Higgs Sector Enrichment

The minimal implementation of electroweak symmetry breaking, using one complex scalar isodoublet, leads to a very tight phenomenology, as we have seen. So far experimental observations are consistent with this scheme, but it is still early days, and it is a timely entertainment to consider augmentations and variations. If nothing else, this activity can help to parameterize just what it is people are excluding as they make new observations, and to point out directions that might be promising.

Of course there are infinitely many ways to complicate things. Here you'll explore three of the simplest, which bring out ideas that are common to almost all speculative extensions of the standard model.

Two Doublet Models

Instead of one isodoublet ϕ with hypercharge $-\frac{1}{2}$, suppose we have two doublets ϕ_1, ϕ_2 with hypercharges $\mp\frac{1}{2}$.

1. Make a census of all the allowed couplings with mass dimension ≤ 4. Discuss the constraints on the potential terms arising from the requirement that the energy density is bounded below.

2. Show that, depending on the coefficients of allowed couplings, either of ϕ_1, ϕ_2 will acquire a vacuum expectation value, or not. Do we always get $SU(2) \times U(1) \rightarrow U(1)$, or are there other possibilities? For each possibility you identify, give a qualitative census of the vector boson / Higgs scalar sector. Specifically: Identify the physical degrees of freedom and their quantum numbers under the residual symmetries, and specify which have zero mass.

3. Now suppose that we have a discrete symmetry

$$\begin{aligned} \phi_1' &= -\phi_1 \\ U_R' &= -U_R \\ D_R' &= -D_R \\ E_R\prime &= -E_R \end{aligned} \tag{1}$$

   with everything else unchanged. Re-do the census. Show that in this case ϕ_1, but not ϕ_2, couples to fermions. Show that we can arrange the potential so that both ϕ_1 and ϕ_2 acquire vacuum expectation values, and we break $SU(2) \times U(1) \rightarrow U(1)$. Show that in this case, after symmetry breaking there is a particle that couples to fermions in the same way as does the minimal Higgs particle, but with a different overall strength. Determine also its couplings to the gauge bosons, and to itself. Be as predictive as this framework allows you to be!

4. Now suppose instead that we have two separate discrete symmetries

$$\begin{aligned} \phi_1' &= -\phi_1 \\ U_R' &= -U_R \end{aligned} \tag{2}$$

and

$$\begin{aligned} \phi_2' &= -\phi_2 \\ D_R' &= -D_R \\ E_R\prime &= -E_R \end{aligned} \tag{3}$$

Re-do the census, and address the same questions. (This structure is what arises in low-energy supersymmetry.)

5. Now specialize further by supposing that that the preceding symmetries are continuous:

$$\begin{aligned} \phi_1' &= e^{i\alpha}\phi_1 \\ U_R' &= e^{-i\alpha}U_R \end{aligned} \tag{4}$$

$$\begin{aligned} \phi_2' &= e^{i\beta}\phi_2 \\ D_R' &= e^{-i\beta}D_R \\ E_R\prime &= e^{-i\beta}E_R \end{aligned} \tag{5}$$

Re-do the census. Show that the same symmetry-breaking pattern is still supported. Show that after symmetry breaking there is a massless scalar field, and work out its couplings to fermions. (This structure is what arises in axion physics, and the formally massless field we meet here is the axion field. Non-perturbative symmetry breaking effects, connected with instantons and anomalies, give the axion a mass and somewhat alter its phenomenology, but for purposes of this exercise we'll ignore those important complications.)

Portal Models

Another simple possibility is that in addition to the minimal doublet ϕ we have an $SU(3) \times SU(2) \times U(1)$ singlet η. For simplicity, suppose that we have a symmetry $\eta \rightarrow -\eta$, and consider only cases in which ϕ acquires a vacuum expectation value, so $SU(2) \times U(1) \rightarrow U(1)$.

1. Re-do the census. Why is it appropriate to say that the Higgs particle opens a new "portal" into physics we could not have accessed before?

2. Suggest experimental signatures for this scenario, both in the cases that ϕ acquires a vacuum expectation value and in cases where it does not.

Minimal Field With Non-Minimal Couplings

Finally, consider the possibility that we do not introduce additional particles, but do allow mass dimension ≤ 6 couplings.

For background on this subsection, consult the preceding note on non-minimal Higgs couplings. A definitive treatment of the following items could be the basis of a publishable research paper. As always, feel free to consult any literature you can find (and to interrogate faculty members!).

1. Derive bounds on flavor-changing couplings of the Higgs particle by considering mixing and rare decay processes. Use the latest experimental results.
2. Compare the magnitudes of these bounds with the predicted magnitude of the coupling of the Higgs particle to electrons.
3. Now that we have Higgs particles to study, what are the prospects for improving the bounds we got from "virtual" exchange?