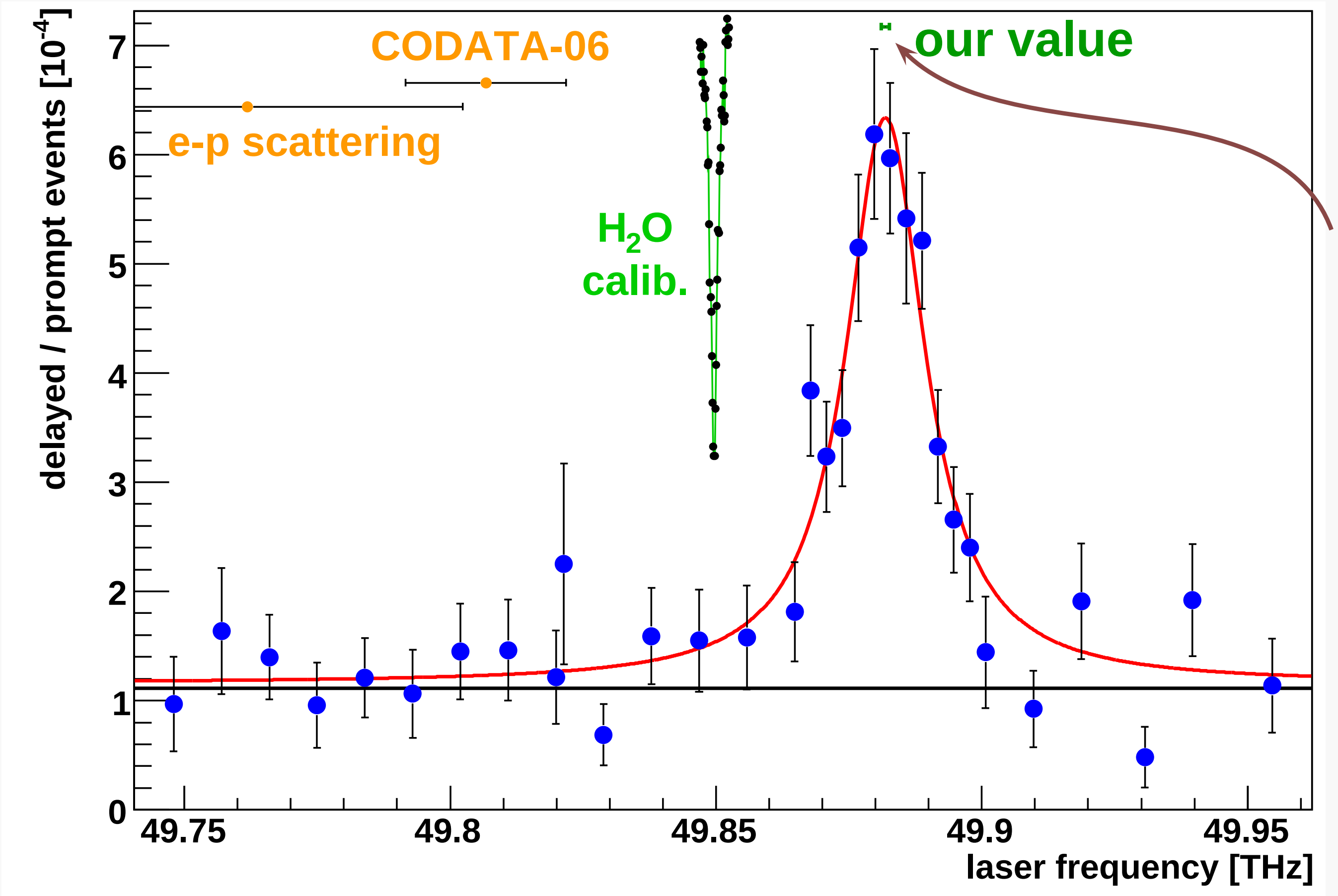

Fitted position:
700 MHz unc.
$\longrightarrow \quad r_p$

Fitted width
as predicted

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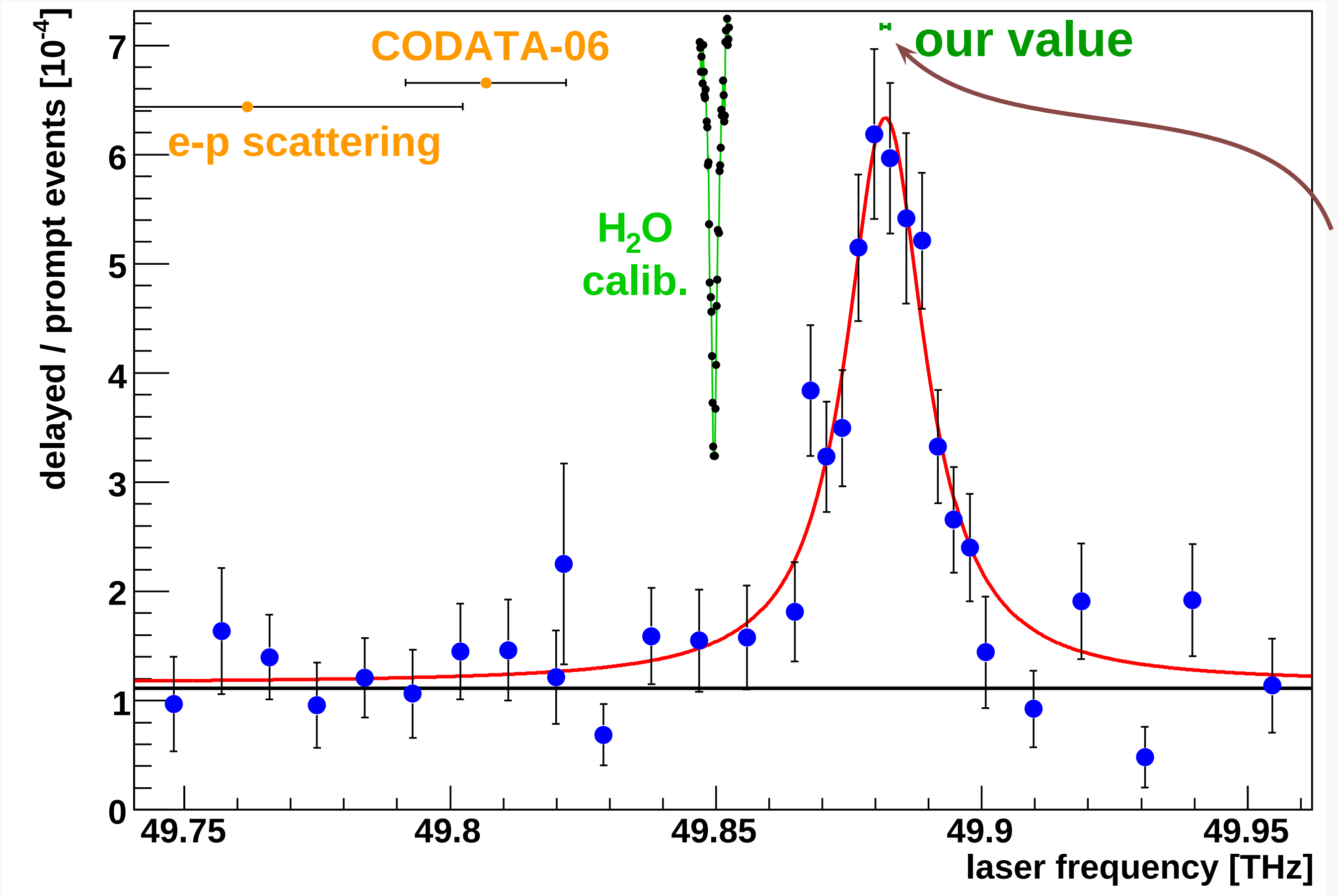
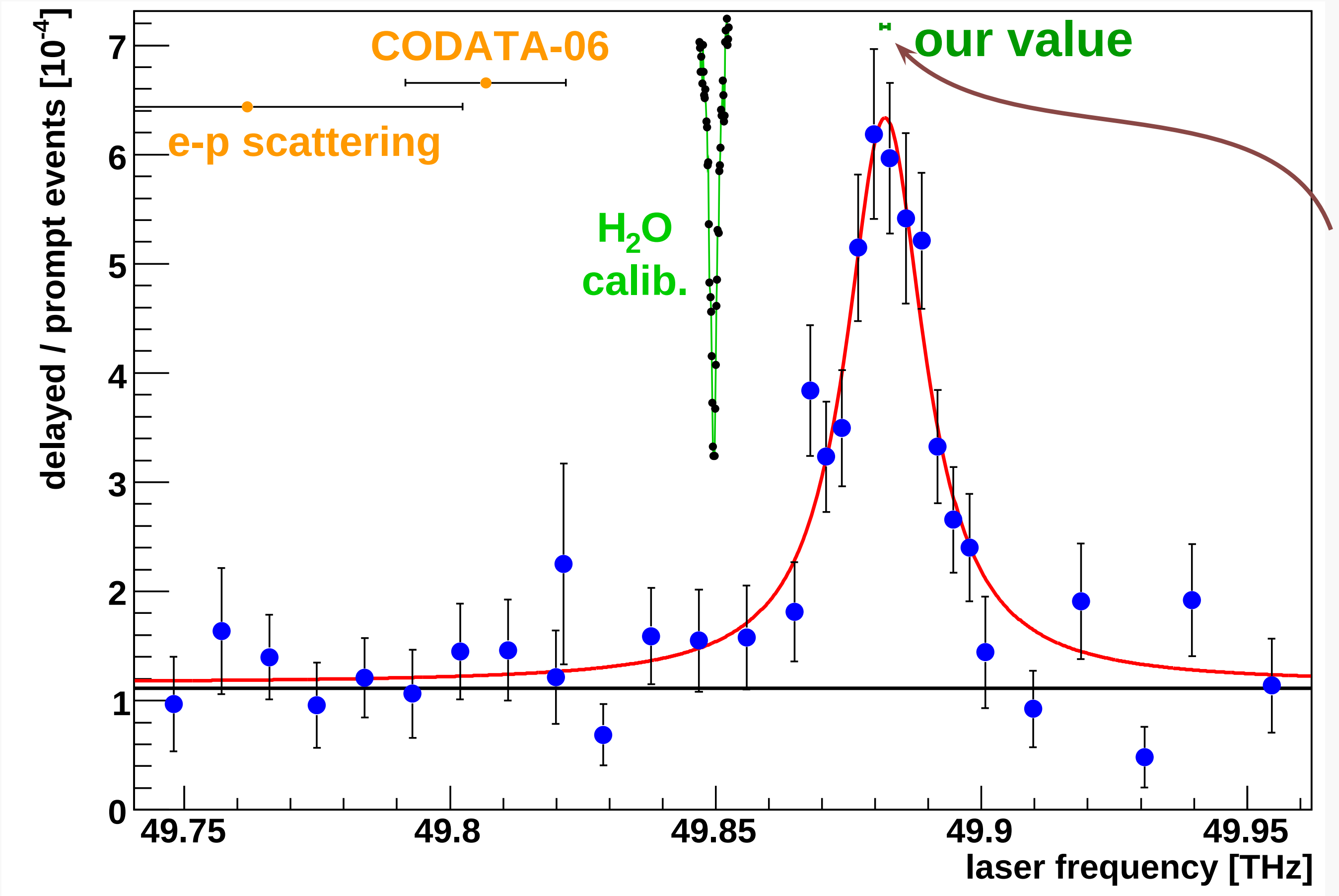


Fitted position: 700 MHz unc. $\longrightarrow$ $r_{\rm p}$

Fitted width as predicted

Laser frequency known with 300 MHz uncertainty

The resonance: discrepancy, sys., stat.



Fitted position: 700 MHz unc.

$\longrightarrow \quad r_p$

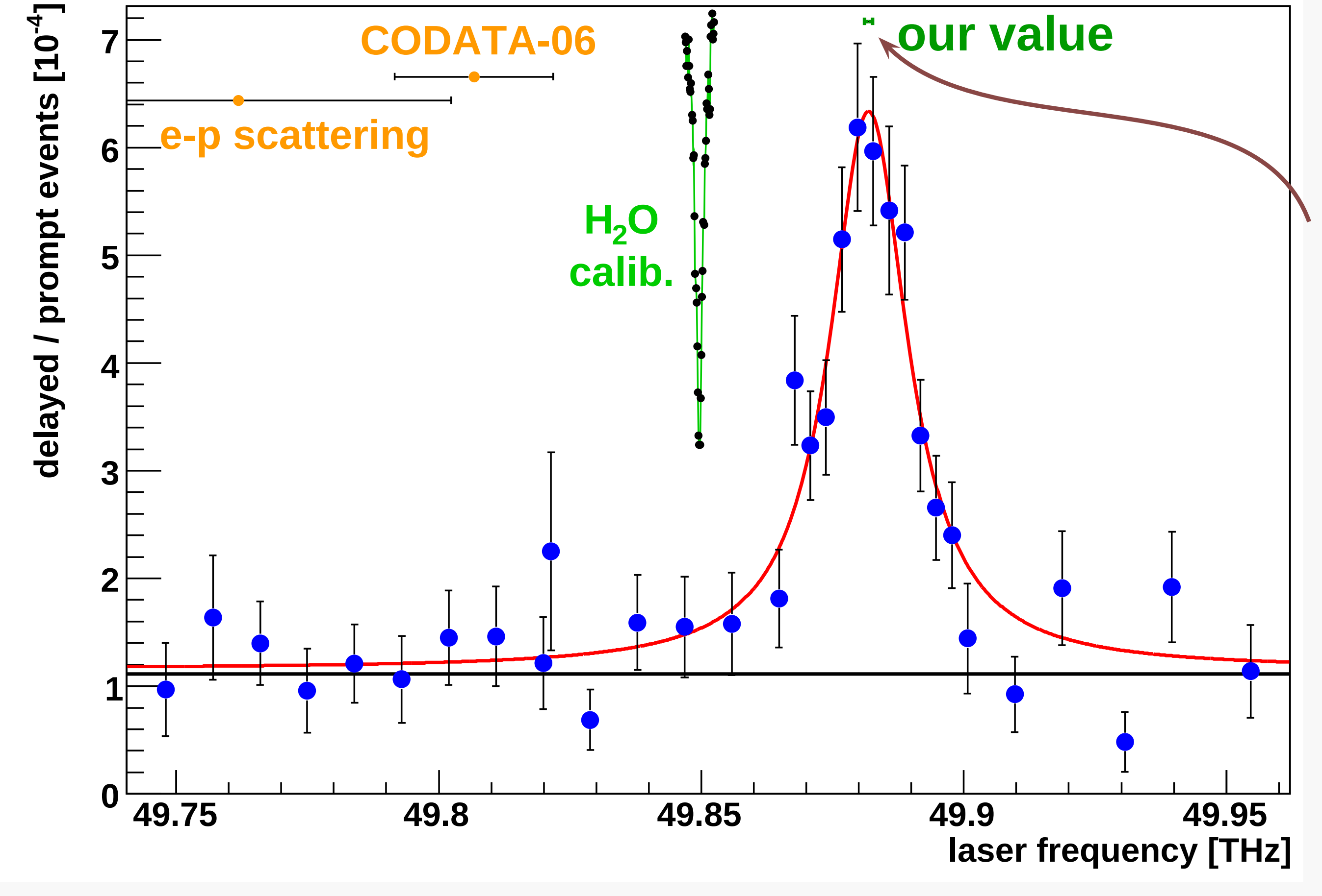
Fitted width as predicted

Systematics: 300 MHz
Statistics: 700 MHz

Laser frequency known with 300 MHz uncertainty

The resonance: discrepancy, sys., stat.

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



Fitted position:
700 MHz unc.
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Fitted width
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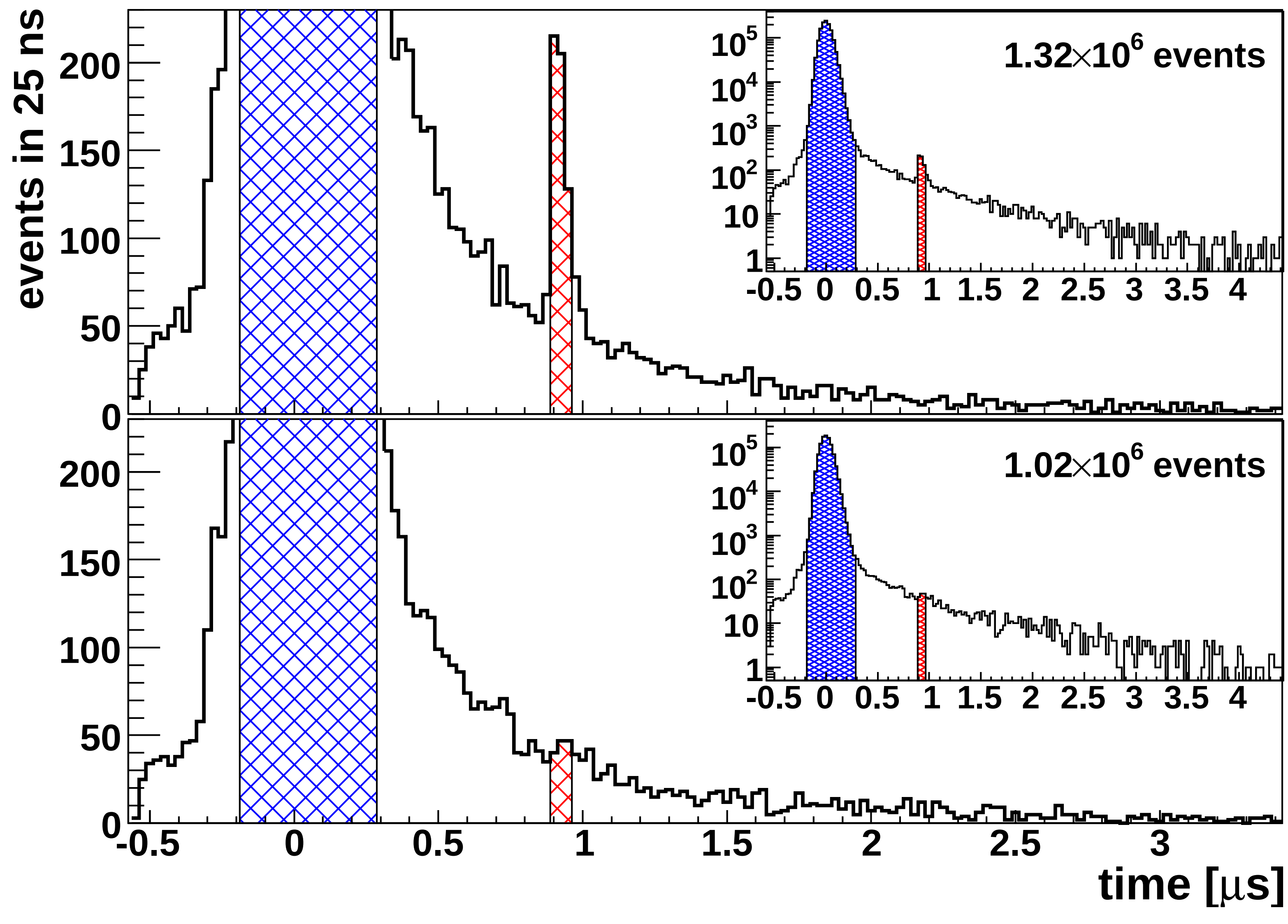
Systematics: 300 MHz
Statistics: 700 MHz

Laser frequency known with 300 MHz uncertainty

. . . and the time spectrum



Laser ON resonance

Laser OFF resonance

Time-spectrum fit around laser time ⇒ Extract precise bgr. value

Proton radius from μp Lamb shift

- Measurement (no theory input needed): $\nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}) = 49881.88(76)$ GHz

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

$$u_r^{\text{exp}} = 4.3 \times 10^{-4}$$
$$u_r^{\text{th}} = 6.7 \times 10^{-4}$$

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

Pohl et al., Nature **466**, issue 7303, 213-216 (2010)

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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 (2%)

3.0σ from e-p scatt.
5.0σ from CODATA
r_p 4% smaller

What may be wrong?

$$L^{\text{th.}}_{\mu p}(r_{\text{p}}^{\text{CODATA}}) - L^{\text{exp.}}_{\mu p} = \begin{cases} 75\ \text{GHz} \\ 0.31\ \text{meV} \\ 0.15\ \% \end{cases}$$

μp th. wrong?

μp exp. wrong?

H th. wrong?

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

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μp experiment wrong?

- Frequency mistake by 75 GHz $\Leftrightarrow u_r = 0.15\%$? (Linewidth =20 GHz)

  (in spectroscopy people measure frequency with $u_r \sim 10^{-14}$ and Hz precison)

- Two consistent ways to calibrate the frequency of the laser:
  1) at 6 μm with H_2O lines (20 measurements of 5 different lines)
  2) at 708 nm with lambdameter, wavemeter and FP calibated to I_2, Rb, Cs lines:

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

- Zeeman + AC/DC Stark + pressure shift $\cdots < 50$ MHz $(\sim 1/m)$

What may be wrong?

$$L_{\mu p}^{\text{th.}}(r_{\text{p}}^{\text{CODATA}}) - L_{\mu p}^{\text{exp.}} = \begin{cases} 75\ \text{GHz} \\ 0.31\ \text{meV} \\ 0.15\ \% \end{cases}$$

μp th. wrong?

μp exp. wrong?

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

μp theory wrong?

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

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	
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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	
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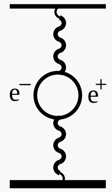

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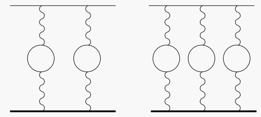
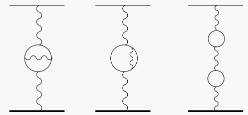
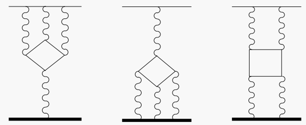
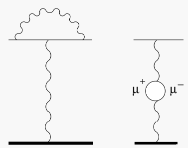
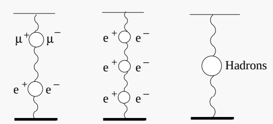

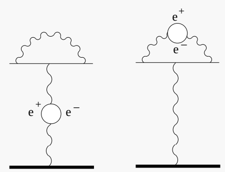

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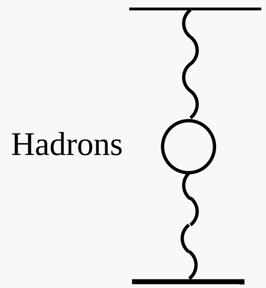

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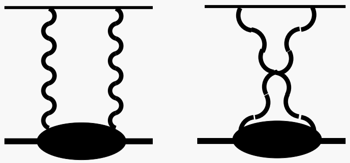
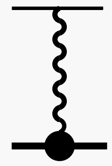
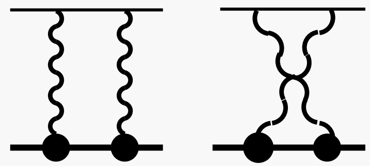


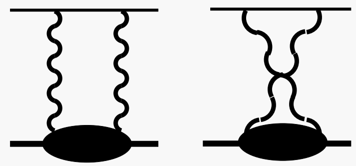
Lamb shift prediction

- radius dependent contributions

Contribution	Value	
Leading nuclear size contribution	-5.19745	$< r_{\rm p}^2 >$
Radiative corrections to nuclear finite size effect	-0.0275	$< r_{\rm p}^2 >$
Nuclear size correction of order $(Z\alpha)^6 < r_{\rm p}^2 >$	-0.001243	$< r_{\rm p}^2 >$
Total $< r_{\rm p}^2 >$ contribution	-5.22619	$< r_{\rm p}^2 >$
Nuclear size correction of order $(Z\alpha)^5$	0.0347	$< r_{\rm p}^3 >$
Nuclear size correction of order $(Z\alpha)^6 < r_{\rm p}^4 >$	-0.000043	$< r_{\rm p}^2 >^2$







- A1 collaboration at MAMI, Mainz
  has started the reevaluation of the various proton moments:
  $< r_{\rm p}^2 >, R_{\rm Zemach}, < r_{\rm p}^4 > \ldots$

New evaluations of structure leads to a shift $< 10\%$ of the measured discrepancy.

$$E(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}) = 209.9779(49) - 5.2262\, r_{\rm p}^2 + 0.0347\, r_{\rm p}^3 \ \text{meV}$$ (HFS+FS included)

Proton radius puzzle

$$L^{\text{th.}}_{\mu p}(r_p^{\text{CODATA}}) - L^{\text{exp.}}_{\mu p} = \begin{cases} 75 \text{ GHz} \\ 0.31 \text{ meV} \\ 0.15 \text{ \%} \end{cases}$$

μp th. wrong?

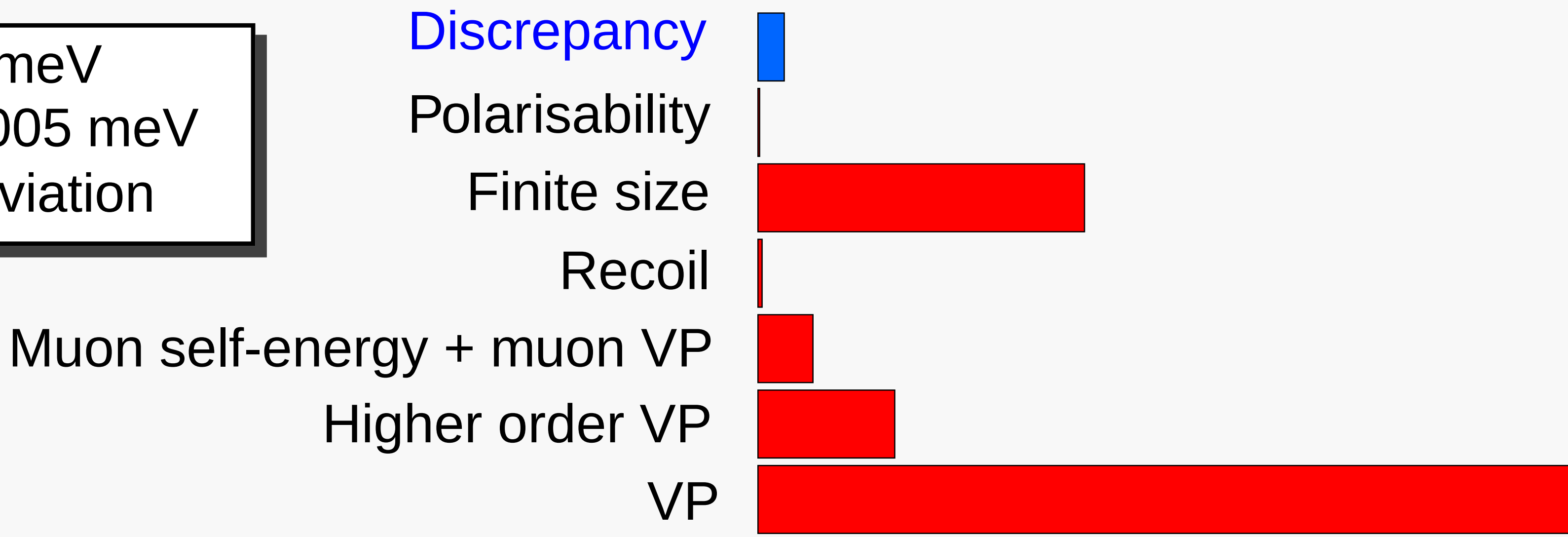
H th. or experiments wrong?

μp exp. wrong?

μp theory wrong?

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

Main contributions to the μp Lamb shift



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What about e-p scattering?!?!

Normalization?

Radiative corrections?

Consistent use of the proton radius definition?

H experiments wrong?

H theory wrong?

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μp th. wrong?

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μp exp. wrong?

Are H experiments wrong?

$$L^{\text{th}}_{1S}(r_p^{\mu p}) - L^{\text{exp}}_{1S} = 96(19)(4)(2) \text{ kHz}$$

δL^{exp} δL^{QED} δL^{r_p}

$$\delta L^{\text{exp}} = \delta L^{R_\infty}$$

L^{exp}_{1S} extracted from $1S - 2S$ and $2S - 8/12S$ transition

- $1S - 2S$ has to be corrected by thousands of σ to explain the discrepancy
- $2S - 8/12S$ has to be corrected by 5σ to explain the discrepancy
  $d\nu/\nu = 1 \times 10^{-11} \sim 1/100\ \Gamma$ (systematics $\sim n^3$)

Free and bound-state QED

- Free QED

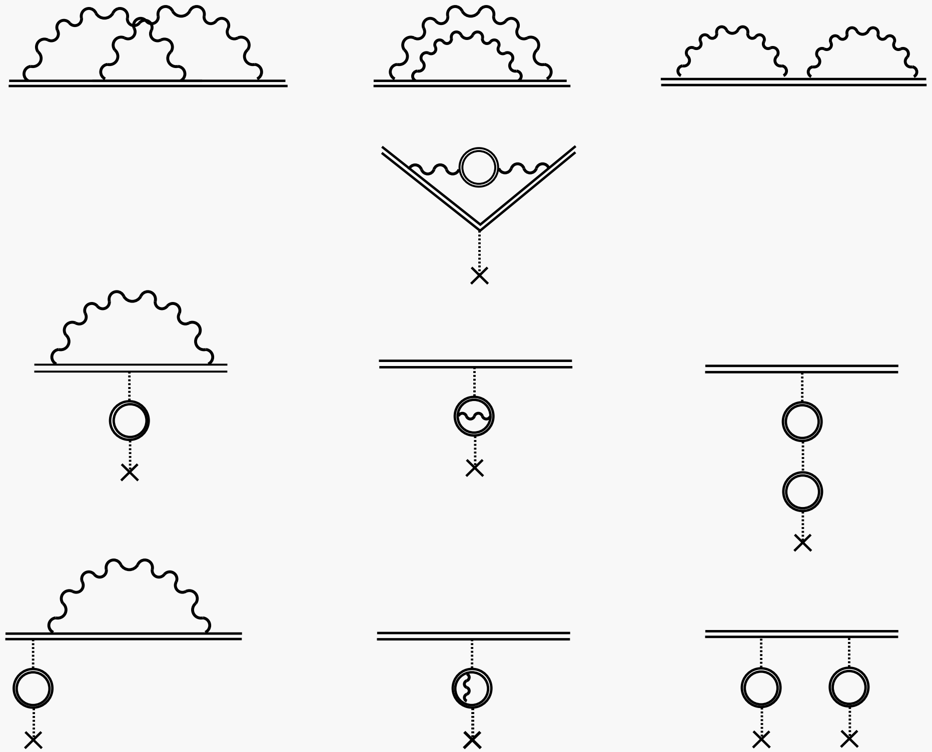
$g-2 \quad \rightarrow \quad$ electron anomaly: test of QED, determination of α, NP

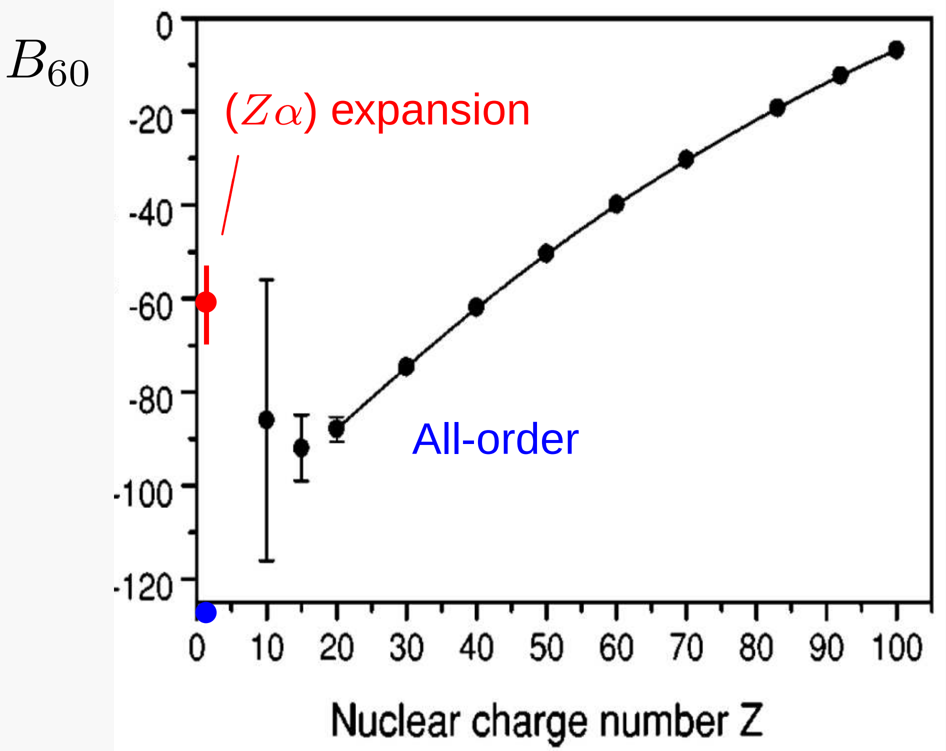
$$a_e = C_2 \left(\frac{\alpha}{\pi}\right) + C_4 \left(\frac{\alpha}{\pi}\right)^2 + C_6 \left(\frac{\alpha}{\pi}\right)^3 + C_8 \left(\frac{\alpha}{\pi}\right)^4 + C_{10} \left(\frac{\alpha}{\pi}\right)^5 + \Delta(\text{had., NP})$$

- Bound-state QED in Hydrogen

  - Binding effects ($Z\alpha$) — bad convergence, all-order approach/expansion
  - Radiative corrections (α and $Z\alpha$)
  - Recoil corrections (m/M and $Z\alpha$) — relativity $\not\Leftrightarrow$ two-body system
  - Radiative–recoil corrections (α, m/M and $Z\alpha$)
  - Proton structure corrections ($r_{\rm p}$, $r_{\rm Zemach}$ and $Z\alpha$)

Critical contributions in hydrogen





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

$B_{60} = -86(15)$, $G_{60}^{h.o.} = -101(15)$ Yerokin (2009)

$$G_n = B_{40} + (Z\alpha)B_{50} + (Z\alpha)^2\left[B_{63}\ln^3(Z\alpha)^{-2} + B_{62}\ln^2(Z\alpha)^{-2} + B_{61}\ln(Z\alpha)^{-2} + G_{h.o}\right] + \cdots$$

$$G_n = 1.409 - 0.177 \quad + [-0.015 - 0.003 + 0.026 - 0.003 + \cdots] \quad + \cdots$$

Bad convergence of the $(Z\alpha)$ expansion

Is the theory in hydrogen wrong?

- The critical terms are coming from two-loop contributions
- The difference between all-order and expansion approaches shifts the L_{1S} by 7 kHz
- Higher order remainder for the two-loop self-energy $G^{h.o}(Z=1) < 15$ kHz

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- The critical terms are coming from two-loop contributions
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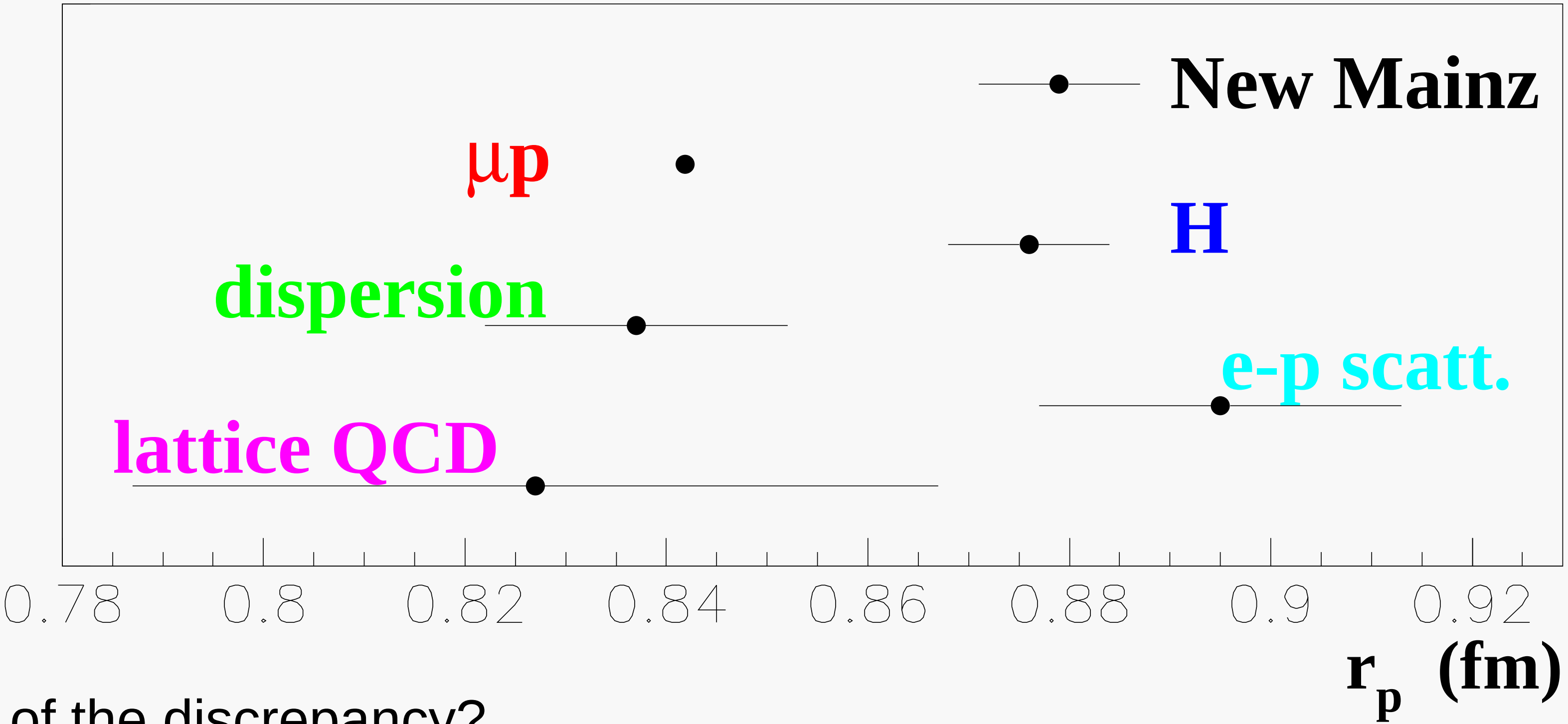
- Higher order remainder for the two-loop self-energy $G^{h.o}(Z=1) < 15$ kHz
- Compare these th. uncertainties with: $L_{1S}^{\rm exp} - L_{1S}^{\rm th}(r_{\rm p}^{\mu \rm p})$=96 kHz

The theory should be corrected by $25 \times \delta(\rm theory)$ to bring the value of $r_{\rm p}$ extracted from H-spectroscopy in agreement with our value

Proton radius puzzle



The origin of the discrepancy?

- QED th. in μp: 60 δ(theory)
- QED th. in H: 25 δ(theory)
- R_∞: 5 σ

- QED term(s) missing?
- Consistent use of r_p definition?
- Something fundametally wrong with bound-state QED? In muonic sector?
- New effects or new physics? In muonic sector? In proton sector?

- Bernauer et al. arXiv:1007.5076v2 (2010)
- Mohr at al., Rev. Mod. Phys. **80** 633 (2008)
- Belushkin et al., Phys. Rev. C **75** 035202 (2007)
- Sick, Phys. Lett. B **576** 62 (2003)
- Wang et al., Phys. Rev. D **79** 094001 (2009)

FAQ

Discrepancy = 75 GHz $\Leftrightarrow u_r = 10^{-3}$

- Pressure shift?

  - pressure shift of H(1S-2S) transition in H_2 gas ~ 10 MHz/mbar
  - μp is m_e/m_μ smaller (stronger E-fields).
    - less disturbed by external fields
    - smaller state mixing

MC simulations give a pressure shift of 1 MHz for 1 mbar

- Molecular formations leading to line shift?

$$\mu\mathrm{p}(2S) + H_2 \rightarrow \{[(\mathrm{pp}\mu)^+]^*\mathrm{p}ee\}^* \rightarrow \mu\mathrm{p}(1S) + \ldots\ .$$

  - If a molecule is formed there is immediate Auger emission followed by a deexcitation to the ground state.

Fitted linewidth corresponds to theoretically expected, and discrepancy=5Γ

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  - Dipole and Gauss models of proton shift the energy by < 500 MHz.
  - Fast convergence of the expansion:-5.19745$< r_{\rm p}^2 >$, -0.000043$< r_{\rm p}^2 >^2$.

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- Dark photons? Vector Bosons with few MeV mass? [Maxim Pospelov]...

  From simple atoms there are constraints on light bosons with ultraweak coupling

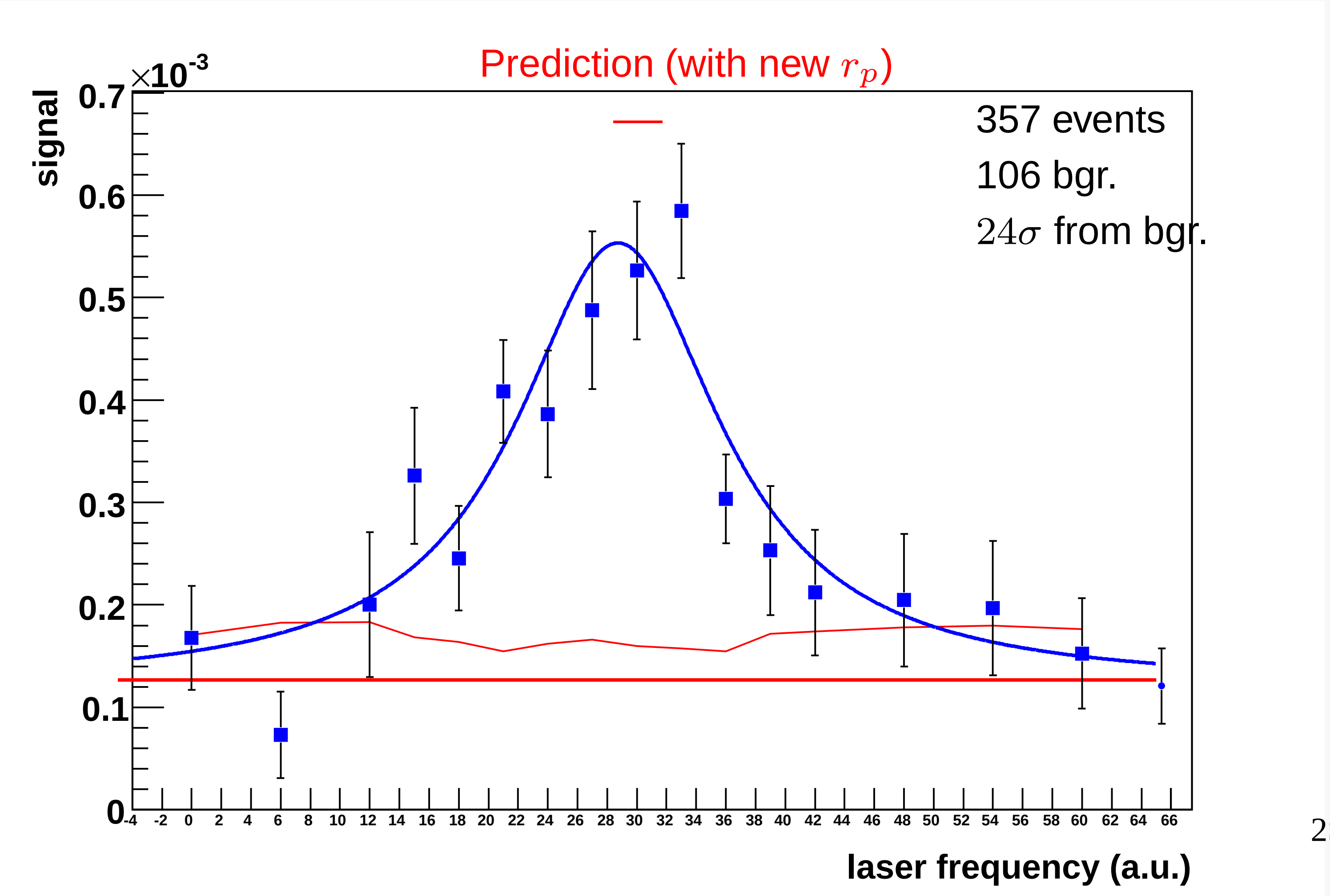
  Mass from 1 eV to 1 keV: $\alpha_{\text{spin}-\text{ind}} = 10^{-13}$, $\alpha_{\text{spin}-\text{dep}} = 10^{-17}$ [PRL 104,220406 (2010)]

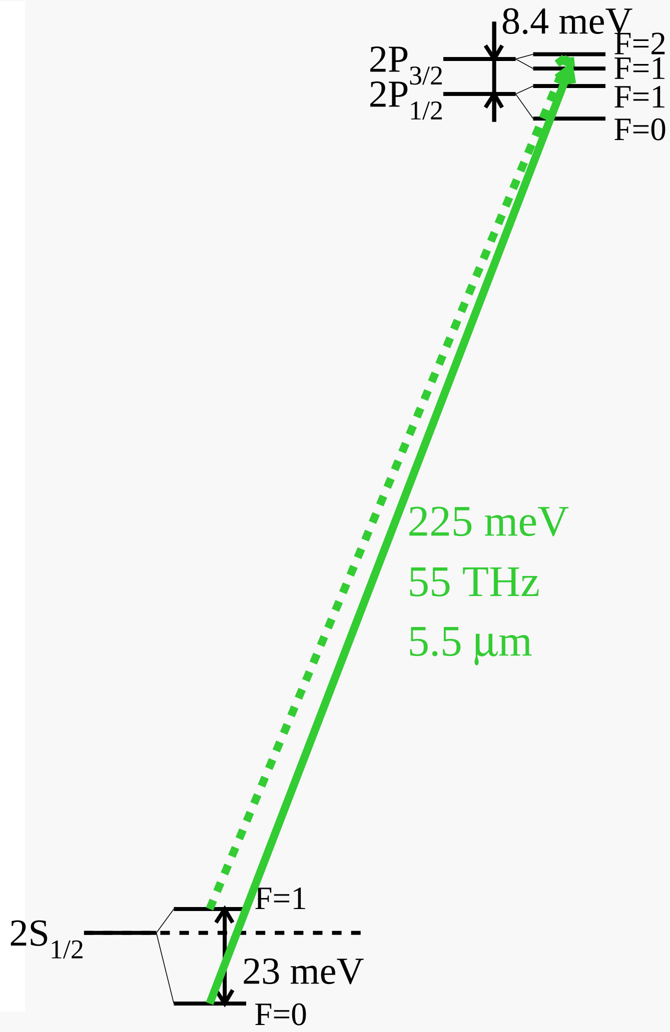
⋮

Suggestions?

Other measurements

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

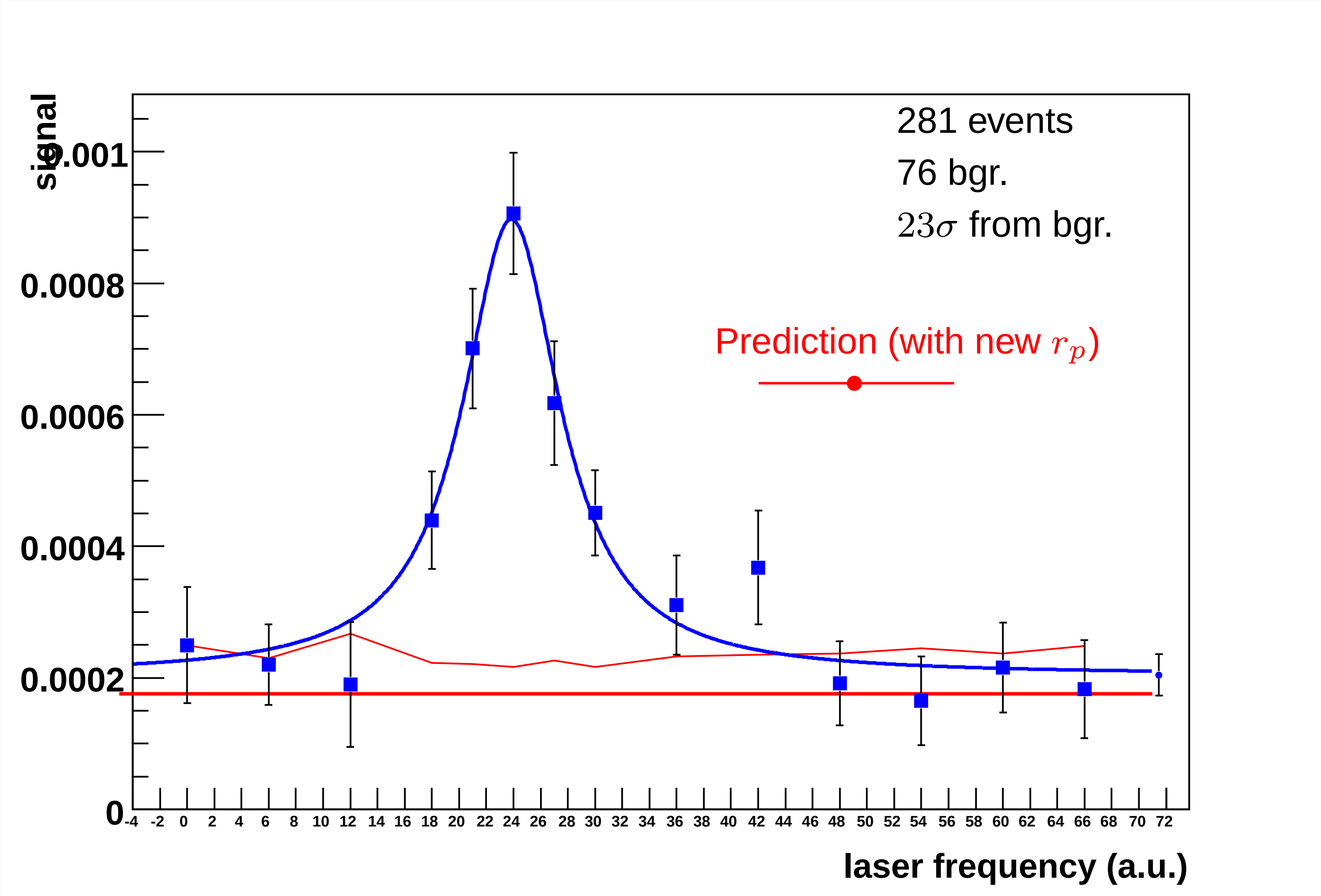




- $\sigma_{\rm position} = 1.1$ GHz $\Longleftrightarrow$ 25 ppm ($\Gamma = 19$ GHz)
- Position fits perfectly with theory using new $r_{\rm p}$

Extract HFS and $r_{\rm Zemach}$

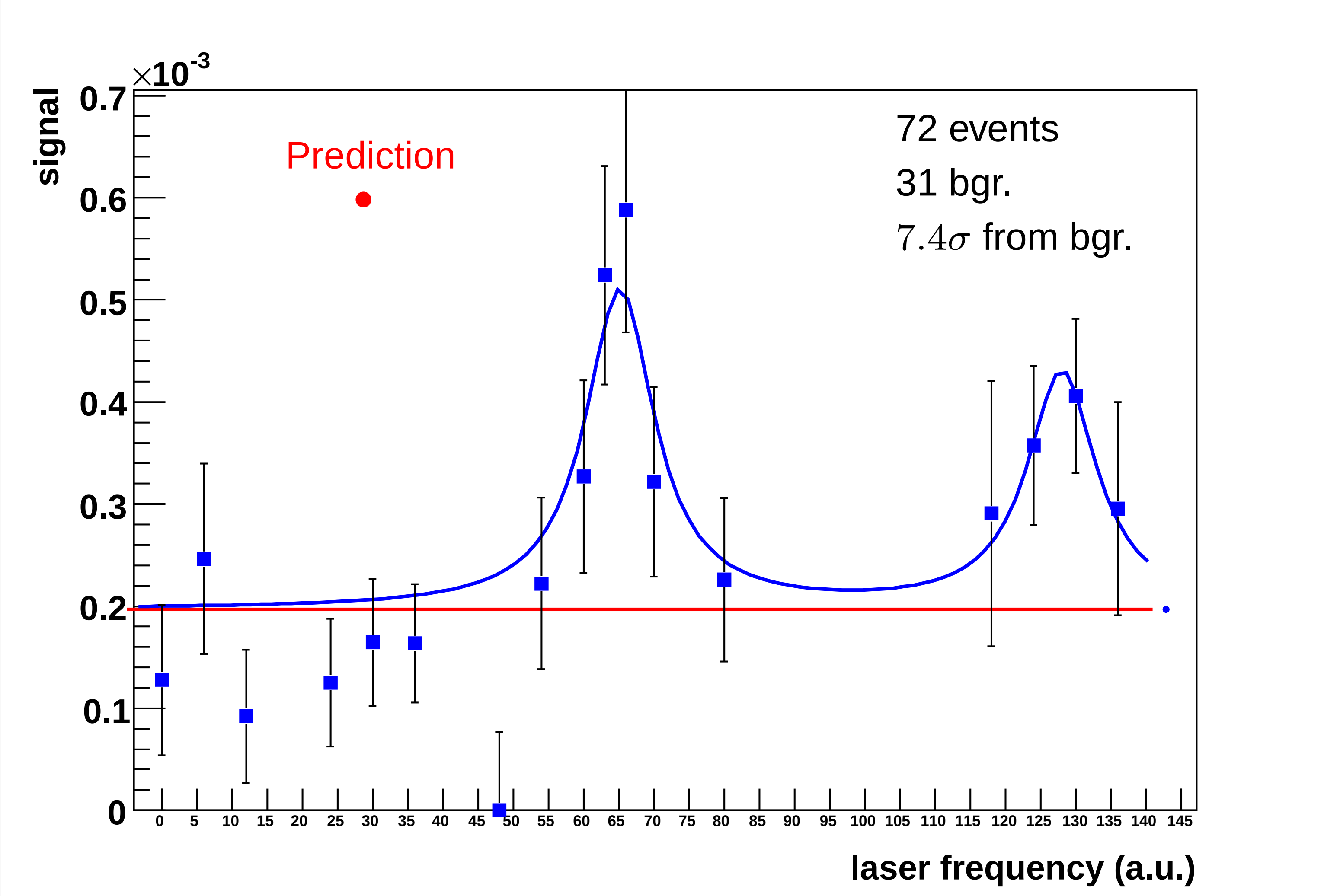
μd ($2S_{1/2}$(F=3/2) $\rightarrow$ $2P_{3/2}$(F=5/2))



- $\sigma_{\text{position}} = 880$ MHz $\Longleftrightarrow$ 17 ppm $(\Gamma = 19$ 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 $(\Gamma = 19$ GHz)
- Relative pos. fit to each others but not with the first μd line
- Background well know from previous μd line

The role of nuclear physics in atomic physics

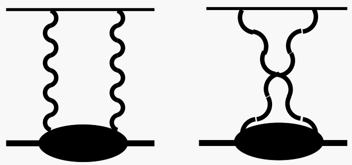
Atomic physics means high-precison measurements.
However their interpertations are usually limited by nuclear-physics effects

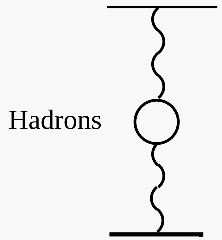
Interpertation of H, D, ^{3,4}He^{+}, μp, μd, $\mu^{3,4}$He^{+}:

- Lamb shifts limited by: r^2, shape, nucl. pol., hadronic VP pol.
- HFS limited by: Zemach radius, shape nucl. pol., hadronic VP pol.

muonic atoms

nucl. physics



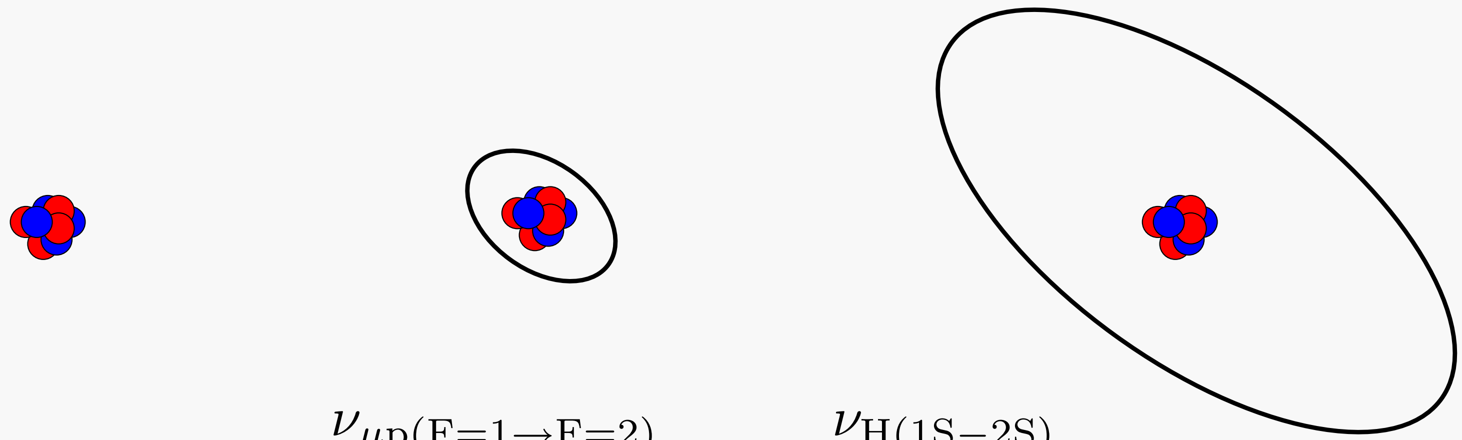


Bound-stated QED is important and interesting:

- Bindings effects and two-body problem (no exact solution)
- QED is essential to extract nucl. parameters from atomic meas. (or bound systems)

Atomic physics $\longleftrightarrow$ nuclear physics

Nucleus — Muonic atoms — "Normal" atoms



$\nu_{\mu p(F=1 \rightarrow F=2)}$ ↓ r_p

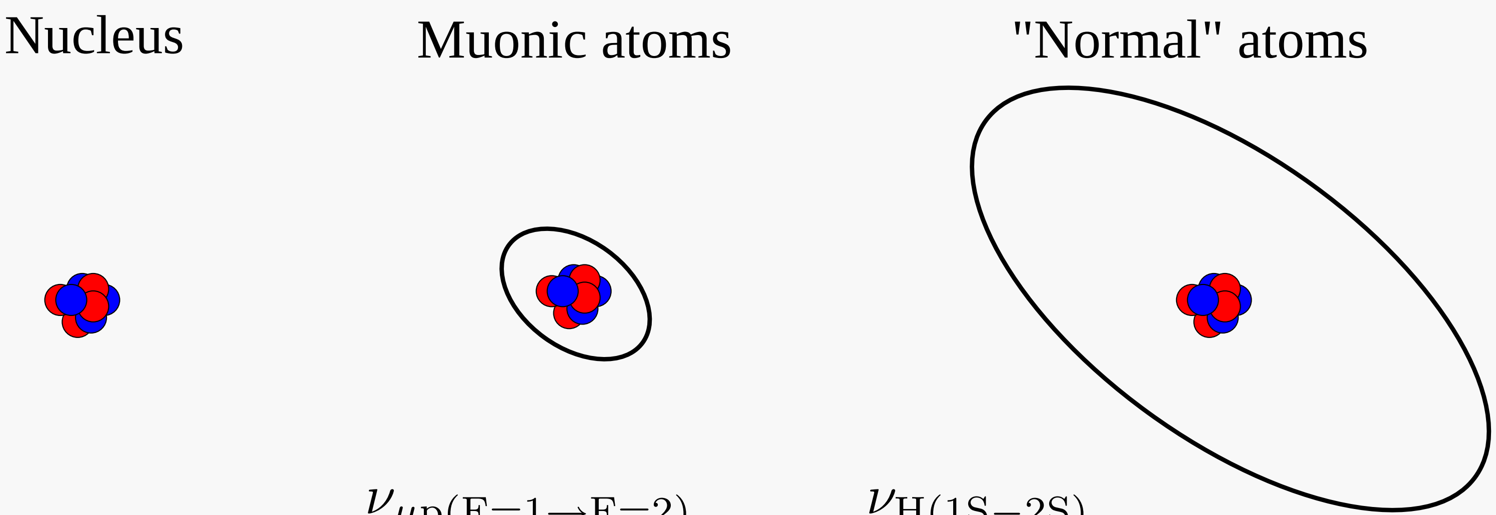
$\nu_{H(1S-2S)}$ ↓ Bound-state QED test

p. pol. ⟶ r_p ⟶ Bound-state QED test, Rydberg constant

r_p ⟶ Check p. model

Bound-state QED test ⟶ Bound-state th.

Atomic physics $\longleftrightarrow$ nuclear physics



$\nu_{\mu p(F=1 \rightarrow F=2)}$ → r_p

$\nu_{H(1S-2S)}$ → Bound-state QED test

p. pol. → r_p → Bound-state QED test

Rydberg constant

r_p → Check p. model

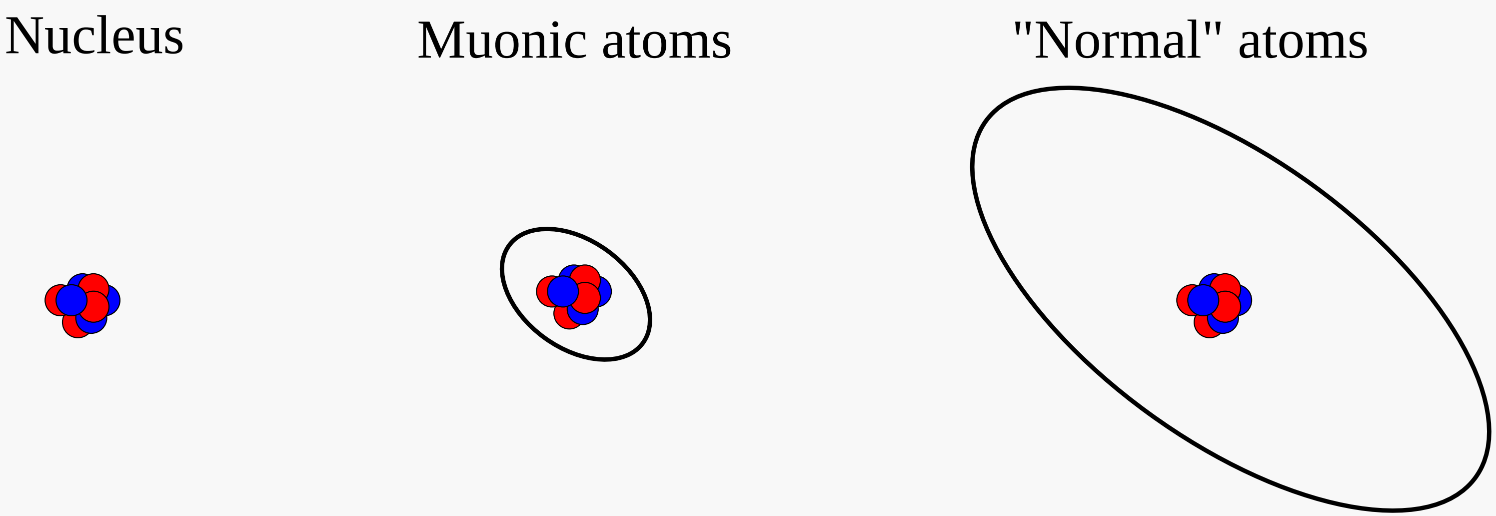
Rydberg constant → Bound-state th.

r_{Zemach} → Check p. spin th.

p. pol. (HFS) → r_{Zemach}

HFS=$\nu_{\mu p(F=1 \rightarrow F=2)} - \nu_{\mu p(F=0 \rightarrow F=1)}$ → r_{Zemach}

Isotope shift, $r_{\rm d}$ and deuteron pol.



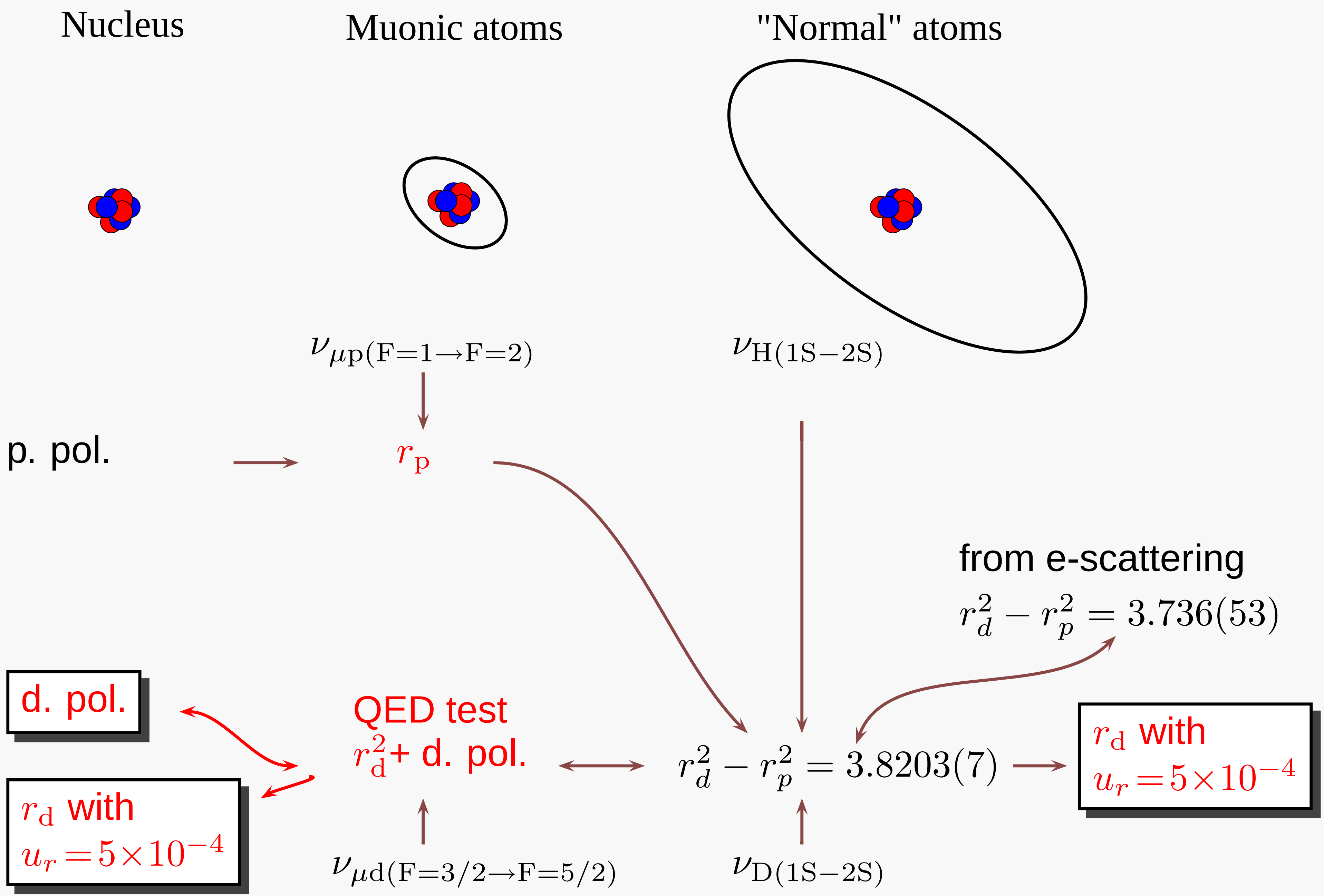
d. pol.

$r_{\rm d}$ with
$u_r = 5\times10^{-4}$

QED test
$r_{\rm d}^2$+ d. pol.

$\nu_{\mu\rm d(F=3/2\to F=5/2)}$

Isotope shift, r_d and deuteron pol.



Summary & outlook

- We have measured 5 transitions in μp and μd with 20 ppm accuracy

Need to solve the large observed discrepancy

H theory? | μp theory? | R_∞ wrong? | r_p definition?

Problems with bound-state QED?
Forgotten effects in proton, new physics?

- When (and if) discrepancy is solved:
  - r_p, r_d determination ($10\times$ better)
  - r_Zemach determination
  - Deuteron polarizability
  - R_∞ determination ($6\times$ better)
  - QED test in hydrogen/deuterium and muonic hydrogen/deuterium

Test of proton and deuteron models:
lattice QCD, few-nucleon ab initio th.

Best test of H energy levels
Fundamental constants

- New experiment: μHe$^+$
  - May illuminate discrepancy, enhance sensitivity to QED effects, few-nucleon th.

Like a Hollywood movie:

Everything goes bad till five minutes before THE END!

The Paul Scherrer Institute

Nothing can hide in hydrogen

The spectrum of hydrogen atom has proved to be the “Rosetta stone” of modern physics.

T.W. Hänsch