Gedanken Worlds without Higgs

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What the LHC *is not really* for . . .

- Find the Higgs boson,
  the Holy Grail of particle physics,
  the source of all mass in the Universe.
- Celebrate.
- Then particle physics will be over.

We are not ticking off items on a shopping list . . .

We are exploring a vast new terrain
. . . and reaching the Fermi scale

Challenge: Understanding the Everyday World

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

Consider the effects of all the $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ *interactions!*

Modified Standard Model: No Higgs Sector: $\overline{\text{SM}}$

$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ with massless u, d, e, ν

(treat $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

$$M_p = C \cdot \Lambda_{\mathrm{QCD}} + \ldots$$

$$3\,\frac{m_u + m_d}{2} = 10 \pm 2\ \mathrm{MeV}$$

Small contribution from virtual strange quarks

QCD accounts for (most) visible mass in Universe

(not the Higgs boson)

Modified Standard Model: No Higgs Sector: $\overline{\text{SM}}$

QCD has exact $\text{SU}(2)_\text{L} \otimes \text{SU}(2)_\text{R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\text{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\text{SU}(2)_\text{L} \otimes \text{SU}(2)_\text{R} \rightarrow \text{SU}(2)_\text{V}$$

$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Induced breaking of $SU(2)_L$

Broken generators: 3 axial currents; couplings to π measured by f_π.
Turn on $SU(2)_L \otimes U(1)_Y$: EW gauge bosons couple to axial currents, acquire masses of order $\sim gf_\pi$.

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4} \quad (b_1, b_2, b_3, \mathcal{A})$$

same structure as standard EW theory.

Diagonalize: $M_W^2 = g^2 f_\pi^2/4$, $M_Z^2 = (g^2 + g'^2) f_\pi^2/4$, $M_A^2 = 0$, so

$$M_Z^2/M_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

Massless pions disappear from physical spectrum, to become longitudinal components of weak bosons. $M_W \approx 30\ \text{MeV}/c^2$

No fermion masses . . .

(Possible division of labor)

Electroweak scale

EW theory: *choose* $v = (G_F\sqrt{2})^{-1/2} \approx 246$ GeV

$\overline{\text{SM}}$: *predict*

$$\overline{G}_F = G_F \cdot (v^2/\bar{f}_\pi^2) \approx 8 \times 10^6\, G_F \approx 93.25\ \text{GeV}^{-2}$$

Scale cross sections by $(\overline{G}_F/G_F)^2 \approx 6.4 \times 10^{13}$

Four-fermion partial-wave unitarity breaks down at $E_{\text{cm}} \approx 600\ \text{GeV} \cdot (\bar{f}_\pi/v) \approx 215$ MeV in $\overline{\text{SM}}$.

Consistent with $\overline{M}_W = 28$ MeV

Nucleon masses . . .

"Obvious" that proton should outweigh neutron

. . . but false in real world: $M_n - M_p \approx 1.293$ MeV

SU(6) flavor-spin wave functions,

$$
\begin{aligned}
|p\uparrow\rangle &= (1/\sqrt{18})\,(2u_\uparrow d_\downarrow u_\uparrow - u_\downarrow d_\uparrow u_\uparrow - u_\uparrow d_\uparrow u_\downarrow \\
&\quad - d_\uparrow u_\downarrow u_\uparrow + 2d_\downarrow u_\uparrow u_\uparrow - d_\uparrow u_\uparrow u_\downarrow \\
&\quad - u_\uparrow u_\downarrow d_\uparrow - u_\downarrow u_\uparrow d_\uparrow + 2u_\uparrow u_\uparrow d_\downarrow)\,,
\end{aligned}
$$

$$
\begin{aligned}
|n\uparrow\rangle &= -(1/\sqrt{18})\,(2d_\uparrow u_\downarrow d_\uparrow - d_\downarrow u_\uparrow d_\uparrow - d_\uparrow u_\uparrow d_\downarrow \\
&\quad - u_\uparrow d_\downarrow d_\uparrow + 2u_\downarrow d_\uparrow d_\uparrow - u_\uparrow d_\uparrow d_\downarrow \\
&\quad - d_\uparrow d_\downarrow u_\uparrow - d_\downarrow d_\uparrow u_\uparrow + 2d_\uparrow d_\uparrow u_\downarrow)\,,
\end{aligned}
$$

Nucleon masses . . .

$$
\begin{aligned}
M &= M_0 + n_d(m_d - m_u) + \left\langle \frac{\alpha}{r} \right\rangle \sum_{i<j} e_i e_j \\
&\quad -\frac{8\pi}{3} \left|\Psi_{ij}(0)\right|^2 \left\langle \sum_{i<j} \mu_i \mu_j \vec{\sigma}_i \cdot \vec{\sigma}_j \right\rangle .
\end{aligned}
$$

$$
\begin{aligned}
M &= M_0 + n_d(m_d - m_u) + \delta M_{\mathrm{C}} \sum_{i<j} e_i e_j \\
&\quad + \delta M_{\mathrm{M}} \left\langle \sum_{i<j} e_i e_j \vec{\sigma}_i \cdot \vec{\sigma}_j \right\rangle ,
\end{aligned}
$$

Nucleon masses . . .

$$M_p = M_0 + (m_d - m_u) \qquad\qquad + \tfrac{4}{3}\delta M_{\mathrm{M}}$$

$$M_n = M_0 + 2(m_d - m_u) - \tfrac{1}{3}\delta M_{\mathrm{C}} + \delta M_{\mathrm{M}}$$

$$M_n - M_p = (m_d - m_u) - \tfrac{1}{3}\delta M_{\mathrm{C}} - \tfrac{1}{3}\delta M_{\mathrm{M}}.$$

in $\overline{\mathrm{SM}}$, proton does outweigh neutron,

$$\overline{M}_n - \overline{M}_p = -\tfrac{1}{3}\delta M_{\mathrm{C}} - \tfrac{1}{3}\delta M_{\mathrm{M}} \approx -1.7\ \mathrm{MeV}.$$

Consequences for β decay

$$p \longrightarrow n e^+ \nu_e$$

Scale decay rate $\Gamma \propto G_F^2 |\Delta M|^5 / 192\pi^3 \rightsquigarrow \bar{\tau}_p \lesssim 1$ ps

No Hydrogen Atom

Lightest nucleus is neutron

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

Strong coupling in $\overline{\text{SM}}$

In SM, Higgs boson regulates high-energy behavior

Gedanken experiment: scattering of

$$W_L^+ W_L^- \quad \frac{Z_L^0 Z_L^0}{\sqrt{2}} \quad \frac{HH}{\sqrt{2}} \quad HZ_L^0$$

In high-energy limit, s-wave amplitudes

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} .$$

Strong coupling in $\overline{\mathrm{SM}}$

In *standard model*, $|a_0| \le 1$ yields

$$M_H \le \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 4v\sqrt{\pi/3} = 1\ \mathrm{TeV}$$

In $\overline{\mathrm{SM}}_1$ *Gedanken* world,

$$\overline{M}_H \le \left(\frac{8\pi\sqrt{2}}{3\overline{G}_F}\right)^{1/2} = 4\bar{f}_\pi\sqrt{\pi/3} \approx 350\ \mathrm{MeV}$$

violated because no Higgs boson $\rightsquigarrow$ strong scattering

Strong coupling in $\overline{\text{SM}}$

SM with (very) heavy Higgs boson:

pw unitarity saturated for $E_{\text{cm}} \approx 1$ TeV

$\overline{\text{SM}}$: $E^{\star}_{\text{cm}} \approx$ few hundred MeV

Massless fermion pathologies . . .

Vacuum readily breaks down to e^+e^- plasma

. . . persists with GUT-induced tiny masses

Add explicit fermion masses (OK for effective theory)

Push unitarity violation above few GeV:

masses $\lesssim$ a few tens of MeV

NGBs become pNGBs

What more we are doing . . .

Effect on nuclear forces

Multiple generations, explicit fermion masses, general N_c

How the world would differ, not how to make our world