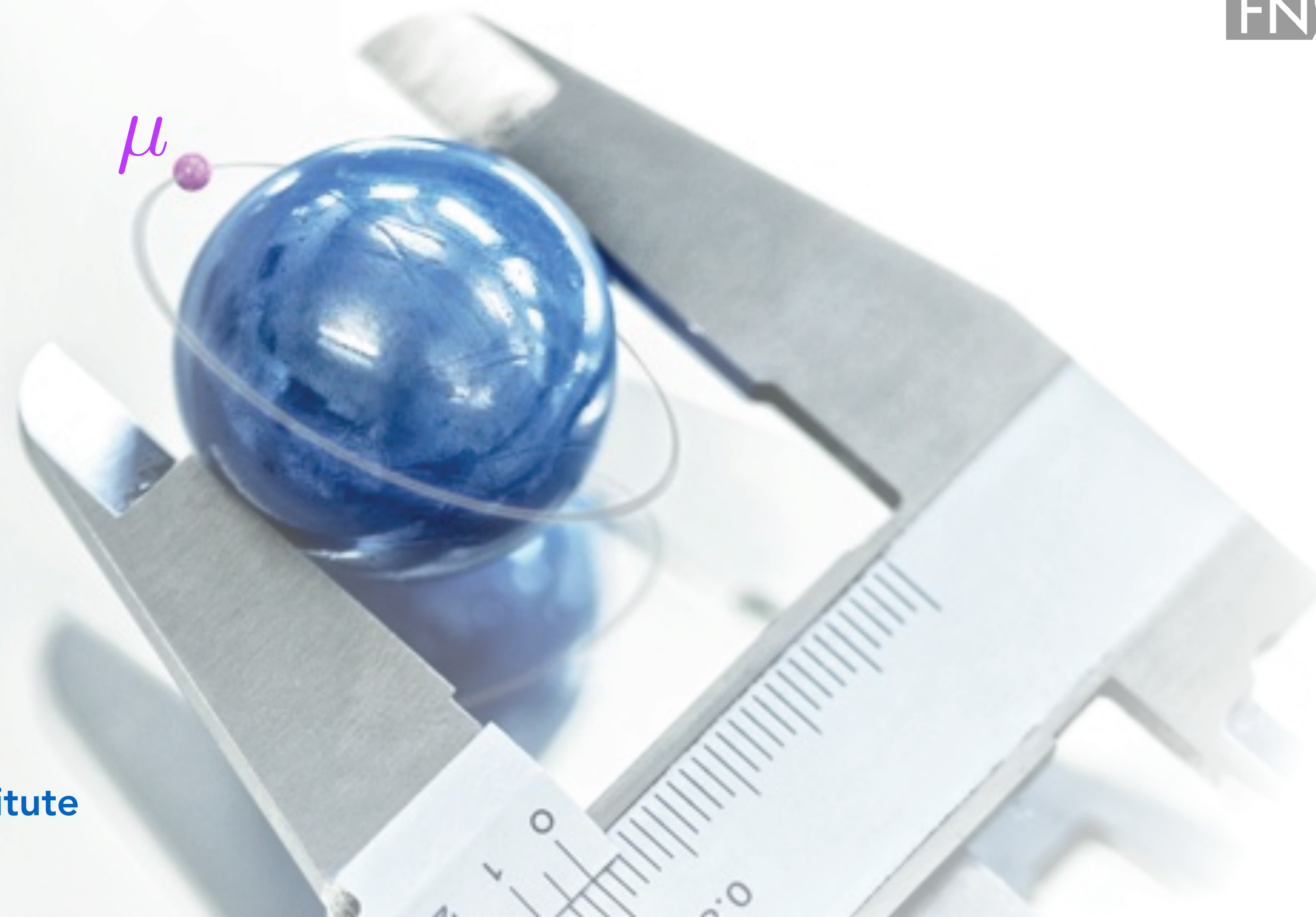
Laser spectroscopy of muonic helium ions

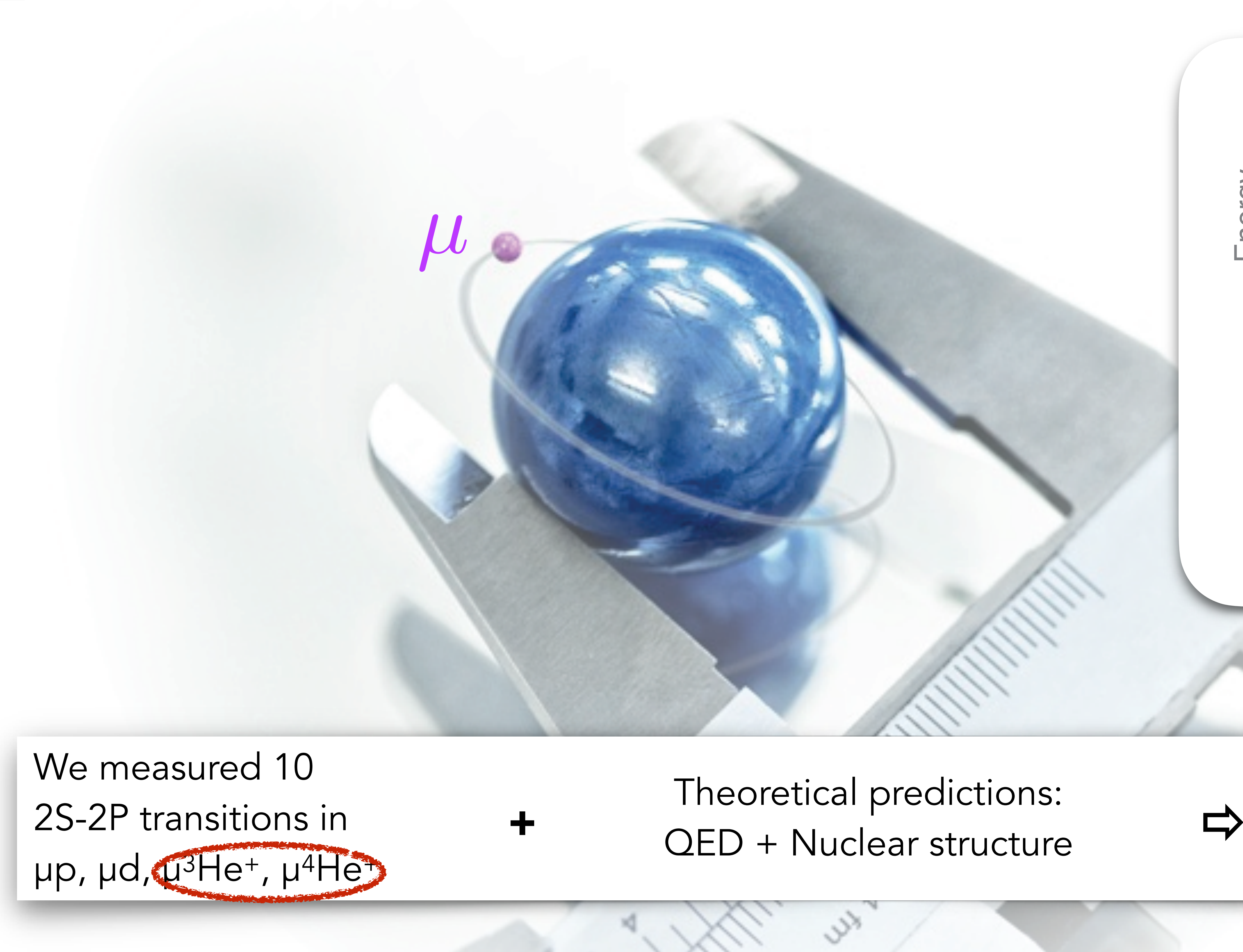
CREMA collaboration

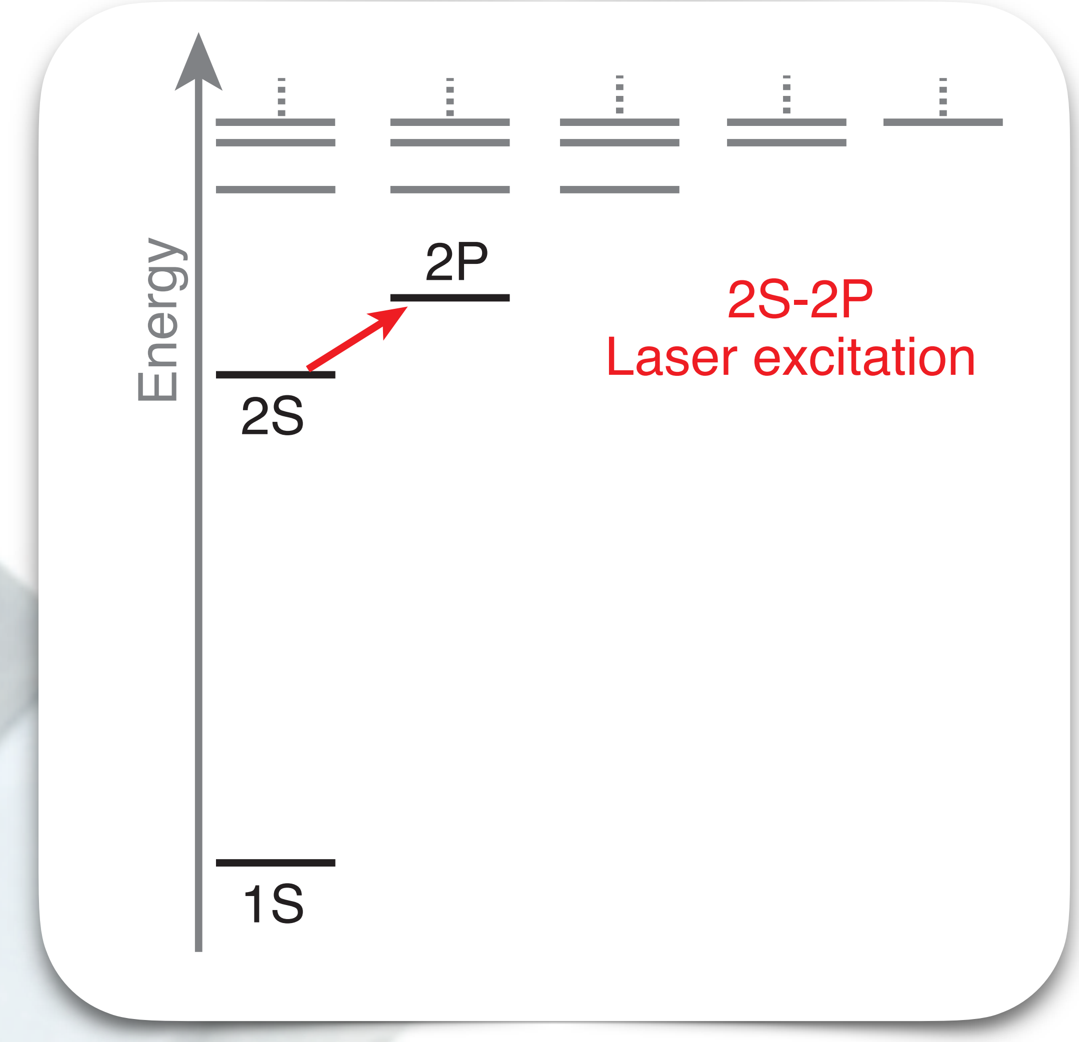


Aldo Antognini

Paul Scherrer Institute
ETH, Zurich

Laser spectroscopy of light muonic atoms





We measured 10 2S-2P transitions in μp, μd, μ^3He^+, μ^4He^+

+

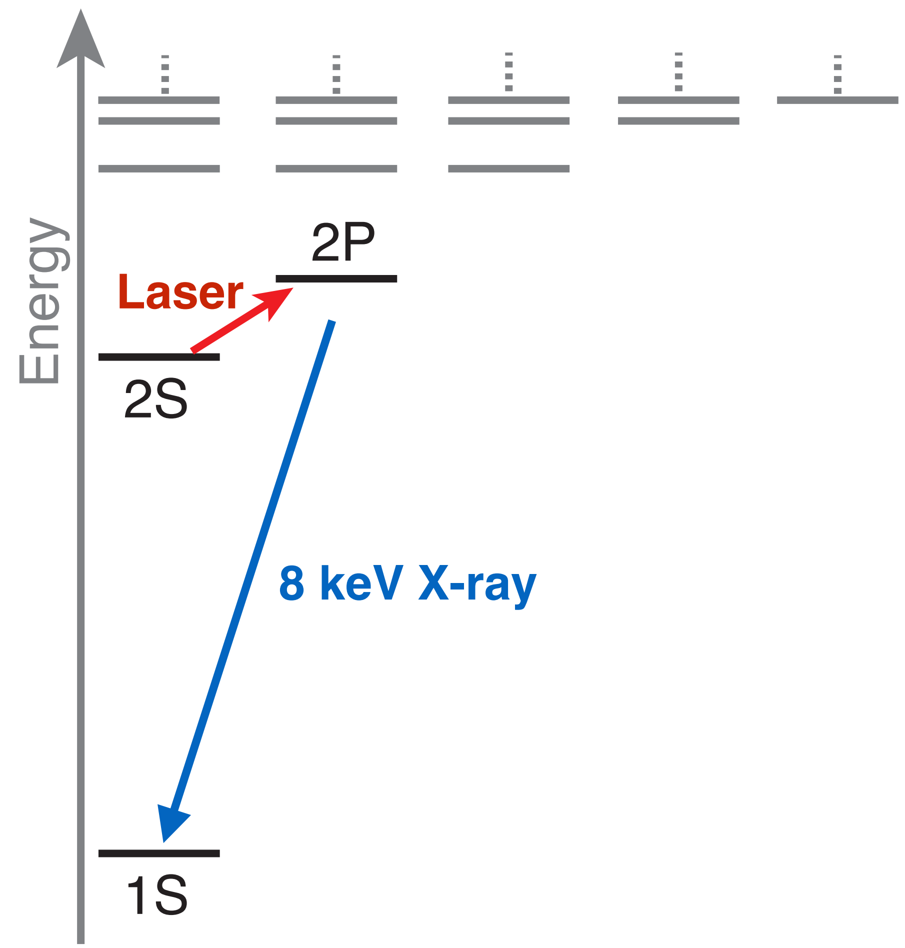
Theoretical predictions:
QED + Nuclear structure

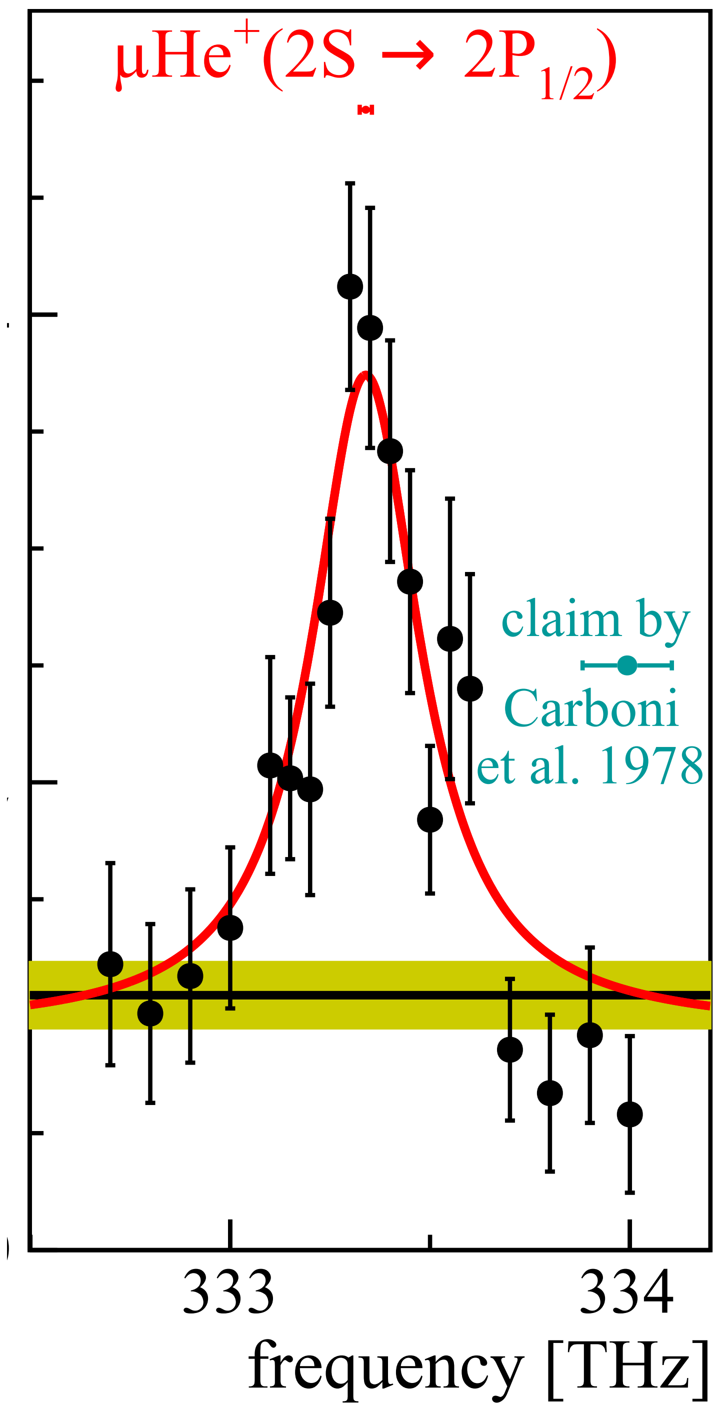
⇨

p, d, ^3He, ^4He charge radii

The μHe⁺ 2S-2P experiment

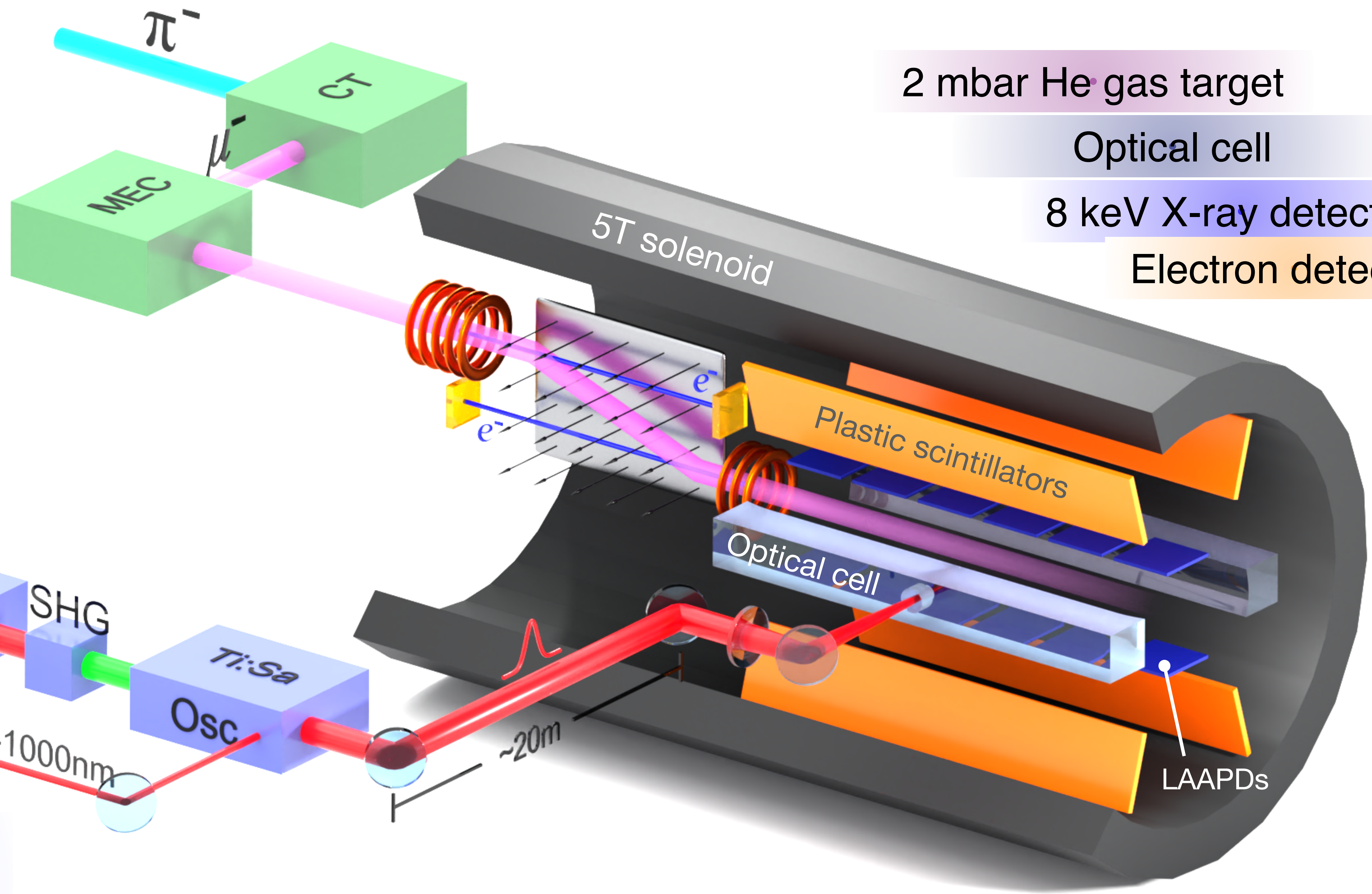
- Stop low-energy muons in 2 mbar Helium gas
- μHe⁺ are formed (1% in the 2S-state)
- Excite 2S-2P transition with laser
- Detect X-ray from 2P-1S de-excitation
- Plot number of X-rays vs. laser frequency





The setup

Beam line delivering slow muons $500\ \mu^- \mathrm{s}^{-1}$ at 1 keV



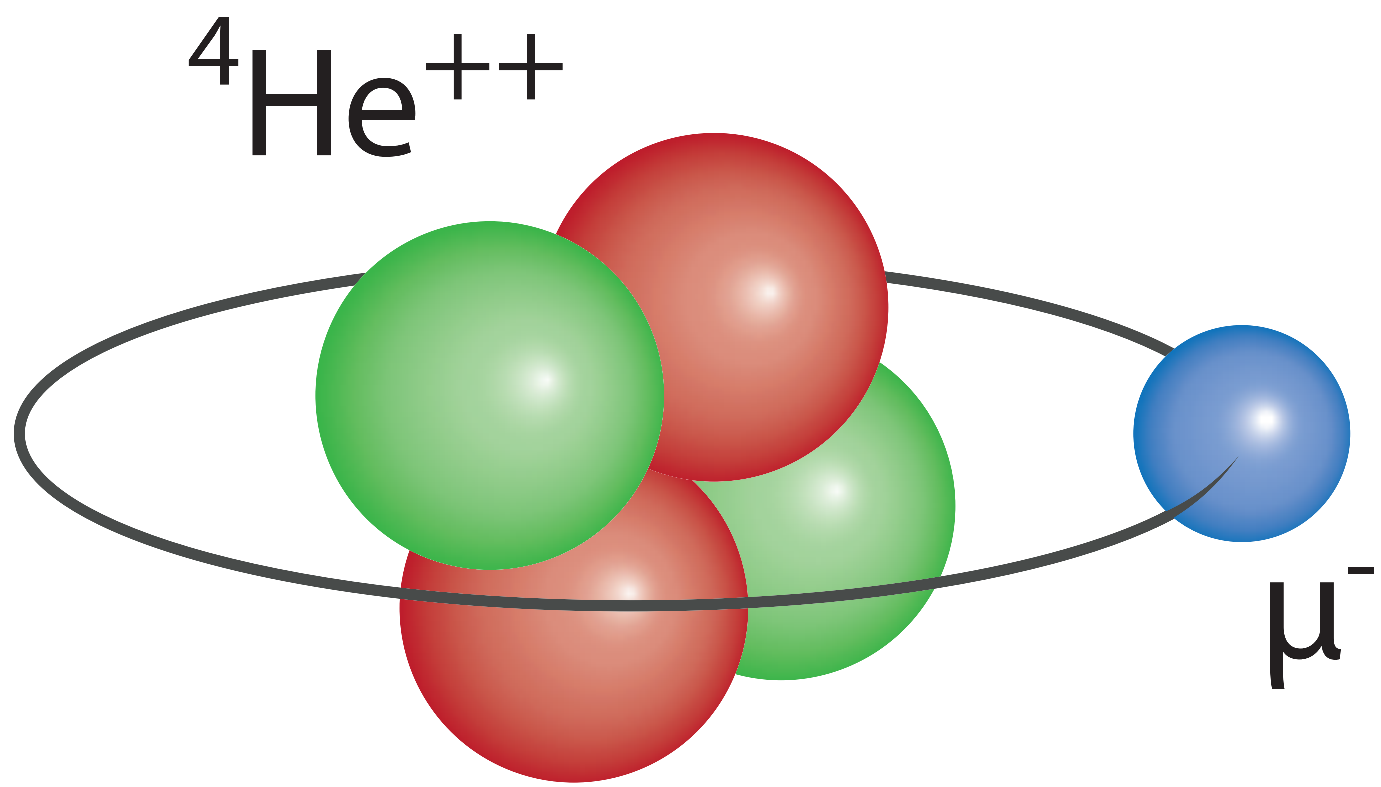
2 mbar He gas target

Optical cell

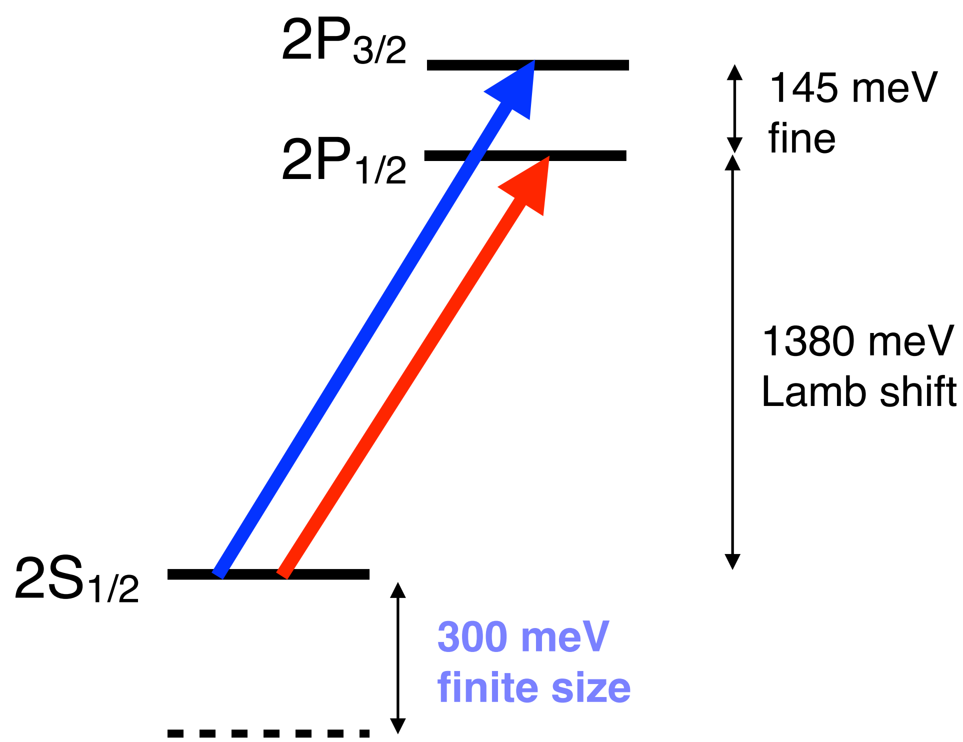
8 keV X-ray detectors

Electron detectors

Laser system delivering the spectroscopy pulses within 1 μs

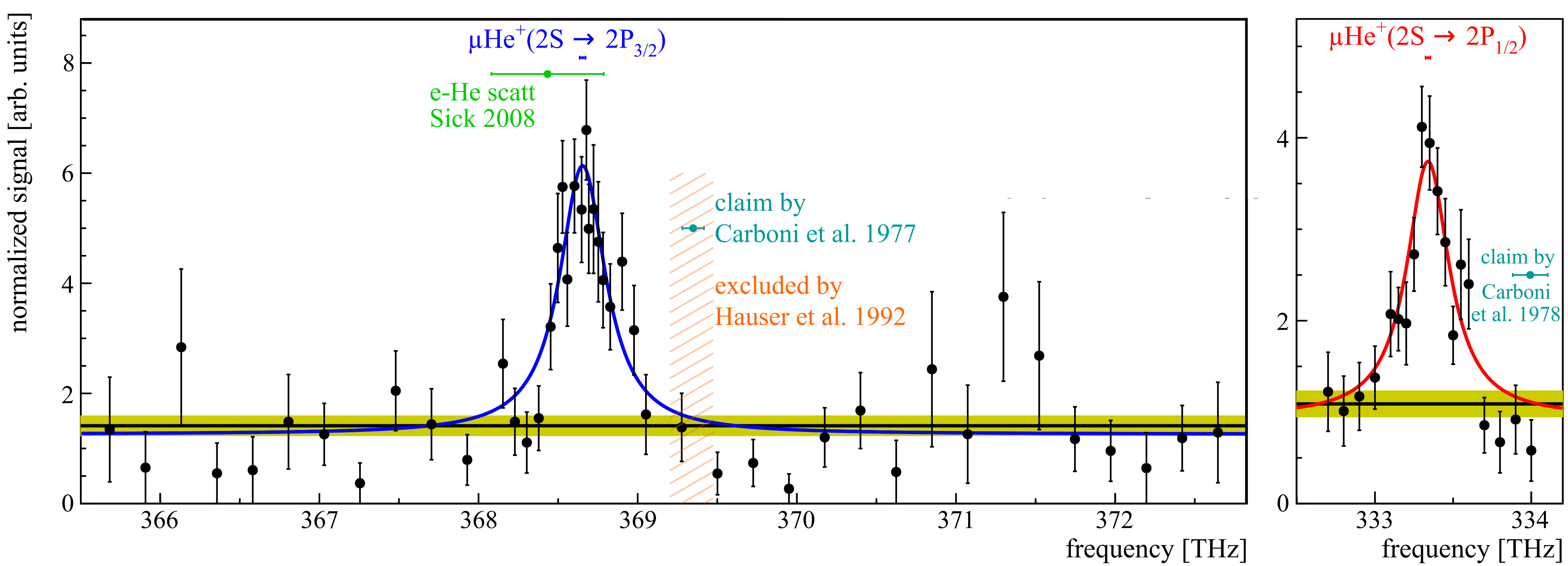

$^4He^{++}$
μ^-

The measured transitions in μ^4He^+



$$\nu^{\mathrm{exp}}(2\mathrm{S} \rightarrow 2\mathrm{P}_{3/2}) = 368{,}653 \pm 18 \text{ GHz}$$

$$\nu^{\mathrm{exp}}(2\mathrm{S} \rightarrow 2\mathrm{P}_{1/2}) = 333{,}339 \pm 15 \text{ GHz}.$$



Numerous laser-off events used to determine the background

High-sensitivity low-precision laser spectroscopy

High sensitivity to finite size

Vacuum polarisation

$$\Delta E_{2S-2P} \sim Z^3$$

Finite-size effect

$$\Delta E_{FNS} = \frac{2}{3n^3} Z^4 \alpha^4 m_r^3 r^2$$

Low precision laser spectroscopy

2S-2P line width

$$\Gamma_{2P} \sim Z^4 m$$

	μH	μ^4He+
Fine-size effect /Lamb shift	2 %	20 %
Line width	19 GHz	320 GHz
Measurement accuracy	1 GHz	15 GHz
Measurement rel. accuracy	10 ppm	50 ppm

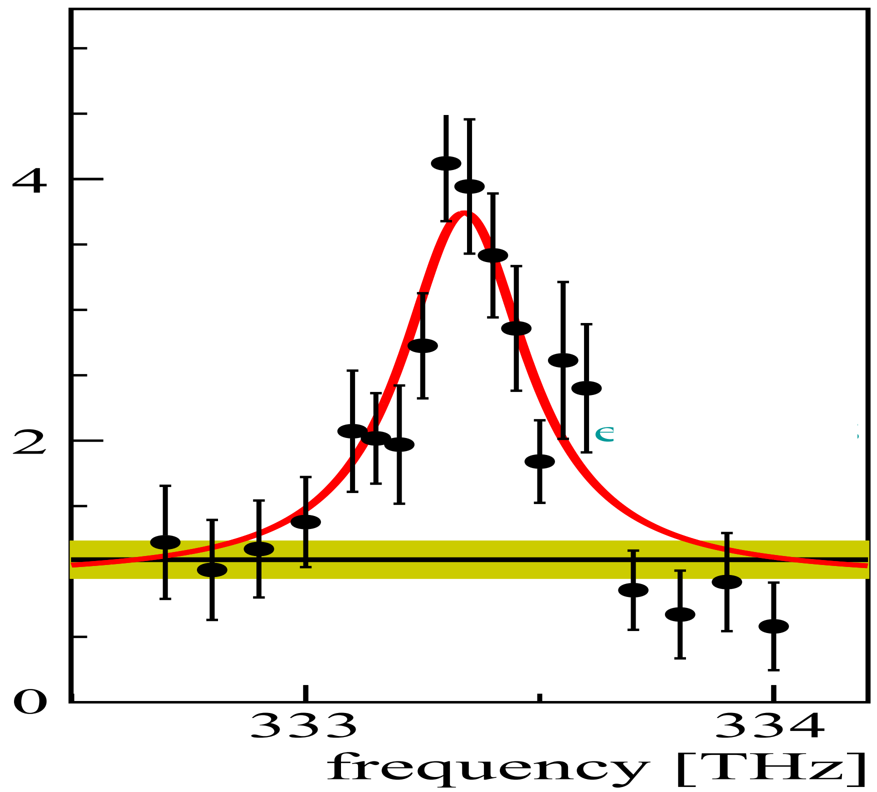
$\frac{1}{20}$ Line width

Insensitivity to systematic effects

Insensitivity to systematics

Statistical uncertainty	15 GHz
Atomic physics systematics	0.1 GHz
Laser frequency calibration	0.1 GHz
Laser energy fluctuations	3 GHz

Resonance fit accounts for energy fluctuations. Yet the energy was measured regularly but not for each pulse



Binding energy

$$E_n = -\frac{m}{m_e} Z^2 \frac{R_\infty}{n^2}$$

Atomic size

$$\langle r \rangle = \frac{h}{Z\alpha c}\frac{n^2}{m}$$

Matrix elements for perturbations

$$\Delta E = \langle \bar{\Psi} | H_1 | \Psi \rangle$$

$$H_1 = -\vec{\mu} \cdot \vec{B} \quad \sim 1/m$$

$$H_1 = -\vec{d} \cdot \vec{E}$$

The 4He charge radius

QED | Finite size | nucl. str.

Theory
$$E_{LS}^{th} = 1668.491(7) - 106.209\, r_\alpha^2 + 9.276(433)\ \text{meV}$$
Pachucki et al., arXiv:2212.13782

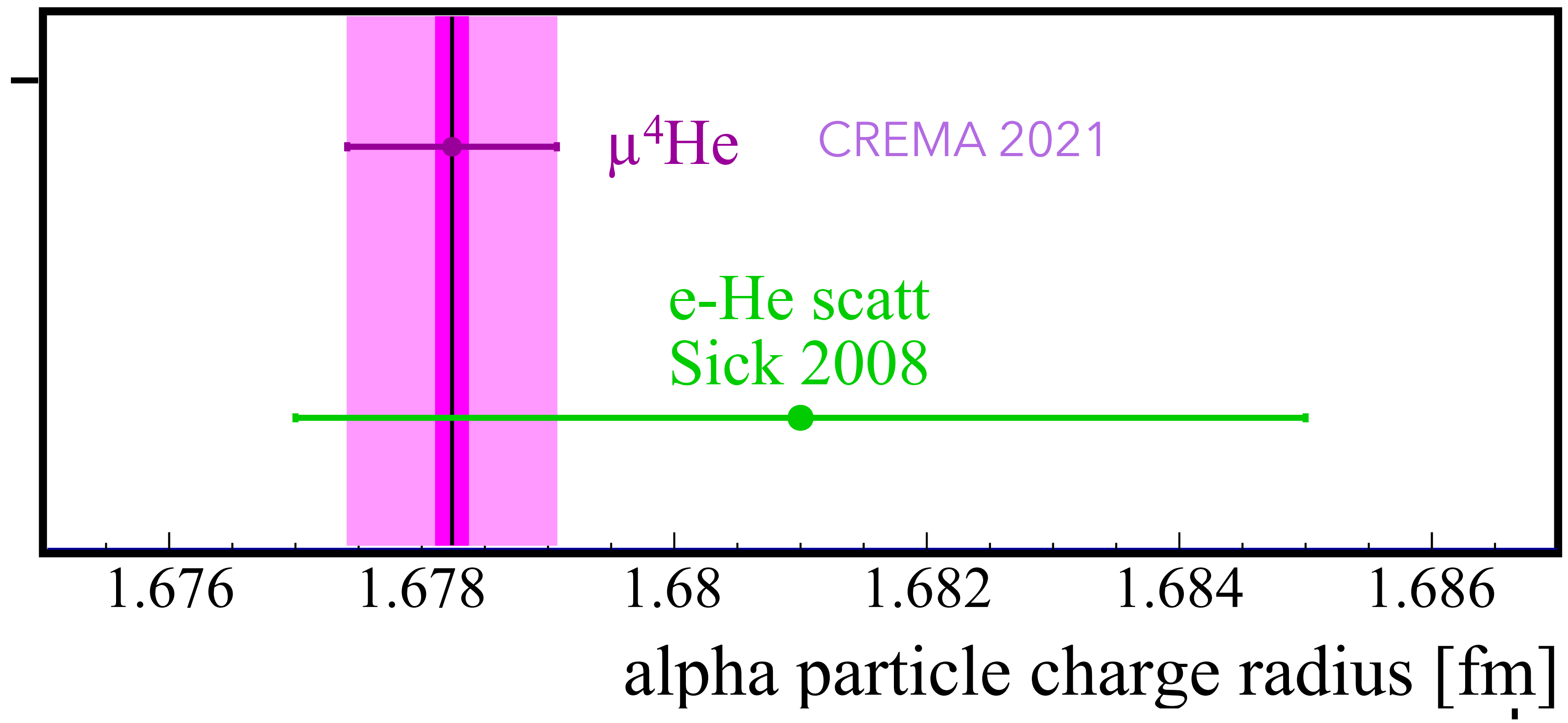
Experiment
$$E_{LS}^{exp} = 1378.521(48)\ \text{meV}$$
Nature 589 (2021) 7843, 527-531

$$r_\alpha = 1.6786\,(12)\ \text{fm}$$
Using 2023 theory

$$r_\alpha = 1.67824\,(13)_{exp}(82)_{th}\ \text{fm}$$
CREMA 2021

Uncertainty 2PE increased by 45%.
No elastic/inelastic separation.
More consistent treatment.

Bacca, Li Muli, Acharya, Ji, Hernandez,Barnea, ….



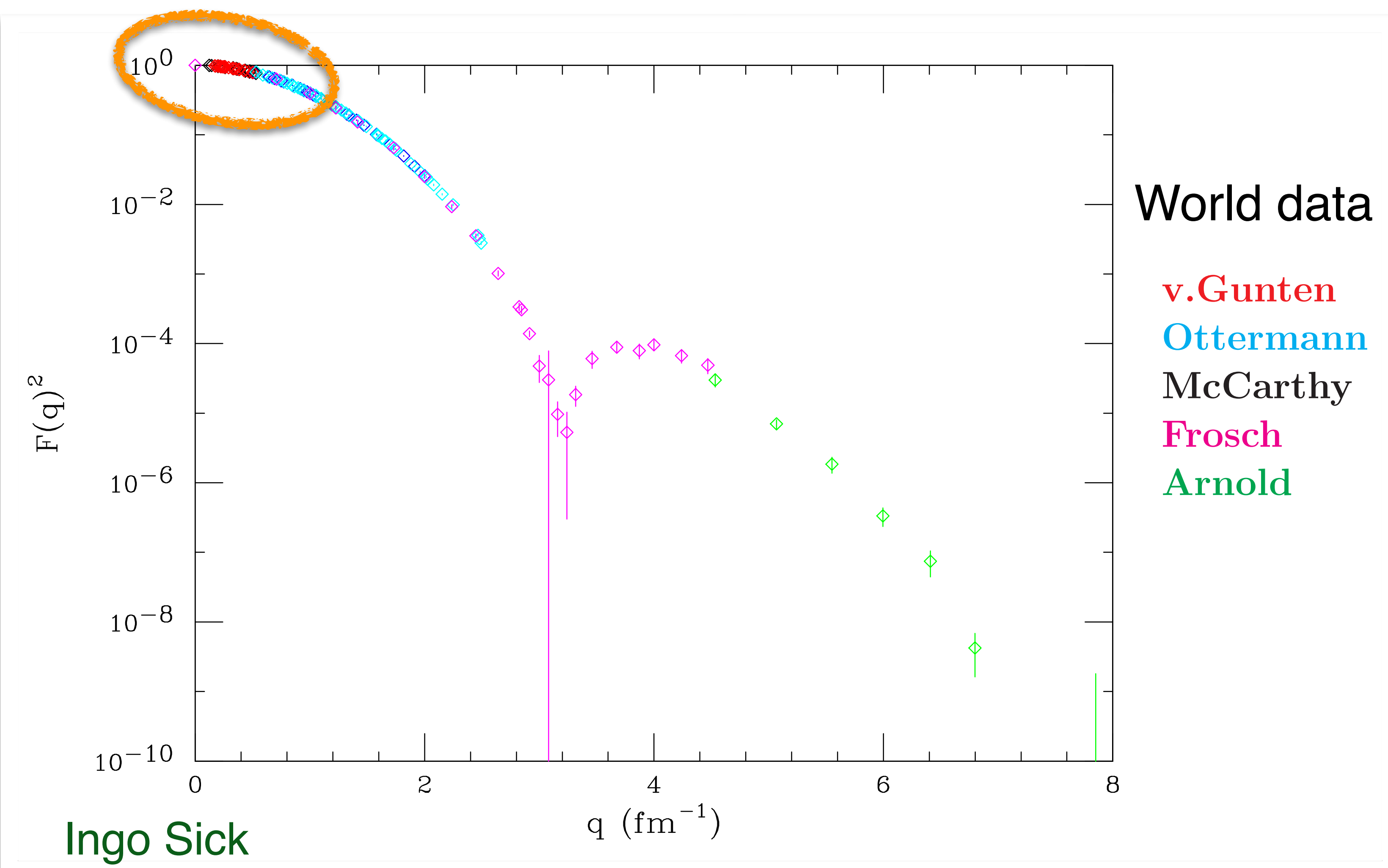
4He charge radius from electron scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{elastic}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} F^2(Q^2)$$

$$r_\alpha^2 = -6\frac{dF(q^2)}{dq^2}\bigg|_{q^2=0}$$

$$r_\alpha = 1.681(4)\text{fm}$$

PRC 77, 041302R (2008)



Good data

Only one form factor

He-nucleous has smaller tail compared to proton

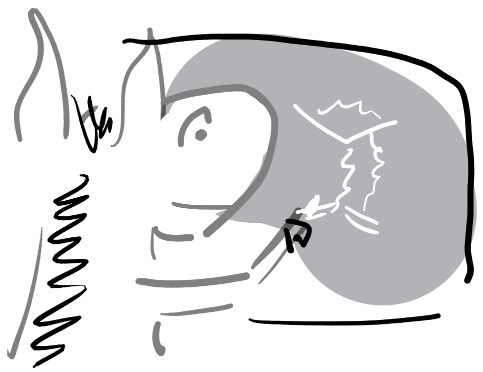
The procedure used by Ingo Sick

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{elastic}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} F^2(Q^2)$$

Assumption: The form factor is the Fourier transform of the charge distribution

- Parametrize $\rho(r)$ with sum of Gaussians including information on large-r behaviour of the proton and the neutron wave function
- Calculate the cross section integrating the Dirac equation with the static potential given by $\rho(r)$
- Fit the calculated cross sections to data (in Born approx. after subtracting radiative corrections)
- Fit the form factor matching better the data and get the slope

After the talk of **A. Signer** we should be very worried about old radiative corrections



Few per mille radiative correction of the NNLO for "total" cross section at the MUSE cinematic

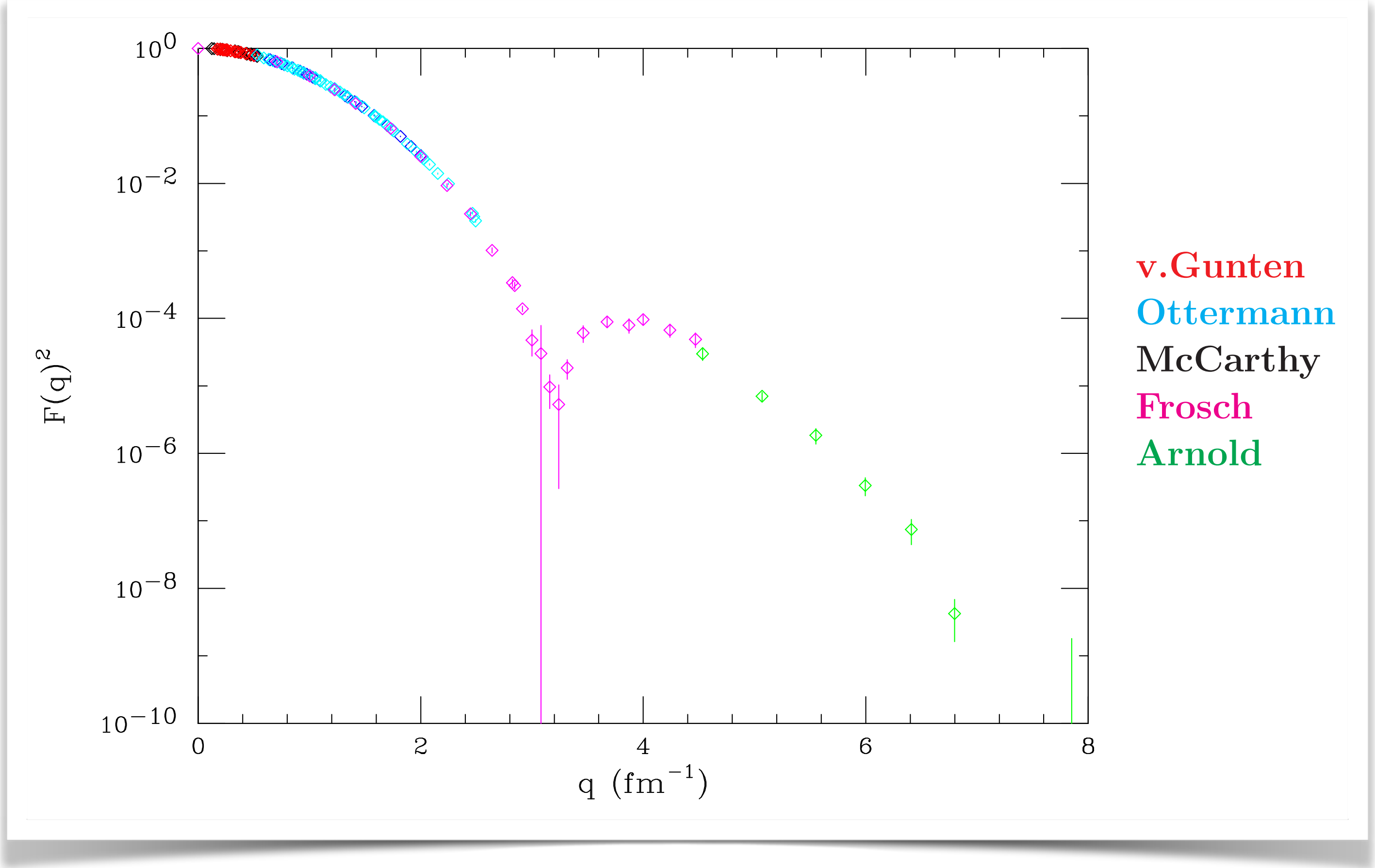
$$r_\alpha = -6\hbar^2 \frac{dF(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

Some proton information is used in this analysis

Residual correlation between proton and ^{4}He charge radii?

It is probably small but some expert could take a look

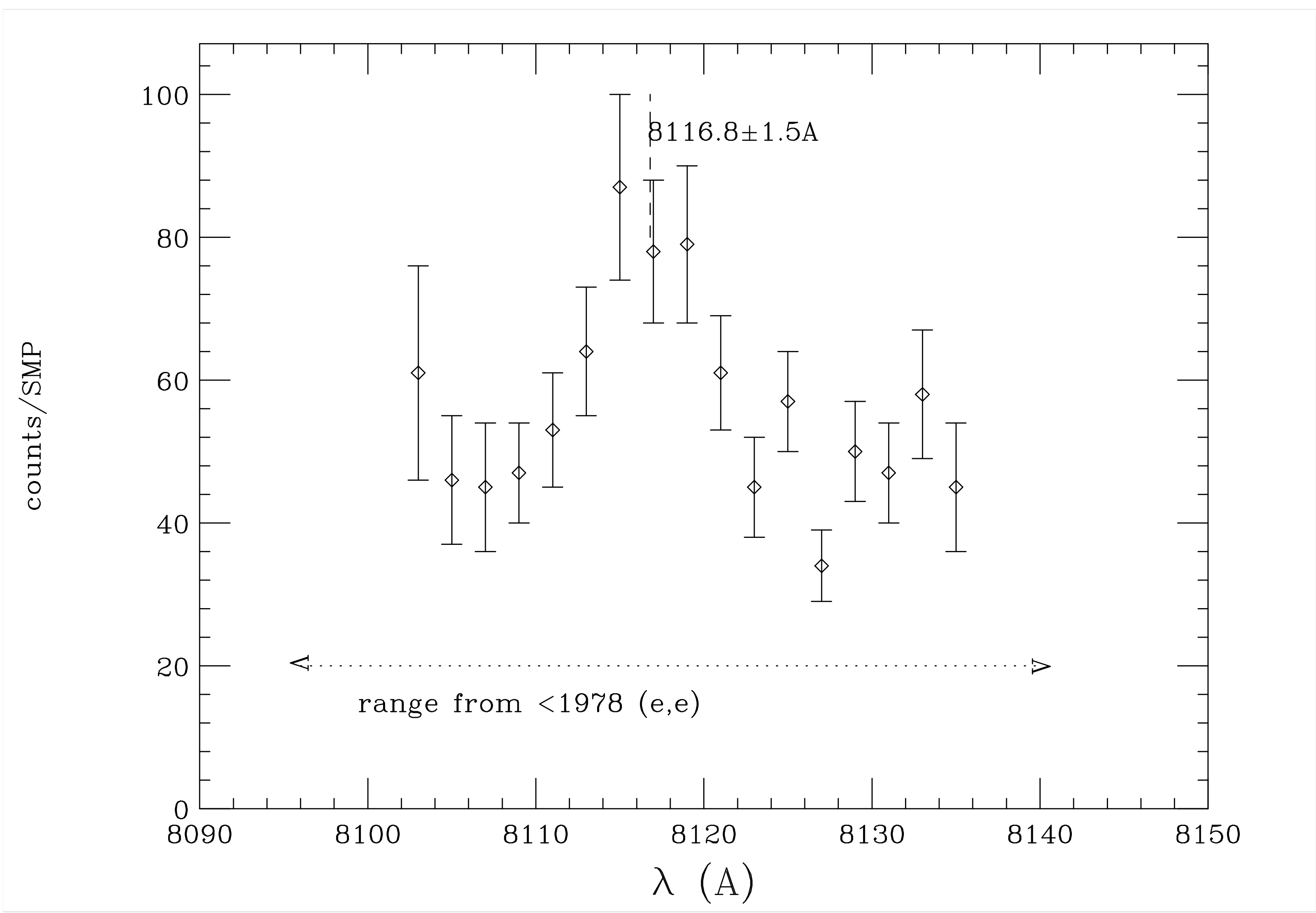
- The proton radius is needed to obtain the charge density at large-r from the proton wave function and point density
- Otterman et al., measured the cross-section ratio e-He/e-p. To obtain absolute e-He cross a modern fit of the e-p data has been used



For the 60+

The μ^4He^+ resonance measured at CERN (1978)

Nucl. Phys. A **278**, 381–386 (1977)
Phys. *Lett. B* **73**, 229–231 (1978)

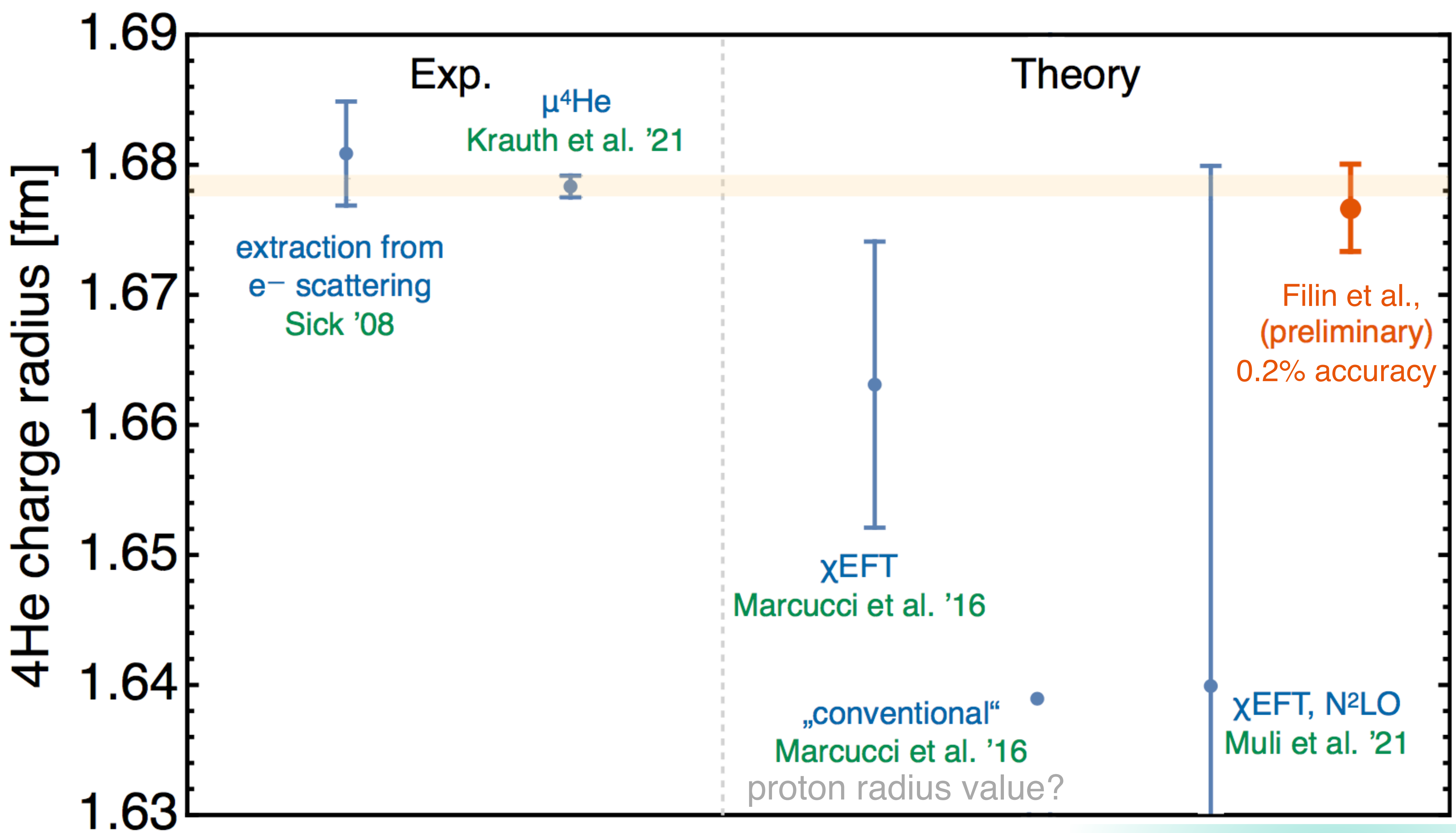


The obtained radius 1.673(1) fm is not far away from our value due to an awkward combination of wrong measurement and incomplete 2S-2P theory.

- 1/200 cases get peak of similar significance
- Peak found after peak-optimising cuts
- Measurement performed at a He pressure of 40 bar, our experiment at 0.002 bar

⇨ collisional quenching of 2S state (17 ps lifetime of the 2S state)

Radius as a benchmark for *ab initio* few-nucleon theories

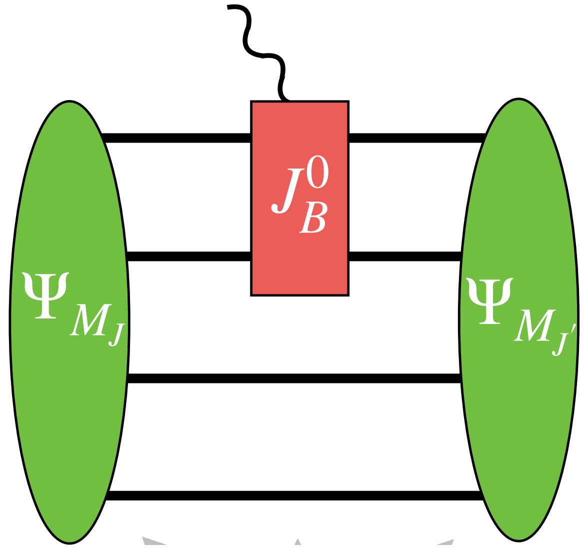


Plot from Filin

Towards consistent treatment of the nuclear structure: TPE and radii

Radius as benchmark for *ab initio* few-nucleon predictions

Filin

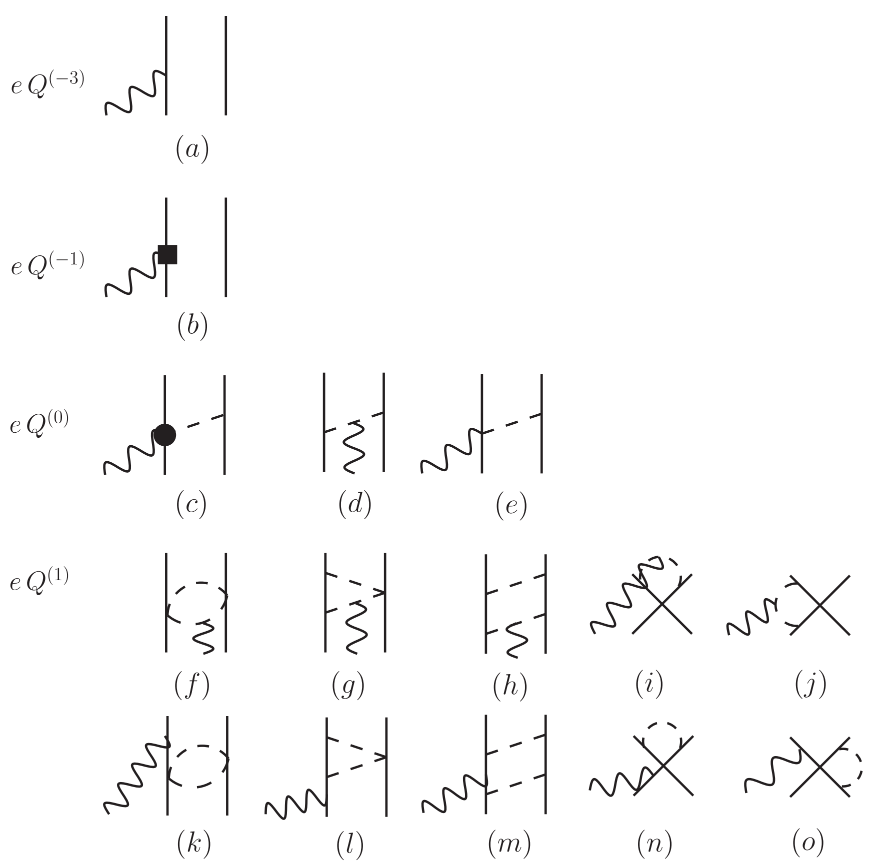


$$F_C(Q^2) = \frac{1}{2J+1}\sum_{M_J} < P', M_J | J_B^0 | P, M_J >$$

In Breit frame

$$r_C^2 = r_{str}^2 + \left(r_p^2 + \frac{3}{4m_p^2}\right) + \frac{A-Z}{Z} r_n^2$$

Current operator



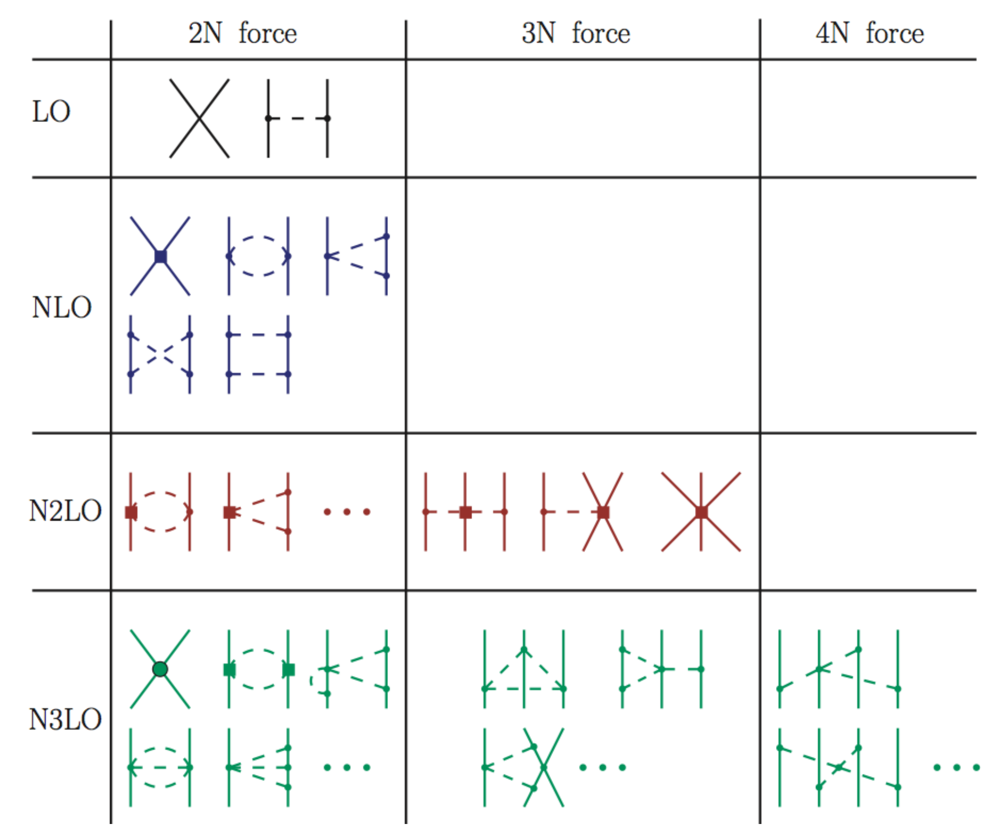
Li Muli

Consistent derivation and regularization of many body forces and nuclear current operators + Rel. Dynamics+ isospin breaking+…

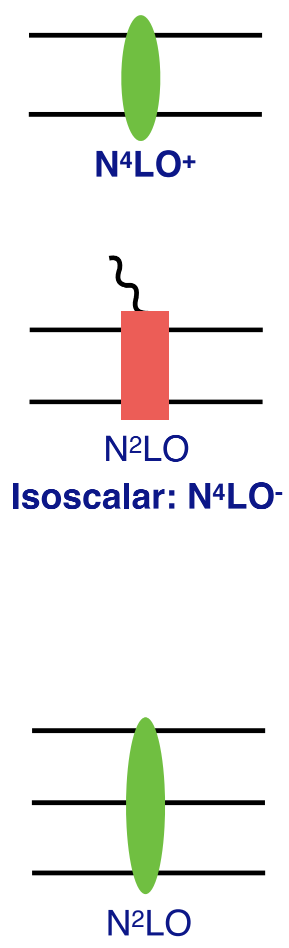
Bochum gruop: Epelbaum

Mainz gruop: Bacca

Nuclear forces



Consistent treatment



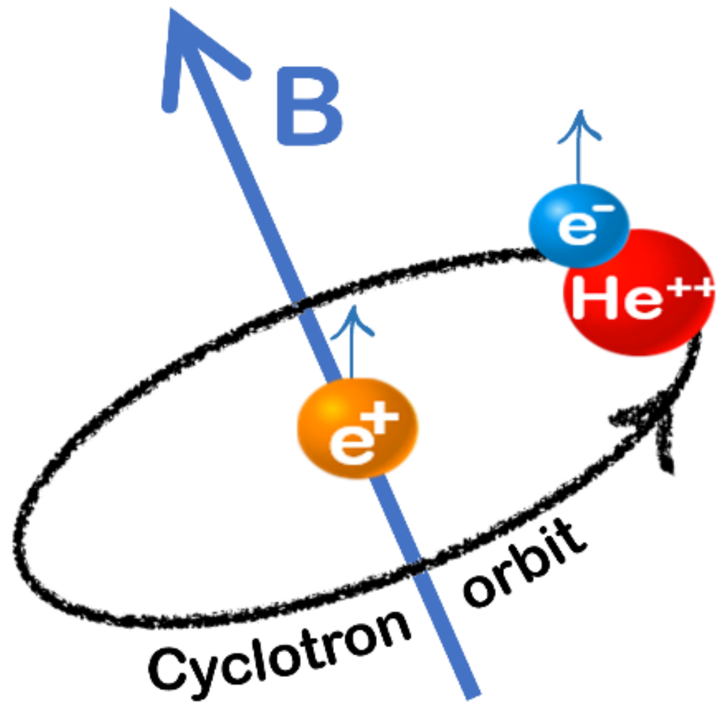
Taken from Filin

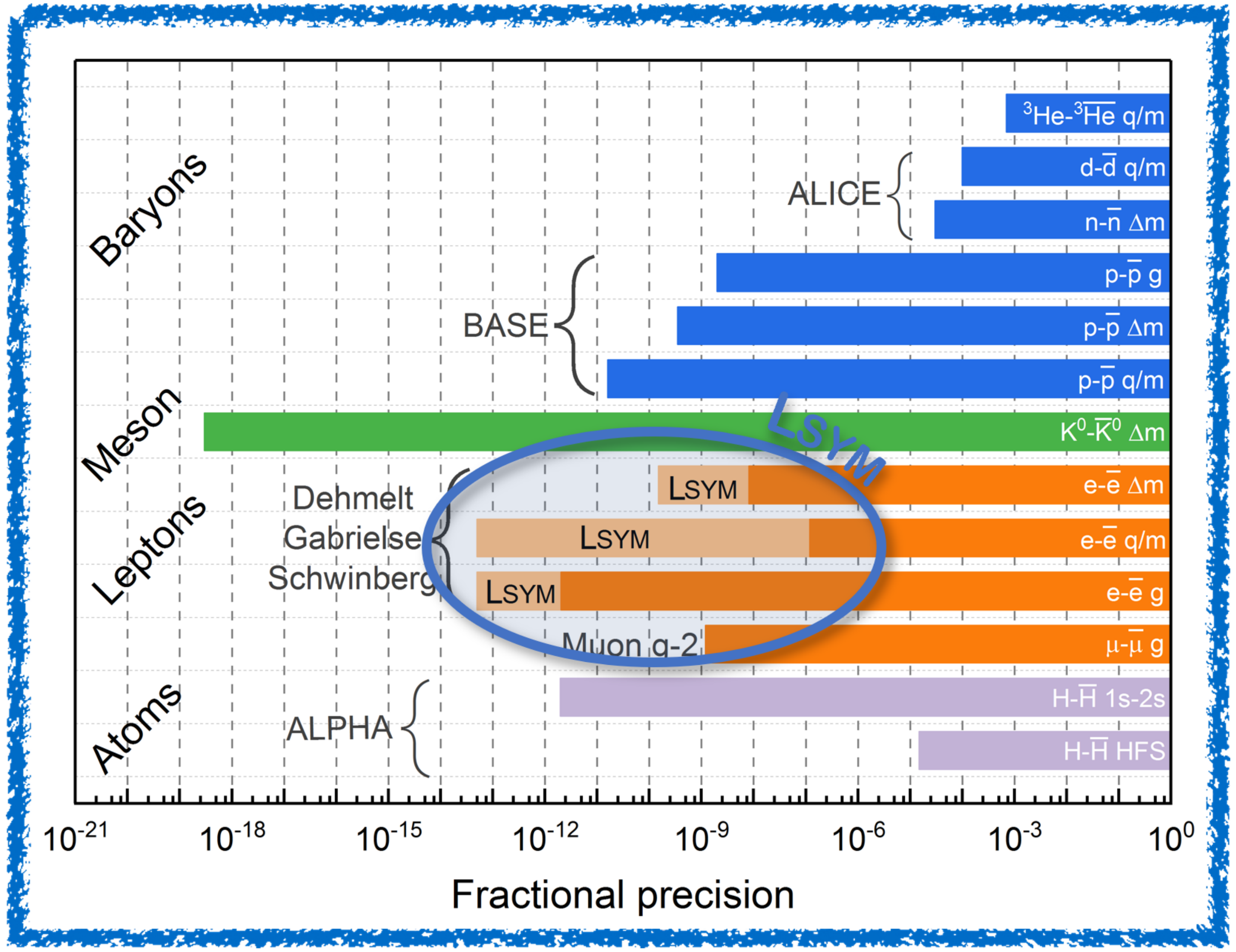
- Advances in the consistent derivation and regularization of the NN and NNN forces. Various optimisation schemes used to define the LEC
- Consistent derivation and regularization of many body forces and nuclear current operators.
- Effort to include the relativistic dynamics of the nucleons ongoing
- Significant advances in uncertainty estimation: EFT, Bayesian approaches, etc

H. Krebs, EPJA 56 (2020) 240
Reinert et al. PRL 126, 092501 (2021)
E. Epelbaum, H. Krebs, and P. Reinert, arXiv:2206.07072.
P. Maris et al., PRC **106**, 064002 (2022)
H.-W. Hammer et al., REVIEWS OF MODERN PHYSICS, 92, (2020)
Ekström et al., Phys. Rev. C **91**, 051301(R) (2015)
Lynn et al., A 2017 *Phys. Rev.* C **96** 0540 (2017)
Li Muli et al., J. Phys. G: Nucl. Part. Phys. **49** 105101 (2022)

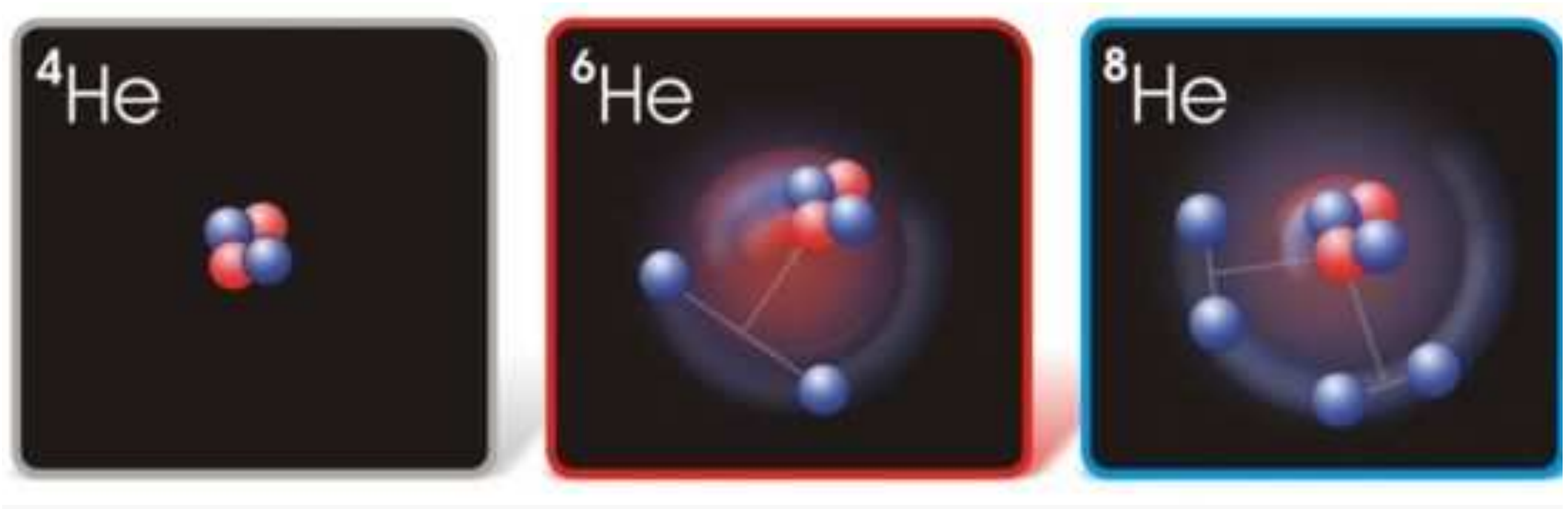
CPT tests (Lsym-project)

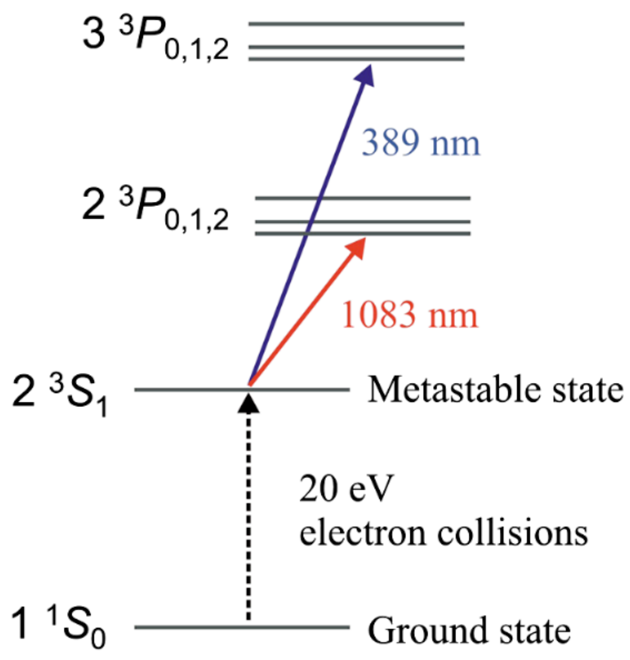
S. Sturm





He charge radius and He structure needed to advance CPT tests





Measured — Measured — Mass shift — Field shift

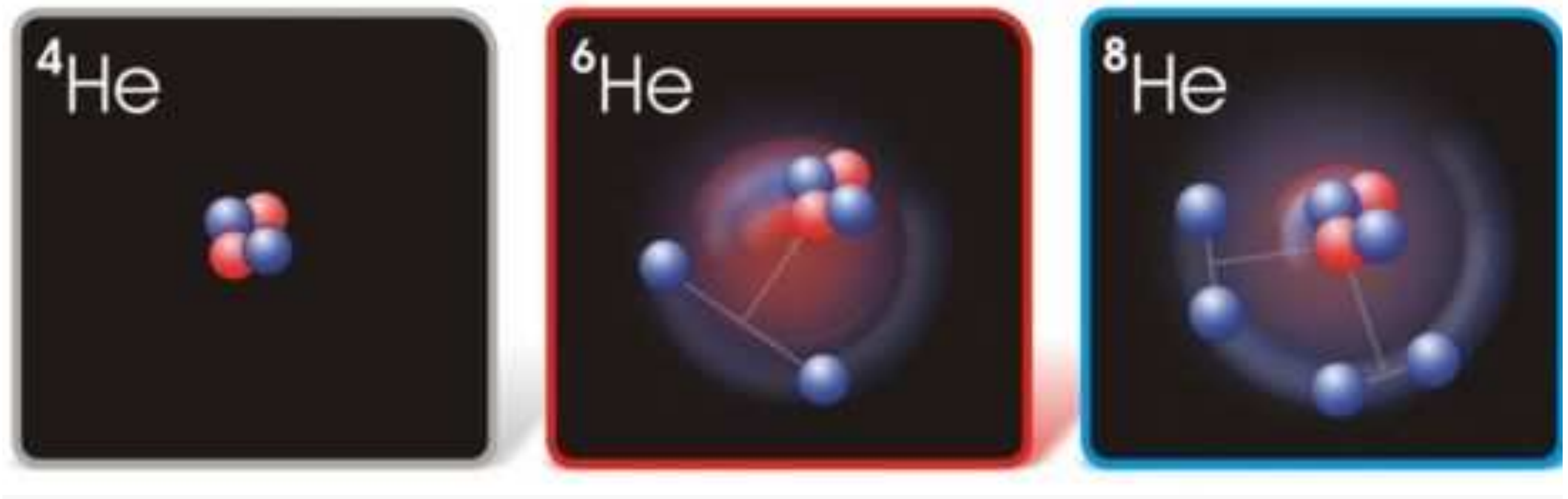
$$\nu(^A\mathrm{He}) - \nu(^4\mathrm{He}) = \Delta\nu_{\mathrm{mass}} + k(r^2_{^A\mathrm{He}} - r^2_\alpha)$$

anchor point:
r_α from μHe^+

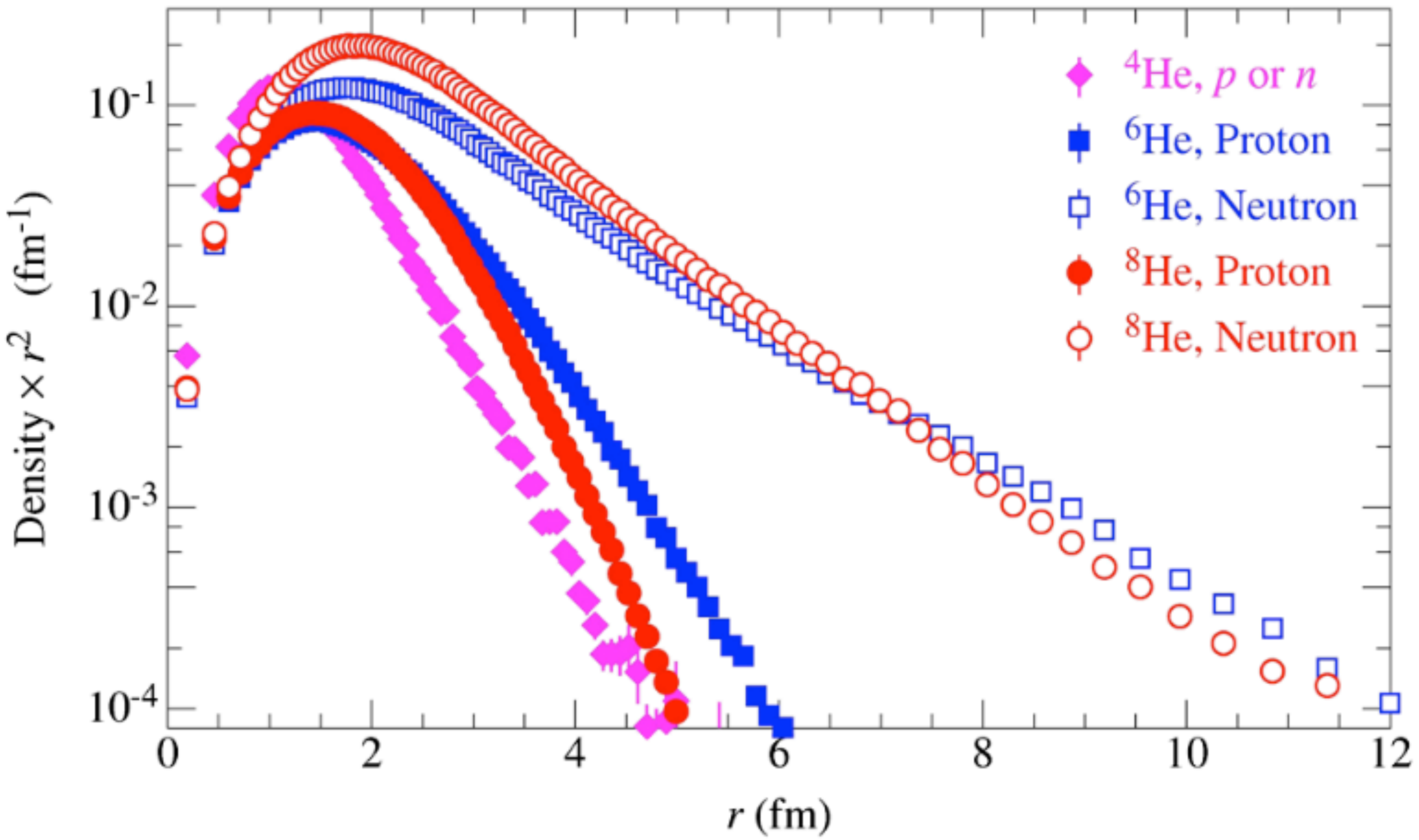
$$r(^6\mathrm{He}) = 2.0571\,(7)_{r_\alpha}\;(\;\;75)_{\mathrm{iso}}\;\mathrm{fm}$$
$$r(^8\mathrm{He}) = 1.9559\,(7)_{r_\alpha}\;(158)_{\mathrm{iso}}\;\mathrm{fm},$$

RMP 85 1383 (2013)

^{6}He and ^{8}He halo nuclei



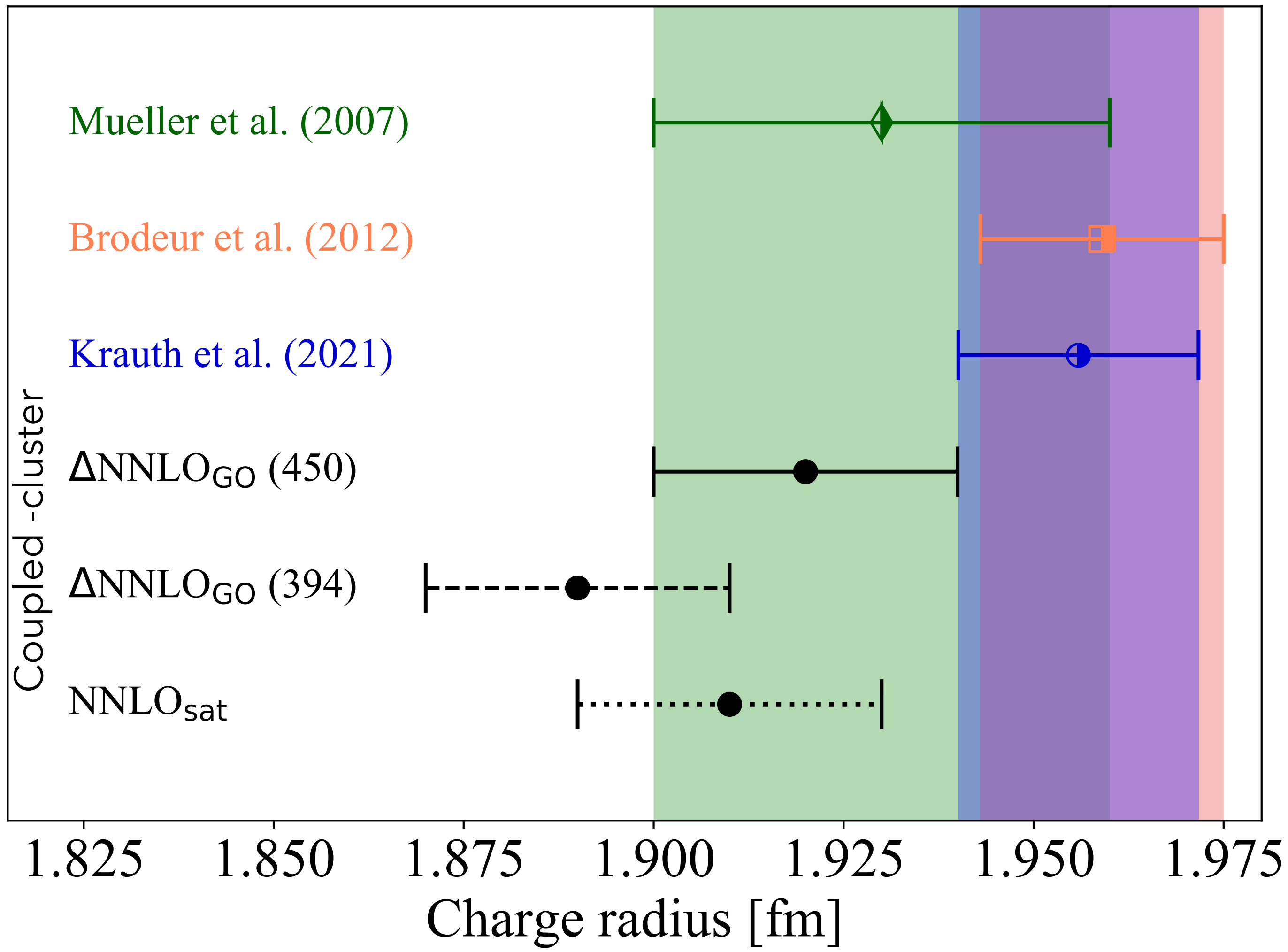
RMP 85 1383 (2013)



- Large matter radius and small neutron separation energy
- The size of the core can be associated to the rms charge radius. Its swelling results from polarisation effects due to the strong interaction

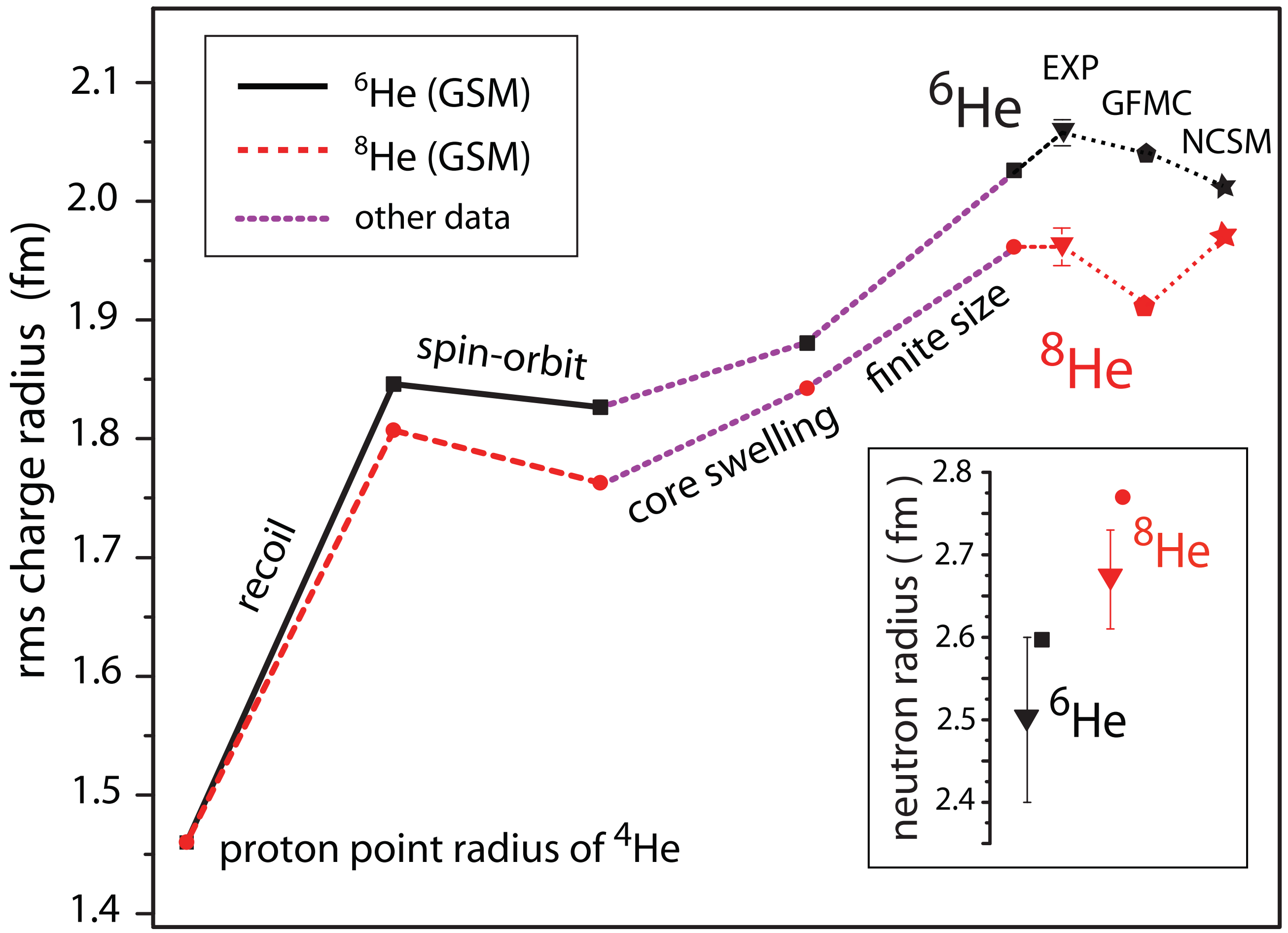
Comparison theory-experiment for 8He and 6He charge radii

F. Bonaiti et al., PRC **105**, 034313 (2022)

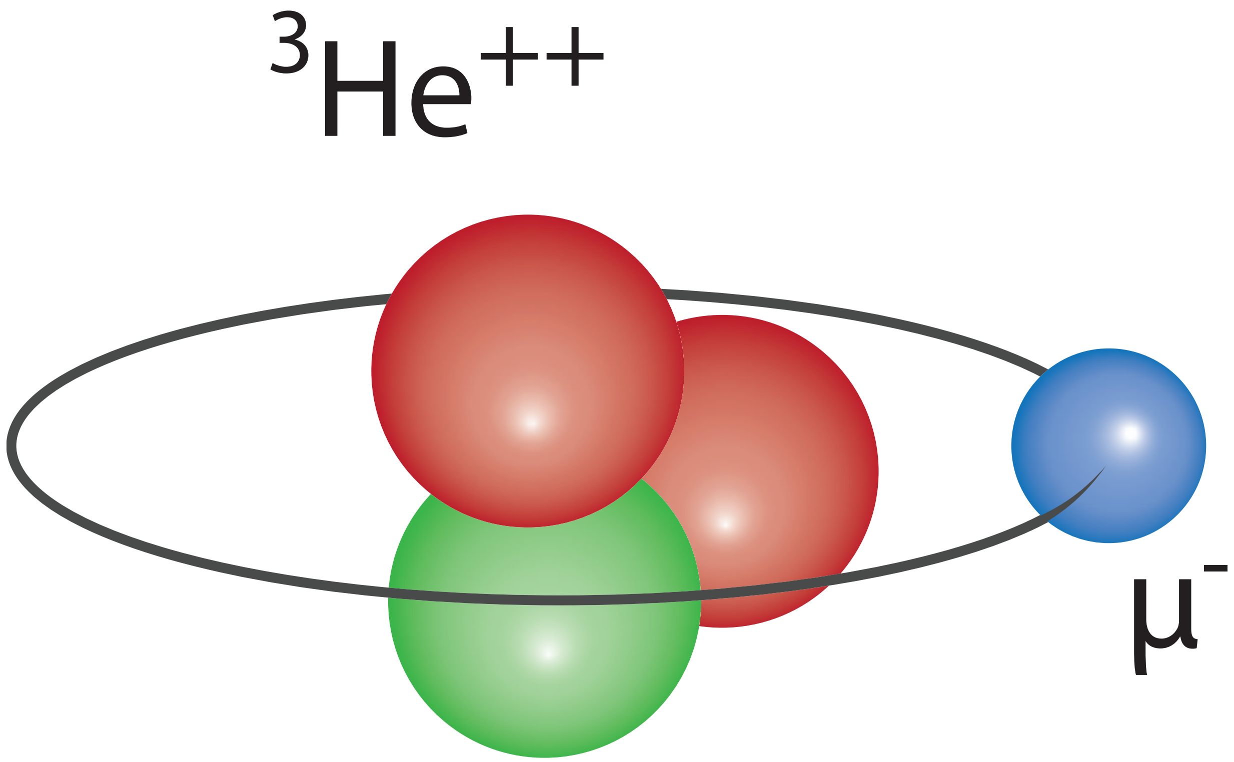


$$\langle R^2_{\mathrm{ch}}\rangle = \langle R^2_{pp}\rangle + R^2_p + \frac{N}{Z}R^2_n + \frac{3}{4M_p^2} + R^2_{\mathrm{SO}},$$

G. Papadimitriou, PRC **84**, 051304(R) (2011)

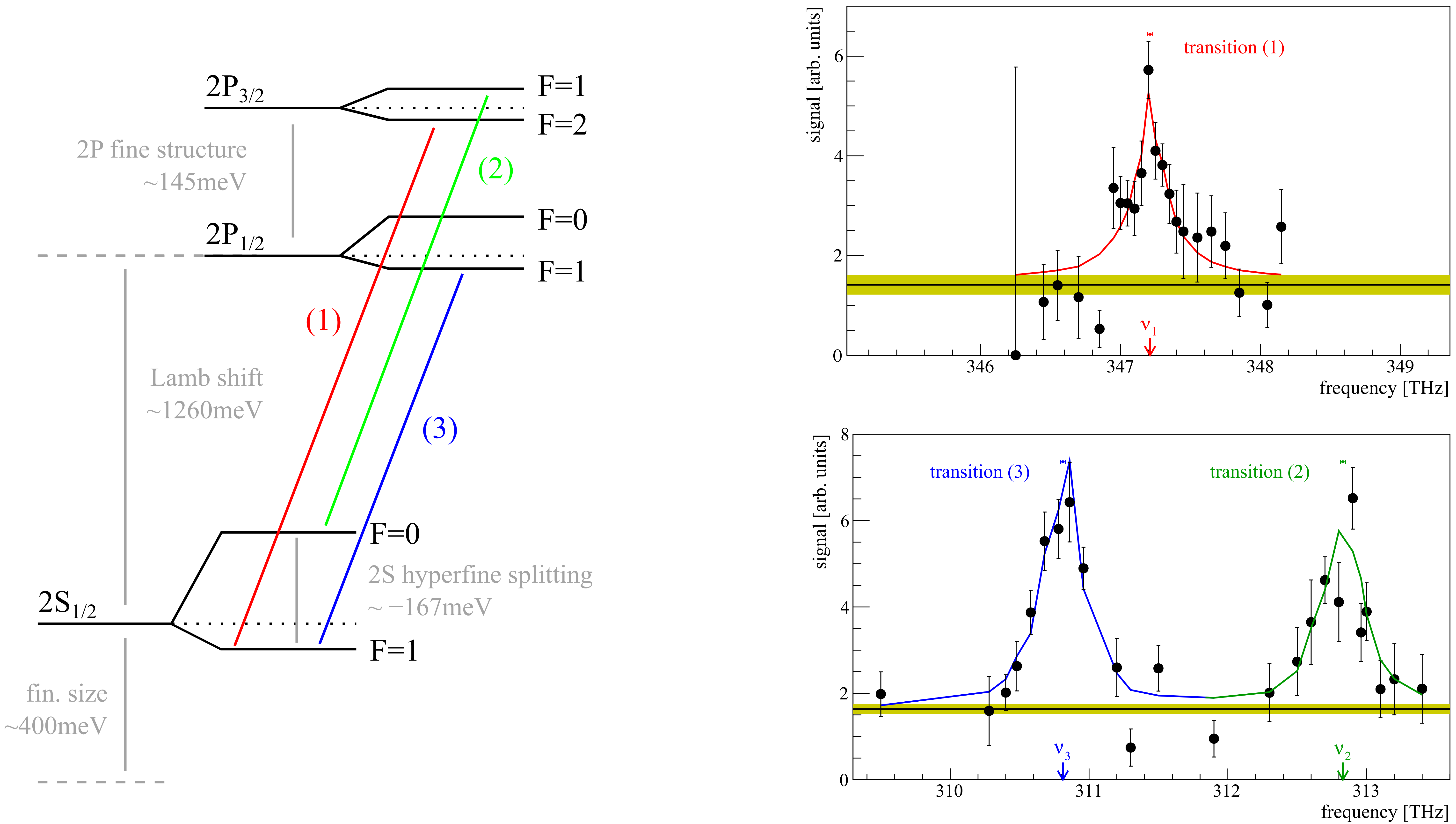


The *ab initio* GFMC calculations predict a 4.58% and 6.66% increase of the α-particle proton point radius in ^{6}He and ^{8}He, respectively

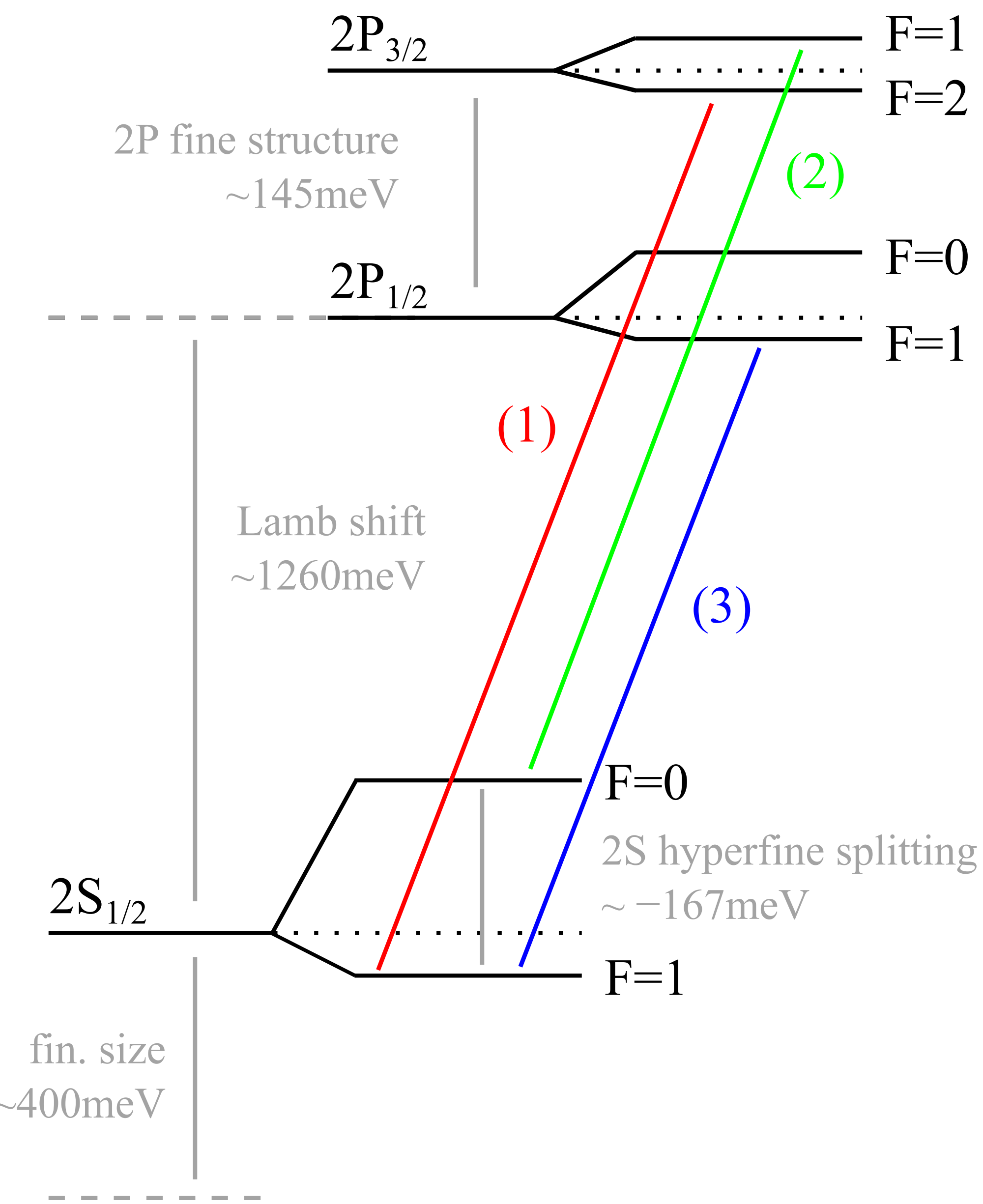


Schuhmann et al., arXiv 2305.11679

The measured transitions



The measured transitions between fine and hyperfine sub-levels



For laser physics

$$\nu_{\text{exp}}^{(1)} = 347.212(20)^{\text{stat}}(1)^{\text{sys}}\ \text{THz}$$

$$\nu_{\text{exp}}^{(2)} = 312.830(21)^{\text{stat}}(1)^{\text{sys}}\ \text{THz}$$

$$\nu_{\text{exp}}^{(3)} = 310.814(20)^{\text{stat}}(1)^{\text{sys}}\ \text{THz}$$

Statistical unc. $\gg$ Systematic

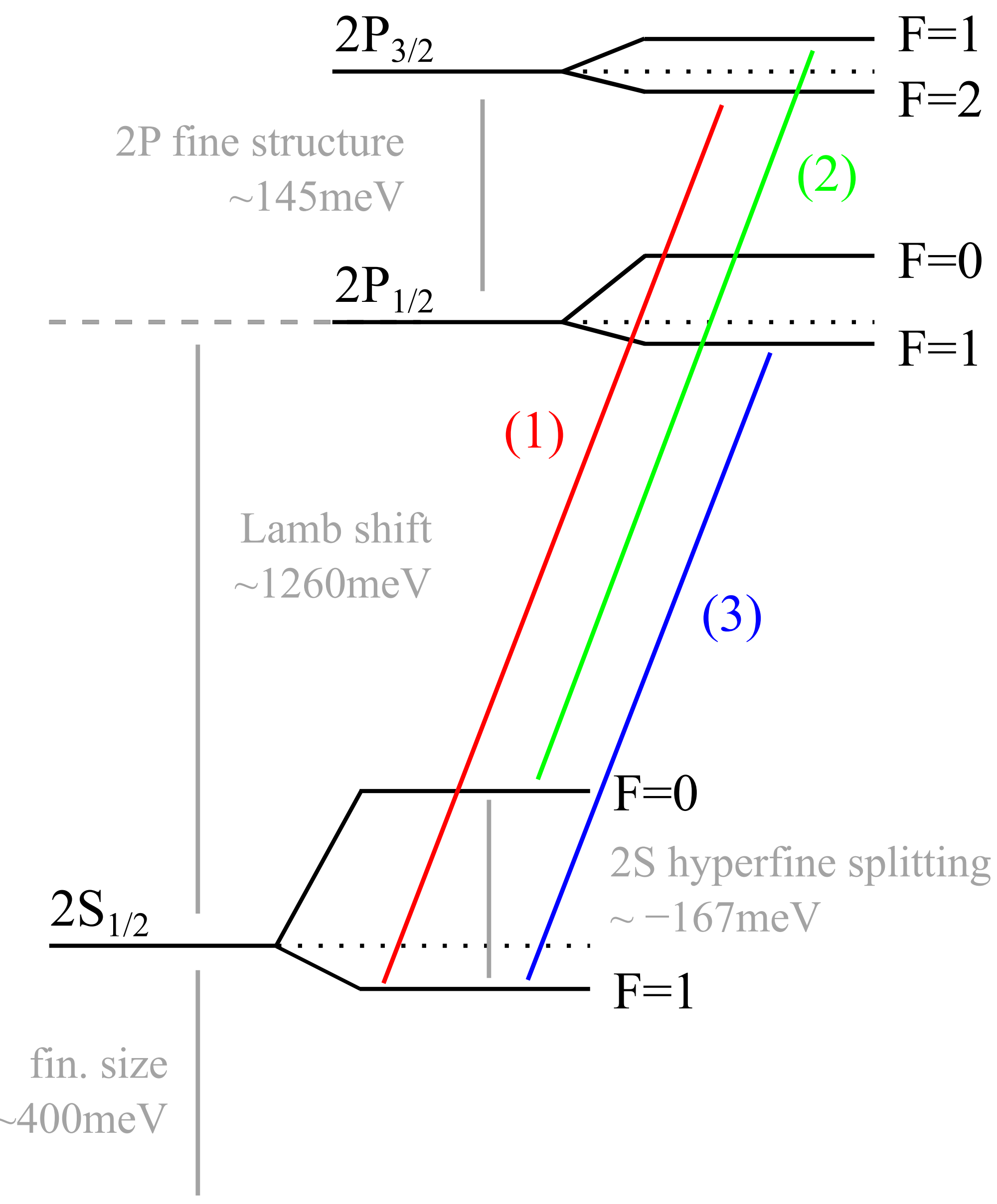
For theorist

$$\Delta E_{\text{exp}}^{(1)} = 1435.951(81)\ \text{meV}$$

$$\Delta E_{\text{exp}}^{(2)} = 1293.759(86)\ \text{meV}$$

$$\Delta E_{\text{exp}}^{(3)} = 1285.425(81)\ \text{meV}$$

From the measured transitions to the quantities of interest



Paying attention at the various definitions of the Lamb shift and centroid positions....

$$\Delta E^{(1)}_{\text{exp}} = E_{\text{LS}} - \frac{1}{4}E_{\text{HFS}} + E_{\text{FS}} - 9.23945(26)\ \text{meV}$$

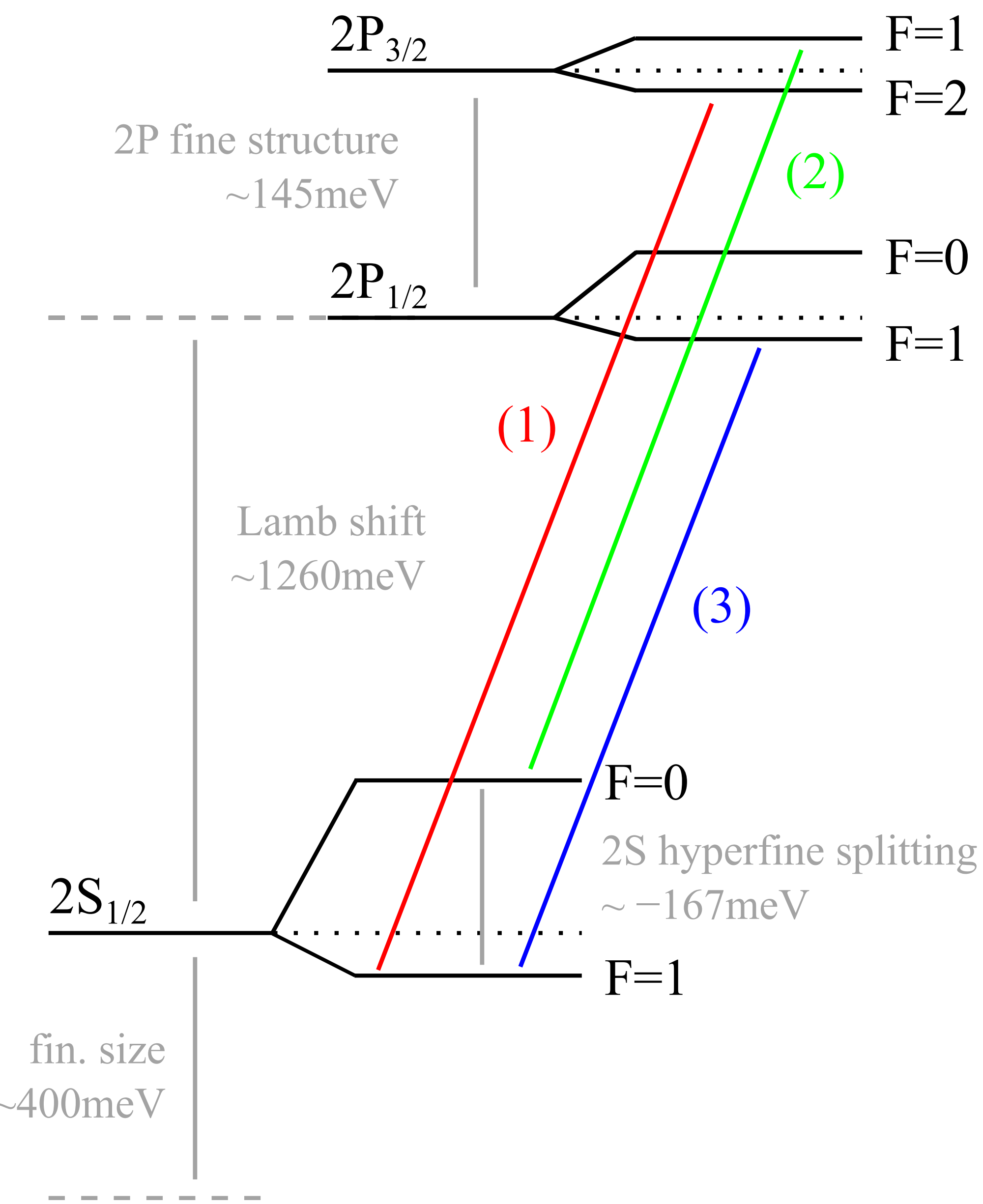
$$\Delta E^{(2)}_{\text{exp}} = E_{\text{LS}} + \frac{3}{4}E_{\text{HFS}} + E_{\text{FS}} + 15.05305(44)\ \text{meV}$$

$$\Delta E^{(3)}_{\text{exp}} = E_{\text{LS}} - \frac{1}{4}E_{\text{HFS}} - 14.80851(18)\ \text{meV}$$

2P hyperfine theory

Karshenboim, et al.
PRA 96, 022505 (2017).

Lamb shift, 2S-hyperfine splitting, 2P fine splitting



Extracted quantities

$$E_{\mathrm{LS}}^{\mathrm{exp}} = 1258.612(\ 86)\,\mathrm{meV}$$
$$E_{\mathrm{HFS}}^{\mathrm{exp}} = -166.485(118)\,\mathrm{meV}$$
$$E_{\mathrm{FS}}^{\mathrm{exp}} = 144.958(114)\,\mathrm{meV}.$$

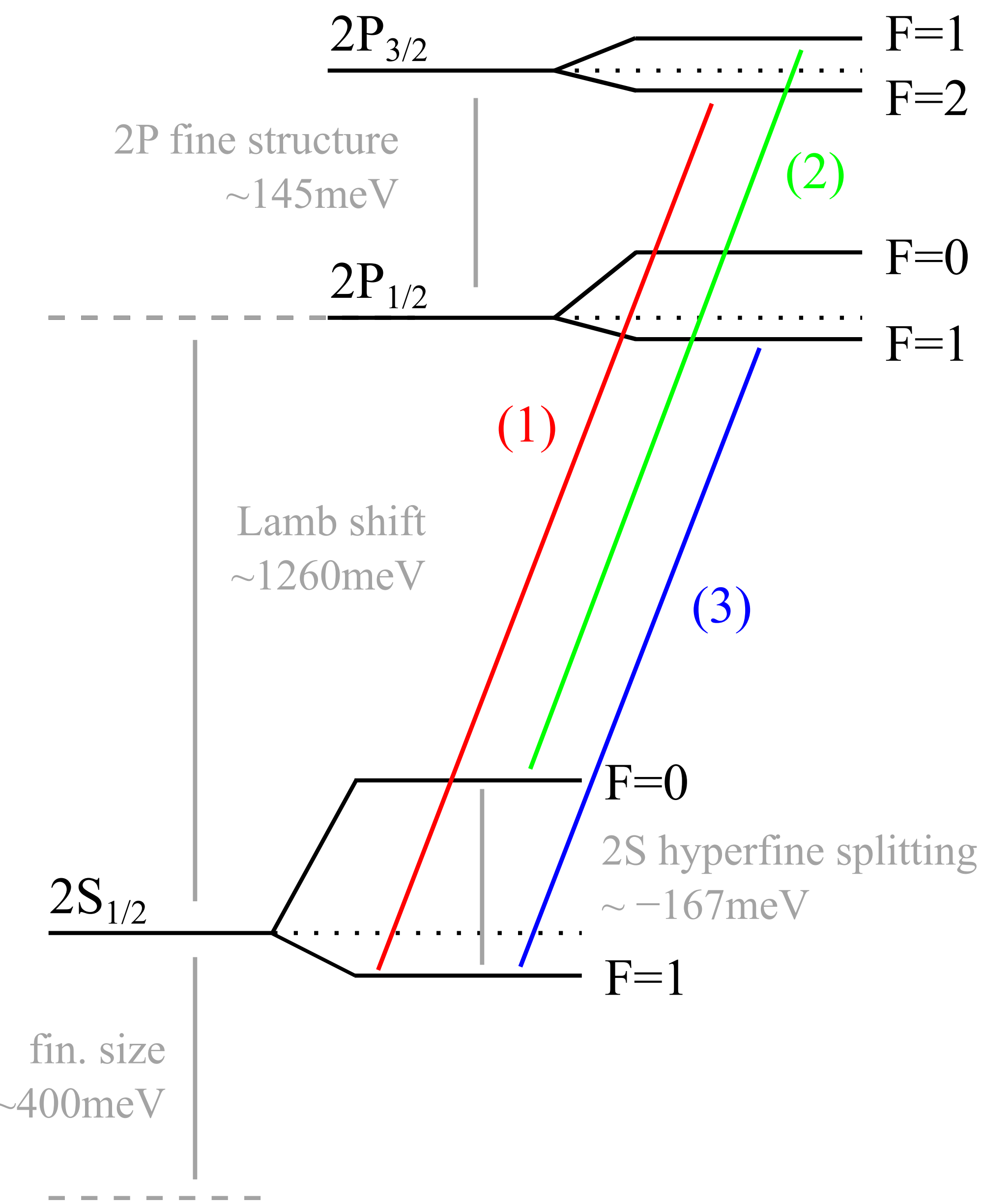
$$E_{\mathrm{FS}}^{\mathrm{th}} = 144.979(5)\ \mathrm{meV}$$

Karshenboim, et al.
PRA 96, 022505 (2017).

Agreement
th-exp

Consistency check

Lamb shift and 2S-hyperfine splitting



Use theory for the 2P fine and hyperfine splittings

$$\Delta E^{(1)}_{\rm exp} = E_{\rm LS} - \frac{1}{4}E_{\rm HFS} + E_{\rm FS} - 9.23945(26)\ \text{meV}$$

$$\Delta E^{(2)}_{\rm exp} = E_{\rm LS} + \frac{3}{4}E_{\rm HFS} + E_{\rm FS} + 15.05305(44)\ \text{meV}$$

$$\Delta E^{(3)}_{\rm exp} = E_{\rm LS} - \frac{1}{4}E_{\rm HFS} - 14.80851(18)\ \text{meV}$$

Improve on the Lamb shift and the 2S-hyperfine splitting

$$E^{\rm exp}_{\rm LS} = 1258.598(\ 48)^{\rm exp}(3)^{\rm theo}\ \text{meV}$$

$$E^{\rm exp}_{\rm HFS} = -166.496(104)^{\rm exp}(3)^{\rm theo}\ \text{meV}\,.$$

The helion charge radius

QED | Finite size | nucl. str.

Theory

$$E_{LS}^{th} = 1644.348(8) - 103.383\, r_h^2 + 15.499(378)\ \text{meV}$$

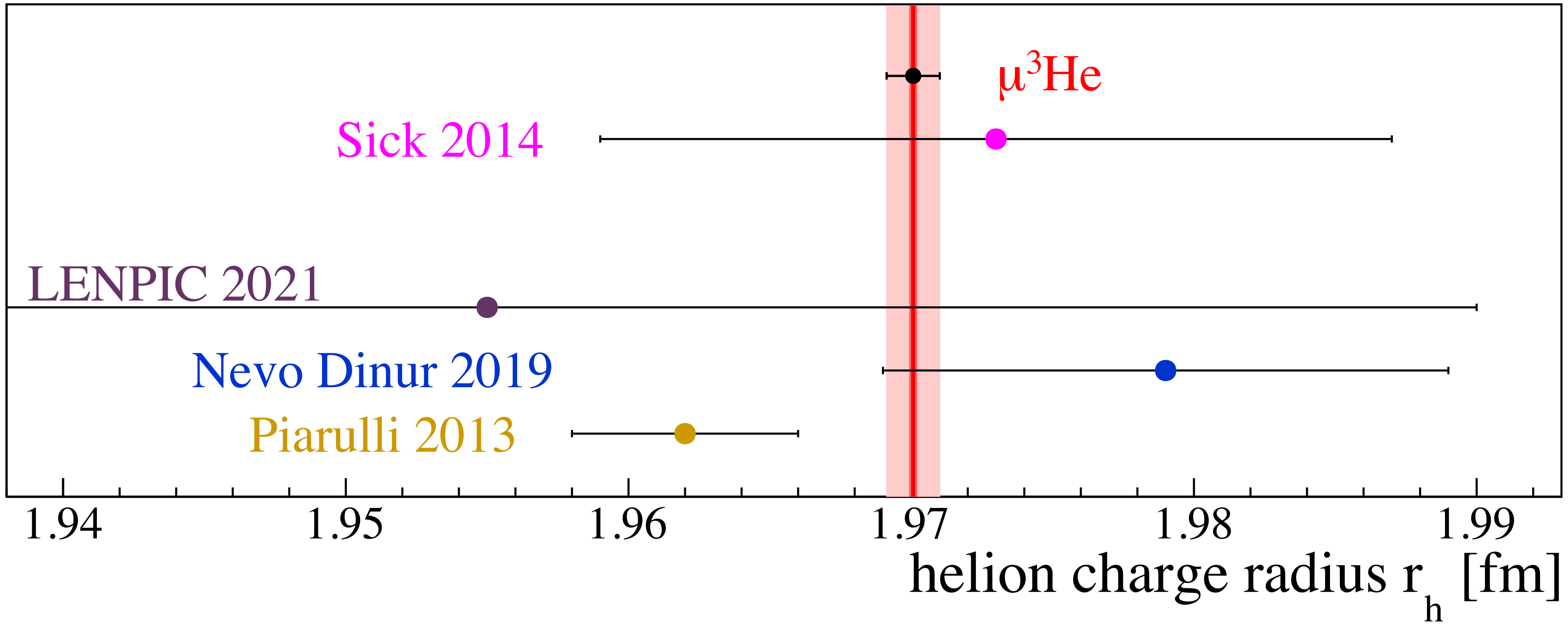
Pachucki et al., arXiv:2212.13782

Experiment

$$E_{LS}^{exp} = 1258.598\,(48)^{exp}(3)^{theo}\ \text{meV}$$

Schuhmann et al., arXiv 2305.11679

$$r_h = 1.97007\,(12)^{exp}(93)^{theo}\ \text{fm} = 1.97007(94)\ \text{fm}\,.$$

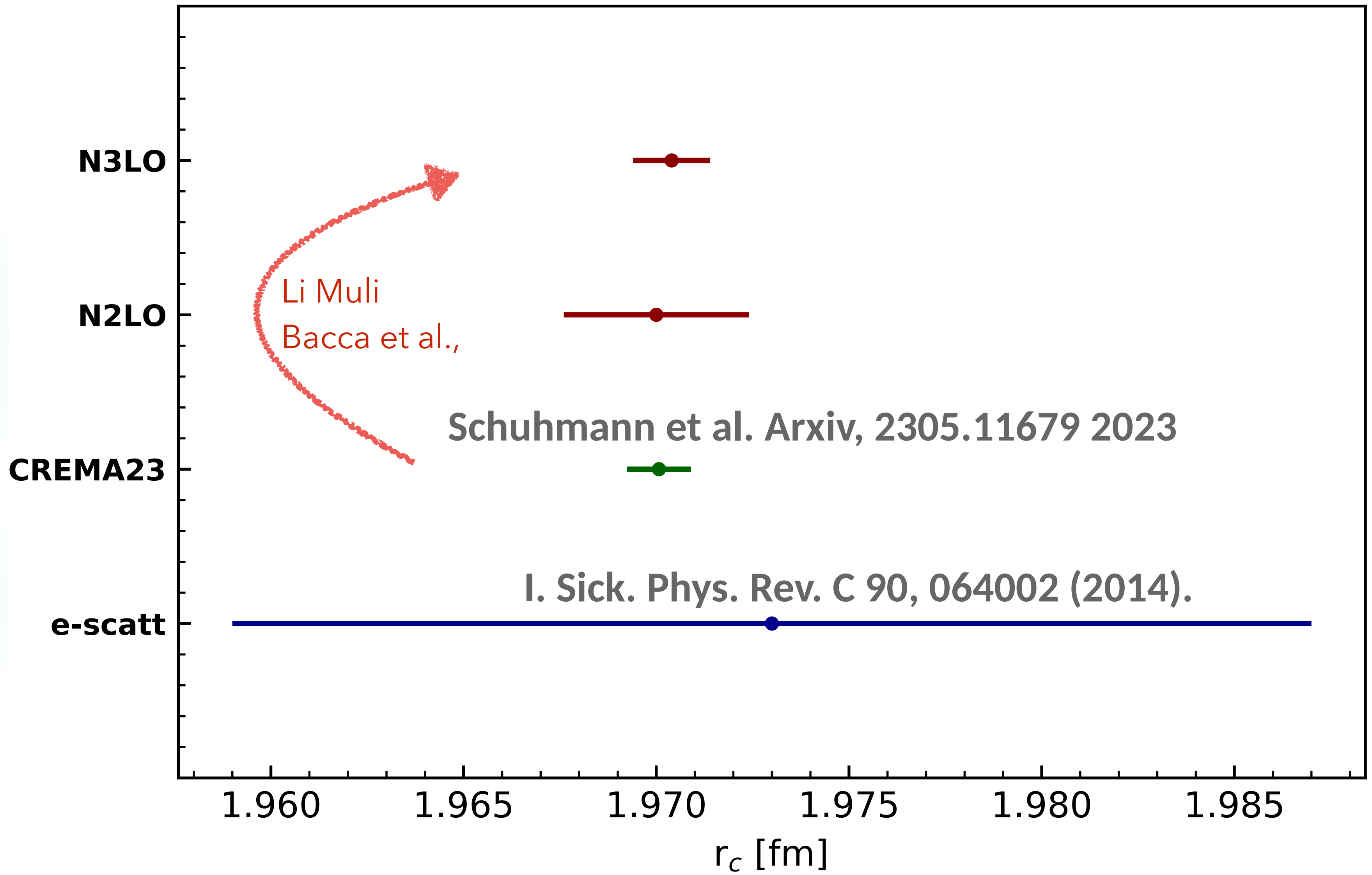


I have a personal complaint

S.S.LM, et al. In preparation for 2023

The error bars will slighlty increase in next future

But they will decrease in next-to-next future

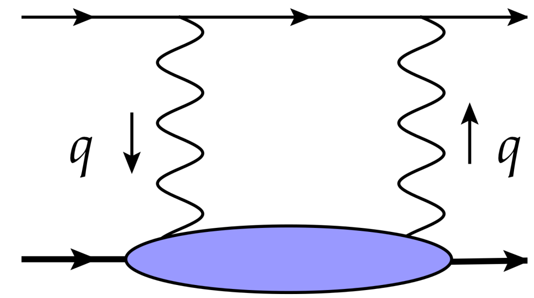


Not yet published and already corrected

Two ways to the two-photon exchange

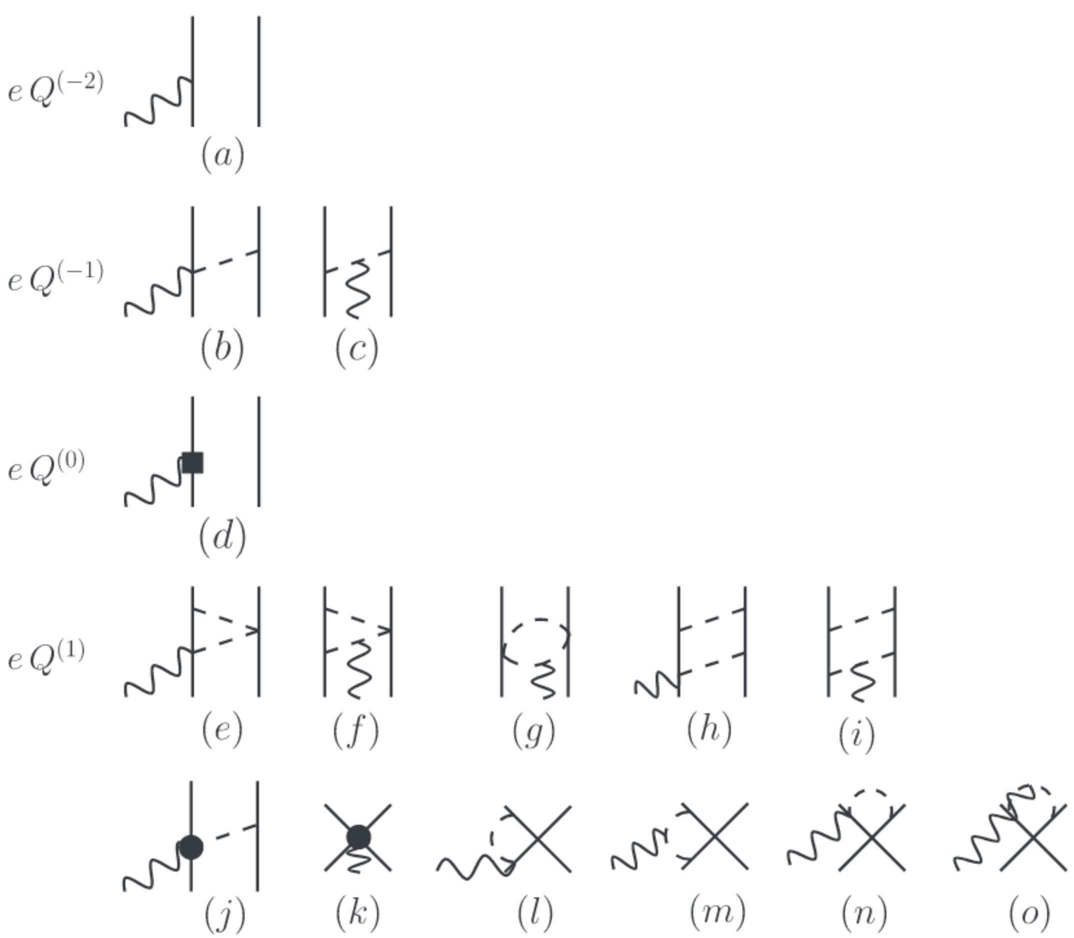
Dinur, Ji, Barnea,
Bacca, Hernandez, Li Muli …

few-nucleon ab initio theory
with chiral-inspired potentials



Dispersion relation
and data

Carlson, Gorchtein,
Vanderhaeghen



Agreement

For μ^3He

Dispersion:	15.14 (49) meV
Few-nucleon th.:	16.38 (31) meV

Another benchmark for nuclear theories: 2S HFS

Fermi+QED | nucl. str.

Theory

$$E^{\text{th}}_{\text{HFS}} = -\,172.7457(89)\ \text{meV} + E^{\text{nucl.struct.}}_{\text{HFS}}$$

Franke et al., EPJD 71, 341 (2017).

Experiment

$$E^{\text{exp}}_{\text{HFS}} = -\,166.496(104)^{\text{exp}}(3)^{\text{theo}}\ \text{meV}$$

Schuhmann et al., arXiv 2305.11679

Nuclear structure contribution (2PE+…)

$$E^{\text{nucl.struct.}}_{2S-\text{HFS}} = 6.25(10)\ \text{meV}$$

$$\Delta E^{\text{Zemach}}_{2\text{PE}} = 6.53(4)\ \text{meV}$$

using $r_Z = 2.528(16)$ fm   Sick. PRC 90, 064002 (2014).

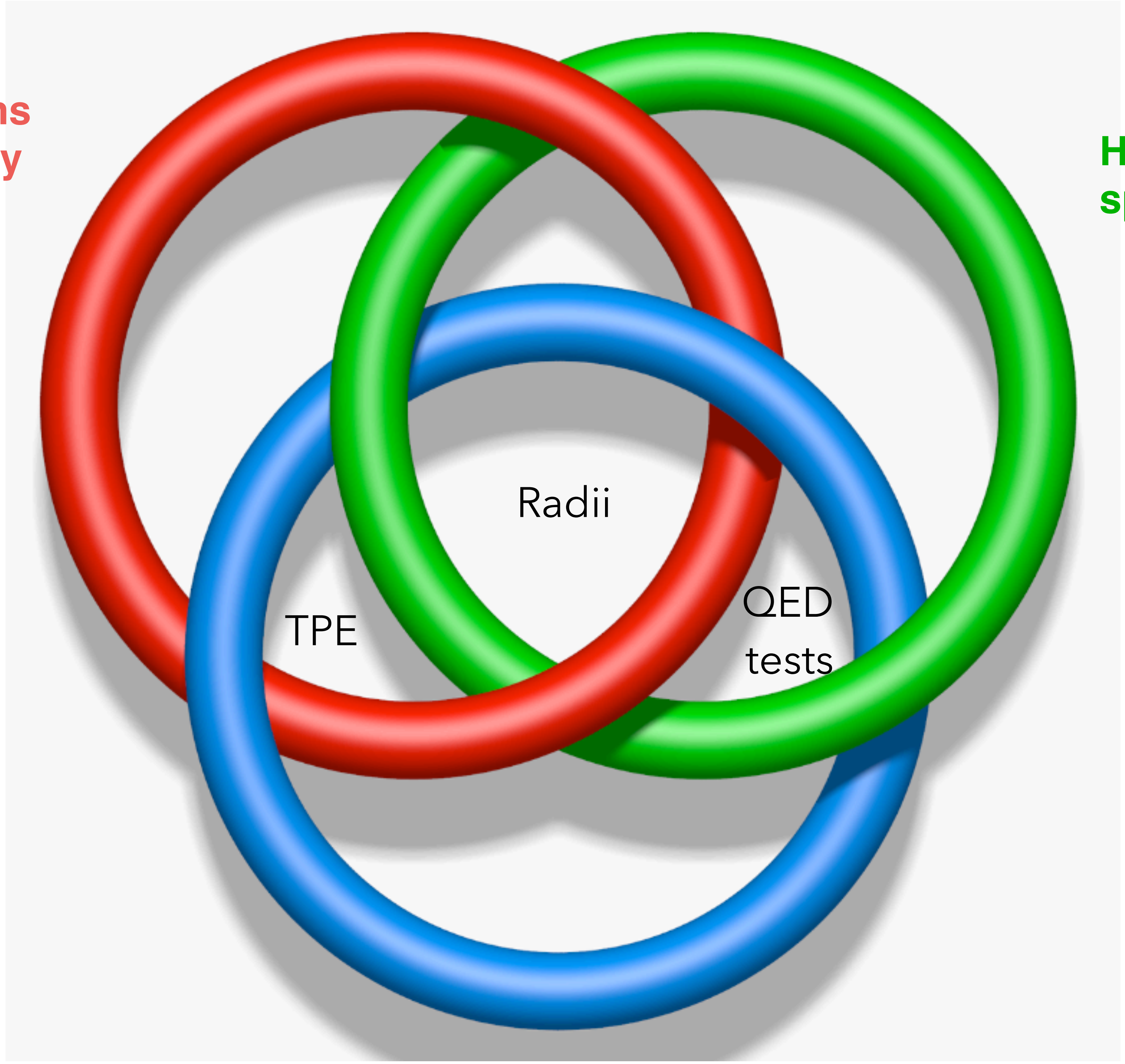
No theory predictions exists to date for the inelastic part

Compare with μD HFS

Kalinowski, Pachucki

Muonic atoms spectroscopy

High-precision laser spectroscopy in He and He^+



Nuclear and hadron theories

The hydrogen-like He^+

Karshenboim et al., PLB795:432(2019)
Yerokhin et al., *Ann.Phys.*531(5):1800324(2019)

Theory sensitive to higher order contributions

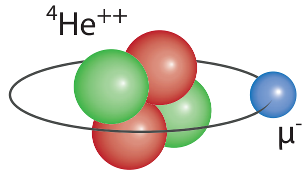
$$f_{2S-1S}(\mathrm{He}^+) \approx \frac{3Z^2 c R_\infty}{4}\,\frac{1}{1+\frac{m_e}{M_\alpha}} + \mathrm{QED}_{\mathrm{He}^+}\left(Z^{3.7}, Z^{5\ldots7}\right) - \frac{7(Z\alpha)c^4}{24\pi\, a_B^3\, \hbar^3}\, r_\alpha^2 + \mathrm{nucl.struct.}$$

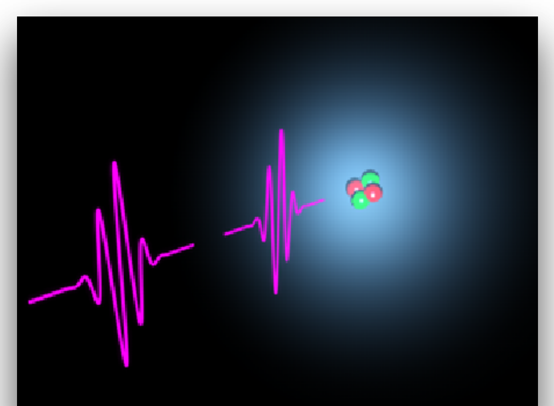
Uncertainty	$(1\,\mathrm{kHz})$	$(9\,\mathrm{kHz})$	$(40\,\mathrm{kHz})$	$(61\,\mathrm{kHz})$	$(3\,\mathrm{kHz})$

Prospected experimental accuracy $u_r = 1 \times 10^{-13}$

Using R_∞ from H+μH

Using r_α from $\mu^4\mathrm{He}^+$





Moreno, et al. EPJD 77, 67 (2023).
Krauth et al. PoS FFK2019, 49 (2019).

Pachucki et al., arXiv:2212.13782 90 kHz
Li Muli, Bacca (in preparation) >90 kHz

Combining $\mu^4\mathrm{He}^+$ with He+

μH + H

He+

$$E_{1S-2S}(\mathrm{He}^+) \approx \frac{3}{4} Z^2 R_\infty + \mathrm{QED}^*(Z^{3.7}, Z^{5...7}) + k' Z^4 r_\alpha^2$$

Determine

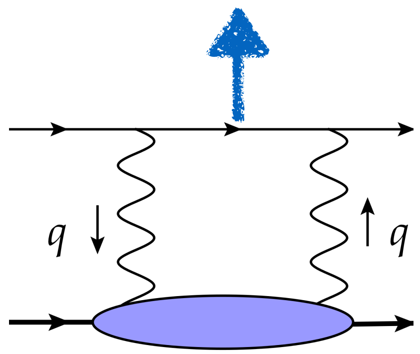
r_α

$\delta \sim 5 \cdot 10^{-4}$

muonic He+

$$E_{2S-2P}(\mu^4\mathrm{He}^+) \approx \mathrm{QED} + k'' r_\alpha^2 + \mathrm{NS}$$

Consistency check



$+3\mathrm{PE}$

Combining $\mu^4\mathrm{He}^+$ with He+

μH + H

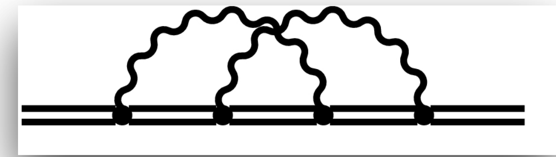
He+

$$E_{1S-2S}(\mathrm{He}^+) \approx \frac{3}{4} Z^2 R_\infty + \mathrm{QED}^*(Z^{3.7}, Z^{5\ldots7}) + k' Z^4 r_\alpha^2$$

Test Bound-state QED

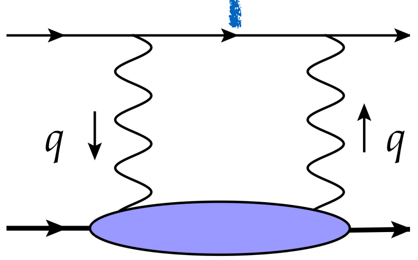
$\delta \sim 5 \cdot 10^{-12}$

Sensitive to interesting higher-order corrections



muonic He+

$$E_{2S-2P}(\mu^4\mathrm{He}^+) \approx \mathrm{QED} + k'' r_\alpha^2 + \mathrm{NS}$$



$+3\mathrm{PE}$

μH + H

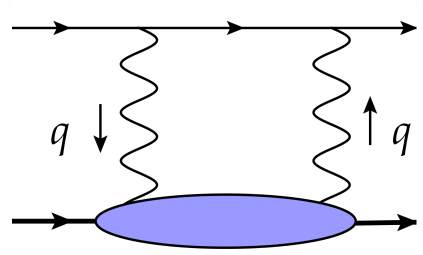
He+

$$E_{1S-2S}(\mathrm{He}^+) \approx \frac{3}{4} Z^2 R_\infty + \mathrm{QED}^*(Z^{3.7}, Z^{5...7}) + k' Z^4 r_\alpha^2$$

muonic He+

$$E_{2S-2P}(\mu\,^4\mathrm{He}^+) \approx \mathrm{QED} + k'' r_\alpha^2 + \mathrm{NS}$$

Benchmark for 2PE+3PE

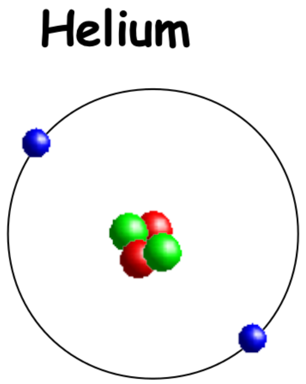


$+3\mathrm{PE}$

$\delta \sim 1 \cdot 10^{-2}$

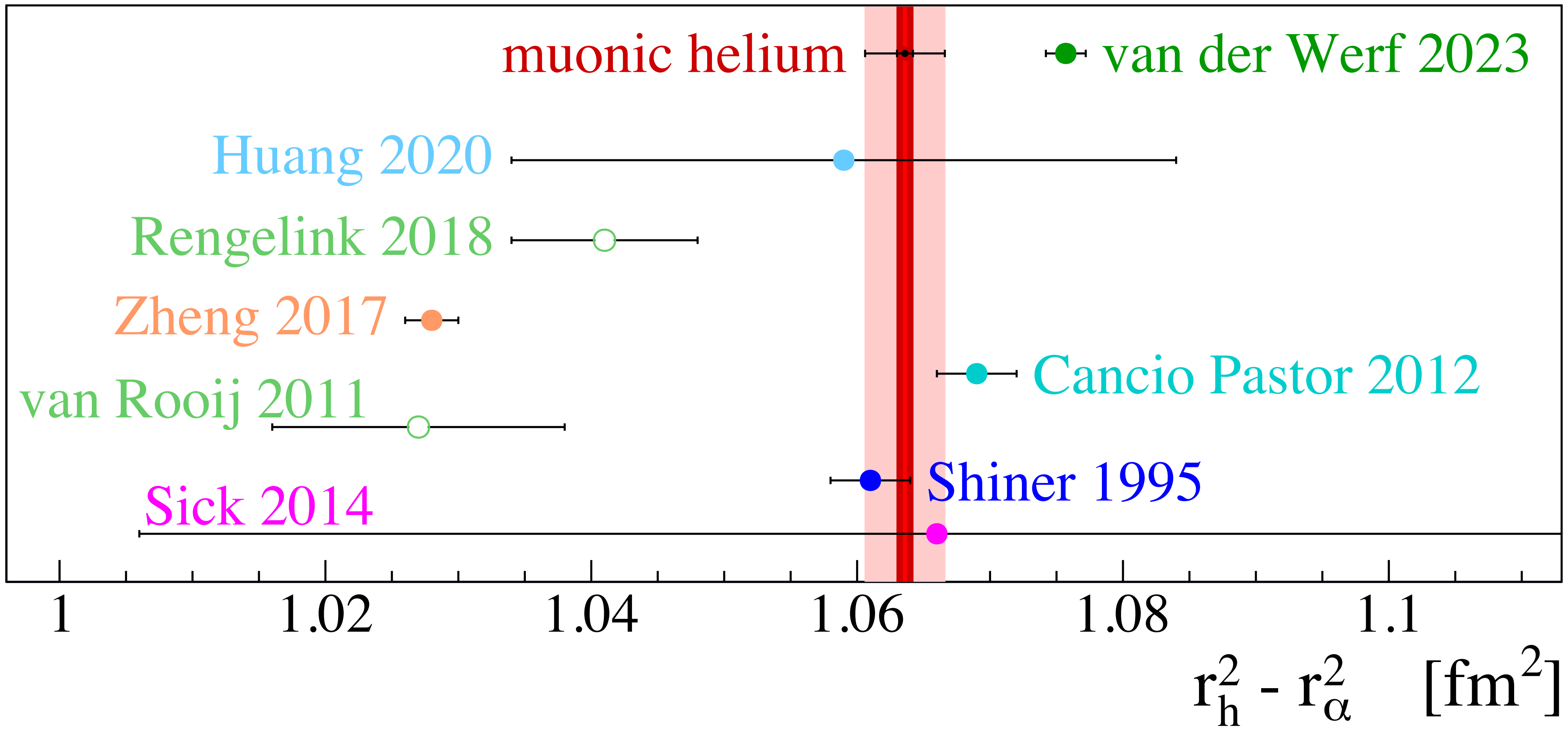
Isotopic shift in He

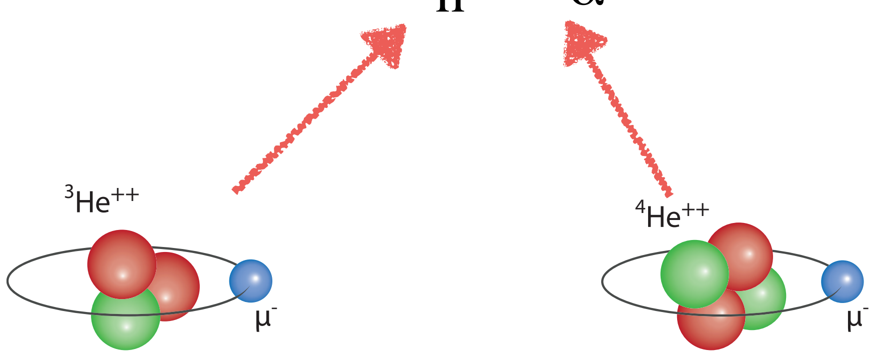
Two electrons are much more than one electron



But **large** theory cancellations are taking place in regular He in the isotopic shift

Minor theory cancellations are taking place in μHe^+





Comments

- Van Rooij results corrected to include a differential ac-stark shift effect. The van der Werf result makes use of the magic wavelength to eliminate this systematic

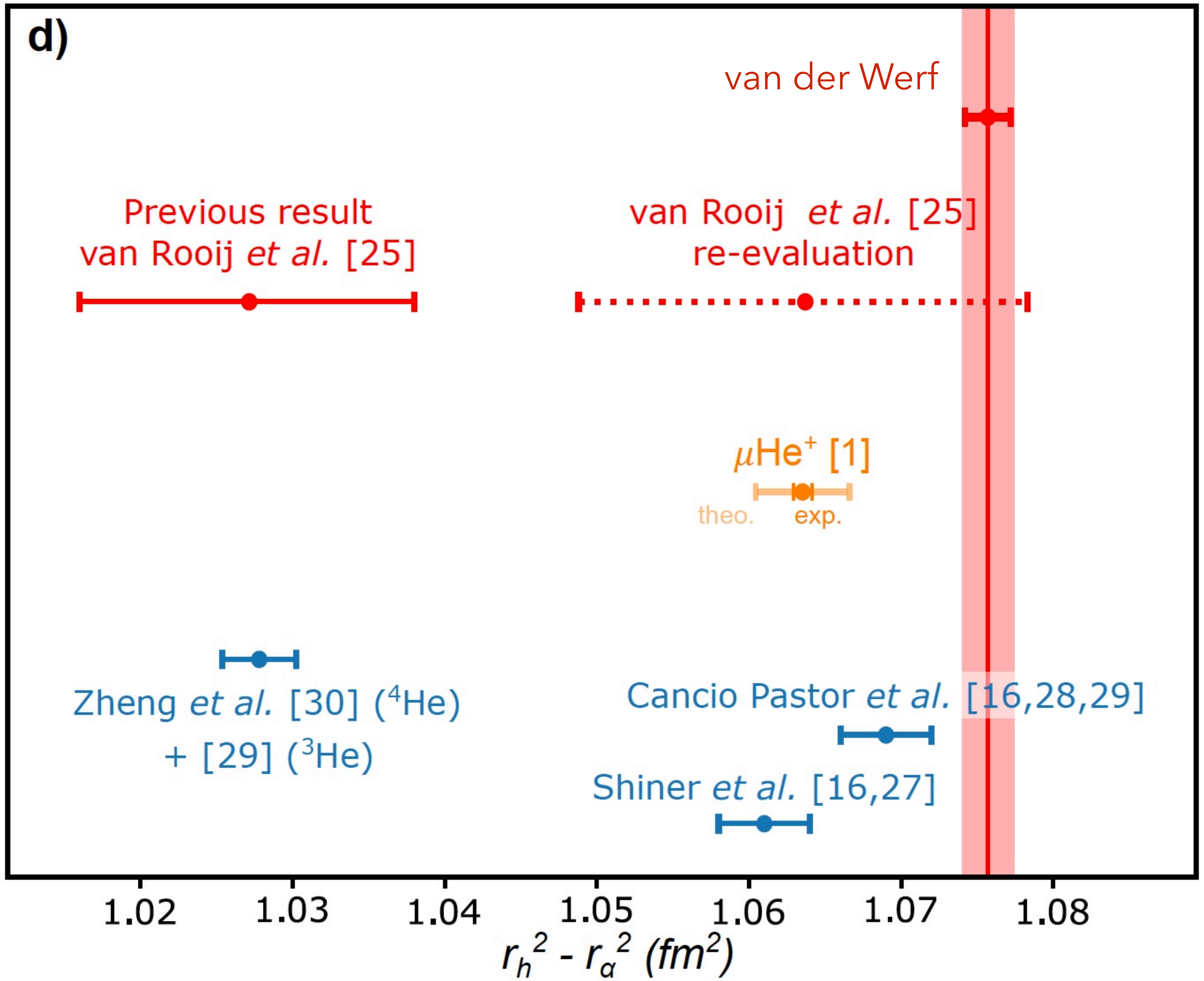
  arXiv:2306.02333 (2023)

- Between $\mu\mathrm{He}^+$ and Amsterdam result there is a 3.6σ tension

- The values of Shiner and Pastor may lack a systematic correction due to quantum interference effects
  Marsman et al., PRA 89, 043403 (2014)

- The value of Zheng may have to be corrected for a systematic Doppler shift
  Wen, et al. PRA 107, 042811 (2023).

Van der Werf et al., arXiv:2306.02333




Two-body QED tests in H-like systems
QED test in simple molecules
BSM searches
Fundamenal constants
Three-body QED tests in He-like systems
Hadron structure
Radiative corrections
Nuclear structure
High-precision laser spectroscopy
Penning traps program
Scattering experiments and accelerator
Muonic atom spectroscopy

The CREMA collaboration

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