New insights into the proton radius puzzle and nuclear structure from muonic deuterium

Julian J. Krauth

on behalf of the CREMA collaboration

PSI workshop 2016

CREMA Collaboration

(Charge Radius Experiment with Muonic Atoms)

Max-Planck-Institut für Quantenoptik, Garching, Germany
- ► M. Diepold, B. Franke, T. W. Hänsch, T. Kohlert,
  J. J. Krauth, F. Mulhauser, T. Nebel and R. Pohl ←now at Uni Mainz!

Institut für Strahlwerkzeuge, Universität Stuttgart, Germany
- ► M. Abdou-Ahmed, T. Graf, A. Voss, B. Weichelt

Institut für Teilchenphysik, ETH Zürich, Switzerland
- ► A. Antognini, F. Kottmann, B. Naar, K. Schuhmann, D. Taqqu

Paul Scherrer Institut, Switzerland
- ► A. J. Dax, M. Hildebrandt, K. Kirch, A. Knecht

LKB, École Supérieure, CNRS, and Université P. et M. Curie, France
- ► F. Biraben, S. Galtier, P. Indelicato, L. Julien, F. Nez, C. Szabo-Foster

LIBPhys, Physics Department, Universidade de Coimbra, Portugal
- ► F. D. Amaro, L. M. P. Fernandes, A. L. Gouvea, J. M. F. dos Santos, J. F. C. A. Veloso

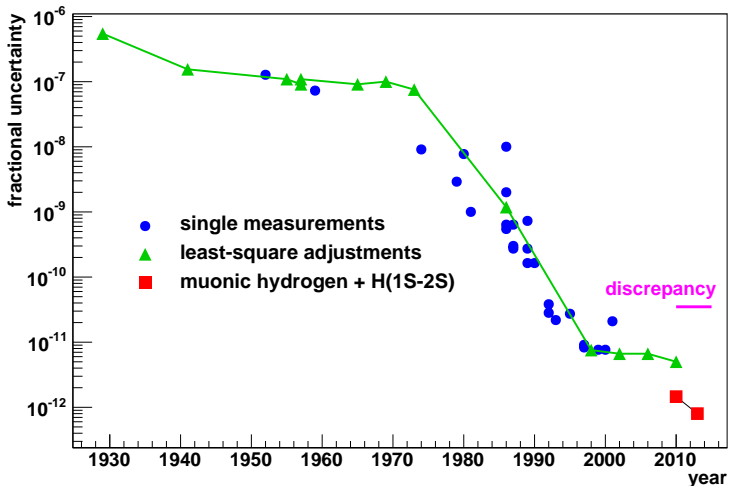*i3N, Universidade de Aveiro, Campus de Santiago, Portugal*
- ► D. S. Covita, C. M. B. Monteiro

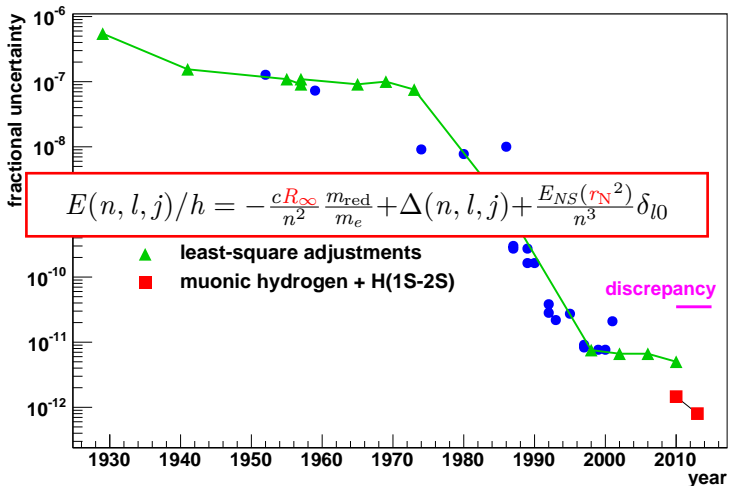*Physics Department, National Tsing Hua University, Taiwan*
- ► T.-L. Chen, Y.-W. Liu
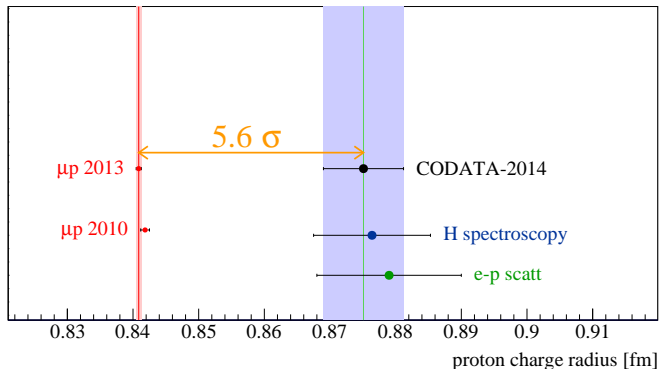
The Rydberg constant

Uncertainty in the last 80 years

The Rydberg constant

Uncertainty in the last 80 years

$$E(n, l, j)/h = -\frac{cR_\infty}{n^2}\frac{m_{\text{red}}}{m_e} + \Delta(n, l, j) + \frac{E_{NS}(r_N{}^2)}{n^3}\delta_{l0}$$

▲ least-square adjustments

■ muonic hydrogen + H(1S-2S)

discrepancy

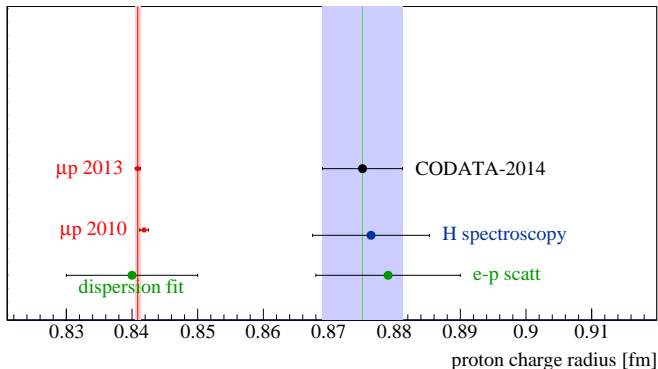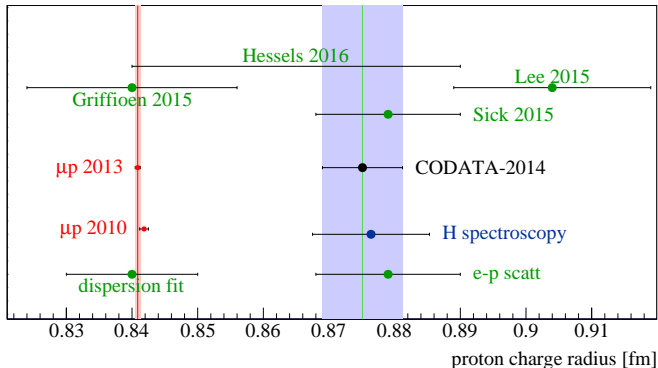# The Proton Radius Puzzle

Summarizing all *electronic* measurements of r_p (spectroscopy and scattering) from hydrogen and deuterium data, yields a $5.6\,\sigma$ discrepancy to the CREMA measurement.
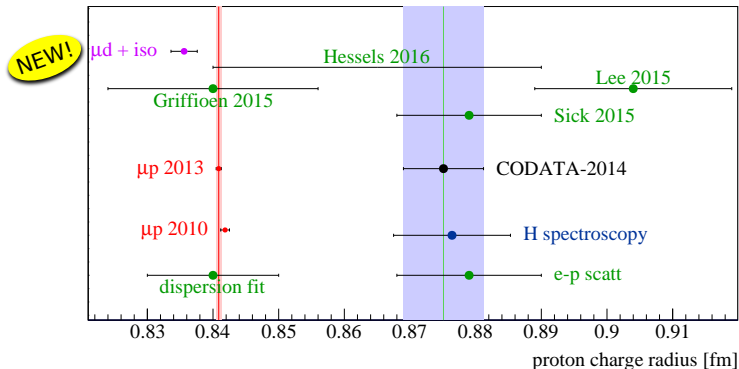
The Proton Radius Puzzle

Summarizing all *electronic* measurements of r_p (spectroscopy and scattering) from hydrogen and deuterium data, yields a $5.6\,\sigma$ discrepancy to the CREMA measurement.

The Proton Radius Puzzle

Summarizing all *electronic* measurements of r_p (spectroscopy and scattering) from hydrogen and deuterium data, yields a $5.6\,\sigma$ discrepancy to the CREMA measurement.
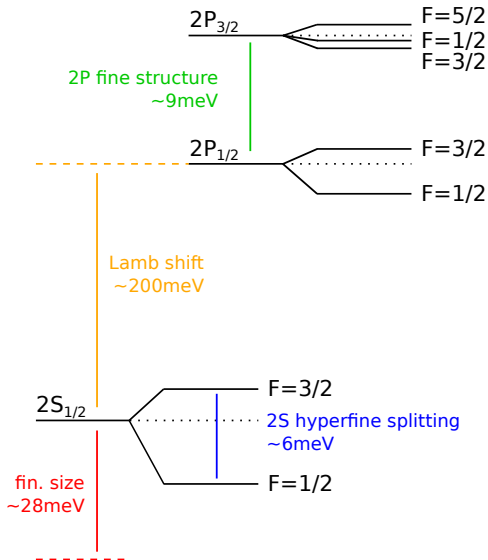
The Proton Radius Puzzle
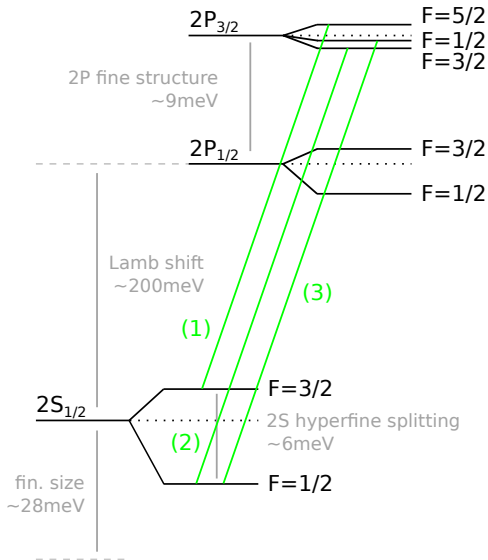

Summarizing all *electronic* measurements of r_p (spectroscopy and scattering) from hydrogen and deuterium data, yields a $5.6\,\sigma$ discrepancy to the CREMA measurement.

muonic deuterium (μd)
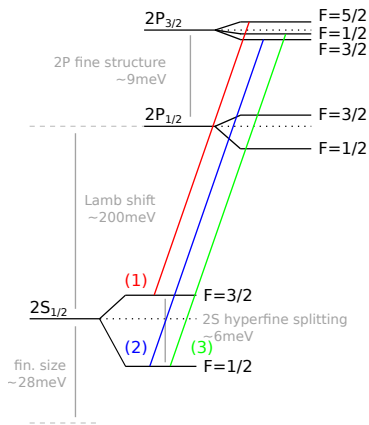
muonic deuterium (μd)

muonic deuterium (μd)

muonic deuterium

experimental results

measured transitions:

muonic deuterium

experimental results

measured transitions:

muonic deuterium

experimental results

measured transitions:

Lamb shift $\left(2\mathrm{S}_{1/2} - 2\mathrm{P}_{1/2}\right)$

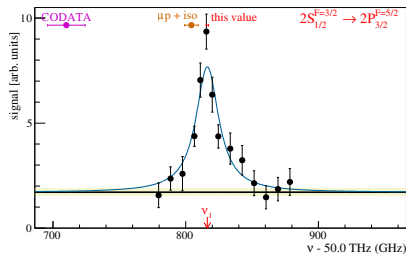(+ Fine and Hyperfine Structure)
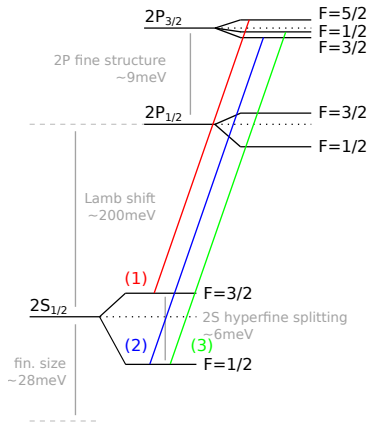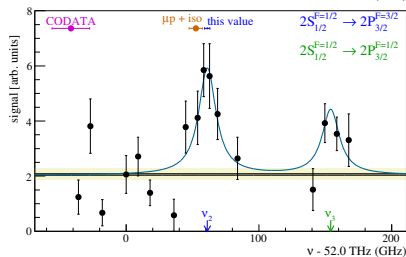
muonic deuterium

experimental results
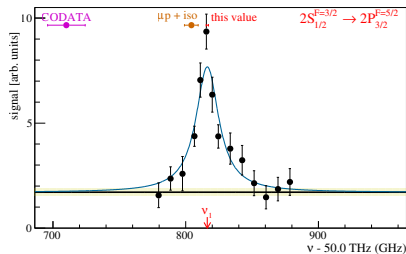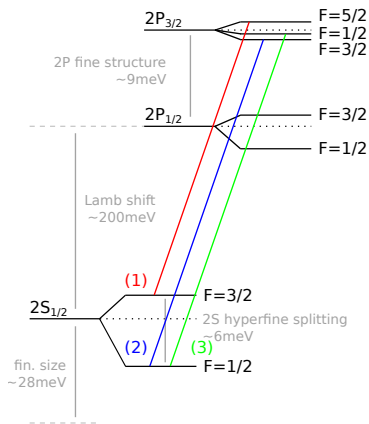
measured transitions:
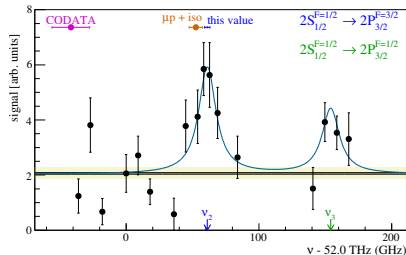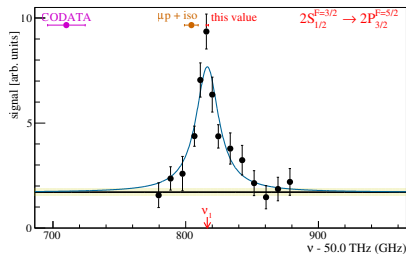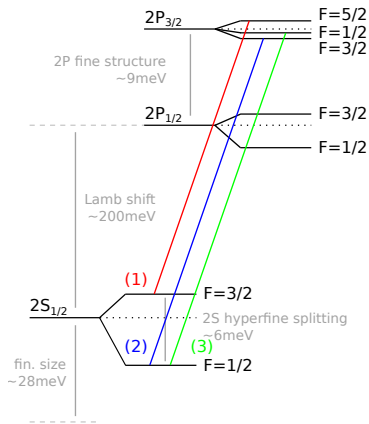
muonic deuterium

experimental results

measured transitions:
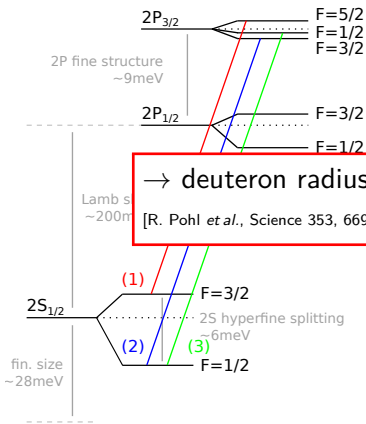
$$\rightarrow \text{ deuteron radius } r_{\rm d}(\mu{\rm d}) = 2.12562(78)\text{ fm!}$$

[R. Pohl *et al.*, Science 353, 669 (2016)]
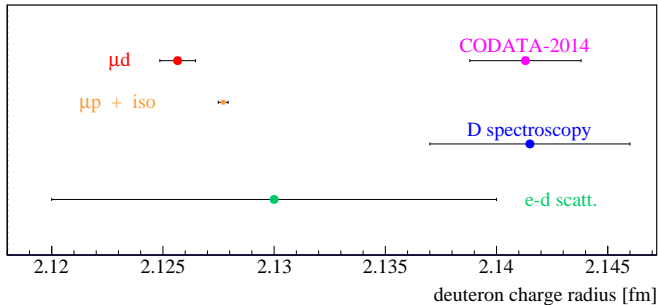
NEW!

muonic deuterium
the size of the deuteron

$\rightarrow 5.9\sigma$ discrepancy between $r_d(\mu d)$ and CODATA-2014.

[R. Pohl *et al.* (CREMA-coll.), Laser spectroscopy of muonic deuterium, Science 353, 669 (2016)]

muonic deuterium

the size of the deuteron

Attention:

- Correlation between r_p and r_d from CODATA
- Data of proton and deuteron can be separated

  [R. Pohl *et al.*, r_d *from spectroscopy in atomic deuterium*, arXiv:1607.03165, submitted]

$\rightarrow$ 2 discrepancies 'as independent as possible' of about

$$4.0\sigma \ (\mu p \leftrightarrow H)$$

and $\quad 3.5\sigma \ (\mu d \leftrightarrow D)!$

$\rightarrow 5.9\sigma$ discrepancy between $r_d(\mu d)$ and CODATA-2014.

[R. Pohl *et al.* (CREMA-coll.), Laser spectroscopy of muonic deuterium, Science 353, 669 (2016)]

muonic deuterium
the size of the deuteron

μd ●—

CODATA-2014
CODATA-2014 ●———

Attention:
• Correlation between r~~...~~ and r~~...~~ from CODATA

still physically correlated: $r_{\mathrm{d}}^2 = r_{\mathrm{struct.}}^2 + r_{\mathrm{p}}^2 + r_{\mathrm{n}}^2 + \frac{3\hbar^2}{4m_{\mathrm{p}}^2 c^2}$

4% smaller proton consistent with 0.8% smaller deuteron!

and 5.5σ (μd $\leftrightarrow D$)!

$\rightarrow 5.9\sigma$ discrepancy between $r_{\mathrm{d}}(\mu$d$)$ and CODATA-2014.

[R. Pohl *et al.* (CREMA-coll.), Laser spectroscopy of muonic deuterium, Science 353, 669 (2016)]

Lamb shift $\left(2\mathrm{S}_{1/2} - 2\mathrm{P}_{1/2}\right)$

QED
r-independent

QED
r-dependent

QCD
two-photon
exchange

Finite size effect

largest uncertainty
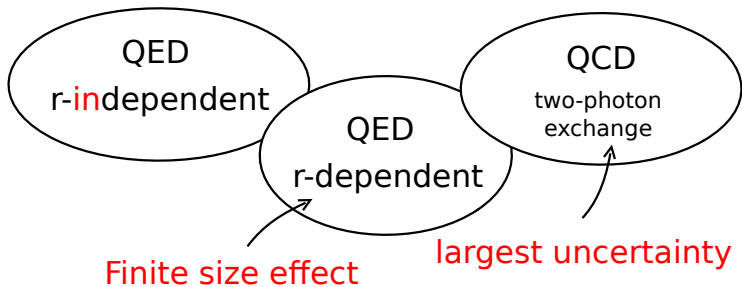
Lamb shift

two-photon exchange (TPE)

extract TPE <u>from muonic data</u>:

- 3 measured transitions, 2 fit parameters (LS, 2S HFS)
- $\Delta E_{\mathrm{LS}} = \Delta E_{\mathrm{QED}} + \Delta E_{\mathrm{fin.size}}(coeff \times r_{\mathrm{d}}^2) + \Delta E_{\mathrm{TPE}}^{\mathrm{LS}}$

use

- $r_{\mathrm{p}}(\mu\mathrm{p}) = 0.84087(39)\,\mathrm{fm}$
- electronic iso-shift: $r_{\mathrm{d}}^2 - r_{\mathrm{p}}^2 = 3.82007(65)\,\mathrm{fm}^2$[Parthey *et al.* (MPQ), PRL 104 (2010)]

$\rightarrow r_{\mathrm{d}}(\mu\mathrm{p} + \mathrm{iso}) = 2.12771(22)\,\mathrm{fm}$[Antognini *et al.*, Science 339 (2013)]

insert deuteron radius in Lamb shift and extract TPE.

Lamb shift

two-photon exchange (TPE)

TPE in history (huge deviations!!!)

Year	Source	Value [meV]	Uncert.
1992	Fukushima *et al.*	$1.24 \ (+ \ \text{el.})^*$	
1994	Lu and Rosenfelder	$1.450 (+ \ \text{el.})^*$	0.060
1995	Leidemann and Rosenfelder	$1.500 (+ \ \text{el.})^*$	0.025
2011	Pachucki	1.680	0.016
2013	Friar (ZRA)	1.941	0.019
2014	TRIUMF/Hebrew group	1.690	0.020
2015	Pachucki and Wienczek	1.717	0.020
2014	Carlson *et al.*	2.011	0.740
2016	our compiled theory value	1.7096	0.0200
2016	our exp. value	1.7638	0.0068

2.6σ

NEW!

* elastic term: $0.424(3) \ \text{meV}$ from Hernandez *et al.*

green: modern determinations, include cancellation of elastic term.

muonic helium (μHe$^+$)

Muonic helium-4 ($\mu{}^4\mathrm{He}^+$)
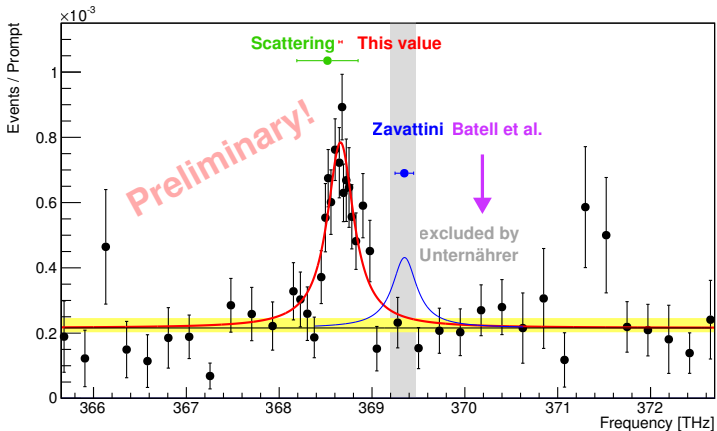
- Analysis by Marc Diepold.
- Theory summary submitted. Publication of experimental results in preparation.
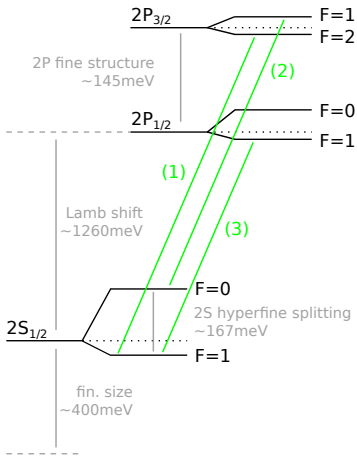
Muonic helium-3 ($\mu\,^3\mathrm{He}^+$)

Analysis by J. J. Krauth

Muonic helium-3 ($\mu^3\mathrm{He}^+$)

2P fine structure
~145meV

2P$_{3/2}$ F=1
         F=2

(2)

2P$_{1/2}$ F=0
         F=1

3He(1) resonance

preliminary!
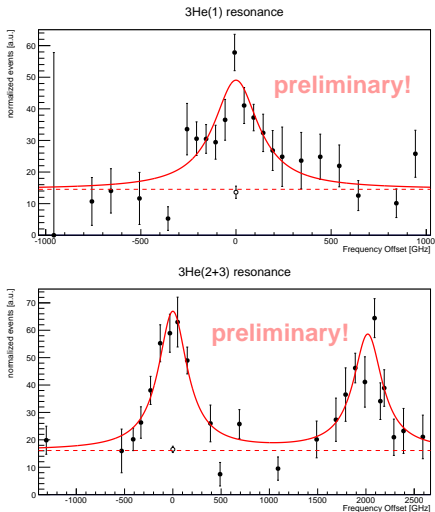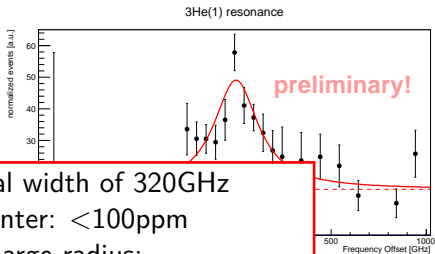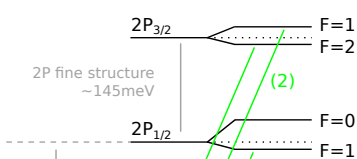
fit agrees with theoretical width of 320GHz
accuracy on each line center: <100ppm
expected accuracy on charge radius:
1.9xxx(7)fm, dominated by TPE.

2S hyperfine splitting
~167meV

2S$_{1/2}$ F=1

fin. size
~400meV

preliminary!
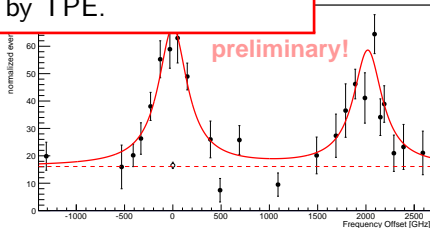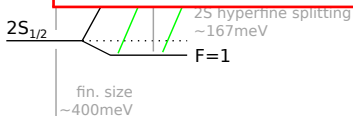
Analysis by J. J. Krauth

Charge radius difference in muonic helium

our uncertainty (very prel.)

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

Shiner *et al.***
PRL 74, 3553 (1995)

van Rooij *et al.**
Science 333, 196 (2011)

helium isotope shift $r^2(^3\text{He}) - r^2(^4\text{He})$ [fm^2]
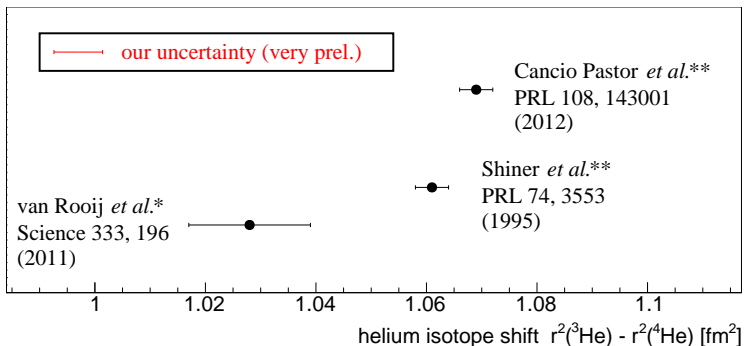
value from re-evaluated theory in

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

** Patkos, Yerokhin, Pachucki, arXiv:1610.04060 (2016)

Conclusions

$r_{\mathrm{d}}(\mu\mathrm{d})$ 5.9σ smaller than CODATA
3.5σ smaller than $r_{\mathrm{d}}(D)$
within 2.6σ of $r_{\mathrm{d}}(r_{\mathrm{p}} + \mathrm{iso})$

Conclusions

$r_\mathrm{d}(\mu\mathrm{d})$ 5.9σ smaller than CODATA
3.5σ smaller than $r_\mathrm{d}(D)$
within 2.6σ of $r_\mathrm{d}(r_\mathrm{p} + \mathrm{iso})$

Scenario 1:

$r_\mathrm{p}(H)$ and $r_\mathrm{d}(D)$ wrong?
$\rightarrow R_\infty$ wrong by 6σ
$\rightarrow r_\mathrm{p}(e - p)$ wrong
$\rightarrow$ TPE in $\mu\mathrm{d}$ 2.6σ larger

$\Rightarrow$

$r_\mathrm{p} = 0.84087(39)\,\mathrm{fm}$
$r_\mathrm{d} = 2.12771(22)\,\mathrm{fm}$ $(\mu\mathrm{p} + \mathrm{iso})$
$\Delta E_\mathrm{TPE}^\mathrm{LS} = 1.7638(68)\,\mathrm{meV}$ $(\mu\mathrm{d})$
$\rightarrow$ shift R_∞ by 6σ!

Conclusions

$r_{\mathrm{d}}(\mu\mathrm{d})$ 5.9σ smaller than CODATA
3.5σ smaller than $r_{\mathrm{d}}(D)$
within 2.6σ of $r_{\mathrm{d}}(r_{\mathrm{p}} + \mathrm{iso})$

Scenario 2:

Beyond SM
$\mu\mathrm{p}$: $0.33\,\mathrm{meV}$
$\mu\mathrm{d}$: $0.45\,\mathrm{meV}$ $\Rightarrow$
$(g - 2)_{\mu}$: 3.5σ

New force carrier w/ $\sim \mathrm{MeV}$ mass
– Batell *et al.* (2011)
   $\rightarrow$ excluded by $\mu^{4}\mathrm{He}^{+}$! (prelim.!)
– Tucker-Smith, Yavin (2011)

Outlook

- proton smaller (*Pohl et al. Nature 2010, Antognini et al. Science 2013*)
- deuteron smaller (*Pohl et al. Science 2016*)

- r_α agrees with e^--scattering (preliminary)
- helium-3: theory in preparation.
  Will give insight into charge radius difference.

- more experiments to come: H(2S-4P), H(2S-6P), H(2S-2P), MUSE, He$^+$, ISR, PRAD, μp(HFS), μ^3He$^+$(HFS) and many more

Thank you for your attention!

J.J. Krauth