Laser spectroscopy of muonic atoms

from benchmarks for nuclear physics to BSM searches

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µ

CREMA collaboration

**Swiss National
Science Foundation**

One possibility to search BSM physics with atomic systems

The simplicity of hydrogen

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 \exists

 $\sqrt{\frac{1}{1}}$

Not so simple

Limited by nuclear

BSM?

The hydrogen atom

$$
f_{1s-2s} = 2466 061 413.187 035(10) \text{ MHz}
$$
\n
$$
f_{1s-2s} = 2466 061 413.187 035(10) \text{ MHz}
$$
\n
$$
QED
$$

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

µ

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Lux Bard B.O

ETH

$$
_{\text{NS}} = \frac{2}{3n^3} Z^4 \alpha^4 m_r^3 r^2
$$

Finite size effects

Laser spectroscopy of muonic hydrogen

 $p-k$
 (1)

 π (

 μ (

 μ (

 μ p

La

 $X-1$

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

The setup

Beam line delivering $\pi^$ slow muons \hat{C} $500 \mu^{-} s^{-1}$ at 1 keV MEC 5T solenoid Plastic scintillators Optical cell Pump^{ors SHG} Pump Ti.Sa Ti.Sa Seed O _{SC} 800-1000nm -20^m Laser system delivering the spectroscopy pulses within 1 *μ*s PAUL SCHERRER INSTITUT Aldo Antognini Ascona 02.07.2023 ETH

 \Box

Gas target X-ray detectors Electron detectors Optical cell

The proton radius puzzle (2013)

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µp spectroscopy

-
-
-
-
-
-

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

New experiments -scattering -spectroscopy

New physics?

 $m_{\mu}\approx 200 m_e$ $m \approx 200m$ p μ ⁻

 $H_1 = -\vec{\mu} \cdot \vec{B} \sim 1/m$ $= -\vec{d} \cdot$ $H_1 = -\vec{d} \cdot \vec{E}$ $\Delta E = \langle \bar{\Psi} | H_1 | \Psi \rangle$

The proton radius puzzle

• μp experiment

 \cdot μp theory

• H experiments

• BSM physics

• e-p scattering

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sensitive to the radius eancitiva to t

- small atomic size
- large binding energy

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

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

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

De insensitive to systematics

Matrix elements for perturbations

The proton radius puzzle

• H experiments an elastic contribution and only calculated by the Marty- $\frac{1}{2}$. It is not parameterized with the charge $\frac{1}{2}$

• BSM physics **Equilibrities**

• e-p scattering which are the calculation of the c

• μp experiment

• μp theory

Discrepancy= 0.3 meV

factor insertions while the gray blobs represent all possible $v_p = 0.64000(35)$ $f = 0.84060(39)$ fm $r_p = 0.84060(39)$ fm

 $E_{LS}^{th} = 206.0344(3) - 5.2259 r_p^2 + 0.0289(25)$ meV $E_{\rm I,S}^{\rm exp}$ LS $= 202.3706(23)$ meV Item #r2b' is a VP correction of order *–*(*Z–*)⁵. It is *µ* $I_{LS}^{III} = 206.0344(3) - 5.2259 r_p^2 + 0.0289(25)$ mo (*a*) $I_{LS}^{III} = 206.0344(3) - 5.2259 r_p^2 + 0.0289(25)$ m Item #r2b' is a VP correction of order *–*(*Z–*)⁵. It is

arXiv:2212.13782 (*b*) iv:22 *µ*

– – –

Hagelstein Pachucki

The proton radius puzzle

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• H experiments

• BSM physics

• e-p scattering

ing ratio for *W* goes to *µ*⌫*^V* + *µ*⌫*^A* must be less than 4%

 $\mathcal{F}_{\mathbf{1}}=\mathcal{F}_{\mathbf{1}}$, the parameter space necessary to satisfy experimental $\mathcal{F}_{\mathbf{1}}$

- Fig. 3: The parameter space necessary to satisfy experimental \mathbf{y} experimental space \mathbf{y} **⋗ luning (e.g. vector vs axial-vector)** lines refer to constraints on *C^µ ^A*. The green band, outlined by **⋗** Preferential coupling to μ and p **≥ Tuning (e.g. vector vs axial-vector)** lines refer to constraints on *C^µ ^A*. The green band, outlined by **⋗** Preferential coupling to µ and p proton radius problem (*±*2). The shaded region is the
- proton radius problem (*±*2). The shaded red region is the *γ* No UV completion Ω **∂** No UV completion? ing ratio for *W* goes to *µ*⌫*^V* + *µ*⌫*^A* must be less than 4%

Altography Constraint on C_A^{μ}

According to solve the muonic *g* - 2 problem (*±*2*σ*) under the According $\frac{m_Z^2}{m_\phi^2}$ - 4 log $\frac{m_Z^2}{m_\phi^2}$: 07. 2023 under the assumption that C_A^{μ} solves the muonic $g-2$ problem. The shaded orange region is the restricted region on *C^µ* lem. The shaded orange region is the restricted region on *C^µ V* Carlson and Freid, PRD92, 095024(2015) due to energy splittings in muonic Mg and Si at 2σ . The α sumpressed is easy Ω^μ *^V* solves the proton radius problem (*±*2). green band, outlined by dashed lines, is the constraint on C_A^{μ}
Algebrary to solve the muonic $g-2$ problem $(\pm 2\sigma)$ under the α \mathcal{V} solves the proton radius problem (12) .

$$
i\mathcal{M} = \frac{i}{2} \frac{g_W}{\cos \theta_W} C_V^{\mu} \alpha(k) \epsilon_{\beta}^4
$$

$$
\times \left\{ \frac{\gamma^{\beta}(\rlap/v_1 + \rlap/v_1)}{(p_1 + p_3)} \right\} \gamma^{\alpha} \eta \epsilon^{-1}
$$

$$
- \gamma^{\alpha} \left(-\frac{1}{2} + i \sin^2 \theta_W^2 \right)
$$

to the decay amplitude squared). to the decay amplitude squared).

In this case, cancellations between the two diagrams sure the Ward identity is satisfied. Therefore, there is poor behavior at high energies when the ϕ is longilinally polarized. This is seen in the logarithmic P_{de} In this case, cancellations between the two diagrams sure the Ward identity is satisfied. Therefore, there is poor behavior at high energies when the ϕ is longi- $\frac{Ward}{d}$ ide

 $\Gamma_Z = \frac{G_F m_Z^3}{2}$ $\Gamma_Z = \frac{G_F m_Z^3 \left[(C''_{1b})^2 e^{\frac{1}{2} \left(\frac{a}{2} \mu \right)} \right] \sqrt{\frac{1}{2} c^2 e^{\frac{2}{3} \mu^2}}}{48 \sqrt{2} \pi^3}$ $\frac{12}{48\sqrt{2}\pi^3}$ ⇥ $\sqrt{ }$ $\log^2\!\frac{m_Z^2}{\Omega^2}$ *Z* \mathcal{R}^2_d $-4\log\frac{m^2}{M^2}$ *Z m*² + 5 ⇡² 3 $-4\log\frac{m^2}{m^2}$:07.202 ⇥ $\sqrt{2}$ $\log^2\!\frac{m_Z^2}{\rm{d}n}$ $\frac{2}{2}$ *Z* $\bigoplus_{m_\phi}^{\infty}$ + 07 \cdot 25

 ϕ

 m_ϕ^2 Ф

• μp experiment particle ϕV, and a further vector boson with the same mass

 \cdot µp theory

(7) (7)

The proton radius puzzle The new interaction terms in the Lagrangian area in the Lagra *2.1.* φ *couplings to u and d quarks*

1 2 $(\partial \phi)^2 - \frac{1}{2}$ $m_\phi^2 \phi^2 + e \epsilon_f \phi \bar{\psi}_f \psi_f$

 \mathcal{A}

$$
\mathcal{L}_{int} = -\phi_{\lambda}^{V} [C_{V}^{\mu} \bar{\psi}_{\mu} \gamma^{\lambda} \psi_{\mu} + C_{V}^{p} \bar{\psi}_{p} \gamma^{\lambda} \psi_{p}] \n- \phi_{\lambda}^{A} [C_{A}^{\mu} \bar{\psi}_{\mu} \gamma^{\lambda} \gamma_{5} \psi_{\mu} + C_{A}^{p} \bar{\psi}_{p} \gamma^{\lambda} \gamma_{5} \psi_{p}] \n- i C_{V}^{\mu} \epsilon_{ijk} W_{\alpha}^{i} W_{\beta}^{j} \partial^{\alpha} W^{k,\beta} + i \{ C_{A}^{\mu} \text{terms} \} \n- \frac{g}{2\sqrt{2}} \bar{\psi}_{\mu} \gamma^{\lambda} (1 - \gamma_{5}) \psi_{\nu} W_{s,\lambda}^{-} + \text{H.c.},
$$

*L*φ ⊃ −

 ϕ

Ф

%*^p* = 2%*^u* + %*^d ,* %*ⁿ* = 2%*^d* + %*u.* (2)

• μp experiment

• μp theory

• H experiments

• BSM physics

• e-p scattering

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Proton charge radii from e-p scattering puzzle from these analyses of electron-proton scattering data. New and function of the function \mathbf{r}_i t on scattering are highly desirable, which we desirable, which we desirable, which we desire in \mathcal{C} SMI G-k

FIG. Aldo Antognini Ascona 02.07.2023

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

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The proton charge radii from 2010 to 2022

Advances in nuclear-structure contributions in H, D and $\mu\mathsf{D}$ atoms removed a 2.5σ tension

*μ*D and H-D isotopic shift

 $H/D \text{ shift:} \quad r_\text{d}^2 - r_\text{p}^2 = 3.820\,07(65) \text{ fm}^2$
 $\mu d: \qquad r_\text{d} = 2.1256(8) \text{ fm}$

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

 $10¹$ **Muonic atoms** Lensky et al. '22 $(\mu D + iso)$ Antognini et al. $13 (\mu H)$ Pohl et al. '10 $\H(\mu H)$ -H spectroscopy

H(2S-8D) Colorado '21 -H(1S-3S) Garching '20 -H(2S-2P) Toronto '19 -H(1S-3S) Paris '18 -H(2S-4P) Garching '17 H pre '14 (CODATA) -

ep scattering

CODATA

 $'18 14$

Xiong et al. '19 (PRad) -Horbatsch et al. '17 -Higinbotham et al. '16 Lee et al. $15⁴$ **Sick '12** Bernauer et al. '10 (MAMI) ·

ep scatt., disp. analysis

J.P. Karr P. Yzombard E. Hessels

The proton charge radii from 2010 to 2022

Aldo Antognini also have a mutu perturbing resonances. Although the bulk of the bulk o down to 85 m/s. These low velocities are achieved by the 1S-2S excitation light that 1S-2S excitation light the 1S-2S excitation light the 1S-2S excitation light th

experiment detailed below the ex p_{source}

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

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

What to do with a precise proton radius?

uH measurements

Muonic hydrogen

 $(\delta = 1 \times 10^{-5})$ $E_{2S-2P}(\mu H) \approx \text{QED} + \kappa r_p^2 + \text{NS}$

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

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

Adding for example the H(1S-3S)…..

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Muonic hydrogen

Hydrogen
\n
$$
E_{1S-2S}(H) \approx \frac{3}{4}R_{\infty} + QED' + k'r_p^2
$$
\n
$$
(\delta = 4 \times 10^{-15})
$$

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

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

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

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

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

Adding H(1S-3S)…..

Adding H(1S-3S)…..

- \triangleright dispersive
- **B** sum rules
- chiral perturbation th.
- **D** lattice QCD
- **Nuclear structure** contribution

Theoretical tools

Adding HD⁺ measurements

Muonic hydrogen

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

19.11.2019 EMMI 200510 (2019) Heiße et al. Phys. Rev. A 100(2):022518 (2019) Sturm et al. Nature 506(7489):467–470 (2014)

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

Muonic hydrogen

 \blacksquare \square \square

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

Test of bound g-factors $\delta \sim 4 \times 10^{-11}$

N. Schwegler

S. Sturm

The fine structure constant

α π) 4 $+ C_{5}$ (*α π*) 5 $+ a_{\text{weak}} + a_{\text{had}} + \cdots$

Hanneke et al, PRL 2008, 100, 120801 Aoyama et al, PRD 2018, 97, 036001

Parker et al., Sciece 360, 191-195 (2018)

Xin Fang

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,**}

Aldo Antognini and anti-fundamental constants, possibly reducing to a constant of α and α 02.07.2023 the claim sensitivity of \mathbb{R}^n subtletted. This subtletted is subtletted. This subtletted is subtletted in

visible decay dominates), NA62 **A**scona (blue) or 300 keV uLD scalar (purple). The solid scalar (purple). The soli DATA22 dataset, the dashed (dotted) lines the CODATA18

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

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*r*2 *^C* = *r*² *str* + *r*² *^p* + *r*² *DF* + *r*² Krauth et al., , Nature 589 (2021) 7843, 527-531

> Towards consistent treatment of the nuclear structure: TPE and radii

The helion charge radius

Aldo Antognini Ascona 02.07.2023 Fig. 4. Ando Antognini determinations of the 3He nucleus (heliopological determination) and 3He nucleus (helio

 $E_{\text{LS}}^{\text{th}} = 1644.348(8) - 103.383 r_h^2 + 15.499(378) \text{ meV}$ $E_{\rm I,S}^{\rm exp}$ LS $= 1258.598 (48)^{exp}(3)$ ^{theo} meV QED Finite size Nuclear structure

Pachucki et al., arXiv:2212.13782 Schuhmann et al., arXiv 2305.11679

A − *Z* r_n^2

 $\langle P', M_J | J_B^0 | P, M_J \rangle$ In Breit frame

Radius as benchmark for ab initio few-nucleon predictions

Z

^p+

str(3

CPT tests (Lsym-project)

Frequency Comb spectroscopy in He+ \mathbf{S} and the the setup for $\mathbf{H}\mathbf{e}^+$

Comb spectroscopy in the XUV

Trapping and cooling

Quantum logic detection

The He atom

Two electrons are much more than one electron

 $ma⁷$ contributions completed

there is perfect

For some transitions agreement, for others perfect disagreement

But this is another story

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

Patkos et al, PRA 103, 042809 (2021)

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Talk Gloria Clausen

Talk Yuri van der Werf

HFS in muonic hydrogen

Impact of the measurement

Provides information on magnetic structure of the proton **cannot**

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with respect to the mass field contributes field contributes field contributes field contributes to the leading potential. The leading potential contributes of \sim 100 km s \sim 100 km s \sim 100 km s \sim 100 km s \sim 1

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Sensitive especially to axial-vector BSM contributions this case, only the light axial-vector contributes to this splitting at leading order in the

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

v can be found in (A.9). Note that the upper C . Peset expression in (3.1) does not have a smooth management of the original of the the vector case, for the axial vector the extra degree of freedom of the massive vector field Y. Stadnik

By the formula for the following matrices:

\n
$$
\mathbf{P} = \begin{cases}\n\mathbf{P} = \frac{2g_A^{(1)}g_A^{(2)}}{3\pi} \left(\frac{e^{-m_\phi r}}{r} + \frac{2\pi \delta^{(3)}(r)}{m_\phi^2} \right) \mathbf{S}_1 \cdot \mathbf{S}_2 \\
\mathbf{S}_2\n\end{cases}
$$
\nFind perturbation theory

\n
$$
\mathbf{P} = \begin{cases}\n-\frac{2g_A^{(1)}g_A^{(2)}}{3\pi} \left(\frac{e^{-m_\phi r}}{r} + \frac{2\pi \delta^{(3)}(r)}{m_\phi^2} \right) \mathbf{S}_1 \cdot \mathbf{S}_2 \\
-\frac{4d_v^{(A)}}{m_1 m_2} \delta^{(3)}(r) \mathbf{S}_1 \cdot \mathbf{S}_2\n\end{cases}
$$
\nfor the given $V_{\text{HF},A}(r) = \begin{cases}\n-\frac{2g_A^{(1)}g_A^{(2)}}{3\pi} \left(\frac{e^{-m_\phi r}}{r} + \frac{2\pi \delta^{(3)}(r)}{m_\phi^2} \right) \mathbf{S}_1 \cdot \mathbf{S}_2\n\end{cases}$

Combined with H \rightarrow Test of HFS theory with rel. acc. $< 10^{-8}$ and LS measurements provide a test for dark forces free from possible cancellations. The reason is that a vector force gives a non-zero contribution to the HFS, while scalars do not.

 $2\pi\delta^{(3)}(r)$ m_ϕ^2 $\sum_{i=1}^{n}$ $\mathbf{S_1} \cdot \mathbf{S_2}$ for $m_{\phi} \lesssim a_0^{-1}$,

 $for m_{\phi} \sim m_r$,

Nuclear and hadron structure

 $-$ FEI

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WALLED BEER

Muonic atom spectroscopy

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QED tests in simple atomic systems

