Probing the Atomic Higgs force

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CD, Y. Soreq hep-ph:1602.04838

LAL Seminar
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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 and New Physics
The Higgs Mechanism and the Flavor Puzzle
The Higgs Mechanism

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

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

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

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

• Within the SM, it is \textit{assumed} to originate from hierarchical Higgs-to-fermion couplings:

\[ y_f^{\text{SM}} \propto m_f \]

\textit{How well can we test?}
Alternative Approaches

• Froggat-Nielsen like: lighter fermions couple to higher powers of the Higgs

\[
\frac{m_f}{v} \propto \frac{v^{n_f}}{\Lambda^{n_f}} \quad y_f \propto (1 + n_f) \frac{m_f}{v}
\]

solving the flavor puzzle: \( n_f \sim \log(\frac{m_f}{v}) \)
Alternative Approaches

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\]

solving the flavor puzzle: \( n_f \sim \log \left( \frac{m_f}{v} \right) \)

• First two generation masses do not come from the Higgs mechanism at all!
  (technicolor?)
The Flavor Puzzle at LHC

![Graph showing the relationship between particle mass and the ratio of certain quantities.](ATLAS-CONF-2015-044)
The Higgs mechanism is likely to be the dominant source of 3rd generation masses.
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

• $\Gamma_h \leq 1.7$ GeV
  Perez-Soreq-Stamou-Tobioka ’15
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Sensitivity to muon-coupling, with high-enough luminosity

ATL-PHYS-PUB-2014-016
The Flavor Puzzle at LHC

What about \(e, u, d\)?
The Flavor Puzzle at LHC

What about $e, u, d$?
The Flavor Puzzle at LHC

What about $e, u, d$?

Probing the couplings to the building blocks of matter is an important test of the Higgs mechanism.
The Flavor Puzzle at LHC

What about $e, u, d$?

$\Gamma_h \leq 1.7 \text{ GeV}$
Perez-Soreq-Stamou-Tobioka '15

$h \rightarrow ee$
Altmannshofer-Brod-Schmaltz '15

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

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The Higgs force in Optical Clock Transitions
The Atomic Higgs Force

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

\[ V_{\text{Higgs}}(r) = - \frac{y_e y_A}{4\pi} \frac{e^{-m_h r}}{r} \approx - \frac{y_e y_A}{4\pi m_h^2} \frac{\delta(r)}{r^2} \]
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• \( y_A = Z y_p + (A - Z) y_n \) with: Shifman-Vainshtein-Zakharov ’78 + nuclear data, see e.g. micrOmegas

\[
\begin{align*}
y_n &\approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g \\
y_p &\approx 11 y_u + 6.5 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g
\end{align*}
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\( \mathcal{O}(10-20\%) \) uncertainties in matching
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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

\[\mathcal{O}(10 - 20\%)\] uncertainties in matching
Higgs Force Strength

- Under current LHC constraints:
  - Higgs width (direct): $y_{n,p} \lesssim 3 \, (0.2)$
  - Global fit (indirect): $y_e \lesssim 1.3 \times 10^{-3}$

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

• Under current LHC constraints:

\[ y_{n,p} \lesssim 3 \pm 0.2 \]

and

\[ y_e \lesssim 1.3 \times 10^{-3} \]

• Higgs force possibly stronger than SM by \( \sim 10^6 \)!

• This shifts transition frequencies by:

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

- Coulomb potential: \[ V(r) = -\frac{Z_{\text{eff}}(r)\alpha}{r} \]
Electron Density in Nuclei

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

- Nuclear charge screened by inner electrons:

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

See e.g. Budker-Kimball-DeMille: Atomic Physics
Electron Density in Nuclei

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

- Nuclear charge screened by inner electrons:
  \[ Z_{\text{eff}}(r) \sim \begin{cases} Z & r < a_0/Z \\ r/a_0 & a_0/Z < r < a_0/(1 + n_e) \\ 1 + n_e & r > a_0/(1 + n_e) \end{cases} \]

- Using non-relativistic hydrogen-like wavefunction:
  \[ |\psi(0)|^2 \simeq \frac{4.2Z}{a_0^3} (1 + n_e)^2 \]

See e.g. Budker-Kimball-DeMille: Atomic Physics
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 $^{40}$Ca$^+$, $^{88}$Sr$^+$ is $\sim$ Hz

\[ \nu_{E2}^{Ca^+} = 411\ 042\ 129\ 776\ 393.2(1.0)\text{Hz} \]
\[ \nu_{E2}^{Sr^+} = 444\ 779\ 044\ 095\ 485.5(9)\text{Hz} \]

\[ y_e y_n \lesssim 4 \times 10^{-5} \sim \text{LHC8/100} \]

Chwalla et al., PRL 102 (2009)
Frequency Comparisons

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

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  \]

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

  sensitivity to the Higgs force

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

- 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...

Chwalla et al., PRL 102 (2009)
Isotope Shifts
and King plots
Isotope Shift

• The Higgs force can’t be switched on and off. Instead, let’s try to cancel the « background ».
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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)
Isotope Shift

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

• 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: \( m_r = \frac{m_e m_A}{m_e + m_A} \approx m_e \left(1 - \frac{m_e}{m_A}\right) \)
  – the nuclear charge distribution: \( \langle r^2 \rangle_A / a_0^2 \)
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• IS for a given transition \( i \) reads:

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

\( \mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1} \)
Isotope Shift Sources

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mass shift

field shift
Isotope Shift Sources

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Isotope Shift Sources

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

• MS/FS effects are typically in the GHz range \( \gg \) HS
The King Plot

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

W. H. King,

The King Plot

- First, define modified IS as \( m\delta \nu_{AA'}^i \equiv \delta \nu_{AA'}^i / \mu_{AA'} \)
- Measure IS in two transitions. Use transition 1 to set \( \delta \langle r^2 \rangle_{AA'} / \mu_{AA'} \) and substitute back into transition 2:

\[
m\delta \nu_{AA'}^2 = K_{21} + F_{21} m\delta \nu_{AA'}^1 - AA' H_{21}
\]

\[
F_{21} \equiv F_2 / F_1 \\
K_{21} \equiv K_2 - F_{21} K_1 \\
H_{21} \equiv H_2 - F_{21} H_1
\]

W. H. King, 
The King Plot

- First, define modified IS as $m\delta \nu_{AA'}^i \equiv \delta \nu_{AA'}^i / \mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta \langle r^2 \rangle_{AA'} / \mu_{AA'}$ and substitute back into transition 2:

$$m\delta \nu_{AA'}^2 = K_{21} + F_{21} m\delta \nu_{AA'}^1 - AA' H_{21}$$

- Plot $m\delta \nu_{AA'}^1$ vs. $m\delta \nu_{AA'}^2$, 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$^+$

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

Gebert et al. PRL 115 (2015)

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

$y_{e\gamma n} \lesssim 40$

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

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

• One needs a material with 2 clock transitions and 4+ isotopes → unique opportunity with \(^{168-176}\)Yb+
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• Not all data available, but current accuracy $\Delta \sim \text{Hz}$

Huntemann et al. PRL 113 (2014)
Godun et al. PRL 113 (2014)
Improved Sensitivity

• One needs a material with 2 clock transitions and 4+ isotopes $\rightarrow$ unique opportunity with $^{168-176}\text{Yb}^+$

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• Expected sensitivity on $u, d, s$ couplings:

$$y_u + 1.2y_d + 0.1y_s \lesssim 0.04 \left[ \frac{1.3 \times 10^{-3}}{y_e} \right] \left[ \frac{\Delta}{\text{Hz}} \right]$$
Improved Sensitivity

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• This is $\sim10$ times better than (comparable to) LHC8 direct (indirect) bounds, with good/better prospect for improvements!
Higher-Order Corrections

• Need to control King’s linearity at least down to:

\[
\frac{H_{Z}}{\text{GHz}} \sim 10^{-9}
\]

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

- LO: \( \propto |\psi(0)|^2 \delta \langle r^2 \rangle_{AA'} \sim \mathcal{O}(\varepsilon_r) \)

- NLO/LO: \( \sim \mathcal{O}(\varepsilon^2, \varepsilon^2, \varepsilon \varepsilon_r) / \varepsilon_r \sim 10^{-7} \)

- NLO is linear up to overlap with the nucleus \( \sim \mathcal{O}(\varepsilon_r) \)

- Hence, non-linearities are only of \( \mathcal{O}(\varepsilon^2_{\mu}) \sim 10^{-14} \)
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:  
  \[
  \sim \alpha^2 m_e^2 (m_A^{-2} - m_{A'}^{-2})
  \]

• Hence, NLO/LO $\sim \mathcal{O}(\alpha^2 \varepsilon_r) \sim 10^{-10}$
Probing EW and BSM Physics
The Weak Force

\[ V_{\text{weak}}(r) = -\frac{8G_F m_Z^2 g_e g_A}{\sqrt{2}} \frac{e^{-m_Z r}}{r} \]

- Z-to-electron couplings known at \(10^{-3}\) level
The Weak Force

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• Z-to-electron couplings known at $10^{-3}$ level
• Yet, the coupling to first-generation quarks (especially $d_R$) are poorly known from LEP

\[
\begin{align*}
[\delta g_{L}^{Zu}]_{ii} &= \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \\
[\delta g_{L}^{Zd}]_{ii} &= \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \\
[\delta g_{R}^{Zu}]_{ii} &= \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \end{pmatrix} \times 10^{-2}, \\
[\delta g_{R}^{Zd}]_{ii} &= \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.
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• IS improved bounds: $|\delta g_V^{Zu} + 2\delta g_V^{Zd}| \lesssim 0.018$

LEPEWWG
Efrati-Falkowski-Soreq '14
The Weak Force

\[ V_{\text{weak}}(r) = -\frac{8G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} e^{-m_Z r} r \]

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\end{align*}
\]

- IS improved bounds: $|\delta g_V^{Zu} + 2\delta g_V^{Zd}| \lesssim 0.018$
- still weaker than APV in Cs: $|\delta g_V^{Zu} + 2\delta g_V^{Zd}| \lesssim 10^{-3}$
Effective Field Theory

- Relevant operators:

\[ \mathcal{O}_{eq}^V = (\bar{e}\gamma^\mu e)(\bar{q}\gamma_\mu q) \quad q = u, d \]
\[ \mathcal{O}_{eq}^S = (\bar{e}e)(\bar{q}q) \quad q = u, d, s, c, b, t \]
\[ \mathcal{O}_{eg} = \alpha_s(\bar{e}e)G_{\mu\nu}^2 \]

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

CD-Soreq to appear
Effective Field Theory

- Relevant operators:

\[ O_{eq}^V = (\bar{e} \gamma^\mu e)(\bar{q} \gamma_\mu q) \quad q = u, d \]
\[ O_{eq}^S = (\bar{e}e)(\bar{q}q) \quad q = u, d, s, c, b, t \]
\[ O_{eg} = \alpha_s(\bar{e}e)G^2_{\mu\nu} \]

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sensitive to scalar operators up to 20 TeV!
750GeV Resonance*

- LHC established its coupling to hadrons
- What if it further couples to electrons?

* to be confirmed
750GeV Resonance*

- LHC established its coupling to hadrons
- What if it further couples to electrons?
- Assuming a scalar resonance $S$:

Unless it’s produced through gluon or heavy quark fusion, IS has more sensitivity to $S$ couplings than LHC searches in $e^+e^-$

<table>
<thead>
<tr>
<th>$S$ couplings $(\mu = 750\text{ GeV})$</th>
<th>LHC $(8, 13)$ bound $[33, 37]$ $(\Gamma_S = 45\text{ GeV})$</th>
<th>IS projection $(\Delta = 1\text{ Hz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y_{e\bar{u}}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>y_{e\bar{d}}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>y_{e\bar{s}}</td>
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<tr>
<td>$</td>
<td>y_{e\bar{c}}</td>
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<tr>
<td>$</td>
<td>y_{e\bar{b}}</td>
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</tr>
<tr>
<td>$</td>
<td>y_{e\bar{t}}</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>y_{e\bar{g}}</td>
<td>$</td>
</tr>
</tbody>
</table>

* to be confirmed
750GeV Resonance*

- $\gamma\gamma$ signal + $g_e - 2$ bounds the $S\bar{e}e$ coupling
- Assuming e.g. $u\bar{u}$ or $b\bar{b}$ production:

* to be confirmed
Conclusions
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• Measurements in Yb+ are already underway!
• Other possibilities envisaged: Ca/Ca+, Sr/Sr+, Dy