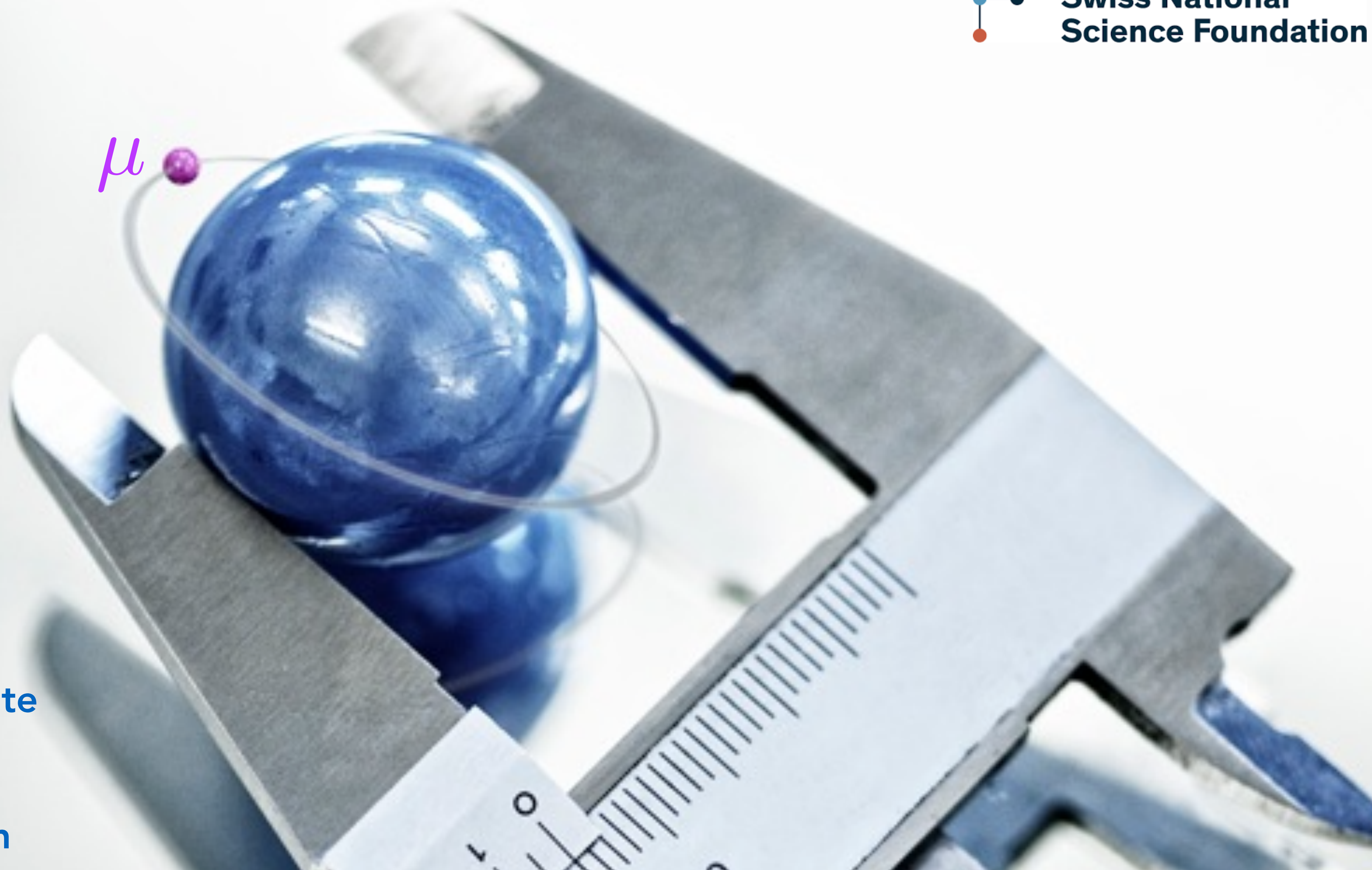
Laser spectroscopy of muonic atoms

from benchmarks for nuclear physics to BSM searches



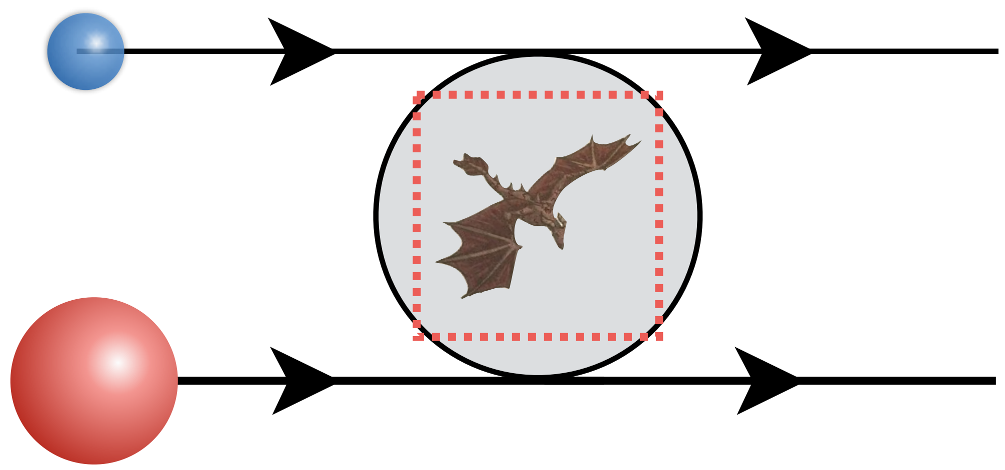
Swiss National Science Foundation

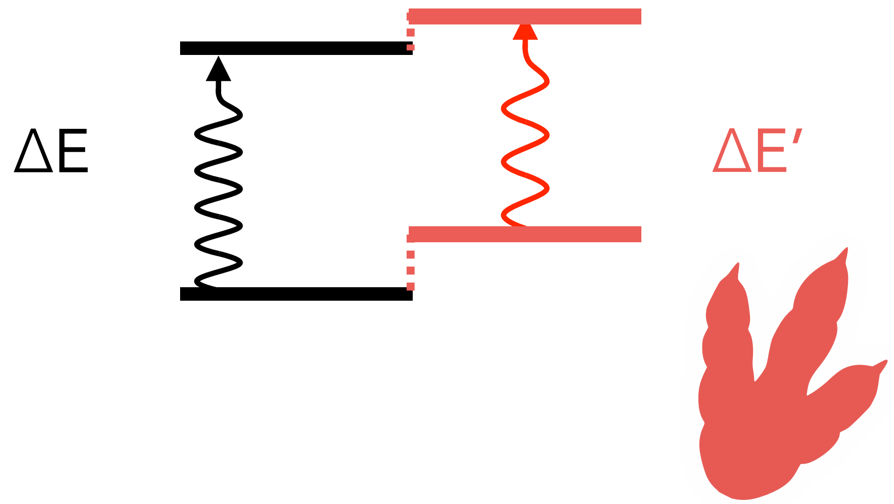
Aldo Antognini

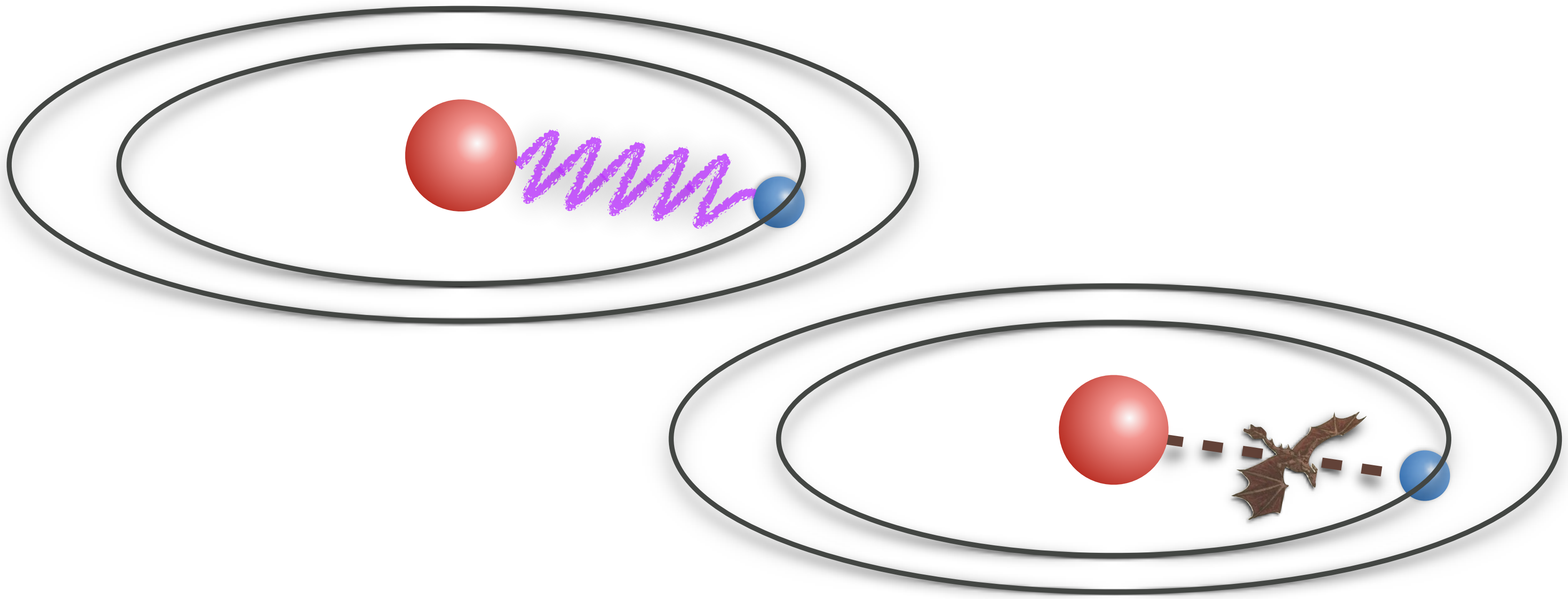
Paul Scherrer Institute
ETH, Zurich

CREMA collaboration

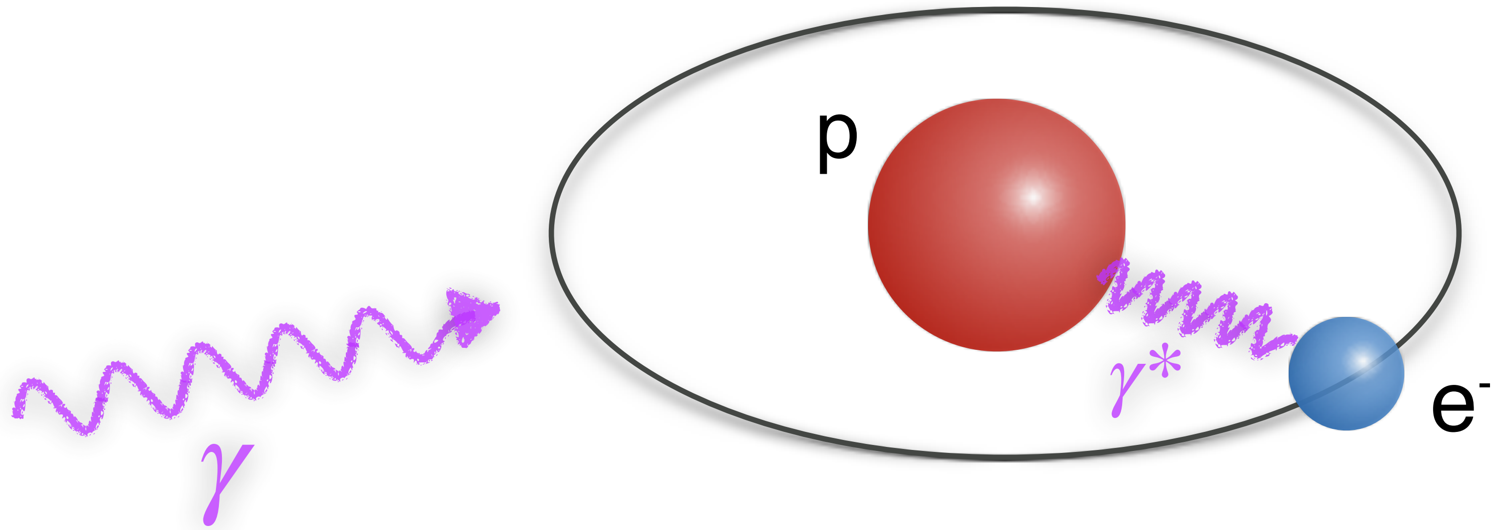
One possibility to search BSM physics with atomic systems



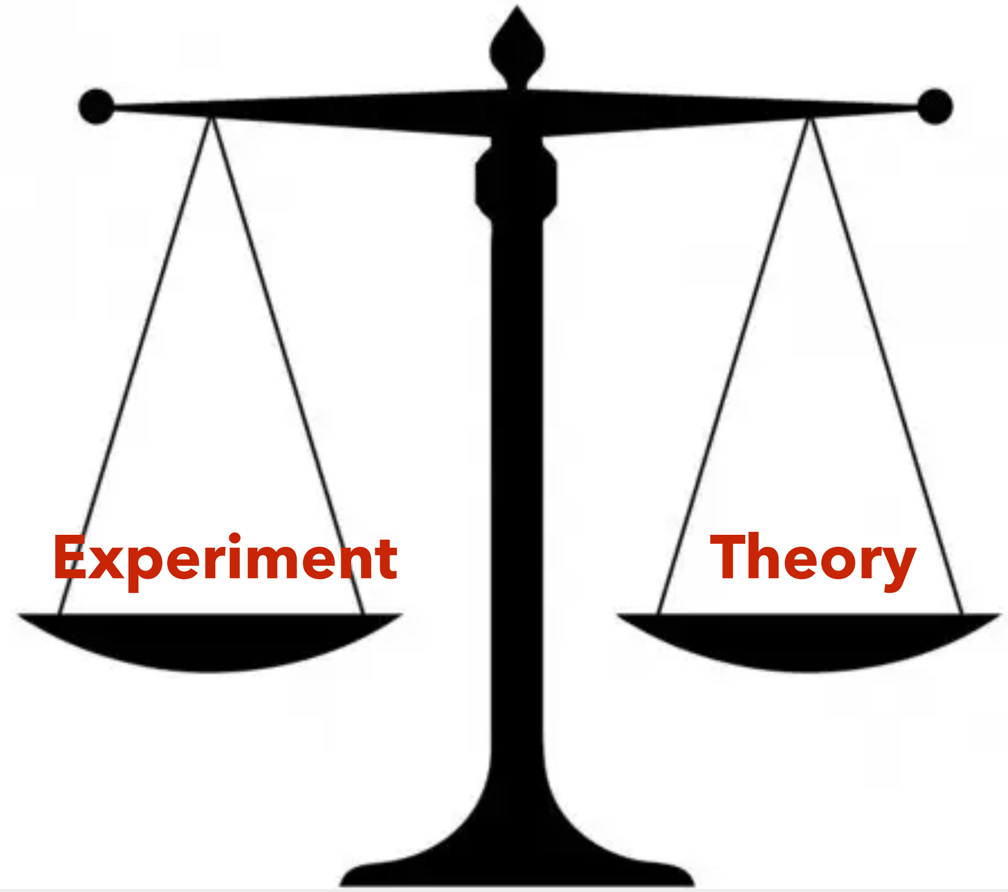




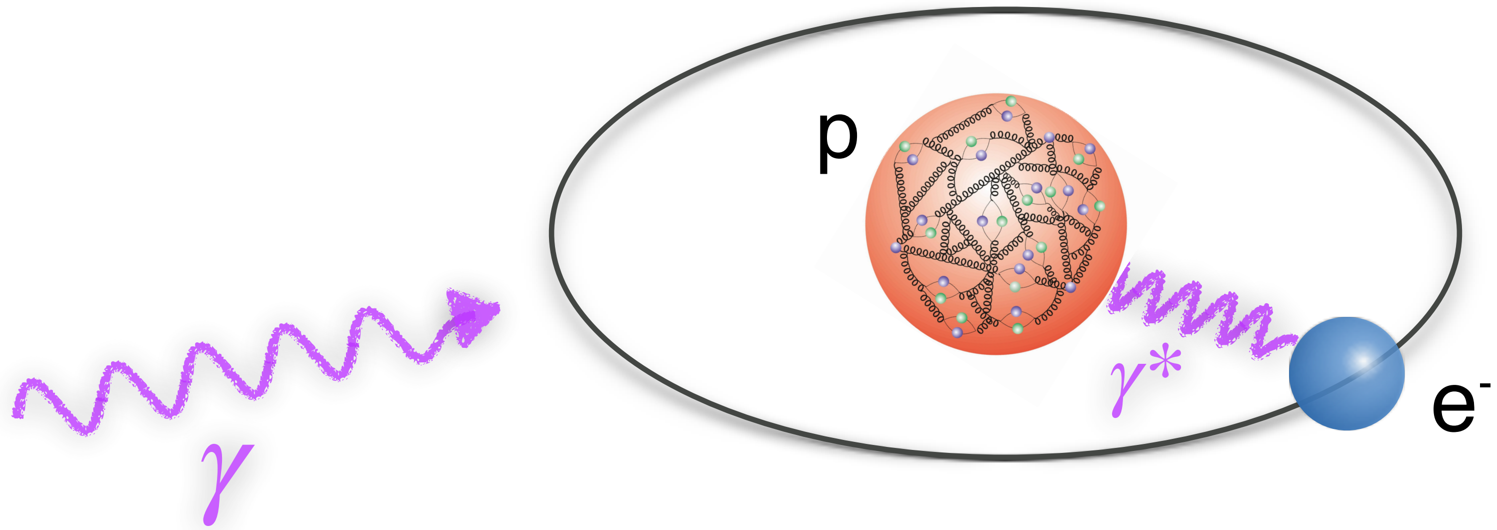
The simplicity of hydrogen



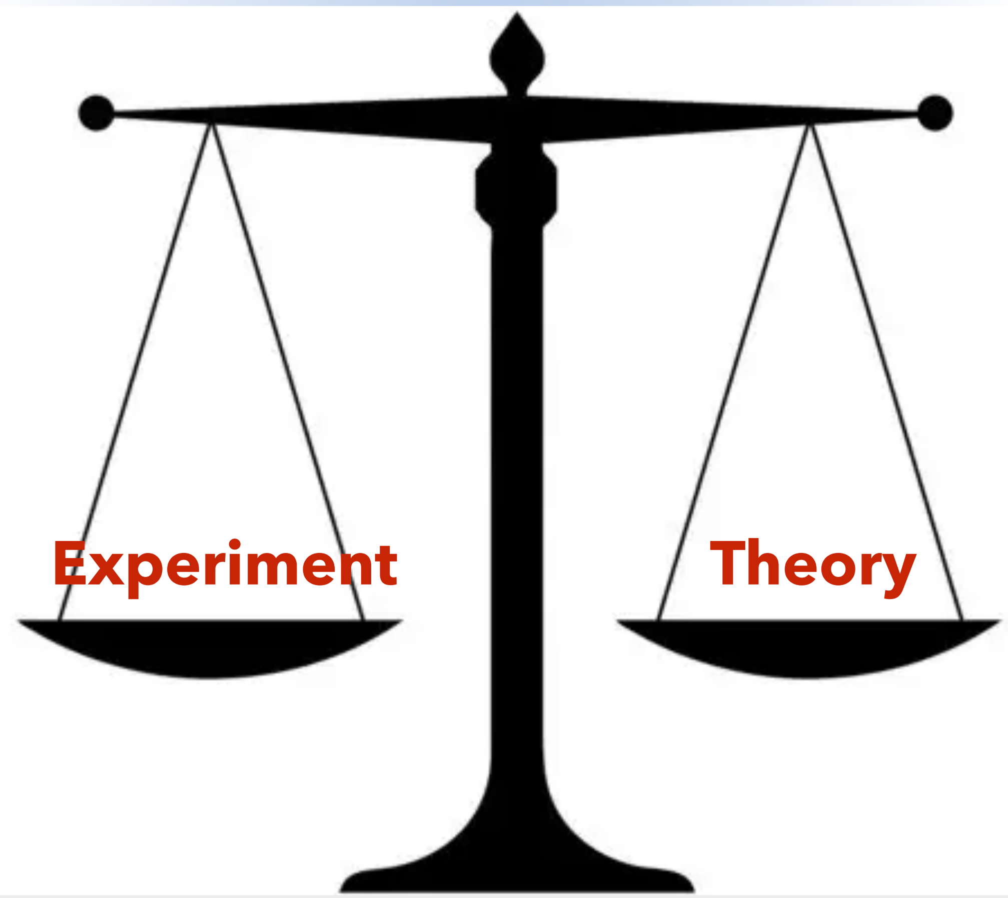
Compare experiment to theory
assuming no BSM physics



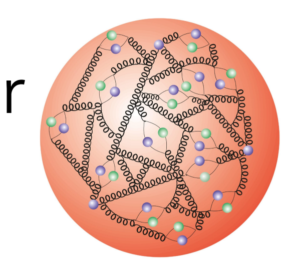
Not so simple



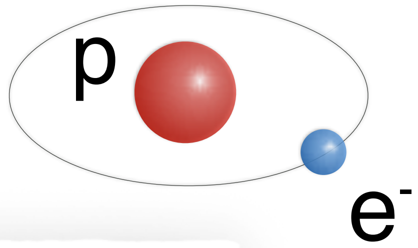
Compare experiment to theory
assuming no BSM physics



Limited by nuclear structure effects



The hydrogen atom

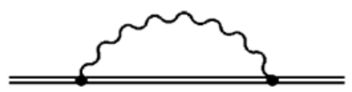


Theory

$$E_n \simeq \left(1-\frac{m_e}{m_p}\right)\frac{R_\infty}{n^2} + \varepsilon_{\mathrm{Dirac}} + \mathrm{QED}(\alpha, m_e \ldots) + \varepsilon_{\mathrm{HFS}} + k m_e^3 R_p^2 + \ldots + \varepsilon_{\mathrm{BSM}}$$

Schrödinger with Coulomb pot.

e- spin, relativity



p mag. moment

p finite size

?

Experiment

Dirac

p finite size

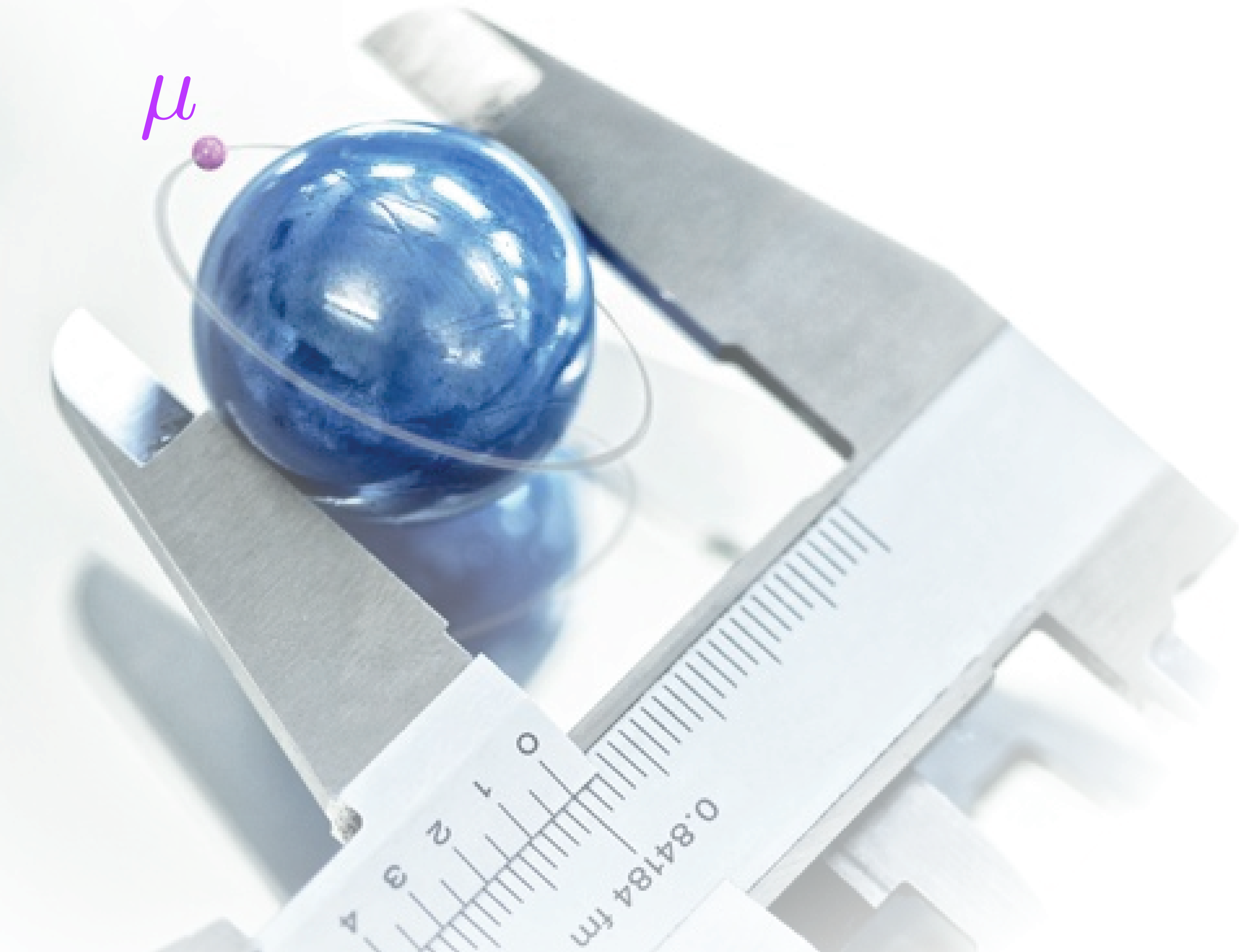
BSM ?

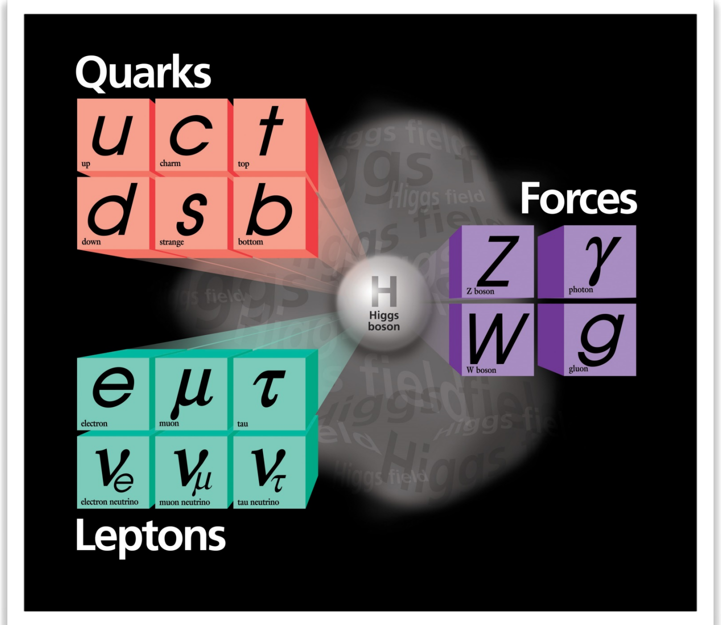
$$f_{1s-2s} = 2\ 466\ 061\ 413.187\ 035(10)\ \mathrm{MHz}$$

QED

Parthey et al., Phys. Rev. Lett. **107**, 203001 (2011)

Laser spectroscopy of muonic hydrogen





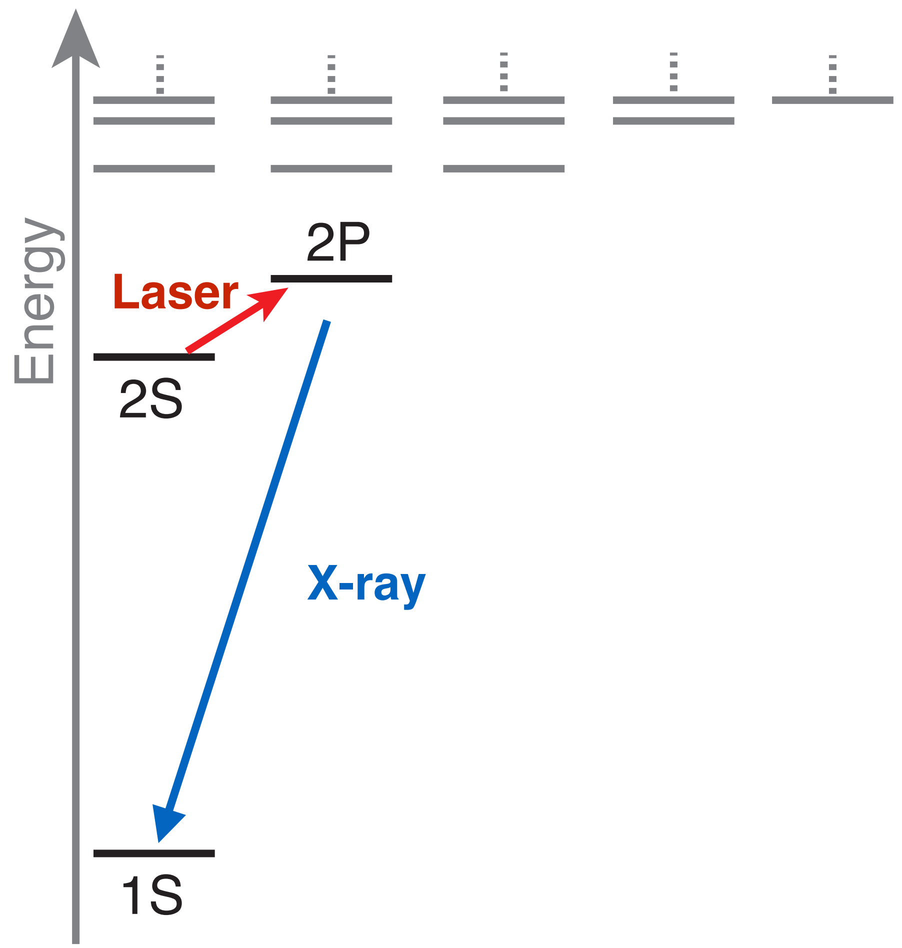
$$m_\mu \approx 200 m_e$$

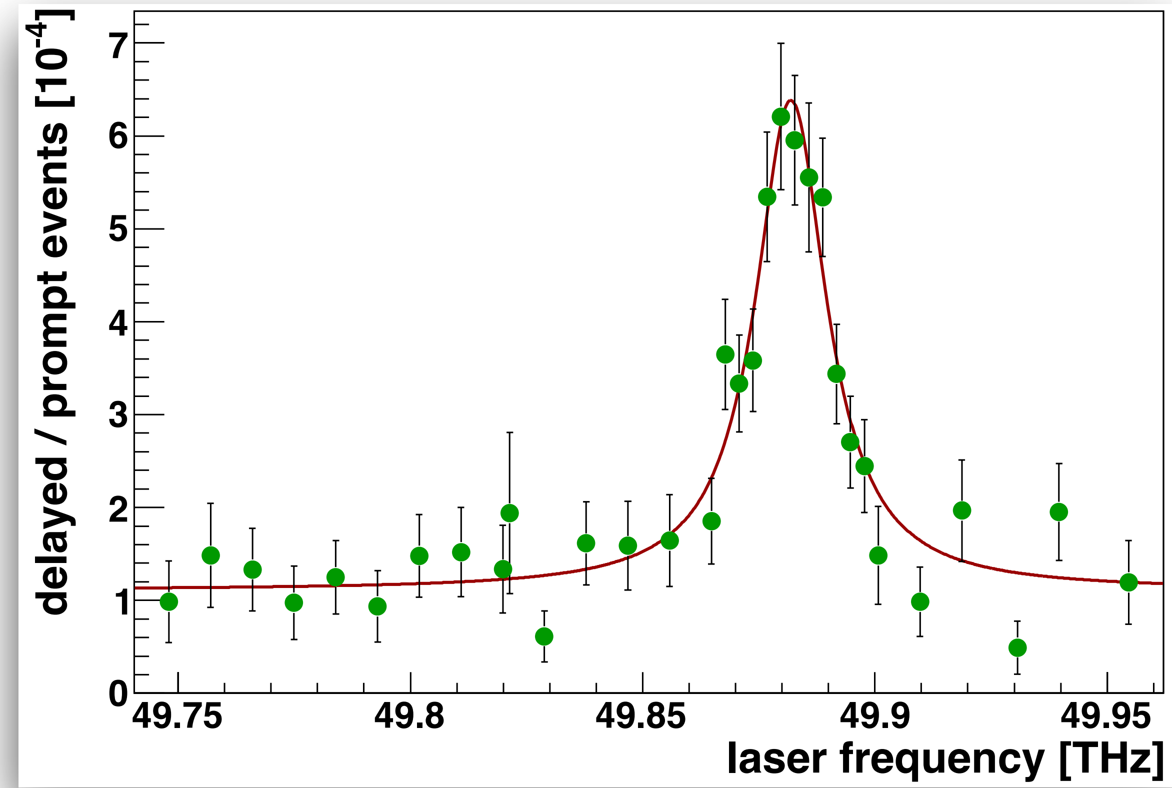
Finite size effects

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

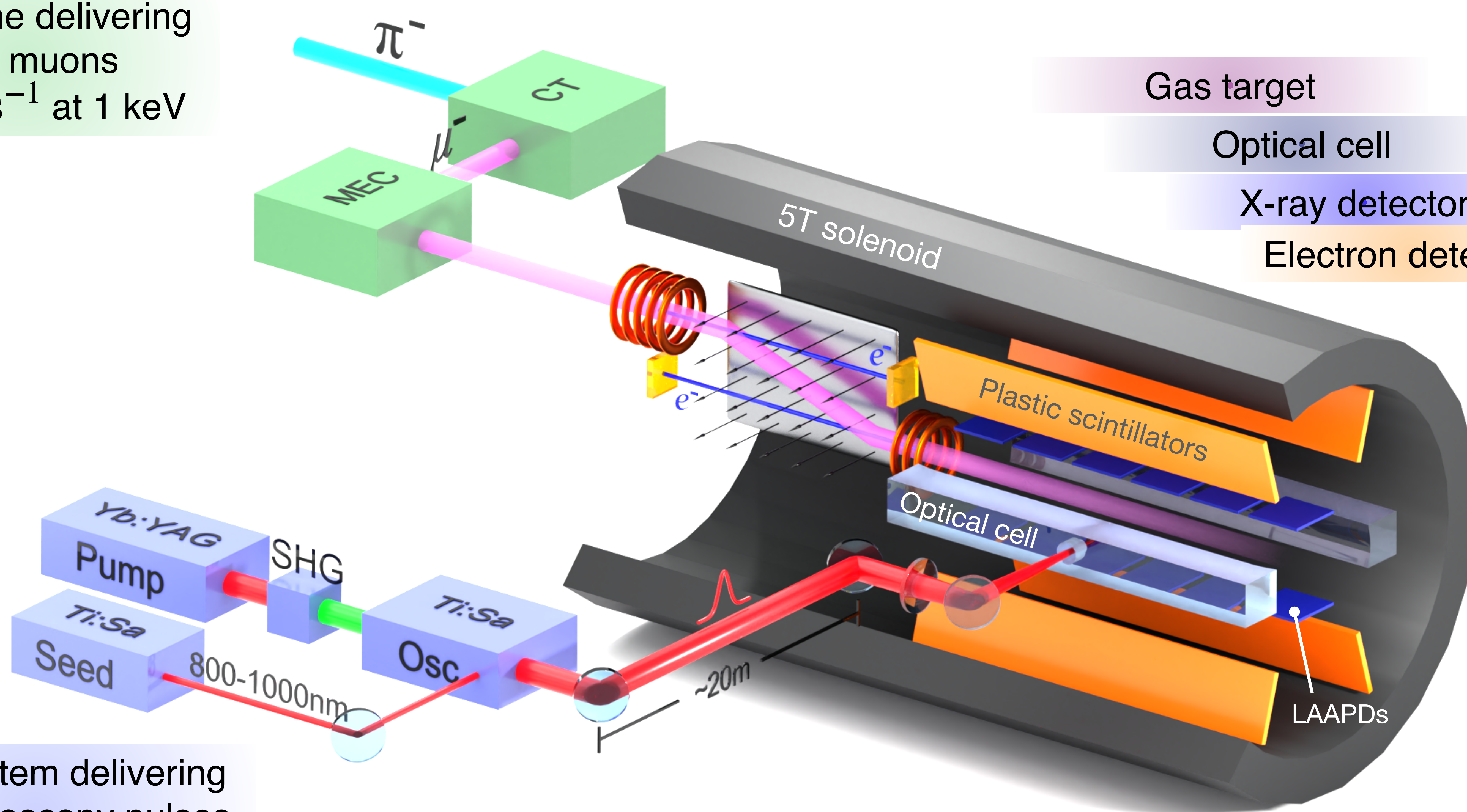
The principle of the muonic atom experiments

- Stop low-energy muons in 1 mbar H2 gas
- μH is 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





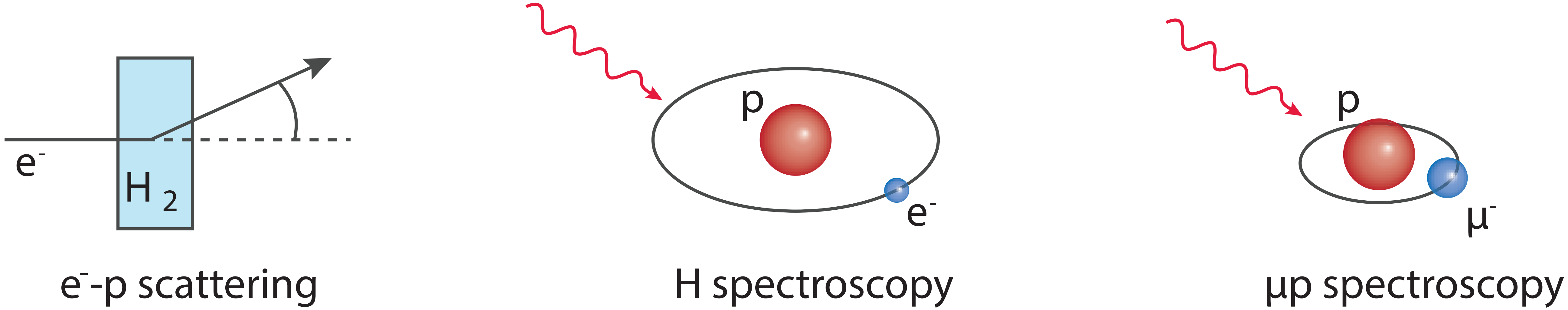
Beam line delivering slow muons
500 $\mu^- \, s^{-1}$ at 1 keV

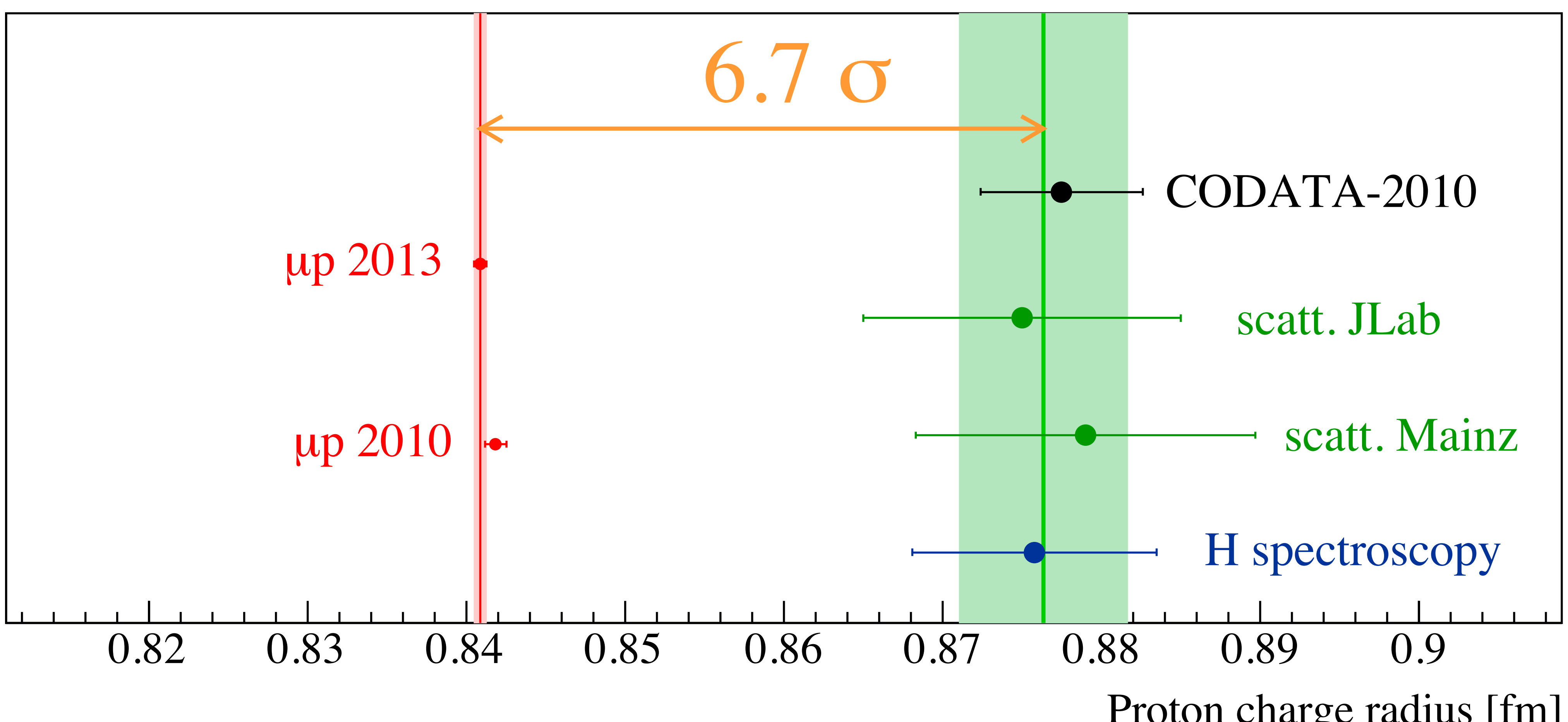


Gas target
Optical cell
X-ray detectors
Electron detectors

Laser system delivering the spectroscopy pulses within 1 μs

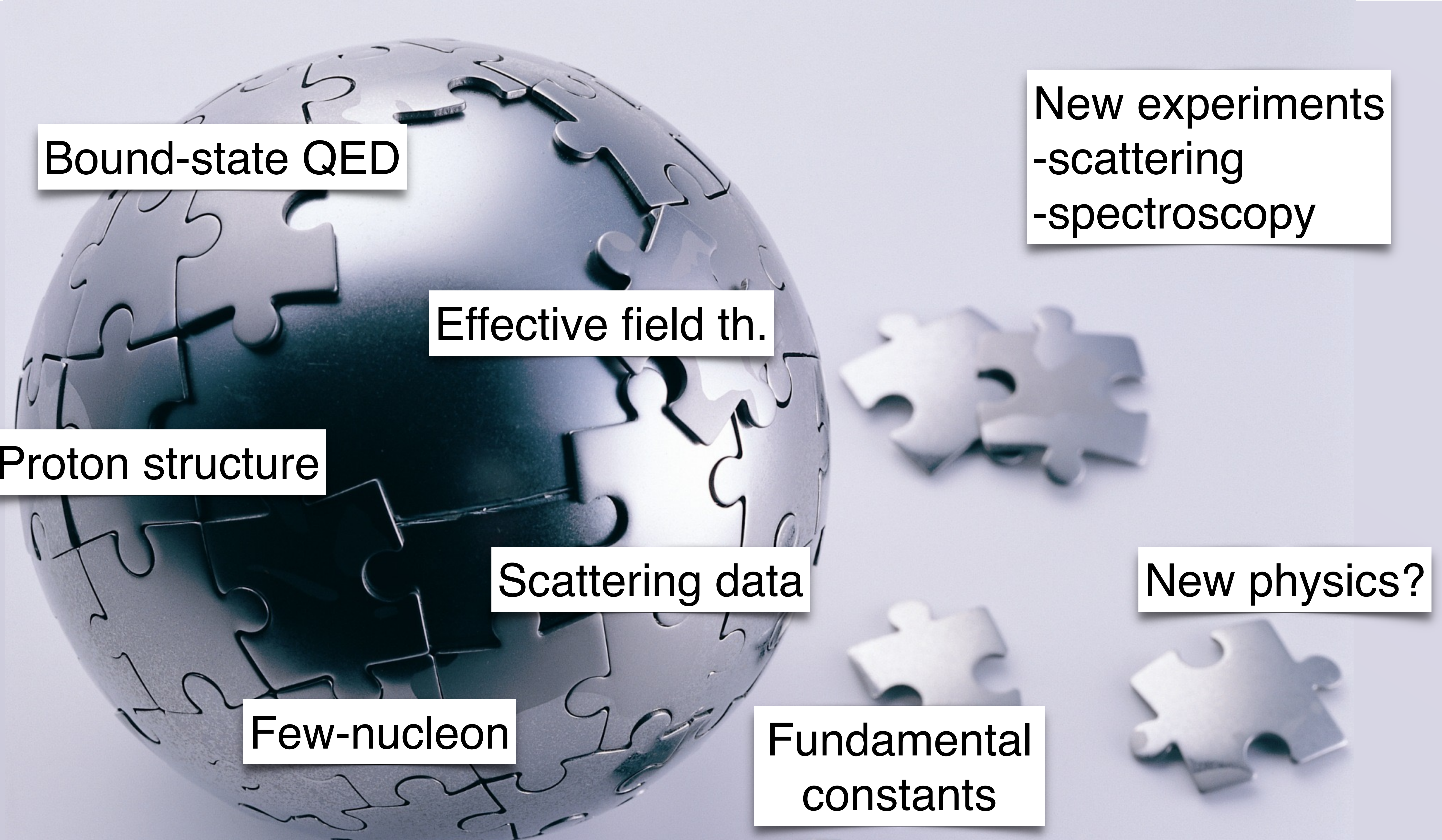
The proton radius puzzle (2013)





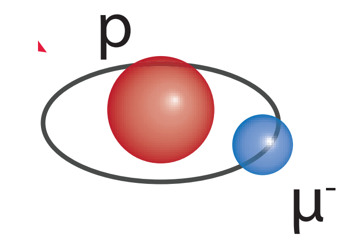
Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)

Many activities were triggered by this puzzle (>1500 citations)



The proton radius puzzle

- **μp experiment**
- μp theory
- H experiments
- BSM physics
- e-p scattering



$m_\mu \approx 200 m_e$

- **sensitive** to the radius

$$\Delta E_{\text{size}} \sim m^3 R_p^2$$

- **insensitive** to systematics
  - small atomic size
  - large binding energy

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

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

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 proton radius puzzle

- μp experiment
- **μp theory**
- H experiments
- BSM physics
- e-p scattering

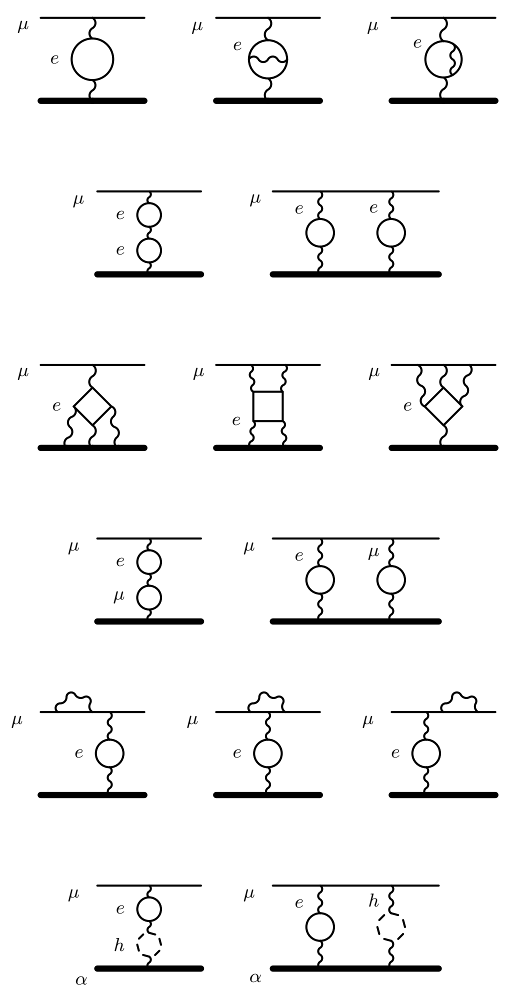
Discrepancy= 0.3 meV

$$E_{\rm LS}^{\rm exp} = 202.3706(23)\ \text{meV}$$

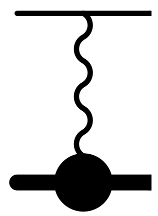
$$E_{\rm LS}^{\rm th} = 206.0344(3) - 5.2259\, r_p^2 \;+ 0.0289(25)\ \text{meV}$$

arXiv:2212.13782

QED



Finite size
~m³



Nuclear structure
~m⁴

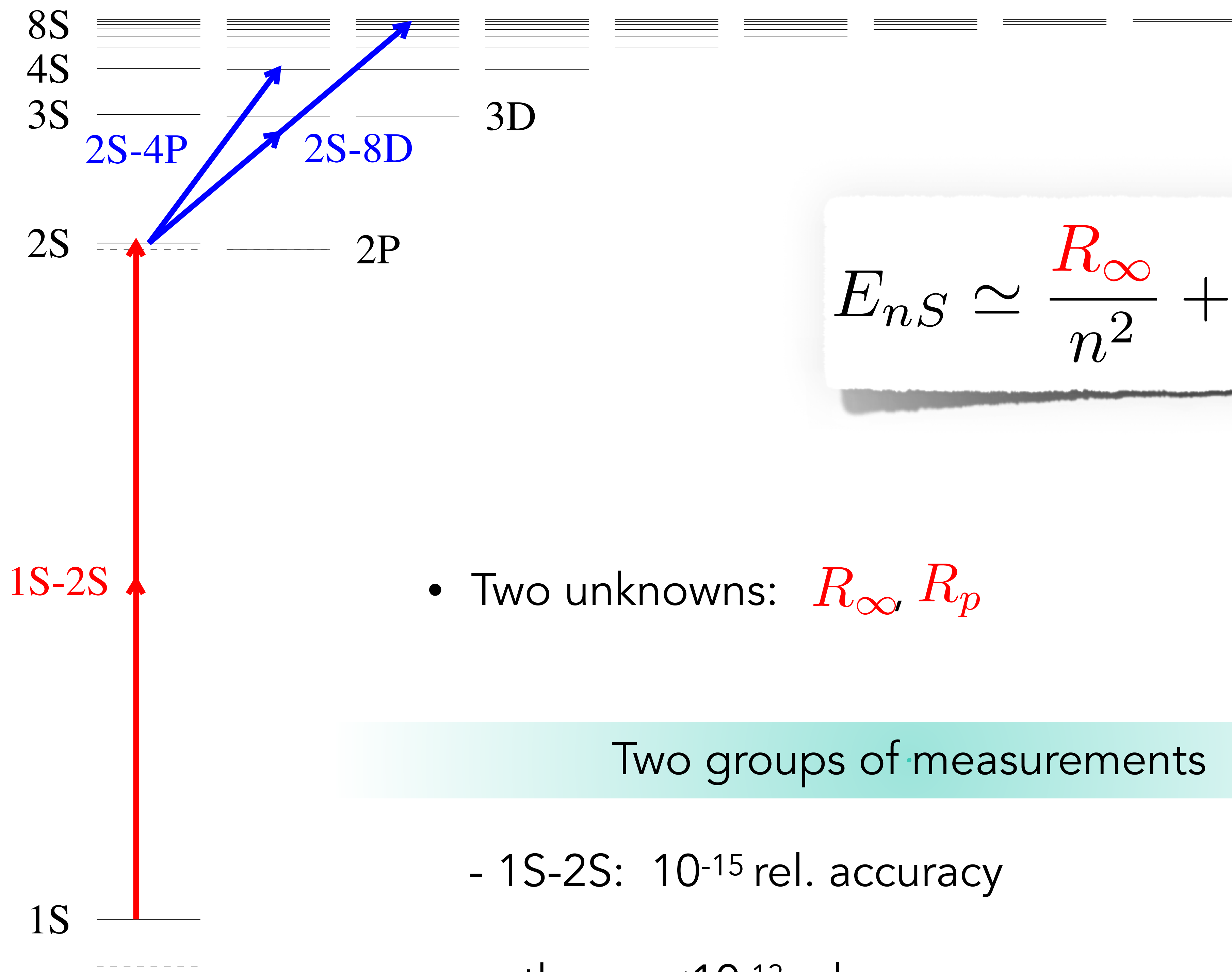
Hagelstein
Pachucki

$$r_p = 0.84060(39)\ \text{fm}$$

The proton radius puzzle

- μp experiment
- μp theory
- **H experiments**
- BSM physics
- e-p scattering

S. Scheidegger
P. Yzombard
T. Udem



$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{\text{QED} + kR_p^2}{n^3}$$

- Two unknowns: R_∞, R_p

Two groups of measurements

- 1S-2S: 10^{-15} rel. accuracy

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

- others: $<10^{-13}$ rel. accuracy
  and more prone to systematics

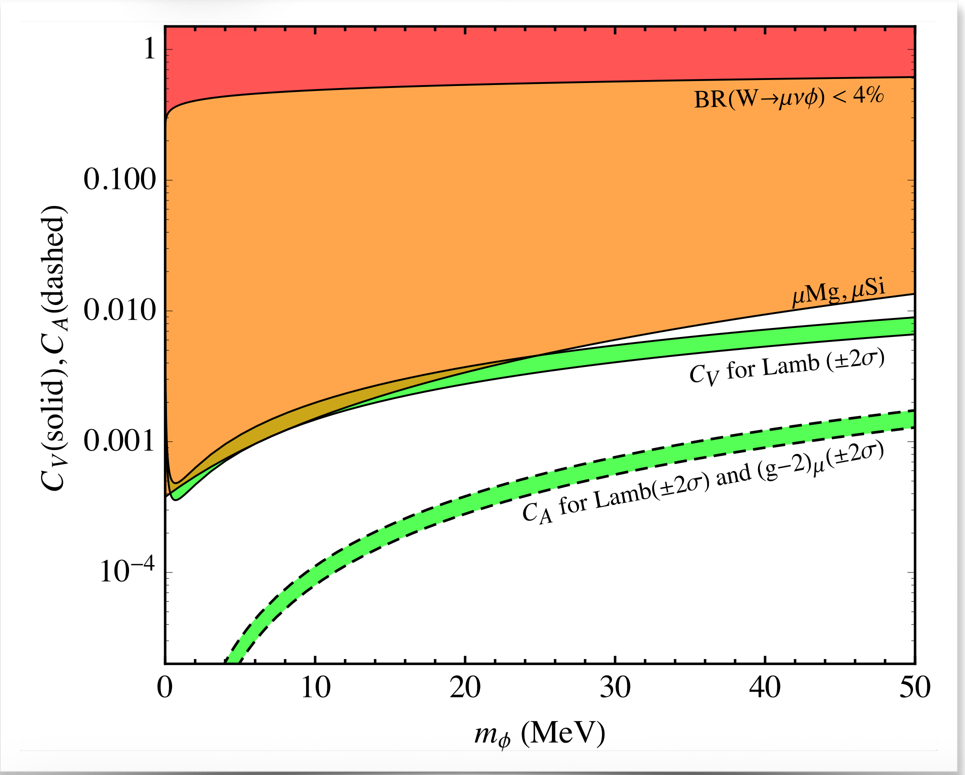
$$\langle r \rangle = \frac{\hbar}{Z\alpha c}\frac{n^2}{m}$$

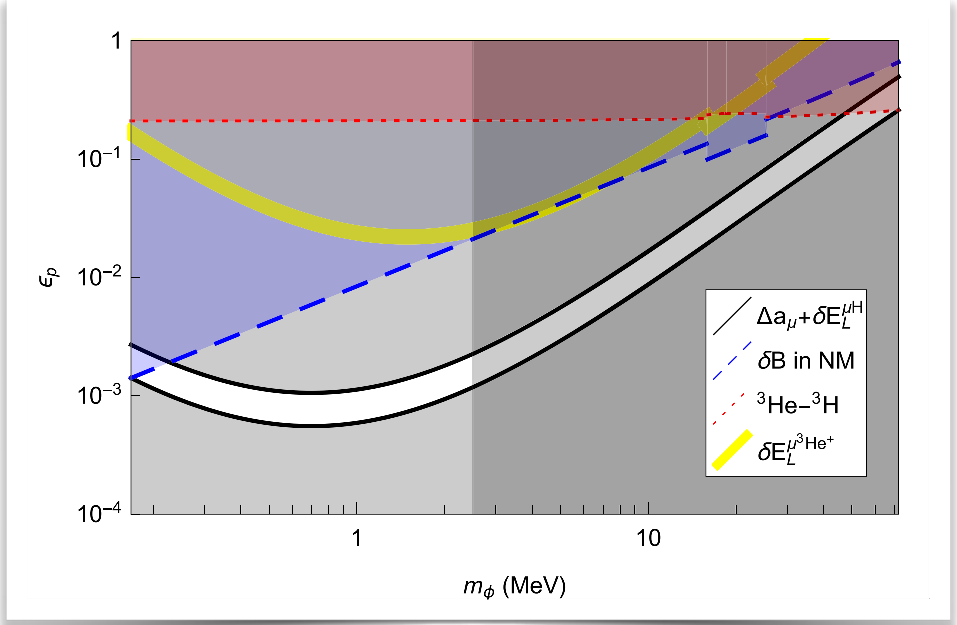
The proton radius puzzle

- μp experiment
- μp theory
- H experiments
- **BSM physics**
- e-p scattering

$$\mathcal{L}_{\rm int} = -\phi^V_\lambda[C^\mu_V\bar{\psi}_\mu\gamma^\lambda\psi_\mu + C^p_V\bar{\psi}_p\gamma^\lambda\psi_p] - \phi^A_\lambda[C^\mu_A\bar{\psi}_\mu\gamma^\lambda\gamma_5\psi_\mu + C^p_A\bar{\psi}_p\gamma^\lambda\gamma_5\psi_p] - iC^\mu_V\epsilon_{ijk}W^i_\alpha W^j_\beta\partial^\alpha W^{k,\beta} + i\{C^\mu_A \text{terms}\} - \frac{g}{2\sqrt{2}}\bar{\psi}_\mu\gamma^\lambda(1-\gamma_5)\psi_\nu W^-_{s,\lambda} + \text{H.c.},$$

$$\mathcal{L}_\phi \supset -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2_\phi\phi^2 + e\epsilon_f\phi\bar{\psi}_f\psi_f$$





- Tuning (e.g. vector vs axial-vector)
- Preferential coupling to μ and p
- No UV completion?

Carlson and Freid, PRD92, 095024(2015)

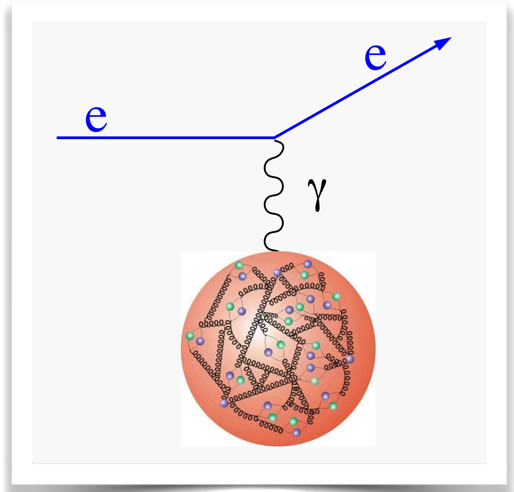
Mass: 160 keV - 6 MeV

Couplings: $\varepsilon_\mu \sim \varepsilon_p \sim \varepsilon_e \sim 10^{-3}$

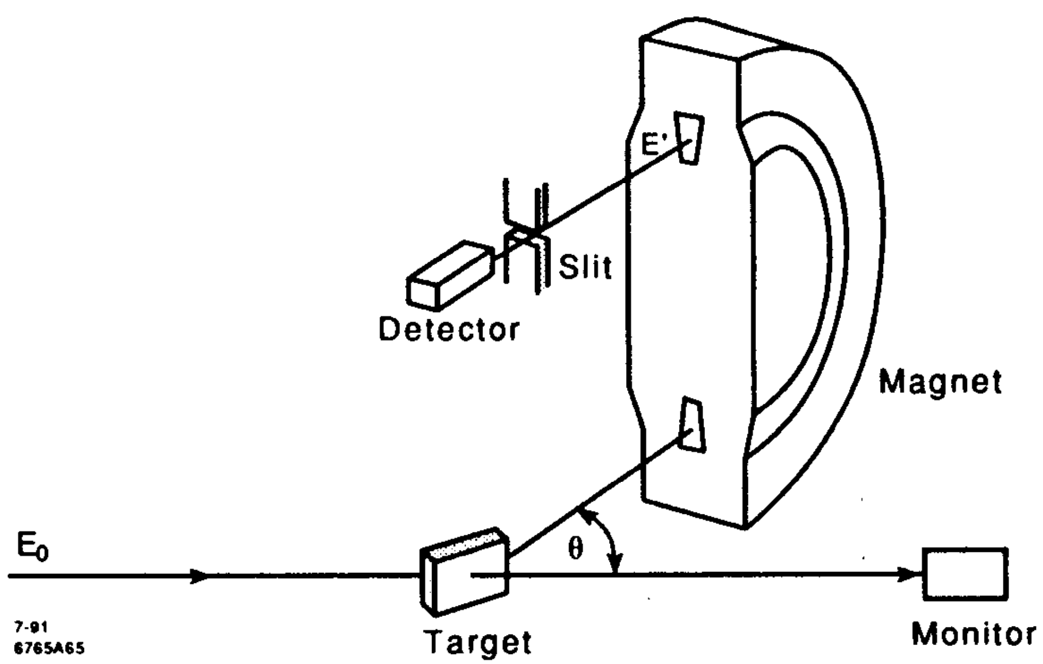
Pospelov and Tsai, PLB785, 288 (2018)
Liu et al., Nuclear Physics B 944, 114638 (2019)

The proton radius puzzle

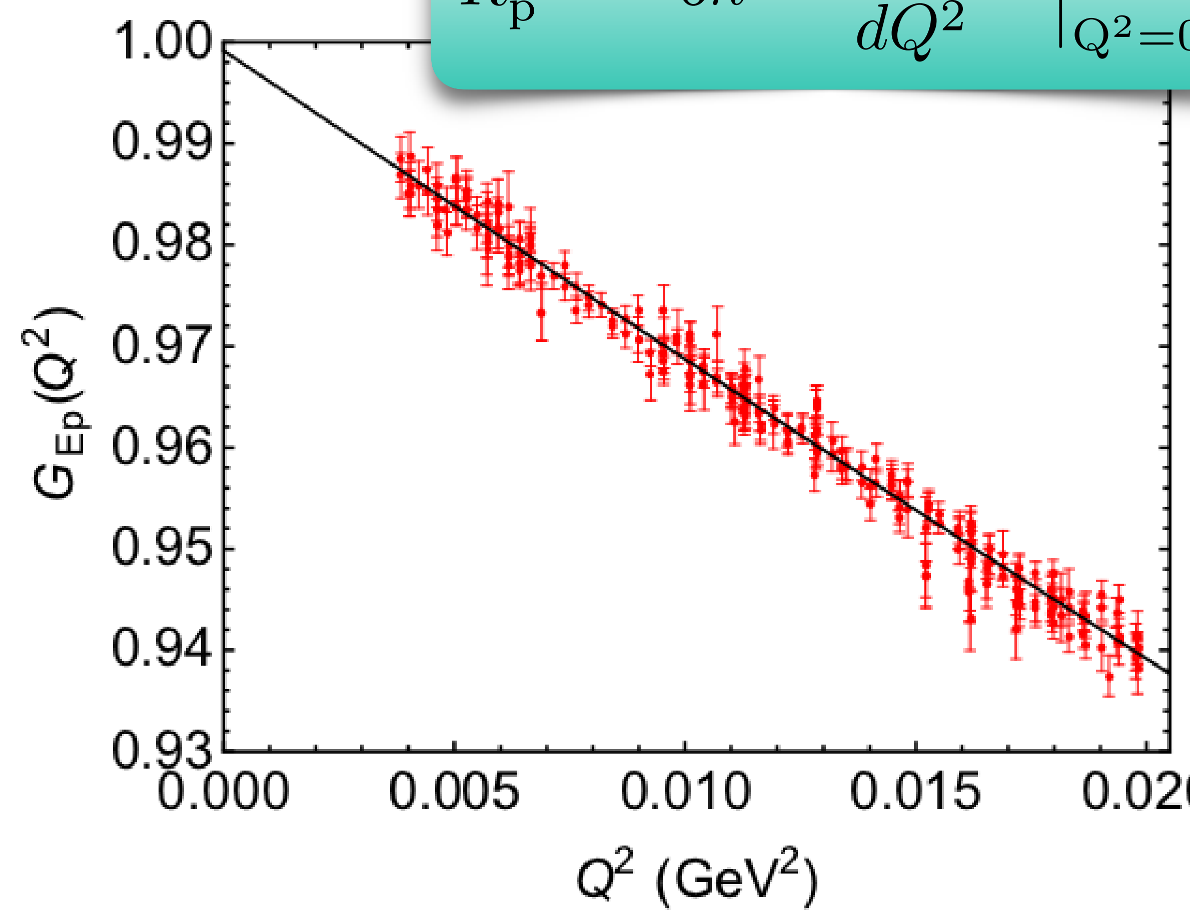
- µp experiment
- µp theory
- H experiments
- BSM physics
- **e-p scattering**



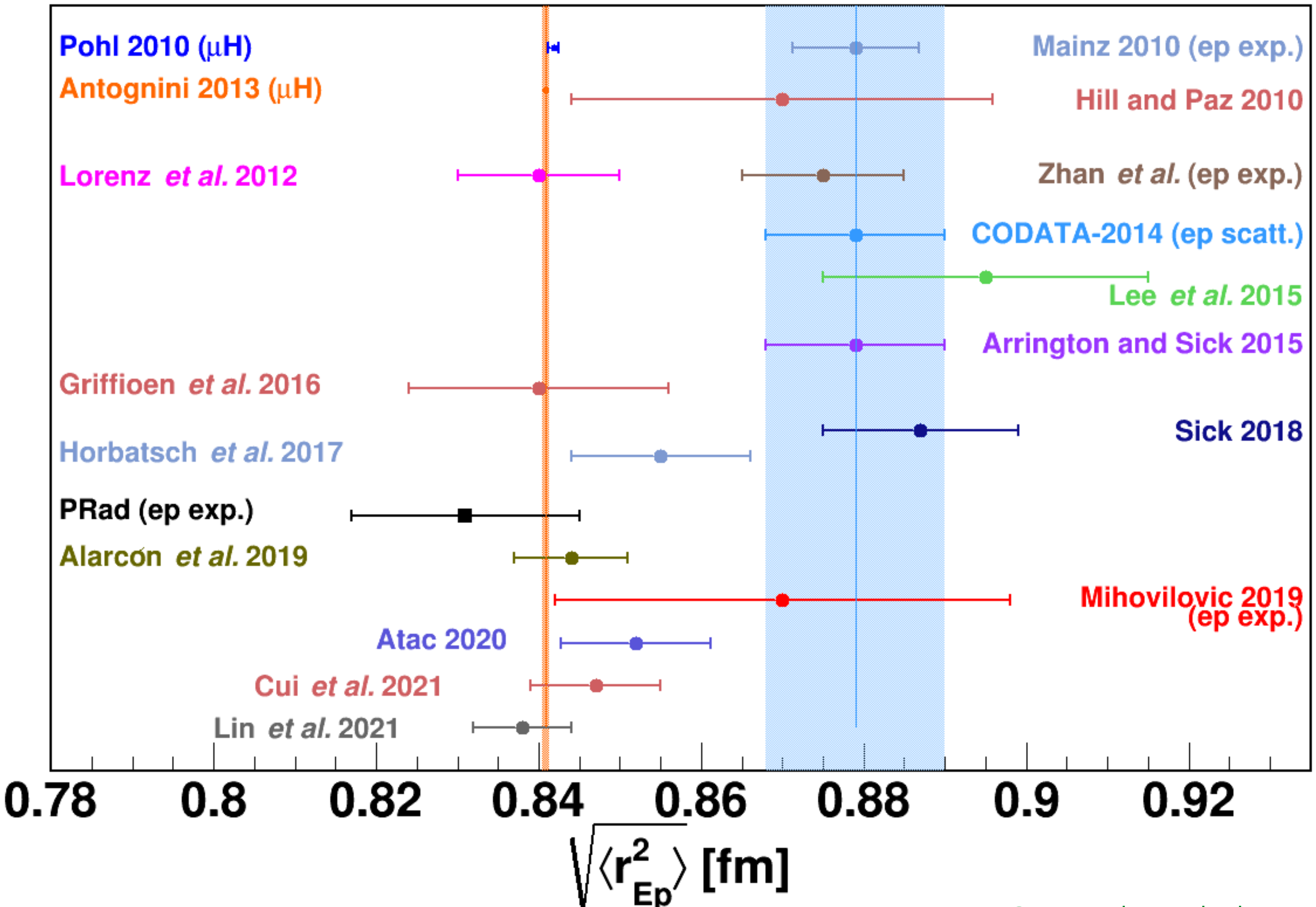
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{elastic}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$



$$R_{\mathrm{p}}^2 = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

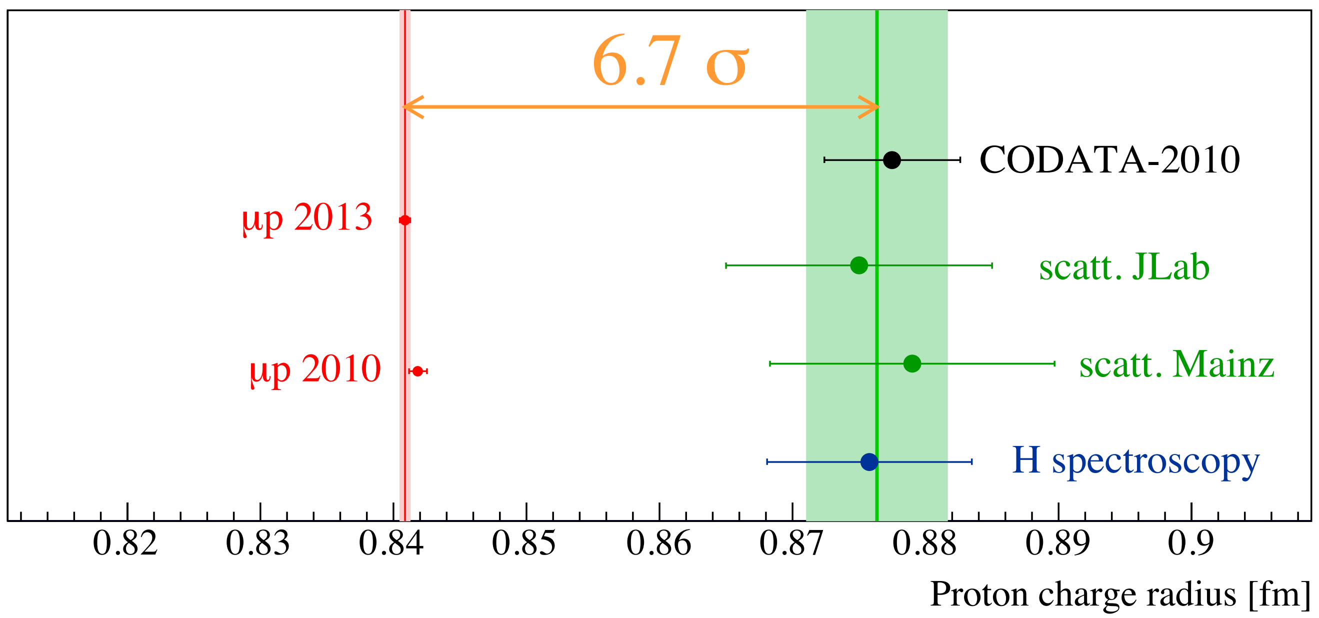


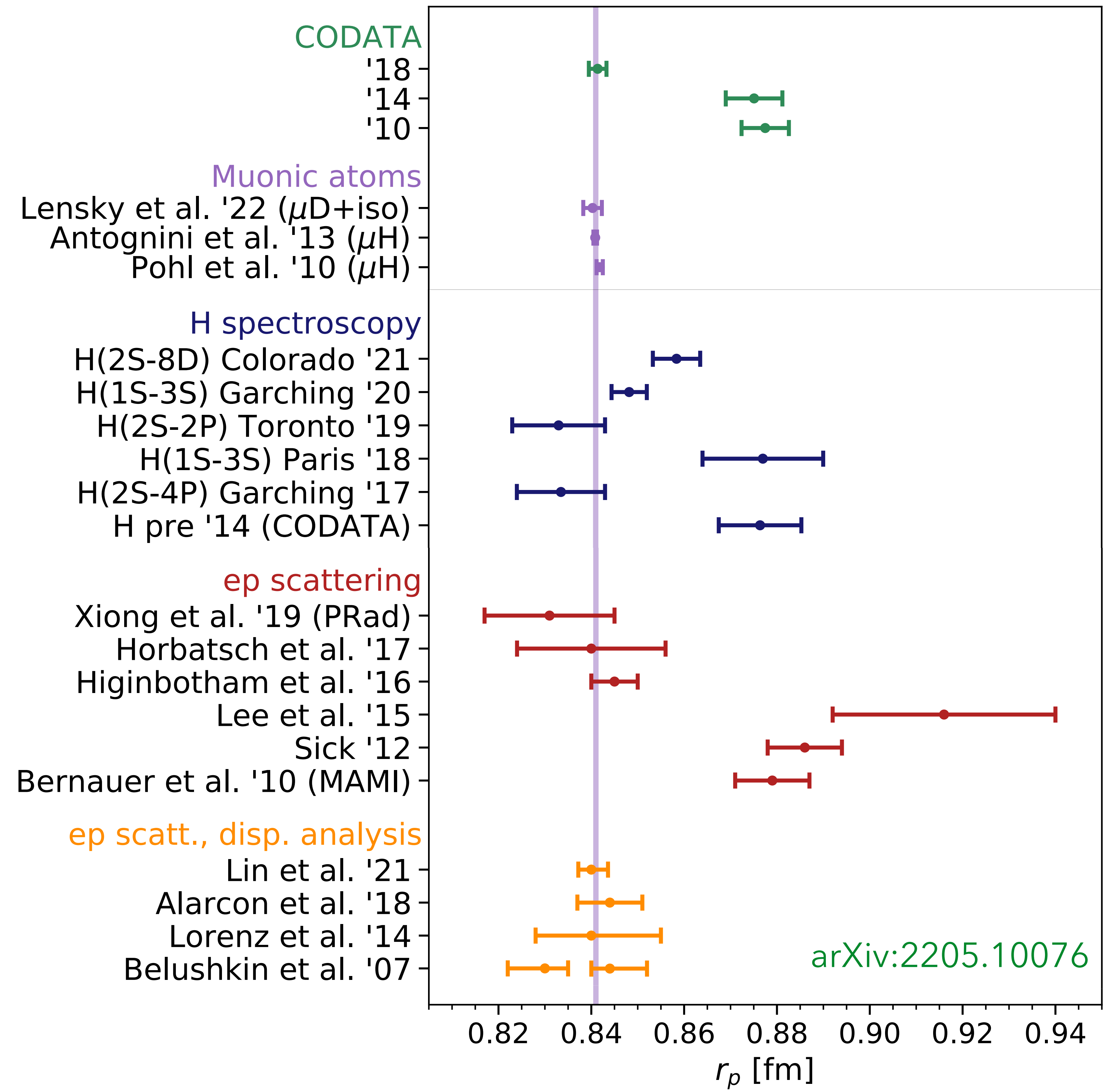
Proton charge radii from e-p scattering



Gao and Vanderhaegen, arXiv:2105.005

The proton charge radii from 2010 to 2022

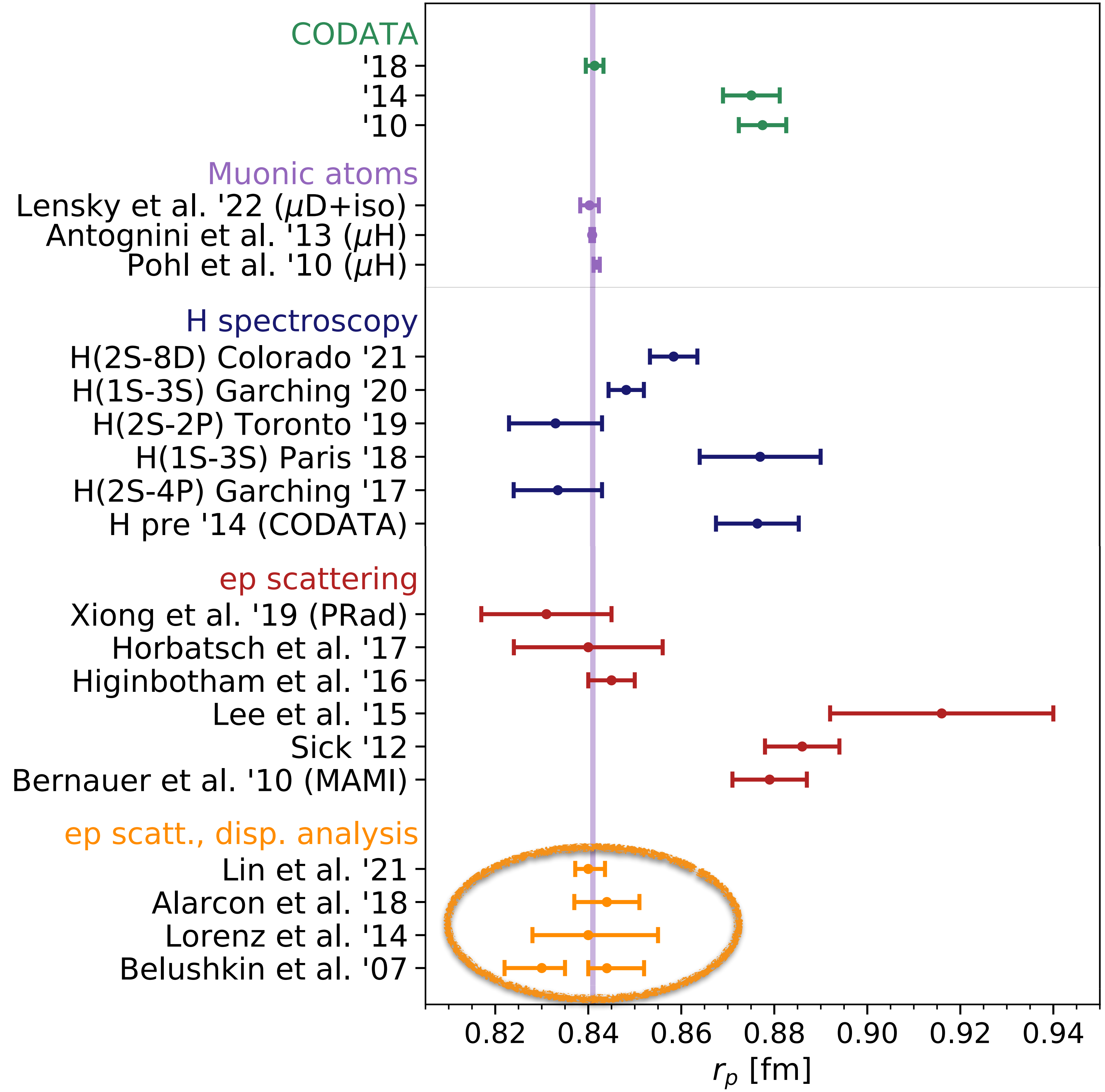




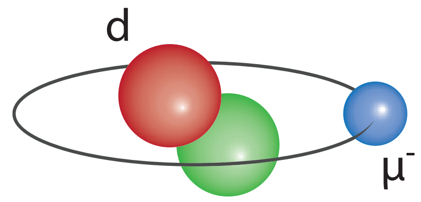
The proton charge radii from 2010 to 2022

Dispersion-based analysis

- Allow for a consistent description of all data (including neutron) in the space- and timelike regions based on fundamental principles.
- Always led to a small proton charge radius



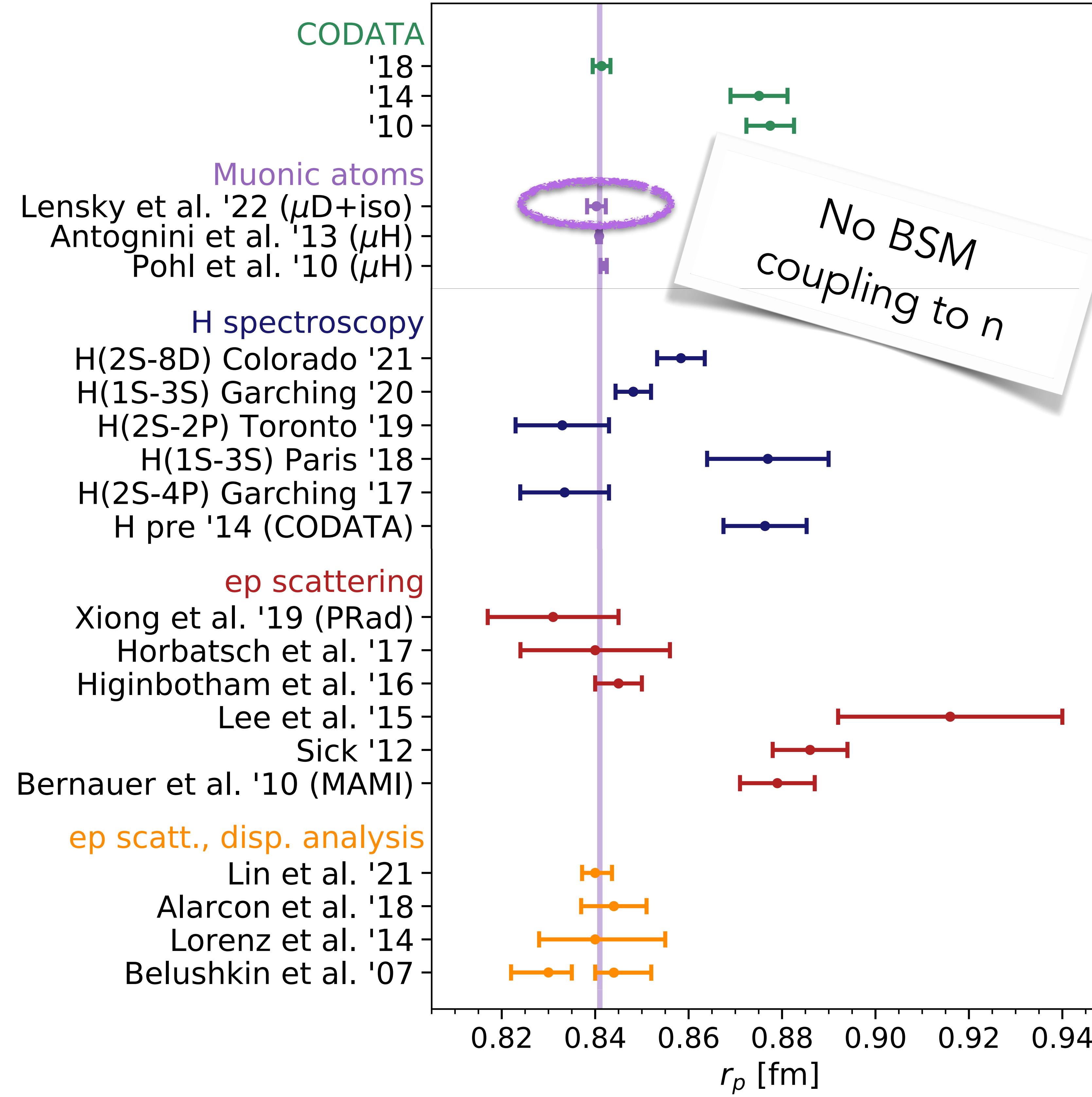
The proton charge radii from 2010 to 2022



μD and H-D isotopic shift

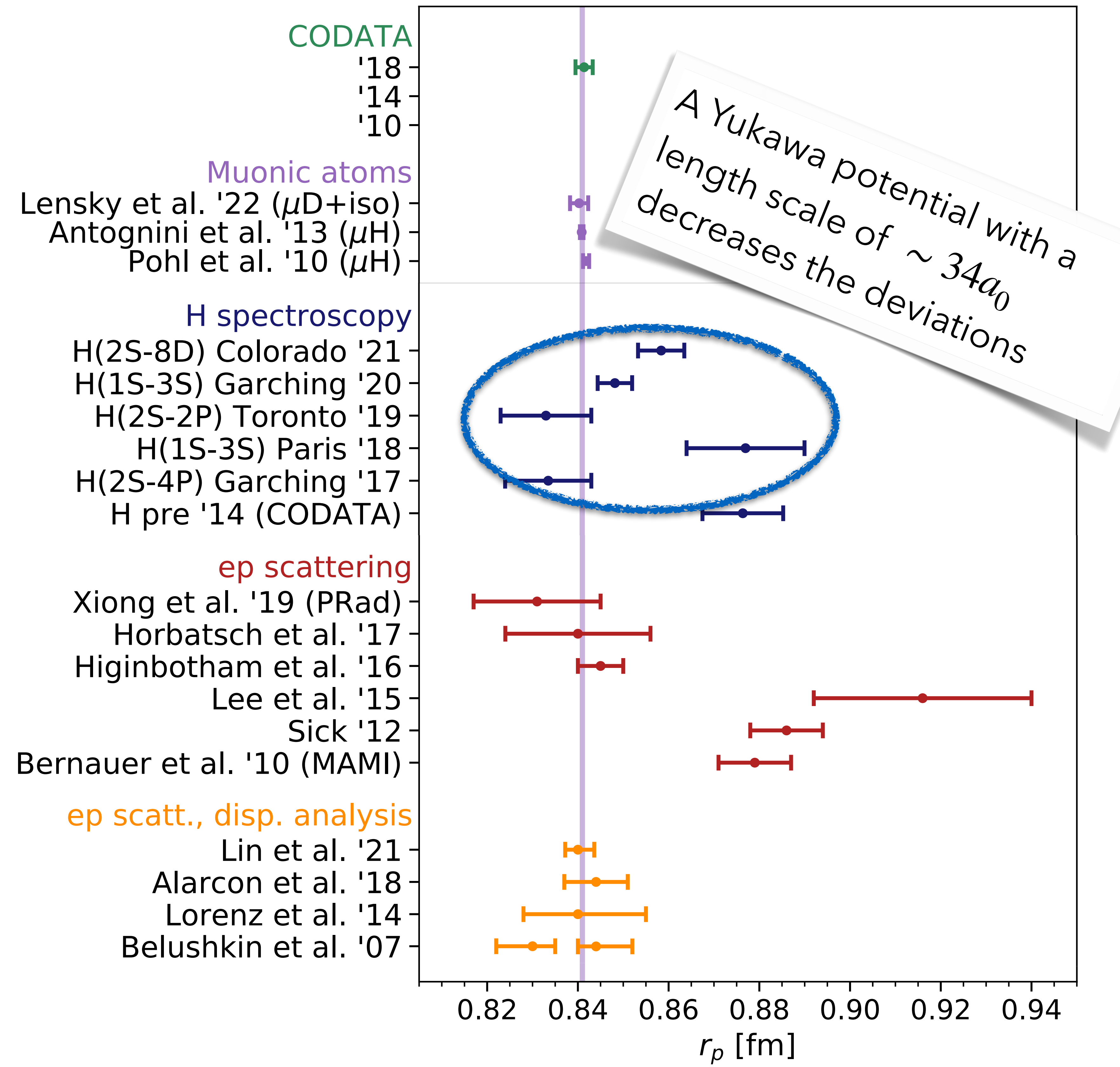
$$\left.\begin{array}{lll} \text{H/D shift:} & r_\mathrm{d}^2 - r_\mathrm{p}^2 & = 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu d: & r_\mathrm{d} & = 2.1256(8)\ \mathrm{fm} \end{array}\right\}$$

Advances in nuclear-structure contributions in H, D and μD atoms removed a 2.5σ tension



Pachucki et al., PRA 97, 062511 (2018)
Kalinowsiet al., PRA 99, 030501 (2019)
Lensky et al., PLB 835 (2022) 137500
Lensky et al., EPJA 58, 224 (2022)

The proton charge radii from 2010 to 2022



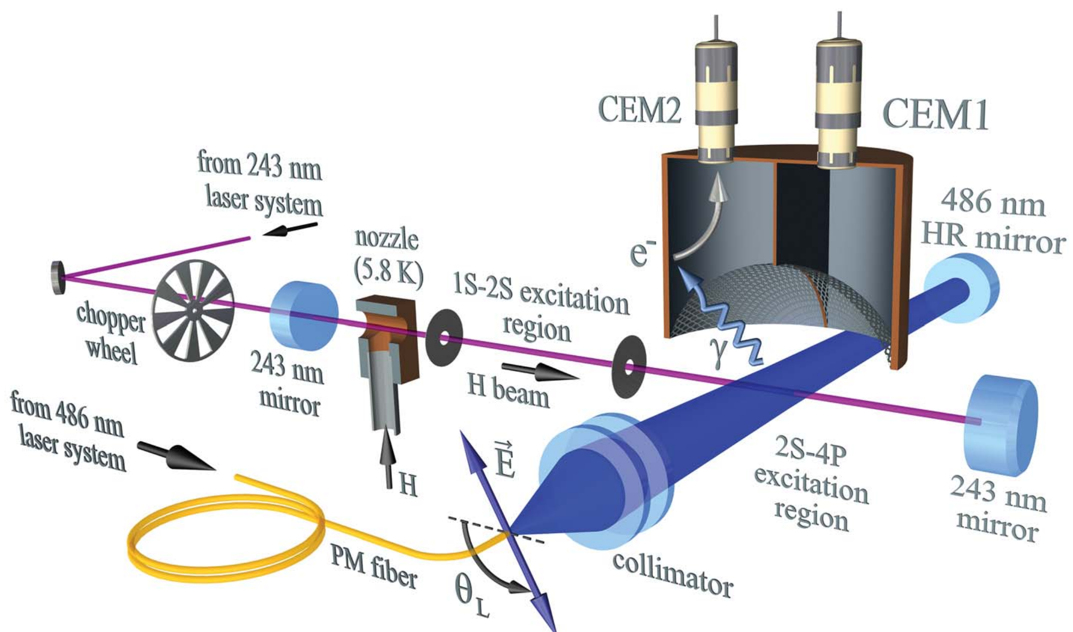
New measurements in H

- Values have moved towards $r_p(\mu\text{H})$, yet, some deviations still exist.
- Deviations tends to decrease as n increases.

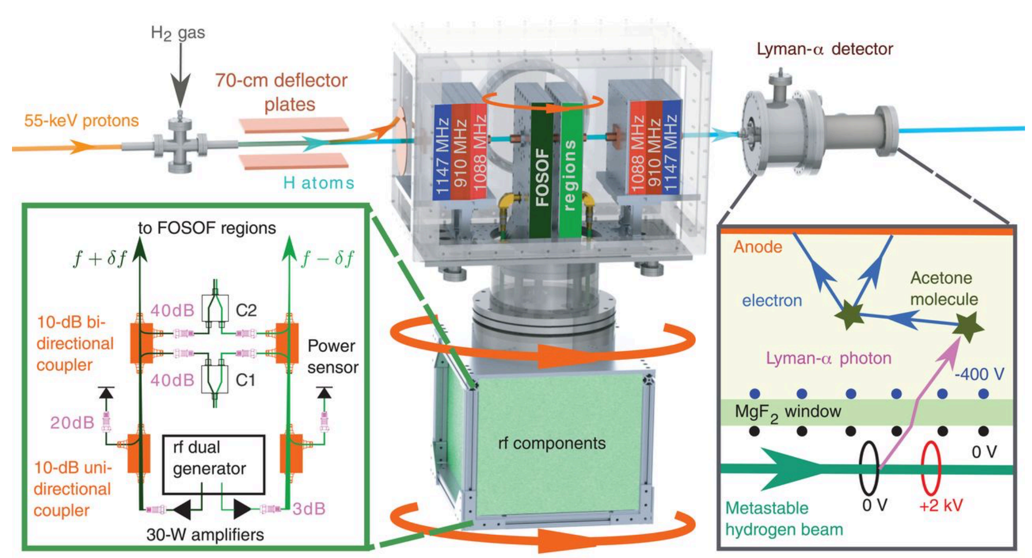
J.P. Karr
P. Yzombard
E. Hessels

The proton charge radii from 2010 to 2022

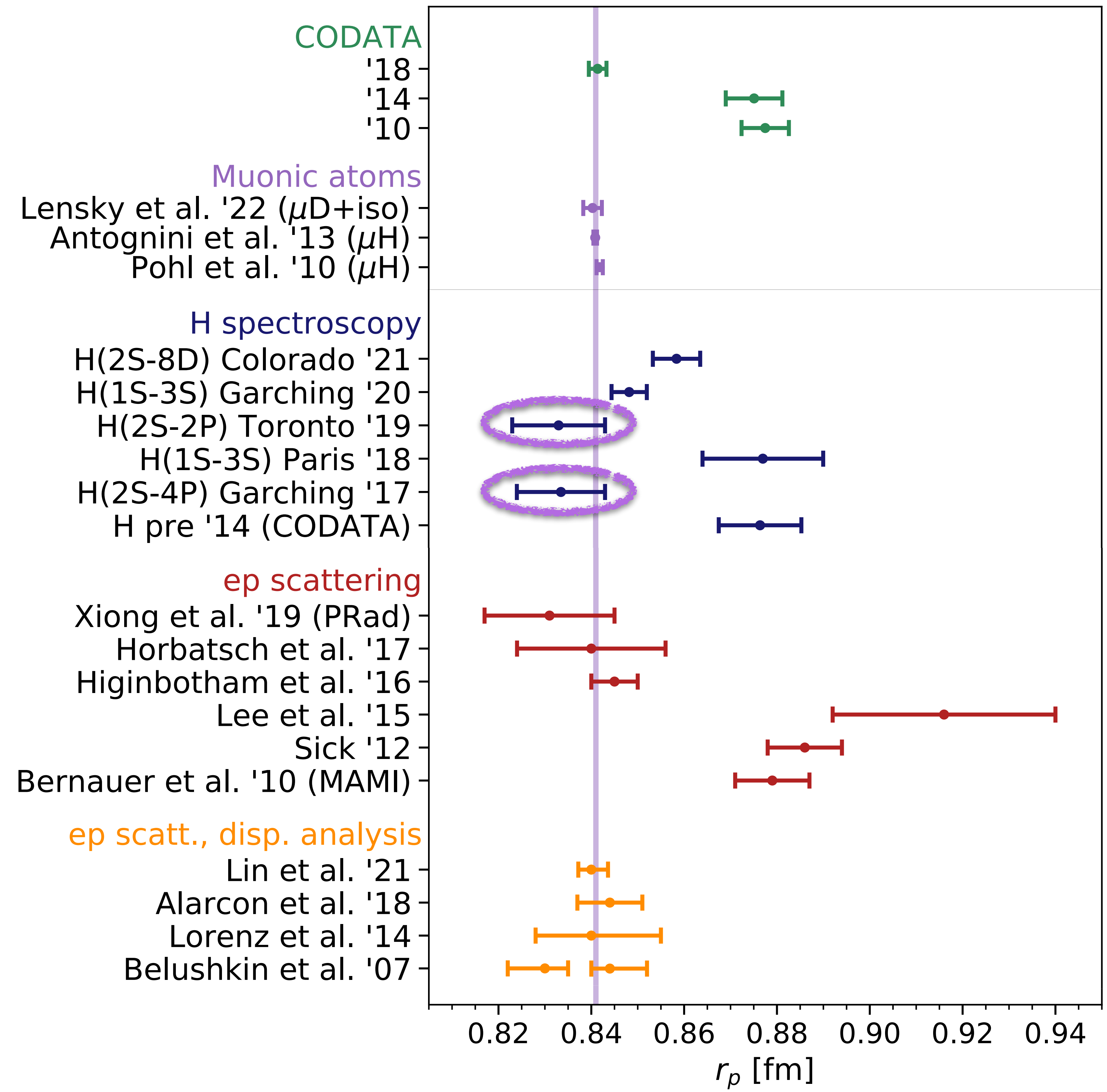
Doppler-free one-photon technique
Modified Ramsey techniques



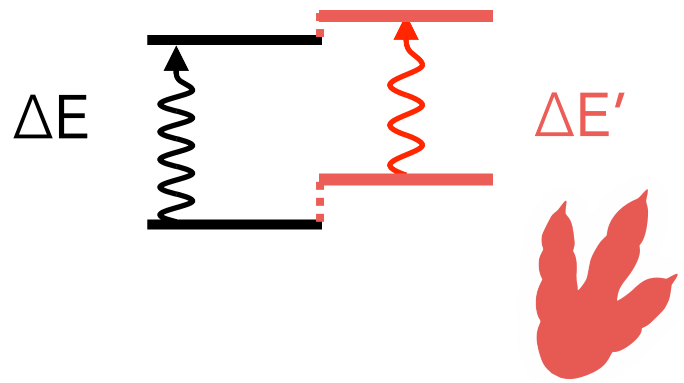
Udem

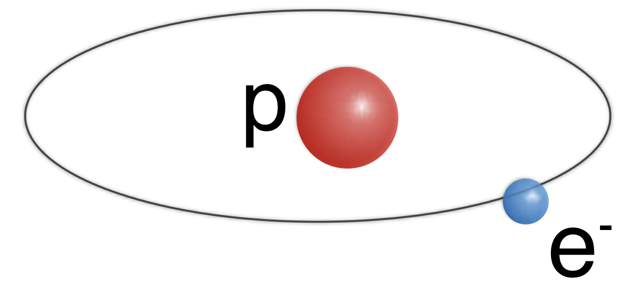


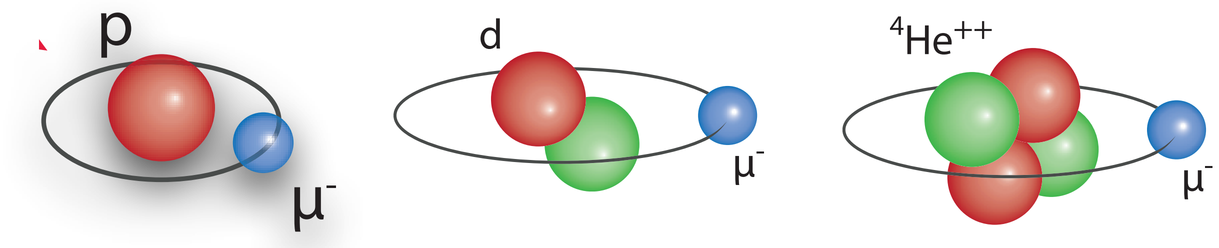
Hessels



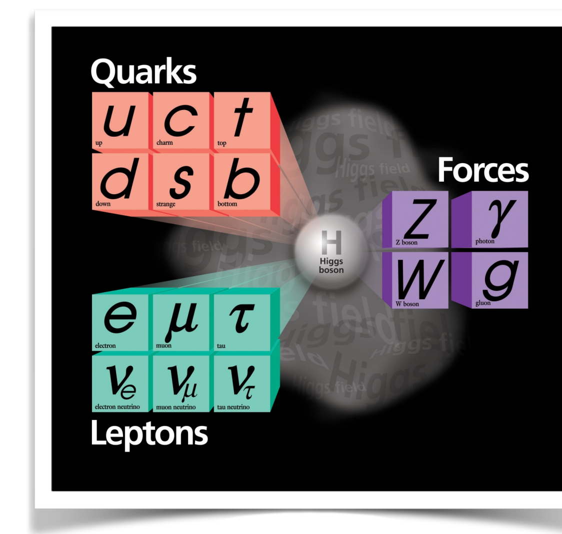
The specificity of muonic atoms as probes of new physics







- Muonic atoms as possible probes of BSM physics
- Sensitive to new forces especially in the MeV-GeV mass range.
- Sensitive to flavour violating coupling
- Can be used also to bound BSM physics coupling to n



Novel effective field theory approaches to low-energy measurements

C. Peset
Y. Stadnik

What to do with a precise proton radius?

- A simplified story (neglecting least square adjustment)
- Slightly muonic-atom centric approach

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

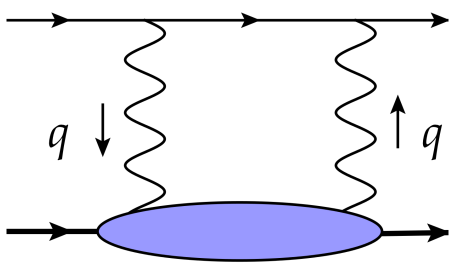
$(\delta = 1 \times 10^{-5})$

Combining μH and H(1S-2S) measurements

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \mathrm{QED} + \kappa r_p^2 + \mathrm{NS}$$

Input from proton structure



$+3\mathrm{PE}$

Extract proton radius

$\delta = 4 \times 10^{-4}$

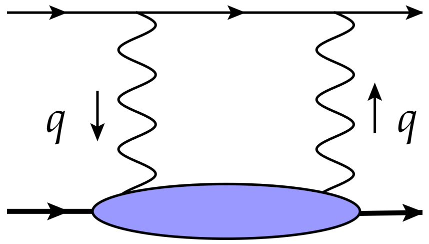
Benchmark for hadron theories

Combining µH and H(1S-2S) measurements

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx QED + \kappa r_p^2 + NS$$

Input from proton structure



$+3PE$

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + QED' + k' r_p^2$$

$(\delta = 4 \times 10^{-15})$

Extract Rydberg constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

$$\delta = 8 \times 10^{-13}$$

Fundamental constant needed for precision predictions in atoms, molecules, ions.

Adding for example the H(1S-3S).....

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

$(\delta = 1 \times 10^{-5})$

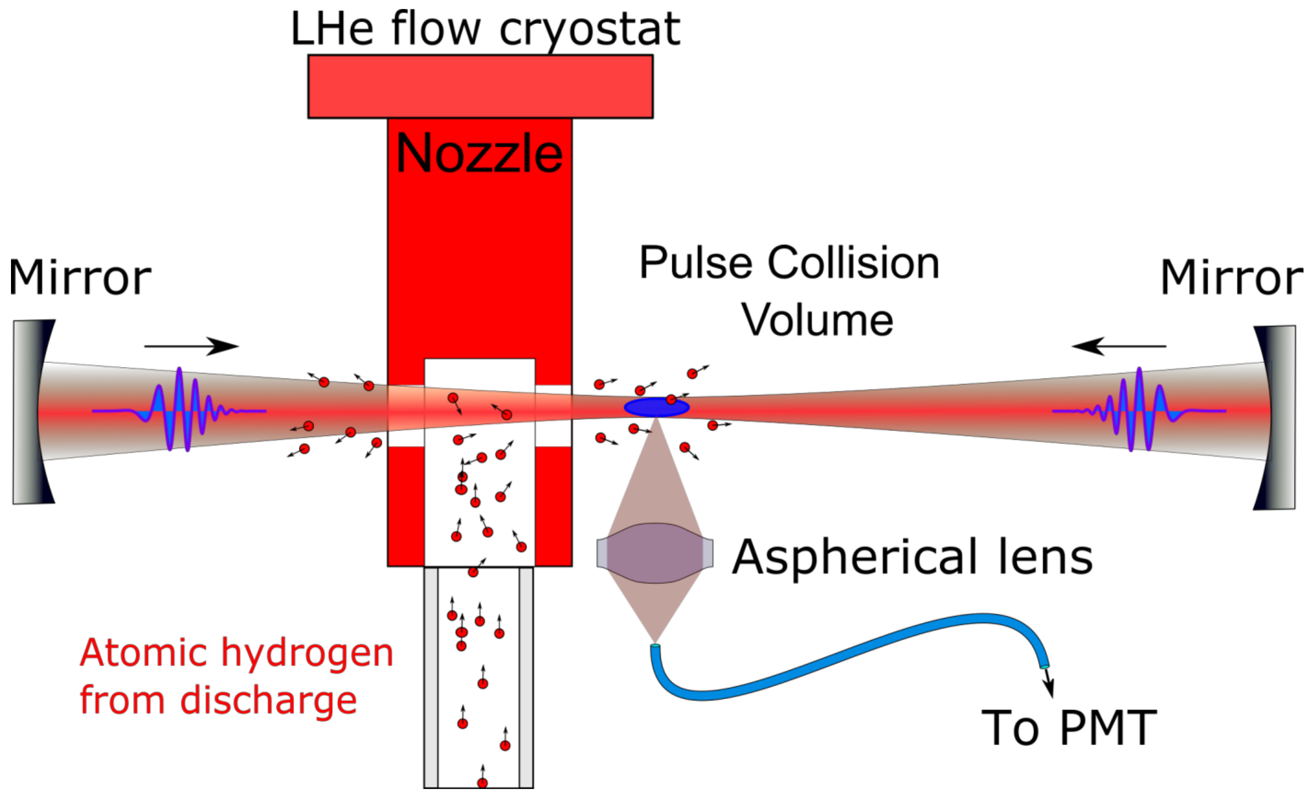
Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + \text{QED}' + k' r_p^2$$

$(\delta = 4 \times 10^{-15})$

$$E_{1S-3S}(H) \approx \frac{8}{9} R_\infty + \text{QED}'' + k'' r_p^2$$

$(\delta = 2.5 \times 10^{-13})$



Grinin et al. Science 370(6520):1061–1066 (2020)

Adding H(1S-3S).....

Muonic hydrogen

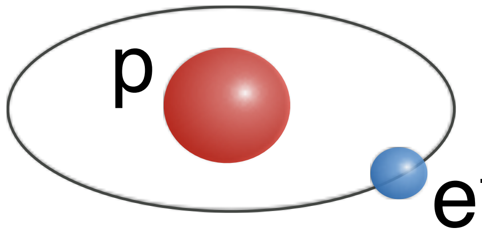
$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

Input from proton structure

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + \text{QED}' + k' r_p^2$$

$$E_{1S-3S}(H) \approx \frac{8}{9} R_\infty + \text{QED}'' + k'' r_p^2$$



Test of H theory
Test of bound-states QED
$\delta \sim 1 \times 10^{-12}$

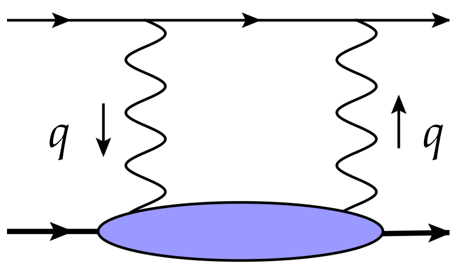
Strong BSM limits

Adding H(1S-3S).....

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

Test proton structure



$+3\text{PE}$

Theoretical tools
- dispersive
- sum rules
- chiral perturbation th.
- lattice QCD
- Nuclear structure contribution

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4}R_\infty + \text{QED}' + k' r_p^2$$

Combine

$$E_{1S-3S}(H) \approx \frac{8}{9}R_\infty + \text{QED}'' + k'' r_p^2$$

Adding HD+ measurements

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \mathrm{QED} + \kappa r_p^2 + \mathrm{NS}$$

$(\delta = 1 \times 10^{-5})$

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + \mathrm{QED}' + k' r_p^2$$

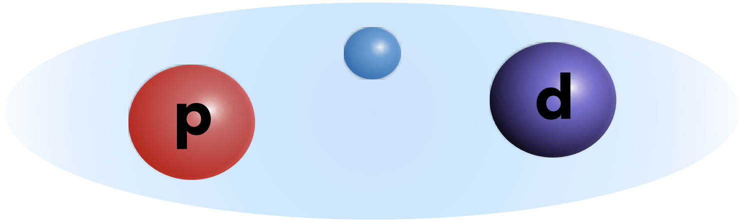
$(\delta = 4 \times 10^{-15})$

HD isotope shift

HD+

$$E(\nu\, L \to \nu'\, L') = R_\infty \mathrm{QED}_{3-\mathrm{body}}\left(\alpha, \frac{m_e}{m_p}, \frac{m_p}{m_d}, r_p, r_d\right)$$

$\delta = \mathcal{O}(10^{-11} - 10^{-12})$



Karr et al., Springer Proc. Phys. 238:75–81 (2020)
Alighanbari et al., Nature 581(7807):152–158 (2020)
Patra et al., Science 369(6508):1238–1241 (2020)

Adding Penning traps measurements

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx QED + \kappa r_p^2 + NS$$

$(\delta = 1 \times 10^{-5})$

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + QED' + k' r_p^2$$

$(\delta = 4 \times 10^{-15})$

HD isotope shift

HD+

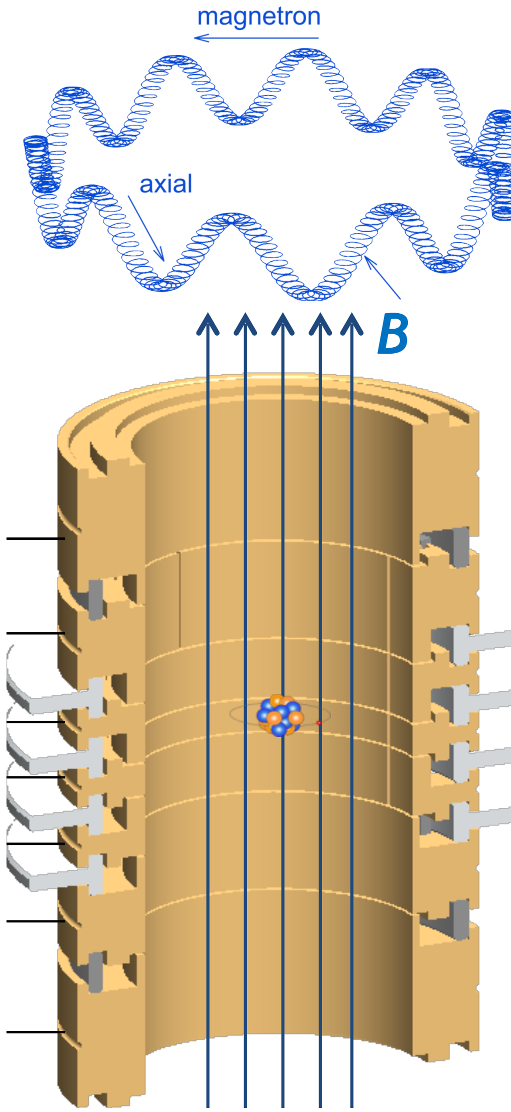
$$E(\nu\, L \to \nu'\, L') = R_\infty \, QED_{3-body}\left(\alpha, \frac{m_e}{m_p}, \frac{m_p}{m_d}, r_p, r_d\right)$$

$\delta = \mathcal{O}(10^{-11} - 10^{-12})$

Penning traps

g-factors, $\frac{\omega_p}{\omega_{^{12}C^{5+}}}$ ...

$\delta \sim \mathcal{O}(10^{-11})$



Heiße et al. Phys. Rev. A 100(2):022518 (2019)
Sturm et al. Nature 506(7489):467–470 (2014)

Combining measurements in μp, H, HD+ and Penning-traps

Muonic hydrogen

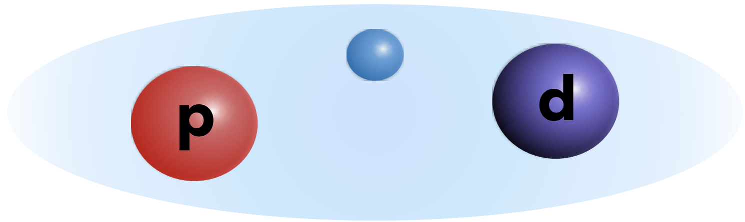
$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + \text{QED}' + k' r_p^2$$

HD+

$$E(\nu\, L \rightarrow \nu'\, L') = R_\infty \text{QED}_{3-\text{body}}\left(\alpha, \frac{m_e}{m_p}, \frac{m_p}{m_d}, r_p, r_d\right)$$



Test of HD+ theory
Test of 3-body QED
$\delta \sim 10^{-11}$

Strong BSM limits

Penning traps

g-factors, $\frac{\omega_p}{\omega_{^{12}C^{5+}}}$ ...

Antognini, Hagelstein, Pascalutsa, arXiv:2205.10076

Combining measurements in μp, H, HD⁺ and Penning-traps

N. Schwegler

Muonic hydrogen

$$E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$$

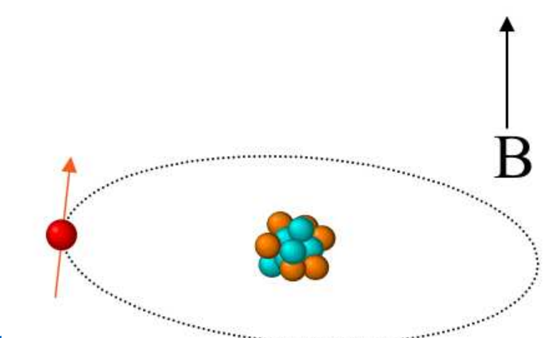
Hydrogen

$$E_{1S-2S}(H) \approx \frac{3}{4} R_\infty + \text{QED}' + k' r_p^2$$

S. Sturm

HD+

$$E(\nu\, L \to \nu'\, L') = R_\infty \text{QED}_{3-\text{body}}\left(\alpha, \frac{m_e}{m_p}, \frac{m_p}{m_d}, r_p, r_d\right)$$



Extract m_e/m_p ratio

$\delta = 2 \times 10^{-11}$

Penning traps measurements

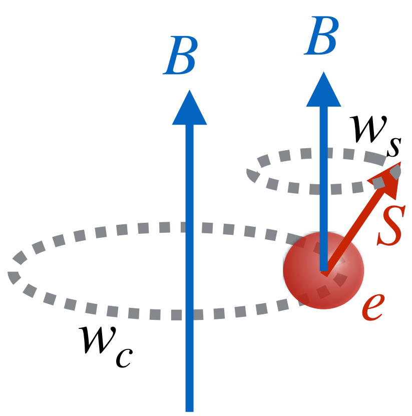
Test of bound g-factors

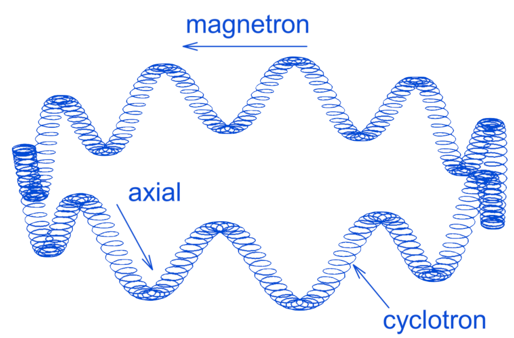
$\delta \sim 4 \times 10^{-11}$

The fine structure constant

Experiment

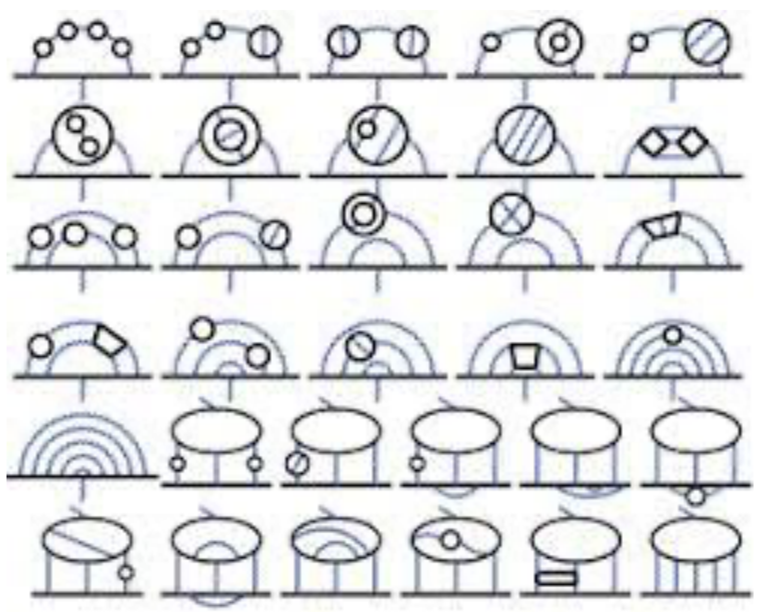
$$a_e^{\mathrm{exp}} = \frac{g_e - 2}{2} = 0.00115965218073(28)$$





Theory

$$a_e^{\mathrm{theory}} = C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + a_{\mathrm{weak}} + a_{\mathrm{had}} +$$



Hanneke et al, PRL 2008, 100, 120801

Aoyama et al, PRD 2018, 97, 036001

Xin Fang

Compare experiment to theory

$$a_e^{\mathrm{exp}} = a_e^{\mathrm{theory}}(\alpha)$$

Extract
Fine structure constant
$\delta \sim 2 \times 10^{-10}$

$$a_e^{\mathrm{exp}} = a_e^{\mathrm{theory}}(\alpha)$$

Test g-factor theory
$\delta \sim 3 \times 10^{-13}$

Parker et al., Sciece 360, 191-195 (2018)
Morel et al., Nature 588, 61-68 (2020)

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_X}{m_e}\frac{h}{m_X}$$

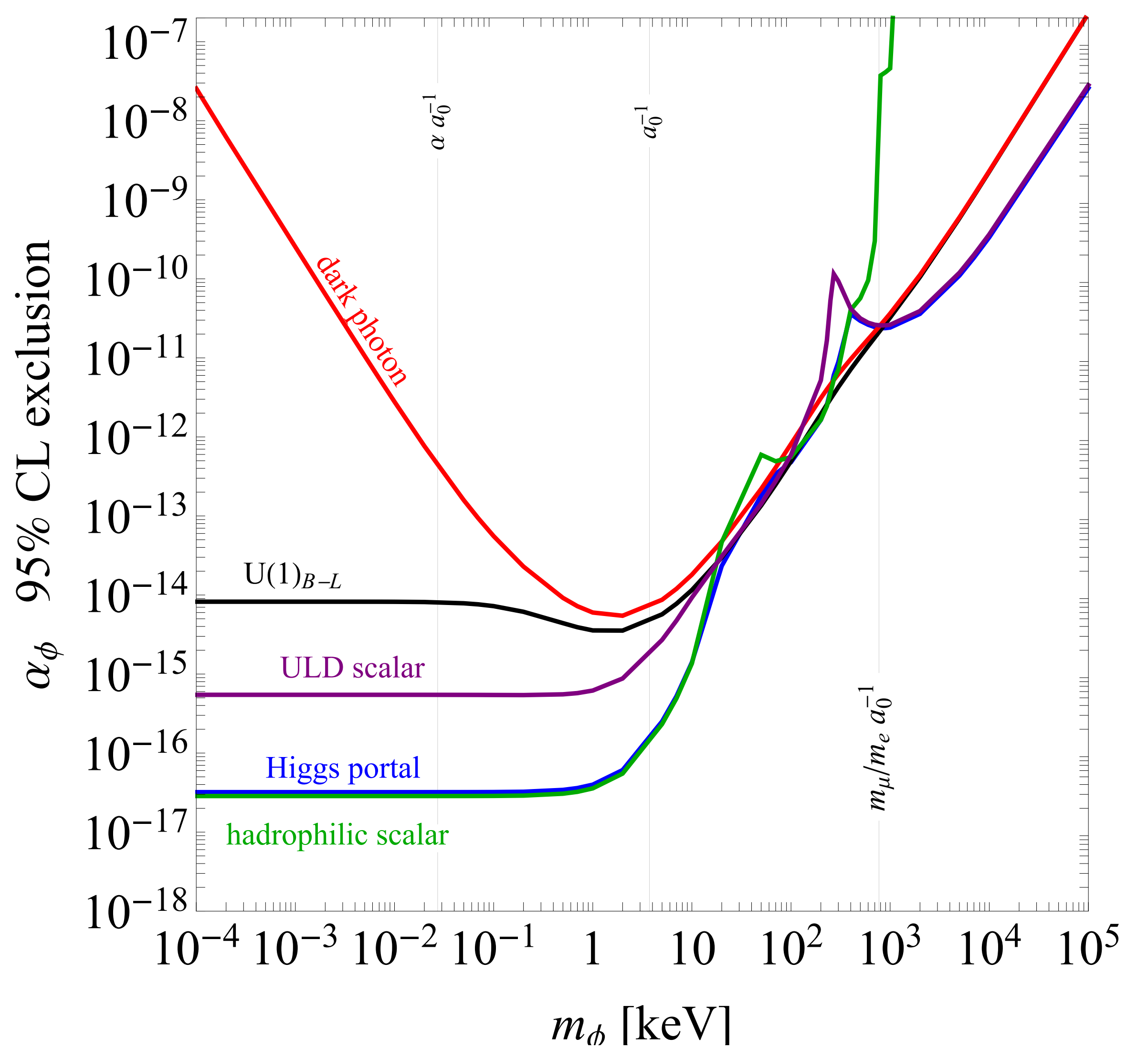
μp+H

P. Cladet

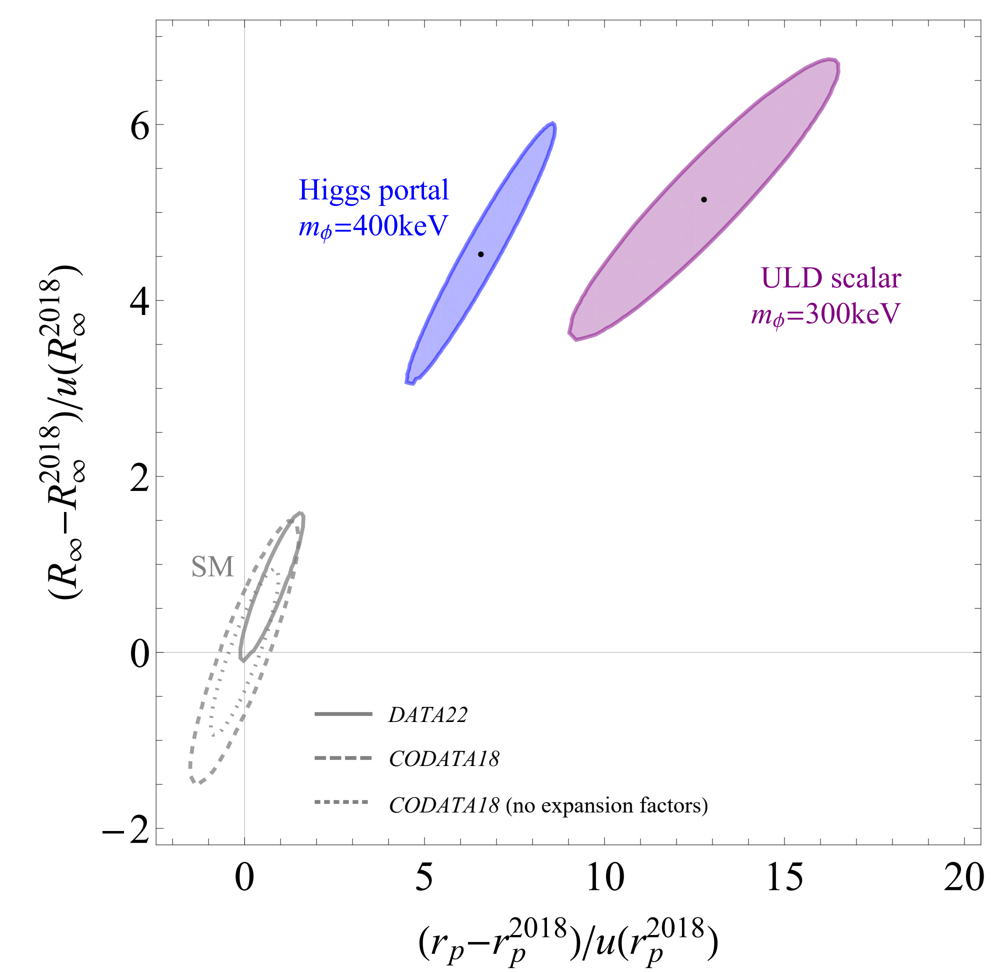
Least square adjustment of fundamental constants with/without BSM

Self-consistent extraction of spectroscopic bounds on light new physics

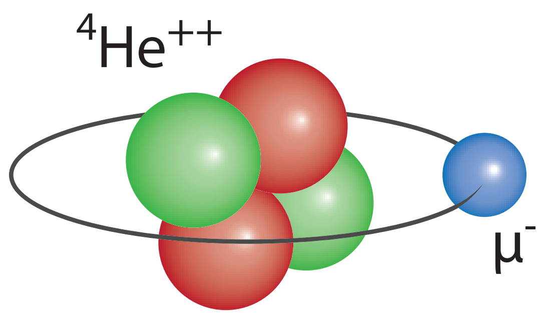
Cédric Delaunay,[1,2,*] Jean-Philippe Karr,[3,4,†] Teppei Kitahara,[5,6,7,‡]
Jeroen C. J. Koelemeij,[8,§] Yotam Soreq,[9,¶] and Jure Zupan[10,**]



The presence of BSM physics would affect the extraction of fundamental constants, possibly reducing the claimed sensitivity of BSM searches.



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



QED | Finite size | Nuclear structure

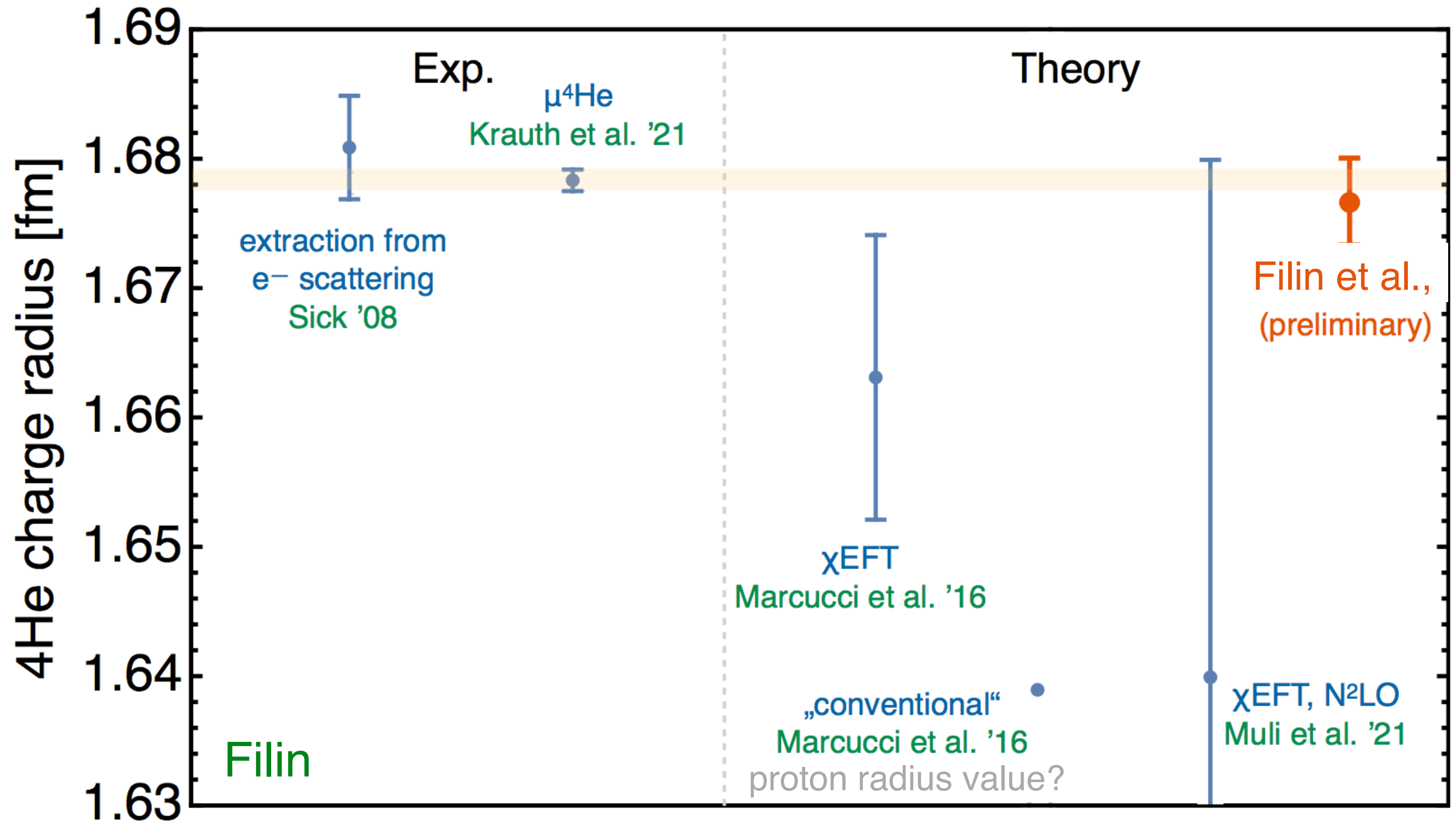
$$E_{LS}^{th} = 1668.491(7) - 106.209\, r_\alpha^2 + 9.276(433)\ \text{meV}$$

Pachucki et al., arXiv:2212.13782

$$E_{LS}^{exp} = 1378.521(48)\ \text{meV}$$

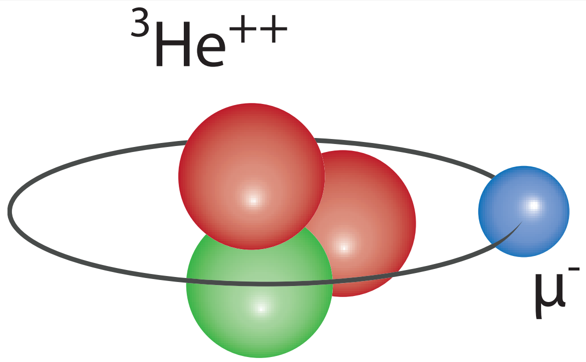
Krauth et al., , Nature 589 (2021) 7843, 527-531

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



Towards consistent treatment of the nuclear structure: TPE and radii

The helion charge radius



QED	Finite size	Nuclear structure

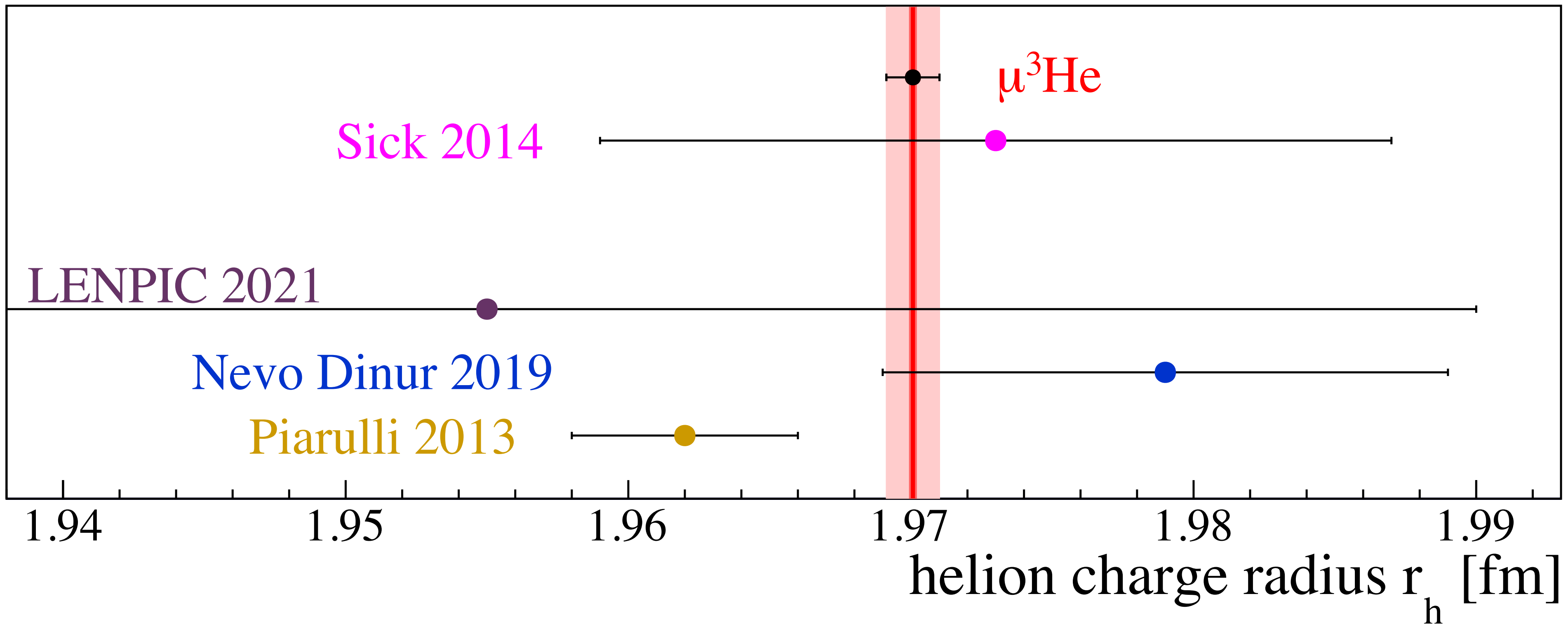
$$E_{LS}^{th} = 1644.348(8) - 103.383\, r_h^2 + 15.499(378)\text{ meV}$$

Pachucki et al., arXiv:2212.13782

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

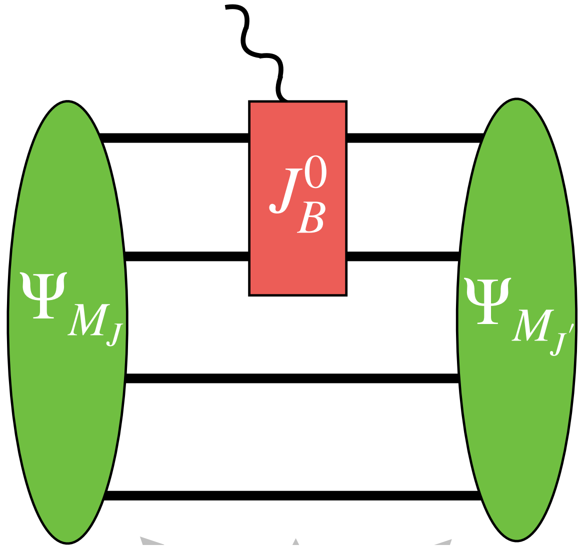
Schuhmann et al., arXiv 2305.11679

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



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

Filin

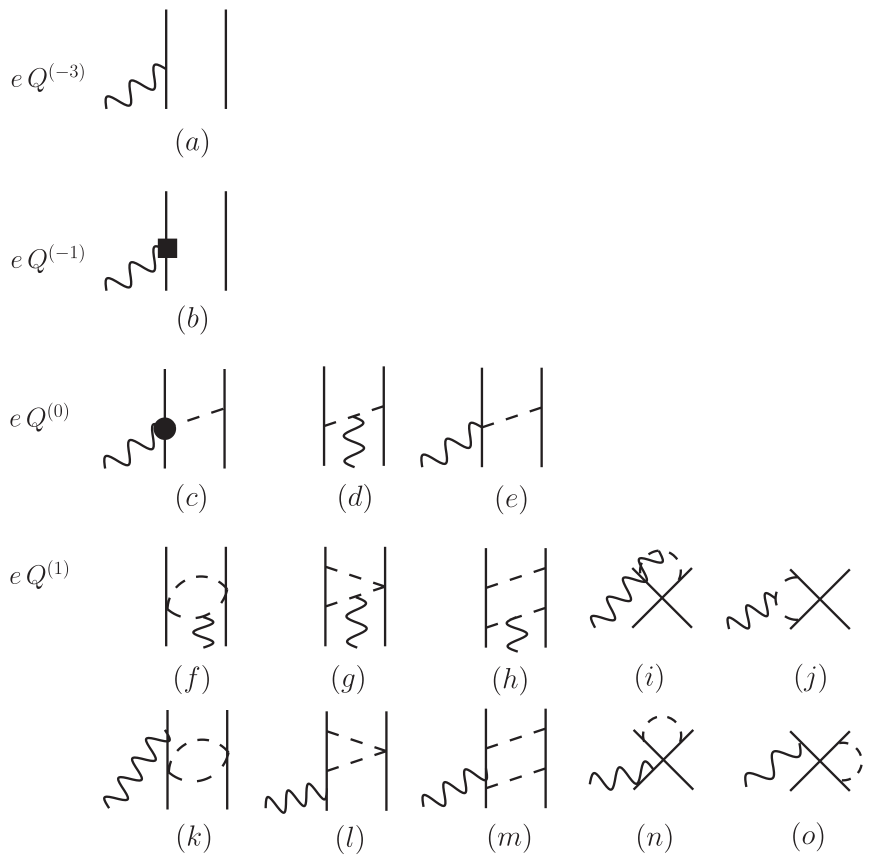


$$F_C(Q^2) = \frac{1}{2J+1} \sum_{M_J} < P', M_J | J_B^0 | P, M_J >$$

In Breit frame

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

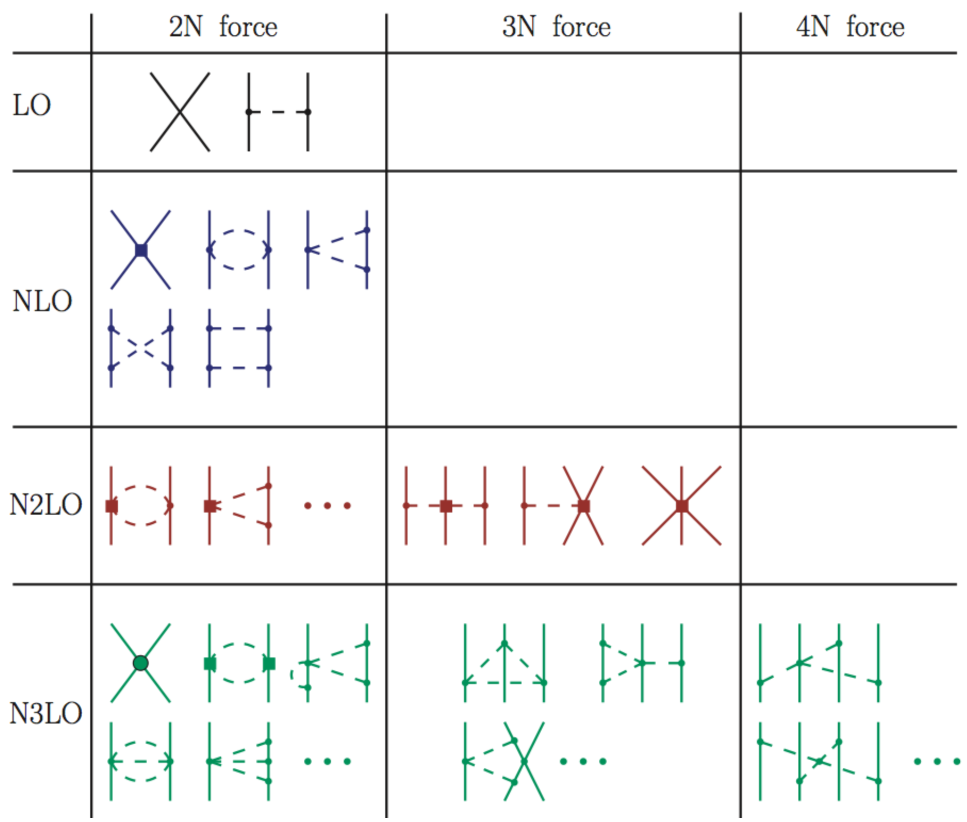
Current operator



Li Muli

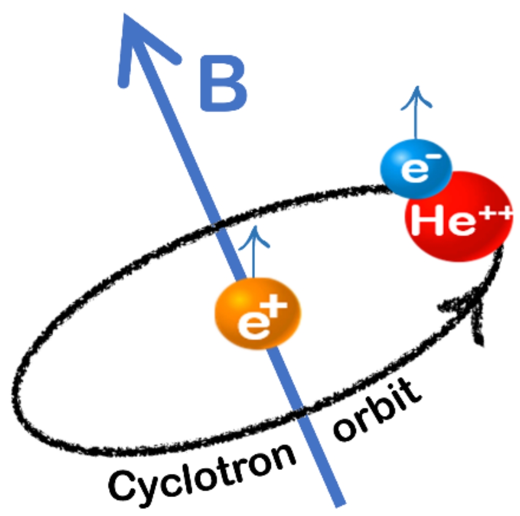
Consistent derivation and regularization of many body forces and nuclear current operators + Rel. dynamics + isospin breaking+…

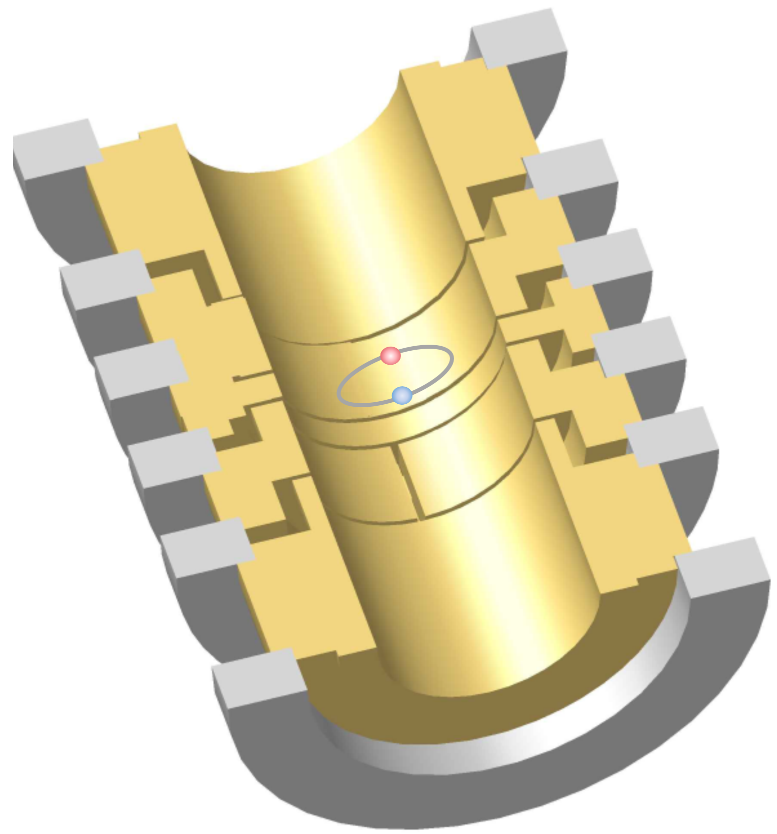
Chiral-based nuclear forces



CPT tests (Lsym-project)

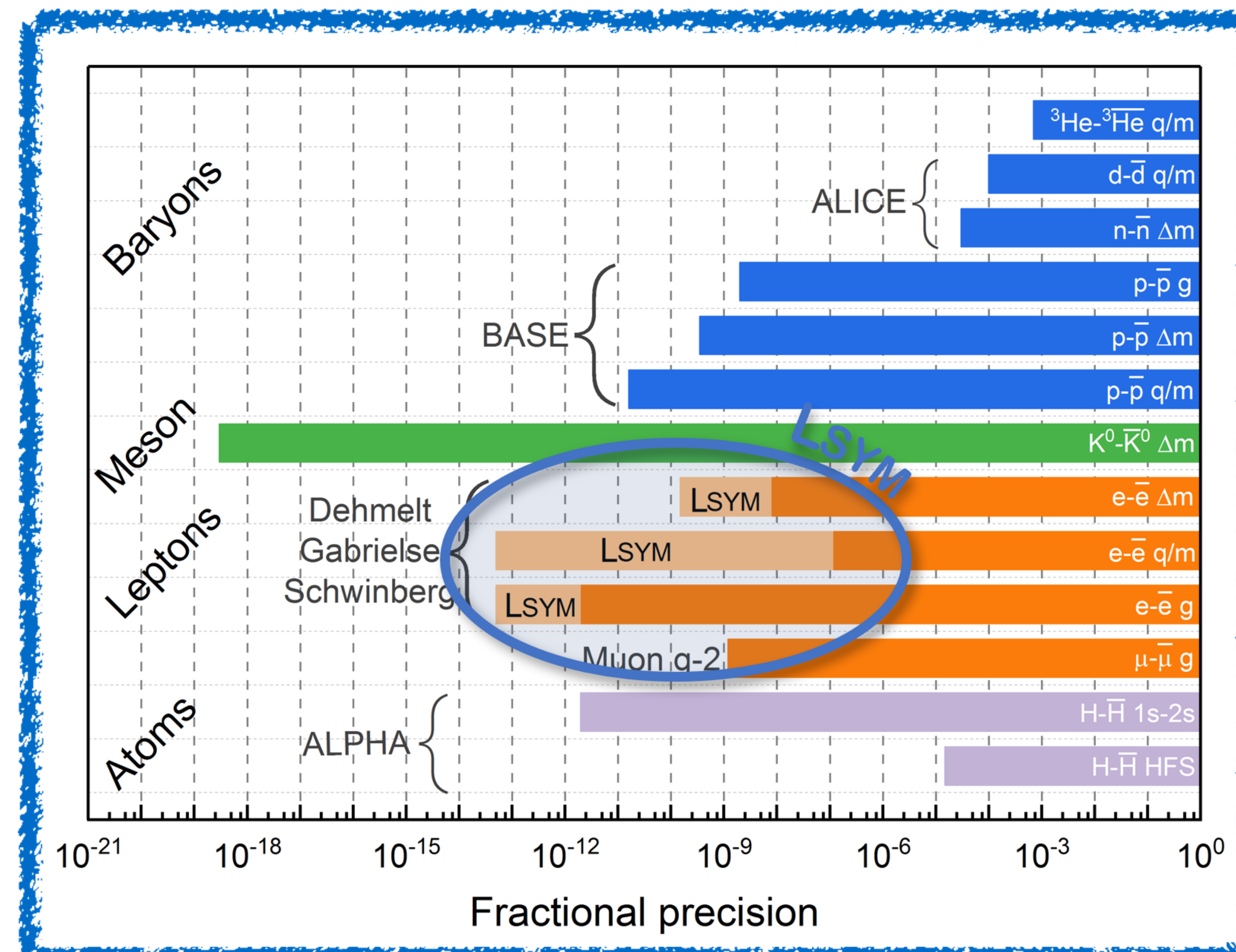
S. Sturm





$$g_{e^-} - g_{e^+} \sim \omega_{L,e^-} - \omega_{L,e^+} \sim \frac{q}{m} g_{e^-} - \frac{q}{m} g_{e^+}$$

He charge radius needed to extract the CPT tests



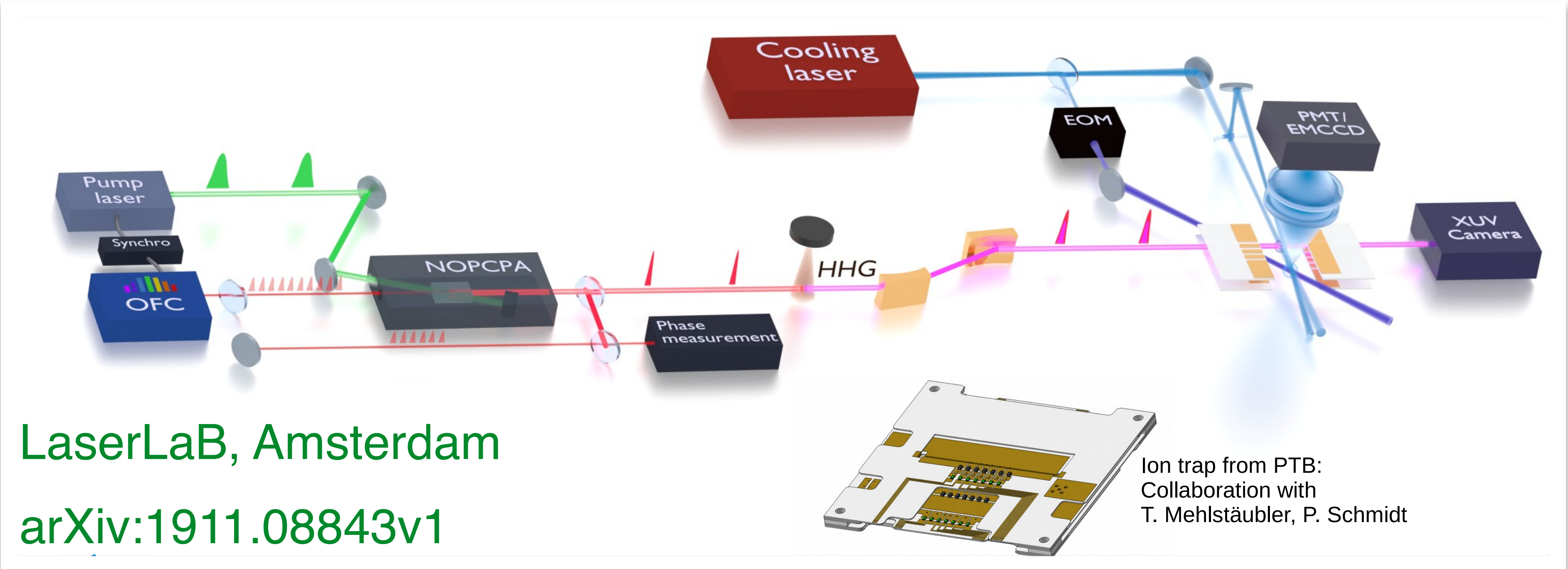
Frequency Comb spectroscopy in He$^+$

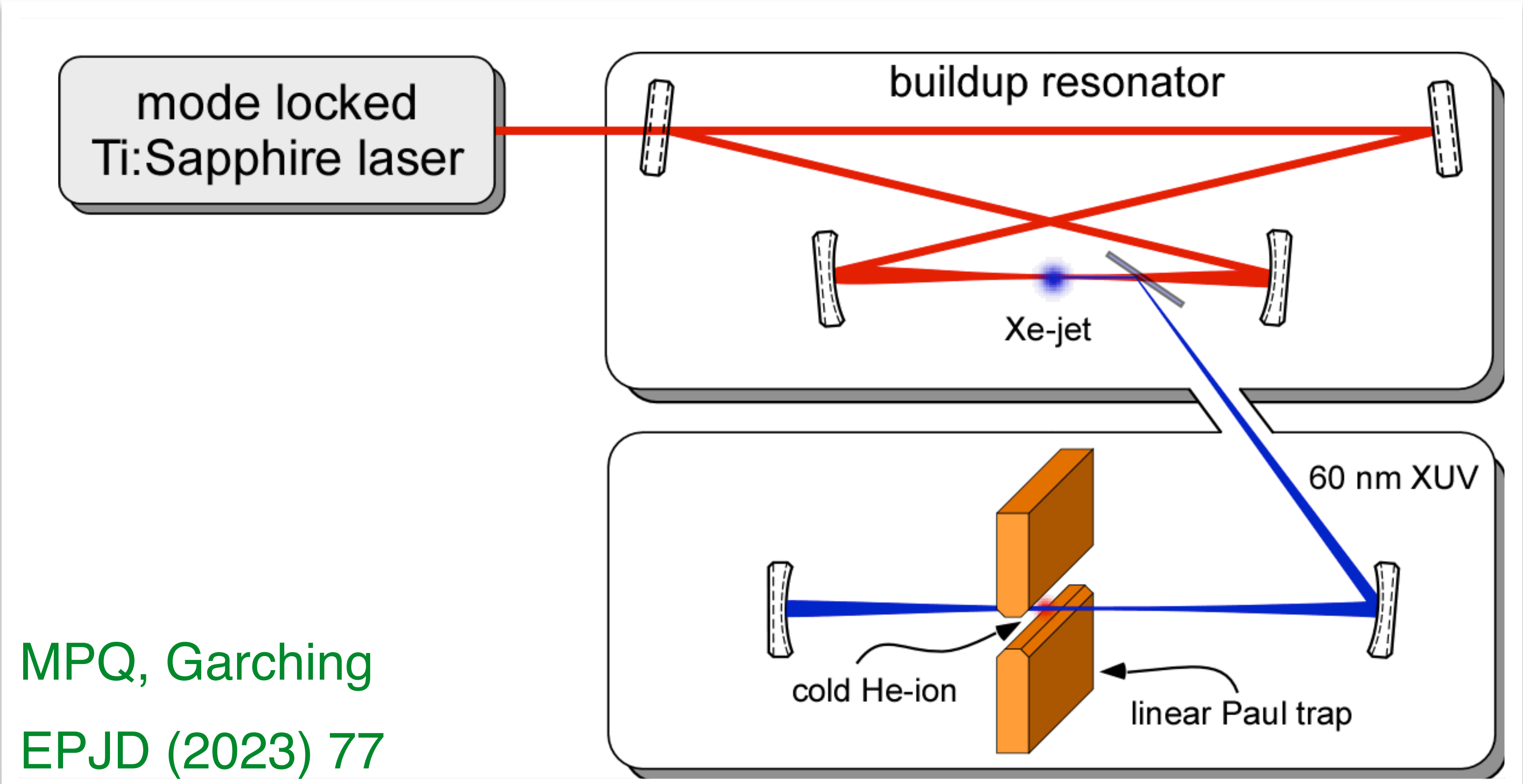
Comb spectroscopy in the XUV

Trapping and cooling

Quantum logic detection

E. Grundeman





The He atom

Two electrons are much more than one electron

$m\alpha^7$ contributions completed

Patkos et al, PRA 103, 042809 (2021)

Clausen et al, PRL 127, 093001 (2021)
Zheng, et al, PRL 119, 263002 (2017)

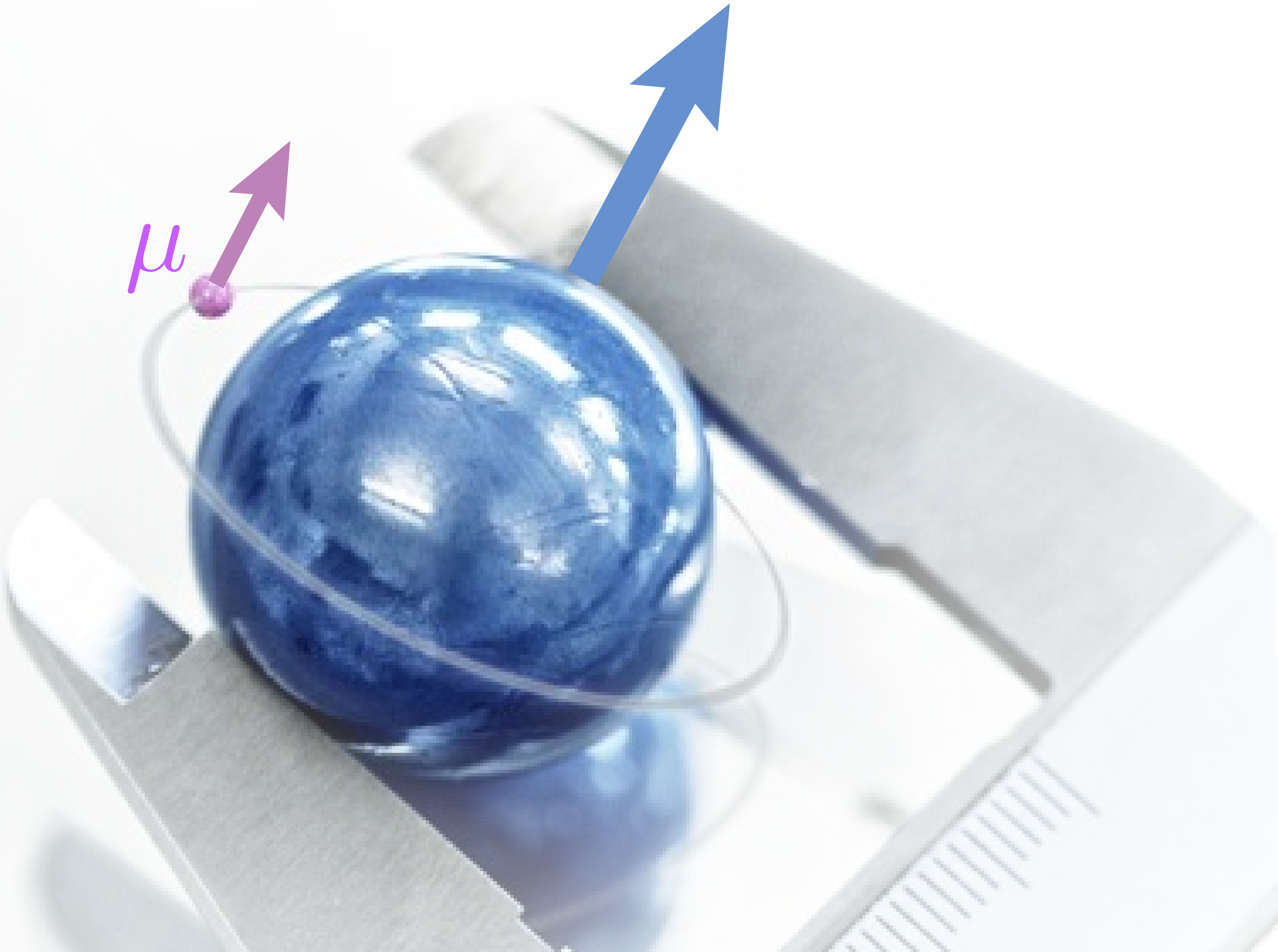
For some transitions there is perfect agreement, for others perfect disagreement

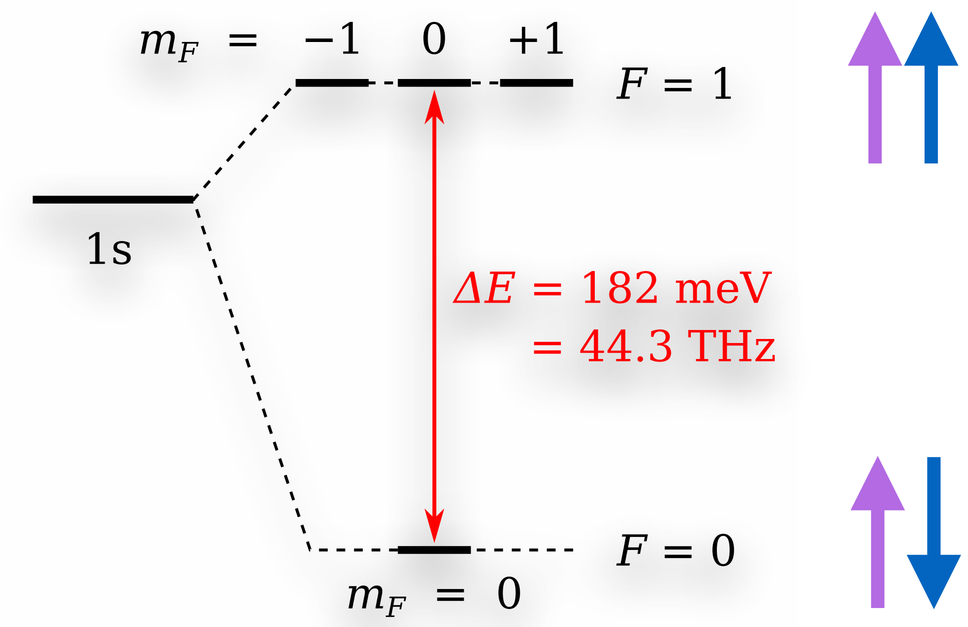
But this is another story

Talk Gloria Clausen

Talk Yuri van der Werf

HFS in muonic hydrogen



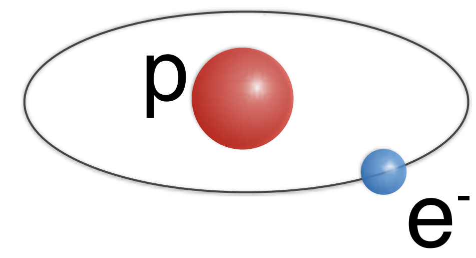


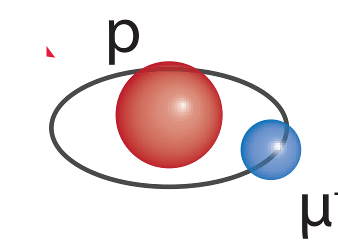
Measure transition with a relative accuracy of $\delta \simeq 1 \times 10^{-6}$

Nuber et al., arXiv: 2211.08297

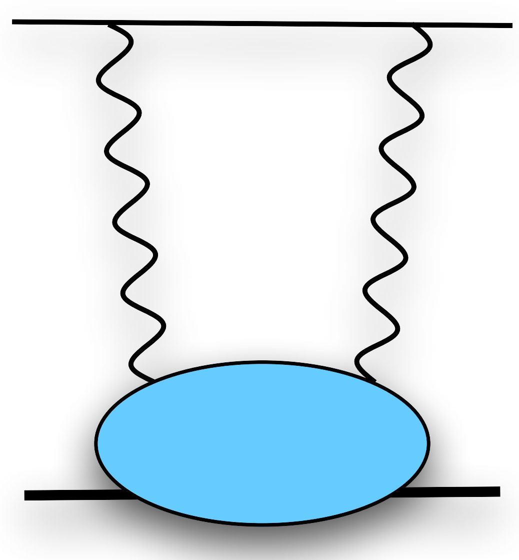
See poster O. Kara

Impact of the measurement





Provides information on magnetic structure of the proton



- Spin structure program
- Form factor program
- Chiral perturbation theory
- Lattice QCD

Combined with H
→Test of HFS theory with rel. acc. $< 10^{-8}$

Sensitive especially to axial-vector BSM contributions

$$V_{\mathrm{HF,A}}(r) = \begin{cases} -\dfrac{2g_A^{(1)}g_A^{(2)}}{3\pi}\left(\dfrac{e^{-m_\phi r}}{r} + \dfrac{2\pi\delta^{(3)}(r)}{m_\phi^2}\right)\mathbf{S_1}\cdot\mathbf{S_2} & \text{for } m_\phi \lesssim a_0^{-1}, \\ -\dfrac{4d_v^{(A)}}{m_1 m_2}\delta^{(3)}(r)\mathbf{S_1}\cdot\mathbf{S_2} & \text{for } m_\phi \sim m_r, \end{cases}$$

Talk Hagelstein

C. Peset
Y. Stadnik


BSM
QED tests in simple atomic systems
Muonic atom spectroscopy
Nuclear and hadron structure