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HIGGS BOSONS STRONGLY COUPLED TO THE TOP QUARK

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Abstract

Several extensions of the Standard Model require the burden of electroweak symmetry breaking to be shared by multiple states or sectors. This leads to the possibility of the top quark interacting with a scalar more strongly than it does with the Standard Model Higgs boson. In top-quark condensation this possibility is natural. We also discuss how this might be realized in supersymmetric theories. The properties of a strongly coupled Higgs boson in top-quark condensation and supersymmetry are described. We comment on the difficulties of seeing such a state at the Tevatron and LEP II, and study the dramatic signatures it could produce at the LHC. The four top quark signature is especially useful in the search for a strongly coupled Higgs boson. We also calculate the rates of the more conventional Higgs boson signatures at the LHC, including the two photon and four lepton signals, and compare them to expectations in the Standard Model.

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1 Introduction

Electroweak symmetry breaking and fermion mass generation are both not understood. The Standard Model (SM) with one Higgs scalar doublet is the simplest mechanism one can envision. The strongest arguments in support of the Standard Model Higgs mechanism is that no experiment presently refutes it, and that it allows both fermion masses and electroweak symmetry breaking. Perhaps the most crucial test of this standard postulate will be its confrontation with a large number of top quark events. The top quark, being the heaviest known chiral fermion, may be the most sensitive to dynamics which produce fermion masses but have little to do with electroweak symmetry breaking.

One consequence of the existence of a Higgs boson strongly coupled to the top quark is that a perturbative description up to the Planck scale is probably not possible. If the top quark Yukawa coupling to the Higgs boson exceeds about 1.3 at the weak scale it will diverge before reaching the Planck scale. The specific scale at which a Landau pole develops for a particular value of the Yukawa coupling depends on the gauge symmetries and particle content of the underlying low energy theory. For top quark condensate models [1–5], this Landau pole development at low scales is welcomed in order to satisfy constituent relations between the low scale effective theory and the more fundamental theory (e.g., topcolor) [6–8]. Strong coupling dynamics are crucial for the success of these theories. For supersymmetry, non-perturbative dynamics are often frowned upon by model builders since one generally loses control over the successful prediction of $\sin^2 \theta_W$ [9], which seems to require perturbative evolution from the grand unified scale down to the weak scale. However, there are numerous examples now of strongly coupled supersymmetric theories that do not disrupt gauge coupling unification [10]. We therefore do not consider gauge coupling unification to be a necessary impediment to strongly coupled Higgs bosons.

Furthermore, it is tempting to consider the top quark as the only fermion with an understandable mass since it has a sizeable Yukawa coupling in the Standard Model while the other fermions have small ones. This attitude leads one to concentrate on finding ways to suppress the other fermion masses, rather than to explain the top mass. Since we know so little about fermion mass generation and electroweak symmetry breaking, it is perhaps dangerous to be aesthetically anchored to this viewpoint. A more general approach would be to consider why the top mass is so different than the other fermion masses. Top-quark condensation models attempt to answer this question, and they lead to the conclusion that

the top quark couples even more strongly to a Higgs boson (top quark boundstate) than in the Standard Model [7, 8, 11].

The prediction that the top quark interacts more strongly in more elaborate theories than it does in the Standard Model should not be too surprising. Many extensions of the Standard Model, which can be parametrized in terms of multiple condensing fundamental scalars, allow the top quark to interact more strongly with at least one of these scalars than it does with the Standard Model scalar. This is true for top-quark condensation, and it is also frequently true in the minimal supersymmetric Standard Model (MSSM).

In the next two sections we will briefly discuss the properties of a strongly interacting top Higgs particle in supersymmetric models and top-quark condensate models. Since top-quark condensation more naturally yields this possibility, we will focus more intently on it as in our example in the following section which discusses the signals of this Higgs boson at the Large Hadron Collider (LHC).

2 Supersymmetry

We are interested in separating top quark mass generation from electroweak symmetry breaking. Although top-quark condensation will be our main illustration for the strongly coupled Higgs boson, weak-scale supersymmetric theories could also accomplish this and predict a strongly coupled top Higgs boson. As we mentioned in the introduction, some of the new developments in supersymmetric model building demonstrate how strongly coupled theories can be desirable, and also how they can still preserve gauge coupling unification. Supersymmetric theories which dynamically generate flavor from strong coupling dynamics can produce a strong top quark Yukawa coupling at the composite scale [12]. By lowering the composite scale the top-quark Yukawa coupling at the weak scale is allowed to be much higher than in conventional supersymmetric models that remain weakly coupled up to the GUT scale. There are challenges to constructing a model of flavor based on strong coupling dynamics. However, the progress made in controlling the predictions for composite models [12], along with the realization that perturbative gauge coupling unification could still be possible [10] encourages us to consider a strongly coupled Higgs boson in supersymmetry.

In the two Higgs doublet model of the MSSM [13] one doublet (H_u) gives mass to the up-type fermions and the other (H_d) to the down-type fermions. In order for the lightest Higgs boson to couple strongly to the top-quark the eigenvalues should be arranged such

that $\langle H_u \rangle \ll \langle H_d \rangle$ and h_u^0 is a mass eigenstate. This arrangement, corresponding to low $\tan \beta$, is possible as can be seen from the Higgs mass matrix in the $\{H_d^0, H_u^0\}$ basis,

$$M^2 = \begin{pmatrix} m_A^2 \sin^2 \beta + m_Z^2 \cos^2 \beta & -\sin \beta \cos \beta (m_A^2 + m_Z^2) \\ -\sin \beta \cos \beta (m_A^2 + m_Z^2) & m_A^2 \cos^2 \beta + m_Z^2 \sin^2 \beta \end{pmatrix} + \begin{pmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{12} & \Delta_{22} \end{pmatrix}, \quad (1)$$

where the Δ_{ij} represent radiative corrections to the Higgs mass matrix [14]. Since the tree level contribution to M_{12} becomes smaller as $\sin \beta \rightarrow 0$ and Δ_{12} generally becomes larger, cancellations between the two are possible and can lead to a pure (or almost pure) h_u^0 mass eigenstate that is strongly coupled to the top quark[†]. Furthermore, the mass of h_u^0 is controlled mostly by m_A (supersymmetry breaking mass scale) and h_d^0 by m_Z (the electroweak symmetry breaking mass scale). The neutral Goldstone boson for general $\tan \beta$,

$$G^0 \propto \cos \beta \operatorname{Im}(H_d^0) - \sin \beta \operatorname{Im}(H_u^0) \quad (2)$$

approaches $G^0 \sim \operatorname{Im}(H_d^0)$ in the $\sin \beta \rightarrow 0$ limit.

The value of m_A is probably larger than m_Z given current experimental limits on other sparticle masses dependent on the overall scale of supersymmetry breaking. The h_d^0 eigenstate is then the lowest one and is not much heavier than m_Z , and the residual scalar components of H_d get eaten by the W and Z . The physical charged Higgs particle and neutral pseudoscalar are mostly components of H_u^0 and have mass close to h_u^0 .

The H_u^0 is then a physical doublet which participates very little in electroweak symmetry breaking. Since it is strongly coupled to the top quark ($x = \sin \beta \ll 1$) it could generate predictions for $b \rightarrow s\gamma$ and R_b which are in disagreement with experimental measurements. Therefore, the Higgs mass must be sizeable. To see how large the charged Higgs mass must be to avoid these constraints, we have plotted in Figs. 1 and 2 the effects due to small $x = \sin \beta$. In Fig. 1 we have indicated the lower limit on m_{H^\pm} versus x in order to be consistent with the currently measured $B \rightarrow X_s \gamma$ rate [16]. In Fig. 2 we plot the negative shift in $R_b = B(Z \rightarrow b\bar{b})/B(Z \rightarrow \text{had})$ due to the charged Higgs vertex corrections. The current measurement [17] is $R_b = 0.2170 \pm 0.0009$ which should be compared with the SM prediction of $R_b = 0.2156 \pm 0.0003$. Therefore, any $|\delta R_b| \gtrsim 0.002$ is probably ruled out by the data. We should also note that in both $B(B \rightarrow X_s \gamma)$ and R_b supersymmetric diagrams involving $\tilde{t}_{1,2}$ and $\tilde{\chi}_{1,2}^\pm$ can also contribute with the opposite sign and cancel the charged

[†]Similar behavior can occur in the $\cos \beta \rightarrow 0$ limit where h_d^0 becomes a heavy mass eigenstate which couples strongly to the bottom quarks [15].

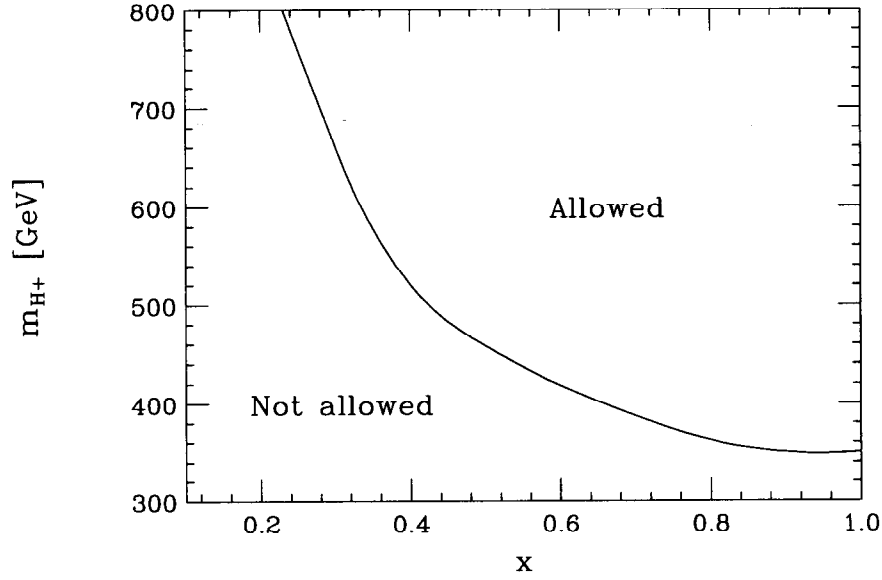


Figure 1: Limits on the charged Higgs mass versus $x = \sin \beta$ obtained [16] from comparing the measured $B(B \rightarrow X_s \gamma)$ rate to the predicted rate.

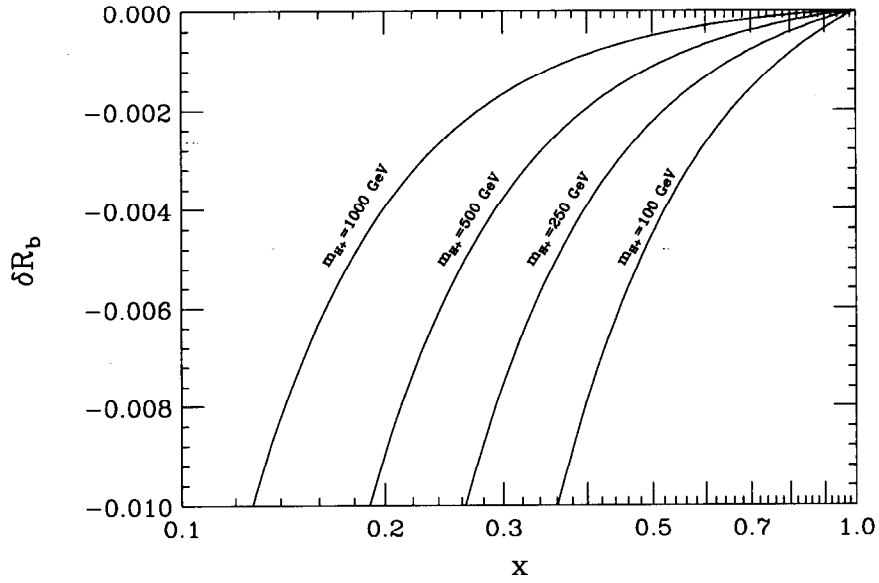


Figure 2: Contours of δR_b versus $x = \sin \beta$ for four values of m_{H^+} . Comparing experimental data to the theoretical prediction requires that $|\delta R_b| \lesssim 0.002$.

Higgs contributions [18, 19]. This would allow smaller charged Higgs masses, and therefore smaller $m_{h_u^0}$ than Figs. 1 and 2 seem to allow.

Thus we conclude that the generic prediction in supersymmetric models is that if h_u^0 is strongly interacting with the top quark, it must be accompanied by three scalar particles with similar mass, and that this whole multiplet must be quite heavy in order to not disrupt b -quark observables too drastically. This heavy mass prediction implies that h_u^0 could decay into numerous supersymmetric particles and also to the lighter h_d^0 , thereby complicating the analysis. For a strongly coupled supersymmetric Higgs boson with mass above $2m_t$, however, these additional decays are all expected to be weakly coupled in this limit except the top quark mode and possibly the top squark mode. Also, since the top squarks receive mass from supersymmetry breaking their masses could be larger than all the Higgs masses making it kinematically impossible for the Higgs particle to decay into them. This is not the most likely possibility since renormalization group effects tend to push the top squarks to small masses when the top Yukawa coupling is large. The h_u^0 interacts with the top squarks via the A -term interactions: $\lambda_t A_t h_u^0 \tilde{t}_L \tilde{t}_R$. However, the A terms can be greatly suppressed due to an approximate R symmetry, which is often present in gauge mediated models, for example [20]. Therefore, it is likely that if a Higgs boson in the MSSM were strongly coupled to the top quark it would be quite heavy and its decays would be dominated by the top quark modes. In general Higgs decays into top squarks and the myriad subsequent cascade decays are also possible, however we will not consider it further here. In the h_u^0 eigenstate limit discussed above, the behavior of this Higgs boson is similar to that of the bound state scalar in top condensation. We next turn our attention to this model with the realization that supersymmetric models can yield a very similar phenomenology.

3 Top-quark condensation

Our main example is that of low scale top-quark condensation [1–5]. These models allow more varied predictions for the top quark coupling to the Higgs boson and more naturally yield top quark mass generation while only mildly affecting electroweak symmetry breaking. Of course, spontaneously generating a chiral fermion mass must necessarily spontaneously break electroweak symmetry. However this gauge symmetry breaking may be weak, just as in the case of the light quark condensate of chiral symmetry breaking in QCD. If the decay constant associated with the pions of top-quark condensation is small compared to

the requirements of electroweak symmetry breaking ($f_{\pi_t} \ll v \approx 174 \text{ GeV}$) then the top-quark can still get its full mass and yet be strongly coupled to the condensing bound-state scalar. We call this condensing bound-state scalar the “top Higgs boson”.

The mass of the top Higgs boson is expected to be near $m_{h_t^0} = 2m_t$ [3, 8, 21, 22]. The top Higgs boson is one state in an $SU(2)$ doublet, and thus is accompanied by scalar fields (π_t^0, π_t^\pm). Depending on the decay constant they may be eaten by the W^\pm and Z vector bosons ($f_{\pi_t} = v$) or are physical eigenstates ($f_{\pi_t} \ll v$). In this latter case the electroweak symmetry must be broken by some other mechanism (e.g., ETC interactions or a fundamental scalar) and the top pions become pseudo-goldstone bosons whose mass depends on the amount of the explicit chiral breaking and also on the scale of top-quark condensation [7, 8]. For this reason, we will not consider the effects from the top pions. It should be noted, however, that if the top pions are light they in general could mediate dangerous flavor changing neutral currents [8, 23] or too small R_b [24], just as the charged Higgs particle does in supersymmetric models with low $\tan \beta$. We assume that a combination of the pions being heavy* and aligning according to some flavor symmetries solves these problems. For our purposes including their effects would only increase the signal event rates that we discuss in the next section.

The π_t -decay constant and the dynamical top quark mass can be related to each other by the Pagels-Stokar formula [7]:

$$f_{\pi_t}^2 \simeq \frac{N_c}{16\pi^2} m_t^2 \log \frac{\Lambda^2}{m_t^2} \quad (3)$$

where Λ is the top-quark condensate scale. Finetuning considerations in the gap equation for the top-quark mass imply that Λ should probably not be much larger than about 1 TeV [7, 25, 26]. For this value of Λ one expects $f_{\pi_t}/v \simeq 1/4$.

It is not clear how much one should trust the quantitative results of the gap equation, the Pagels-Stokar formula, or any other equation which attempts to be precise in the strong coupling regime. For this reason, it is perhaps best to treat $x \equiv f_{\pi_t}/v$ and $m_{h_t^0}$ as free parameters. Unless otherwise indicated, however, we will use $x = 1/4$ in sympathy with the standard approximation schemes and fine-tuning considerations.

*Small corrections to the NJL approximations and a larger “explicit” top quark mass (e.g., from ETC interactions) can substantially increase $m_{\pi_t}^2$.

4 Collider signatures

The Tevatron and LEP II will both have difficulties detecting h_t^0 because both of these colliders rely on “gauge coupled” production modes such as $e^+e^- \rightarrow Zh_t^0$ and $q\bar{q}' \rightarrow Wh_t^0$. Since h_t^0 couples weakly to gauge bosons, it is not likely that the Tevatron would see it even if it were light.[†] With enough luminosity it is possible that LEP II could see h_t^0 in its ordinary Higgs searches. The cross section for h_t^0 is

$$\sigma(e^+e^- \rightarrow Zh_t^0) = x^2 \sigma(e^+e^- \rightarrow Zh_{SM}^0). \quad (4)$$

Therefore, if x is low LEP II might miss this state even if it is kinematically accessible. Unlike LEP II and Tevatron, the prospects for h_t^0 discovery at LHC increase as x decreases. For this reason we focus on LHC observables.

The top Higgs boson couples appreciably only to $t\bar{t}$ and somewhat more weakly to WW and ZZ pairs. However, the coupling to the top quark is enhanced by a factor of $1/x$ in comparison with the top quark coupling to the Standard Model Higgs boson [7, 11]. This is obvious since

$$\lambda_t \simeq \frac{m_t}{f_{\pi_t}} = \frac{1}{x} \frac{m_t}{v} = \frac{\lambda_t^{SM}}{x}. \quad (5)$$

Similarly, the coupling to the vector bosons is suppressed by a factor of x . The branching fractions are presented in Fig. 3. All relevant radiative corrections are included according to Ref. [27, 28].

One striking difference between the top Higgs boson and the SM Higgs boson is the lack of a $b\bar{b}$ channel. Thus, b -tagged final states are not important for a light h_t^0 . Furthermore, when $m_{h_t^0} > 2m_t$ the branching ratio into $t\bar{t}$ is close to 100%, which should be compared with the SM Higgs boson, whose WW decay mode is always greater than $t\bar{t}$ for any mass [27, 29]. The large $t\bar{t}$ branching fraction for h_t^0 arises since its partial width is enhanced by $1/x^2$ and the WW partial width simultaneously decreases by x^2 .

The production cross sections are also quite unusual compared to the Standard Model. In Fig. 4 we plot the production cross sections of h_t^0 in different modes for the LHC with $\sqrt{s} = 14$ TeV. We include the full NLO QCD corrections to $gg \rightarrow h_t^0$ [27, 30], $q\bar{q} \rightarrow h_t^0 q\bar{q}$ [31] and $q\bar{q} \rightarrow h_t^0 V$ [$V = W, Z$] [32]. In these cross sections we adopted the CTEQ4M parton

[†]Since the $gg \rightarrow h_t^0$ process is enhanced by $1/x^2$, the dominant gluon fusion mechanism may become visible at the Tevatron. This, however, requires a detailed detector simulation.

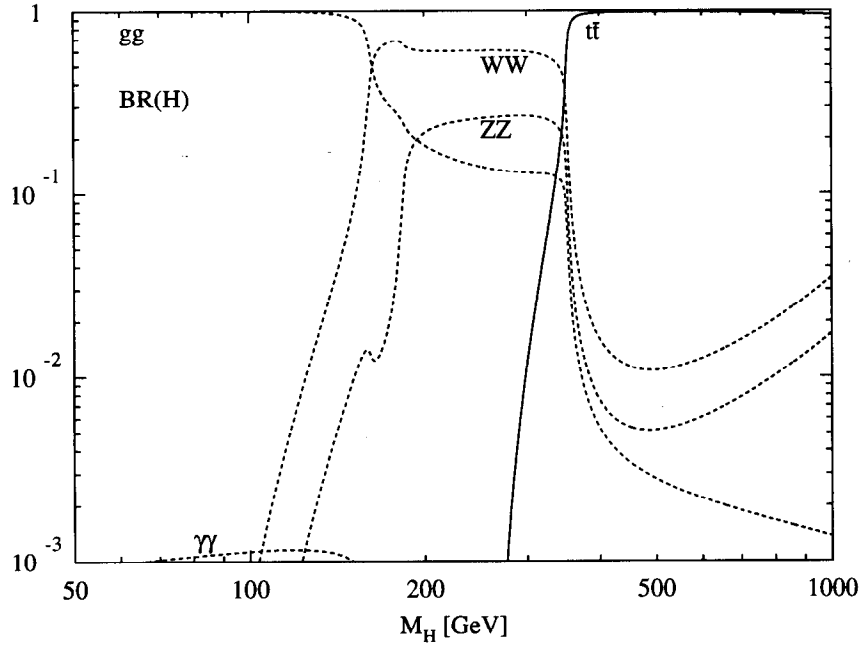


Figure 3: Branching fractions of $H \equiv h_t^0$ versus its mass for $x \equiv f_{\pi_t}/v = 1/4$.

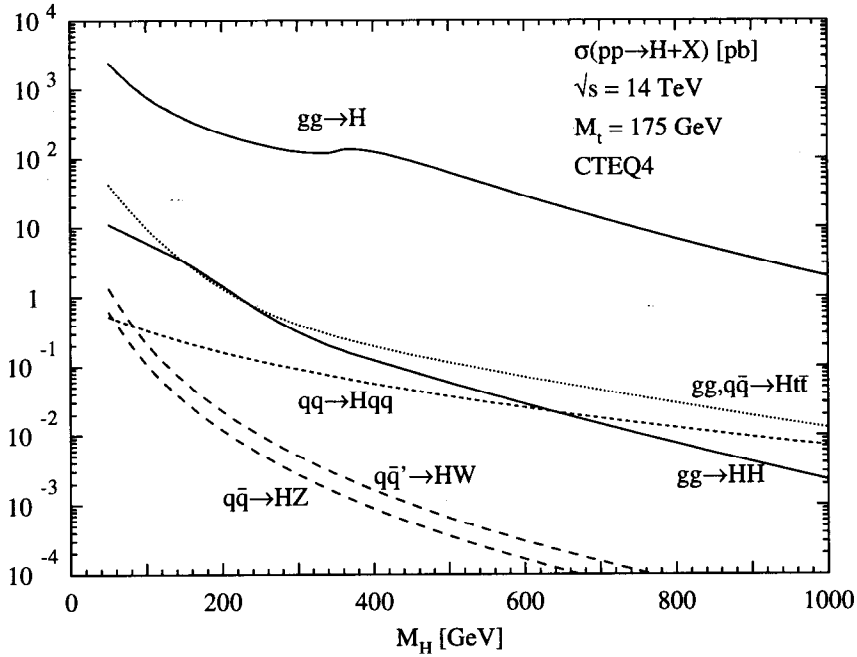


Figure 4: Production cross sections of the top Higgs boson $H \equiv h_t^0$ at the LHC with $\sqrt{s} = 14$ TeV for $x \equiv f_{\pi_t}/v = 1/4$.

densities [33] with $\alpha_s^{NLO}(M_Z^2) = 0.116$. The QCD corrections to the processes $gg, q\bar{q} \rightarrow h_t^0 t\bar{t}$ and $gg \rightarrow h_t^0 h_t^0$ are unknown, so that we evaluated them using CTEQ4L parton densities with $\alpha_s^{LO}(M_Z^2) = 0.132$. The “gauge processes” such as $q\bar{q} \rightarrow h_t^0 Z$ and $q\bar{q}' \rightarrow h_t^0 W^\pm$ are smaller by x^2 in comparison to the Standard Model, and the “Yukawa processes” such as $gg \rightarrow h_t^0$ and $gg, q\bar{q} \rightarrow h_t^0 t\bar{t}$ are enhanced by $1/x^2$. Note also that the $gg \rightarrow h_t^0 h_t^0$ production process is enhanced by a factor of $1/x^4$ with respect to the Standard Model. [For $x = 1/4$ one finds a factor of 256 enhancement above the same process in the Standard Model with equal Higgs boson mass.] In the Standard Model the two Higgs production cross section is not large enough to play a significant role in the phenomenology at the LHC [34]. However, when the Higgs boson strongly interacts with the top quark this process is most affected and becomes relevant. We will make use of this later.

At the LHC the “gold-plated” Higgs discovery mode for the SM Higgs boson in the mass range $140 \text{ GeV} \lesssim m_{h_{SM}^0} \lesssim 800 \text{ GeV}$ is the $gg \rightarrow h_{SM}^0 \rightarrow ZZ^{(*)} \rightarrow 4l^\pm$ signature [29]. Although the $gg \rightarrow h_t^0$ cross section has been enhanced by a factor of $1/x^2$ in the top Higgs case, it turns out that this mode would be more difficult than it is for the SM Higgs boson for two reasons: First, the branching fraction into ZZ decreases by *more* than x^2 beyond the $t\bar{t}$ threshold since the partial width into ZZ decreases by x^2 and the total Higgs width increases because of the enhanced $t\bar{t}$ partial width. The total rate of $gg \rightarrow h_t^0 \rightarrow ZZ$ is plotted in Fig. 5. Second, since the total width of the Higgs particle is significantly larger above the $t\bar{t}$ threshold due to the increased coupling of the top Higgs boson to the top quarks, the invariant mass “bump” of the $h \rightarrow ZZ \rightarrow 4l^\pm$ is no longer narrow, but quite broad. The Higgs width is already at about 70 GeV for $m_{h_t^0} = 400 \text{ GeV}$ (see Fig. 6), while the SM Higgs particle has a width of less than 30 GeV for the same mass. As the mass of the top Higgs scalar gets larger the problem worsens, and finding a bump above the background is more difficult. For low values of x the gold-plated mode is probably only useful for Higgs masses between about 180 GeV and 400 GeV.

Another useful signature is the $gg \rightarrow h_t^0 \rightarrow WW$ leptonic decay mode [35, 36] in the mass region of $160 \text{ GeV} \lesssim m_{h_t^0} \lesssim 340 \text{ GeV}$. This is also plotted in Fig. 5. In this range, $h_t^0 \rightarrow WW$ is competing successfully with loop mediated decays into gg or off-shell t^*t decays. Therefore, the production cross section $gg \rightarrow h_t^0$ is enhanced by the strong top interactions, but the branching fraction is not significantly suppressed. In this region the methods of ref. [36] can be used to extract a signal and furthermore perhaps even extract the Higgs mass.

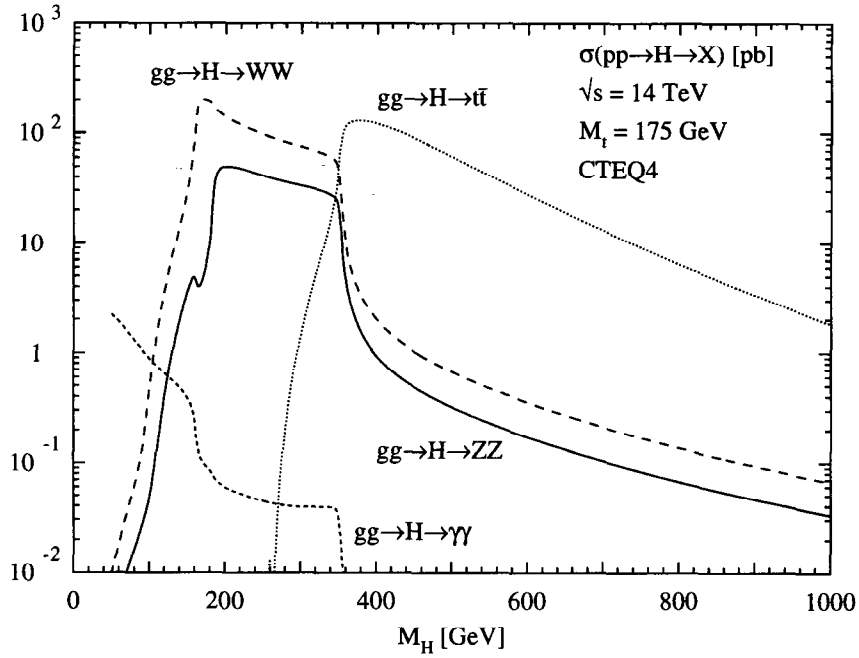


Figure 5: Cross sections for the production and two-body decays of the top Higgs boson $H \equiv h_t^0$ for $x \equiv f_{\pi_t}/v = 1/4$.

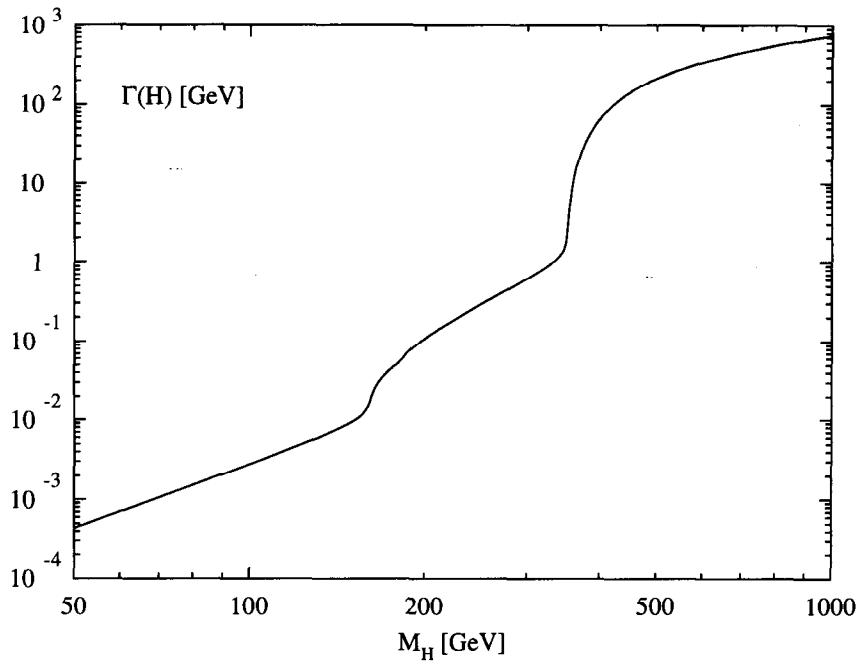


Figure 6: Total width of $H \equiv h_t^0$ as a function of its mass for $x \equiv f_{\pi_t}/v = 1/4$.

For a light SM Higgs boson ($m_{h_{SM}^0} \lesssim 150$ GeV) it has been found [29] that the most useful signature for the Higgs search is $gg \rightarrow h_{SM}^0 \rightarrow \gamma\gamma$. The cross section varies between 35 fb and 85 fb in the mass range $100 \text{ GeV} < m_{h_{SM}^0} < 150$ GeV. For the top Higgs boson, the cross section is at about 1 pb for $m_{h_t^0} = 100$ GeV and stays above 40 fb for $m_{h_t^0} < 340$ GeV as can be seen in Fig. 5. Therefore, photon final states can be a very useful signature of the top Higgs particle at mass scales twice as large as the applicable region for the SM Higgs boson. This result depends crucially on the fact that h_t^0 is a pure mass eigenstate and does not mix with other electroweak symmetry breaking mechanisms, especially those that give mass to the bottom quarks. Even with some mixing of other sectors with the top Higgs boson the photon final states should still be enhanced over that of the Standard Model. Also, in the topcolor models of top-quark condensation, the instanton associated with the strongly coupled topcolor gauge group could generate part or all of the bottom quark mass [7, 8]. This also will mediate an effective coupling between the top Higgs particle and the bottom quarks which could even be larger than the Standard Model Higgs coupling to bottom quarks. Clearly, such a large coupling to the bottom quarks if present would spoil the $\gamma\gamma$ signal for the top Higgs boson.

The Higgs mediated production of $t\bar{t}$ is enhanced by more than a factor of $1/x^2$ for the top Higgs scalar. It might be possible to utilize this excess to extract a signal against the background [37]. The maximum expected Higgs mediated cross section of $t\bar{t}$ production is 100 pb at a top Higgs mass just below 400 GeV. Although this is a large cross section it is still more than an order of magnitude below the enormous Standard Model background of about 2 nb for $m_t = 175$ GeV. Since we can always find other modes more significant than $t\bar{t}$ we do not consider it further here.

Perhaps the most striking signal for the top Higgs boson is $4W + X$ production. All the production modes leading to this final state are shown in Fig. 7. The underlying processes contributing to these modes include $pp \rightarrow h_t^0 t\bar{t} \rightarrow t\bar{t}t\bar{t}, WWt\bar{t}$ and $pp \rightarrow h_t^0 h_t^0 \rightarrow t\bar{t}t\bar{t}, WWt\bar{t}, WWW$ and the top quarks subsequently decay into Wb . In addition to these modes there are four gauge boson modes involving the Z bosons.

The Standard Model background for these processes is small. The largest source of $4W + X$ in the Standard Model is $gg \rightarrow t\bar{t}t\bar{t}$ which has a cross section less than 10 fb [38, 39]. If x is near one then the top Higgs boson acts very similar to the Standard Model Higgs particle and contributes less than 2 fb to the four top rate. The maximum rate occurs if

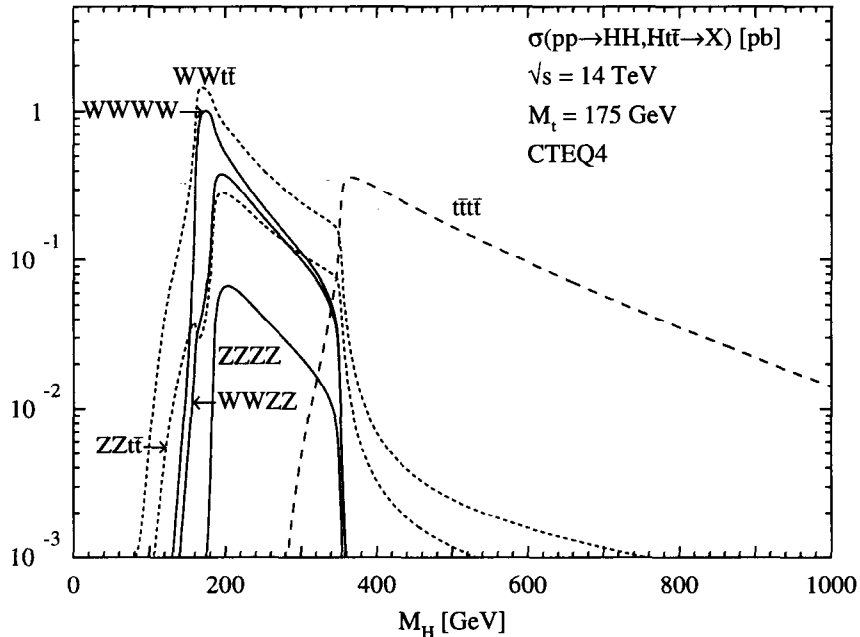


Figure 7: Cross sections for the production and four-body decays of the top Higgs boson $H \equiv h_t^0$ for $x \equiv f_{\pi_t}/v = 1/4$.

$m_{h_{SM}^0} \simeq 450$ GeV. However, the top Higgs boson with smaller x can exceed the Standard Model rate by more than one order of magnitude. With $x = 1/4$, as is plotted in Fig. 7, even a 1 TeV Higgs mass contributes more than 10 fb to the four top rate. And when the Higgs mass is at its preferred value of $m_{h_t^0} = 2m_t$ we find a four top cross section in excess of 100 fb. We note also that in topcolor there are other sources of four top production. Namely, if the gauge bosons associated with the topcolor gauge group are light enough they can be pair produced and will subsequently decay into four top quarks [40].

Reconstructing the mass is a bit ill-defined task for the heavier top Higgs boson since its width is greater than 100 GeV when its mass is above ~ 400 GeV (see Fig. 6). If the mass is at its preferred value of $m_{h_t^0} = 2m_t$ or lighter then the width is still narrow enough (less than 5 GeV) such that extracting a top Higgs mass is possible in principle.

If the top Higgs mass is in the range of $170 \text{ GeV} \lesssim m_{h_t^0} \lesssim 340 \text{ GeV}$ the $4W$ and $WWt\bar{t}$ modes dominate. The total expected cross section of four vector bosons in the Standard Model from $WWWW$ and $WWt\bar{t}$ modes is less than 20 fb [38]. The SM rate from just $WWWW$ is about 1 fb [38]. Therefore, the large enhancement of $WWWW$ production with zero or two b -jets is a good signal for an intermediate top Higgs boson. Mass reconstruction

mode	mass range	Is mass reconstructable?
$gg \rightarrow h_t^0 \rightarrow \gamma\gamma$	$m_{h_t^0} \lesssim 340 \text{ GeV}$	✓
$gg \rightarrow h_t^0 \rightarrow WW^{(*)}$	$150 \text{ GeV} \lesssim m_{h_t^0} \lesssim 340 \text{ GeV}$	✓
$gg \rightarrow h_t^0 \rightarrow ZZ$	$180 \text{ GeV} \lesssim m_{h_t^0} \lesssim 400 \text{ GeV}$	✓
$gg \rightarrow h_t^0 h_t^0 \rightarrow WWWW$	$150 \text{ GeV} \lesssim m_{h_t^0} \lesssim 340 \text{ GeV}$?
$gg, q\bar{q} \rightarrow h_t^0 t\bar{t} \rightarrow WWt\bar{t}$ $gg \rightarrow h_t^0 h_t^0 \rightarrow WWt\bar{t}$ }	$150 \text{ GeV} \lesssim m_{h_t^0} \lesssim 350 \text{ GeV}$?
$gg, q\bar{q} \rightarrow h_t^0 t\bar{t} \rightarrow t\bar{t}t\bar{t}$ $gg \rightarrow h_t^0 h_t^0 \rightarrow t\bar{t}t\bar{t}$ }	$350 \text{ GeV} \lesssim m_{h_t^0} \lesssim 1 \text{ TeV}$	X

Table 1: Summary of top Higgs production and decay modes for $x = 1/4$.

might be possible in this region using similar techniques as in Ref. [36]; however, combinatoric ambiguities of the final state leptons with a $4W$ final state may subvert such attempts. Furthermore, the two different production topologies of $t\bar{t}h_t^0$ and $h_t^0 h_t^0$ each contribute to the $WWt\bar{t}$ final state signal. This further complicates the analysis for the $4W$ plus two b -jet mode, and more detailed Monte Carlo simulations are required to find out the maximal amount of information that can be extracted.

5 Conclusion

Table 1 is a summary of the most useful modes to discover the top Higgs boson for various mass regions. In the first column we list final states arising through h_t^0 production and in the second column we list the top Higgs boson mass range for which this signature is applicable. We stress that the large enhancement of the four top rate is a somewhat unique and spectacular signature of the heavy top Higgs boson. In fact, the enhancement of the four top mode may be the *only* discernible signal of the top Higgs boson at the LHC.

Many results that we presented in the previous section were based upon the choice $x = 1/4$. The rates for different values of x can in principle be extracted from the plots we have provided. The production cross sections are straightforward to generalize for different values of x . We have already noted above that the $gg \rightarrow h_t^0 h_t^0$ production cross section is

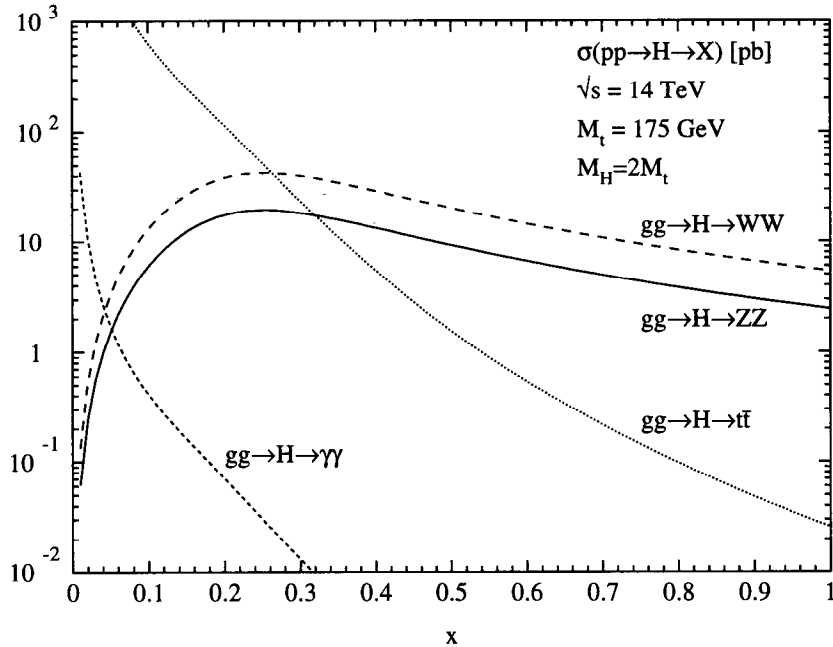


Figure 8: Cross sections for the production and two-body decays of the top Higgs boson for $m_{h_t^0} = 2m_t$.

enhanced over the Standard Model by a factor of $1/x^4$. Similarly, the $gg \rightarrow h_t^0$ cross section is enhanced by $1/x^2$. The decay branching fractions are somewhat more complicated. Some partial widths are suppressed by x^2 and some are enhanced by $1/x^2$. In Fig. 8 we plot the cross sections for the production and two-body decays and in Fig. 9 for the production and four-body decays of h_t^0 as a function of x with $m_{h_t^0} = 2m_t$ – the preferred top Higgs boson mass of top-quark condensate models. For $x = 1/4$ the WW and $t\bar{t}$ modes have almost identical branching fractions. As $x \rightarrow 1$ the branching fractions tends more and more to the Standard Model values. Thus for the two-body final states at small values of x the $t\bar{t}$ final state dominates, while beyond $x \sim 0.3$ it is more and more suppressed thus leaving only the WW, ZZ final states as visible signals similar to the SM. The $\gamma\gamma$ final state is only significant for $x \lesssim 0.3$. For larger values of x the $t\bar{t}h_t^0$ production mode becomes more important for the phenomenology of the top Higgs boson at the LHC compared to $h_t^0h_t^0$ production, and the four-body $t\bar{t}t\bar{t}$ signal loses significance. However, the $h_t^0 \rightarrow ZZ$ mode becomes more important as x goes to 1, and the phenomenology approaches that of the SM Higgs boson.

Much of the known phenomenology associated with Higgs boson signatures at high energy colliders has been closely related to the Standard Model. Even light Higgs collider studies in

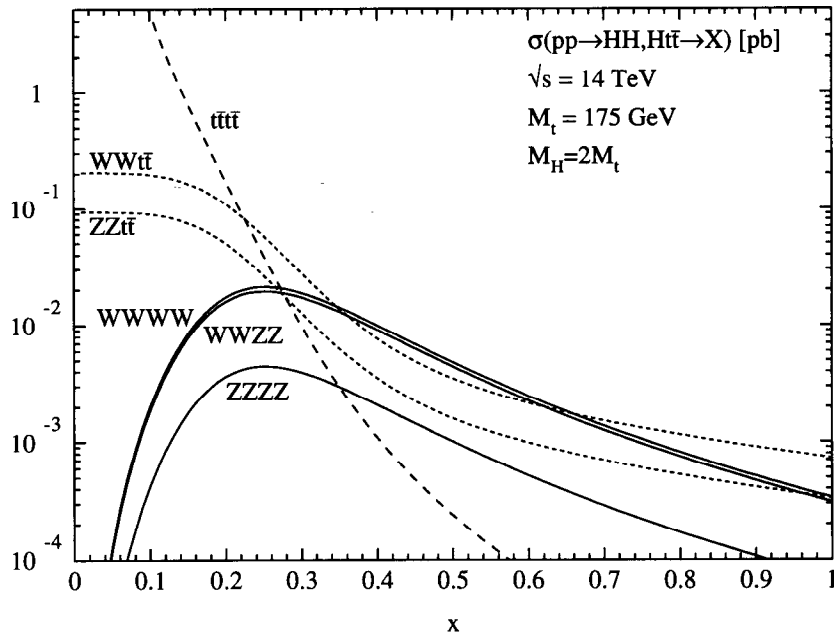


Figure 9: Cross sections for the production and four-body decays of the top Higgs boson for $m_{h_t^0} = 2m_t$.

supersymmetric models often deviate only mildly from a Standard Model Higgs boson [27, 30, 41]. This is especially true in the MSSM. However, if electroweak symmetry breaking and fermion mass generation arise through a more sophisticated mechanism than in the SM or MSSM, the relevant Higgs states may be more difficult to detect, and may require signatures that are not useful in SM Higgs searches. For example, in top condensate models, electroweak symmetry breaking may be accomplished by one Higgs scalar h_{ew}^0 and top quark mass generation by another h_t^0 . In this case, h_{ew}^0 will be difficult to find [26] at the LHC and might be seen only by extracting a three lepton signal above background [15], and we have shown above that the top Higgs boson signature might only be seen through four vector bosons or four top quarks. This is just one clear illustration of how a strongly coupled Higgs boson in the spectrum can dramatically change Higgs phenomenology at high energy colliders.

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