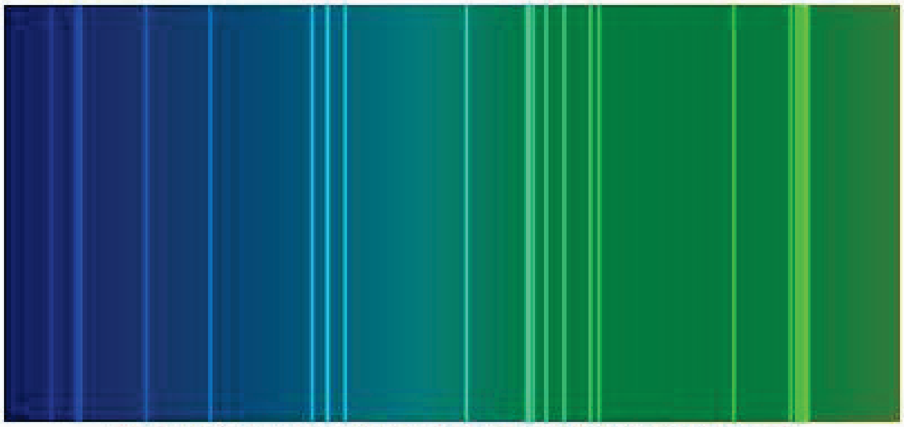
Probing the Atomic Higgs force

-and more-



Shifting lines: has the Higgs affected this spectrum?

Cédric Delaunay
CNRS/LAPTh
Yotam Soreq
MIT

CD, R. Ozeri, G. Perez, YS
hep-ph: 1601.05087 + in progress
CD, YS hep-ph:1602.04838
C. Frugiuele, E. Fuchs, G. Perez, M. Schlaffer hep-ph:1602.04822

Higgs tasting
20-05-2016 | Benasque

Outline

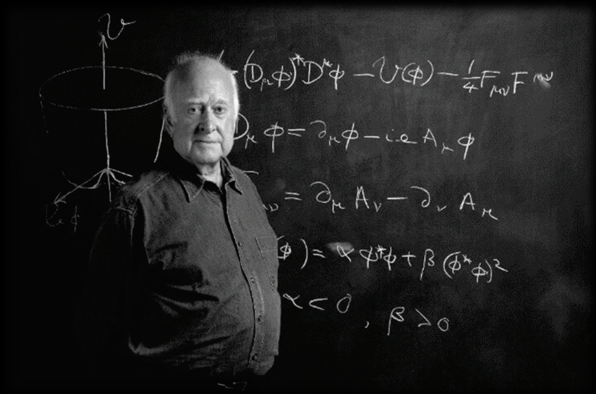
1. The Higgs Mechanism and the Flavor Puzzle
2. Higgs Force in Atoms
3. Probing Higgs Couplings with Isotope Shift
4. The Weak Force
5. New Physics Forces

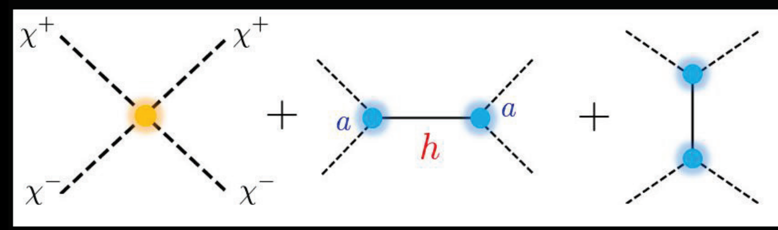
Yotam's talk

The Higgs Mechanism and the Flavor Puzzle

The Higgs Mechanism

- breaks EW symmetry: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to U(1)_{\mathrm{QED}}$





$\propto \frac{E^2}{v^2}(1 - a^2)$

ATLAS+CMS: $|a-1| \lesssim \mathcal{O}(10\%)$

ATLAS-CONF-2015-044

- provides charged fermion masses:

in the SM: $m_f = y_f \times v$

The flavor Puzzle

- Charged fermion masses are highly hierarchical:

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- Charged fermion masses are highly hierarchical:

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- The origin of this hierarchy is unknown, despite a host of precision flavor measurements.

- Within the SM, it is ***assumed*** to originate from hierarchical Higgs-to-fermion couplings:

$$y_f^{\mathrm{SM}} \propto m_f$$

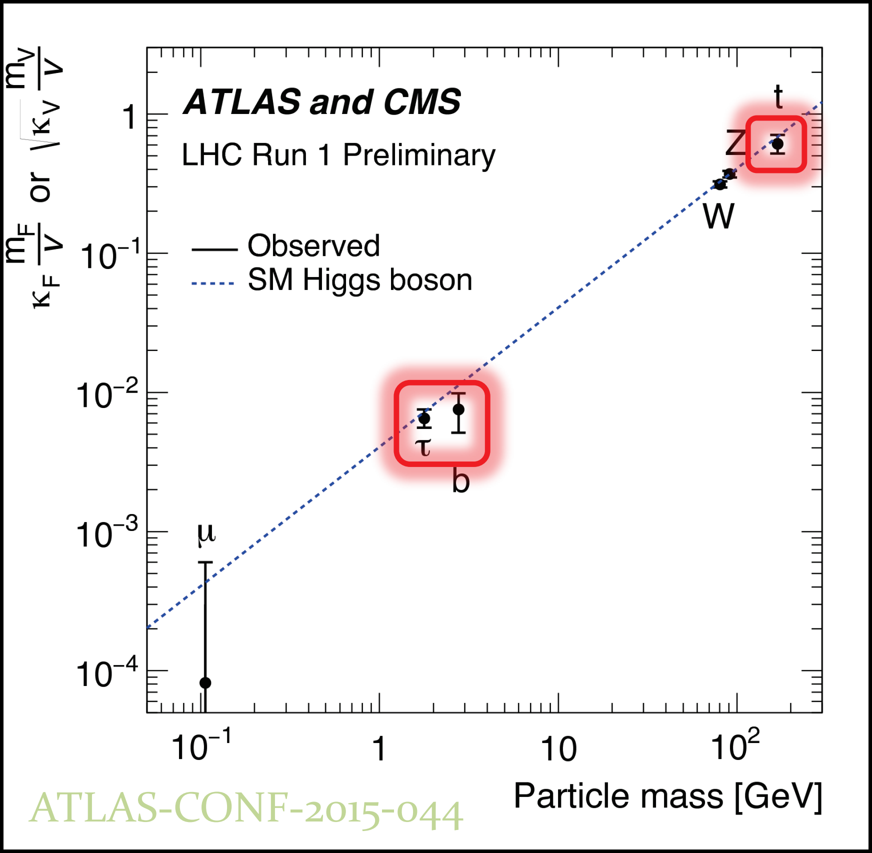
How well can we test?

The Flavor Puzzle at LHC

ATLAS+CMS
Higgs-signal/SM:

$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

μ_{ttH}	$2.3^{+0.7}_{-0.6}$



→ the Higgs mechanism is likely to be the dominant source of 3rd generation masses

The Flavor Puzzle at LHC

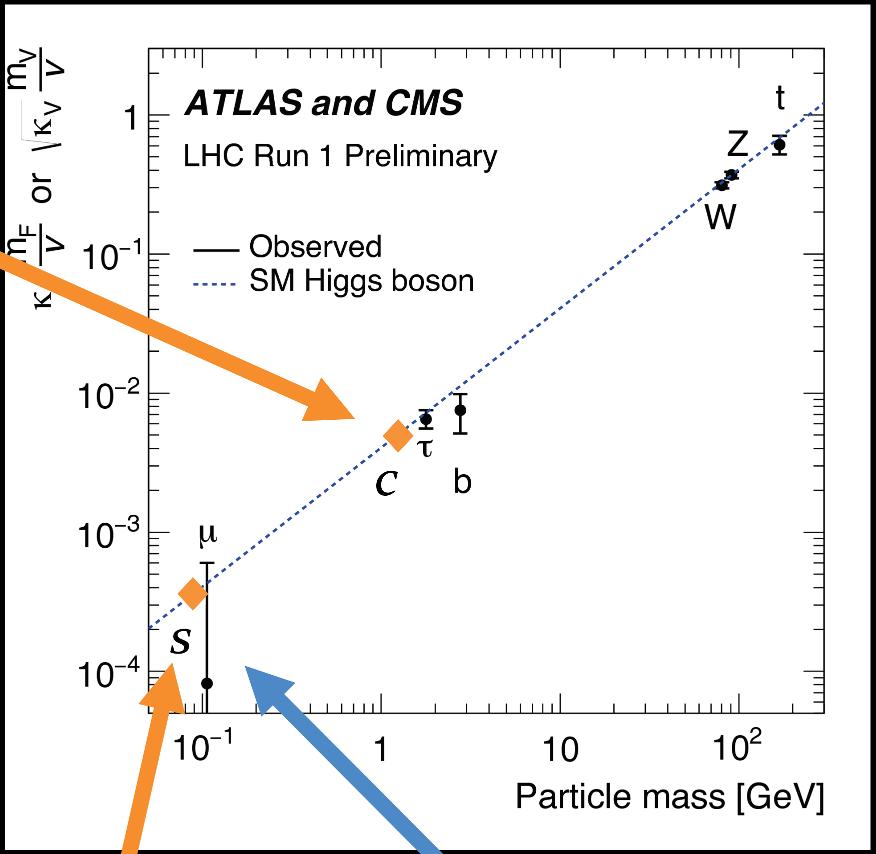
There is an opportunity to probe *c*-coupling directly, thanks to charm-tagging:

in VH production

Perez-Soreq-Stamou-Tobioka '15

in Hc production

Isidori-Goertz '15



Other probes exist:

- $h \to J/\psi\gamma$

  Perez-Soreq-Stamou-Tobioka '15

- global fits

  CD-Golling-Perez-Soreq '13

- $\Gamma_h \leq 1.7\,\mathrm{GeV}$

  Perez-Soreq-Stamou-Tobioka '15

$h \to \phi\gamma$?

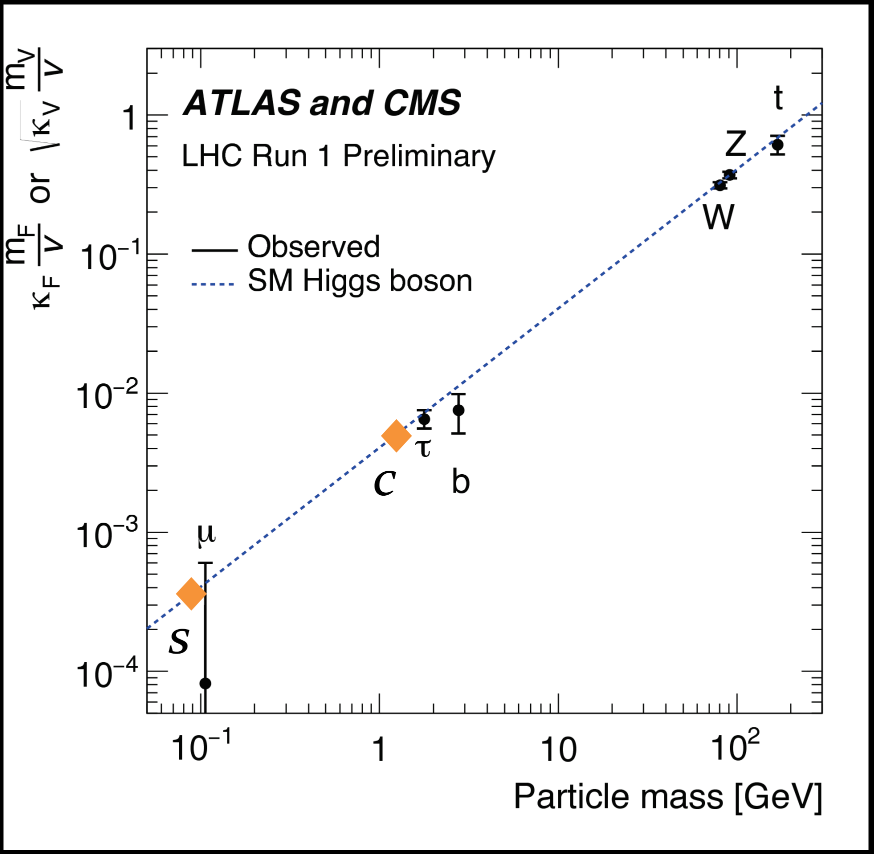
Kagan et al. '14

Sensitivity to muon-coupling, with high-enough luminosity

ATL-PHYS-PUB-2014-016

The Flavor Puzzle at LHC

What about e, u, d?



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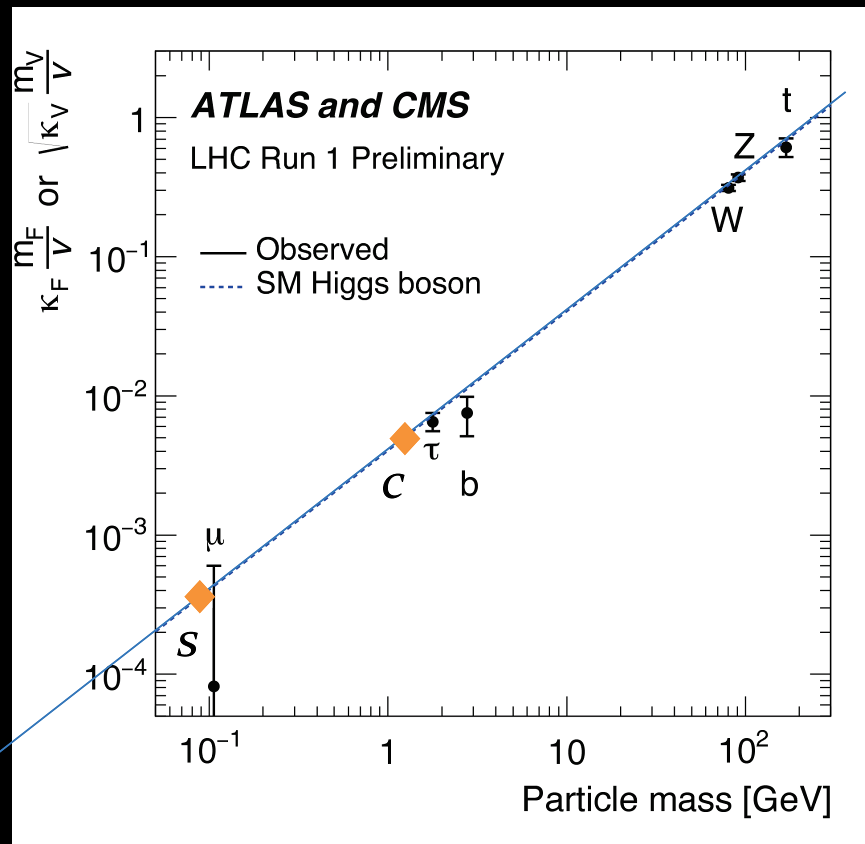
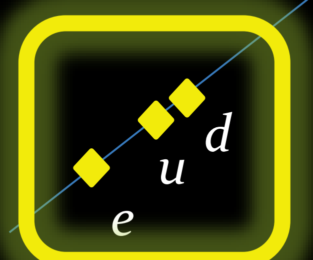




[stable nuclei]
[chemistry]

Probing the couplings to the building blocks of matter is an important test of the Higgs mechanism

The Flavor Puzzle at LHC

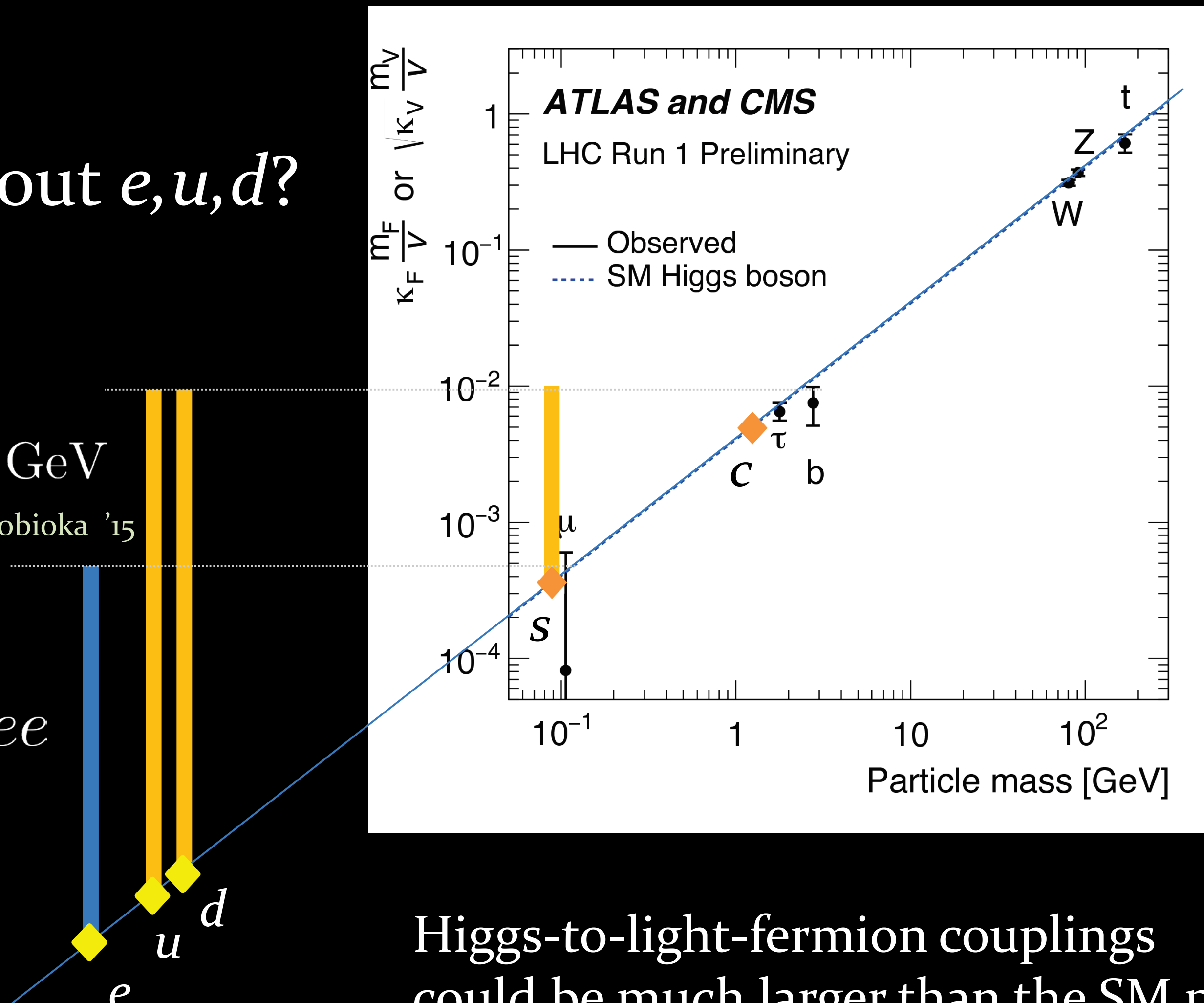
What about e, u, d?

$\Gamma_h \leq 1.7\,\mathrm{GeV}$

Perez-Soreq-Stamou-Tobioka '15

$h \to ee$

Altmannshofer-Brod
-Schmaltz '15



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could be much larger than the SM prediction.
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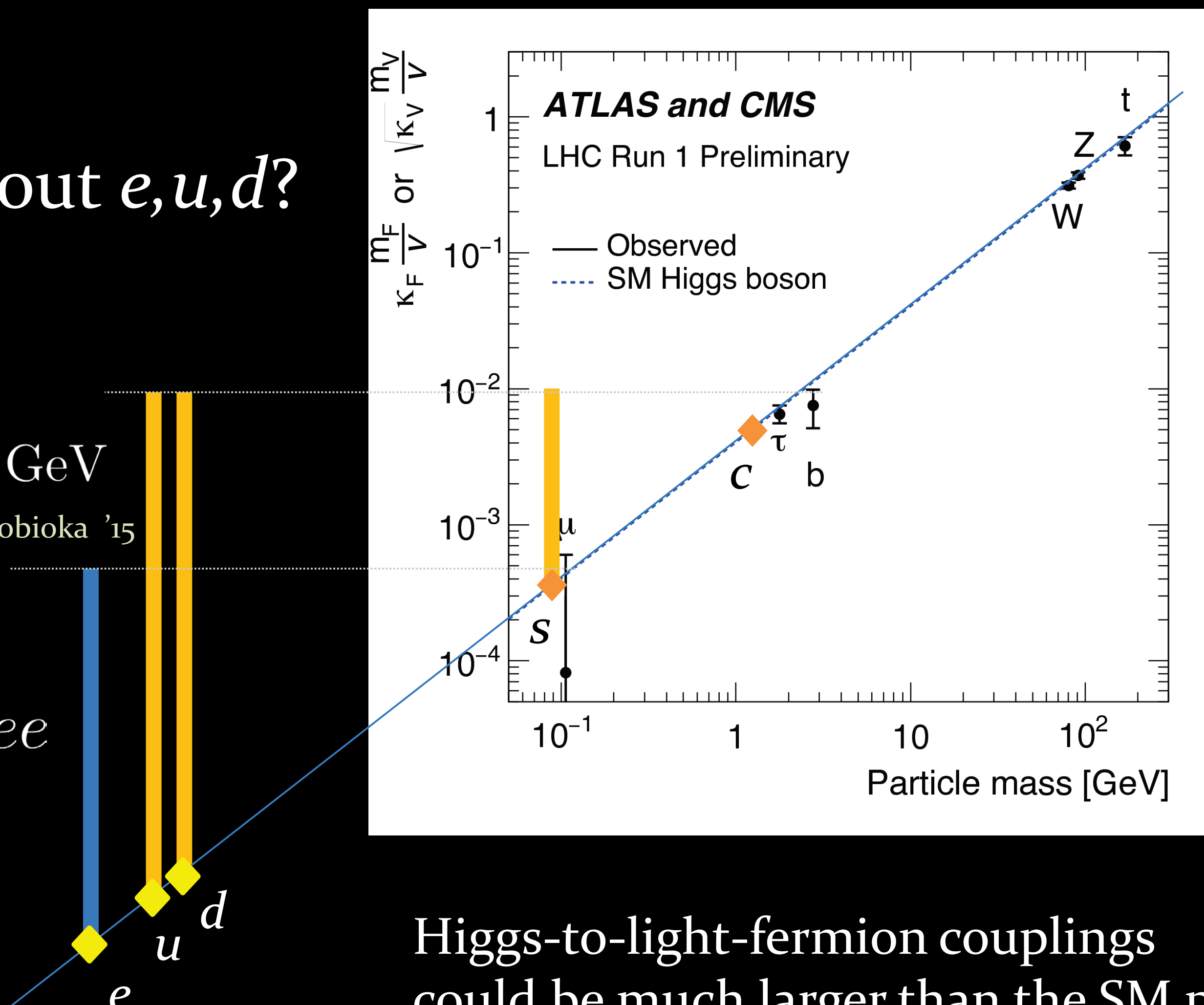

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The atomic
Higgs force

The Atomic Higgs Force

- The Higgs results in an attractive force between nuclei and their bound electrons (à la Yukawa):

$$V_{\rm Higgs}(r) = -\frac{y_e y_A}{4\pi}\frac{e^{-m_h r}}{r} \approx -\frac{y_e y_A}{4\pi m_h^2}\frac{\delta(r)}{r^2}$$

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- $y_A = Z y_p + (A - Z) y_n$ with:

Shifman-Vainshtein-Zakharov '78
+ nuclear data, see *e.g.* micrOmegas

$$y_n \approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$
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$\mathcal{O}(10-20\%)$ uncertainties in matching

- c_g constrained by LHC, weaker sensitivity to s-coupling

Higgs Force Strength

- Under current LHC constraints:

Higgs width (direct)

$$y_{n,p} \lesssim 3 \ (0.2) \qquad \text{and} \qquad y_e \lesssim 1.3 \times 10^{-3}$$

global fit (indirect)

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- Higgs force possibly stronger than SM by $\sim 10^6$!
- This shifts transition frequencies by:

electron-density at the nucleus

$$\Delta\nu^{\text{Higgs}}_{nS\to n'D,F} \approx 1\,\text{Hz} \times A\,\frac{y_e y_{n,p}}{0.004}\,\frac{|\psi(0)|^2}{4n^3 a_0^{-3}}$$

Bohr radius $(\alpha m_r)^{-1}$

Optical Atomic
Clock Transitions

Optical Atomic Clocks

- State-of-the-art accuracy at the 10^{-18} level

Bloom et al., Nature 506, 71-76 (2014)

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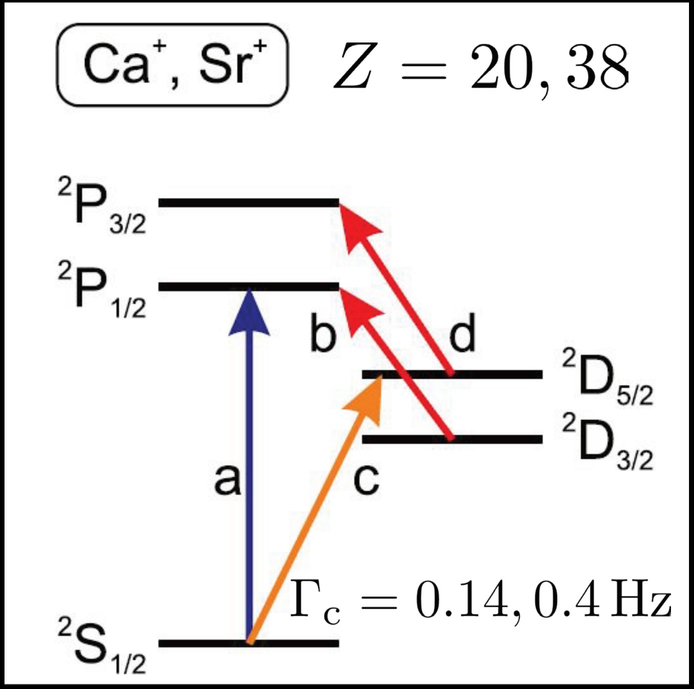
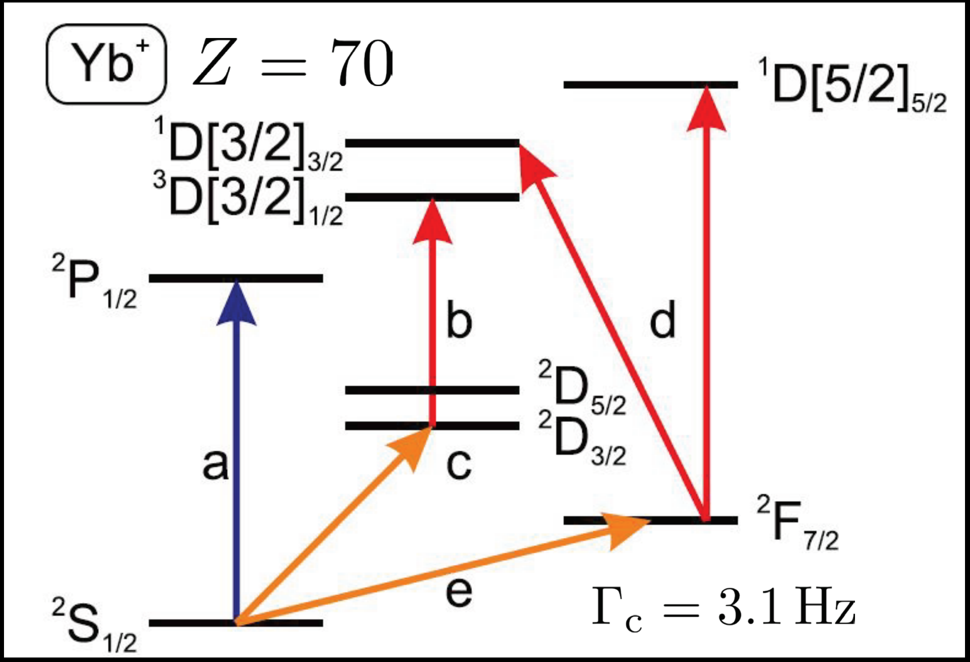
Bloom et al., Nature 506, 71-76 (2014)

- Narrow transitions with S-wave are needed:

Ludlow-Boyd-Ye, Rev. Mod. Phys. 87 (2015)





$\Gamma_e = 10^{-9}\,\mathrm{Hz}$

Frequency Comparisons

- Experimental accuracy in $^{40}\mathrm{Ca}^+$, $^{88}\mathrm{Sr}^+$ is $\sim \mathrm{Hz}$

Dube et al., Phys. Rev. A87 (2013)
Chwalla et al., PRL 102 (2009)

$$\nu_{E2}^{\mathrm{Ca}^+} = 411\ 042\ 129\ 776\ 393.2(1.0)\mathrm{Hz}$$

$$\nu_{E2}^{\mathrm{Sr}^+} = 444\ 779\ 044\ 095\ 485.5(9)\mathrm{Hz}$$

$$\sim 10^{15}\mathrm{Hz}$$

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- Theory side is however much less promising:

electron-electron correlations, nuclear finite-size, relativistic corrections, QED...

are not accounted for at the 10^{-15} level...

Isotope Shifts and King plots

Isotope Shift

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- Transition frequencies are largely dominated by EM effects, most of which remains unchanged for different A, A' isotopes, because same charge

(consider $A' - A = 2, 4, \ldots$ *to avoid influence of nuclear spin)*

- The Higgs force however scales like the nuclear mass A, so there is still a net shift between isotopes!

Isotope Shift Sources

- There are yet non-trivial IS from changes in:
  - the reduced mass: $m_r = \frac{m_e m_A}{m_e + m_A} \simeq m_e(1 - m_e/m_A)$
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mass shift   field shift   Higgs shift

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- MS/FS effects are typically in the GHz range $\gg$ HS

The King Plot

W. H. King,
J. Opt. Soc. Am. 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$

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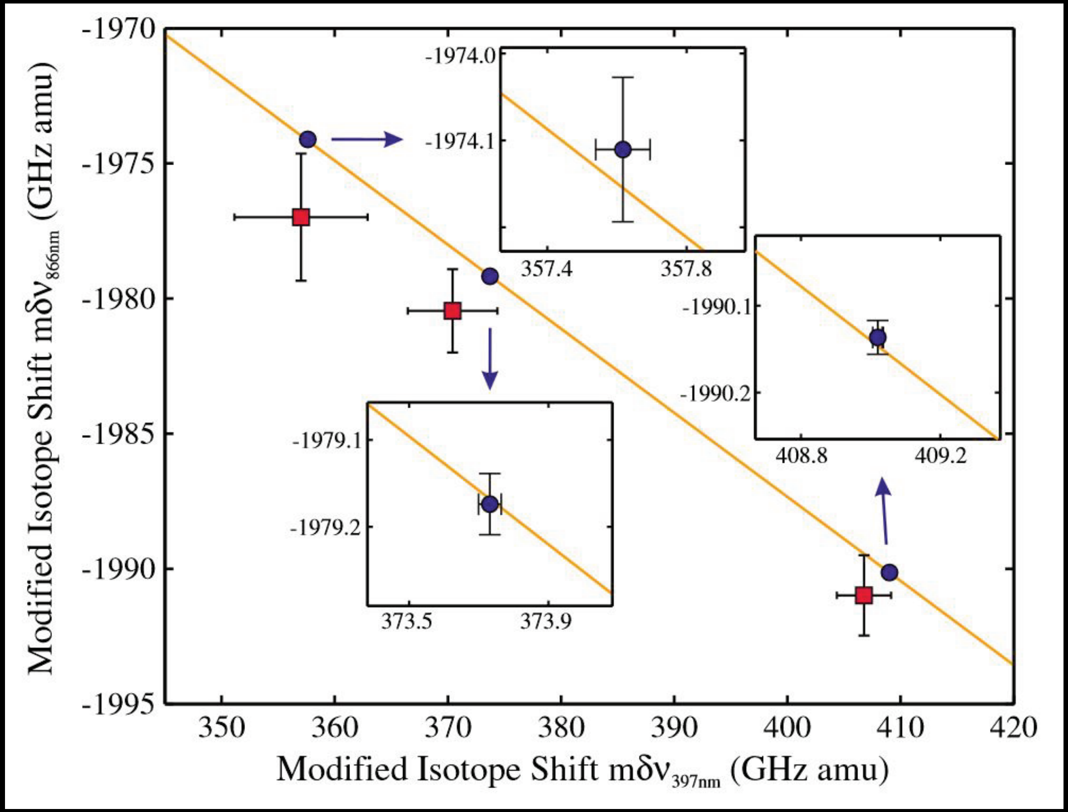
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain and as long as linearity is observed, H_{21} can be bounded (unless accidentally $m\delta\nu \propto A'$)

Proof of Concept in Ca^+

Gebert et al. PRL 115 (2015)

$A = 40, A' = 42, 44, 48$

$4S \to 3D_{5/2}$



$4S \to 4P_{1/2}$ (not-clock)

IS ~ 1 GHz

error ~ 100 kHz

$y_e y_n \lesssim 40$

Improved Sensitivity

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- This is ~10 times better than (comparable to) LHC8 direct (indirect) bounds, with good/better prospect for improvements!

probing new physics with isotope shift spectroscopy

Probing generic new physics

isotope shits including non QED or QCD

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- Z^0 exchange (vector operators)
- Higgs exchange (scalar operators)
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Ytterbium (Yb^+) - as a test case

EFT analysis

capture new physics by

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}\left[\sum_q c^S_{eq}\mathcal{O}^S_{eq} + c^V_{eq}\mathcal{O}^V_{eq}\right] + \frac{c_{eg}}{\Lambda^3}\mathcal{O}_{eg}$$

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$$X^i_{AA'}\big|_{\rm EFT} = 4\,{\rm Hz}\times y_{en}(A-A')\frac{|\psi(0)|^2}{4a_0^{-3}}\left(\frac{\rm TeV}{\Lambda}\right)^2$$

$$y_{en} \approx 8.8\,c^S_{eu} + 11\,c^S_{ed} + 0.86\,c^S_{es} - 2.4\times 10^{-3}\,c_{eg}$$

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$$|y_{en}| \lesssim \frac{0.02}{|1-F_{21}|}\left(\frac{\Lambda}{\rm TeV}\right)^2\left(\frac{\Delta}{\rm Hz}\right)\left(\frac{8}{A-A'}\right)$$

EFT analysis

operator $\mathcal{O}_i$	Upper bound on $|c_i|$ ($\Lambda = 1$ TeV)	Lower bound on Λ_i [TeV] ($c = 1$)
$\mathcal{O}^V_{eu}$	2.3×10^{-2}	6.6
$\mathcal{O}^V_{ed}$	1.1×10^{-2}	9.3
$\mathcal{O}^S_{eu}$	2.6×10^{-3}	20
$\mathcal{O}^S_{ed}$	2.1×10^{-3}	22
$\mathcal{O}^S_{es}$	2.7×10^{-2}	6.1
$\mathcal{O}^S_{ec}$	0.20	2.3
$\mathcal{O}^S_{eb}$	0.87	1.1
$\mathcal{O}^S_{et}$	56	0.13
$\mathcal{O}_{eg}$	9.6	0.47

~ LHC8, ×2 LEP2

×10 LEP2

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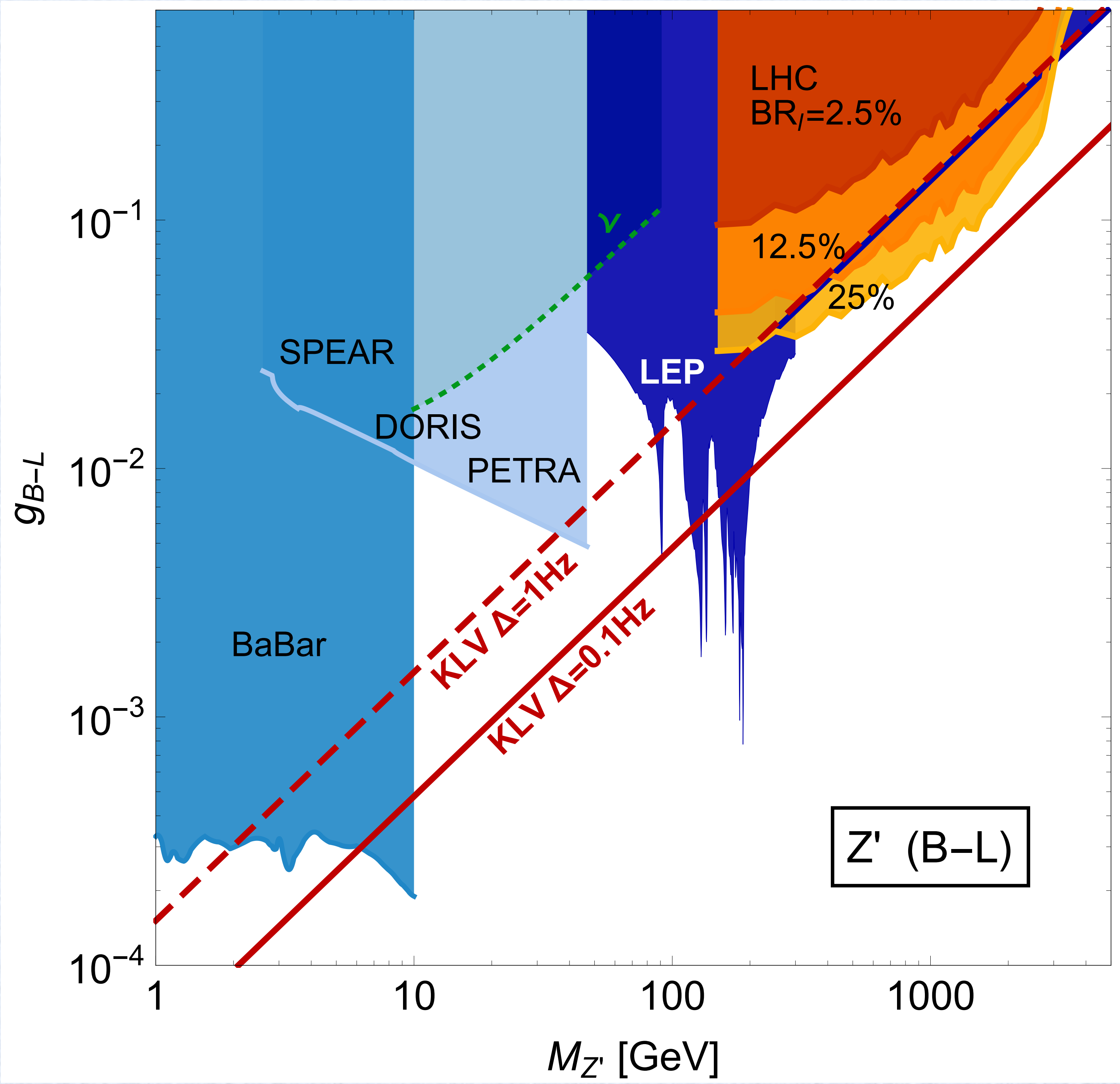
Z' BENCHMARK MODEL



C. Frugiele, E. Fuchs, G. Perez, M. Schlaffer 1602.04822

Probing the Z couplings

the effect of *Z⁰* on isotope shift:

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neutron nuclear weak charge (SM=-1)

Probing the Z couplings

the effect of Z^0 on isotope shift:

$$X^i_{AA'}\big|_{\rm weak} = -1.3\,{\rm Hz} \times q_W (A - A') \frac{|\psi(0)|^2}{4a_0^{-3}}$$

neutron nuclear weak charge (SM=-1)

deviation from the SM can be constrained

$$|\delta q_W| \lesssim \frac{7.4 \times 10^{-2}}{|1 - F_{21}|} \left(\frac{\Delta}{\rm Hz}\right) \left(\frac{8}{A - A'}\right) \quad \text{or} \quad |\delta g_u + 2\delta g_d| \lesssim 1.8 \times 10^{-2}$$

stronger than model independent bounds, but weaker than atomic parity violation

On possbile 750GeV Resonance

from LHC: coupled to hadrons

S couplings ($\mu = 750\,\mathrm{GeV}$)	LHC $(8, 13)$ bound [33, 37] ($\Gamma_S = 45\,\mathrm{GeV}$)	IS projection ($\Delta = 1\,\mathrm{Hz}$)
$\lvert y_e y_u \rvert$	$(5.6,\ 6.0) \times 10^{-3}$	1.5×10^{-3}
$\lvert y_e y_d \rvert$	$(7.3,\ 7.8) \times 10^{-3}$	1.2×10^{-3}
$\lvert y_e y_s \rvert$	$(2.9,\ 2.5) \times 10^{-2}$	1.5×10^{-2}
$\lvert y_e y_c \rvert$	$(3.6,\ 3.0) \times 10^{-2}$	9.6×10^{-2}
$\lvert y_e y_b \rvert$	$(5.6,\ 4.5) \times 10^{-2}$	0.49
$\lvert y_e y_t \rvert$	$(0.19,\ 0.16)$	32
$\lvert y_e c_g \rvert$	$(0.72,\ 0.60)$	150

ON POSSBILE 750GEV RESONANCE

from LHC: coupled to hadrons

S couplings ($\mu = 750\,\mathrm{GeV}$)	LHC (8, 13) bound [33, 37]	IS projection
$\lvert y_e y_u \rvert$		
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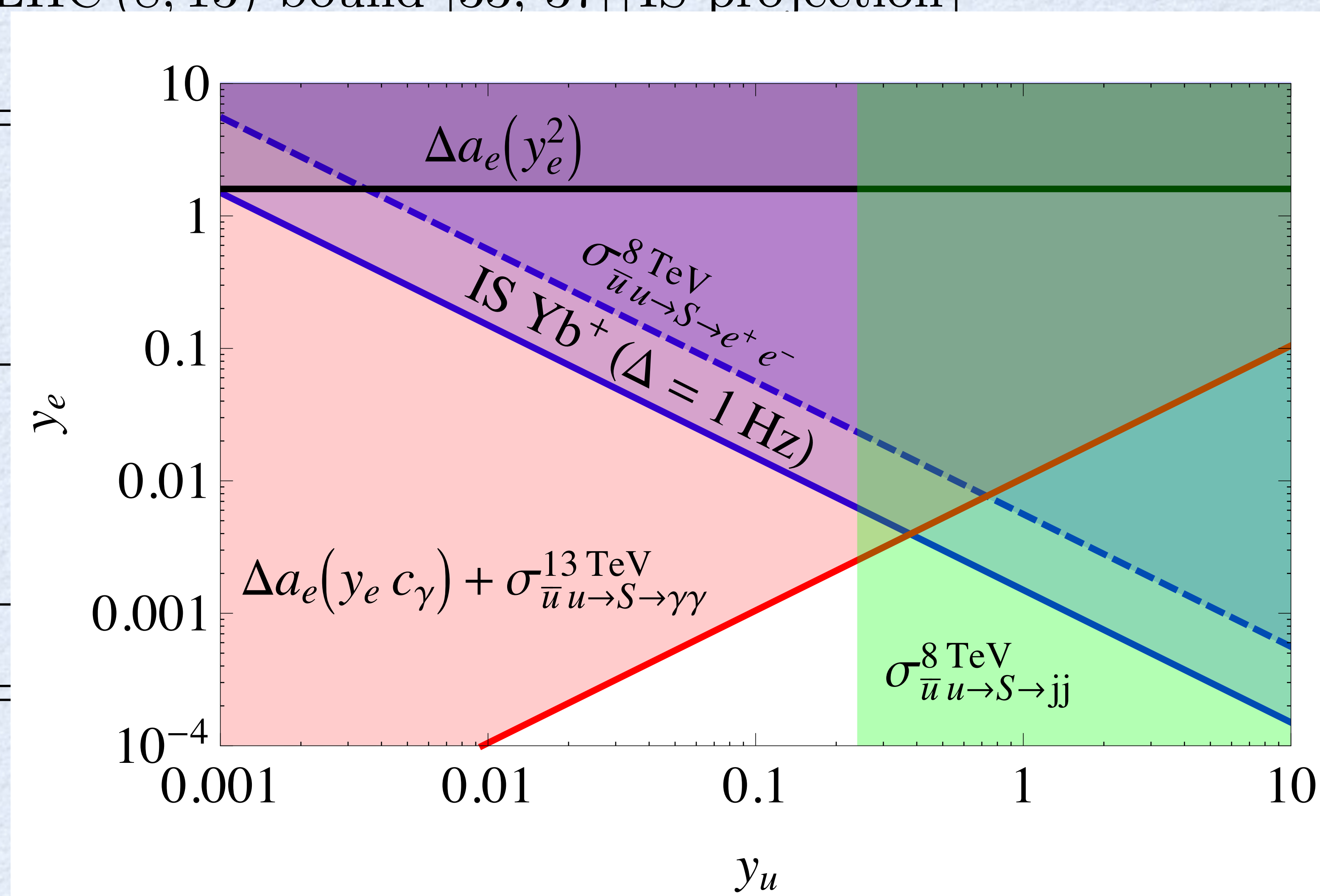
$\lvert y_e y_t \rvert$		
$\lvert y_e c_g \rvert$		



Light New Physics

the EFT breaks → long range interaction

$$V_{\text{light}}(r) = (-1)^{s+1}\alpha_\phi N_e N_A \frac{e^{-m_\phi r}}{r}$$

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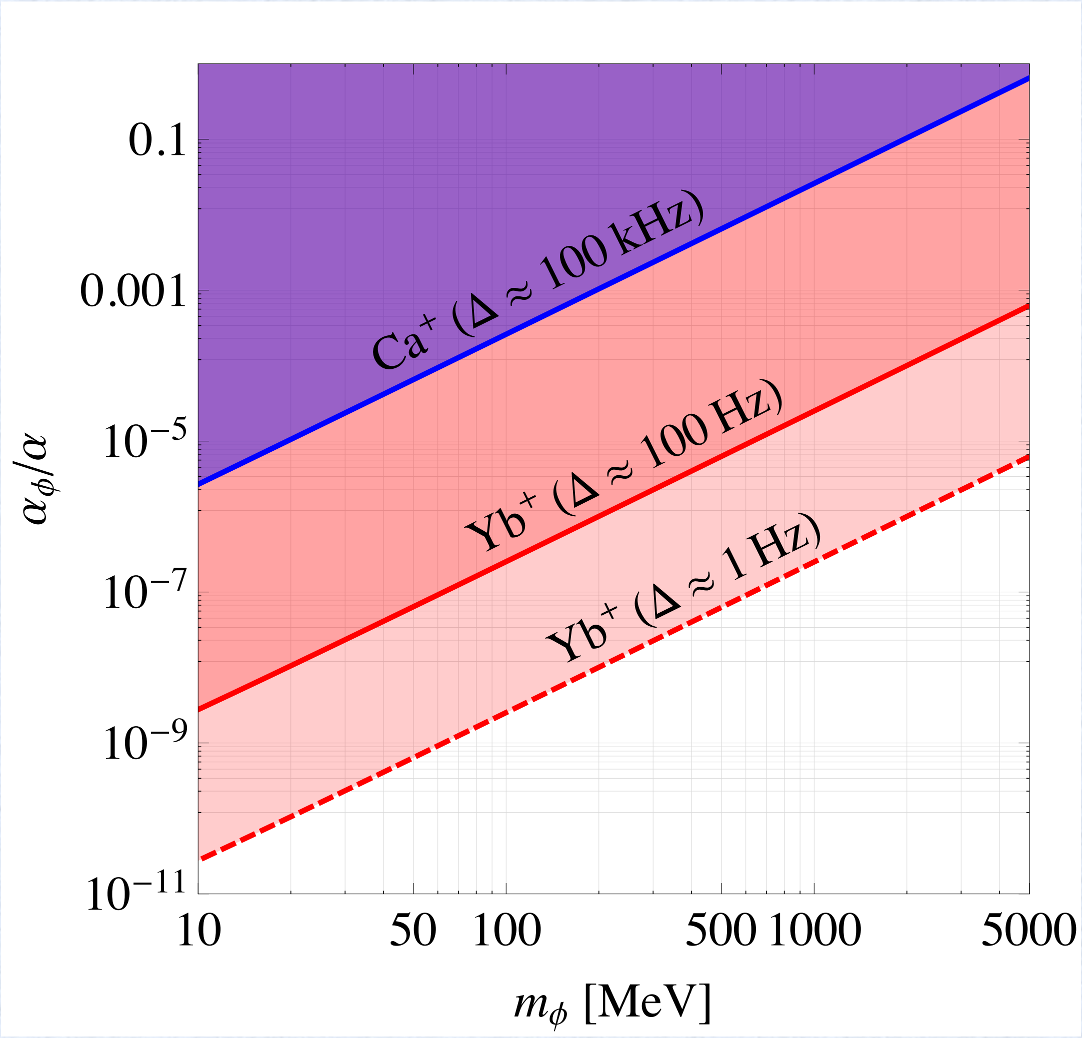
$$\psi(r \lesssim a_0/Z) \simeq \psi(0) e^{-Zr/a_0}$$

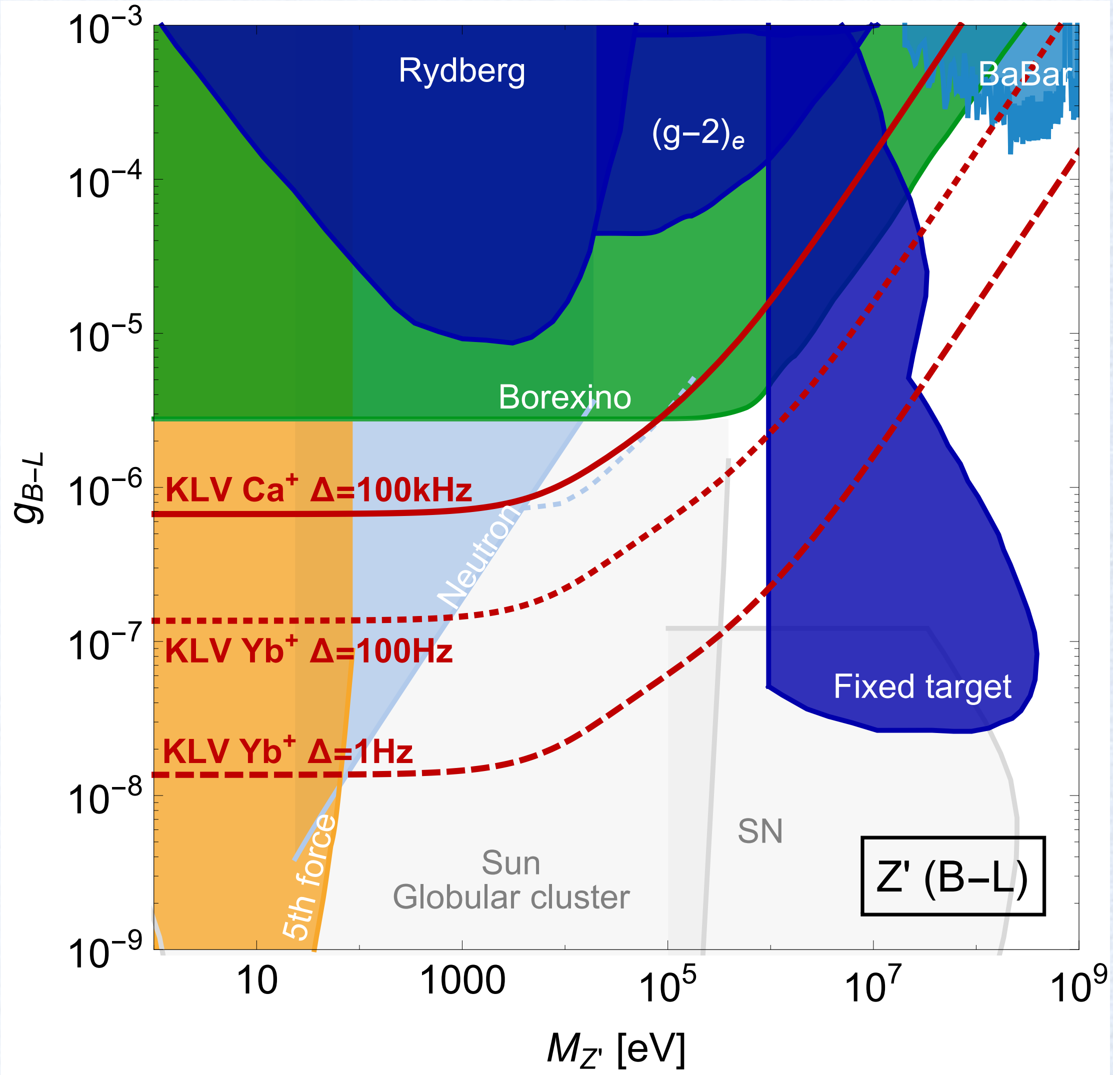
$$X^i_{AA'}\big|_{\text{light}} \simeq 5\times 10^7\,\text{Hz} \times (-1)^s \alpha_\phi N_e (N_A - N_{A'}) \times \frac{|\psi(0)|^2}{4a_0^{-3}} \left(\frac{\text{GeV}}{m_\phi + 2Za_0^{-1}}\right)^2 . \quad (18)$$

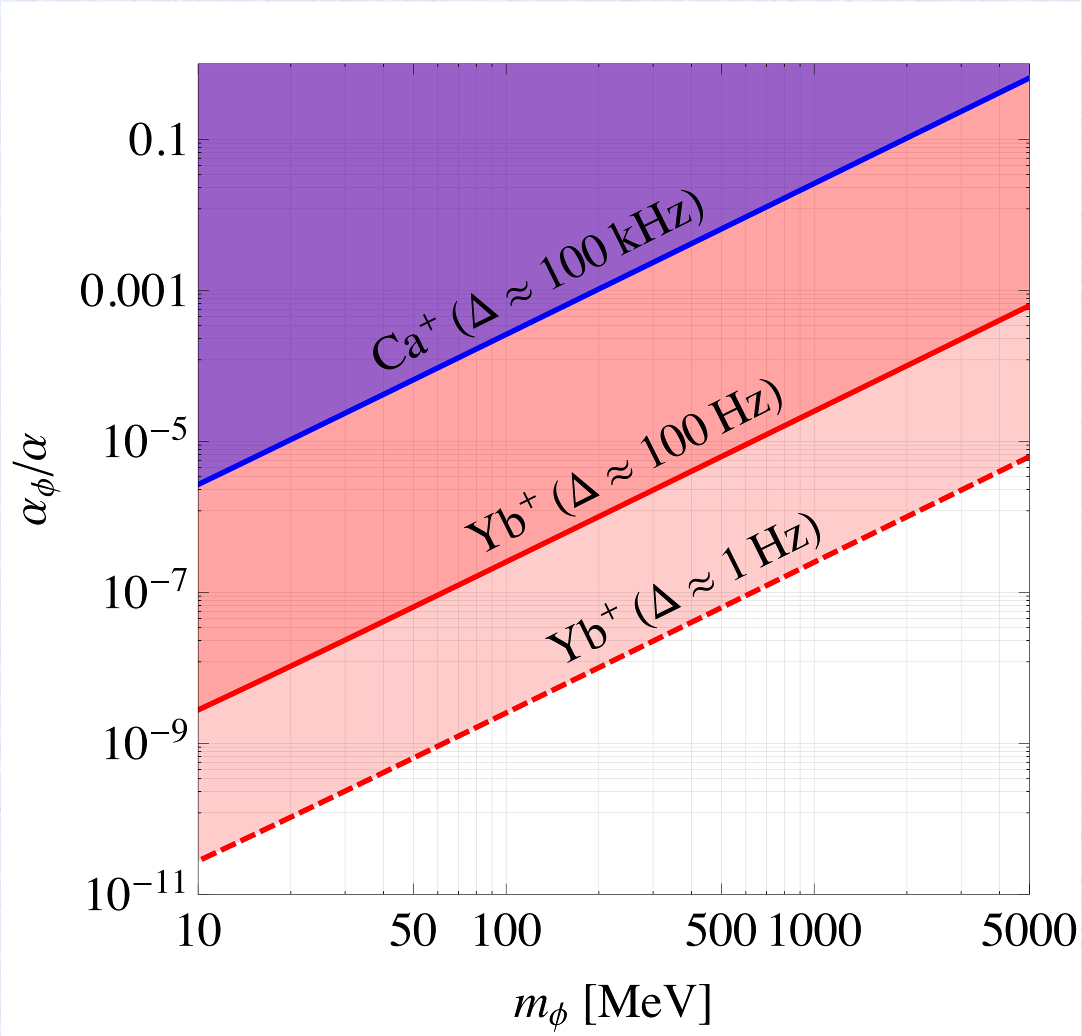


Light New Physics

the EFT breaks → long range interaction

$$V_{\rm light}(r) = (-1)^{s+1}\alpha_\phi N_e N_A \frac{e^{-m_\phi r}}{r}$$





C. Delanunay, C. Frugiele, E. Fuchs, C. Grojean, R. Harnik,
G. Perez, R. Ozeri, Y. Soreq - Work in progress

Summary

- the atomic Higgs force can be probed by the state-of-the-art isotope shift measurements, and may shed light on the flavor puzzle
- isotope shift can also probe
  - the Z^0 couplings
  - generic new physics, which is not aligned with QED
- not only Yb^+, can consider also Ca/Ca^+, Sr/Sr^+, Dy

BACKUP SLIDES

Higher order corrections

isotope shift can be written as

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

depends on the transition-*i*:

K_{i} - mass shift

F_{i} - field shift

nucleus parameters:

$\mu_{AA'} = 1/m_A - 1/m_{A'}$

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

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need to control isotope shit to the level of

$$\frac{\text{Higgs Shift}}{\text{total IS}} \sim \frac{\text{Hz}}{\text{GHz}} \sim 10^{-9}$$

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$$\frac{\text{Higgs Shift}}{\text{total IS}} \sim \frac{\text{Hz}}{\text{GHz}} \sim 10^{-9}$$

isotope shift are controlled by two small parameters

$$\varepsilon_\mu = m_e \mu_{AA'} \sim (A - A') \times 10^{-8}$$

$$\varepsilon_r = \delta\langle r^2\rangle_{AA'}/a_0^2 \sim (A - A') \times 10^{-11}$$

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Field Shift NDA

$$\text{LO} : |\psi(0)|^2 \delta\langle r^2\rangle_{AA'} \sim \varepsilon_r$$
$$\text{NLO/LO} : \mathcal{O}(\varepsilon_r^2, \varepsilon_\mu^2, \varepsilon_r\varepsilon_\mu)/\varepsilon_r \sim 10^{-7}$$

BUT NLO is linear up to overlap - extra suppression of ε_r

non linear effect in the King plot $(\varepsilon_r)^2 \sim 10^{-14}$

Higher order corrections

isotope shift are controlled by two small parameters

$$\varepsilon_\mu = m_e \mu_{AA'} \sim (A - A') \times 10^{-8}$$

$$\varepsilon_r = \delta\langle r^2\rangle_{AA'}/a_0^2 \sim (A - A') \times 10^{-11}$$

Mass Shift NDA

$$\text{LO} : m_e \mu_{AA'} \sim \mathcal{O}(\varepsilon_\mu)$$

$$\text{NLO} : \sim \alpha^2 m_e^2 (1/m_A^2 - 1/m_{A'}^2)$$

$$\text{NLO/LO} \sim \alpha^2 \varepsilon_r \sim 10^{-10}$$

Palmer 87

more details

Electron Density in Nuclei

- Coulomb potential: $$V(r) = -\frac{Z_{\text{eff}}(r)\alpha}{r}$$

- Nuclear charge screened by inner electrons:

ion charge

$$Z_{\text{eff}}(r) \sim \begin{cases} Z & r < a_0/Z \\ r/a_0 & a_0/Z < r < a_0/(1+n_e) \\ 1+n_e & r > a_0/(1+n_e) \end{cases}$$

See *e.g.* Budker-Kimball-DeMille: Atomic Physics

- Using non-relativistic hydrogen-like wavefunction:

$$|\psi(0)|^2 \simeq \frac{4.2Z}{a_0^3}(1+n_e)^2$$

Higher-Order Corrections

- Need to control King's linearity at least down to:

Higgs force

$$\frac{\mathrm{Hz}}{\mathrm{GHz}} \sim 10^{-9}$$

total IS

- Higher-order corrections are not trivial to compute, many-body, relativistic simulations are needed [in progress]
- Yet, IS are controlled by two small parameters:

$$\varepsilon_\mu = m_e \mu_{AA'} \sim (A - A')10^{-8}$$
$$\varepsilon_r = \delta\langle r^2\rangle_{AA}/a_0^2 \sim (A - A')10^{-11}$$

- So, we can entertain NDA...

Field Shift

- Perturbation theory:

Seltzer '69
Blundell et al. '87

nuclear charge distribution

$$\delta\nu^{\mathrm{FS}}_{AA'} = -e\int d^3 r_e |\psi(r_e)|^2 \delta V(r_e)\,, \qquad \delta V(r_e) = \frac{Ze}{4\pi}\int d^3 r_N \frac{\delta\rho(r_N)}{|\vec{r}_e - \vec{r}_N|}$$

electron density

nuclear potential

- LO: $\propto |\psi(0)|^2 \delta\langle r^2\rangle_{AA'} \sim \mathcal{O}(\varepsilon_r)$
- NLO/LO: $\sim \mathcal{O}(\varepsilon_\mu^2, \varepsilon_r^2, \varepsilon_\mu\varepsilon_r)/\varepsilon_r \sim 10^{-7}$
- NLO is linear up to overlap with the nucleus $\sim \mathcal{O}(\varepsilon_r)$
- Hence, non-linearities are only of $\mathcal{O}(\varepsilon_\mu^2) \sim 10^{-14}$

Specific Mass Shift

- MS arises from:
  - « rescaling » Rydberg constant (normal MS)
  - electron-electron correlation, relativistic… (specific MS)

- at LO, both scale like $m_e \mu_{AA'} \sim \mathcal{O}(\varepsilon_\mu)$
- NLO correction is parametrically: Palmer '87

$$\sim \alpha^2 m_e^2 (m_A^{-2} - m_{A'}^{-2})$$

- Hence, NLO/LO $\sim \mathcal{O}(\alpha^2 \varepsilon_r) \sim 10^{-10}$