SCALE SEPARATION IN EXOTIC ATOMS

PRECISION SPECTROSCOPY AS WINDOW TO NEW PHYSICS

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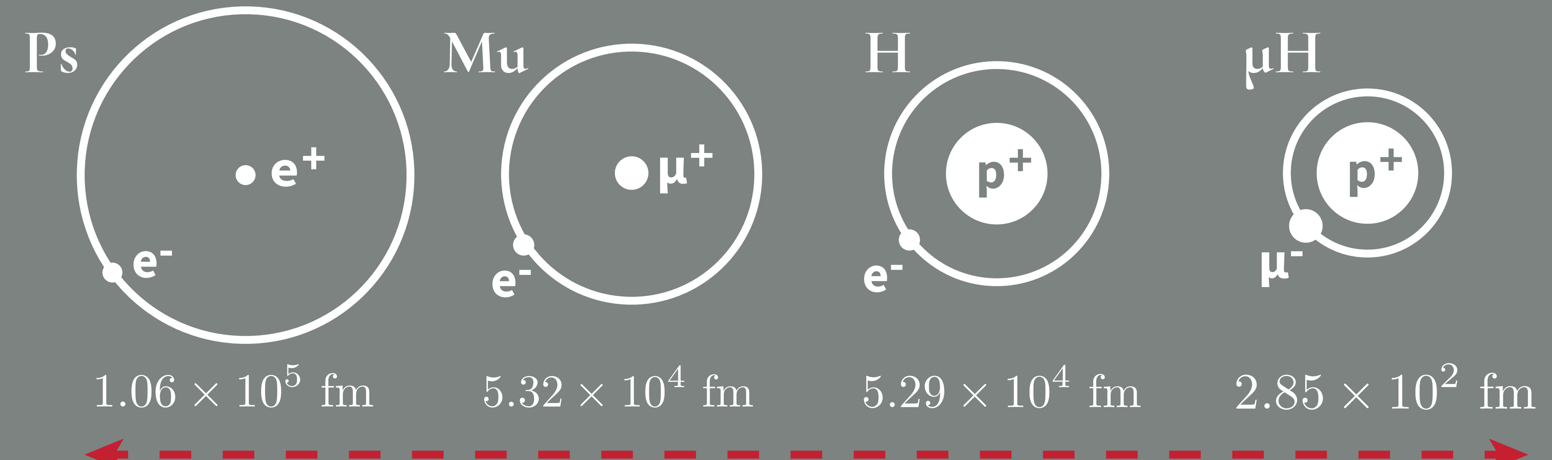
SEPARATION OF SCALES
ACROSS HYDROGEN-LIKE ATOMS

The **Bohr radii** of hydrogen-like atoms vary based on the **reduced mass** of the atom:



Bohr radii separated by ~3 **ORDERS OF MAGNITUDE**

This leads to **significant differences** in their atomic spectra.

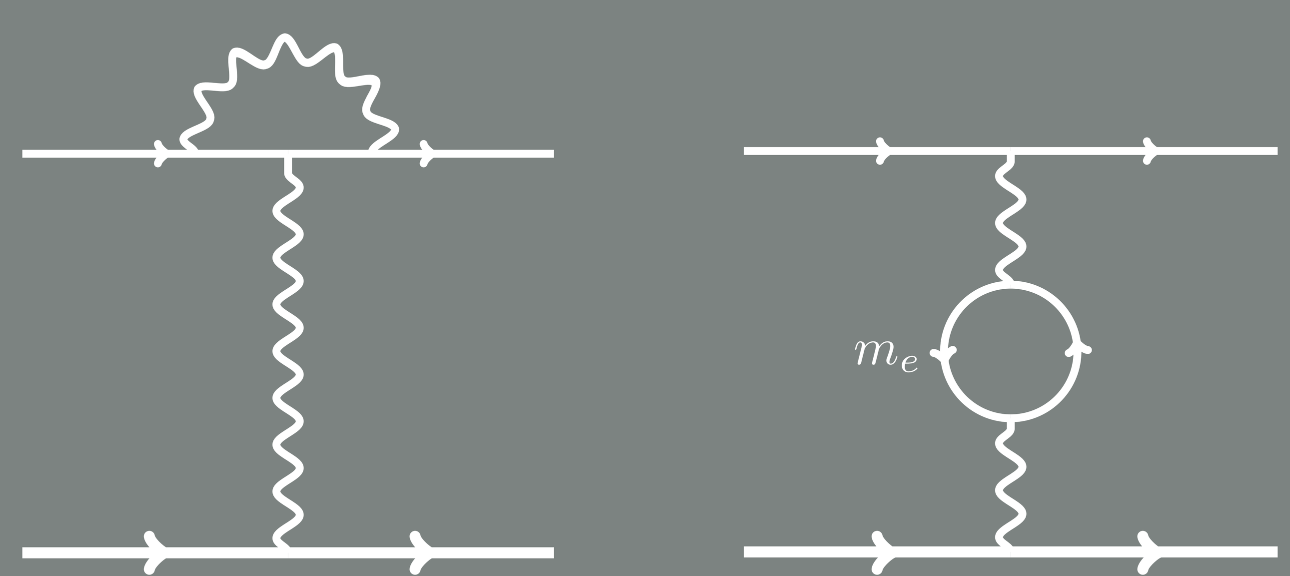
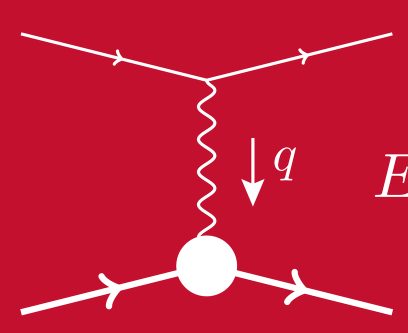


FIG 1: Leading contributions to the H (left) and μH (right) Lamb Shift.

FINITE-SIZE CONTRIBUTION:
TO EXPAND OR NOT?

- Finite-size contribution to the 2P-2S Lamb shift in hydrogen-like systems due to the proton electric Sachs form factor $G_E(Q^2)$:



$$E_{\text{LS}}^{\text{fin.}} = -\frac{(Z\alpha)^4 m_r^3}{2\pi} \int_{t_0}^{\infty} \mathrm{d}t \frac{\operatorname{Im} G_E(t)}{\left(\sqrt{t} + Z\alpha m_r\right)^4}$$

m_r is the reduced mass of the proton-lepton system, $Q^2 = -q^2$ is the squared momentum transfer, and t_0 is the lowest particle-production threshold in the t channel.

- Finite-size expansion:

$$E_{\text{LS}}^{\text{fin.}} \simeq -\frac{(Z\alpha)^4 m_r^3}{12} \left[\langle r^2 \rangle_E - Z\alpha m_r \langle r^3 \rangle_E\right] + O(\alpha^6)$$

where $\langle r^2 \rangle_E$ and $\langle r^3 \rangle_E$ are the second and third moments of the proton charge distribution.

  - Breaks down when $\sqrt{t_0}$ becomes comparable to $Z\alpha m_r$, which is the inverse Bohr radius of the system.

TABLE I: Inverse Bohr radii of hydrogen-like atoms

SYSTEM	Ps	Mu	H	μH
$Z\alpha m_r$ [MeV]	1.86×10^{-3}	3.71×10^{-3}	3.73×10^{-3}	0.693

How does this affect our calculations?

ENHANCED SOFT CONTRIBUTIONS
IN THE STANDARD MODEL

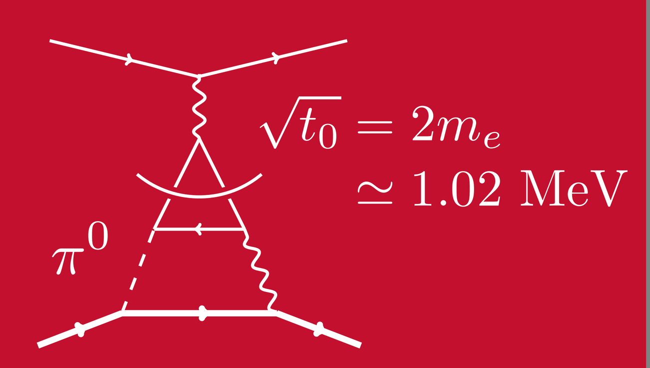


FIG 2: Soft SM contribution to the proton form factor which breaks the finite-size expansion

- Soft contributions can break the finite-size expansion: see f.i. the **light particle cut** across the upper loop of the diagram in **FIG 2**.
- Breaking occurs in systems with $Z\alpha m_r \sim 2m_e$, like μH.
- Not a problem with current experimental accuracy, but...

In hydrogen-like atoms, contributions may be enhanced depending on their lightest t-channel cut compared to the scale of the Bohr radius!

TABLE II: Breaking of the expansion in moments of charge distribution for the 2-loop diagram in **FIG 2**. <u>Contribution to LS</u>

SYSTEM	EXACT CALCULATION	EXPANSION	CURRENT EXPERIMENTAL ACCURACY
H [kHz]	4×10^{-11}	3×10^{-11}	3.2
μH [μeV]	-8×10^{-10}	3×10^{-8}	2.3

Each observable should be studied separately. For instance, the expansion of the HFS contribution is breaking for both H and μH.

TABLE III: Breaking of the expansion in moments of charge distribution for the 2-loop diagram in **FIG 2**. <u>Contribution to 1S HFS</u>

SYSTEM	EXACT CALCULATION	EXPANSION	CURRENT EXPERIMENTAL ACCURACY
H [10^{-6} kHz]	-0.009	-0.4	2
μH [μeV]	-10^{-7}	-10^{-5}	3 (1 ppm, projected)

NEW PHYSICS SEARCHES:
PICKING THE RIGHT TOOL FOR THE JOB

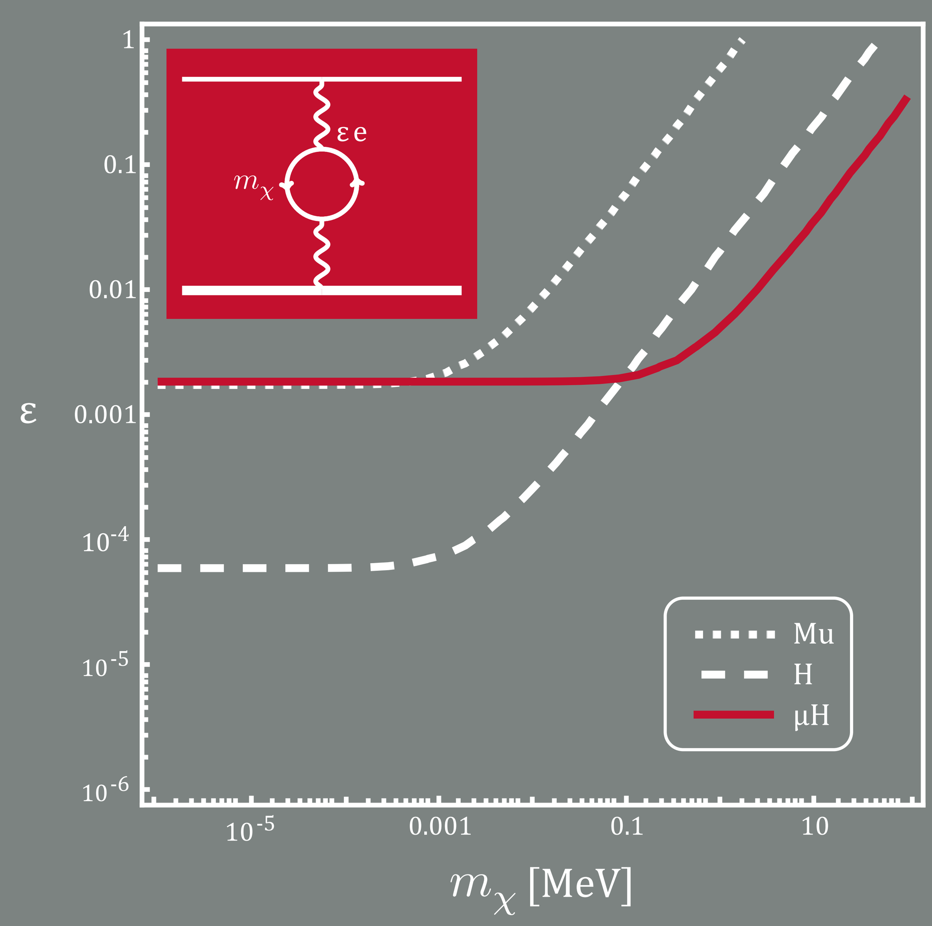


FIG 3: Sensitivity plot for a potential dark matter fermion contribution, indicating when the size of the contribution reaches the present experimental accuracy for the individual atoms

- Different atoms are sensitive to different ranges of New Physics parameters.

<u>A dark matter example:</u>

- State of the art results for the Lamb shift (in μeV):

  Mu: 4.3309(105)
  H: 4.37483(1)
  μH: 202 370.6(2.3)

- μH is less accurately measured than Mu, but it is **equally or more sensitive**.
- H is measured most accurately, but μH is still more sensitive at higher m_χ!

When using hydrogen-like atoms as labs for New Physics searches, we can use the range of their Bohr radii to our advantage!

LIGHT NEW PHYSICS?
DISCUSS!

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