WHEN IS A HIGGS THE HIGGS?

OR

THE PHENOMENOLOGY OF A NON-STANDARD HIGGS BOSON

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ABSTRACT

The one-Higgs-doublet standard model is necessarily incomplete because of the triviality of the scalar symmetry-breaking sector. If the Higgs mass is approximately 600 GeV or higher, there must be additional dynamics at a scale $\Lambda$ which is less than a few TeV. In this case the properties of the Higgs resonance can differ substantially from those predicted by the standard model. In this talk we construct an effective Lagrangian description of a theory with a non-standard Higgs boson and analyze the features of a theory with such a resonance coupled to the Goldstone Bosons of the breaking of $SU(2) \times U(1)$.

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1. Apologia

Let me begin by stating the reason that I believe a talk of this sort has a place in a conference on QCD. QCD, in addition to its intrinsic interest and relevance, is a prototype of a theory with a dynamically broken chiral symmetry. It is, therefore, a prototype of a theory of dynamical electroweak symmetry breaking. The simplest example of a theory with dynamical electroweak symmetry, Technicolor\(^1\), is a vector-like $SU(N)$ gauge theory, just like QCD, with a dynamical scale of approximately 1 TeV instead of 1 GeV. Unfortunately, this type of QCD-like theory is disfavored for a number of phenomenological reasons\(^2\). It is important, therefore, to investigate and understand other members of the class of theories which allow for dynamical
electroweak symmetry breaking. This investigation will clearly employ some of the
tools (e.g. Chiral Perturbation Theory) which have been successfully applied
to QCD. Furthermore, progress in understanding the dynamics of chiral symmetry
breaking in QCD may allow us to construct new, phenomenologically acceptable,
theories of dynamical electroweak symmetry breaking. I hope that the QCD experts
gathered here will keep this last point in mind.

The standard one-doublet Higgs model of the weak interactions is in spectacular
agreement with experimental results. However:

- There is no direct experimental evidence for the existence of a Higgs Boson.
- (Non-supersymmetric) Theories with fundamental scalars are unnatural.

Furthermore, the symmetry-breaking sector of the standard model is trivial. That
is, the theory can only be understood as a low-energy effective theory for some, more
fundamental, high-energy theory.

If the mass of the Higgs Boson is greater than about 600 – 700 GeV, the scale $\Lambda$
of the new dynamics cannot be greater than of order one or a few TeV. Turning this
last argument around: if the electroweak symmetry breaking sector involves a heavy
(iso-)scalar resonance that couples to the electroweak gauge Bosons, then (since the
scale of the new dynamics is relatively low) this particle will likely have properties
rather different from those of the SM Higgs Boson. We call such a resonance a “non-
standard” Higgs Boson.

As an existence proof, note that there are (at least) two classes of dynamical
electroweak symmetry breaking models known where a “non-standard” Higgs may be
present:

- Georgi-Kaplan Composite Higgs models: in these models, all four members of
  a Higgs doublet are Goldstone Bosons arising from chiral symmetry breaking
due to a strong hypercolor interaction. $SU(2) \times U(1)$ breaking is due to vacuum
  misalignment.

- Top-Mode Standard Models: in these models it is assumed that the strength of
  some strong short-distance interaction (perhaps a spontaneously broken gauge
  theory) is tuned close to the critical value for chiral symmetry breaking.

If the intrinsic scale of the high-energy interactions (either the hypercolor interactions
in the first case or the short-distance interactions in the second) is not too much larger
than 1 TeV, the properties of the lightest spin-0 isospin-0 scalar can differ substantially
from the standard model predictions.

If a (iso-scalar) resonance which couples to $WW$ is discovered, how will we know if it is THE Higgs?

In this talk I will report on the first steps in an analysis of this question. In
particular, I will briefly describe the calculation of the leading non-analytic corrections
to the decay width and to $W_L W_L$ scattering. The details of the calculations may be
found in ref. 5.
2. The Effective Lagrangian

We wish to describe a theory in which, in addition to the Goldstone Bosons (which are, in the sense of the equivalence theorem\textsuperscript{10}, the longitudinal weak gauge bosons) has an iso-singlet scalar field $H$ which is much lighter than any other states in the theory. (Note that, in this way, the theory is very different than QCD. The “sigma” particle in QCD, to the extent it is a distinguishable resonance, is not lighter than other resonances.) The lowest-order interactions of $H$ coupled to the Goldstone Bosons of $SU(2)_L \times SU(2)_R$ symmetry breaking are summarized by the following effective low-energy Lagrangian:

\begin{equation}
\mathcal{L} = \frac{1}{4} (v^2 + 2\xi v H + \xi' H^2 + \xi'' \frac{H^3}{6v}) \text{Tr} (\partial_\mu \Sigma^\dagger \partial^\mu \Sigma) + \mathcal{L}_H, \tag{1}
\end{equation}

\begin{equation}
\mathcal{L}_H = \frac{1}{2} (\partial_\mu H)^2 - \frac{m^2}{2} H^2 - \frac{\lambda_3 v^3}{3!} H^3 - \frac{\lambda_4 v^4}{4!} H^4, \tag{2}
\end{equation}

where,

\begin{equation}
\Sigma = \exp \left( \frac{i\vec{w} \cdot \vec{\tau}}{v} \right), \quad \text{Tr} (\tau^a \tau^b) = 2\delta^{ab}, \tag{3}
\end{equation}

$v \approx 250$ GeV, and the $\vec{w}$ are the “eaten” Goldstone Bosons.

The ordinary linear sigma-model corresponds to the limit:

\begin{equation}
\xi, \xi' = 1, \quad \xi'' = 0 \tag{4}
\end{equation}

and

\begin{equation}
\lambda_3, \lambda_4 = \frac{3m^2}{v^2}. \tag{5}
\end{equation}

For a non-standard Higgs, we expect deviations from these values of order $v^2/\Lambda^2$.

3. Phenomenology

We begin by considering the width of the non-standard Higgs Boson. At tree-level, we find:

\begin{equation}
\Gamma^{(0)}_H = \frac{3m^3}{32\pi v^2}\epsilon^2. \tag{6}
\end{equation}
Note that \( \xi \) is the only parameter which appears\(^{11,12}\).

The other parameters in eq. (1) appear at one-loop. As usual, loops induce infinities which can be absorbed in the effective Lagrangian in the traditional way\(^{13}\): namely the infinities associated with non-derivative interactions are absorbed in the renormalization of the scalar self couplings in eq. (2), while the ones associated with vertices involving derivatives are absorbed in the counterterms of order \( p^4 \). In general, these introduce further unknown parameters in our amplitudes. We compute the leading corrections in the \( \overline{MS} \) scheme, setting the \( \mathcal{O}(p^4) \) counterterms to zero when the renormalization scale \( \mu \) is equal to \( \Lambda \). These results include the so-called “chiral logarithms”, which are the leading (non-analytic) contributions if \( p^2/\Lambda^2 \) is sufficiently small\(^{14}\), and in any case are expected to be comparable to the full \( \mathcal{O}(p^4) \) corrections\(^{13}\).

In addition, when the parameters take the values of the linear sigma model eqs. (4,5), the \( \mu \)-dependence disappears (as it must for a renormalizable theory) and our results reduce to those previously computed in the standard Higgs model.

The one-loop corrections to the Higgs boson decay width in eq. (6), written as

\[
\Gamma_H^{(1)} = \Gamma_H^{(0)} \left\{ \frac{\xi' \lambda_3}{2 \xi} \left[ \frac{\pi}{\sqrt{3}} - 1 \right] + \frac{\lambda_3^2 v^2}{4 m^2} \left[ 1 - \frac{2 \pi \sqrt{3}}{9} \right] + \frac{\xi'' m^2}{\xi v^2} L \right\} 
\]

where \( L = 1 - \ln\left(\frac{m^2}{\mu^2}\right) \). While this result is \( \mu \)-dependent, we can estimate the effect of higher-order interactions by setting \( \mu = \Lambda \). In the linear sigma model limit our calculation reproduces the one-loop result of ref. 15:

\[
\frac{\Gamma_H^{(1)}}{\Gamma_H^{(0)}} = \frac{m^2}{2 \pi^2 v^2} \left( \frac{19}{16} - \frac{3 \sqrt{3} \pi}{8} + \frac{5 \pi^2}{48} \right) 
\]

Next we consider the effects of a non-standard Higgs on Goldstone Boson scattering. The tree-level amplitude for \( w^+w^- \rightarrow zz \) is

\[
\mathcal{A}_{tr} = \frac{s}{v^2} - \left( \frac{\xi^2}{v^2} \right) \frac{s^2}{s - m^2 - \Sigma(s)} 
\]

The calculation of the one-loop corrections is straightforward, though somewhat lengthy. The full analytical expressions may be found in ref. 5. At energies small compared to the mass of the Higgs, the one-loop amplitude is:

\[
\mathcal{A}(s, t, u) = \frac{s}{v^2} + \frac{1}{(4\pi v^2)^2} T + \frac{\xi^2 s^2}{m^2 v^2} 
\]
\[ T = \frac{s^2}{2} \ln \frac{\mu^2}{-s} + \frac{t}{6}(s + 2t) \ln \frac{\mu^2}{-t} + \frac{u}{6}(s + 2u) \ln \frac{\mu^2}{-u} \]

\[ + s^2 P + Q(t^2 + u^2) + R \ln \frac{m^2}{\mu^2} \tag{11} \]

where

\[ P = \frac{5}{9} + 2\xi \xi'' + \xi^2 \left( \frac{7}{2} \xi' + \frac{22}{9} \right) - \frac{65}{9} \xi^4 + \frac{\xi \lambda_3}{2 \lambda'} \left( \xi' - \frac{\xi^2}{2} \right) + \xi^2 \frac{\lambda_3^2}{8 \lambda'^2} \left( \frac{\pi}{\sqrt{3}} - 2 \right) \tag{12} \]

\[ Q = \frac{13}{18} - \frac{11}{9} \xi^2 + \frac{5}{18} \xi^4 \tag{13} \]

\[ R = s^2 \left[ \frac{37}{6} \xi^4 - \xi^2 \left( \frac{10}{3} + 2 \xi' \right) + 2\xi \xi'' - \frac{\xi'^2}{2} \right] + \frac{\xi^2}{3} \left( 2 - \xi^2 \right) (t^2 + u^2) \tag{14} \]

where \( \lambda' = m^2/2v^2 \). Also in eq. (10), since \( m < 4\pi v \), we have retained the \( 1/m^2 \) correction to this order in the momentum expansion. In the linear sigma model limit and to leading order in \( s/m^2 \) this amplitude explicitly agrees with that of ref. 16.

The differential cross section for longitudinal gauge Boson scattering is obtained from the amplitude by

\[ \frac{d\sigma}{dt} = \frac{1}{16\pi s^2} |A|^2 \tag{15} \]

where \( A = A_{\text{tree}} + A_{\text{loop}} \). Since we neglected higher order corrections, we have

\[ |A|^2 = |A_{\text{tree}}|^2 + 2 \left\{ \Re(A_{\text{tree}}) \Re(A_{\text{loop}}) + \Im(A_{\text{tree}}) \Im(A_{\text{loop}}) \right\} . \tag{16} \]

The total cross section is then

\[ \sigma_{\text{tot}}(s) = \int_{-s}^{0} dt \frac{d\sigma}{dt}(s, t) \tag{17} \]

The amplitude for \( W^+_L W^-_L \) scattering can be calculated from those given above:

\[ A(W^+_L W^-_L \to W'^+_L W'^-_L) = A(s, t, u) + A(t, s, u) . \tag{18} \]
Figure 1: The total cross section for $W_L^+W_L^- \rightarrow W_L^+W_L^-$, for a non-standard Higgs with mass $m = 718$ GeV, and using the values in eq. (19) as a function of $s$. Solid lines correspond to tree level and dashed lines to one-loop.

In Fig. 1 we show the total cross section for the $W_L^+W_L^- \rightarrow W_L^+W_L^-$ channel as a function of $s$ for a Higgs mass of $m = 718$ GeV, with the parameters

$$
\xi = 0.62 \ , \ \xi' = -0.21 \ , \ \xi'' = 0.71 \ , \ \lambda_3 = 18.26 \ , \ \lambda_4 = 4.79 \ ,
$$

and $\Lambda = 2.2$ TeV. These parameters are motivated by a composite Higgs model based on an $SU(4)/Sp(4)$ symmetry structure. The solid line corresponds to tree level and the dashed lines to one-loop. The corresponding curves for a Standard model Higgs with the same mass are shown in Fig. 2. The sharp fall in the cross section in the region above the peak in Fig. 1 can be understood by noticing that for $\xi < 1$ the tree amplitude in eq. (1) vanishes at some energy greater than $m^2$ (if one does not include a finite width). This only signals that higher order effects are expected to be significant there. Also, far above the peak the amplitude presented is not trustworthy due to the breakdown of the expansion in powers of $1/\Lambda$.

Qualitatively, however, for gauge-Boson scattering below a TeV, the width and shape of the peak appear to be the most important features differentiating a standard from a non-standard Higgs resonance.

The cross sections discussed above are not directly measurable in hadron colliders like the LHC; one must first convolute them with the $W_LW_L$ luminosities inside the proton. A more detailed study of how well the LHC be able to differentiate a standard from a non-standard Higgs can only be answered after detailed analysis of a specific detector. This question is currently under investigation.
Figure 2: The total cross section for $W_L^+W_L^- \rightarrow W_L^+W_L^-$ in the Standard Model with a Higgs mass $m = 718$ GeV, as a function of $s$. Solid lines correspond to tree level and dashed lines to one-loop.

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5. References

1. S. Weinberg, Phys. Rev. D19, (1979) 1277; L. Susskind, Phys. Rev. D20 (1979) 2619.
2. E. Eichten and K. Lane, Phys. Lett. B90 (1980) 125; S. Dimopoulos and L. Susskind, Nucl. Phys. B155 (1979) 237; M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964; M. Golden and L. Randall, Nucl. Phys. 361 (1991) 3; B. Holdom and J. Terning, Phys. Lett. B247 (1990) 88.
3. K. G. Wilson, Phys. Rev. B 4 (1971) 3184; K. G. Wilson and J. Kogut, Phys. Rep. 12 (1974) 76.
4. M. Lüscher and P. Weisz, Nucl. Phys. B318 (1989) 705; J. Kuti, L. Lin and Y. Shen, Phys. Rev. Lett. 61 (1988) 678;
A. Hasenfratz, K. Jansen, C. B. Lang, T. Neuhaus and H. Yoneyama, Phys. Lett. **B199** (1987) 531;
A. Hasenfratz, K. Jansen, J. Jersák, C. B. Lang, T. Neuhaus and H. Yoneyama, Nucl. Phys. **B317** (1989) 81;
G. Bhanot, K. Bitar, U. M. Heller and H. Neuberger, Nucl. Phys. **B353** (1991) 551.

5. R. S. Chivukula and V. Koulovassilopoulos, Phys. Lett. **B309** (1993) 371 and Boston University preprint BUHEP-93-30, hep-ph/9312317.

6. D. B. Kaplan and H. Georgi, Phys. Lett. **B136** (1984) 183;
D. B. Kaplan, S. Dimopoulos and H. Georgi, Phys. Lett. **B136** (1984) 187;
T. Banks, Nucl. Phys. **B243** (1984) 125;
H. Georgi, D. B. Kaplan and P. Galison Phys. Lett. **B143** (1984) 152;
H. Georgi and D. B. Kaplan, Phys. Lett. **B145** (1984) 216;
M. J. Dugan, H. Georgi and D. B. Kaplan, Nucl. Phys. **B254** (1985) 299.

7. M.E. Peskin, Nucl. Phys. **B175** (1980) 197;
J. Preskill, Nucl. Phys. **B177** (1981) 21.

8. Y. Nambu, Enrico Fermi Institute Preprint EFI 88-39;
V. A. Miransky, M. Tanabashi, and K. Yamawaki, Phys. Lett. **B221** (1989) 177 and Mod. Phys. Lett. **A4** (1989) 1043;
W. A. Bardeen, C. T. Hill, and M. Lindner, Phys. Rev. **D41** (1990) 1647.

9. R.S. Chivukula, A.G. Cohen and K. Lane, Nucl. Phys. **B343** (1990) 554.
10. J. Cornwall, D. Levin, and G. Tiktopoulos, Phys. Rev. **D10**, (1974) 1145;
C. Vayonakis, Lett. Nuovo Cimento 17 (1976) 383;
B.W. Lee, C. Quigg and H. Thacker, Phys. Rev. **D16** (1977) 1519.

11. D. A. Kosower, in *Proceedings of the 1986 Summer Study on the Physics of the Superconducting Supercollider*, Snowmass, CO June 23 - July 11, 1986, R. Donaldson and J. Marx eds.

12. J. Bagger, Lectures given at TASI 1991, JHU-TIPAC-910038 (1992).
13. L.-F. Li and H. Pagels, Phys. Rev. Lett. **26**, (1971) 1089;
see also H. Pagels, Phys. Rep. **16C**, (1975) 221.

14. S. Weinberg, Physica 96 A (1979) 327;
H. Georgi and A. Manohar, Nucl. Phys. **B234** (1984) 189;
H. Georgi, Phys. Lett. **B298** (1993) 187.

15. W. J. Marciano, S.D. Willenbrock, Phys. Rev. **D37**, (1988) 2509.
16. S. Dawson and S. D. Willenbrock, Phys. Rev. **D40** (1989) 2880; Phys. Rev. Lett. **62** (1989) 1232.