Spectroscopy of muonic atoms and the proton radius puzzle

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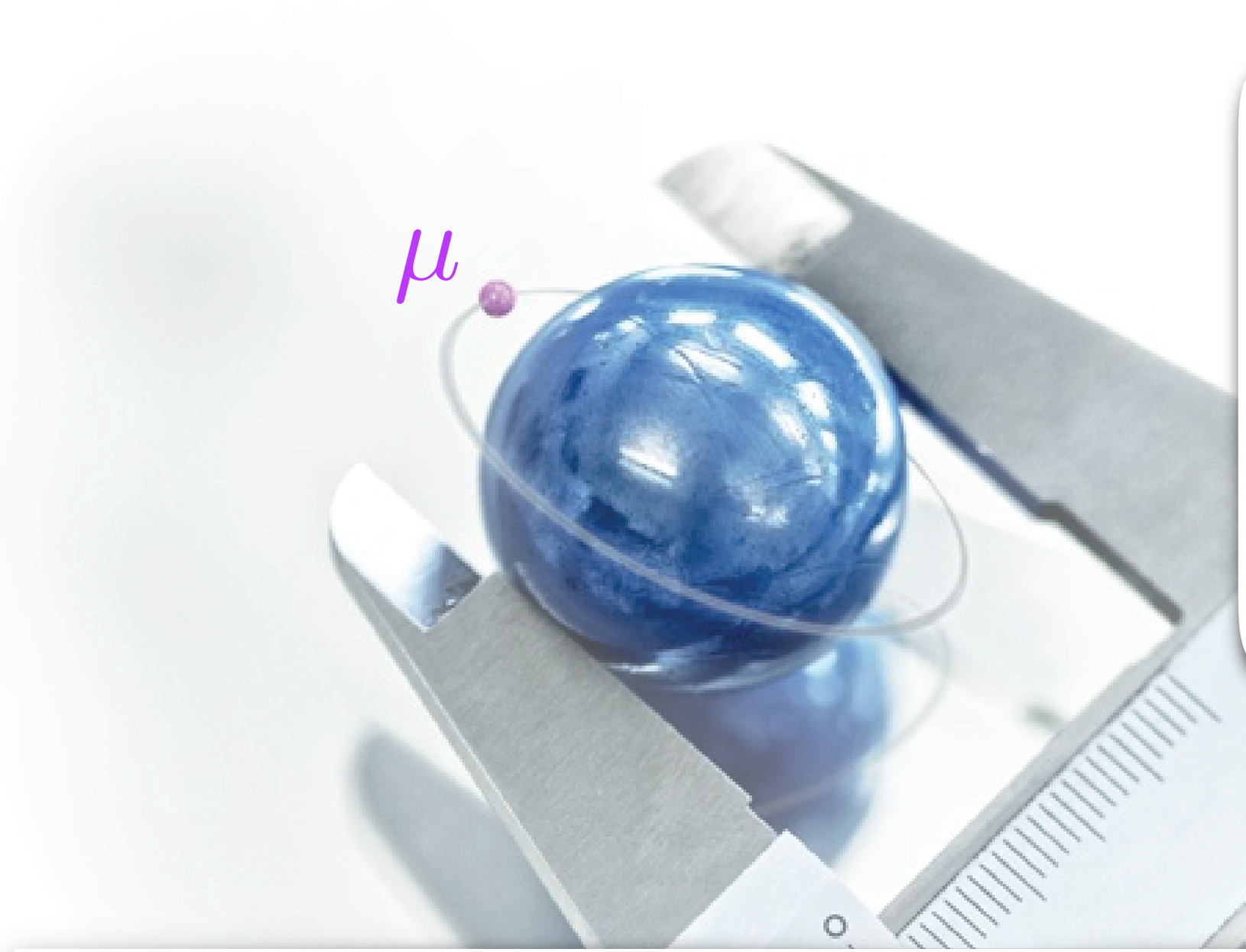
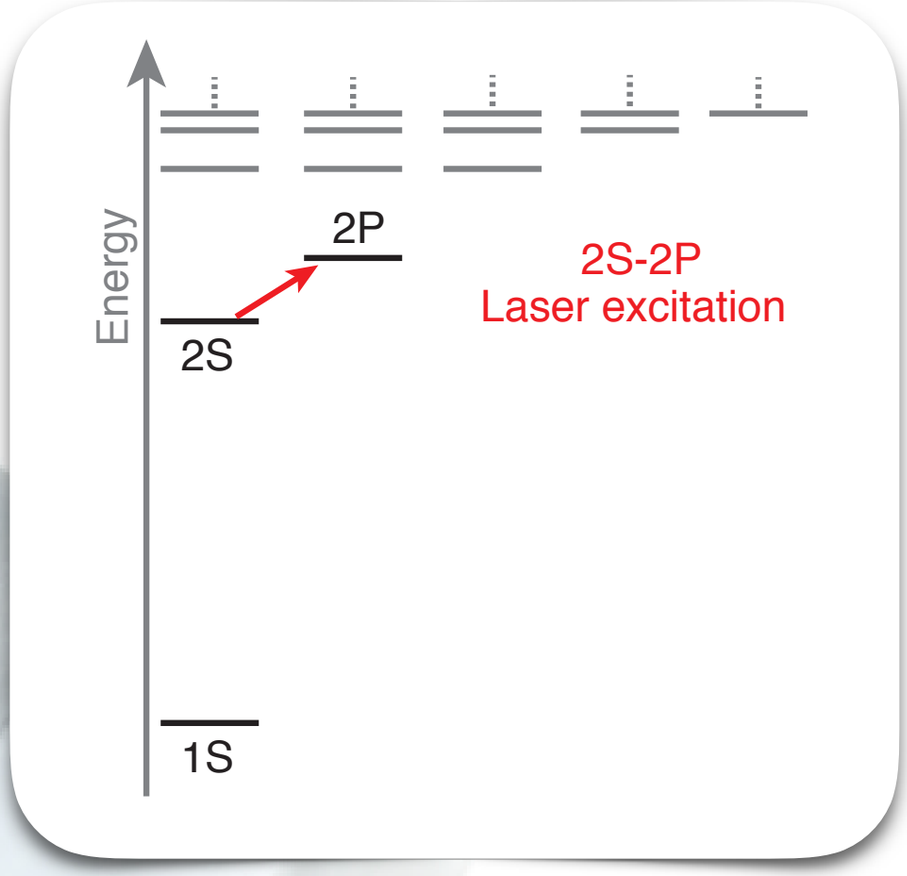
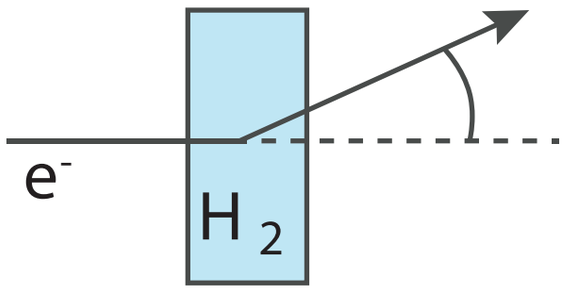
Laser spectroscopy of muonic atoms



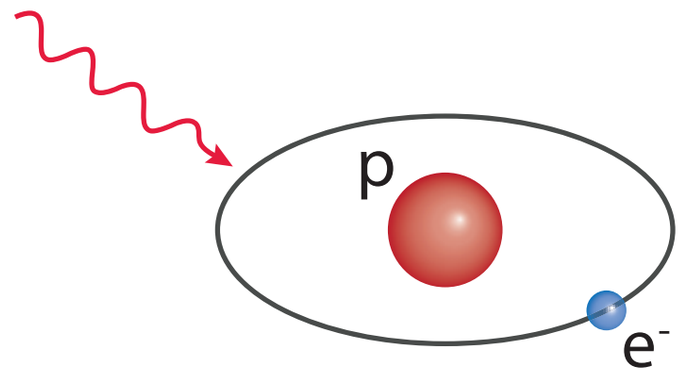


We measured 10 2S-2P transitions in μp, μd, μ^3He^+, μ^4He^+ **+** Theoretical predictions: QED + Nuclear structure ⇨ p, d, ^{3}He, ^{4}He charge radii

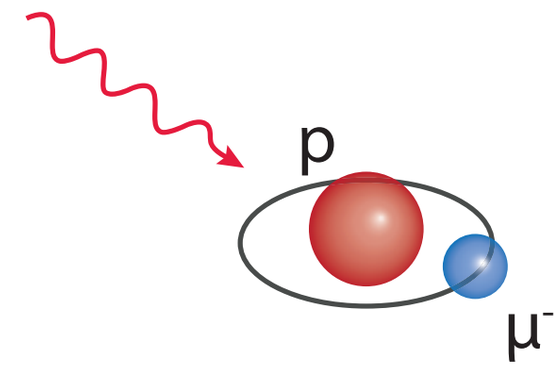
Three ways to the proton radius



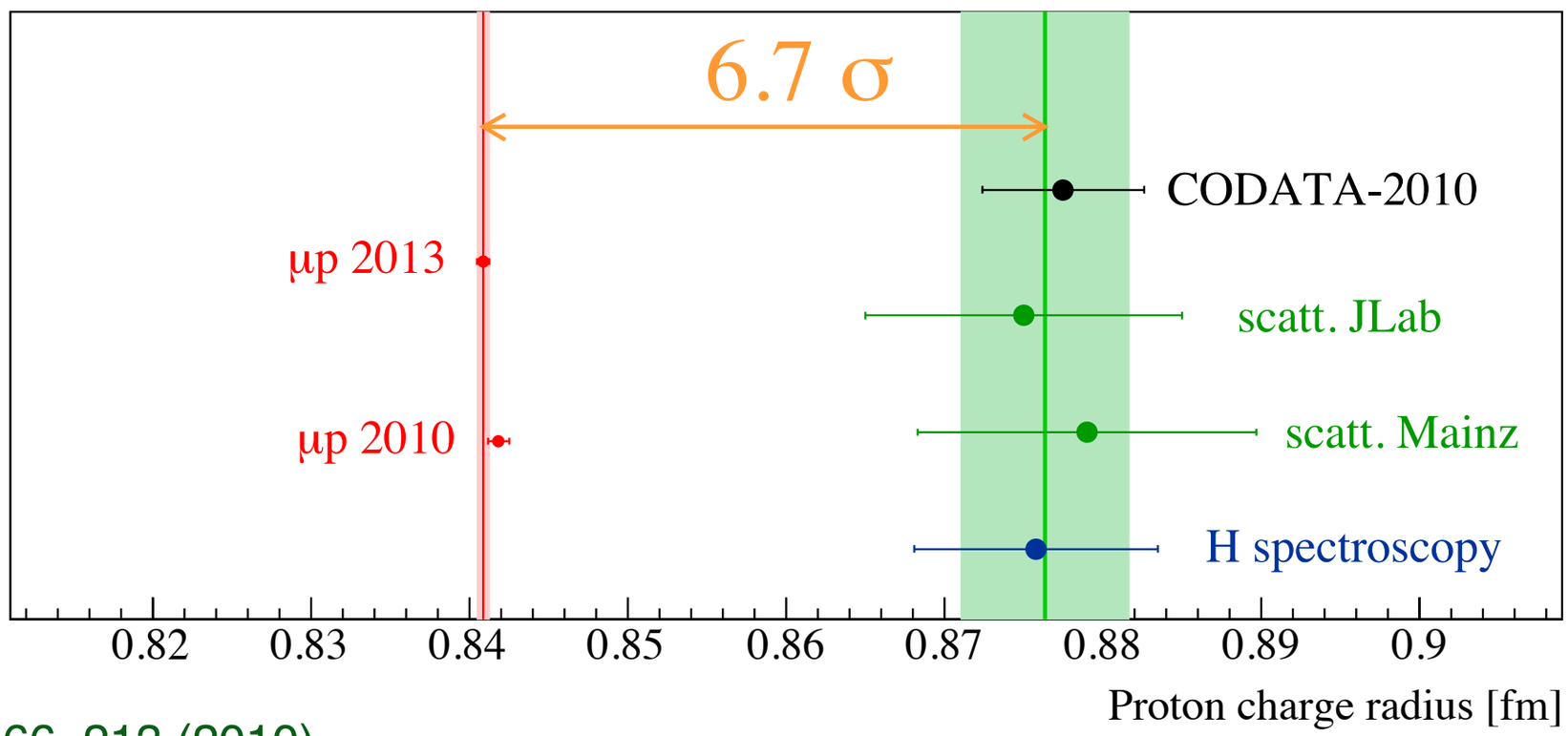
e-p scattering



H spectroscopy



μp spectroscopy



Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

The proton radius puzzle

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

Rarely criticised since:

$m_\mu \approx 200 m_e$

- **sensitive** to the radius

$\sim m^3 R_p^2$ ✓

- **insensitive** to systematical effects

$\sim 1/m$ ✓

The proton radius puzzle

- μp experiment
- μp theory
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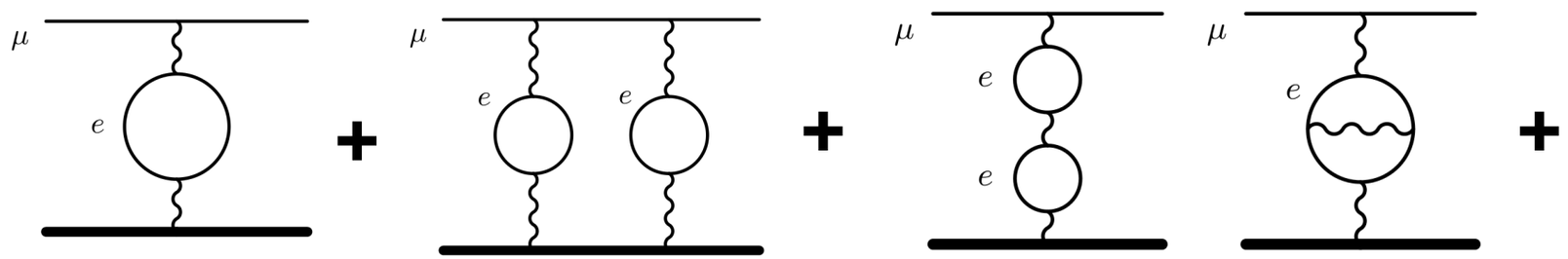
- e-p scattering

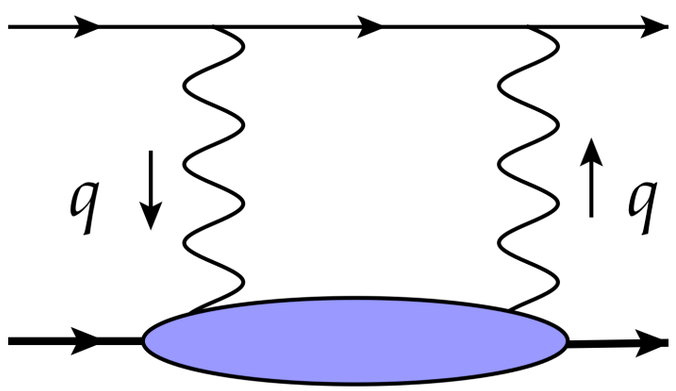
QED ✓✓✓✓

Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda…



many more

Two-photon exchange ✓✓✓✓ ✗



Can be computed with dispersion th. + data

But subtraction term is needed ⇒ modelling of proton

Pachucki, Carlson, Birse, McGovern, Pineda, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill…

The proton radius puzzle

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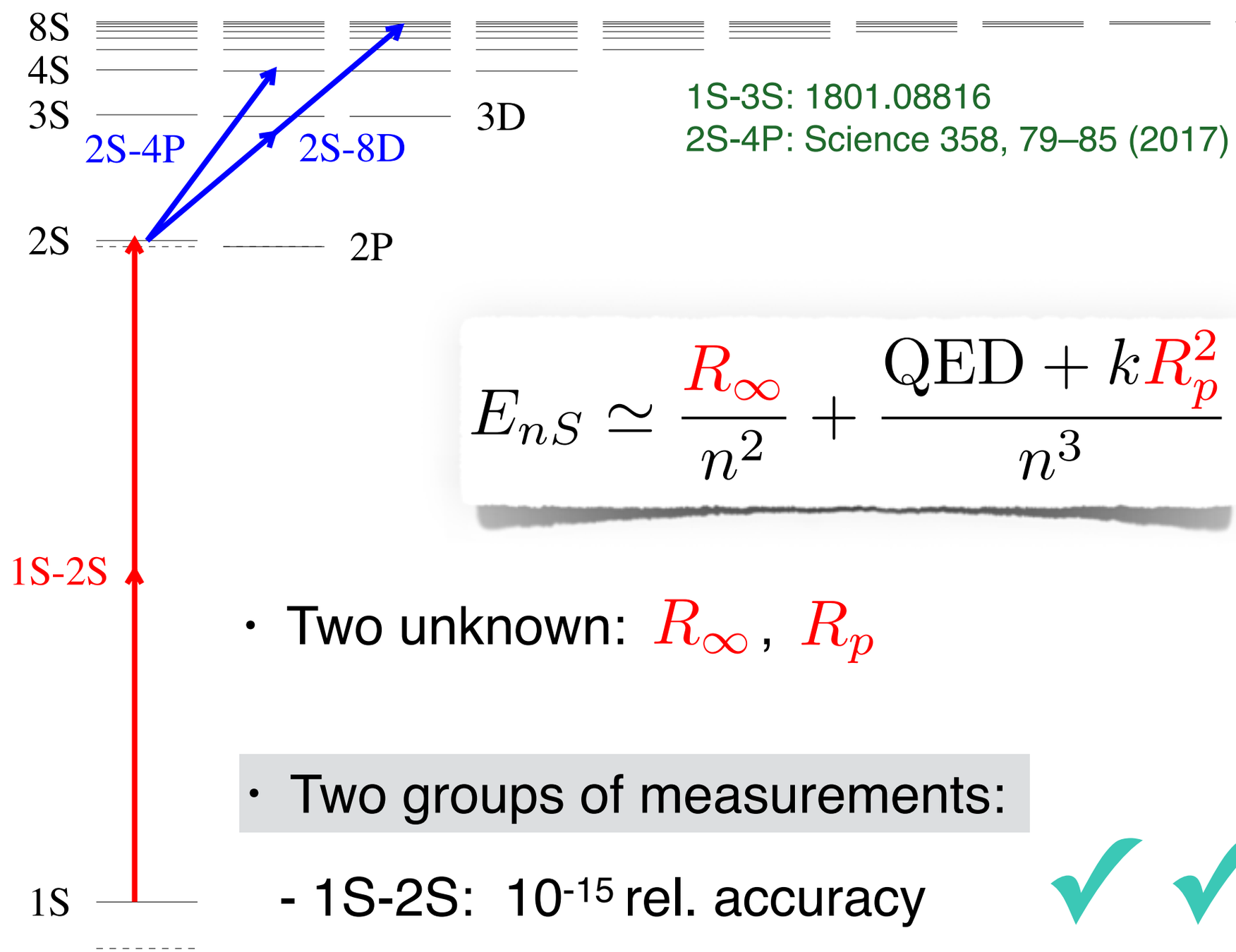

$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{\mathrm{QED} + k R_p^2}{n^3}$$

- Two unknown: R_∞ , R_p

- Two groups of measurements:
  - 1S-2S: 10^{-15} rel. accuracy ✓ ✓
  - others: $<10^{-13}$ rel. accuracy and more prone to systematics ✓ ✗

The proton radius puzzle

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- μp theory
- H experiments
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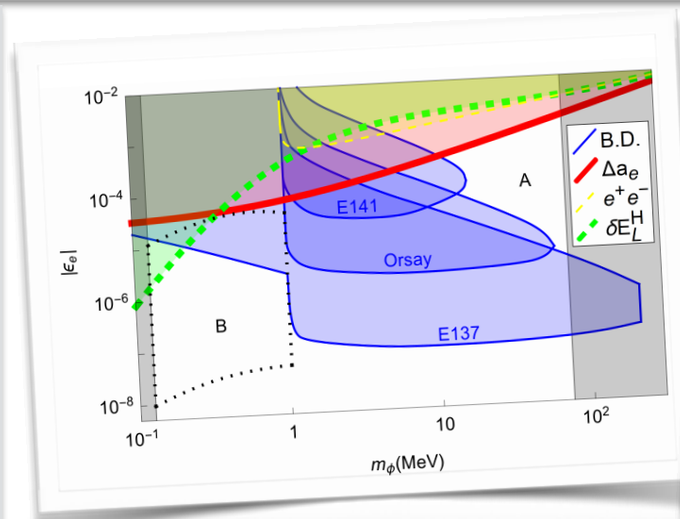
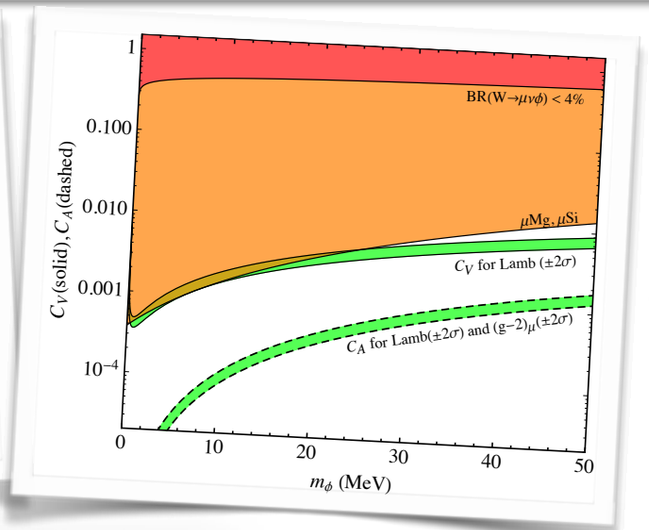
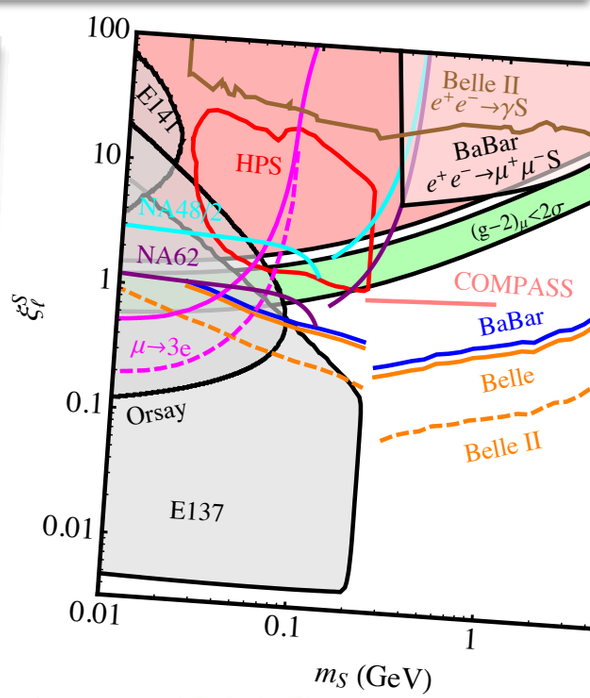
- e-p scattering



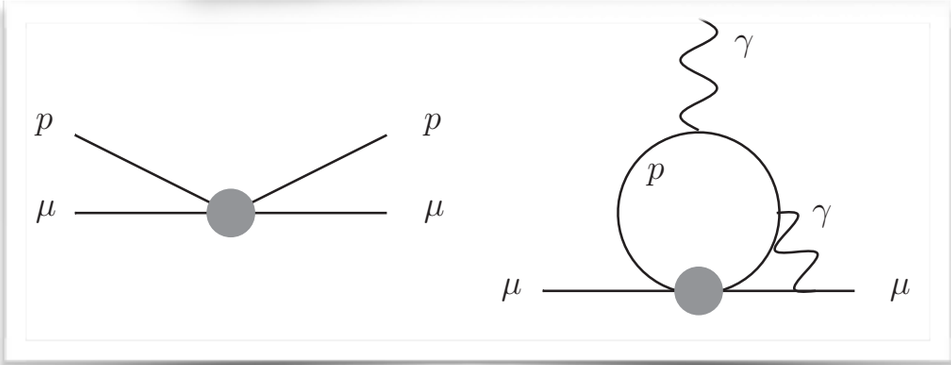




Some open regions for MeV force carrier still resist

Martens & Ralston (2016), Liu, McKeen & Miller (2016), Batell et. al (2016)

- Tuning (e.g. vector vs axial-vector)
- Preferential coupling to μ and p
- No UV completion and no full SM gauge inv.



✓ ✓ ✓

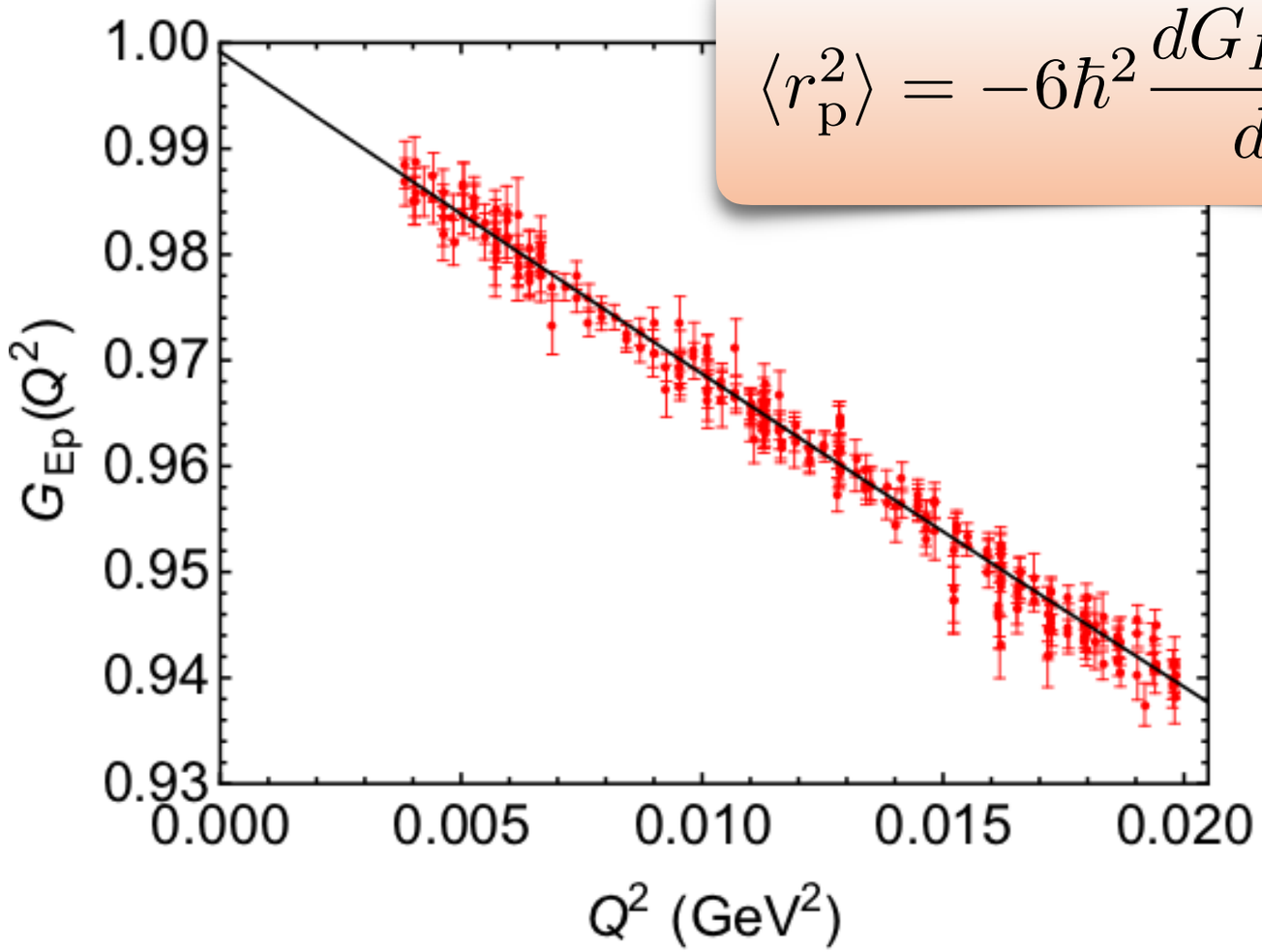
✗ ✗ ✗ ✗ ✗

The proton radius puzzle

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

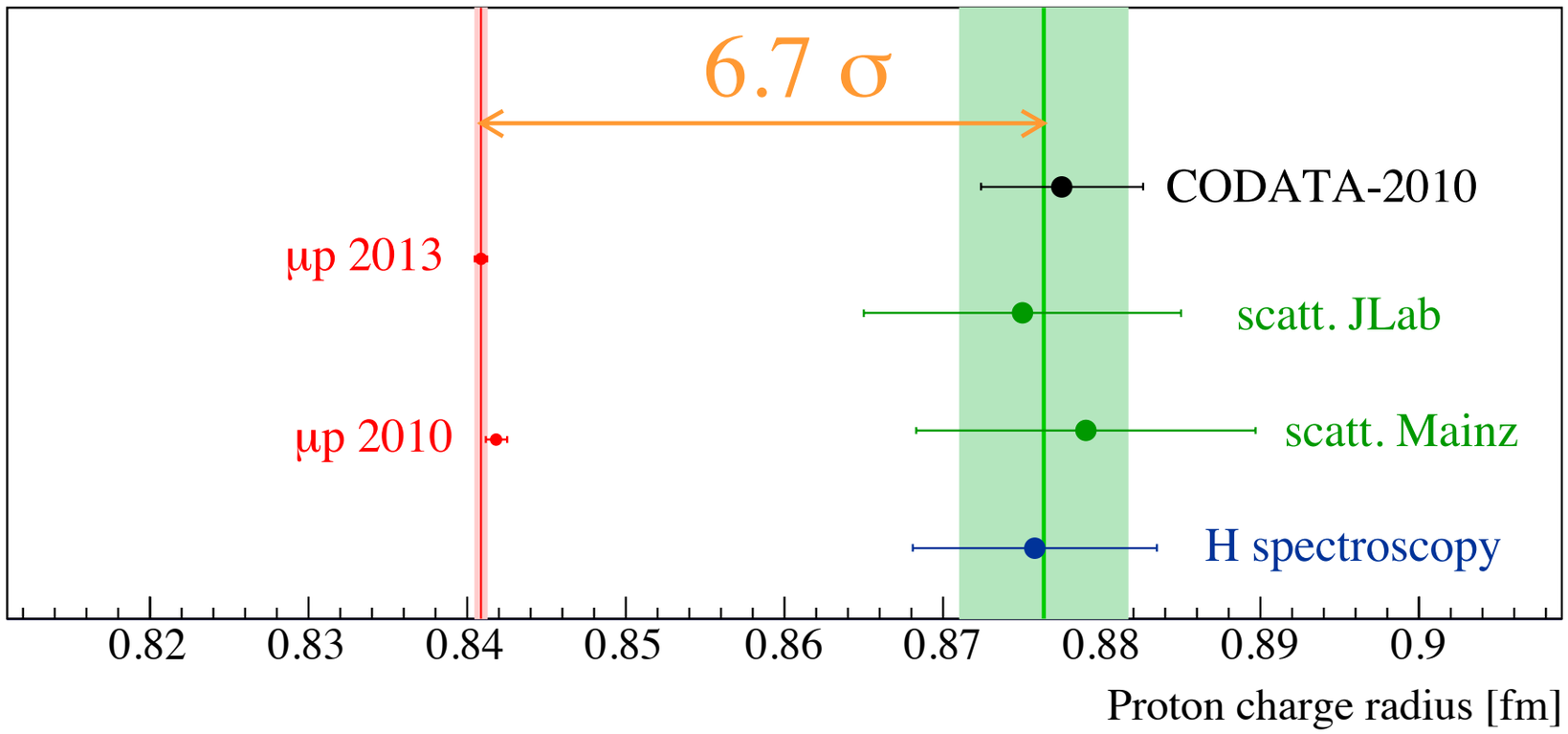
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

$$\langle r_{\text{p}}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$



✓✓✓✓✓ ✗✗✗✗✗

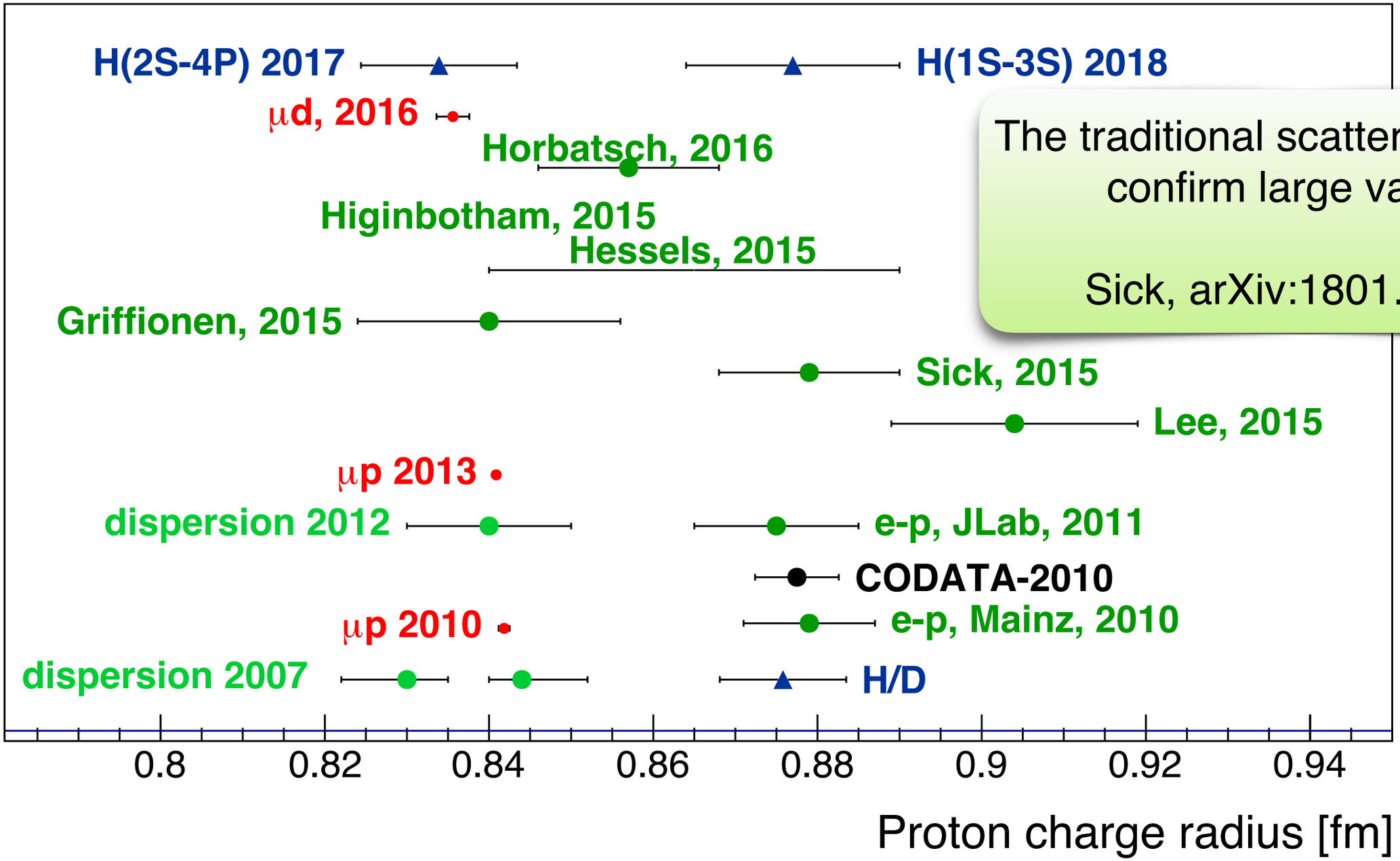
The proton charge radii



The proton charge radii

Higinbotham et al.,, arXiv: 1510.01293
Griffioen et al., arXiv:1509.06676
Lorenz et al., PRD 91, 014023 (2015)
Horbatsch, Hessels, Pineda, arXiv:1610.09760

Bernauer, Distler, arXiv:1606.02159
Sick, Trautmann, arXiv:1701.01809
Lee, Arrington, Hill, arXiv:1505.01489
Hoferichter et al., EPJA 52, 331 (2016)
Alarcon, Weiss, arXiv:1710.06430



The traditional scattering experts confirm large values.

Sick, arXiv:1801.01746

The race to the proton radius solution

The race to the proton radius solution

Atomic spectroscopy

- H(2S-2P) (Toronto)
- H(1S-3S) (LKB, MPQ)
- H(2S-4P) (MPQ)
- H_2, H_2^+, HD, HD^+, HT (LKB, LaserLaB, ETH)
- He^+ (LaserLaB, MPQ)
- He (LaserLab, MPQ)
- Li^+ (Mainz)
- Muonium (ETH, PSI)
- Positronium (ETH, UC London)
- Rydberg states in H-like ions (NIST)
- Rydberg states in optical lattice (Ann Arbor)

Muonic spectroscopy

- μd
- μ^3He, μ^4He
- μp HFS
- μLi ?

Scattering

- e-p, PRad (JLAB)
- e-p, ISR & MAGIX (Mainz)
- μ-p, e-p, MUSE (PSI, UniBasel)
- μ-p, COMPASS (CERN)
- e-p, ProRad (Orsay)
- Tohoku, (Sendai)

New physics searches

$$K^+ \to \mu^+ \nu e^+ e^-$$

MUSE

Measure

$\mu^{\pm}$-p, $e^{\pm}$-p scattering
down to $Q^2_{min} = 2\times10^{-3}$ GeV^2

Extract charge radius

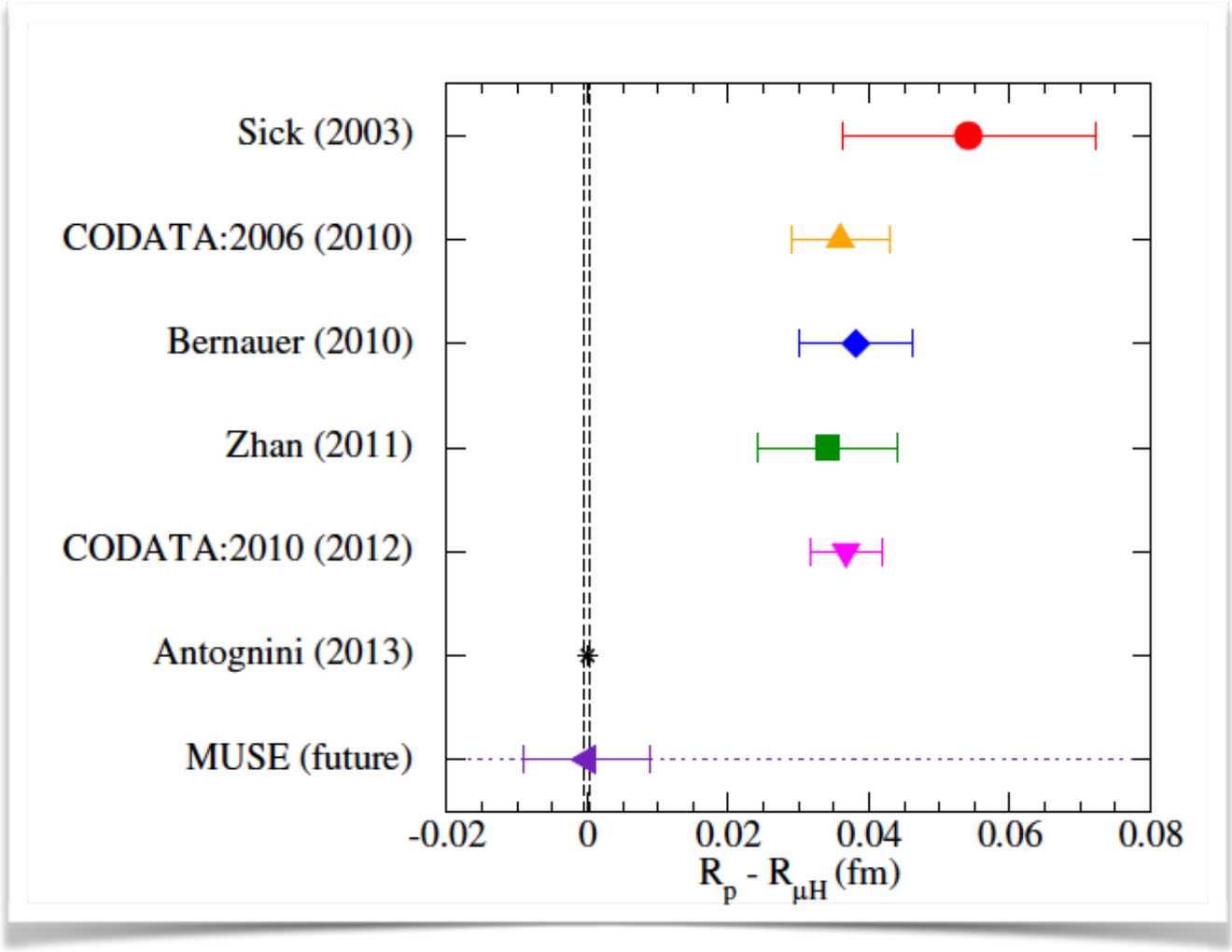
with comparable accuracy than other scattering experiments

BUT

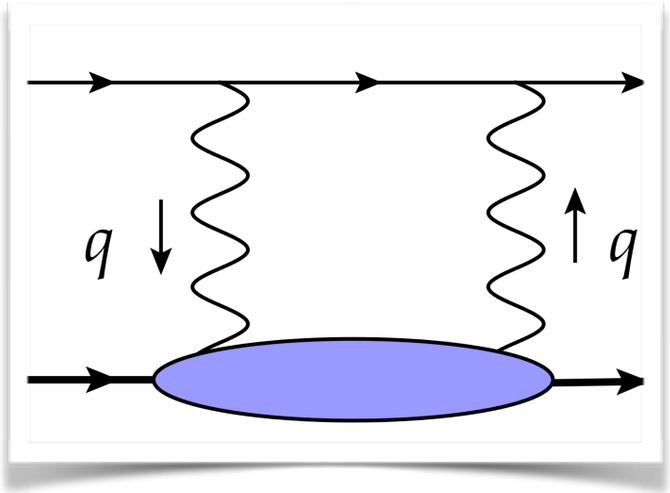
Comparing $\mu^{\pm}$-p / $e^{\pm}$-p
gets rid of most of the systematics as well as truncation errors

⇨ $\Delta r = r_p^{\mu} - r_p^{e}$ with 0.0045 fm acc.

⇨ test of lepton universality



arXiv:1709.09753

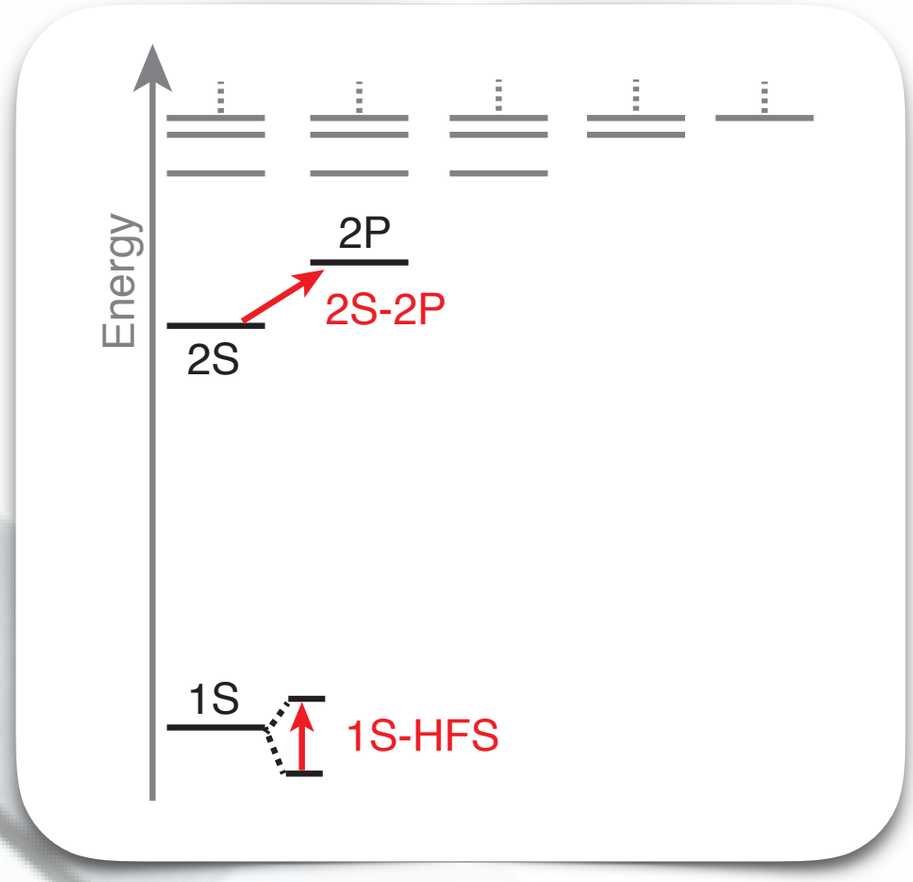


Moreover

Comparing μ^+ with μ^- and e^+ with e^-

⇨ Test of TPE

Next experiment: HFS



- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^3He, μ^4He
- 1S-HFS μp

- From 2S-2P
  → charge radii
- From HFS
  → magnetic (Zemach) radii

Hyperfine goals

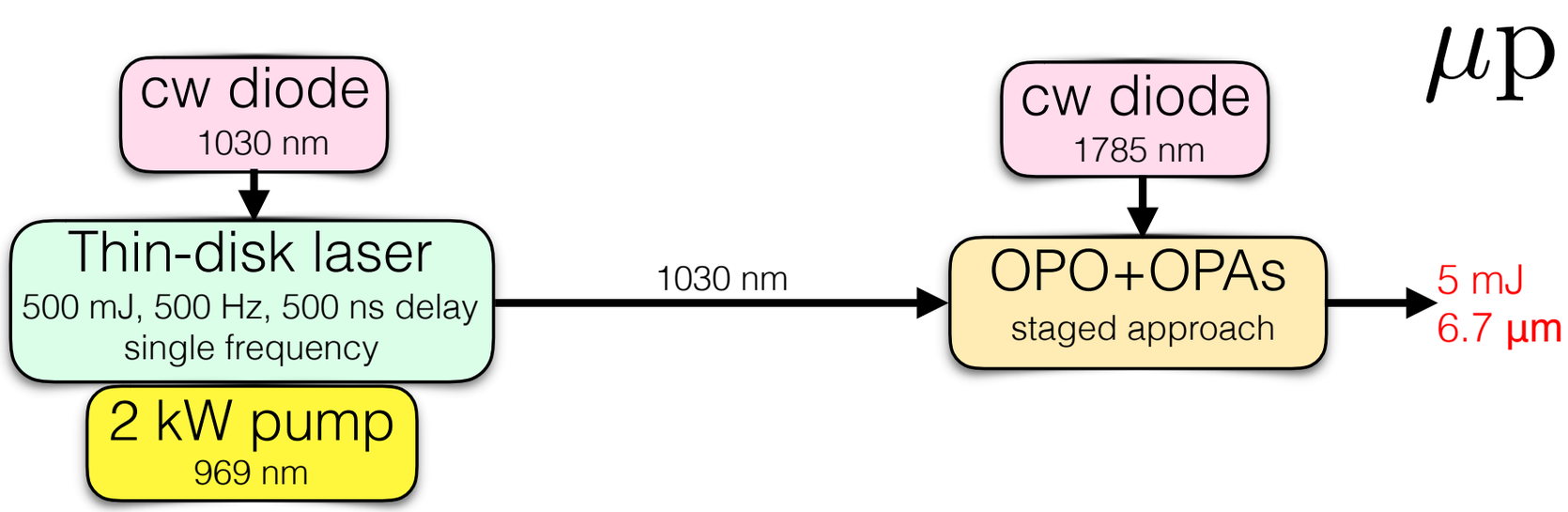
Measure

the 1S-HFS in μp
with few ppm accuracy

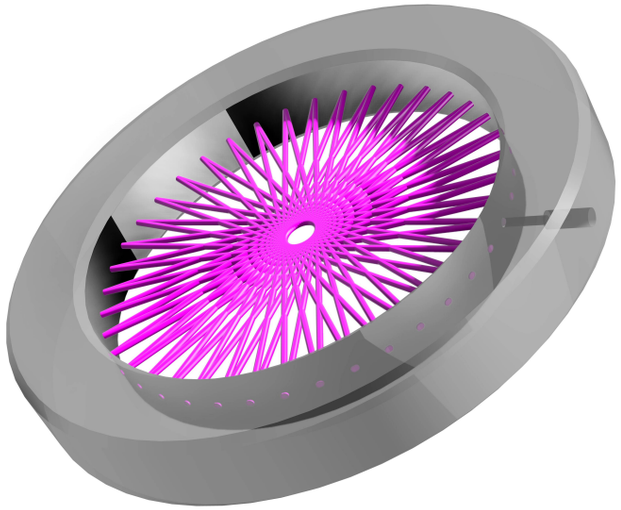
Goals

- TPE contribution with 10^{-4} rel. accuracy
- Zemach radius and polarisability contributions

Technological development



μp

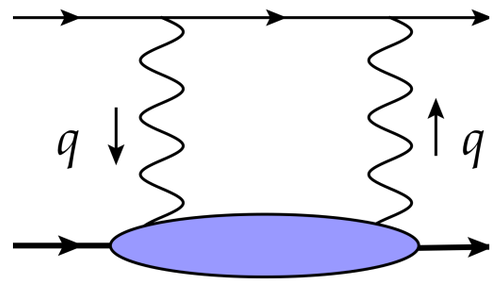


Thin-disk laser technology

Parametric down-conversion stages

Multi-pass enhancement cavity

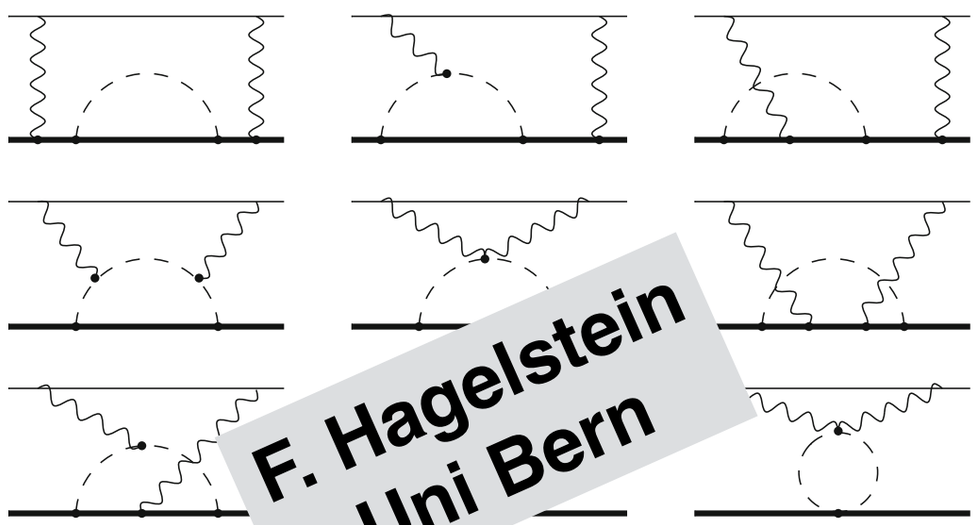
TPE in HFS of μp



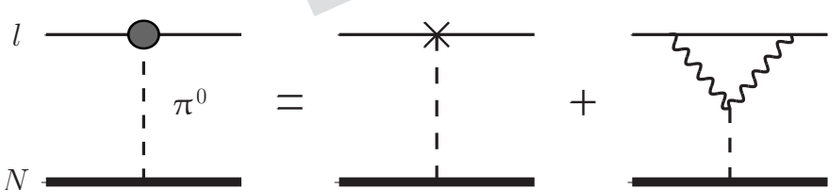
Dispersion relation
+ data: $g_1(x,Q^2)$, $g_2(x,Q^2)$…

JLAB

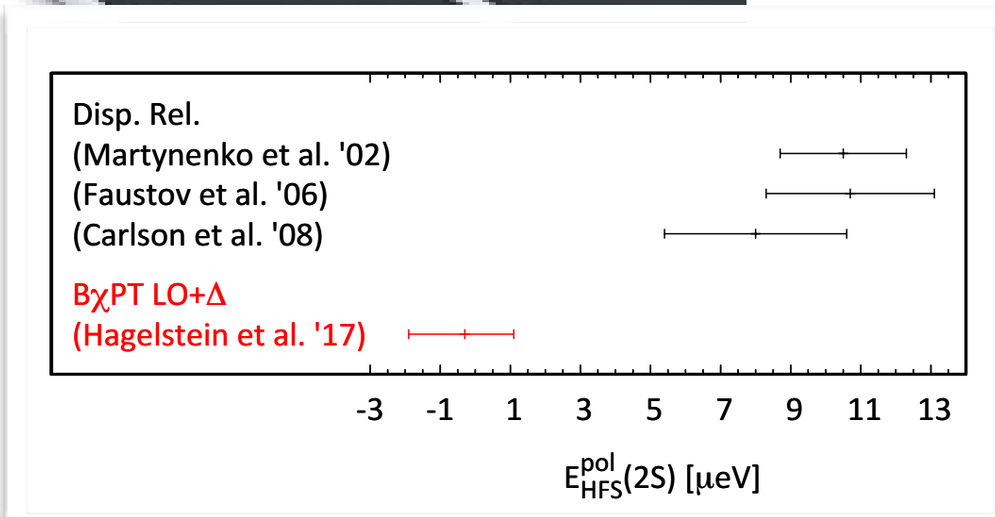
Dispersion relation
+ Chiral EFT



F. Hagelstein
Uni Bern

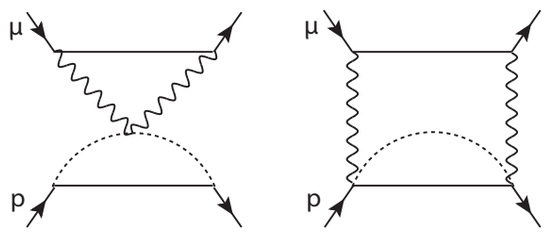


$$E_{\rm HFS}^{\langle\pi^0\rangle}(nS) = -E_{\rm F}(nS)\,\frac{g_A M m_r}{2\pi(1+\kappa)f_\pi m_\pi}\left[\alpha^2 g_{\pi\ell\ell} + \frac{\alpha^2 m}{2\pi^2 f_\pi}\,I\left(\frac{m_\pi}{2m}\right)\right]$$

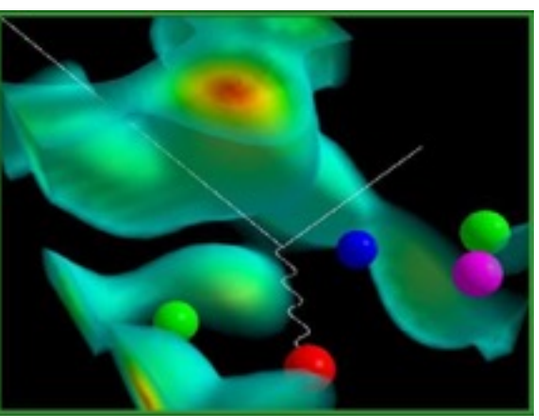


related to…

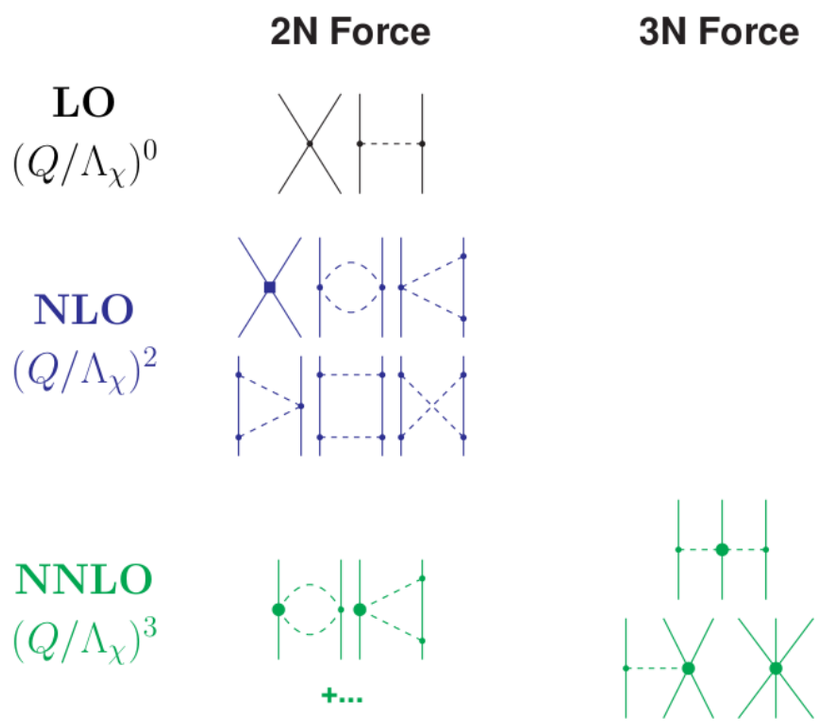
Chiral PT



Lattice

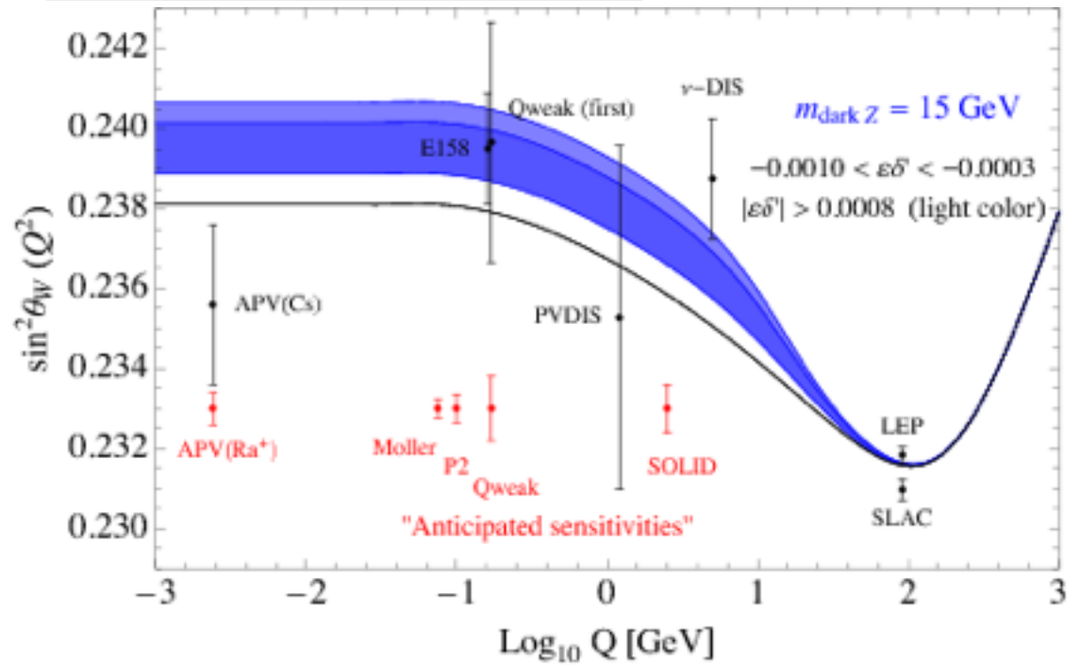


Few-Nucleon EFT

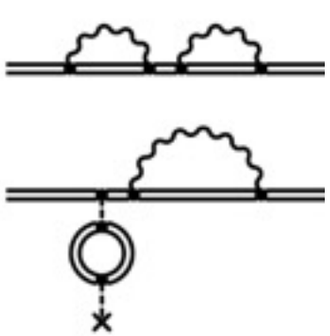


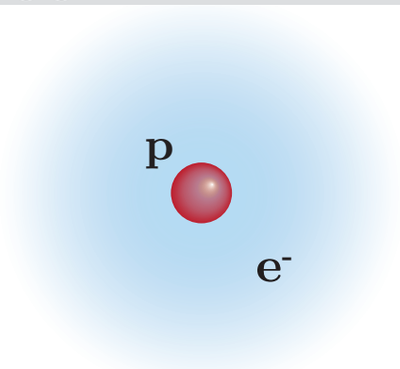
muX project at PSI

A. Knecht



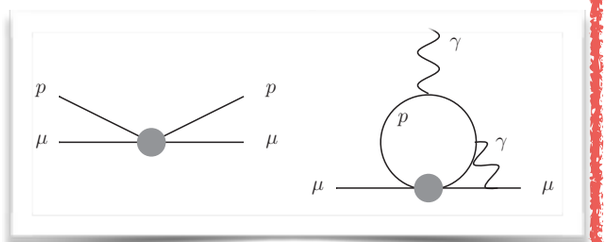
Bound-state QED, ions, molecules, Rydberg atoms and R_∞





BSM

?



New hadronic effects?

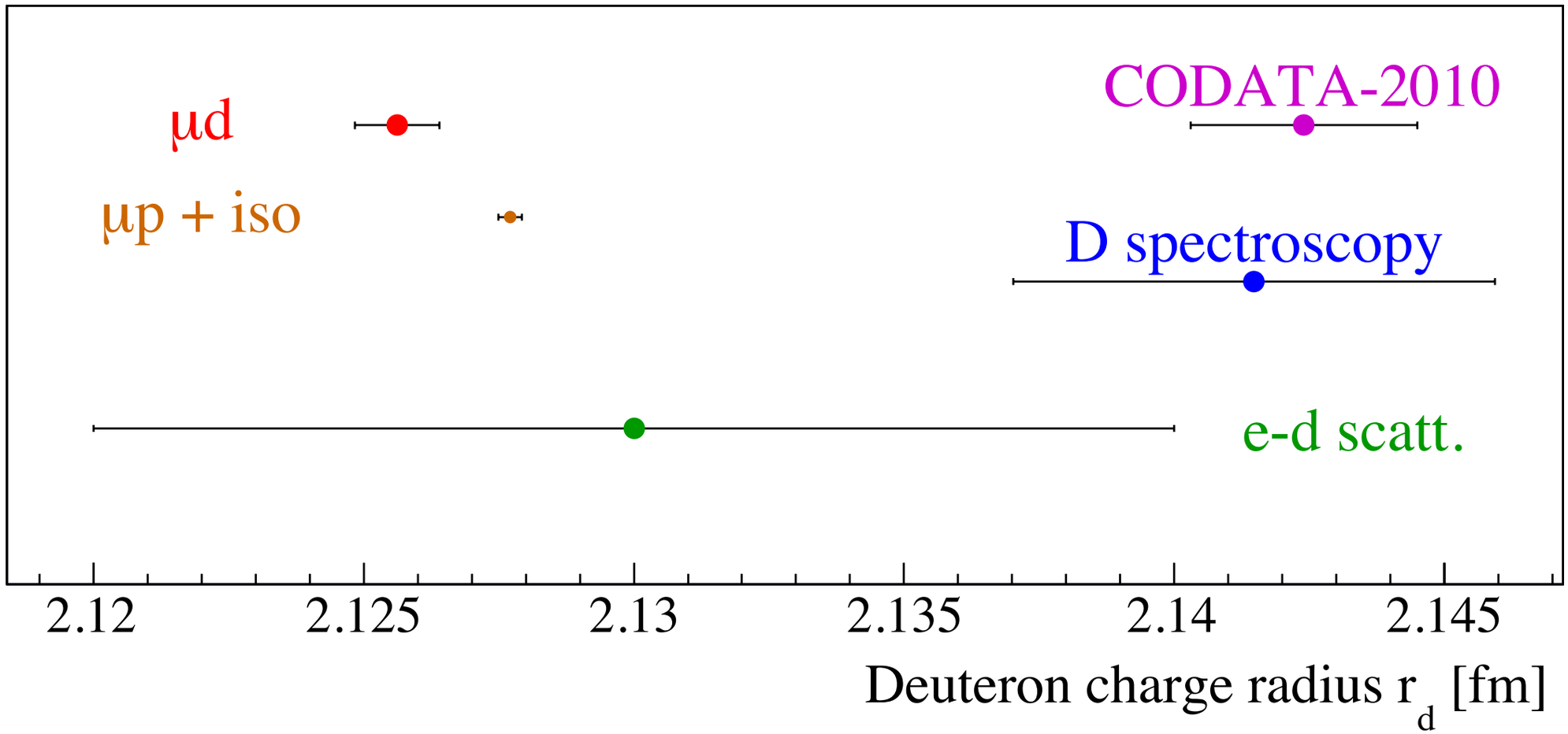
Dispersion-based approaches.

Polarizabilities, form factors and structure functions program

Analysis of e-p scattering

The same issues are critical for the HEP accelerator neutrino program.

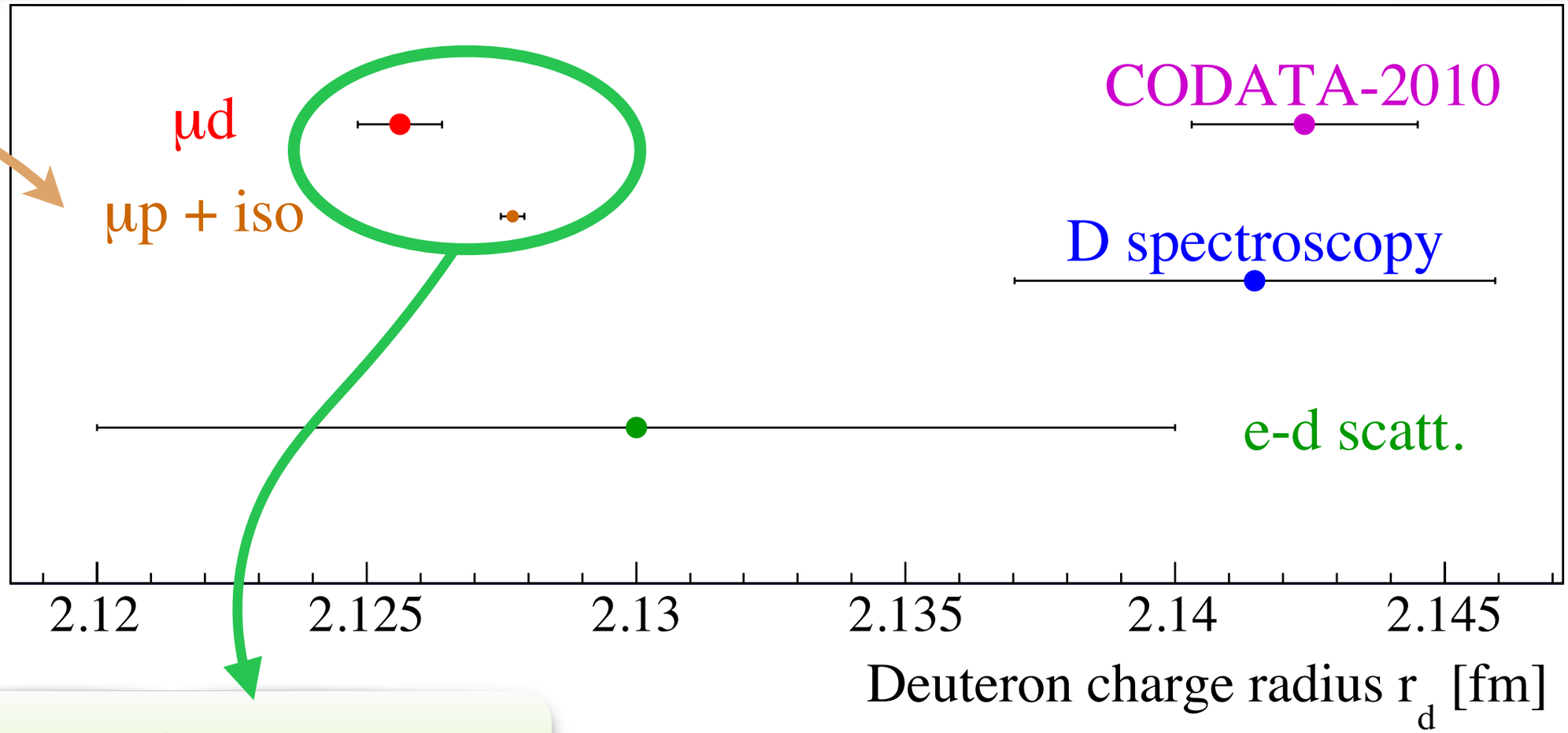
2S-2P spectroscopy of muonic deuterium (μd)



Pohl et al., Science 353, 669 (2016)
Krauth et al., Ann. Phys. 336 168 (2016)
Hernandez et. al., PLB 736, 344 (2014)
Pachucki et al., PRA 91, 040503(R) (2015)

2S-2P spectroscopy of muonic deuterium (μd)

$$\left.\begin{array}{lll} \text{H/D shift:} & r_{\rm d}^2 - r_{\rm p}^2 & = 3.820\,07(65)\ \text{fm}^2 \\ \mu p: & r_{\rm p} & = 0.84087(39)\ \text{fm} \end{array}\right\} \Rightarrow \quad r_{\rm d} = 2.12771(22)\ \text{fm}$$



Consistency of muonic results with 1S-2S H/D isotopic-shift

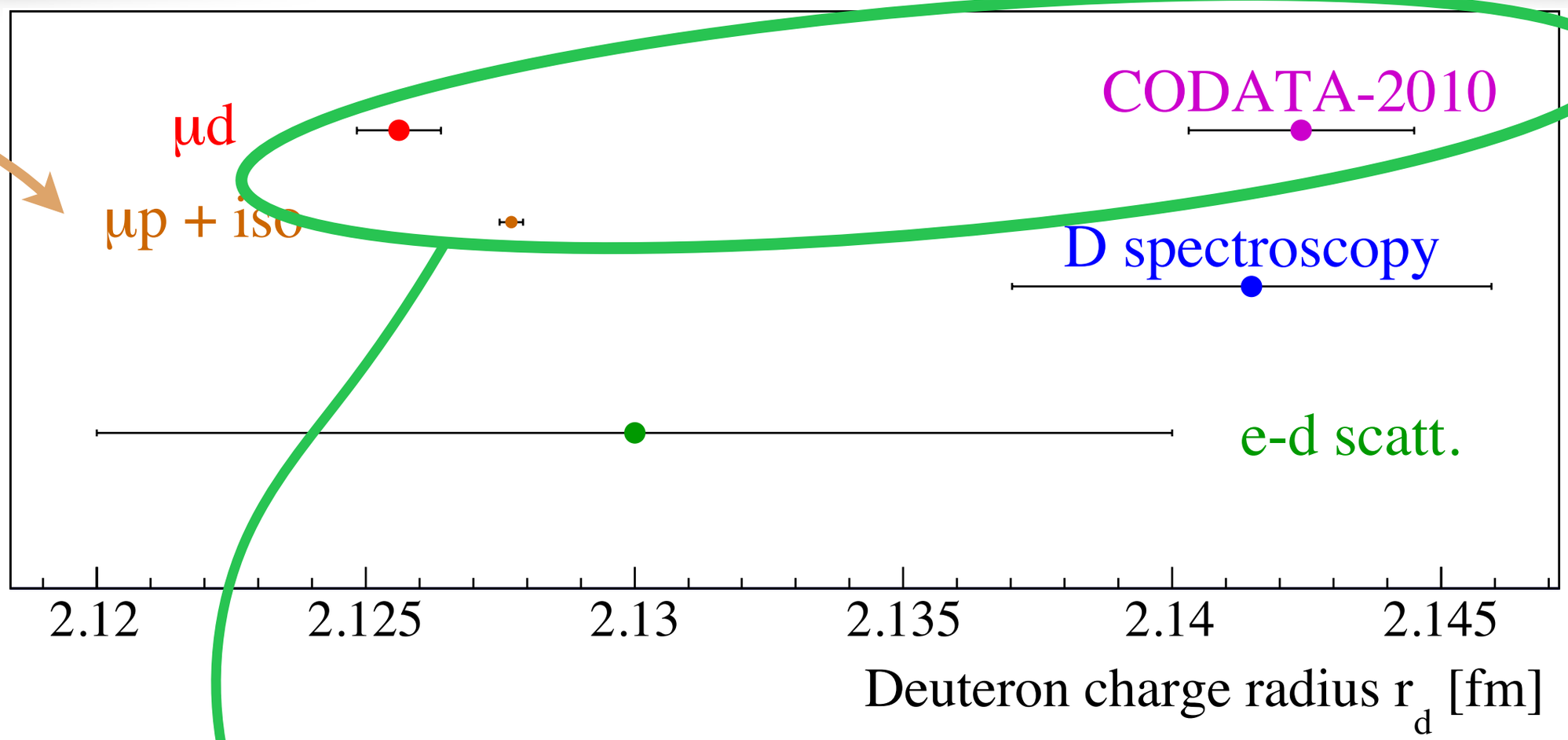
The 2.5σ difference:

- incomplete nuclear polarizabilty?
- BSM physics NOT coupling to n (reduced mass effect)?

Pachucki, Bacca, Barnea, Gorchtein, Carlson….

2S-2P spectroscopy of muonic deuterium (μd)

$$\left.\begin{array}{lll} \text{H/D shift:} & r_{\rm d}^2 - r_{\rm p}^2 & = 3.820\,07(65)\ \text{fm}^2 \\ \mu p: & r_{\rm p} & = 0.84087(39)\ \text{fm} \end{array}\right\} \Rightarrow \quad r_{\rm d} = 2.12771(22)\ \text{fm}$$

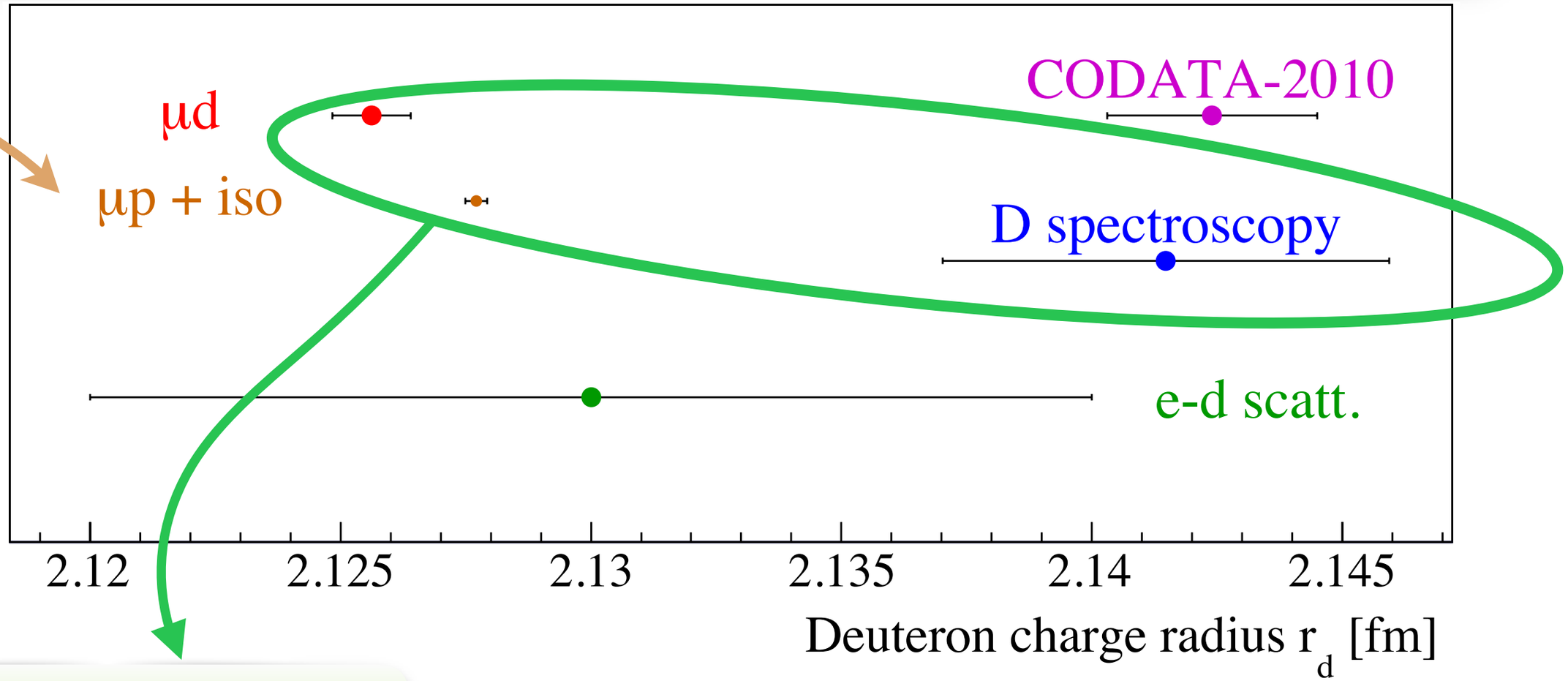


7σ from CODATA

BUT CODATA
contains proton-data

2S-2P spectroscopy of muonic deuterium (μd)

$$\left.\begin{array}{lll} \text{H/D shift:} & r_{\rm d}^2 - r_{\rm p}^2 & = 3.820\,07(65)\ \text{fm}^2 \\ \mu p: & r_{\rm p} & = 0.84087(39)\ \text{fm} \end{array}\right\} \Rightarrow \quad r_{\rm d} = 2.12771(22)\ \text{fm}$$



3.5σ from ONLY D-data

⇨ double discrepancy
- proton sector
- deuteron sector

⇨ Problem with H/D exp (R_∞)?
⇨ Problem with H/D th.?
⇨ BSM with no coupling to n?