LIGHT NEW PHYSICS & FUNDAMENTAL CONSTANTS

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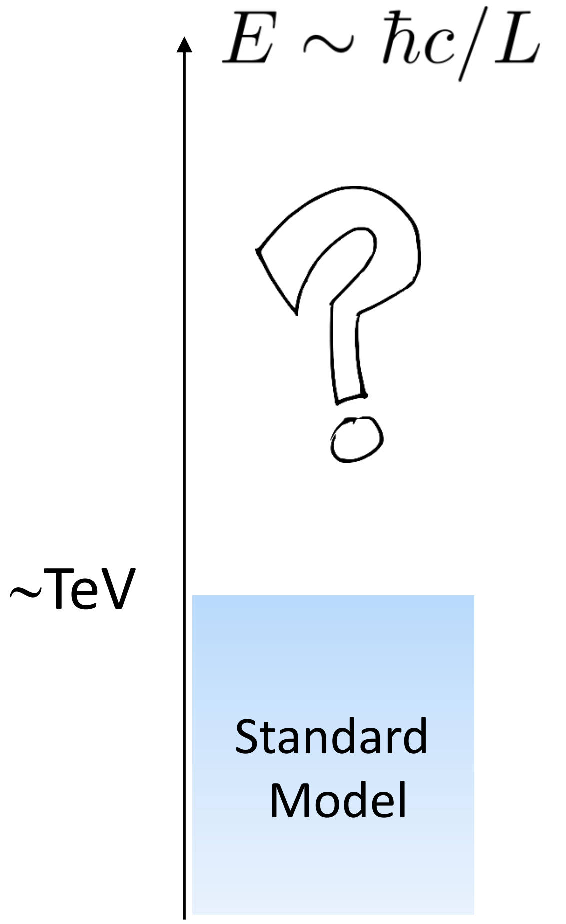
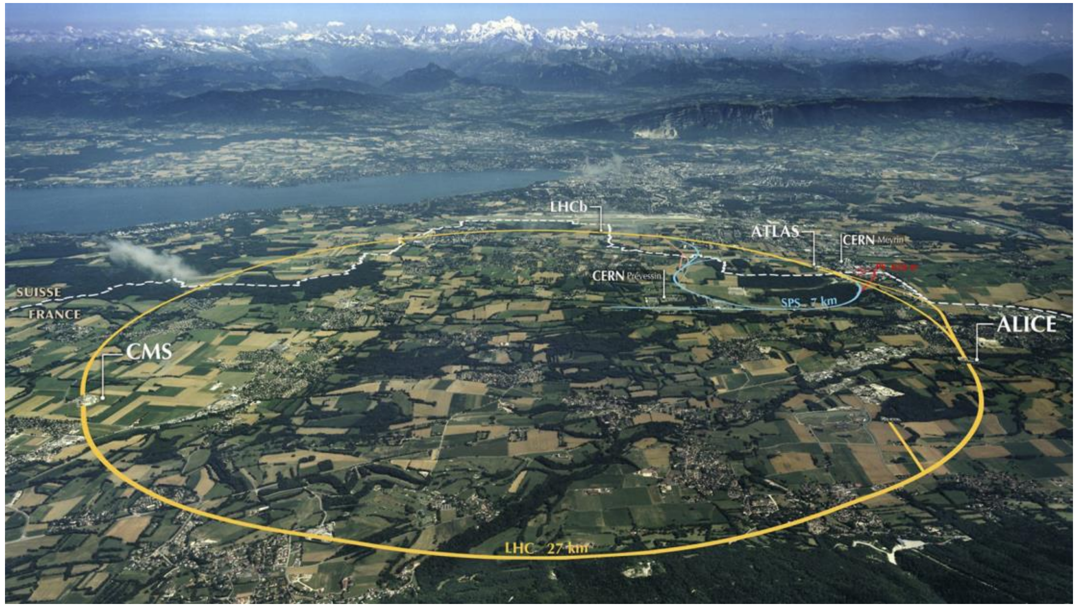
Challenging the Standard Model



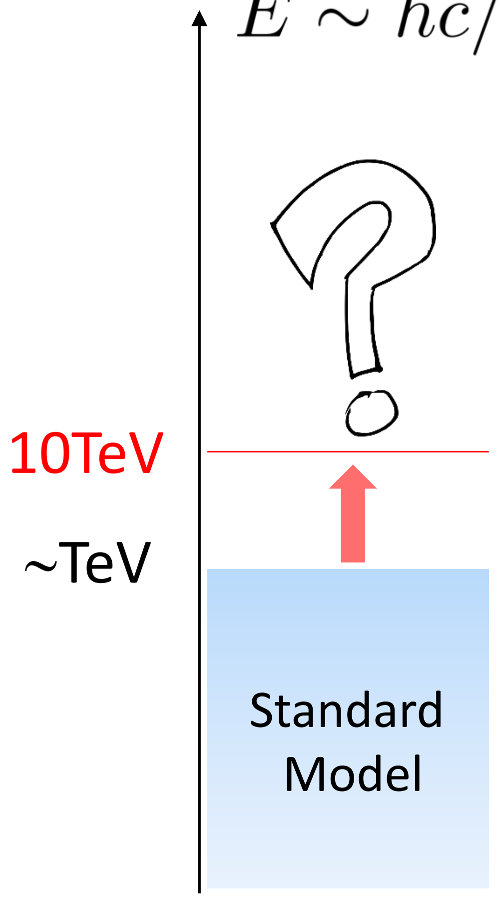
The Standard Model was tested experimentally up to TeV energies $\sim$ 10^{-18}m at the **Large Hadron Collider**

(and indirectly at LEP and flavor factories)

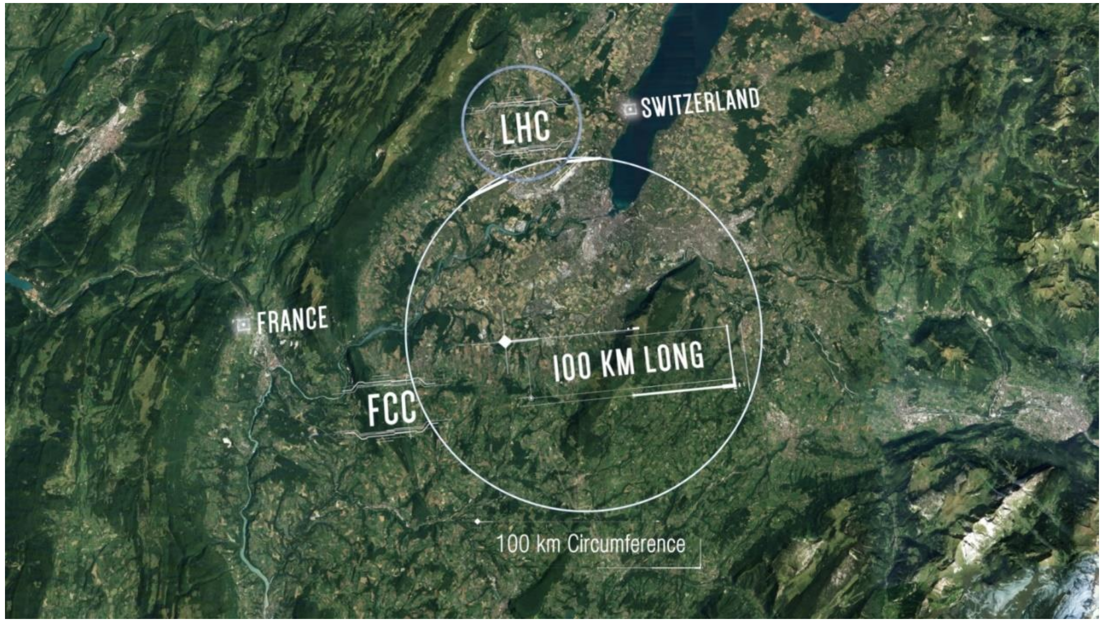


Challenging the Standard Model

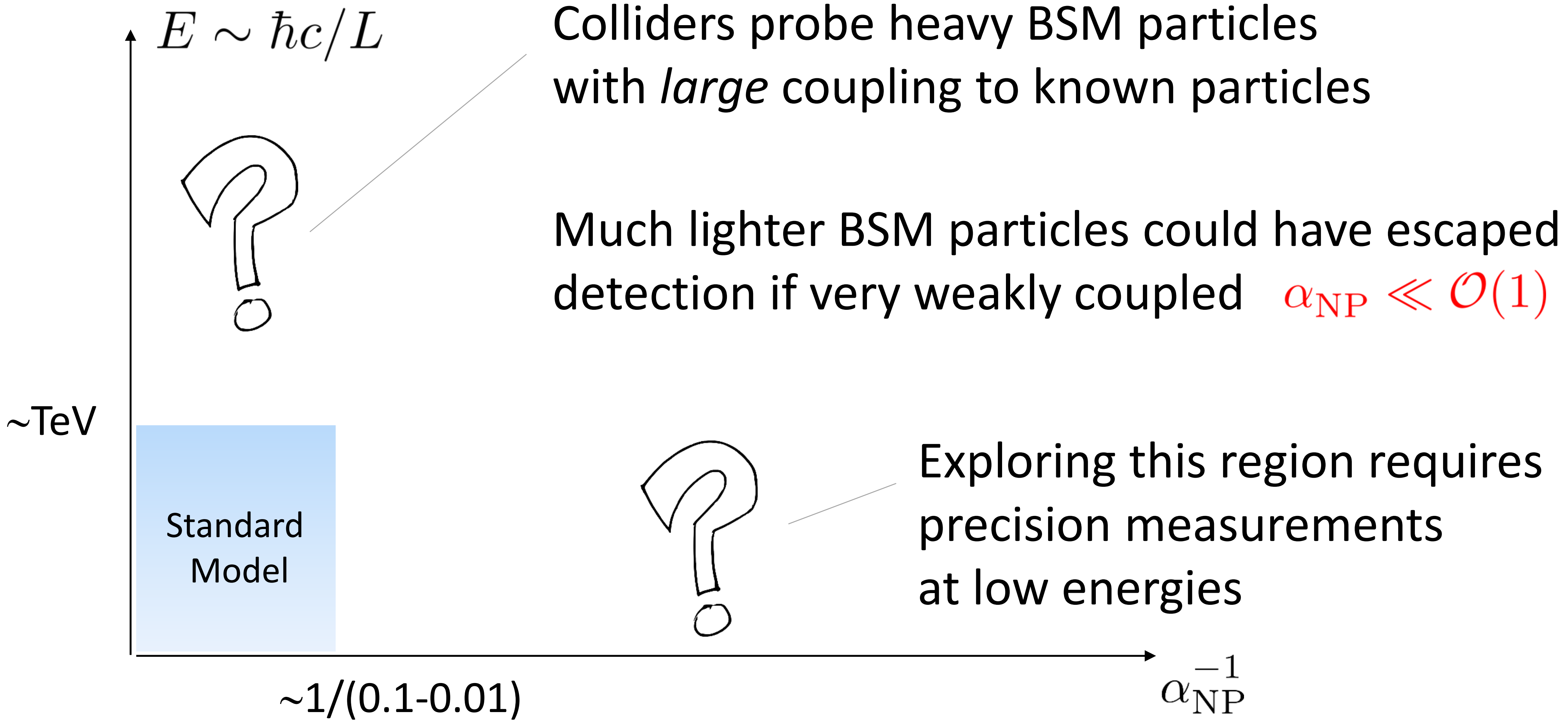
$$E \sim \hbar c / L$$



Next generation of high-energy colliders plan to extend the reach by a factor ~10



Challenging the Standard Model



Light New Physics

Sub-GeV physics beyond the SM is well-motivated theoretically :

- moduli fields in String theory compactifications
- approximate new global symmetries, *e.g.* QCD axion, ALPs, dilaton
- light (mediators for) non-thermal DM, *e.g.* DM produced by freeze-in
- cosmological solutions to the Higgs hierarchy problem, *e.g.* relaxion

The Precision Frontier

Atomic Spectrometry

Accuracy of spectroscopic measurements is very (very!) high:

18 digits in optical clock frequency comparison, e.g. ytterbium vs. strontium

BACON coll. (Nature **591**, 2021)

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

Can it be used to probe BSM physics?

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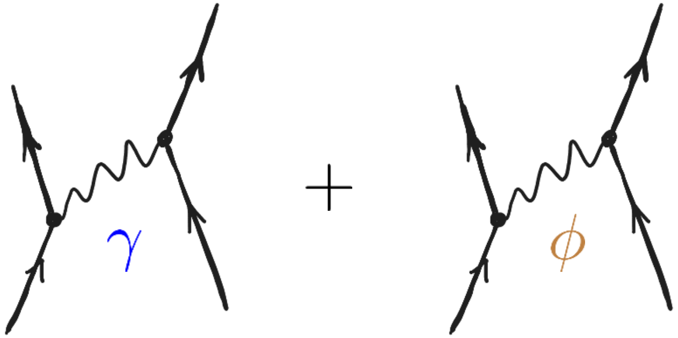
New bosons coupled to electrons and/or nuclei in a *parity-preserving* way will induce an exotic atomic force

$V(r) =$



$-\alpha/r \qquad -(-1)^s \alpha_{\mathrm{NP}} e^{-m_\phi r}/r$

Extracting New Physics

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

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

MBPT theory uncertainty $\sim \mathcal{O}(1\%)$

finite nuclear size $\sim \alpha m_e/\Lambda_{\rm QCD}$

The range of the NP interaction must extend beyond the nucleus.

(NP interactions that breaks P or CP are well-known exceptions. Those are better probed in APV and EDM experiments)

Many-body effects need to be controlled for multi-electron atoms.

A Possible Strategy

Focus on few-body systems where precision QED calculation is possible, *e.g.* Hydrogen, μH, Helium or positronium (e^+e^-), muonium (μ^+e^-)

Hydrogen and muonic hydrogen spectral lines are best measured.
They have the highest sensitivity to NP.

However, these lines are used to determine the values of fundamental (= not predicted by the SM) constants, *assuming the SM holds!*

FCs and NP parameters most be determined together.

Phys.Rev.Lett. 130 (2023) 25, 121801
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Y. Soreq (Technion),
and J. Zupan (U. Cincinnati)

The BSM CODATA

The 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:

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

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

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:

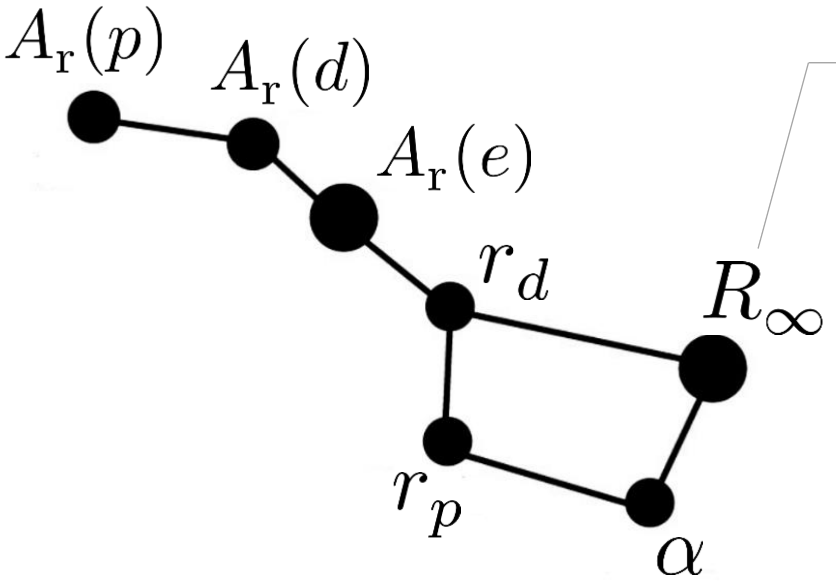
$$u_{R_\infty} = 1.9 \times 10^{-12}$$

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!

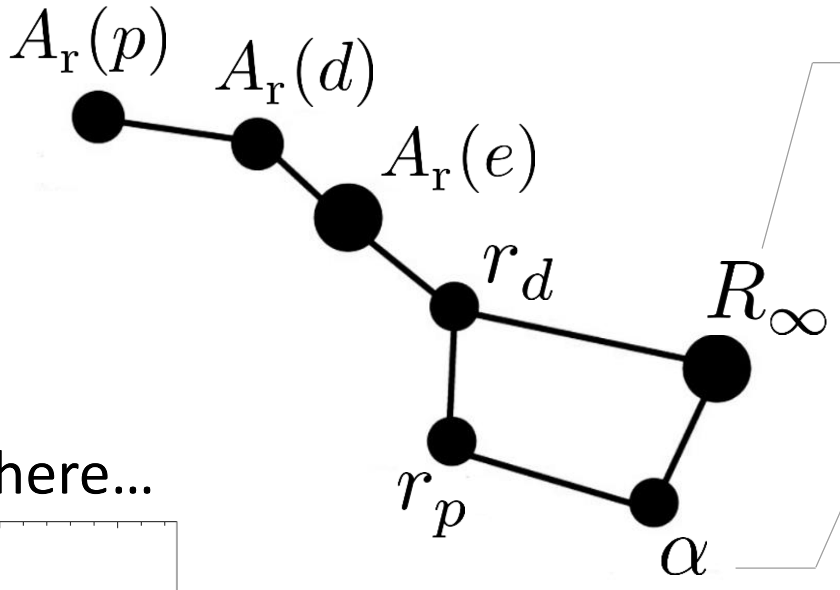
A Constellation of Constants



Rydberg constant

hydrogen ν_{1S-2S} (+22 other lines)

A Constellation of Constants



Rydberg constant

hydrogen ν_{1S-2S} (+22 other lines)

fine structure constant

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

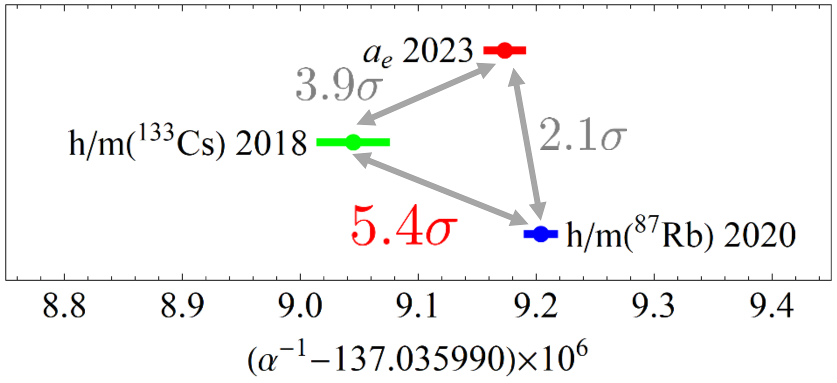
or atomic recoil

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

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

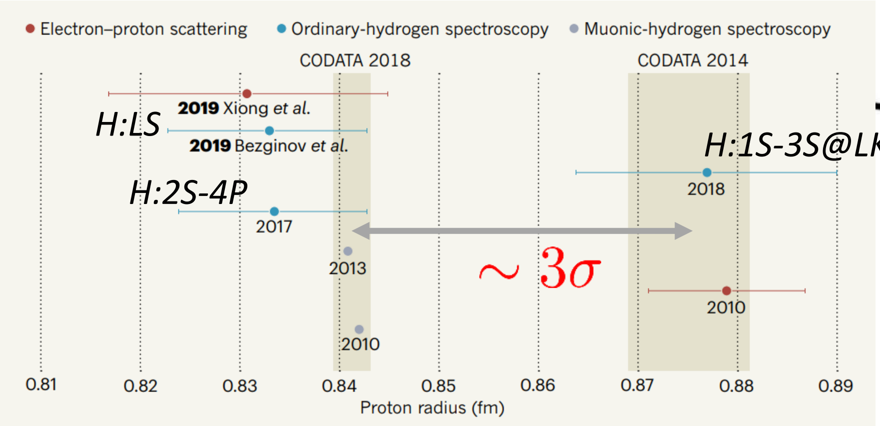
^{133}Cs **Parker** et al. [2018]

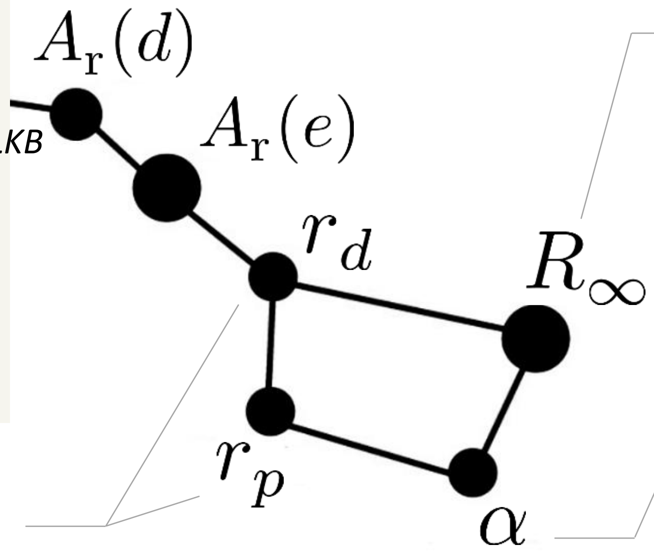
There are **tensions** there...



A Constellation of Constants

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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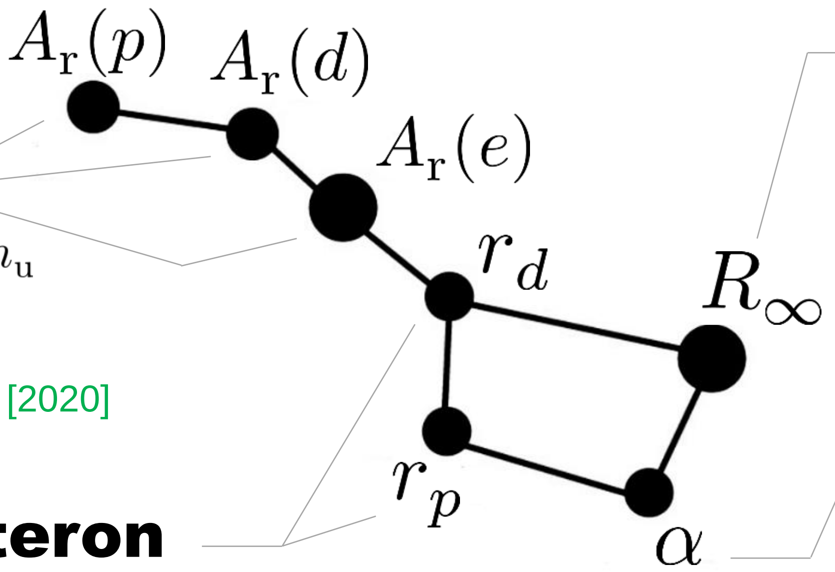

atomic mass constants $m_X = A_r(X) m_u$

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

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

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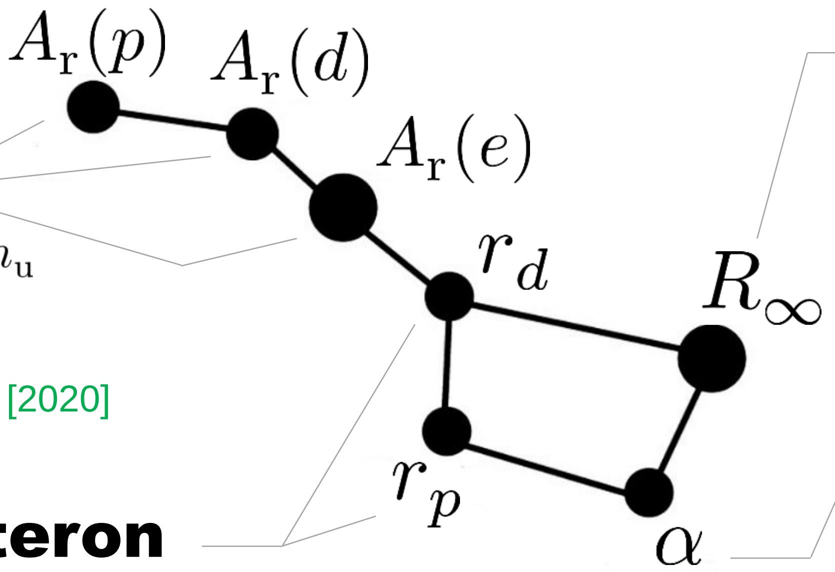

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to be determined together in a global fit

$\rightarrow$ **CODATA** recommended values

https://pml.nist.gov/cuu/Constants/

CODATA 2018 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 this robust to **BSM**?

BSM CODATA

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

spin: s

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

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

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 $\mathcal{O}$:

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

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

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	$a_e \equiv \frac{1}{2}(g-2)_e$	$1.159\,652\,180\,73(28)\times10^{-3}$	2.4×10^{-10}
D2	δ_e	$0.000(18)\times10^{-12}$	1.5×10^{-11}
D3	$h/m_{\rm Rb}(^{87}{\rm Rb})$	$4.591\,359\,272\,9(57)\times10^{-9}\ {\rm m^2s^{-1}}$	
D4	$h/m_{\rm Cs}(^{133}{\rm Cs})$	$3.002\,369\,472\,1(12)\times10^{-9}\ {\rm m^2s^{-1}}$	
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	$\Delta E_{\rm B}(^{12}{\rm C}^{5+})/hc$	$43.563\,233(25)\times10^{7}\ {\rm m^{-1}}$	
D9	$\delta_{\rm C}$	$0.0(2.5)\times10^{-11}$	
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	$\Delta E_{\rm B}(^{28}{\rm Si}^{13+})/hc$	$420.6467(85)\times10^{7}\ {\rm m^{-1}}$	
D13	$\delta_{\rm Si}$	$0.0(1.7)\times10^{-9}$	
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	$\Delta E_{\rm B}(^{1}{\rm H}^{+})/hc$	$1.096\,787\,717\,430\,7(10)\times10^{7}\ {\rm m^{-1}}$	
D23	$\Delta E_{\rm B}(^{12}{\rm C}^{6+})/hc$	$83.083\,850(25)\times10^{7}\ {\rm m^{-1}}$	

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 lines, ***g*$_e$-2** and **atomic 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	$a_e \equiv \frac{1}{2}(g-2)_e$	$1.159\,652\,180\,59(13)\times10^{-3}$	1.1×10^{-10}	Fan *et al.* [70]
D3	$h/m_{\rm Rb}(^{87}{\rm Rb})$	$4.591\,359\,258\,90(65)\times10^{-9}\ {\rm m^2s^{-1}}$	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	$\delta_{\rm C}$	$0.0(9.4)\times10^{-12}$	4.9×10^{-12}	Czarnecki *et al.* [71]
D13	$\delta_{\rm Si}$	$0.0(5.8)\times10^{-10}$	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	$\Delta E_{\rm B}(^{2}{\rm H}^{+})/hc$	$1.097\,086\,145\,529\,9(10)\times10^{7}\ {\rm m^{-1}}$	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	$\nu_{\bar{p}^4{\rm He}}((32,31)-(31,30))$	1 132 609 226.7(4.0) MHz	3.5×10^{-9}	Hori *et al.* [37]
G2	$\nu_{\bar{p}^4{\rm He}}((33,32)-(31,30))$	2 145 054 858(7) MHz	3.4×10^{-9}	Hori *et al.* [36]
G3	$\nu_{\bar{p}^3{\rm He}}((32,31)-(31,30))$	1 043 128 581(6) MHz	6.2×10^{-9}	Hori *et al.* [37]
G4	$\nu_{\bar{p}^3{\rm He}}((35,33)-(33,31))$	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]

New Physics Models

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

$q_\ell = -q_p = -1$

$q_n = 1$ $\leftarrow$ highlights deuterium

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

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

$q_\ell = -q_p = -1$

$q_n = 0$

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

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

$q_\ell = m_\ell/\sqrt{m_e \kappa_p m_p}$ $\leftarrow$ 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

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

$q_\ell = 0$ $\leftarrow$ highlights molecules

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

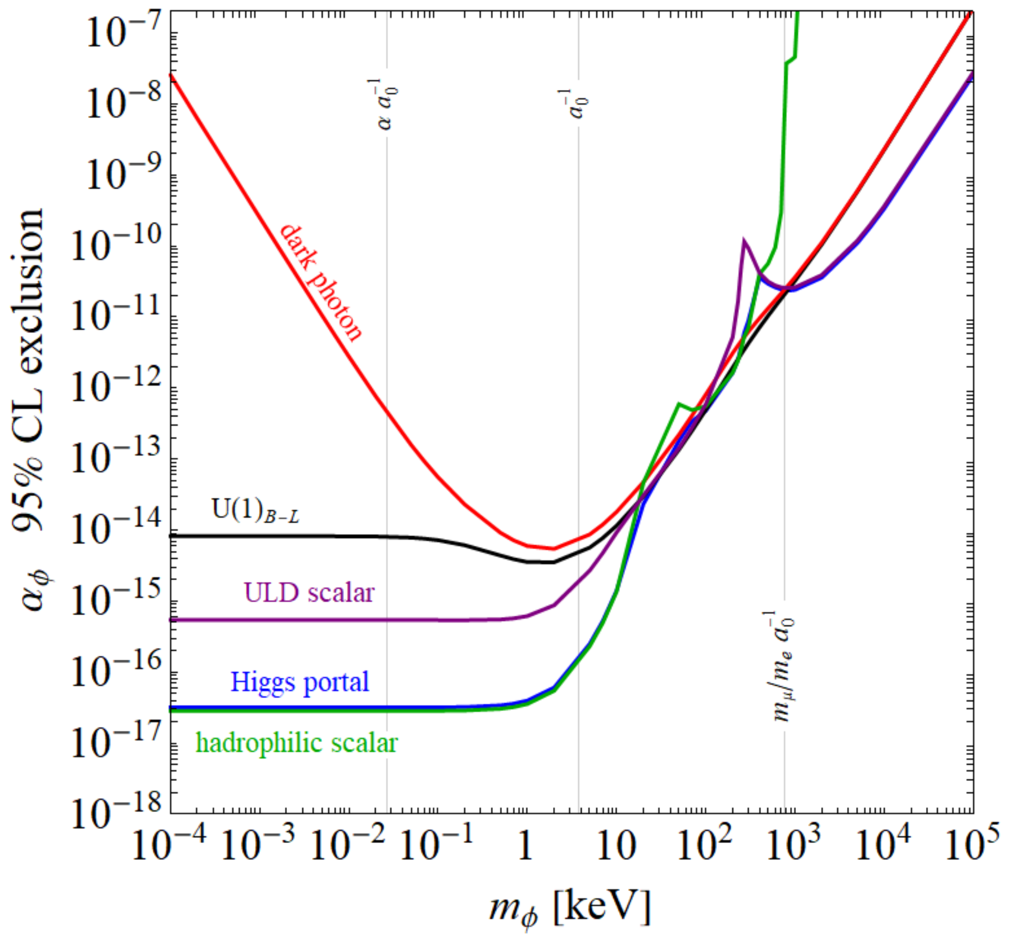
Up-Lepto-Darko-philic (ULD) scalar $\alpha_\phi = k^2 m_e \kappa'_p m_p/(4\pi v^2)$

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

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

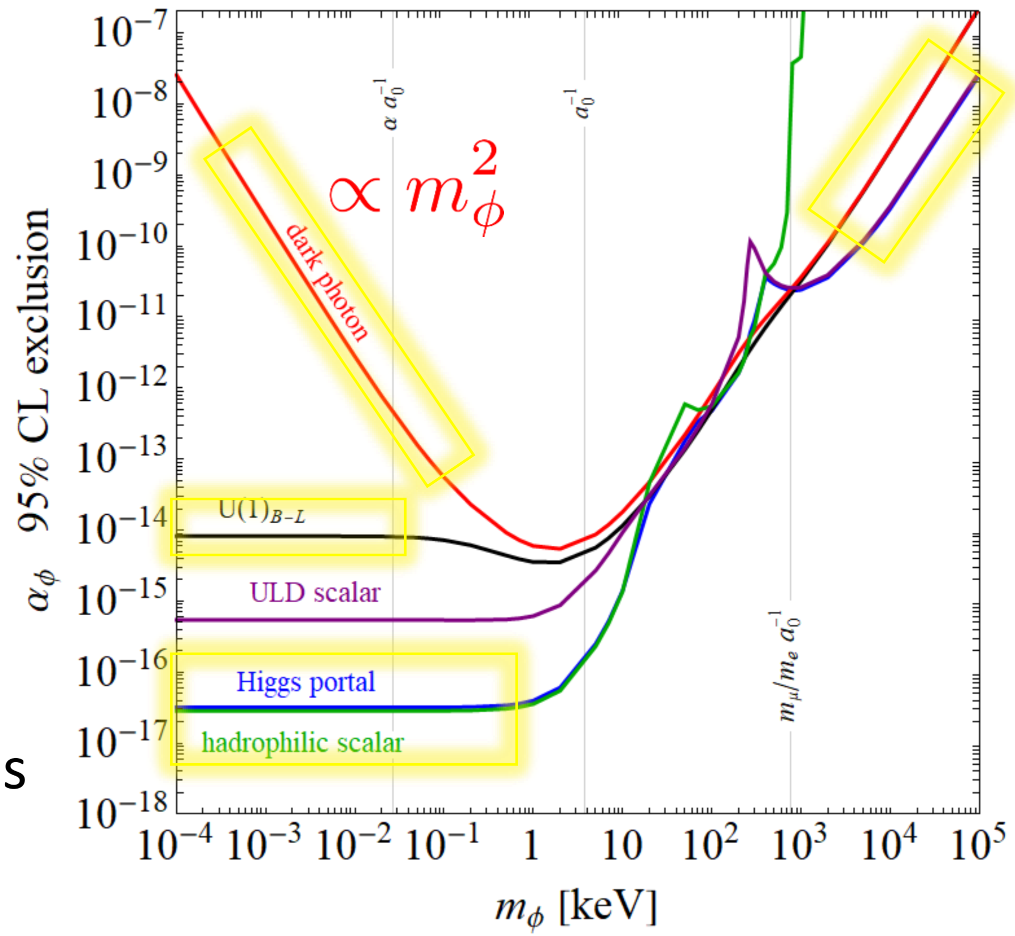
+ dominant ϕ decay to invisible states *(see later)*

New Physics Bounds



New Physics Bounds

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



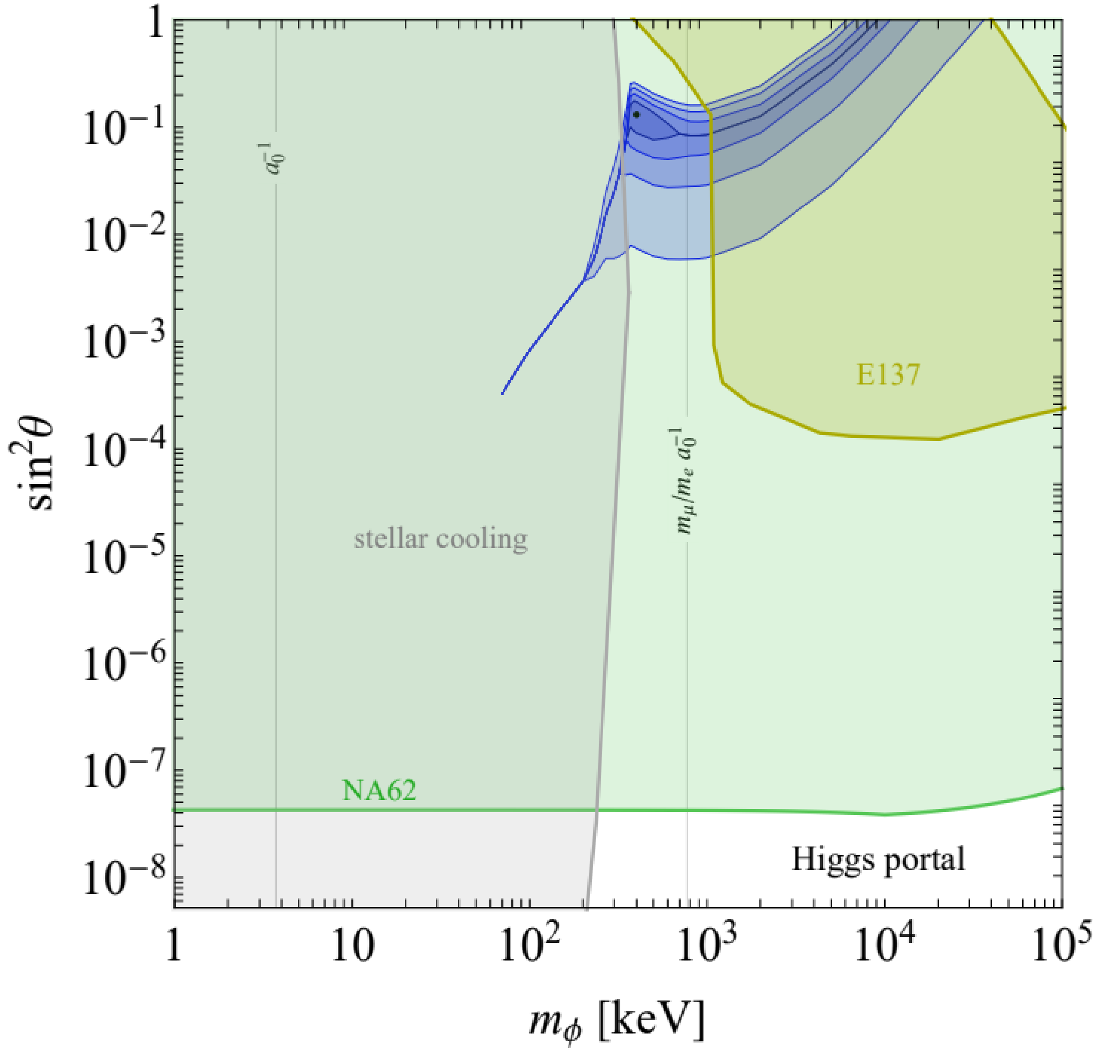
stronger sensitivity from **muonic** atoms in models where

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

stronger sensitivity from internuclear forces in **molecules** in models where

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

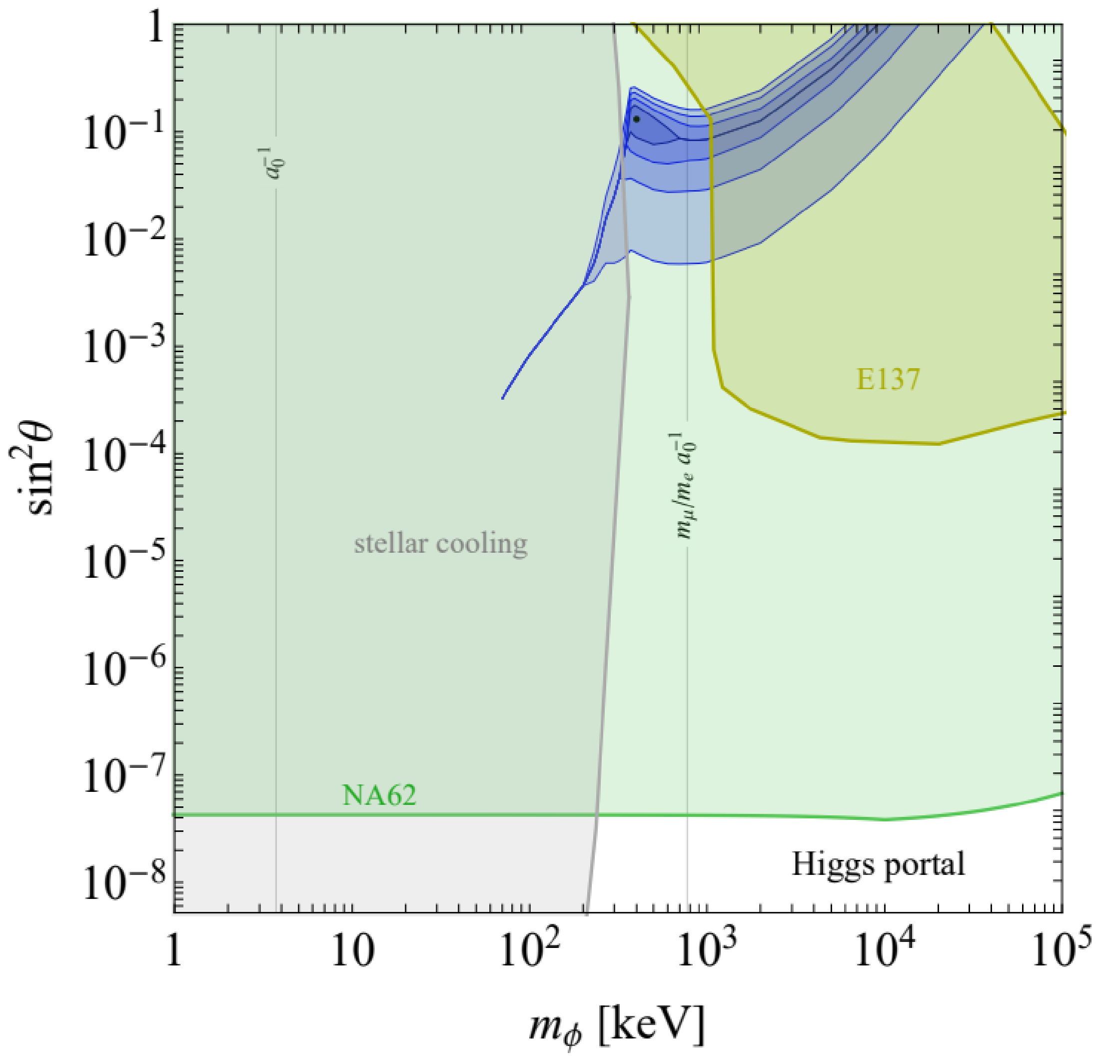
Non-zero Higgs Portal?



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?



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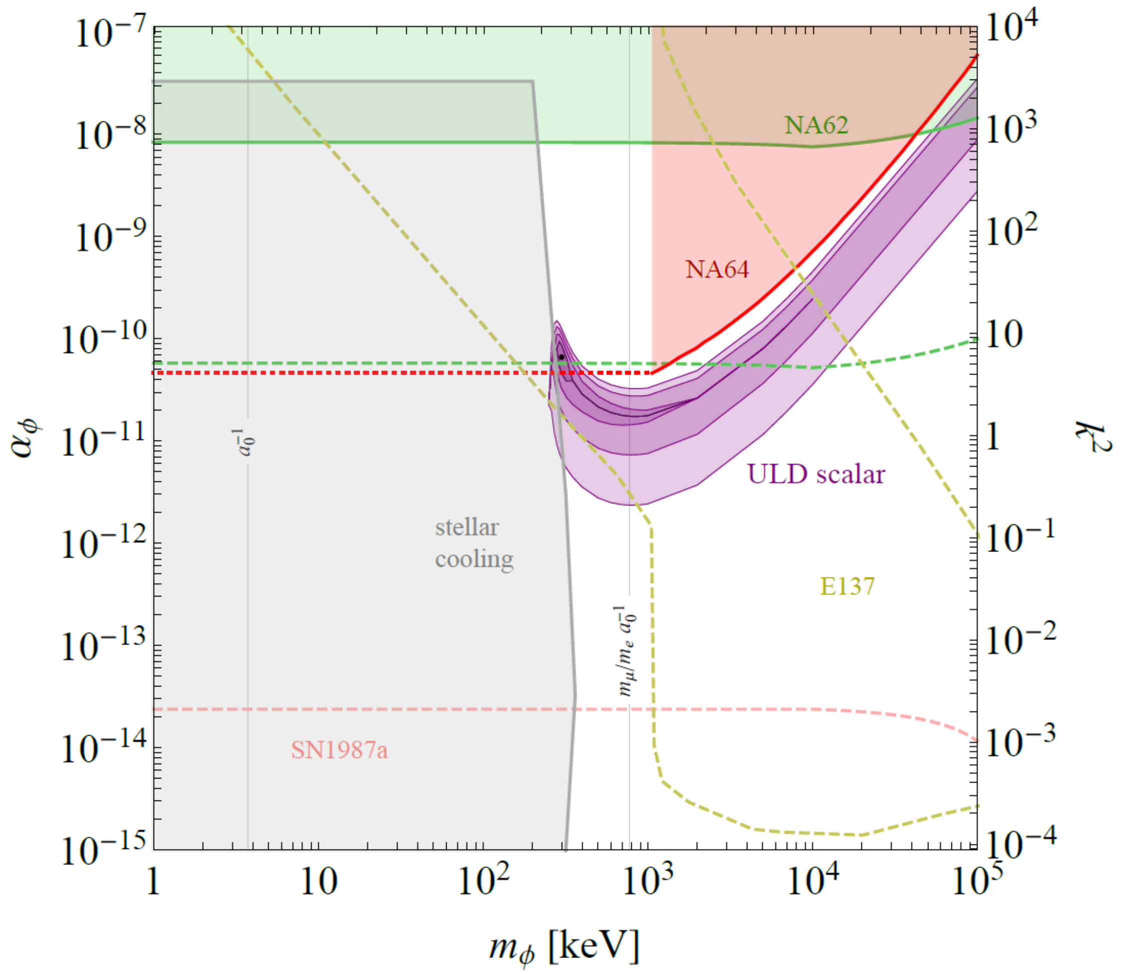
The **NA62** bound is driven by coupling to heavy quarks through one-loop penguins

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

Evidence for ULD 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 ($\phi \to \mathrm{DMDM}$?)

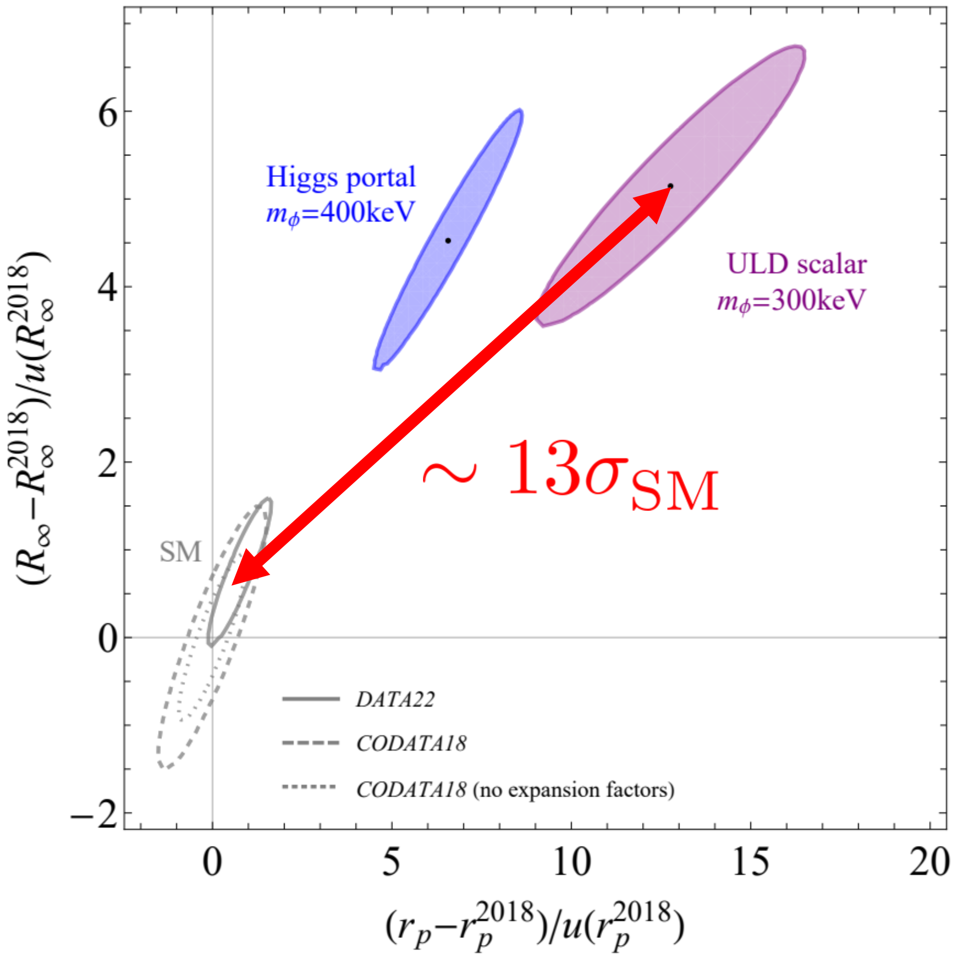
In that case **NA64** is relevant

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

Andreev et al. [2021]

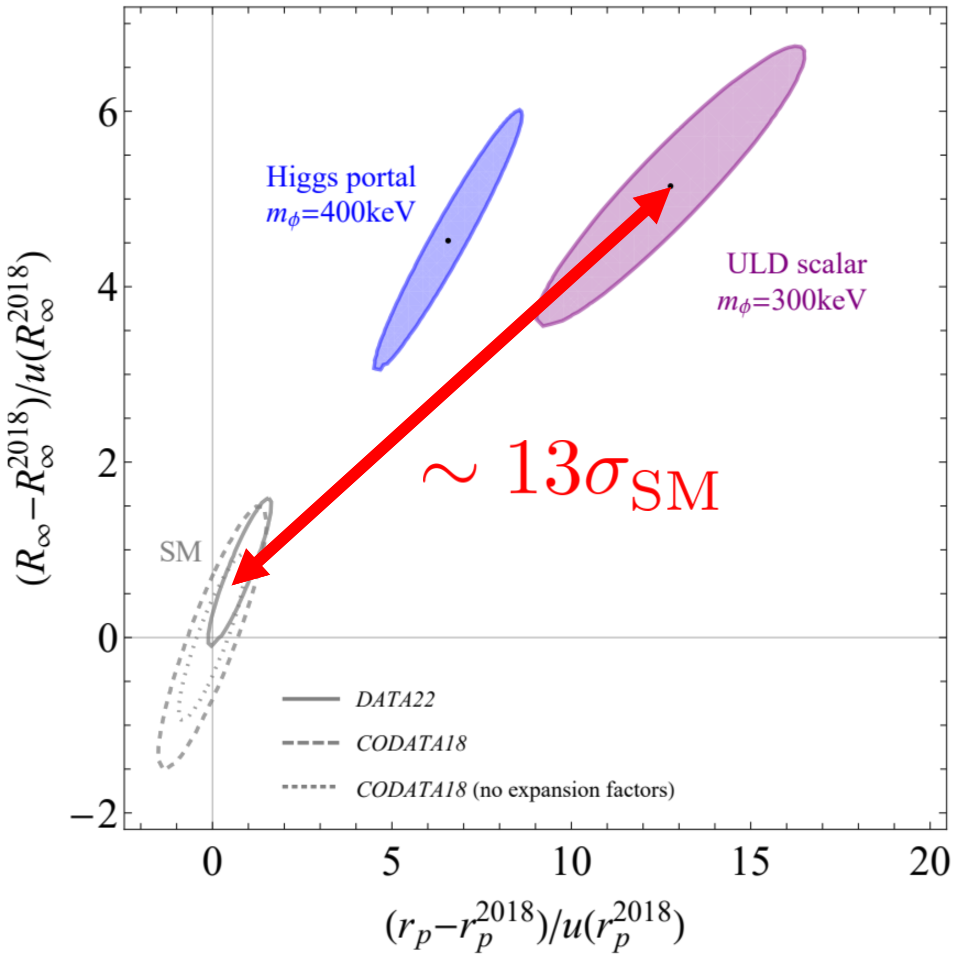
yielding a weaker bound but NP sensitivity not clear below MeV

Impact on fundamental constants



Fondamental Contants undergo **huge shifts** in the presence of NP

Impact on fundamental constants



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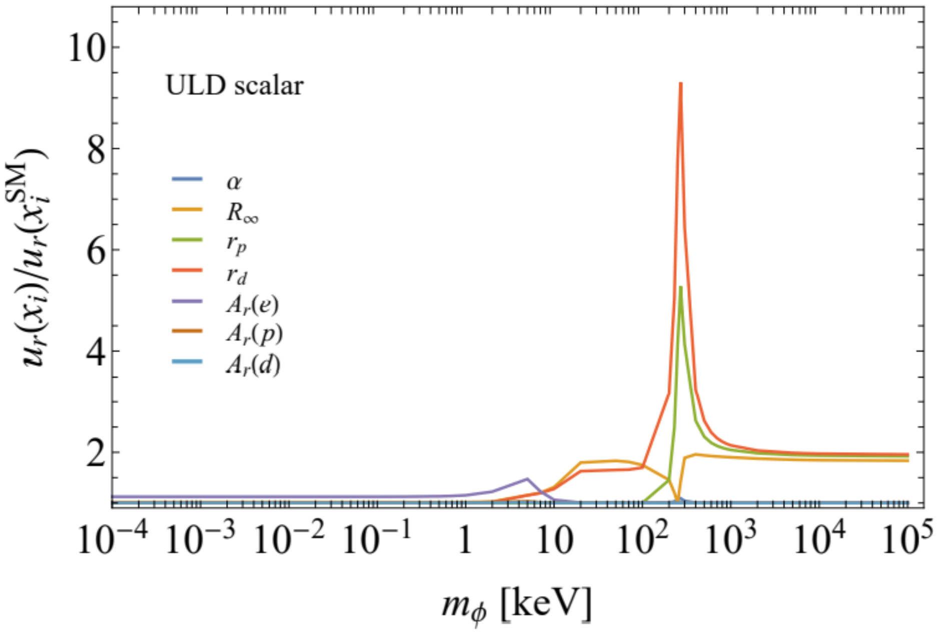

and their uncertainty *significantly* inflates relative to the SM-only hypothesis

Conclusions

Conclusions

Physicists (almost) exclusively searched for BSM at TeV energies and above, thinking physics at lower energies is very well understood.

Light & weakly-coupled New Physics is well motivated theoretically.
Atomic spectroscopy can be repurposed to search for it.

Such low-energy probes complement the efforts (to be) invested at colliders

$\rightarrow$ « multi-messenger » program for HEP searches

PhysTeV 2025 workshop in Les Houches

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backups

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:

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

massless dark photon is **unobservable**!

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

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

would fictitiously distinguish photon from darkphoton

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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**

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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 $\delta q_i Q_j + Q_i \delta q_j$