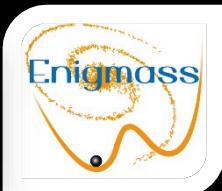
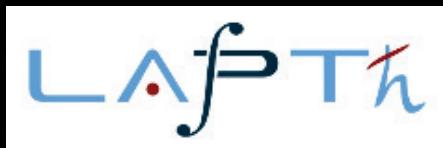


# *Atomic Higgs Physics:* probing the Higgs force with isotope shifts

*CD, R. Ozeri, G. Perez, Y. Soreq:*  
*hep-ph: 1601.05087*  
*hep-ph: 1602.appear*  
*CD, Y. Soreq: in progress*

*Cédric Delaunay*  
CNRS/LAPTh  
Annecy-le-Vieux  
France



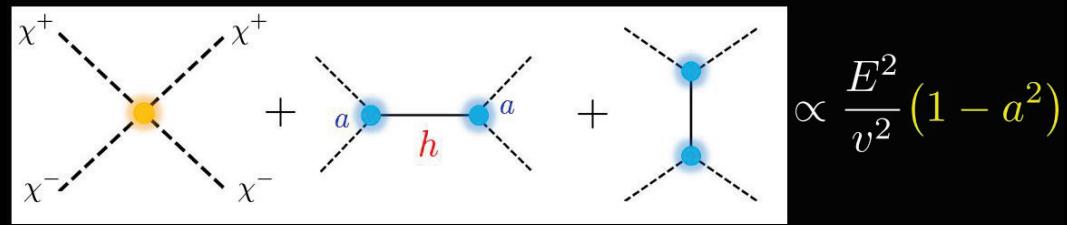
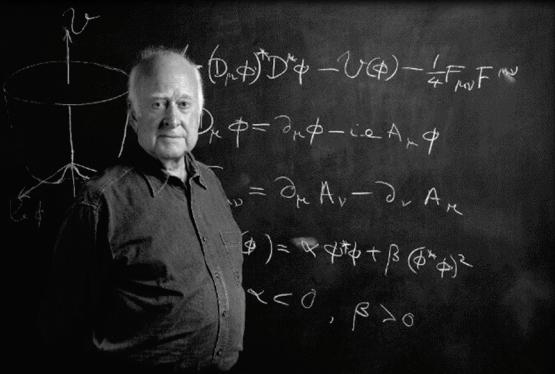
RPP2016  
26-01-2016 | LAPTh

# *Outline*

1. The Higgs and the flavor puzzle
2. Higgs force in atoms
3. Probing the Higgs with isotope shifts

# The Higgs Mechanism

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



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:

$$m_t \sim 10^5 m_e$$

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

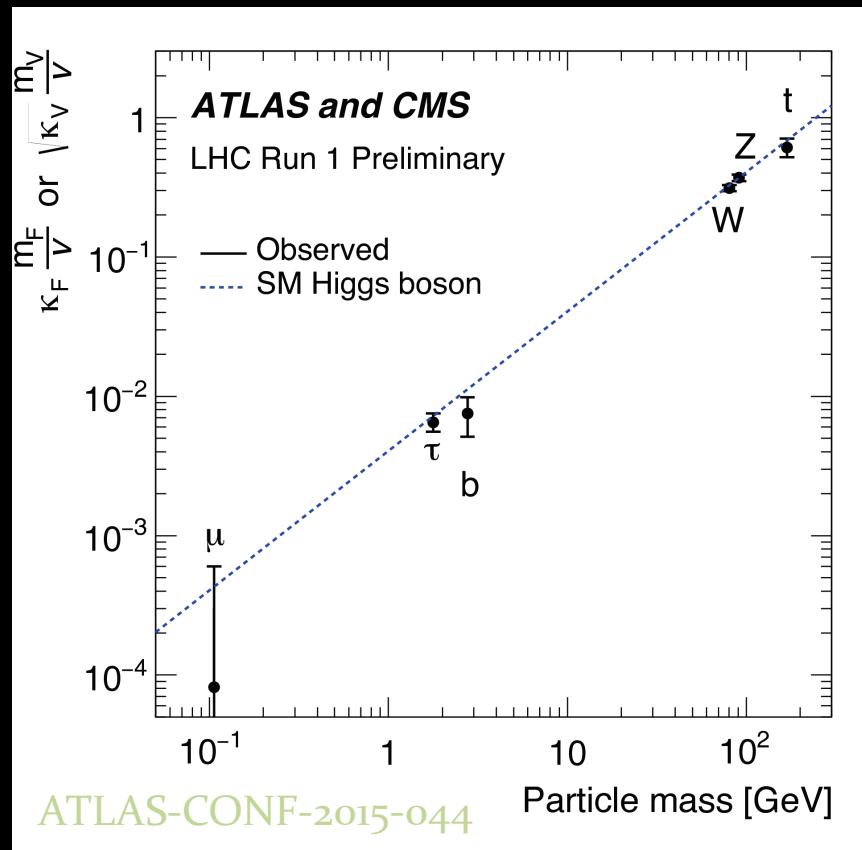
# The flavor puzzle

- Charged fermion masses are highly hierarchical:  
$$m_t \sim 10^5 m_e$$
- 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:

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

*How well can we test?*

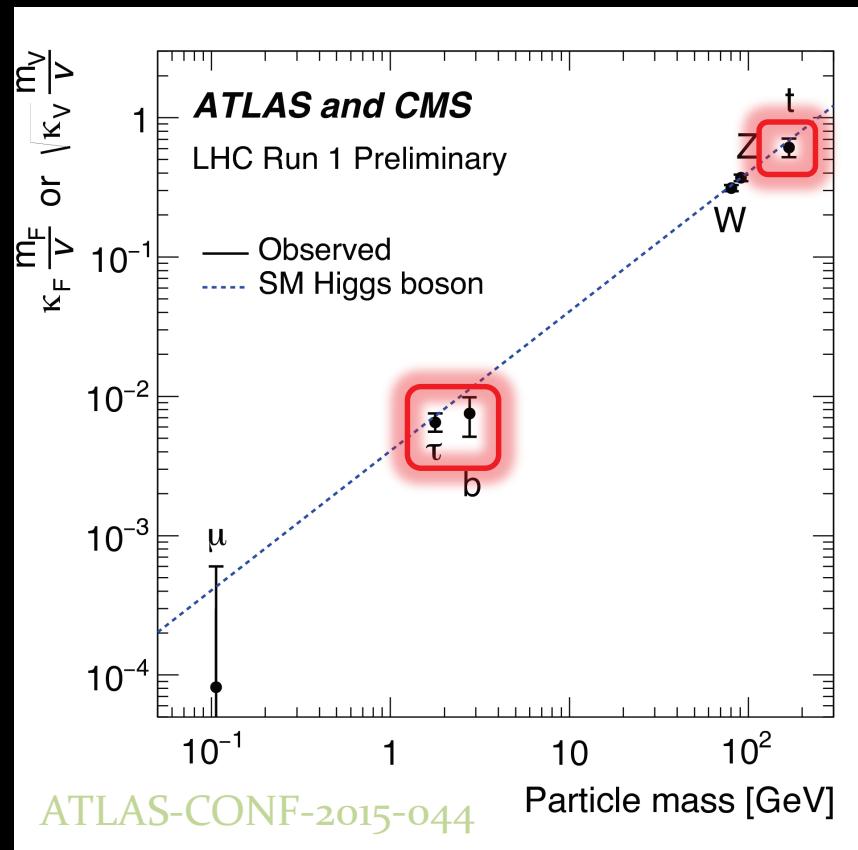
# The flavor puzzle at the LHC



# The flavor puzzle at the LHC

ATLAS+CMS  
Higgs-signal/SM:

$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
$\mu^{bb}$	$0.69^{+0.29}_{-0.27}$
$\mu_{ttH}$	$2.3^{+0.7}_{-0.6}$



→ the Higgs mechanism is likely to be  
the dominant source of 3<sup>rd</sup> generation masses

# The flavor puzzle at the 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:

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

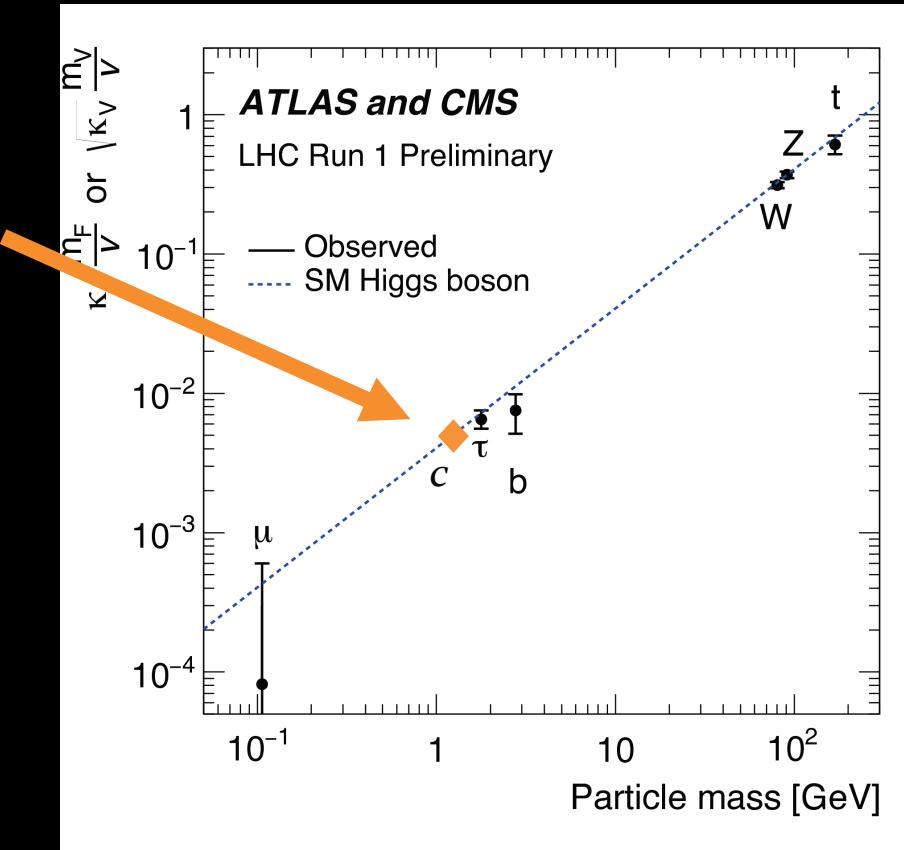
Perez-Soreq-Stamou-Tobioka '15

- global fits

CD-Golling-Perez-Soreq '13

- $\Gamma_h \leq 1.7 \text{ GeV}$

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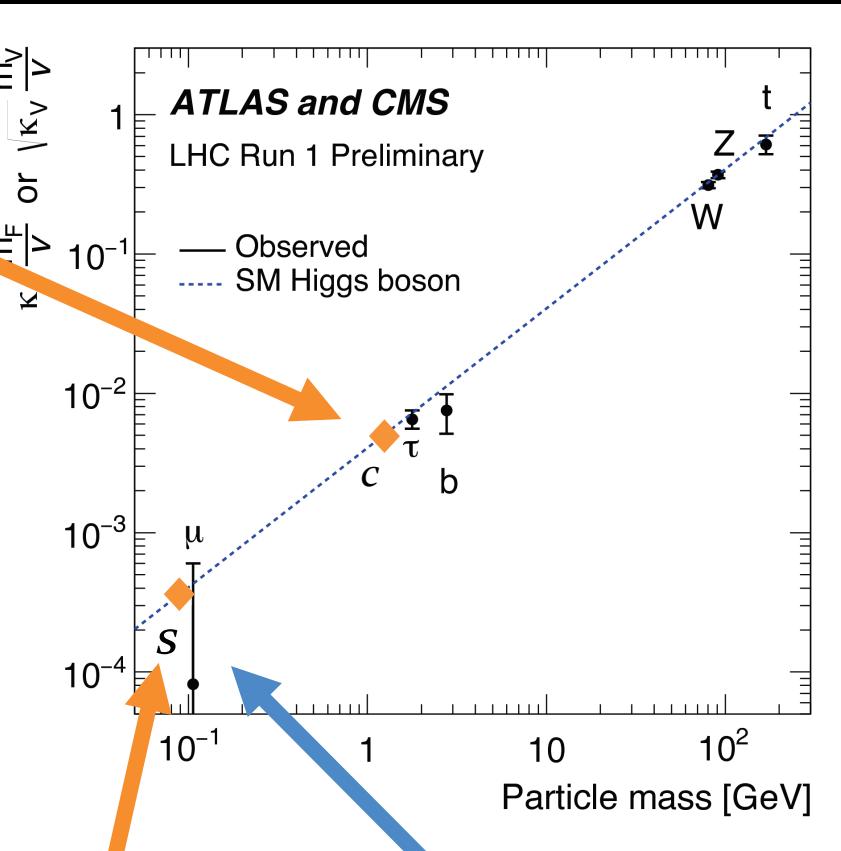
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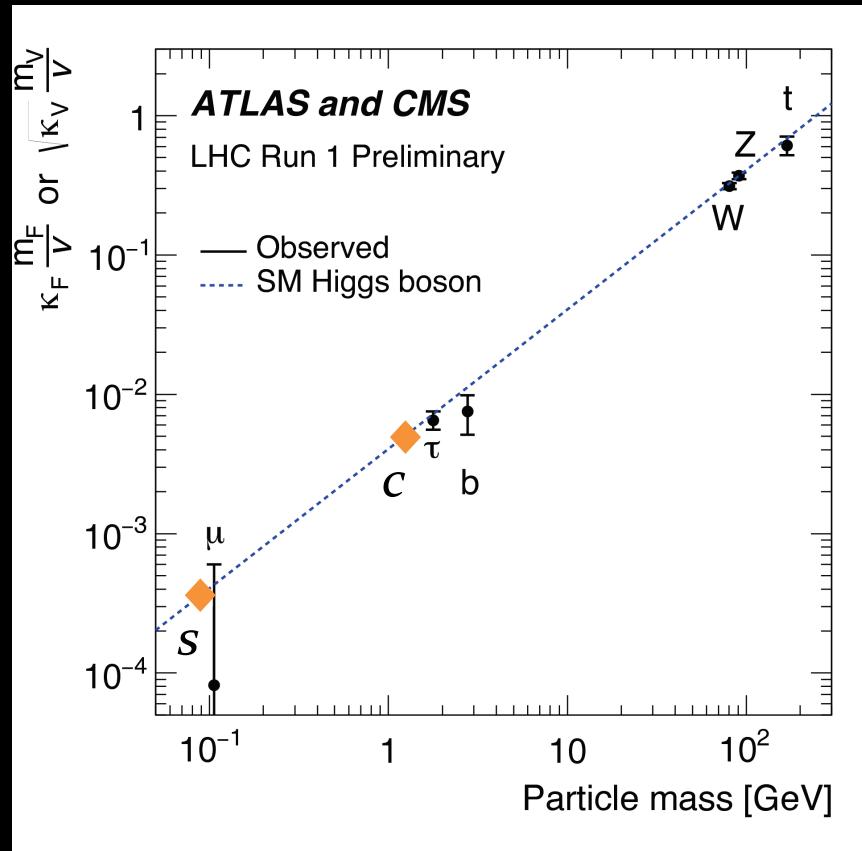


$h \rightarrow \phi\gamma$  ?  
Kagan et al. '14

Sensitivity to muon-coupling,  
with high-enough luminosity  
ATL-PHYS-PUB-2014-016

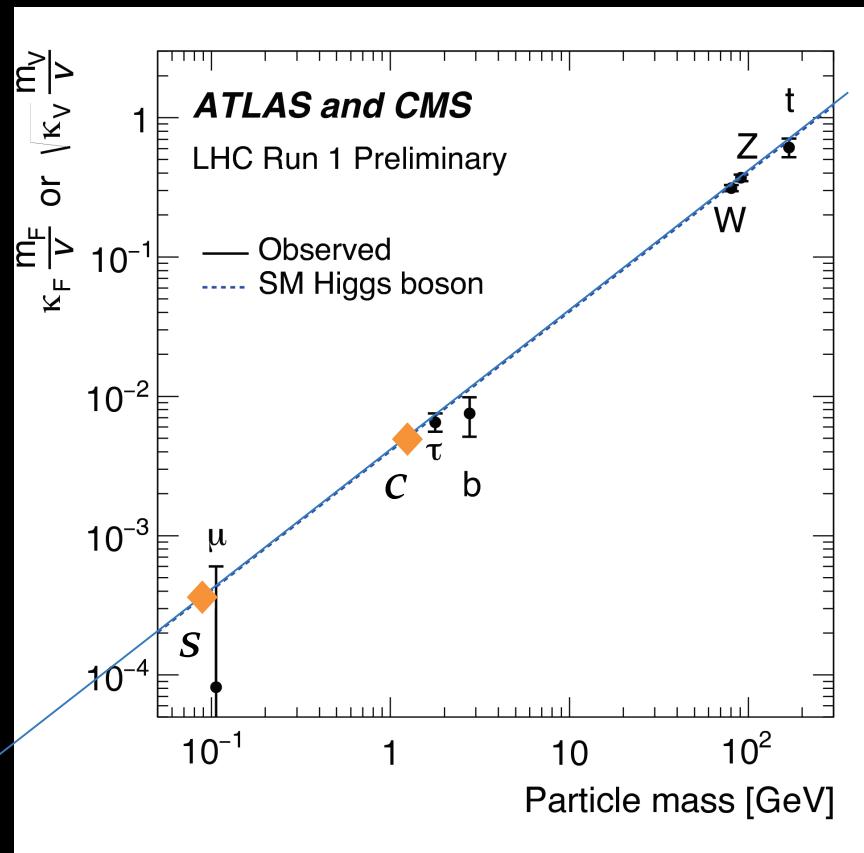
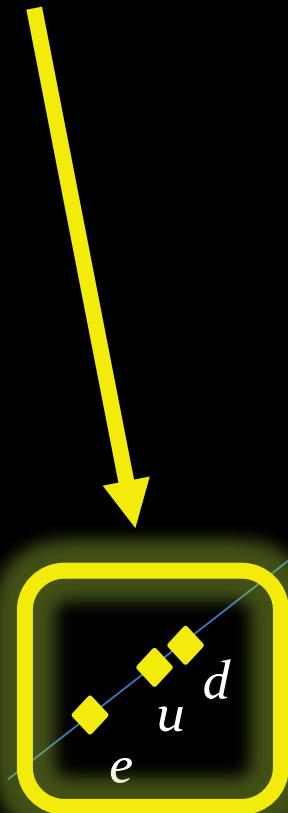
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What about  $e, u, d$ ?



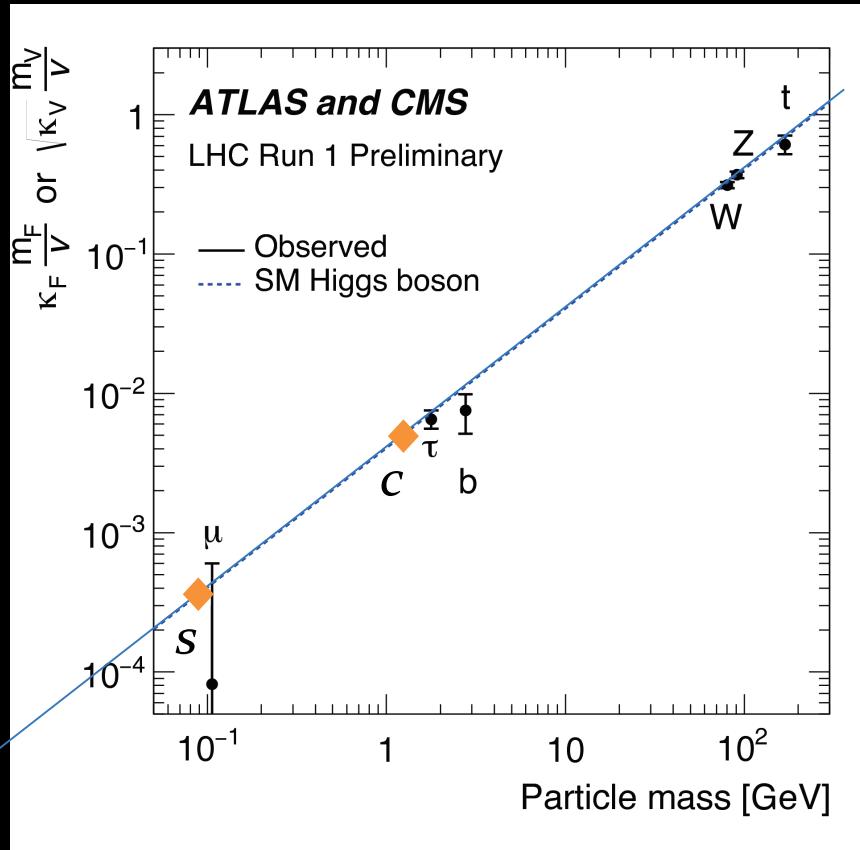
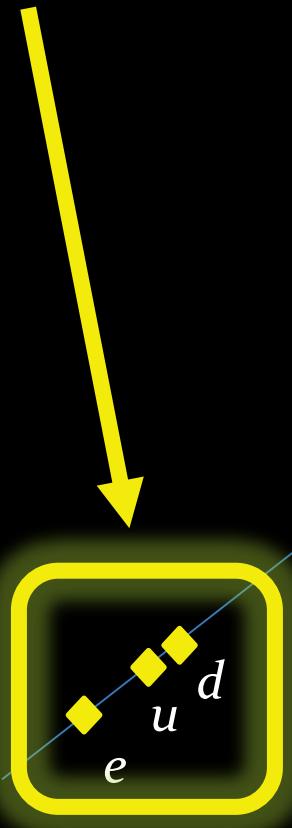
# The flavor puzzle at the LHC

What about  $e, u, d$ ?



# The flavor puzzle at the LHC

What about  $e, u, d$ ?



[stable nuclei]  
[chemistry]

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

# The flavor puzzle at the LHC

What about  $e, u, d$ ?

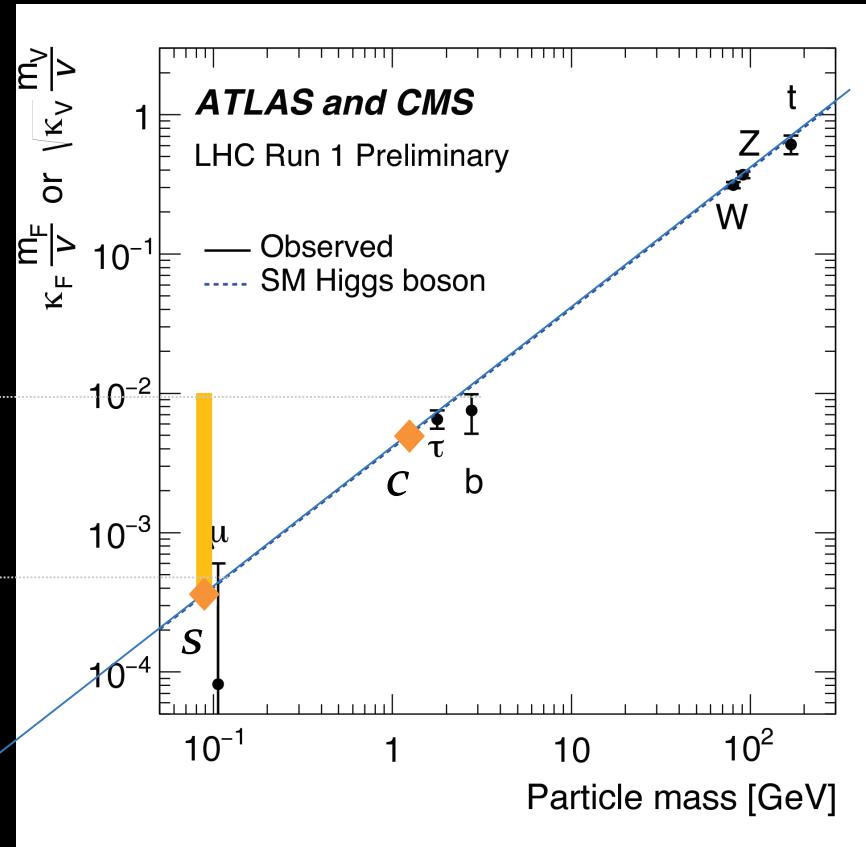
$$\Gamma_h \leq 1.7 \text{ GeV}$$

Perez-Soreq-Stamou-Tobioka '15

$$h \rightarrow ee$$

Altmannshofer-Brod  
-Schmaltz '15

$e$      $u$      $d$



Higgs-to-light-fermion couplings  
could be much larger than the SM prediction.  
LHC is and will remain weak in bounding them.

# Higgs force in atoms

- The Higgs results in an attractive force between nuclei and their bound electrons:

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

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- $y_A = Z y_p + (A - Z) y_n$  with: Shifman-Vainshtein-Zakharov '78  
+ nuclear data, see *e.g.* micrOmegas

$$y_n \approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$

$\mathcal{O}(10 - 20\%)$   
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$$y_p \approx 11 y_u + 6.5 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$

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

# Atomic Higgs Force Strength

- Under current LHC constraints:

$$y_{n,p} \lesssim 3 \text{ (0.2)} \quad \begin{matrix} \text{Higgs width (direct)} \\ \text{global fit (indirect)} \end{matrix} \quad \text{and} \quad y_e \lesssim 1.3 \times 10^{-3}$$

- Higgs force possibly stronger than SM by  $\sim 10^6$  !

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and       $y_e \lesssim 1.3 \times 10^{-3}$

Higgs width (direct)  
global fit (indirect)

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

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

electron-density  
at the nucleus

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

# Optical Atomic Clocks

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

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

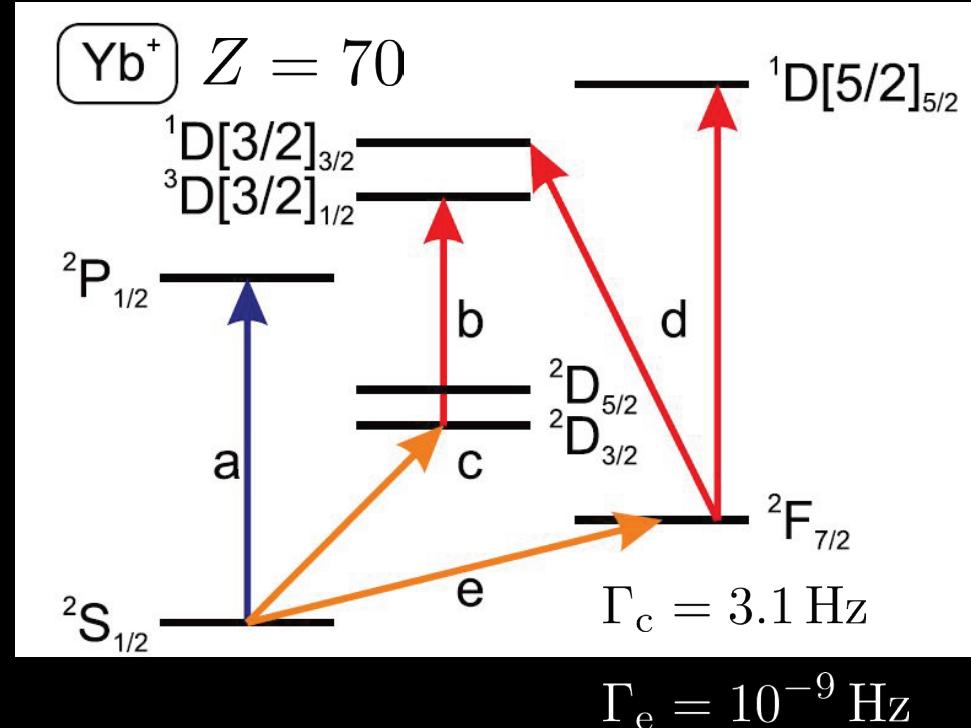
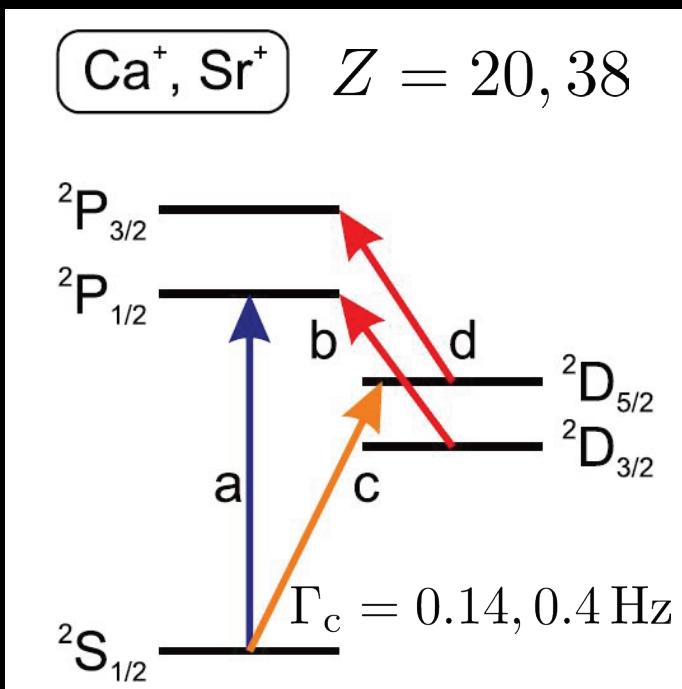
# Optical Atomic Clocks

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

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

- Narrow transitions with S-wave are needed:

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



# Frequency comparisons

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

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

$$\nu_{E2}^{\text{Ca}^+} = 411\ 042\ 129\ 776\ 393.2(1.0)\text{Hz} \quad \sim 10^{15}\text{Hz}$$

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sensitivity to  
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sensitivity to  
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$$y_e y_n \lesssim 4 \times 10^{-5} \sim \text{LHC8/100}$$

- Theory side is however much less promising:  
strong electron-electron effects, electron-nucleus  
interactions, relativistic corrections, QED  
are not accounted for at the  $10^{-15}$  level...

# Isotope shifts

- The Higgs force can't be switched on and off.  
Instead, let's try to cancel the « background ».

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

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*(consider  $A' - A = 2, 4, \dots$  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 Theory

- There are yet non-trivial IS from changes in:
  - the reduced mass:  $m_r = \frac{m_e m_A}{m_e + m_A} \simeq m_e(1 - m_e/m_A)$
  - the nuclear charge distribution:  $\langle r^2 \rangle_A / a_0^2$

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- Hence, to leading order, IS for a transition  $i$  reads:

$$\delta\nu_{AA'}^i = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + H_i (A - A')$$

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

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mass shift                          field shift

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mass shift                          field shift                          Higgs shift

- MS/FS effects are typically in the GHz range....

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

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

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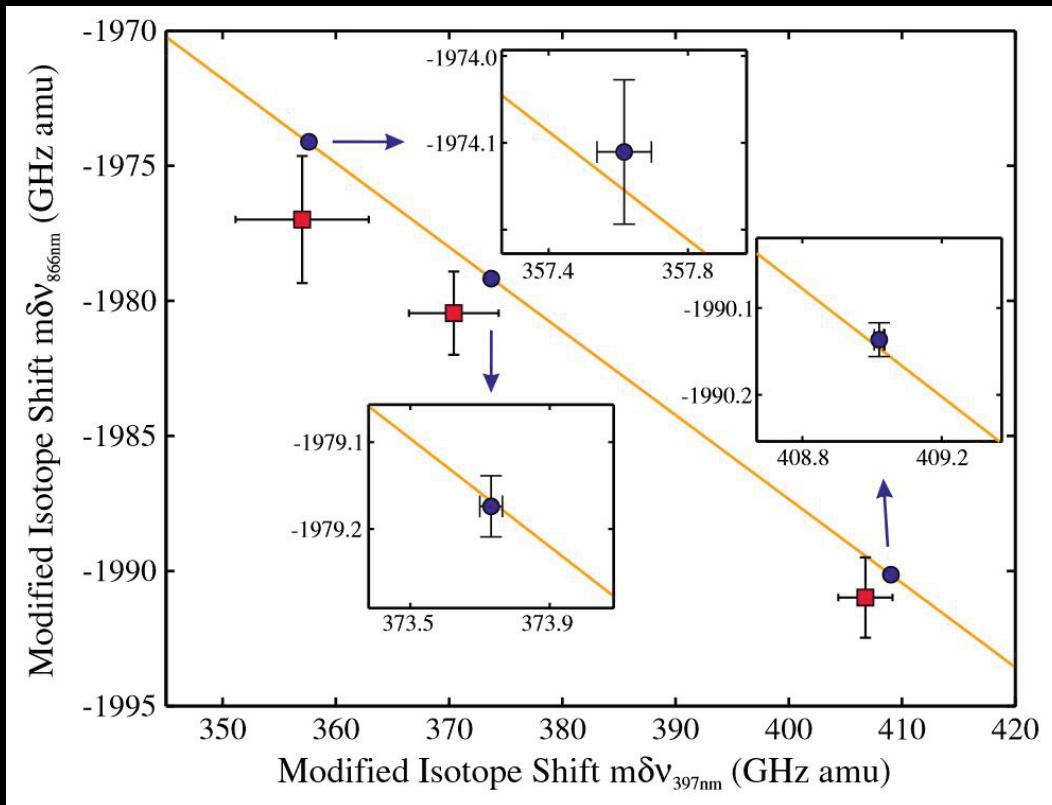
- Plot  $m\delta\nu_{AA'}^1$  vs.  $m\delta\nu_{AA'}^2$  along the isotopic chain
- As long as linearity is observed, one can bound  $H_{21}$  unless (accidentally)  $m\delta\nu \propto A'$  which is unlikely.

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

# Proof of concept with $\text{Ca}^+$ data

Gebert et al. PRL 115 (2015)

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



IS  $\sim 1$  GHz  
error  $\sim 100$  kHz

$y_e y_n \lesssim 40$

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

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Huntemann et al. PRL 113 (2014)

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- This is  $\sim 10$  times better than (comparable to) LHC8 direct (indirect) bounds, with very good prospect for improvements!

# Higher-orders?

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

$$\begin{array}{l} \text{Higgs force} \rightarrow \frac{\text{Hz}}{\text{GHz}} \sim 10^{-9} \\ \text{total IS} \rightarrow \end{array}$$

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- 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...

# NLO Field Shift

- Perturbation theory:

Seltzer '69  
Blundell et al. '87

nuclear charge  
distribution  


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

  
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  $\mathcal{O}(\varepsilon_\mu^2) \sim 10^{-14}$

# NLO Mass Shift

- MS arises from:
  - rescaling Rydberg (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  $\sim \mathcal{O}(\alpha^2 \varepsilon_r) \sim 10^{-10}$

# Outro

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  - BSM, as long as not aligned with QED... [to appear]
- Measurements in Yb+ are already underway!

# So, get ready!

Friday, 22 January 2016

## Higgs force awakens

The Higgs boson couples to particles that constitute matter around us, such as electrons, protons, and neutrons. Its virtual quanta are constantly being exchanged between these particles.

In other words, it gives rise to a force - the *Higgs force*. I'm surprised why this PR-cool aspect is not explored in our outreach efforts.

Higgs bosons mediate the Higgs force in the same fashion as gravitons, gluons, photons, W and Z bosons mediate the gravity, strong, electromagnetic, and weak forces. Just like gravity, the Higgs force is always attractive and its strength is proportional, in the first approximation, to particle's mass. It is a force in a common sense; for example, if we bombarded long enough a detector with a beam of particles interacting only via the Higgs force, they would eventually knock off atoms in the detector.



courtesy of A.Falkowski