Another example where

"Size does matter"

Aldo Antognini

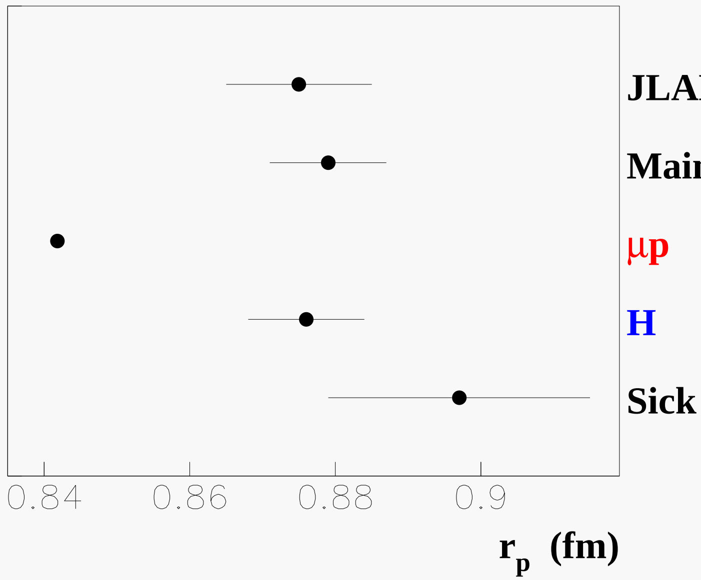
for the *CREMA* collaboration

The proton radius puzzle

Measure the $2S - 2P$ splitting in μp

$\downarrow$

determine the proton rms radius r_{p}



But large discrepancy observed:

- 4σ from H spectroscopy value
- 7σ from e-proton scattering value

The proton radii puzzle

Who is the bad?

- Muonic hydrogen?
- Hydrogen?
- Scattering?

The difference between a good film and a bad film is that in the bad film you immediately see who is the good guy and who is the bad guy. But the interesting movies are the ones where all the characters have qualities and shadows and only together they can develop!

Overview of my talk: a total chaos

Test of H energy levels

Bound-state QED

New physics

$e + p \to e + p$ scattering

p-structure

charge distr.
magn. distr.

$G_E(q^2)$,
$F_i(\nu, q^2)$, g_i

EFT, χpt, VMD
Lattice QCD

H-spectroscopy

$\mu p(2S - 2P) \to r_p$

Where are we **going**?

Test of H energy levels

Bound-state QED

Few nucleons ab-initio th.
Nuclear potentials

Parity viol.
in μ-Atoms ?

New physics

$\mu + p \rightarrow \mu + p$?

$e + p \rightarrow e + p$
scattering

Mainz & JLab

Compton scatt.

p-structure

charge distr.
magn. distr.

$G_E(q^2)$, $G_M(q^2)$
$F_i(\nu, q^2)$, g_i

EFT, χpt, VMD
Lattice QCD

Several studies

H-spectroscopy

New R_∞ meas.
New 2S-2P meas.

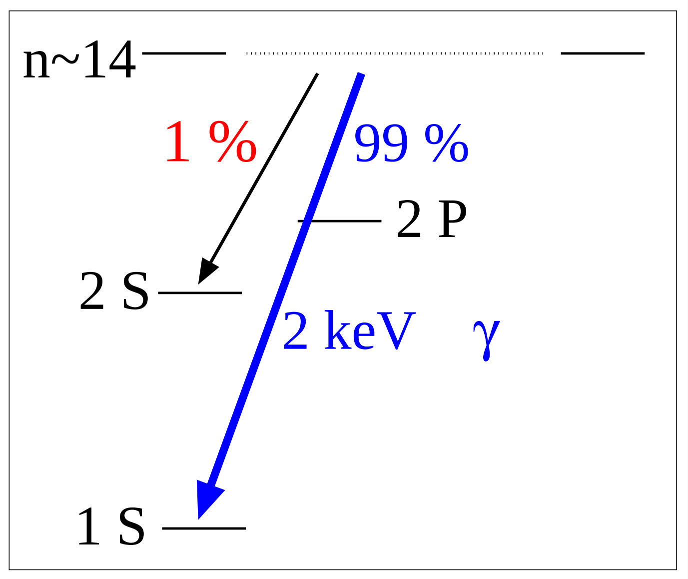
$\mu p(2S - 2P) \rightarrow r_p$

$\mu p(\mathrm{HFS}) \rightarrow r_Z$
$\mu\mathrm{D} \rightarrow r_\mathrm{D}$, Pol.

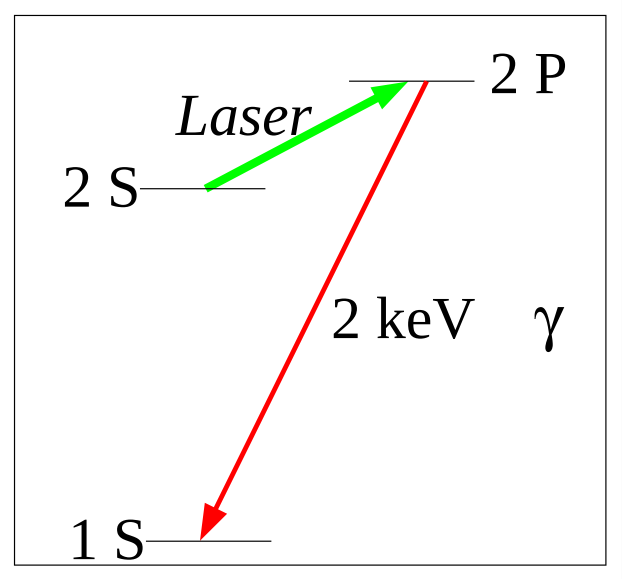
$\mu\mathrm{He} \rightarrow r_\mathrm{He}$ ...

Principle of the μp Lamb shift experiment

“prompt” ($t = 0$)



“delayed” ($t \approx 1\mu$s)



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

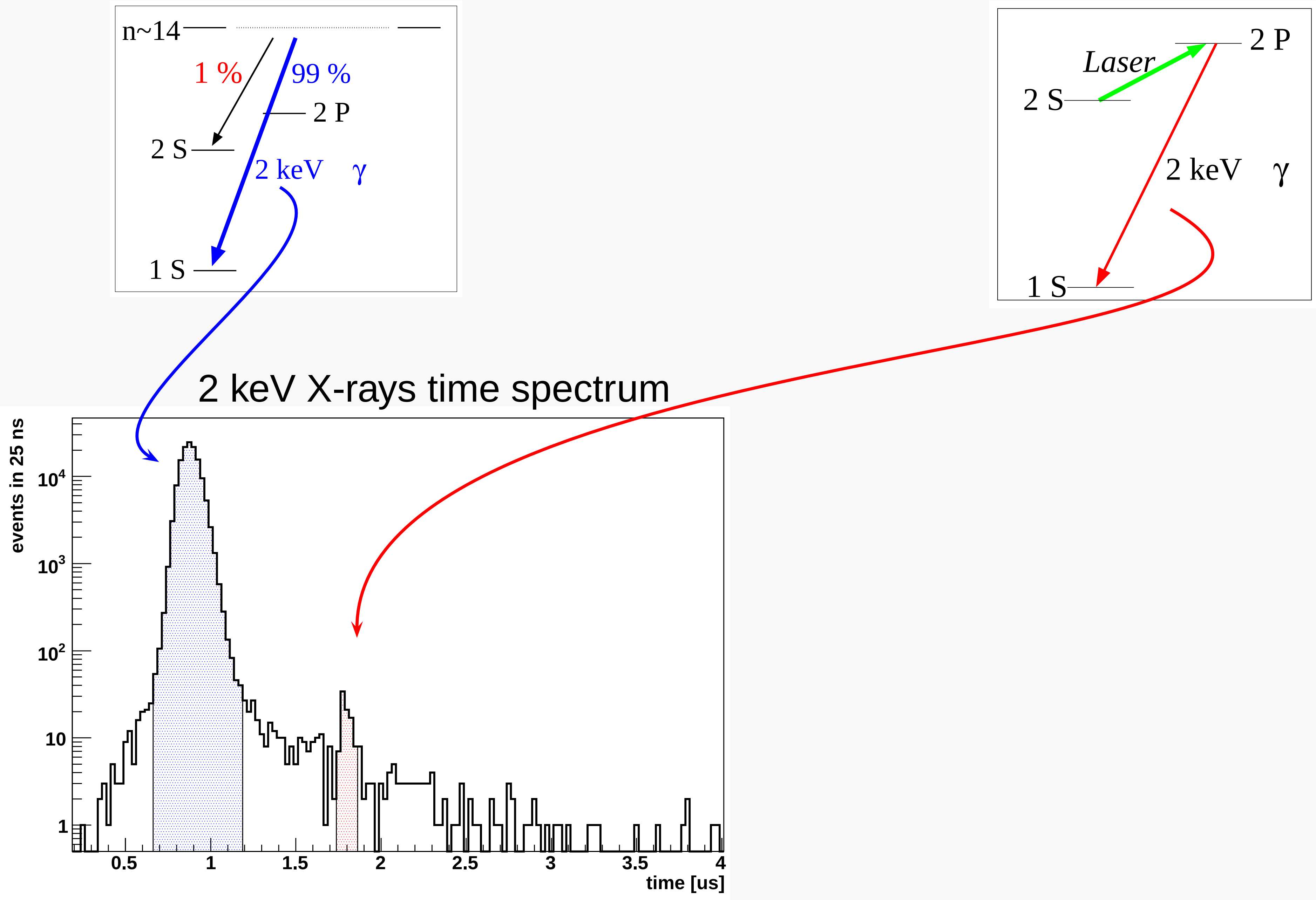
fire laser at $\lambda = 6\mu$m, ΔE=0.2 eV

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

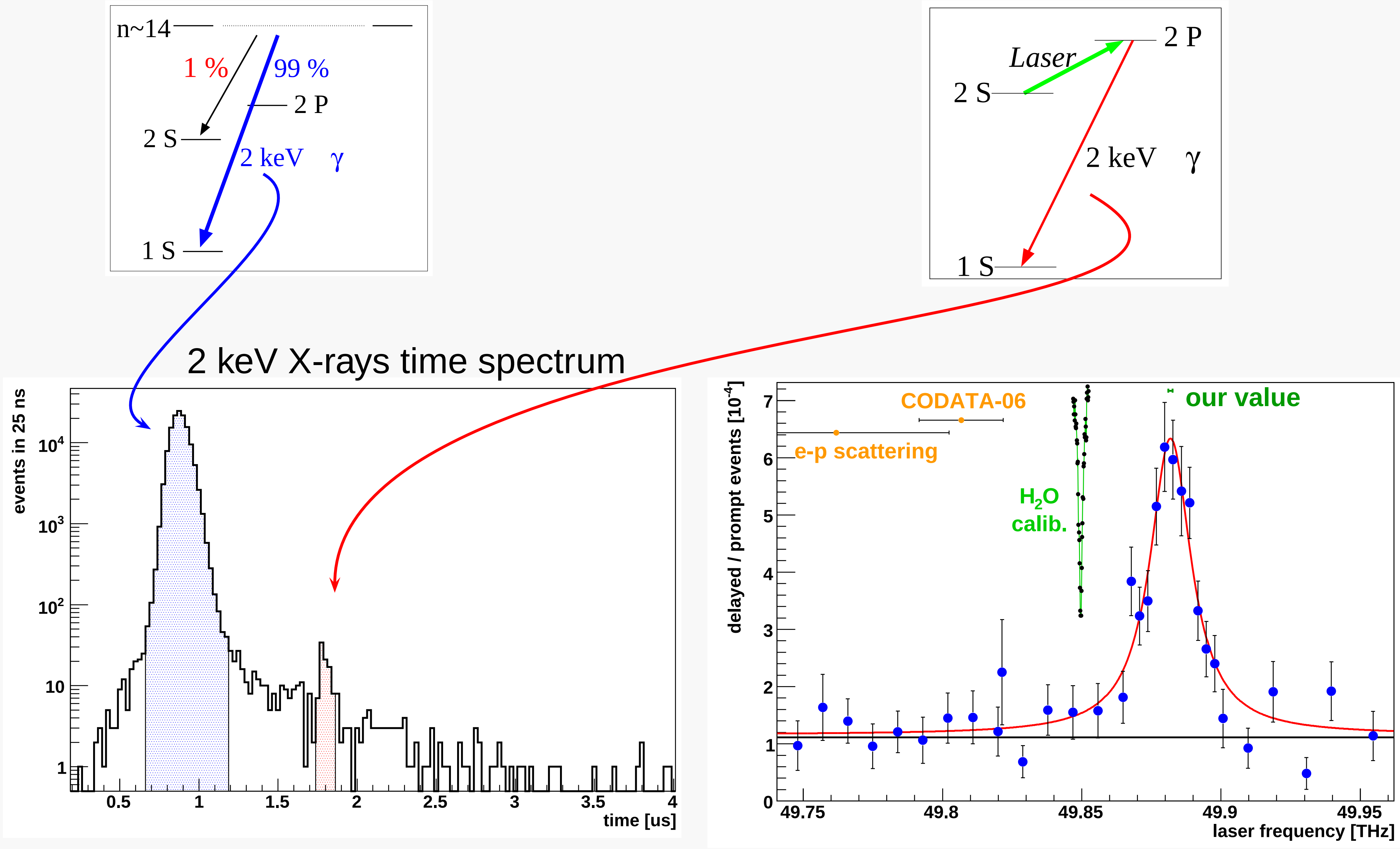
$\Rightarrow$ observe delayed K_α x-rays

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

Principle of the experiment



Principle of the experiment



The Paul Scherrer Institute (PSI)

The μp Lamb shift setup

p-beam

$\downarrow$

π (MeV)

$\downarrow$

μ (MeV)

$\downarrow$

μ (keV)

$\downarrow$

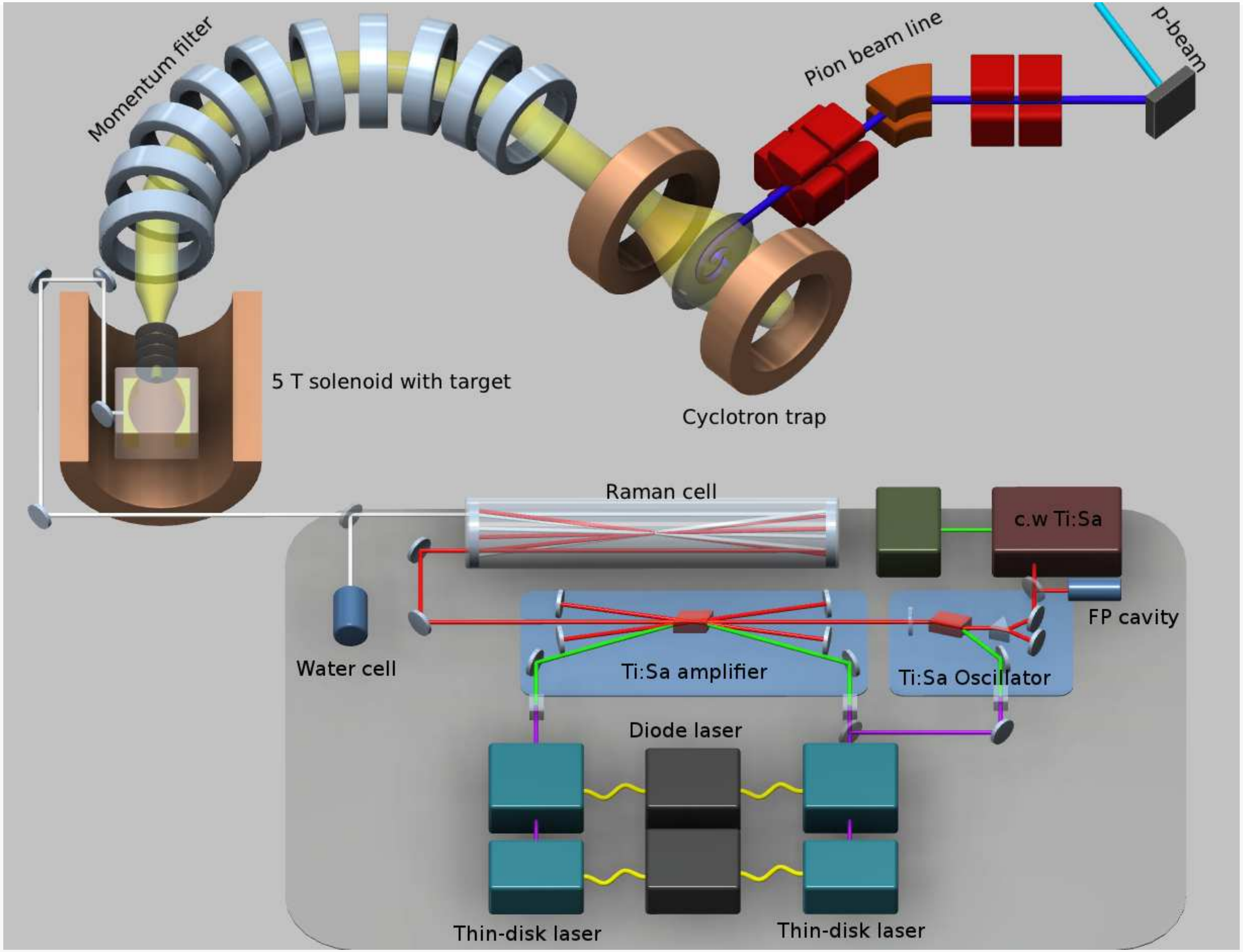
μp(2S)

$\downarrow$

Laser

$\downarrow$

X-ray



940 nm

$\downarrow$

1030 nm

$\downarrow$

515 nm

$\downarrow$

708 nm

$\downarrow$

1.0 μm

$\downarrow$

1.6 μm

$\downarrow$

6.0 μm

Aim of the μp Lamb shift experiment

Measure $\Delta E(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$ in μp with 30 ppm precision

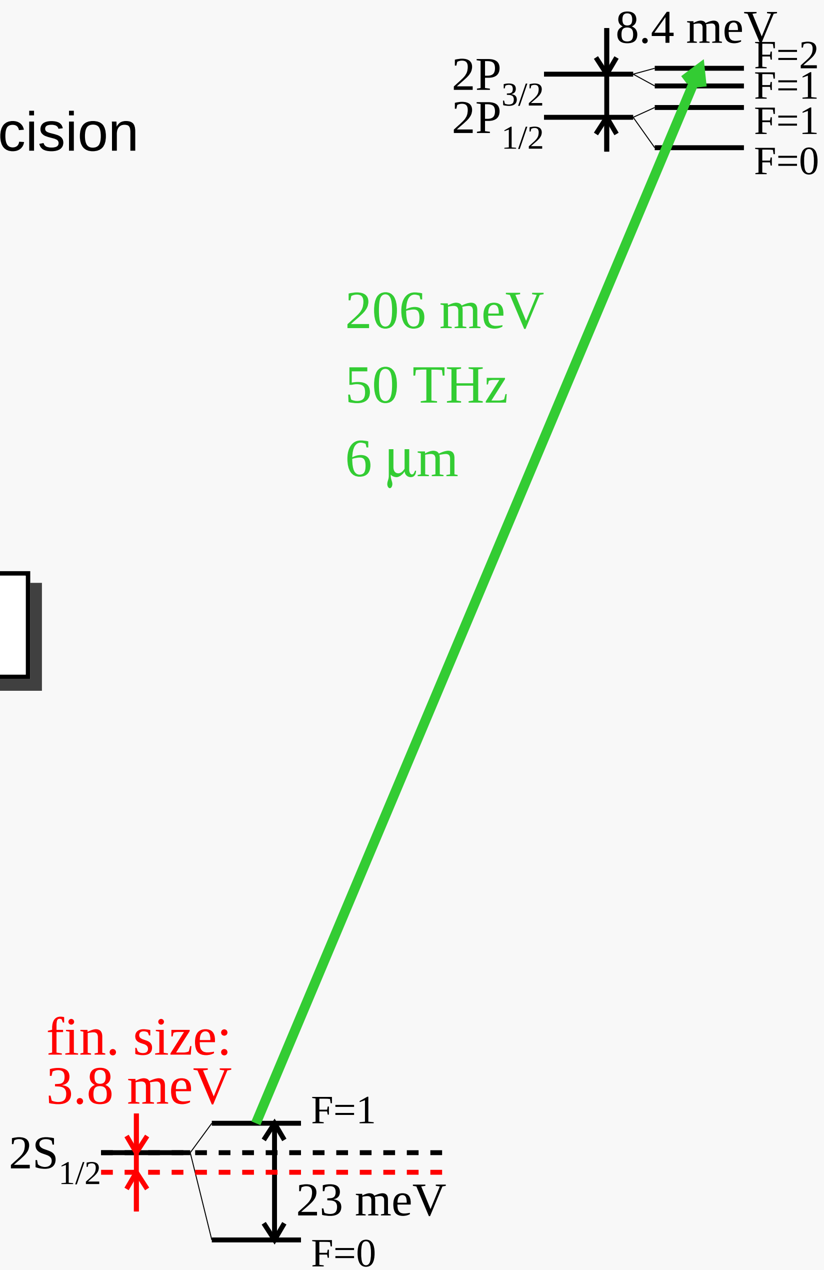
$\Longrightarrow$ r_p with $u_r \leq 10^{-3}$ (rel. accuracy)

using the theory prediction

$$\Delta E = 209.9779(49) - 5.2262\, r_\mathrm{p}^2 + 0.0347\, r_\mathrm{p}^3 \;\; \mathrm{meV}$$

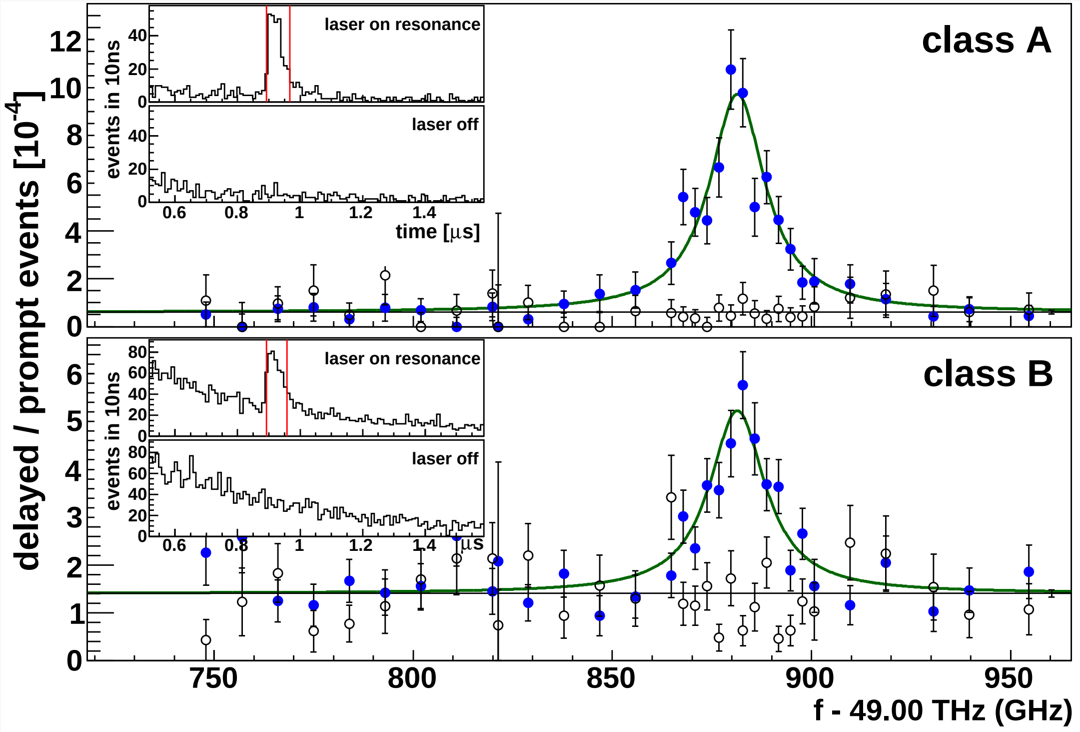
- Finite size contribution: $\frac{\Delta E_\mathrm{fs}}{\Delta E} \approx 2\%$
- Exp. accuracy: 30 ppm $\leftrightarrow$ 1.5 GHz $\leftrightarrow$ $\Gamma/10$

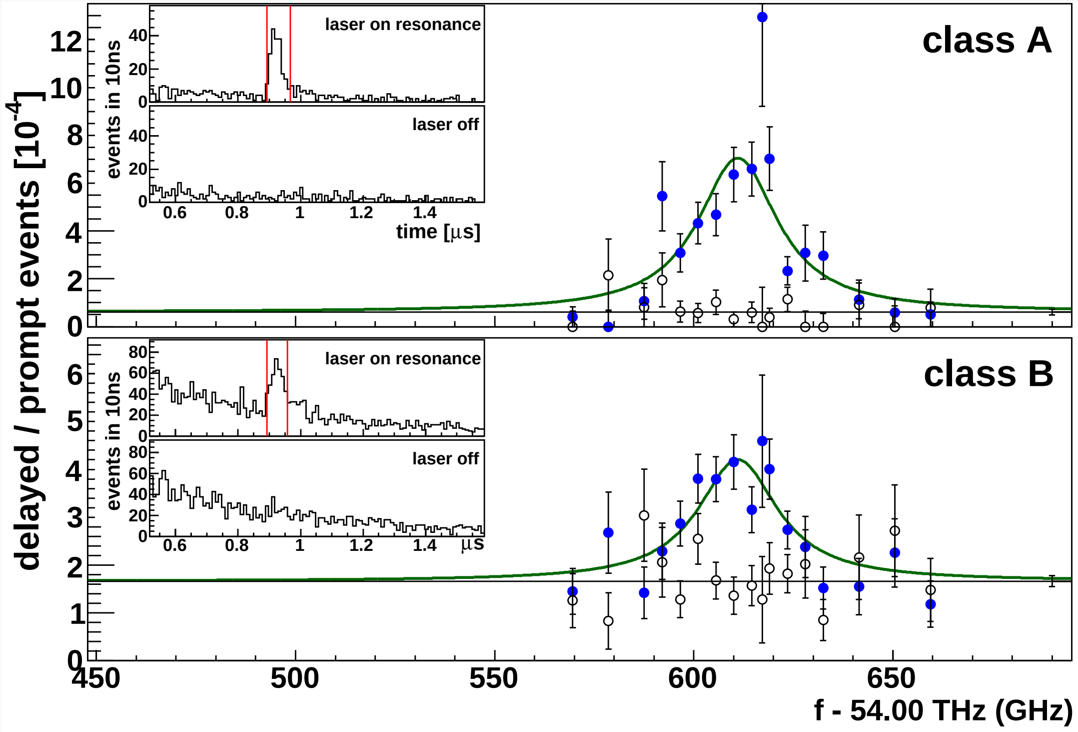
$\Gamma = 18.6$ GHz



We have measured two transitions in μp!

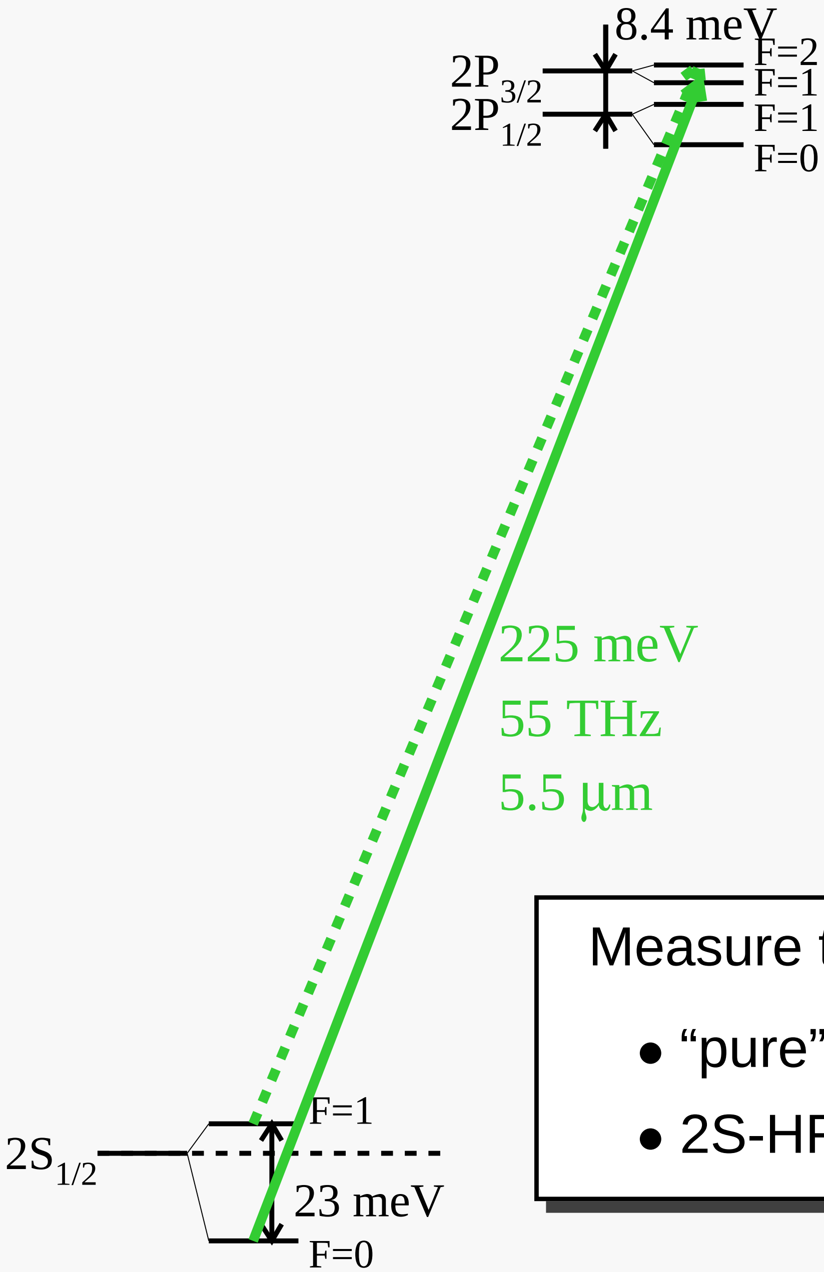
$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$ $\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$





Both resonances are 0.3 meV discrepant from predictions using $r_{\rm p}$ from CODATA

Combining the two transitions



$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$

$\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$

2P fine and hyperfine contr.
(finite size effects $< 10^{-4}$ meV)

$$\frac{3}{4}\nu_t + \frac{1}{4}\nu_s = \Delta E_{\mathrm{L}} + 8.8123 \text{ meV}$$
$$\nu_s - \nu_t = \Delta E_{\mathrm{HFS}} - 3.2480 \text{ meV}$$

Measure the two transitions ν_t and ν_s, and determine

- “pure” Lamb shift: $\Delta E_{\mathrm{L}} = \Delta E(2P_{1/2} - 2S_{1/2})$
- 2S-HFS: $\Delta E_{\mathrm{HFS}} = \Delta E(2S_{1/2}^{F=1} - 2S_{1/2}^{F=0})$

Preliminary results: $r_{\rm p}$, $r_{\rm Z}$ and r_m

$$\nu_t = 49881.39(56)^{\rm stat}(30)^{\rm sys}\ {\rm GHz}$$
$$\nu_s = 54611.06(99)^{\rm stat}(30)^{\rm sys}\ {\rm GHz}$$

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$$r_\mathrm{p}^2 = \int d^3r\, \rho_E(r) r^2$$

$$r_\mathrm{Z} = \int d^3r_1\, d^3r_2\, \rho_E(r_1)\rho_M(r_2)|r_1 - r_2|$$

$$\Delta E^{\mathrm{exp}}_{\mathrm{LS}} = 202.371(2)\ \mathrm{meV}$$
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Polariz.   H.O. fs

$$\Delta E^{\mathrm{th}}_{\mathrm{LS}} = 206.0466(15) - 5.2278(10) r_\mathrm{p}^2 + 0.0353(30) r_\mathrm{p}^3 + 0.0129(40) + 1\times 10^{-5}\ \mathrm{meV}$$
$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = 22.9781(10) - 0.0021(2)\, r_\mathrm{p}^2 - 0.1621(10) r_\mathrm{Z} + 0.0080(26) + 1\times 10^{-5}\ \mathrm{meV}$$

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$$r_{\rm p} = 0.842(1)\ \text{fm}$$
$$r_{\rm Z} = 1.086(35)\ \text{fm}$$

- 7σ from CODATA
- limited by theory

- 1.086(12) [Sick], 1.045(4) [Distler], 1.047(16) [Volodka]
- limited by experiment

Preliminary results: r_p, r_Z and r_m

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Polariz. H.O. fs

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Using dipol approx.
$\rightarrow r_m = 0.88(5)$ fm

- 7σ from CODATA
- limited by theory

$$r_\mathrm{p} = 0.842(1)\ \mathrm{fm}$$
$$r_\mathrm{Z} = 1.086(35)\ \mathrm{fm}$$

- $1.086(12)$ [Sick], $1.045(4)$ [Distler], $1.047(16)$ [Volodka]
- limited by experiment

Proton radius puzzle: What may be wrong?

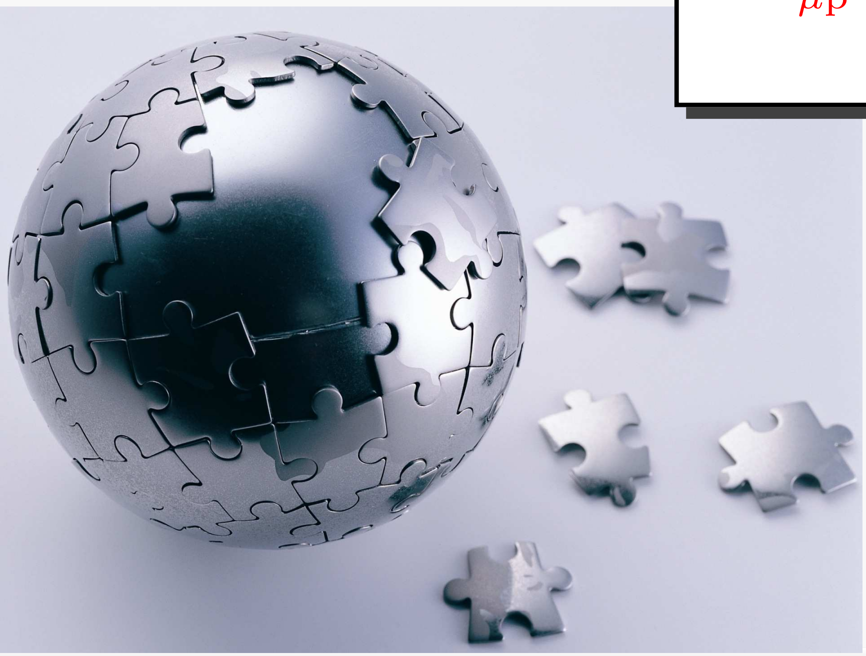
(2) μp theory wrong ? but

- 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

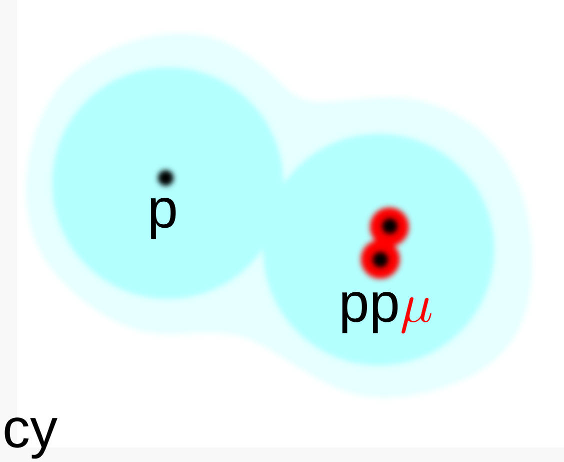
- 2S-8S, 2S-8D, 2S-12S, etc. all consistent ...

(5) H theory wrong ? but

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

$r_{\rm p}$ puzzle (1): Is the μp experiment wrong ?

Spectroscopy of $({\rm pp}\mu)^*$-molecules instead of μp ?



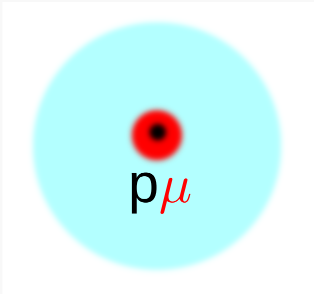
$$\mu{\rm p}(2S) + {\rm H}_2 \rightarrow \{[({\rm pp}\mu)^+]^*{\rm p}ee\}^* \rightarrow \mu{\rm p}(1S) + \ldots\ .$$

Three-body calculations including Lamb shift:

$\rightarrow$ No bound-states exist which can explain the discrepancy

arXiv:1205.0633

Spectroscopy of $(\mu{\rm p}_{2S})e^-$-ions instead of μp ?



$$\mu{\rm p}^* + {\rm H}_2 \rightarrow (\mu{\rm p}_{2S})e + \cdots$$

$\Delta E \sim 0.4$ meV **if** an e^- exists with $\langle r_e \rangle = a_0$ [EJPD 61, 7 (2011)]

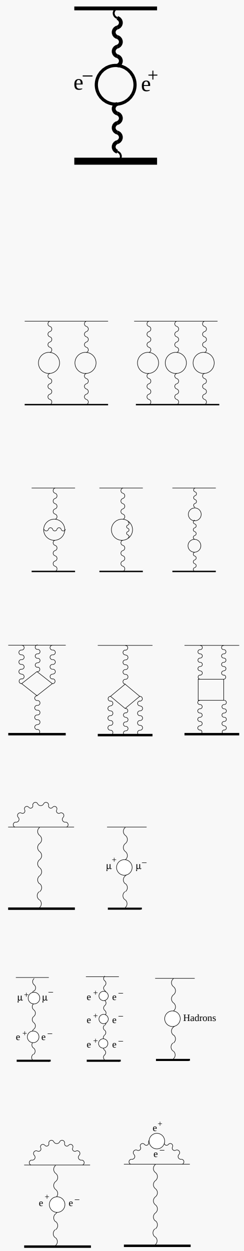
Does $(\mu{\rm p}_{2S})e$ exist?

Three-body calculations: no resonace $(\mu{\rm p}_{2S})e$ states below the $\mu{\rm p}(n=2)$ th.

Two consistent measurements (ν_t and ν_s), no broadening, no double-line observed

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

#	Contribution	Value	Unc.
3	Relativistic one loop VP — Vac.pol.	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 $\alpha(Z\alpha)^4 m_r$ — Hadron	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 — Recoil	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



Bound-state QED

Several expansions all mixed up

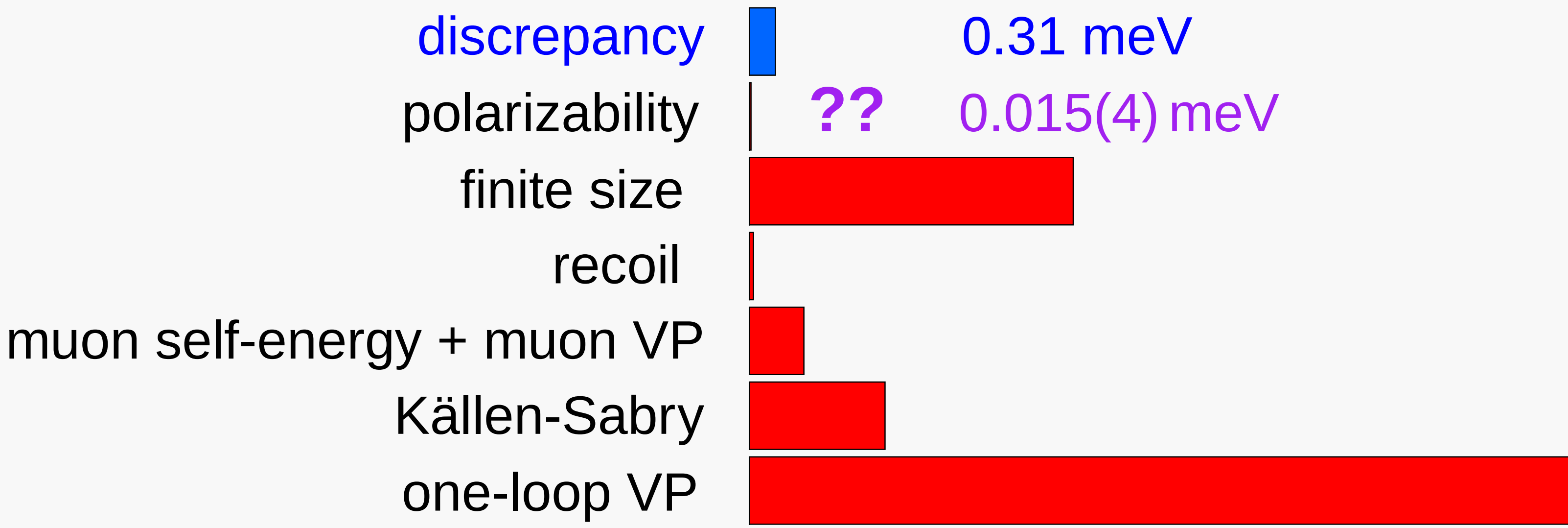
- Binding effects ($Z\alpha$) — bad convergence, all-order approach/expansion
- Radiative corrections (α and $Z\alpha$)
- Recoil corrections (m/M and $Z\alpha$) — relativity $\not\Leftrightarrow$ two-body system
- Radiative–recoil corrections (α, m/M and $Z\alpha$)
- Proton structure corrections (r_{p},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

- All corrections are mixed up: $\alpha^x \cdot (Z\alpha)^y \cdot (m/M)^z \rightarrow$ "book-keeping"?
- Cannot develop the calculation in a systematic way, like in free $g-2$
- Difficulty in finding out a source of desired order of corrections.
- Relativistic QED is not suitable for precision calculation of bound-states

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

Discrepancy$= 60\times$(th. uncertainty)

Main contributions to the μp Lamb shift:



Discrepancy can't be explained by missing/wrong higher order effects

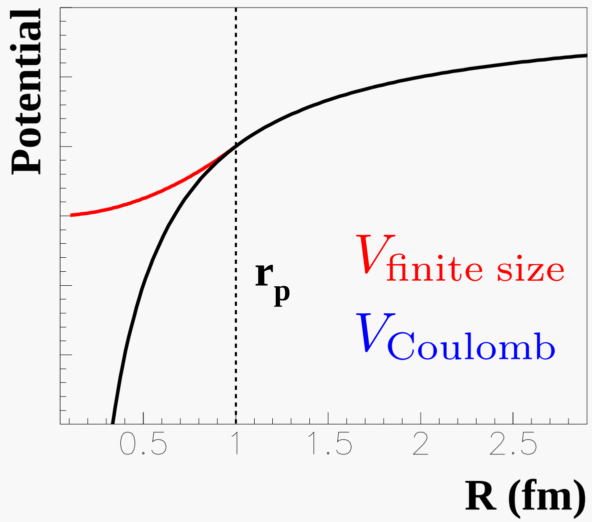
Atomic energy levels and proton size

Atomic energy levels

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

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

$$m_\mu \approx 200 m_e$$



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 proton size

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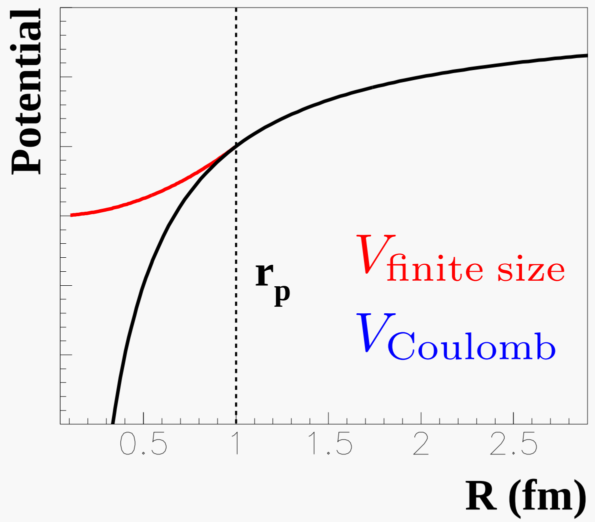


From $\bar\nabla \cdot \bar E = 4\pi\rho \rightarrow$ potential V

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

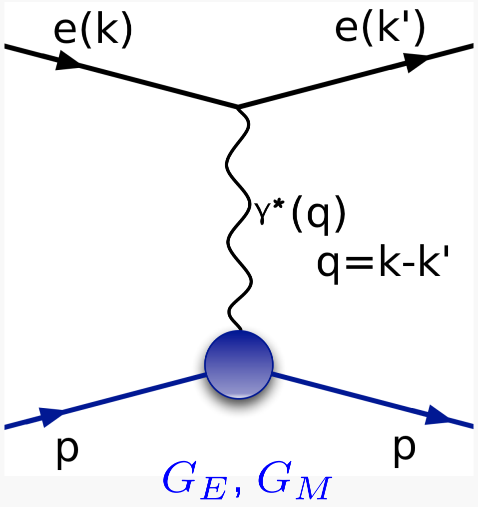
$$G_E(\mathbf{q^2}) = \int d^3r\, \rho_E(\mathbf{r}) e^{-i\mathbf{q}\cdot\mathbf{r}} \simeq Z(1 - \frac{\mathbf{q^2}}{6} r_{\rm p}^2 + \cdots)$$

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

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

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

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



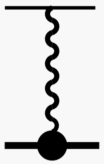
r_p puzzle (2): Is μp(2S-2P) theory wrong ?

Higher order finite size effects

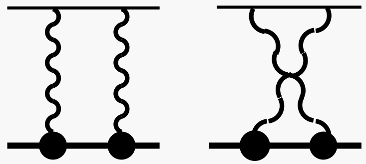
potential corr.

wave function corr.

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



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



Discrepancy = 0.31 meV

3.7 meV

0.02 meV

This term is important for μp

Third Zemach moment:

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

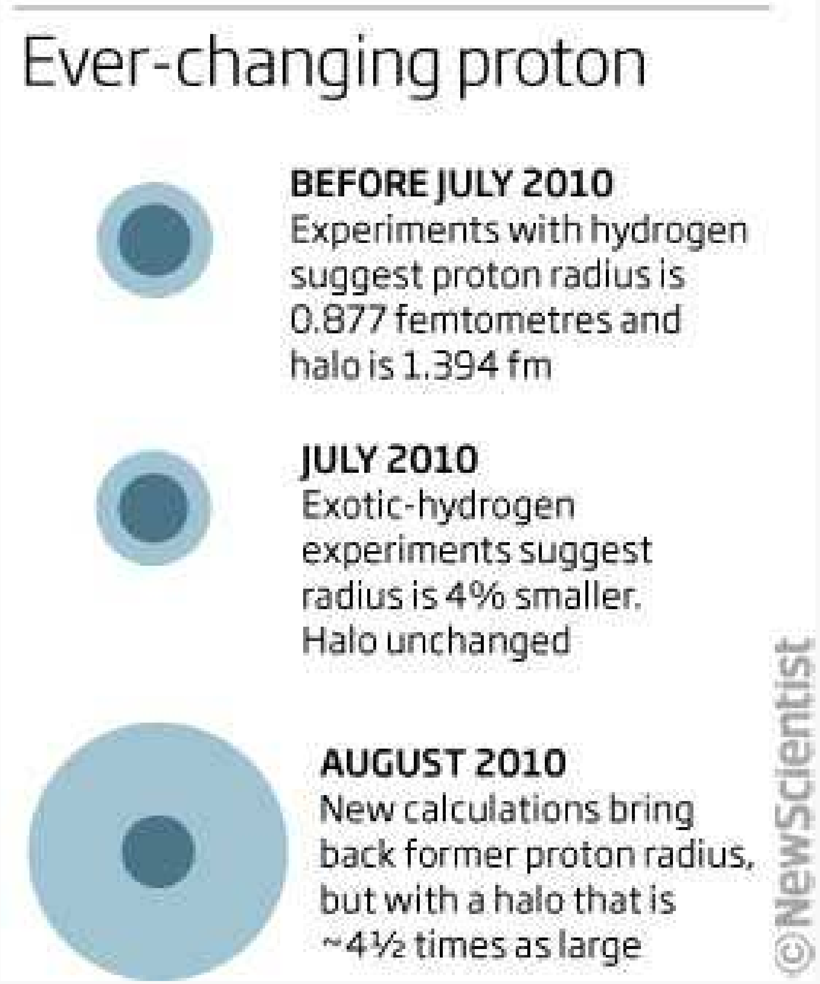
r_p puzzle (2): Is μp(2S-2P) theory wrong ?

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

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

[PL B 693, 555 (2010)]

Measurable

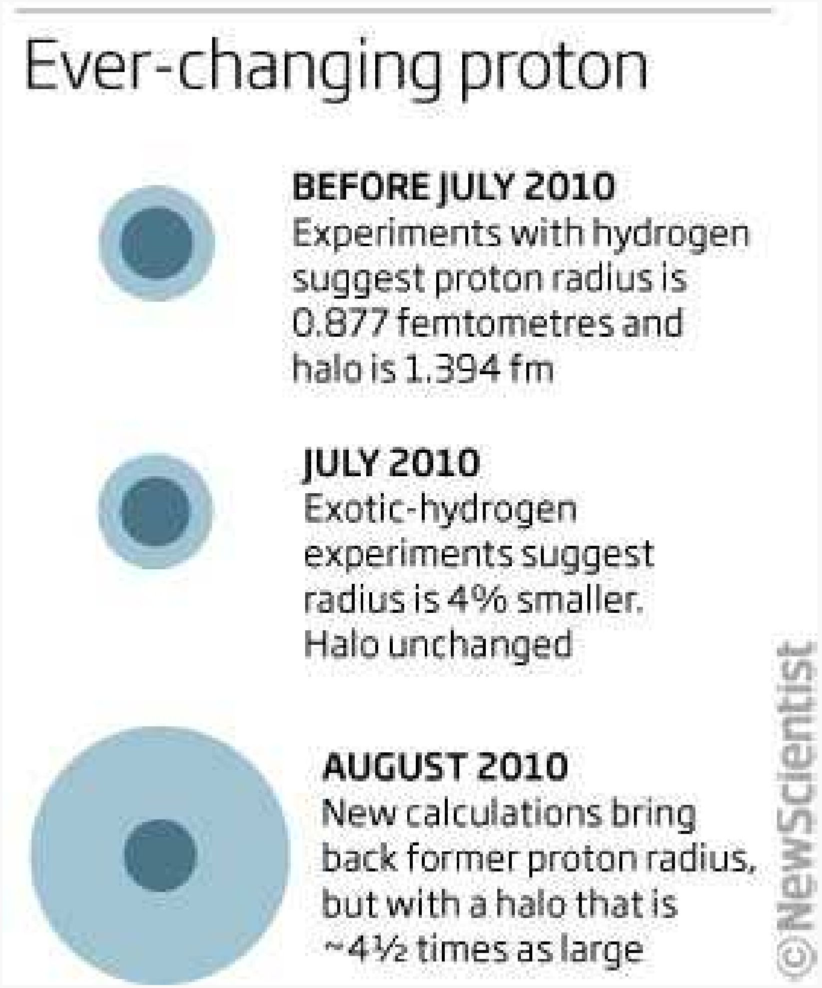
$$\langle r_{\rm p}^3 \rangle_{(2)} = \frac{48}{\pi} \int \frac{dq}{q^4} [G_E^2(q^2) - 1 + \frac{1}{3} q^2 \langle r_{\rm p}^2 \rangle]$$

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

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

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

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



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

Proton shape dependence of the μp theory?

[PLB 696, 343 (2011)]

Model dependent approximation

$$\langle r_p^3 \rangle_{(2)} \approx f {r_p}^3$$

$$f = \begin{cases} 3.48 & \text{(Gaussian)} \\ 3.789 & \text{(standard dipole)} \\ 3.78(31) & \text{(Friar and Sick)} \\ 3.91 & \text{(Arrington)} \\ 4.18(13) & \text{(Bernauer-Arrington)} \\ 52.2 & \text{(De Rújula)} \end{cases}$$

$$\Delta E_{LS}^{th.} = 206.0592(50) - 5.2278(10)\, r_p^2 + \underbrace{0.0091\, \langle r_p^3 \rangle_{(2)}}_{0.0365(18)\, r_p^3} + \ldots \text{ meV}$$

for $f = 4.0(2)$

Model dependence small

What about the higher order of the charge distribution?

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

- Several moments have been determined [Distler et al, PLB 696, 343 (2011)]:

	std. dipole	Bernauer-Arrington
$\langle r_\mathrm{p} \rangle$	0.7026	0.7381(17)
$\langle r_\mathrm{p}^2 \rangle$	0.6581	0.774(8)
$\langle r_\mathrm{p}^3 \rangle$	0.7706	1.16(4)
$\langle r_\mathrm{p}^4 \rangle$	1.083	2.63(19)
$\langle r_\mathrm{p}^5 \rangle$	1.773	9.0(1.2)
$\langle r_\mathrm{p}^6 \rangle$	3.325	42.4(7.6)

Deviation from standard dipole visible but ....

...still converging $\Delta E_\mathrm{fs}^{(n)} = k_n \langle r_\mathrm{p}^n \rangle$

$$\Delta E_\mathrm{fs} = -\frac{2\pi\alpha}{3}|\Psi(0)|^2 \left[r_\mathrm{p}^2 - \frac{\alpha}{2} m_r \langle r_\mathrm{p}^3 \rangle_{(2)} + (Z\alpha)^2 \left(F_\mathrm{REL} + m_r^2 F_\mathrm{NR} \right) \right]$$

[Friar, 1978]

$$F_\mathrm{REL} = -\langle r^2 \rangle \left[\gamma - \frac{35}{16} + \ln(Z\alpha) + \langle \ln(m_r r) \rangle \right] - \frac{1}{3} \langle r^3 \rangle \langle \frac{1}{r} \rangle + I_2^\mathrm{REL} + I_3^\mathrm{REL}$$

$$F_\mathrm{NREL} = \frac{2}{3} (\langle r^2 \rangle)^2 \left[\gamma - \frac{5}{6} + \ln(Z\alpha) \right] + \frac{2}{3} \langle r^2 \rangle \langle r^2 \ln(m_r r) \rangle - \frac{\langle r^4 \rangle}{40} + \langle r^3 \rangle \langle r \rangle + \frac{1}{9} \langle r^5 \rangle \langle \frac{1}{r} \rangle + I_2^\mathrm{NREL} + I_3^\mathrm{NREL}$$

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

Accounting for measured shape of the proton

Measured form factor (Arrington)

$$G_E(\vec{Q}^2) = \frac{1+\sum_{i=0}^{2} a_i \tau^i}{1+\sum_{j=0}^{4} b_j \tau^j}$$

$$G_E(\vec{Q}^2) = \int d\vec{r}\, e^{-i\vec{q}\cdot\vec{r}} \rho(\vec{r})$$

P. Indelicato

Numerically solve the Dirac eq.
with Uehling (eVP) pot. + finite size
using $\rho(r)$ from measured form factor

2γ-contributions?

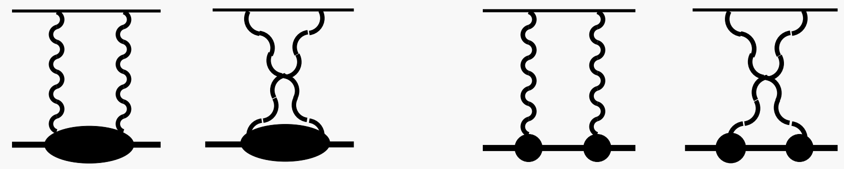
$$\Delta E_{LS}^{\mathrm{th.}} = 206.0466(15) - 5.2278(10)\, r_\mathrm{p}^2 + \overbrace{0.0353(17)\, r_\mathrm{p}^3 + 0.0129(40)}$$

$$+5.6\times10^{-5}\, r_\mathrm{p}^4 + 4.7\times10^{-6}\, r_\mathrm{p}^5 + 5.2\times10^{-7}\, r_\mathrm{p}^6 + \cdots$$

$$+0.0002 r_\mathrm{p}^2 \log(\mathrm{r_p}) - 4.9\times10^{-5} r_\mathrm{p}^4 \log(\mathrm{r_p}) + \cdots \ \mathrm{meV}$$

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

Two-photons contributions

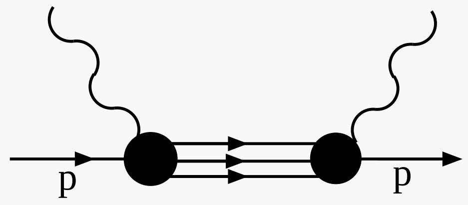


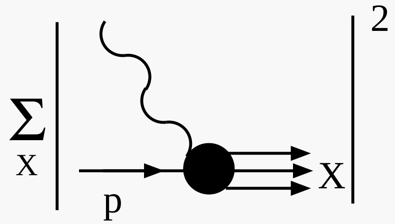
[Carlson, PRA84 020102 (2011)]
[Pachucki, PRA60 3593 (1999)]

- The energy shift can be expressed in terms of forward doubly virtual Compton scatt

$$T^{\mu\nu} = \alpha^{\mu\nu}\, T_1(\nu, Q^2) + \beta^{\mu\nu}\, T_2(\nu, Q^2)$$

We do not know T_1 and T_2 but





Im(forward scatt. amp) $\approx$ total cross section

$\left\{ \begin{array}{l} \text{dispersion relation} \\ \mathrm{Im}\, T_i(\nu, Q^2) = \frac{1}{4M} F_i(\nu, Q^2) \end{array} \right.$

Elastic form factors and spin avg. structure functions measured at SLAC, DESY, Bonn, JLab, Mainz, etc. are needed to calculate the two-photons contributions

- BUT dispersion for T_1 diverges $\rightarrow$subtraction term needed

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

- BUT the subtraction term $W_1(0,Q^2)$ NOT determined by 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	($\gamma p \to l^+ l^- p'$ planned at HIGS, Duke)
	known at large Q^2	from OPE expansion

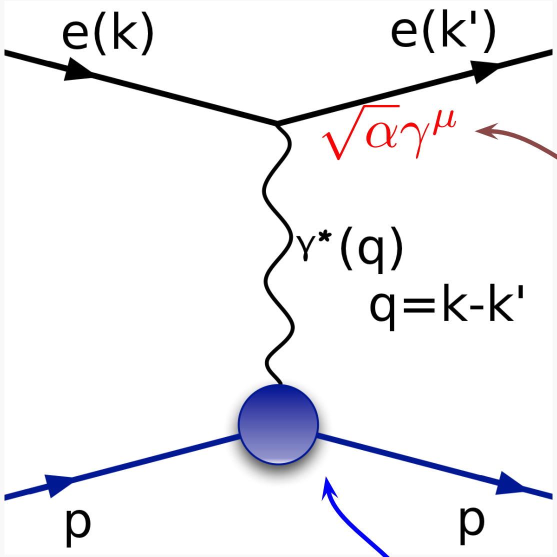
Uncertainty of this term underestimated? [PRL107,160402 (2011)]

- Old: intermediate Q^2 calculated assuming one-photon on-shell form factors
- New: forth order χpt (including Δ-res.)$\to$ model independent

Two-photon exchange under control!
$\Delta E_{2\gamma} = -33(2) \times 10^{-3}$ meV

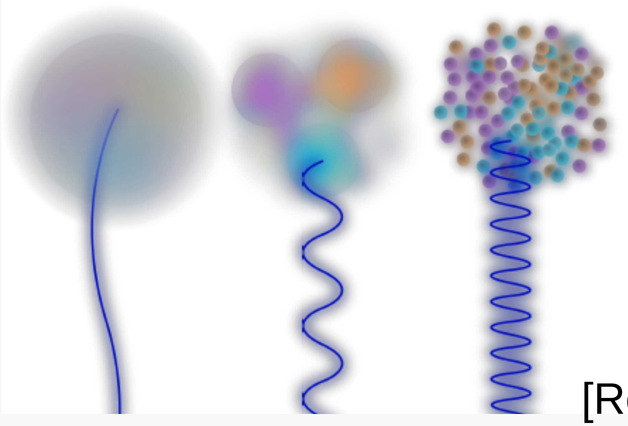
[Birse and McGovern, arXiv:1206.3030v1]

Leptonic probes to determine the p structure



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

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

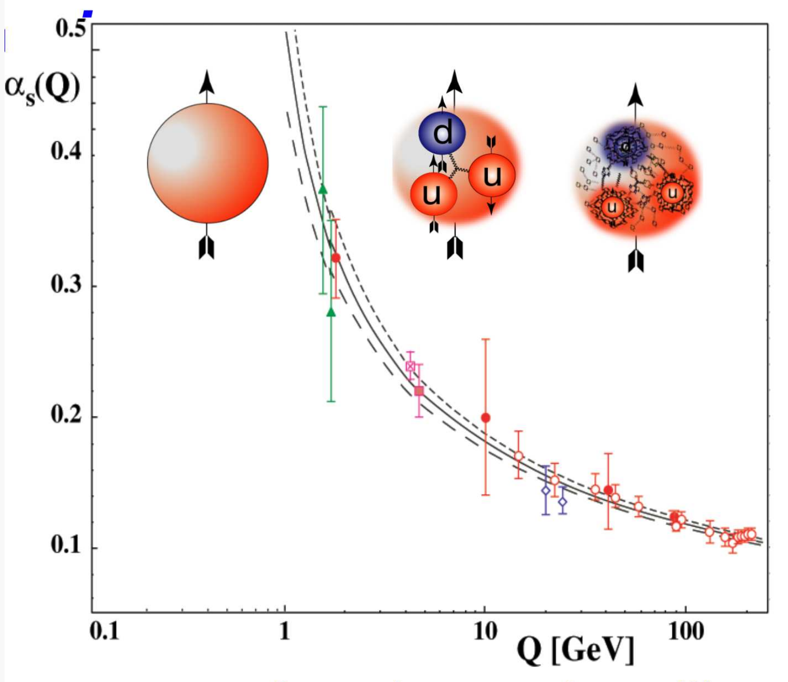


[Ron]

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

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

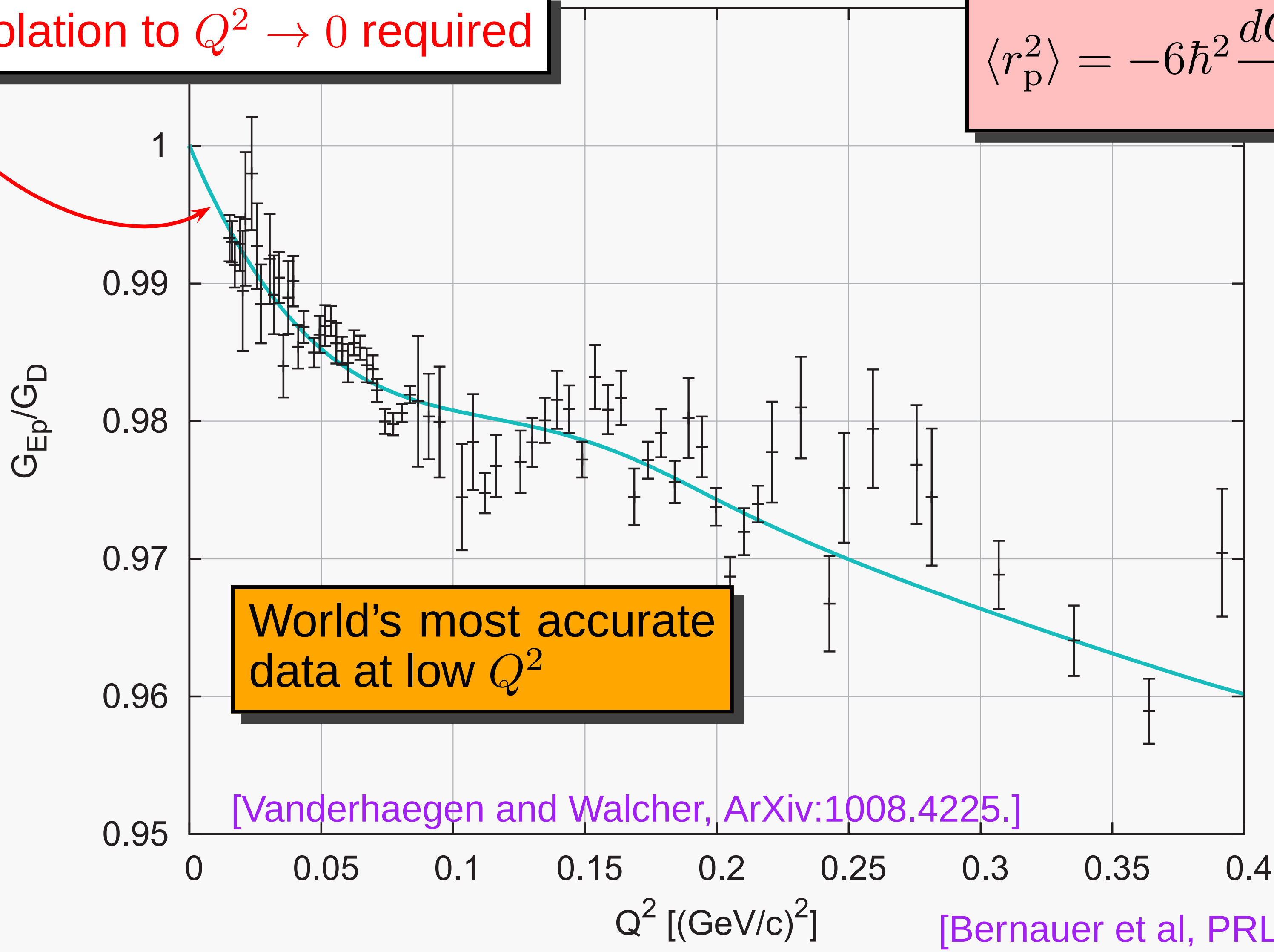
$$Q^2[\ (\mathrm{GeV/c})^2] \sim \begin{cases} (4\cdot 10^{-6})^2 & (H) \\ (8\cdot 10^{-4})^2 & (\mu\text{p}) \\ (>6\cdot 10^{-2})^2 & \text{(e-p scatt.)} \end{cases}$$



Summary of the 2010 Mainz data

extrapolation to $Q^2 \to 0$ required

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



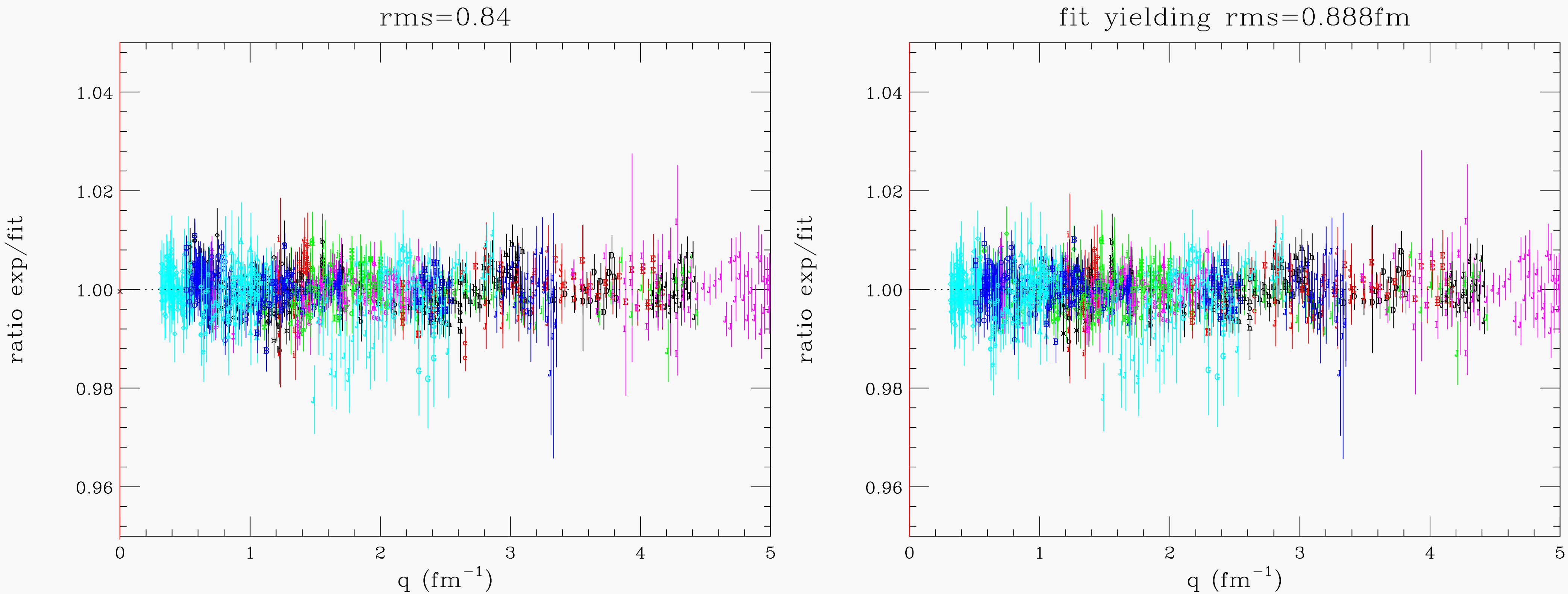
World's most accurate data at low Q^2

[Bernauer et al, PRL 105, 242001 (2010)]

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

The fitting industry

Fit Bernauer data w/o muonic constraint



χ^2 increase of $\Delta\chi^2 \approx 5\%$

[Ingo Sick]

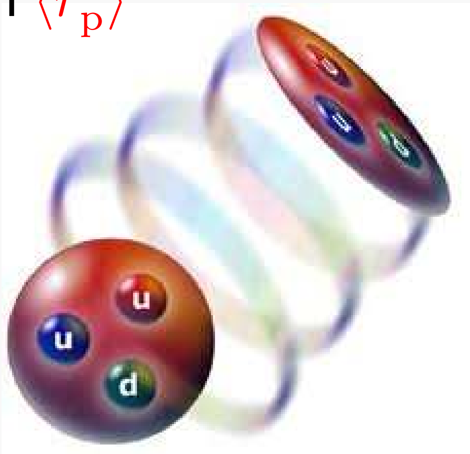
Extrapolation $Q^2 \to 0$

- Validity of Taylor expansion

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

limited to $Q^2 \ll 4m_\pi^2 \approx 0.08$GeV^2 where data are scarce. [Vanderhaeghen]

- Use low Q to make $\langle r_\text{p}^4\rangle$ small, $\to$ get model-independent term $\langle r_\text{p}^2\rangle$



$\to$ also $\langle r_\text{p}^2\rangle$-contribution is small
$\to$ high sensitivity to uncertainties of data
$\to$ must include not-so-low-Q data
$\to$ sensitive to higher moments [Ingo Sick]
$\to$ **Extrapolation model-dependent**

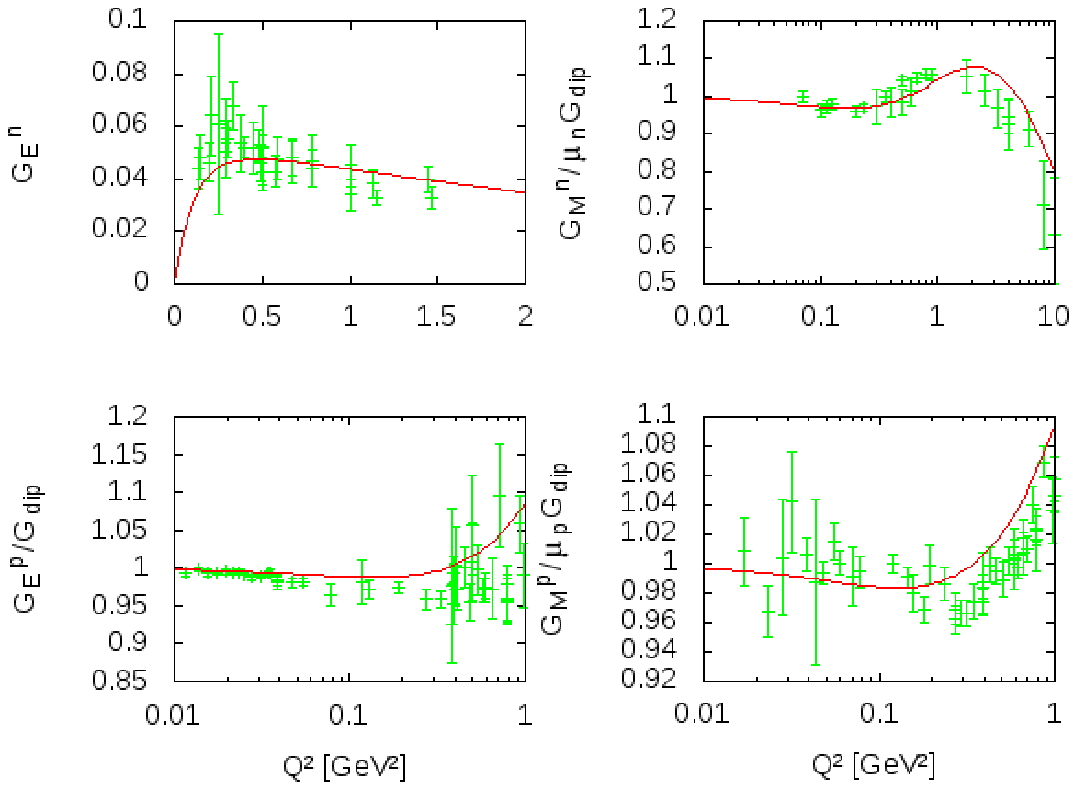
- Functional dependence of this extrapolation? Theory is needed: χPT...
- G_E, G_M aren't true densities because of Lorentz contraction and $\langle P|J(0)|P'\rangle$.
- Normalization and acceptance issues makes it hard to get high precision

$r_{\rm p}$ puzzle (3): Is e-p scattering wrong ?

Functional form of the form factor for extrapolation to $Q^2 \to 0$!?

Model dependence? Uncertainties?

[Hill and Paz, PRL 107, 160402 (2011)]



[arXiv:1205.6628v1]

Dispersion (unitarity, analyticity)+VMD
$\to r_{\rm p} = 0.84(1)$ fm in agreement with our result

Interesting physics hidden in this extrapolation

r_p puzzle (4): Is H-spectroscopy wrong ?

- 1S Lamb shift and R_∞ can be deduced from two measurements in H

$$\left.\begin{array}{rl} \nu_{1S-2S} & (u_r \sim 10^{-15}) \\ \nu_{2S-8S/D} & (u_r \sim 10^{-11}) \\ & \vdots \end{array}\right\} \Rightarrow \left\{\begin{array}{l} L_{1S}^{\mathrm{exp}} = 8172.840(15)\,\mathrm{MHz} \\ R_\infty = 3.289\,841\,960\,364(17) \times 10^{15}\,\mathrm{Hz} \end{array}\right.$$

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

- 1S Lamb shift, theoretical prediction in H

$$\left.\begin{array}{r} \mathrm{QED} \\ r_\mathrm{p} \\ \alpha,\ m_e,\ m_p\ c\ldots \end{array}\right\} \Rightarrow \quad L_{1S}^{\mathrm{th}}(r_\mathrm{p}) = 8171.636(4) + 1.5645\, r_\mathrm{p}^2 \quad \mathrm{MHz}$$

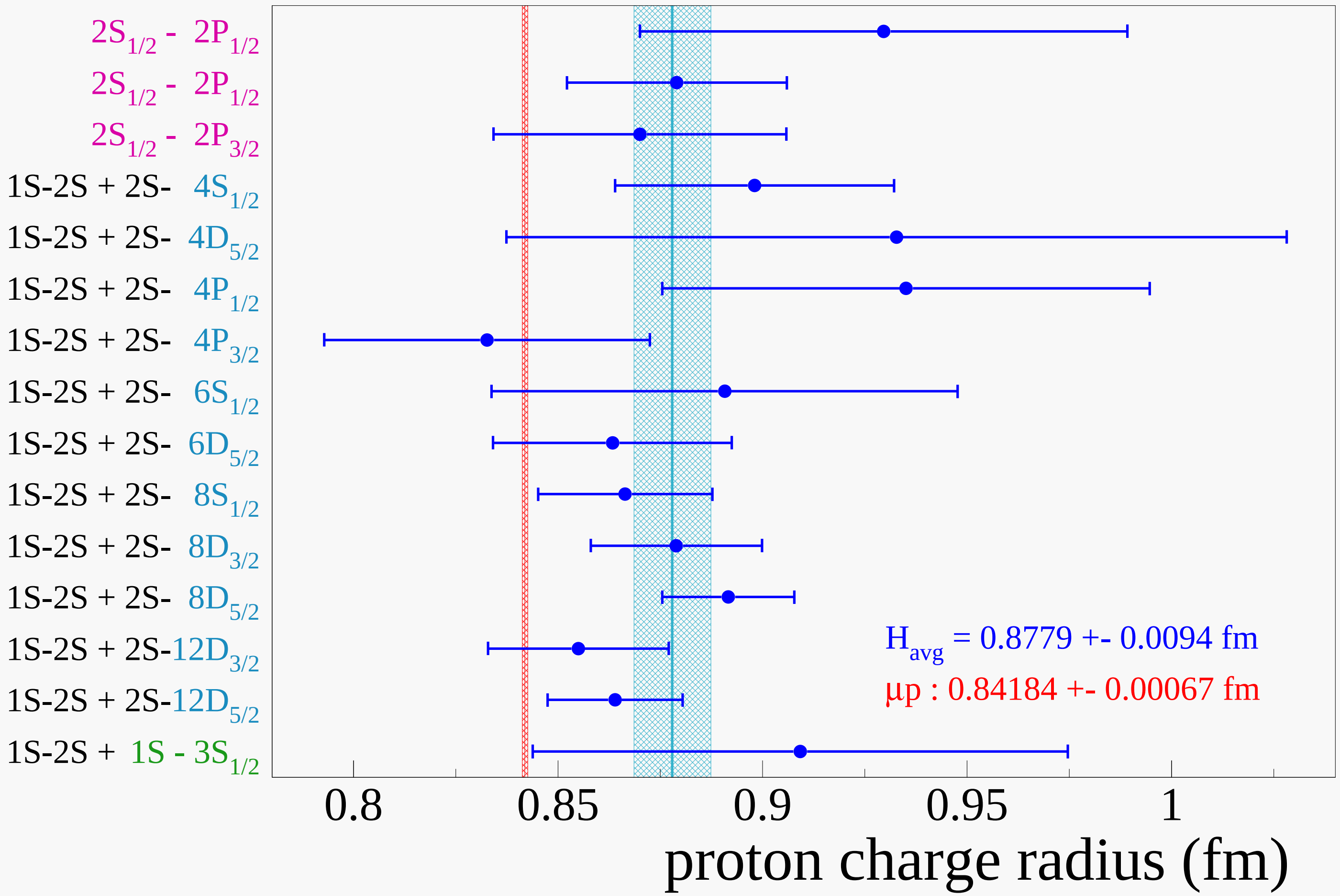
$$L_{1S}^{\mathrm{th}}(r_\mathrm{p}) = L_{1S}^{\mathrm{exp}} \implies r_\mathrm{p} = 0.873(8)\ \text{fm, with } u_r = 1\%$$

- To bring r_p from H in agreement with r_p from μp:
  - shift $L_{1S}^{\mathrm{exp}} \Leftrightarrow R_\infty \Leftrightarrow \nu_{2S-8S/D}$ by 95 kHz (i.e. by 5σ) ?
  - shift L_{1S}^{th} by 95 kHz (i.e. by $25\times$ its uncertainty) ?

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

r_p from H spectroscopy:

- 2S-2P transition in H (independent on R_∞)
- two transitions $n \rightarrow n'$ in H ($\Rightarrow r_p$ and R_∞)



Systematics? ($\sim n^3$!)

$u_r \sim 10^{-11} \Leftrightarrow$ linewidth$/100$

For SINGLE measurement the deviation from our result is $< 3\sigma$

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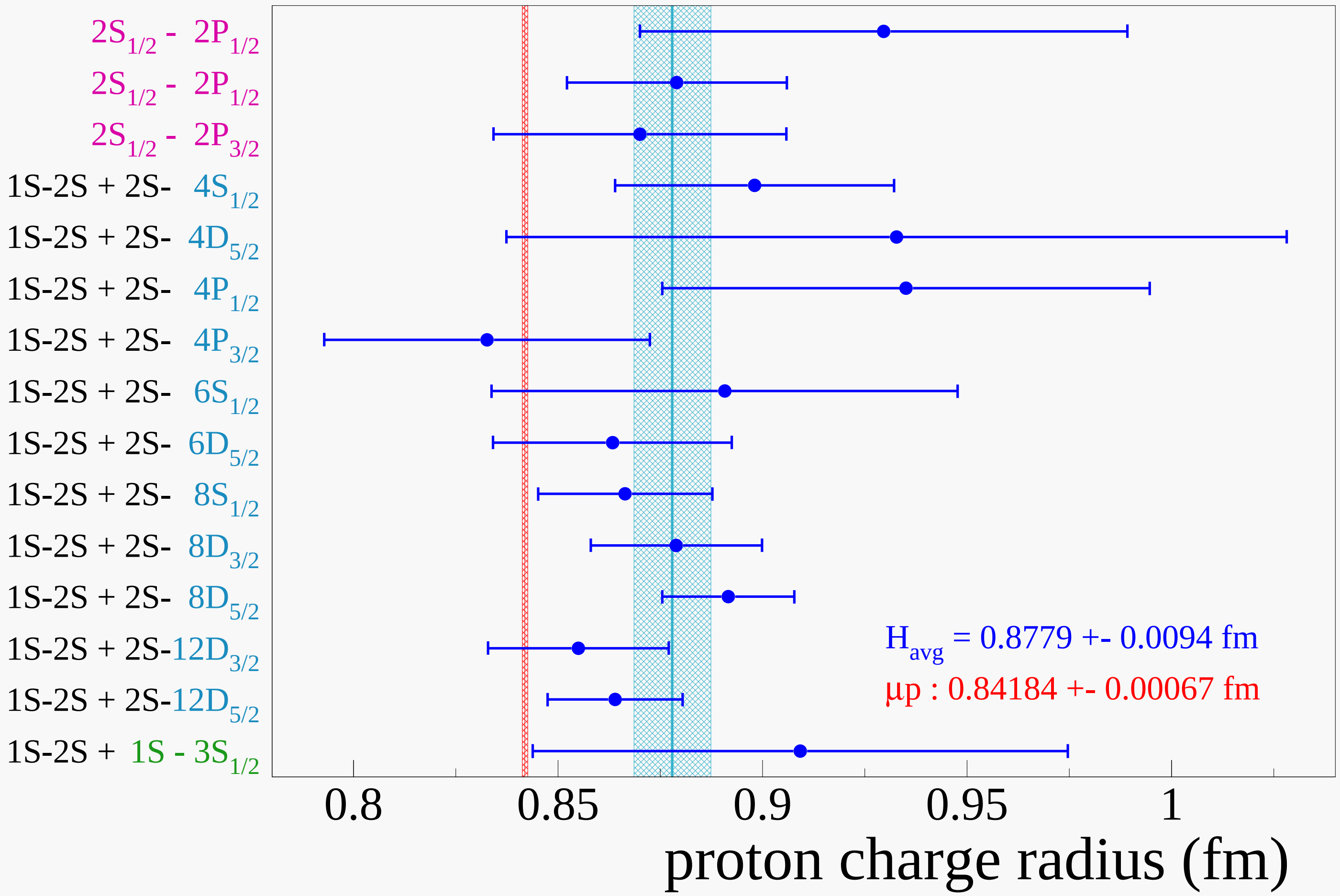

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Several groups active

For SINGLE measurement the deviation from our result is $< 3\sigma$

New physics?

r_p values provides not only consistency check of QED theory but also constraints a variety of new-physics scenarios

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

Strange survivors:

- MeV force carrier coupling only to right-handed muons *[PRL 107, 011803 (2011)]*
- MeV force carrier coupling to electron and neutron stronger than to muon and proton *[PRD 83, 101702 (2011)]*
- MeV masses, with fine-tuning (e.g. scalar-pseudoscalar) coupling, preferential coupling to second-generation *[arXiv:1206.3587]*

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Window for new physics very small
BUT more natural models could come to play if $r_p^{\mathrm{H}} < r_p^{\mu\mathrm{p}} < r_p^{\mathrm{scatt}}$

New parity violating muonic force? [PRL 107, 011803 (2011)]

- r_p and $(g-2)_\mu$ may be manifestation of new sub-GeV force carrier
- r_p difference $\rightarrow$ new interaction $O(10^4 G_F)$ $\rightarrow$ new light states < 1 GeV

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- New U(1) gauge boson kinetically mixed with hypercharge

  $\rightarrow$ light mediator between dark matter and standard model

  $\rightarrow$ r_p would depend on exchanged $|q|$ $\rightarrow$ $r_p^{\mathrm{H}} < r_p^{\mu\mathrm{p}} < r_p^{\mathrm{scatt}}$ against observations
  if new R_∞ would shift $r_p^{\mathrm{H}} \rightarrow r_p^{\mu\mathrm{p}}$: indications for this model!

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• New vector and scalar force carrier with gauged right-handed muon number

$$V_\alpha \bar{l} \gamma_\alpha l \sim V_\alpha (c_1 \bar{L} \gamma_\alpha L + c_2 \bar{R} \gamma_\alpha R)$$

No new interaction stronger than G_F between ν and $e, u, d \rightarrow c1 = 0$

$U(1)_R$ with gauged μ_R $\rightarrow$ effective field valid below a UV cutoff well above 1 TeV

$\rightarrow$ solves r_p and $(g-2)_\mu$ discrepancies and accounts for μe, H, μSi, α, J/Ψ...
$\rightarrow$ is visible in: one-γ decay of 2S-state in μ-atoms, $\mu\,\mathrm{He}^+$ $(2S-2P)$, μ-scatt. asym.

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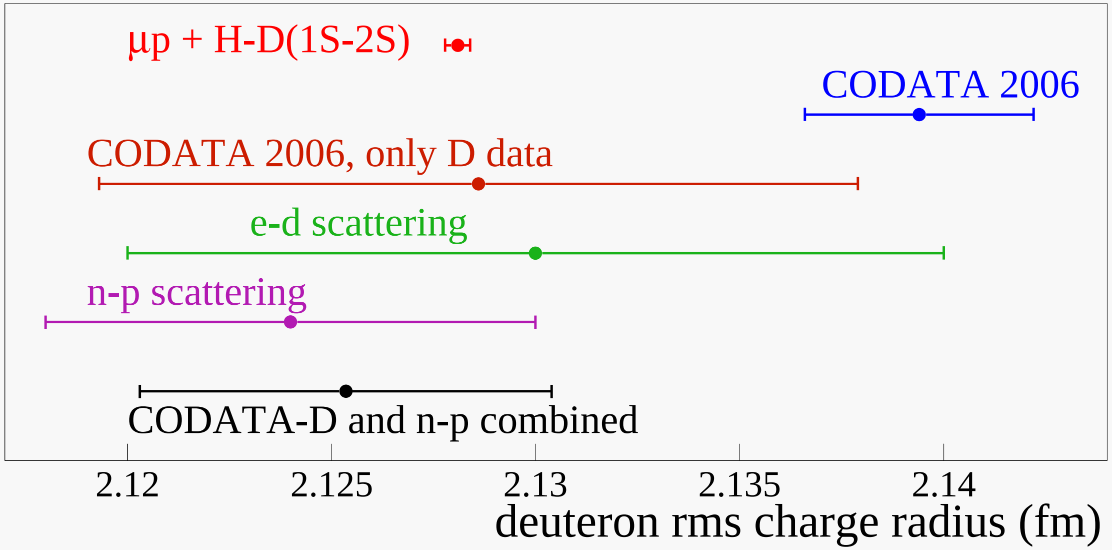
Model accounts for many obsrevalbles but it is quite un-natural.
Window for new physics is very small but...

Deuteron radius and polarizability

Deuteron radius from the H-D isotope shift and muonic hydrogen

$$\left.\begin{aligned} r_\mathrm{d}^2 - r_\mathrm{p}^2 &= 3.820\,07(65)\ \mathrm{fm}^2 \\ r_\mathrm{p} &= 0.84184(67)\ \mathrm{fm} \end{aligned}\right\} \Rightarrow \quad r_\mathrm{d} = 2.12808(27)\ \mathrm{fm}$$



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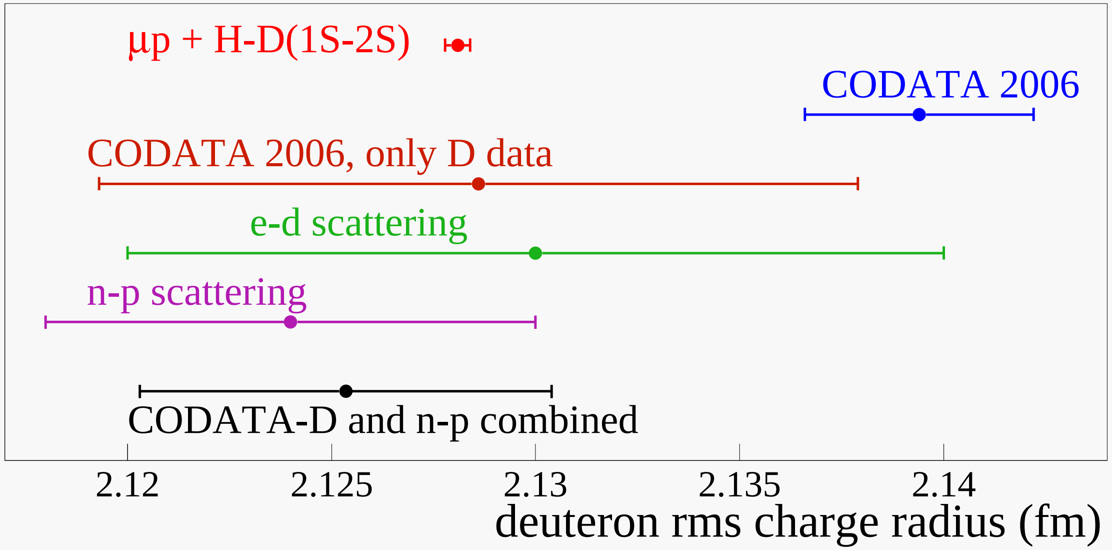

From measured μd(2S-2P) transitions
$\rightarrow$ deuteron radius r_d
$\rightarrow$ μd polarizability contr.

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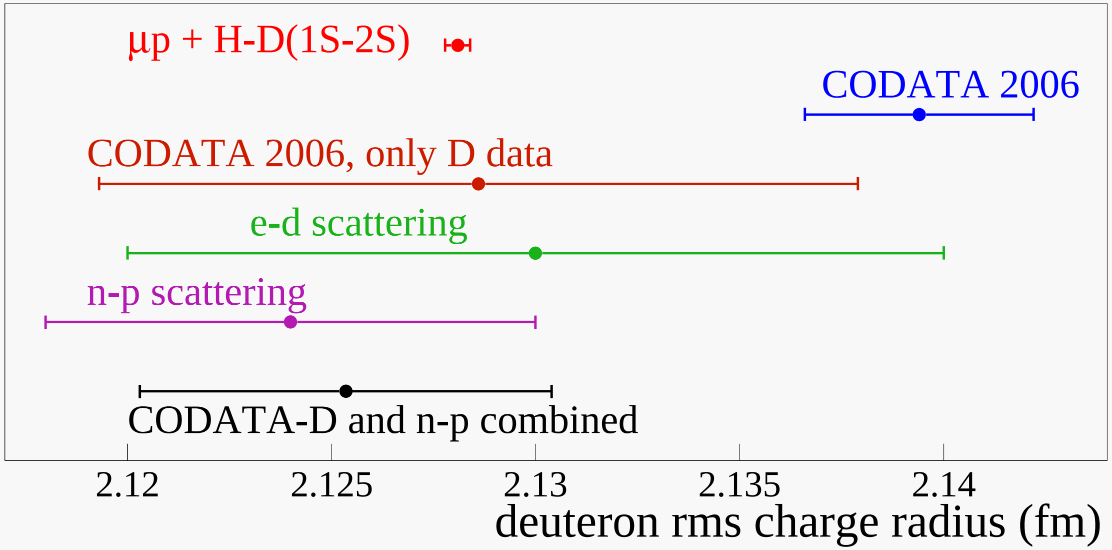

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r_d from scattering

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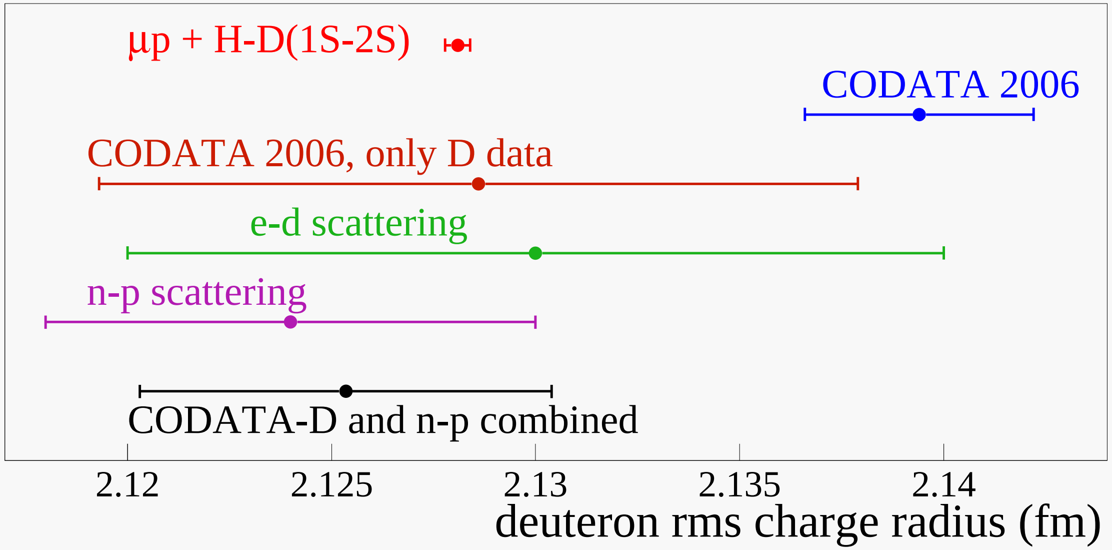

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r_d from scattering

r_d from few-nucleon th.?

μHe^+ Lamb shift

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

$\Downarrow$

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

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

- finite size contr. $\sim 20\%\ \Delta E$
- polarisability contr. $\sim 0.2\%\ \Delta E$

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Proton radius puzzle
- new muonic force?

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μHe^+ Lamb shift

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

$\Downarrow$

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

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

- finite size contr. $\sim 20\% \ \Delta E$
- polarisability contr. $\sim 0.2\% \ \Delta E$

Proton radius puzzle
- new muonic force?

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

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

Few-nucleon theories and He-radius

- Mathematics under control: observables deduced on the $\lesssim 0.1\%$ level

> Given a potential from phenomenolgy or EFT
> $\Downarrow$
> $\sqrt{< r^2 >}$ from the various methods agree within 1×10^{-3}

- EFT and the ^{4}He radius [*Navratil et al., PRL99, 042501 (2007)*]

  Constants of the effective Lagrangian may be deduced from QCD or low-E exp.
  All the low-E const. extracted from the A=2 with excepion of c_D, c_E which describe the NNN-int:

  c_D: NN-π-N contact terms strength
  c_E: NNN contact terms strength

> The charge radius (with other observables) is used to dedude c_D and c_E.
> $\Downarrow$
> potential

Few-nucleon th. $\leftrightarrow$ p, n, d and ^{3,4}He radii

- $r_{\rm He}$ measurement $\Rightarrow$ low-E const. of the NNN interaction (alt: nd-scatt., binding)
- low-E const. from $\tau_{1/2}$ and E_b of A=3 system $\Rightarrow$ $r_{\rm He}$ prediction

How the varius radii are interconnected [*Gazit et al., PRL 103, 102502 (2009)*]

$$r^2_{\rm He\,point} = r^2_{\rm He\,charge} - r^2_{\rm p} + r^2_{\rm n} \cdot \frac{N}{Z}$$

$\updownarrow$ Few-nucleon th. — $\updownarrow$ μHe — $\updownarrow$ μp — $\updownarrow$ Experiment

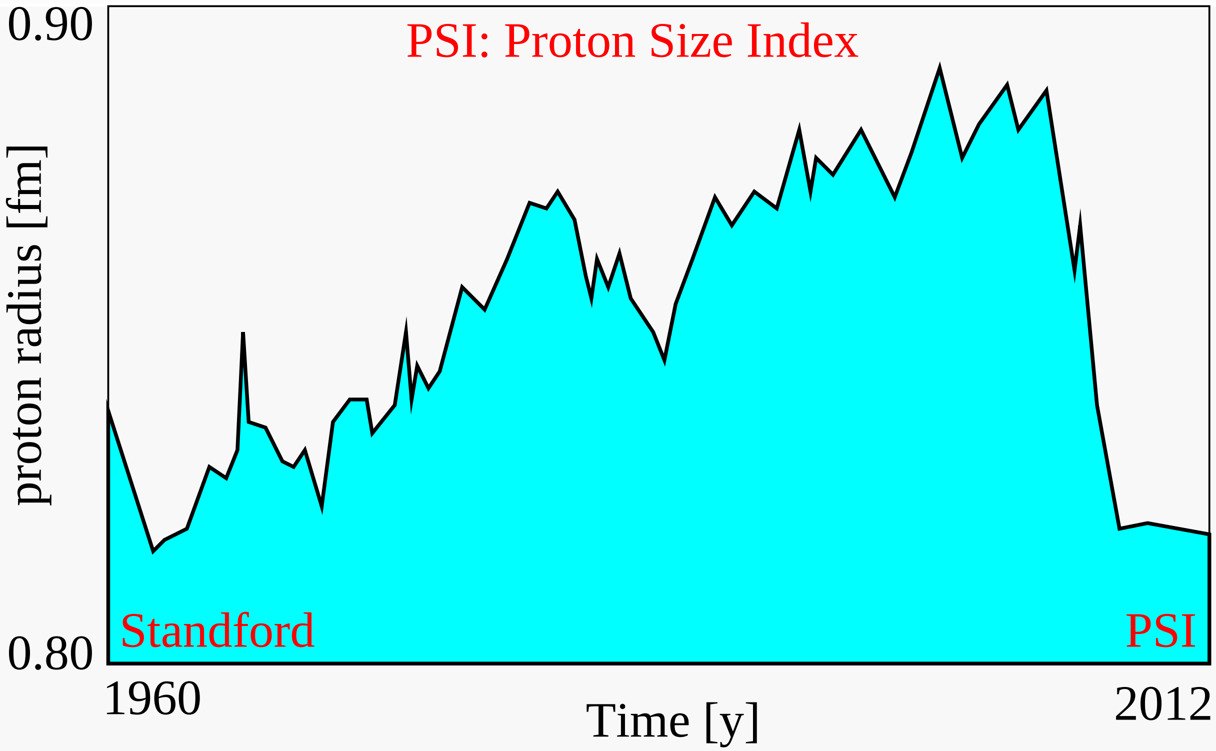
From C. Forssen, ECT, Trento, 20.10.2009

	NN (N^{3}LO)		+NNN (N^{3}LO)		Exp.
	NCSM	HH	NCSM	HH	
$< r_p^2 >^{1/2}$ [fm]	1.515(2)	1.518	1.475(2)	1.476	1.467(13)

P. Navratil et al., Phys. Rev. Lett. 99 (2007) 042501
A Kievsky J. Phys. G 35 (2008) 063101

Similar situation for ^{3}He and d [*L.E. Marcucci et al., PRC* **72** *014001 (2005)*]

The proton size crisis



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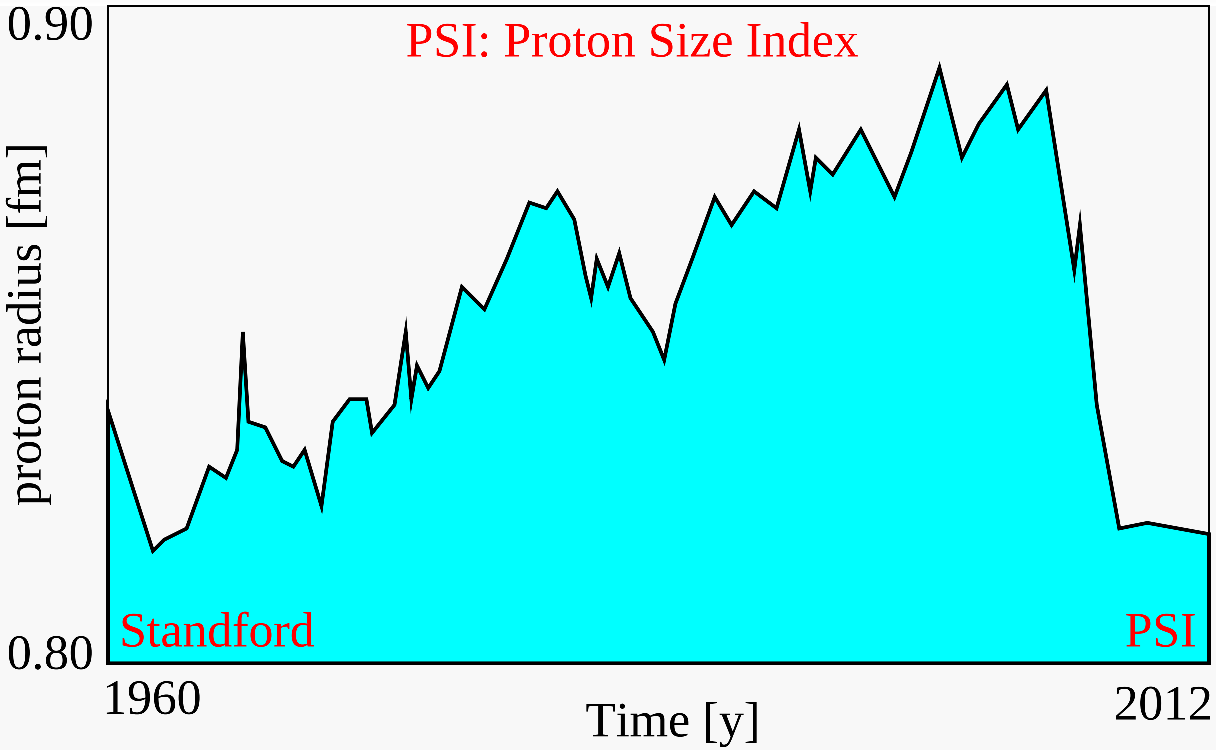

Central Scientific Institutes Interventions:

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- μ-p scatt. at PSI **[JLab-Rudgers-Argonne-MIT-...]**
- e-p scatt. **[JLab and Mami Mainz]**
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  EFT, ChPT, VMD, Lattice,...
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- few-nucleon th. and pot.
- new physics

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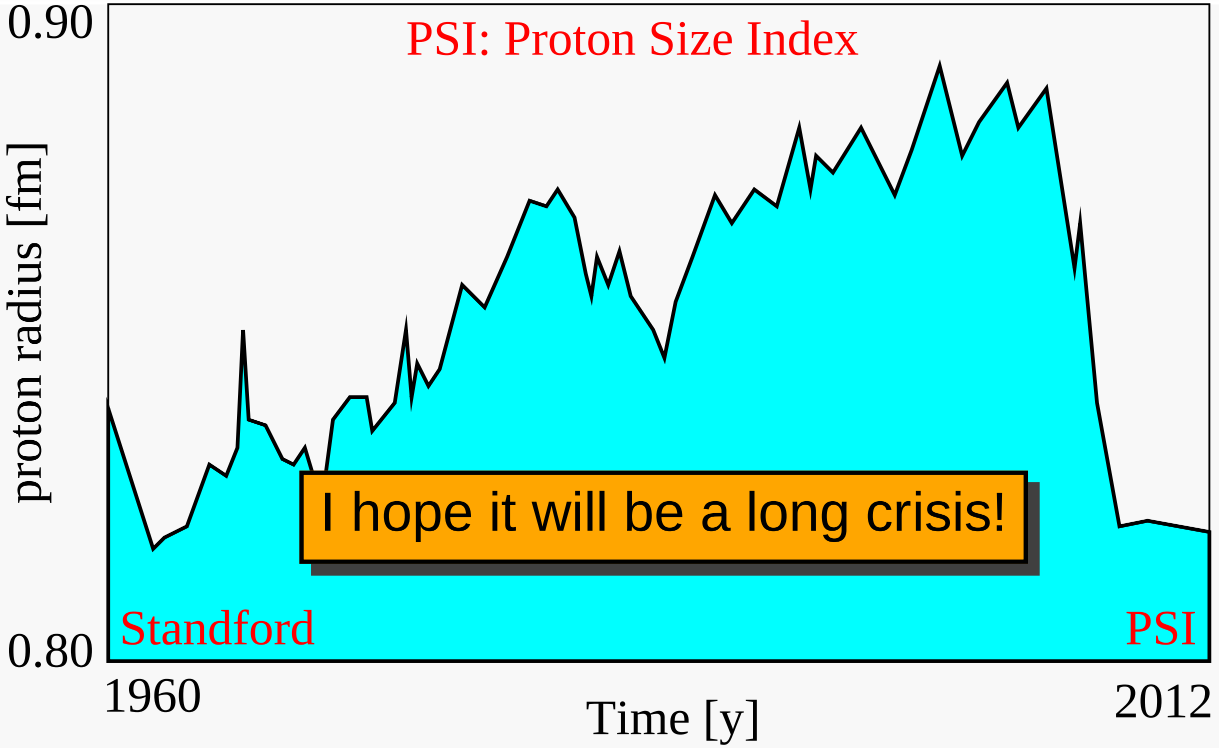

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