

Possible Form of Non-minimal Higgs Couplings

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Abstract

Operator analysis of effective interactions suggests specific possibilities as likely forms for non-minimal Higgs particle couplings. They are particularly interesting for otherwise suppressed or forbidden channels, such as $Hee, He\mu$. Connections to anthropic reasoning, and to the possible existence heavy vectorlike families, are indicated – as are, alas, some tight constraints.

Framework

The discovery of the Higgs particle, with properties close to those suggested in a minimal implementation of electroweak symmetry breaking, opens a window to observation of new processes, that might reveal physics beyond the standard model. Operator analysis of possible interactions – basically, a sophisticated form of dimensional analysis – can offer plausible suggestions as to the form of such new processes.

To orient our discussion, let us begin with a toy model, containing just one real scalar field ϕ and one fermion ψ , subject to the discrete symmetry $(\phi, \psi_R) \rightarrow -(\phi, \psi_R)$. Starting with a Yukawa type interaction, the fermion can acquire mass from condensation of ϕ , according to

$$\mathcal{L}_m = -g\bar{\psi}\phi\psi \rightarrow -m\bar{\psi}\psi - \kappa\rho\bar{\psi}\psi \quad (1)$$

where we expand $\phi = \langle\phi\rangle + (\phi - \langle\phi\rangle) \equiv v + \rho$ about its vacuum expectation value, and identify the mass $m_\psi = gv$. ρ is the analogue of the Higgs field, and its coupling to ψ obeys the characteristic relation

$$\kappa = \frac{m}{v} \quad (2)$$

Since v appears elsewhere in the theory, and can be determined separately, this represents a predicted relationship among observables. Now suppose that we include, together with the standard Yukawa interaction, a mass dimension six (nonrenormalizable) interaction, so that

$$\mathcal{L}_m = -g\bar{\psi}\phi\psi - g'\phi^2\bar{\psi}\phi\psi \quad (3)$$

Then the induced mass of ψ , after condensation, is

$$m = gv + g'v^3 \quad (4)$$

while the residual Yukawa coupling $\rho\bar{\psi}\psi$ occurs with coefficient

$$\kappa = g + 3g'v^2 = \frac{m}{v} + 2g'v^2 \quad (5)$$

Thus including the new interaction has altered the relationship between the mass and the coupling. The effect can be extreme if m is “unnaturally” small, for then the enhancement factor $\kappa/(m/v) = 1 + 2g'v^3/m$ can be large.

This very simple analysis carries over, in its essence, to the standard model, with interesting implications. For definiteness, let us consider the coupling of the minimal Higgs doublet ϕ to the left-handed quark doublets Q_L and the right-handed charge $\frac{2}{3}$ quark singlets U_R , in the form allowing for dimension 6 contributions:

$$\mathcal{L}_m = -\overline{Q_{Lar}}U_R^s\phi^a M_{0s}^r - \phi_b^\dagger\phi^b\overline{Q_{Lar}}U_R^s\phi^a M_{1s}^r + \text{h.c.} \quad (6)$$

Here the early Latin indices are for weak isospin, the middle Latin indices are for flavor, color and space-time spinor indices have been suppressed, and M_0, M_1 are numerical matrices. Upon condensation, with $\langle\phi^a\rangle = v\delta^{a1}$, and identifying the Higgs field $H = \text{Re}(\phi^1 - v)$, we get the mass matrix for up-type quarks

$$\begin{aligned} \mathcal{L}_{\text{mass}} &= -\overline{U}_L M U_R + \text{h.c.} \\ M &= M_0 v + M_1 v^3 \end{aligned} \quad (7)$$

and the coupling matrix, for linear terms in H ,

$$\begin{aligned} \mathcal{L}_{\text{coupling}} &= -H\overline{U}_L\Xi U_R + \text{h.c.} \\ \Xi &= M_0 + 3M_1 v^2 = M + 2M_1 v^2 \end{aligned} \quad (8)$$

The interpretation of this structure is particularly transparent if we have chosen our fermion fields to make M diagonal and positive, as is always

possible (and conventional). We see that the effect of a non-zero M_1 is to alter the familiar prediction that Higgs particle couplings are diagonal in flavor, and proportional to mass (i.e., $\Xi = M/v$). The new terms are particularly significant if they are corrections to terms that were previously small, or zero. Thus they can, for example, generate an enhanced $H\bar{u}u$ coupling of the Higgs field to the up quark, or induce flavor-changing processes $H\bar{c}u$.

Terms involving charge $-\frac{1}{3}$ quarks and charged leptons can be analyzed in the same way. The possibility of enhanced $H\bar{e}e$ couplings is particularly significant, because such couplings can be accessed experimentally at electron-positron colliders, but are ordinarily predicted to be tiny. Also intriguing is the possibility of $H\bar{e}\mu$, which provides a striking decay mode.

Plausibilities

If we ascribe the anomalously small masses of e, u, d to anthropic requirements, then we constrain the corresponding masses to be small, even if that requires “unnatural” cancellations. In our context, this corresponds to a constraint on the M_S , but not separately on the M_0, M_1 s. Conversely, it becomes more “natural” to expect large enhancements of the Higgs couplings, relative to conventional expectations, in these cases.

Coupling to one or more additional vector-like families can, according to Feynman diagrams such as that displayed in Figure 1, induce the sort of effective low energy interactions envisaged here. The existence of additional vector-like families is fully consistent with all known general requirements and phenomenological constraints, so long as they are not too light.

One can also consider a variety of other dimension 6 interactions affecting Higgs particles, by multiplying any allowed coupling of the standard model by $\phi^\dagger\phi$. They also lead to quantitative modifications of the predicted Higgs couplings, along the same lines. The consequences generally appear less dramatic, however, since with one exception there are no accidentally small or vanishing quantities subject to correction. That exception is the appearance of

$$\mathcal{L}_{\bar{\theta}} \propto \phi^\dagger\phi \text{Tr} G_{\alpha\beta}G_{\gamma\delta} \epsilon^{\alpha\beta\gamma\delta} \quad (9)$$

where G is the field strength for any of the gauge groups of $SU(3) \times SU(2) \times U(1)$. This leads directly to P and T violation in Higgs particle production and decay; unfortunately, the consequences will be difficult to observe, unless the effect is surprisingly large.

Of course non-minimal Higgs particle couplings can easily arise, through mixing, in theories with more elaborate low energy field content, notably

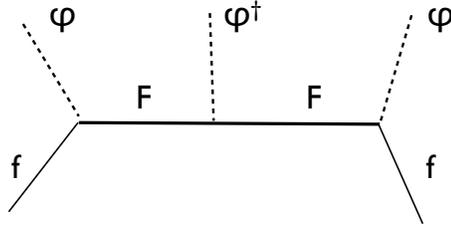


Figure 1: Integrating out the heavy fermion F , connecting to the light fermion f through Higgs doublets, will induce dimension 6 couplings of the kind analyzed in the text.

including “portal” models featuring additional $SU(3) \times SU(2) \times U(1)$ singlet scalars. Here we have shown that it is a plausible possibility, even if the Higgs sector and low-energy field content is minimal.

Constraints

Some of the same things that make all this interesting also lead to constraints. Higgs couplings that change flavor can lead to processes $ss \rightarrow dd$, that affect $K - \bar{K}$ mixing, or to $\mu \rightarrow eee$ decays, are especially dangerous. If one assumes that the relevant M_1, M_2 are simultaneously diagonalizable, so that there is no violation of flavor quantum numbers, then the constraints are much less severe, but offhand I don’t see an attractive way to insure that.

If the generic coupling parameters are as small as the *conventional* Hee coupling, then it appears that all the constraints are comfortably satisfied. (They could be a hundred times larger, or so, before running into trouble.) If that impression holds up to closer scrutiny, it indicates that there is some

room for unconventional, but plausible, physics to enhance the Hee coupling.

References and acknowledgement

Buchmüller and Wyler, Nucl. Phys. **B268** 621-653 (1986), is an encyclopedic reference on operator analysis of flavor constraints. I thank Al Shapere for bringing this paper to my attention.