THE HIGGS BOSON

(by I. Hinchliffe, LBNL)

The Standard Model [1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2) $\times$ U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. Consequently its coupling to stable matter is very small, and its production and detection in experiments is difficult. An exception is its production in the decay of the Z boson. Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses. The branching ratio of the Higgs boson into various final states is shown in Fig. 1.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV [2]. While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass (for $M_H > 2M_Z$) and that a boson of mass 1 TeV has a width of 500 GeV.

It is believed that scalar field theories of the type used to describe Higgs self-interactions can only be effective theories valid over a limited range of energies if the Higgs self-coupling and hence Higgs mass is nonzero. A theory of this type that is valid at all energy scales must have zero coupling. The range of energies over which the interacting theory is valid is a function of the Higgs self-coupling and hence its mass. An upper bound on the Higgs mass can then be determined by requiring that the theory be valid (*i.e.*, have a nonzero value of the renormalized Higgs self-coupling) at all scales up to the Higgs mass [3]. Nonperturbative calculations using lattice [4] gauge theory that

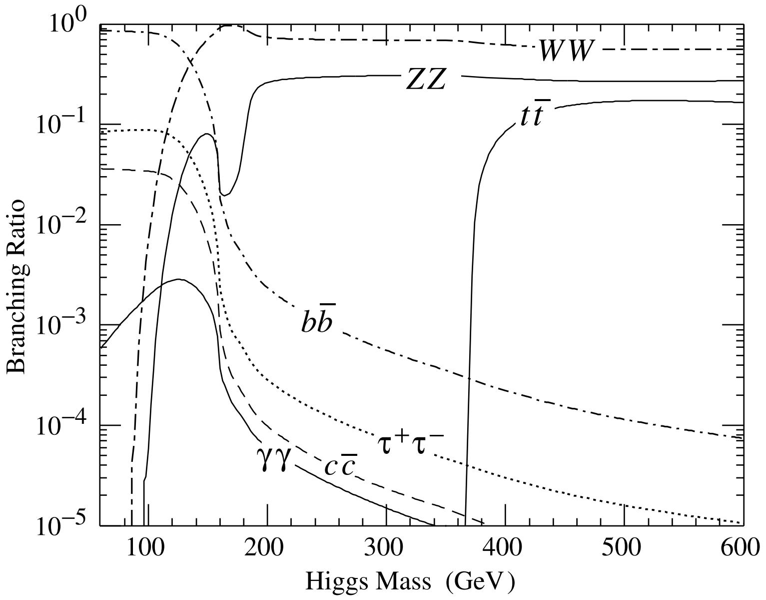

Figure 1: The branching ratio of the Higgs boson into $\gamma\gamma$, $\tau\overline{\tau}$, $b\overline{b}$, $t\overline{t}$, $c\overline{c}$, ZZ, and WW as a function of the Higgs mass. In the latter cases, if $M_H < 2M_Z$ (or $M_H < 2M_W$), the value indicated is the rate to ZZ^* (or WW^*) where Z^* (W^*) denotes a virtual Z (W). The $c\overline{c}$ rate depends sensitively on the poorly-determined charmed quark mass.

can be used to compute at arbitrary values of the Higgs mass indicate that $M_H \lesssim 770$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory [5]. A theoretical constraint can then be obtained from the requirement that this is not the case, *i.e.*, that our universe is in the true minimum of the Higgs potential. The constraint depends upon the top quark mass and upon the scale (Λ) up to which the Standard Model remains valid. This scale must be at least 1 TeV, resulting in the constraint [7] $M_H > 72$ GeV$+0.9$ ($m_{\rm top}$–174 GeV). The bound increases monotonically with the scale, for $\Lambda = 10^{19}$ GeV, $M_H > 135$ GeV + 2.1 ($m_{\rm top}$–174 GeV). This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age [8,9]. For $\Lambda = 1$ TeV there is no constraint; and for $\Lambda = 10^{19}$ GeV $M_H > 120$ GeV $+ 2.3$ $(m_{\rm top} - 174$ GeV) [10].

Experiments at LEP are able to exclude a large range of Higgs masses. They search for the decay $Z \rightarrow HZ^*$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (*i.e.*, missing energy) or hadrons. The experimental searches have considered both $H \rightarrow$ hadrons and $H \rightarrow \tau^+\tau^-$. The best limits are shown in the Full Listings below.

Precision measurement of electroweak parameters such as M_W and the various asymmetries at LEP and SLC are becoming sensitive enough that they can in principle constrain the Higgs mass through its effect in radiative corrections. Currently, the precision tests allow the entire range from the direct LEP limit ($M_H \gtrsim 60$ GeV) to 1 TeV [11] at 95% confidence level although fits prefer the lower end of this range. The recent determination of the top mass has improved the constraint on M_H. See the article in this volume on the "Standard Model of Electroweak Interactions."

The search range for Higgs bosons will expand shortly when LEP begins operation at higher energy. The process $e^+e^- \rightarrow ZH$ [12] should enable neutral Higgs bosons of masses up to ~ 0.97 $(\sqrt{s} - M_Z)$ to be discovered [13]. If the Higgs is heavier than this, its discovery will probably have to wait until experiments at the LHC have data. If the neutral Higgs boson has mass greater than $2M_Z$, it will likely be discovered via its decay to ZZ and the subsequent decay of the Z's to charged leptons (electrons or muons) or of one Z to charged leptons and the other to neutrinos. A challenging region is that between the ultimate limit of LEP and $2M_Z$. At the upper end of this range the decay to a real and a virtual Z, followed by the decay to charged leptons is available. The decay rate of the Higgs boson into this channel falls rapidly as M_H is reduced and becomes too small for $M_H \lesssim 140$ GeV. For masses below this, the decays $H \rightarrow \gamma\gamma$ and possibly $H \rightarrow b\overline{b}$ [14] are expected to be used. The former has a small branching ratio and large background, the latter has a large branching ratio, larger background and a final state that is difficult to fully reconstruct [15].

Extensions of the Standard Model, such as those based on supersymmetry [16], can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^{\pm}$), two neutral scalars (H_1, H_2),* and one pseudoscalar (A). In the simplest version of the supersymmetric model, the mass the lightest of these scalars depends upon the top quark mass, the ratio v_2/v_1, and the masses of the other supersymmetric particles. For $m_t = 174$ GeV, there is a bound $M_{H_1} \lesssim 125$ GeV [18,19]. In models where all fermions of the same electric charge receive their masses from only one of the two doublets (v_2 gives mass to the charge 2/3 quarks, while v_1 gives mass to the charged leptons and the charge 1/3 quarks), there are, as in the Standard Model, no flavor-changing neutral currents at lowest order in perturbation theory. The H_1, H_2^0, and A couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the Standard Model. Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. These ranges depend on the values of v_2/v_1. See the Full Listings below on H_1^0, Mass Limits in Supersymmetric Models.

Charged Higgs bosons can be pair produced in e^+e^- annihilation. Searches for charged Higgs bosons depend on the assumed branching fractions to $\nu\tau$, $c\overline{s}$, and $c\overline{b}$. Data from LEP now exclude charged Higgs bosons of mass less than 43.5 GeV [20]. See the Full Listings for details of the $H^{\pm}$ Mass Limit.

A charged Higgs boson could be produced in the decay of a top quark, $t \to H^+b$ with a rate comparable to $t \to Wb$. Searches for this decay at hadron colliders should be possible [21].

Notes and References

*H_1 and H_2 are usually called h and H in the literature.

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