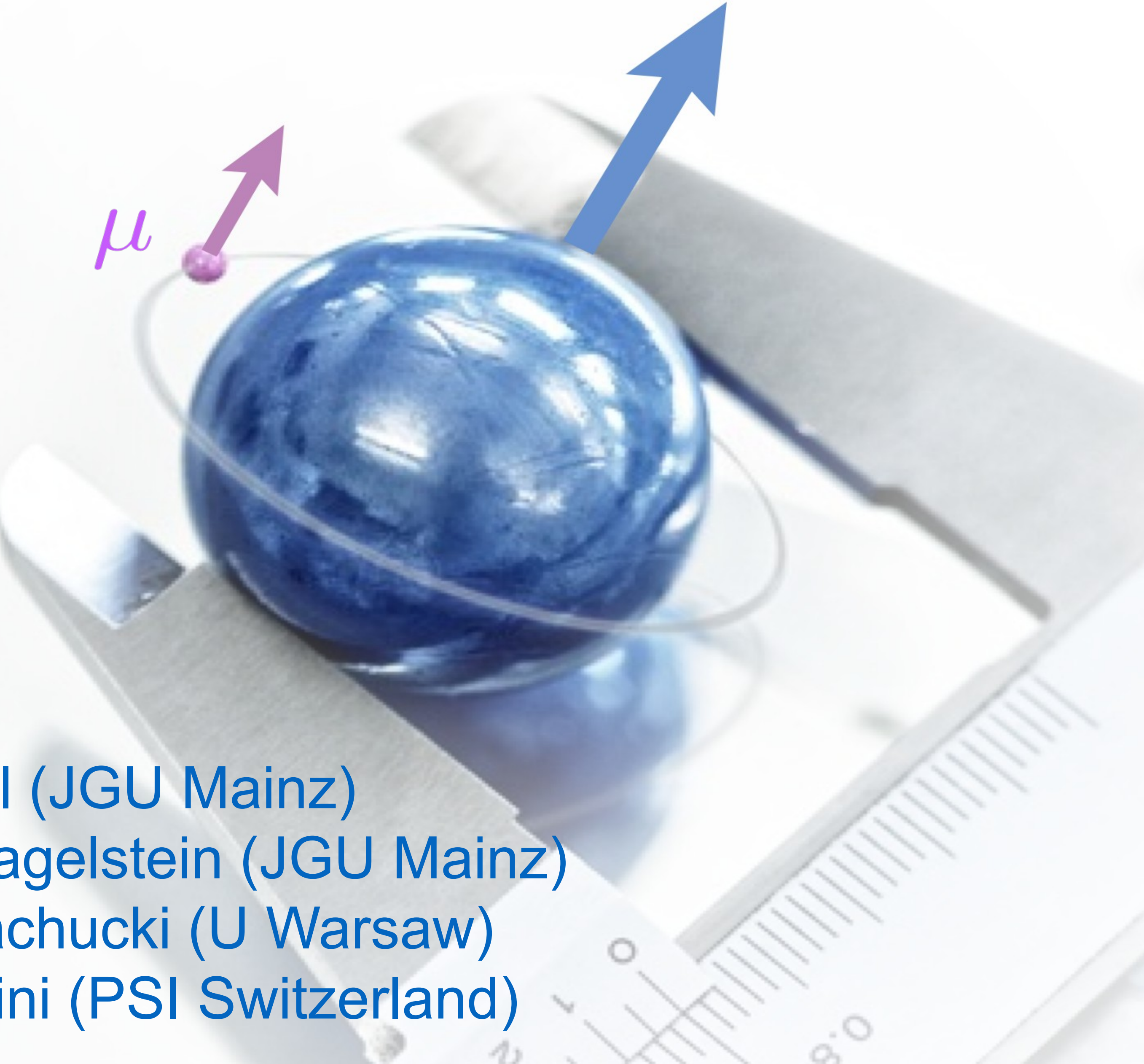
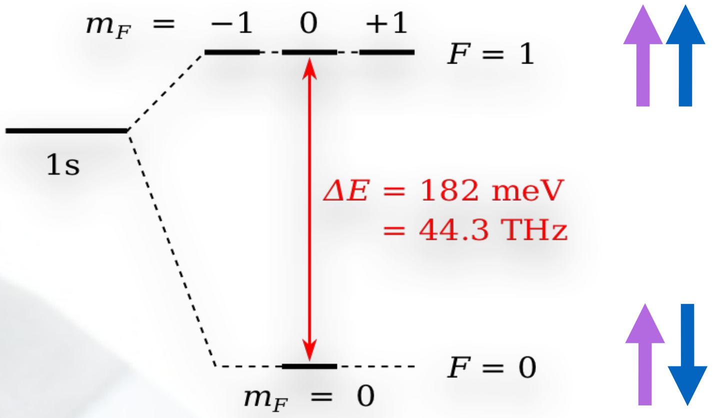
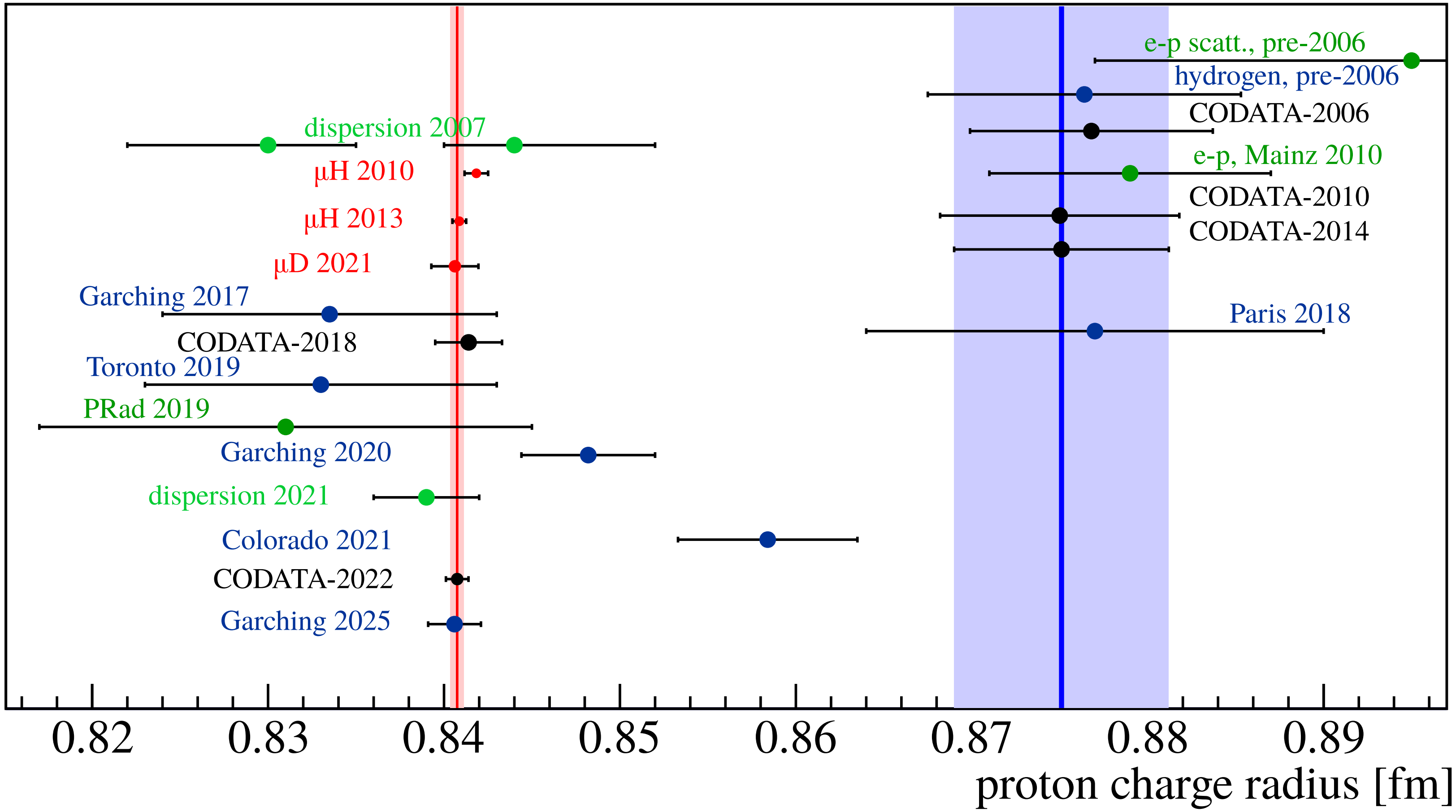
MagP: Magnetic properties of the proton and deuteron





Randolf Pohl (JGU Mainz)
Franziska Hagelstein (JGU Mainz)
Krzysztof Pachucki (U Warsaw)
Aldo Antognini (PSI Switzerland)

Muonic Hydrogen and the Proton CHARGE Radius



e-p scattering

slope of G_E at $Q^2 = 0$

$$r_p^2 \equiv -6 \frac{d\,G_E}{d\,Q^2}\bigg|_{Q^2=0}$$

hydrogen spectroscopy

muonic atoms

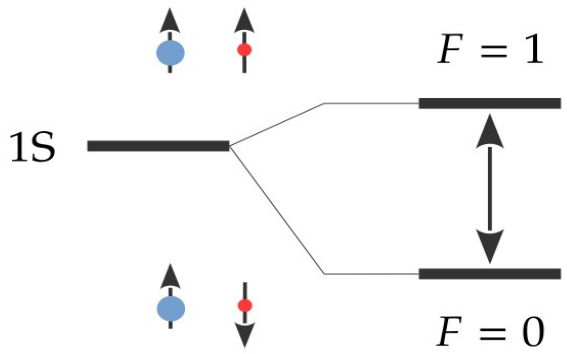
Lamb shift

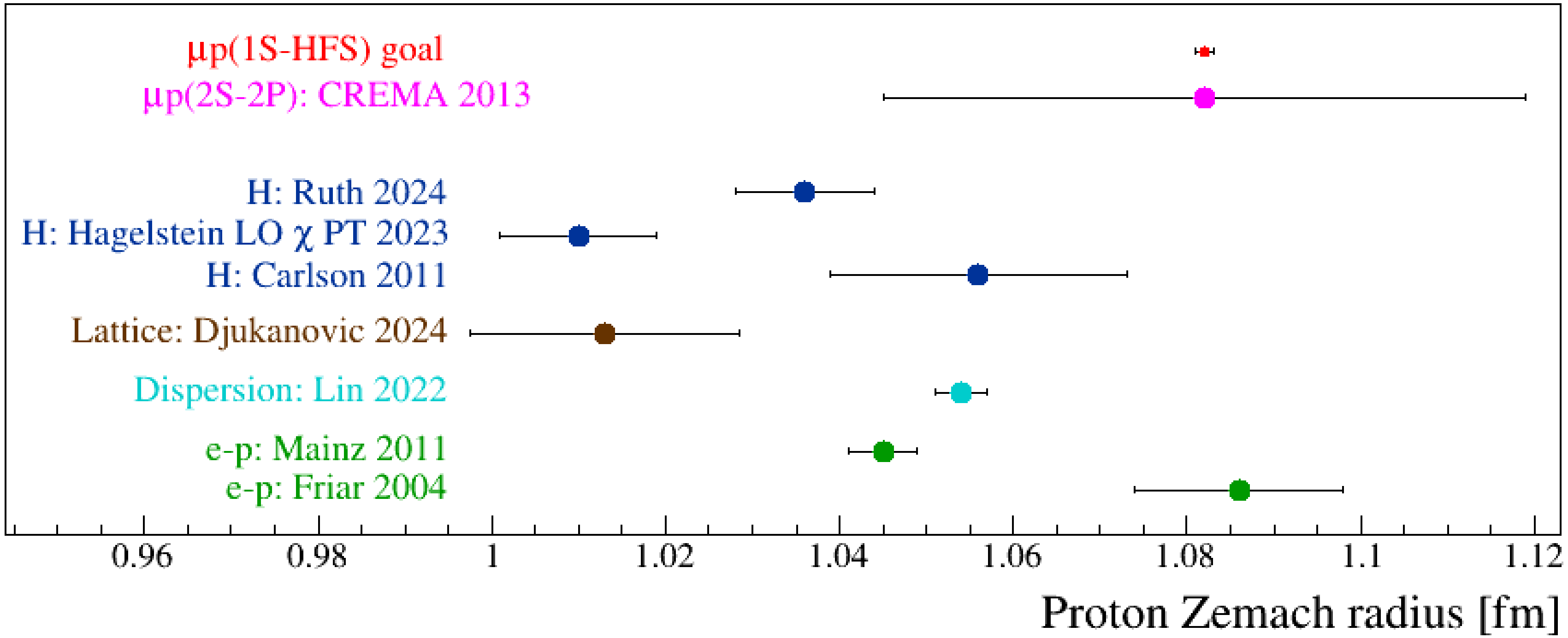
$$\Delta E = \frac{2}{3}\pi\alpha\,|\Psi_S(0)|^2 r_p^2$$

CODATA / PDG average

Magnetic properties of the proton

Hyperfine splitting

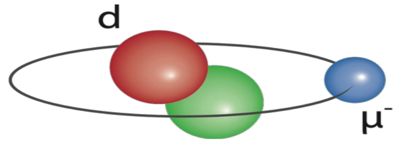


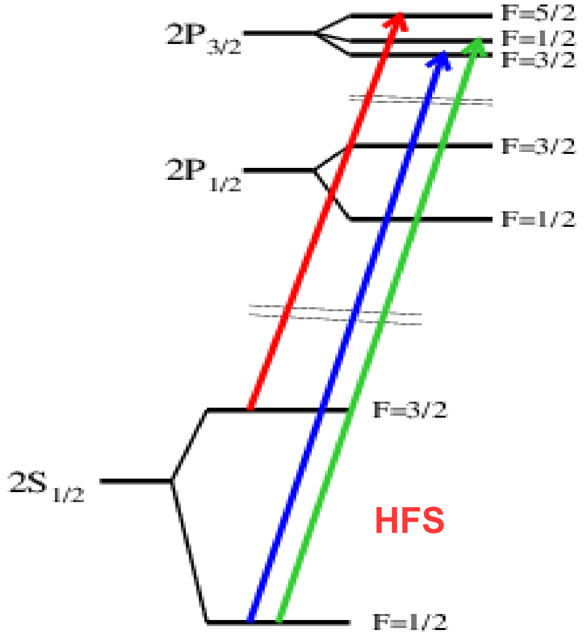


Zemach radius (elastic two-photon contribution)

$$r_Z = \frac{8\,Z\,\alpha\,m_r}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[\frac{G_E(Q^2) G_M(Q^2)}{1+\kappa_N} - 1 \right]$$

HFS in muonic **Deuterium**





PHYSICAL REVIEW A **98**, 062513 (2018)

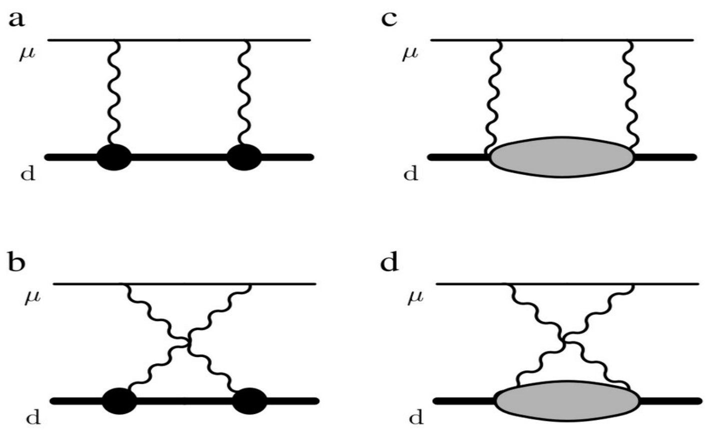
Nuclear-structure corrections to the hyperfine splitting in muonic deuterium

Marcin Kalinowski* and Krzysztof Pachucki†
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

Vladimir A. Yerokhin
Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

(Received 15 October 2018; revised manuscript received 7 November 2018; published 17 December 2018)

Nuclear structure corrections of orders $Z\alpha\, E_F$ and $(Z\alpha)^2 E_F$ are calculated for the hyperfine splitting of the muonic deuterium. The obtained results disagree with previous calculations and lead to a 5 σ disagreement with the current experimental value of the 2S hyperfine splitting in muonic deuterium.



5σ disagreement between theory and experiment !!!

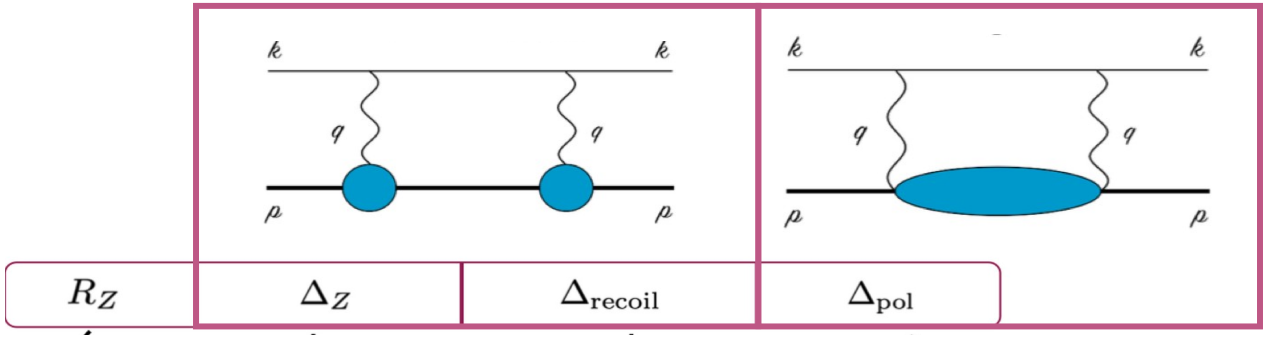
probably 2-photon exchange on the deuteron

1S Hyperfine Splitting in Muonic Hydrogen

$$E_{1S\text{-HFS}}(\mu\mathrm{H}) = \Big[\underbrace{182.443}_{E_F}\ \underbrace{+1.350(7)}_{\text{QED+weak}}\ \underbrace{+0.004}_{\text{hVP}}\ \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_F\left(1.01656(4)\,\Delta_{\text{recoil}} + 1.00402\,\Delta_{\text{pol}}\right)}_{2\gamma\text{ incl. radiative corr.}}\Big]\,\text{meV}$$

Two-photon exchange contributions

→ Franziska Hagelstein
+ PhD



1S Hyperfine Splitting in Muonic Hydrogen

$$E_{1S\text{-HFS}}(\mu\mathrm{H}) = \Big[\underbrace{182.443}_{E_F}\ \underbrace{+1.350(7)}_{\text{QED+weak}}\ \underbrace{+0.004}_{\text{hVP}}\ \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_F\left(1.01656(4)\,\Delta_{\text{recoil}} + 1.00402\,\Delta_{\text{pol}}\right)}_{2\gamma\ \text{incl. radiative corr.}}\Big]\,\text{meV}$$

Two-photon exchange contributions

→ Franziska Hagelstein
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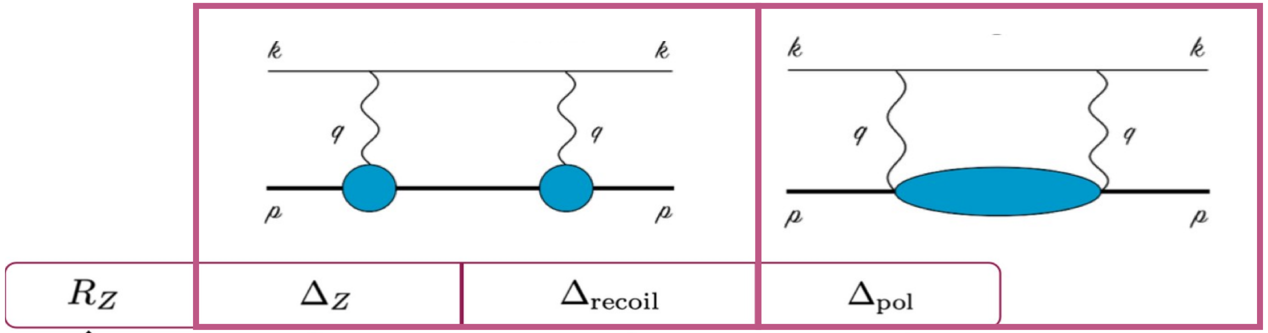


Radiative two-photon, Three-photon corrections

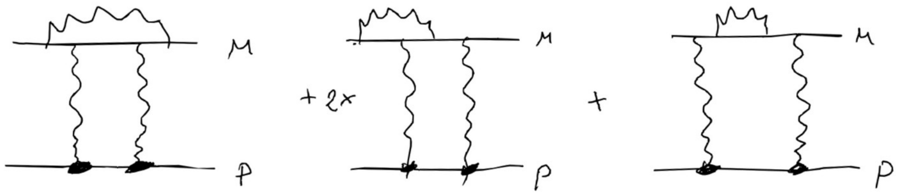
$$E_F\,(\,1 + \alpha/2\pi + Z\alpha\,\delta^{(1)} + (Z\alpha)^2\,\delta^{(2)} + \alpha(Z\alpha)\,\delta^{(1)}_{\text{rad}} + \ldots$$

→ Krzysztof Pachucki
+ PhD

3-photon

radiative 2-photon

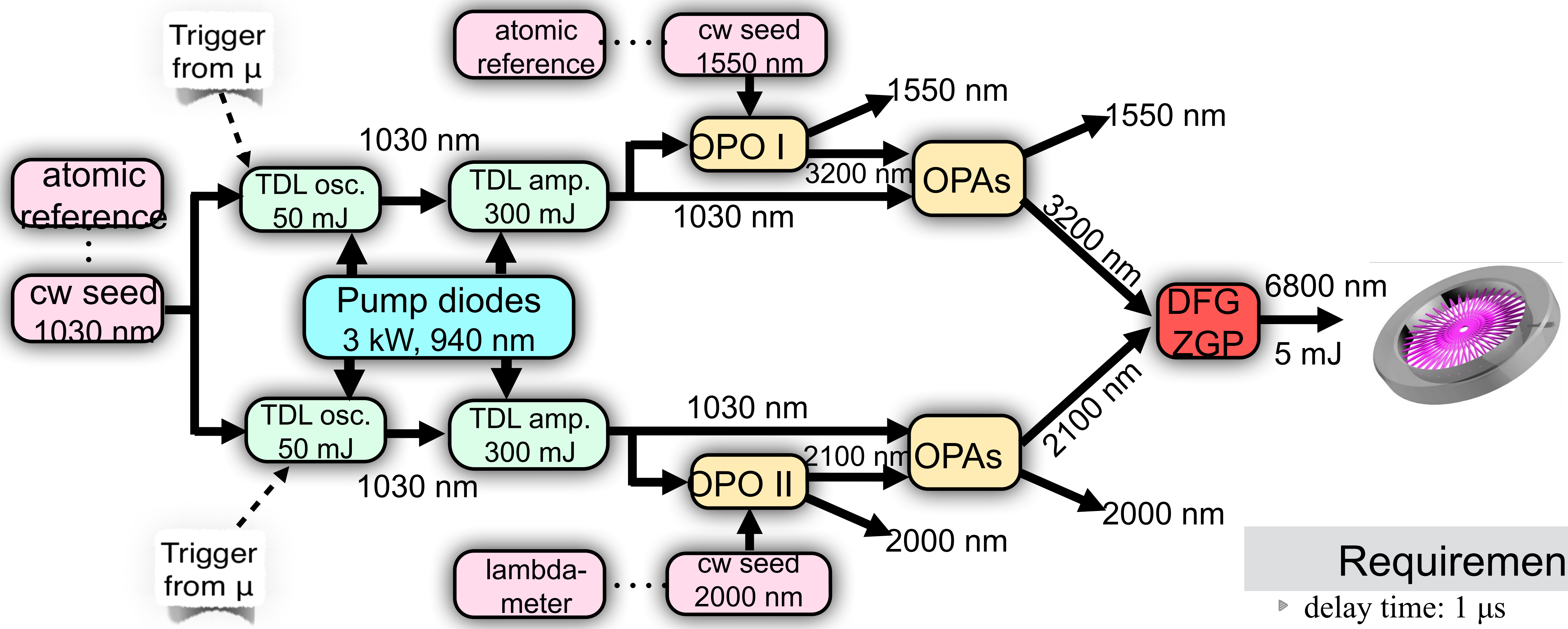
$$\delta^{(2)} = \delta^{(2,0)} + m_\mu/M_p\,\delta^{(2,1)}$$



difficult,

K.P. PRA 109, 052822 (2024)

HyperMu@PSI Experiment: The Laser System

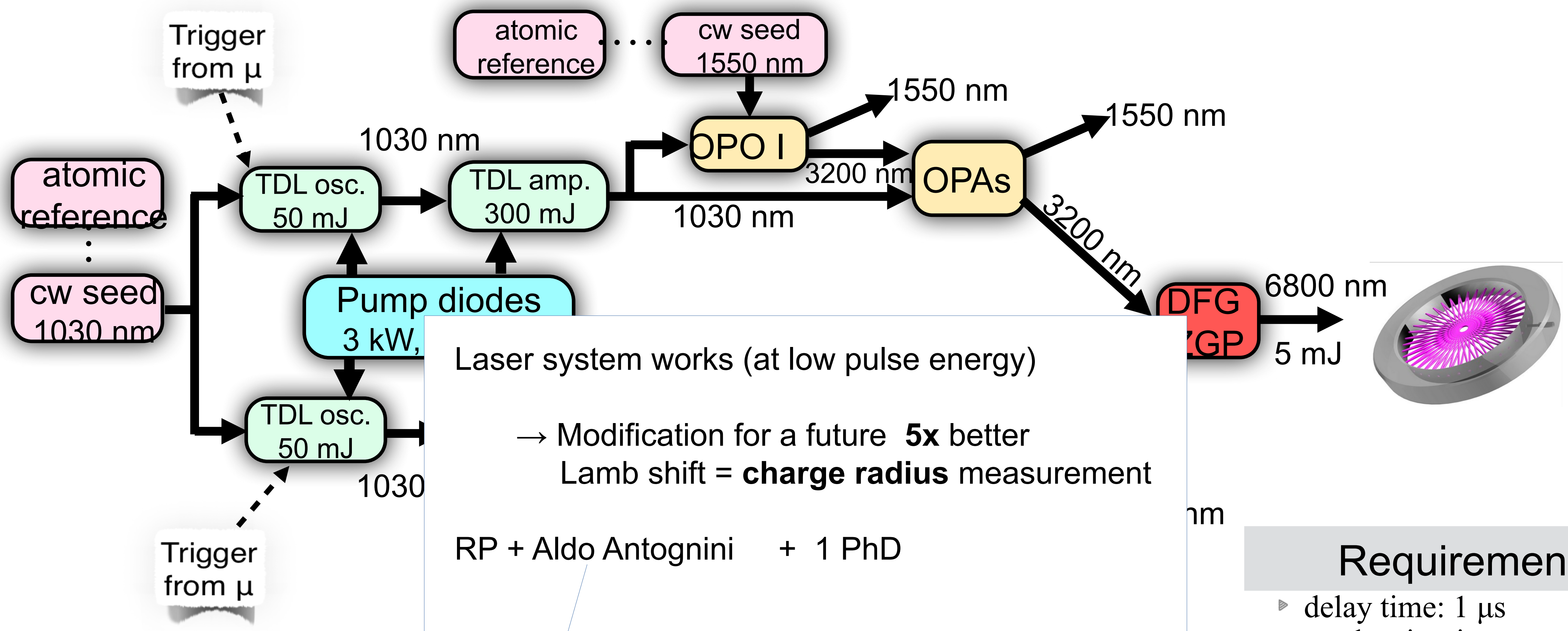


Requirements

- delay time: 1 µs
- stochastic trigger
- energy: 5 mJ
- repetition rate: 200 1/s
- wavelength: 6.8 µm
- bandwidth: < 100 MHz

Same technology will allow improving on the Lamb shift measurements

HyperMu@PSI Experiment: The Laser System



Laser system works (at low pulse energy)

→ Modification for a future **5x** better
Lamb shift = **charge radius** measurement

RP + Aldo Antognini + 1 PhD

Requirements

- delay time: 1 µs
- stochastic trigger
- energy: 5 mJ
- repetition rate: 200 1/s
- wavelength: 6.8 µm
- bandwidth: < 100 MHz

Same technology will allow improving on the Lamb shift measurements

Summary

HyperMu experiment at PSI aims at a measurement of the HFS in muonic hydrogen.
→ Zemach radius, $G_E + G_M$

1 PhD student (theo) for nuclear two-photon exchange (Franziska Hagelstein)

1 PhD student (theo) for higher-order mixed QED + nuclear corr. (Krzysztof Pachucki)

1 PhD student (exp) for data taking + laser development for a future better charge radius

(DFG: 61,200 EUR p.a.)

200 kEUR for laser development: laser crystals (Yb:YAG), nonlinear crystals (PPLN, ZGP)

280 kEUR for travel (data taking, laser development at PSI) → TNA for PSI?

15 kEUR for one workshop on “nuclear precision physics for hyperfine splitting”

dream: total 1536 kEUR (incl. 25% indirect costs)

Backup

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]
[1] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*
[3] *Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[4] *Helmholtz-Institut Mainz, Johannes Gutenberg Universität Mainz, 55099 Mainz, Germany*
[5] *Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

(Dated: May 19, 2023) Rev. Mod. Phys. **96** (2024) 1, 015001

E_{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_{NS}	nuclear structure	0.028 9(25)	1.750 3(200)	15.499(378)	9.276(433)
$E_L(\mathrm{exp})$	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)

μH: present accuracy comparable with experimental precision

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

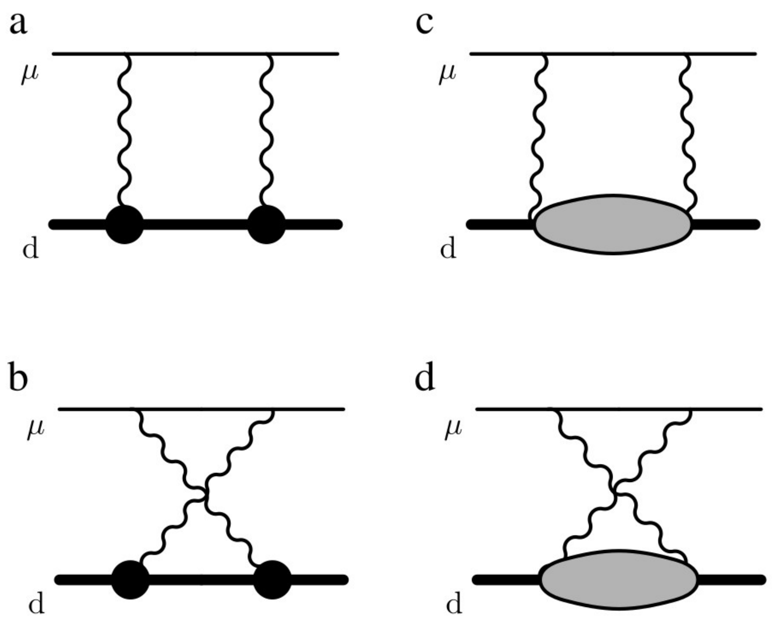
- Experiments will improve by up to a factor of 5
- Theoretical improvement needed for nuclear/nucleon 2- and 3-photon exchange

Theory: Lamb shift in muonic D

$\Delta E_{\text{Lamb}}^{\mu D} = 228.7740\ (3)\ \text{meV}_{\text{QED}} + 1.7503\ (\mathbf{200})\ \text{meV}_{\text{TPE}} - 6.1074\ \ \text{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$

$$\Delta E_{\text{LS}}^{\text{exp}} = 202.8785(31)_{\text{stat}}(14)_{\text{syst}}\ \text{meV}$$

Nuclear structure two (and three!)-photon contributions to the Lamb shift in muonic deuterium.



Pachucki, RP et al, arXiv 2212.13782

see also Krauth, RP et al. (2016) using calculations from
Pachucki (2011), Friar (2013), Carlson, Gorchtein, Vanderhaeghen (2014), Hernandez et al. (2014), Pachucki + Wienczek (2015)

+ Pachucki et al., PRA 97, 062511 (2018): Sizeable three-photon !!

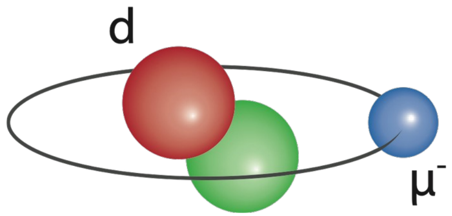
+ Hernandez et al., PLB 778, 377 (2018): χEFT

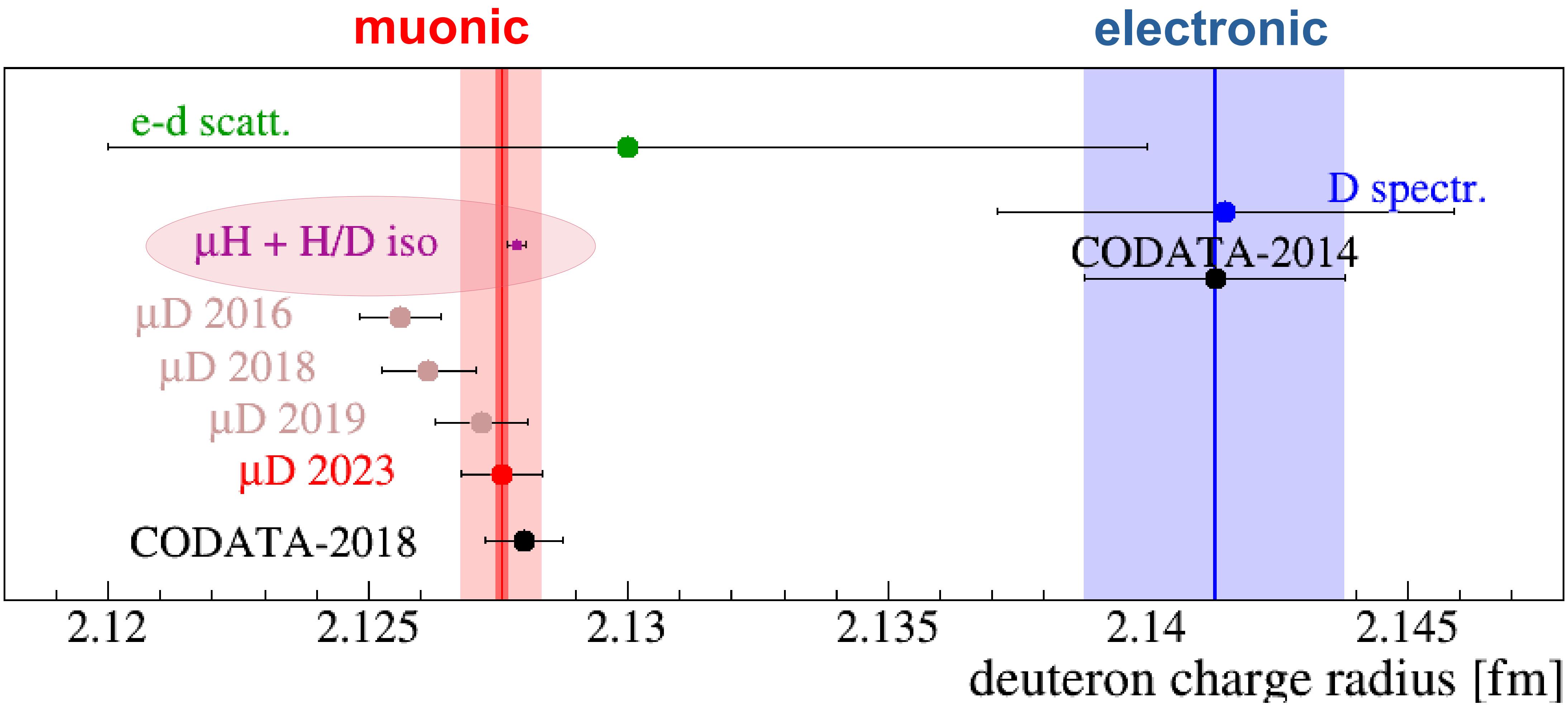
+ Kalinowski (2019): eVP to nucl. struct.

+ Acharya et al., PRC 103, 024001 (2021)
χEFT + Disperson relations

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

Muonic Deuterium





μD: 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

μH + H/D(1S-2S): 2.12785 (17) fm

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7740\ (3)\ \mathrm{meV}_{QED} + 1.7503\ (\mathbf{200})\ \mathrm{meV}_{TPE} - 6.1074\ \ \mathrm{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$$

ΔE_{TPE} (theo) = 1.7503 +- 0.0200 meV **Bacca group**

vs. +- 0.0034 meV experimental uncertainty

(1) **charge radius**, using **calculated TPE**

r_d (μD) = 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

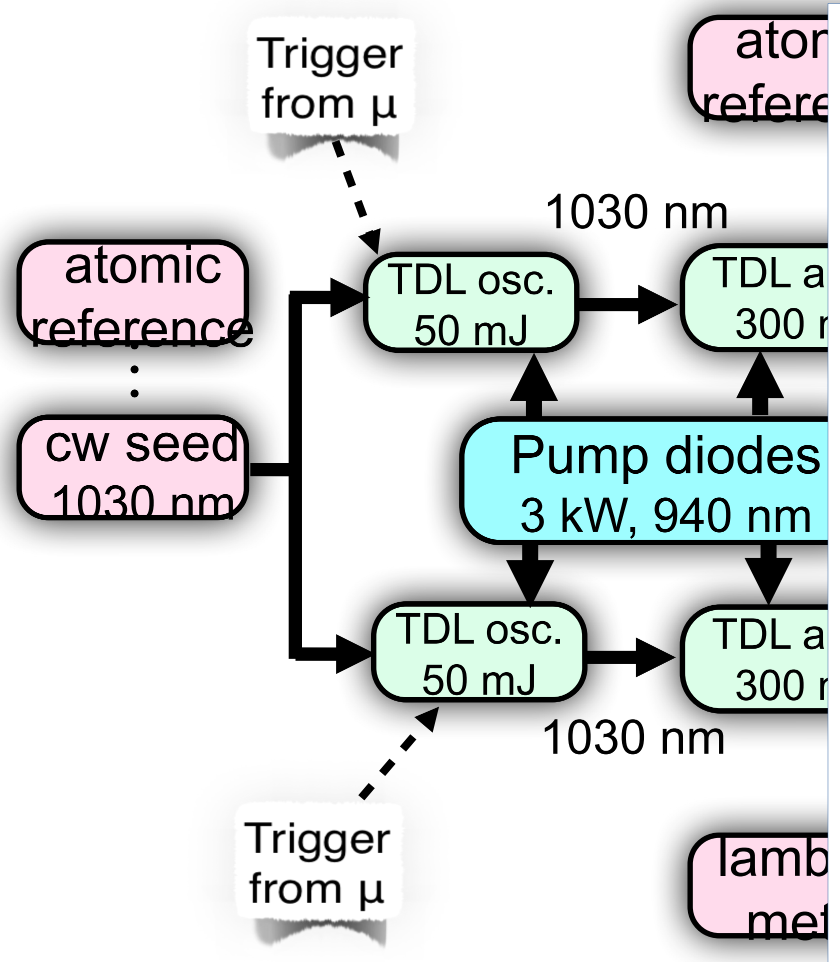
(2) **polarizability**, using **charge radius from isotope shift**

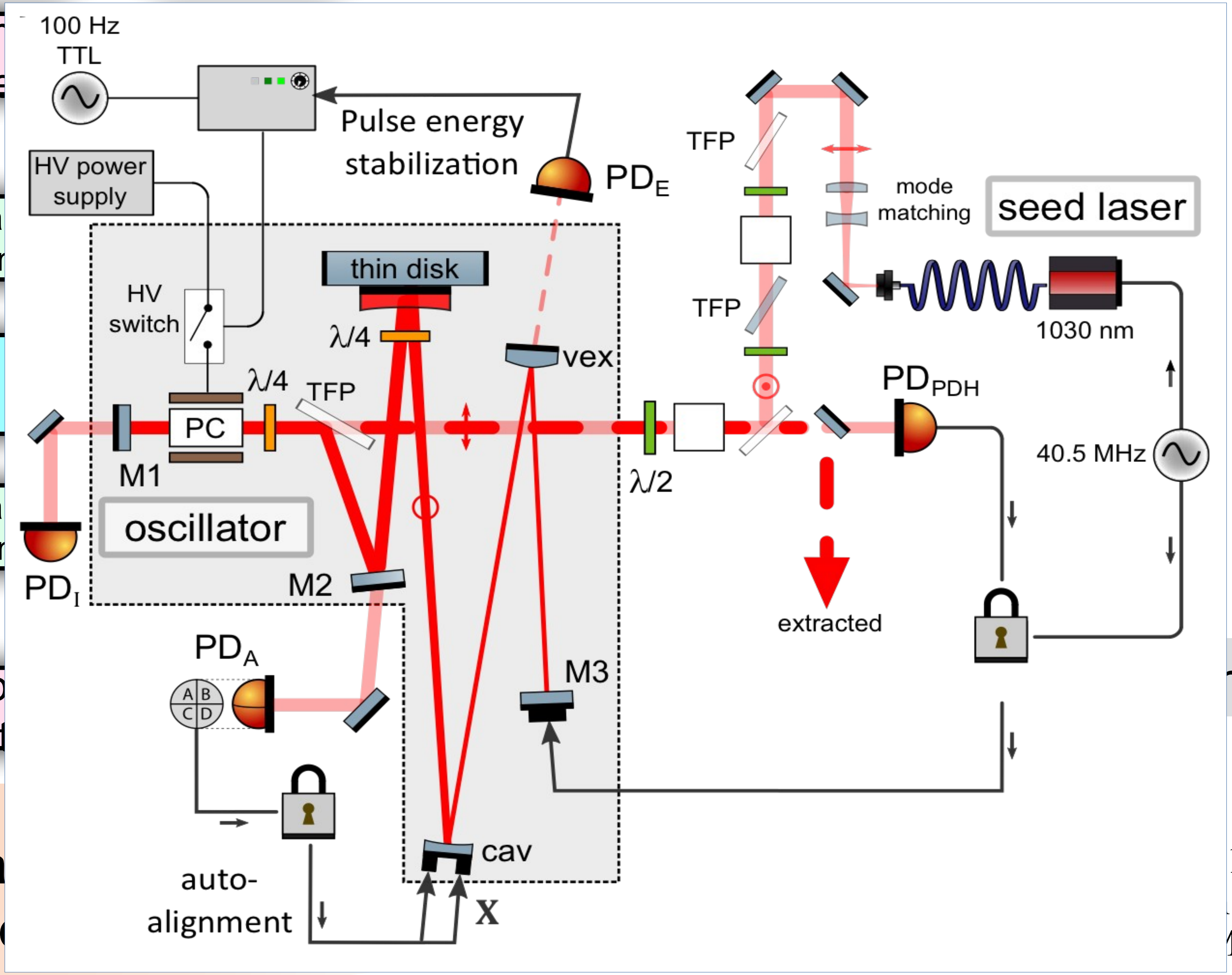
ΔE_{TPE} (theo) = 1.7503 (200) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3x more accurate

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

The HyperMu Laser System





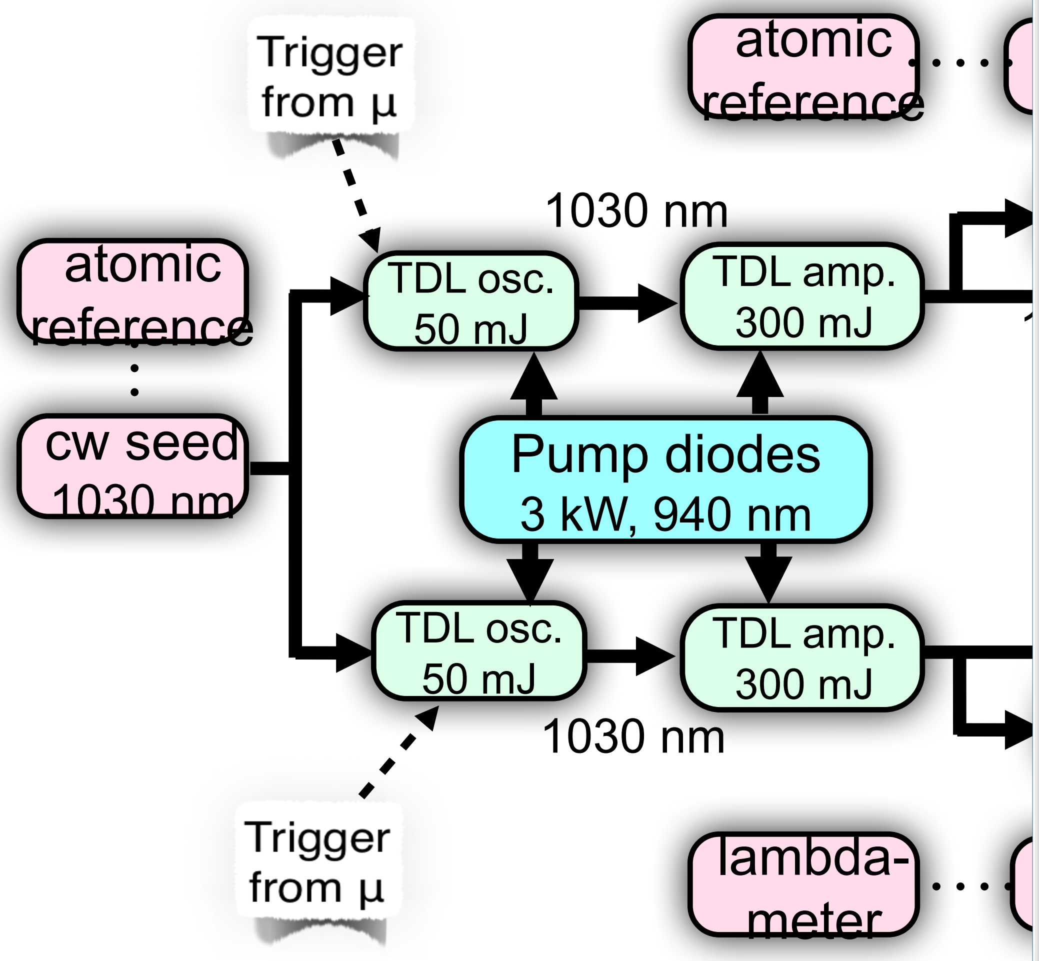
nts

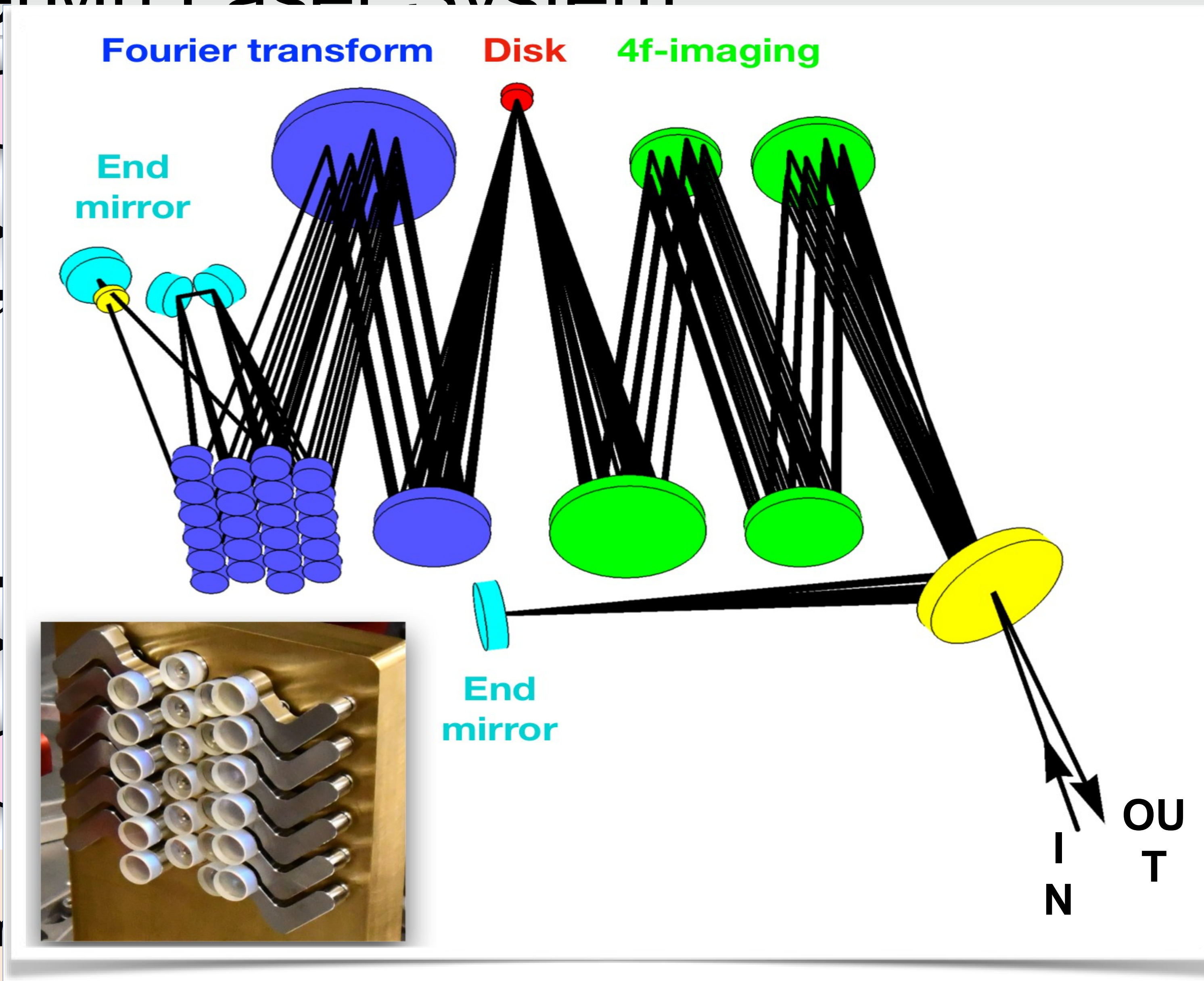
1/s

MHz

Same technology will a
Lamb shift m

The HyperMu Laser System



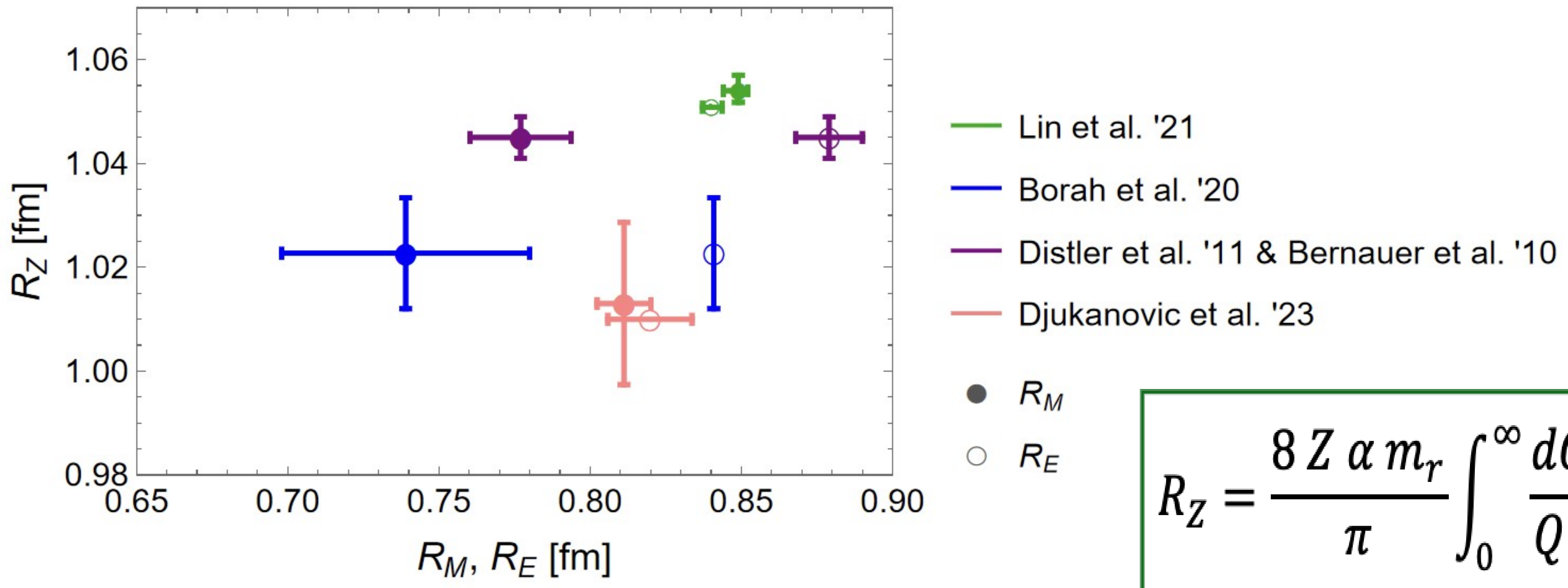


Same technology will allow im
Lamb shift measurements

1S Hyperfine Splitting in Muonic Hydrogen

$$E_{1S\text{-HFS}}(\mu H) = \Big[\underbrace{182.443}_{E_F} \underbrace{+1.350(7)}_{\text{QED+weak}} \underbrace{+0.004}_{\text{hVP}} \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_F\left(1.01656(4)\,\Delta_{\text{recoil}} + 1.00402\,\Delta_{\text{pol}}\right)}_{2\gamma \text{ incl. radiative corr.}}\Big]\,\text{meV}$$

- Zemach radius allows to pin down magnetic properties of the proton

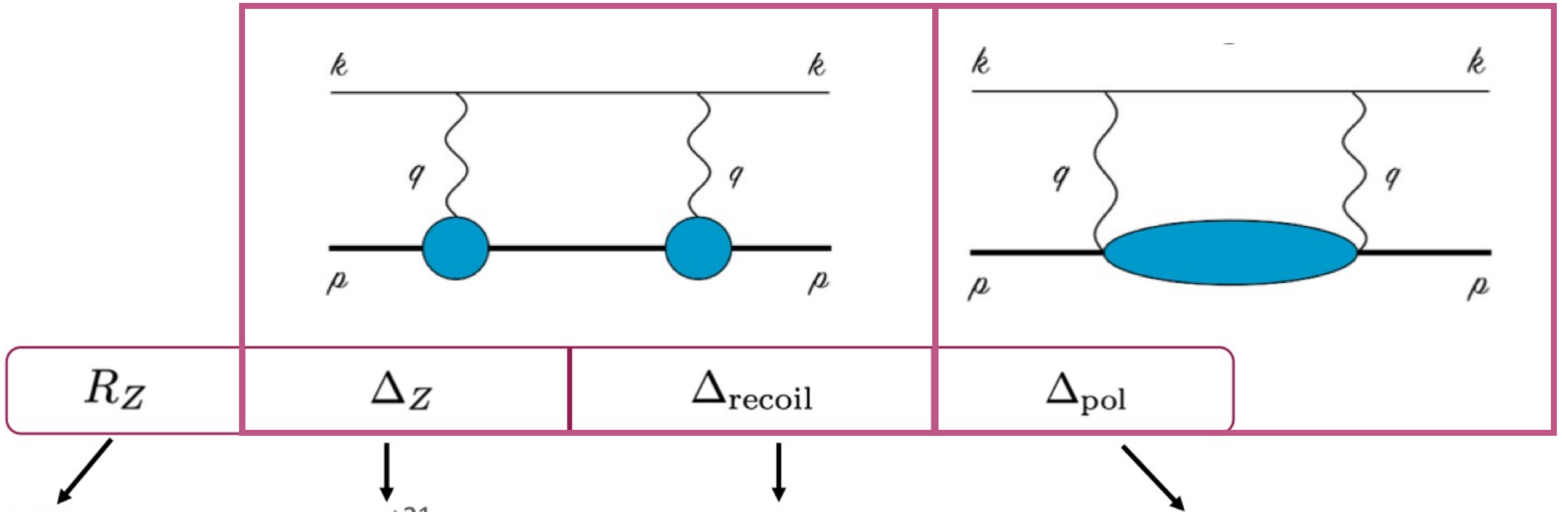


$$R_Z = \frac{8\,Z\,\alpha\,m_r}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\kappa} - 1\right]$$

1S Hyperfine Splitting in Muonic Hydrogen

$$E_{1S\text{-HFS}}(\mu\mathrm{H}) = \Big[\underbrace{182.443}_{E_\mathrm{F}} \underbrace{+1.350(7)}_{\text{QED+weak}} \underbrace{+0.004}_{\text{hVP}} \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\mathrm{fm}}\right) + E_\mathrm{F}\left(1.01656(4)\,\Delta_\mathrm{recoil} + 1.00402\,\Delta_\mathrm{pol}\right)}_{2\gamma\text{ incl. radiative corr.}}\Big]\,\mathrm{meV}$$

- Zemach radius allows to pin down magnetic properties of the proton
- Theory prediction is limited by two-photon-exchange (2γ) contributions



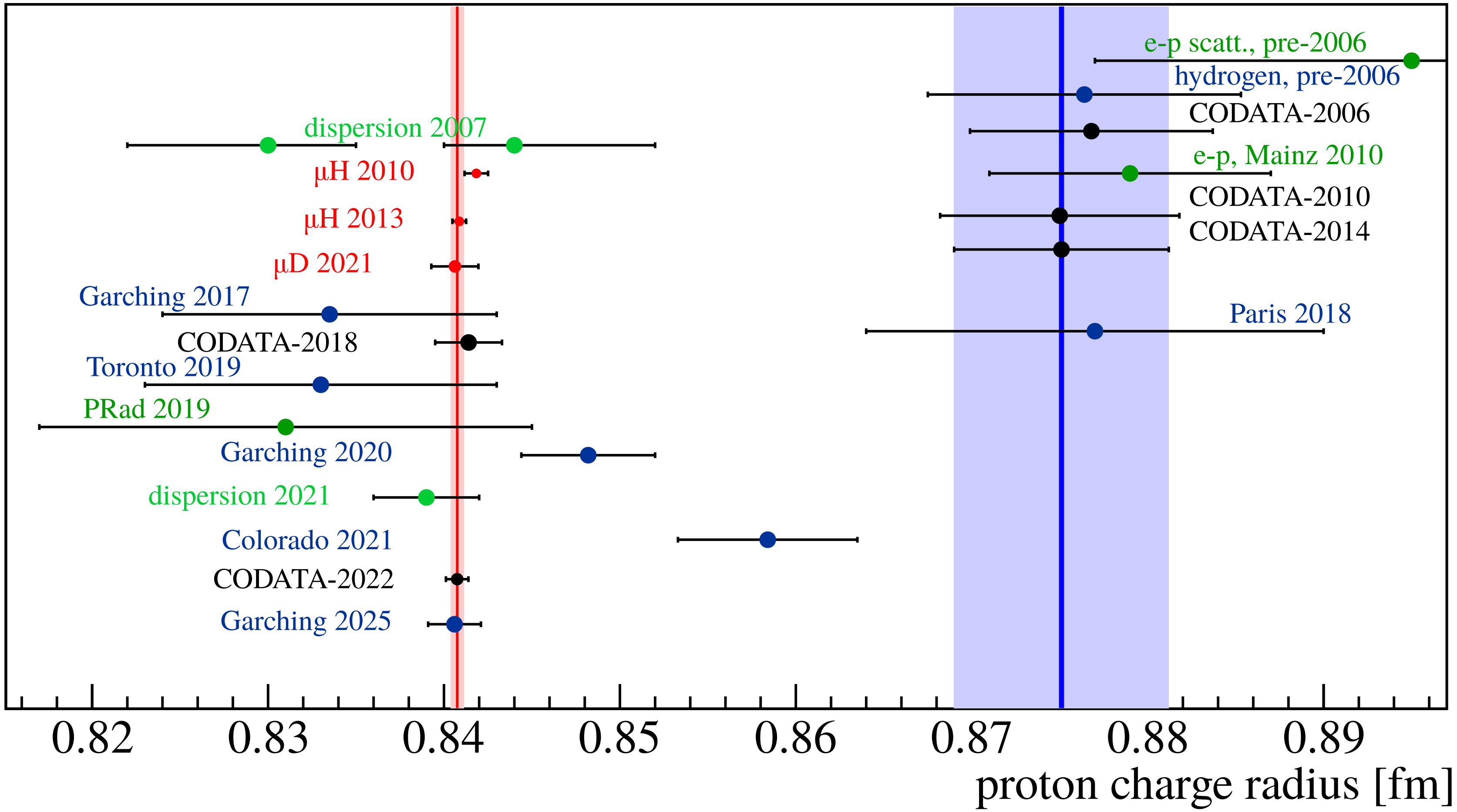
$1.054^{+0.003}_{-0.002}$ fm
[Lin, et al. '22]

-7403^{+21}_{-16} ppm
[Antognini, et al. '22, annual reviews]

850 ppm
[Antognini, et al. '22]

37(95) ppm (LO BChPT)
[Hagelstein, et al. '23]

Muonic Hydrogen and the Proton CHARGE Radius



e-p scattering

$$r_p^2 \equiv -6 \frac{d G_E}{d Q^2}\bigg|_{Q^2=0}$$

hydrogen spectroscopy

muonic atoms

$$\Delta E = \frac{2}{3}\pi\alpha \left|\Psi_S(0)\right|^2 r_p^2$$

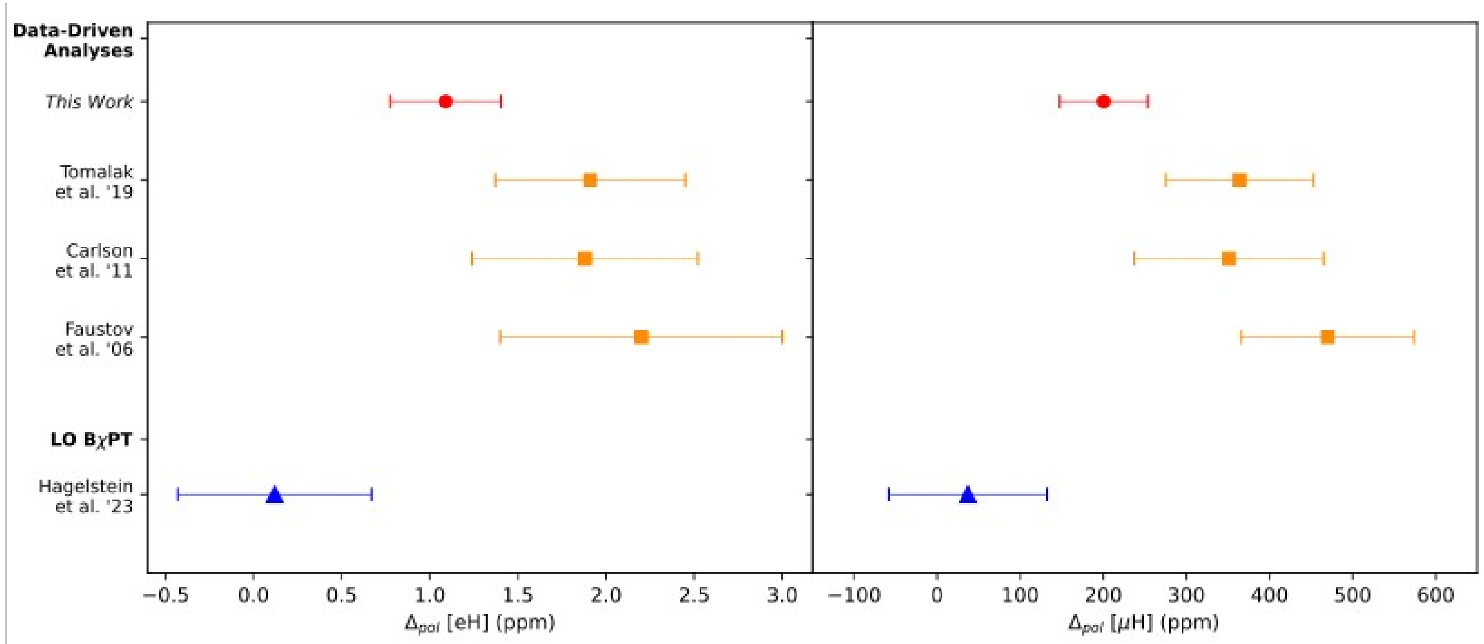
CODATA / PDG average

$$\delta V(\mathbf{r}) \equiv V_C(\mathbf{r}) - V_C^{\mathrm{pt}}(\mathbf{r}) = -4\pi\alpha \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{[G_E(\mathbf{q}^2) - 1]e^{iqr}}{\mathbf{q}^2}$$

1S Hyperfine Splitting in Muonic Hydrogen

$$E_{1S\text{-HFS}}(\mu\text{H}) = \Big[\underbrace{182.443}_{E_\text{F}} \underbrace{+1.350(7)}_{\text{QED+weak}} \underbrace{+0.004}_{\text{hVP}} \underbrace{-1.30653(17)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_\text{F}\left(1.01656(4)\,\Delta_\text{recoil} + 1.00402\,\Delta_\text{pol}\right)}_{2\gamma\text{ incl. radiative corr.}}\Big]\,\text{meV}$$

- Zemach radius allows to pin down magnetic properties of the proton
- Theory prediction is limited by two-photon exchange (2γ) contributions
  - Discrepancy between data-driven dispersive & BChPT prediction of polarizability effect



1S Hyperfine Splitting in Muonic Hydrogen

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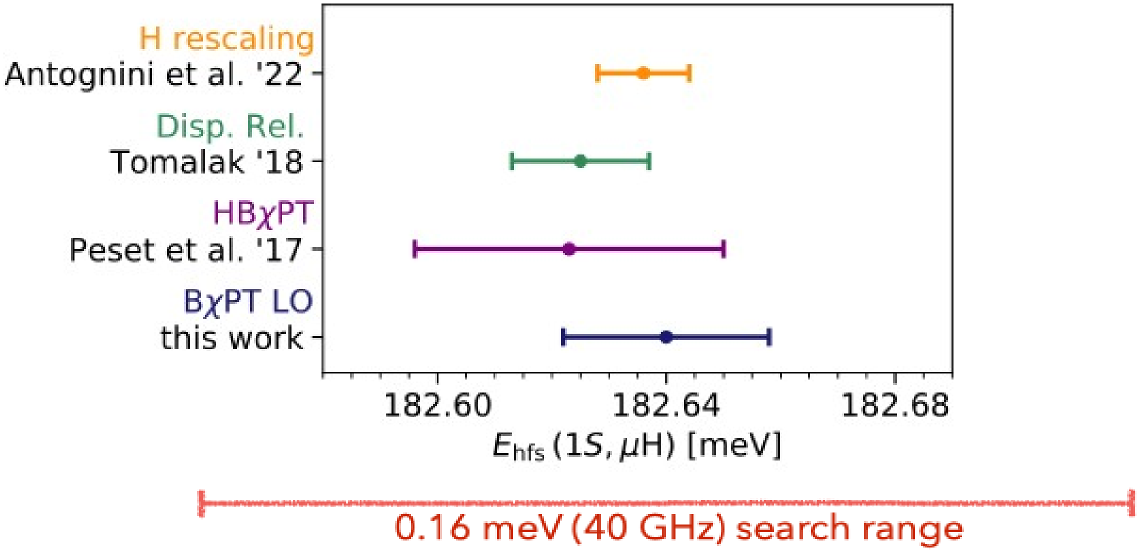
  - Discrepancy between data-driven dispersive & BChPT prediction of polarizability effect
- Theory needed to guide and interpret the spectroscopy experiments



1S Hyperfine Splitting in Muonic Hydrogen

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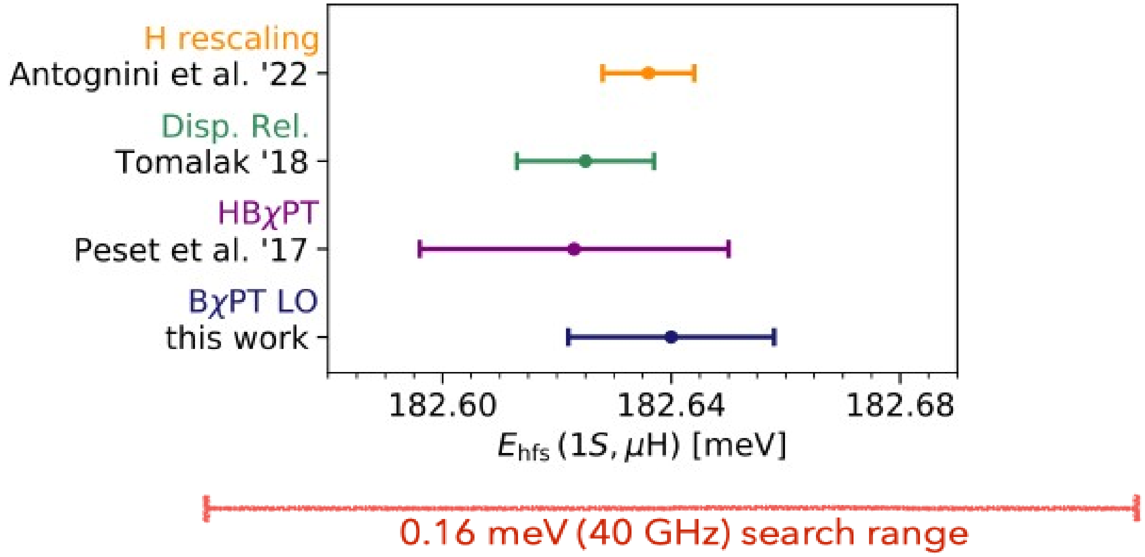
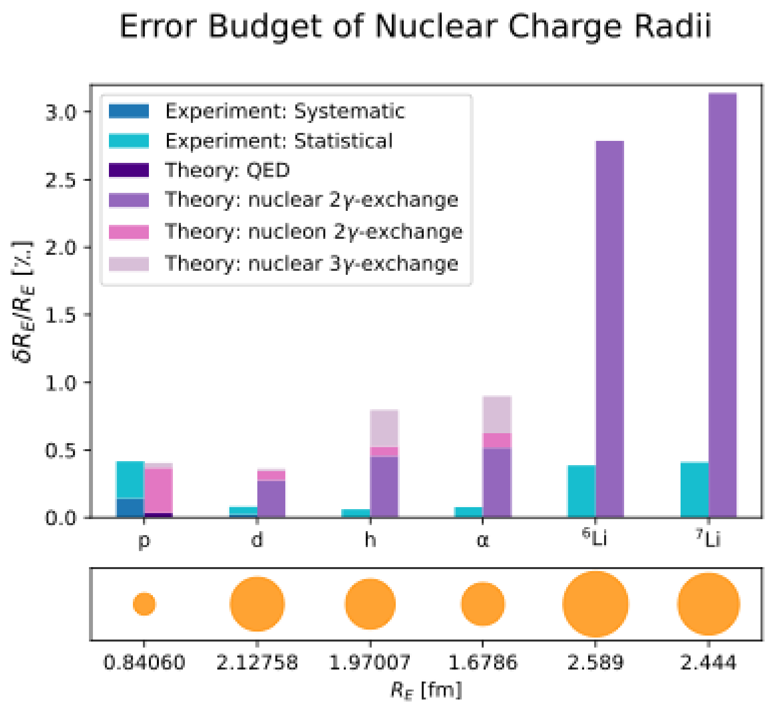
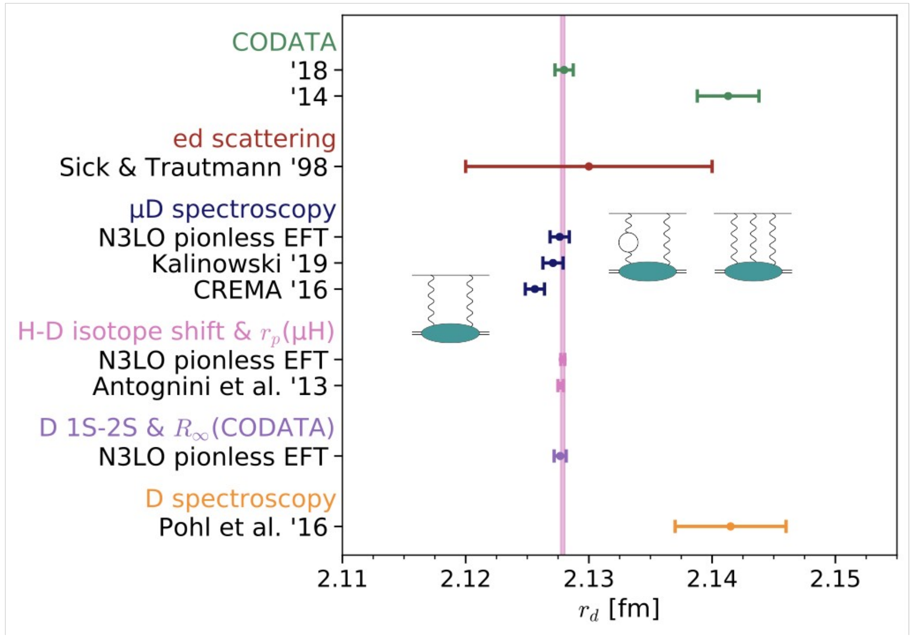
- Zemach radius allows to pin down magnetic properties of the proton
- Theory prediction is limited by two-photon exchange (2γ) contributions
  - Discrepancy between data-driven dispersive & BChPT prediction of polarizability effect
- Theory needed to guide and interpret the spectroscopy experiments
- Anticipated measurements require further theory improvements:
  - Higher-order QED corrections
  - Hadronic vacuum polarization



Muonic Deuterium Lamb Shift

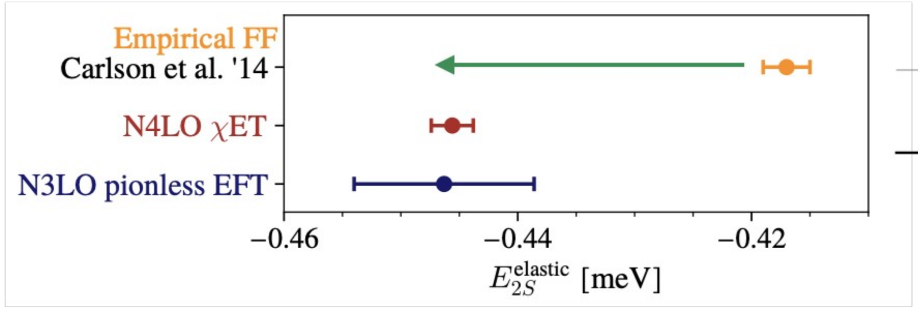
- Deuteron (proton) charge radius extractions from μH & μD Lamb shift, and 1S-2S H-D isotope shift are consistent
- Higher-order radiative corrections are important
  - Nuclear and nucleon two-photon exchange (2γ)
  - Three-photon exchange (3γ)
  - Radiative corrections to 2γ, e.g., electron vacuum polarization
- Extraction of nuclear structure from atomic spectroscopy factor 4 more precise than (chiral and pionless) EFT predictions or data-driven evaluations
  - Experiment as benchmark for nuclear theory

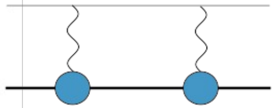


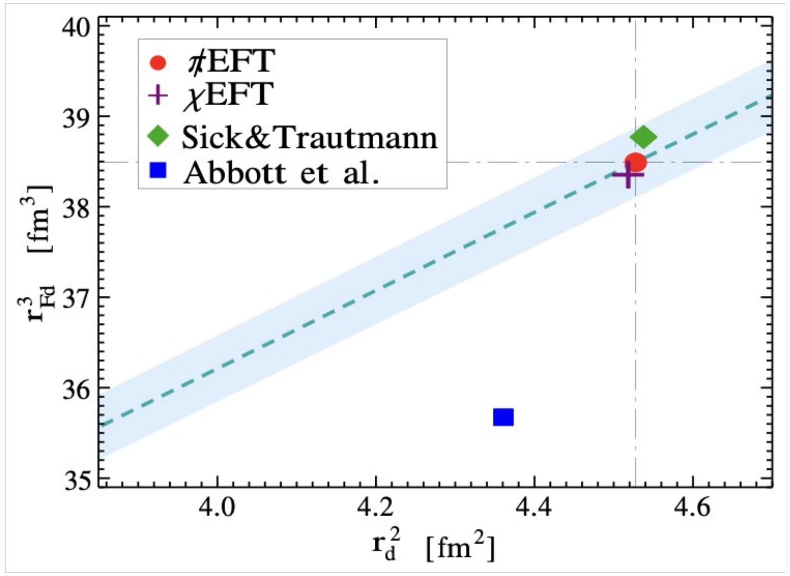


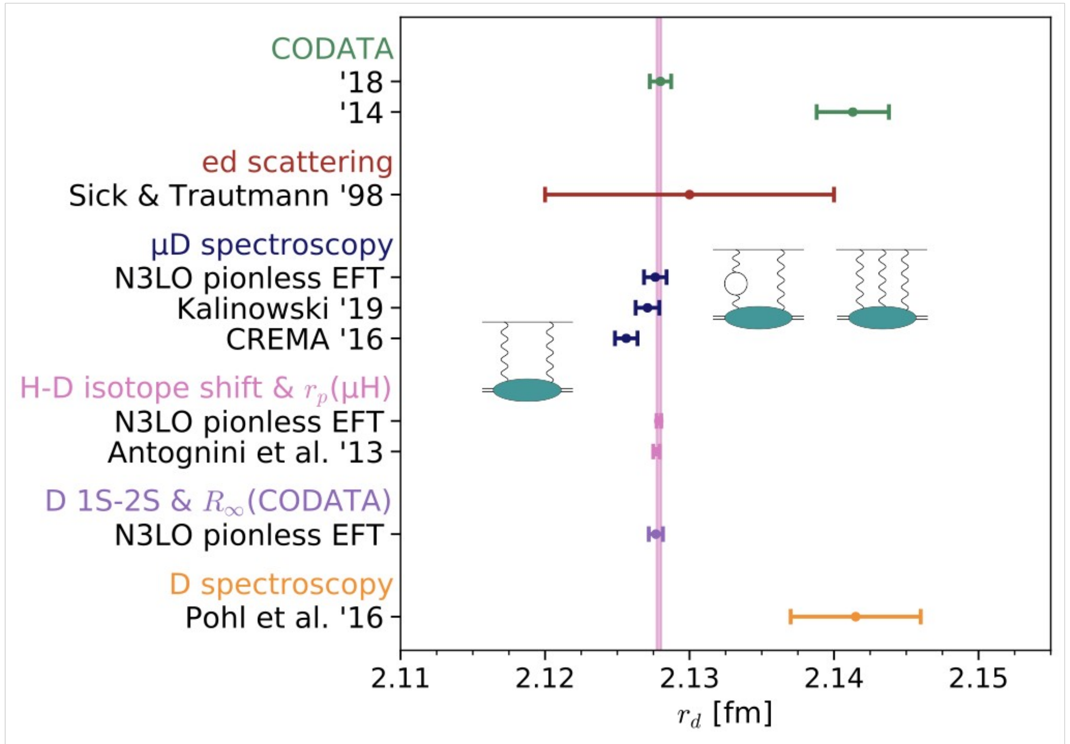
Nuclear Structure In and Out of (Muonic) Deuterium

EFFECTIVE FIELD THEORIES CONFRONT EMPIRICAL PARAMETRIZATIONS









- Higher-order radiative corrections are important
- Extraction of empirical nuclear structure is factor of 4 more precise than theory predictions

EXPERIMENT TESTS NUCLEAR THEORIES

from PUZZLE to PRECISION

Muonic Atom Spectroscopy Theory Initiative

https://asti.uni-mainz.de

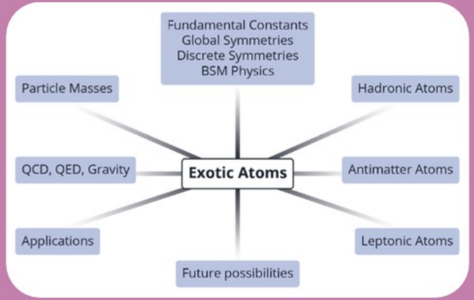
- Coordinated effort to support the experiments (inspired by “Muon g-2 Theory Initiative”)
- Initials objectives:
  - Accurate theory predictions for light muonic atoms to test fundamental interactions by comparing to electronic atoms
  - Community consensus on SM predictions
  - Emphasis on the hyperfine splitting in μH
- Steering committee: Aldo Antognini (PSI), Carl Carlson (William & Mary), Franziska Hagelstein (Mainz), Paul Indelicato (CNRS), Krzysztof Pachucki (Warschau), Vladimir Pascalutsa (Mainz)
- So far 5 (satellite-)workshops @ PSI, Crete, Mainz, Stony Brook, ETH Zurich
- Next workshop: “New perspectives in the charge radii determination of light nuclei”, ECT* Trento, 28.07.25 — 01.08.25

NuPECC Long Range Plan: nucl-ex/2503.15575

submitted community input: A. Antognini, FH, et al., 2210.16929

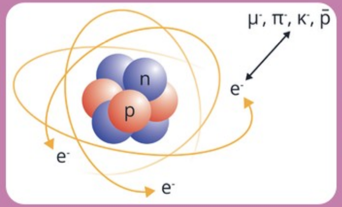
Box 6.2: Exotic Atoms: unique probes of the Standard Model and Beyond

Exotic atoms offer a unique and complementary approach to extracting fundamental constants, testing all known interactions including the validity of the weak equivalence principle for antimatter and searching for new physics while probing fundamental symmetries. Recent years have witnessed impressive progress in the field of exotic atoms driven by the development of improved beamlines and trapping techniques, manipulation of the constituent particles, quantum logic spectroscopy and tremendous advancement in technology (e.g. lasers, microcalorimeters, etc.). The next decade offers great prospects for this multidisciplinary research area, which merges different fields such as nuclear, atomic, particle, laser, quantum information and plasma physics.

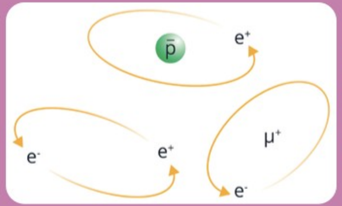


What are exotic atoms? Ordinary atoms: positive nucleus which interacts electromagnetically with e^-

Exotic Atoms: replace at least one of the two:

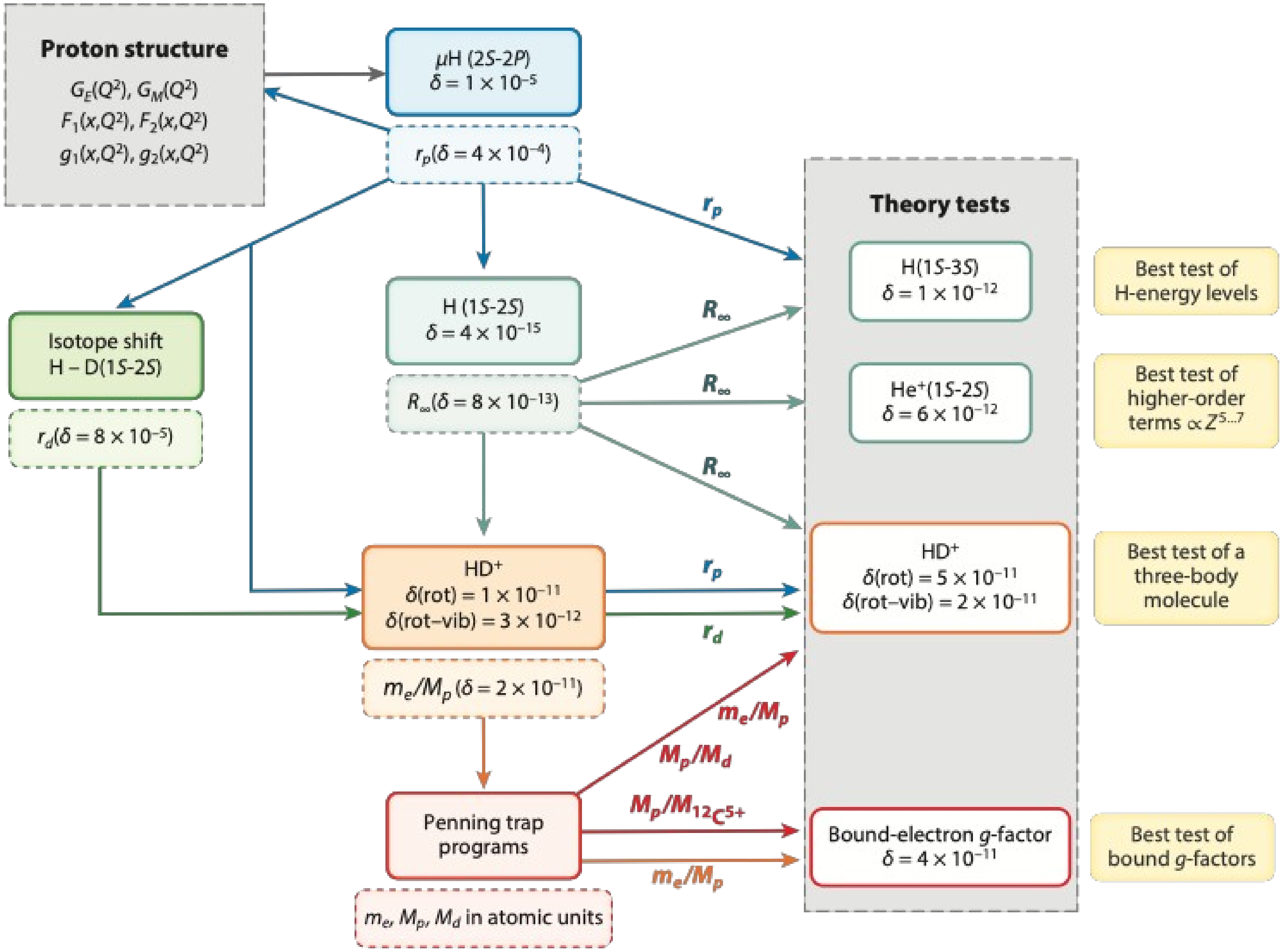


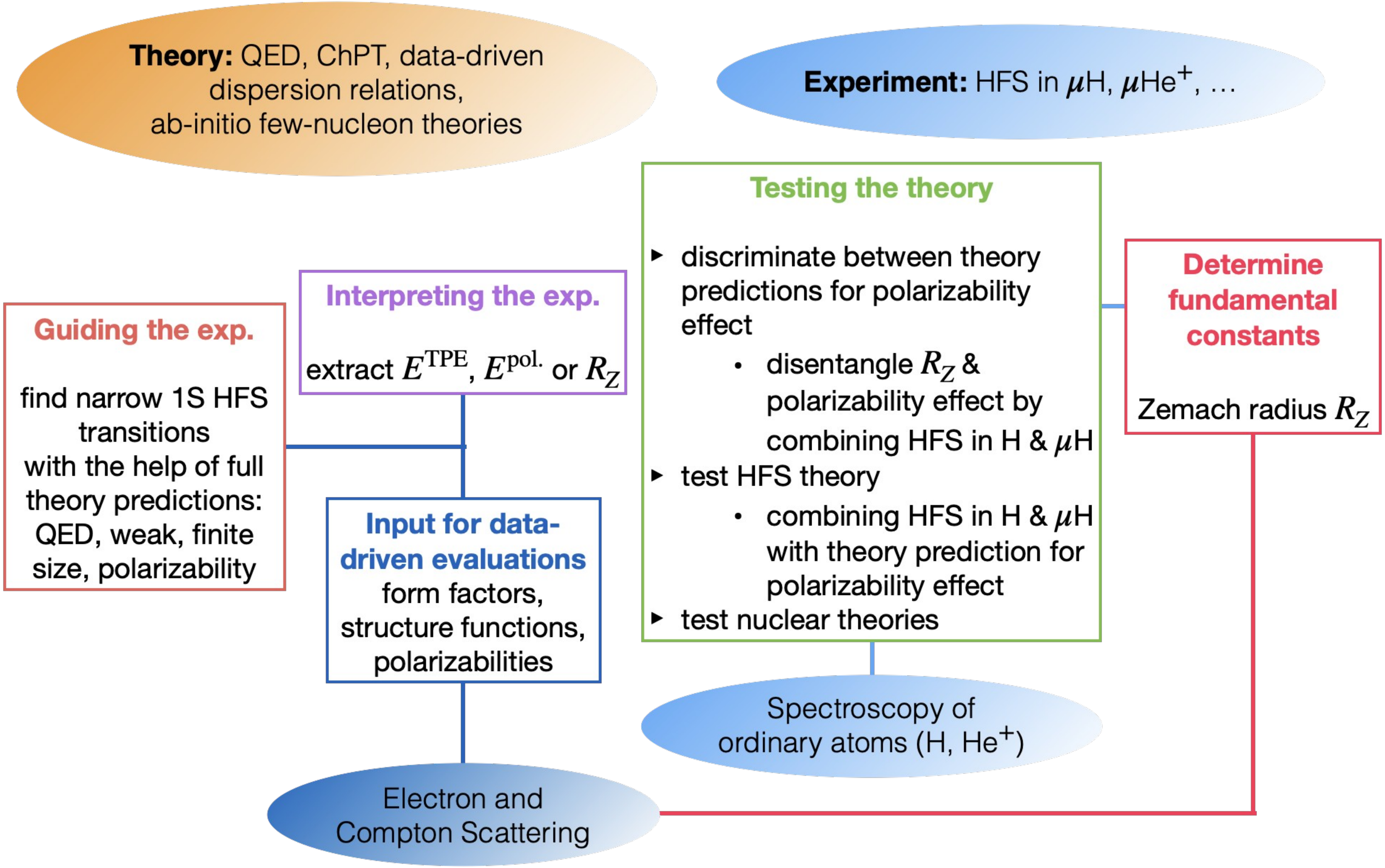
- an e^- replaced by any negatively charged particle (muonic, pionic, kaonic and anti- proton atoms)



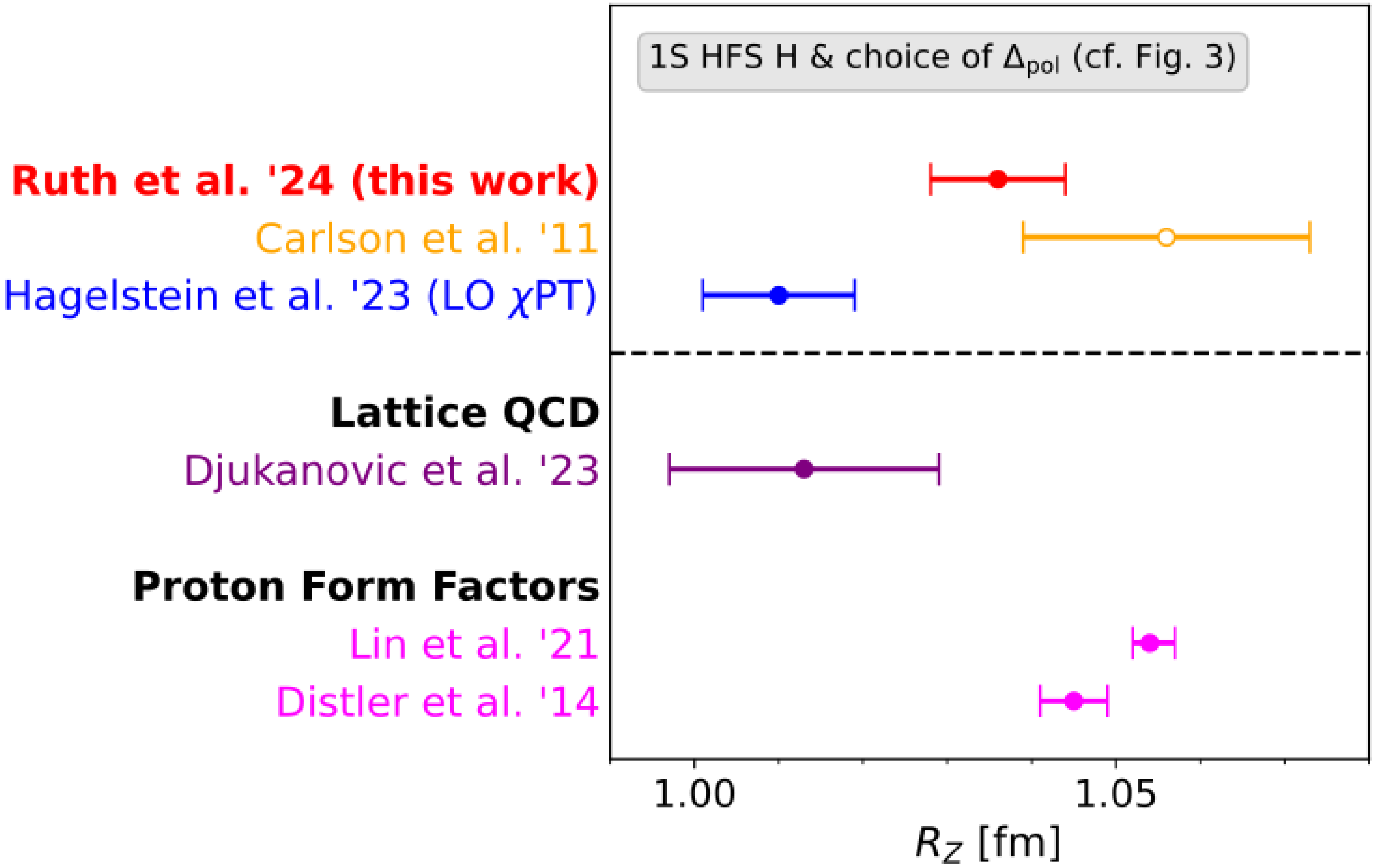
- negative nucleus and positive orbiting particle (anti-hydrogen) or nucleus replaced by a positive particle (e+e- positronium (Ps), μ+e- muonium

Precision Tests of the SM





Theory: QED, ChPT, data-driven dispersion relations, ab-initio few-nucleon theories
Experiment: HFS in μH, μHe$^+$, …
Testing the theory
discriminate between theory predictions for polarizability effect
disentangle R_Z & polarizability effect by combining HFS in H & μH
test HFS theory
combining HFS in H & μH with theory prediction for polarizability effect
test nuclear theories
Determine fundamental constants
Zemach radius R_Z
Interpreting the exp.
extract E^{TPE}, $E^{\mathrm{pol.}}$ or R_Z
Guiding the exp.
find narrow 1S HFS transitions with the help of full theory predictions: QED, weak, finite size, polarizability
Input for data-driven evaluations
form factors, structure functions, polarizabilities
Spectroscopy of ordinary atoms (H, He$^+$)
Electron and Compton Scattering


1S HFS H & choice of Δ_{pol} (cf. Fig. 3)
Ruth et al. '24 (this work)
Carlson et al. '11
Hagelstein et al. '23 (LO χPT)
Lattice QCD
Djukanovic et al. '23
Proton Form Factors
Lin et al. '21
Distler et al. '14
1.00
1.05
R_Z [fm]