Higgs Boson Theory and Phenomenology

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Abstract

Precision electroweak data presently favors a weakly-coupled Higgs sector as the mechanism responsible for electroweak symmetry breaking. Low-energy supersymmetry provides a natural framework for weakly-coupled elementary scalars. In this review, we summarize the theoretical properties of the Standard Model (SM) Higgs boson and the Higgs sector of the minimal supersymmetric extension of the Standard Model (MSSM). We then survey the phenomenology of the SM and MSSM Higgs bosons at the Tevatron, LHC and a future e^+e^- linear collider. We focus on the Higgs discovery potential of present and future colliders and stress the importance of precision measurements of Higgs boson properties.

1 Introduction—Origin of Electroweak Symmetry Breaking

Deciphering the mechanism that breaks the electroweak symmetry and generates the masses of the known fundamental particles is one of the central challenges of particle physics. The Higgs mechanism [1] in its most general form can be used to explain the observed masses of the $W^\pm$ and Z bosons as a consequence of three Goldstone bosons ($G^\pm$ and G^0) that end up as the longitudinal components of the gauge bosons. These Goldstone bosons are generated by the underlying dynamics responsible for electroweak symmetry breaking. However, the fundamental nature of this dynamics is still unknown. Two broad classes of electroweak symmetry breaking mechanisms have been pursued theoretically. In one class of theories, electroweak symmetry breaking dynamics is weakly-coupled, while in the second class of theories the dynamics is strongly-coupled.

The electroweak symmetry breaking dynamics that is employed by the Standard Model posits a self-interacting complex doublet of scalar fields, which consists of four real degrees of freedom [2]. Renormalizable interactions are arranged in such a way that the neutral component of the scalar doublet acquires a vacuum expectation value, $v = 246$ GeV, which sets the scale of electroweak symmetry breaking. Consequently, three massless Goldstone bosons are generated, while the fourth scalar degree of freedom that remains in the physical spectrum is the CP-even neutral Higgs boson ($h_{\rm SM}$) of the Standard Model. It is further assumed in the Standard Model that the scalar doublet also couples to fermions through Yukawa interactions. After electroweak symmetry breaking, these interactions are responsible for the generation of quark and charged lepton masses. This approach is an example of weak electroweak symmetry breaking. Assuming that $m_{h_{\rm SM}} \lesssim 200$ GeV, all fields remain weakly interacting at energies up to the Planck scale. In the weakly-coupled approach to electroweak symmetry breaking, the Standard Model is very likely embedded in a supersymmetric theory [3] in order to stabilize the large gap between the electroweak and the Planck scales in a natural way [4,5]. These theories predict a spectrum of Higgs scalars [6], with the properties of the lightest Higgs scalar often resembling that of the Standard Model (SM) Higgs boson.

Alternatively, strong breaking of electroweak symmetry is accomplished by new strong interactions near the TeV scale [7]. More recently, a new approach to electroweak symmetry breaking has been explored, in which extra space dimensions beyond the usual $3+1$ dimensional spacetime are introduced [8] with characteristic sizes of order $(\rm TeV)^{-1}$. In such scenarios, the mechanisms for electroweak symmetry breaking are inherently extra-dimensional, and the resulting phenomenology may be significantly different from the usual approaches mentioned above.

Although there is as yet no direct evidence for the nature of electroweak symmetry breaking dynamics, present data can be used to discriminate among the different approaches. For example, precision electroweak data, accumulated in the past decade at LEP, SLC, the Tevatron and elsewhere, strongly support the Standard Model with a weakly-coupled Higgs boson [9]. Moreover, the contribution of new physics, which can enter through $W^\pm$ and Z boson vacuum polarization corrections, is severely constrained. This fact has already served to rule out several models of strongly-coupled electroweak symmetry breaking dynamics. The Higgs boson contributes to the $W^\pm$ and Z boson vacuum polarization through loop effects, and so a global Standard Model fit to the electroweak data yields information about the Higgs mass. The results of the LEP Electroweak Working Group analysis shown in fig. 1(a) yield [9]: $m_{h_{\rm SM}} = 85^{+54}_{-34}$ GeV, and provides a 95% CL upper limit of $m_{h_{\rm SM}} < 196$ GeV. These results reflect the logarithmic sensitivity to the Higgs mass via the virtual Higgs loop contributions to the various electroweak observables. The 95% CL upper limit is consistent with the direct searches at LEP [10] that show no conclusive evidence for the Higgs boson, and imply that $m_{h_{\rm SM}} > 114.1$ GeV at 95% CL. Fig. 1(b) exhibits the most probable range of values for the SM Higgs mass [11]. This mass range is consistent with a weakly-coupled Higgs scalar that is expected to emerge from the Standard Model scalar dynamics (although the Standard Model does not predict the mass of the Higgs boson; rather it relates it to the strength of the scalar self-coupling).

There are some loopholes that can be exploited to circumvent this conclusion. It is possible to construct models of new physics where the goodness of the global Standard Model fit to precision electroweak data is not compromised while the strong upper limit on the Higgs mass is relaxed. In particular, one can construct effective operators [12,13] or specific models [14] of new physics where