New Physics, Fundamental Constants & Muon g-2

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- *Phys.Rev.Lett.* 127 (2021) 25, 251801
  with Ohayon (ETHZ→Technion) and Soreq (Technion)

- hep-ph/2210.10056, to appear in *PRL*
  with Karr (LKB), Kitahara (Nagoya), Koelemeij (Amsterdam), Soreq (Technion) and Zupan (Cincinnati)

Outline

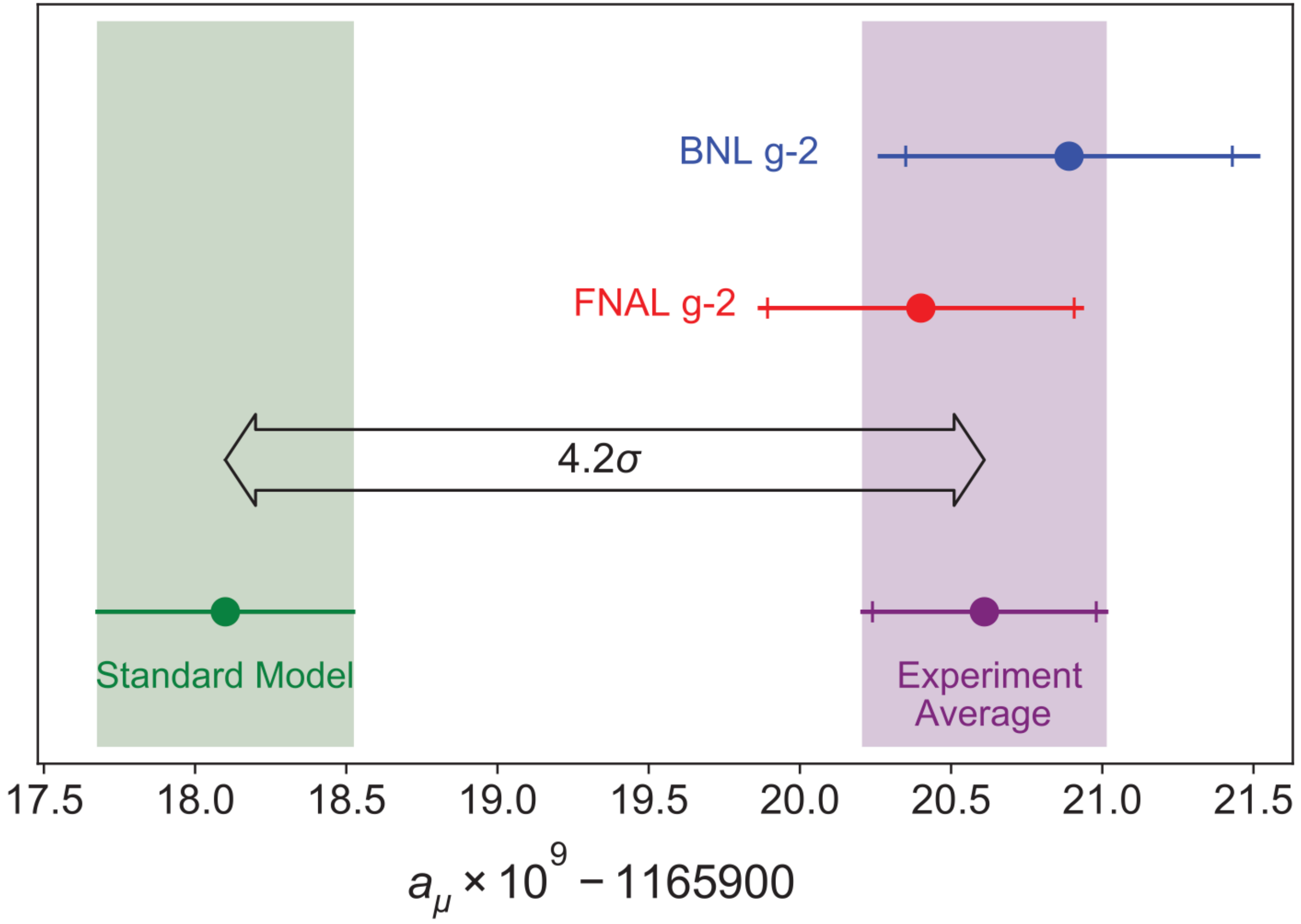
- Accurate muon g-2 from muonium
  - Spin-precession measurements disagree with the SM
  - Is the SM prediction well under control?
  - New test with forthcoming precision muonium spectroscopy

- Do we truly understand fundamental constants?
  - New physics below $\sim 1\,\mathrm{GeV}$ affects the determination of the FCs
  - Modified CODATA makes associated measurements a sensitive NP search
  - Several observed inconsistencies, explained by a single new particle

Muon(ium) g-2

muon magnetic moment below 1ppm from $\mu^+ e^-$ spectroscopy

The Muon g-2 puzzle



Is this really an evidence of BSM Physics?

$$a_\mu^{\rm BSM} = 251(59) \times 10^{-11}$$

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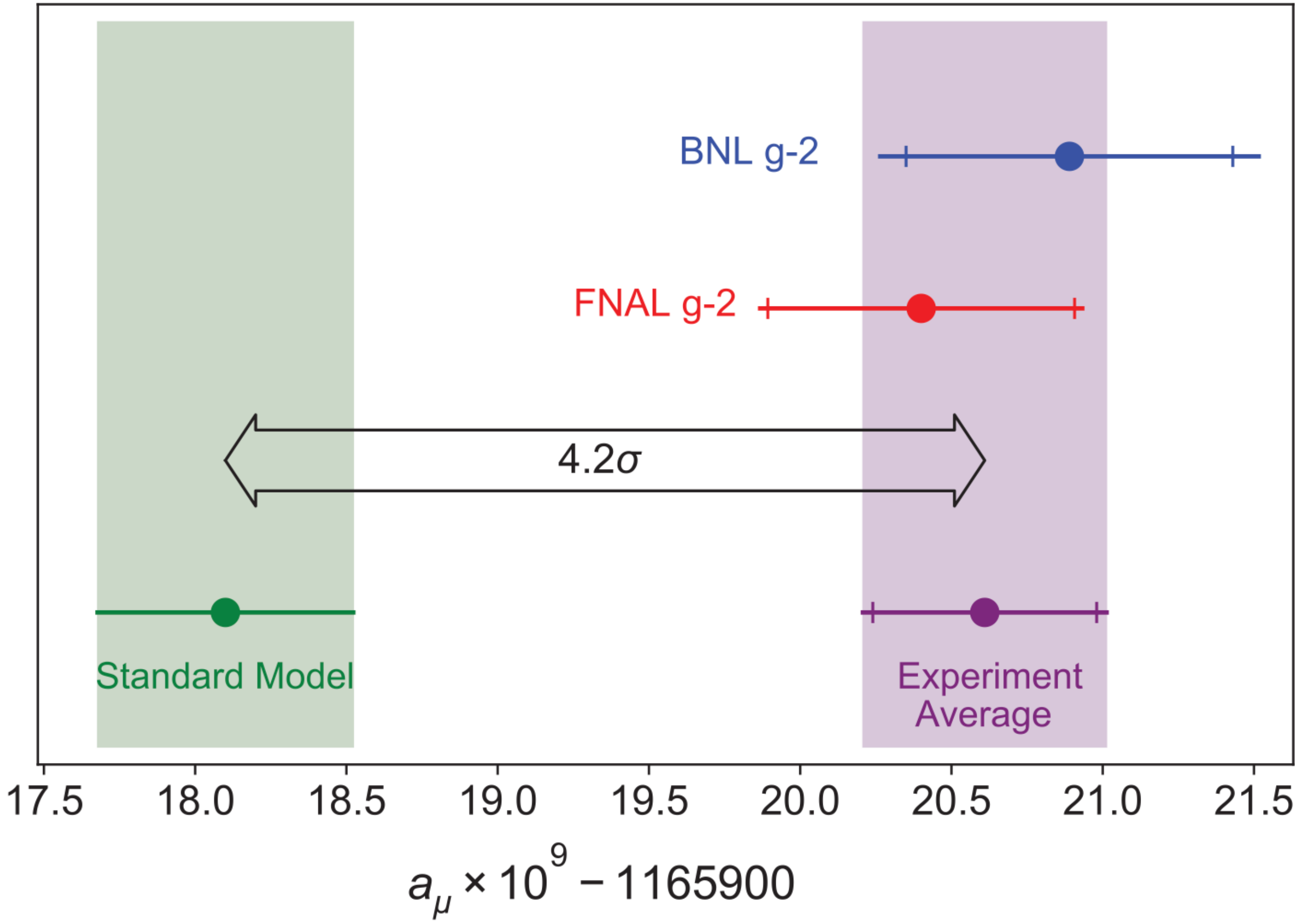

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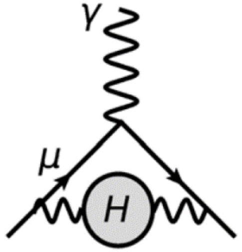
$$a_\mu^{\mathrm{BSM}} = 251(59) \times 10^{-11}$$

Do we really control the SM prediction?



R-ratio method:

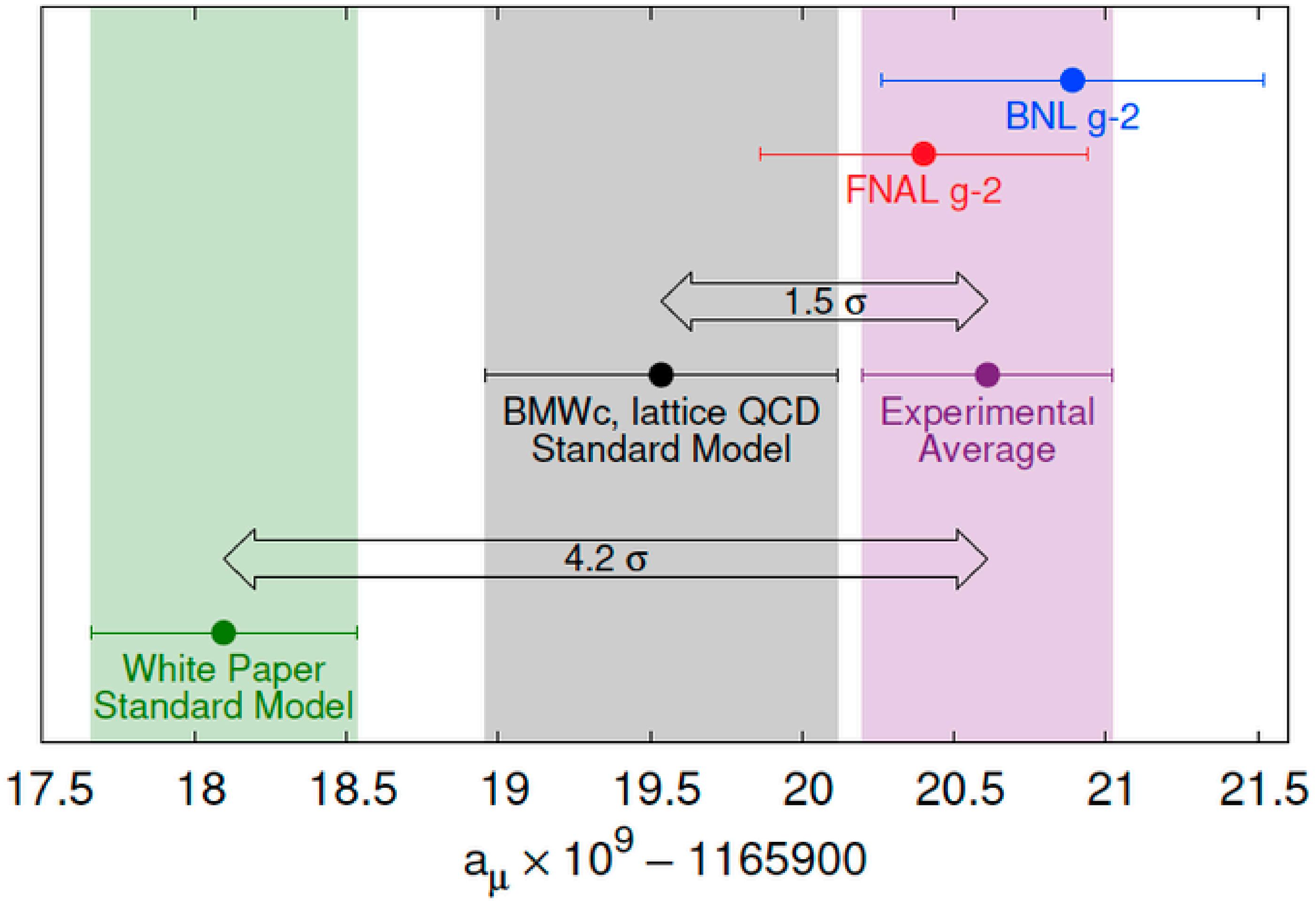
[Bouchiat-Michel 1961]

$$a_\mu^{\mathrm{HVP-LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{3s}{4\pi\alpha^2}\sigma(e^+e^- \to \mathrm{hadrons})$$

$\pi\pi \sim 70\%$

The Muon g-2 puzzle



New lattice results cast doubts

[BMW coll. Nature 593 (2021) 7857]

$$a_\mu^{\mathrm{HVP-LO}} = 7075(55) \times 10^{-11}$$

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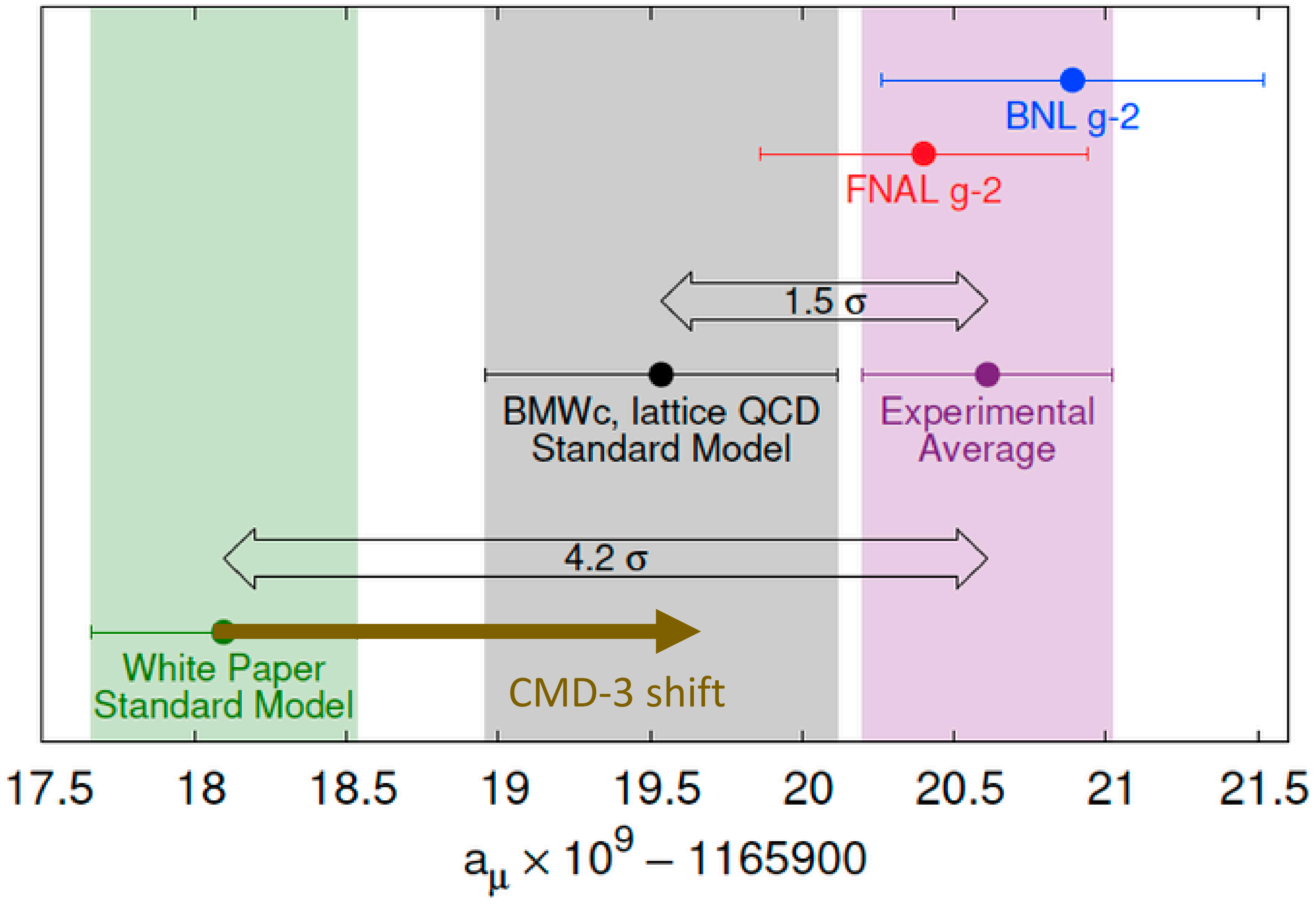

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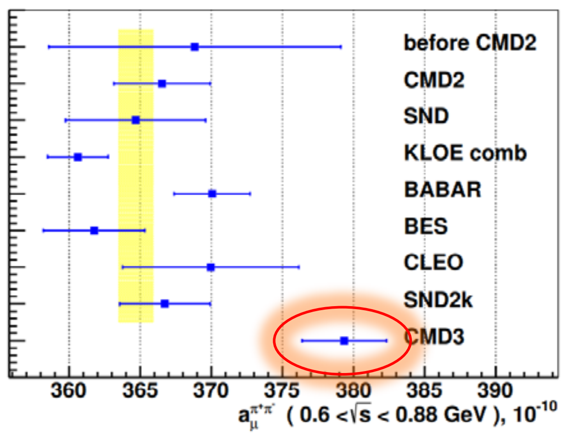
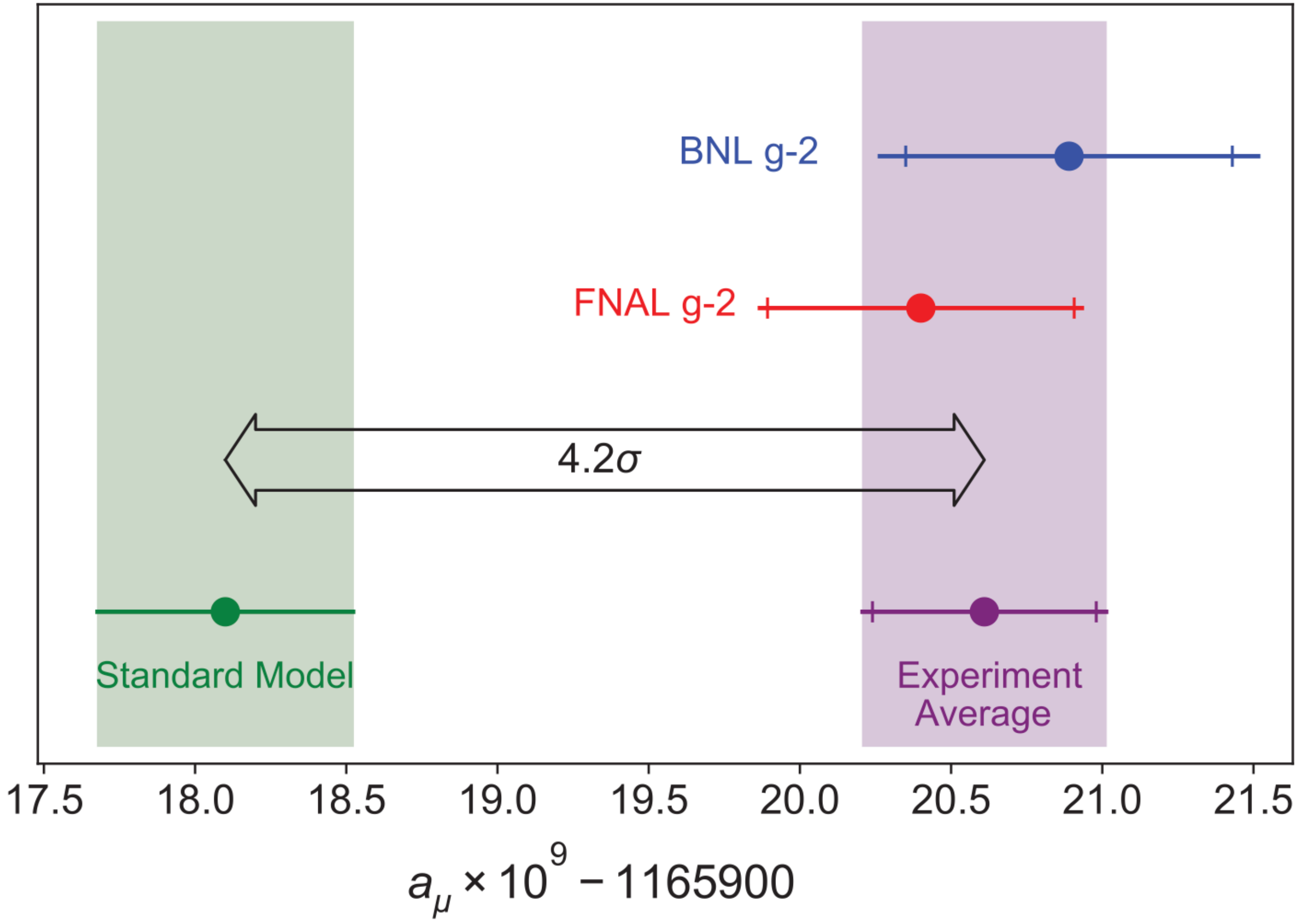
Recent $e^+e^- \to \pi\pi$ VEPP data also [CMD-3 coll. hep-ex/2302.08834]

$$a_\mu^{\mathrm{HVP-LO}}[\pi\pi] = 3793(30) \times 10^{-11}$$
$$(0.6 < \sqrt{s} < 0.9\,\mathrm{GeV})$$



Towards solving the puzzle



New experimental determinations of a_μ are more than welcome!

JPARC is coming up, but like BNL/FNAL it could be affected by « environmental » NP effects, *e.g.* [Davoudiasl-Szafron hep-ph/2210.14959] [Agrawal et al. hep-ph/2210.17547]

MUonE will measure HVP directly, should be clean from NP, see *e.g.* [Masiero-Paradisi-Passera PRD 2020]

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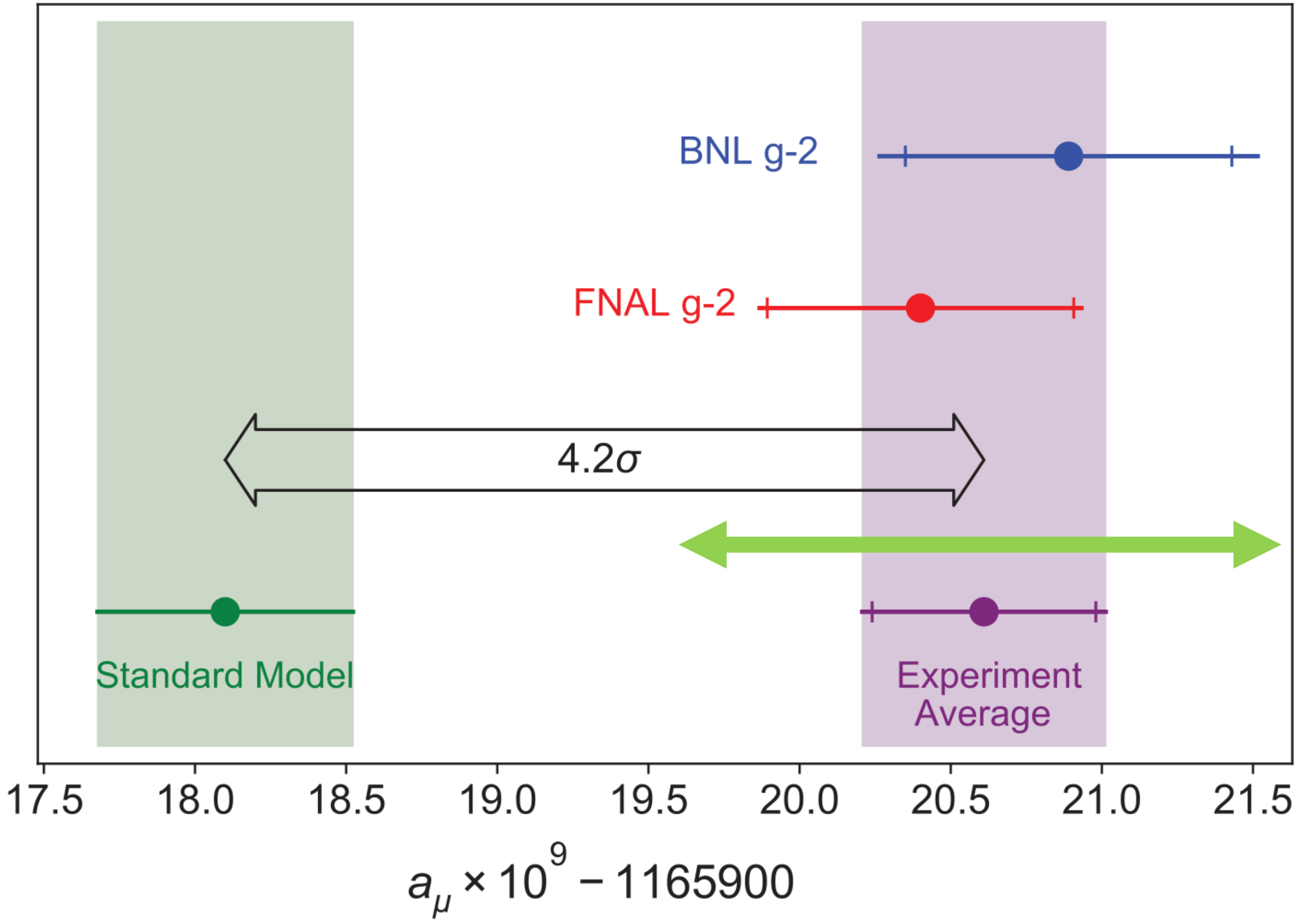

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Muonium spectroscopy in <10yrs will offer another test at 1ppm!

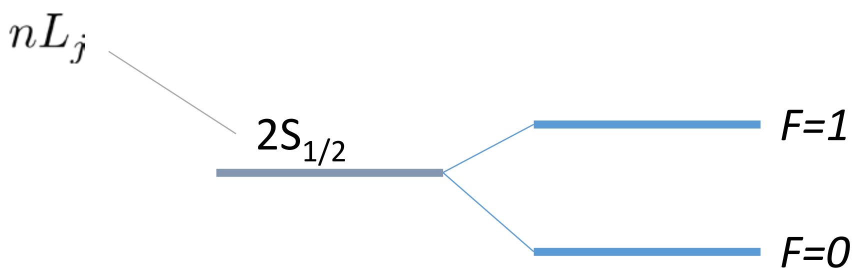
Muonium energy levels

full angular momentum:

$$\vec{F} = \vec{L} + \vec{S}_e + \vec{S}_\mu$$

Hyperfine splitting (HFS) for S levels
arises from magnetic dipole-dipole interaction

$$H_{\rm HFS} = -\frac{2\mu_0}{3}\vec{\mu}_e \cdot \vec{\mu}_\mu\, \delta^3(r)$$

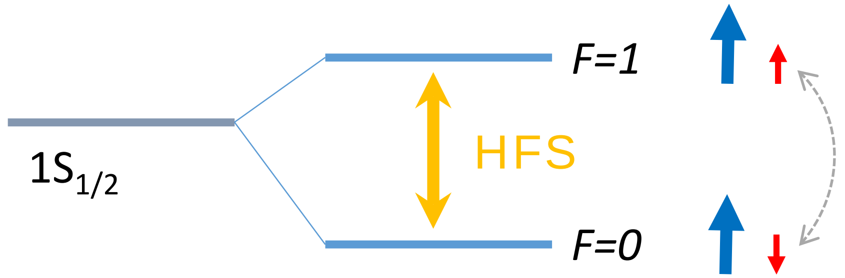


The electron spin flips in the (static) magnetic field sourced by the muon,
which lifts the degeneracy of the S state.

The 1S-HFS in muonium is very precisely measured:

$$\nu_{\rm HFS}^{\rm exp} = 4\,463\,302\,765(53)\,{\rm Hz}\ (12{\rm ppb})$$

[Liu et al. PRL 1999]



Ground-state HFS theory

Rydberg constant
$R_\infty \equiv \alpha^2 m_e c/(2h)$

fine-structure constant

nonrelativistic Fermi energy from H_{HFS}

$$\nu_{\mathrm{HFS}} = \frac{16}{3}(1 + a_\mu)\frac{m_e}{m_\mu}\frac{R_\infty c\alpha^2}{(1+m_e/m_\mu)^3}[1 + \delta_{\mathrm{HFS}}]$$

electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction
[CODATA 2018 + refs therein]

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electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction
[CODATA 2018 + refs therein]

Z-exchange
$-65\,\rm Hz$

$$\delta_{\rm HFS} = \delta_{\rm Dirac} + \delta_{\rm rad} + \delta_{\rm rec} + \delta_{\rm rad-rec} + \delta_{\rm weak} + \delta_{\rm had}$$

hadronic vacuum pol.
$= 237.7(1.5)\,\rm Hz$

relativistic (exact)

radiative
known up to $\mathcal{O}(Z\alpha^4)$
including a_e

recoil
known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^3]$
$\sim 60\,\rm Hz$ uncertainty

radiative-recoil
known up to $\mathcal{O}[(m_e/m_\mu)\alpha^3]$
$\sim 10\,\rm Hz$ uncertainty

antimuon charge
$Z=1$

Total TH uncertainty $\sim 70\,\rm Hz\,(16ppb)$
dominanted by (yet) uncalculated QED corrections at three-loop order

[Eides-Shelyuto IJMPA 2016]

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Need to extract from another observable → electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction
[CODATA 2018 + refs therein]

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Alternative muon mass determination

To extract a_μ from muonium HFS, another observable is needed to fix the muon mass

The second best determination of m_e/m_μ
is provided by the muonium 1S-2S transition

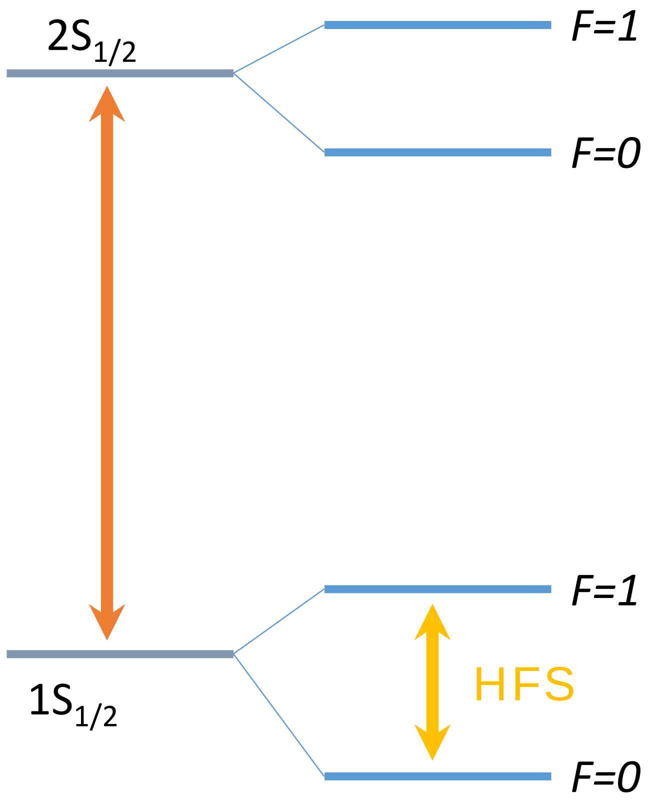
The muon mass enters as a recoil correction to all Mu energies through the reduced mass $m_r \equiv m_e m_\mu/(m_e + m_\mu)$

$$E_n^{\mathrm{Mu}} \simeq -\alpha^2 \frac{m_r c^2}{2n^2} = -\frac{R_\infty ch}{1+m_e/m_\mu}\frac{1}{n^2}$$

The 1S-2S is the best measured Mu transition between different n's:

$$\nu_{\mathrm{1S-2S}}^{\mathrm{exp}} = 2\,455\,528\,941.0(9.8)\,\mathrm{MHz}\ (4\mathrm{ppb})$$

[Meyer et al. PRL 2000]



1S-2S theory

nonrelativistic energy
(including recoil)

$\mathcal{O}(\alpha^2)$ correction

$$\nu_{1S-2S} = \frac{3}{4} \frac{R_\infty c}{(1+m_e/m_\mu)} [1 + \delta_{1S-2S}]$$

[CODATA 2018 + refs therein]
rescaling hydrogen formulae
with the muon mass and removing
nuclear finite size and pol. effects

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rescaling hydrogen formulae with the muon mass and removing nuclear finite size and pol. effects

vacuum pol. known up to $\mathcal{O}[\alpha(Z\alpha)^4]$

2+3 photon exchange known up to $\mathcal{O}[\alpha^3(Z\alpha)^4]$

muon self-E

$$\delta_{1S-2S} = \delta_{\rm Dirac} + \delta_{\rm rel-rec} + \delta_{e\rm SE} + \delta_{\rm VP} + \delta_{2\gamma} + \delta_{3\gamma} + \delta_{\rm rad-rec} + \delta_{\mu\rm SE}$$

relativistic (exact)

relativistic-recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^4]$

electron self-E $\mathcal{O}[\alpha(Z\alpha)^4]$ known

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha(Z\alpha)^3]$

Total TH uncertainty $\sim 20\,\mathrm{kHz}\ (8\mathrm{ppt})$
from (yet) uncalculated QED (rad-rec) corrections at three-loop order

[Karshenboim et al. PLB 2019]

Least-square adjustment of muonium data

Following the CODATA procedure [see CODATA 1998]
we construct a least-square fit
of the Mu HFS and 1S-2S transitions
to extract *both* m_e/m_μ and a_μ
from spectroscopy

input datum	value	relative uncertainty	identification	reference
ν_{1S-2S}	2 455 528 941.0(9.8) MHz	4.0×10^{-9}	RAL-99	[40]
ν_{HFS}	4 463 302 776(51) Hz	1.2×10^{-8}	LAMPF-99	[38]
ν_{HFS}	4 463 302.88(16)kHz	3.6×10^{-8}	LAMPF-82	[55]
$\delta E(1S)/h$	0.000(14) MHz	4.3×10^{-12}	theory	[43]
$\delta E(2S)/h$	0.0(1.8) kHz	2.2×10^{-12}	theory	[43]
$\delta E(HFS)/h$	0.000(70) kHz	1.6×10^{-8}	theory	[52]

Using CODATA 2018 recommended values
for R_∞ and α, current Mu data yield:

input datum	observational equation
ν_{1S-2S}	$\nu_{1S-2S} \doteq [E_M(2S; m_e/m_\mu) + \delta_{2S}^{th} - E_M(1S; m_e/m_\mu) - \delta_{1S}^{th}]/h$
ν_{HFS}	$\nu_{HFS} \doteq \nu_{HFS}^{th}(m_e/m_\mu, a_\mu) + \delta_{HFS}^{th}/h$
$\delta E(1S)/h$	$\delta E(1S) \doteq \delta_{1S}^{th}$
$\delta E(2S)/h$	$\delta E(2S) \doteq \delta_{2S}^{th}$
$\delta E(HFS)/h$	$\delta E(HFS) \doteq \delta_{HFS}^{th}$

$$m_e/m_\mu = 4\,836\,329(4) \times 10^{-9}$$

$$a_\mu^{Mu} = 116\,637(82) \times 10^{-8} (700\text{ppm})$$

← very large uncertainty (Muon g-2 coll. result is $\sim 0.35\text{ppm}$)
dominated by the 1S-2S measurement uncertainty

larger value than Muon g-2 coll. result
$a_\mu^{Mu} - a_\mu^{exp} \simeq 4.5 \times 10^{-7}$ but consistent w/in uncertainties

However, there is room for improvement
in muonium spectroscopy!

Big improvements coming up!

The Mu-MASS experiment at PSI plans to reduce the 1S-2S uncertainty to

[Crivelli Hyperfine Interact. 2018] $\sim 10\,\mathrm{kHz}(4\mathrm{ppt})$

$\sim 10^3$ improvement!

This could be further reduced to $\sim$ few kHz after the High-Intensity Muon Beam upgrade at PSI

[Kiselev et al. J-PARC symbosium 2019]

The MuSEUM experiment using a high-intensity pulsed muon beam at J-PARC will reduce the HFS uncertainty to

[Tanaka et al. 2021] $\sim 10\,\mathrm{Hz}(2.2\mathrm{ppb})$

~ 10 improvement!

The linewidth can be reduced by selecting the « old muonium » tail (if statistics is high enough) which could bring down the HFS uncertainty to

$\sim 4\,\mathrm{Hz}(1\mathrm{ppb})$

Theory is expected to also improve with a complete calculation of the 3-loop contribution in bound-state QED [Eides 2018]

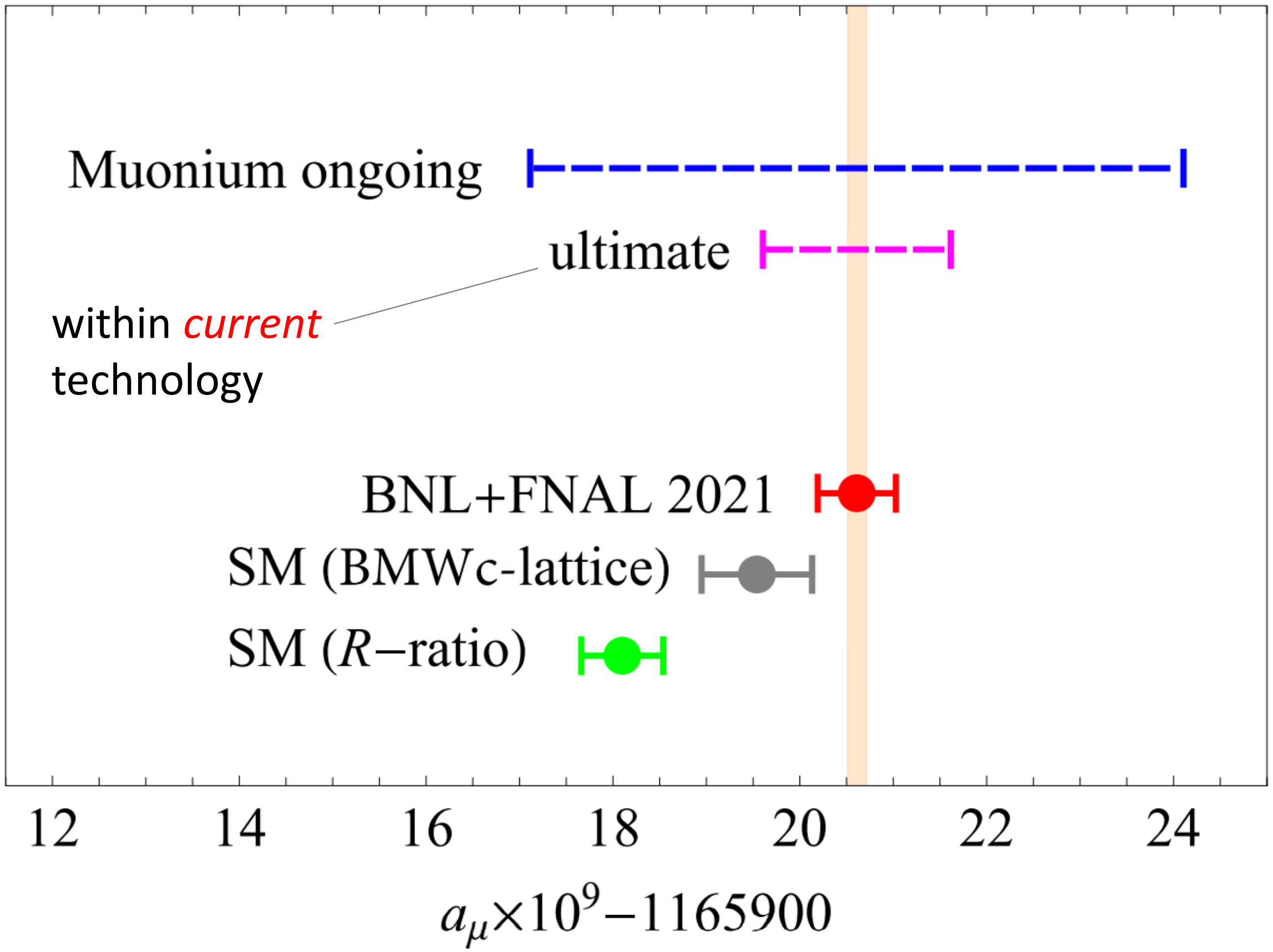
Expected a_μ uncertainty from muonium

parameter (unit)	quantity	u_r current	ongoing	ultimate
m_e/m_μ (ppb)	ν_{1S-2S}(exp)	825	0.84	0.34
	QED(1S-2S)	1.7	1.2	0.1
	R_∞	0.40	0.13	
	total	825	1.5	0.37
a_μ (ppm)	ν_{1S-2S}(exp)	708	0.73	0.29
	ν_{HFS}(exp)	10	1.9	0.77
	QED(1S-2S)	1.4	1.0	0.07
	QED(HFS)	14	1.9	0.2
	HVP(HFS)	0.29	0.16	
	R_∞	0.35	0.13	
	α	0.26	0.14	
	total	708	3.0	0.88

$\mathcal{O}(1\text{ppm})$
assuming plausible future improvements

with official goals of Mu-MASS/MuSEUM

Shedding light on Muon g-2 puzzle



A value of a_μ^{Mu} at $\mathcal{O}(1\mathrm{ppm})$ is not competitive to current spin-precession measurements

However, it may help to understand the origin of the $\sim 2\mathrm{ppm}$ difference between (R-ratio) SM and experiment

* Committee on Data for Science and Technology

BSM CODATA *

Light new particles affect the determination of fundamental constants

The precision atomic frontier

Measurements of atomic lines in hydrogen are very precise:

$$\nu_{1S-2S} = 2\,466\,061\,413\,187\,035(10)\ \mathrm{Hz}$$

$$u_\nu = 4.2 \times 10^{-15}$$

Parthey et al. (2011)

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QED prediction is even better:

$R_\infty \equiv \alpha^2 m_e c/2h$

$$\nu_{1\mathrm{S}-2\mathrm{S}} = \frac{3}{4}\frac{R_\infty c}{(1+m_e/m_p)}\left[1 + \delta^{\mathrm{QED}}_{1\mathrm{S}-2\mathrm{S}}(\alpha) + \delta^{\mathrm{FNS}}_{1\mathrm{S}-2\mathrm{S}}(r_p)\right]$$

TH uncertainty $\sim 2\,\mathrm{Hz}$

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TH uncertainty $\sim 2\,\mathrm{Hz}$

limited by proton radius

Direct comparison fixes the Rydberg constant:

$$u_{R_\infty} = 1.9 \times 10^{-12}$$

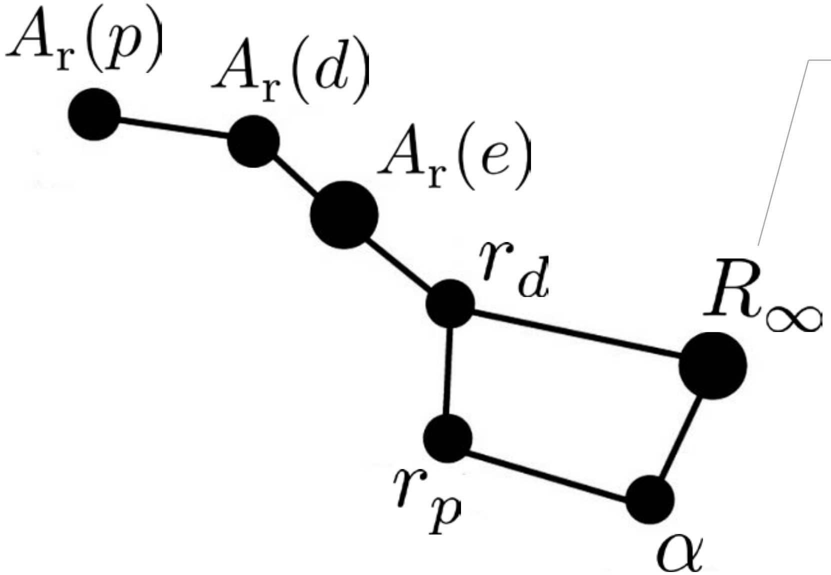
Tiesinga et al. [CODATA 2018]

$$R_\infty c = 3.289\,841\,960\,2508(64) \times 10^{15}\ \mathrm{Hz}$$

most precisely known fundamental constant in physics!

A constellation of constants

R_∞ is *interconnected* with other constants



Rydberg constant

hydrogen ν_{1S-2S} (+22 other lines)

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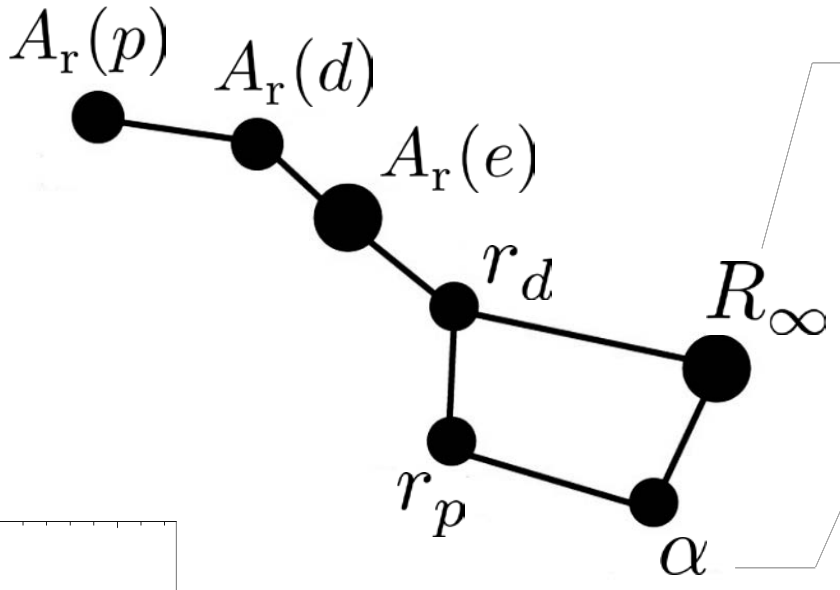

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fine structure constant

electron $g-2$ **Fan** et al. [2023]

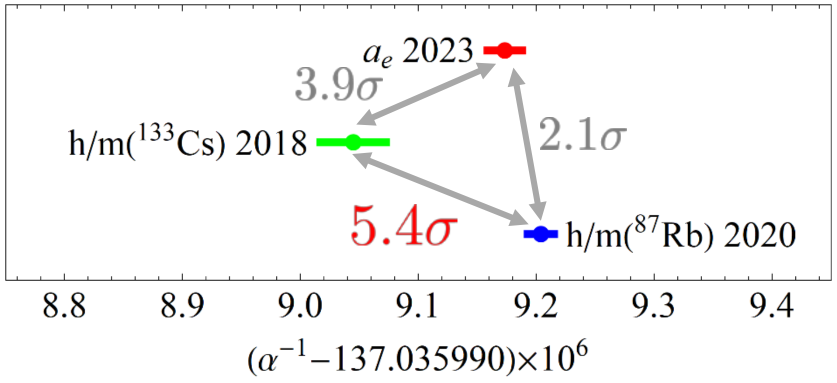
or atomic recoil

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

^{87}Rb **Morel** et al. [2020]

^{133}Cs **Parker** et al. [2018]

There are tensions…



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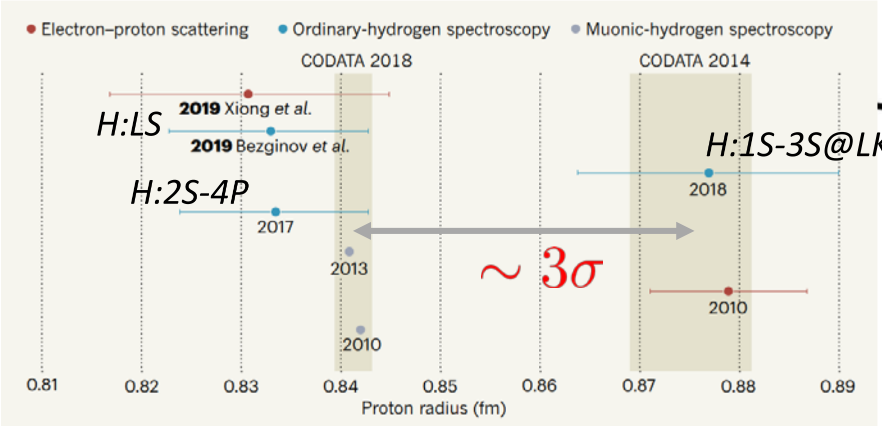
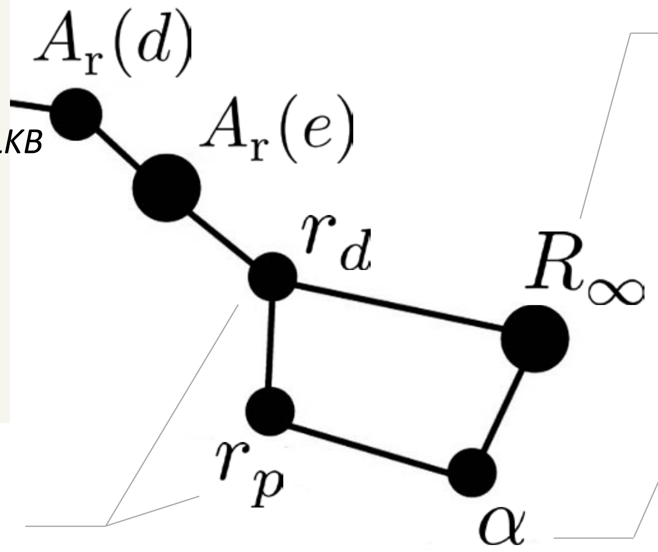
still a proton size puzzle...





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proton|deuteron (charge) radius

muonic hydrogen|deuterium Lamb shifts

or ordinary hydrogen|deuterium lines

or e-proton|e-deuteron scattering data

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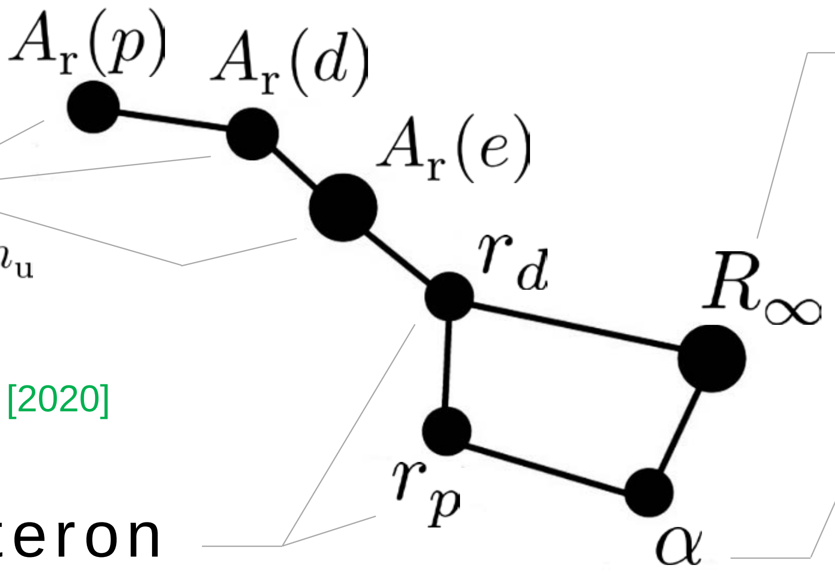

atomic mass constants $m_X = A_\mathrm{r}(X) m_\mathrm{u}$

$[A_\mathrm{r}(^{12}\mathrm{C}) \equiv 12]$

cyclotron motion

or HD+ molecular lines **Patra** et al. [2020]

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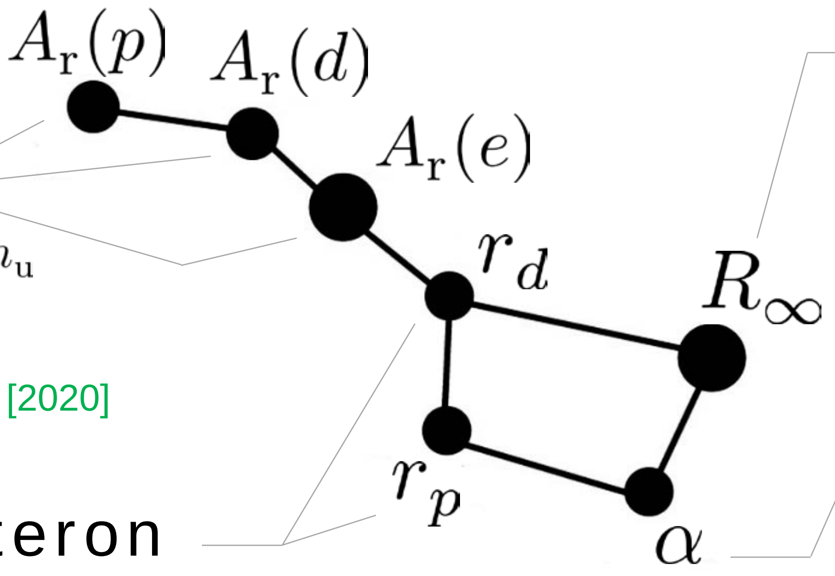

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to be determined together in a global fit
→ CODATA recommended values
https://pml.nist.gov/cuu/Constants/

CODATA 2018 (selected) values

TABLE XXXI. The CODATA recommended values of the fundamental constants of physics and chemistry based on the 2018 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
Rydberg frequency $\alpha^2 m_e c^2/2h = E_h/2h$	cR_∞	$3.289\,841\,960\,2508(64) \times 10^{15}$	Hz	1.9×10^{-12}
deuteron mass	m_d	$3.343\,583\,7724(10) \times 10^{-27}$	kg	3.0×10^{-10}
		$2.013\,553\,212\,745(40)$	u	2.0×10^{-11}
electron mass	m_e	$9.109\,383\,7015(28) \times 10^{-31}$	kg	3.0×10^{-10}
		$5.485\,799\,090\,65(16) \times 10^{-4}$	u	2.9×10^{-11}
proton mass	m_p	$1.672\,621\,923\,69(51) \times 10^{-27}$	kg	3.1×10^{-10}
		$1.007\,276\,466\,621(53)$	u	5.3×10^{-11}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5693(11) \times 10^{-3}$		1.5×10^{-10}
inverse fine-structure constant	α^{-1}	$137.035\,999\,084(21)$		1.5×10^{-10}
deuteron rms charge radius	r_d	$2.127\,99(74) \times 10^{-15}$	m	3.5×10^{-4}
proton rms charge radius	r_p	$8.414(19) \times 10^{-16}$	m	2.2×10^{-3}

This accuracy relies on assuming the SM! How robust is it to BSM?

CODATA with light new physics

New particles below $\sim \mathrm{GeV}$ will affect the observables used to determine the fundamental constants:

$$\mathcal{L}_{\rm int} = \sum_{\psi = e, \mu, p, n} g_\psi \bar{\psi}[\Gamma \cdot \phi]\psi$$

$\Gamma \cdot \phi$:

- ϕ scalar
- $\gamma^\mu \phi_\mu$ vector

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ϕ scalar

$\gamma^\mu \phi_\mu$ vector

$$V_{\rm NP}^{ij} = (-1)^{s+1} \alpha_\phi q_i q_j \frac{e^{-m_\phi r}}{r}$$

spin

$\alpha_\phi \equiv \frac{|g_e g_p|}{4\pi} \geq 0$

$q_i \equiv \frac{g_i}{\sqrt{|g_e g_p|}}$

Yukawa potentials contributing to spectral lines

hydrogen $\sim \alpha_\phi q_e q_p = \pm\alpha_\phi$

deuterium $\sim \alpha_\phi [1 + q_e q_n]$

μH/μD $\sim \alpha_\phi q_\mu q_{p/n}$

HD^+ $\sim \alpha_\phi [1, q_e q_n, q_p q_n]$

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spin: s

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One-loop correction to a_e

$\sim \alpha_\phi q_e^2 / 4\pi$

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spin

$\equiv \frac{|g_e g_p|}{4\pi} \geq 0$

$q_i \equiv \frac{g_i}{\sqrt{|g_e g_p|}}$

Yukawa potentials contributing to spectral lines

One-loop correction to a_e

$\sim \alpha_\phi q_e^2 / 4\pi$

Theoretical prediction for any observable:

$$\mathcal{O} = \mathcal{O}_{\text{SM}}(g_{\text{SM}}) + \mathcal{O}_{\text{NP}}(g_{\text{SM}}, \alpha_\phi, m_\phi) + \delta\mathcal{O}_{\text{th}}$$

$R_\infty, \alpha, r_p, \ldots$

evaluated @LO in α_ϕ

TH uncert.

Datasets

CODATA18 ← used for validation

Hydrogen/Deuterium

Label	Input datum	Value (kHz)
A1	$\nu_H(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	4 797 338(10)
A2	$\nu_H(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	6 490 144(24)
A3	$\nu_D(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	4 801 693(20)
A4	$\nu_D(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	6 494 841(41)
A5	$\nu_D(1S_{1/2} - 2S_{1/2}) - \nu_H(1S_{1/2} - 2S_{1/2})$	670 994 334.606(15)
A6	$\nu_H(1S_{1/2} - 2S_{1/2})$	2 466 061 413 187.035(1
A7	$\nu_H(1S_{1/2} - 2S_{1/2})$	2 466 061 413 187.018(1
A8	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 659(17)
A9	$\nu_H(2S_{1/2} - 4P)$	616 520 931 626.8(2.3)
A10	$\nu_H(2S_{1/2} - 8S_{1/2})$	770 649 350 012.0(8.6)
A11	$\nu_H(2S_{1/2} - 8D_{3/2})$	770 649 504 450.0(8.3)
A12	$\nu_H(2S_{1/2} - 8D_{5/2})$	770 649 561 584.2(6.4)
A13	$\nu_D(2S_{1/2} - 8S_{1/2})$	770 859 041 245.7(6.9)
A14	$\nu_D(2S_{1/2} - 8D_{3/2})$	770 859 195 701.8(6.3)
A15	$\nu_D(2S_{1/2} - 8D_{5/2})$	770 859 252 849.5(5.9)
A16	$\nu_H(2S_{1/2} - 12D_{3/2})$	799 191 710 472.7(9.4)
A17	$\nu_H(2S_{1/2} - 12D_{5/2})$	799 191 727 403.7(7.0)
A18	$\nu_D(2S_{1/2} - 12D_{3/2})$	799 409 168 038.0(8.6)
A19	$\nu_D(2S_{1/2} - 12D_{5/2})$	799 409 184 966.8(6.8)
A20	$\nu_H(2S_{1/2} - 6S_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 3S_{1/2})$	4 197 604(21)
A21	$\nu_H(2S_{1/2} - 6D_{5/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 4S_{1/2})$	4 699 099(10)
A22	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 678(13)
A23	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 671.5(2.6)
A24	$\nu_H(2S_{1/2} - 4P_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	4 664 269(15)
A25	$\nu_H(2S_{1/2} - 4P_{3/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	6 035 373(10)
A26	$\nu_H(2S_{1/2} - 2P_{3/2})$	9 911 200(12)
A27	$\nu_H(2P_{1/2} - 2S_{1/2})$	1 057 862(20)
A28	$\nu_H(2P_{1/2} - 2S_{1/2})$	1 057 845.0(9.0)
A29	$\nu_H(2P_{1/2} - 2S_{1/2})$	1 057 829.8(3.2)

g_e-2, masses...

Label	Input datum	Value	Rel. uncert.
D1	$a_e \equiv \frac{1}{2}(g-2)_e$	$1.159\,652\,180\,73(28) \times 10^{-3}$	2.4×10^{-10}
D2	δ_e	$0.000(18) \times 10^{-12}$	1.5×10^{-11}
D3	$h/m_{Rb}(^{87}Rb)$	$4.591\,359\,272\,9(57) \times 10^{-9}\ m^2s^{-1}$	
D4	$h/m_{Cs}(^{133}Cs)$	$3.002\,369\,472\,1(12) \times 10^{-9}\ m^2s^{-1}$	
D5	$A_r(^{87}Rb)$	86.909 180 531 2(65)	
D6	$A_r(^{133}Cs)$	132.905 451 961 0(86)	
D7	$\omega_s/\omega_c(^{12}C^{5+})$	4376.210 500 87(12)	
D8	$\Delta E_B(^{12}C^{5+})/hc$	$43.563\,233(25) \times 10^7\ m^{-1}$	
D9	δ_C	$0.0(2.5) \times 10^{-11}$	
D10	$\omega_s/\omega_c(^{28}Si^{13+})$	3912.866 064 84(19)	
D11	$A_r(^{28}Si)$	27.976 926 534 99(52)	
D12	$\Delta E_B(^{28}Si^{13+})/hc$	$420.6467(85) \times 10^7\ m^{-1}$	
D13	δ_{Si}	$0.0(1.7) \times 10^{-9}$	
D14	$\omega_c(d)/\omega_c(^{12}C^{6+})$	0.992 996 654 743(20)	
D15	$\omega_c(^{12}C^{6+})/\omega_c(p)$	0.503 776 367 662(17)	
D19	$A_r(^1H)$	1.007 825 032 241(94)	
D21	$\Delta E_B(^1H^+)/hc$	$1.096\,787\,717\,430\,7(10) \times 10^7\ m^{-1}$	
D23	$\Delta E_B(^{12}C^{6+})/hc$	$83.083\,850(25) \times 10^7\ m^{-1}$	

8.5×10^{-12}
4.9×10^{-6}
2.2×10^{-6}
4.4×10^{-12}

μH/μD

Label	Input datum	Value	Rel. uncert.
C1	$E_{LS}(\mu H)$	202.3706(23) meV	1.1×10^{-5}
C2	$E_{LS}(\mu D)$	202.8785(34) meV	1.7×10^{-5}
C7	$\delta E_{LS}(\mu H)$	0.0000(129) meV	6.4×10^{-5}
C8	$\delta E_{LS}(\mu D)$	0.0000(210) meV	1.0×10^{-4}
C9	r_p	0.880(20) fm	2.3×10^{-2}
C10	r_d	2.111(19) fm	9.0×10^{-3}

DATA22 ← used for NP analysis

including post-CODATA18 improvements from

Hydrogen, HD+, pbar-He
μHe, g_e-2 and masses

Label	Input datum	Value	Rel. uncert.	Reference
A30	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 665.79(72) kHz	2.5×10^{-13}	Grinin *et al.* [21]
A31	$\nu_H(2S_{1/2} - 8D_{5/2})$	770 649 561 570.9(2.0) kHz	2.6×10^{-12}	Brandt *et al.* [20]
D1	$a_e \equiv \frac{1}{2}(g-2)_e$	$1.159\,652\,180\,59(13) \times 10^{-3}$	1.1×10^{-10}	Fan *et al.* [70]
D3	$h/m_{Rb}(^{87}Rb)$	$4.591\,359\,258\,90(65) \times 10^{-9}\ m^2s^{-1}$	1.4×10^{-10}	Morel *et al.* [69]
D5	$A_r(^{87}Rb)$	86.909 180 529(6)	6.9×10^{-11}	AME 2020 [73]
D6	$A_r(^{133}Cs)$	132.905 451 958(8)	6.0×10^{-11}	AME 2020 [73]
D9	δ_C	$0.0(9.4) \times 10^{-12}$	4.9×10^{-12}	Czarnecki *et al.* [71]
D13	δ_{Si}	$0.0(5.8) \times 10^{-10}$	2.8×10^{-10}	Czarnecki *et al.* [71]
D11	$A_r(^{28}Si)$	27.976 926 534 42(55)	2.0×10^{-11}	AME 2020 [73]
D14	$A_r(^2H)$	2.014 101 777 844(15)	7.4×10^{-12}	AME 2020 [73]
D15	$\Delta E_B(^2H^+)/hc$	$1.097\,086\,145\,529\,9(10) \times 10^7\ m^{-1}$	9.1×10^{-13}	NIST ASD 2021 [62]
D19	$A_r(^1H)$	1.007 825 031 898(14)	1.4×10^{-11}	AME 2020 [73]
D23	$\Delta E_B(^{12}C^{6+})/hc$	— — —	— — —	— — —
E1	$\nu_{HD^+}((0,0)-(0,1))$	1 314 925 752.910(17) kHz	1.3×10^{-11}	Alighanbari *et al.* [33]
E2	$\nu_{HD^+}((0,0)-(1,1))$	58 605 052 164.24(86) kHz	1.5×10^{-11}	Kortunov *et al.* [35]
E3	$\nu_{HD^+}((0,3)-(9,3))$	415 264 925 501.8(1.3) kHz	3.1×10^{-12}	Patra *et al.* [34] + Germann *et al.* [14]
G1	$\nu_{\bar{p}^4He}((32,31)-(31,30))$	1 132 609 226.7(4.0) MHz	3.5×10^{-9}	Hori *et al.* [37]
G2	$\nu_{\bar{p}^4He}((33,32)-(31,30))$	2 145 054 858(7) MHz	3.4×10^{-9}	Hori *et al.* [36]
G3	$\nu_{\bar{p}^3He}((32,31)-(31,30))$	1 043 128 581(6) MHz	6.2×10^{-9}	Hori *et al.* [37]
G4	$\nu_{\bar{p}^3He}((35,33)-(33,31))$	1 553 643 100(10) MHz	6.7×10^{-9}	Hori *et al.* [36]
I1	$E_{LS}(\mu^4He)$	1378.521(48) meV	3.5×10^{-5}	Krauth *et al.* [78]
I2	$E_{LS}(\mu^3He)$	1258.586(49) meV	3.9×10^{-5}	Krauth [79]

Benchmark NP models

Dark photon $\mathcal{L}_{\text{int}} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

$$\alpha_\phi = \alpha\epsilon^2$$
$$q_\ell = -q_p = -1$$
$$q_n = 0$$

U(1)$_{\text{B-L}}$ $\alpha_\phi = g^2_{\text{B}-\text{L}}/4\pi$

$$q_\ell = -q_p = -1$$
$$q_n = 1$$ ← highlights deuterium

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$\alpha_\phi = \alpha\epsilon^2$

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Higgs portal $\alpha_\phi = \sin\theta^2 m_e \kappa_p m_p/(4\pi v^2)$

$\kappa_p = 0.306(14),\ \kappa_n = 0.308(14)$ ← from nucleon form-factors

$q_\ell = m_\ell/\sqrt{m_e \kappa_p m_p}$ ← larger effects in muonic atoms and molecules

$q_{p,n} = \kappa_{p,n} m_{p,n}/\sqrt{m_e \kappa_p m_p}$

Hadrophilic scalar

$\alpha_\phi = \sin\theta^2 m_e \kappa_p m_p/(4\pi v^2)$

$q_\ell = 0$ ← highlights molecules

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$q_\ell = 0$ ← highlights molecules

$$q_{p,n} = \kappa_{p,n} m_{p,n}/\sqrt{m_e \kappa_p m_p}$$

Up-Lepto-Darko-philic (ULD) scalar $\alpha_\phi = k^2 m_e \kappa'_p m_p/(4\pi v^2)$

$$q_\ell = m_\ell/\sqrt{m_e \kappa'_p m_p},\ q_{p,n} = \kappa'_{p,n} m_{p,n}/\sqrt{m_e \kappa'_p m_p}$$

$\kappa'_p = 0.018(5),\ \kappa'_n = 0.016(5)$ ← couples *only* to up-quark

+ dominant ϕ decay to invisible states *(see later)*

The light vector case

inverse Bohr radius

Vectors with $m_\phi \ll \alpha m_e \simeq 4\,\mathrm{keV}$ induce a long-range force

Then, effects are suppressed for couplings aligned with QED ($q_i \simeq Q_i$) because:

$$\mathcal{L}_{\mathrm{QED}}(\alpha) + \mathcal{L}_{A'_\mu}(\alpha', m_{A'} \to 0) \to \mathcal{L}_{\mathrm{QED}}(\alpha + \alpha')$$

massless dark photon is unobservable!

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inverse Bohr radius

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massless dark photon is unobservable!

This behavior is only manifest for $\mathcal{O}_{\mathrm{NP}}(\alpha')$ and $\mathcal{O}_{\mathrm{SM}}(\alpha)$ calculated at the *same* order in couplings. Otherwise:

$$\mathcal{O} \to \mathcal{O}_{\mathrm{SM}}^{\mathrm{LO}}(\alpha + \alpha') + \mathcal{O}_{\mathrm{SM}}^{\mathrm{NLO}}(\alpha)$$

would distinguish the photon from massless DP

The light vector case

inverse Bohr radius

Vectors with $m_\phi \ll \alpha m_e \simeq 4\,\mathrm{keV}$ induce a long-range force

Then, effects are suppressed for couplings aligned with QED ($q_i \simeq Q_i$)

Instead, we use a simple *prescription*:

$$V_{\rm NP}^{ij} = \alpha_\phi \frac{Q_i Q_j}{r} + \tilde{V}_{\rm NP}^{ij} \quad \text{with} \quad \tilde{V}_{\rm NP}^{ij} \equiv \alpha_\phi (q_i q_j e^{-m_\phi r} - Q_i Q_j)/r$$

included to all orders by shifting $\alpha \to \alpha + \alpha_\phi$ in $\mathcal{O}_{\rm SM}$

deviations from either $m_\phi \neq 0$ or $q_i \neq Q_i$ can be treated as perturbations at LO

The light vector case

inverse Bohr radius

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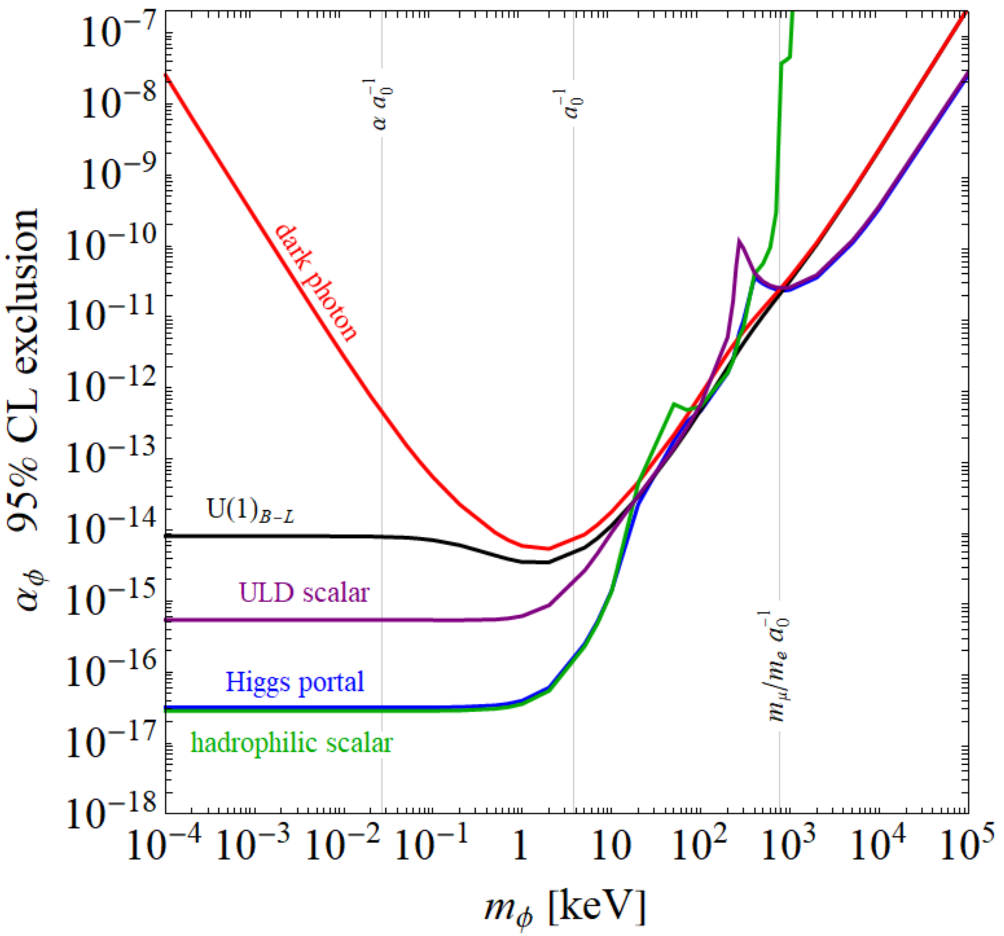
included to all orders by shifting $\alpha \to \alpha + \alpha_\phi$ in $\mathcal{O}_{\rm SM}$

deviations from either $m_\phi \neq 0$ or $q_i \neq Q_i$ can be treated as perturbations at LO

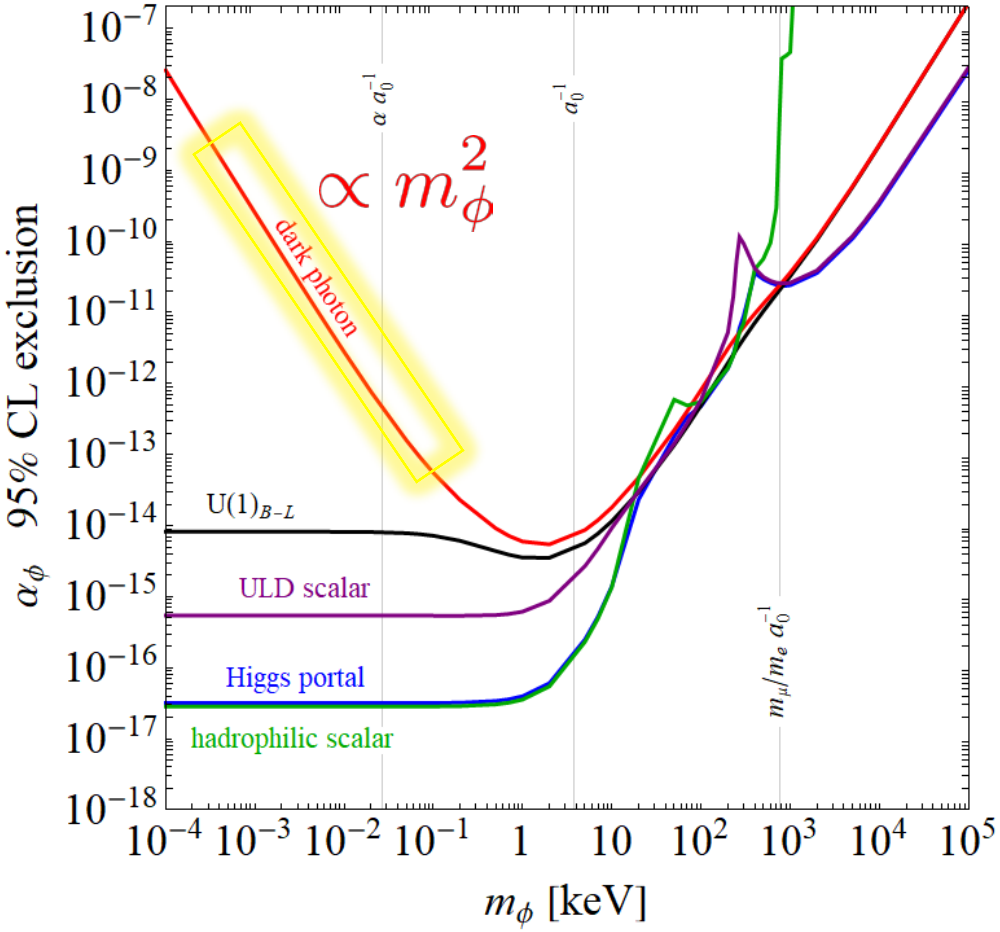
Hence: $\mathcal{O} = \mathcal{O}_{\rm SM}(\alpha + \alpha_\phi) + \tilde{\mathcal{O}}_{\rm NP}(\alpha + \alpha_\phi, \alpha_\phi, m_\phi) + \delta\mathcal{O}_{\rm th}$

$\propto m_\phi^2$ or $\delta q_i Q_j + Q_i \delta q_j$

CODATA as a new physics search

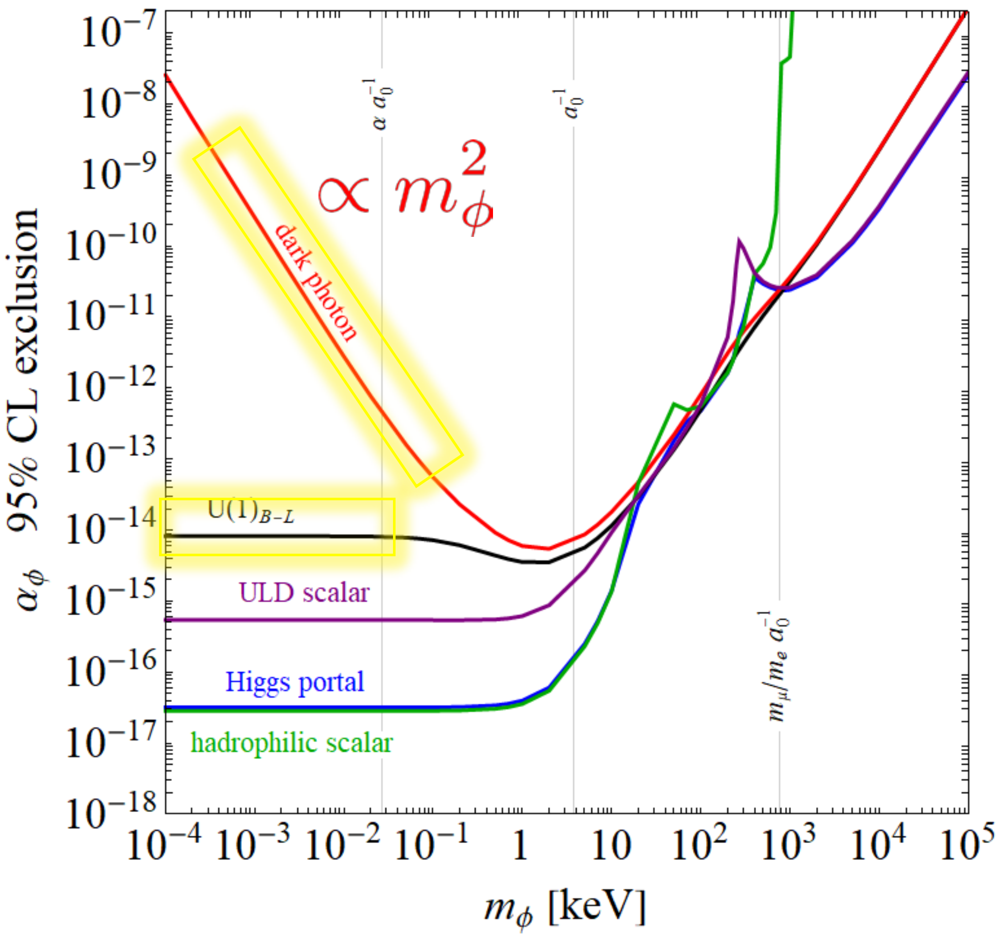


CODATA as a new physics search



CODATA as a new physics search

$\propto m_\phi^0$ thanks to Deuterium data

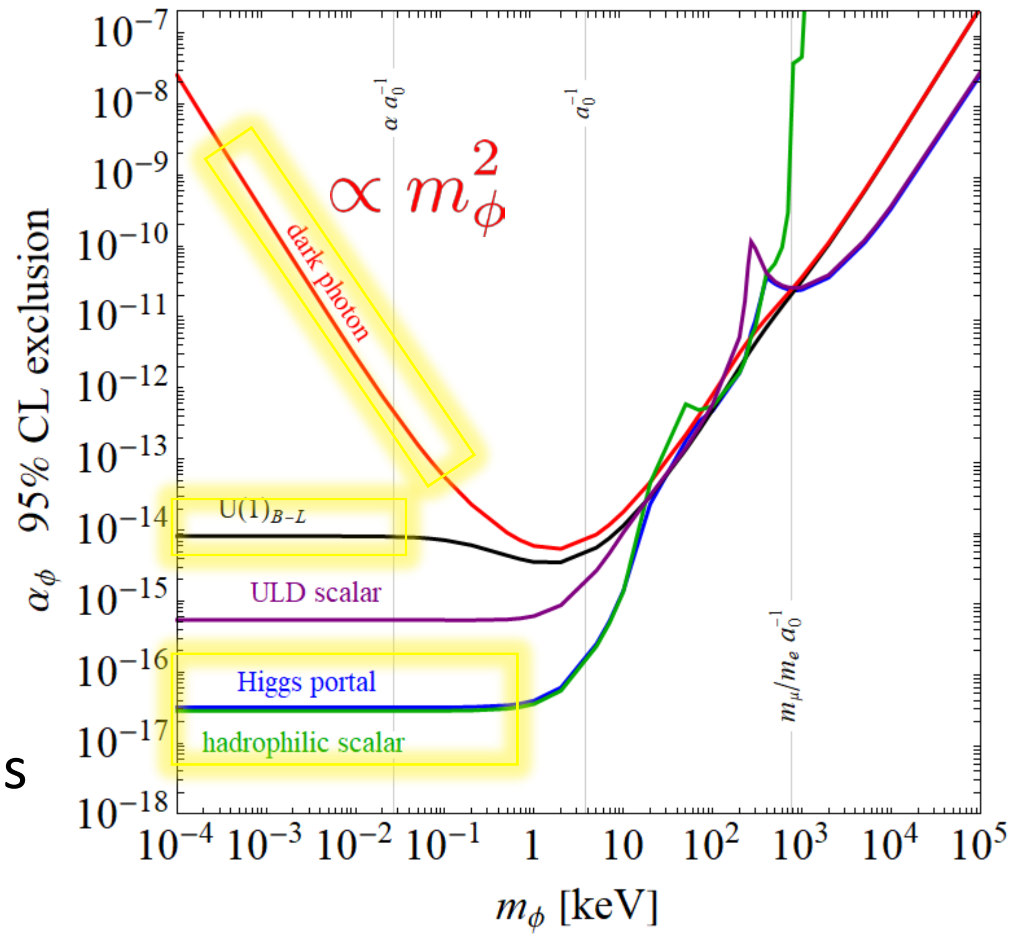


CODATA as a new physics search

$\propto m_\phi^0$ thanks to Deuterium data

stronger sensitivity from internuclear forces in molecules in models where

$$q_N/q_e \sim m_N/m_e \sim 10^3$$



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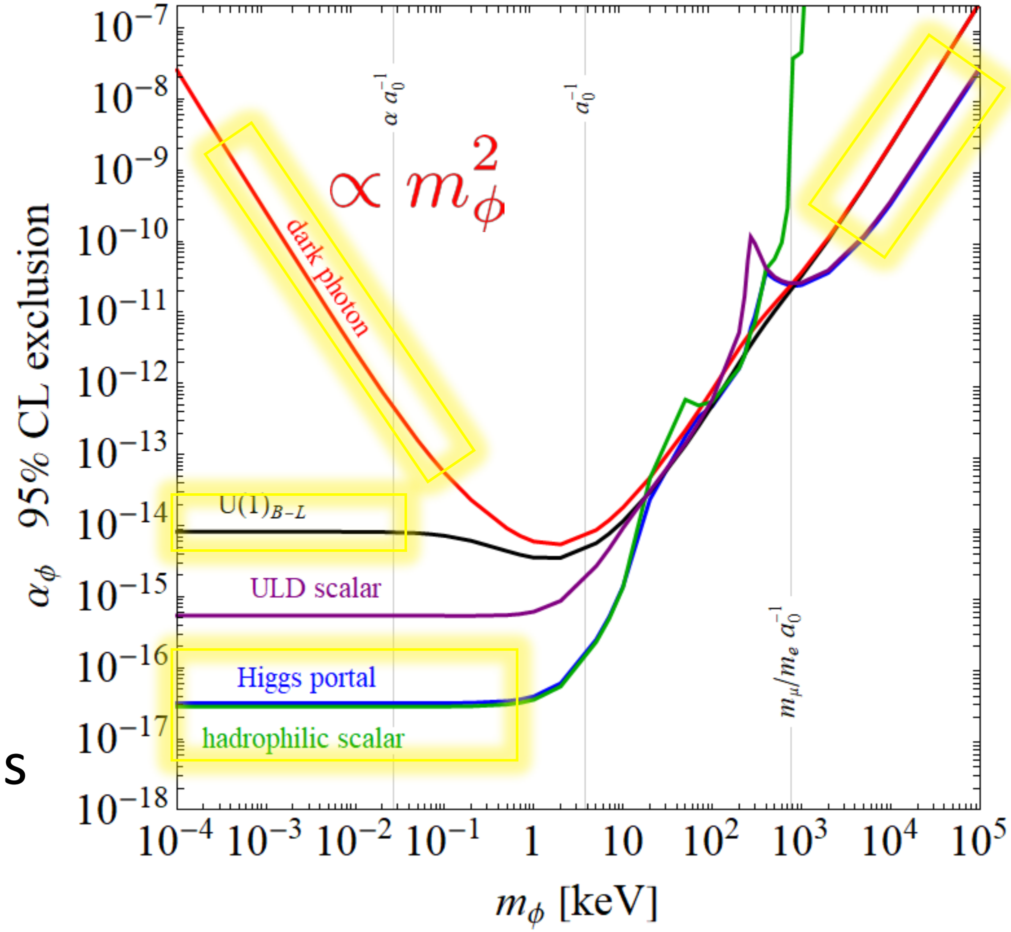

stronger sensitivity from muonic atoms in models where

$$q_\mu/q_e \sim m_\mu/m_e \sim 200$$

stronger sensitivity from internuclear forces in molecules in models where

$$q_N/q_e \sim m_N/m_e \sim 10^3$$

CODATA as a new physics search

$\propto m_\phi^0$ thanks to Deuterium data

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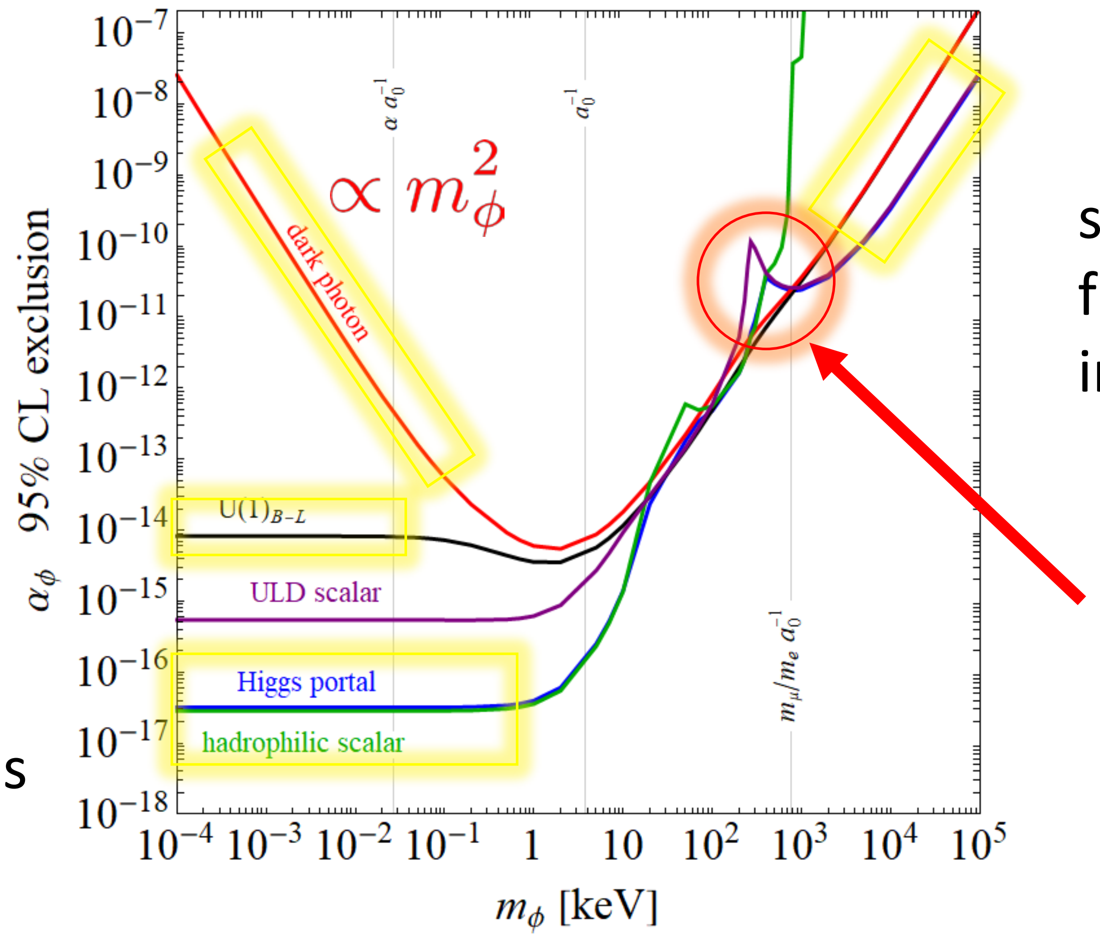
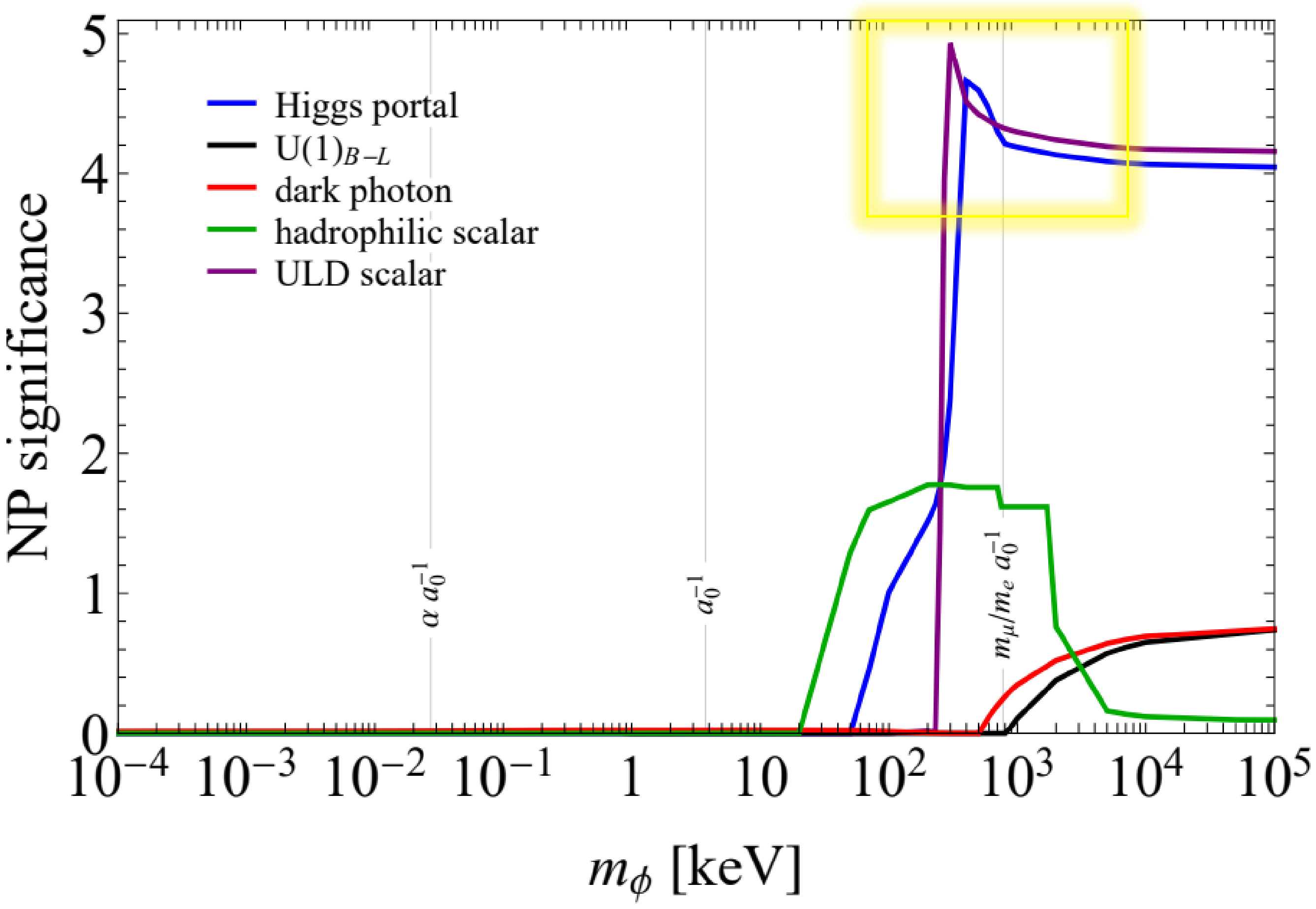


stronger sensitivity from muonic atoms in models where

$q_\mu/q_e \sim m_\mu/m_e \sim 200$

Data *favors* $\alpha_\phi \neq 0$ for Higgs portal and ULD scalars

New physics significance $= \sqrt{\chi^2_{\rm SM}/\nu_{\rm dof} - \chi^2_{\rm NP}/\nu_{\rm dof}}$

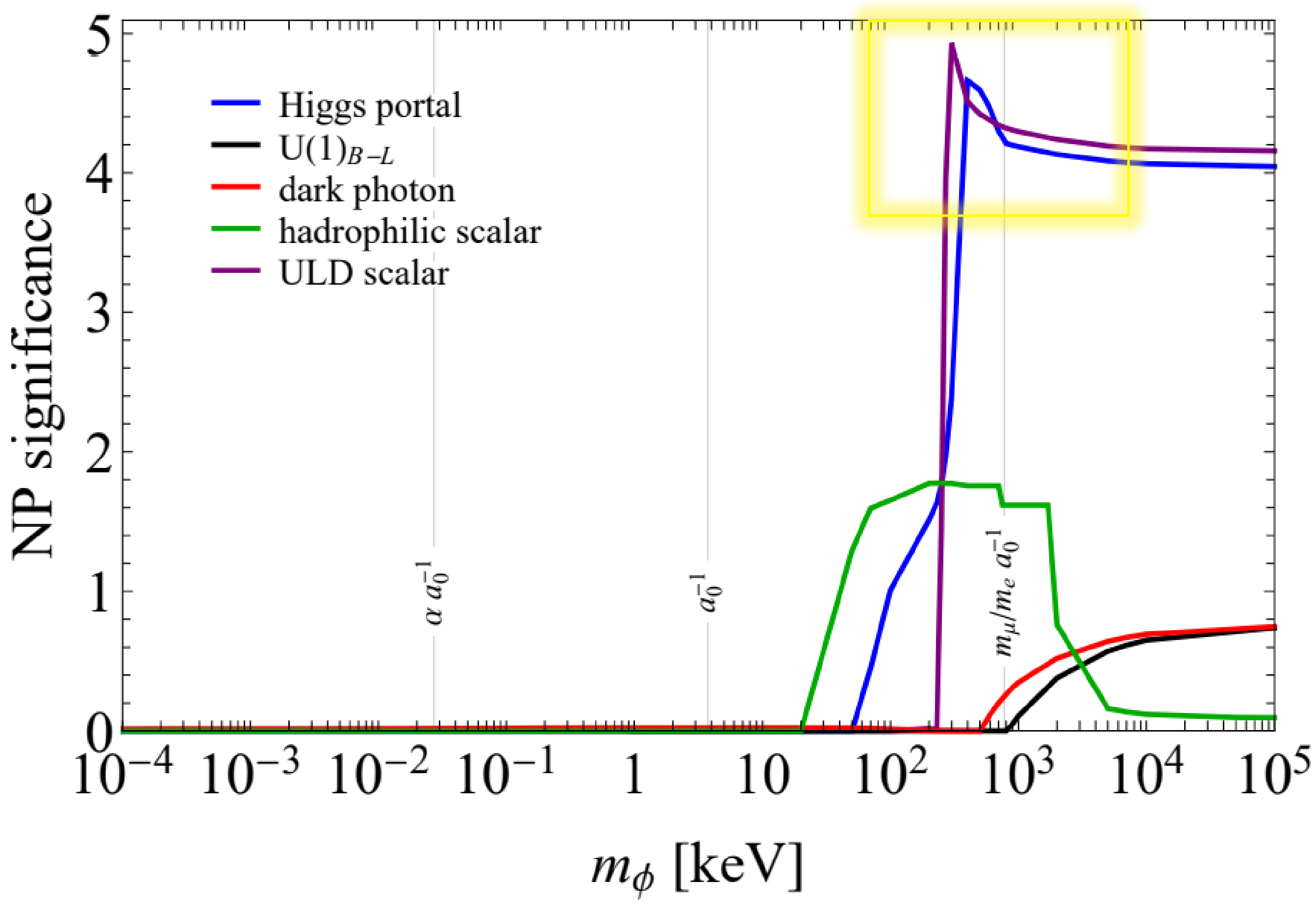


$\sim 4.5\sigma$ pull

for scalar masses around

$300 - 600\,\mathrm{keV}$

New physics significance $= \sqrt{\chi^2_{\rm SM}/\nu_{\rm dof} - \chi^2_{\rm NP}/\nu_{\rm dof}}$



$\sim 4.5\sigma$ pull

for scalar masses around

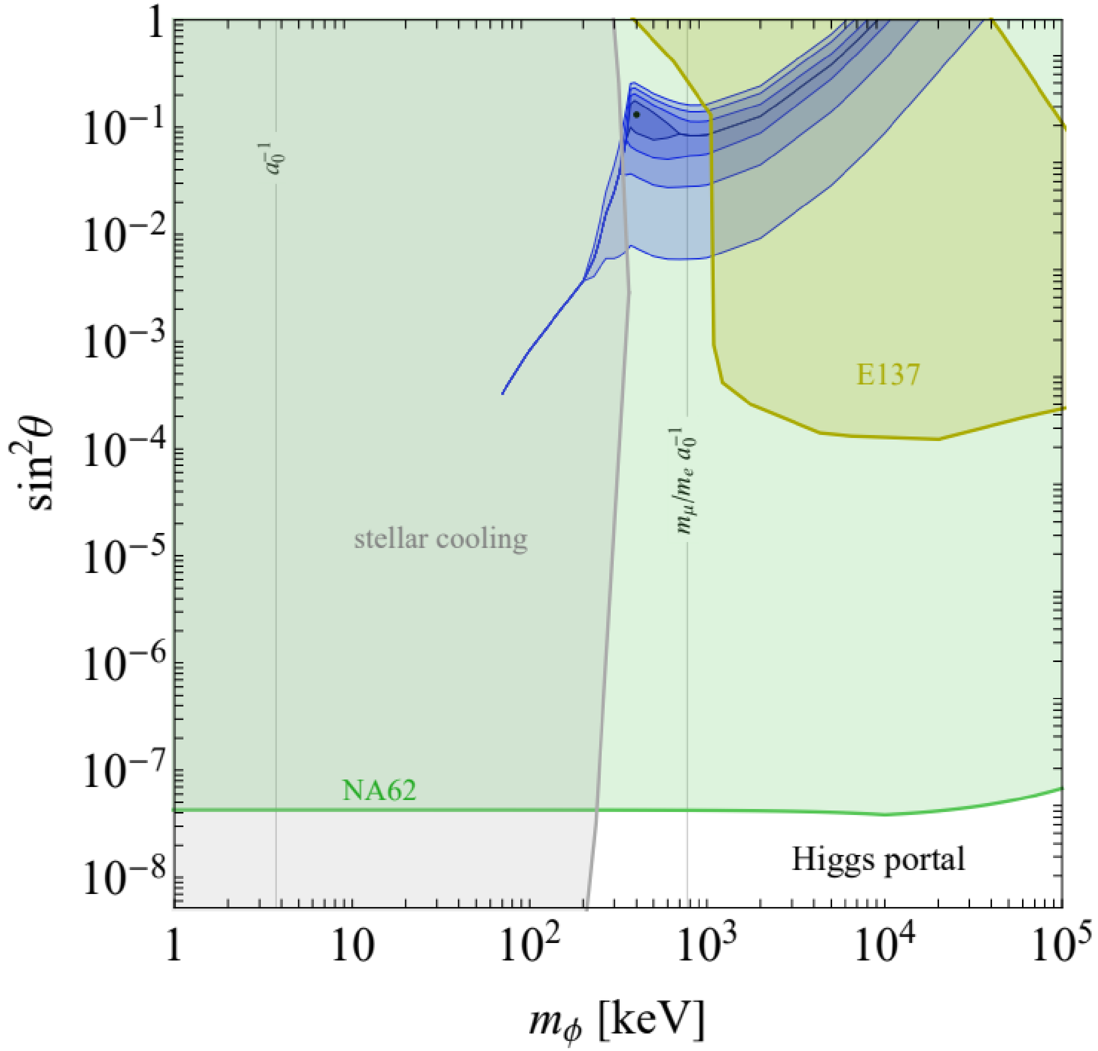
$300 - 600\,\mathrm{keV}$

solving several tensions between data and SM with a *single* NP state:

- g_e-2 vs. atomic recoil $\sim 2\sigma$
- μH vs. H (w/in CODATA18) $\sim 3\sigma$
- CODATA18 vs. H 2S-8D $\sim 3\sigma$

Brandt et al. [2022]

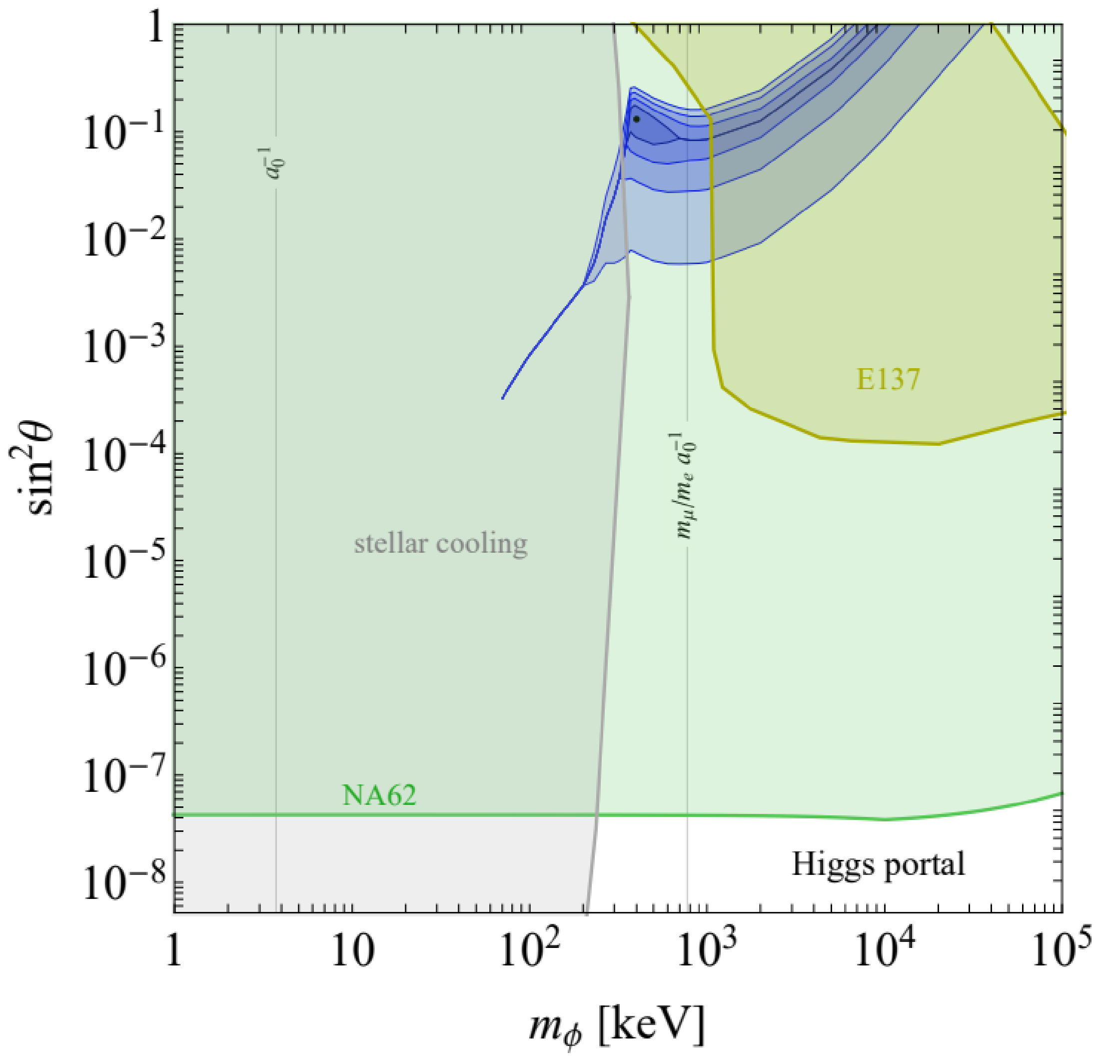
Non-zero Higgs Portal?



Best-fit point $\begin{array}{l} \sin\theta \simeq 0.35 \\ m_\phi \simeq 400\,\mathrm{keV} \end{array}$

is largely excluded by $K^+ \to \pi^+ X_{\rm inv}$ searches

Non-zero Higgs Portal?



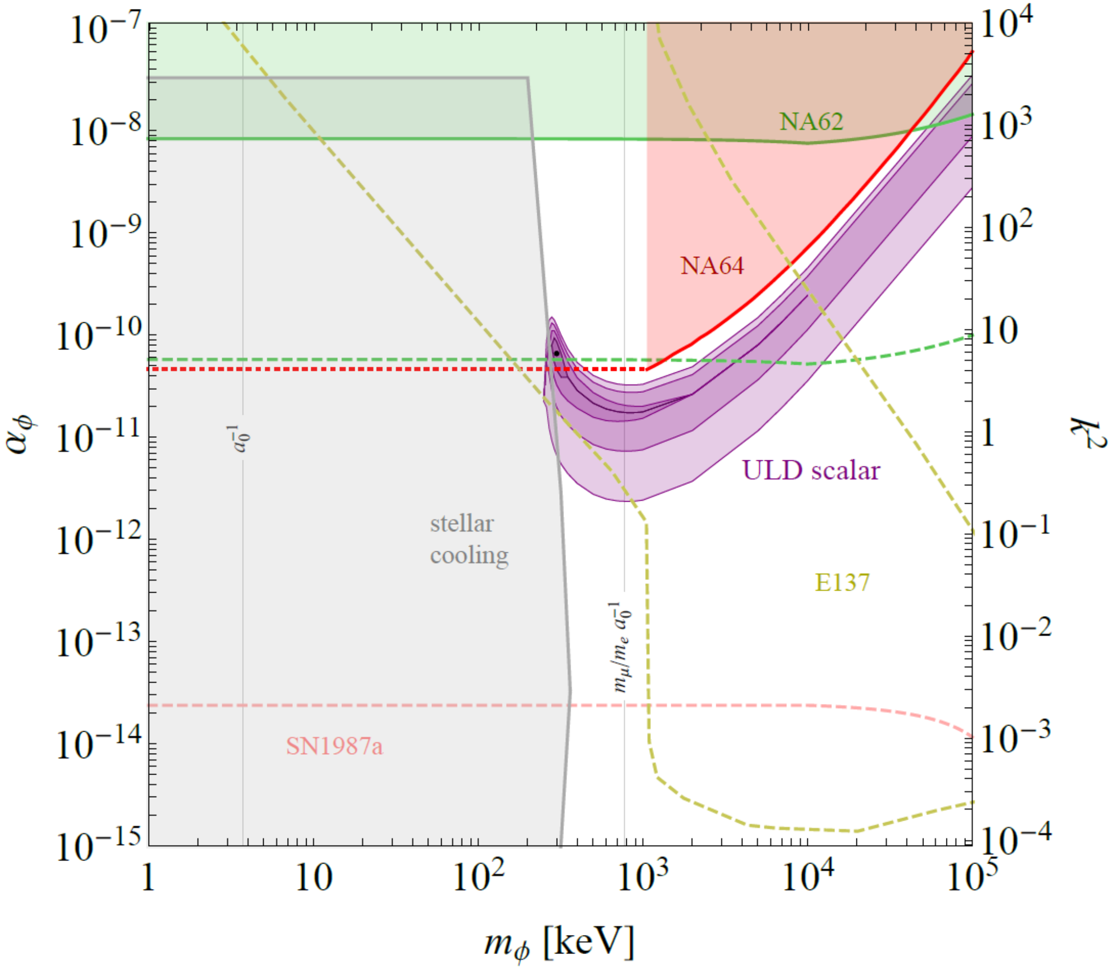
Best-fit point $\begin{array}{l} \sin\theta \simeq 0.35 \\ m_\phi \simeq 400\,\mathrm{keV} \end{array}$

is largely excluded by $K^+ \to \pi^+ X_{\rm inv}$ searches

The NA62 bound is driven by coupling to heavy quarks through one-loop penguins

The E137 beam-dump bound relies on scalars dominantly decaying to $\phi \to e^+ e^-$

Evidence for a ULD-philic scalar?



Best-fit point $\alpha_\phi \simeq 6.7 \times 10^{-11}$, $m_\phi \simeq 300\,\mathrm{keV}$

evades the NA62 bound by coupling only to up quarks

The E137 bound does not apply assuming invisible decay dominantes ($\phi \to \mathrm{DMDM}$?)

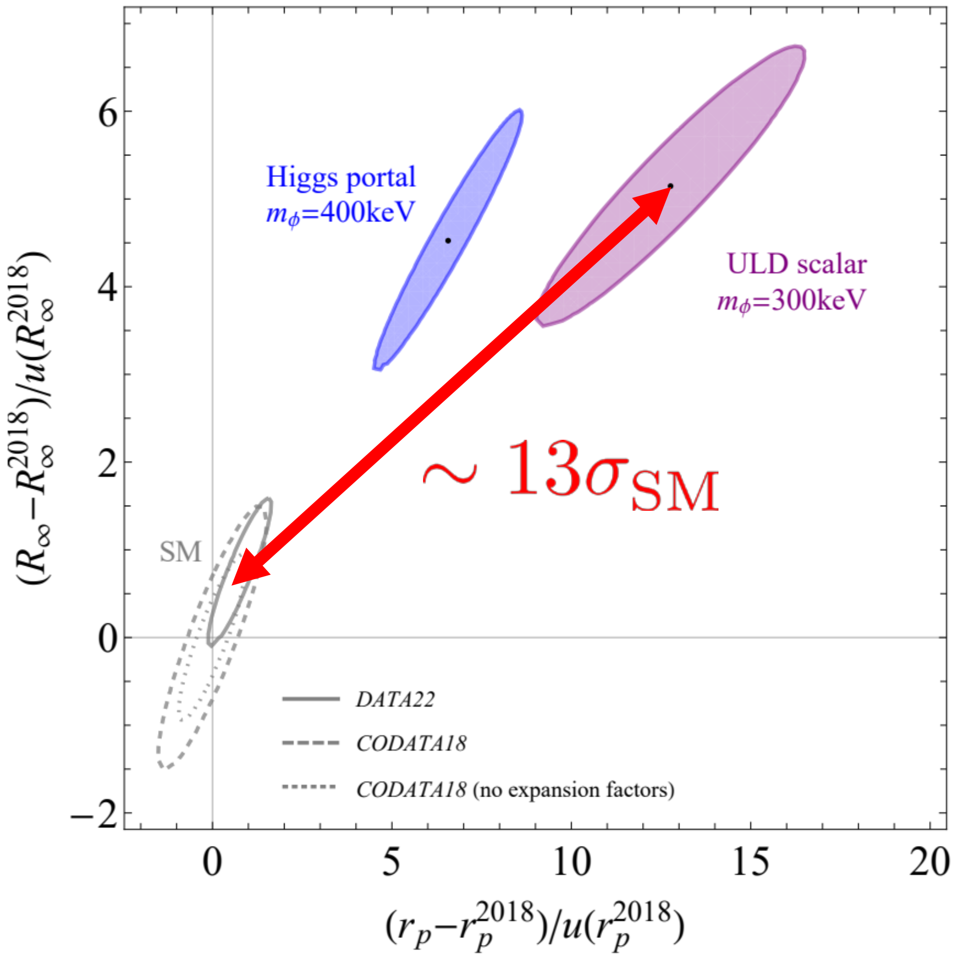
In that case NA64 is relevant

$$e^- Z \to e^- Z \phi$$

Andreev et al. [2021]

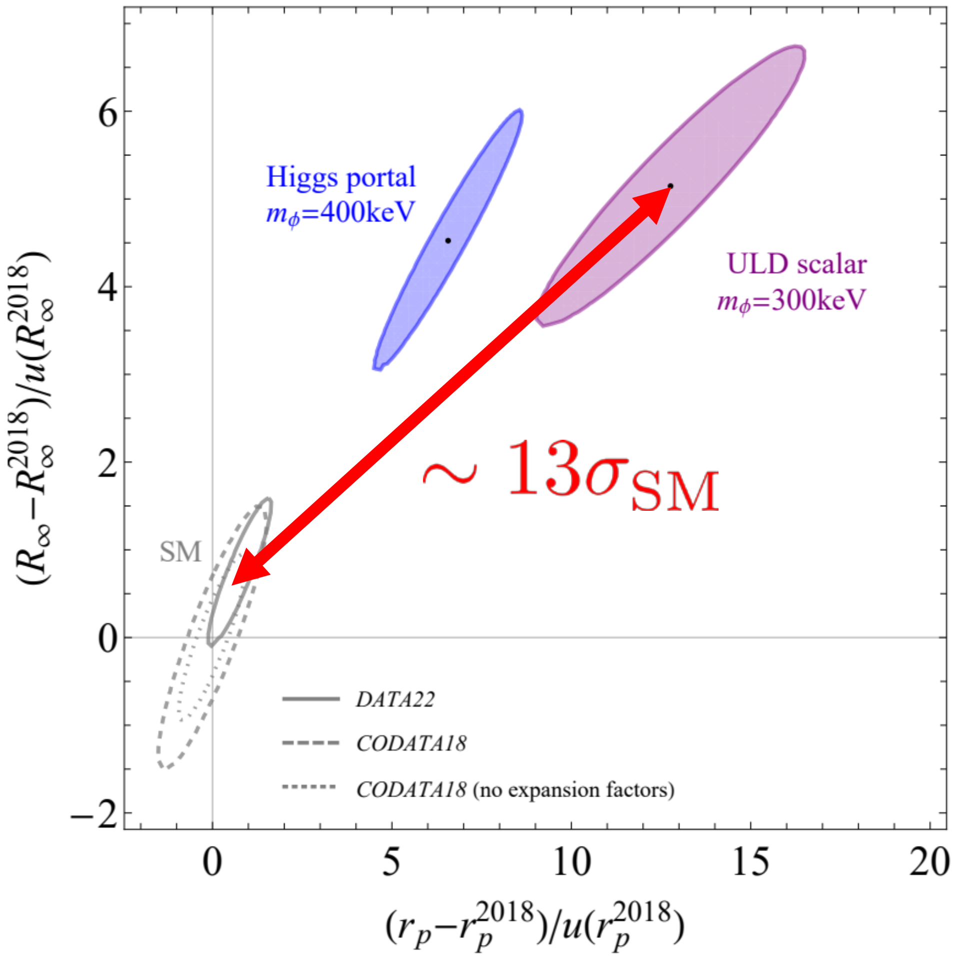
yielding a weaker bound but NP sensitivity not clear below MeV

Impact on fundamental constants



FCs can undergo huge shifts in the presence of NP

Impact on fundamental constants



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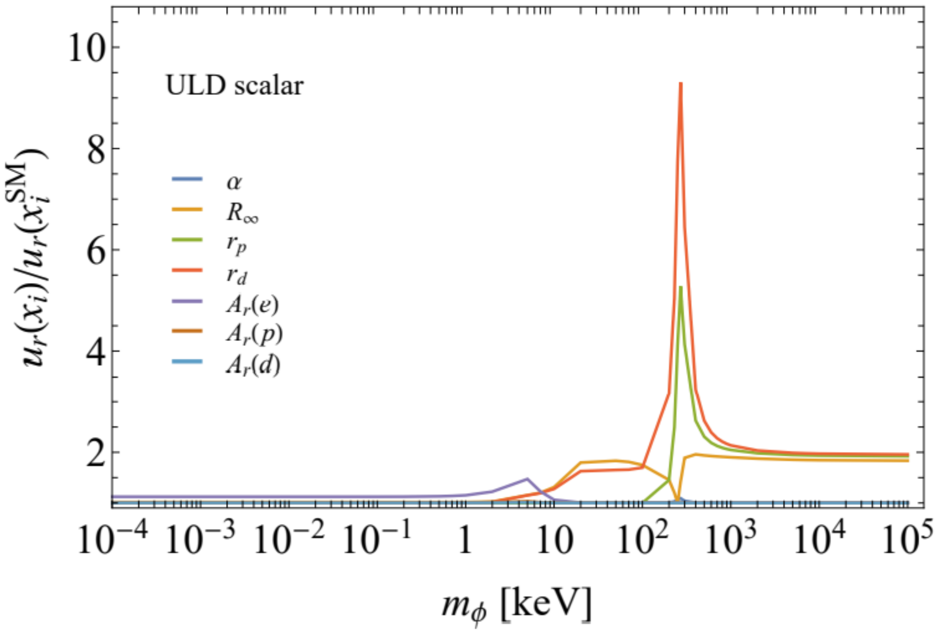

and their uncertainty *significantly* inflates relative to the SM-only hypothesis

Do we truly know α?

The fine-structure constant is determined
from keV-scale observables (hydrogen lines + atomic recoil)…

…which could hide the presence of
a dark photon with $m_{A'} \ll \mathrm{keV}$

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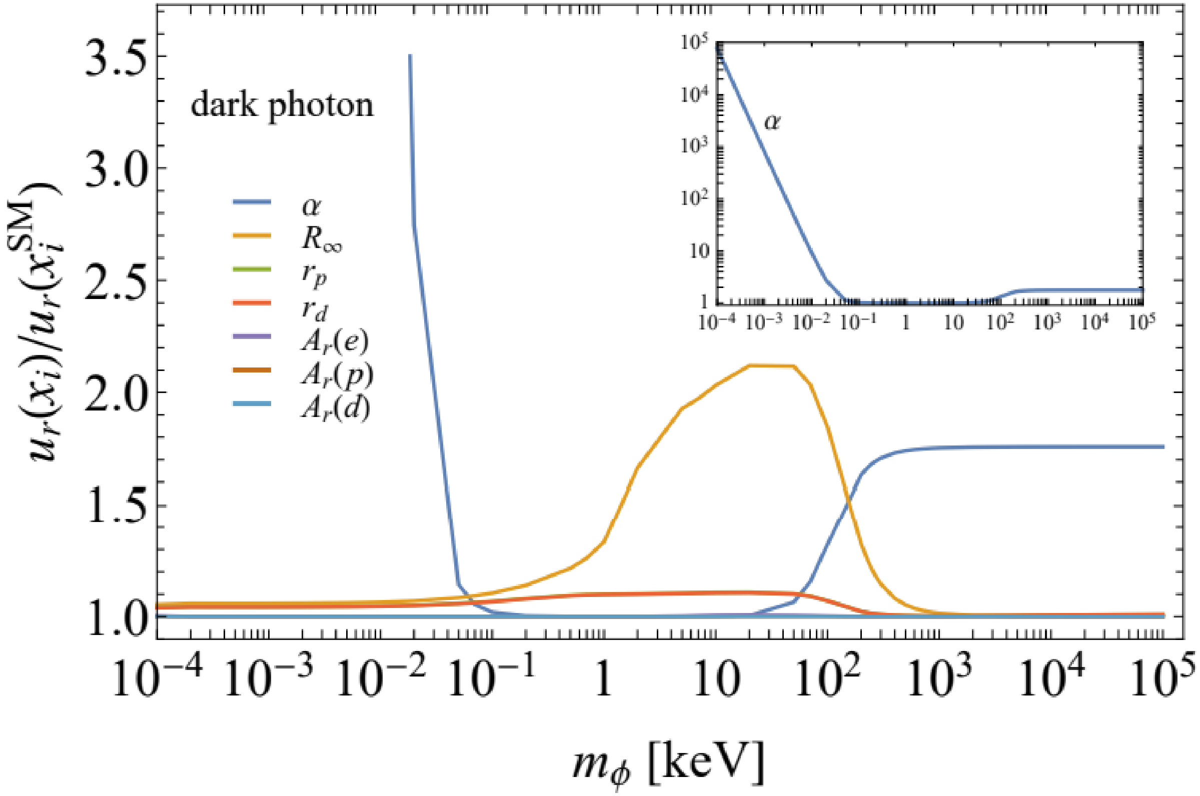

…which could hide the presence of a dark photon with $m_{A'} \ll \mathrm{keV}$

As a result, only $\alpha + \alpha'$ is well determined

$$u_r(\alpha + \alpha') \sim u_r^{\mathrm{SM}}(\alpha) \sim 10^{-10}$$

and α alone is poorly known…

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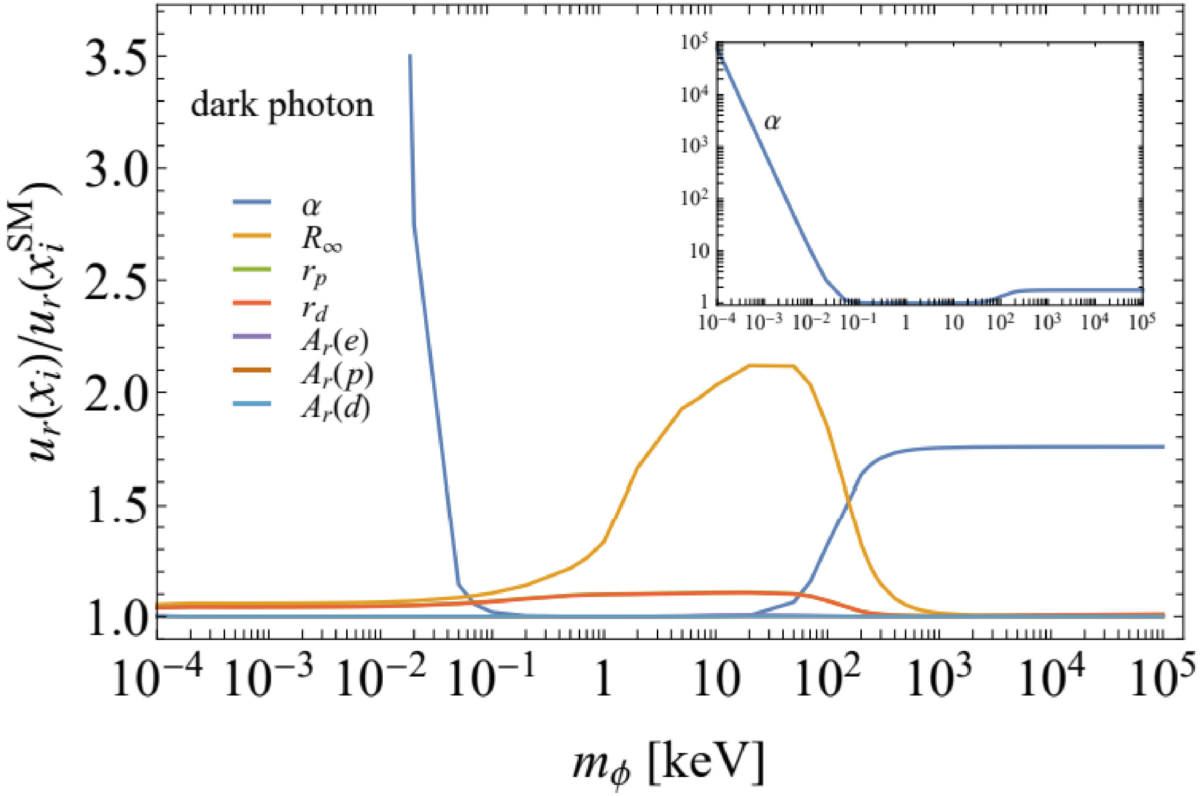

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($u_r^{\max}(\alpha) \sim 1$ for $m_{A'} \lesssim 10\,\mathrm{meV}$)

Conclusions

- Muonium could provide a new measurement of a_μ at $\sim 1\,\mathrm{ppm}$
  - Improved measurements coming up (Mu-MASS@PSI+MuSEUM@JPARC)
  - This requires completing the 3-loop QED calculation in Mu (underway)

- Fundamental constants are affected by light NP states
  - We proposed a consistent way to modify the CODATA adjustment
  - This turns high-precision spectroscopy into a new sensitive search for NP!
  - Interesting interplay with kaon physics (work in progress)

backups

Improving 1S-2S measurement

The 1S-2S is a two-photon transition ($\Delta L = 0$) with low excitation efficiency.

To increase the transition probability, a high-power pulsed laser was used in previous experiments. The price to pay was a broadening of the linewidth from $\simeq 145\,\mathrm{kHz}$ (muon lifetime) to $\sim 20\,\mathrm{MHz}$ and an extra $\sim 10\,\mathrm{MHz}$ systematic uncertainty from « chirping »

The Mu-MASS experiment at PSI proposed to circumvent this limitation by using cavity-enhanced continuous-wave excitation, together with an intense low-energy muon beam, thus planning to reduce the 1S-2S uncertainty to $\sim 10\,\mathrm{kHz}(4\mathrm{ppt})$ [Crivelli Hyperfine Interact. 2018]

This could be further reduced to $\sim \mathrm{few\,kHz}$ after the High-Intensity Muon Beam upgrade at PSI

[Kiselev et al. J-PARC symbosium 2019]

Improving HFS measurement

The a_μ^{Mu} uncertainty can be further reduced by improving the HFS measurement

Previous measurements at LAMPF were statistics limited.
The MuSEUM experiment using a high-intensity pulsed muon beam at J-PARC
is expected to bring down the statistics uncertainty to $\sim 10\,\mathrm{Hz}(2.2\mathrm{ppb})$ [Tanaka et al. 2021]

A reduction of systematics is also needed at this level of uncertainty.
The dominant one is due to pressure shift from the finite gas density in the experiment. [Kanda et al. 2021]
which could be reduced by measuring the HFS in vacuum or in a gas admixture with opposite shifts.

Further improvements are <u>*very*</u> challenging.
A $10\,\mathrm{Hz}$ uncertainty already requires resolving the line to 10^{-4} of the linewidth (from muon decay),
only done once in spectroscopy: the 2S-4P transition in hydrogen [Beyer et al. Science 2017]

The linewidth can be reduced by selecting the « old muonium » tail (if statistics is high enough)
which could bring down the HFS uncertainty to $\sim 4\,\mathrm{Hz}(1\mathrm{ppb})$

Improving 1S-2S theory

Once experimental uncertainty is down to $\sim \text{few kHz}$, the theory must be improved by a factor ~ 10

The main theory uncertainty comes from the uncalculated radiative-recoil terms at three-loop QED of $\mathcal{O}[(m_e/m_\mu)\alpha(Z\alpha)^6]$

There is extra insentive to calculate them:
Once the proton radius puzzle is fully resolved,
such terms will become the limiting factor
to further improvements of R_∞ in hydrogen.

Subleading uncertainty from uncalculated recoil terms of $\mathcal{O}[(m_e/m_\mu)^2(Z\alpha)^6]$ at three-loop QED should also be reduced.

R_∞ should also improve by a factor few.
The QED uncertainty in hydrogen was recently reduced to $\sim 1\,\text{kHz}$ [Karshenboim et al. PLB 2019]
meaning that a three-fold improvement
is already possible relative to CODATA 2018.

All of the above would then allow to determine
the electron-muon mass ratio to $\sim 0.37\text{ppb}$
thus making it a subleading source of uncertainty for a_μ^{Mu}

Improving HFS theory

The HFS theory should improve in the meantime by a factor ~ 20.

To this level the uncertainty is only limited by uncalculated terms in QED.
(The HVP uncertainty is $\sim 1\,\mathrm{Hz}$, still subdominant.)

The required QED calculation is currently being done, with a goal of $\sim \mathrm{few\,Hz}$. [Eides 2018]
This is motivated by the upcoming MuSEUM measurement,
aiming at a reduced uncertainty of m_e/m_μ and thus of a_μ in future Fermilab/J-PARC runs.

New physics contamination

The extraction of $a_\mu^{\rm Mu}$ from spectroscopy is somehow indirect
since it assumes that the muonium theory follows from QED.

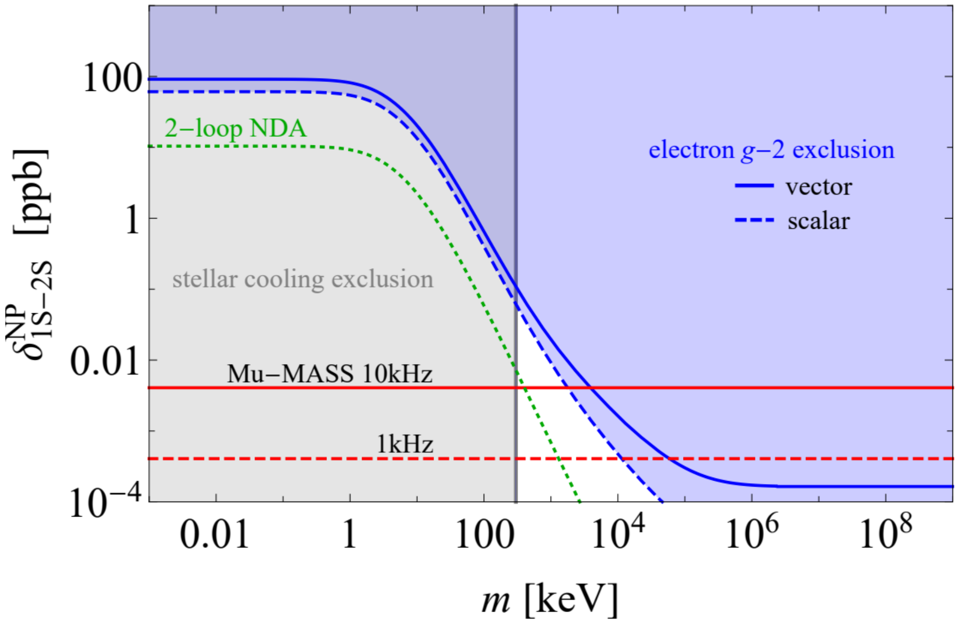
As one popular interpretation of the current puzzle
is the existence of new physics, an immediate question is:

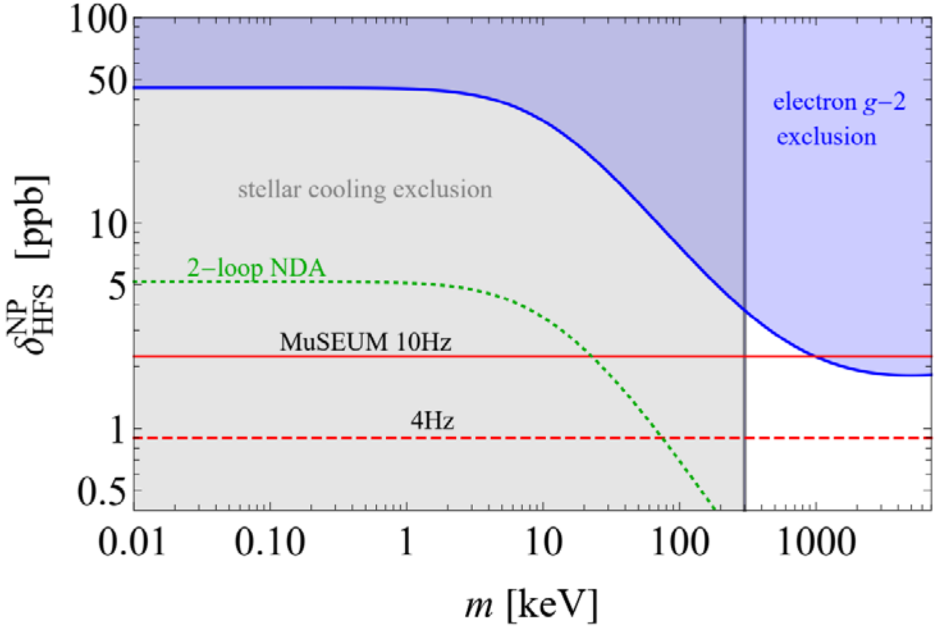
Could NP *contaminate* the muonium lines used to extract a_μ?

We addressed the question by assuming
the existence of the new boson (scalar or vector)
with a muon-coupling that resolves the muon g-2 puzzle
and a free coupling to electrons

If NP *only* to muons, muonium theory is *unchanged*.
An additional coupling to electrons is *constrained* by
the th/exp agreement for electron g-2,
and astrophysics from stellar cooling.

Maximal NP effects in muonium





Except a small range of NP mass around $\sim 1\text{MeV}$
possible NP effects are sufficiently constrainted to below the expected Mu-MASS/MuSEUM uncertainty.