Higgs Theory—A Brief Overview

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Abstract

A brief overview is given of the theory of Higgs bosons and electroweak symmetry breaking that is relevant for the Higgs physics program at the Linear Collider.

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1 Introduction

One of the highest priorities of particle physics today is the discovery of the dynamics responsible for electroweak symmetry breaking (EWSB). In the Standard Model (SM), this dynamics is achieved by the self-interactions of a complex scalar doublet of fields. This approach predicts the existence of one physical elementary scalar—the Higgs boson [1]. It has been argued that if the mass of the SM Higgs boson ($h_{SM}$) lies between about 130 and 200 GeV [2], then the SM can be valid at energy scales all the way up to the Planck scale.

However, it is difficult to imagine a fundamental theory of elementary particles and their interactions with no explanation for the origin of the large hierarchy of mass scales from $m_Z$ to the Planck mass. Thus, most theorists expect new physics beyond the SM at the TeV-scale to emerge and provide a “natural” explanation of the connection between these two disparate mass scales. To fully probe the nature of EWSB and the associated new TeV-scale physics, one must conduct experiments at the LHC and the LC.

2 Can A Light Higgs Boson Be Avoided?

Based on the most recent fits to electroweak data, the LEP Electroweak Working Group [3] concludes that “the Standard Model is able to describe nearly all the LEP measurements rather well,” with no compelling need for physics beyond the SM. This analysis yields a prediction for the Higgs mass: $m_{h_{SM}} = 114^{+69}_{-45}$ GeV or a one-sided 95% CL upper limit of $m_{h_{SM}} < 260$ GeV. These results have definite consequences for the anticipated Higgs studies at the LHC and LC, so it is natural to ask whether these conclusions can be avoided.

The probability of the goodness of the SM electroweak fit based only on high $Q^2$ data is 26% (this figure is reduced if the NuTeV results are included). Taking the SM electroweak fit at face value, one can use the data to constrain

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theories of new physics (whose low-energy effective theory closely approximates the SM). An example of such a procedure employs the $S$ and $T$ parameters of Peskin and Takeuchi [4], under the assumption that the main effects of the new physics enter through the modification of the $W$ and $Z$ boson self-energies. The precision electroweak data impose strong constraints on any new physics beyond the SM. For example, if the Higgs mass is significantly larger than the upper bound quoted above, new physics beyond the SM must contribute positively to $T$ (and perhaps negatively to $S$) in order to be consistent with the precision electroweak fits.

3 The Nature Of EWSB Dynamics

In addition to scalar dynamics of the SM, there have been many theories proposed in the literature to explain the mechanism of EWSB. Some theories employ weakly-coupled scalar dynamics, while others employ strongly-coupled dynamics of a new sector of particles. The motivation of nearly all proposed theories of EWSB beyond the SM is to address the theoretical problems of naturalness and hierarchy. The four main theoretical approaches are as follows:

**Higgs bosons of low-energy supersymmetry** [5]. As in the SM, these models employ weakly-coupled scalar dynamics, and all Higgs scalars are elementary particles. Supersymmetry eliminates all quadratic sensitivity to the Planck scale, at the price of TeV-scale supersymmetry breaking whose fundamental origin is unknown.

**Little Higgs models** [6]. The light Higgs bosons of these models are nearly indistinguishable from the elementary scalars of weakly-coupled EWSB theories. However, new physics must enter near the TeV scale to cancel out one-loop quadratic sensitivity of the theory to the ultraviolet scale. These theories have an implicit cutoff of about 10 TeV, above which one would need to find their ultraviolet completions.

**Extra-dimensional theories of EWSB** [7]. Such approaches lead to new models of EWSB dynamics, including the so-called “Higgsless” models [8] in which there is no light Higgs scalar in the spectrum. Such models also require an ultraviolet completion at a scale characterized by the inverse radius of the extra dimension.

**Strongly-coupled EWSB sectors** [9]. Models of this type include technicolor models, composite Higgs models of various kinds, top-quark condensate models, etc.

New physics beyond the SM can be of two types—decoupling or non-decoupling. The virtual effects of “decoupling” physics beyond the SM typically scale as $m_Z^2/M^2$, where $M$ is a scale characteristic of the new physics.
Examples of this type include “low-energy” supersymmetric theories with soft-supersymmetry-breaking masses of $O(M)$. In contrast, some of the virtual effects of “non-decoupling” physics do not vanish as the characteristic scale $M \to \infty$. A theory with a fourth generation fermion and technicolor models are examples of this type. Clearly, the success of the SM electroweak fit places stronger restrictions on non-decoupling new physics. Nevertheless, some interesting constraints on decoupling physics can also be obtained. For example, even in theories of new physics that exhibit decoupling, the scale $M$ must be somewhat separated from the scale $m_Z$ (to avoid conflict with the SM electroweak fit). This leads to a tension with the requirements of naturalness, which has been called the “little hierarchy problem” [10] in the literature.

4 Approaching The Decoupling Limit

Many models of EWSB yield a lightest Higgs boson whose properties are nearly identical to those of the SM Higgs boson (the so-called decoupling limit [11]). Thus, to probe the physics of EWSB, one must either detect deviations of the lightest CP-even Higgs boson from the decoupling limit and/or directly observe the additional degrees of freedom associated with the EWSB sector. The latter is expected to be connected with the TeV-scale physics responsible for a natural explanation of the electroweak scale. Examples include: non-minimal Higgs states (additional CP-even neutral scalars, CP-odd scalars and charged scalars), supersymmetric particles, new gauge bosons, vector-like fermions, Kaluza-Klein excitations and radions.

As an example consider the Higgs sector of the minimal supersymmetric extension of the Standard Model (MSSM), which in the decoupling limit contains a CP-even Higgs boson, $h$, with properties nearly identical to the SM Higgs boson. The decoupling limit is achieved in the limit of $m_A \gg m_Z$, where $m_A$ is the mass of the CP-odd scalar of the model. To illustrate these statements, we exhibit the following ratio of MSSM Higgs couplings [12]

\begin{align}
\left( g_{hVV}^2 \right)^{\text{SM}} & \simeq 1 - \frac{c^2 m_Z^2 \sin^2 4\beta}{4m_A^2}, & \frac{g_{hVV}^2}{g_{hSMV}^2} & \simeq 1 + \frac{c m_Z^2 \sin 4\beta \cot \beta}{m_A^2}, \\
\left( g_{hbb}^2 \right)^{\text{SM}} & \simeq 1 - \frac{4c m_Z^2 \cos 2\beta}{m_A^2} \left[ \sin^2 \beta - \frac{\Delta_b}{1 + \Delta_b} \right],
\end{align}

where $c \equiv 1 + O(g^2)$ and $\Delta_b \equiv \tan \beta \times O(g^2)$ [here, $g$ is a generic gauge or Yukawa coupling]. The quantities $c$ and $\Delta_b$ depend on the MSSM spectrum. \footnote{Eqs. (1) and (2) include the leading $\tan \beta$-enhanced radiative corrections, where $\tan \beta$ is the ratio of the two neutral Higgs vacuum expectation values.}
The approach to decoupling is fastest for the $h$ couplings to vector boson pairs and slowest for the couplings to down-type quarks. More generally, deviations from the decoupling limit implicitly contain information about the EWSB sector and the associated TeV-scale dynamics.

5 Main Goals Of The Higgs Hunter

In preparing for a program of Higgs physics at present day and future colliders, one must first determine the discovery reach of the colliders (Tevatron, LHC, LC, ...) for the $h_{\text{SM}}$ and any additional states of a non-minimal Higgs sector that might exist. If evidence for the latter are found, one must then establish the number of such states in the low-energy spectrum. Once a candidate scalar state is discovered, one should ask whether it is a Higgs boson (and whether it could be the SM Higgs boson). Evidence for a non-minimal Higgs sector could emerge if deviations from SM Higgs behavior is observed or Higgs states beyond the $h_{\text{SM}}$ are produced.

The decoupling limit, in which the lightest Higgs state closely resembles the $h_{\text{SM}}$, presents an especially difficult challenge for interpreting the underlying EWSB dynamics, since numerous theoretical approaches can yield a lightest Higgs boson that is nearly indistinguishable from the $h_{\text{SM}}$. Nevertheless, small deviations from the SM encode the physics of EWSB and new physics beyond the SM. In this case, a program of precision Higgs measurements at the LC is essential. One will need to accurately measure the mass, width, branching ratios and couplings of the candidate Higgs states. One must check the spin and CP-quantum numbers (keeping an eye out for potential CP-violating effects). Ideally, one would like to reconstruct the full Higgs potential and directly verify the nature of the EWSB scalar dynamics.

If nature chooses a path far from the decoupling limit, the challenges are of a different nature. One must first determine if there there are any light scalar states that are associated with EWSB dynamics. It may be that the theory of EWSB is based on an extended Higgs sector far from the decoupling limit. In this case, one expects numerous light Higgs states accessible to both the LHC and LC. Otherwise, one must identify the source of EWSB dynamics and any associated phenomena. In all such cases, one expects to have many light states with a rich phenomenology anticipated at the LHC and LC and precision measurements will again be essential in order to distinguish among different theoretical approaches and models.

\footnote{Here, one needs further theoretical study to see if there are viable counter-examples (perhaps Higgsless theories?) in which no new physics below, say, 1 TeV is present.}
6 Conclusions

Recent approaches to EWSB dynamics have led to many new ideas and models. Theorists have an important role to play in the development of strategies for studying EWSB at future colliders. We must begin to systematize the attendant phenomenology that appears in new approaches, with an eye toward finding some universal features. We must also devise new phenomenological techniques for distinguishing among the various new approaches. The precision Higgs studies can be employed in this regard, although it is important to identify where conventional assumptions could fail. Finally, it will be especially fruitful to refine and extend the studies, initiated in [13], of the complementarity and interplay of the LHC and LC searches for EWSB dynamics. These will surely be significant steps toward unlocking the secrets of the TeV scale.

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