New Perspectives in the Charge Radii Determination for Light Nuclei

2025 ECT* Workshop Report

FONDAZIONE BRUNO KESSLER | ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

INFN Istituto Nazionale di Fisica Nucleare

FRIB Theory Alliance

Franziska Hagelstein (JGU Mainz)

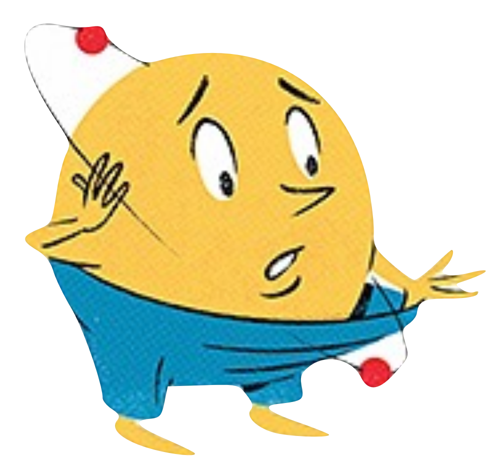
12th April 2026

NREC + µASTI + PREN 2024

6th Max - 10th May 2024, Stony Brook

Muonic Atom Spectroscopy Theory Initiative

from PUZZLE to PRECISION

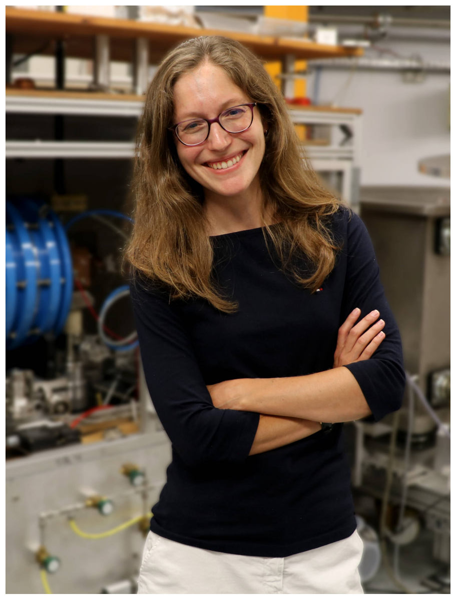


What’s next …?

ECT* Workshop

New Perspectives in the Charge Radii Determination for Light Nuclei

Loredana Gastaldo



Nancy Paul

Randolf Pohl

+

- Microcalorimeter X-ray detector technology
- High-resolution X-ray and laser spectroscopy

- Theory of muonic atoms
- Nuclear & nucleon structure
- BSM searches

R. Pohl: “Light muonic atoms - fruitful collaboration between experiment and theory”

- Strengthen the crucial collaboration between experiment and theory
- 31 participants (near-even split between experimental and theoretical physicists)

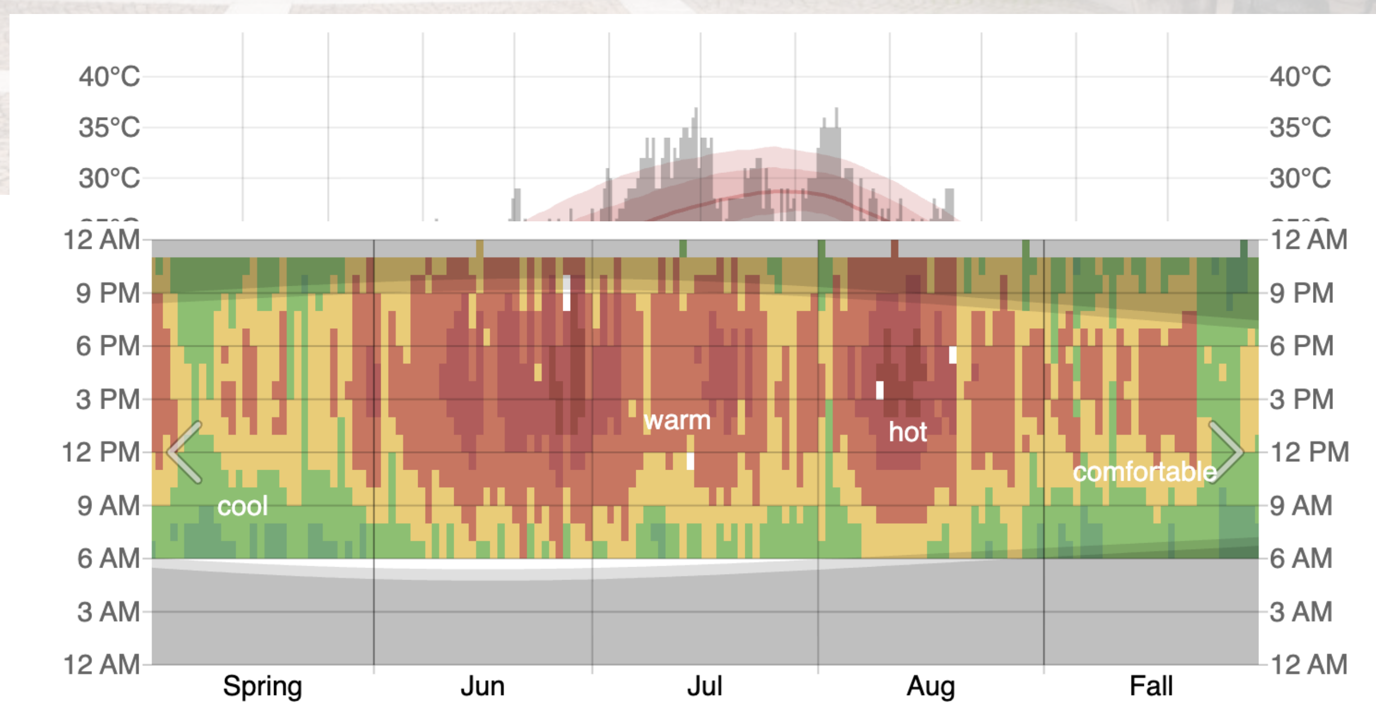
ECT* Workshop

28th July - 1st August 2025

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE
BRUNO KESSLER

Trento (Italy)



WeatherSpark.com

ECT* Workshop

28th July - 1st August 2025, Trento (Italy)

https://indico.ectstar.eu/event/240/overview

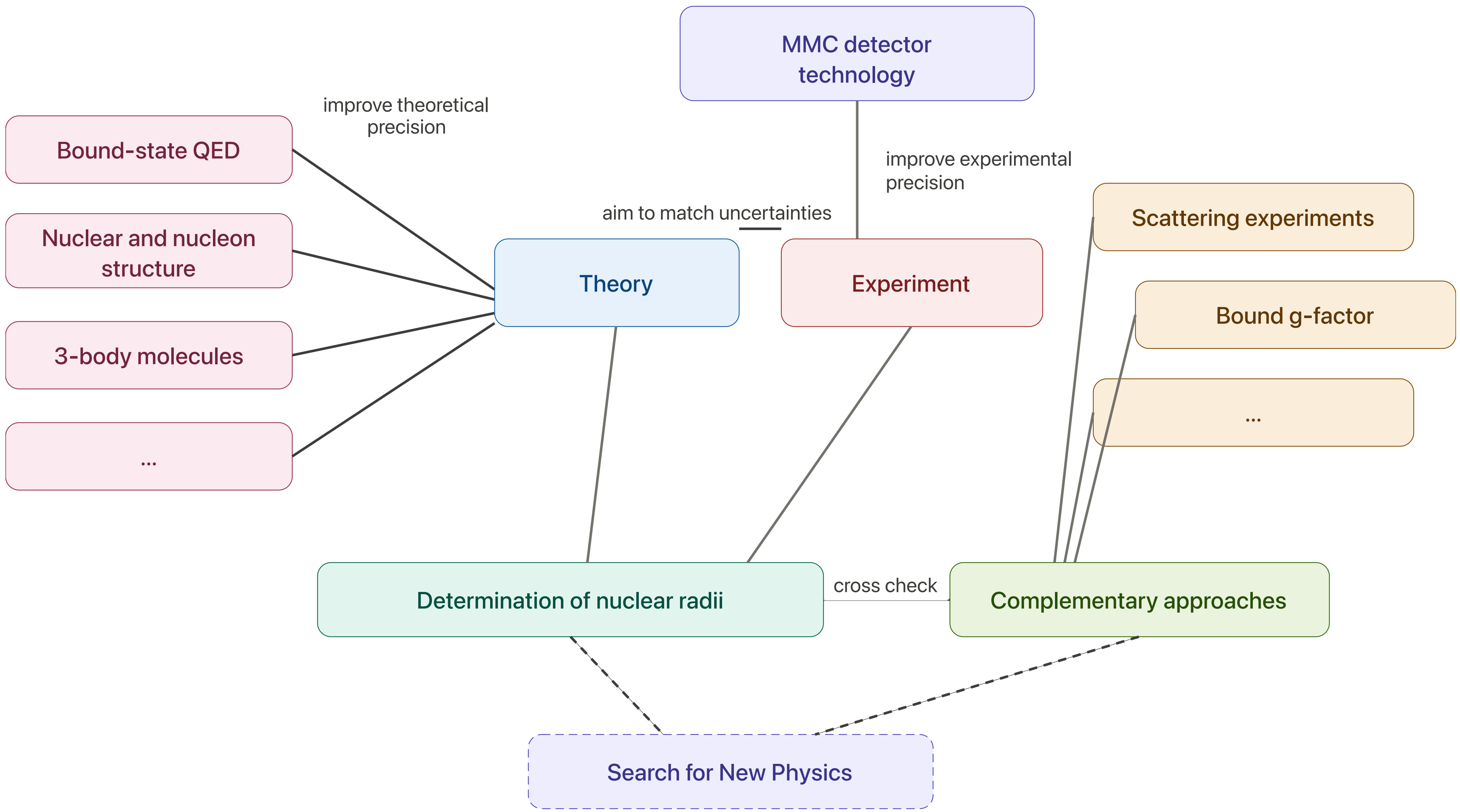
27 Talks

https://indico.ectstar.eu/event/240/contributions/

1. S. Bacca (Johannes Gutenberg University, Mainz, Germany) *"Nuclear structure effects in light muonic atoms"*
2. G. Baptista (Laboratoire Kastler Brossel, Paris, France) *"PAX (antiProtonic Atom X-ray spectroscopy)"*
3. T.E. Cocolios (KU Leuven, Belgium) *"Reference Radii for odd-Z and heavy elements"*
4. D.P.L. Aude Craik (ETH Zürich, Switzerland) *"Nonlinear calcium King plot: implications for new bosons and nuclear properties"*
5. M. Deseyn (KU Leuven, Belgium) *"Muonic x-ray spectroscopy on Si"*
6. M. Drissi (TU Darmstadt, Germany) *"Ab initio nuclear corrections to muonic lithium atoms"*
7. T. Egert (Johannes Gutenberg University and HIM, Mainz, Germany) *"Artificial Neural Networks for nuclear structure corrections"*
8. X. Feng (Peking University, China) *"Corrections to muonic atoms from Lattice QCD"*
9. A. Fleischmann (KIP, Heidelberg University, Germany) *"MMCs for high resolution x-ray spectroscopy"*
10. A. Gasparian (NC A and T State University, NC, USA) *"Update on the new PRad-II experiment and plans for the deuteron radius measurement at Jefferson Laboratory"*
11. C. Godinho (LIBPhys-UNL, Portugal) *"Isotope-shift measurements in muonic 10B and 11B 2p-1s transitions with a Metallic Magnetic Calorimeter"*
12. M. Gorshteyn (Johannes Gutenberg University, Mainz, Germany) *"Nuclear polarization, nuclear radii and Vud"*
13. Z. Harman (Max Planck Institute for Nuclear Physics, Heidelberg, Germany) *"Precision physics with few-electron ions: testing the Standard Model and Beyond"*
14. **F. Heiße (Max Planck Institute for Nuclear Physics, Heidelberg, Germany) *"Charge radius determination via bound electron g-factors"***
15. D. Kreuzberger (KIP, Heidelberg University, Germany) *"MMC Array to Study X-ray transitions in muonic atoms"*
16. V. Lensky (Johannes Gutenberg University, Mainz, Germany) *"Muonic hydrogen: theoretical challenges"*
17. W. Nörtershäuser (TU Darmstadt, Germany) *"Charge radii determined by laser spectroscopy of He-like ions"*
18. **B. Ohayon (Technion IIT, Israel) *"New perspectives in the charge radii determination for light nuclei"***
19. N.S. Oreshkina (Max Planck Institute for Nuclear Physics, Heidelberg, Germany) *"Nuclear radii from muonic atoms spectroscopy"*
20. A. Ouf (Johannes Gutenberg University, Mainz, Germany) *"The ground state hyperfine splitting in muonic hydrogen experiment (HyperMu) at PSI"*
21. S. Pastore (Washington University, USA) *"Electromagnetic radii of light nuclei from variational Monte Carlo calculations"*
22. C. Peset (University of Madrid Complutense, Spain) *"New physics bounds from the spectroscopy of muonic atoms"*
23. S. Pitelis (Johannes Gutenberg University, Mainz, Germany) *"Finite-size effects & New Physics"*
24. R. Pohl (Johannes Gutenberg University, Mainz, Germany) *"Light muonic atoms - fruitful collaboration between experiment and theory"*
25. R. Potvliege (Durham University, UK) *"BSM: Bounds based on muonic hydrogen, muonic deuterium and muonic helium spectroscopy"*
26. S. Rathi (Technion IIT, Israel) *"QUAdRupole Moment MeasuremenT of mid-Z Transition Elements with Microcalorimeters"*
27. G. Weber (Helmholtz Institute Jena, Germany) *"Precision spectroscopy of helium-like uranium"*

Main Topics

Nuclear Radii Determination from Atomic Spectroscopy



- New innovative metallic magnetic calorimeter (MMC) X-ray detector technology
- Theoretical improvements needed to match anticipated experimental accuracies
- Identify prospects for testing physics Beyond the Standard Model (BSM)

Experimental Programmes

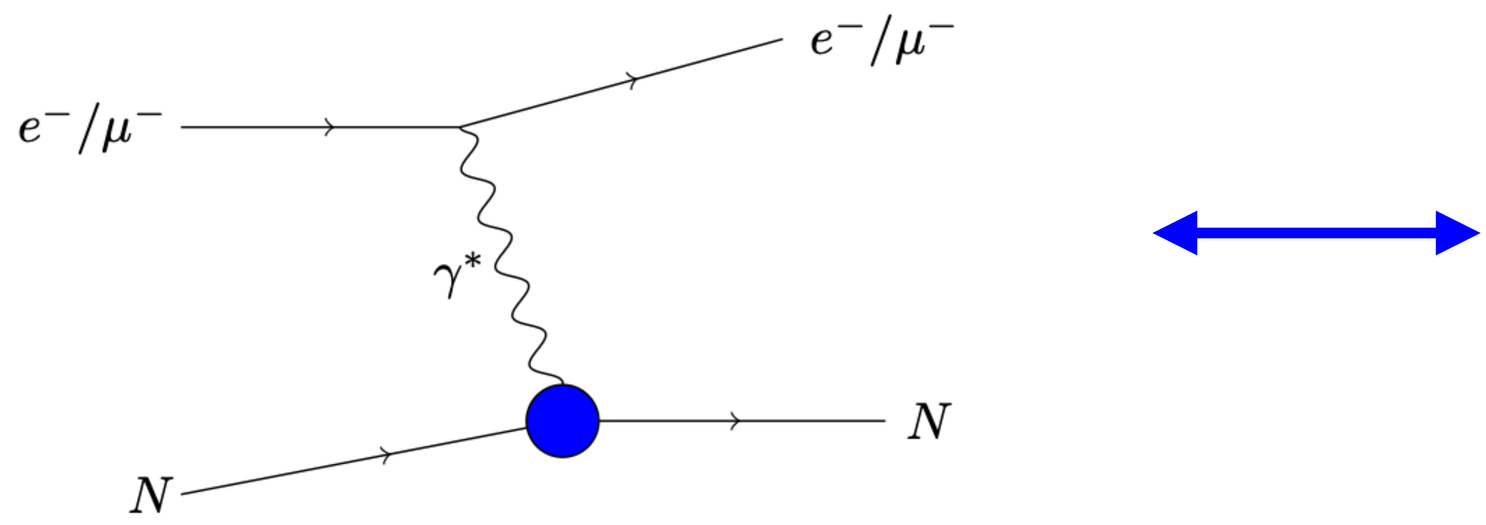
@ECT*-2025 and @NREC-2026

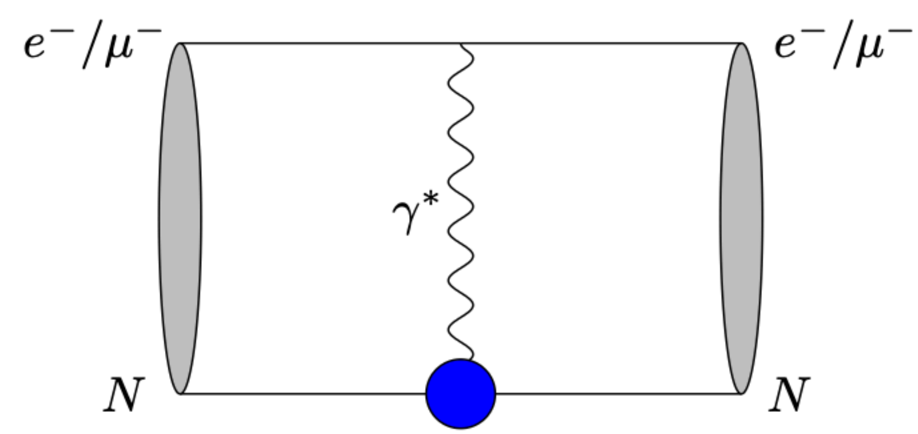
- High-resolution X-ray and laser spectroscopy
  - Light and medium-Z muonic atoms (CREMA, QUARTET, Reference Radii, muX @PSI) → Ben Ohayon (Wednesday)
  - Antiprotonic atoms (PAX @CERN … GBAR @CERN) → Christian Regenfus (Monday)
  - Isotope-shifts and King plots → Gil Paz (Monday), Shane Wilkins (Wednesday)
  - Highly-charged and He-like ions → Kristian König (Wednesday)
  - Hydrogen molecular ions → Soroosh Alighanbari (Monday)
  - Hydrogen spectroscopy → Lothar Maisenbacher (Monday)
- Bound electron g-factors → Fabian Heiße (Monday)
- Electron and muon scattering (PRad-II … Amber, MAGIX, MUSE, ULQ2)
- …

Electromagnetic Properties of Nuclei

Experimental Probes

- Lepton scattering





bound-state wave functions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \underbrace{\underbrace{\left(\frac{1}{4\pi\varepsilon_0}\frac{Ze^2}{2p_\mathrm{i}c}\right)^2 \frac{1}{\sin^4(\vartheta/2)}}_{\text{Rutherford scattering}} \underbrace{\frac{1}{1+\frac{2p_\mathrm{i}}{Mc}\sin^2(\vartheta/2)}}_{\text{recoil}} \underbrace{\cos^2(\vartheta/2)}_{\text{Spin}}}_{\text{Mott scattering}}$$

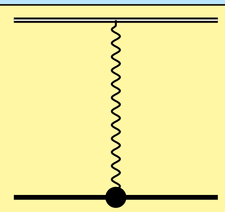
- Nuclear response function $R(\omega, \vec{q})$
- Elastic form factors $\frac{1}{(1+\tau)}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right]$

Electromagnetic Properties of Nuclei

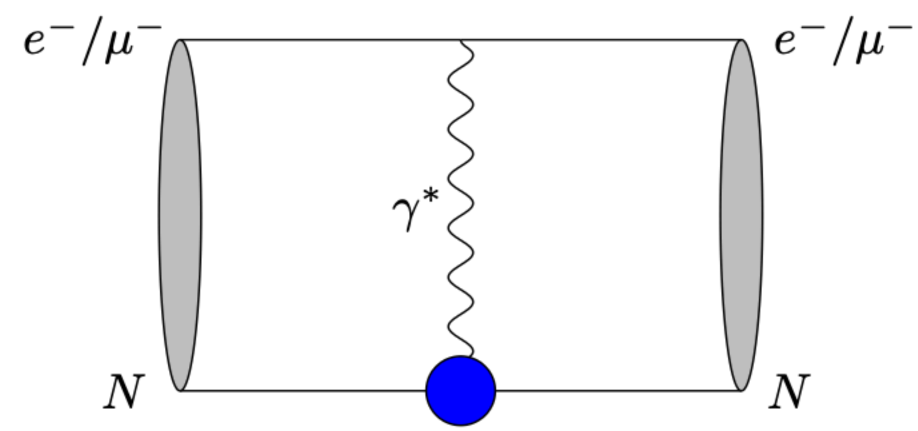
Experimental Probes

- Lepton scattering

One-photon exchange potentials with inclusion of electromagnetic form factors



$$V_{\mathrm{C}}(r) = -\frac{4\pi Z\alpha}{r}\,,$$

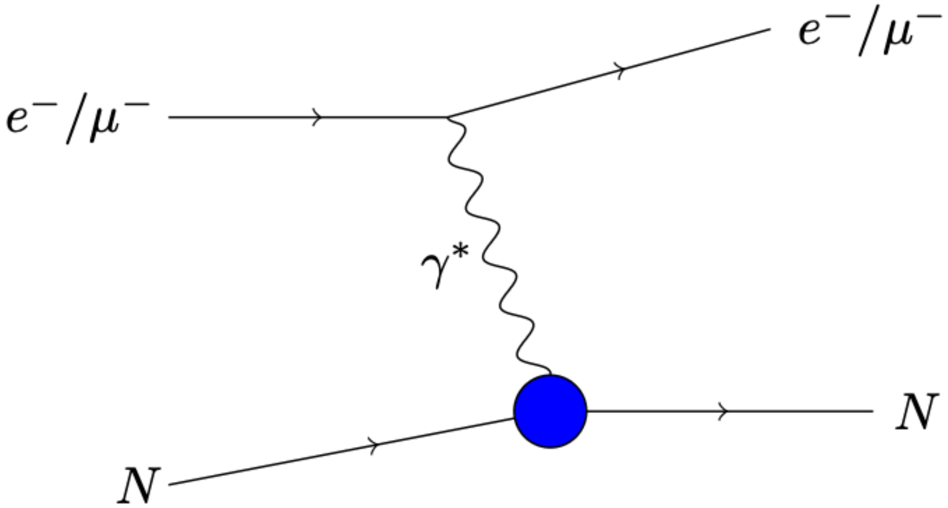


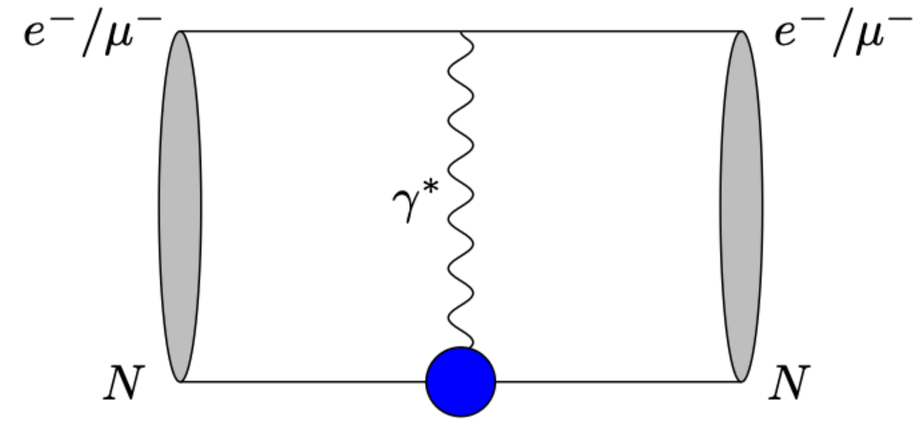
bound-state wave functions

Electromagnetic Properties of Nuclei

Experimental Probes

- Lepton scattering





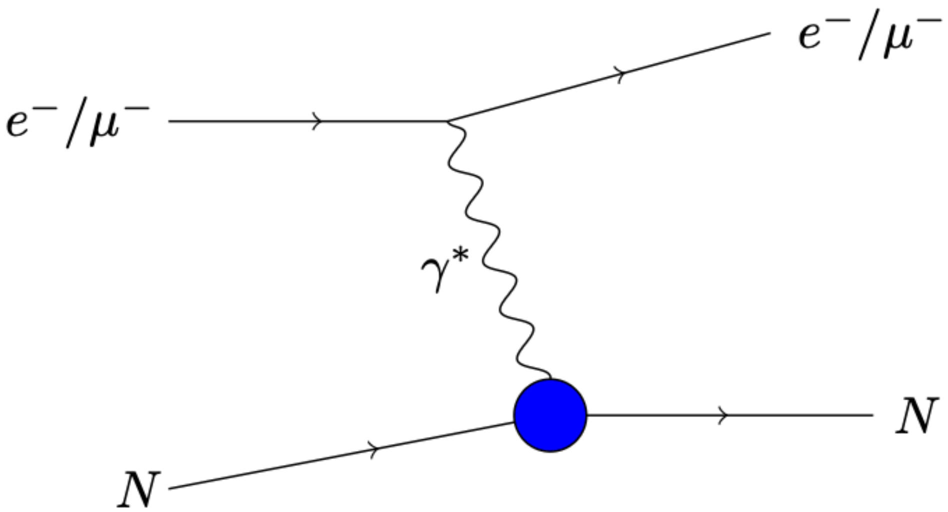
bound-state wave functions

- Laser and X-ray spectroscopy of electronic and muonic atoms

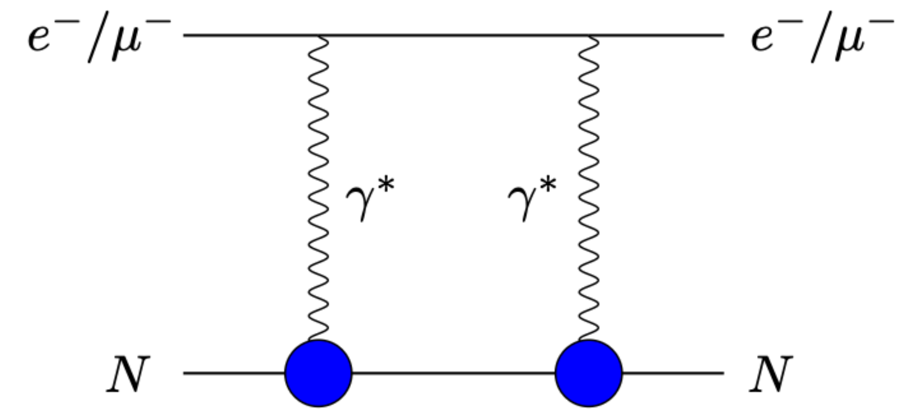
Electromagnetic Properties of Nuclei

Experimental Probes

- Lepton scattering



+ radiative corrections …



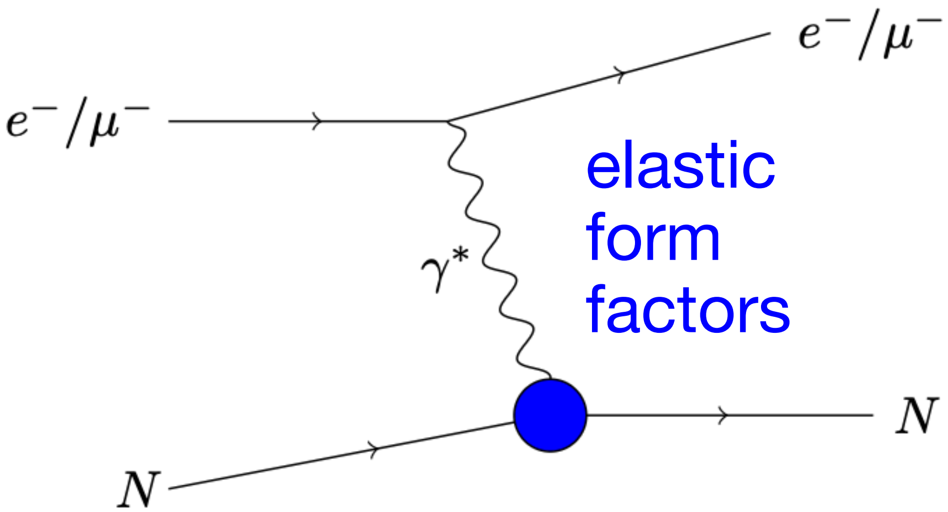
two-photon exchange

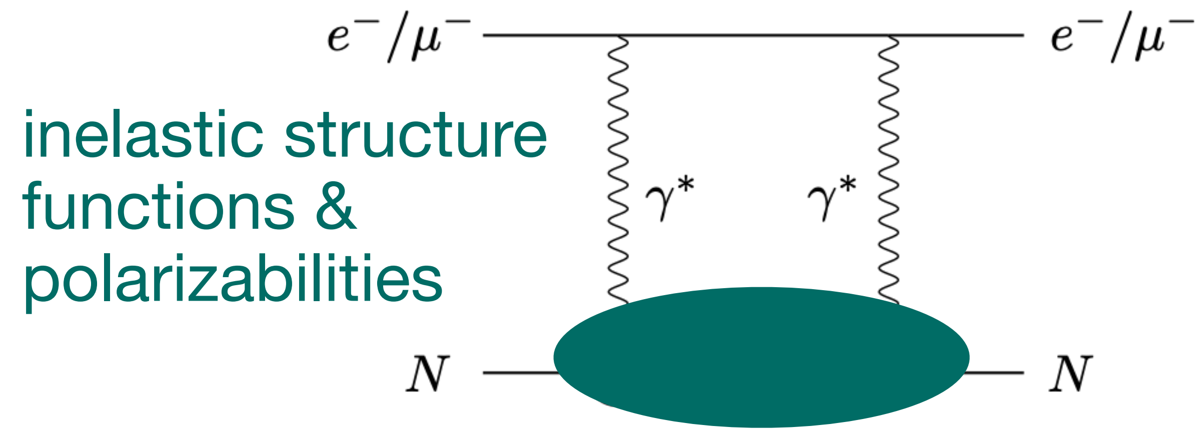
- Laser and X-ray spectroscopy of electronic and muonic atoms

Electromagnetic Properties of Nuclei

Experimental Probes

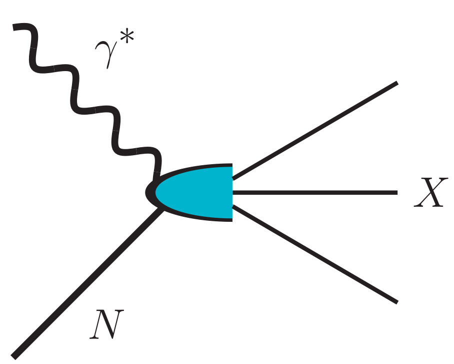
- Lepton scattering

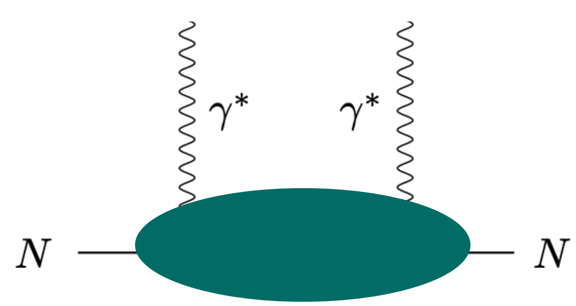




- Laser and X-ray spectroscopy of electronic and muonic atoms

- Photoabsorption and Compton scattering





Nuclear Radii / Moments

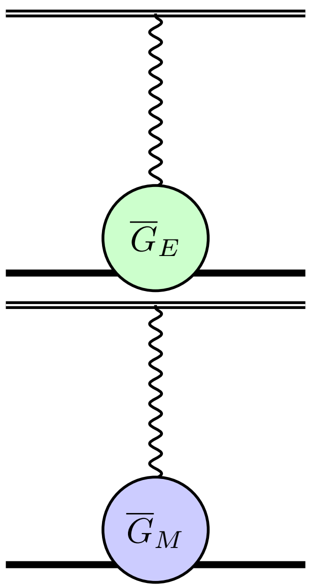
Definition and Interpretation

emergence in
finite-size potentials

- Charge and magnetic radii:

$$\langle r^N \rangle = \int_0^\infty \mathrm{d}\boldsymbol{r}\, r^{N+2} \rho(r)$$

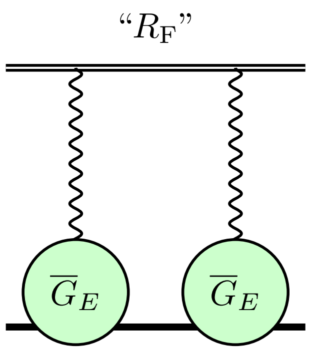
(assuming spherically symmetric distribution)



- Friar radius (3rd Zemach moment):

$$\langle r^3 \rangle_{E(2)} \equiv \int \mathrm{d}\boldsymbol{r}\, r^3 \int \mathrm{d}\boldsymbol{r}'\, \rho_E(|\boldsymbol{r}' - \boldsymbol{r}|)\, \rho_E(\boldsymbol{r}')$$

$$= \frac{48}{\pi} \int_0^\infty \frac{\mathrm{d}Q}{Q^4} \left[G_E^2(Q^2) - 1 + \frac{1}{3} R_E^2 Q^2 \right]$$

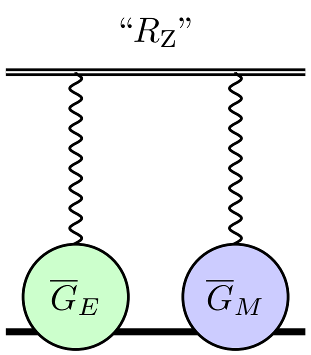


- Zemach radius:

$$R_Z \equiv \int \mathrm{d}\boldsymbol{r}\, r \int \mathrm{d}\boldsymbol{r}'\, \varrho_E(|\boldsymbol{r}' - \boldsymbol{r}|)\, \varrho_M(\boldsymbol{r}')$$

$$= -\frac{4}{\pi} \int_0^\infty \frac{\mathrm{d}Q}{Q^2} \left[\frac{G_E(Q^2) G_M(Q^2)}{1+\kappa} - 1 \right]$$

1S hyperfine splitting in muonic hydrogen
(talk by Ahmed Ouf)

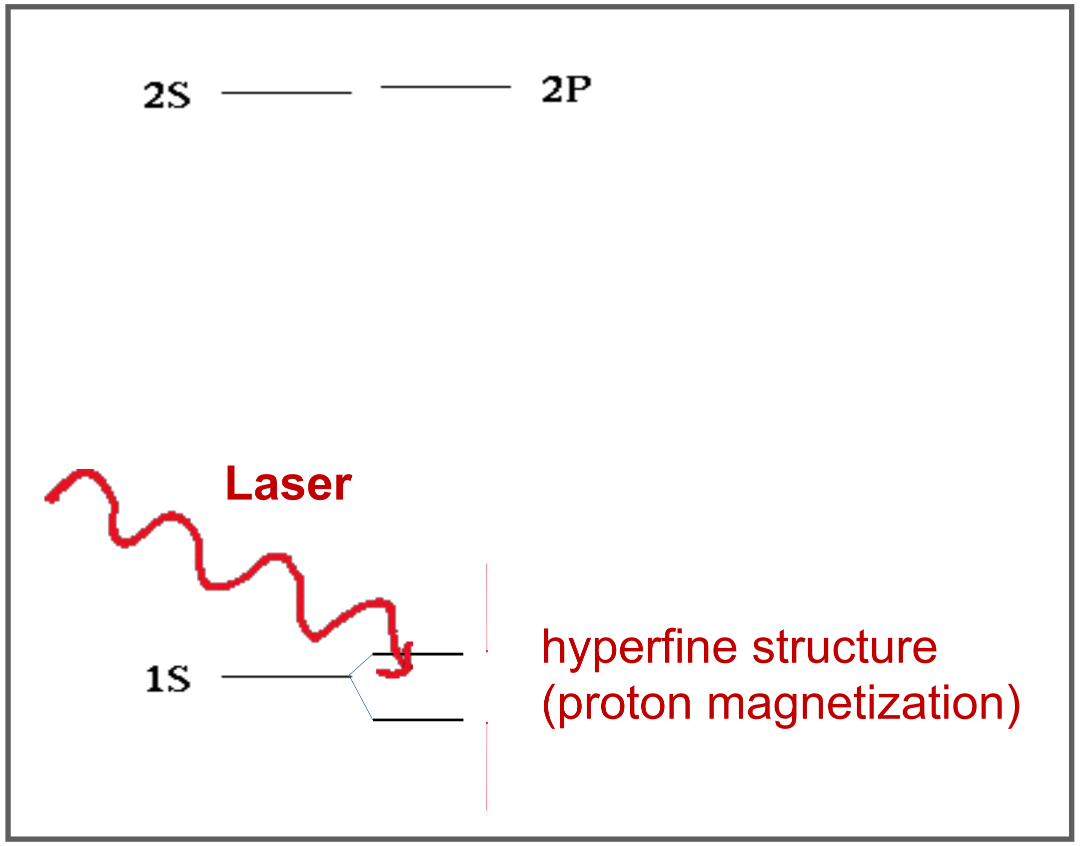


(Muonic) Atom Experiments

Laser vs. X-ray Spectroscopy

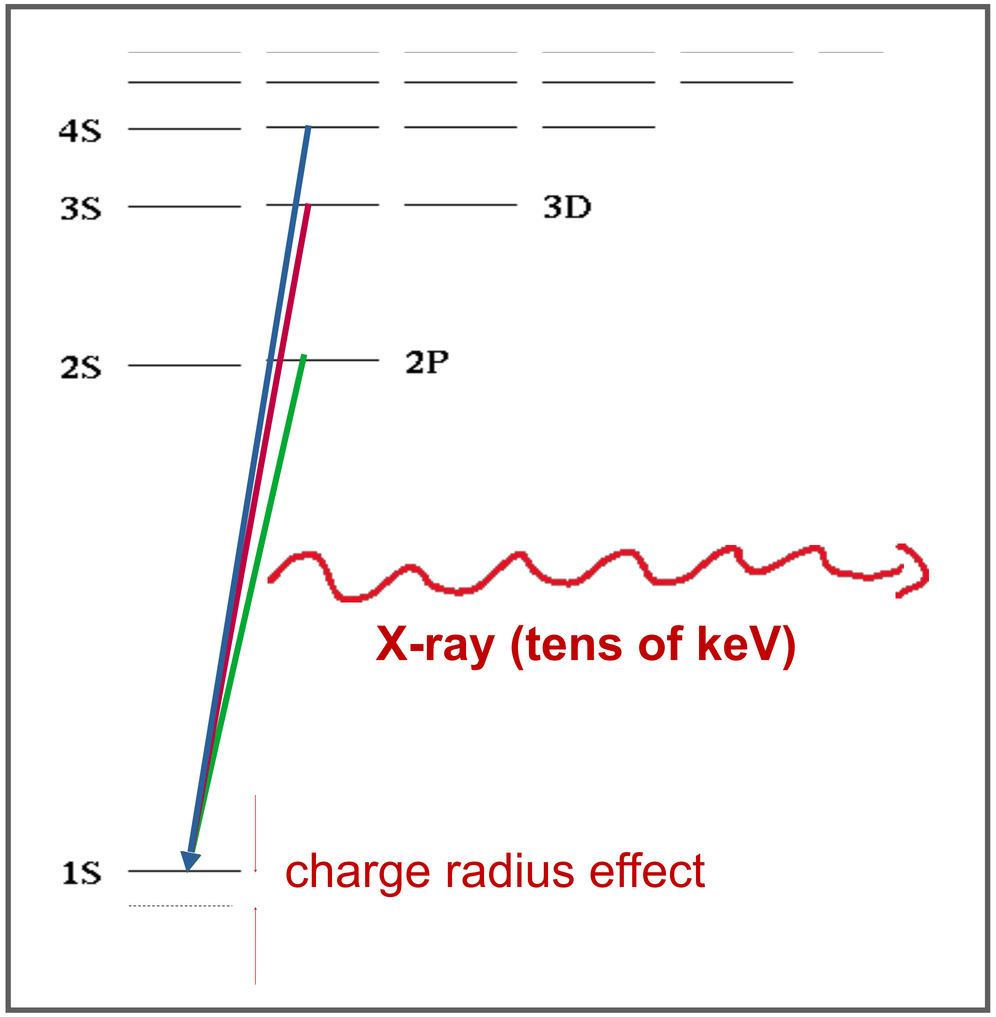
Laser spectroscopy

- Muonic H, D and He (CREMA @PSI)
- He-like ions (LaserSpHERe)



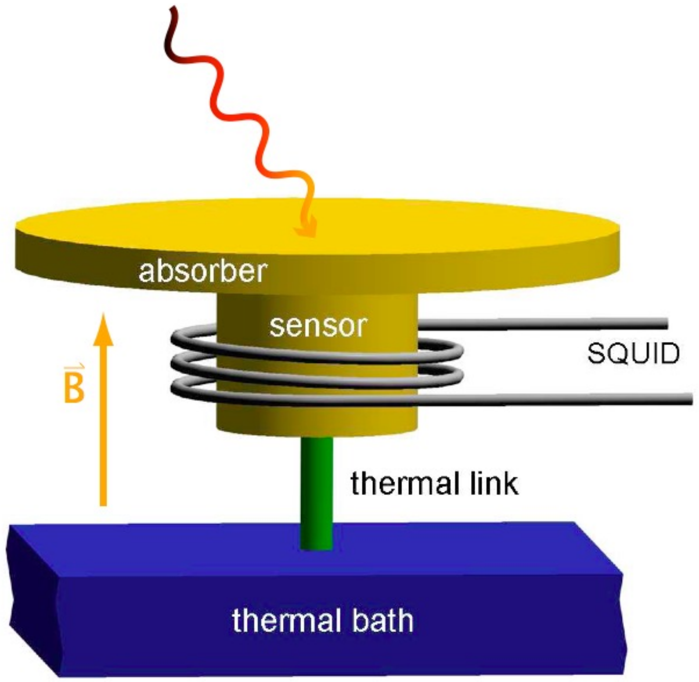
X-ray spectroscopy

- nP→ 1S transitions in muonic Li, Be, … (QUARTET @PSI)
- Reference Radii / muX @PSI

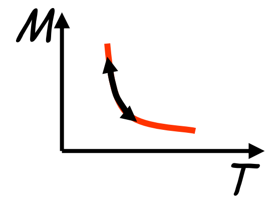


see slides R. Pohl

Metallic Magnetic Calorimeters (MMCs)

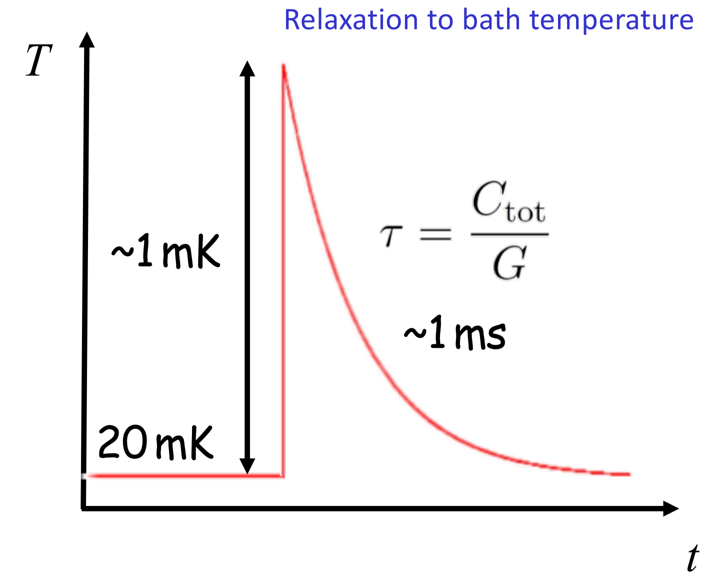


paramagnetic sensor: **Au**:Er$_{500ppm}$, **Ag**:Er



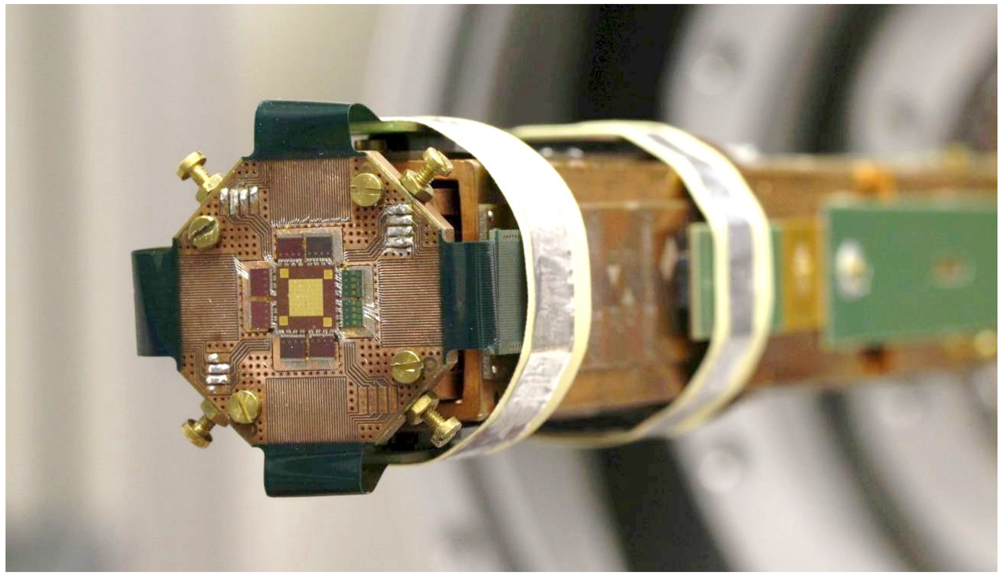
signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{tot}}$$



maXs-30

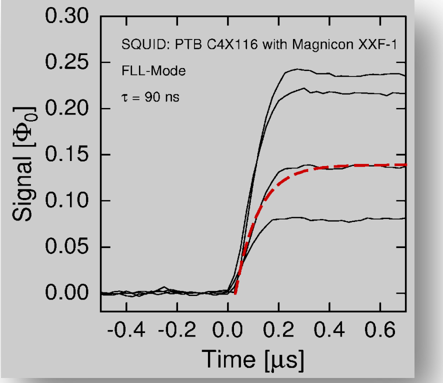
maXs-30 mounted on coldfinger of a dry dilution fridge



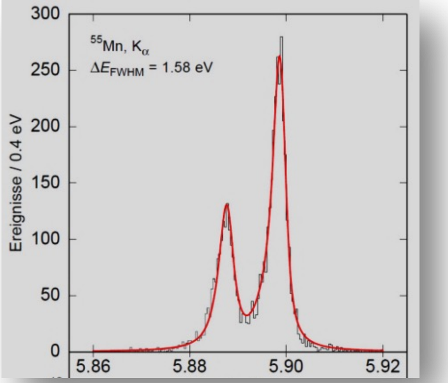
summary & outlook

- metallic magnetic calorimeters combine in a unique way

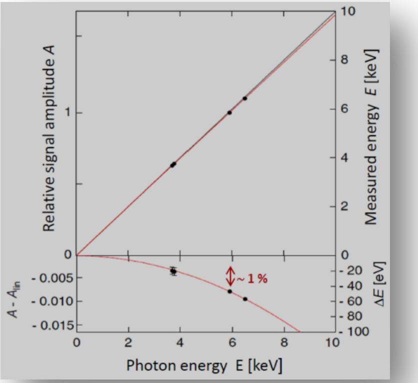
time resolution



energy resolution



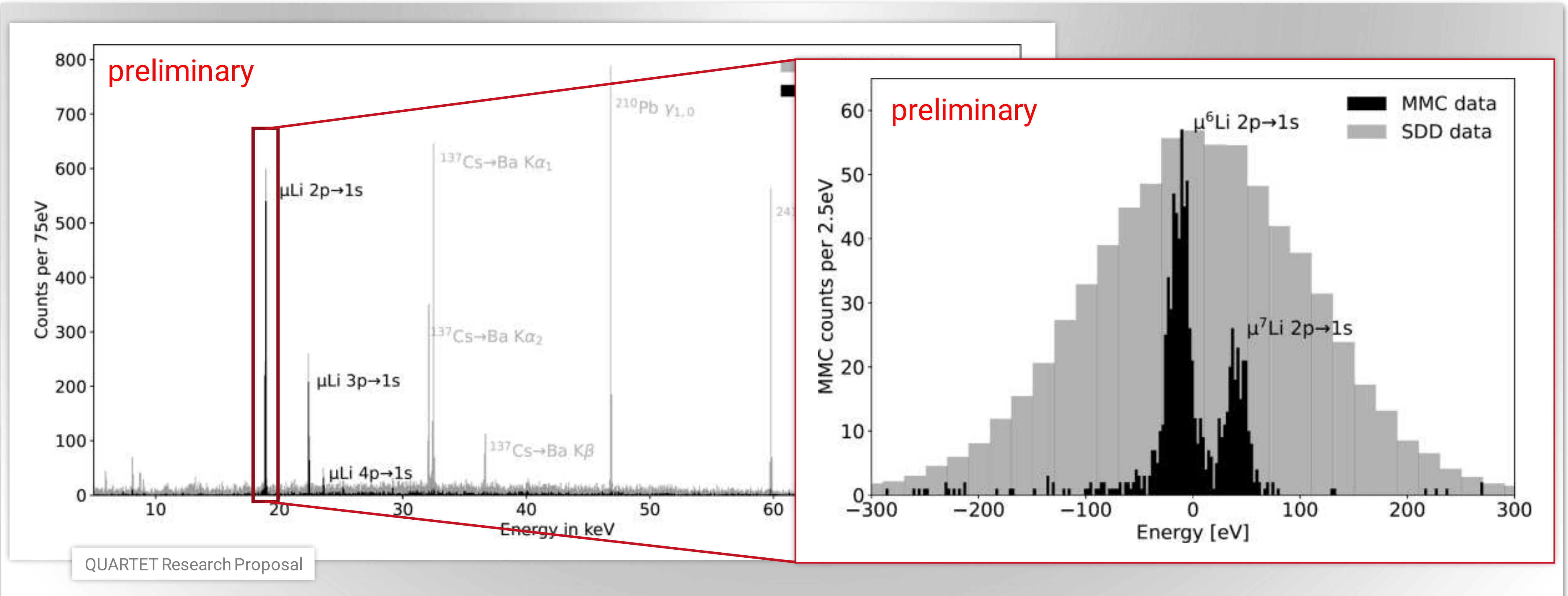
linearity



see slides A. Fleischmann

QUARTET Collaboration

Successful Li measurements



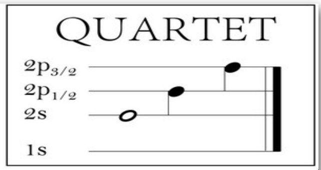
Isotope shift of muonic ^{6}Li and ^{7}Li resolved !

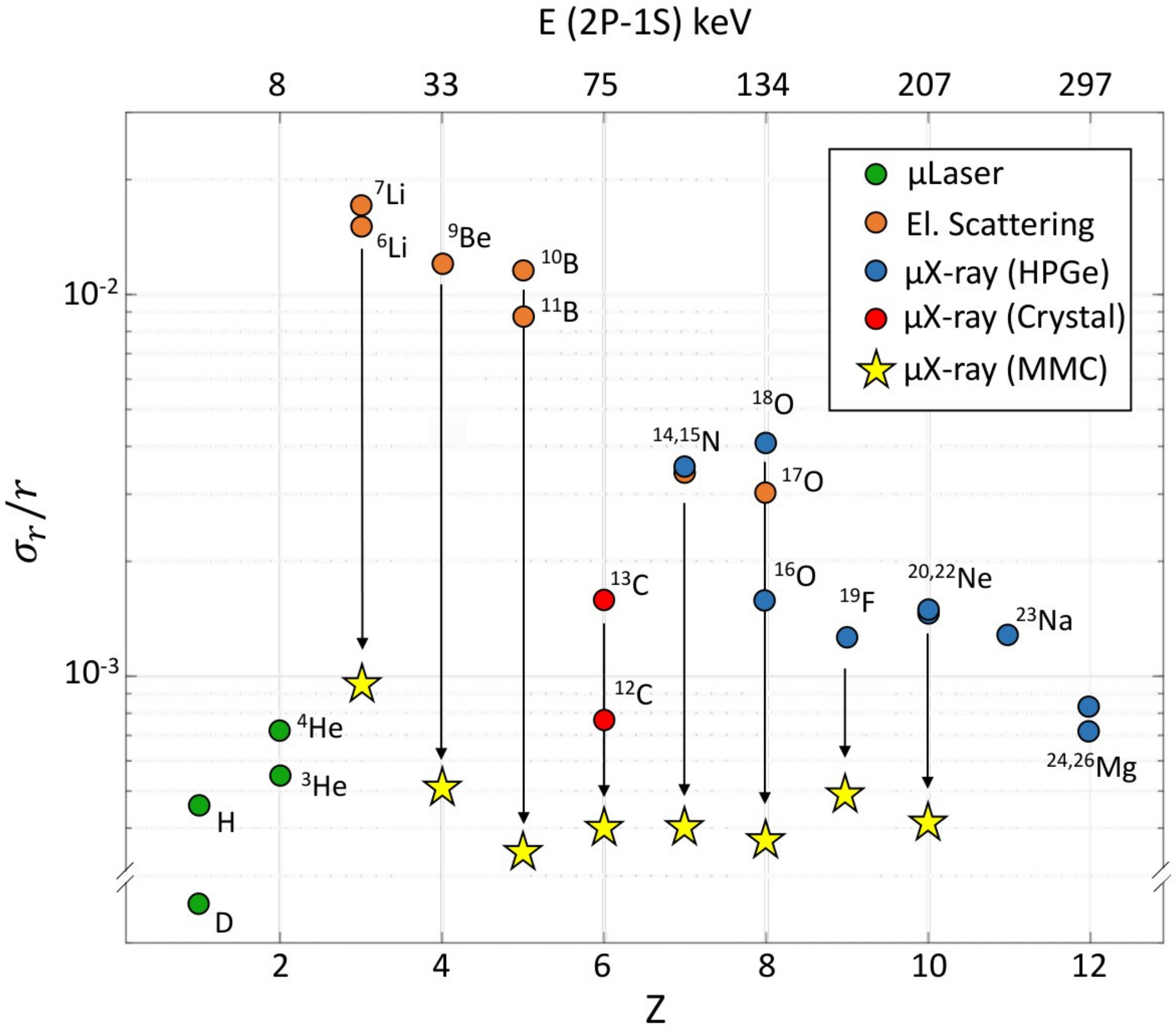
see slides R. Pohl & D. Kreuzberger → Ben Ohayon (Wednesday)

QUARTET Collaboration

Successful Li, Be, B and O measurements

QUARTET Goals





Current knowledge on radii of the lightest nuclei:

Z=1,2: muonic atom laser spectroscopy

Z>3: mostly e-scattering

Z=6: some muonic X-rays (crystal spectrometer)

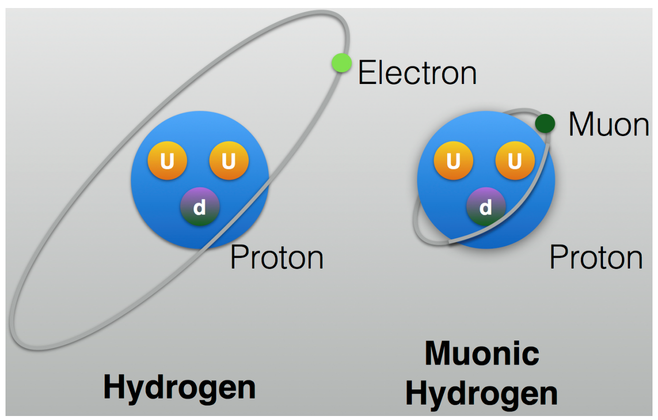
Z>8: muonic X-rays (Ge detectors)

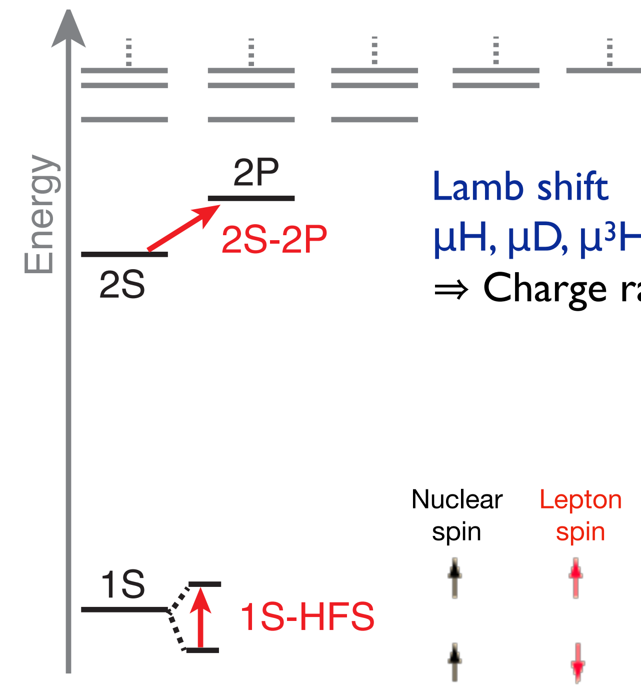
10x improved nuclear charge radii → challenging nuclear few-body calculations

see slides R. Pohl & D. Kreuzberger → Ben Ohayon (Wednesday)

Nuclear Structure in Muonic Atoms

Why muonic atoms ?





Lamb shift
μH, μD, μ^3He^+, μ^4He^+
⇒ Charge radii

Hyperfine splitting (HFS)
μH, μ^3He^+
⇒ Zemach radii, magnetic properties

- **Lamb shift:**

wave function at the origin

charge radius

Friar radius or 3rd Zemach moment

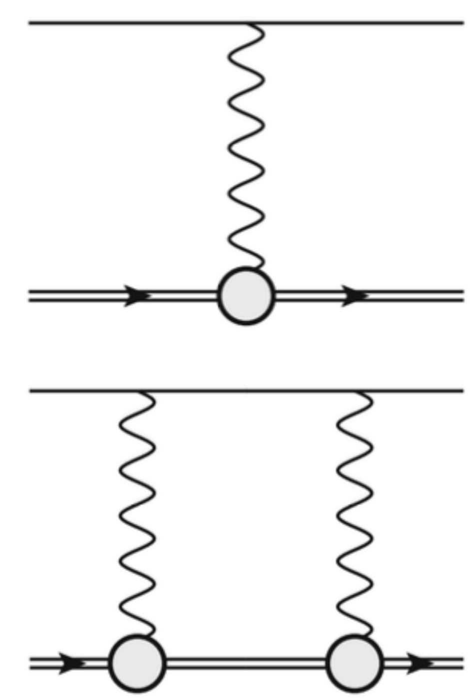
$$\Delta E_{nl}(\mathrm{LO{+}NLO}) = \delta_{l0}\,\frac{2\pi Z\alpha}{3}\,\frac{1}{\pi(an)^3}\left[R_E^2 - \frac{Z\alpha m_r}{2} R^3_{E(2)}\right]$$

NLO becomes appreciable in μH

Zemach radius

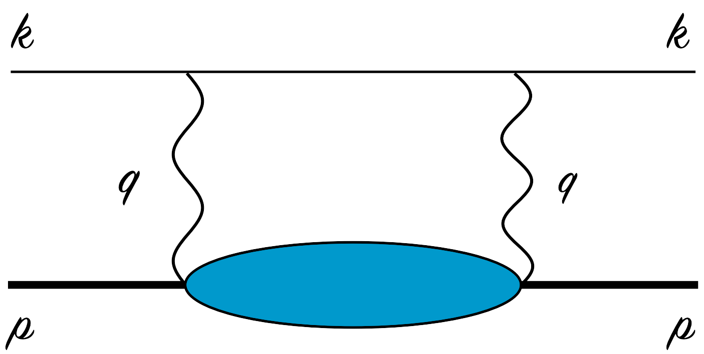
- **HFS:**

$$\Delta E_{nS}(\mathrm{LO}+\mathrm{NLO}) = E_F(nS)\,[1 - 2\,Z\alpha m_r\,R_Z]$$

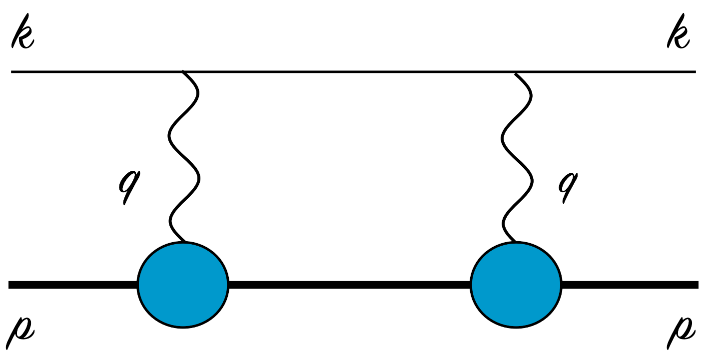


Two- and Three-Photon Exchange

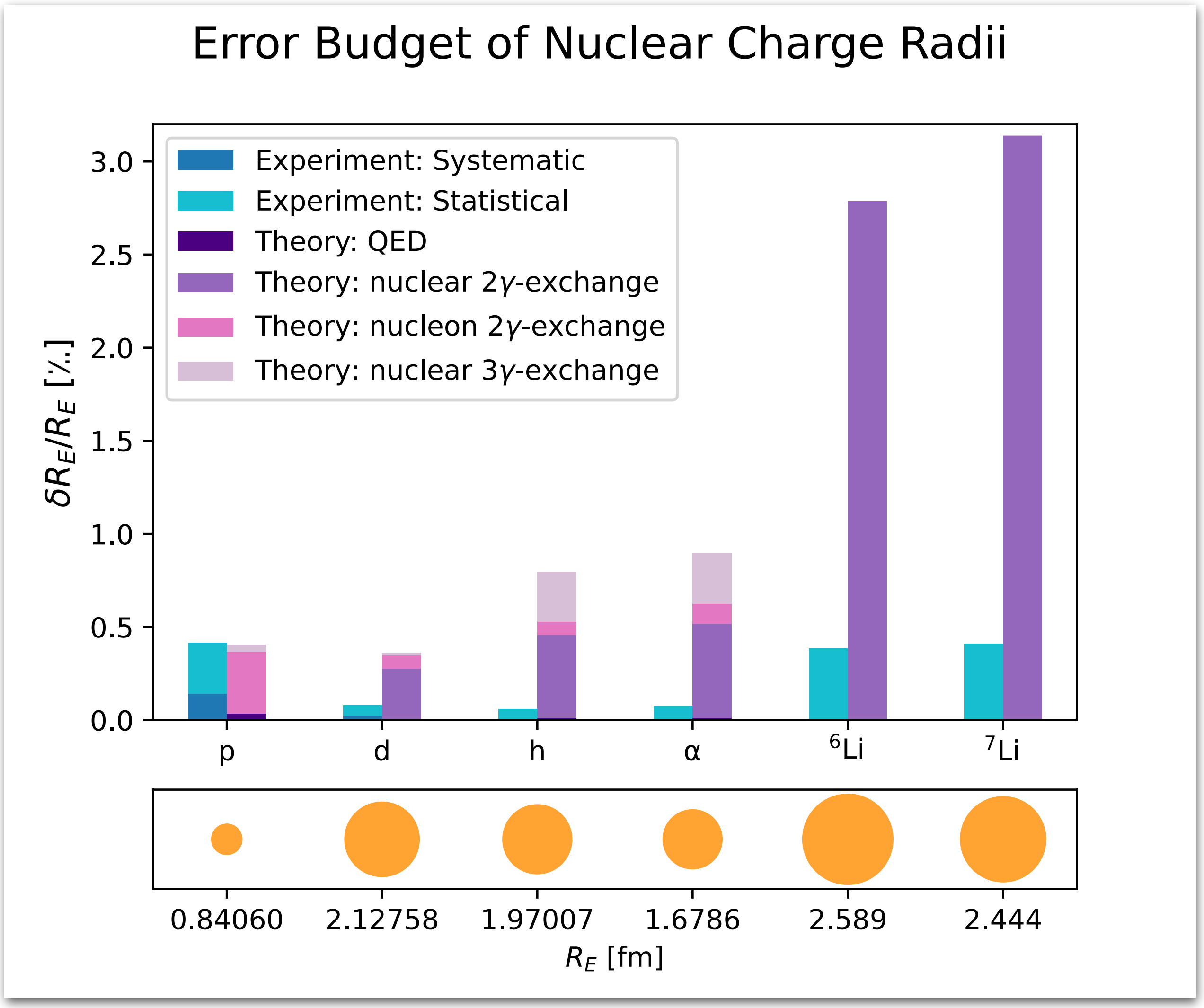
forward
two-photon exchange (2γ)



polarizability contribution
(non-Born VVCS)



elastic contribution:
finite-size recoil,
3rd Zemach moment (Lamb shift),
Zemach radius (Hyperfine splitting)



Comprehensive theory of the Lamb shift in light muonic atoms

K. Pachucki,[1] V. Lensky,[2] F. Hagelstein,[2,3] S. S. Li Muli,[2] S. Bacca,[2,4] and R. Pohl[5]
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(Dated: May 19, 2023) Rev. Mod. Phys. **96** (2024) 1, 015001

$E_{\rm QED}$	point nucleus	206.034 4(3)	228.774 0(3)	1644.348(8)	1668.491(7)
$\mathcal{C}\, r_C^2$	finite size	$-5.225\,9\, r_p^2$	$-6.107\,4\, r_d^2$	$-103.383\, r_h^2$	$-106.209\, r_\alpha^2$
$E_{\rm NS}$	nuclear structure	0.028 9(25)	1.750 3(200)	15.499(378)	9.276(433)
$E_L(\exp)$	experiment[a]	202.370 6(23)	202.878 5(34)	1258.598(48)	1378.521(48)
r_C	this work	0.840 60(39)	2.127 58(78)	1.970 07(94)	1.678 6(12)
r_C	previous[a]	0.840 87(39)	2.125 62(78)	1.970 07(94)	1.678 24(83)

μH: present accuracy comparable with experimental precision

μD, μ^3He^+, μ^4He^+: present accuracy factor 5-10 worse than experimental precision

- Experiments will improve by up to a factor of 5
- Theoretical improvement needed for nuclear/nucleon 2- and 3-photon exchange

Comprehensive theory of the Lamb shift in light muonic atoms

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$E_L(\mathrm{exp})$	experiment[a]	202.370 6(23)	202.878 5(34)	1258.598(48)	1378.521(48)
r_C	this work	0.840 60(39)	2.127 58(78)	1.970 07(94)	1.678 6(12)
r_C	previous[a]	0.840 87(39)	2.125 62(78)	1.970 07(94)	1.678 24(83)

$(Z\alpha)^5$	TPE	0.029 2(25)	1.979(20)	16.38(31)	9.76(40)
$\alpha^2(Z\alpha)^4$	Coulomb distortion	0.0	−0.261	−1.010	−0.536
$(Z\alpha)^6$	3PE	−0.001 3(3)	0.002 2(9)	−0.214(214)	−0.165(165)
$\alpha\,(Z\alpha)^5$	$\mathrm{eVP}^{(1)}$ with TPE	0.000 6(1)	0.027 5(4)	0.266(24)	0.158(12)
$\alpha\,(Z\alpha)^5$	$\mu\mathrm{SE}^{(1)} + \mu\mathrm{VP}^{(1)}$ with TPE	0.000 4	0.002 6(3)	0.077(8)	0.059(6)

- Theoretical improvement needed for nuclear/nucleon 2- and 3-photon exchange

Nuclear Structure Contributions

Aim: first full comparison of predictions for He and Li across various approaches

- Ab-initio nuclear theory:
  - η expansion for the Lamb shift with phenomenological (AV4) or chiral EFT nuclear potentials (S. Bacca)
  - η-less approach for the Lamb shift in Li-6 and Li-7 with N4LO-E7 and N3LO chiral interactions (M. Drissi)
  - Extension to the HFS, including pionless EFT predictions for deuterium (C. Ji)
- Data-driven estimates of nuclear- and nucleon polarizability correction for $4 < Z < 41$ nuclei (M. Gorshteyn)
- Novel method employing ANN to model nuclear dipole responses (T. Egert)
- Electromagnetic radii for light nuclei from variational Monte Carlo (S. Pastore)

Example of cancellation: $\mu\ ^{6,7}\mathrm{Li}^{2+}$

δ^A_{Zem} — elastic piece

δ^A_{pol} — inelastic piece

Alarming 95% cancellation!

Maybe OK because 100% correlated

Intrinsic approximations may destroy

this correlation — dangerous!

Compare with my simple model

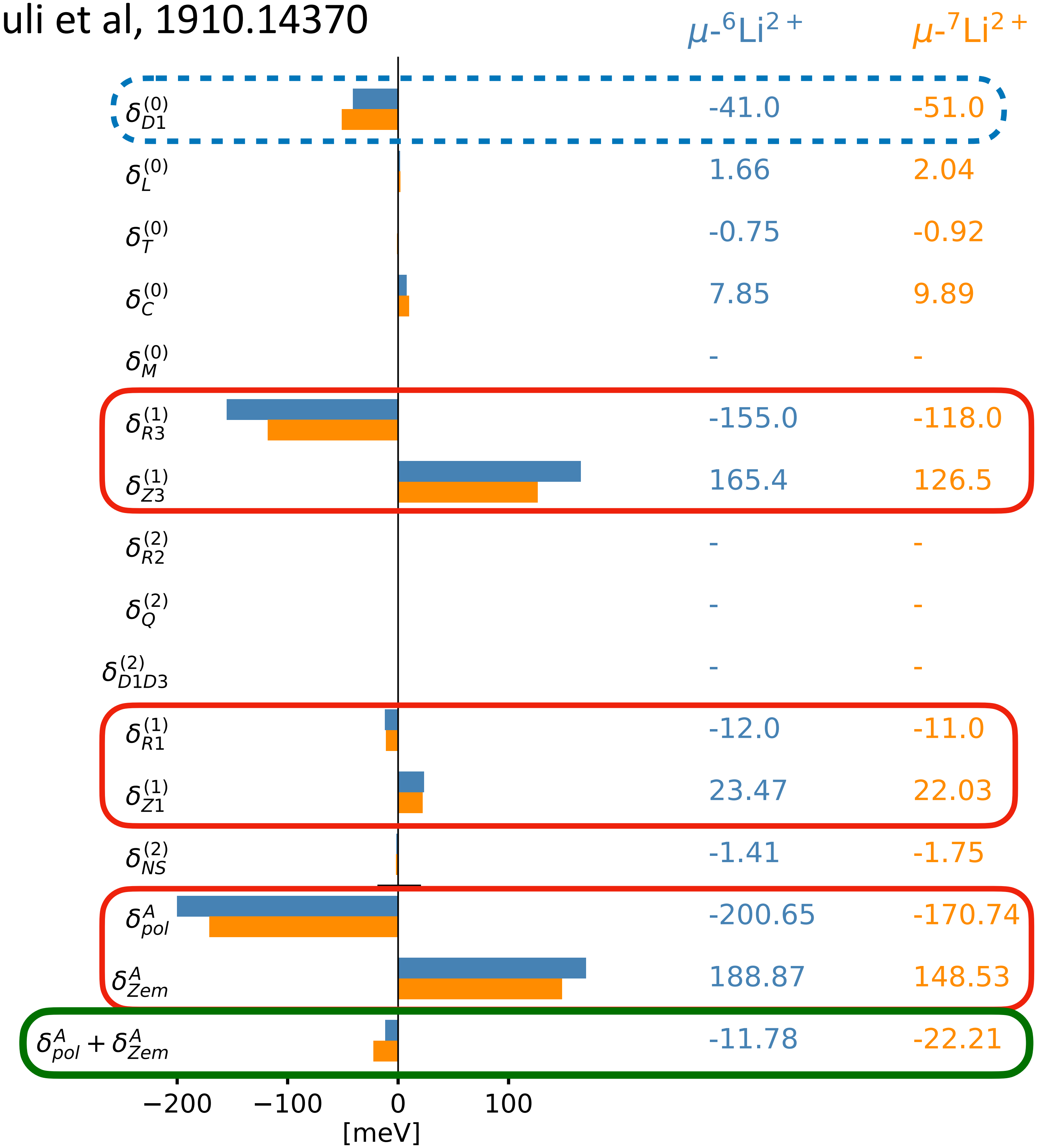
	$\mu\ ^{6}\mathrm{Li}^{2+}$	$\mu\ ^{7}\mathrm{Li}^{2+}$
$\Delta E^{NP}_{2P-2S} =$	23(2) meV	24(2) meV

Factor 2 off for Li-6, OK for Li-7

Relativistic effects expected to matter

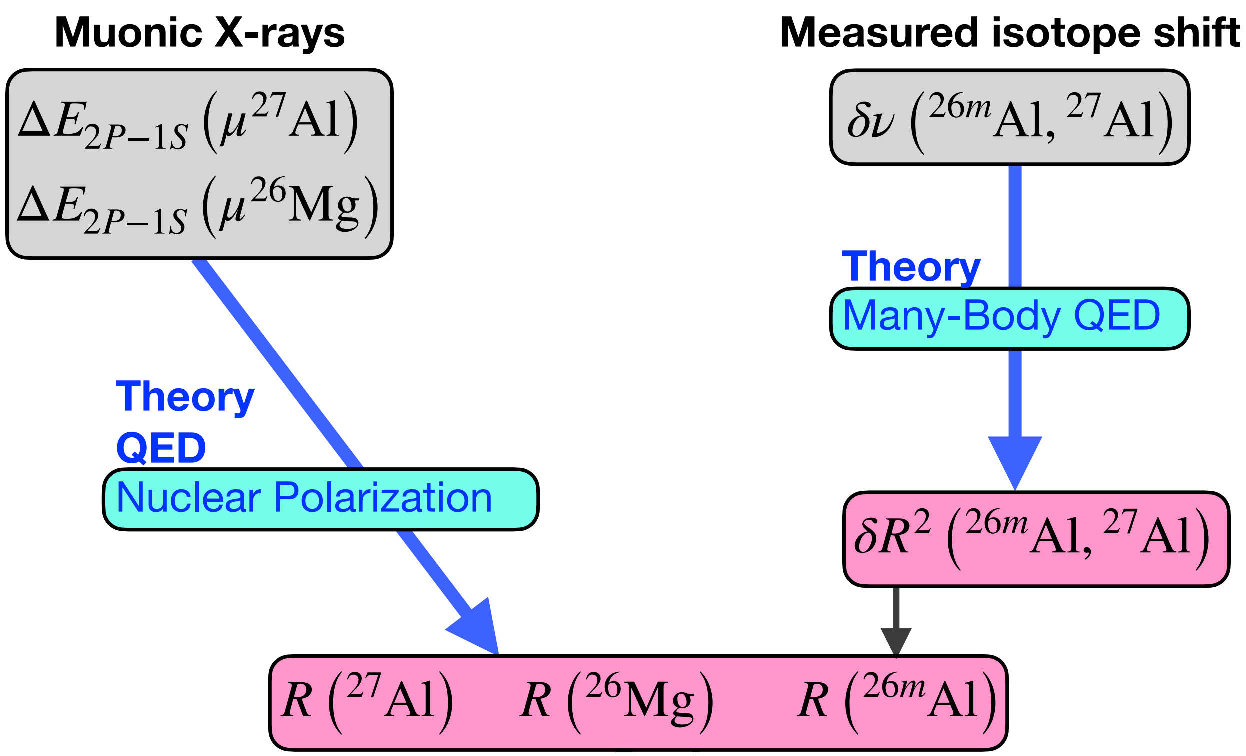
for lightest systems

Li Muli et al, 1910.14370



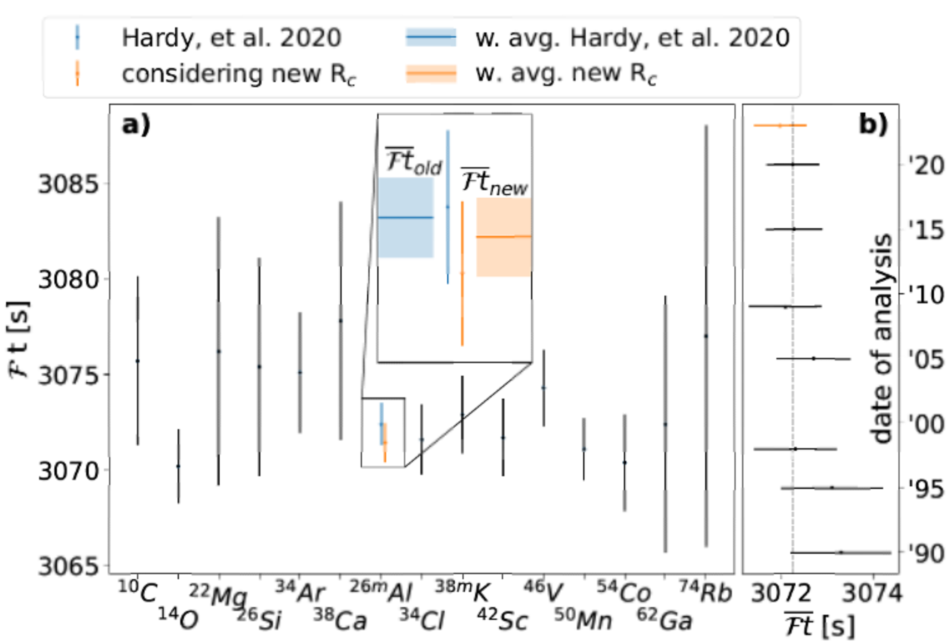
Reference Radii

Isotope Shift & Muonic Atoms



Implications for V_{ud}

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

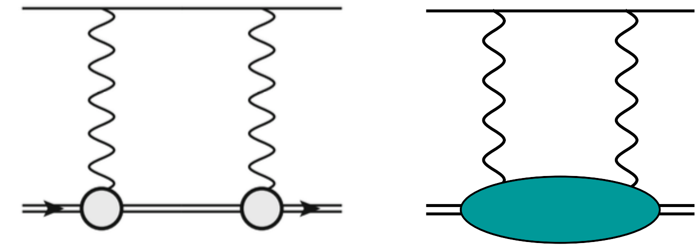


74Rb: Mane et al., Phys. Rev. Lett. 107, 212502 (2011)
26mAl: Plattner et al., Phys. Rev. Lett. 131, 222502 (2023)

see slides M. Gorshteyn

TPE Effect in μH Lamb Shift

$$\Delta E^{\rm TPE}_{nS} = \Delta E^{\rm Born}_{nS} + \Delta E^{\rm inel.}_{nS}(\nu_0) + \Delta E^{\rm subtr.}_{nS}(\nu_0)$$



CROSS CHECK BETWEEN 3 COMPLEMENTARY APPROACHES

Table 1 Forward 2γ-exchange contributions to the 2S-shift in μH, in units of μeV.

Reference	$E^{\rm (subt)}_{2S}$	$E^{\rm (inel)}_{2S}$	$E^{\rm (pol)}_{2S}$	$E^{\rm (el)}_{2S}$	$E^{\langle 2\gamma\rangle}_{2S}$
DATA-DRIVEN					
(73) Pachucki '99	1.9	−13.9	−12(2)	−23.2(1.0)	−35.2(2.2)
(74) Martynenko '06	2.3	−16.1	−13.8(2.9)		
(75) Carlson *et al.* '11	5.3(1.9)	−12.7(5)	−7.4(2.0)		
(76) Birse and McGovern '12	4.2(1.0)	−12.7(5)	−8.5(1.1)	−24.7(1.6)	−33(2)
(77) Gorchtein et al.'13 [a]	−2.3(4.6)	−13.0(6)	−15.3(4.6)	−24.5(1.2)	−39.8(4.8)
(78) Hill and Paz '16					−30(13)
(79) Tomalak'18	2.3(1.3)		−10.3(1.4)	−18.6(1.6)	−29.0(2.1)
LEADING-ORDER BχPT					
(80) Alarcòn *et al.* '14			$-9.6^{+1.4}_{-2.9}$		
(81) Lensky *et al.* '17 [b]	$3.5^{+0.5}_{-1.9}$	−12.1(1.8)	$-8.6^{+1.3}_{-5.2}$		
LATTICE QCD					
(82) Fu *et al.* '22					−37.4(4.9)
Fu et al. '24*			−11.7*		−32.2*

$$\Delta E^{\rm TPE}_{nS} = \underbrace{\Delta E^{\rm Born}_{nS} - \Delta\mathcal{E}^{\rm Born\ subtr.}_{nS}}_{=\Delta\mathfrak{E}^{\rm Born}_{nS}} + \underbrace{\Delta\mathcal{E}^{\rm subtr.}_{nS} + \Delta\mathcal{E}^{\rm Born\ subtr.}_{nS}}_{=\Delta\mathfrak{E}^{\rm subtr.}_{nS}} + \Delta\mathcal{E}^{\rm inel.}_{nS}$$

*our preliminary results based on their LQCD prediction for $\Delta\mathfrak{E}^{\rm subtr.}_{nS} = -7.22(81)(57)\,\mu{\rm eV}$

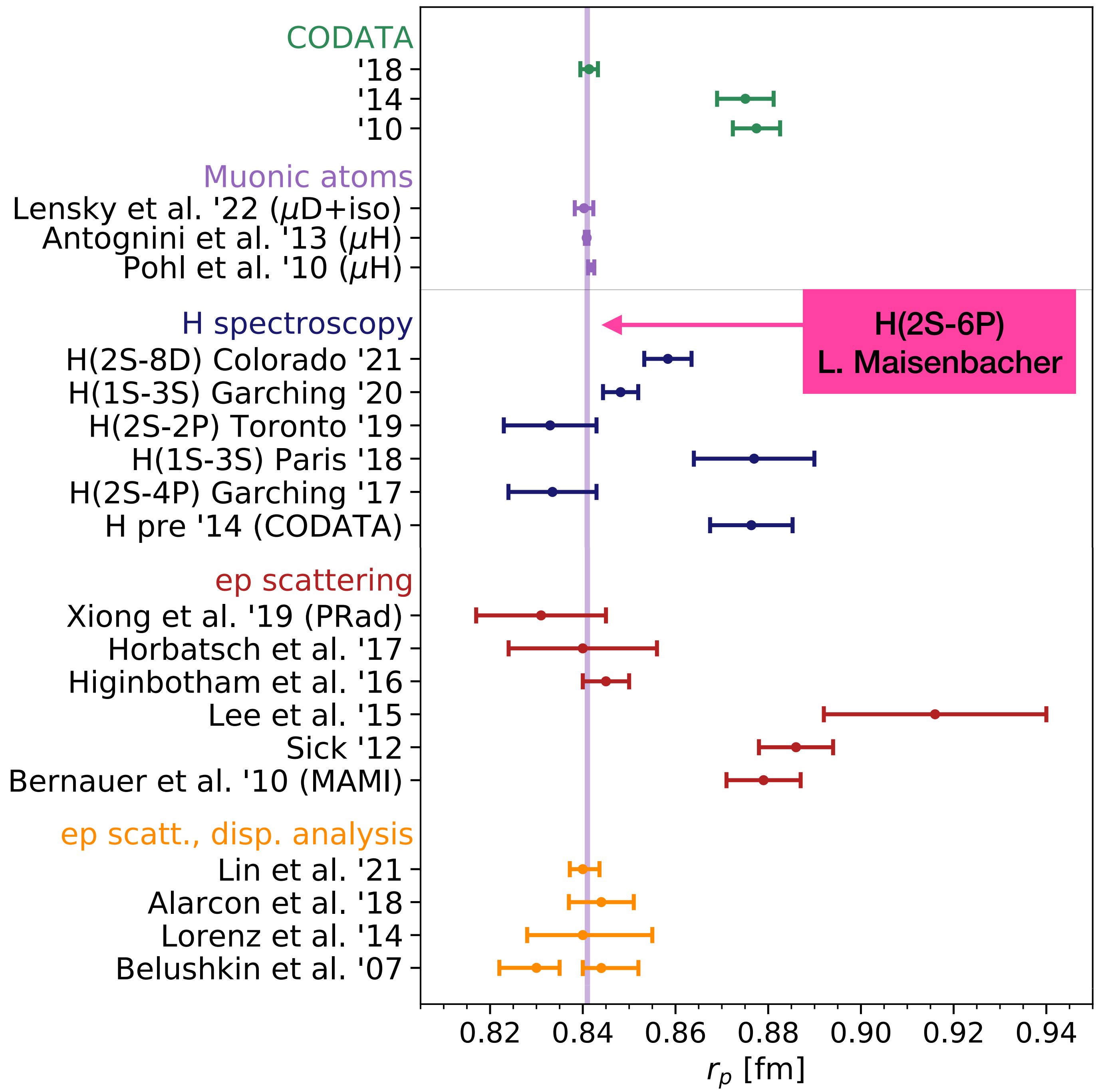
Data-driven dispersive approach

Baryon Chiral Perturbation Theory

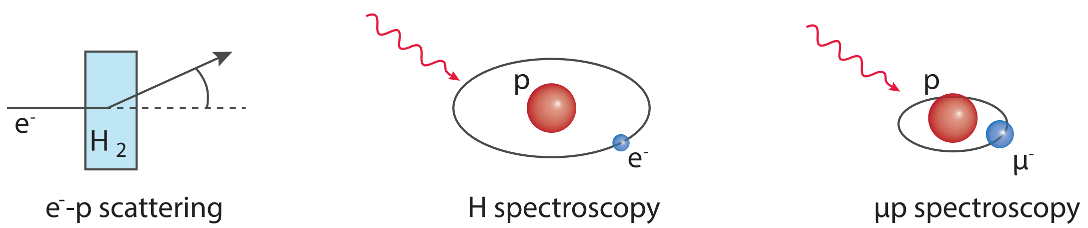
Lattice QCD

(talk by X. Feng)

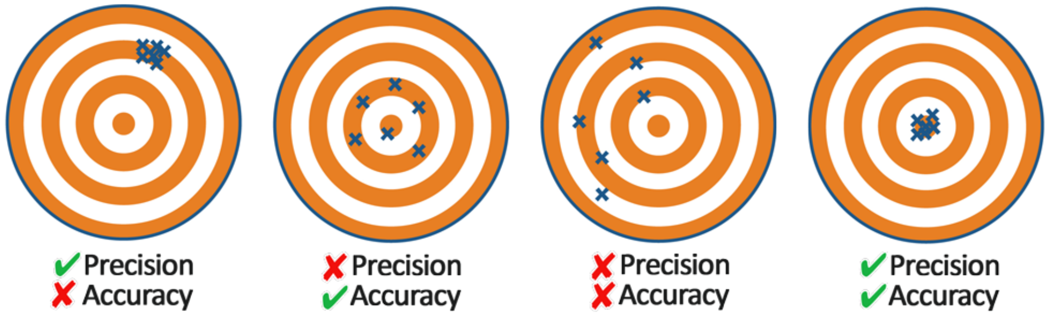
Proton Radius Puzzle



- Complementary experimental approaches:



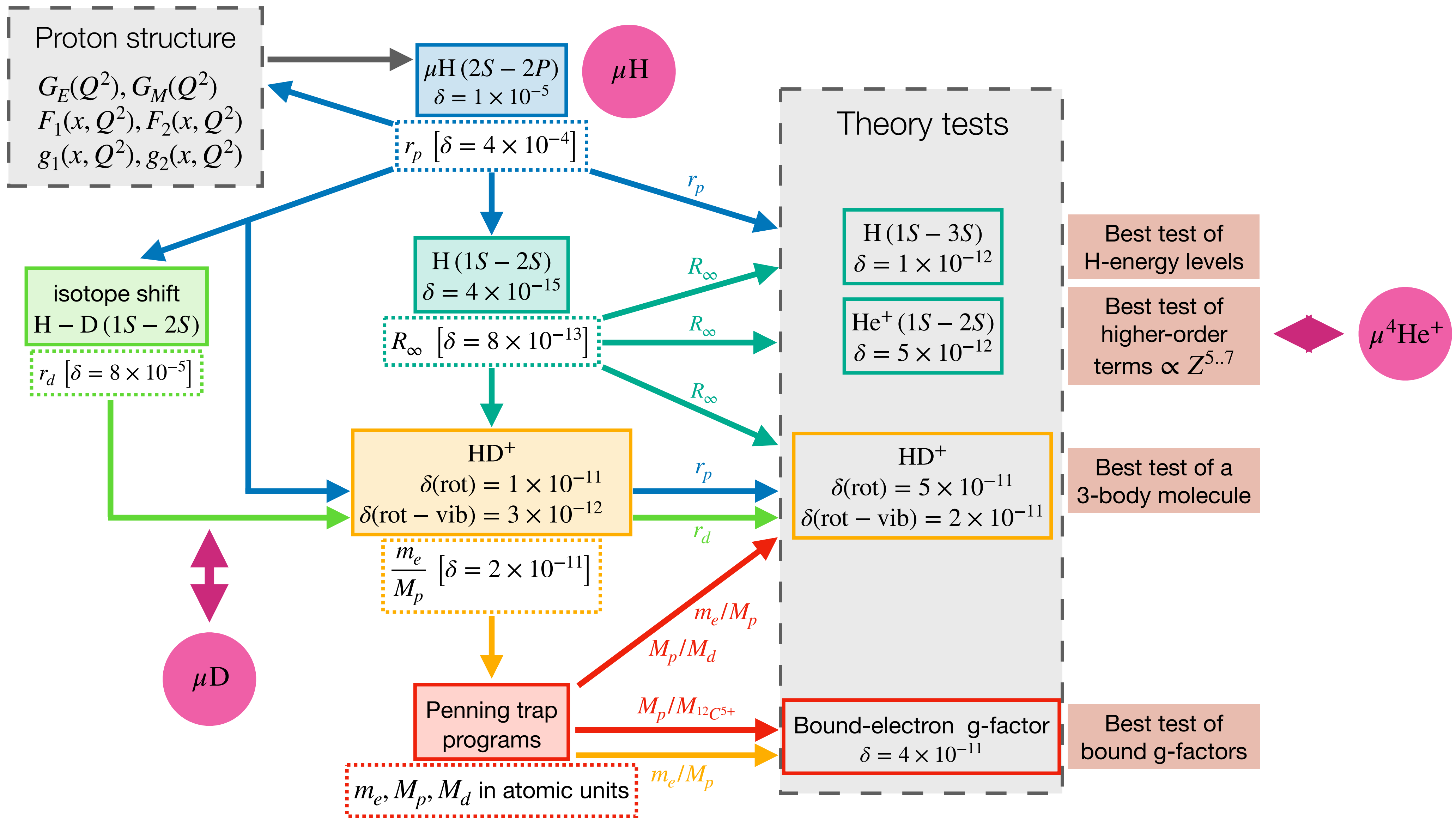
- Muonic atoms allow for PRECISE extractions of nuclear charge and Zemach radii
- CODATA since 2018 included the μH result for r_p
- Still open issues: H(2S-8D) and H(1S-3S)
- Precise and accurate!



Physics at the Precision Frontier

Complementary Measurements, Determination of Fundamental Constants, Theory Tests & BSM Searches

Example $Z = 1{,}2$:



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1S Hyperfine Splitting in μH

- Measurements of the μH ground-state HFS planned
  - FAMU results in summer? [EPJA (2025) 61:284]
  - CREMA aims at 10^{-7} accuracy
- Very precise input for the 2-photon-exchange effect needed to narrow down frequency search range for experiment
- Predictions for HFS in μH are driven by 1S HFS in H

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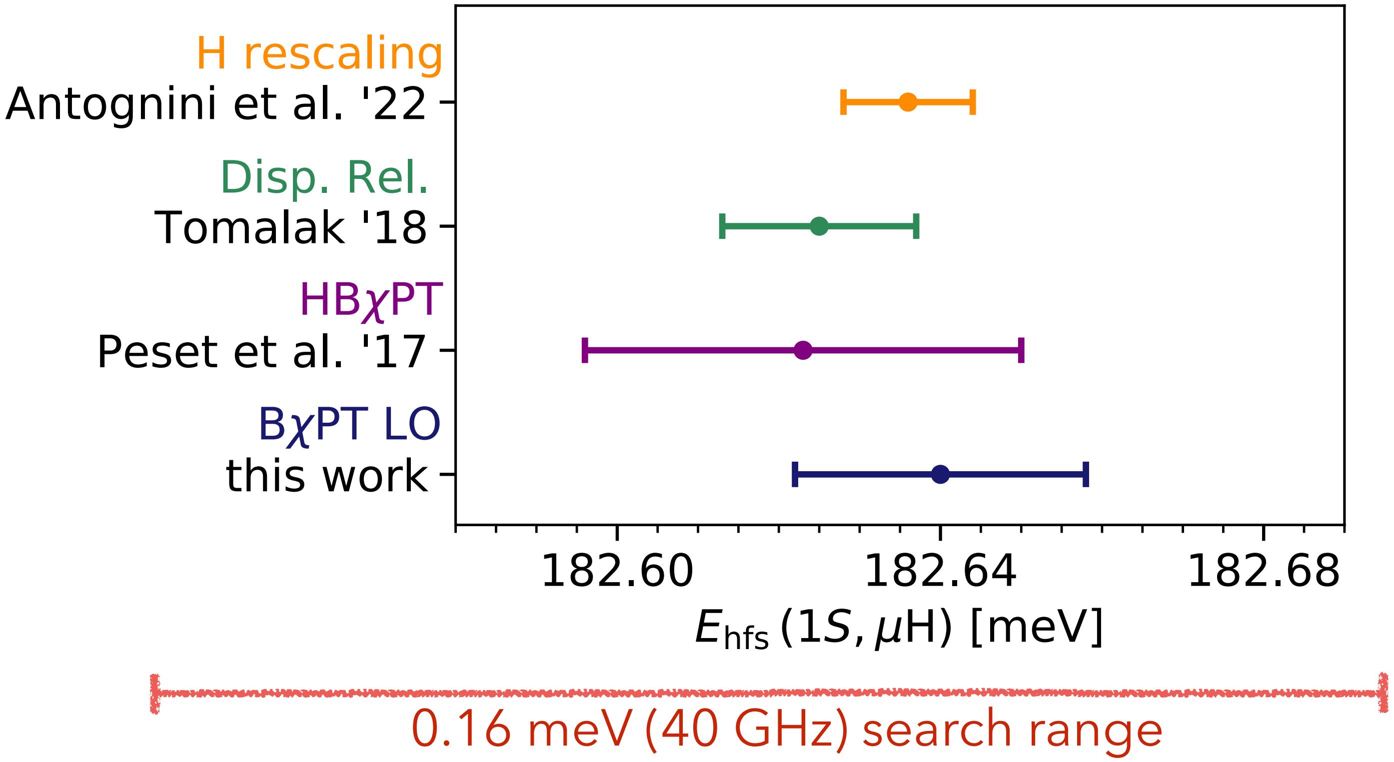
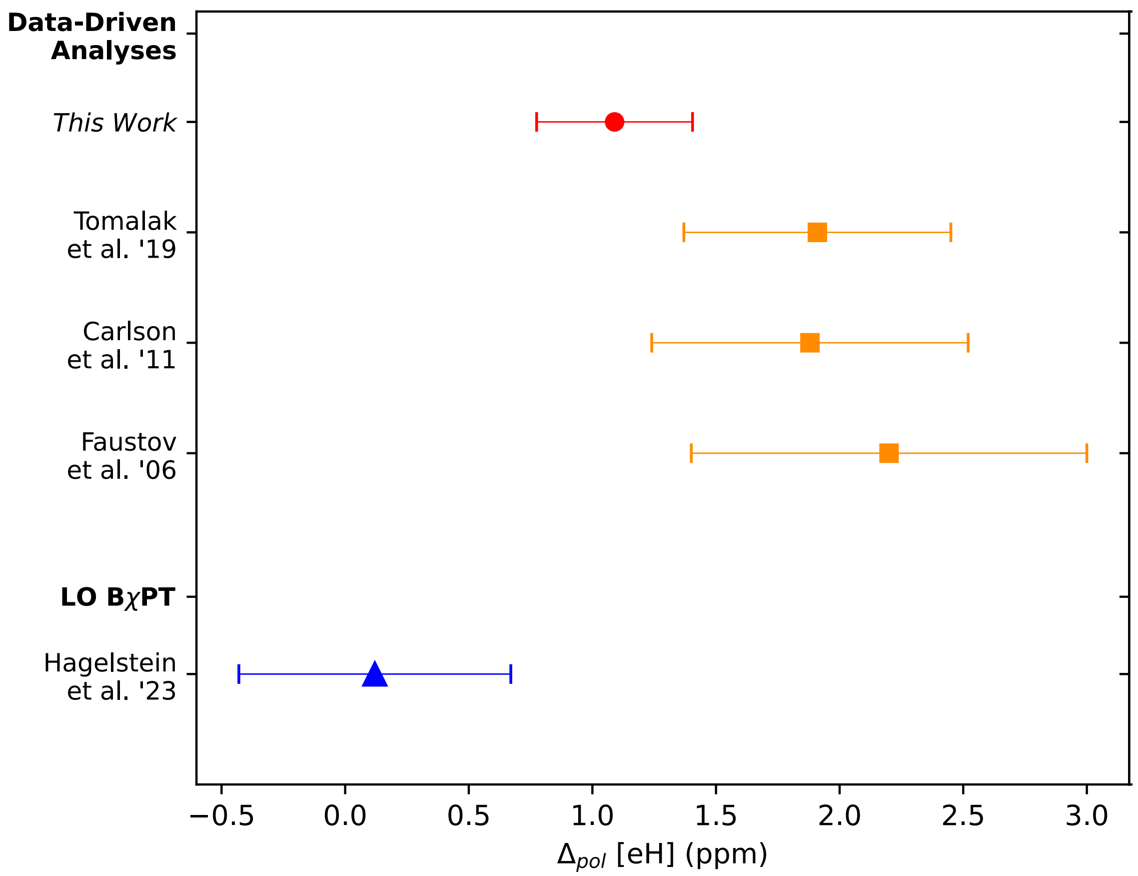


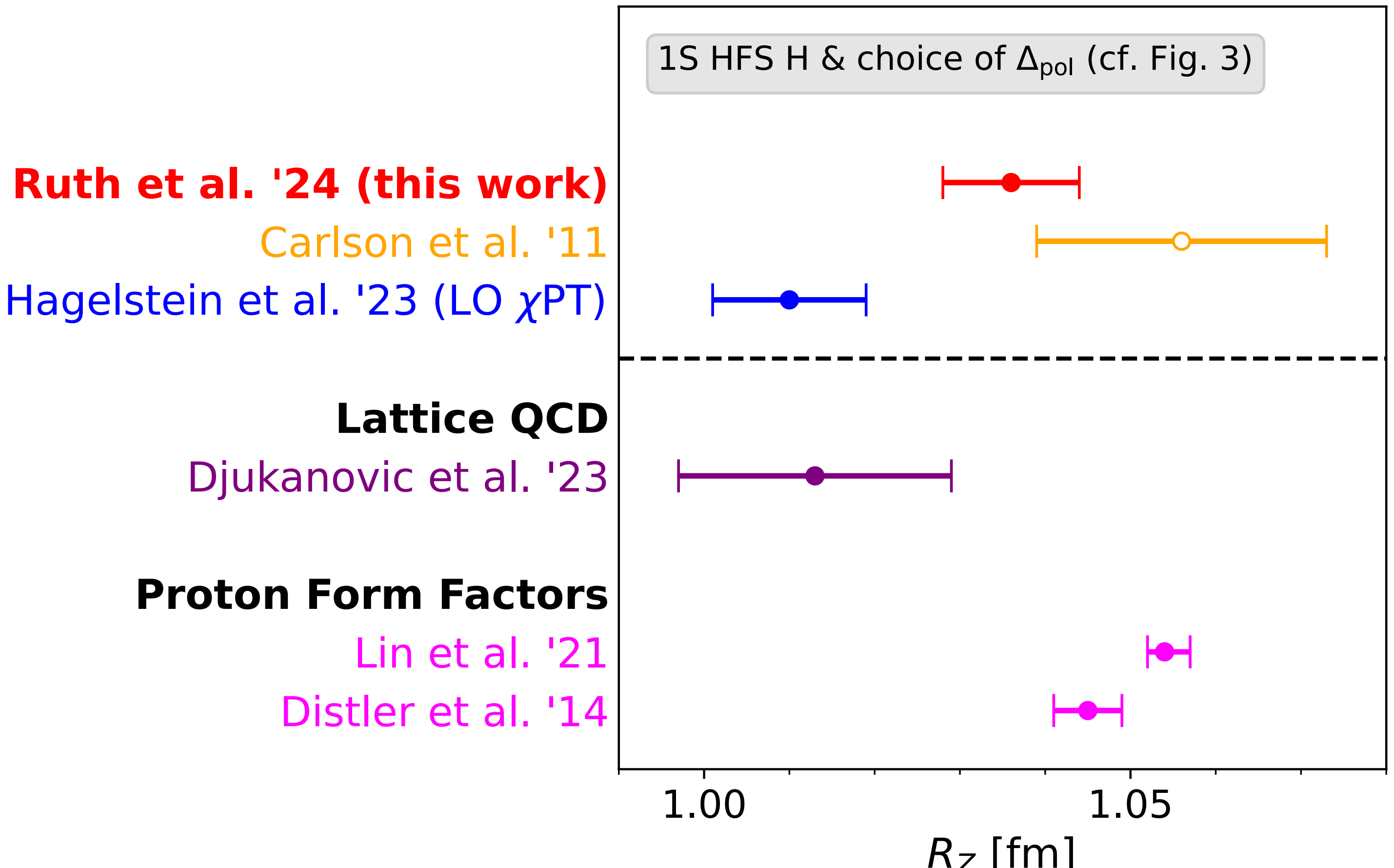
Proton Zemach Radius



- Discrepancy between data-driven and BChPT predictions of the polarizability effect in the (muonic-)hydrogen hyperfine splitting

CAREFUL ASSESSMENT OF THEORETICAL UNCERTAINTIES AND MODEL DEPENDENCE

THEORY COMPLEMENTS UNMEASURED DATA REGIONS



- BChPT polarizability prediction implies smaller Zemach radius (smaller, just like the charge radius)

Thank you for your attention!