NEW PHYSICS SEARCHES FROM BELOW

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LAPTh

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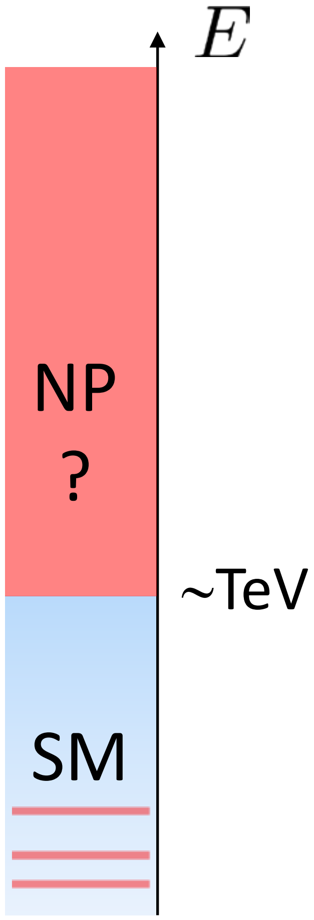
Usual Paradigm

Fundamental Physics at low energies is well known

New Physics states show up only at higher scales



However..

Light NP states could be hidden at low-energies

if very weakly coupled to the SM

Light New Physics Rationale

NP exists, indirectly discovered through $m_\nu, \eta_B, \Omega_{\rm DM}$ $\rightarrow$ What's the scale?

The Higgs sector and thermal DM point(*ed?*) to ~TeV scale NP
but no experimental evidence so far (from LHC and direct detection experiments)

The theory motivation for (much) lighter NP states is actually plenty:

- cosmological solutions to the hierarchy problem, *e.g.* relaxion
- approximate NP global symmetries, *e.g.* QCD axion and ALPs
- light (mediators for) non-thermal DM, *e.g.* DM freeze-in production
- …

This invites us to (re)consider NP signals at low-energy observables

Atomic Spectroscopy: A Precision Frontier

Today's accuracy of AMO experiments is very (very!) high:

18 digits with optical clocks!

BACON coll. (2020)

weak force $\sim \alpha m_e^2 G_F$

QED $\sim \alpha/4\pi$ correction

$$\nu_{\rm Yb}/\nu_{\rm Sr} = 1.207\ 507\ 039\ 343\ 337\ 8482(82)$$

$\Lambda \sim 100\,\mathrm{TeV}$ NP force

w/ $\mathcal{O}(1)$ coupling

If NP exists below $\Lambda \sim 100\,\mathrm{TeV}$

it *is* there somewhere in this number.

How to extract NP?

Nuclear finite size is a major obstacle to $m_{\rm NP} \gtrsim \Lambda_{\rm QCD} \simeq 200\,{\rm MeV}$

$$\nu_{\rm Yb}/\nu_{\rm Sr} = 1.207\ 507\ 039\ 343\ 337\ 8482($$

finite nuclear size

$\sim \alpha m_e/\Lambda_{\rm QCD}$

The range of NP interaction must be larger than nuclear size.

(NP interactions that breaks P and/or CP are well-known exceptions)

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Nuclear finite size is a major obstacle to $m_{\rm NP} \gtrsim \Lambda_{\rm QCD} \simeq 200\,{\rm MeV}$

~1/coupling

$$\nu_{\rm Yb}/\nu_{\rm Sr} = 1.207\,507\,039\,343\,337\,8482$$

MBPT theory uncertainty

$\sim \mathcal{O}(1\%)$

finite nuclear size

$\sim \alpha m_e/\Lambda_{\rm QCD}$

The range of NP interaction must be larger than nuclear size.

(NP interactions that breaks P and/or CP are well-known exceptions)

Many-body effects need to be precisely controlled for heavy atoms.

Two types of NP probes

Consider simple systems like H, μH, He or positronium, muonium less accurate but there precise calculation is possible → These observables are used to fix fundamental constants of the SM This is the CODATA* fit Light NP affects their determination « BSM CODATA » is required

Consider isotope shifts of clock transitions like Yb, Sr or Ca to cancel electron-electron interactions → Nuclear uncertainties are challenging They can be controlled in a systematic way by constructing King plots

* Committee on Data for Science and Technology

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BSM CODATA *

Light new particles affect the determination of fundamental constants

The precision hydrogen 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:

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

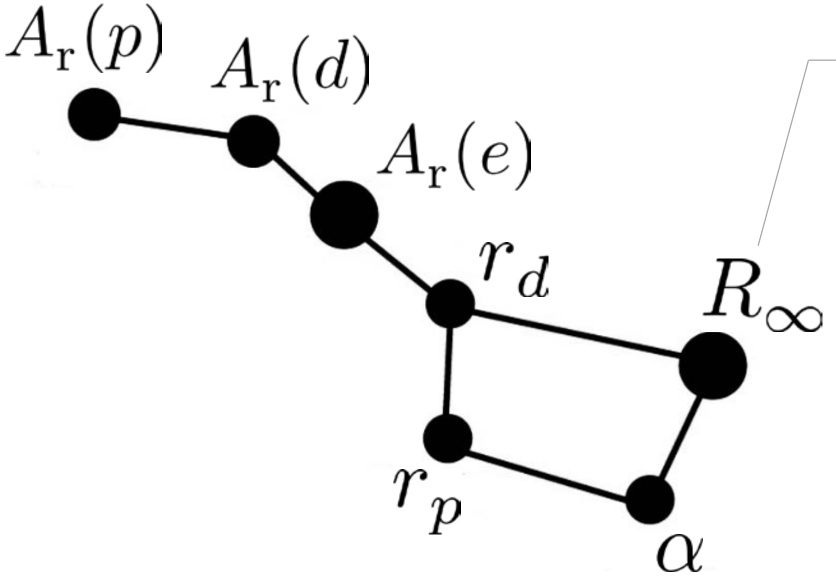
Tiesinga et al. [CODATA 2018]

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

most precisely known fundamental constant in physics!

A constellation of constants

R_∞ is *interconnected* with other constants



Rydberg constant

hydrogen $\nu_{1\mathrm{S}-2\mathrm{S}}$ (+22 other lines)

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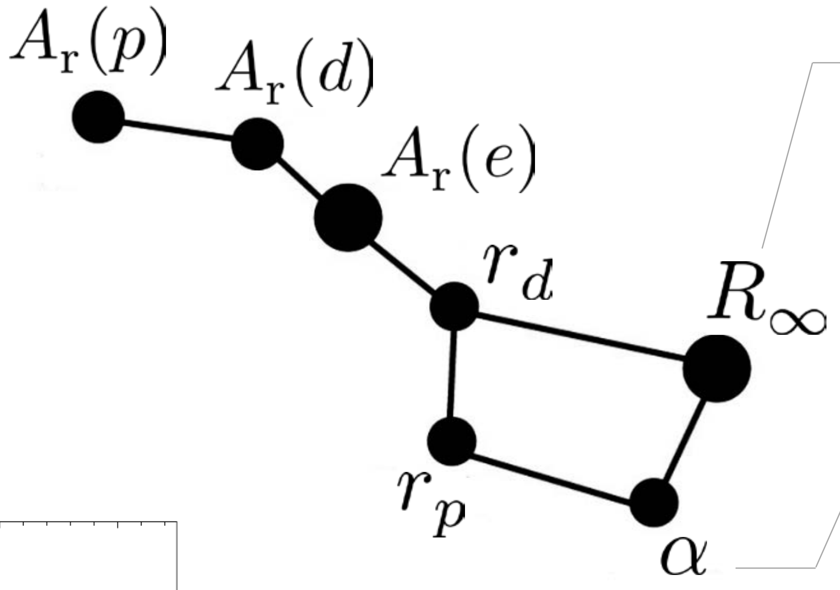


Rydberg constant

hydrogen ν_{1S-2S} (+22 other lines)

fine structure constant

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

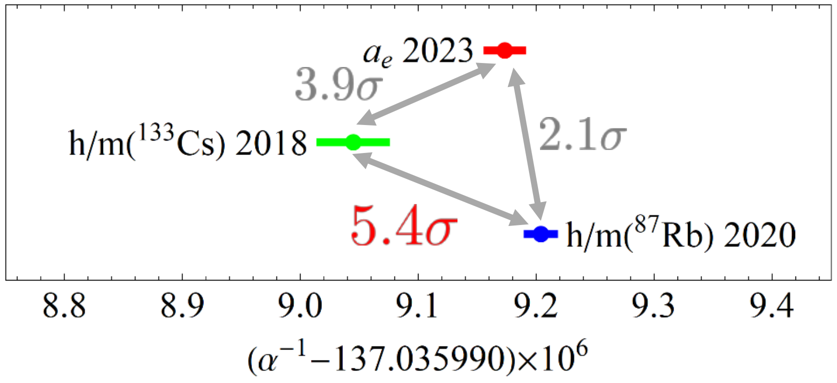
or atomic recoil

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

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

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

There are tensions…



A constellation of constants

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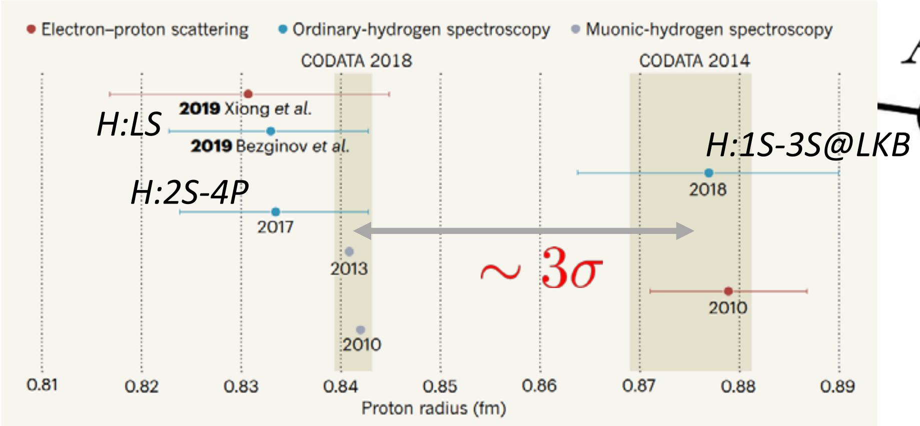
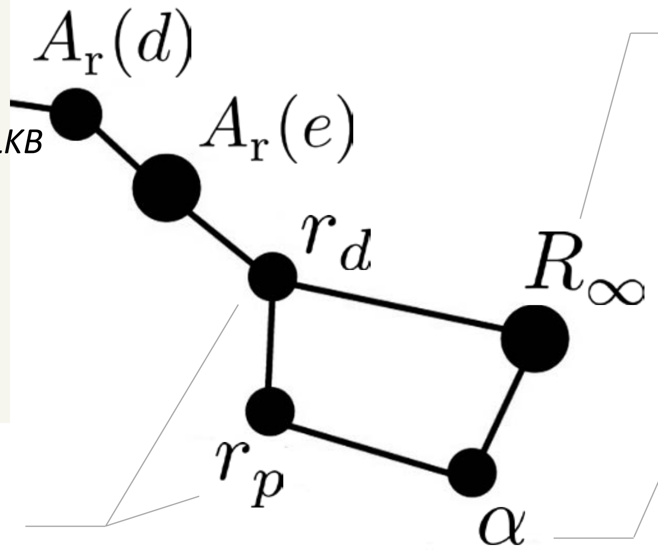
still a proton size puzzle…





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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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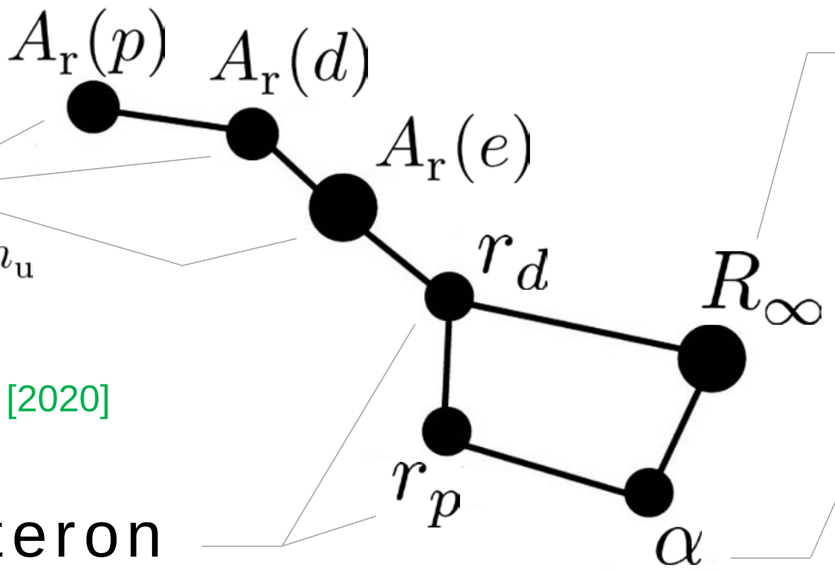

atomic mass constants

$m_X = A_r(X) m_u$

$[A_r(^{12}C) \equiv 12]$

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

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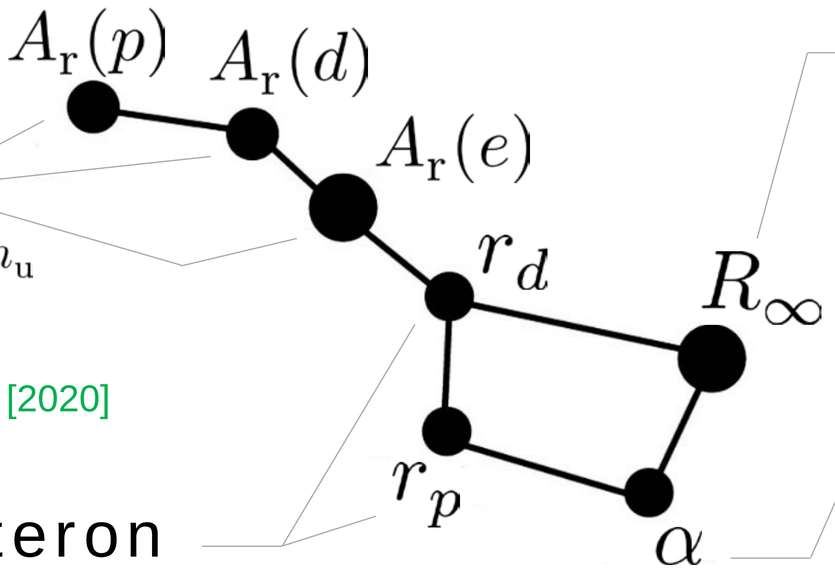

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to be determined together in a global fit

$\rightarrow$ 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! Is it robust to BSM?

CODATA with light new physics

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

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

ϕ scalar

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

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

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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One-loop correction to a_e

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

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Theoretical prediction for an observable $\mathcal{O}$:

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

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

evaluated @LO in α_ϕ

TH uncert.

Datasets

CODATA18

← used for validation

Hydrogen/Deuterium

Label	Input datum	Value (kHz)
A1	$\nu_{\rm H}(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	4 797 338(10)
A2	$\nu_{\rm H}(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	6 490 144(24)
A3	$\nu_{\rm D}(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_{\rm D}(1S_{1/2}-2S_{1/2})$	4 801 693(20)
A4	$\nu_{\rm D}(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_{\rm D}(1S_{1/2}-2S_{1/2})$	6 494 841(41)
A5	$\nu_{\rm D}(1S_{1/2}-2S_{1/2})-\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	670 994 334.606(15)
A6	$\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	2 466 061 413 187.035(1
A7	$\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	2 466 061 413 187.018(11
A8	$\nu_{\rm H}(1S_{1/2}-3S_{1/2})$	2 922 743 278 659(17)
A9	$\nu_{\rm H}(2S_{1/2}-4P)$	616 520 931 626.8(2.3)
A10	$\nu_{\rm H}(2S_{1/2}-8S_{1/2})$	770 649 350 012.0(8.6)
A11	$\nu_{\rm H}(2S_{1/2}-8D_{3/2})$	770 649 504 450.0(8.3)
A12	$\nu_{\rm H}(2S_{1/2}-8D_{5/2})$	770 649 561 584.2(6.4)
A13	$\nu_{\rm D}(2S_{1/2}-8S_{1/2})$	770 859 041 245.7(6.9)
A14	$\nu_{\rm D}(2S_{1/2}-8D_{3/2})$	770 859 195 701.8(6.3)
A15	$\nu_{\rm D}(2S_{1/2}-8D_{5/2})$	770 859 252 849.5(5.9)
A16	$\nu_{\rm H}(2S_{1/2}-12D_{3/2})$	799 191 710 472.7(9.4)
A17	$\nu_{\rm H}(2S_{1/2}-12D_{5/2})$	799 191 727 403.7(7.0)
A18	$\nu_{\rm D}(2S_{1/2}-12D_{3/2})$	799 409 168 038.0(8.6)
A19	$\nu_{\rm D}(2S_{1/2}-12D_{5/2})$	799 409 184 966.8(6.8)
A20	$\nu_{\rm H}(2S_{1/2}-6S_{1/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-3S_{1/2})$	4 197 604(21)
A21	$\nu_{\rm H}(2S_{1/2}-6D_{5/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-4S_{1/2})$	4 699 099(10)
A22	$\nu_{\rm H}(1S_{1/2}-3S_{1/2})$	2 922 743 278 678(13)
A23	$\nu_{\rm H}(1S_{1/2}-3S_{1/2})$	2 922 743 278 671.5(2.6)
A24	$\nu_{\rm H}(2S_{1/2}-4P_{1/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	4 664 269(15)
A25	$\nu_{\rm H}(2S_{1/2}-4P_{3/2})-\frac{1}{4}\nu_{\rm H}(1S_{1/2}-2S_{1/2})$	6 035 373(10)
A26	$\nu_{\rm H}(2S_{1/2}-2P_{3/2})$	9 911 200(12)
A27	$\nu_{\rm H}(2P_{1/2}-2S_{1/2})$	1 057 862(20)
A28	$\nu_{\rm H}(2P_{1/2}-2S_{1/2})$	1 057 845.0(9.0)
A29	$\nu_{\rm H}(2P_{1/2}-2S_{1/2})$	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	$h/m_{\rm Rb}(^{87}{\rm Rb})$	$4.591\,359\,272\,9(57)\ \times 10^{-9}\ {\rm m^2 s^{-1}}$	
D4	$h/m_{\rm Cs}(^{133}{\rm Cs})$	$3.002\,369\,472\,1(12)\ \times 10^{-9}\ {\rm m^2 s^{-1}}$	
D5	$A_{\rm r}(^{87}{\rm Rb})$	86.909 180 531 2(65)	
D6	$A_{\rm r}(^{133}{\rm Cs})$	132.905 451 961 0(86)	
D7	$\omega_{\rm s}/\omega_{\rm c}(^{12}{\rm C}^{5+})$	4376.210 500 87(12)	
D8	$\Delta E_{\rm B}(^{12}{\rm C}^{5+})/hc$	$43.563\,233(25)\ \times 10^{7}\ {\rm m^{-1}}$	
D9	$\delta_{\rm C}$	$0.0(2.5)\ \times 10^{-11}$	
D10	$\omega_{\rm s}/\omega_{\rm c}(^{28}{\rm Si}^{13+})$	3912.866 064 84(19)	
D11	$A_{\rm r}(^{28}{\rm Si})$	27.976 926 534 99(52)	
D12	$\Delta E_{\rm B}(^{28}{\rm Si}^{13+})/hc$	$420.6467(85)\ \times 10^{7}\ {\rm m^{-1}}$	
D13	$\delta_{\rm Si}$	$0.0(1.7)\ \times 10^{-9}$	
D14	$\omega_{\rm c}({\rm d})/\omega_{\rm c}(^{12}{\rm C}^{6+})$	0.992 996 654 743(20)	
D15	$\omega_{\rm c}(^{12}{\rm C}^{6+})/\omega_{\rm c}(p)$	0.503 776 367 662(17)	
D19	$A_{\rm r}(^{1}{\rm H})$	1.007 825 032 241(94)	
D21	$\Delta E_{\rm B}(^{1}{\rm H}^{+})/hc$	$1.096\,787\,717\,430\,7(10)\ \times 10^{7}\ {\rm m^{-1}}$	
D23	$\Delta E_{\rm B}(^{12}{\rm C}^{6+})/hc$	$83.083\,850(25)\ \times 10^{7}\ {\rm m^{-1}}$	

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	$E_{\rm LS}(\mu{\rm H})$	202.3706(23) meV	1.1×10^{-5}
C2	$E_{\rm LS}(\mu{\rm D})$	202.8785(34) meV	1.7×10^{-5}
C7	$\delta E_{\rm LS}(\mu{\rm H})$	0.0000(129) meV	6.4×10^{-5}
C8	$\delta E_{\rm LS}(\mu{\rm D})$	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

including post-CODATA18 improvements from

Hydrogen, HD+, pbar-He

μHe, g_e-2 and masses

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

Benchmark NP models

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

$q_\ell = -q_p = -1$

$q_n = 1$ ← highlights deuterium

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

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

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$q_n = 0$

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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

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

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

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

Up-Lepto-Darko-philic (ULD) scalar

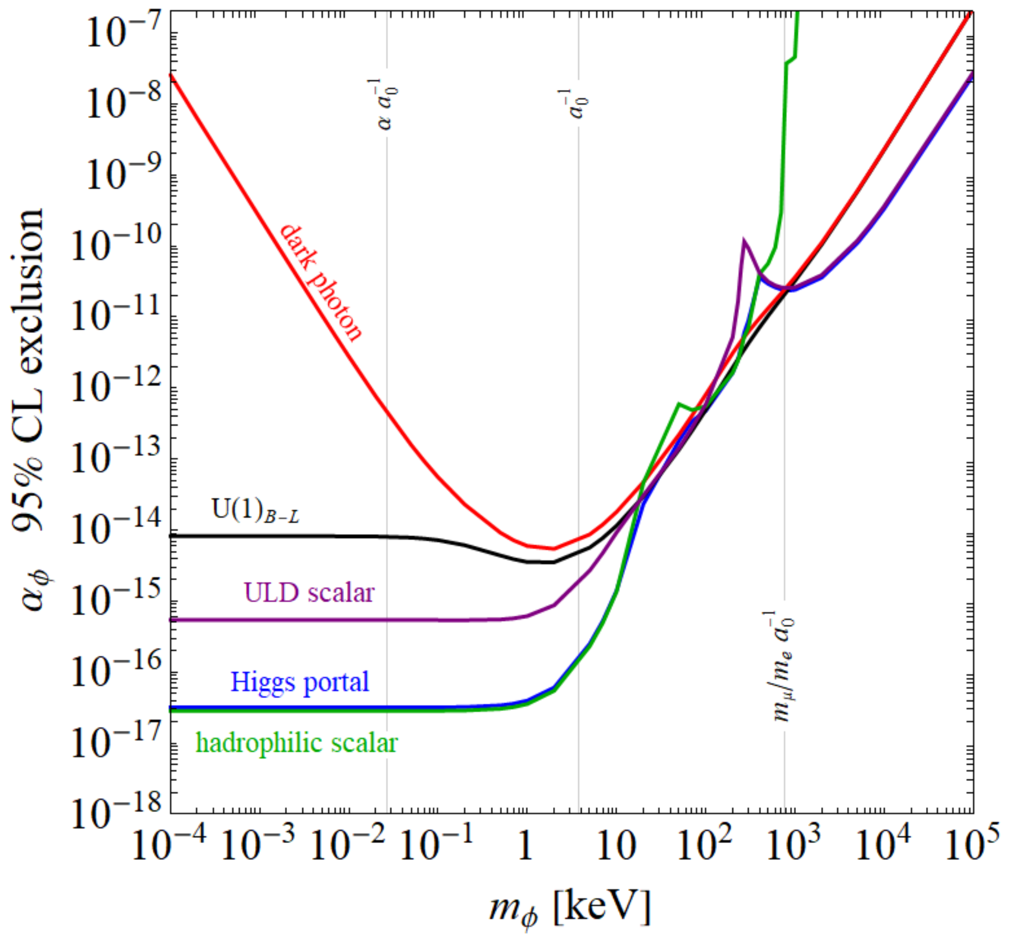
$\alpha_\phi = k^2 m_e \kappa'_p m_p/(4\pi v^2)$

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

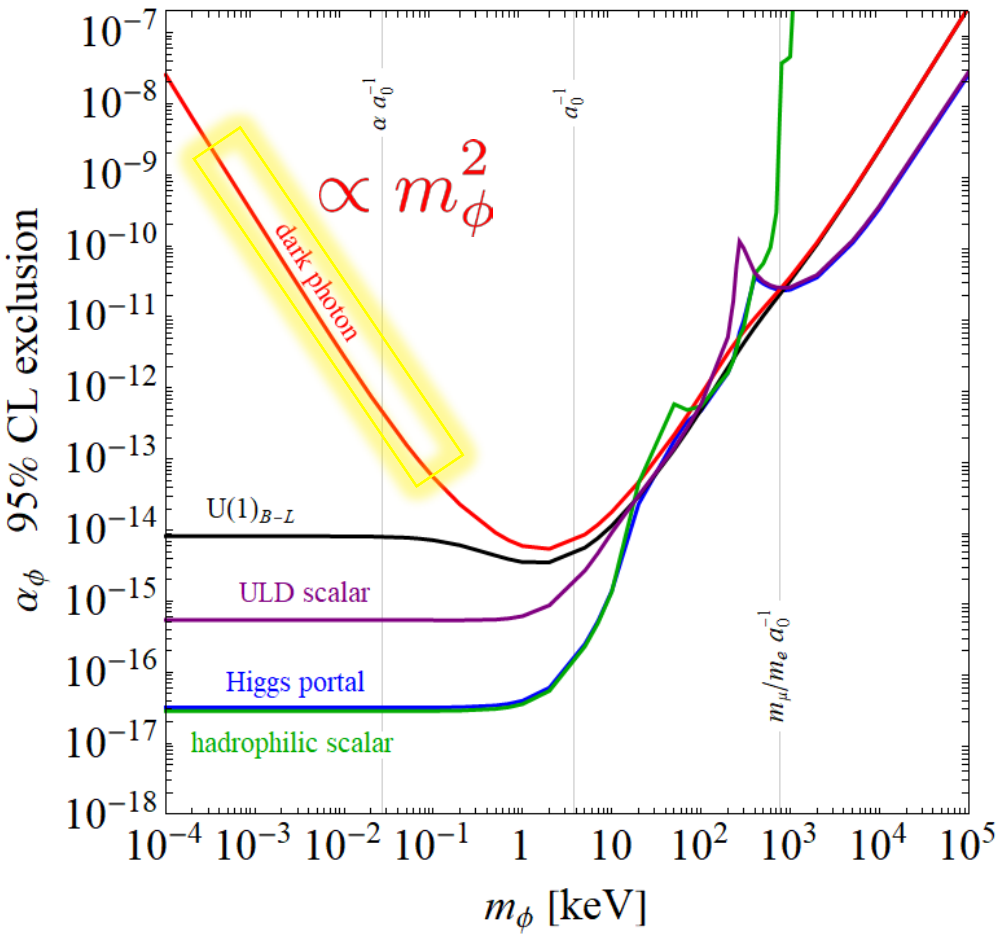
$\kappa'_p = 0.018(5),\ \kappa'_n = 0.016(5)$ ← couples *only* to up-quark

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

CODATA as a NP search

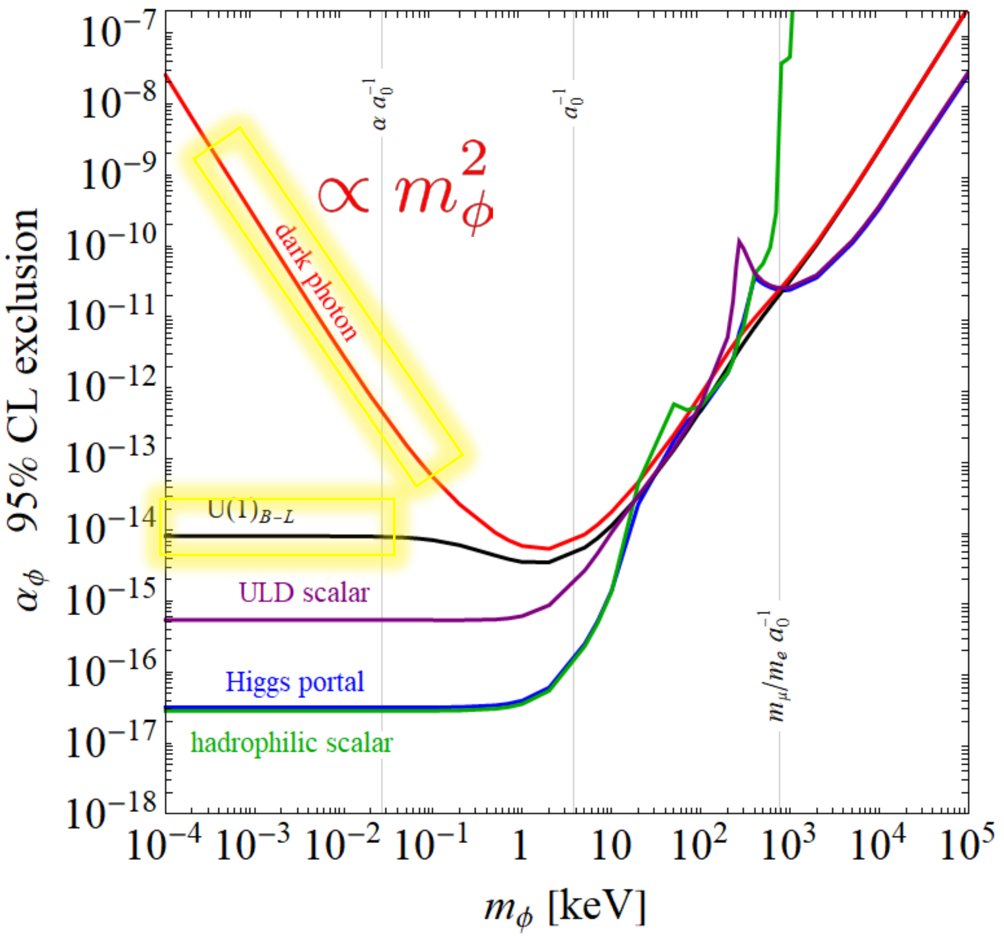


CODATA as a NP search



CODATA as a NP search

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

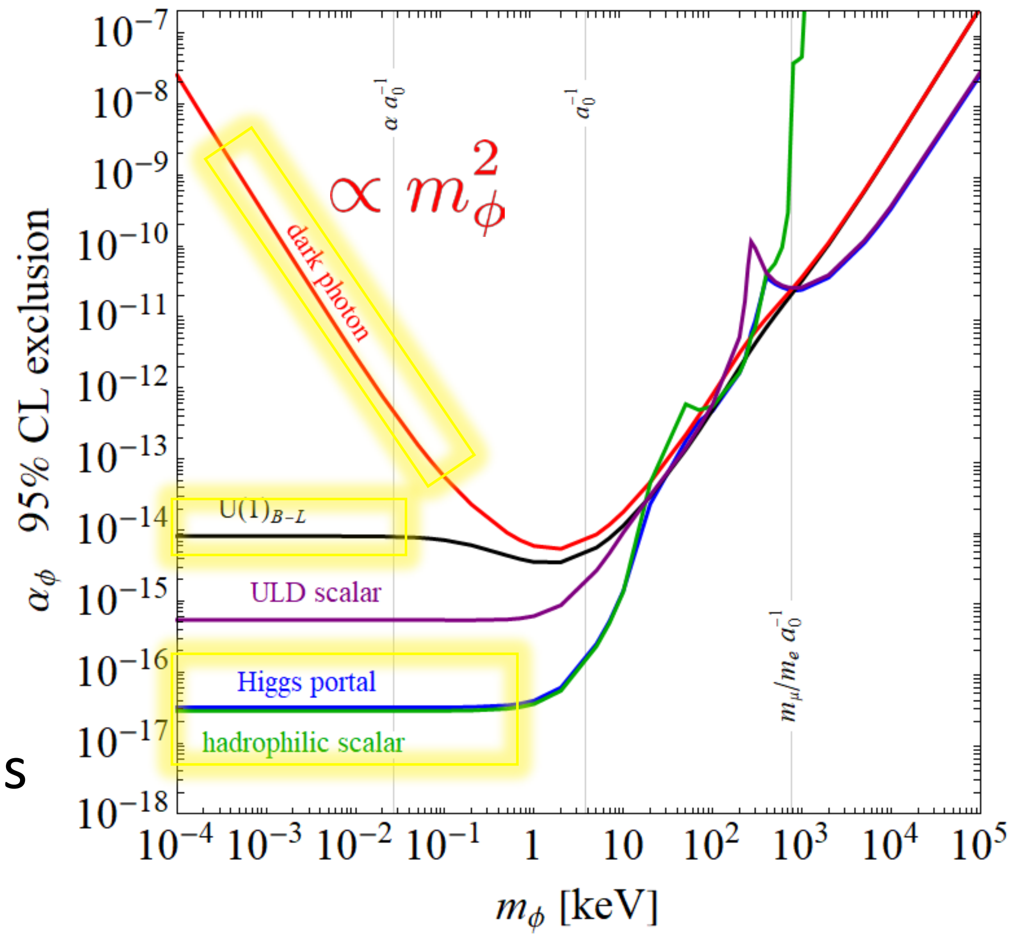


CODATA as a NP search

$\propto m_\phi^0$ 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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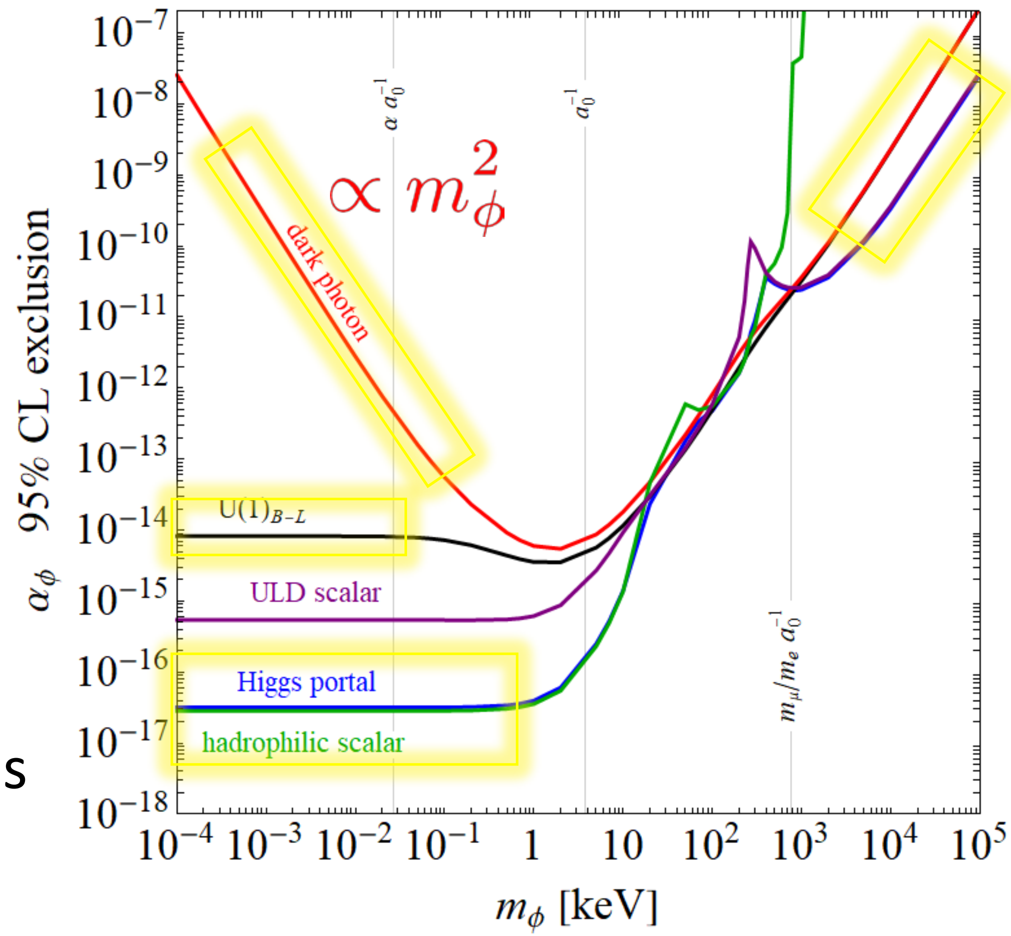


stronger sensitivity from muonic atoms in models where

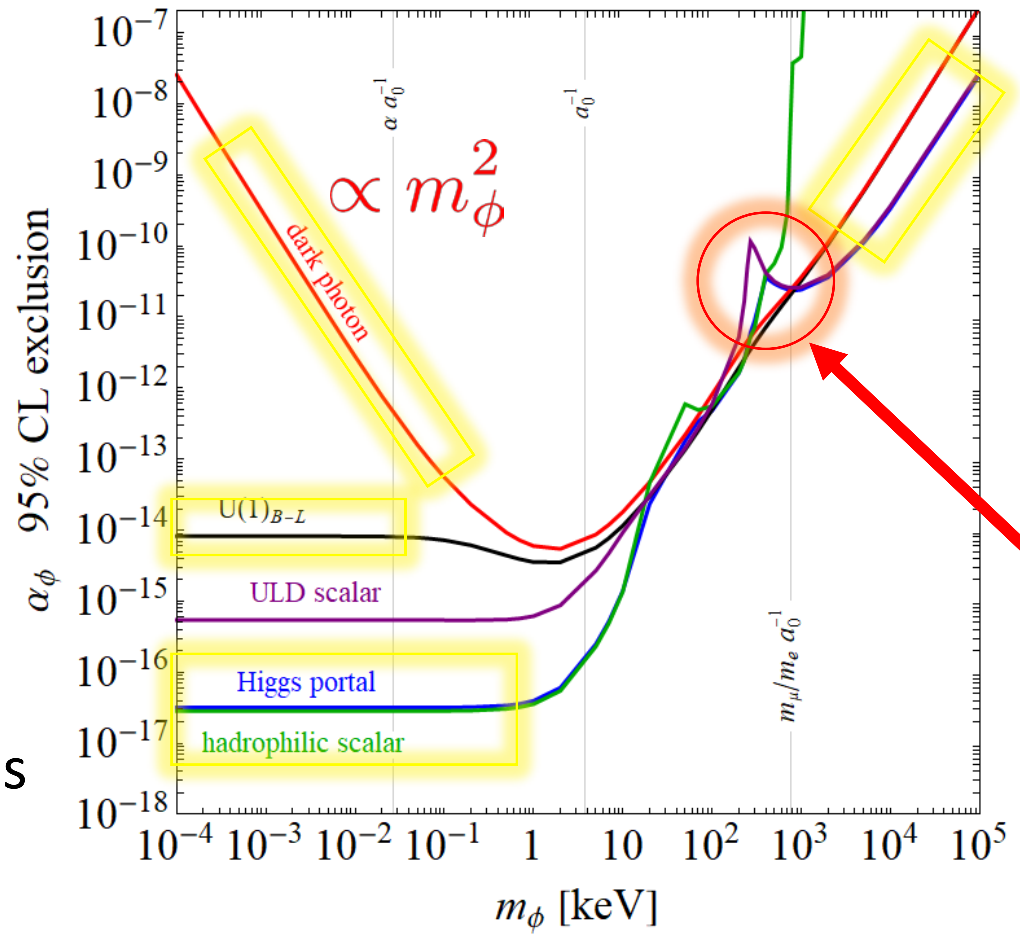
$$q_\mu/q_e \sim m_\mu/m_e \sim 200$$

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 NP search

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



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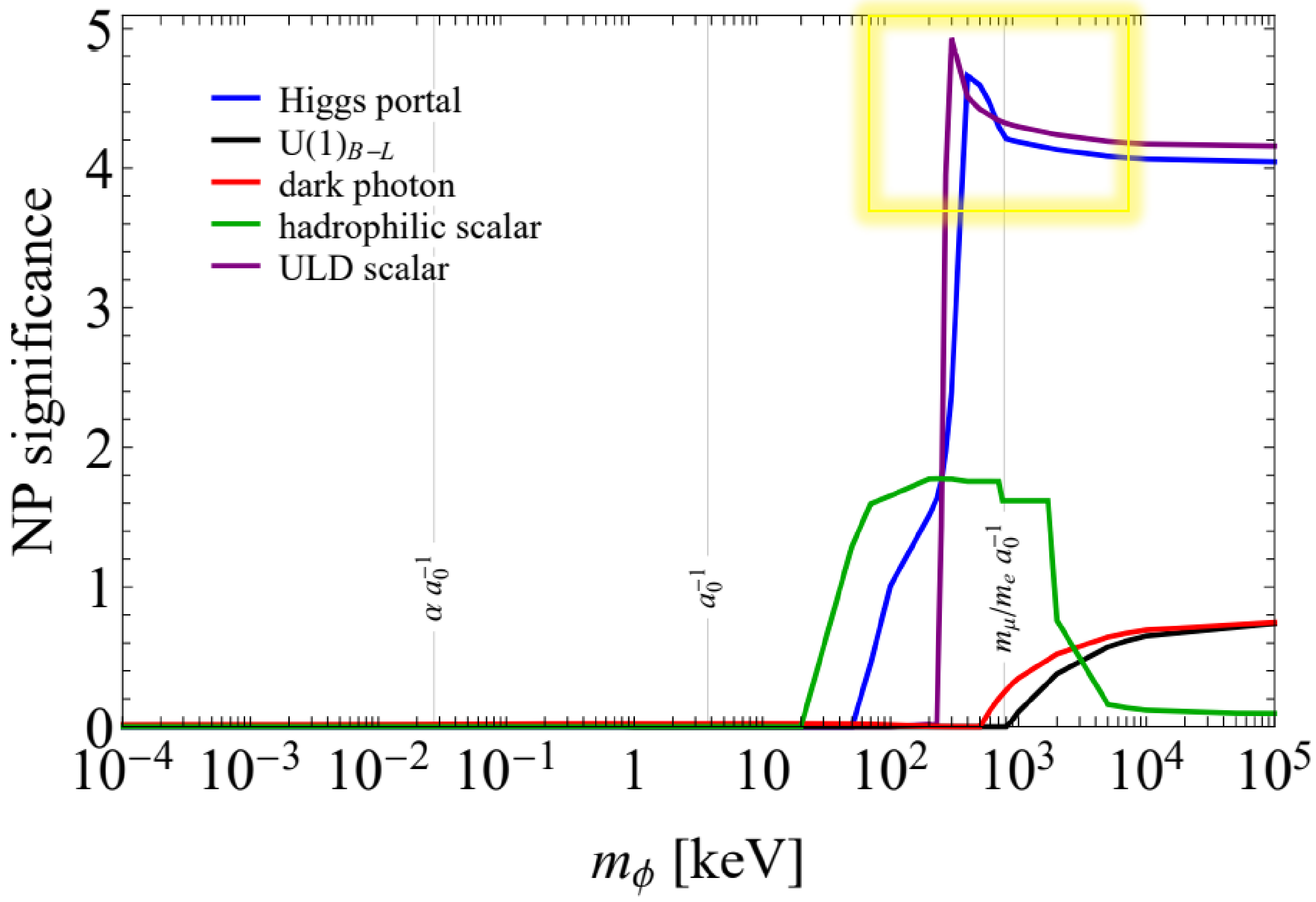
stronger sensitivity from internuclear forces in molecules in models where

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

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

NP 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

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

NP significance

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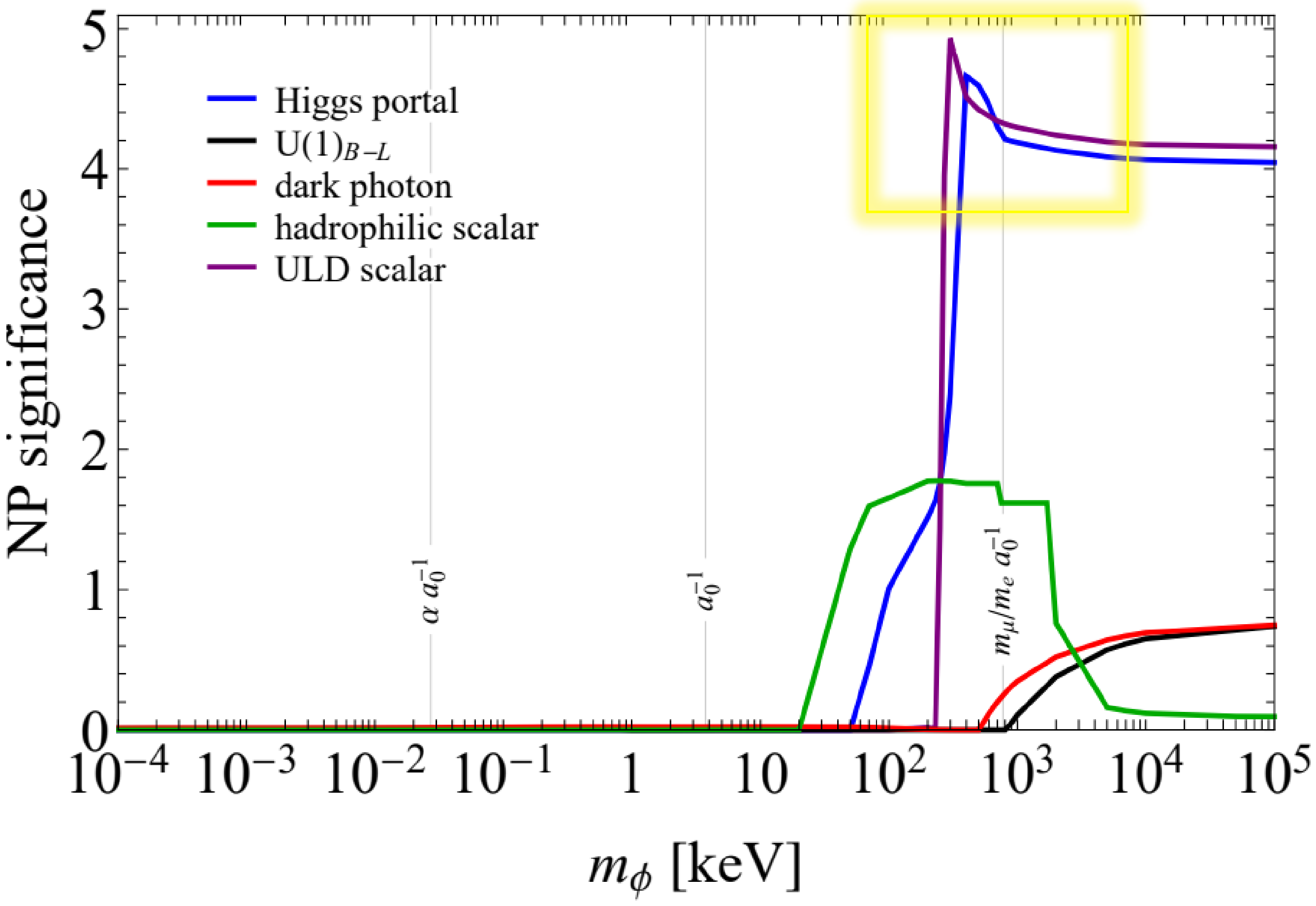


$\sim 4.5\sigma$ pull

for scalar masses around

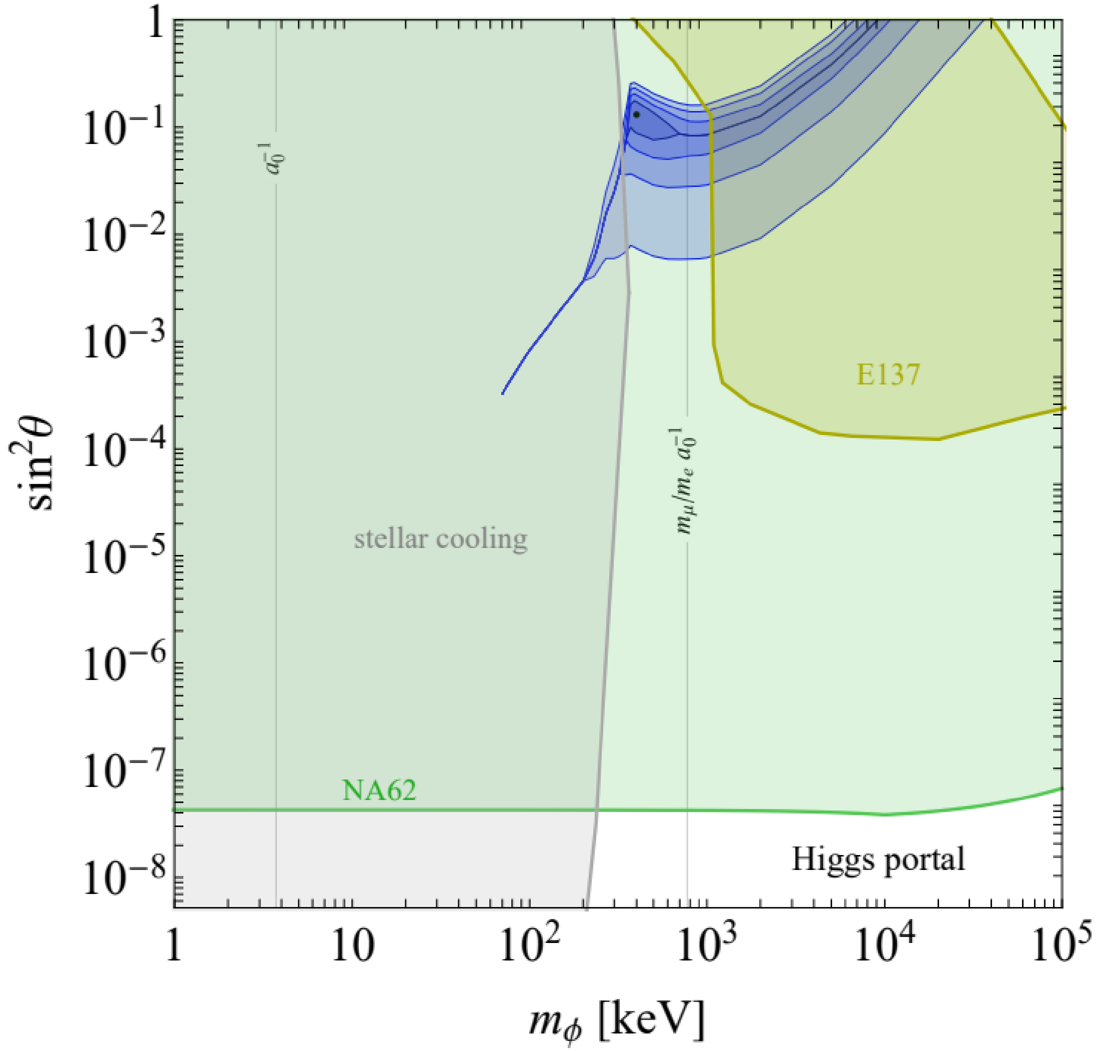
$300 - 600\,\text{keV}$

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) $\sim 2\sigma$
- CODATA18 vs. H 2S-8D $\sim 3\sigma$

Brandt et al. [2022]

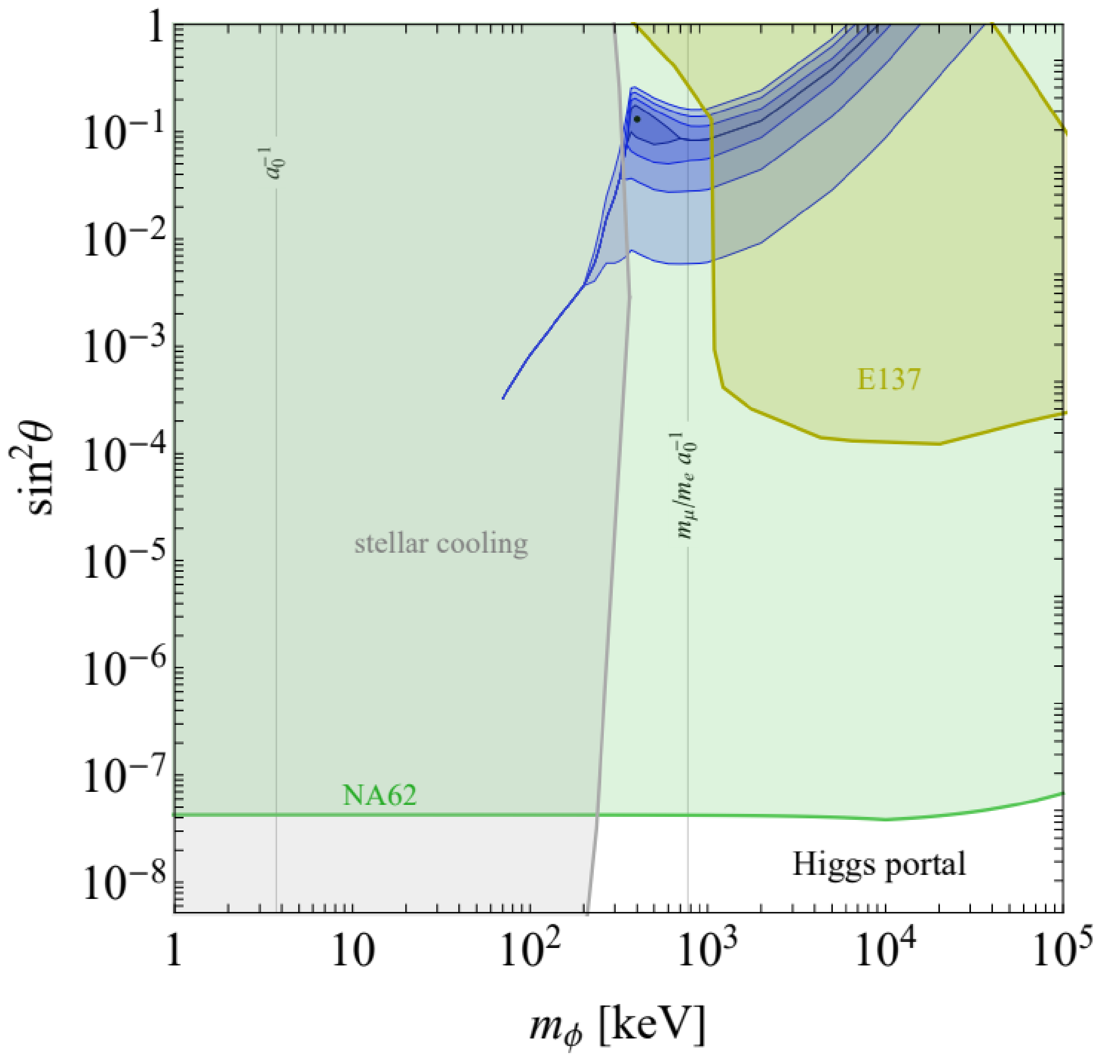
Non-zero Higgs Portal?



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

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

Non-zero Higgs Portal?



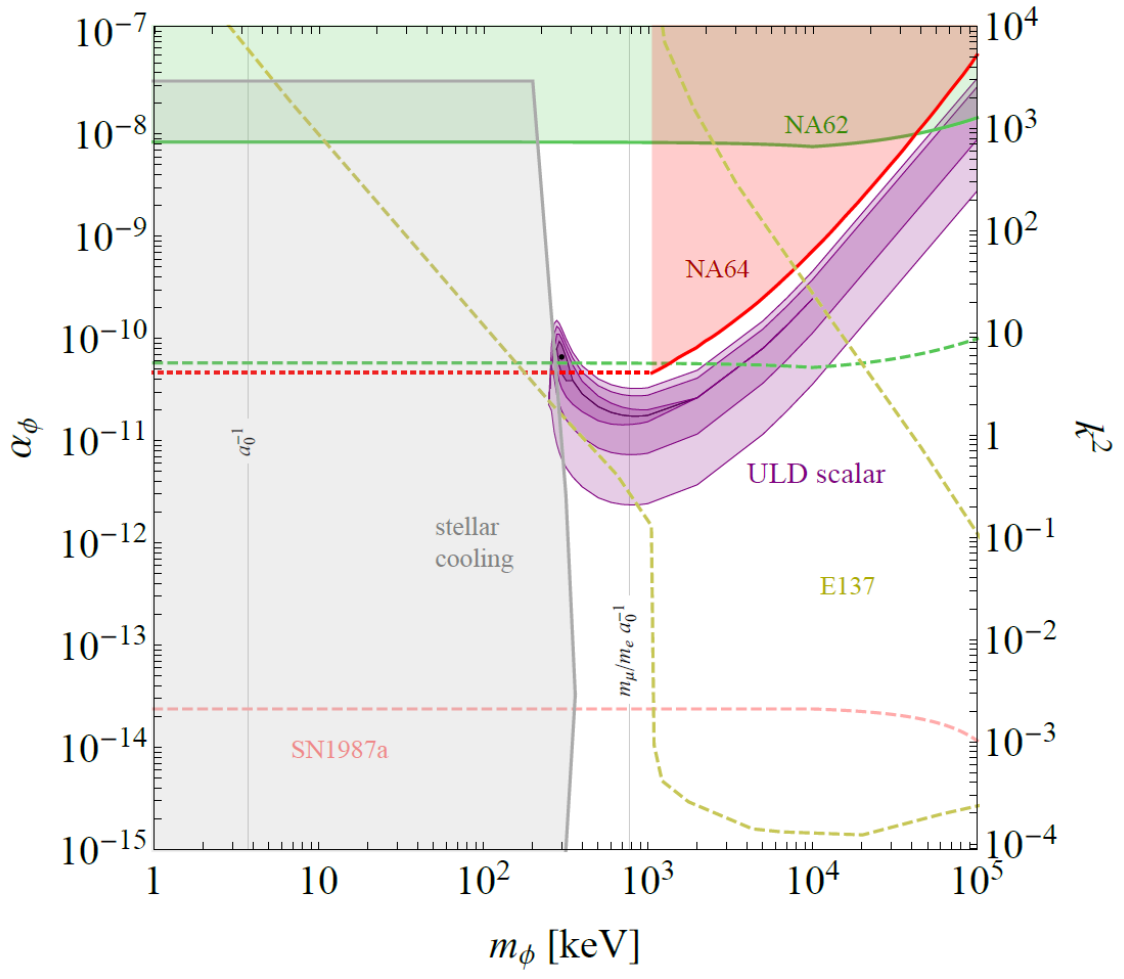
Best-fit point $\sin\theta \simeq 0.35$, $m_\phi \simeq 400\,\mathrm{keV}$

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

Atomic/Flavor connexion

work in progress

CD, T. Kitahara, Y. Soreq and J. Zupan

NP flavor structures like MFV or favoring third generation couplings face strong flavor constraints (e.g. from $K \to \pi\phi$ penguins)

Suppressing effects in atomic/molecular spectroscopy

electronic coupling cannot compensate if electron g-2 closely follows QED

nuclear coupling has to be small to accomodate flavor bounds

$$\delta_{\rm NP}\nu \propto g_e \times g_p$$

How much? This is model dependent and requires matching to the weak chiral Lagrangian beyond the Higgs portal

Leutwyler-Shifman [1990]

Weak chiral Lagrangian for a Generic Scalar

CD-Kitahara-Redigolo-Soreq-Zupan to appear

Consider a light scalar with generic CP-even couplings to the SM fields:

$$\mathcal{L}_{\rm int}(\mu \simeq m_W) = \frac{\phi}{v}\left[\kappa_g \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{\mu\nu\,a} - \sum_{\psi=q,Q} \kappa_\psi m_\psi \overline{\psi}\psi + 2\kappa_W m_W^2 W^+_\mu W^{\mu\,-} - c_W W^+_{\mu\nu} W^{\mu\nu\,-}\right]$$

Matching the trace anomaly $T_\mu^{\ \mu}$ in presence of the weak interaction yields the scalar interactions to the light (pNGB) mesons

$$\mathcal{L}_{\rm eff}(U,\phi) = \frac{f_\pi^2}{8}\left[\langle\left(1+\Omega\frac{\phi}{v}\right)\partial_\mu U^\dagger \partial^\mu U\rangle + \langle\left(1+\Sigma\frac{\phi}{v}\right)\chi U + \text{h.c.}\rangle - \frac{a}{N_c}\left(-i\log\det U\right)^2\left(1+\frac{8}{9}K_T\frac{\phi}{v}\right)\right]$$

CCWZ kinetic term

explicit breaking from quark masses

explicit breaking from instantons

FCNC amplitudes

CD-Kitahara-Redigolo-Soreq-Zupan to appear

This provides generic $\Delta S = 1$ decay amplitudes at $\mathcal{O}(p^2)$ in χPT,
e.g. (assuming isospin symmetry $m_u = m_d$)

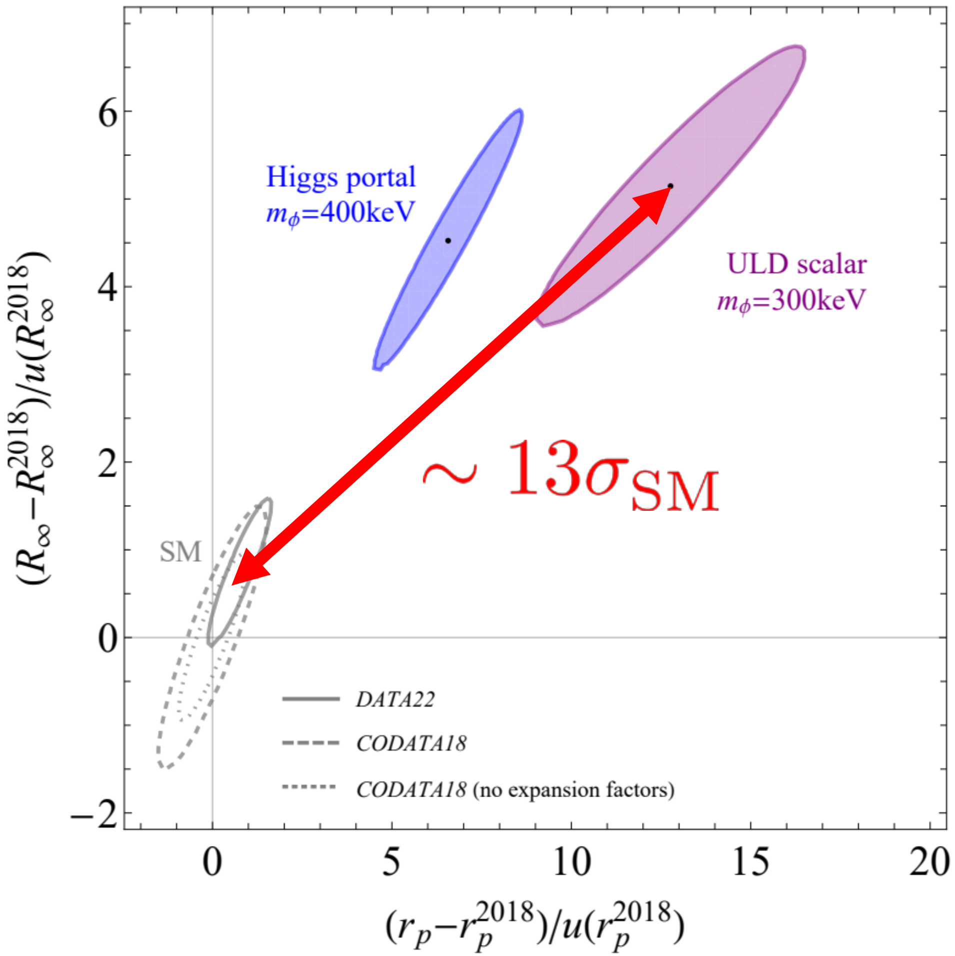
$$\mathcal{M}(K^+ \to \pi^+ \phi) = \frac{m_K^2}{v}\left[\frac{7}{18} K_W \gamma_1 \left(1 - \frac{m_\phi^2 - m_\pi^2}{m_K^2}\right) + \left(\frac{1}{2}\zeta^* - \frac{7}{9} K_W \gamma_2\right) + \frac{7}{72}(K_s - K_d)(\gamma_1 - 2\gamma_2)\frac{(2m_K^2 - m_\pi^2)m_\pi^2}{(m_K^2 - m_\pi^2)m_K^2}\right]$$

one-loop penguins

Note that up-quark philic scalars do not yield $K \to \pi$ transitions at LO

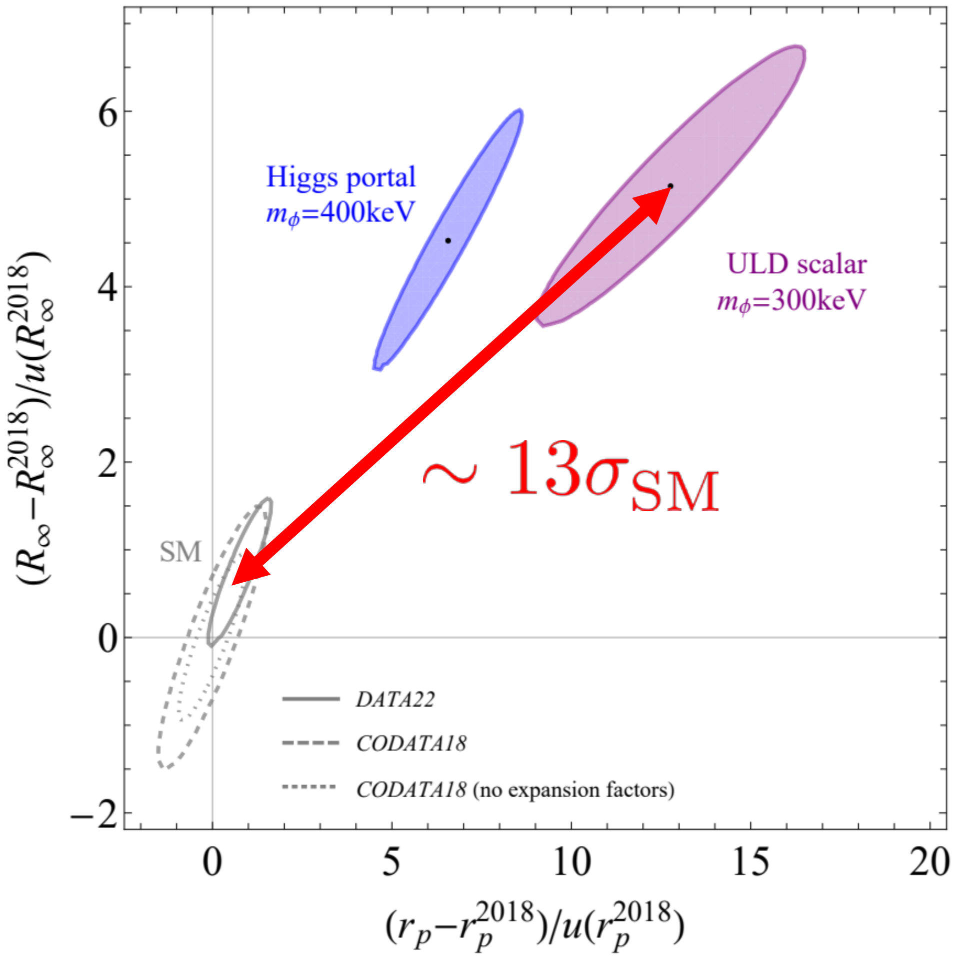
Such scalars are interesting for atomic physics since less sensitive to flavor physics and allowing a larger nuclear/electron coupling ratio.

Impact on fundamental constants



FCs can undergo huge shifts in the presence of NP

Impact on fundamental constants



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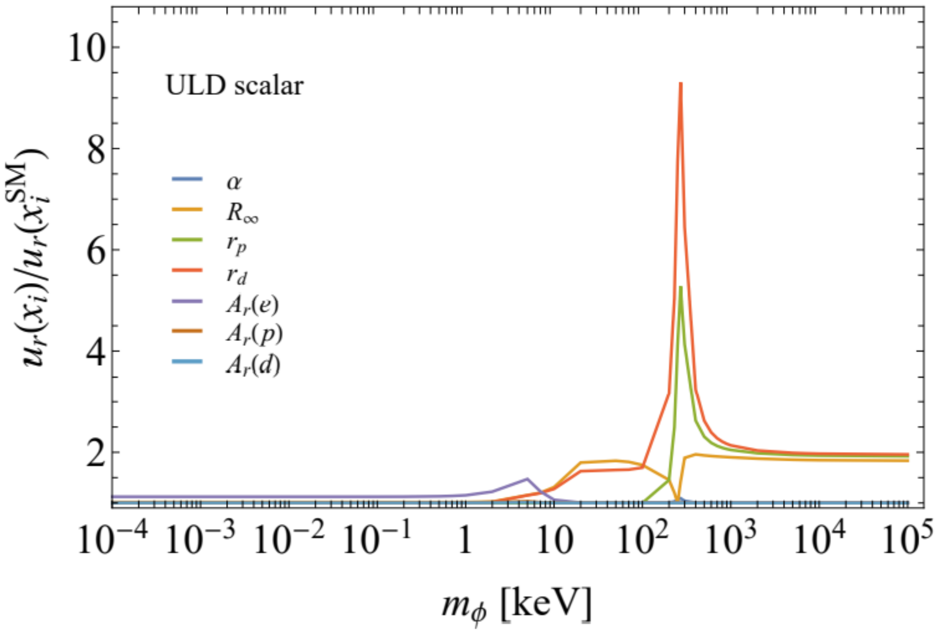


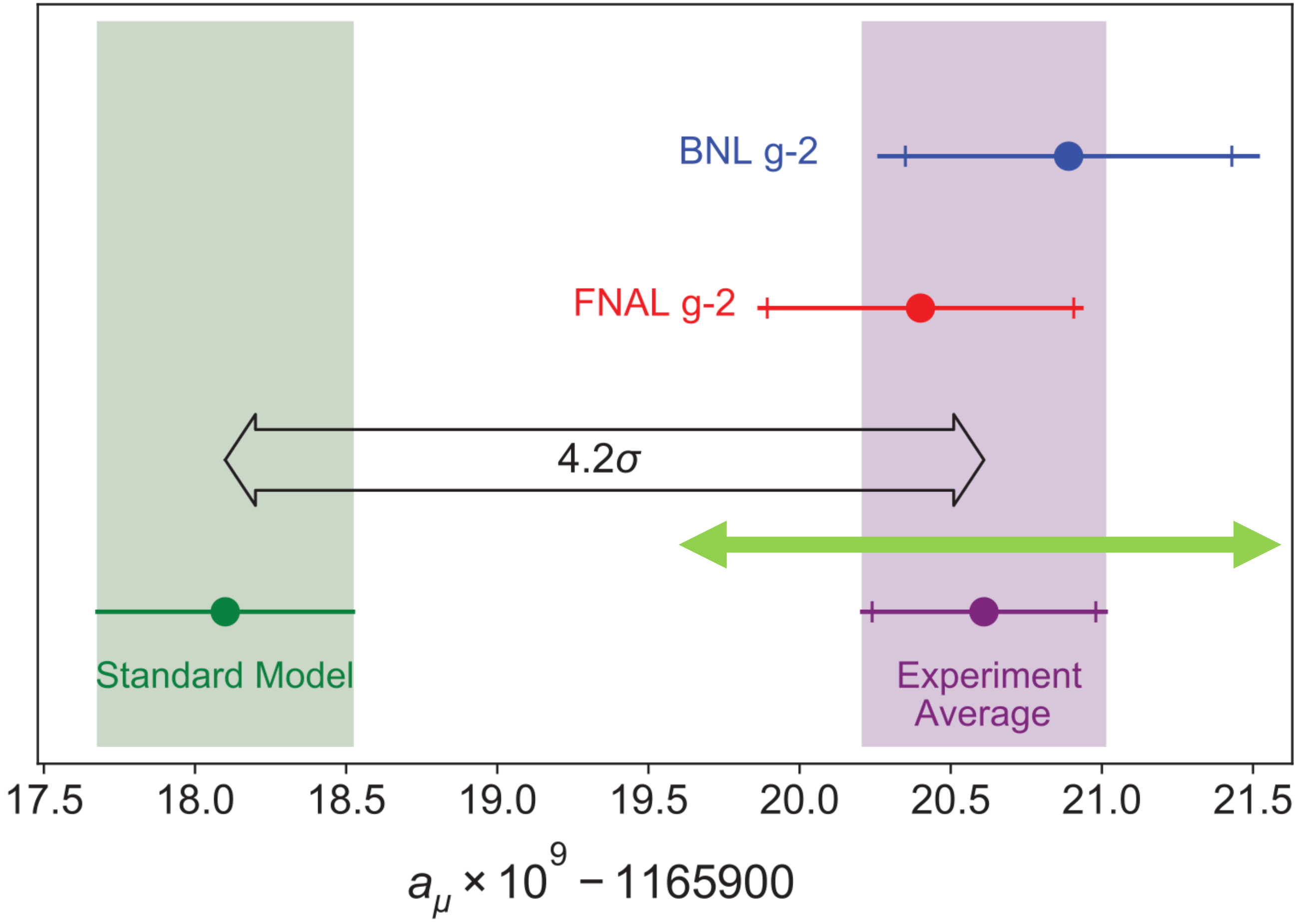
and their uncertainty *significantly* inflates relative to the SM-only hypothesis

Phys.Rev.Lett. 127 (2021) 25, 251801
CD (LAPTh),
B. Ohayon (Technion),
and Y. Soreq (Technion),

Muon(ium) g-2

muon magnetic moment below 1ppm from μ^+e^- spectroscopy

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]

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

Phys. Rev. D 96, 093001 (2017) CD, Ozeri, Perez and Soreq
*Phys. Rev. Lett. **120**, 091801 (2018)* Berengut, Budker, CD, et al
Phys.Rev.Res. 2, 043444 (2020) Berengut, CD, Geddes and Soreq

ISOTOPE SHIFTS

Constraining light new particles with optical clocks

Why isotope shifts?

The theory of many-electron atoms is not accurate (~1% from MBPT)

Frenquencies are (mostly) set by EM interactions which are universal for isotopes with same ***Z***

Therefore EM contributions cancel out in isotope shifts: $(\nu - \nu')/\nu \sim 10^{-6}$

$$\nu_{\mathrm{Yb}}/\nu_{\mathrm{Sr}} = 1.207\ 507\ 039\ 343\ 337\ 8482(82)$$

$\rightarrow$ No need to calculate the first **6 digits**!

NP (conserving P&CP) couples to the entire nucleus ***A*** and is only mildy suppressed in the frequency difference: $(A - A')/A \sim 0.1$

Isotope Shift Theory

IS involve nuclear physics and are challenging to calculate.

However $\Lambda_{\rm QCD} \gg \alpha m_e$ so one can do perturbation theory

There are two nuclear effects @LO:

constants depending on the electronic configuration

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'} = K_i \, \mu_{AA'} + F_i \, \delta\langle r^2\rangle_{AA'}$$

transition index

field shift

adding/removing neutrons affects the nuclear charge distribution, represented @LO by the charge radius

$$\delta\langle r^2\rangle_{AA'} \equiv \langle r^2\rangle_A - \langle r^2\rangle_{A'}$$

mass shift

changing the nuclear mass modifies:
the center-of-mass (normal MS)
and electron-electron repulsion terms (specific MS)

$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

Isotope Shift Theory

Nuclear masses are measured at $\sim 10^{-11}$ accuracy (from spin precession in Penning traps).

However, charge radii are poorly known and electronic constants can be obtained within ~1% from atomic structure calculations.

$\rightarrow$ *Are we stuck again?*

No. The nuclear parameters are common to all electronic states and the electronic states are the same for all isotopes (at least at LO in these perturbations).

This simple observation grants us with a trick, noticed by King in the 60's

King's linearity

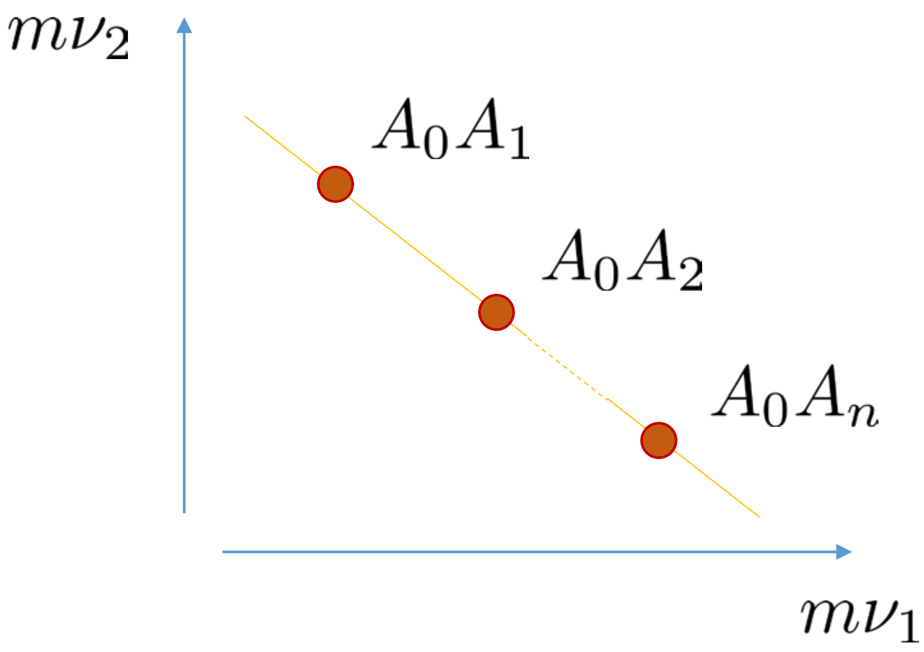
The trick is to use two distinct transitions, one being used to fix the unknown nuclear parameter $\delta\langle r^2\rangle/\mu$

This yields a **linear** relation among the IS of the two transitions.

$$m\nu_2^{AA'} = F_{21}\, m\nu_1^{AA'} + K_{21}$$

$m\nu \equiv \nu/\mu$

F_2/F_1 $\quad$ $K_2 - F_{21}K_1$



Testing King's linearity does not require calculation of K, F

New Physics nonlinearities

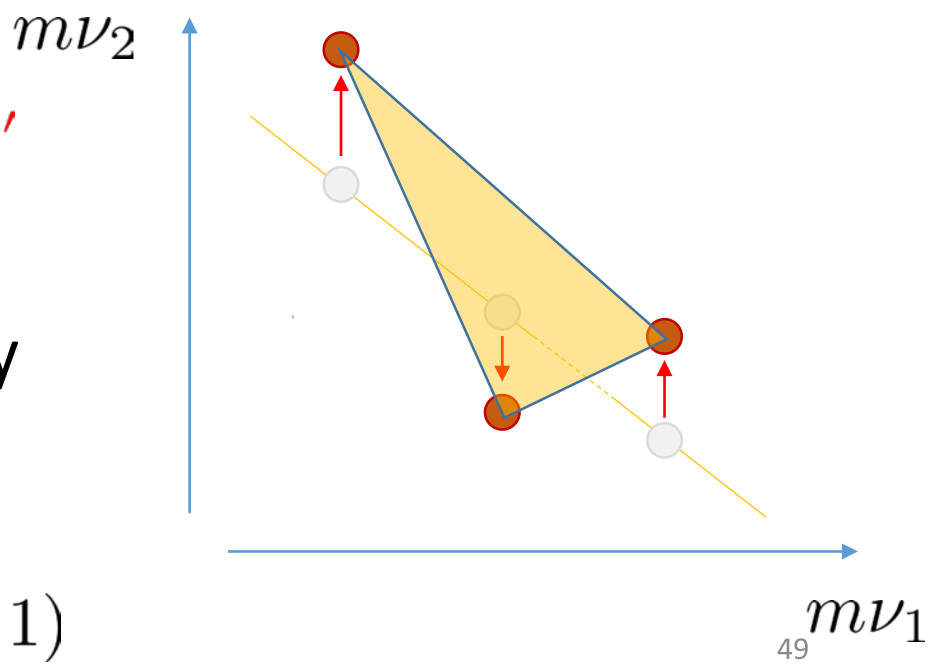
NP brings about another nuclear parameters:

$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'}$$

e.g. $\gamma_{AA'} = A - A'$

breaking King's linearity :

$$m\nu_2^{AA'} = F_{21}\, m\nu_1^{AA'} + K_{21} + \alpha_{\rm NP} X_{21} h_{AA'}$$



The nonlinearity is conveniently quantified by

$$\mathrm{NL} = \det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\mu})$$

$$\vec{m\mu} = (1,1,1)$$

Extracting the NP coupling

Directly solving King's equation gives:

NL in data

$$\alpha_{\rm NP} = \frac{\det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\mu})}{\det[X_1 \vec{m\nu}_2 - X_2 \vec{m\nu}_1, \vec{h}, \vec{m\mu}]}$$

NL predicted by IS theory

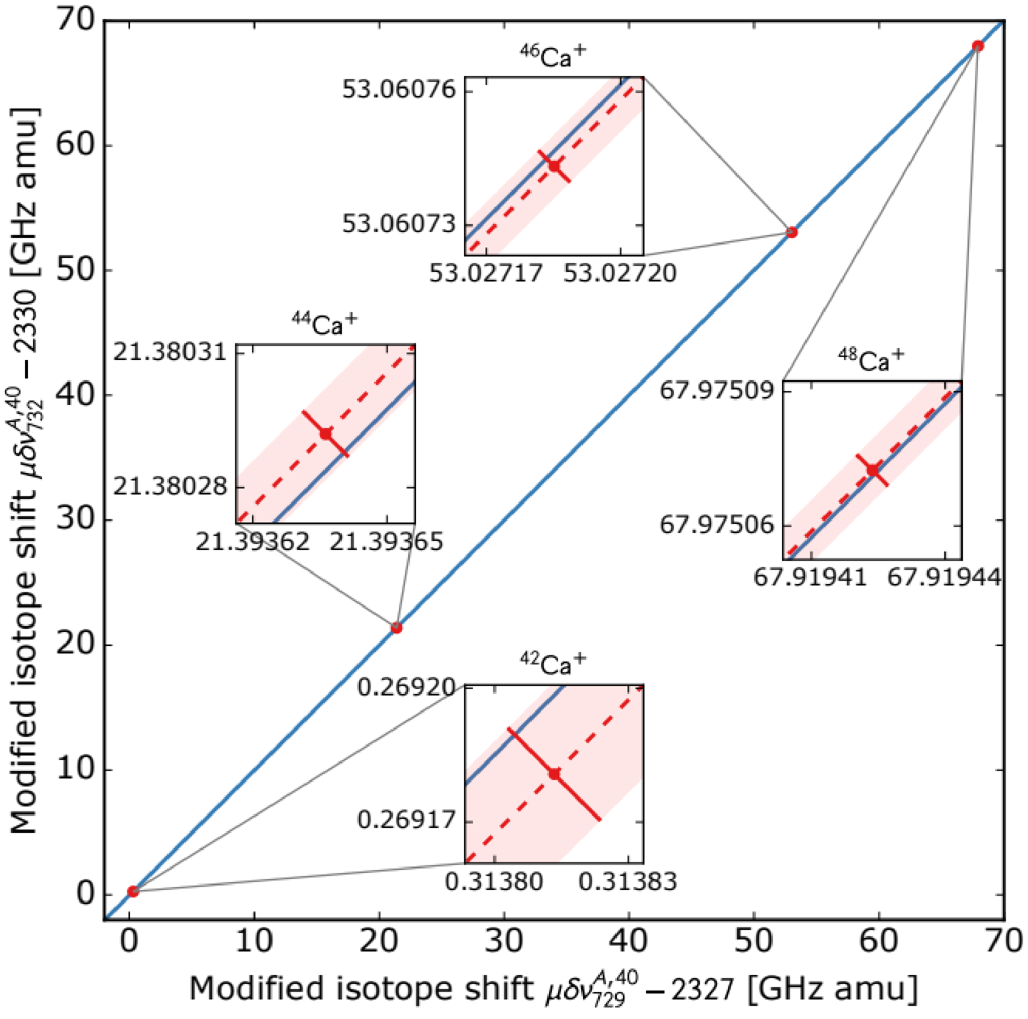
$$= \epsilon_{ij} F_i X_j \times \det(\vec{m\delta\langle r^2\rangle}, \vec{h}, \vec{m\mu})$$

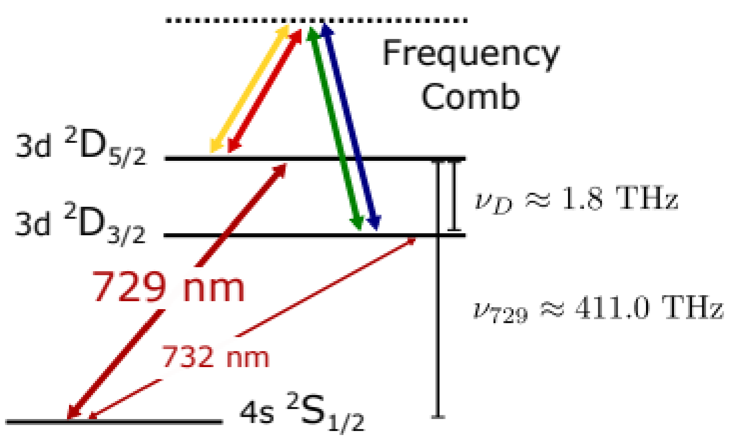
Electronic alignment
→ strong suppression for $m_{\rm NP} > \Lambda_{\rm QCD}$
$X_i \propto F_i$

Nuclear alignment
→ suppression of $\delta m_A^{\rm max}/m_A \sim \mathcal{O}(10)$

IS linearity in Ca+

Solaro et al. | Phys. Rev. Lett. **115**, 123003 (2020)



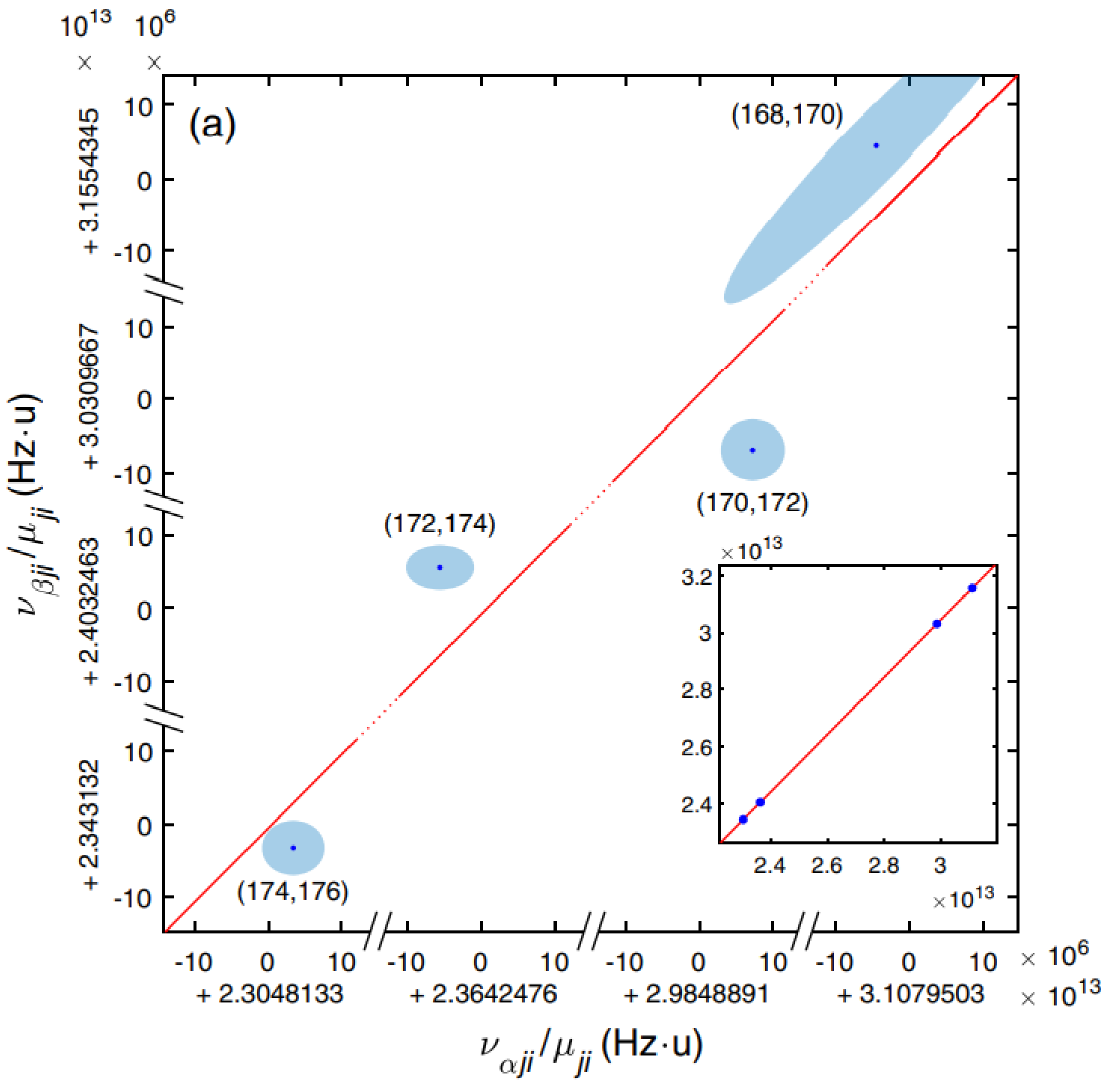


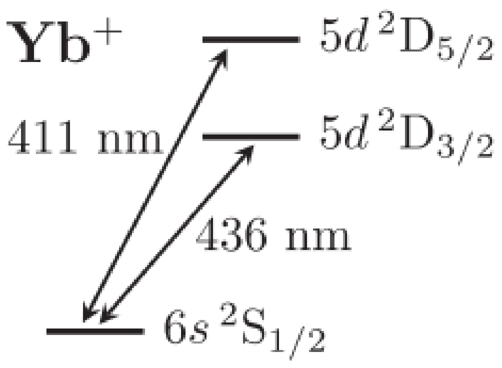
Using optical clock (S→D) transitions with ~20Hz accuracy $\sim \mathcal{O}(10^{-13})$

Measurements are consistent with linearity within uncertainties

Nonlinearities observed in Yb+

Counts et al. **|** Phys. Rev. Lett. **125**, 123002 (2020)

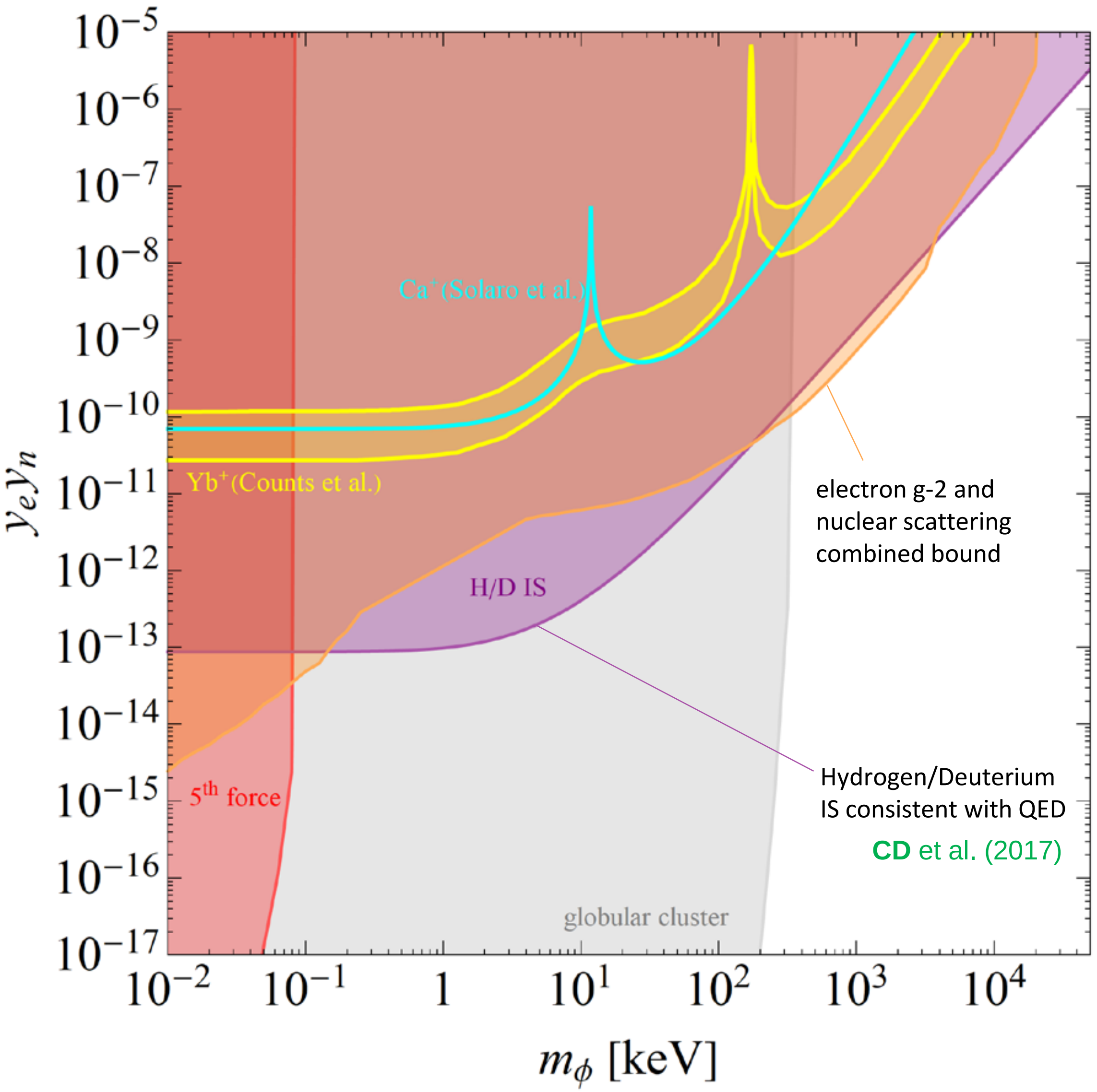




Using optical clock (S→D) transitions with ~300Hz accuracy

Nonlinearities at 3σ → *NP evidence?*

NP in different systems is correlated



Ca+ bound excludes NP as the origin of the Yb+ nonlinearities in most of the mass range

Moreover, the NP coupling needed is excluded by other observables

Subleading nuclear effects are the dominant cause of what is observed in Yb+

Flambaum et al. (2017)
first-time calculation of NLs

Nuclear nonlinearities

Beyond LO, electrons adapt to the change of nucleus

$$\nu_i^{AA'} = K_i^{AA'}\,\mu_{AA'} + F_i^{AA'}\,\delta\langle r^2\rangle_{AA'} + \cdots$$
$$= K_i\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + \sum_{k\geq 1} G_{i,k}\lambda^k_{AA'}$$

Only a finite # of terms are relevant for a fixed accuracy.

How many? What A dependence?

There are candidates e.g. higher-moments of the nuclear charge distribution. Unfortunately, no EFT-like expansion is known…

Overcoming Nonlinearities

Nonetheless, NP can still be probed without theory calculation of NLs

Using more transitions (and isotopes) to fix the nuclear parameters sourcing the nonlinearities.

For instance, assuming only one term dominates (like FS^2):

(generalization to any number of independent nuclear parameters is straightforward)

$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + G_i\lambda_{AA'}$$

Then the mIS of 3 transitions are linearly related

$$m\nu_3^{AA'} = f_{3\alpha} m\nu_\alpha^{AA'} + [K_3 - f_{3\alpha}K_\alpha] \qquad \alpha = 1, 2$$

Generalized King Plots

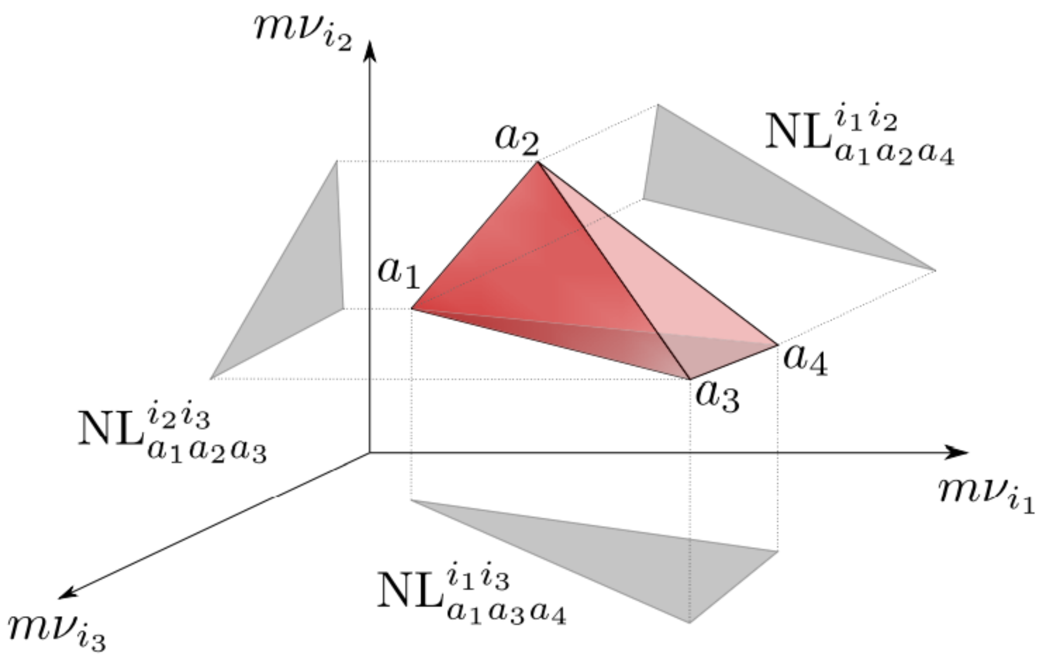
IS data for 4 isotope pairs are predicted to lie in a plane in 3D $\rightarrow$ *generalized King's linearity*

Again NP breaks this prediction

$$m\nu_3^{AA'} = f_{3\alpha} m\nu_\alpha^{AA'} + [K_3 - f_{3\alpha} K_\alpha] + \alpha_{\rm NP}[X_3 - f_{3\alpha} X_\alpha] h_{AA'}$$

NL measured by the volume

$$\mathrm{NL}_3 = \det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\nu}_3, \vec{m\mu})$$



NP coupling

The NP coupling can be extracted using only spectroscopy, without knowledge of $K, F, \delta\langle r^2 \rangle$ or G, λ :

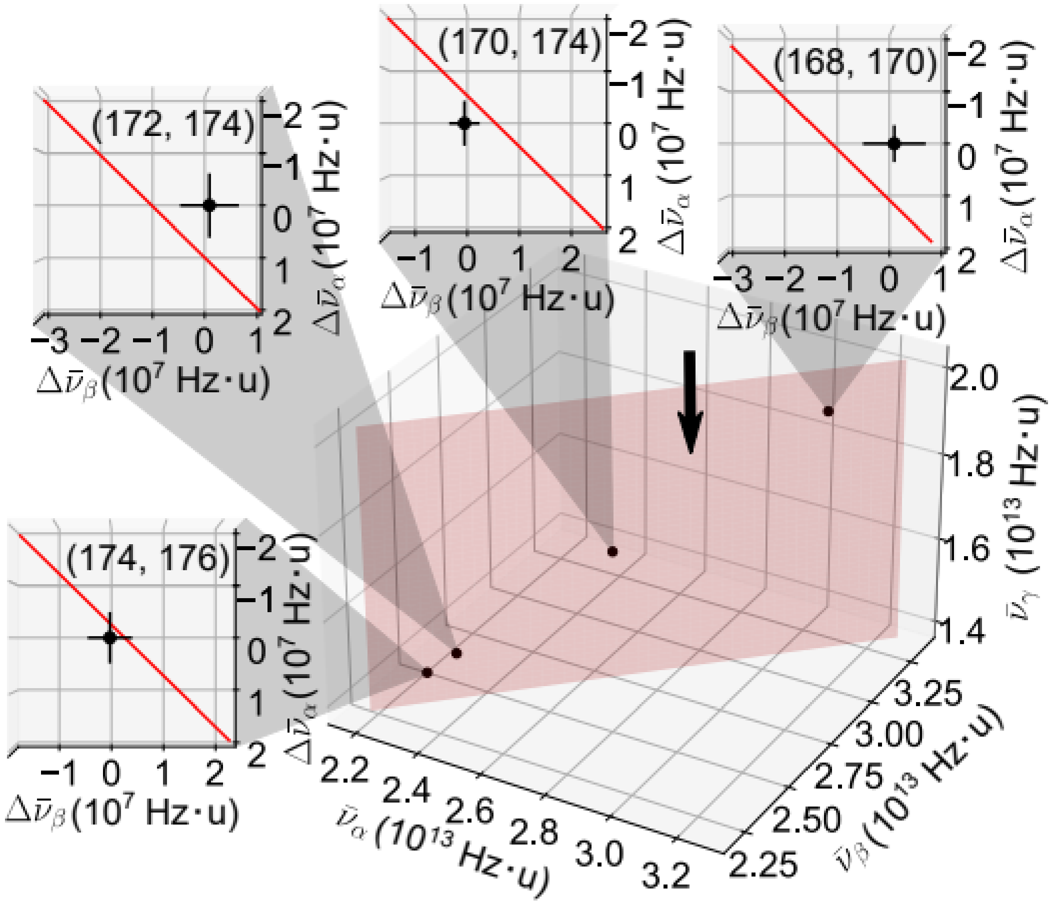
volume in data

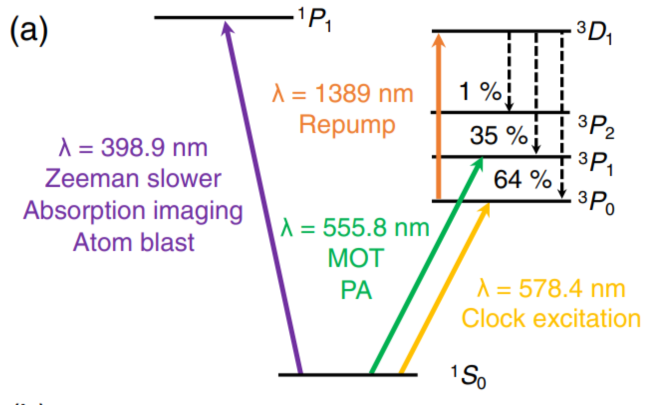
$$\alpha_{\rm NP} = \frac{\det(\vec{m\nu}_1, \vec{m\nu}_2, \vec{m\nu}_3, \vec{m\mu})}{\frac{1}{2}\epsilon_{ijk}\det(\vec{m\nu}_i, \vec{m\nu}_j, X_k\vec{h}, \vec{m\mu})}$$

volume predicted by IS theory with one nuclear source of NL

Generalized King plot with Yb/Yb+ data

Ono et al. | Phys. Rev. X **12**, 021033 (2022)





Experimental 3D King plot using different transitions in Yb/Yb+ shows ~3σ evidence for a second source of NL!

This calls for a 4D King plot…

Conclusions

Light NP is well motivated theoretically.

Atomic/molecular spectroscopy can be repurposed to search for it.

This requires to revisit the determination of fundamental constants.

There is an interesting interplay with flavor physics observables which *cannot* be fully decoupled.

Will the first sign of a deeper understanding of physics come from understanding atoms *again*?

Backup slides

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!

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!

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

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Instead, we use a simple *prescription*:

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

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

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

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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 $\delta q_i Q_j + Q_i \delta q_j$

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

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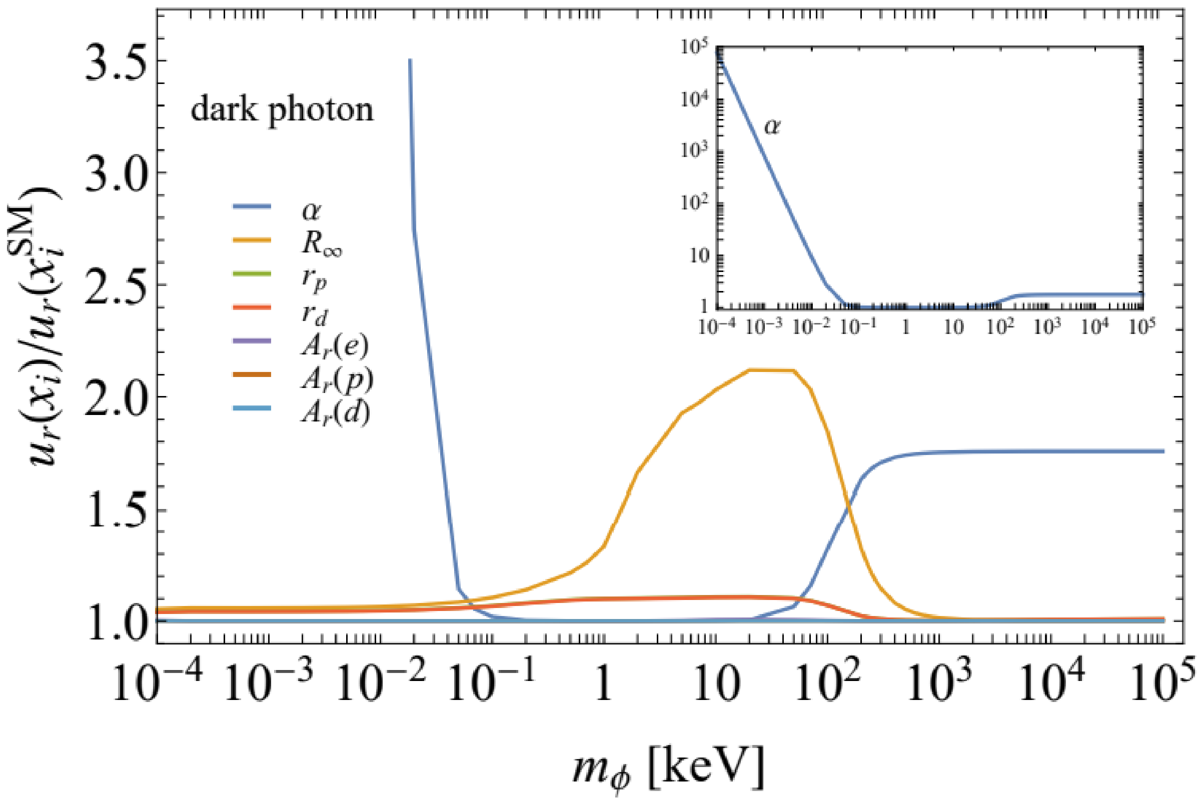

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As a result, only $\alpha + \alpha'$ is well determined

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

and α alone is poorly known...

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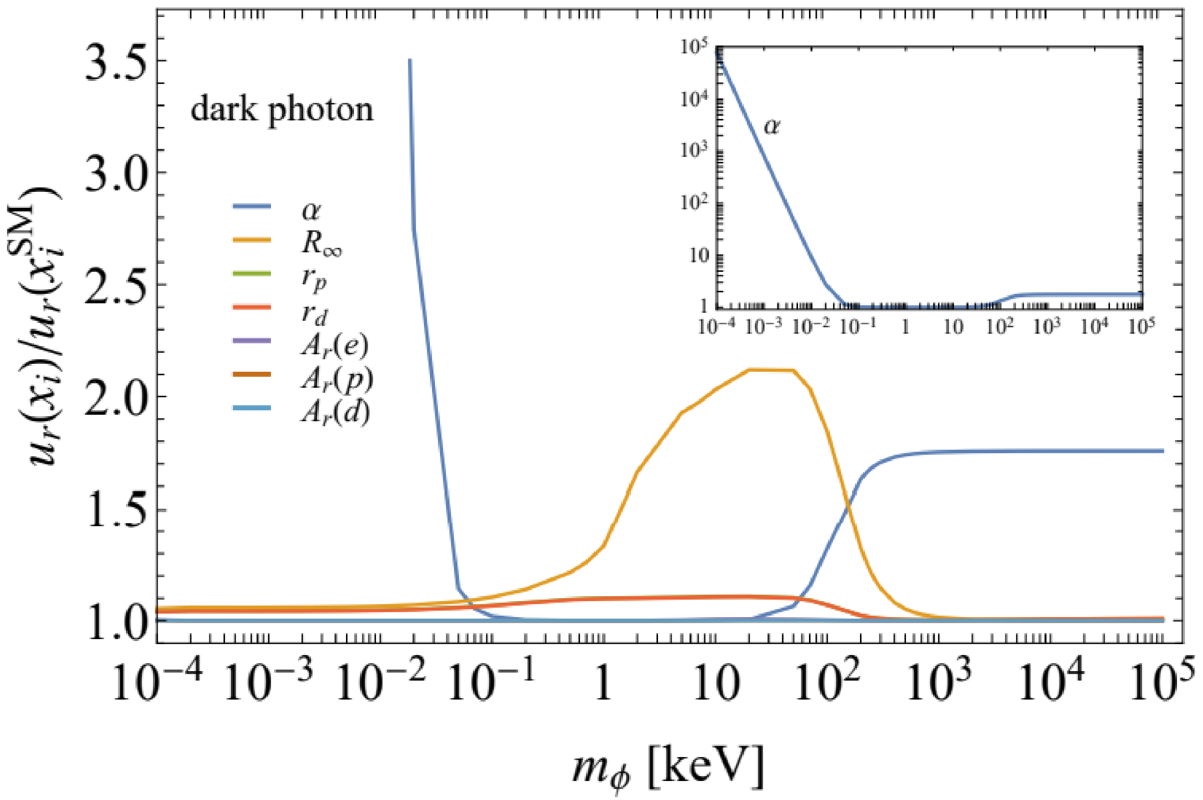

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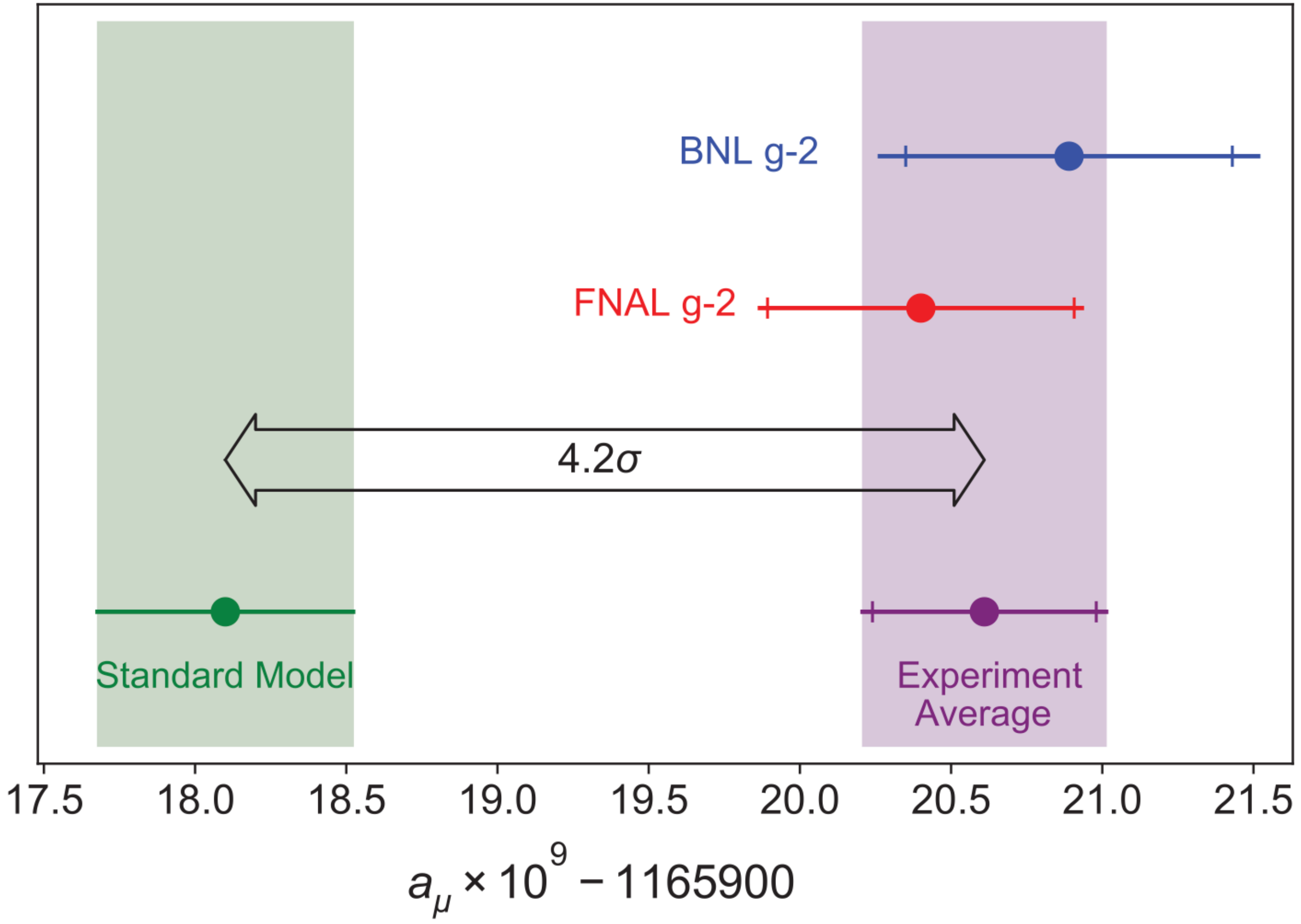
($u_r^{max}(\alpha) \sim 1$ for $m_{A'} \lesssim 10\,\mathrm{meV}$)

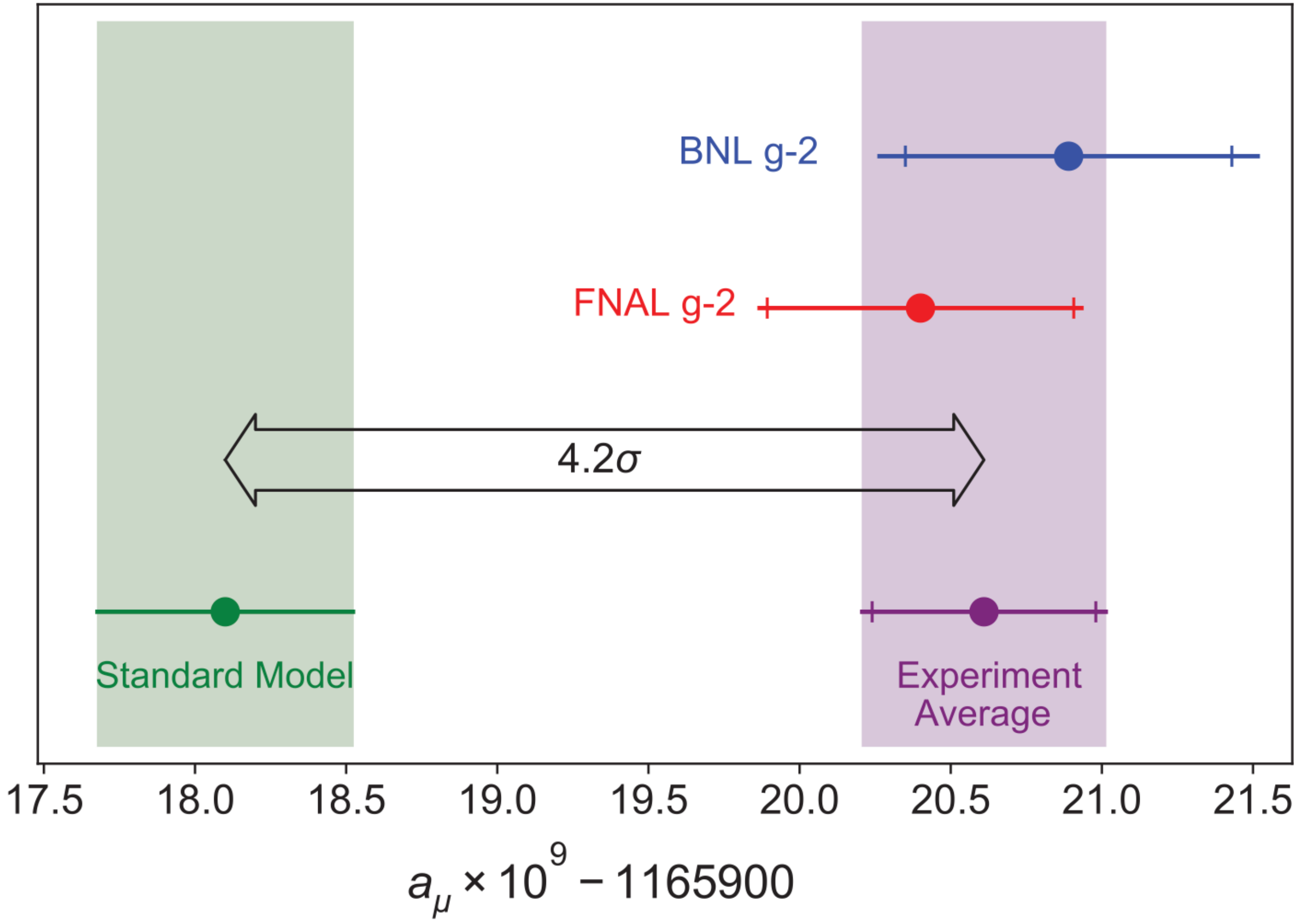
The Muon g-2 puzzle



Is this really an evidence of BSM Physics?

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

The Muon g-2 puzzle



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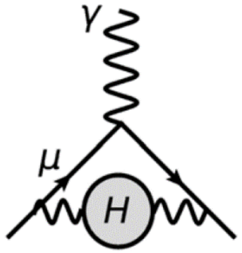
Do we really control the SM prediction?



R-ratio method:

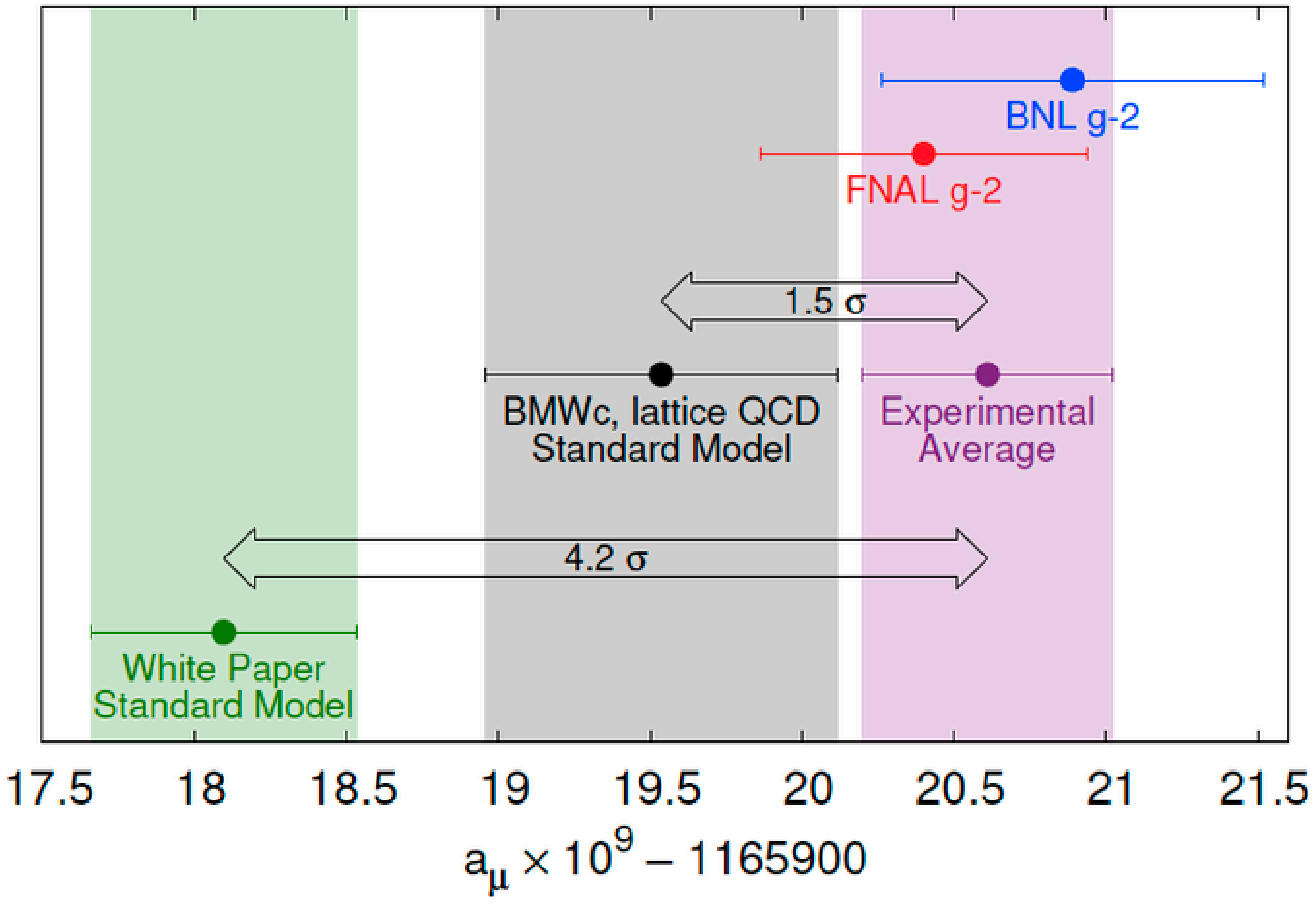
[Bouchiat-Michel 1961]

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

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

$\pi\pi \sim 70\%$

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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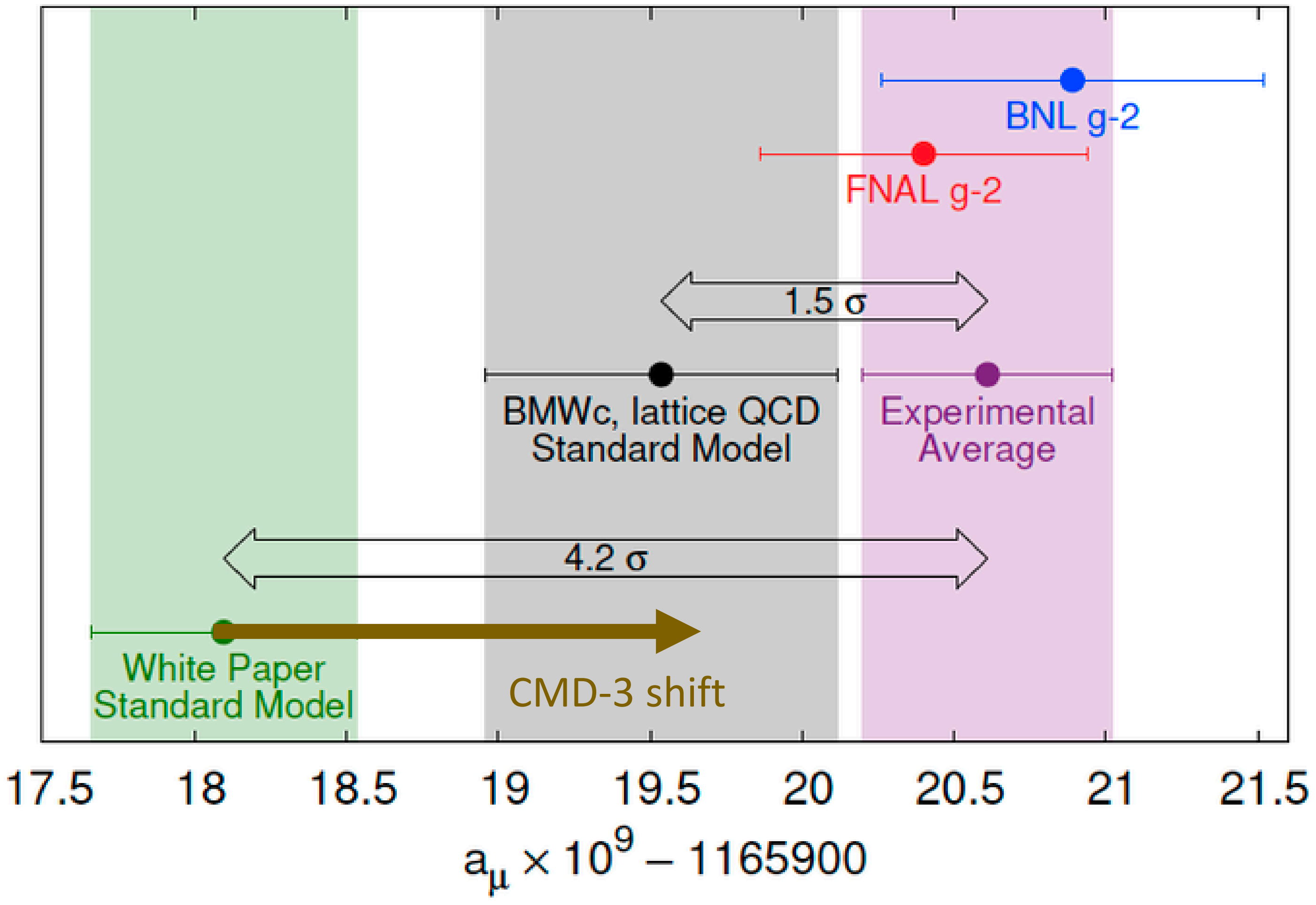

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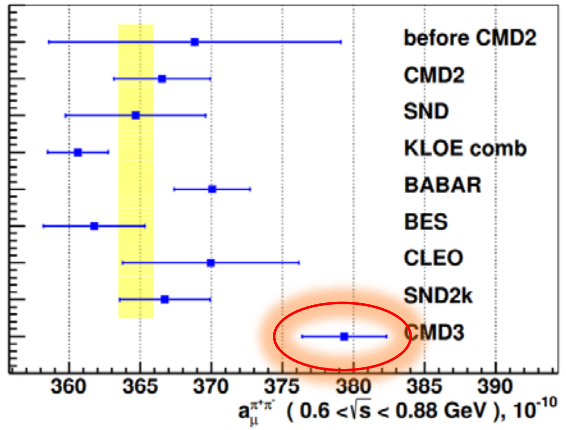
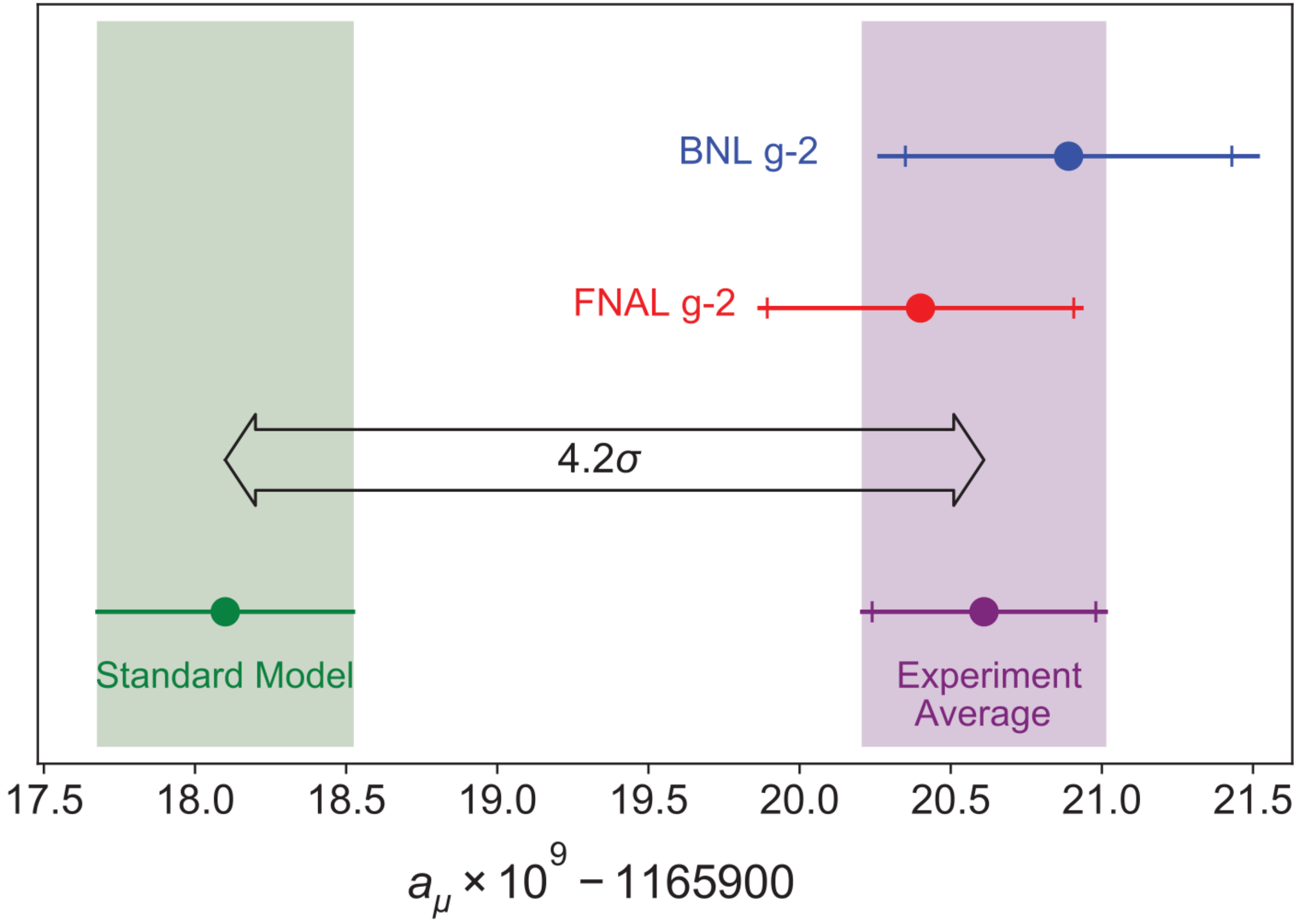
Recent $e^+e^- \to \pi\pi$ VEPP data also [CMD-3 coll. hep-ex/2302.08834]

$$a_\mu^{\mathrm{HVP-LO}}[\pi\pi] = 3793(30) \times 10^{-11}$$

$$(0.6 < \sqrt{s} < 0.9\,\mathrm{GeV})$$



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]