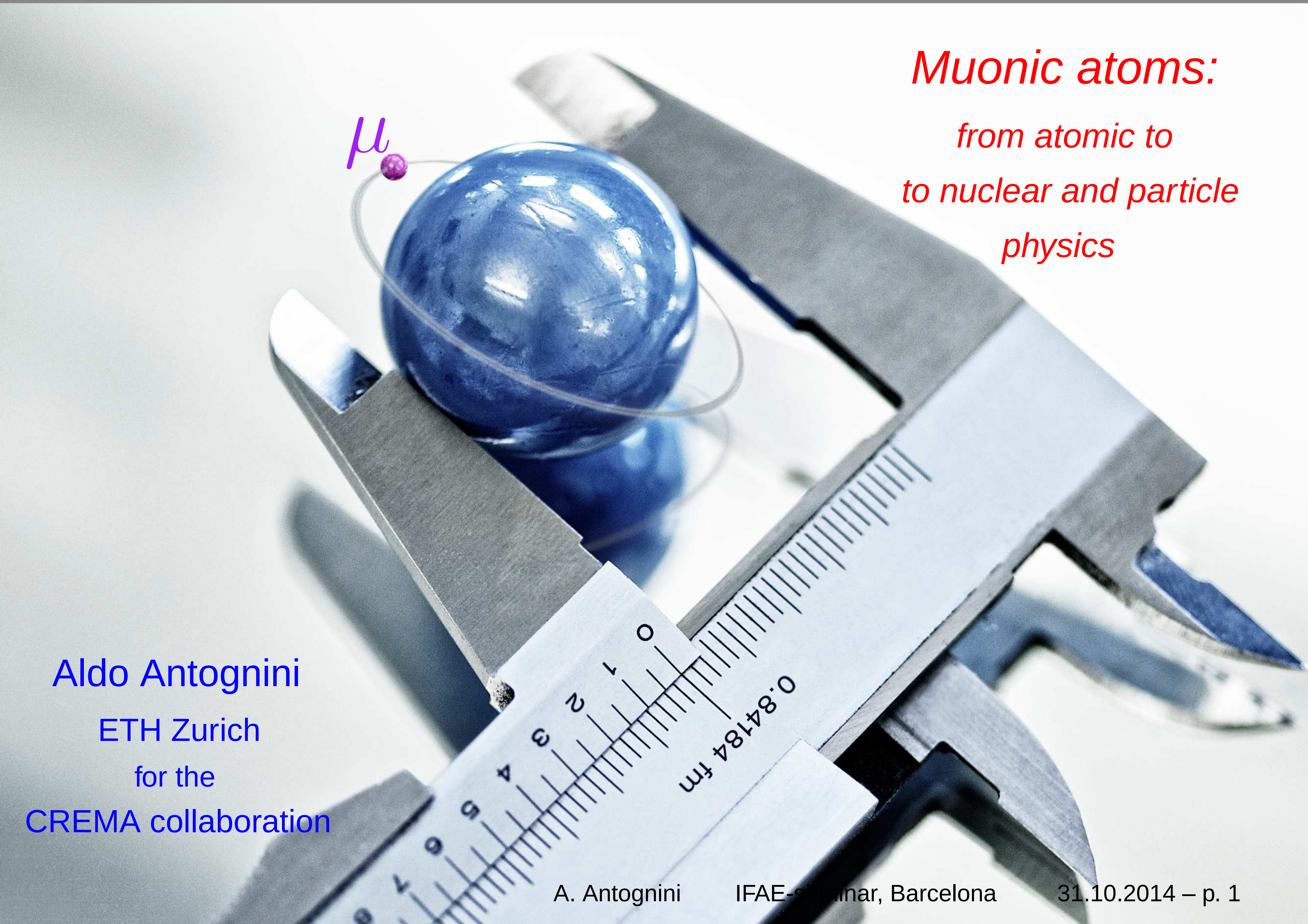


Muonic atoms:

from atomic to

to nuclear and particle physics

Aldo Antognini

ETH Zurich

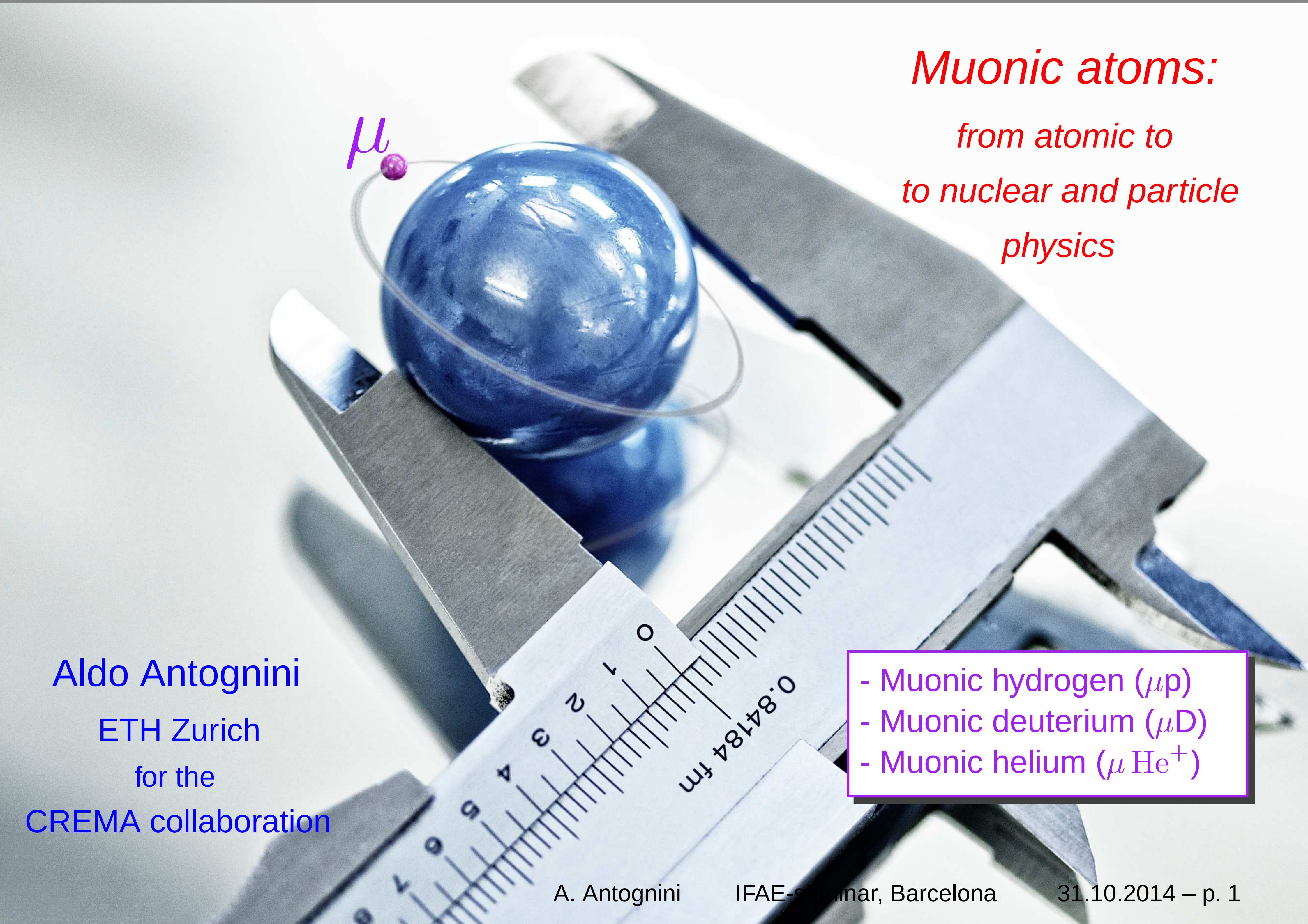
for the

CREMA collaboration

Muonic atoms:

from atomic to

to nuclear and particle physics



Aldo Antognini

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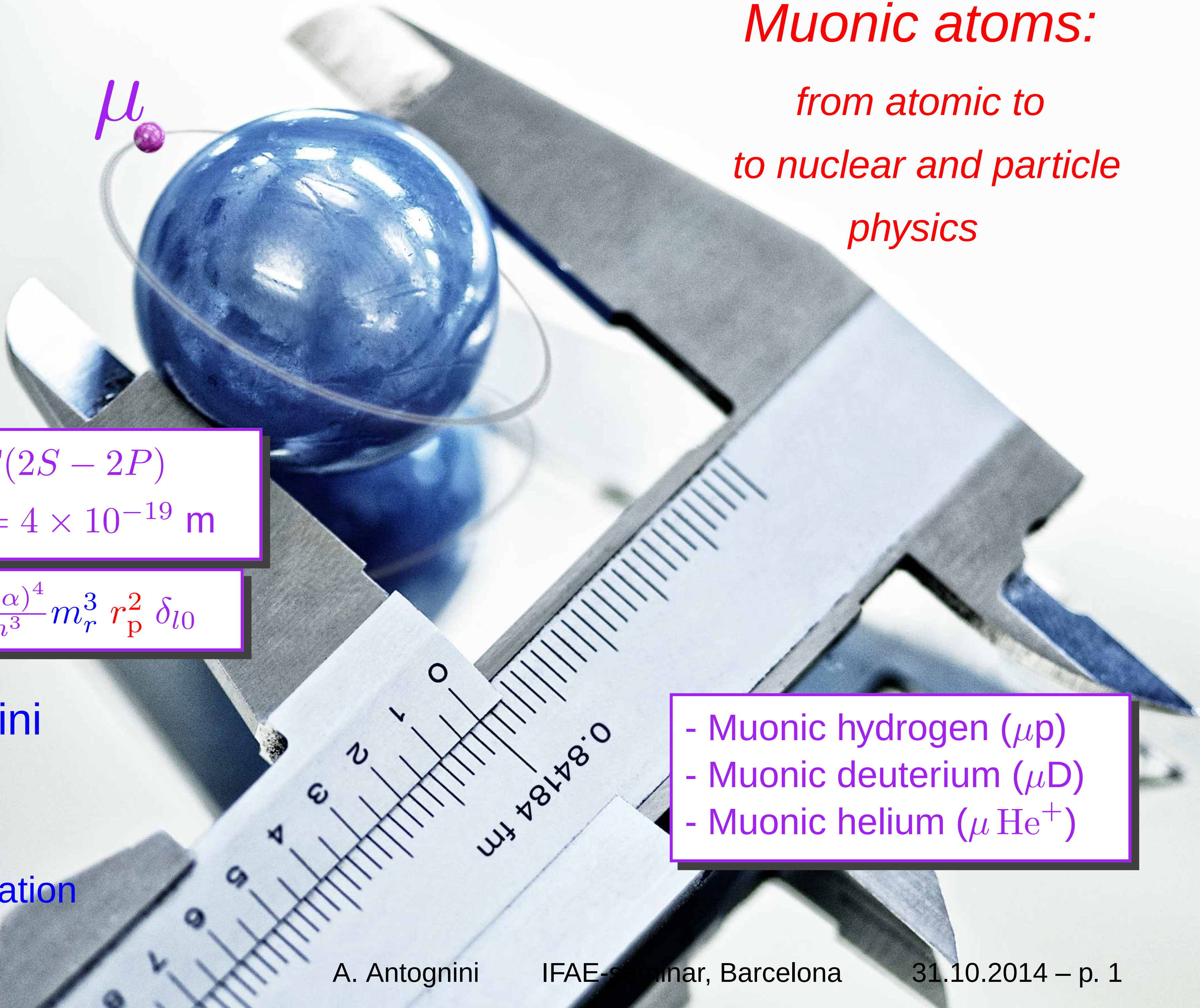
- Muonic hydrogen (μp)
- Muonic deuterium (μD)
- Muonic helium ($\mu\,\mathrm{He}^+$)

Muonic atoms:

from atomic to

to nuclear and particle physics



Measure $\Delta E(2S - 2P)$

$\rightarrow\ r_{\rm p}$ with $\delta r_{\rm p} = 4 \times 10^{-19}$ m

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

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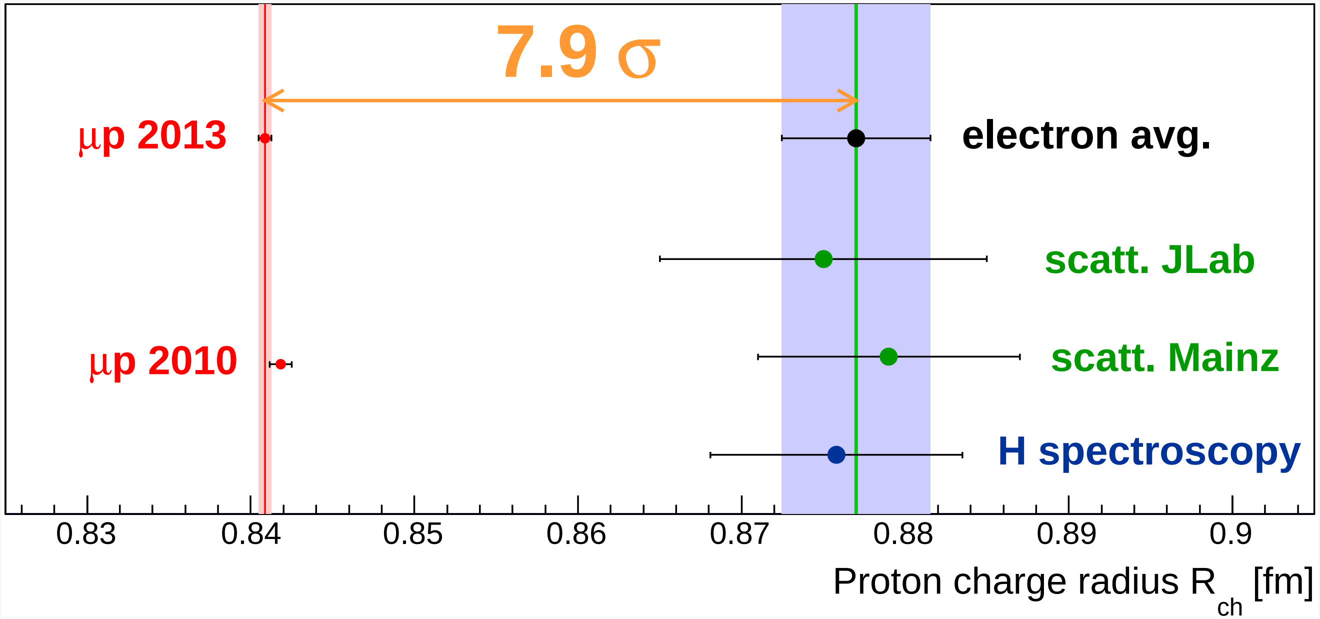
CREMA collaboration

- Muonic hydrogen (μp)
- Muonic deuterium (μD)
- Muonic helium ($\mu\,\mathrm{He}^+$)

The proton radii puzzle

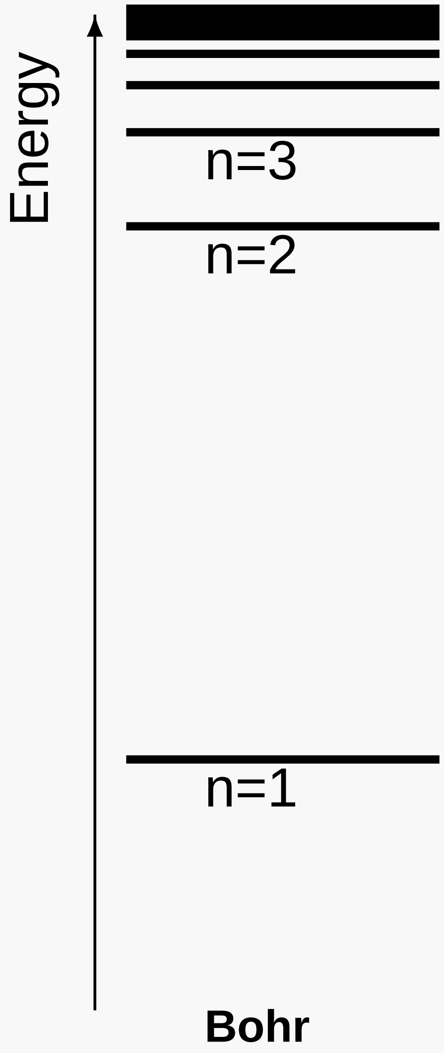
3 ways to the proton radius

e-p scattering
H precision laser spectroscopy
μp laser spectroscopy



Pohl *et al.*, Nature 466, 213 (2010)
Antognini *et al.*, Science 339, 417 (2013)

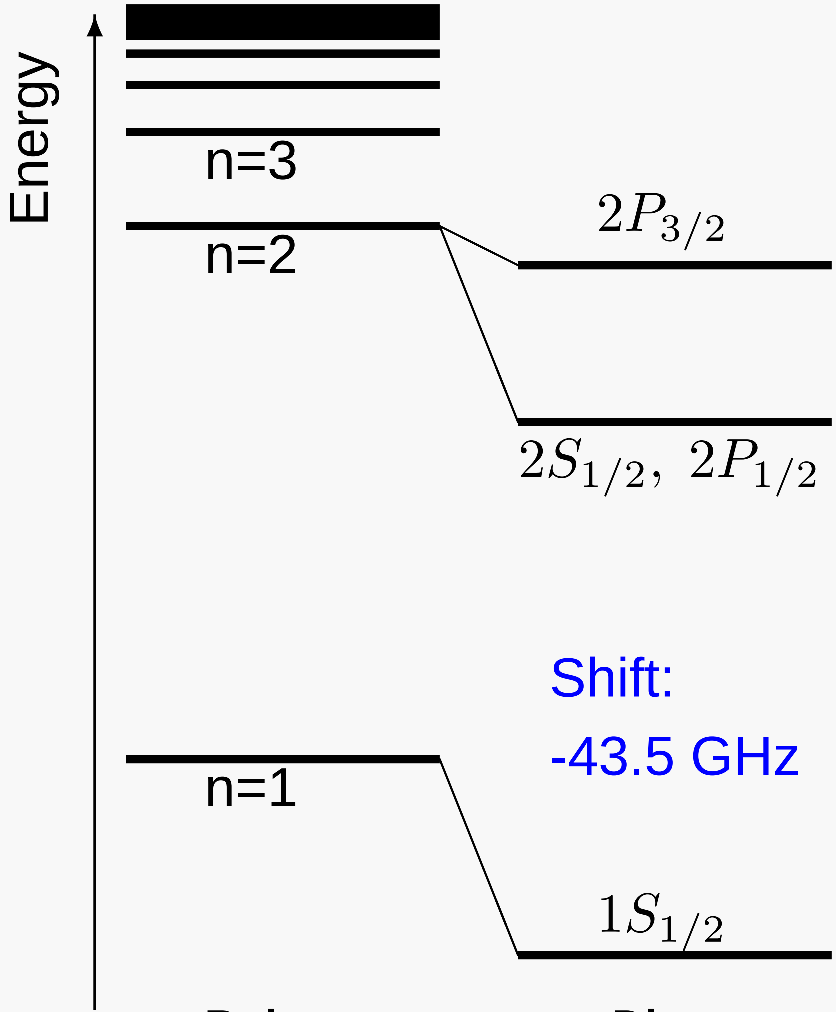
Hydrogen energy levels and r_p



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

$$V \sim 1/r$$

Hydrogen energy levels and $r_{\rm p}$



Bohr

$E = R_\infty / n^2$

$V \sim 1/r$

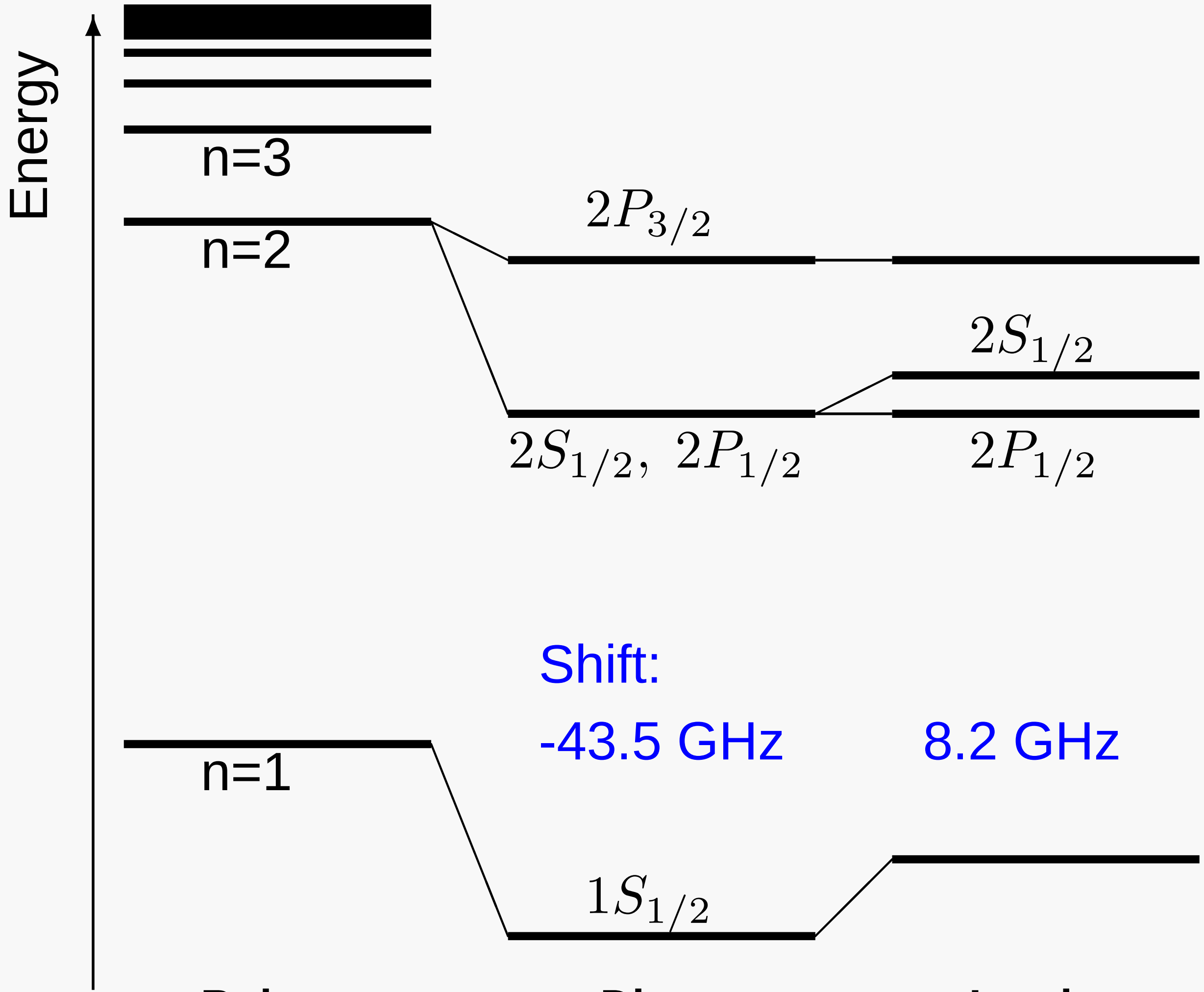
Dirac

e$^-$ spin

relativity

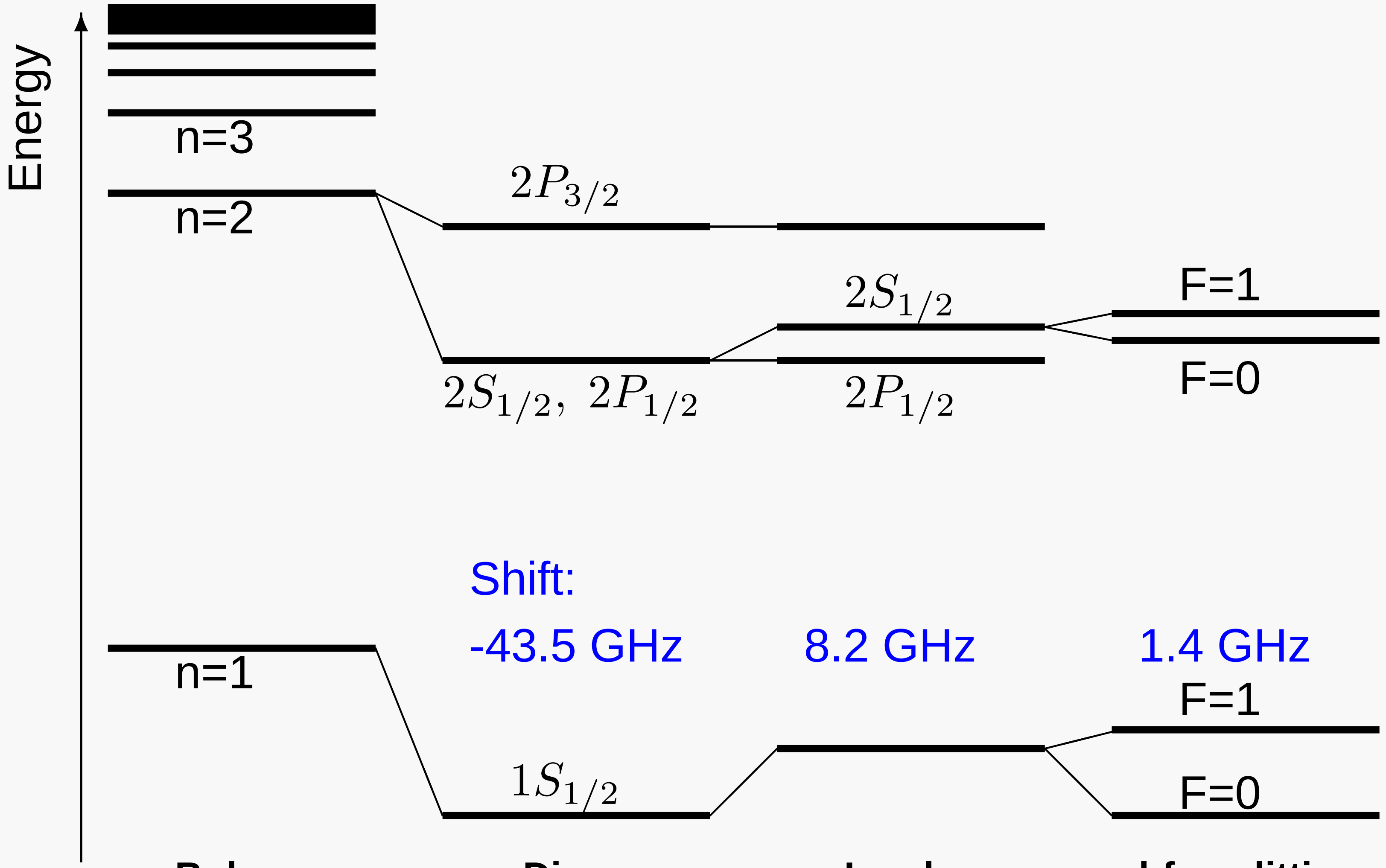
$(H^{\rm fs} \sim \vec{L}\cdot\vec{S})$

Hydrogen energy levels and r_p



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

Hydrogen energy levels and r_p



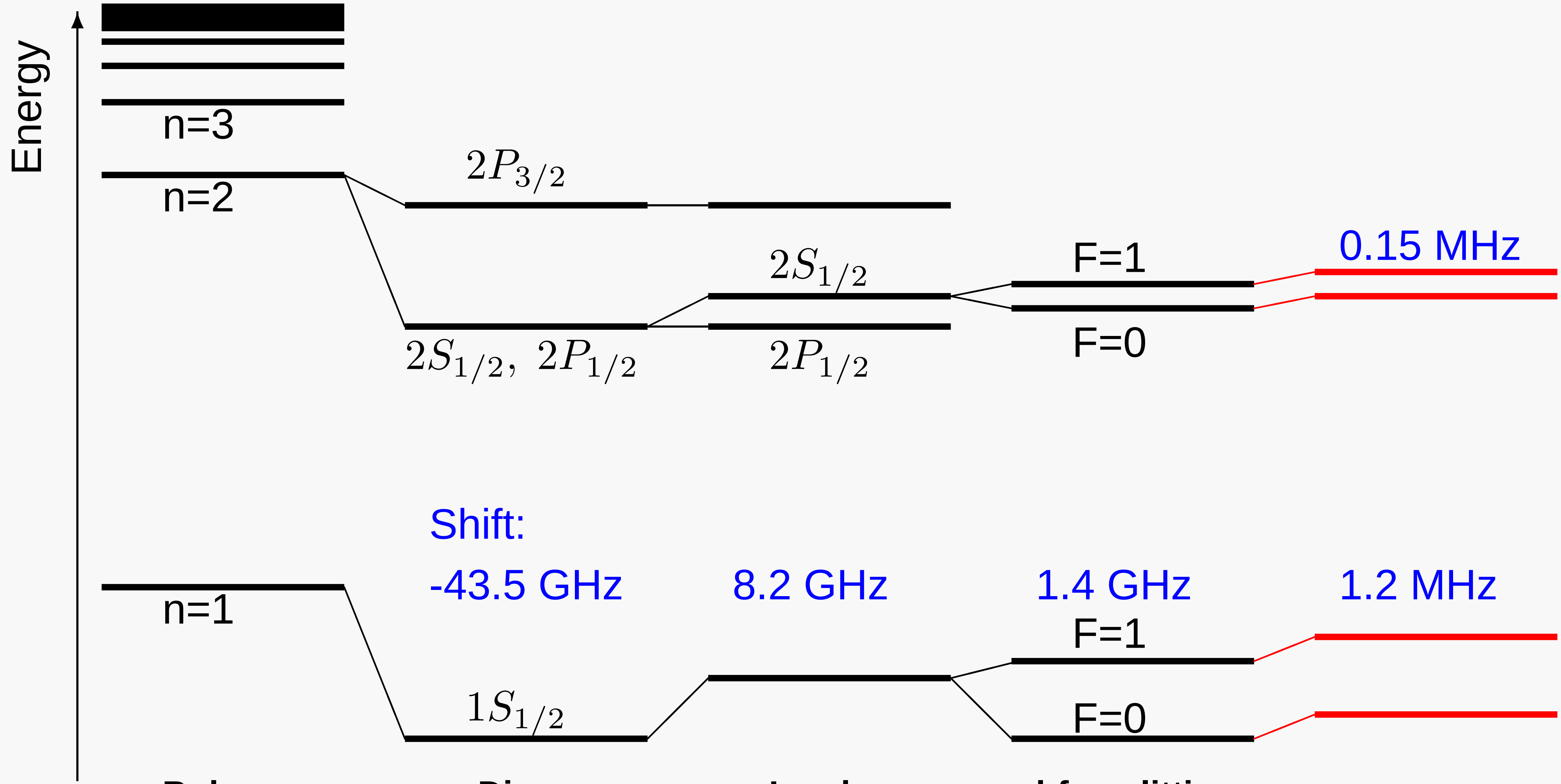
$E = R_\infty / n^2$
$V \sim 1/r$

e$^-$ spin
relativity
($H^{\mathrm{fs}} \sim \vec{L}\cdot\vec{S}$)

QED

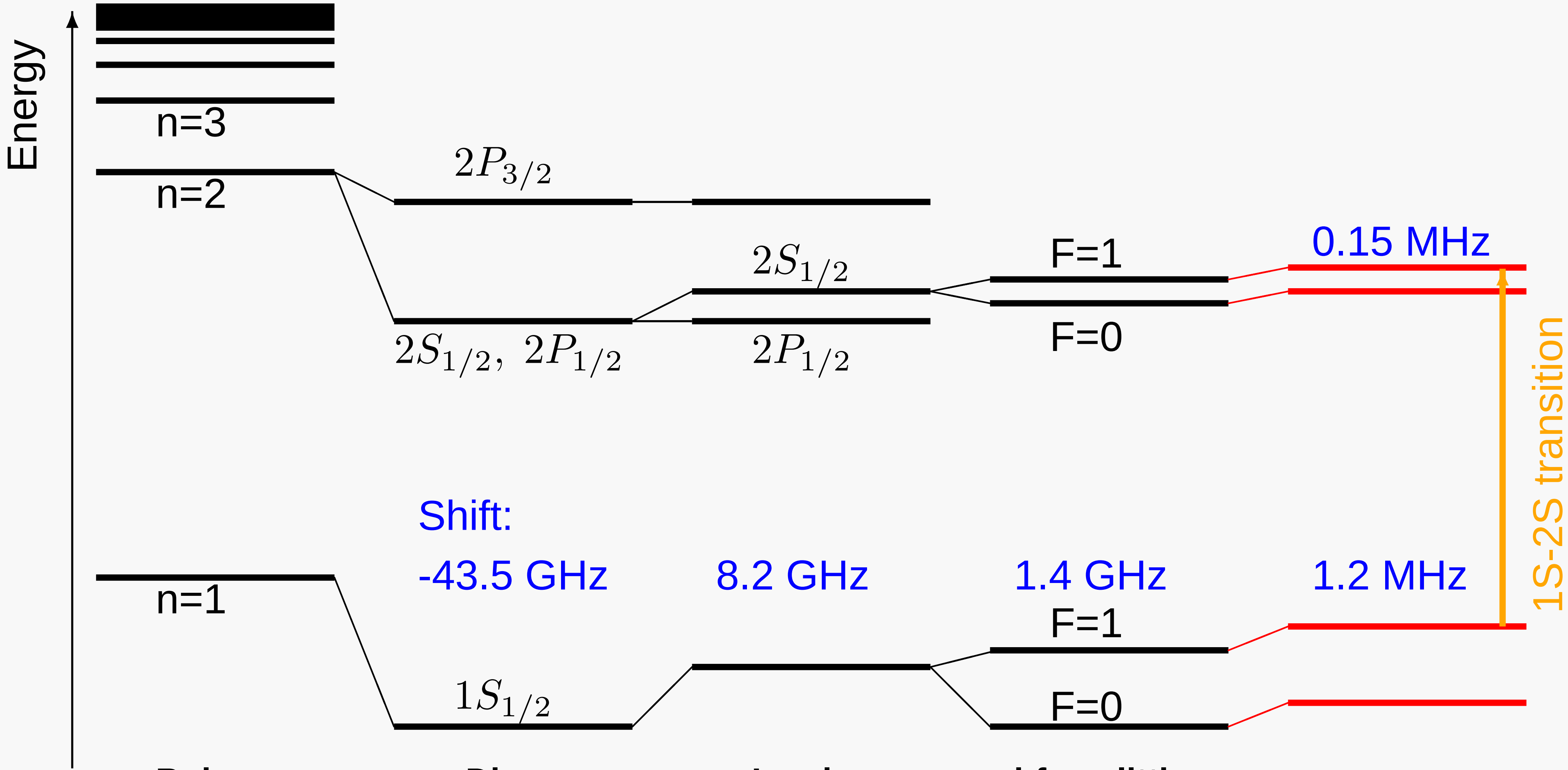
proton-spin
$H^{\mathrm{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$

Hydrogen energy levels and r_p



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

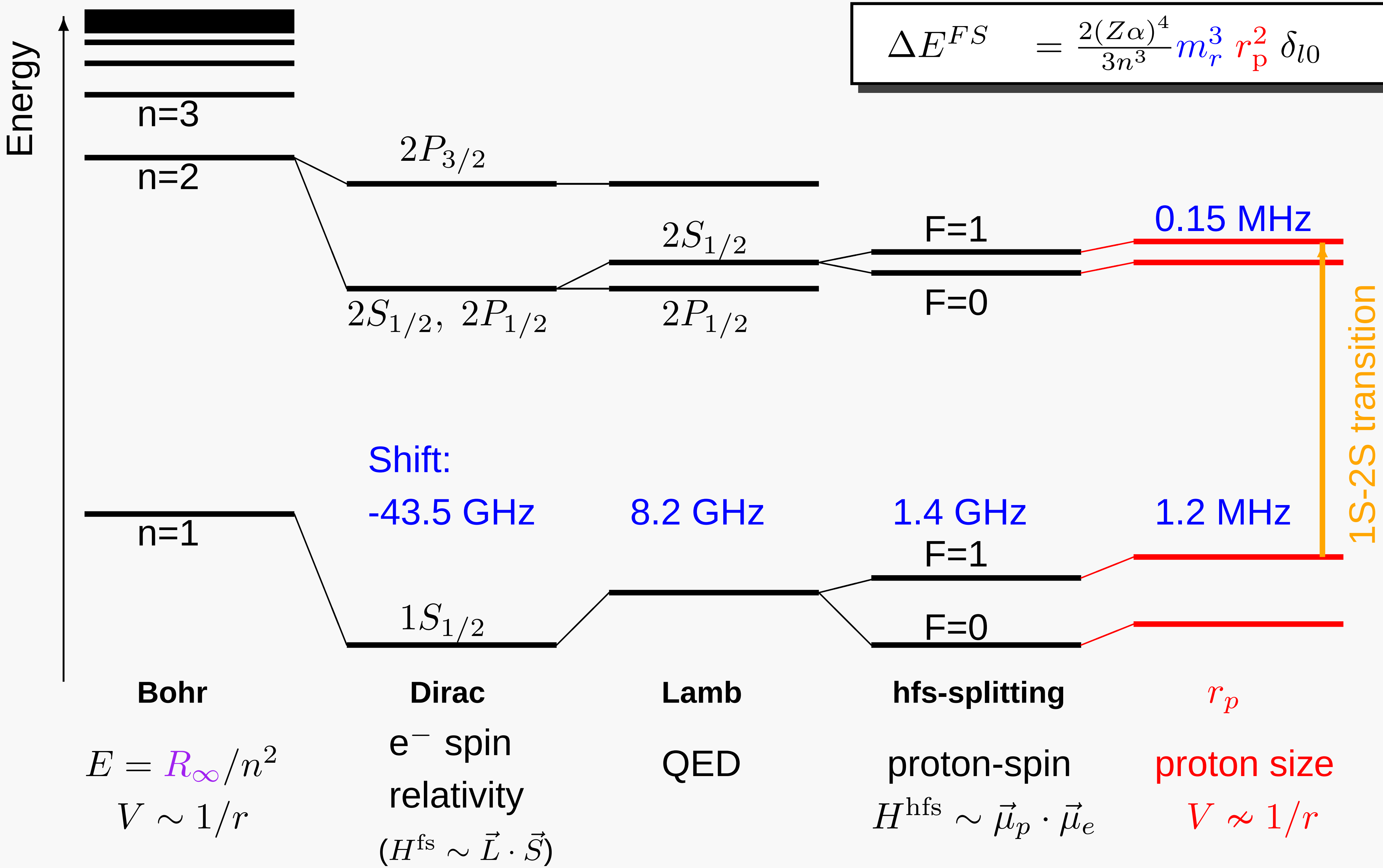
Hydrogen energy levels and r_p



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

Hydrogen energy levels and r_p

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

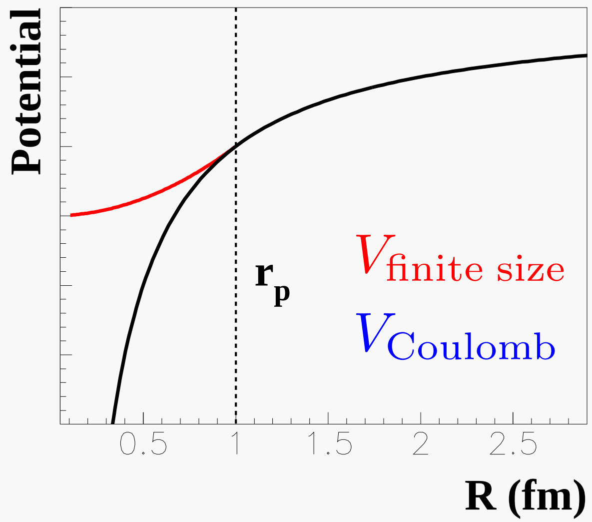


Atomic energy levels and the proton size

$$\Delta E = \Delta E_{\rm QED} + \Delta E_{\rm fs}$$

$$\Delta E^{(0)}_{\rm fs} = \frac{2\pi(Z\alpha)}{3}\,\langle r_{\rm p}^2\rangle\,|\Psi_n(0)|^2 = \frac{2(Z\alpha)^4}{3n^3} m_r^3\,\langle r_{\rm p}^2\rangle\,\delta_{l0}$$

$$m_\mu \approx 200 m_e$$



From $\bar{\nabla}\cdot\bar{E} = 4\pi\rho \rightarrow$ potential V

$$\Delta E^{(0)}_{\rm fs} = \langle\bar{\Psi}|V_{\rm Coulomb} - V_{\rm fin.size}|\Psi\rangle$$

Atomic energy levels and the proton size

$$\Delta E = \Delta E_{\rm QED} + \Delta E_{\rm fs}$$

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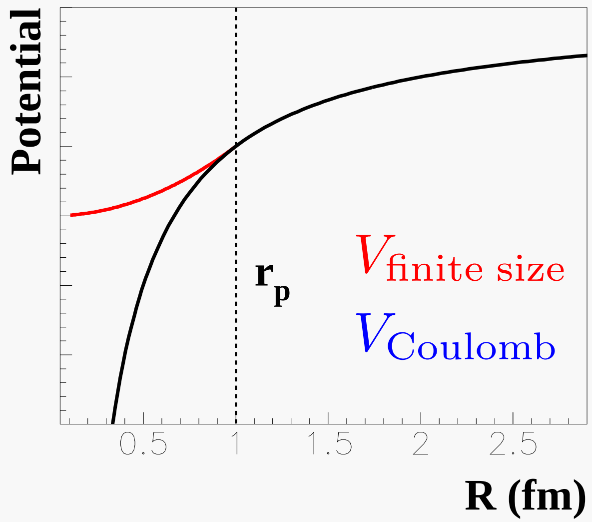


From $\bar{\nabla} \cdot \bar{E} = 4\pi\rho \rightarrow$ potential V

$$\Delta E^{(0)}_{\rm fs} = \langle \bar{\Psi} | V_{\rm Coulomb} - V_{\rm fin.size} | \Psi \rangle$$

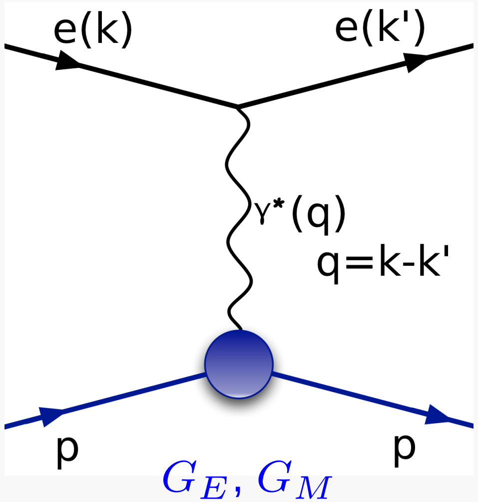
$$G_E(\mathbf{q^2}) = \int d^3r \, \rho_E(\mathbf{r}) e^{-i\mathbf{q}\cdot\mathbf{r}} \simeq Z(1 - \frac{\mathbf{q^2}}{6} r_{\rm p}^2 + \cdots)$$

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

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

$$\Delta V(\mathbf{q}) = \frac{4\pi Z\alpha}{\mathbf{q}^2} \left(1 - G_E(\mathbf{q^2})\right) \simeq \frac{2\pi(Z\alpha)}{3} r_{\rm p}^2$$

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

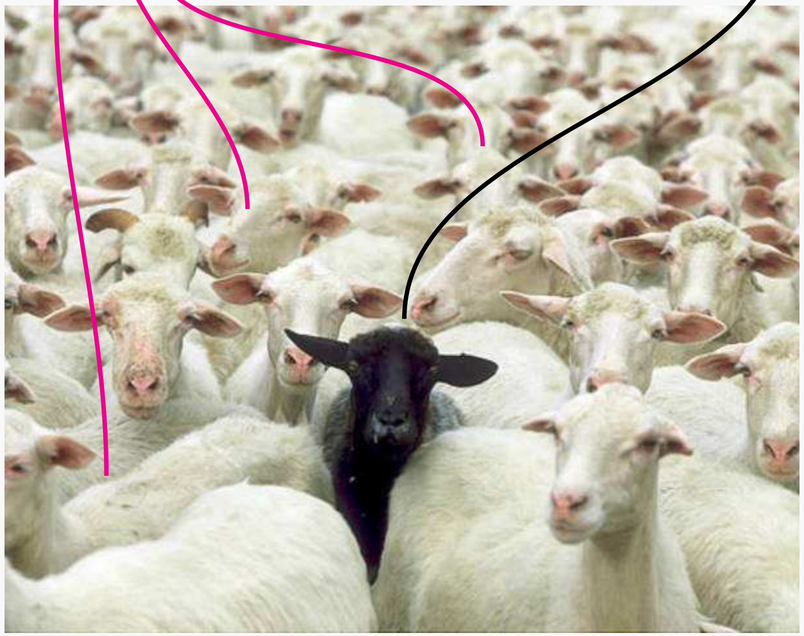


Proton radius from muonic hydrogen

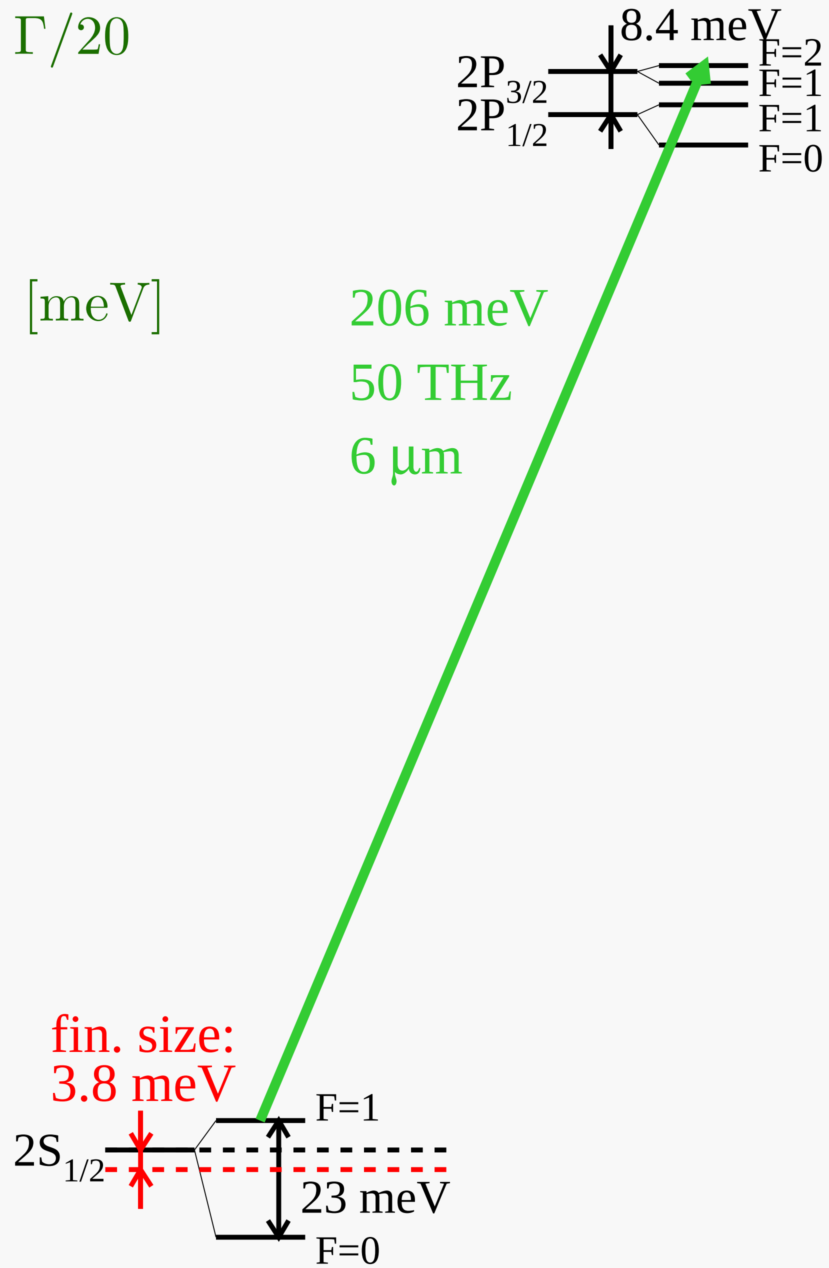
- Measure $\Delta E^{\rm exp}_{2P-2S}$ in μp with $u_r = 10^{-5} \leftrightarrow 0.5$ GHz $= \Gamma/20$

- Compute theoertical prediction

$$\Delta E^{\rm th}_{2P-2S} = 206.0336(15) - 5.2275(10)\, r_{\rm p}^2 + 0.0332(20) \quad [\text{meV}]$$



The Lamb shift contributions



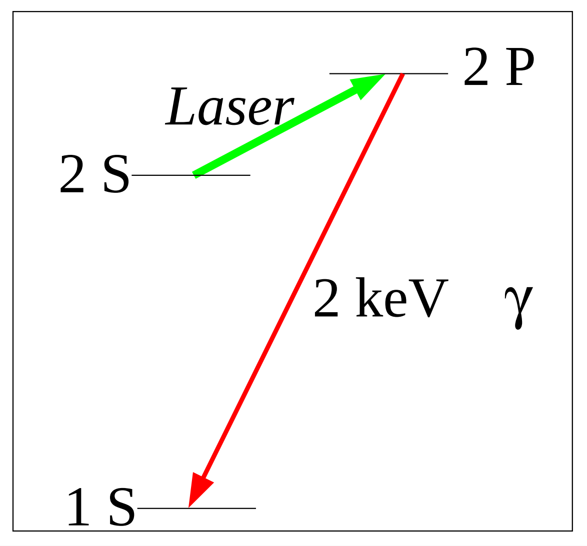
Comparing theory with experiment $\Longrightarrow r_{\rm p}$

Principle of the μp Lamb shift experiment

- Produce many μ^- → PSI accelerator

- Stop μ^- in 1 mbar H_2 gas
  $\rightarrow$ μp formation
  (1% in the 2S-state with 1μs lifetime) → Dedicated low-energy μ^- beam line

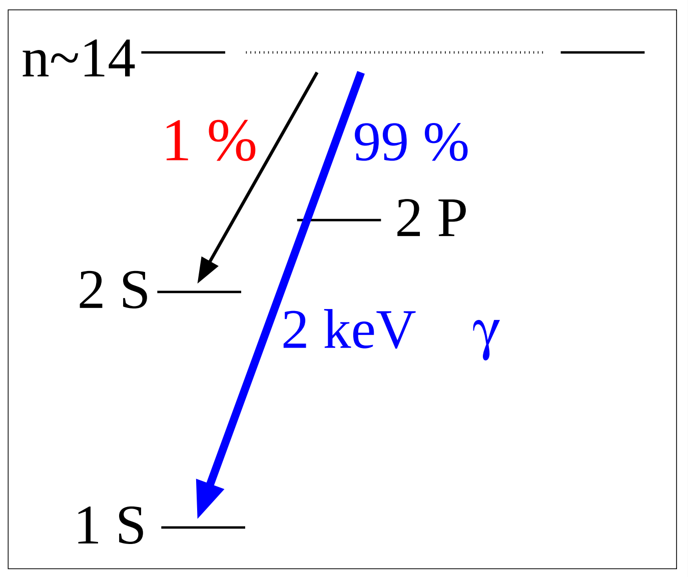
- Fire laser at $\lambda = 6\mu$m
  $\rightarrow$ to induce $\mu\text{p}(2S) \rightarrow \mu\text{p}(2P)$ transition → Dedicated laser system with "strange" requirements



- If laser resonant
  $\rightarrow$ observe 2 keV x-rays → 2 keV x-ray detectors

Principle of the μp Lamb shift experiment

"prompt" ($t = 0$)



μ^- stop in H_2 gas

$\rightarrow \mu$p* formation ($n \sim 14$)

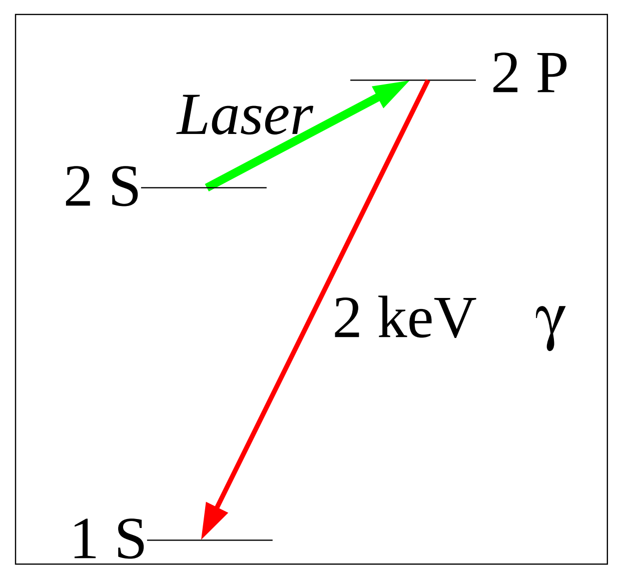
99% cascate to μp(1S)

emitting prompt K_α, $K_\beta \ldots$

1% long-lived μp($2S$)

$\tau_{2S} \approx 1\mu$s at 1 mbar H_2 pressure

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



fire laser at $\lambda = 6\mu$m, ΔE=0.2 eV

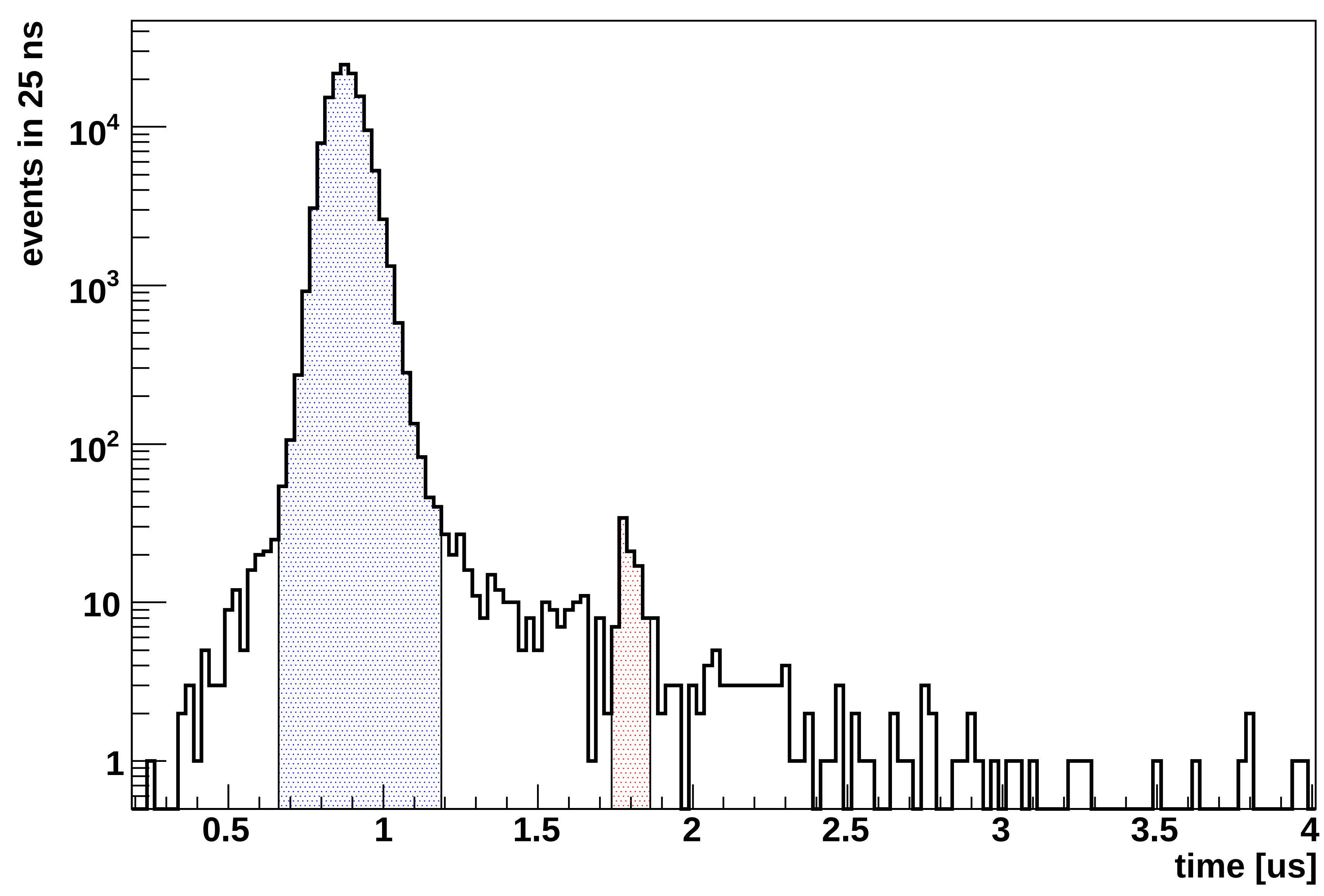
$\Rightarrow$ induce $\mu\mathrm{p}(2S) \rightarrow \mu\mathrm{p}(2P)$ transition

$\Rightarrow$ observe delayed K_α x-rays

$\Rightarrow$ normalize $\frac{\mathrm{delayedK}_\alpha}{\mathrm{promptK}_\alpha}$

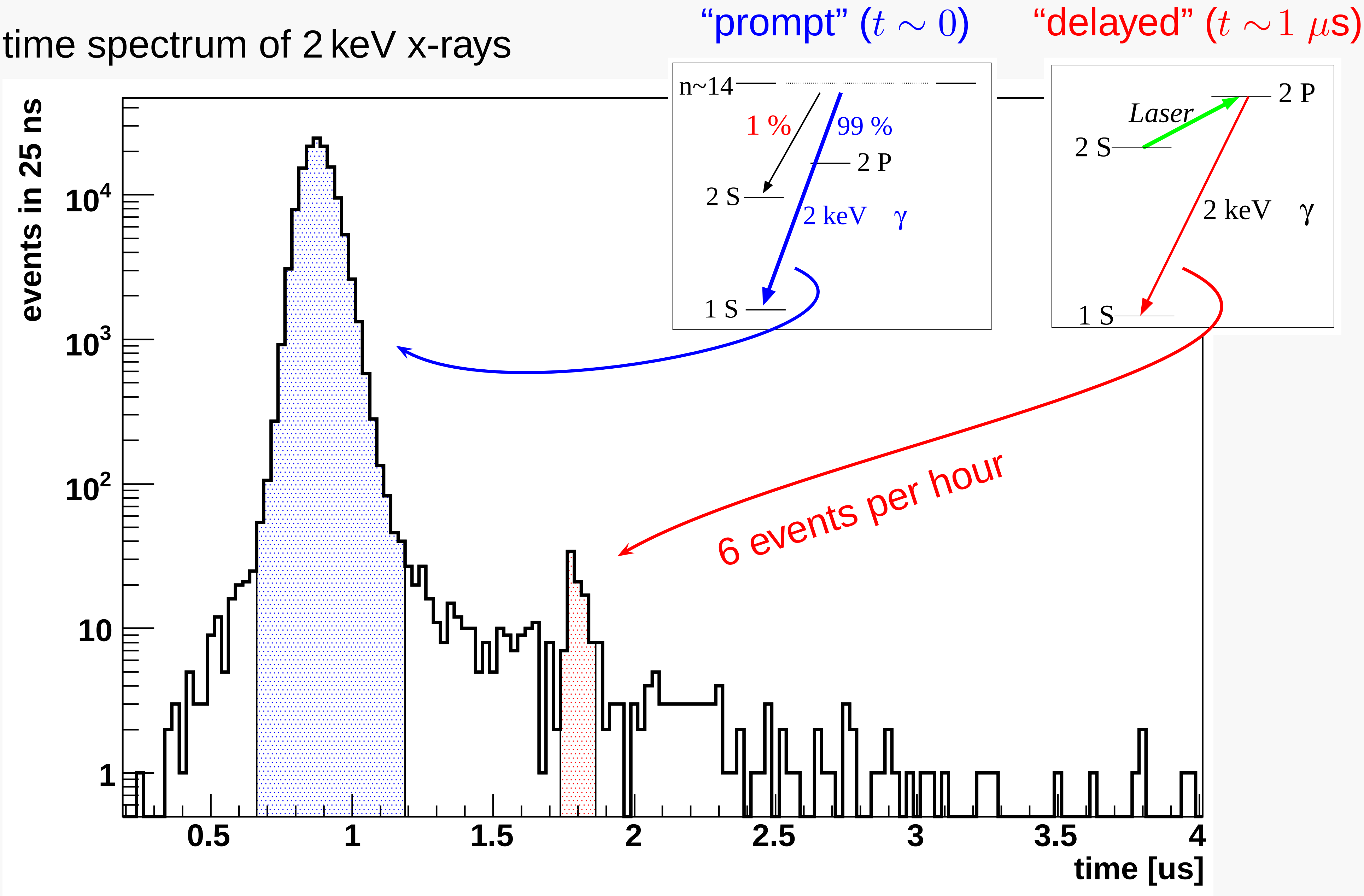
Principle of the μp Lamb shift experiment

time spectrum of 2 keV x-rays



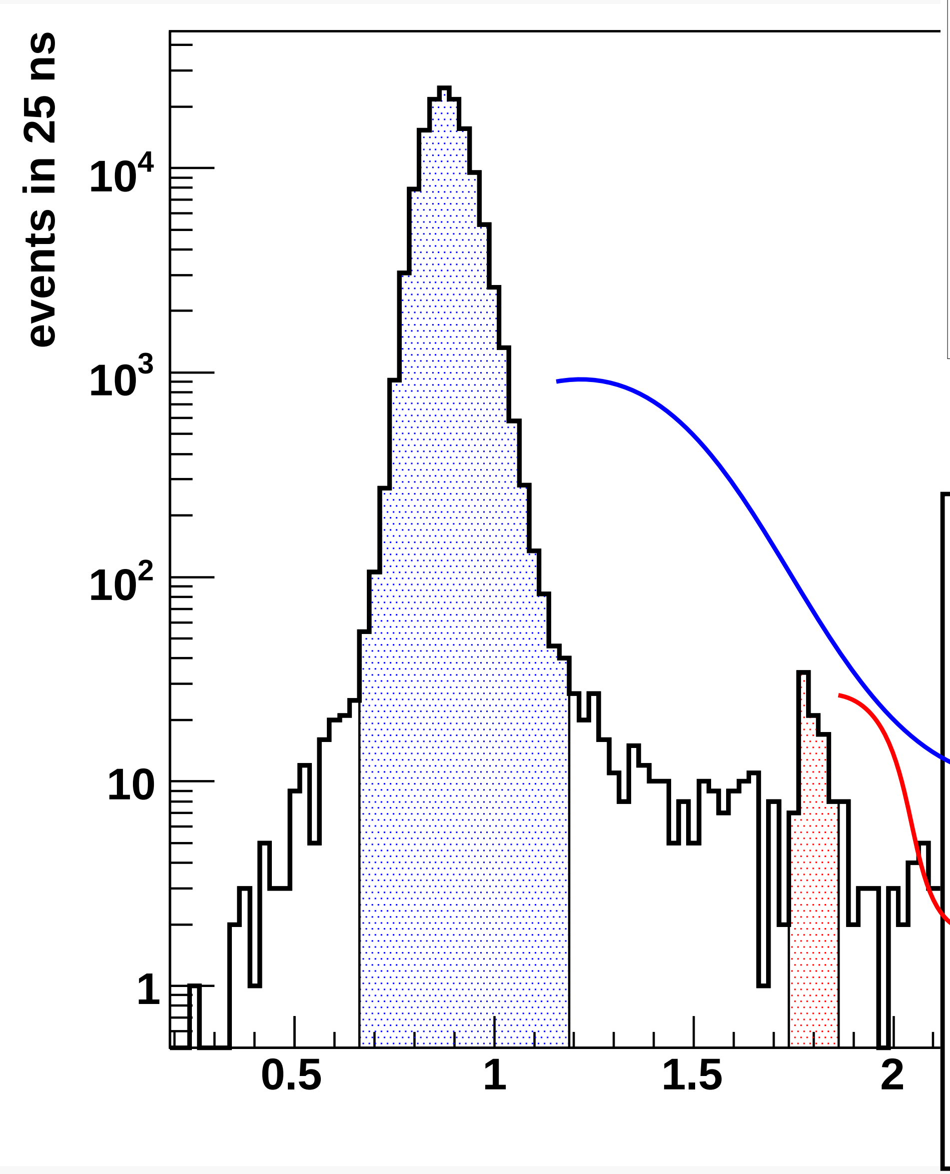
Principle of the μp Lamb shift experiment

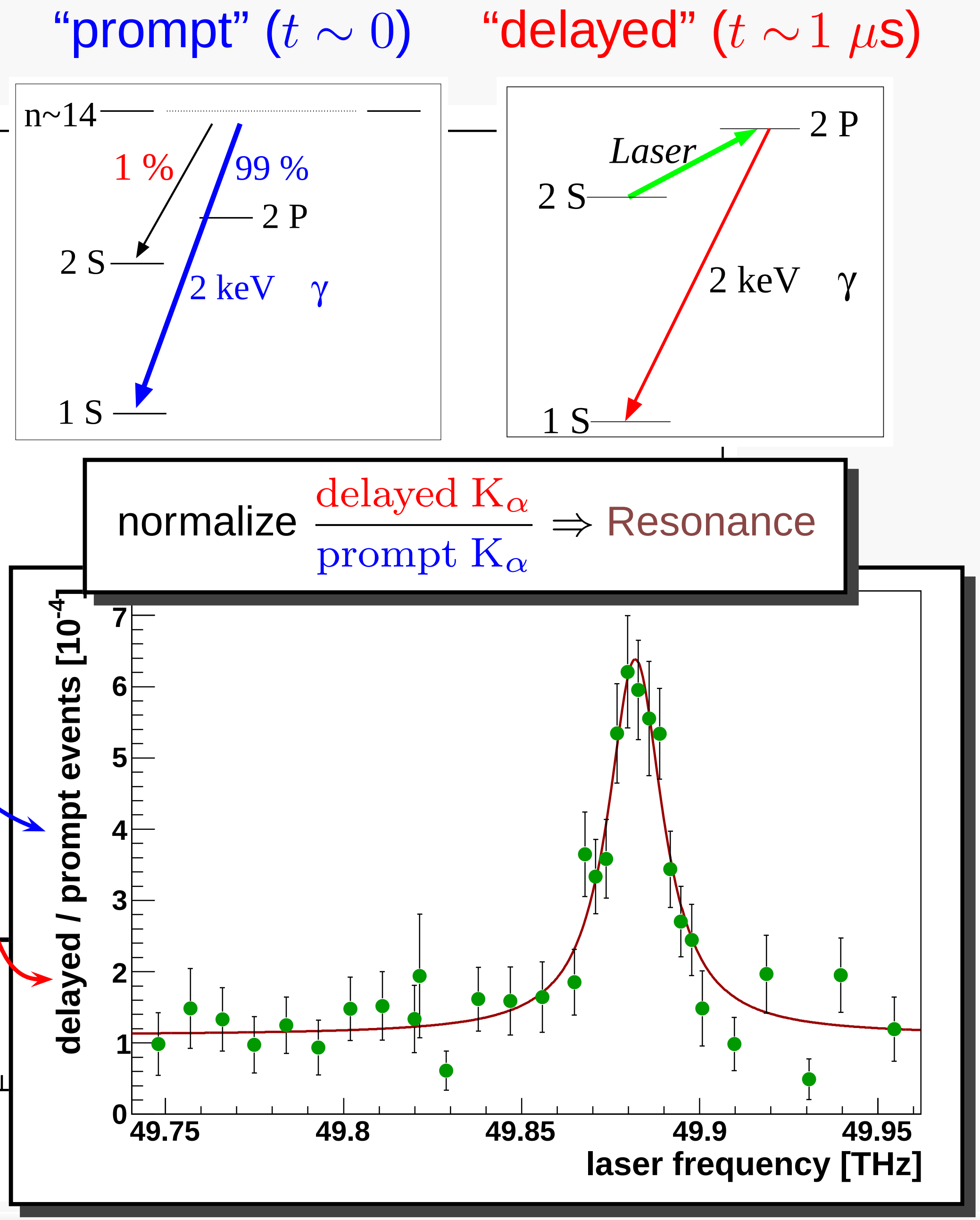
time spectrum of 2 keV x-rays



Principle of the μp Lamb shift experiment

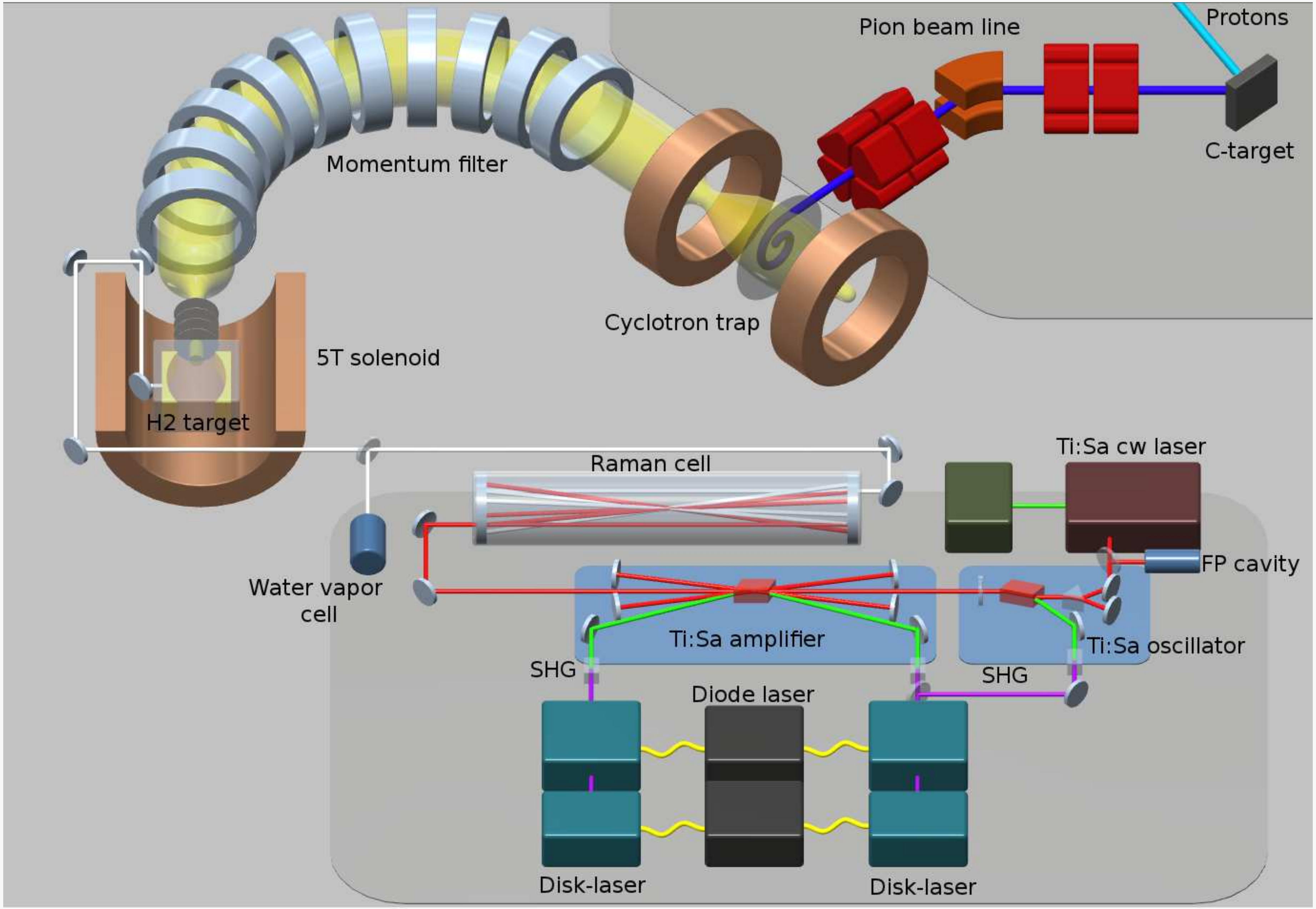
time spectrum of 2 keV x-rays





The μp Lamb shift setup

p-beam
(1 MW)
↓
π (MeV)
↓
μ (MeV)
↓
μ (keV)
↓
μp(2S)
↓
Laser
↓
X-ray

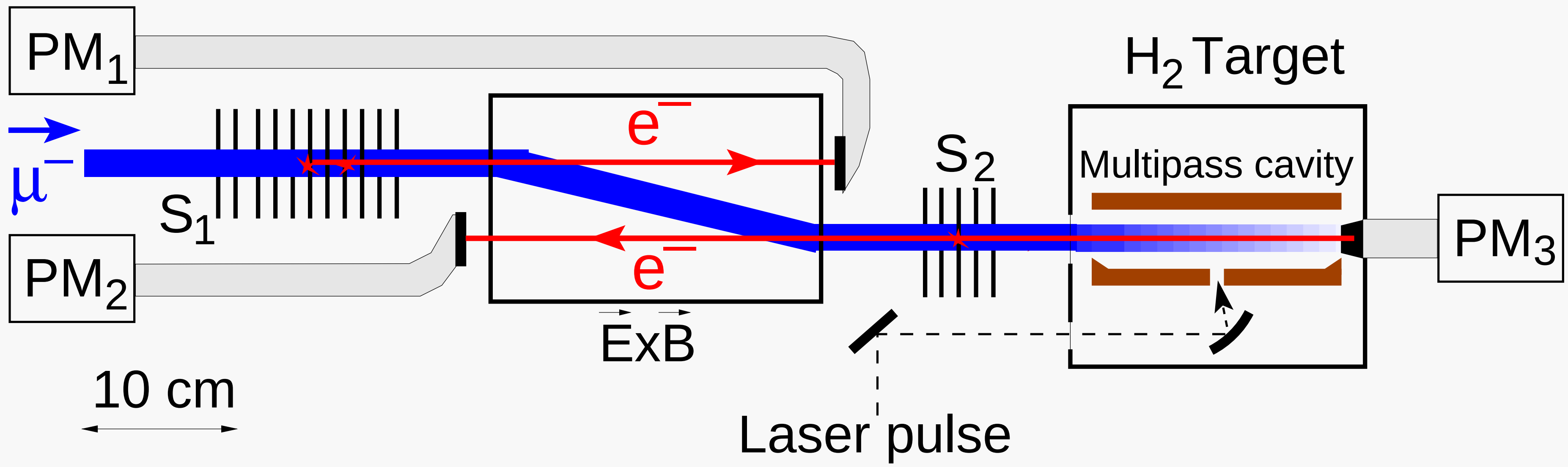


940 nm
(2 kW)
↓
1030 nm
↓
515 nm
↓
708 nm
↓
1.0 μm
↓
1.6 μm
↓
6.0 μm

Inside the 5 Tesla solenoid

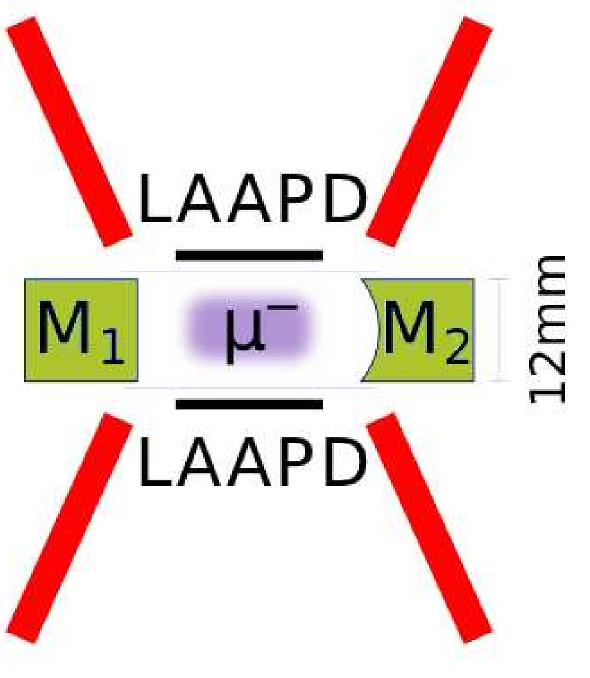
5 keV μ^- with a rate of 500 s^{-1}

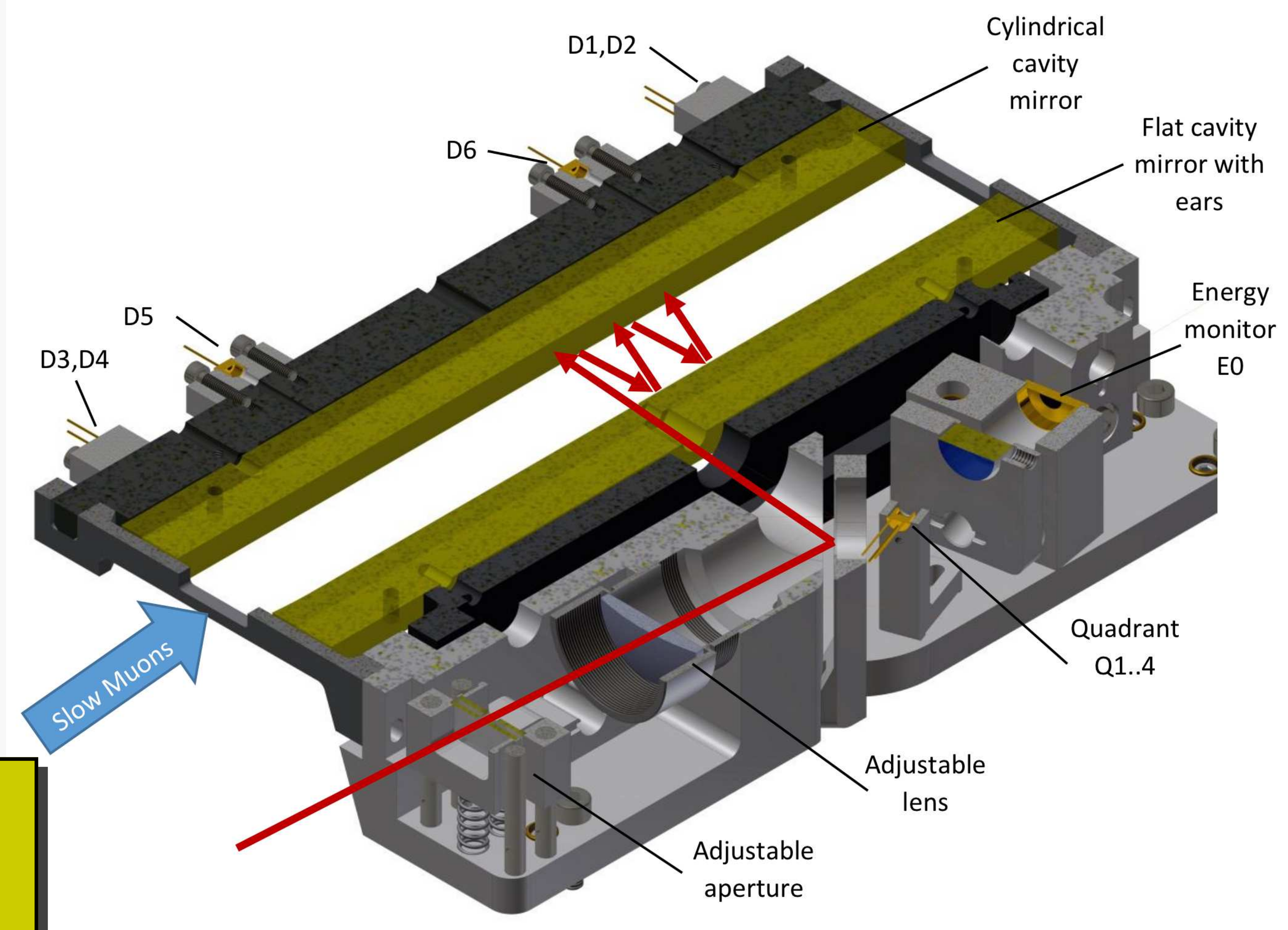
- Stacks of C foils are used as non-destructive muon detector
- Laser is triggered by the electrons signals from the C stacks (coincidence with TOF)



Isn't trivial to stop muons in 1 mbar H_2

Inside the 5 Tesla solenoid

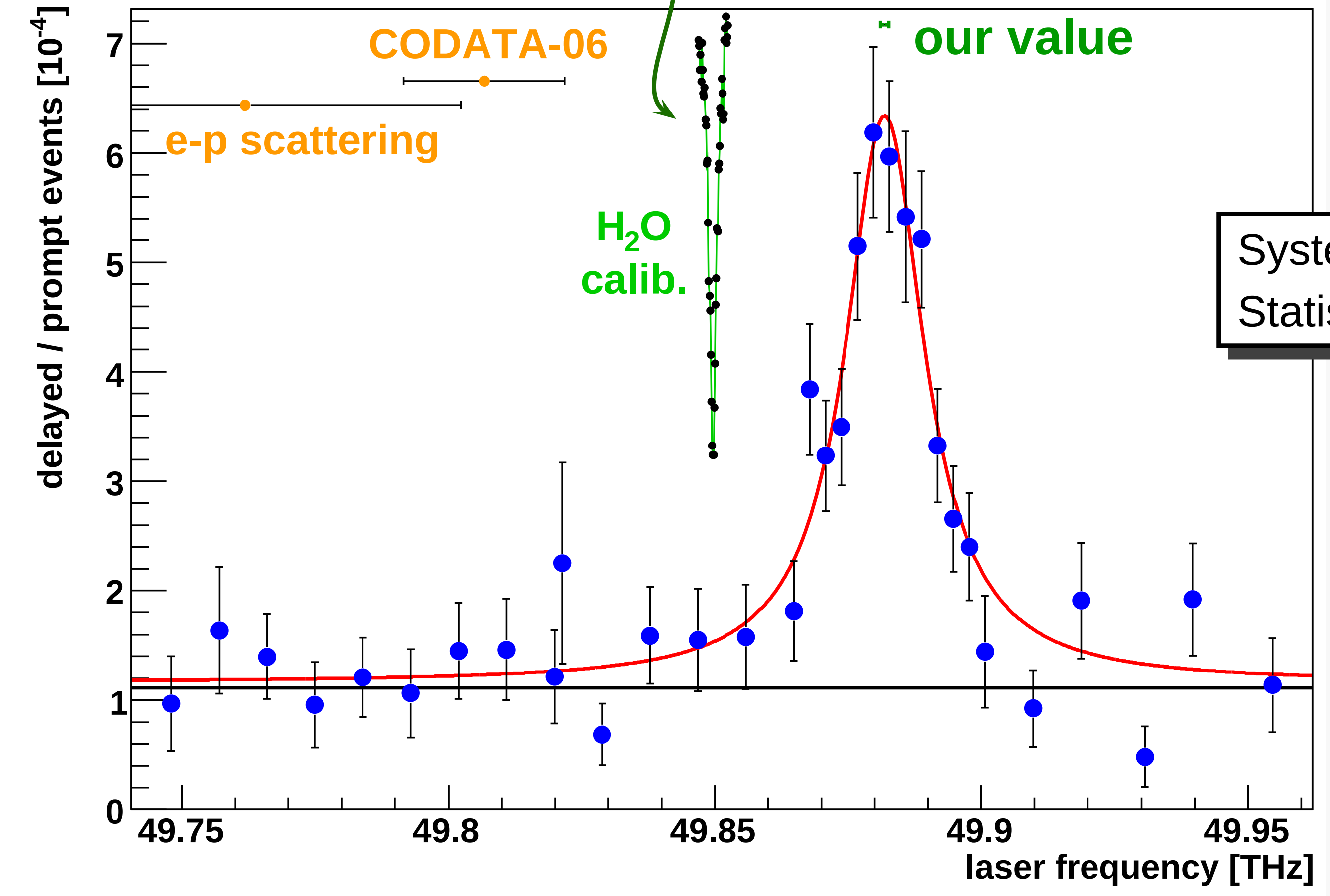




- μp formation
- laser drives 2S-2P transition
- 2P-1S x-ray deexcitation
- detect e^- from μ^- decay

The resonance: discrepancy, sys., stat. (2010)

Water line scan:
Laser frequency known with 300 MHz uncertainty



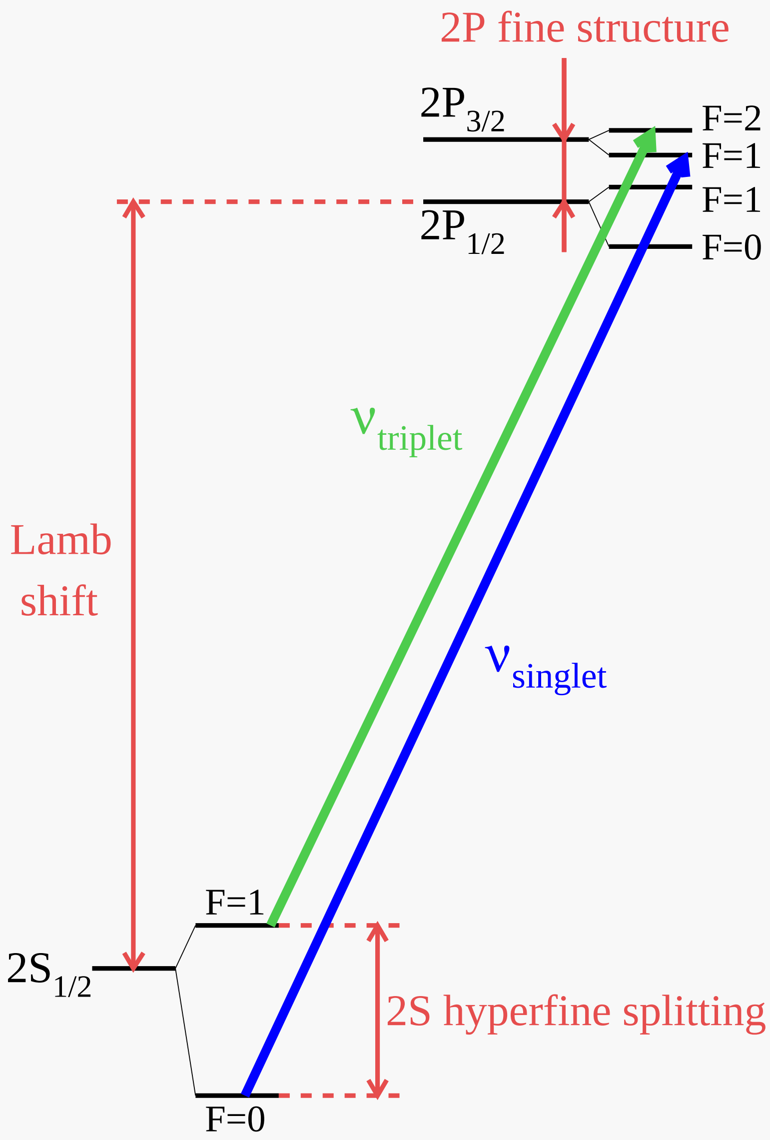
Systematics: 300 MHz
Statistics: 700 MHz

Fitted width
as predicted

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

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

We have measured two transitions in μp



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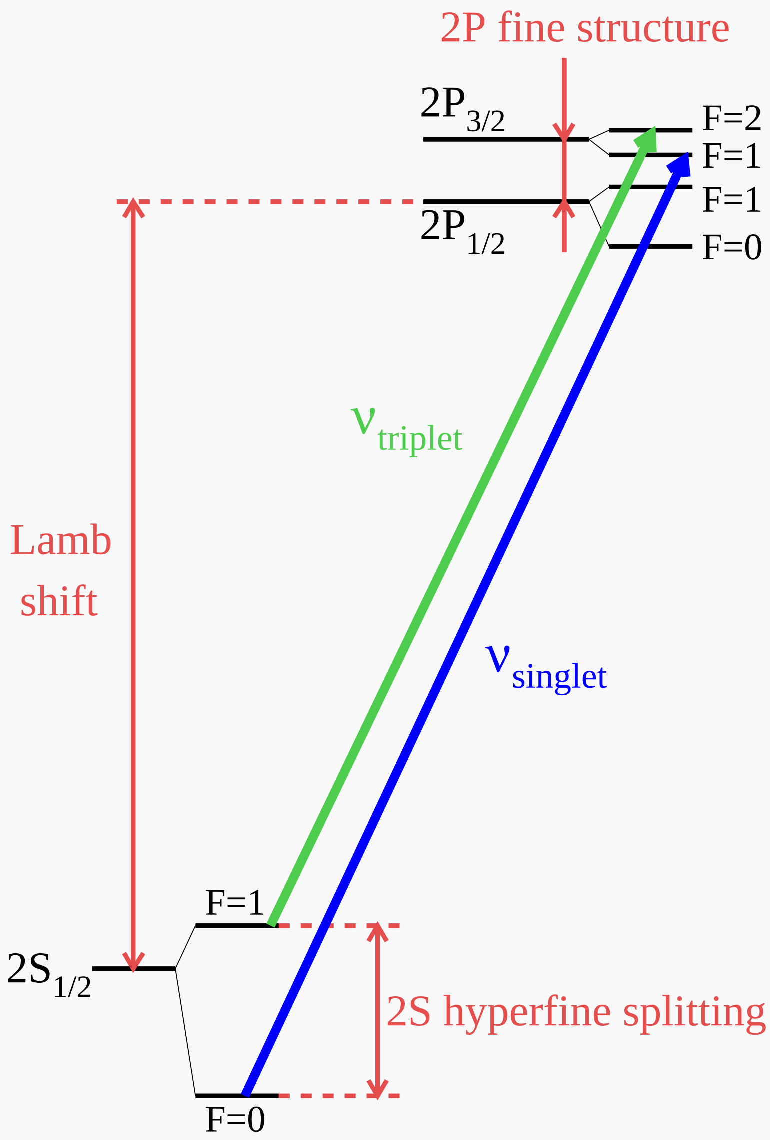
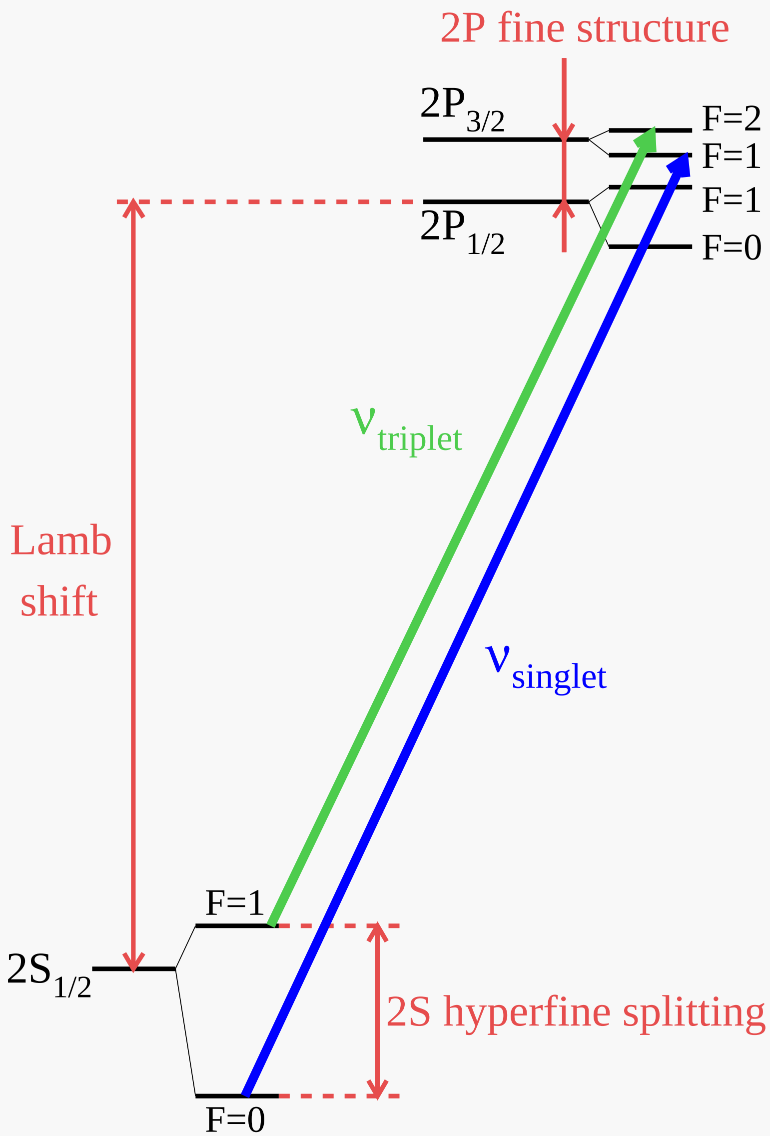


- Considering the two measurements separately

  Two independent determinations of r_p

  ($\nu_t \rightarrow r_\mathrm{p}$, $\nu_s \rightarrow r_\mathrm{p}$) **Consistent results !!!**

We have measured two transitions in μp



- Considering the two measurements separately

  Two independent determinations of r_p

  $(\nu_t \rightarrow r_p\ ,\ \nu_s \rightarrow r_p)$ **Consistent results !!!**

- Combining the two measurements

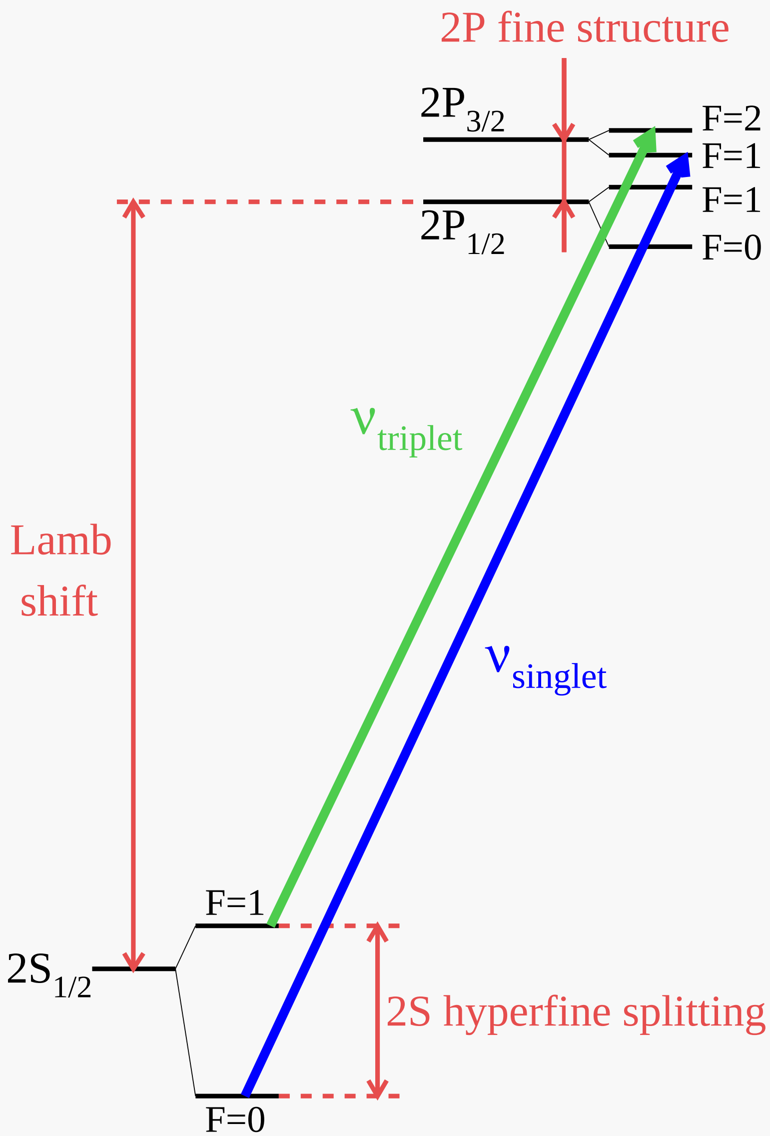
  Two measurements $\rightarrow$ determine two parameters

  $\nu_t, \nu_s \rightarrow \Delta E_L, \Delta E_{HFS} \rightarrow$ r_p, r_Z

  $$r_Z = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$$

$$\begin{aligned} \tfrac{3}{4}\nu_t + \tfrac{1}{4}\nu_s &= \Delta E_L(r_p) + 8.8123 \text{ meV} \\ \nu_s - \nu_t &= \Delta E_{HFS}(r_Z) - 3.2480 \text{ meV} \end{aligned}$$

We have measured two transitions in μp



- Considering the two measurements separately

Two independent determinations of r_p

$(\nu_t \to r_p \; , \; \nu_s \to r_p)$ **Consistent results !!!**

Using the 2S-HFS prediction

- Combining the two measurements

Two measurements $\to$ determine two parameters

$\nu_t, \nu_s \to \Delta E_L, \Delta E_{HFS} \to$ **r_p, r_Z**

$$r_Z = \int d^3 r_1 \, d^3 r_2 \, \rho_E(r_1) \rho_M(r_2) |r_1 - r_2|$$

$$\begin{aligned} \tfrac{3}{4}\nu_t + \tfrac{1}{4}\nu_s &= \Delta E_L(r_p) + 8.8123 \text{ meV} \\ \nu_s - \nu_t &= \Delta E_{HFS}(r_Z) - 3.2480 \text{ meV} \end{aligned}$$

New r_p does NOT dependend on 2S-HFS prediction

Results on μp: r_p

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

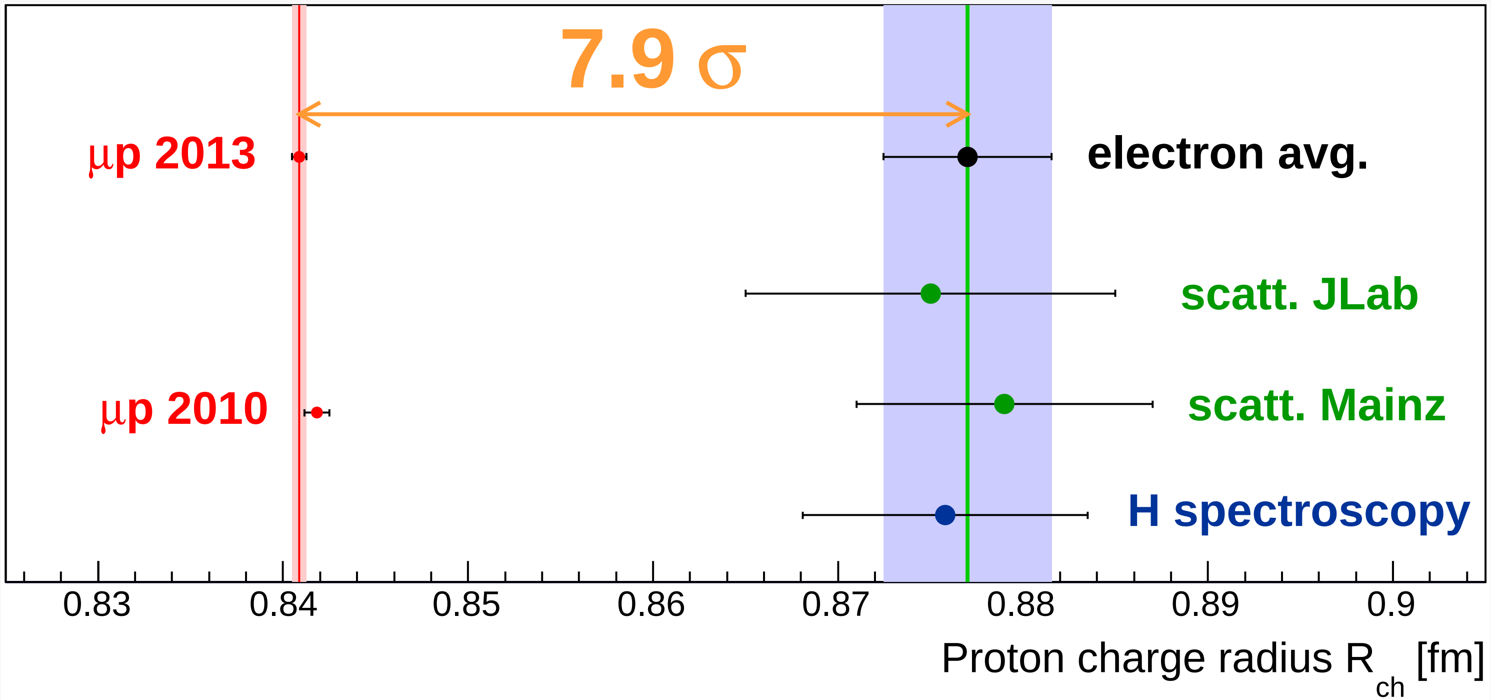
49881.35(65) GHz

$\nu(2S_{1/2}^{F=0} \to 2P_{3/2}^{F=1})$ = 54611.16(1.05) GHz

} Antognini *et al.*, Science 339, 417 (2013)

$\Longrightarrow$ **Proton charge radius:** r_p = 0.84087 (26)$_\mathrm{exp}$ (29)$_\mathrm{th}$ = 0.84087 (39) fm

using μp theory summary: Antognini *et al.*, Ann. Phys. 331, 127 (2013) [arXiv:1208.2637]



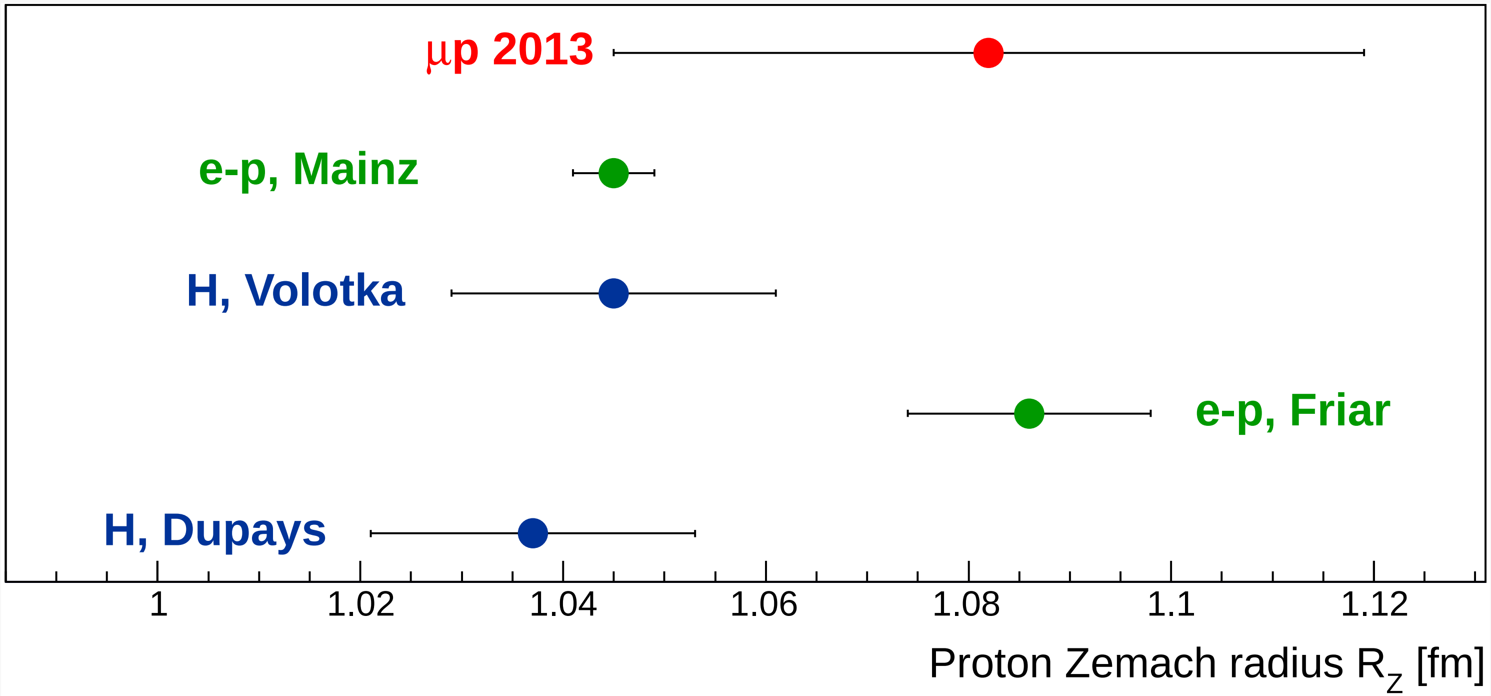
The 2S-HFS in μp and Zemach radius r_Z

Difference of the two transitions $\rightarrow$ 2S-HFS in μp: $\Delta E_{\mathrm{HFS}} = 22.8089(51)$ meV

$\Longrightarrow$ Proton Zemach radius: $r_Z = 1.082(31)_{\mathrm{exp}}(20)_{\mathrm{th}} = 1.082(37)$ fm

$$r_Z = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$$

Contains information of the magnetic distributions of the proton



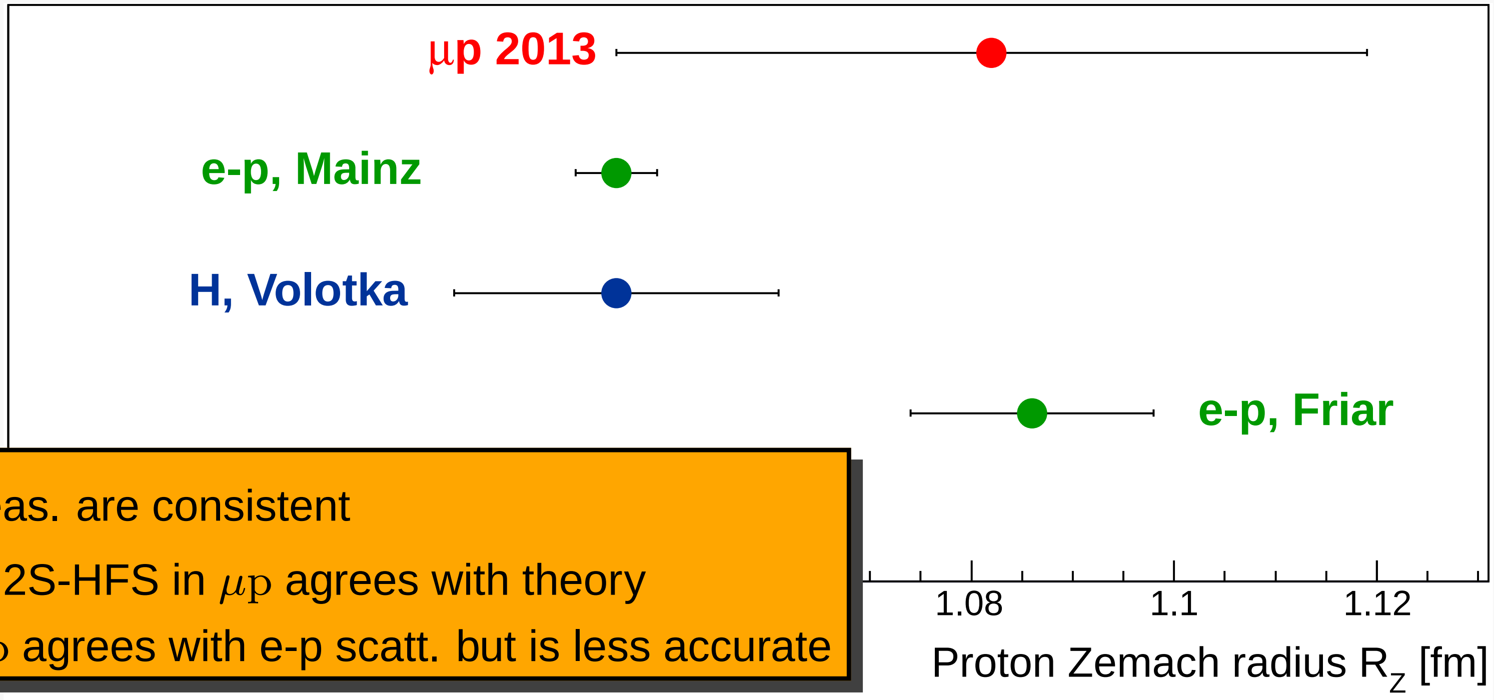
The 2S-HFS in μp and Zemach radius r_Z

Difference of the two transitions $\rightarrow$ 2S-HFS in μp: $\Delta E_{\rm HFS} = 22.8089(51)$ meV

$\Longrightarrow$ Proton Zemach radius: $r_Z = 1.082(31)_{\rm exp}(20)_{\rm th} = 1.082(37)$ fm

$$r_Z = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$$

Contains information of the magnetic distributions of the proton



- the two μp meas. are consistent
- the measured 2S-HFS in μp agrees with theory
- the r_Z from μp agrees with e-p scatt. but is less accurate

Proton radius puzzle: What may be wrong?

Bound-state QED?

Proton structure?

Measurements?

Definition p-radius?

"New physics"?

More than 250 publications

Politically correct discussion

Everybody is right!..?

Proton radius puzzle: What may be wrong?

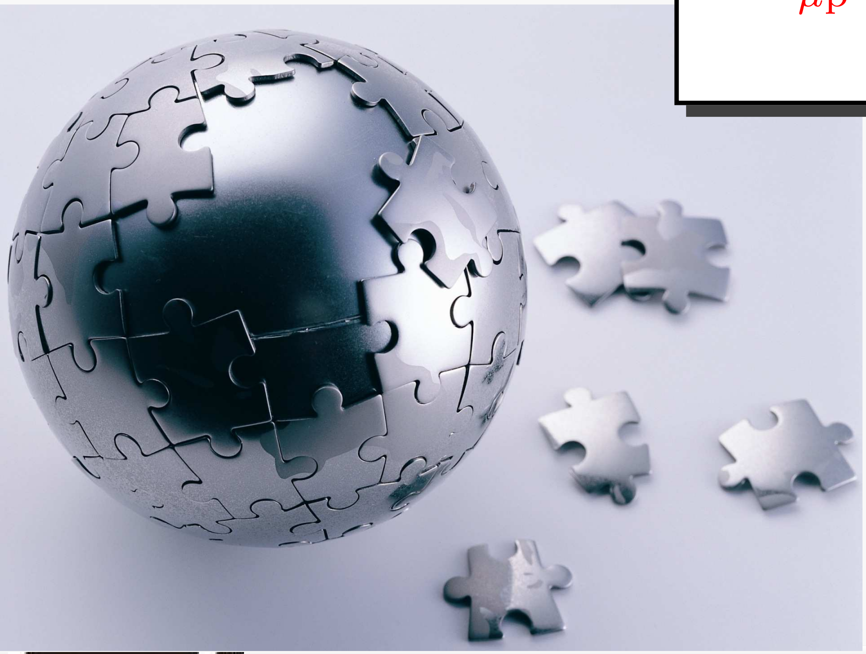
(2) μp theory wrong ? but

- mainly pure QED (vac.pol., etc.)
- 'huge' relative discrepancy
- hadronic terms small
- pol. term = 0.015(4) meV

(1) μp exp. wrong ? but

- good statistics ($\sigma = 0.76$ GHz $\ll$ discrepancy)
- linewidth ~ 19 GHz $\ll$ discrepancy
- several methods for frequency calibration
- another μp(2S-2P) measured !

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



(3) e-p scattering wrong ? but

- new Mainz and JLab results ...

(4) H spectroscopy wrong ? but

- 2S-8S, 2S-8D, 2S-12S, etc. all consistent ...

(5) H theory wrong ? but

- uncertainties at leat 25$\times$ smaller than discrepancy ...

r_p puzzle (1): Is the μp experiment wrong ?

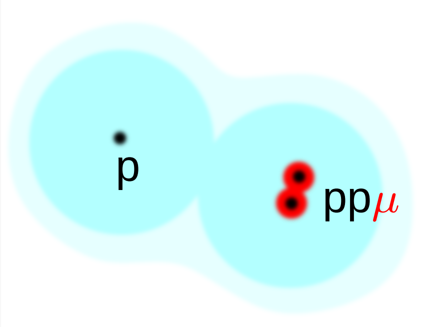
- Systematics?

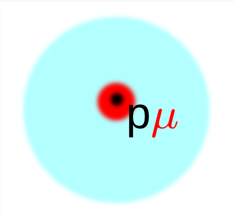
- laser frequency calibration	300 MHz
- Zeeman effect ($B = 5$ Tesla)	30 MHz
- AC-Stark, DC-Stark shift	< 1 MHz
- Doppler shift	< 1 MHz
- pressure shift (1 mbar)	1 MHz

Systematics shift $\sim 1/m$

Finite size shift $\sim m^3$

- Spectroscopy of $pp\mu$ molecules or $p\mu e$ ions?





Do not exist or too short lived (in 2S state)

Karr and Hilico, PRL 109, 103401 (2012)

Pohl *et al.*, PRL 97, 193402 (2006)

- Frequency mistake by 75 GHz ?

- Huge difference for laser spectroscopy accuracies
- Two ways to calibrate the frequency (consistent)

Discrepancy = 75 GHz $\approx 4\Gamma$

Two consistent μp transition measurements

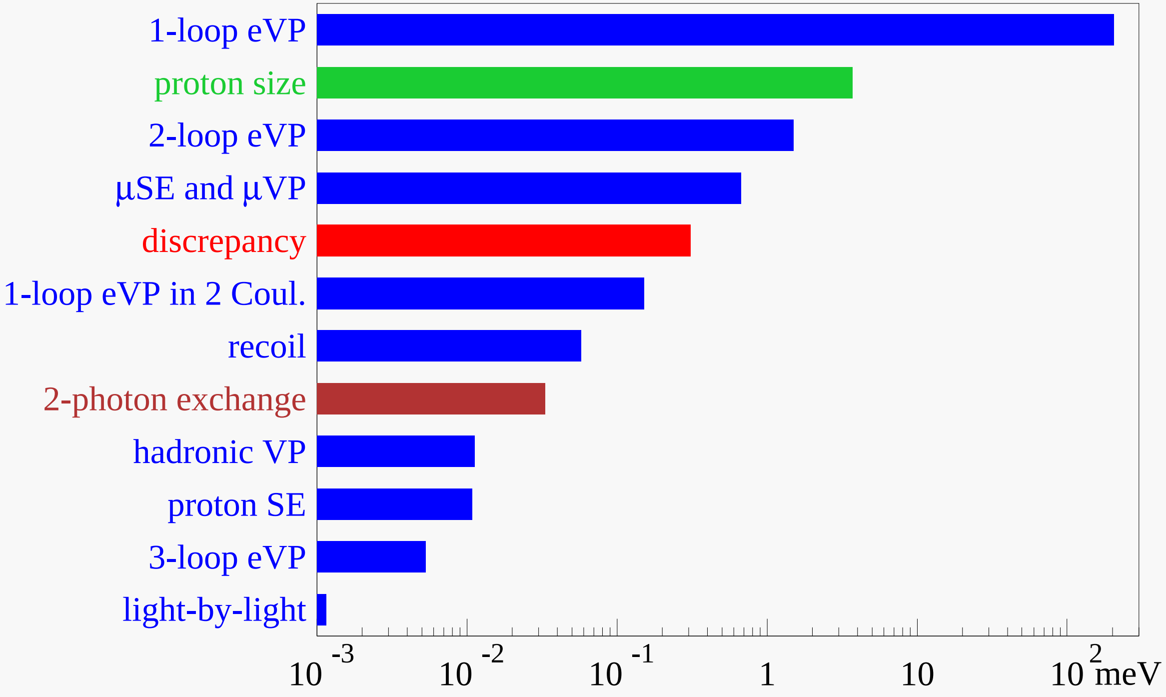
μp experiment is probably not wrong by 100 σ

r_{p} puzzle (2): Is the μp theory wrong ?

Discrepancy	= 0.31 meV
Theory uncertainty	= 0.0025 meV

$\Rightarrow$ 120δ(theory) deviation?

$$\Delta E^{\mathrm{th}} = 206.0668(25) - 5.2275(10)\, r_{\mathrm{p}}^2 \ \ [\mathrm{meV}]$$



Pachucki, PRA 60, 3593 (1999)

Borie, arXiv: 1103.1772-v6

Jentschura, Ann. Phys. 326, 500 (2011)

Karshenboim *et al.*, PRA 85, 032509 (2012)

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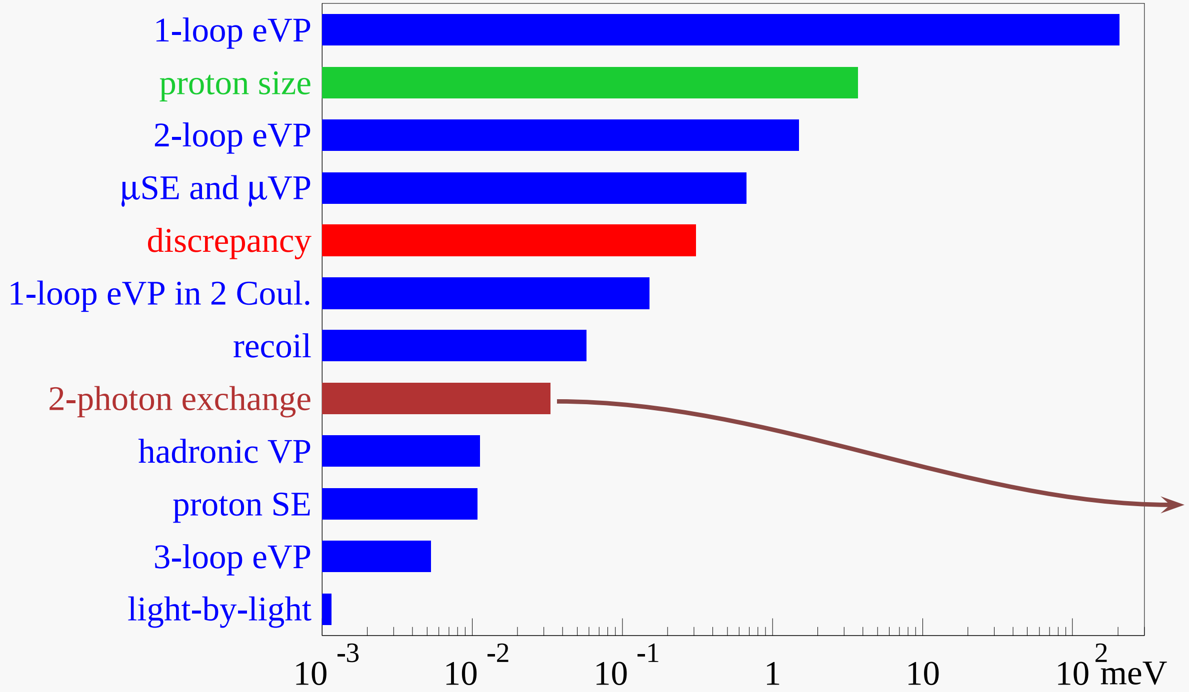

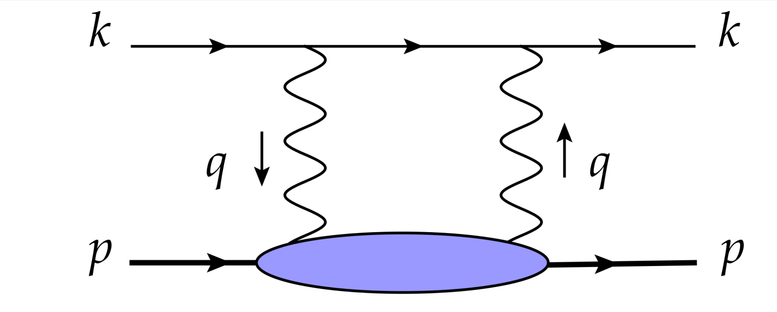

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Peset *and* Pineda, arXiv:1406.4524
Alarcon *et al.* , arXiv:1312.1219

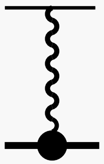
r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Higher order finite size effects

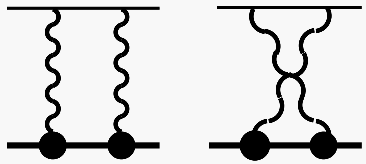
Potential corr.

Wave function corr.

$$\Psi(r) \approx \Psi(0)\big(1 - m_r\alpha \int d^3r\ \rho(\vec{r})|\vec{r}-\vec{r'}| + \dots\big)$$



$$E_\mathrm{FS} = -\frac{2\pi\alpha}{3}|\Psi(0)|^2 \left[\, r_\mathrm{p}^2 - \frac{\alpha}{2}\, m_r\, \langle r_\mathrm{p}^3\rangle_{(2)} + \dots \right]$$



Discrepancy = 0.31 meV

3.7 meV

0.02 meV

This term is important for μp

Third Zemach moment:

$$\langle r_\mathrm{p}^3\rangle_{(2)} = \int d^3r \int d^3r'\ \rho(\vec{r})\rho(\vec{r'})|\vec{r}-\vec{r'}|^3$$

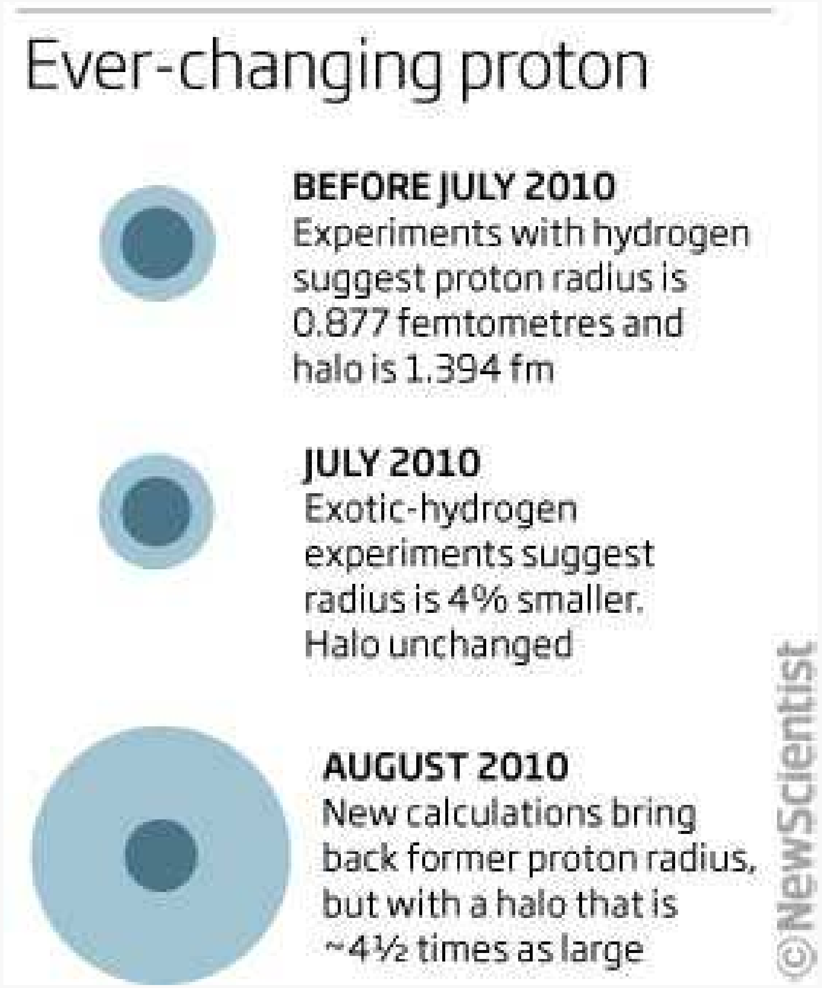
r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Can we find a p-shape to solve the discrepancy?

Third Zemach moment:
$\langle r_\mathrm{p}^3 \rangle_{(2)} = \int d^3r \int d^3r' \, \rho_E(\vec{r})\rho_E(\vec{r'})|\vec{r} - \vec{r'}|^3$

In principle yes $\Leftrightarrow$ $\langle r_\mathrm{p}^3 \rangle_{(2)} = 37(7)$ fm^3

[PL B 693, 555 (2010)]



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In principle yes $\Leftrightarrow$ $\langle r_\mathrm{p}^3\rangle_{(2)} = 37(7)$ fm^3

[PL B 693, 555 (2010)]

$\Leftrightarrow$ But community not very happy

Measurable

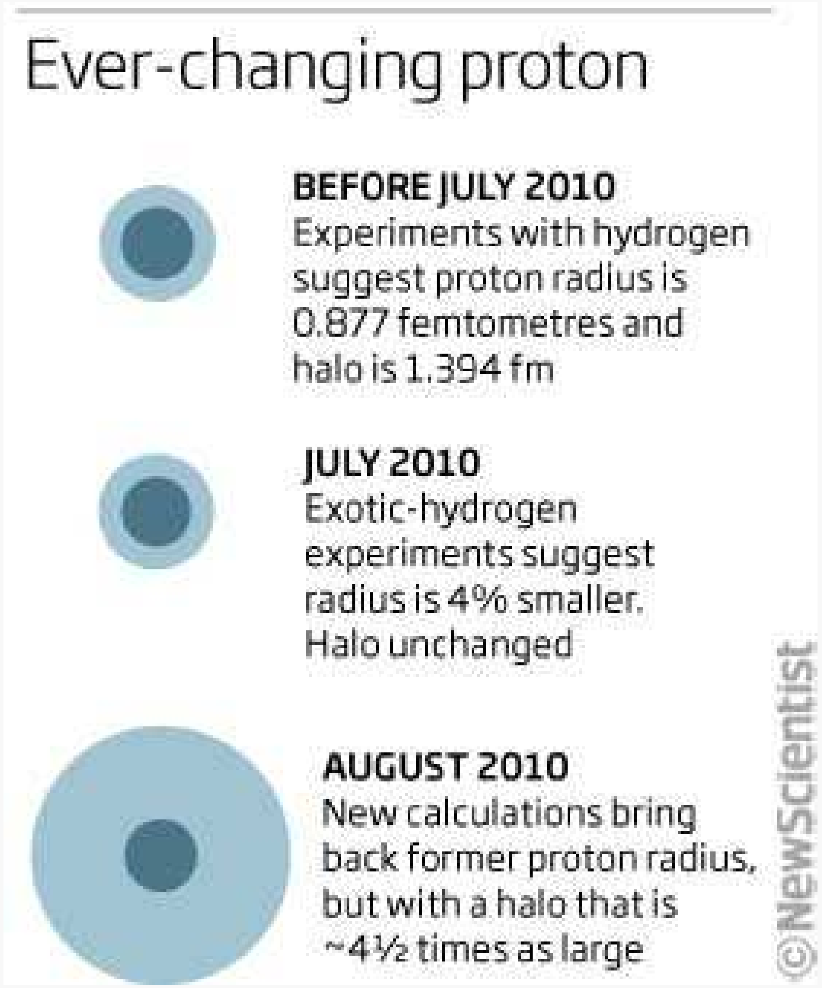
$$\langle r_\mathrm{p}^3\rangle_{(2)} = \frac{48}{\pi}\int \frac{dq}{q^4}\left[G_E^2(q^2) - 1 + \frac{1}{3}q^2\langle r_\mathrm{p}^2\rangle\right]$$

$\langle r_\mathrm{p}^3\rangle_{(2)} = 2.71(13)$ fm^3 [PRA 72 040502 (2005)]

$\langle r_\mathrm{p}^3\rangle_{(2)} \leq 4.5$ fm^3 [PRC 83, 012201 (2011)]

$\langle r_\mathrm{p}^3\rangle_{(2)} = 2.85(8)$ fm^3 [PLB 696, 343 (2011)]

$\langle r_\mathrm{p}^3\rangle(\chi\mathrm{PT}) \sim \langle r_\mathrm{p}^3\rangle(\mathrm{experiments})$ [hep-ph/0412142]



r_{p} puzzle (2): Is μp(2S-2P) theory wrong ?

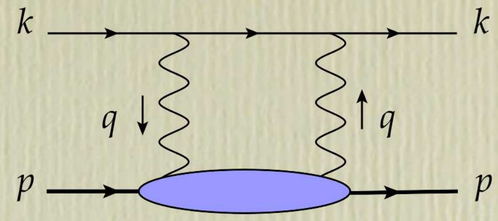
Two ways to the 2γ exchange

Both agrees but...

r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Two photon exchange contribution to Lamb shift

Kinematics: 2 loop variables
q^2 and ν=(pq)/M



+ crossed

$$\mathcal{M} = e^4 \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^4} \bar{u}(k) \left[\gamma^\nu \frac{1}{\not{k} - \not{q} - m_l + i\epsilon} \gamma^\mu + \gamma^\mu \frac{1}{\not{k} + \not{q} - m_l + i\epsilon} \gamma^\nu \right] u(k) T_{\mu\nu}$$

Forward virtual Compton amplitude

$$T^{\mu\nu} = \frac{i}{8\pi M} \int d^4 x e^{iqx} \langle p | T\, j^\mu(x) j^\nu(0) | p \rangle$$
$$= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) T_1(\nu, Q^2) + \frac{1}{M^2} (p - \frac{pq}{q^2} q)^\mu (p - \frac{pq}{q^2} q)^\nu T_2(\nu, Q^2)$$

Lamb shift (nS-nP)

$$\Delta E = -\frac{\alpha^2}{2\pi m_l M_d} \phi_n^2(0) \int d^4 q \frac{(q^2 + 2\nu^2) T_1(\nu, q^2) - (q^2 - \nu^2) T_2(\nu, q^2)}{q^4 [(q^2/2m_l)^2 - \nu^2]}$$

[Slide stolen from Gorshteyn]

r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Two photon exchange contribution to Lamb shift

T_1, T_2 - the imaginary parts known (Optical theorem)

$$\mathrm{Im}T_1(\nu,Q^2)=\frac{1}{4M}F_1(\nu,Q^2)$$

$$\mathrm{Im}T_2(\nu,Q^2)=\frac{1}{4\nu}F_2(\nu,Q^2)$$

Inelastic structure functions = data
(real and virtual photoabsorption, FF)

Real parts - from forward dispersion relation

$F_1(\nu\to\infty,q^2)\sim\nu^{1+\epsilon}$ - subtraction needed

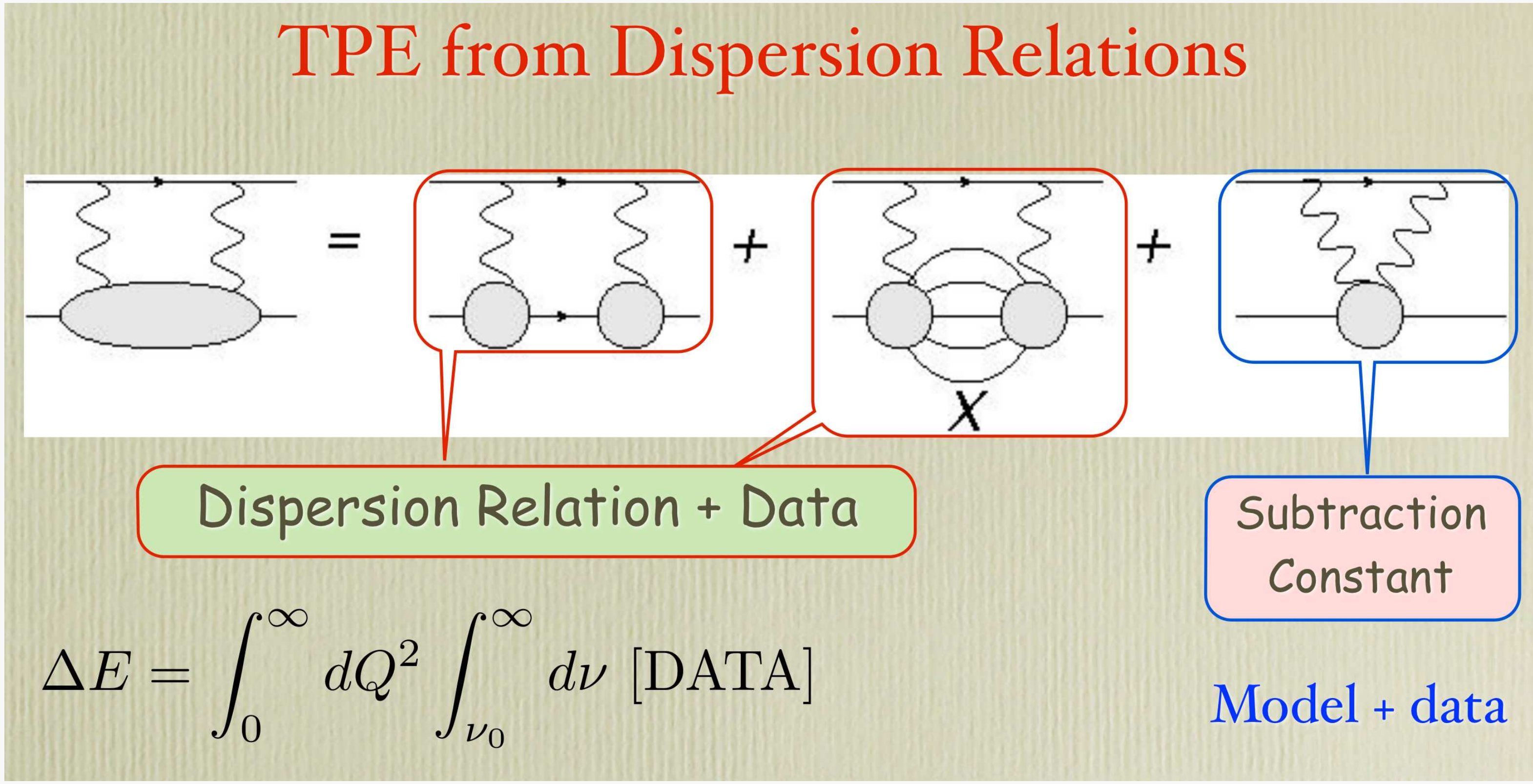
$F_2(\nu\to\infty,q^2)\sim\nu^{\epsilon}$ - no subtraction

$$\mathrm{Re}T_1(\nu,Q^2)=\bar{T}_1(0,Q^2)+T_1^{pole}(\nu,Q^2)+\frac{\nu^2}{2\pi M}\int_{\nu_0}^{\infty}\frac{d\nu'}{\nu(\nu'^2-\nu^2)}F_1(\nu',Q^2)$$

$$\mathrm{Re}T_2(\nu,Q^2)=T_2^{pole}(\nu,Q^2)+\frac{1}{2\pi}\int_{\nu_0}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}F_2(\nu',Q^2)$$

[Slide stolen from Gorshteyn]

$r_{\rm p}$ puzzle (2): Is μp(2S-2P) theory wrong ?



[Slide stolen from Gorshteyn]

The controversy:
How well do we know the subtraction term?

r_{p} puzzle (2): Is μp(2S-2P) theory wrong ?

- The subtraction term $W_1(0,Q^2)$ is NOT determined by the imaginary part (data)

$W_1(0,Q^2)$	known at small Q^2	via NRQED + Wilson coeff. from data
	NOT known at intermediate Q^2	($\gamma p \rightarrow l^+ l^- p'$ planned at HIGS, Duke)
	known at large Q^2	from OPE expansion

Uncertainty of this term underestimated? [PRL107,160402 (2011), Miller PLB 2012]

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- Could the two-photon exchange explain the discrepancy?

Unknown:	Could be MUCH larger as previosly assumed	Hill *and* Paz, PRL 107, 160402 (2011), Miller
Under control:	Direct calc. of whole contribution in LO χPT	Nevado *and* Pineda, PRC 77, 035202 (2008)
Under control:	χPT expansion to bridge low-Q^2 to high-Q^2	McGovern *and* Birse, EPJA 48 120 (2012)
Under control:	Sum rule + Regge +...photoabsorbtion data	Gorchtein *et al*, PRA 84, 052501 (2013)
Under control:	Barion χPT + $\Delta(1232)$ contribution	Alarćon *et al*, arXiv 1312.1219
Under control:	Direct calc. of whole contribution in χPT	Peset *and* Pineda, ArXiv1403.3408 (2014)

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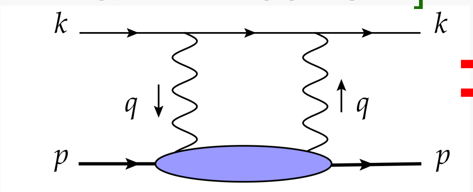
$\Delta E_\mathrm{sub} = -0.0042(10)$ meV $\longleftrightarrow$ Discrepancy=0.3 meV

$r_{\rm p}$ puzzle (2): Is μp(2S-2P) theory wrong ?

BχPT vs HBχ PT:

Main part of pol. contribution comes from the low Q^2 regime $\rightarrow$ Chiral EFT

[Peset *and* Pineda, arXiv:1406.4524]



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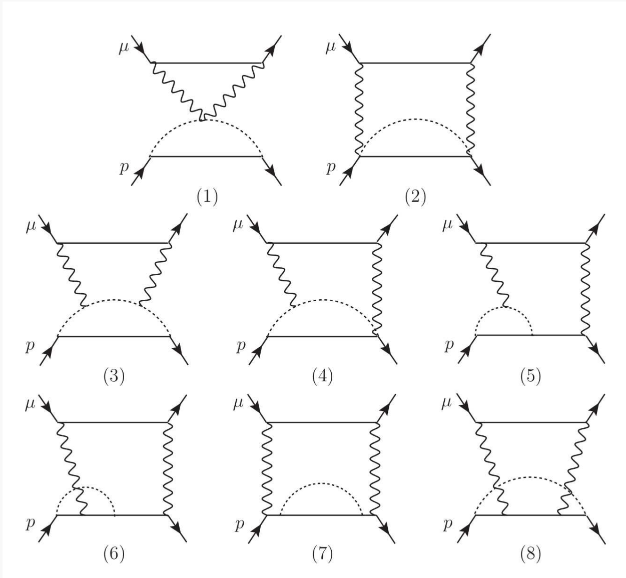

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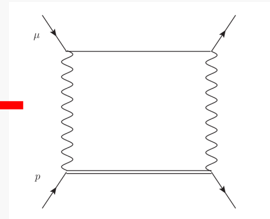

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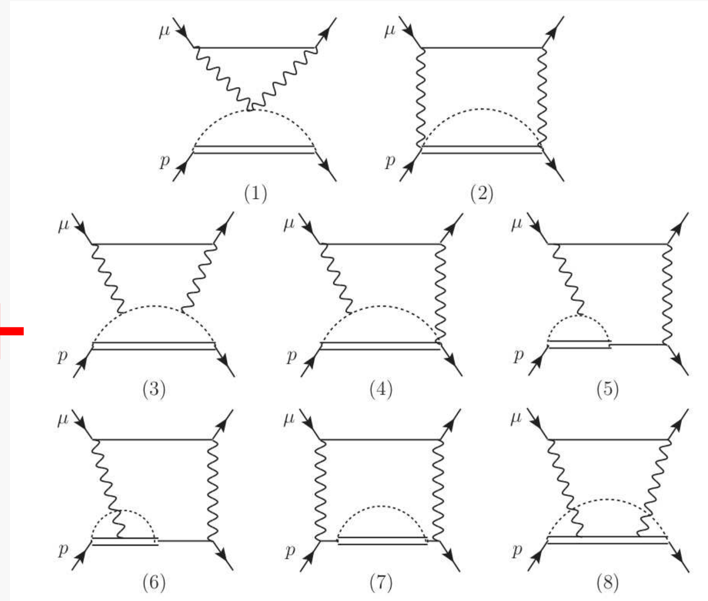


Two approaches have been develped:

BχPT [Pascalutsa, Lensky, Alarcon] and HBχPT [Pineda, Nevado, Peset]

There are some not yet understood disagreement between the two approaches.

However when summing up all contributions to the TPE

$\Delta E_{TPE} = 33(2)$ μeV (Dispersive approach)

$\Delta E_{TPE} = 34(12)$ μeV (HBχPT)

r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Polarizability contribution

(μeV)	DR + Model [33]	[34]	[35]	[36]	BχPT [22] (π)	HBET [6] (π)	[12] (π&Δ)
ΔE_{pol}	12(2)	11.5	7.4(2.4)	15.3(5.6)	$8.2(^{+1.2}_{-2.5})$	18.5(9.3)	26.2(10.0)

[33] Pachucki, PRL A 60, 3593, (1999)
[34] Martynenko, hep-ph/0509236
[35] Carlson and Vanderhaeghen, PRA 84, 020102 (2011)
[36] Gorchtein et al., PRA 87, 052501
[22] Alarcon et al., EPJC 74, 2854 (2014)
[6] Nevado and Pineda, PRC 77, 035202 (2008)
[12] Peset and Pineda, arXiv:1403.3408

Very interesting physics

Proton charge moments

	$\langle r^3\rangle$	$\langle r^4\rangle$	$\langle r^5\rangle$	$\langle r^6\rangle$	$\langle r^7\rangle$	$\langle r^3\rangle_{(2)}$
π	0.4980	0.6877	1.619	5.203	20.92	0.9960
π&Δ	0.4071	0.6228	1.522	4.978	20.22	0.8142
[25]	0.7706	1.083	1.775	3.325	7.006	2.023
[26]	0.9838	1.621	3.209	7.440	19.69	2.526
[27]	1.16(4)	2.59(19)(04)	8.0(1.2)(1.0)	29.8(7.6)(12.6)	− − −	2.85(8)

[25] Janssens et al., PR 142, 922 (1966)
[26] Kelly, PRC 70, 068202 (2004)
[27] Distler et al, PLB 696, 343 (2011)

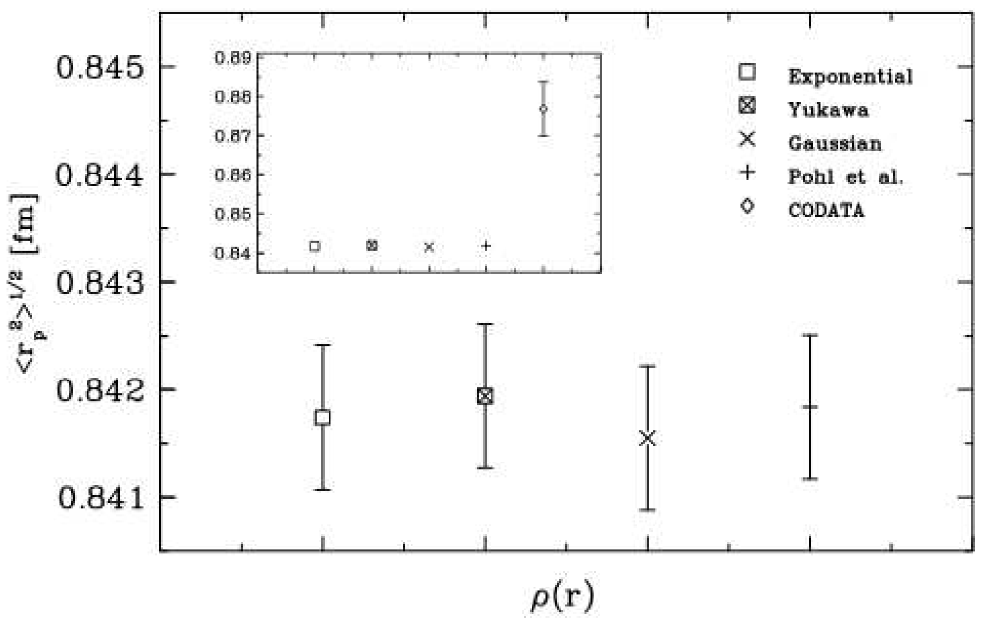
[Peset *and* Pineda, arXiv:1406.4524]

$r_{\rm p}$ puzzle (2): Is the μp theory wrong ?

Can we find a p-shape to solve the discrepancy?

NO, but the question is interesting. DeRujula

How does the radius extracted from μp depends on the assumed proton shape? [Miller]



Finite size contributions

$$\Delta E_{\rm finite\ size} = \sum_n a_n \langle r_{\rm p}^n \rangle$$

bound-state QED expansion	$\rightarrow$	a_n decreases rapidly	Friar, Indelicato
e-p scattering data	$\rightarrow$	$\langle r_{\rm p}^n \rangle$ sufficiently small for $n < 6$	Distler, Miller
χPT	$\rightarrow$	$\langle r_{\rm p}^n \rangle$(HB$\chi$PT) $<$ $\langle r_{\rm p}^n \rangle$(scatt)	Peset, Pineda

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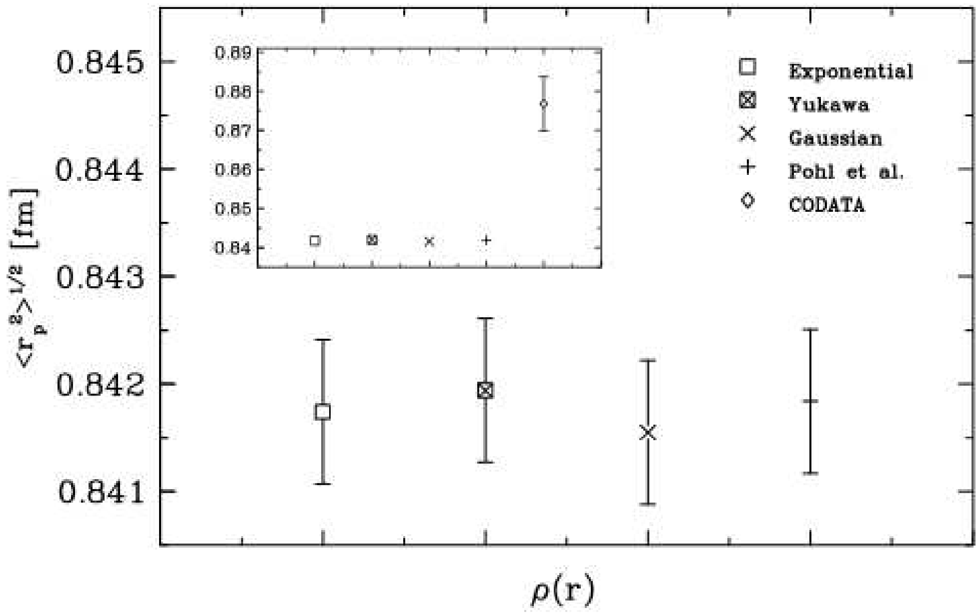

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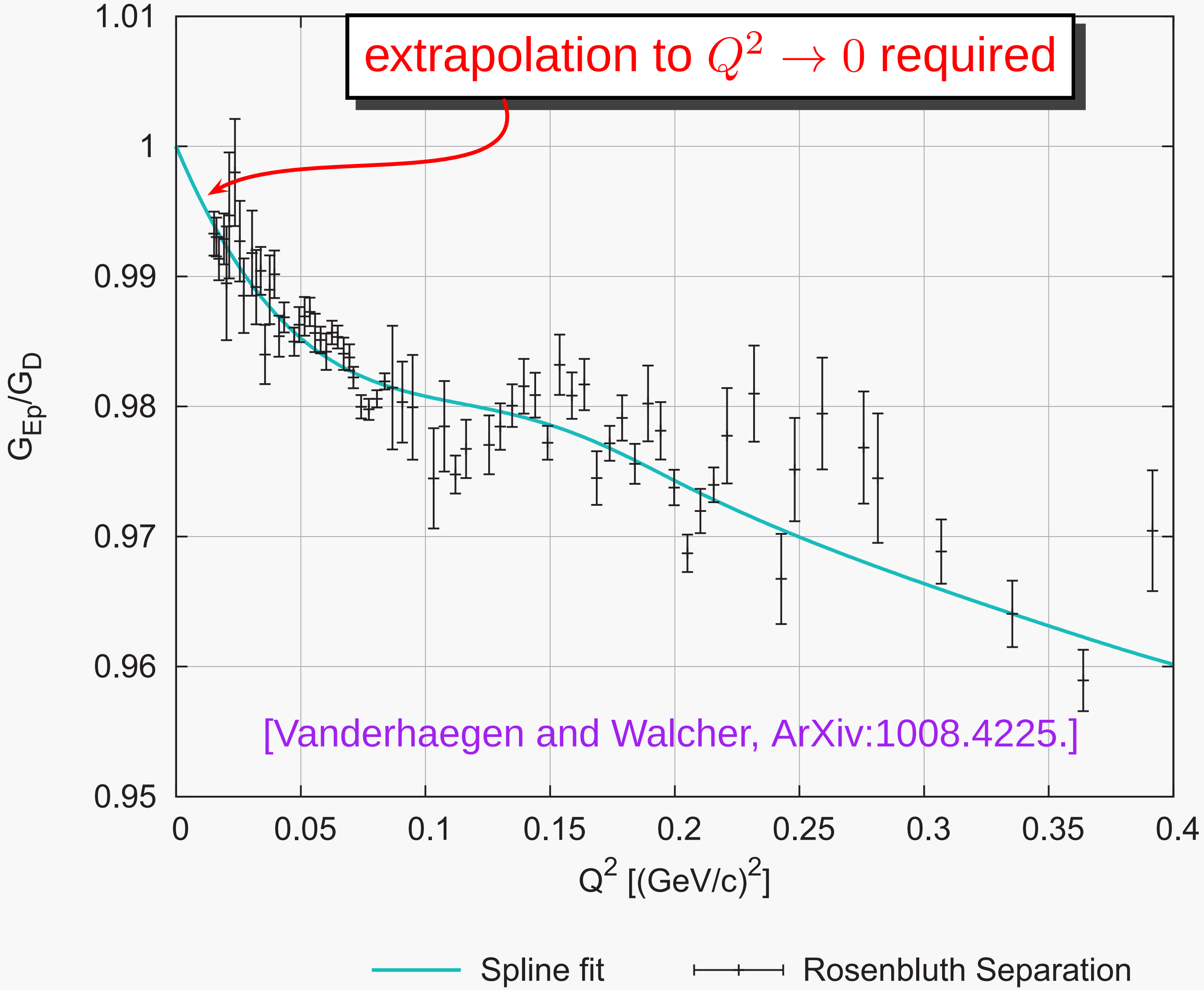
Chiral EFT are important for 3 reasons:

- provide a value of the TPE (polarizability + elastic) contribution
- give values of the various charge moments of the proton
- provide a model of the proton shape that could be used to analyze scattering data

r_p puzzle (5): Is e-p scattering wrong ?

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

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



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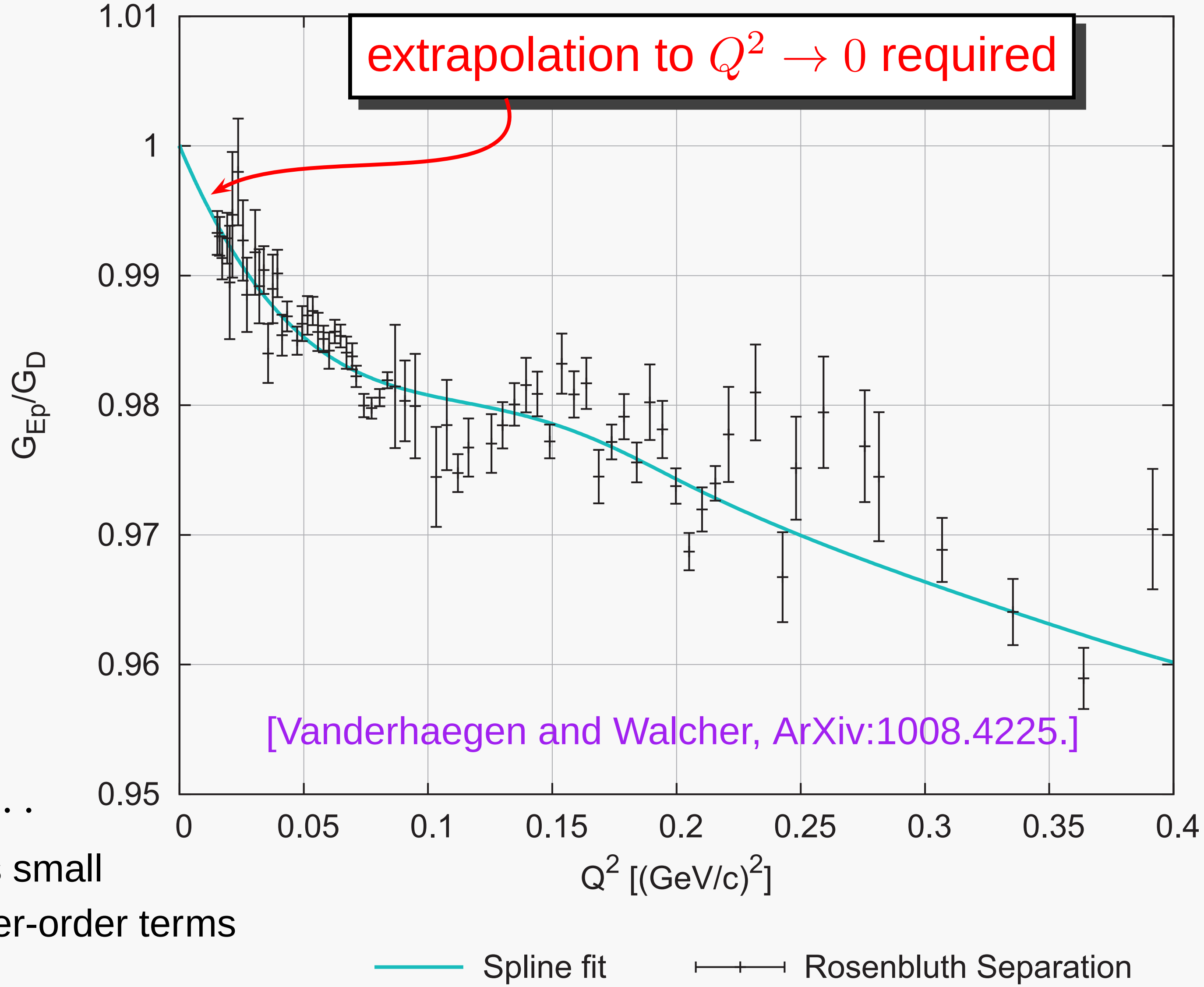
$$\langle r_{\rm p}^2\rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

Needs a fit
Model dependence?

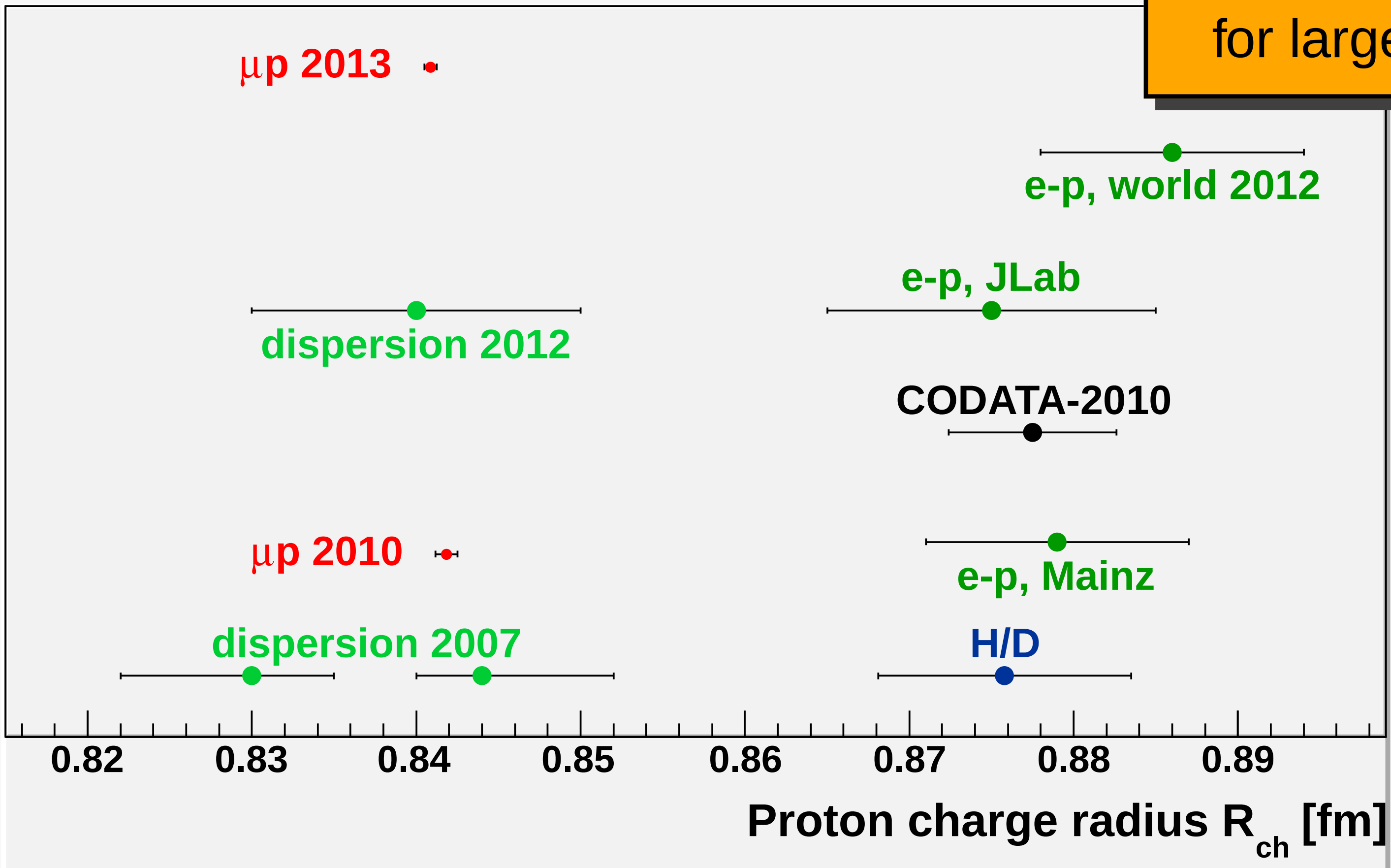
Sick, PLB 576, 62 (2003)
Hills and Paz, PRD 82, 113005 (2010)
Bernauer et al, PRL 105, 242001 (2010)
Lorenz and Meissner, arXiv:1406.2962



$$G_E(Q^2) = 1 + \frac{Q^2}{6}\langle r_{\rm p}^2\rangle + \frac{Q^4}{120}\langle r_{\rm p}^4\rangle + \ldots$$

- Very low Q^2 yields slope but sensitivity is small
- Larger Q^2 more sensitive but larger higher-order terms

Proton charge radii



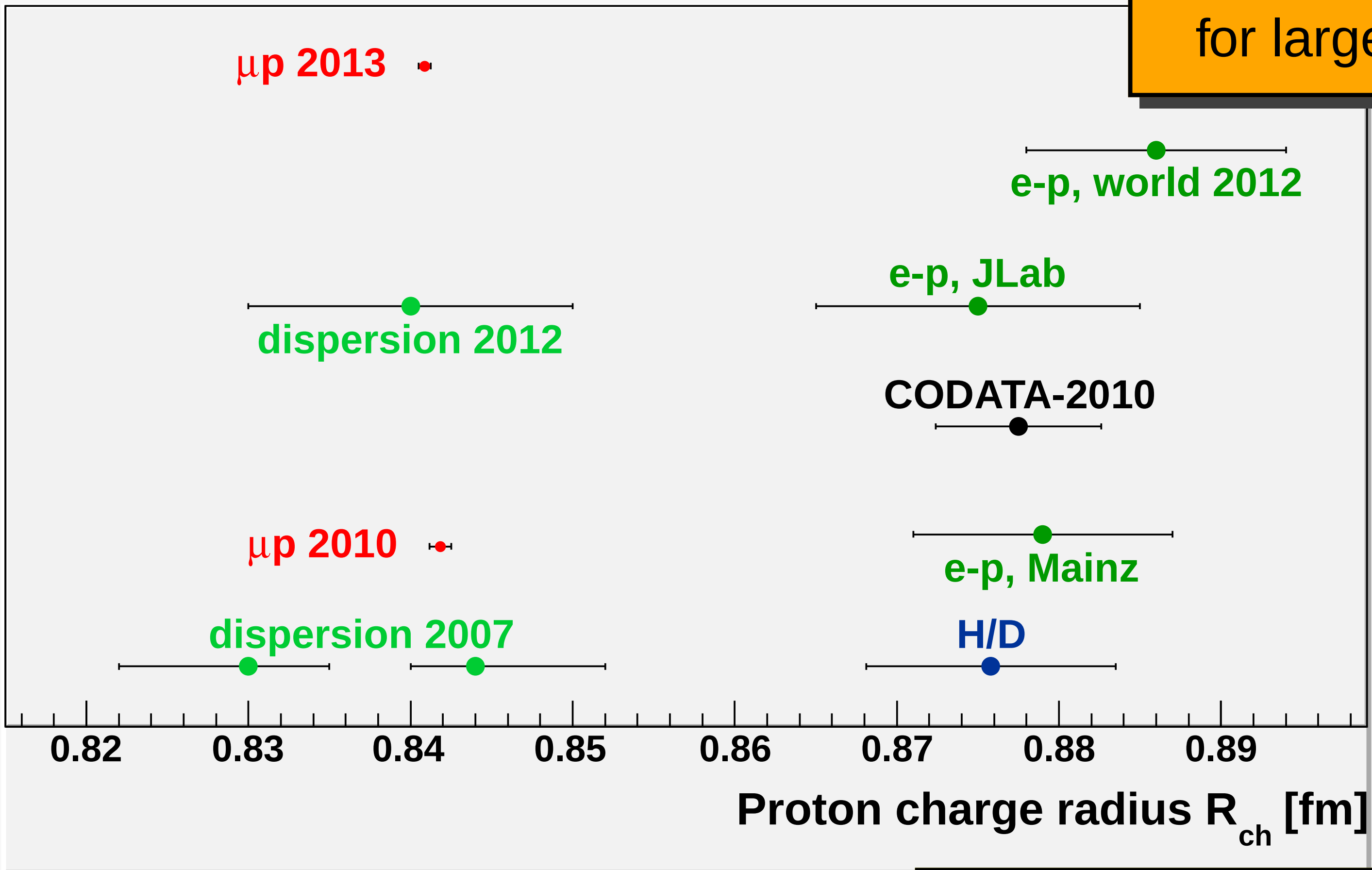
Extrapolation accounting for large-r tail

Analysis of e-p, e-n scattering data using VMD and dispersion relations gives radii in agreement with μp (arXiv:1406.2962)

Extrapolation of scattering data?

Proton charge radii

Extrapolation accounting for large-r tail



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Extrapolation of scattering data?

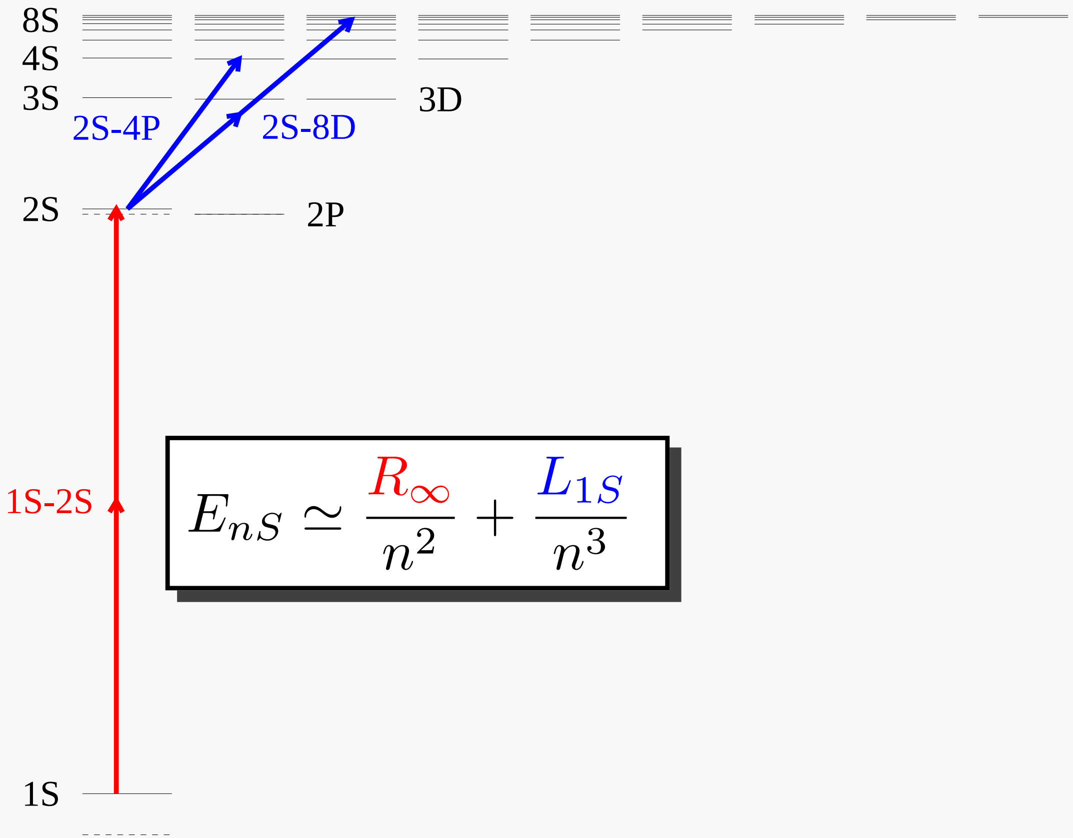
What about H?

r_p puzzle (3): Is H-spectroscopy wrong ?

Two measurements $\rightarrow$ two unknown: R_∞ and L_{1S}^{exp}

$$\Updownarrow$$

$$L_{1S}^{\mathrm{th}}(r_\mathrm{p}) = 8171.636(4) + 1.5645\, r_\mathrm{p}^2 \quad \mathrm{MHz}$$



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

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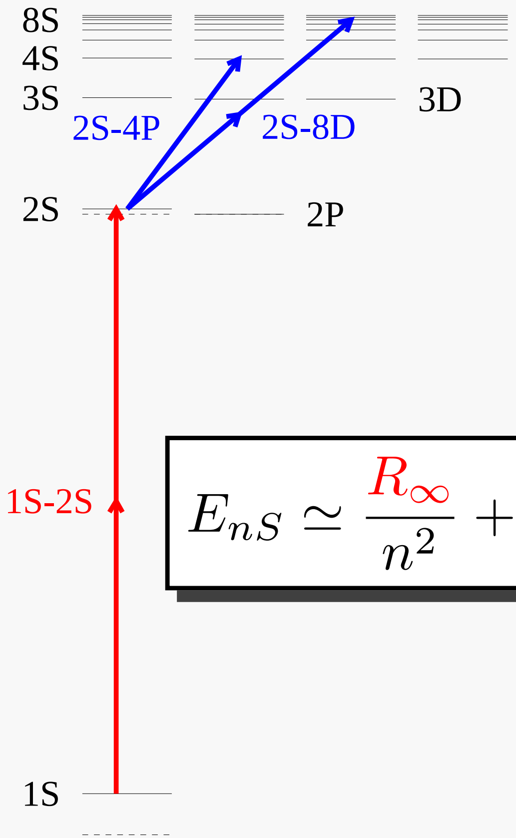

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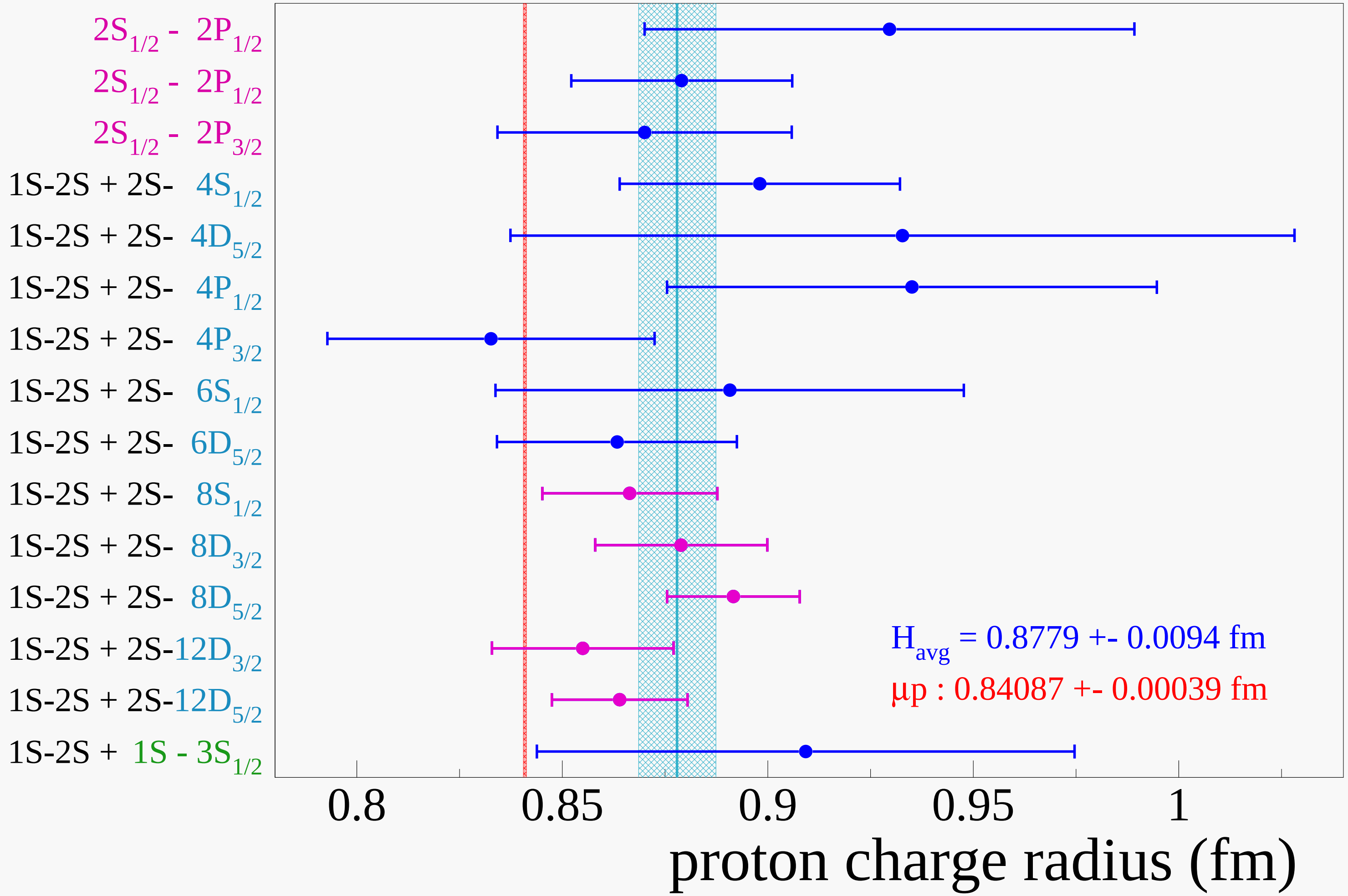

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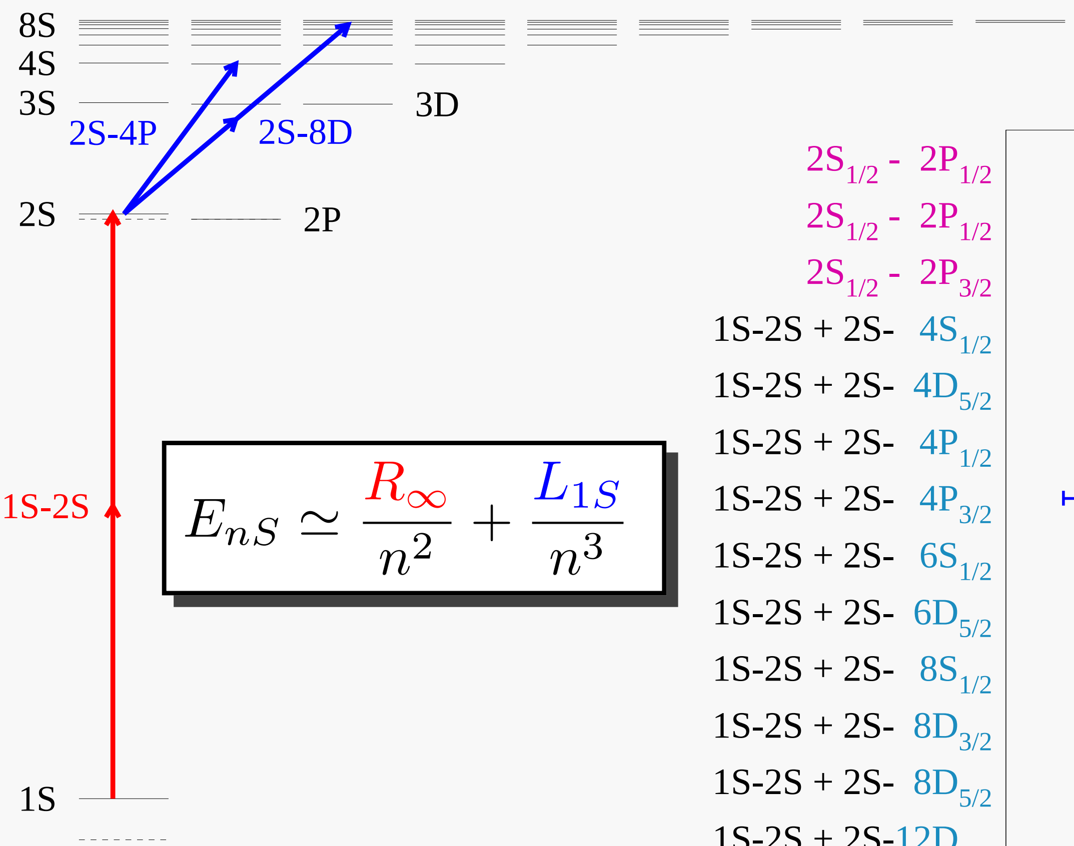
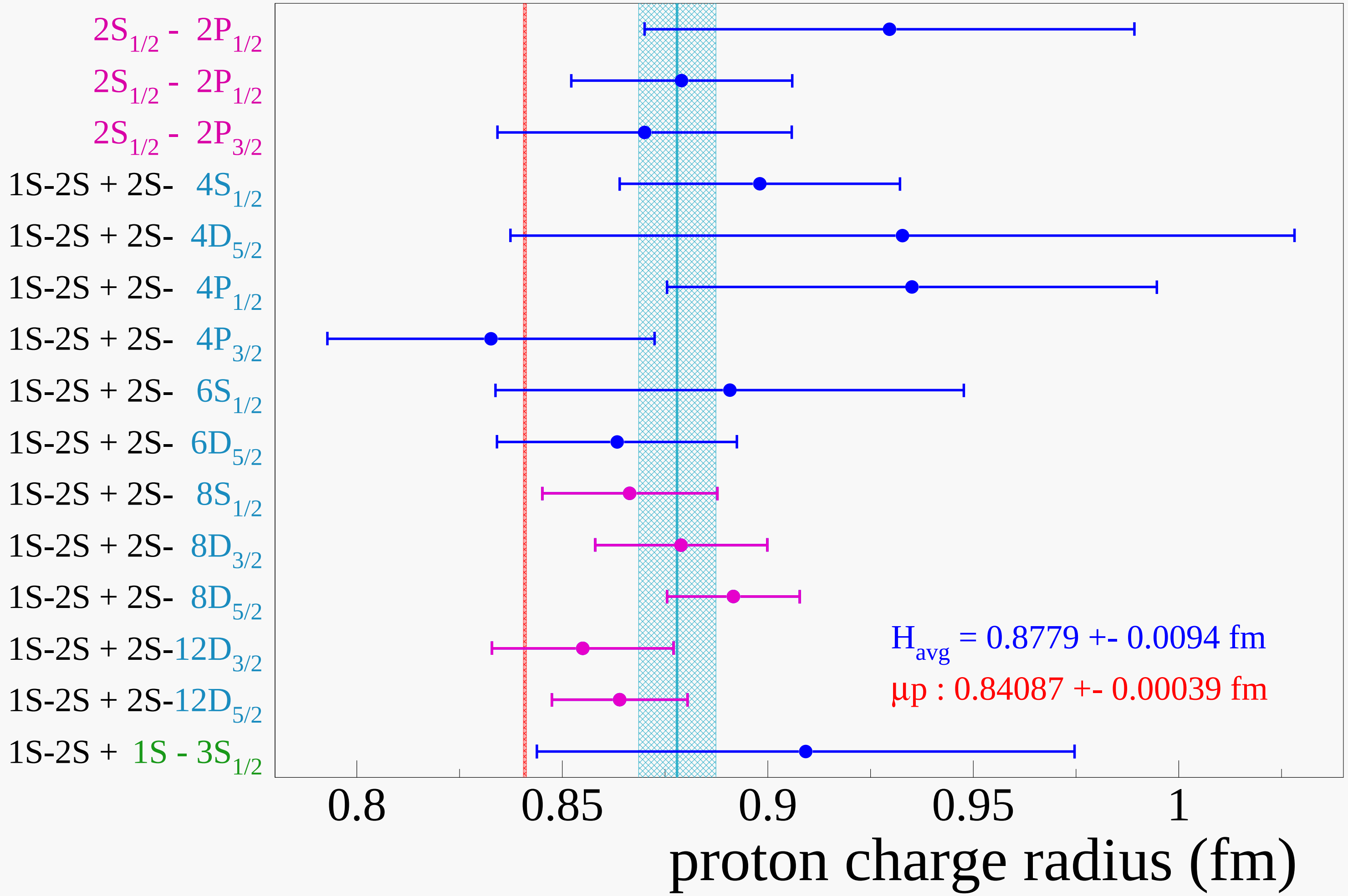


$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$



Discrepancy $< 3\sigma$
for individual H meas.

r_{p} puzzle (6): New physics?

- Several models have been discussed and discarded because of low energy constraints $(g-2)_{\mu/e}$, μe, H, μSi spectroscopy, J/Ψ, π, K, η decay widths, n-scattering ...

Models exist which escape the many constrains but at "high price":
- Tuning (e.g. vector vs axial-vector) and target coupling
- No UV completion and no full SM gauge invariance

$m_x \sim$ MeV
coupling $\sim 10^{-4}$

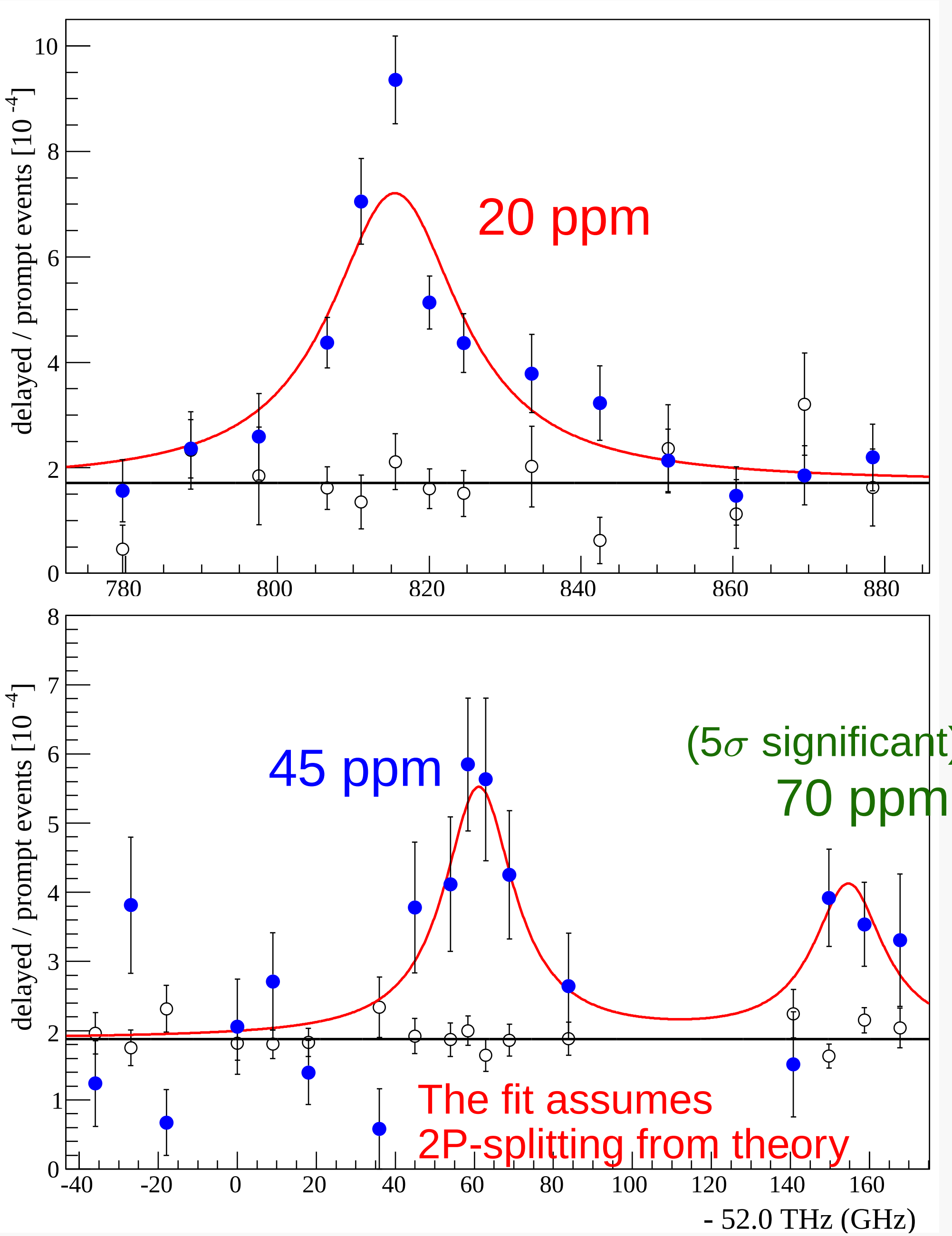
[arXiv:1401.6154 / PRL 107, 011803 (2011) / PRD 86, 035013 (2012) / PRD 83, 101702 (2011)]

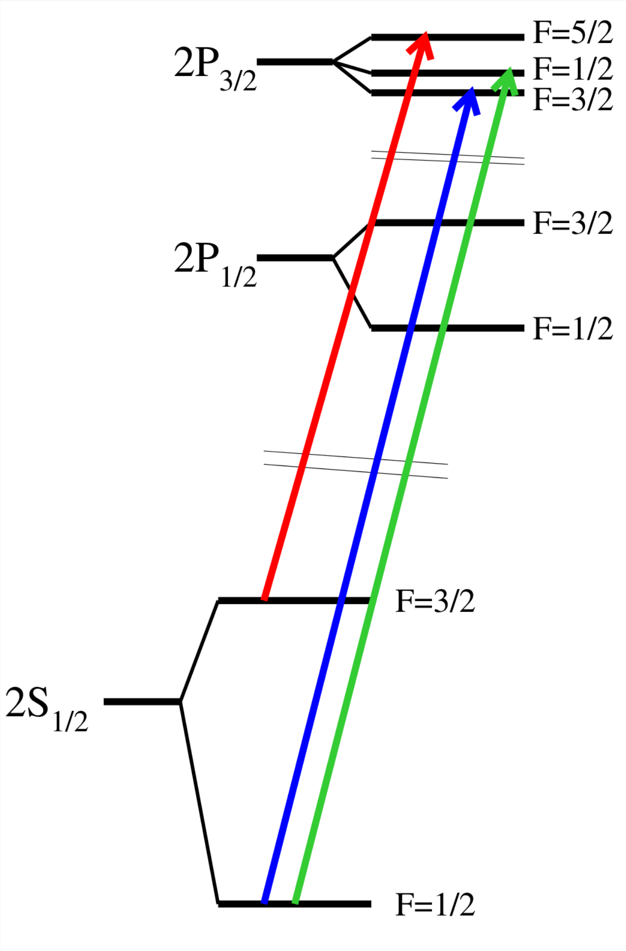
Window for new physics is very small.
BUT more "natural" extensions could come into play IFF $r_p^{\mathrm{H}} < r_p^{\mu\mathrm{p}} < r_p^{\mathrm{scatt}}$
$\rightarrow$ e.g. dark photons
[Pospelov]

- Maybe the "new physics" or new effects have to be searched elsewhere: strange proton structure, non-perturbative QED inside proton, quantum gravity etc.

Muonic deuterium and muonic helium
will soon provide stringent additional information

Measurements in muonic deuterium μd





In the last week of 2009 beam time we measured 2.5 transitions in μd

Deuteron radius from μd and μp (preliminary)

Directly from μd spectroscopy

$\Delta E^{\text{th}} = 230.495(30) - 6.109(1) r_{\text{d}}^2$ meV

$\Delta E^{\text{exp}} = 202.8759(34)$ meV

Deuteron radius from μd and μp (preliminary)

H-D shift: $r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.820\,07(65)\ \mathrm{fm}^2$

μp : $r_\mathrm{p} = 0.84087(39)\ \mathrm{fm}$

$\Rightarrow r_\mathrm{d} = 2.12771(22)\ \mathrm{fm}$

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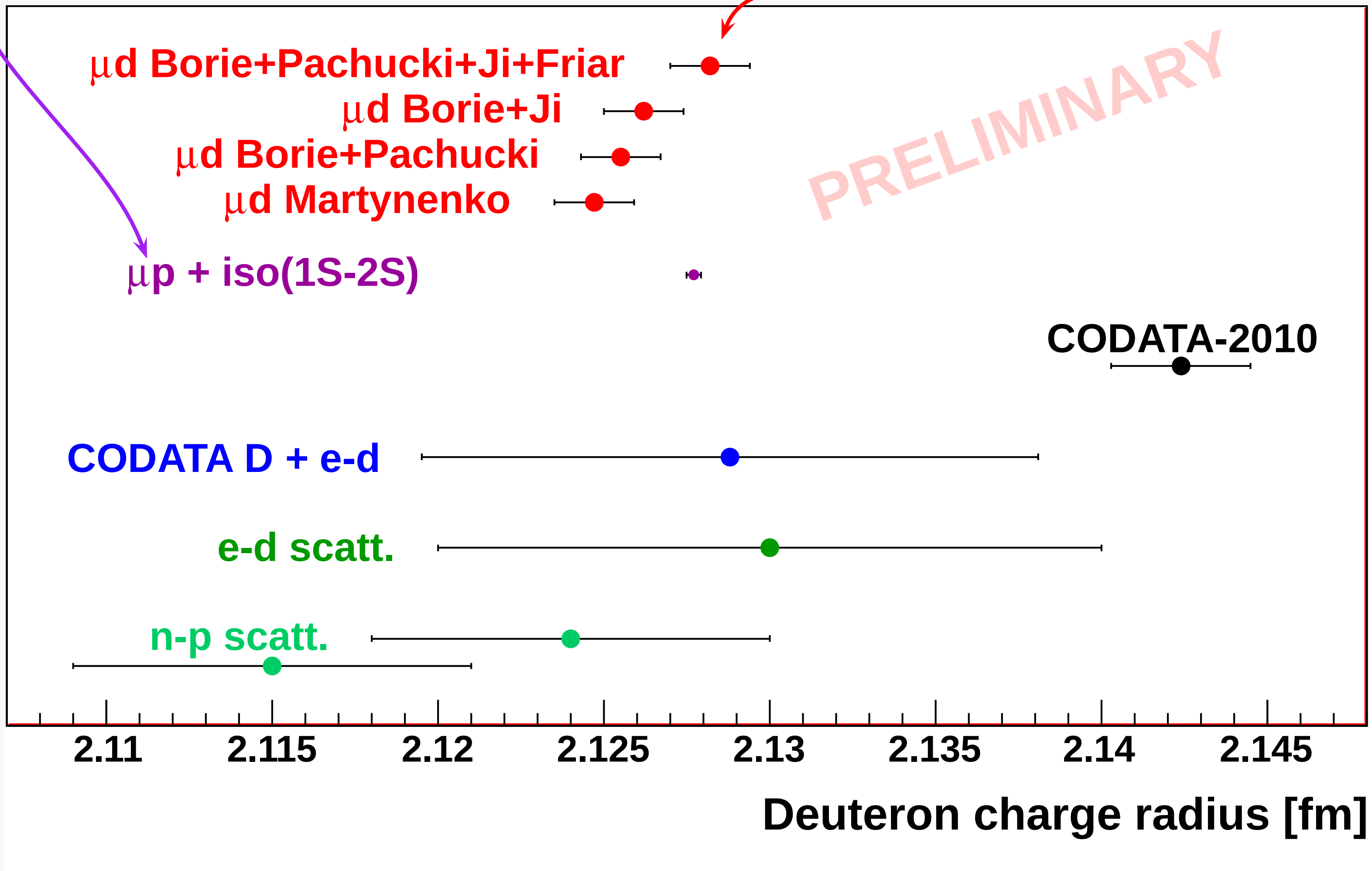

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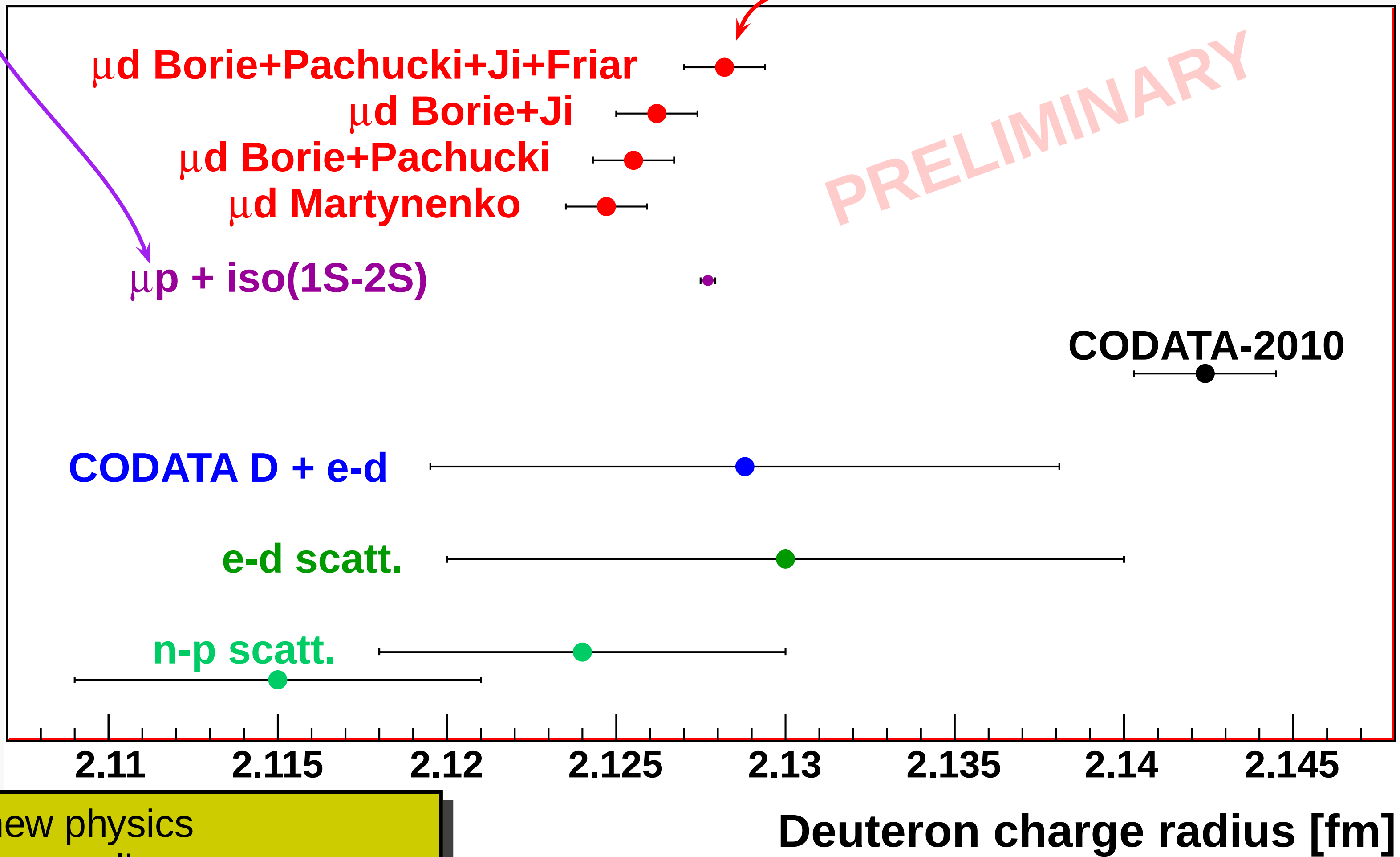

Consistency of muonic results!

IFF new physics
→ not coupling to neutrons

μHe^+ Lamb shift

Measure ΔE(2S-2P) in $\mu\,{}^3\text{He}^+$ and $\mu\,{}^4\text{He}^+$ with 50 ppm

$$\Downarrow$$

$r_{^3\text{He}}$ and $r_{^4\text{He}}$ with $u_r = 3 \times 10^{-4} \Longleftrightarrow$ 0.0005 fm

if polarisability contribution known with $u_r = 5\%$

Antognini et al., Can. J. Phys. 89, 47 (2011)

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Proton radius puzzle
- new muonic force?

Antognini et al., Can. J. Phys. 89, 47 (2011)

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- new muonic force?

Benchmark for few-nucleon theories
- absolute radii of ^{3}He, ^{4}He and ^{6}He, ^{8}He via isotopic shifts

R. van Rooij et al. Science 333, 196 (2011)
Cancio Pastor et al., arXiv:1201.1362
Müller, Wang, Shiner...

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Cancio Pastor et al., arXiv:1201.1362
Müller, Wang, Shiner...

Enhanced bound-state QED test when combined with He$^+$(1S-2S)
- Finitite size $\sim Z^4 R^2$
- Bohr structure $\sim Z^2 R_\infty$
- Challenging QED contributions $\sim (Z\alpha)^{5\ldots6}$

[MPQ and Amsterdam]

Why testing bound-state QED?

• Free QED

$$a_e = C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \Delta(\text{had.}, ...)$$

• Bound-state QED

- 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 $Z\alpha$)
- Nuclear structure corrections

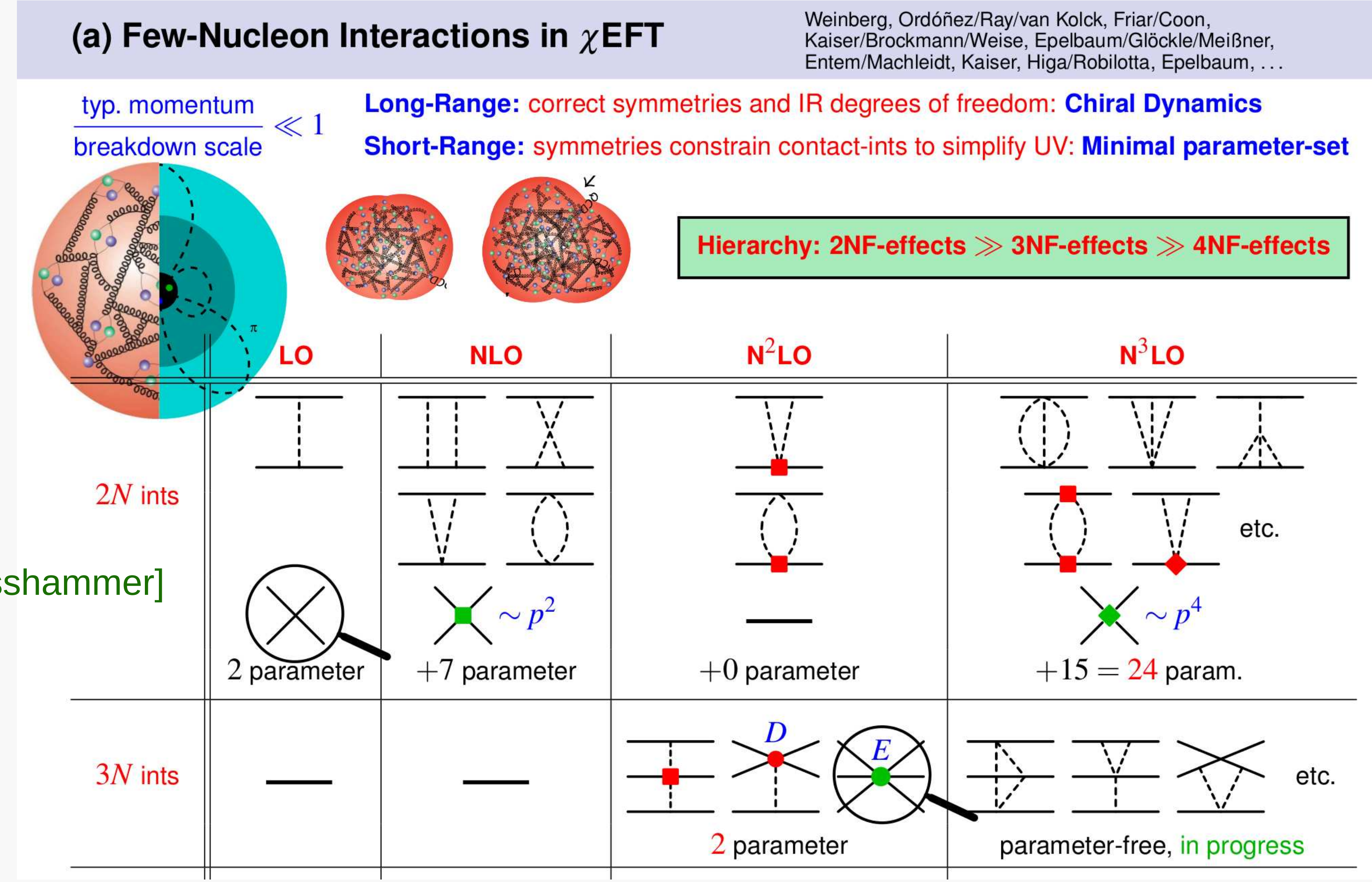
$\rightarrow$ Cannot develop the calculation in a systematic way
$\rightarrow$ Corrections are mixed up: $\alpha^x \cdot (Z\alpha)^y \cdot (m/M)^z$
$\rightarrow$ Difficulty in finding out the desired order of corrections

New development: NRQED

[after Nio]

QED	$g-2$ free particle particle mass only perturbative around free particle	Lamb shift bound-state particle three scales, hierarchy non-perturbative
QCD	deep inelastic scattering pQCD	hadron lattice, Chiral perturbation

Few-nucleon theories and He-radius



[from Griesshammer]

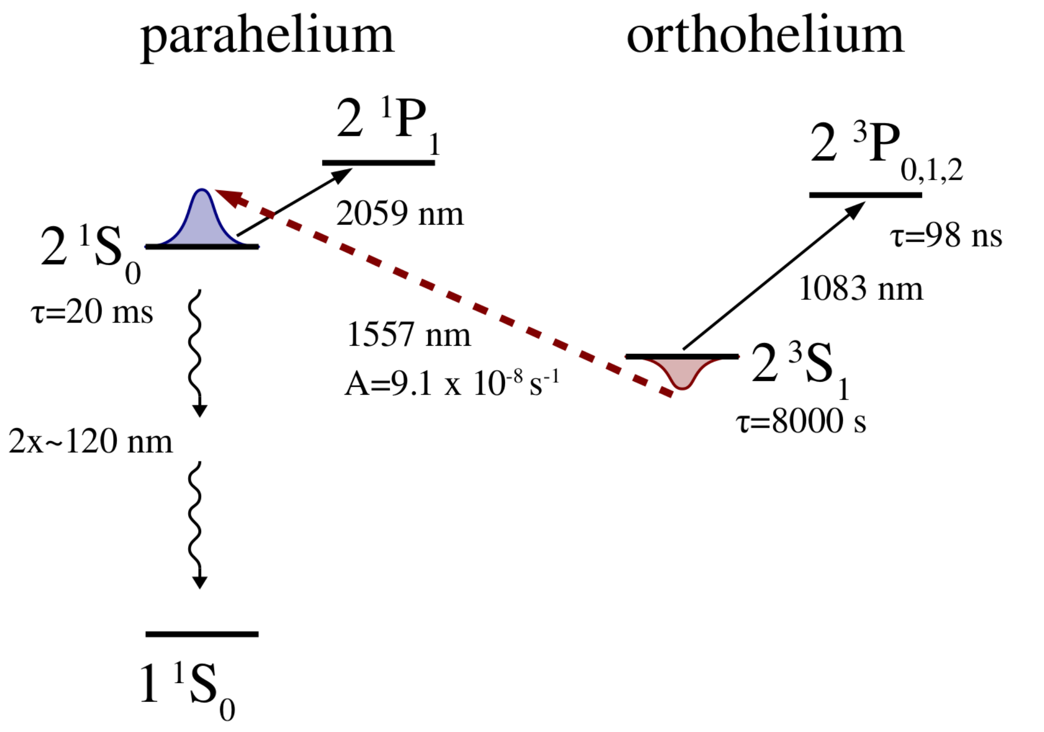
From $r_{\mathrm{He}} \to c_D$ or c_E.

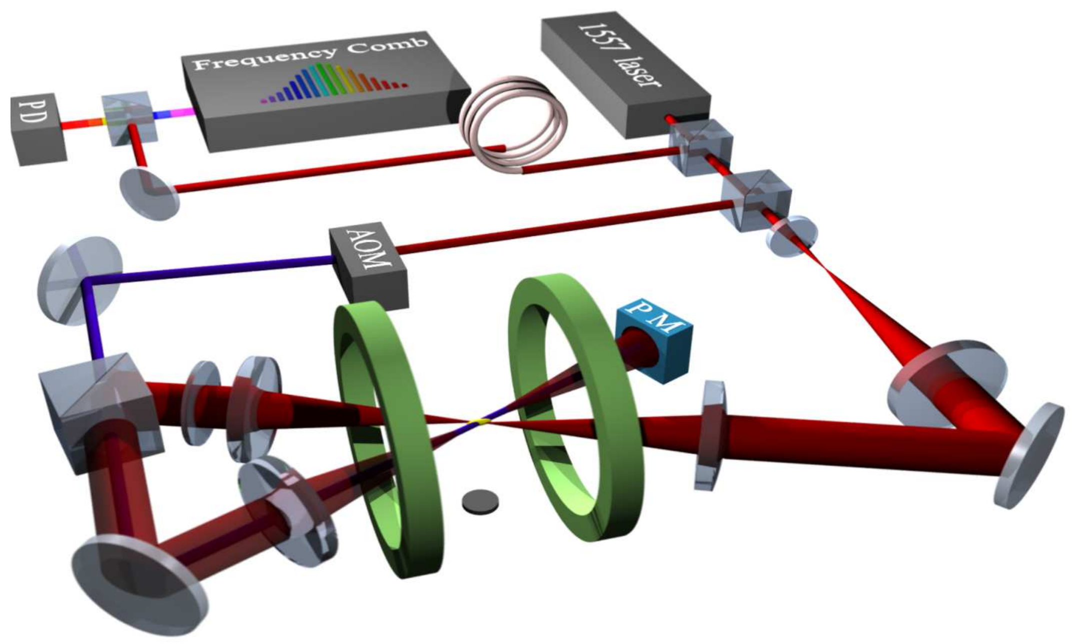
[Navratil et al., PRL99, 042501 (2007)]

Radii are "clean" benchmarks to test few-nucleons theories or to fix LEC

[Gazit, Marcucci, Forssen, Kievsky, Stadler, Krebs...]

Helium spectroscopy in Amsterdam



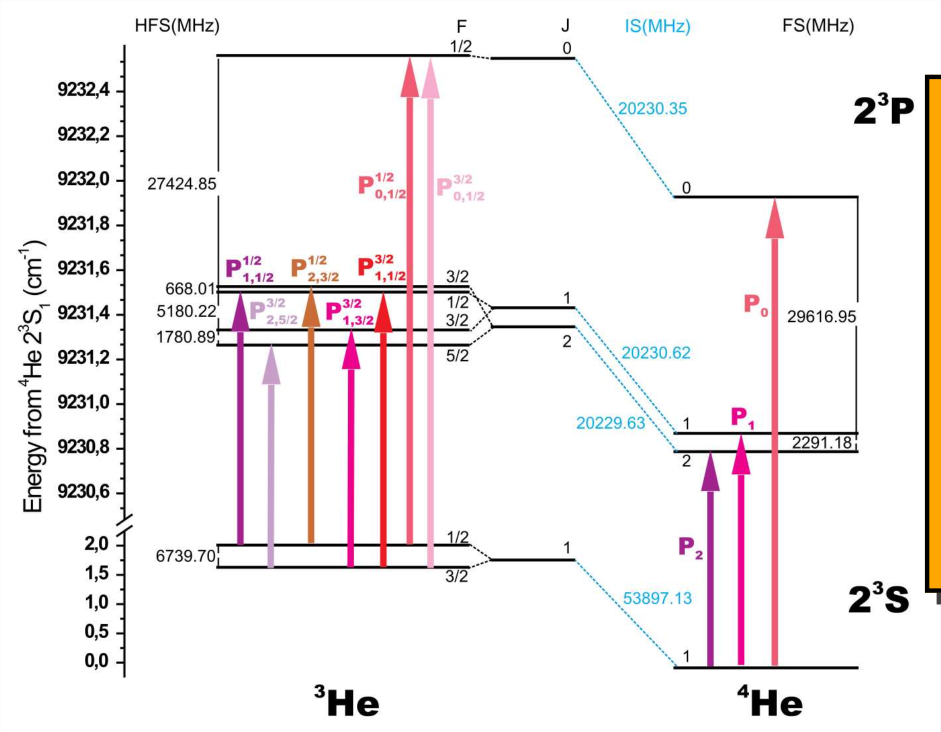


- Trap μK cold ^{4}He* and ^{3}He*.
- Measure the double forbidden 1557 nm line (M1 transition between two metastable states). (200'000 times narrower than 2^3P states
- Precision of $u_r = 8 \times 10^{-12}$ (1.5 kHz).

From isotope shift
$R^2_{^3\mathrm{He}} - R^2_{^4\mathrm{He}} = 1.028(11)$ fm^2

[R. van Rooij et al., Science 333, 196 (2011)]

2S-2P metrology of ^{3}He and ^{4}He in Florence

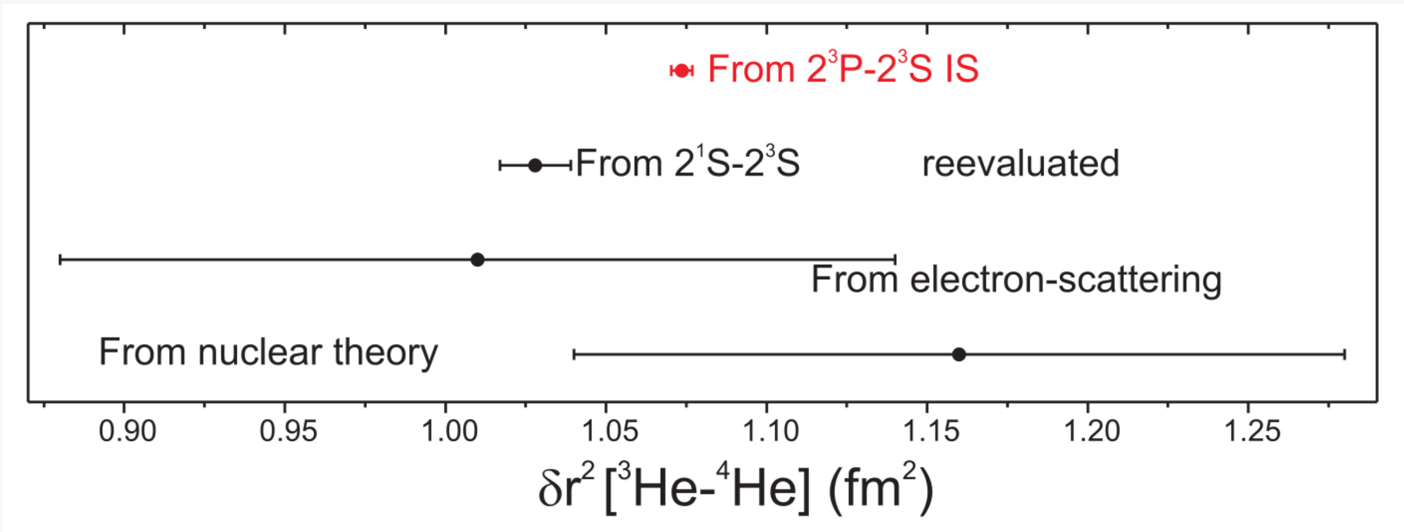


- Measure transitions between the 2S-2P hypefine mannifolds in metastable ^{3,4}He beams with $u_r \approx 5 \times 10^{-12}$ (2.5 kHz) using saturation spectroscopy at 1083 nm
- From isotope shift theory

$$R^2_{^3\text{He}} - R^2_{^4\text{He}} = 1.074(3) \text{ fm}^2$$

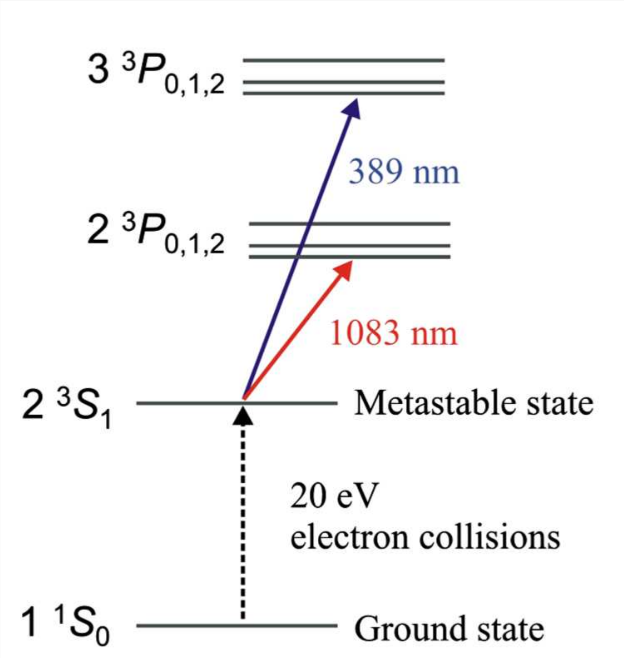
- Test of three-body bound-state QED

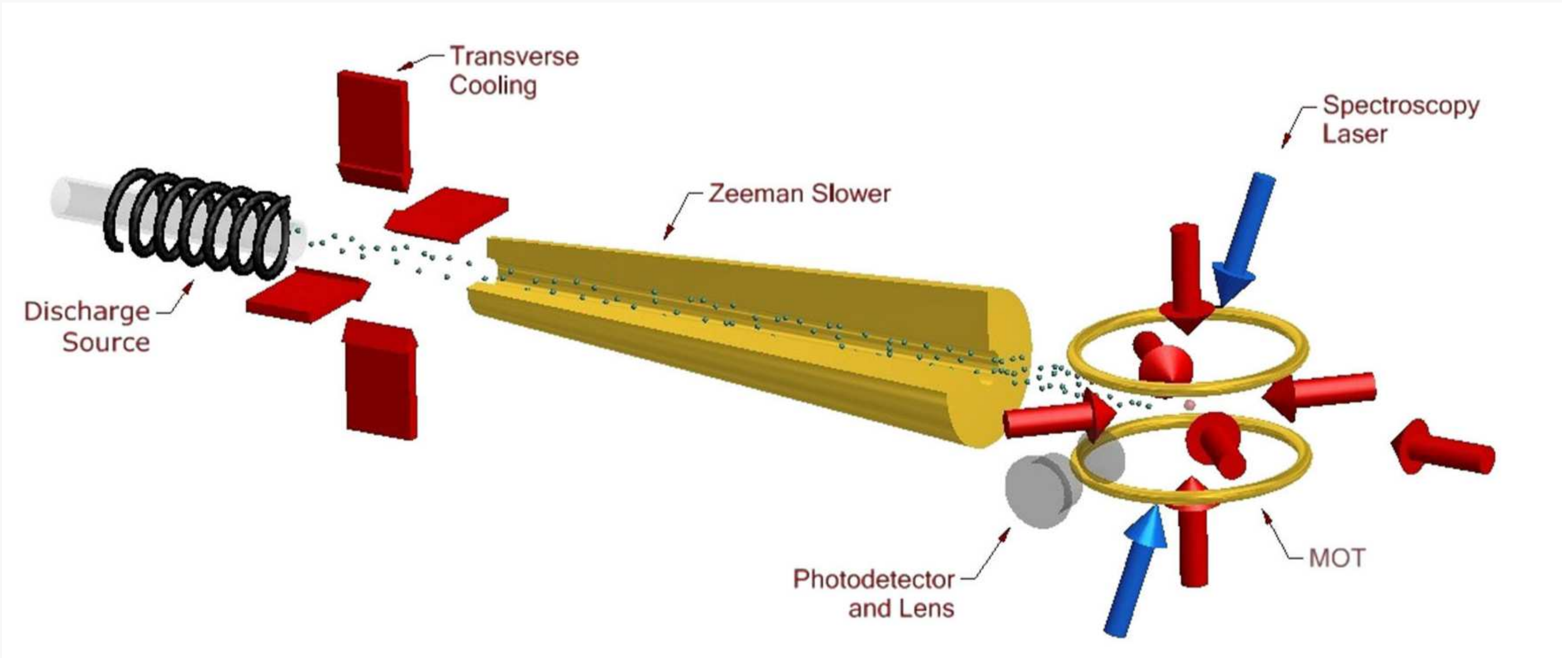
[Cancio Pastor et al., PRL 108, 143001 (2012)]



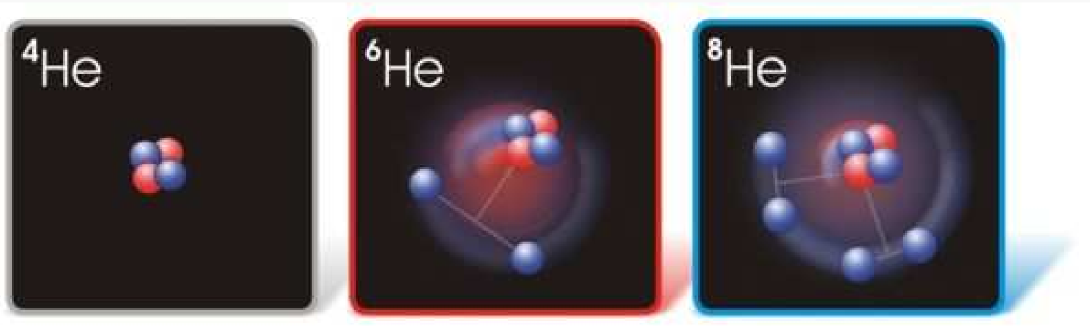
4σ discrepancy

^{6}He and ^{8}He spectroscopy at GANIL





- Finite size shift: 1 MHz
- Mass shift: 50 GHz

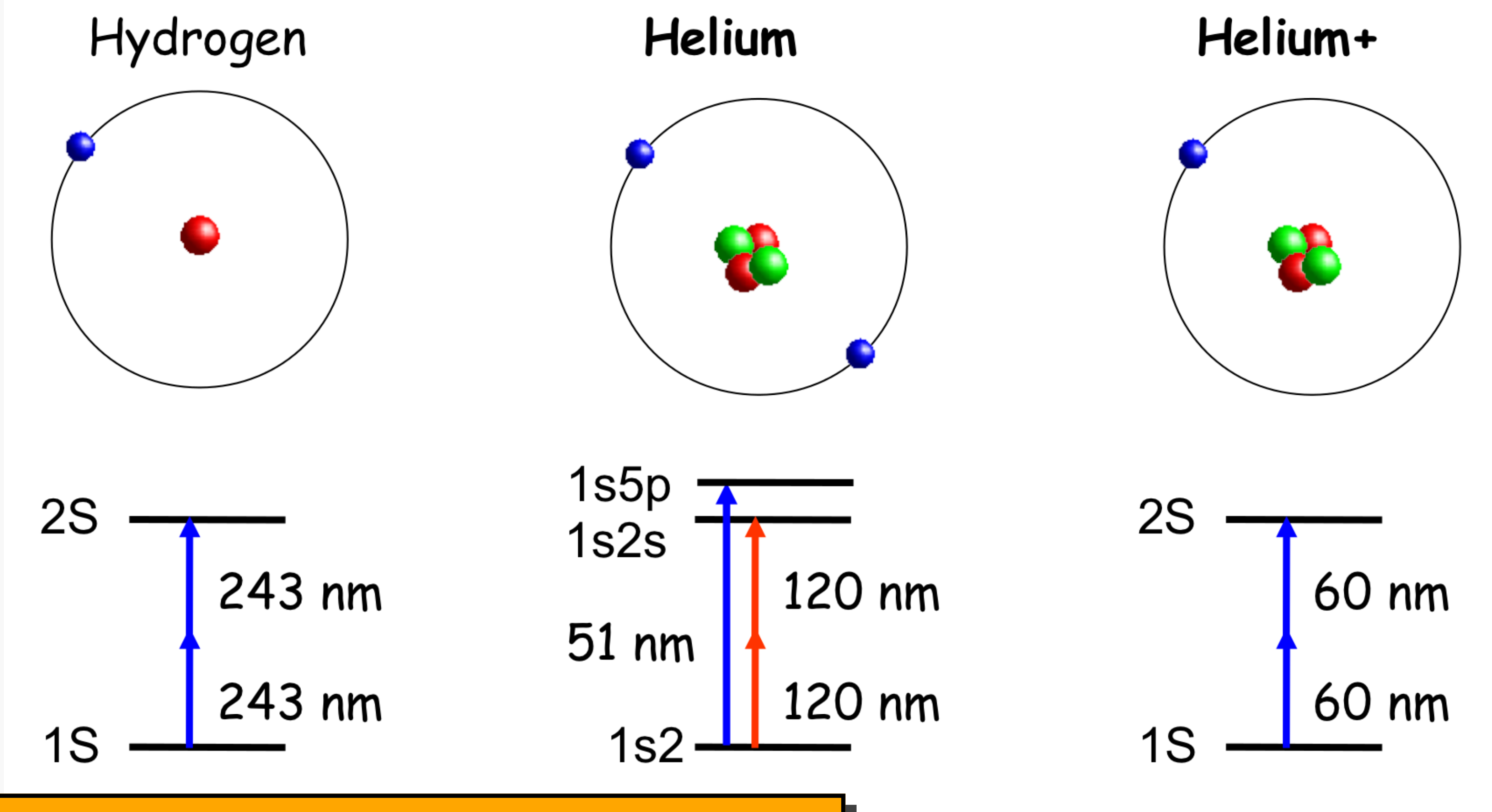


- Measure the 389 nm transitions with 10...70 kHz precison.
- From isotope shift theory and knowledge of ^{4}He charge radius

$R_{^6\mathrm{He}} = 2.059(8)$ fm
$R_{^8\mathrm{He}} = 1.958(16)$ fm

[Lu, Müller, Drake et al., RMP 85 1383 (2013)]

He^+(1S-2S) and He(1S2-1S5P)



Both experiments are performing XUV comb spectrocopy:

- two-photon, on a trapped He^+ ion (MPQ)
- one-photon Ramsey technique, on a He jet (Amsterdam)

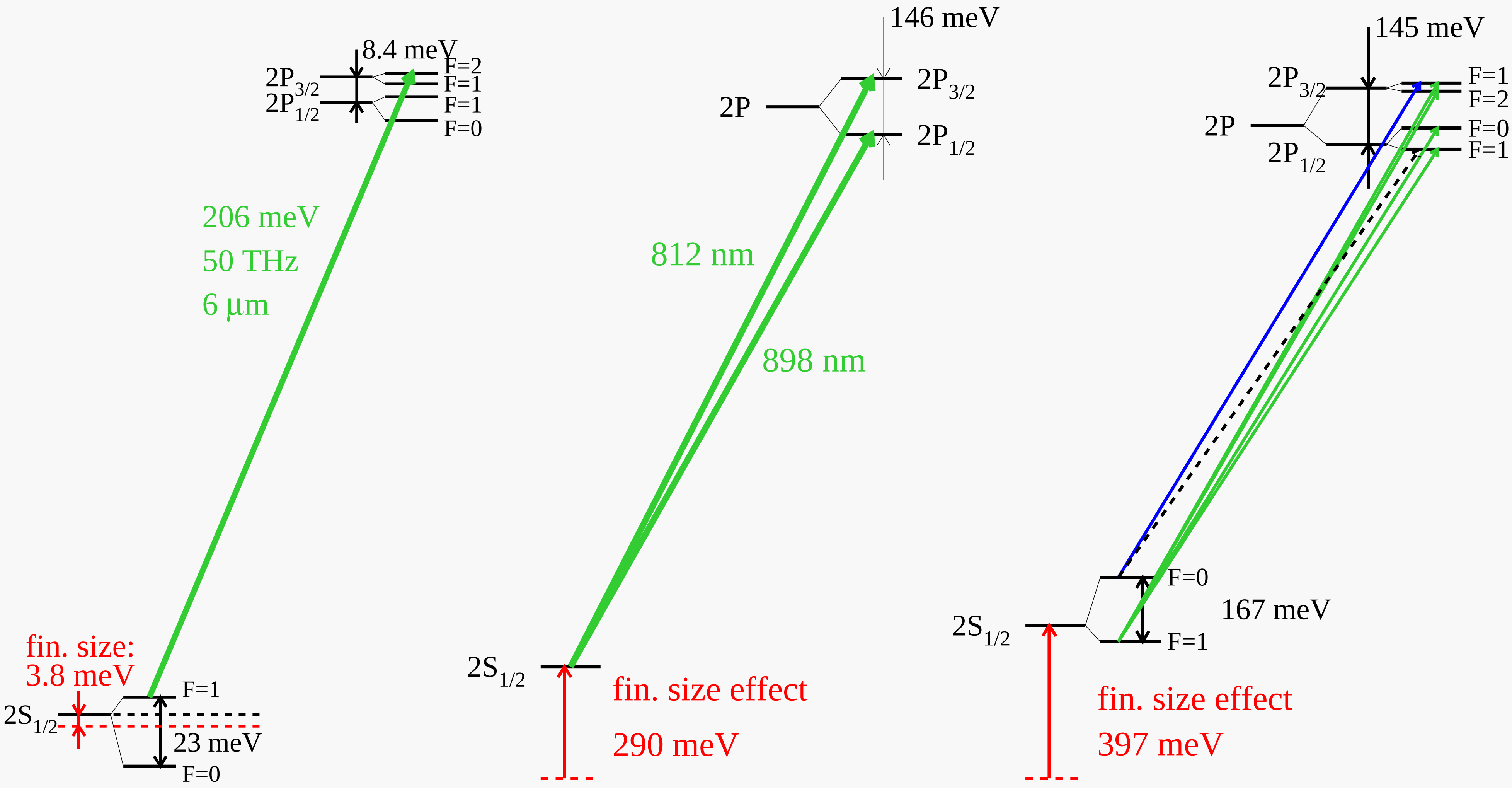
From these measuremsnts

$\rightarrow R_{^4\mathrm{He}}$ or one/two-electrons bound-state QED test

[Hermann et al., PRA 79, 052505 (2009)]

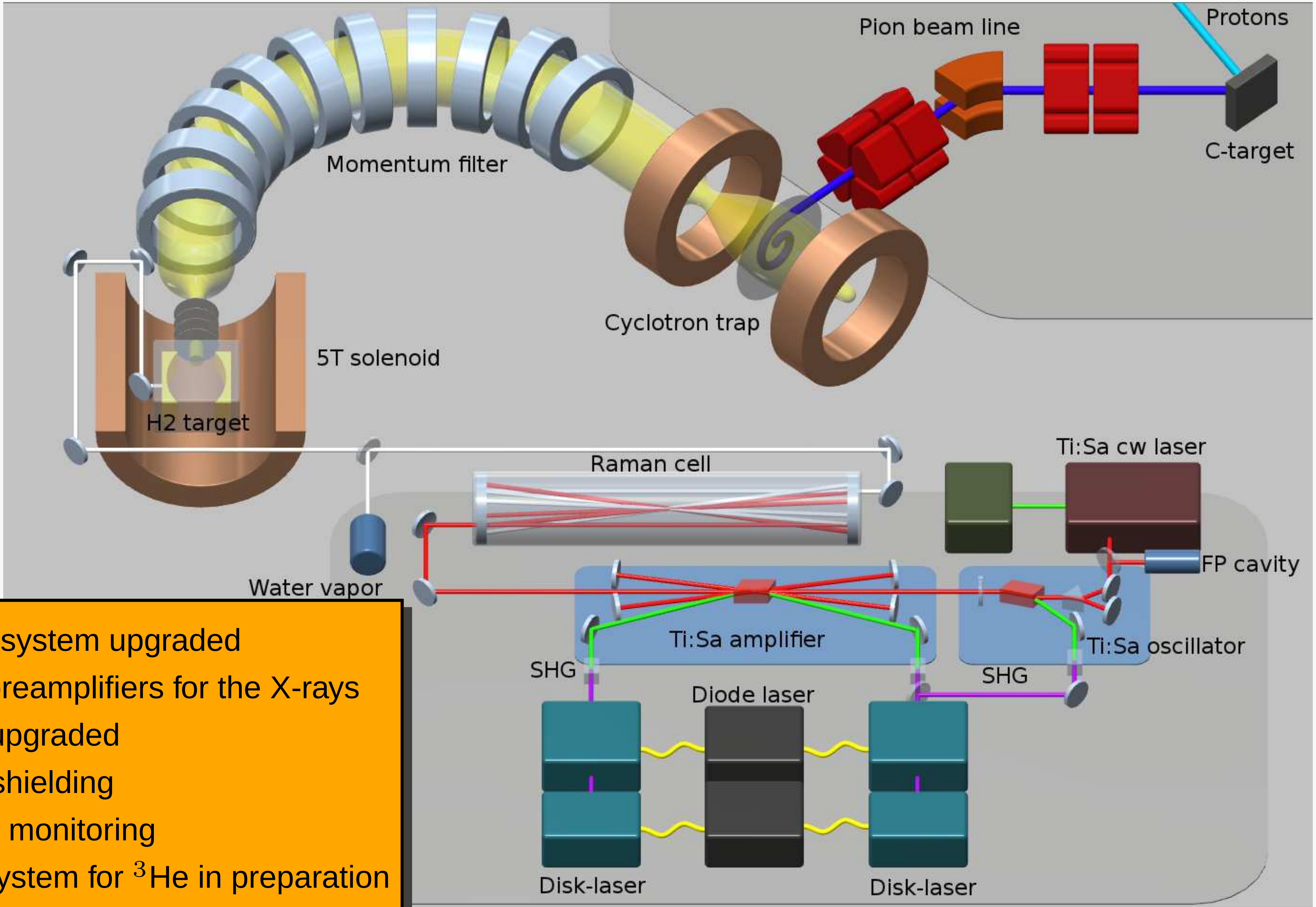
[Kandula et al., PRA 84, 062512 (2011)]

Muonic helium transitions



μp	$\mu\,^4He^+$	$\mu\,^3He^+$
$\lambda = 5.5 - 6\mu m$	$\lambda = 812$ and 898 nm	$\lambda = 850 - 1100$ nm
finite size: 2%	finite size: 20%	finite size: 25%

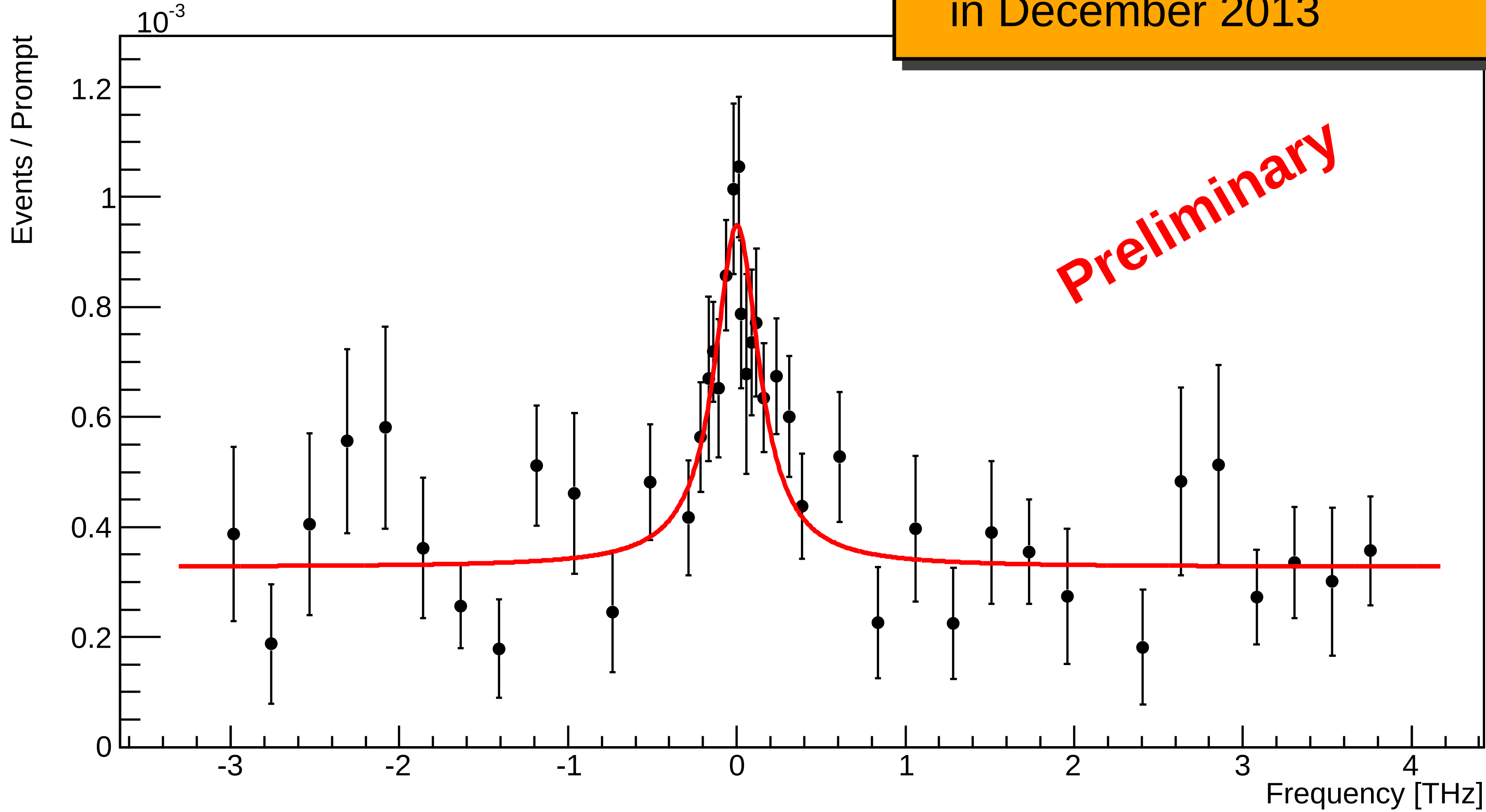
The setup for $\mu\,\mathrm{He}^+$ is similar to μp



- Laser system upgraded
- New preamplifiers for the X-rays
- DAQ upgraded
- Light shielding
- Cavity monitoring
- Gas system for ^{3}He in preparation

The $2S_{1/2} - 2P_{3/2}$ resonance in $\mu\,^4\mathrm{He}^+$

Two weeks of measurements in December 2013



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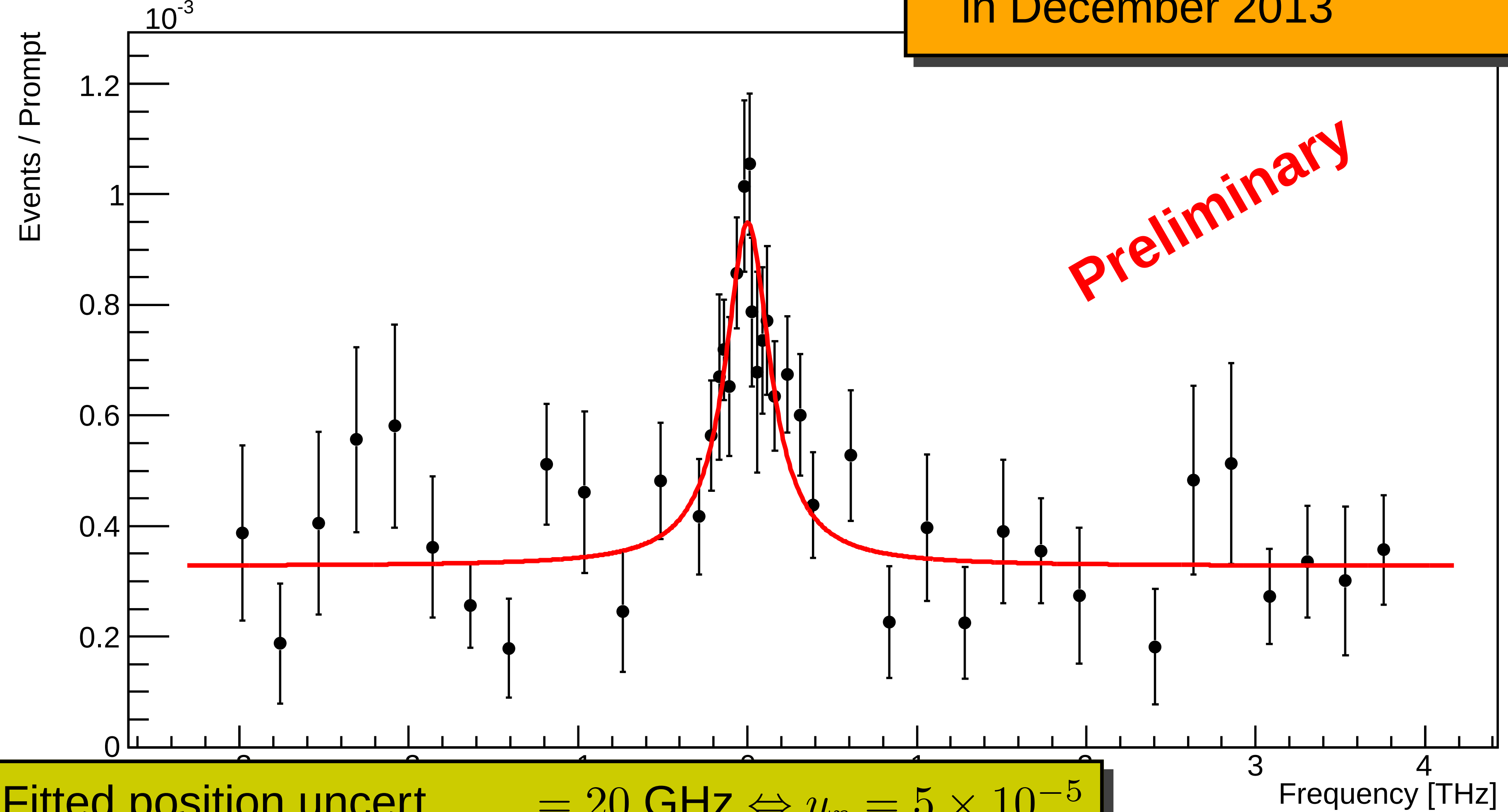
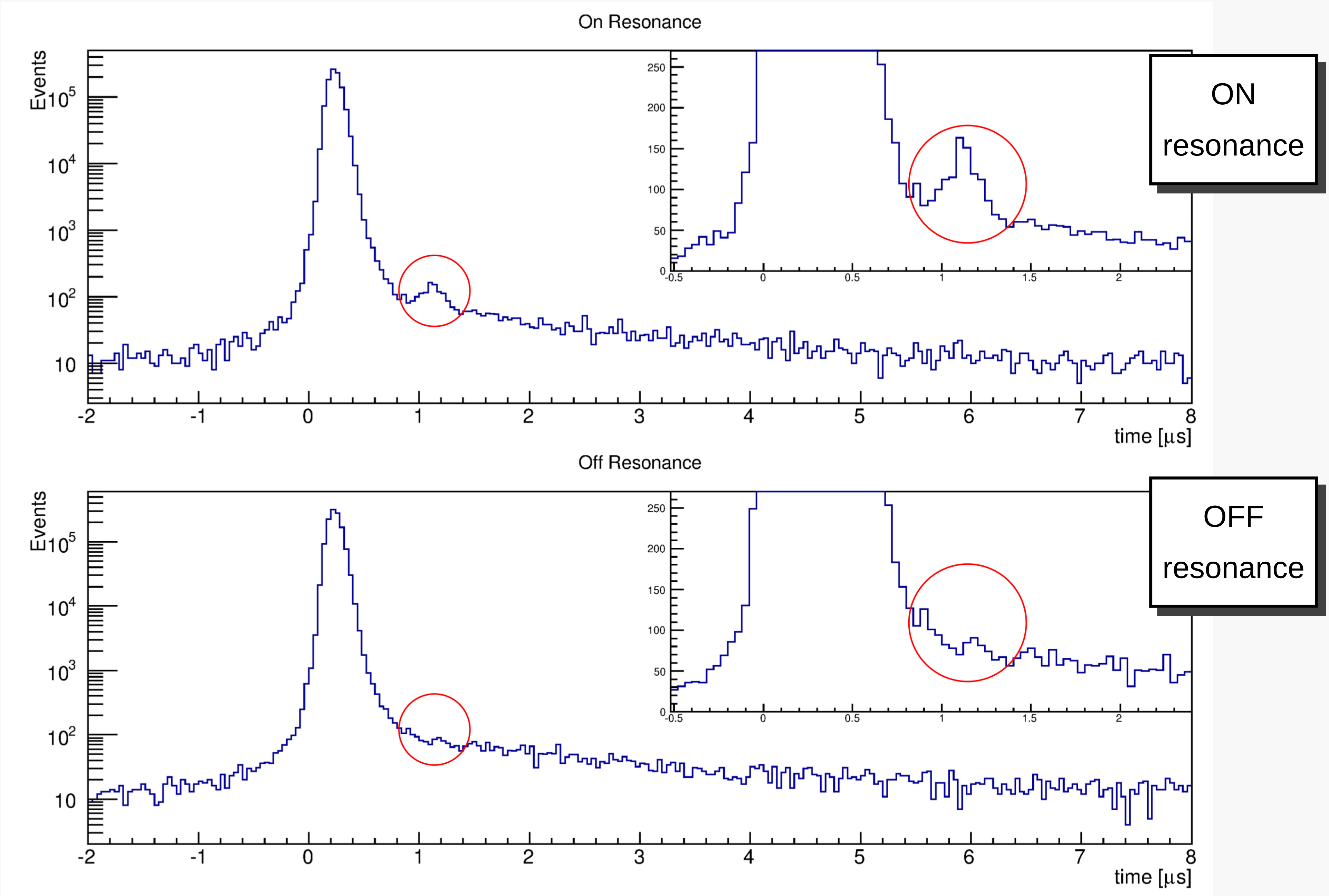
Two weeks of measurements
in December 2013



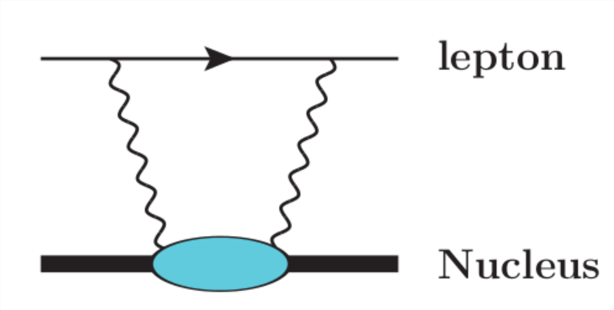
Fitted position uncert. $= 20$ GHz $\Leftrightarrow u_r = 5 \times 10^{-5}$
Laser frequency uncert. < 100 MHz
Systematics < 10 MHz

The K_α time spectra



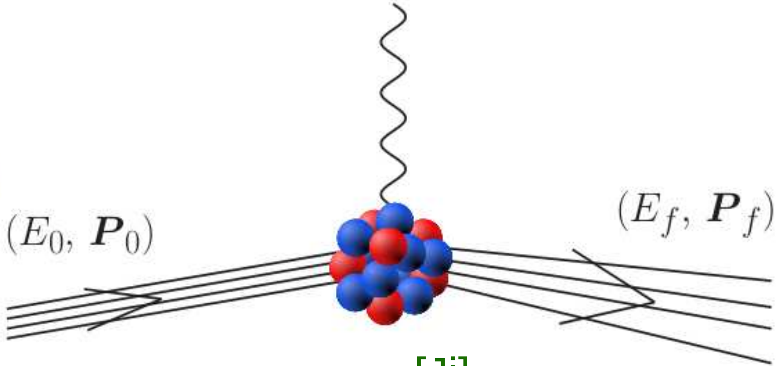
Nuclear polarization contribution in $\mu\,\mathrm{He}^+$

$$\Delta E_{\mathrm{LS}}^{\mathrm{th}} = \Delta E_{\mathrm{QED}} - \frac{m_r^3}{12}(Z\alpha)^4\langle r^2\rangle + \frac{m_r^3}{12}(Z\alpha)^4\langle r^3\rangle_{(2)} + \delta_{\mathrm{pol}}$$



- From nuclear response function $S_0(\omega) \rightarrow$ nuclear polarization contribution

$$S_O(\omega) = \sum\!\!\!\!\!\!\int_f |\langle\psi_f|\hat{O}|\psi_0\rangle|^2\delta(E_f - E_0 - \omega)$$



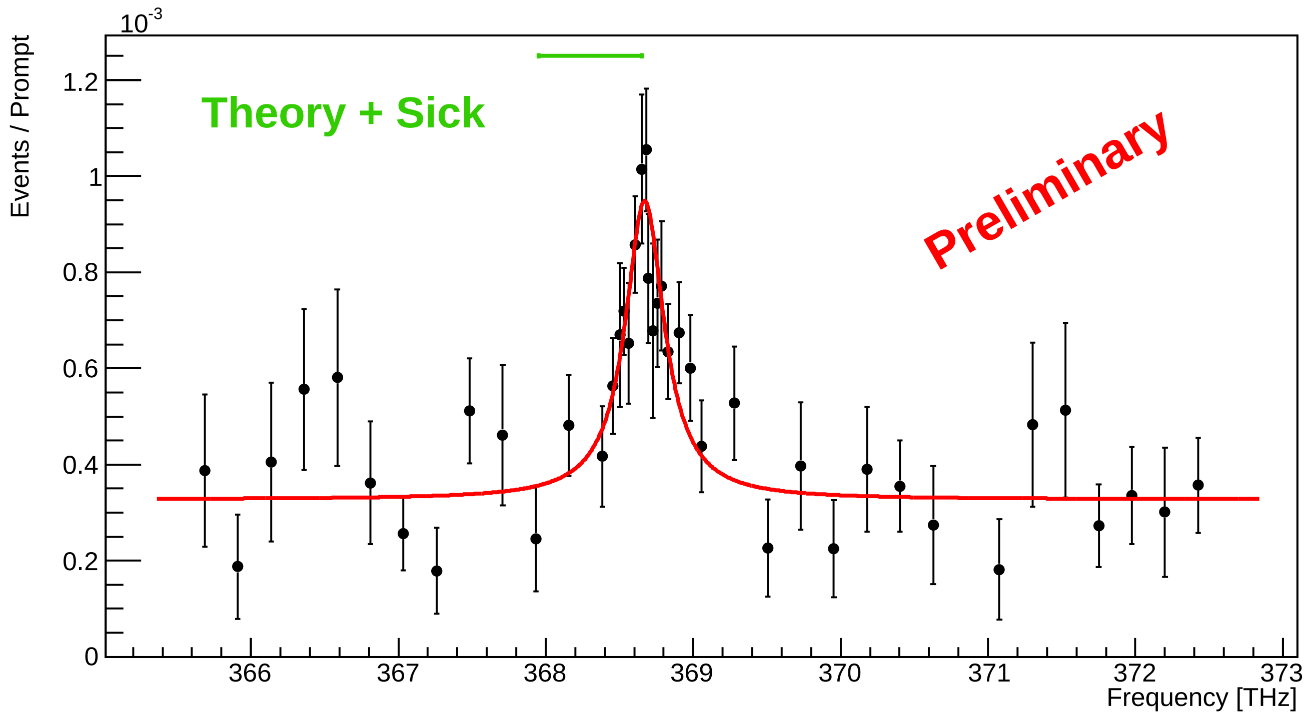
[Ji]

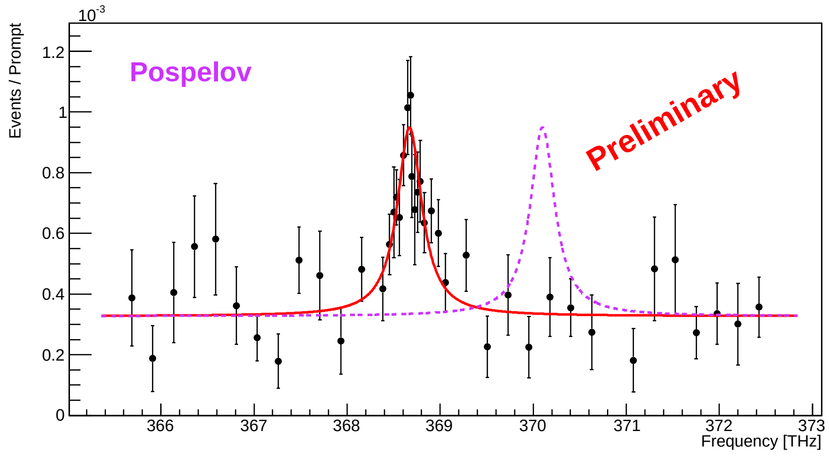
- Two ways to get the response function:

  - From photo-absorption [Bernabeau & Jarlskog, Rinker, Friar]
    $\delta_{\mathrm{pol}} = 3.1$ meV $\pm 20\%$

  - From state-of-the-art potentials (chiral EFT, AV18/UIX) [Ji, Nevo Dinur, Bacca...]
    $\delta_{\mathrm{pol}} = 2.47$ meV $\pm 6\%$

Secret results!





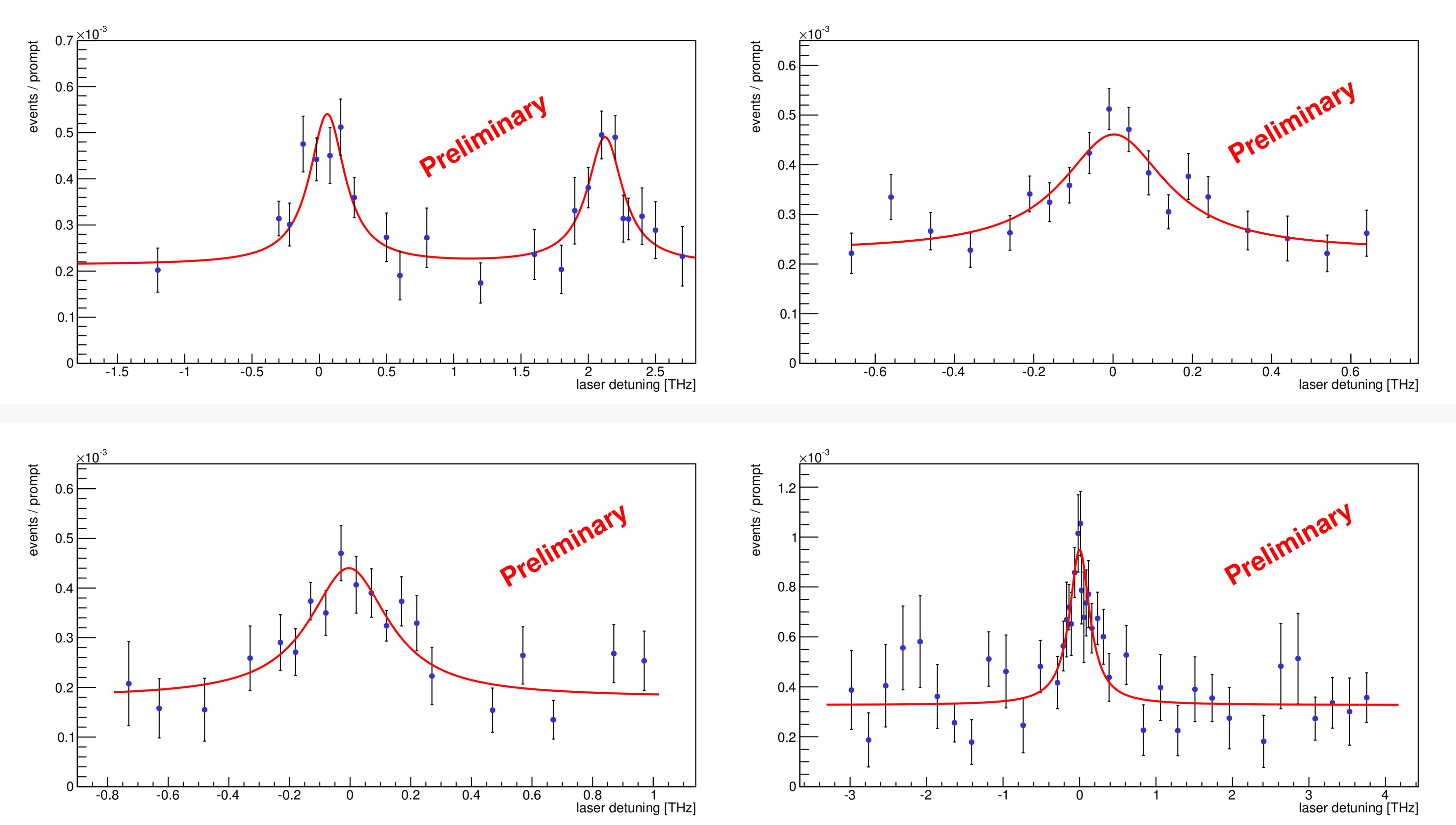
- The transition has been found at the expected position i.e., whithin the uncert. given by r_{He} from $e-$He scattering.
- New physics model of Pospelov excluded
- Zavattini value from old $\mu\,\mathrm{He}^+$ experiment excluded

Need to summarize all 2S-2P contributions

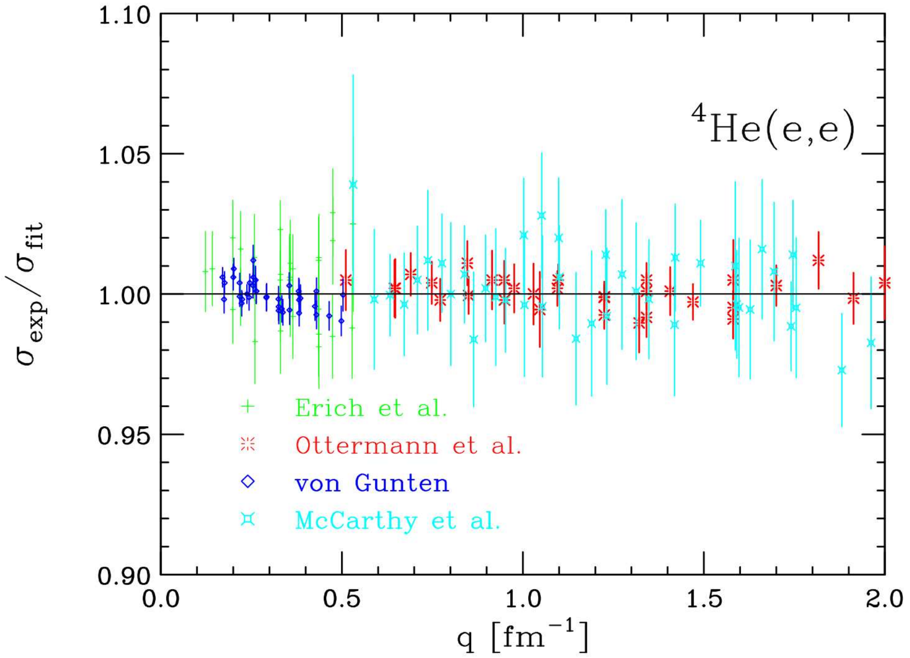
^{4}He nuclear charge radius

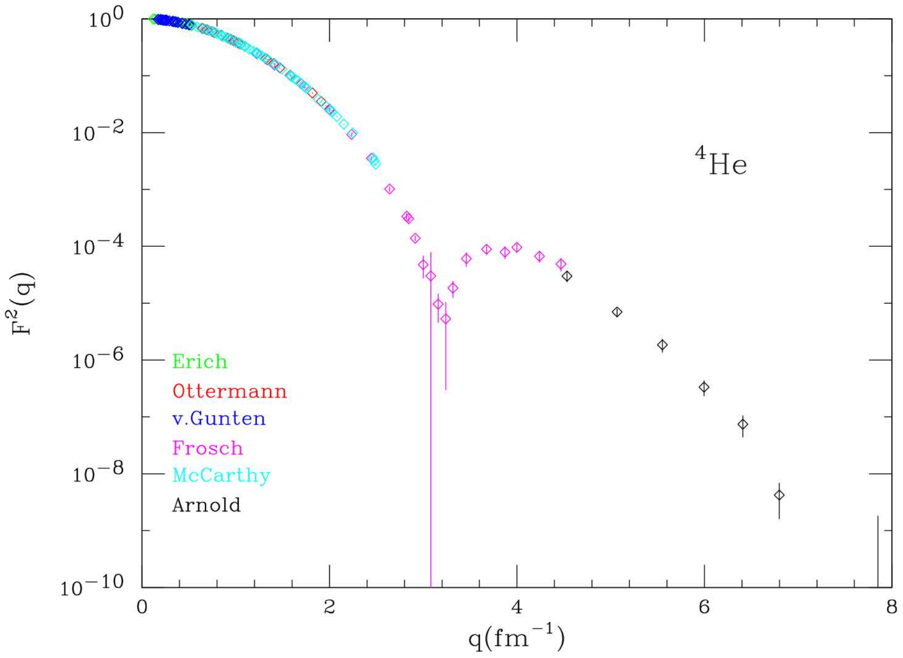
$1.681(4)$ fm	$u_r = 2 \times 10^{-3}$	[Sick]
$1.677(1)$ fm	(VERY preliminary)	[$\mu\,\mathrm{He}^+$]

Measured $\mu\,^4\mathrm{He}^+$ and $\mu\,^3\mathrm{He}^+$ resonances



He radius from e-scattering





- world data of e-scattering.
- constraints density at large r:
  - shape: from p-wavefunction $\sim$ Whittaker.
  - absolute density: from p-He scattering + FDR.
- point density from potential + GFMC (small r) + FDR (large r).
- fold point density with charge density distribution of p and n.
- include Coulomb distortions.

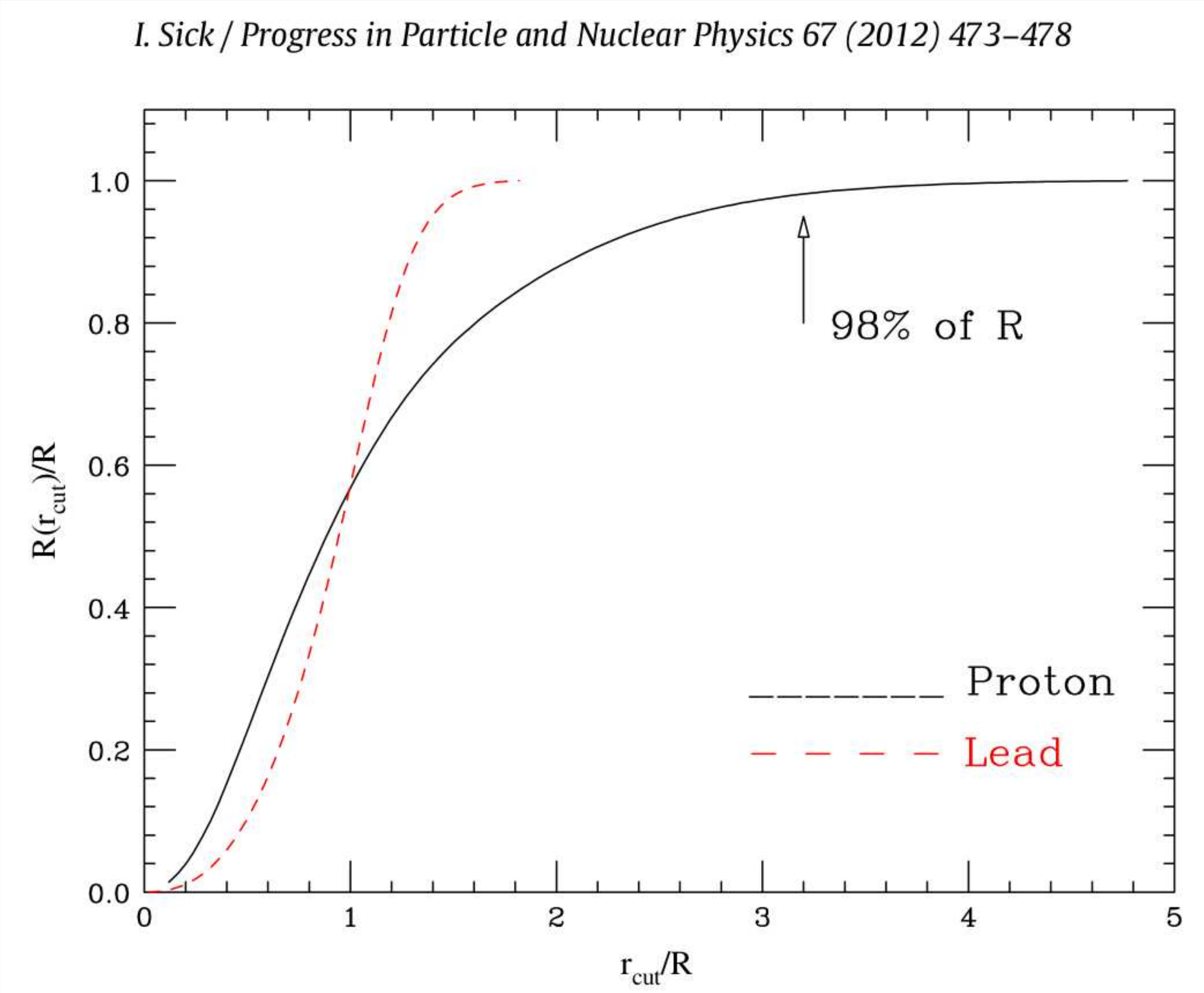
Fit with SOG

$\rightarrow R = 1.681(4)$ fm

(best known radius from e-scattering)

[Sick, PRC 77, 941392(R) (2008)]

Difficulties due to large-r tail (from I. Sick)



The extrapolation from finite q to $q = 0$ is much more difficult for p than for nuclei with $A > 2$

Extrapolation of $G(q)$ is not fully reliable. Needs to consider $\rho(r)$ at large r.

Most $e - p$ scattering fits have not been checked for large-r behavior

Need a physical model to constrains the large-r behavior

Slow convergence of the p rms radius vs upper cutoff $r_{\rm cut}$ calculated over the integral of the charge density $\rho(r)$

Conclusions

From two transitions in muonic hydrogen:

- Proton charge radius: $r_{\mathrm{E}} = 0.84087(39)$ fm
- Proton Zemach radius: $r_{\mathrm{Z}} = 1.802(37)$ fm

deducing also

- Deuteron charge radius: $r_{\mathrm{d}} = 2.12771(22)$ fm
- $R_\infty = 3.289\,841\,960\,249\,5\,(10)^{\mathrm{radius}}(25)^{\mathrm{QED}} \times 10^{15}$ Hz/c

Proton radius puzzle persist:

- Experimental problem(s)?
- New physics?
- Weird QCD or bound-state QED?
- Proton structure?

From 2.5 transitions in muonic deuterium:

$\rightarrow$ deuteron radius

The deuteron and proton radii extracted from $\mu\mathrm{p}$ and $\mu\mathrm{d}$ are consistentwith the 1S-2S isotope shift in H

From transitions in $\mu\,{}^4\mathrm{He}^+$ with $u_r = 5 \times 10^{-5}$.

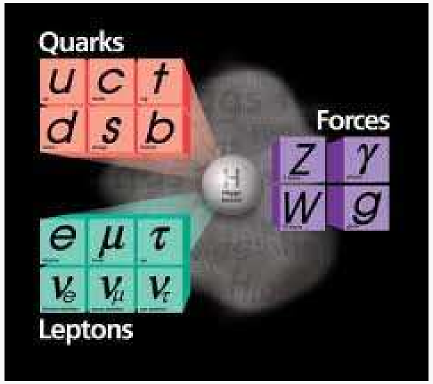
$\longrightarrow$ ^{4}He charge radius with $u_r = 3 \times 10^{-4}$

$\longrightarrow$ agreement with the e-scattering value ($u_r = 2 \times 10^{-3}$)

$\longrightarrow$ important information for the proton puzzle (spin-, isospin-dependence etc.)

$\longrightarrow$ interesting information for few-nucleons theory, to disentangle potentials....

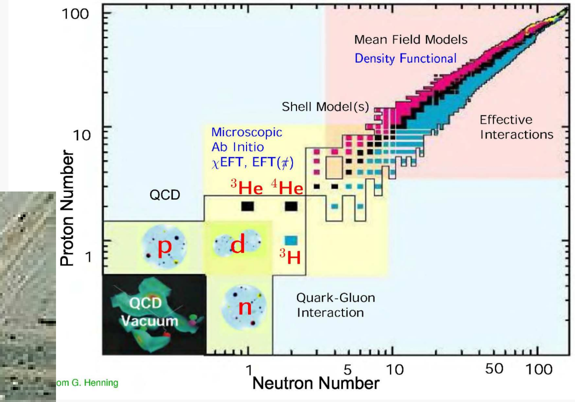
Motivation, summary, outlook



Test of H energy levels
Bound-state QED

Mu$= \mu^+ e^-$

Ps$= e^+ e^-$



New physics?

Low-energy QCD
EFT, χpt, lattice
strong bound-state
p-structure
few-nucleon th.

Scattering
$e + p \rightarrow e + p$
$e + d \rightarrow e + d$
$\mu + p \rightarrow \mu + p$
$\gamma + p \rightarrow \gamma + p$
...

H-spectroscopy

μp and μd

$\mu\,\mathrm{He}^+$

Proton charge radius
Proton Zemach radius
Deuteron charge radius

$R_\infty = 3.2898419602495(10)(25)10^{15}$ Hz/c
combining μp with H spectroscopy

F. Biraben, S. Galtier, P. Indelicato, L. Julien, F. Nez, C. Szbabo — Labor. Kastler Brossel, Paris

M. Diepold, B. Franke, J. Götzfried, T.W. Hänsch, J. Krauth,, F. Mulhauser, R. Pohl — MPQ, Garching, Germany

F.D. Amaro, J.M.R. Cardoso, L.M.P. Fernandes, A. L. Gouvea, J.A.M. Lopes, C.M.B. Monteiro, J.M.F. dos Santos — Uni Coimbra, Portugal

D.S. Covita, J.F.C.A. Veloso — Uni Aveiro, Portugal

M. Abdou Ahmed, T. Graf, A. Voss, B. Weichelt — IFSW, Uni Stuttgart

J. Alpstäg, A. Antognini, K. Kirch, F. Kottmann, K. Schuhmann, D. Taqqu — ETH Zürich

A. Dax, M. Hildebrandt, A. Knecht — PSI, Switzerland

T.-L. Chen, Y.-W. Liu — N.T.H. Uni, Hsinchu, Taiwan

P.E. Knowles — Uni Fribourg, Switzerland

P. Amaro, J.P. Santos — Uni Lisbon, Portugal

Atomic physics

- Tan @ NIST: Ne^{9+}
- Hänsch @ MPQ: $2S - 4P$
- Nez @ LKB: $1S - 3S$
- Hessels @ York: $2S - 2P$
- Udem @ MPQ: He^{+}
- Eikema @ Amsterdam: He^{+}
- Cancio @ Florence: He
- Müller @ Ganil: halo He nuclei
- Ubachs @ Laserlab: H2
- Hilico @ LKB: H2^{+}

Scattering

- E08-007 @ JLAB, e-p at very low Q^2
- A1-1/12 @ Mainz, e-d at very low Q^2
- MUSE @ PSI, μ-p/e-p

- E05-015 and CLASS @ JLAB, test 2γ
- OLYMPUS@ DESY and VEPP3, test 2γ

- Structure functions
- Compton scattering

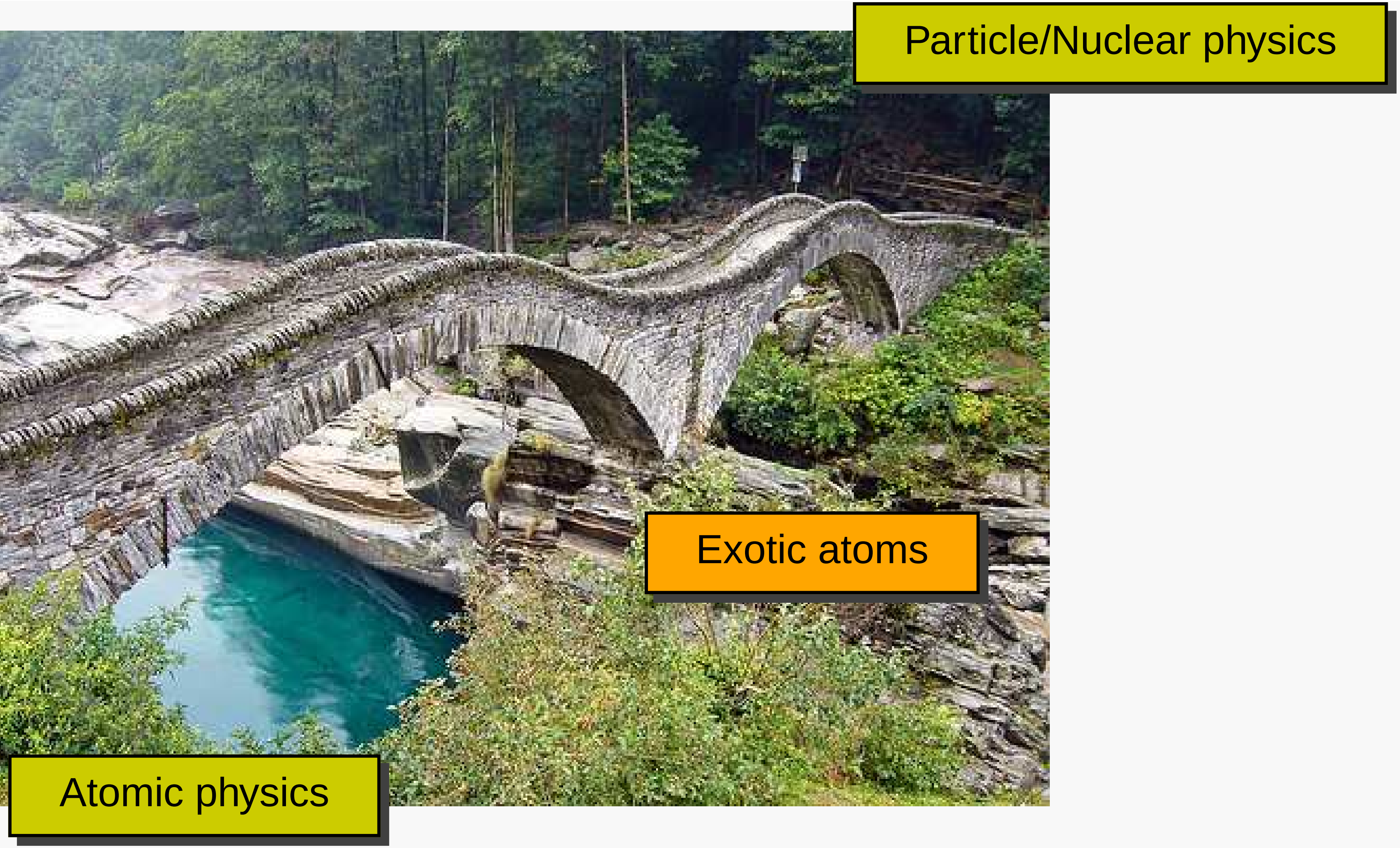
Exotic atoms spectroscopy

- CREMA, $\mu\,\mathrm{He}^{+}$
- ETHZ-PSI-MPQ, Muonium and positronium

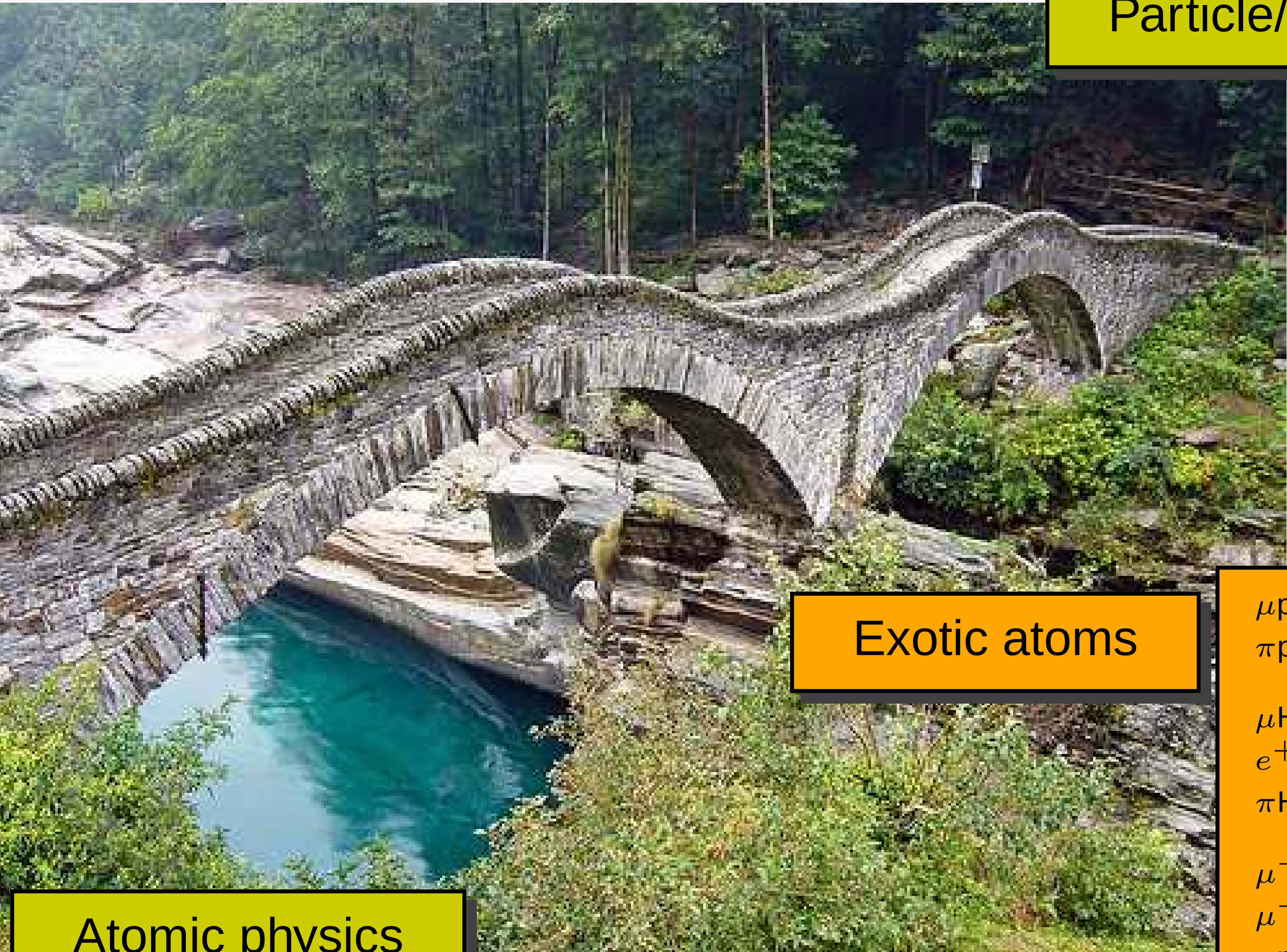
Theory and theoretical theory

- Bound-state QED
- Few-nucleon theories
- New physics, including weird QCD and QED
- Hadronic effects and proton structure (EFT, χPT, lattice?...)
- Analysis of scattering data

Exotic atoms



Exotic atoms



Particle/Nuclear physics

- Bound-state QED
- Low-energy QCD
- EFT theories, χPT....
- Lattice QCD
- Ab-initio few nucleon th.
- Fundamental constants
- Symmetry test
- New physics

Exotic atoms

μp (2S-2P)	(2010)	[r_{p}]
πp and πD	(2011)	[scatt. length]
μHe$^+$ (2S-2P)	(2014)	[r_{He}]
e^+e^- (1S-2S)	(ongoing)	
πHe	(ongoing)	[pion mass]
μ^+e^- (1S-2S)	(in preparation at PSI)	
μ^+e^- (HFS)	(ongoing at JPARK)	
μp, μ^3He (HFS)	(PSI?, JPARK)	[Zemach rad.]
μLi	(PSI?)	
$\mu\mathrm{Ra}$	(PSI?)	[for Ra EDM]
$\bar{\mathrm{H}}$, $\bar{p}$He	(CERN, ongoing)	

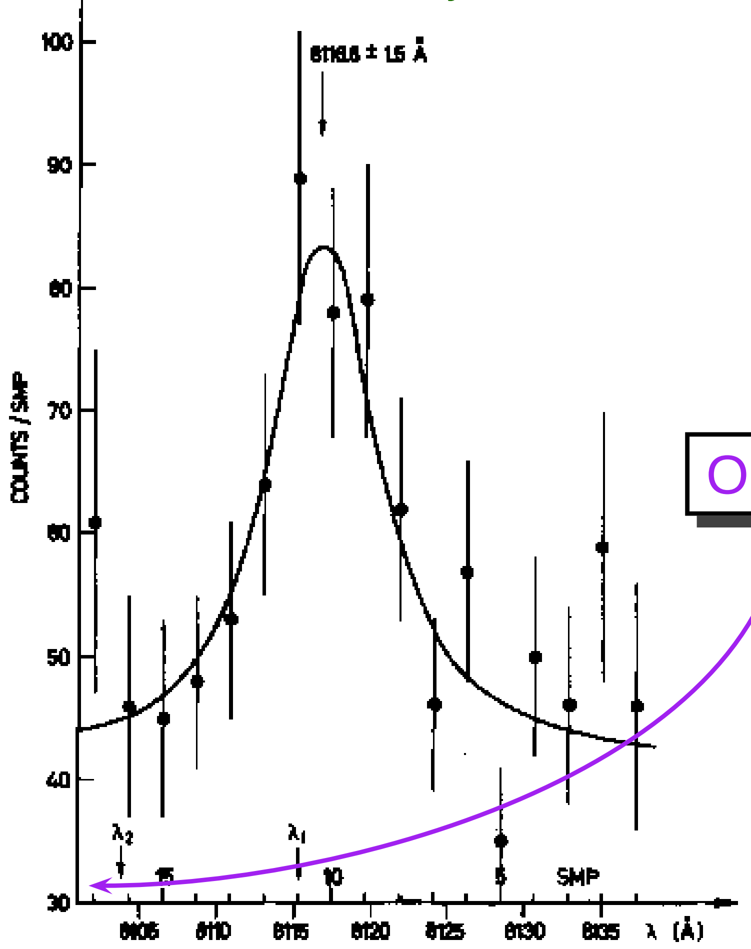
Atomic physics

Back up slides

Zavattini “resonance”

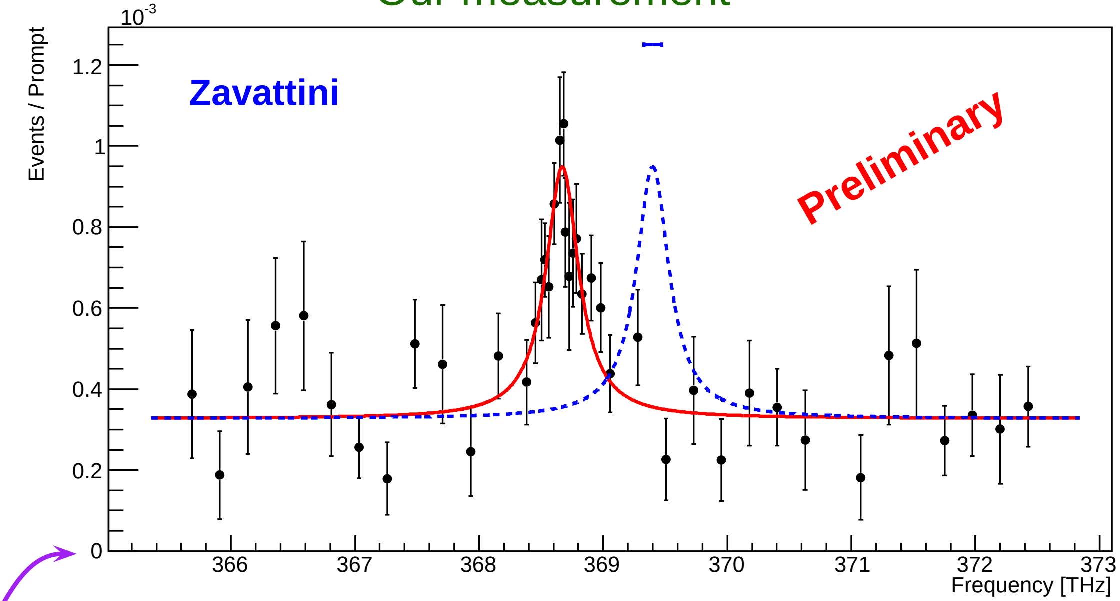
Zavattini radius seems apparently correct
but it results from a wrong experiment
combined with an incomplete theory!

[Carboni et al., Nucl. Phys. A 278, 381 (1977)]



OFFSET

Our measurement



Zavattini experiment was performed at 50 bar pressure:

⇒ 2S-population is collisionally quenched.

⇒ No population left for a laser experiment.

(for comparison: we are measuring $\mu\,\mathrm{He}^+$ at 2 mbar)

[Hauser et al., PRA 46, 2363 (1992)]

Precision test of B_{50}, B_{60}... contributions

	H [kHz]	He^+ [kHz]	ratio	
ΔE_{2S-1S}	2.466×10^{12}	9.869×10^{12}	Z^2	$[= \frac{3}{4} Z^2 R_\infty + \delta(L_{1S} - L_{2S})]$
$\delta(L_{1S} - L_{2S})^{\text{exp}}$ (from δR_∞)	16 *(2.2 ppm)*	65 *(0.7 ppm)*	Z^2	$[= \delta(\Delta E_{2S-1S} - \frac{3}{4} Z^2 R_\infty)]$
$(L_{1S} - L_{2S})^{\text{th}}$	$7\,127\,887(44)$	$93\,856\,127(348)$	$Z^{3.7}$	[Jentschura, 2006]
$\delta(L_{1S} - L_{2S})^{\text{th}}$	*(6.3 ppm)*	*(3.7 ppm)*		
B_{60} and B_{7i} terms	$-8(3)$	$-543(185)$	$Z^6\ldots$	
nuclear size (p, ^{4}He)	$1102(44)$	$62\,079(295)$	$Z^4 r^2$	

after μp ↓ ↓ μHe experiments

	H	He^+	
uncert. of nucl. size	(2)	(40)	$\mu\,He^+$-pol. 5%
		(16)	$\mu\,He^+$-pol. 2%
check B_{60} and B_{7i} with	25%	7%	$\mu\,He^+$-pol. 5%
		3%	$\mu\,He^+$-pol. 2%

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	H [kHz]	He$^+$ [kHz]	ratio	
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	(2.2 ppm)	~~*(0.7 ppm)*~~		
		(0.1 ppm)		$(H_{1S-2S}+\mu\text{p})$
$(L_{1S}-L_{2S})^{\text{th}}$	$7\,127\,887(44)$	$93\,856\,127(348)$	$Z^{3.7}$	[Jentschura, 2006]
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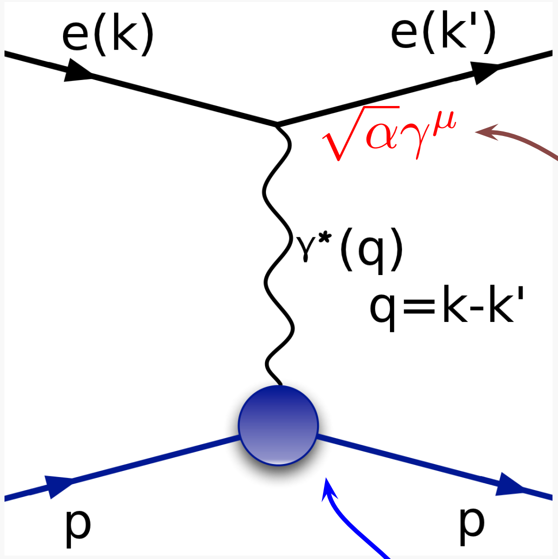
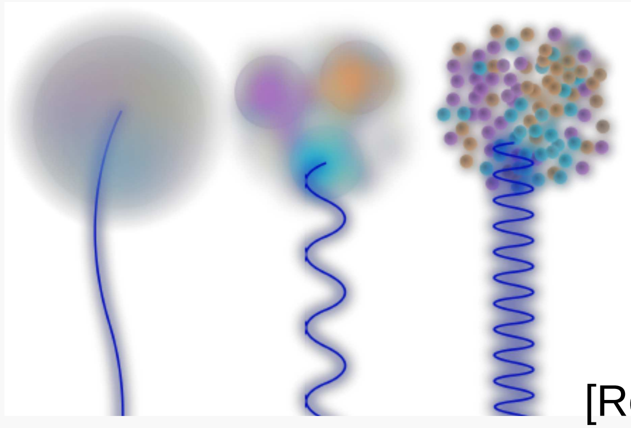
Leptonic probes to determine the p structure



Electron vertex
well know from QED
and $(g-2)_e$

$\sqrt{\alpha}[\gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2m}F_2(q^2)]$



[Ron]

Resolving power: $\lambda = \hbar/\sqrt{-q^2}$

$$Q^2[\,(\mathrm{GeV/c})^2] \sim \begin{cases} < 0.1 & \text{(Static Properties)} \\ 0.1 - 10 & \text{(Distributions, structure)} \\ \geq 20 & \text{(Perturbative QCD)} \end{cases}$$

$$Q^2[\,(\mathrm{GeV/c})^2] \sim \begin{cases} (4 \cdot 10^{-6})^2 & (H) \\ (8 \cdot 10^{-4})^2 & (\mu\text{p}) \\ (> 6 \cdot 10^{-2})^2 & \text{(e-p scatt.)} \end{cases}$$