THE HIGGS BOSON

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The Standard Model [1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2) × 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. The branching ratio of the Higgs boson into various final states is shown in Fig. 1.

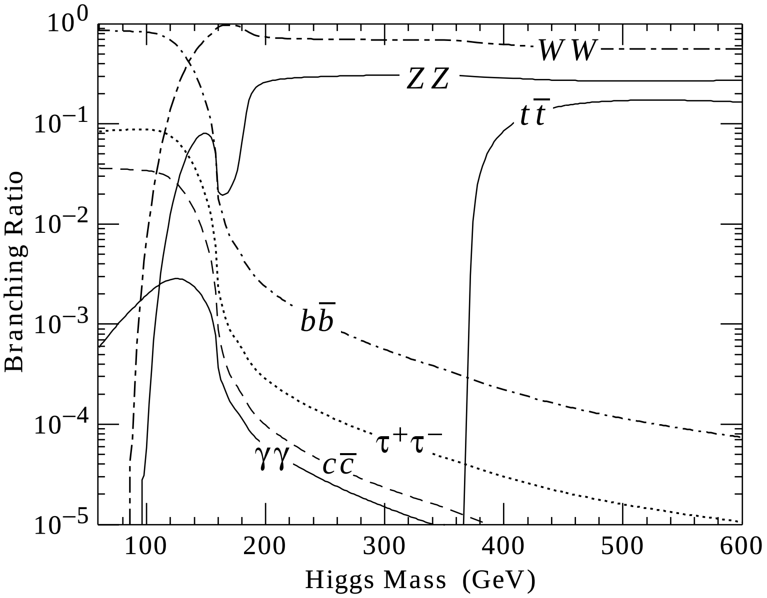

Figure 1: The branching ratio of the Higgs boson into $\gamma\gamma$, $\tau\overline{\tau}$, $b\overline{b}$, $t\overline{t}$, $c\overline{c}$, ZZ, and WW as a function of the Higgs mass. For ZZ and WW, if $M_H < 2M_Z$ (or $M_H < 2M_W$), the value indicated is the rate to ZZ^* (or WW^*) where Z^* (W^*)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

The Higgs coupling to stable matter is very small while its coupling to the top quark and to W and Z bosons is substantial. Hence its production is often characterized by a low rate and a poor signal to background ratio. A notable exception would be its production in the decay of the Z boson (for example $Z \to Hq\overline{q}$). 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.

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.

A scalar field theory of the type that is used to describe Higgs self-interactions can only be an effective theory (valid over a limited range of energies) if the Higgs self-coupling and hence the Higgs mass is finite. An upper bound on the Higgs mass can then be determined by requiring that the coupling has a finite value at all scales up to the Higgs mass [3]. Nonperturbative calculations using lattice [4] gauge theory that compute at arbitrary values of the Higgs coupling 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 our universe is in the true minimum of the Higgs potential [6]. 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] $M_H > 52 \text{ GeV} + 0.64\ (M_{\text{top}}\text{–}175 \text{ GeV})$. This constraint is weaker than that from the failure to directly observe the Higgs boson. The bound increases monotonically with the scale, for $\Lambda = 10^{19}$ GeV, $M_H > 135$ GeV $+ 1.9$ ($M_{\rm top}$–175 GeV) $- 680$ ($\alpha_s(M_Z) - 0.117$). 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 meaningful constraint; and for $\Lambda = 10^{19}$ GeV $M_H >$ 130 GeV $+ 2.3$ ($M_{\rm top} -$ 175 GeV) $- 815(\alpha_s(M_Z) - 0.117)$ [10].

Experiments at LEP are able to exclude a large range of Higgs masses. They search for the decay $Z \rightarrow HZ^*$ or $e^+e^- \rightarrow ZH$. 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 Particle Listings below.

Precision measurement of electroweak parameters such as M_W, $M_{\rm top}$, and the various asymmetries at LEP and SLC are sensitive enough that they can constrain the Higgs mass through its effect in radiative corrections. The current unpublished limit is $M_H <$ 450 GeV, at 95% CL with a central value of $M_H = 127^{+127}_{-72}$ GeV [11]. See also the article in this *Review* on the “Electroweak Model and Constraints on New Physics.”

The process $e^+e^- \rightarrow ZH$ [12] should enable neutral Higgs bosons of masses up to 95 GeV to be discovered at LEP at a center-of-mass energy of 190 GeV [13]. The current unpublished limits corresponding to the failure to observe this process at LEP imply $M_H > 77.5$ GeV at 95% CL [14]. If the Higgs is too heavy to be observed at LEP, there is a possibility that it could be observed at the Tevatron via the processes $p\overline{p} \rightarrow HZX$ [15] and $p\overline{p} \rightarrow WHX$ [16]. Failing this, its discovery will have to wait until experiments at the LHC. 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 $H \to \gamma\gamma$ and possibly $H \to b\bar{b}$ [17] 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 [18].

Extensions of the Standard Model, such as those based on supersymmetry [19], 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_1^0, H_2^0),* and one pseudoscalar (A) [20]. See also the articles in this *Review* on Supersymmetry.

In the simplest version of the supersymmetric model (see the *Reviews* on Supersymmetry), the mass of the lightest of these scalars depends upon the top quark mass, the ratio v_2/v_1 ($\equiv \tan\beta$), and the masses of the other supersymmetric particles. For $M_{\text{top}} = 174$ GeV, there is a bound $M_{H_1^0} \lesssim 130$ GeV [21,22] at large $\tan\beta$. The bound reduces as $\tan\beta$ is lowered.

The H_1^0, 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. As the masses of H_2^0 and A increase, the mass of H_1^0 approaches the bound, and the properties of this lightest state become indistinguishable from those a Standard Model Higgs boson of the same mass. This observation is important since the discovery of a single Higgs boson at LEP with Standard Model couplings would not be evidence either for or against the minimal supersymmetric model. However the failure to find a Higgs boson of mass less than 130 GeV would be definite evidence against the minimal supersymmetric Standard Model. In more complicated supersymmetric models, there is always a Higgs boson of mass less than 160 GeV.

Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. Production processes that are exploited are $e^+e^- \to ZH_1^0$ and $e^+e^- \to AH_1^0$. No signal is seen; the mass limits are (weakly) dependent upon the masses of other supersymmetric particles and upon $\tan\beta$.

Currently $M_{H_1^0}, M_A > 62$ GeV. See the Particle 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 54.5 GeV [23]. See the Particle Listings for details of the $H^\pm$ Mass Limit.

A charged Higgs boson could also be produced in the decay of a top quark, $t \rightarrow H^+b$. A search at CDF excludes $M_{H^+} < 147$ GeV for $\tan\beta > 100$ where the branching ratio $H^+ \rightarrow \tau\nu$ is large and at $\tan\beta < 1$ where the $\mathrm{BR}(t \rightarrow H^+b)$ is large [24]. The region at intermediate values of $\tan\beta$ will be probed as the number of produced top quarks increases. Searches for these non-standard Higgs bosons will be continued at LEP [13] and at LHC [25]

Notes and References

$^*H_1^0$ and H_2^0 are usually called h and H in the literature.

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