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Higher Higgs Representations

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- Outline

I. Introduction

II. Generic Higgs representations

III. Custodial symmetry

IV. Final remarks

Mostly following the presentation of Low & Lykken, 1005.0872

I. Introduction

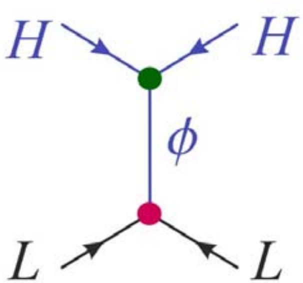
Some of the questions we want to address

Is the scalar sector entirely made of the SM scalar doublet?

- T = 0 : Additional singlets (axions, NMSSM,...)?
- T = 1/2 : More than one doublet (2HDM, MSSM,...)?
- T ≥ 1 : Higher representations?

Mostly Higgs triplets T = 1 (no fermion coupling for T > 1)

$$\mathcal{L}_{seesaw} = y_{\Delta L=2}\overline{L}^C\vec{\phi}\cdot\vec{\sigma}L + \mu_{HH\phi}H^\dagger\vec{\phi}\cdot\vec{\sigma}H^C + \ldots$$



$$\rightarrow \frac{\mu_{HH\phi}y_{\Delta L=2}}{M_\phi^2}\overline{L}^C H\, LH \rightarrow m_\nu \sim v^2\frac{\mu_{HH\phi}y_{\Delta L=2}}{M_\phi^2}$$

Some of the questions we want to address

Phenomenologically, two central questions:

- What are the EW quantum numbers of the 125 GeV state?
- How can we test for the presence of more scalar states?

Direct searches:

- T ≥ 0 : more H^0's left over
- T ≥ 1/2 : new H^+ state(s)
- T ≥ 1 (Y≠0): $H^{++} \to W^+W^+$
- T ≥ 2 (Y≠0): $H^{n+}, n > 2$

Seems difficult to see…

How heavy should the
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Seems difficult to see…

mixing

loops

Indirect searches:

$$\mathcal{L}_{eff} \sim c_W hW_\mu^+ W^{-\mu} + c_Z hZ_\mu Z^\mu + c_b h\bar{b}b + c_t h\bar{t}t + c_\tau h\bar{\tau}\tau + c_g hG_{\mu\nu}^a G^{a,\mu\nu} + c_\gamma hF_{\mu\nu}F^{\mu\nu} + c_{Z\gamma} hF_{\mu\nu}Z^{\mu\nu} + \ldots$$

How heavy should the new Higgs states be?

How much room is left now that couplings begin to be constrained?

II. Generic representations

What happens if many Higgs representations are present?

In terms of $SU(2)_L \otimes U(1)_Y$ quantum numbers, let us include

$\phi_k = \phi_k^\lambda, \lambda = 1, \ldots, n_k$: scalars in a complex representation,

$\eta_i = \eta_i^\lambda, \lambda = 1, \ldots, m_i$: scalars in a real (Y=0) representation.

Then, the scalar kinetic terms are:

$$\mathcal{L}_{scalar}(\phi_k, \eta_i) = \sum_k D_\mu \phi_k^\dagger D^\mu \phi_k + \frac{1}{2}\sum_i D_\mu \eta_i^T D^\mu \eta_i - V(\phi_k, \eta_i)$$

$$D_\mu = \partial_\mu - igW_\mu^a T^a - ig' B_\mu \frac{Y}{2}$$

What happens if many Higgs representations are present?

When the scalars acquire vevs as $\phi_k \to \phi_k + \langle \phi_k \rangle$ and $\eta_i \to \eta_i + \langle \eta_i \rangle$:

$$M_W^2 = \frac{1}{8} g^2 \sum_k (4T_k(T_k+1) - Y_k^2) v_k^2 + \frac{1}{2} g^2 \sum_i T_i(T_i+1) v_i^2$$

$$M_Z^2 = \frac{1}{4} \frac{g^2}{\cos^2\theta_W} \sum_k Y_k^2 v_k^2$$

The couplings to WW and ZZ are directly related to these masses:

$$v_k \to v_k \left(1 + \frac{\phi_k^0}{v_k}\right), \quad v_i \to v_i \left(1 + \frac{\eta_i^0}{v_i}\right)$$

But, experimentally, $\rho = M_W^2 / M_Z^2 \cos^2\theta_W = 1.0004(4).$

What happens if many Higgs representations are present?

Case 1: Doublets and the SM

T=1/2 → |Y|= 1 : $\phi_k = \begin{pmatrix} \phi_k^+ \\ \phi_k^0 \end{pmatrix}$

$$M_W^2 = \frac{1}{4} g^2 \sum_k v_k^2$$

$$M_Z^2 = \frac{1}{4} \frac{g^2}{\cos^2\theta_W} \sum_k v_k^2$$

Automatically ensures $\rho = 1$.

Only doublets can give mass to all fermions.

With many doublets, charged and neutral states remain.

$$\underbrace{\frac{c_Z}{c_W} = \frac{M_Z^2}{M_W^2} = \frac{1}{\cos^2\theta_W}}, \quad \underbrace{c_t\,,\ c_b\,,\ c_\tau}\,, \quad \underbrace{c_\gamma^{loop}\,,\ c_g^{loop}}\,, \ \ldots$$

What happens if many Higgs representations are present?

Case 2: Complex and real triplets

T=1 → |Y|= 2, 0 : $\phi = \begin{pmatrix} \phi^{++} \\ \phi^{+} \\ \phi^{0} \end{pmatrix}$ $\eta = \begin{pmatrix} \eta^{+} \\ \eta^{0} \\ \eta^{-} \end{pmatrix}$

Each triplet violates $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = \dfrac{v_\phi^2 + 2v_\eta^2}{2v_\phi^2} \neq 1$.

→ There is also a doublet, and $v_\eta, v_\phi \ll 174\,GeV$,

→ Both are present but $2v_\eta^2 = v_\phi^2$.

Non-standard couplings to WW, ZZ : $\dfrac{c_Z^\eta}{c_W^\eta} = 0,\ \dfrac{c_Z^\phi}{c_W^\phi} = \dfrac{2}{\cos^2\theta_W}$.

What happens if many Higgs representations are present?

Case 3: Singlet

T=0 → |Y|= 0 : $\eta = \eta^0$

No couplings at tree-level; arise at dimension five:

$$\mathcal{L}_{eff} = \frac{\kappa_2}{\Lambda}\eta^0 W^a_{\mu\nu} W^{a,\mu\nu} + \frac{\kappa_1}{\Lambda}\eta^0 B_{\mu\nu} B^{\mu\nu}$$

$$\begin{cases} c^5_{WW} = \kappa_2 \\ c^5_{ZZ} = \kappa_2\, c^2_{\theta W} + \kappa_1 s^2_{\theta W} \\ c_{Z\gamma} = c_{\theta W}\, s_{\theta W}\,(\kappa_2 - \kappa_1) \\ c_{\gamma\gamma} = \kappa_2 s^2_{\theta W} + \kappa_1 c^2_{\theta W} \end{cases} \xrightarrow{c_{\gamma\gamma} \ll c^5_{WW}} \begin{cases} c^5_{WW} = \kappa_2 \\ c^5_{ZZ} = \kappa_2\, c^2_{\theta W} + \delta s^2_{\theta W} + \mathcal{O}(s^4_{\theta W}) \\ c_{Z\gamma} = s_{\theta W}\,(\kappa_2 - \delta) + \mathcal{O}(s^3_{\theta W}) \\ c_{\gamma\gamma} = \delta \end{cases}$$

III. Custodial symmetry

Custodial symmetry and Higgs doublets

The SM scalar sector has an accidental $SU(2)_L \otimes SU(2)_R$ symmetry:

$$\Phi = \begin{pmatrix} H^{0\dagger} & H^{+} \\ -H^{-} & H^{0} \end{pmatrix}, \qquad \mathcal{L}_{scalar}(\Phi) = D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi)$$

Potential is invariant under $\Phi \to U_L \Phi U_R^\dagger$

This symmetry partially gauged: $D_\mu \Phi = \partial_\mu \Phi + igW_\mu^a T_L^a \Phi - ig' B_\mu \Phi T_R^3$

The vev $\langle \Phi \rangle = \dfrac{1}{\sqrt{2}} \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$ is invariant under $\langle \Phi \rangle \to U_{L=R} \langle \Phi \rangle U_{R=L}^\dagger$:

$$SU(2)_L \otimes SU(2)_R \to SU(2)_{L+R} \equiv SU(2)_C$$

Higgs = $SU(2)_C$ singlet, would-be Goldstones = $SU(2)_C$ triplet,

Weak gauge bosons = $SU(2)_C$ triplet → same mass → $\rho = 1$.

Custodial symmetry beyond the doublets

To generalize to higher representations:

$$\Phi = \begin{pmatrix} H_1^0 & \dots & H^{N+} \\ \vdots & \ddots & \vdots \\ H^{N-} & \dots & H_N^0 \end{pmatrix}, \qquad \langle \Phi \rangle = \frac{1}{\sqrt{N}} \begin{pmatrix} v & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & v \end{pmatrix}$$

This corresponds to $N_L \otimes N_R \to 1_C^H \oplus 3_C^H \oplus 5_C^H \oplus \dots \oplus (2N-1)_C^H$

($1_C^H, 5_C^H, \dots$ are CP-even, the rest is odd)

$SU(2)_C$ invariance of the potential prevents mixings between R_C^H's.

The only CP-even couplings are $3_C^V \otimes 3_C^V \otimes (1_C^H \oplus 5_C^H)$, with

$$\frac{c_{ZZ}^{I=0}}{c_{WW}^{I=0}} = \frac{1}{\cos^2\theta_W} = -\frac{1}{2}\frac{c_{ZZ}^{I=2}}{c_{WW}^{I=2}} \quad .$$

Custodial symmetry beyond the doublets

Examples:

(= Standard model)

T=1/2, Y=1

$$\Phi = \begin{pmatrix} \phi^{0\dagger} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}$$

(Georgi, Machacek 1985)

T=1, Y=0

T=1, Y=2

$$\Phi = \begin{pmatrix} \phi^{0\dagger} & \eta^{+} & \phi^{++} \\ \phi^{-} & \eta^{0} & \phi^{+} \\ \phi^{--} & \eta^{-} & \phi^{0} \end{pmatrix}$$

T=3/2, Y=3

T=3/2, Y=1

$$\Phi = \begin{pmatrix} \phi_1^{0\dagger} & \phi_2^{+} & \phi_2^{++} & \phi_1^{3+} \\ \phi_1^{-} & \phi_2^{0\dagger} & \phi_2^{+} & \phi_1^{++} \\ \phi_1^{--} & \phi_2^{-} & \phi_2^{0} & \phi_1^{+} \\ \phi_1^{3-} & \phi_2^{--} & \phi_2^{-} & \phi_1^{0} \end{pmatrix}$$

Custodial symmetry beyond the doublets

Examples:

$$\Phi = \begin{pmatrix} h^0 + \pi^0 & \pi^+ \\ \pi^- & h^0 - \pi^0 \end{pmatrix}$$ (= Standard model)

$2_L \otimes 2_R \to 1_C^h \oplus 3_C^\pi$

(Georgi, Machacek 1985)

$$\Phi = \begin{pmatrix} h^0 + \pi^0 - a^0 & \pi^+ + a^+ & a^{++} \\ \pi^- + a^- & h^0 + 2a^0 & \pi^+ - a^+ \\ a^{--} & \pi^- - a^- & h^0 - \pi^0 - a^0 \end{pmatrix}$$

$3_L \otimes 3_R \to 1_C^h \oplus 3_C^\pi \oplus 5_C^a$

$$\Phi = \begin{pmatrix} b^0, b^\pm, b^{\pm\pm}, b^{\pm\pm\pm} \\ a^0, a^\pm, a^{\pm\pm} \\ \pi^0, \pi^\pm \\ h^0 \end{pmatrix}$$

$4_L \otimes 4_R \to 1_C^h \oplus 3_C^\pi \oplus 5_C^a \oplus 7_C^b$

Isospin 2 channel and sum rule

Falkowski et al., 1202.1532

The presence of 5_C^a permits to increase $c_V \equiv c_W = c_Z \cos^2\theta_W$,

- without upsetting $\rho = 1$ since the custodial symmetry is active,
- while preserving unitarity, thanks to the new 5_C^a contributions.

$$1 - c_V^2 \sim \int_0^\infty \frac{ds}{s}\left(2\sigma_{I=0}(s) + 3\sigma_{I=1}(s) - 5\sigma_{I=2}(s)\right)$$

So, there would be a doubly charged Higgs boson:

$$\mathcal{L}_{HVV} \sim \sqrt{\frac{2}{3}}\frac{m_W^2}{v}a^0 W_\mu^+ W^{-,\mu} - \sqrt{\frac{2}{3}}\frac{m_Z^2}{v}a^0 Z_\mu Z^\mu$$
$$+\sqrt{2}\frac{m_W m_Z}{v}a^+ W_\mu^- Z + m_W^2 a^{++} W_\mu^- W^{-,\mu} + h.c.$$

$1_C^h \otimes 5_C^a \otimes 5_C^a$ → Charged Higgses contribute to the gg/$\gamma\gamma$ loops.

IV. Final remarks

Higher representations offer some freedom.

But experiments may not…

The SM gauge & accidental symmetries are constraining:

Higher representations introduce multi-charged states.

Several such representations are in general needed.

In addition, doublets are called in for fermion masses.

With many representations, the potential is very involved.

Is it worth to go beyond the triplet?

We still hope for less minimal New Physics to occur:

Seesaw mechanism for the small neutrino masses.

Impact on the unification of gauge couplings / fermion masses.

One may want to supersymmetrize all this (avoid real Higgs).