Higgs Boson Mass as the Discriminator of Electroweak Models

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In the standard model (SM), vacuum stability implies a *lower* limit on the Higgs boson mass. In supersymmetric (SUSY) extensions, there is an *upper* bound on the lightest Higgs boson mass. We show that for a top quark mass $m_t \lesssim 165$ GeV, a gap exists between the SM and both the minimal (MSSM) and next-to-minimal SUSY model [(M + 1)SSM] bounds. Thus, if the new m_t measurement by the Collider Detector at Fermilab remains valid, a first measurement of the Higgs boson mass will exclude either the SM or the simplest SUSY Higgs sectors. We further discuss SUSY grand unified models, other extensions of the SM, and the potential for discovery of a light Higgs boson.

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After roughly 20 years of experimental efforts to expose the origin of broken electroweak (EW) symmetry, not a single clue has been found. The simplest and most motivated possibilities for the symmetry-breaking sector of the EW interaction are the single Higgs doublet of the minimal standard model (SM), and the two Higgs doublets of the minimal supersymmetric (SUSY) standard model (MSSM). Recently, hope has risen that a new window to the symmetry-breaking sector may have been found: the Collider Detector at Fermilab (CDF) experiment has announced [1] the probable discovery of the top quark with mass at 174 ± 16 GeV. This range of m_t values encompasses the EW symmetry-breaking scale, defined by the vacuum expectation value (VEV) of the complex Higgs field Φ: $\langle 0|\Phi|0\rangle = v_{\rm SM}/\sqrt{2} = 175$ GeV. The fact that the central CDF value is nearly identical to the Φ VEV is intriguing, and presumably coincidental. The fact that the eventual true value of m_t will be comparable to the symmetry-breaking scale is fortuitous, for it suggests that the top quark may communicate the secrets of the symmetry breaking to us either through top properties or through large quantum corrections to classical physics. One observation [2] which we quantify in this Letter is the following: inputting the CDF value for the top mass into quantum loop corrections for the symmetry-breaking Higgs sector leads to mutually exclusive, reliable bounds on the SM Higgs boson mass and on the lightest MSSM Higgs boson mass. A mass gap develops with increasing m_t. We demonstrate the onset of the mass gap in Fig. 1. From this we infer that *if the CDF value for m_t is verified in the 1994–95 data run, then the first Higgs boson mass measurement will rule out one of the two main contenders (SM with no new physics below 10^{10} GeV vs MSSM with a supersymmetry breaking scale $M_{\rm SUSY} \lesssim 1$ TeV) for the electroweak theory, independent of any other measurement.* Here and throughout, we make the standard assumption that the MSSM SUSY breaking scale satisfies $M_{\rm SUSY} \lesssim 1$ TeV as required by the *raison d'être* for supersymmetry: stabilization of the EW scale in the face of renormalization.

Furthermore, *there may be no discernible difference between the lightest MSSM Higgs boson and the SM Higgs boson, except for their allowed mass values.* The Feynman rules connecting the lightest Higgs boson in the MSSM to ordinary matter become exactly the SM Feynman rules, in the limit where the "other" Higgs boson masses (these are m_A, m_H, and $m_{H^\pm}$, found in any two-Higgs-doublet models) are taken to be large [3]. When the masses are taken large compared to M_Z, of the order of a TeV, for example, the lightest MSSM Higgs boson behaves very much like the SM Higgs boson in its production channels and decay modes [4], and the mass of the lightest MSSM Higgs boson rises toward its upper bound. Thus, the SM Higgs boson and the lightest MSSM Higgs boson will not be distinguishable by branching ratio or width measurements if the Higgs boson mass falls in the region where the SM lower bound and the MSSM upper bound overlap. Only if the two bounds are separated by a gap is this ambiguity avoided.

SM vacuum stability requires a positive Higgs self-coupling throughout the SM desert. (If the Universe is allowed to reside in an unstable minimum, then a similar, but slightly weaker (by $\lesssim 5$ GeV for heavy m_t [5]), bound results [6].) This in turn constrains the coupling at the weak scale, and therefore the Higgs boson mass, from below [5],

$$m_H > 132 + 2.2(m_t - 170) - 4.5\left(\frac{\alpha_s - 0.117}{0.007}\right), \quad (1)$$

valid for a top mass in the range 160 to 190 GeV. In this equation, mass units are in GeV, and α_s is the strong coupling constant at the scale of the Z mass. This equation is the result of renormalization-group-equation improved two-loop calculations, and includes radiative corrections to the Higgs boson and top masses. It is reliable, and accurate to 1 GeV in the top mass, and 2 GeV in the Higgs boson mass [5]. (If we use the generous value $\alpha_s = 0.129$, the lower bound on the SM Higgs boson mass decreases by about 8 GeV for $m_t >$ 160 GeV. A decrease of even this magnitude in the SM

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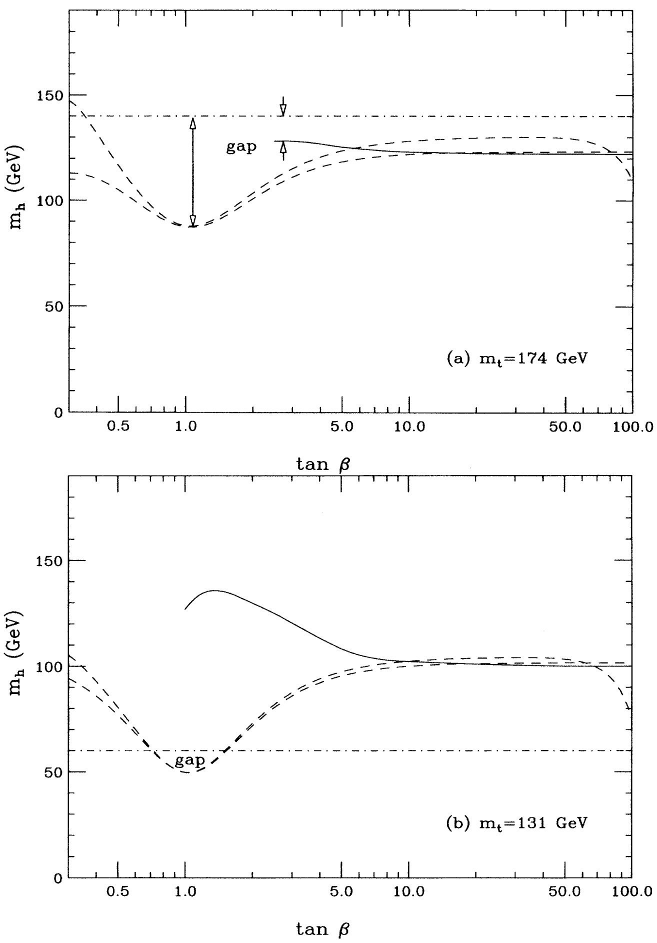

FIG. 1. Higgs boson mass bounds as a function of $\tan\beta$ for the two different values (a) $m_t = 174$ and (b) $m_t = 131$ GeV. Shown are the SM lower bound (dot-dashed), the MSSM upper bound (dashed), and the (M + 1)SSM upper bound (solid) assuming GUT scale unification. MSSM curves are shown for maximal squark mixing ($\mu = A = 1$ TeV) and no squark mixing ($\mu = A = 0$); the latter curve approaches a constant as $\tan\beta$ increases. In all SUSY cases, every superparticle and Higgs boson mass other than the lightest are assumed to be of order 1 TeV. We have also calculated the MSSM bound for $\mu = -1$ TeV; in this case the dip in the curve near $\tan\beta \sim 1$ is significantly filled in, due to nonleading logarithmic contributions proportional to powers of $(\mu - A)/m_t$.

lower bound is compensated by the decrease in the MSSM upper bound due to two-loop contributions not included in our calculations.) Since vacuum stability of the SM breaks down for large scalar field fluctuations, an implicit assumption in this SM bound is no new physics below the large scale, $\sim 10^{10}$ GeV [5].

The D0 Collaboration has used its nonobservation of top candidates to report a 95% C.L. lower bound on the top mass of 131 GeV [7]. Thus, the D0 lower bound, and the CDF mass value including 1σ allowances are, respectively, 131, 158, 174, and 190 GeV. Inputting these top mass values into Eq. (1) and the equivalent for the lower range of m_t [5] with $\alpha_s = 0.117$ then yields SM Higgs boson mass lower bounds of 60, 106, 140, and 176 GeV, respectively.

This lower limit on the SM Higgs boson rises linearly with m_t, for $m_t \gtrsim 100$ GeV. On the other hand, the upper limit on the lightest MSSM Higgs boson mass rises quadratically with m_t, also for $m_t \gtrsim 100$ GeV [8]. In fact, *the radiatively corrected observable most sensitive to the value of the top mass is the mass of this lightest Higgs particle in SUSY models:* for large top mass, the top and scalar-top ($\tilde{t}$) loops dominate all other loop corrections, and *the light Higgs boson mass squared grows as* $m_t^4 \ln(m_{\tilde{t}}/m_t)$. (Note that the correction grows logarithmically as $m_{\tilde{t}}$ gets heavy, rather than decoupling. For heavy $m_{\tilde{t}}$ the large logarithms can be summed to all orders in perturbation theory using renormalization group techniques. Interestingly, the effect is to *lower* the MSSM upper bound [9].) Thus, for very heavy m_t, the two bounds will inevitably overlap. Also, for relatively light m_t the bounds may overlap; e.g., we have just seen that the SM lower bound is 60 GeV for $m_t = 131$ GeV, whereas for large or small $\tan\beta$ ($\tan\beta$ is the ratio of the two MSSM VEVS) the MSSM upper bound is at least the Z mass. However, for m_t around the value reported by the CDF collaboration, we demonstrate by careful calculation that there is a gap between the SM Higgs boson mass lower bound and the MSSM upper bound, at all values of $\tan\beta$. Thus, the first measurement of the lightest Higgs boson mass will serve to exclude either the SM Higgs sector, or the MSSM Higgs sector. (We ignore the $\tan\beta \ll 1$ region; perturbative validity argues against this small $\tan\beta$ region [10].)

We include in our calculation the sizable one-loop corrections to the lightest MSSM Higgs boson mass, m_h, including the full one-loop corrections from the top and bottom quarks and squarks, and the leading-log corrections from the remaining fields (charginos, neutralinos, gauge bosons, and Higgs bosons) [11]. Full one-loop corrections from charginos, neutralinos, and gauge and Higgs bosons [12] are well approximated by their leading logarithm terms used here. Two-loop corrections have recently been calculated [13], *lowering* the MSSM upper bound by several GeV. The resulting widening of the gap (not included in our figure) further enables a Higgs boson mass measurement to distinguish the SM and MSSM models.

The lightest Higgs boson mass bound as a function of $\tan\beta$ is shown in Fig. 1. For the case $\tan\beta \sim 1$, the SM lower bound and the MSSM upper bound are already nonoverlapping at $m_t = 131$ GeV. However, for larger $\tan\beta$ values, the overlap persists until $m_t \gtrsim 165$ GeV. For the preferred CDF value of $m_t = 174$ GeV, the gap is present for all $\tan\beta$, allowing discrimination between the SM and the MSSM based on the lightest Higgs boson mass alone. At $m_t = 190$ GeV the gap is still widening, showing no signs of the eventual gap closure at still higher

m_t. It is reassuring that the upper bounds in the region of acceptable $\tan\beta$ are similar for small and large squark mixing.

The results for extensions of the minimal SUSY model tend to be similar [14]. In general, the mass of the lightest Higgs boson at tree level is limited by M_Z times a factor proportional to the dimensionless coupling constants in the Higgs sector. The assumption of perturbative unification restricts the value of these coupling constants at the electroweak scale, and the maximum value of m_h is therefore never much larger than M_Z. The prototype for extended MSSM is obtained in straightforward fashion by adding an SU(2) singlet S with vanishing hypercharge to the theory [15]. A tree-level analysis of the scalar mass matrix of this (M + 1)SSM yields for the lightest Higgs boson mass upper bound:

$$m_h^2 \leq M_Z^2\{\cos^2 2\beta + 2\frac{\lambda^2}{g_1^2 + g_2^2}\sin^2 2\beta\}.$$

The new Higgs self-coupling λ is *a priori* free, and so the second term may *considerably* weaken the upper bound [16,17]. However, there are two cases where the bound will suffer only a minor adjustment. The first is the large $\tan\beta$ scenario, where $\cos^2 2\beta$ is necessarily $\gg \sin^2 2\beta$. The second is when the theory is embedded into a grand unified theory (GUT); even if λ assumes a high value at the GUT scale, the nature of the renormalization group equations (RGEs) is such that its evolved value at the SUSY-breaking scale is a rather low, pseudo fixed point. Under the assumption that all coupling constants remain perturbative up to the GUT scale, it is therefore possible to calculate a maximum value for m_h [16,17]. The upper bound depends on the value of the top Yukawa coupling at the GUT scale through the RGEs, as seen by comparing Figs. 1(a) and 1(b).

There is a minimum allowed $\tan\beta$ in the (M + 1)SSM, implied by the top Yukawa pseudo fixed point. The minimum rises with m_t, and is evident in the figure. The (M + 1)SSM and MSSM bounds are very similar at $\tan\beta \gtrsim 6$ [the only viable region in the (M + 1)SSM model for m_t at or above the CDF value]. Since the (M + 1)SSM model was originally constructed to test the robustness of the MSSM, it is gratifying that the two models show a very similar upper bound. Further gratification arises from the insensitivity of the m_h bound to the choice of $M_{\rm SUSY}$: the m_h bound increases very slowly as $M_{\rm SUSY}$ increases [16].

We have seen that the SM, MSSM, and the (M + 1)SSM electroweak models can be disfavored or ruled out by a measurement of m_h, and that a "forbidden" mass gap exists separating the SUSY and non-SUSY models if $m_t \gtrsim 165$ GeV. A summary of these mass bounds is provided in Table I, for four possible m_t values. However, some other models do not tightly constrain the lightest Higgs boson mass. Examples of such models are the SM without a desert [18], nonminimal SUSY with unconstrained Higgs self-coupling, and low energy effective models of strongly coupled theories [19]. These models cannot be ruled out by a single Higgs boson mass measurement.

Many supersymmetric grand unified theories (SUSY GUTs) reduce at low energies to the MSSM with additional constraints on the parameters. Accordingly, the upper limit on m_h in such SUSY GUTs is in general *more restrictive* than the bound presented in this Letter. For example, with the additional assumptions that (i) the electroweak symmetry is radiatively broken, (ii) the low energy MSSM spectrum is defined by a small number of "universal" parameters at the GUT scale, and (iii) the large top mass is the pseudo-fixed-point solution of the RGE, there emerge two compact, disparate allowed ranges for $\tan\beta$: $1.0 \leq \tan\beta \leq 1.4$ [20], and a large $\tan\beta$ solution $\sim m_t/m_b$ disfavored by proton stability arguments [21]. Similarly, a highly constrained low $\tan\beta$ region ~ 1 and high $\tan\beta$ region $\gtrsim 40-70$ emerge when b-τ Yukawa unification at the GUT scale is imposed on the radiatively broken model [22]. Resulting mass bounds in the literature for favored SUSY GUT models are basically our bound in Fig. 1 for $\tan\beta \sim 1-3$. Thus, the popular SUSY GUTs widen the mass gap between the light MSSM Higgs boson and the heavier SM Higgs boson, which strengthens the potential for experiment to distinguish the models.

We arrive at interesting conclusions on detectability of the lightest Higgs boson. A SM mass up to (80,105) GeV is detectable at (LEP 178, LEP 200) [23], and a SM mass up to 130 GeV is detectable at a High Luminosity Di-Tevatron (HLDT) [24]. We find that if $m_t \sim 131$ GeV, then the SM Higgs boson has a mass lower bound from vacuum stability of 60 GeV, and so may be detectable at LEP II, but there is no guarantee (since the SM Higgs boson may be as heavy as $\sim 600-800$ GeV [3], it is guaranteed detectable only at the CERN Large Hadron Collider); the MSSM h^0 is certainly detectable at LEP 178 for $\tan\beta \sim 1-2$, and certainly detectable at LEP 200 for all $\tan\beta$. If $m_t \sim 174$ GeV, then the SM Higgs boson mass exceeds 140 GeV and so is out of reach for LEP II and the HLDT; the MSSM Higgs boson is certainly detectable at LEP 200 if $\tan\beta \sim 1-2$. It is interesting that m_h is most accessible to experiment if $\tan\beta \sim 1-3$, just the parameter range favored by SUSY GUTs. Conclusions for $m_t = 158$ and 190 GeV can be inferred from Table I. For the (M + 1)SSM with the assumption of perturbative unification, conclusions are the same as for the MSSM.

TABLE I. The SM lower bound and the MSSM and (M + 1)SSM upper bounds on m_h for various values of m_t. All units are in GeV.

m_t		131	158	174	190
SM	$m_h >$	60	106	140	176
MSSM	$m_h <$	104	119	130	143
(M + 1)SSM	$m_h <$	136	129	128	133

In conclusion, we have shown that for a top quark mass $\sim$174 GeV as reported by CDF, a gap exists between the SM Higgs boson mass ($\gtrsim$140 GeV) and the lightest MSSM Higgs boson mass ($\lesssim$130 GeV). Thus, the first Higgs boson mass measurement will eliminate one of these popular models. Most of the MSSM mass range, but none of the SM mass range, is accessible to LEP II. If a Higgs boson is discovered at LEP II, the SM Higgs sector is ruled out. We remind the reader that our conclusions result from the canonical assumptions that the SM desert extends up to (at least) $\sim 10^{10}$ GeV, and that the SUSY breaking scale is at $\sim$TeV or less.

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Note added.—After this work was submitted, two preprints appeared [25] in which the calculation of the SM lower bound on the Higgs boson mass is refined by taking into account next to leading order logarithmic corrections. These corrections tend to lower the bound, and are in excess of the sensitivity expected in the calculation by Sher [5]. The net result is to move the onset of the mass gap from $m_t = 165$ GeV as presented in our work, to a bit above $m_t = 170$ GeV.

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