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DYNAMICAL ELECTROWEAK SYMMETRY BREAKING AT
TEVATRON RUN II AND LHC

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M.S. degree in Physics

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DYNAMICAL ELECTROWEAK SYMMETRY BREAKING AT TEVATRON RUN II AND LHC

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Physics and Astronomy

2005

ABSTRACT

DYNAMICAL ELECTROWEAK SYMMETRY BREAKING AT TEVATRON RUN II AND LHC

By

Alexander Simon Blum

The Standard Model (SM) of particle physics unifies the electromagnetic and the weak force under an SU(2) x U(1) gauge group. The fact that these forces are observed to be so different in strength and range is explained by spontaneous breaking of this symmetry, induced by the nonzero vacuum expectation value of a scalar Higgs field. There is however no experimental evidence for the Higgs field and there are also theoretical difficulties. In one class of extensions of the SM designed to deal with these problems, the electroweak symmetry is broken dynamically. This thesis provides a framework in which SM Higgs searches at Tevatron Run II and at the Large Hadron Collider (LHC) can be extended to new scalar or pseudoscalar states predicted in dynamical models of electroweak symmetry breaking. These states can have enhanced visibility in standard Higgs search channels, making them potentially discoverable at Tevatron Run II and definitely visible at the LHC. I discuss the likely sizes of the enhancements in the various search channels for each model and identify the model features having the largest influence on the degree of enhancement. I suggest the mass reaches of Higgs searches at Tevatron and LHC for these non-standard scalar states. I compare signals for the non-standard scalars across models and also with expectations in the SM and the Minimal Supersymmetric Model, another theory beyond the SM, to show how one could start to identify which state has actually been found.

ACKNOWLEDGEMENTS

I would like to thank my advisor Professor Elizabeth Simmons, as well as Dr. Alexander Belyaev and Professor Sekhar Chivukula for their constant input and support. I also would like to acknowledge a scholarship of the German National Academic Foundation (Studienstiftung des deutschen Volkes).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

Even though the electromagnetic and weak forces have been unified under a single SU(2) x U(1) gauge group, the origin of the breaking of this electroweak symmetry (manifest in the massless photon as gauge particle of the electromagnetic force compared to the massive W and Z Bosons of the weak force) remains unknown. While the Standard Model (SM) of particle physics, which accomplishes the symmetry breaking by predicting a scalar Higgs field with nonzero vacuum expectation value, is consistent with existing data, theoretical considerations show that this theory is only a low-energy effective theory and must be supplanted by a more complete description of the underlying physics at energies above those reached so far by experiment.

The CDF and D0 experiments at the Fermilab Tevatron are currently searching for the Higgs boson of the Standard Model. The production cross-section and decay branching fractions for this state have been predicted in great detail for the mass range accessible to Tevatron Run II. Search strategies have been carefully planned and optimized.

However, if the Tevatron does find evidence for a new scalar state, it may not necessarily be the SM Higgs. Many alternative models of electroweak symmetry breaking have spectra that include new scalar or pseudoscalar states whose masses could easily lie in the range to which Run II is sensitive. The new scalars tend to have cross-sections and branching fractions that differ from those of the SM Higgs. The potential exists for one of these scalars to be more visible in a standard search than the SM Higgs would be.

In this paper we provide a framework in which one can extract the maximum possible information about the origin of electroweak symmetry breaking from SM Higgs searches at Tevatron Run II and CERN LHC.

The idea of using standard Higgs searches to place limits on new scalar states associated with electroweak symmetry breaking beyond the standard model has been applied to LEP results (see e.g. Refs. [1, 2, 3, 4, 5, 6, 7, 8]). The Tevatron and the LHC can potentially access significantly heavier scalars than those to which LEP was sensitive, particularly in models of dynamical symmetry breaking. Reference [9] has studied the potential of Tevatron Run II to search for the SM Higgs boson in $gg \to h_{SM} \to \tau\tau$ and determined what enhancement of the rate would be needed to make a non-standard Higgs boson, e.g. from the Minimal Supersymmetric Model (MSSM), a popular extension of the SM, visible in this channel. Similar studies have been done for LHC for $gg \to h_{MSSM} \to \tau\tau$ [10] and for $gg \to h_{SM} \to \gamma\gamma$ [11] processes.

My work builds on these results, considering an additional production mechanism (b-quark annihilation), more decay channels ($b\bar{b}$, WW, ZZ, and $\gamma\gamma$), and, most importantly, shifting the focus from theories of Supersymmetry to models of Dynamical Electroweak Symmetry Breaking (DEWSB), an extension of the Standard Model mentioned briefly in [9] and not at all in [10] and [11]. I discuss the likely sizes of the enhancements in the various search channels for several different models and pinpoint the model features having the largest influence on the degree of enhancement. I suggest the mass reach of the standard Higgs searches for each kind of non-standard scalar state. I also compare the key signals for the non-standard scalars across models and also with expectations in the SM and the MSSM, to show how one could start to identify which state has actually been found.

In Section 2, I discuss Higgs searches and the enhancement factors needed to make scalars of various masses visible. In Section 3, I talk about DEWSB in general and show how to calculate elements of the enhancement factors in the various models. In Section 4, I present my results for each model. In Section 5, I compare the different models to one another and to the SM and MSSM. Section 6 holds my conclusions.

Part of this thesis will appear in a paper submitted for publication in June 2005 by Alexander Belyaev, R. Sekhar Chivukula, Elizabeth H. Simmons and me [12].

2 Higgs Searches and Enhancement Factors

As mentioned in the Introduction, [9] studied the potential of Tevatron Run II to augment its search for the SM Higgs boson by considering the process $gg \to h_{SM} \to \tau^+\tau^-$. While this channel would not suffice as a sole discovery mode,[1] the authors found that it could usefully be combined with other channels such as $h_{SM} \to WW$ or associated Higgs production to enhance the overall visibility of the Higgs. At the same time, the authors determined what additional enhancement of scalar production and branching rate, such as might be provided in a non-standard model like the MSSM, would enable a scalar to become visible in the $\tau\tau$ channel alone at Tevatron Run II.

As these results are easily reinterpreted for DEWSB models, I take this as my starting point, and examine how various Tevatron Run II searches for the SM Higgs may provide information about the possible existence and properties of various Higgs-like states that arise in DEWSB models. I look not only at the production and decay channels which dominate in the SM, but also consider those which may be more relevant in non-standard theories. I then go on (using [10] and [11]) to make some predictions about visibility at the LHC.

Much of my discussion will focus on the degree to which certain standard Higgs search channels are enhanced in non-standard models due to changes in the production rate or branching fractions of the non-standard scalar ($\mathcal{H}$) relative to the values for the standard Higgs boson (h_{SM}). I define the enhancement factor for the process $yy \to \mathcal{H} \to xx$ as the ratio of the products of the width of the (exclusive) production mechanism and the branching ratio of the decay:

$$\kappa^{\mathcal{H}}_{yy/xx} = \frac{\Gamma(\mathcal{H} \to yy) \times BR(\mathcal{H} \to xx)}{\Gamma(h_{SM} \to yy) \times BR(h_{SM} \to xx)} = \kappa^{\mathcal{H}}_{yy\ prod} \times \kappa^{\mathcal{H}}_{xx\ dec} \qquad (1)$$

[1]The authors established that discovery of h_{SM} in this channel alone (assuming a mass in the range 120 - 140 GeV) would require an integrated luminosity of 14-32 fb^{-1}, which is unlikely to be achieved.

I will consider both gluon fusion and $b\bar{b}$ annihilation as possible production mechanisms, and will study a variety of decay channels. Analytic formulas for the decay widths of the SM Higgs boson are taken from [13], [14] and numerical values are calculated using the HDECAY program [15] [2].

[2] With input parameters $\alpha_s(M_Z^2) = 0.118$, $M_b = 4.60$ GeV and $M_t = 178$ GeV.

3 Dynamical Electroweak Symmetry Breaking

3.1 General Remarks

The Standard Higgs Model of particle physics, based on the gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$, accommodates electroweak symmetry breaking by including a fundamental weak doublet of scalar ("Higgs") bosons $\phi = \binom{\phi^+}{\phi^0}$ with potential function $V(\phi) = \lambda\left(\phi^\dagger\phi - \frac{1}{2}v^2\right)^2$. However the SM does not explain the dynamics responsible for the generation of mass. Furthermore, the scalar sector suffers from two serious problems. The scalar mass is unnaturally sensitive to the presence of physics at any higher scale (e.g. the Planck scale), through contributions of loops of SM particles to the Higgs self-energy. This is known as the gauge hierarchy problem [16]. In addition, if the scalar must provide a good description of physics up to arbitrarily high scale (i.e., be fundamental), the scalar's self-coupling (λ) is driven to zero at finite energy scales. That is, the scalar field theory is free (or "trivial") ([17], [18]). Then the scalar cannot fill its intended role: if $\lambda = 0$, the electroweak symmetry is not spontaneously broken. The scalars involved in electroweak symmetry breaking must therefore be a party to new physics at some finite energy scale – e.g., they may be composite, as in the DEWSB models discussed here. The SM is merely a low-energy effective field theory, and the dynamics responsible for generating mass must lie in physics outside the SM.

In this section, I briefly introduce those aspects of dynamical electroweak symmetry breaking which are most germane to my analysis. For a more complete introduction to dynamical electroweak symmetry breaking, see [19].

3.2 Technicolor

An intriguing class of models, generally referred to as dynamical electroweak symmetry breaking models, supposes that the scalar states involved in electroweak symmetry breaking could be manifestly composite at scales not much above the electroweak scale $v \sim 250$ GeV. In these theories, a new asymptotically free strong gauge interaction (technicolor) breaks the chiral symmetries of approximately massless technifermions f, which differ from the regular quarks and leptons of the SM in that they also carry a technicolor charge, at a scale $\Lambda \sim 1$ TeV ([20], [21]). If the fermions carry appropriate electroweak quantum numbers (e.g. left-handed weak doublets and right-handed weak singlets), the resulting condensate $\langle \bar{f}_L f_R \rangle \neq 0$ breaks the electroweak symmetry as desired. Three of the Nambu-Goldstone Bosons (technipions) of the chiral symmetry breaking become the longitudinal modes of the W and Z. The logarithmic running of the strong gauge coupling renders the low value of the technicolor scale (and thereby the electroweak scale) natural. The absence of fundamental scalars obviates concerns about triviality.

Many models of DEWSB have additional light neutral pseudo Nambu-Goldstone bosons (PNGBs) which could potentially be accessible to a standard Higgs search; these are called "technipions" in technicolor models. There is not one particular DEWSB model that has been singled out as a benchmark, in the manner of the MSSM among supersymmetric theories. Rather, several different classes of models have been proposed to address various challenges within the DEWSB paradigm of the origins of mass. In this thesis, I look at several representative technicolor models. I both evaluate the potential of standard Higgs searches to discover the lightest PNGBs of each of these models, and also draw some inferences about the characteristics of technicolor models that have the greatest impact on this search potential.

My analysis will assume, for simplicity, that the lightest PNGB state is significantly lighter than other neutral (pseudo)scalar technipions, so as to heighten the comparison to the SM Higgs boson. The precise spectrum of any technicolor model generally depends on a number of parameters, particularly those related to whatever "extended technicolor" ([26, 31]) interaction transmits electroweak symmetry breaking to the ordinary quarks and leptons. Models in which several light neutral PNGBs were nearly degenerate would produce even larger signals than those discussed here.

The specific models we examine are: 1) the traditional one-family model [22] with a full family of techniquarks and technileptons, 2) a variant on the one-family model [23] in which the lightest technipion contains only down-type technifermions and is significantly lighter than the other pseudo Nambu-Goldstone bosons, 3) a multiscale walking technicolor model [24] designed to reduce flavor-changing neutral currents, and 4) a low-scale techneiolor model (the Technicolor Straw Man model) [25] in which the lightest technipion is composed of technileptons. It must be noted, that in model 4) we do not consider the lightest technipion for exactly that reason: Since it is only composed of technileptons it will have no anomalous coupling to gluons, the main production mechanism for technipions in technicolor models. We therefore consider a slightly heavier (or possibly degenerate) technipion which is composed of techniquarks. For simplicity however, the lightest neutral technipion of each model which couples to gluons will be generically denoted by P; where a specific model is meant, a superscript will be used.

One of the key differences among these models is the value of the technipion decay constant F_P, which is related to the number N_D of weak doublets of technifermions that contribute to electroweak symmetry breaking. In a model like 2), in which only a single technifermion condensate breaks the electroweak symmetry, the value of F_P is simply the weak scale: $F_P^{(2)} = v = 246$ GeV. In models where more than one technifermion condensate breaks the EW symmetry, one finds $v^2 = f_P^2 + f_2^2 + f_3^2 + ...$ For example, in the one-family model 1), all four technidoublets corresponding to a technifermion "generation" condense, so that the decay constant is fixed to be $F_P^{(1)} = \frac{v}{2}$. In the lowscale model 4), the number of condensing technidoublets is much higher, of order 10; setting $N_D = 10$ yields $F_P^{(4)} = \frac{v}{\sqrt{10}}$. And in the multiscale model 3), the scales at which various technicondensates form are assumed to be significantly different, so that the lowest scale is simply bounded from above. In keeping with [24] and to ensure that the technipion mass will be in the range to which the standard Tevatron Higgs searches are sensitive, I set $F_P^{(3)} = \frac{v}{4}$.

In section 4, I study the enhancement factors for several production and decay modes of the lightest eligible PNGBs of each technicolor model. Then in section 5, I compare the signatures of these PNGBs to those of a SM Higgs and the Higgs bosons of the MSSM in order to determine how the standard search modes (or additional channels) can help tell these states apart.

In section 4.2, I briefly discuss topcolor models, in which new strong interactions among top quarks form top-pion bound states with masses of order $2m_t$. The signature of this PNGB will then again be compared to the Higgs boson of the Standard Model. I will always compare standard and non-standard scalars of the same mass, so I will be comparing the top-pion with a rather heavy SM Higgs boson.

Table 1: Anomaly Factors for the models under study [23, 25, 30, 2, 3]

	1) one-family	2) variant one-family	3) multiscale	4) low-scale
$\mathcal{A}_{gg}$	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{6}}$	$\sqrt{2}$	$\frac{1}{\sqrt{3}}$
$\mathcal{A}_{\gamma\gamma}$	$-\frac{4}{3\sqrt{3}}$	$\frac{16}{3\sqrt{6}}$	$\frac{4\sqrt{2}}{3}$	$\frac{34}{9}$

4 Results For Each Model

In this section, I examine the single production of technicolor PNGBs via the two dominant methods at the Tevatron: gluon fusion and $b\bar{b}$ annihilation. I determine the degree to which these production channels are enhanced relative to production of a SM Higgs, and find which channel dominates for each scalar state. I likewise study the major decay modes: $b\bar{b}$, $\tau\tau$, $\gamma\gamma$, and WW in order to determine the branching fractions relative to those of an SM Higgs.

4.1 Technicolor

4.1.1 PNGB Production via Gluon Fusion

Single production of a technipion can occur through the axial-vector anomaly which couples the technipion to pairs of gauge bosons. For an $SU(N_{TC})$ technicolor group with technipion decay constant F_P, the anomalous coupling between the technipion and a pair of gauge bosons is given, in direct analogy with the coupling of a QCD pion to gluons, by [27, 28, 29]

$$N_{TC}\mathcal{A}_{V_1V_2}\frac{g_1g_2}{8\pi^2F_P}\epsilon_{\mu\nu\lambda\sigma}k_1^\mu k_2^\nu\epsilon_1^\lambda\epsilon_2^\sigma \tag{2}$$

where $\mathcal{A}_{V_1V_2}$ is the anomaly factor (determined by the symmetry structure of the model), g_i are the gauge boson couplings, and the k_i and ϵ_i are the four-momenta and polarizations of the gauge bosons. The values of the anomaly factors for the lightest PNGB coupling to gluons is given in Table 1 for each model.

Table 2: Calculated enhancement factors for production at the Tevatron and LHC of a 130 GeV technipion via gg alone, via $b\bar{b}$ alone, and combined. Note that the small enhancement in the $b\bar{b}$ process slightly reduces the total enhancement relative to that of gg alone.

	1) one family	2) variant one-family	3) multiscale	4) low scale
$\kappa^P_{gg\ prod}$	48	6	1100	120
$\kappa^P_{bb\ prod}$	4	0.67	16	10
$\kappa^P_{total\ prod}$	47	5.9	1100	120

The rate of single technipion production in this channel is proportional to the decay width to gluons. In the technicolor models, we have

$$\Gamma(P \to gg) = \frac{1}{2}\frac{8}{32\pi} m_P^3 \left(\frac{\alpha_S N_{TC} \mathcal{A}_{gg}}{2\pi F_P}\right)^2 . \tag{3}$$

while in the SM, the expression looks like [13]

$$\Gamma(h \to gg) = \frac{1}{2}\frac{8}{32\pi} m_h^3 \left(\frac{\alpha_S}{3\pi v}\right)^2 \tag{4}$$

Comparing a PNGB to a SM Higgs boson of the same mass, we find the enhancement in the gluon fusion production rate is

$$\kappa_{gg\ prod} = \frac{\Gamma(P \to gg)}{\Gamma(h \to gg)} = \frac{9}{4} N_{TC}^2 \mathcal{A}_{gg}^2 \frac{v^2}{F_P^2} \tag{5}$$

The main factors influencing $\kappa_{gg\ prod}$ for a fixed value of N_{TC} are the anomalous coupling to gluons and the technipion decay constant. The value of $\kappa_{gg\ prod}$ for each model (taking $N_{TC} = 4$) is given in Table 2.

4.1.2 Production via Bottom Quark Annihilation

The PNGBs couple to b-quarks courtesy of the extended technicolor interactions responsible for producing masses for the ordinary quarks and leptons. The extended technicolor (ETC) group (of which $SU(N_{TC})$ is an unbroken subgroup) includes gauge bosons that couple to both ordinary and technicolored fermions so that the ordinary fermions can interact with the technicondensates that break the electroweak symmetry.

The rate of technipion production via $b\bar{b}$ annihilation is proportional to $\Gamma(P \to b\bar{b})$. In general, the expression for the decay of a technipion to fermions is

$$\Gamma(P \to f\bar{f}) = \frac{N_C\, \lambda_f^2\, m_f^2\, m_P}{8\pi\, F_P^2} \left(\sqrt{1 - \frac{4m_f^2}{m_P^2}}\right)^S \tag{6}$$

where N_C is 3 for quarks and 1 for leptons. The phase space exponent S is 3 for scalars and 1 for pseudoscalars; the lightest PNGB in models 1) and 4) is a scalar, while in models 2) and 3) it is assumed to be a pseudoscalar. For the technipion masses considered here, the value of the phase space factor in (6) is so close to one that the value of s makes no practical difference. The factor λ_f is a non-standard Yukawa coupling distinguishing leptons from quarks. Model 2) has $\lambda_{quark} = \sqrt{\frac{2}{3}}$ and $\lambda_{lepton} = \sqrt{6}$; model 3) also includes a similar factor, but with average value 1. Finally, it should be noted that Model 2) assumes that the lightest technipion is composed only of down-type fermions and cannot decay to $c\bar{c}$; since this decay would usually have a small branching ratio and $c\bar{c}$ is not a preferred final state for Higgs searches, this has little impact.

For comparison, decay width of the SM higgs into b-quarks is:

$$\Gamma(h \to b\bar{b}) = \frac{3\, m_b^2\, m_h}{8\pi\, v^2} \left(\sqrt{1 - \frac{4m_b^2}{m_h^2}}\right)^3 \tag{7}$$

The production enhancement for $b\bar{b}$ annihilation is (again assuming Higgs and Technipion have the same mass):

$$\kappa_{bb\ prod} = \frac{\Gamma(P \to b\bar{b})}{\Gamma(h \to b\bar{b})} = \frac{\lambda_b^2\, v^2}{F_P^2} \left(\sqrt{1 - \frac{4m_b^2}{m_h^2}}\right)^{S-3} \tag{8}$$

The value of $\kappa_{bb\ prod}$ (shown in Table 4) is controlled by the size of the technipion decay constant.

We see from Table 2 that $\kappa_{bb\ prod}$ is at least one order of magnitude smaller than $\kappa_{gg\ prod}$ in each model. Taking the ratio of equations (5) and (8)

$$\frac{\kappa_{gg\ prod}}{\kappa_{bb\ prod}} = \frac{9}{4} N_{TC}^2 \mathcal{A}_{gg}^2 \lambda_b^{-2} \tag{9}$$

we see that the larger size of $\kappa_{gg\ prod}$ is due to the factor of N_{TC}^2 coming from the fact that gluons couple to a technipion via a techniquark loop. The ETC interactions coupling b-quarks to a technipion have no such enhancement.

In addition, the production cross-section for a SM Higgs boson via $b\bar{b}$ annihilation is 2 to 3 orders of magnitude smaller than that for gluon fusion at the Tevatron [32] and the LHC [33]. With a smaller SM cross-section and a smaller enhancement factor, it is clear that technipion production via $b\bar{b}$ annihilation is negligible at Tevatron and LHC. However, since including the $b\bar{b}$ production channel reduces the enhancement in general, I will include it in my calculations to get a more conservative estimate. I therefore define a combined total enhancement factor:

$$\begin{aligned}
\kappa^{\mathcal{H}}_{total/xx} &= \frac{\sigma(gg \to \mathcal{H} \to xx) + \sigma(bb \to \mathcal{H} \to xx)}{\sigma(gg \to h_{SM} \to xx) + \sigma(bb \to h_{SM} \to xx)} \\
&= \frac{\kappa^{\mathcal{H}}_{gg/xx} + \sigma(bb \to \mathcal{H} \to xx)/\sigma(gg \to h_{SM} \to xx)}{1 + \sigma(bb \to h_{SM} \to xx)/\sigma(gg \to h_{SM} \to xx)} \\
&= \frac{\kappa^{\mathcal{H}}_{gg/xx} + \kappa^{\mathcal{H}}_{bb/xx}\sigma(bb \to h_{SM} \to xx)/\sigma(gg \to h_{SM} \to xx)}{1 + \sigma(bb \to h_{SM} \to xx)/\sigma(gg \to h_{SM} \to xx)} \\
&\equiv [\kappa^{\mathcal{H}}_{gg/xx} + \kappa^{\mathcal{H}}_{bb/xx} R_{bb:gg}]/[1 + R_{bb:gg}].
\end{aligned} \tag{10}$$

Here $R_{bb:gg}$ is the ratio of $b\bar{b}$ and gg initiated Higgs boson production, at Tevatron and LHC respectively, in the Standard Model. The total production enhancement is also given in Table 2. Note that the small differences in $R_{bb:gg}$ between Tevatron and

Table 3: Branching ratios of a technipion/Higgs of mass 130 GeV

Decay Channel	1) one family	2) variant one family	3) multiscale	4) low scale	SM Higgs
$b\bar{b}$	0.60	0.53	0.23	0.60	0.53
$c\bar{c}$	0.05	0	0.03	0.05	0.02
$\tau^+\tau^-$	0.03	0.25	0.01	0.03	0.05
gg	0.32	0.21	0.73	0.32	0.07
$\gamma\gamma$	2.7×10^{-4}	2.9×10^{-3}	6.1×10^{-4}	6.4×10^{-3}	2.2×10^{-3}
W^+W^-	0	0	0	0	0.29

LHC are negligible, so we get the same total production enhancement for both.

4.1.3 Decays

The decay width of a light technipion into gluons or fermion/anti-fermion pairs has been discussed above. Since, in the interesting mass range, the technipions do not decay to W bosons and decays to Z Bosons (through the axial vector anomaly) are negligible, the remaining possibility is a decay to photons. Again, this proceeds through the axial vector anomaly (cf. Equation (2)) and the anomaly factors $\mathcal{A}_{\gamma\gamma}$ are shown in Table 3.

I now calculate the technipion branching ratios from the above information, taking $N_{TC} = 4$. The values are essentially independent of the size of m_P within the range 120 GeV - 160 GeV; the branching fractions for $m_P = 130$ GeV are shown in Table 5. The branching ratios for the SM Higgs at NLO are given for comparison; they were calculated using HDECAY [15]. Note that, in contrast to the technipions, a SM Higgs in this mass range already has a noticeable decay rate to off-shell vector bosons.

Comparing the technicolor and SM branching ratios in Table 5, we see immediately that decay enhancements will be generally of order one, and therefore much smaller than the production enhancements. Decays to $b\bar{b}$ are slightly enhanced, if at all. Decays to $c\bar{c}$ are enhanced in our tree-level calculations – but note that it is higher-order corrections that suppress this mode for the SM higgs; in any case, this is not a primary discovery channel. Decays to τ leptons have a small enhancement in general; again, the comparison of tree-level technicolor and loop-level SM Higgs calculations may be a factor here. Model 2) is an exception; its unusual Yukawa couplings yield a decay enhancement in the $\tau\tau$ channel of order the technipion's (low) production enhancement. In the $\gamma\gamma$ channel, the decay enhancement strongly depends on the group-theoretical structure of the model, through the anomaly factor. Table 6 includes the decay enhancements κ_{dec}^{P} for the most experimentally promising search channels.

4.2 Top-Pions

For additional comparison, I discuss a different DEWSB model, a topcolor-assisted Technicolor (TC2) model ([34], [35], [36]), which I will be referring to as model 5). TC2 models address the difficulty of simultaneously generating the large mass of the top quark (which places an upper bound on the symmetry breaking scale Λ_{ETC} of the ETC gauge group) and suppressing the experimentally-not-observed flavor-changing neutral currents (FCNC), which can show up as a relic of ETC symmetry breaking at low energies (thereby placing a lower bound on Λ_{ETC}). In these models, the top quark mass is partially generated by another new strong interaction (topcolor) between top quarks. The Higgs-like scalar here is a heavy top-pion, which I will be referring to as T, since it is very different from the PNGBs of the other examples. T is a linear combination of technipions and the composite scalars created by top quark condensation.

In the TC2 model 5), there are two scales, one for technifermion condensation and the other for top condensation. F_T, the scale of top-pion condensation, is thereby, as in model 3), only bounded from above. As I am taking the phenomenological expressions from [37], I will also adhere to their choice of parameters, setting $F_T =$ 70 GeV.

Model 5) requires a top-pion heavier than the top quark, so we can not calculate the anomalous coupling to gauge bosons in the limit $m_{\mathcal{H}} \ll m_t$. Instead we must insert the mass-dependent function ([37])

$$\mathcal{A}_{gg}^{(5)} = 4\frac{m_t^2}{m_T^2}\sqrt{1 - \frac{F_T^2}{v^2}}(1-\epsilon)\arcsin^2\left(\frac{m_T}{2m_t}\right) \tag{11}$$

Further parameters need explaining here: ϵ denotes the fraction of the top mass generated by ETC-interactions (as opposed to being generated by topcolor interactions). We will set it to be $\epsilon = 0.01$ (It must be on the order of the ratio of bottom to top quark mass). m_t is the top quark mass. Note that there is no equivalent to the N_{TC} parameter of technicolor models. Also it is important to mention, that the square-root is neither a real anomaly nor a phase-space factor: it reflects the mixing of techni- and top-pions and will show up several times Using equation 5 we then find, setting $m_P = 220 GeV$ (a value at the lower end of, but well within, the theoretically predicted top-pion mass range)

$$\kappa_{gg\ prod}^{T} = 36\frac{m_t^4}{m_T^4}\left(\frac{v^2}{F_T^2} - 1\right)(1-\epsilon)^2\arcsin^4\left(\frac{m_T}{2m_t}\right) \approx 34. \tag{12}$$

The top-pion of 5) couples most strongly to the third generation of quarks. It is expected to be heavier than the technipions of the other models, but since it is not heavier than $2m_t$, its main fermionic decay mode is:

$$\Gamma(T \to b\bar{b}) = \frac{N_C}{8\pi} m_T\left(\frac{1}{F_T^2} - \frac{1}{v^2}\right)\left(m_b - \frac{m_S}{m_C}\ \epsilon\ m_t\right)^2\sqrt{1 - \frac{4m_b^2}{m_T^2}} \tag{13}$$

where the slight correction to m_b arises because there are two distinct sources of the mass of the bottom quark(ETC and topcolor). The charm and strange masses are denoted m_C and m_S respectively.

We then get for the production enhancement by bottom quark annihilation (again setting m_T = 220 GeV):

$$\kappa^T_{bb\ prod} = (1 - \frac{4m_b^2}{m_P^2})^{-1}(\frac{v}{F_T m_b}(m_b - \frac{m_8}{m_C}\ \epsilon\ m_t))^2 \approx 9.6 \tag{14}$$

Comparing this with the production enhancement for gluon fusion (Equation 14), we see that the production enhancements are of the same order of magnitude. Even though we expect a somewhat larger impact of bottom quark annihilation as a production mechansim (since the factor of N_{TC}^2 does not appear in this model), it turns out that it is in fact negligible at the Tevatron and at the LHC for model 5).

Model 5) has a second fermionic decay mode for the top-pion - T is heavier then a top quark and due to flavor-non-universality has the following FCNC decay mode:

$$\Gamma(T \to \bar{t}c) = K_{tc}^2 N_C \frac{1}{8\pi}(\frac{1}{F_T^2} - \frac{1}{v^2})(m_t(1-\epsilon))^2 m_T \sqrt{1 - \frac{m_t^2}{m_T^2}} \tag{15}$$

The factor K_{tc} is included in the coupling, and must be kept small due to experimental constraints. Following [37], I set it to be $K_{tc} = 0.05$. Again, the PNGBs of model 5) do not decay to W bosons and anomalous decay to Z bosons is negligible, so we are left with decay to photons, where, for the same reasons as for gluons, we have to insert the following mass-dependant function instead of the anomaly factor:

$$\mathcal{A}^{(5)}_{\gamma\gamma} = \frac{16}{3}\frac{4m_t^2}{m_T^2}\sqrt{1 - \frac{F_T^2}{v^2}}(1-\epsilon)\arcsin^2(\frac{m_T}{2m_t}) \tag{16}$$

The "pure" anomaly factor, derived from the group theoretical structure of the coupling is the $\frac{16}{3}$ at the beginning of the equation (note that this was 1 in the case of gluons). The branching ratios for the top-pion (Table 4) are again calculated using a mass of 220 GeV.

Table 4: Branching ratio of top-pion/Higgs of mass 220 GeV

Decay	5) Topcolor-assisted TC	Heavy SM Higgs
$b\bar{b}$	0.26	1.7×10^{-3}
$\bar{t}c$	0.63	0
gg	0.11	0.69×10^{-3}
$\gamma\gamma$	1.4×10^{-3}	3.7×10^{-5}
W^+W^-	0	0.71
ZZ	0	0.29

5 Comparison and Interpretation

5.1 Technicolor vs SM

My results for the Tevatron Run II (LHC) production enhancements (including both gg fusion and $b\bar{b}$ annihiliation), decay enhancements, and overall enhancements of each technicolor model relative to the SM are shown in Table 5 (6) for a technipion or Higgs mass of 130 GeV. Multiplying $\kappa^P_{tot/xx}$ by the cross-section for SM Higgs production via gluon fusion [33] yields an approximate technipion production cross-section, as shown in the right-most column of Table 5 (6).

In each technicolor model, the main enhancement of the possible technipion signal relative to that of an SM Higgs arises at production, making the size of the technipion decay constant the most critical factor in determing the degree of enhancement. An equally important role is played by the number of technicolors, which is not as apparent here, since I have assumed it to be the same for all the models I considered. Still, along with the absence of decays to vector bosons for the technipions, the factor of N^2_{TC} is responsible for the fact, that we actually observe a net enhancement for all models and in all decay channels.

Each decay enhancement is in general of order 1, making it significantly smaller than the typical production enhancement. In model 3) the decay "enhancement" is actually a suppression, but a tiny one compared to the production enhancement. We

Table 5: Enhancement Factors for 130 GeV technipions produced at the Tevatron, compared to production and decay of a SM Higgs Boson of the same mass. The slight suppression of κ^P_{prod} due to the b-quark annihilation channel has been included.The rightmost column shows the cross-section (pb) for $p\bar{p} \to P \to xx$ at Tevatron Run II.

Model	Decay mode	κ^P_{prod}	κ^P_{dec}	$\kappa^P_{tot/xx}$	Cross Section
1) one family	$b\bar{b}$	47	1.1	52	14 pb
	$\tau^+\tau^-$	47	0.6	28	0.77 pb
	$\gamma\gamma$	47	0.12	5.6	6.4×10^{-3} pb
2) variant one family	$b\bar{b}$	5.9	1	5.9	1.8 pb
	$\tau^+\tau^-$	5.9	5	30	0.84 pb
	$\gamma\gamma$	5.9	1.3	7.7	8.7×10^{-3} pb
3) multiscale	$b\bar{b}$	1100	0.43	470	130 pb
	$\tau^+\tau^-$	1100	0.2	220	6.1 pb
	$\gamma\gamma$	1100	0.27	300	0.34 pb
4) low scale	$b\bar{b}$	120	1.1	130	36 pb
	$\tau^+\tau^-$	120	0.6	72	2 pb
	$\gamma\gamma$	120	2.9	350	0.4 pb

find that $P \to b\bar{b}$ is very similar to $h_{SM} \to b\bar{b}$. In contrast, $P \to c\bar{c}$ generally has significant decay enhancement. However, this may be an artifact of our comparing a tree-level technicolor result to an NLO result for h_{SM}; radiative corrections to $h_{SM} \to c\bar{c}$ tend to suppress the branching fraction. The decay $P \to \tau\tau$ generally has a suppressed rate relative to SM expectations; again, this may relate to comparing leading technicolor and NLO SM results. An exception is model 2), where the special structure of the Yukawa coupling leads to a $\tau\tau$ decay enhancement of the same order as the production enhancement. The $P \to \gamma\gamma$ decay enhancement factor depends strongly on the group-theoretic structure of the model through the anomaly factor, ranging from a distinct enhancement in model 4) to a factor-of-10 suppression in model 1).

The net result for the models considered is a distinct enhancement of the P signal in each of the $\tau\tau$, $b\bar{b}$ and $\gamma\gamma$ search channels. Given the large QCD background for the $b\bar{b}$ final state, the $\tau\tau$ and $\gamma\gamma$ channels are likely to be the most promising ways

Table 6: Enhancement Factors for 130 GeV technipions produced at the LHC, compared to production and decay of a SM Higgs Boson of the same mass. The slight suppression of κ^P_{prod} due to the b-quark annihilation channel has been included.The rightmost column shows the cross-section (pb) for $p\bar{p} \to P \to xx$ at the LHC.

Model	Decay mode	κ^P_{prod}	κ^P_{dec}	$\kappa^P_{tot/xx}$	Cross Section
1) one family	$b\bar{b}$	47	1.1	52	890 pb
	$\tau^+\tau^-$	47	0.6	28	48 pb
	$\gamma\gamma$	47	0.12	5.6	0.4 pb
2) variant one family	$b\bar{b}$	5.9	1	5.9	100 pb
	$\tau^+\tau^-$	5.9	5	30	52 pb
	$\gamma\gamma$	5.9	1.3	7.7	0.55 pb
3) multiscale	$b\bar{b}$	1100	0.43	473	8000 pb
	$\tau^+\tau^-$	1100	0.2	220	380 pb
	$\gamma\gamma$	1100	0.27	300	21 pb
4) low scale	$b\bar{b}$	120	1.1	130	2200 pb
	$\tau^+\tau^-$	120	0.6	72	120 pb
	$\gamma\gamma$	120	2.9	350	25 pb

to discover a technipion. As illustrated in Figure 1, the available enhancement is well above what is required to render the P of any of these models visible in the $\tau\tau$ channel at the Tevatron. In models 3 and 4, the visibility in the $\gamma\gamma$ final state can be even more striking, making this a possible discovery channel even at the Tevatron. Of course since we have net enhancements in all cases, all these models should have visible technipions at the LHC, where even an SM Higgs would be detectable in the mass range I have considered (cf. Figure 2).

5.2 MSSM vs Technicolor

A brief comparison between the models I have been considering and the MSSM is in order here. The MSSM is an alternate expansion of the Standard Model, addressing similar problems as DEWSB models but taking a different approach, proposing a symmetry of nature relating fermions and bosons. The MSSM introduces two Higgs

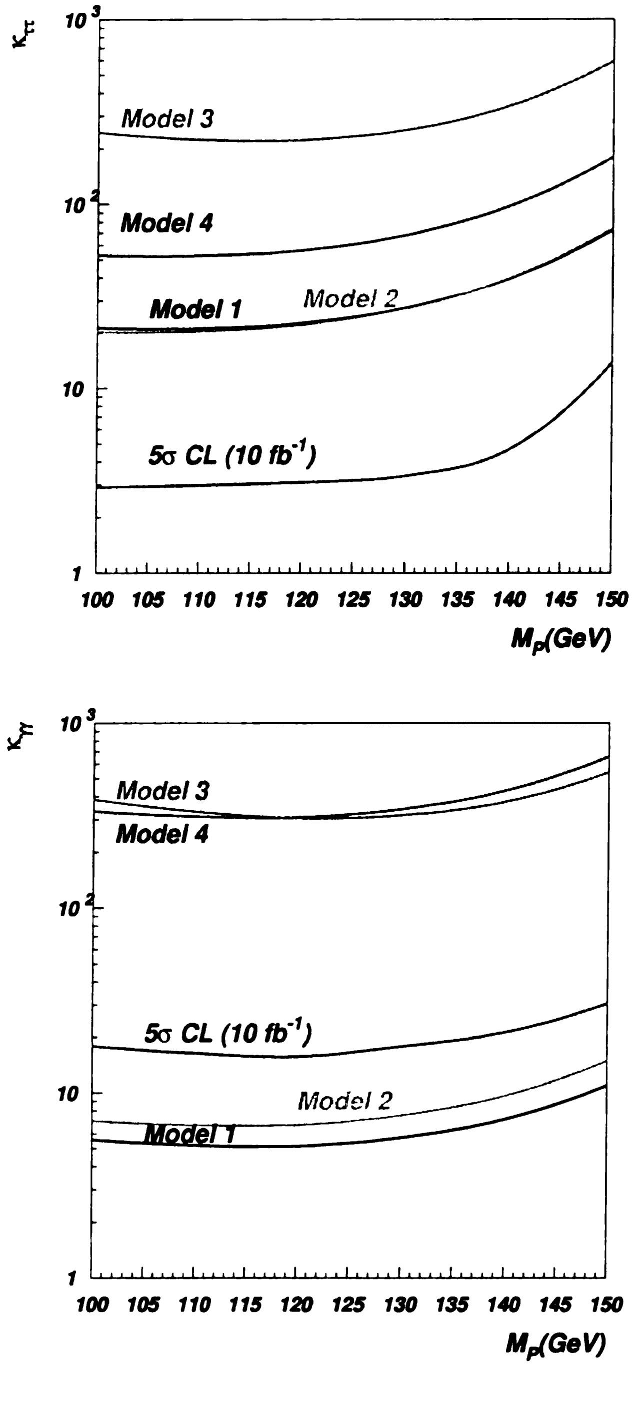

Figure 1: Total enhancement factor for each technicolor model plotted as a function of technipion mass and assuming the final state is a tau (photon) pair. The lowest curve is the enhancement factor required to make a Higgs-like particle visible (5σ discovery) in tau(photon)-pairs at Tevatron Run II with a total luminosity of 10 fb^{-1} [9], [38].

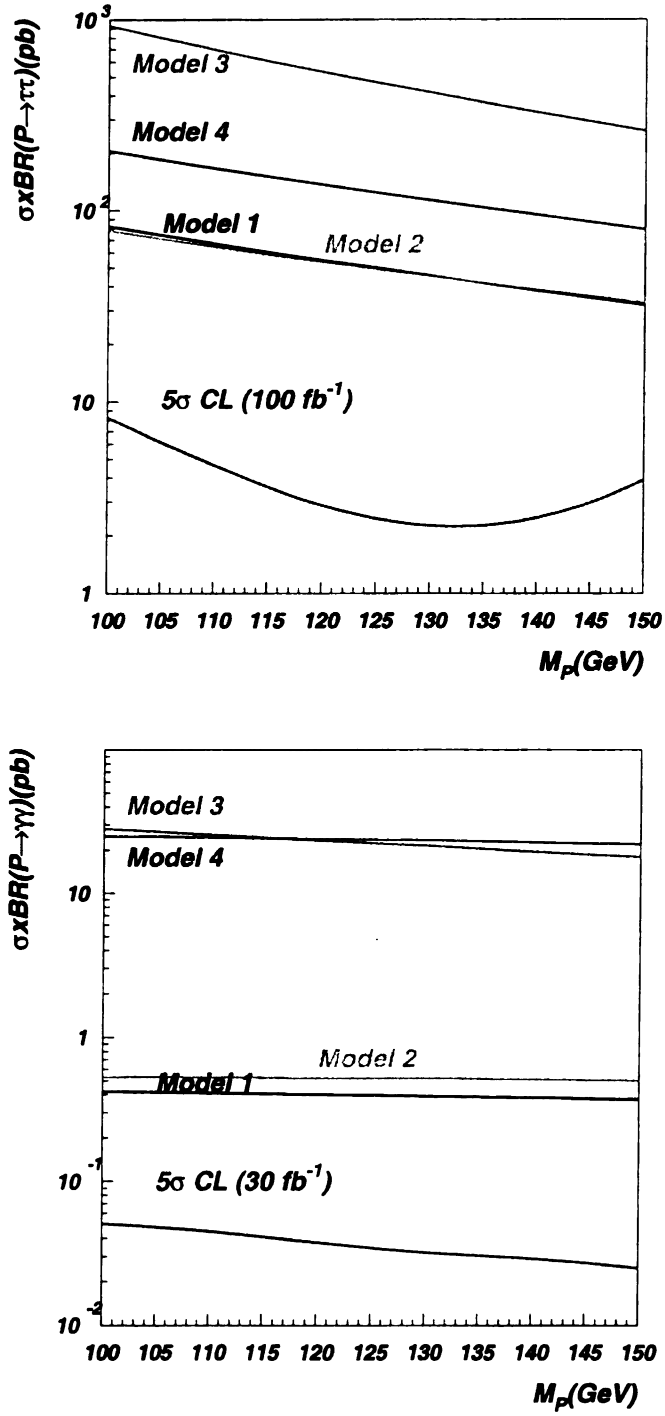

Figure 2: Total cross-section times branching ratio for each technicolor model plotted as a function of technipion mass and assuming the final state is a tau (above) or γ (below) pair at LHC. The lowest curve is the cross-section times branching ratio required to make a Higgs-like particle visible (5 σ discovery, total luminosity given in brackets) in tau- or γ-pairs, respectively [10], [11].

doublets which break the electroweak symmetry and give mass to the fermions of the SM. Calculations similar to the ones I have done for DEWSB models in this thesis are performed for supersymmetric models in the paper "The Meaning of Higgs: $\tau^+\tau^-$ and $\gamma\gamma$ at the Tevatron and the LHC" [12] mentioned earlier. I describe some of the major differences between DEWSB models and the MSSM here.

One notable difference concerns the production mechanism: While bottom quark annihilation is, as we have seen, negligible for technipions, this channel can become very important and even dominant in large sections of the MSSM parameter space.

The more important (since more observable) difference is however the difference in branching rates for some important decay modes. While $\tau\tau$ decays are enhanced in both models compared to the SM, decays to photons are heavily suppressed in the MSSM as opposed to the moderate to large enhancements I have calculated for technicolor models. While this will probably play no role in analyzing data from Tevatron Run II, this significant difference could be the perfect way to distinguish between these two non-standard models at the LHC.

5.3 Top-Pion vs Heavy SM Higgs

Model 5) has a special role for several reasons: Mainly of course, its main decay mode is flavor changing and not even open to the SM higgs. But also, it necessitates a top-pion with a mass beyond the WW-decay threshold, which can nonetheless not decay to massive vector bosons. This absence of a signature is almost as striking as the FCNC, since the SM Higgs boson has a branching ratio of almost 100 percent to massive vector bosons at a mass of 220 GeV. So this model has very large decay enhancements (on the order of the production enhancement) in it's allowed decay channels, making it easily detectable if the Higgs Search in this mass range is not limited to only vector-boson-decays (whose mere absence would of course not necessarily indicate the existence of the top-pion!). Note however the absence of leptonic decays, since leptons get their

Table 7: Enhancement Factors for 220 GeV top-pions produced at the Tevatron and the LHC, compared to production and decay of a SM Higgs Boson of the same mass. The slight suppression of κ^P_{prod} due to the b-quark annihilation channel is negligible.The rightmost column shows the cross-section (pb) for $p\bar{p} \to P \to xx$ at Tevatron Run II.

Decay mode	κ^P_{prod}	κ^P_{dec}	$\kappa^P_{tot/xx}$	Cross Section (Tev)	Cross Section (LHC)
$b\bar{b}$	34	150	5100	0.77 pb	110 pb
$\tau^+\tau^-$	34	0	0	0 pb	0 pb
$\gamma\gamma$	34	38	1290	4.2×10^{-3} pb	0.6 pb

mass entirely from ETC.

The enhancement factors for 5) (Table 7) seem excessive at first glance, but that is only because the branching ratios for non-vector-boson decays get extremely small for the light SM higgs. The ratio of total width to mass for the top-pion is still of the order of 0.1 percent, which is narrower than the SM Higgs of the same mass. Looking at the estimated cross-sections brings things back into proportion. For example at the Tevatron, the cross-section for $p\bar{p} \to P \to b\bar{b}$ in model 5) is only about ten times larger than that of $p\bar{p} \to h \to W^+W^-$ in the SM, so we have a much less drastic effect than just looking at the enhancement factors would indicate and it is unlikely that top-pions could be detected at the Tevatron. Since the SM background for $b\bar{b}$ decays is probably still too large and the $\tau\tau$ mode is not allowed, the only feasible detection channel at the LHC is the decay to photons. To my knowledge, no calculations have been made for visibilty in the $\gamma\gamma$ channel at this mass range, since such a heavy SM Higgs would be perfectly visible through its decays to vector bosons. It seems probable however, that a top-pion would be detectable through decay to photons at the LHC.

6 Conclusions

I have shown that searches for a Standard Model Higgs boson at Tevatron Run II and LHC can provide significant results even if the electroweak symmetry is dynamically broken. The new scalar and pseudoscalar states of DEWSB models can have enhanced visibility in standard $\tau^+\tau^-$ and $\gamma\gamma$ search channels, making them potentially discoverable at Tevatron Run II and CERN LHC. This enhancement mainly comes from an increased production rate, rather than from differences in the branching fractions. The model parameters exerting the largest influence on the enhancements are N_{TC} and the technipion decay constant.

I also considered a topcolor-assisted technicolor model and compared the top-pion of this model with a heavy SM Higgs boson. I found that the experimental signatures of top-pions are so different from the SM Higgs that it is less easy to simply transfer predictions for the SM. The main conclusion to be drawn is that even for Higgs-like particles with masses beyond the WW-threshold, the search should not be limited to decays to vector bosons, which are so dominant in the SM.

For the technicolor models, where a direct comparison to the SM is easier, I investigated the likely mass reach of the Higgs searches at Tevatron and LHC in $p\bar{p} \to P \to \tau^+\tau^-$ and $p\bar{p} \to P \to \gamma\gamma$ for each model and found that in all cases there exist DEWSB models with visible scalar or pseudoscalar states, warranting a close look even when predictions for the SM Higgs are far from promising, such as for decay to photons at Tevatron Run II. The enhancement (or suppression) of $p\bar{p} \to P \to \gamma\gamma$ is also the best way of distinguishing DEWSB models from supersymmetric extensions of the standard model at the LHC.

References

[1] G. Rupak and E. H. Simmons, Phys. Lett. B **362**, 155 (1995) [arXiv:hep-ph/9507438].

[2] V. Lubicz and P. Santorelli, Nucl. Phys. B **460**, 3 (1996) [arXiv:hep-ph/9505336].

[3] K. R. Lynch and E. H. Simmons, Phys. Rev. D **64**, 035008 (2001) [arXiv:hep-ph/0012256].

[4] R. Barate *et al.* [ALEPH Collaboration], Phys. Lett. B **565**, 61 (2003) [arXiv:hep-ex/0306033].

[5] P. Bechtle [LEP Collaboration], Eur. Phys. J. C **33** (2004) S723 [arXiv:hep-ex/0401007].

[6] G. L. Kane, T. T. Wang, B. D. Nelson and L. T. Wang, Phys. Rev. D **71**, 035006 (2005) [arXiv:hep-ph/0407001].

[7] G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **40**, 317 (2005) [arXiv:hep-ex/0408097].

[8] G. Sguazzoni, Acta Phys. Slov. **55**, 93 (2005) [arXiv:hep-ph/0411096].

[9] A. Belyaev, T. Han and R. Rosenfeld, JHEP **0307**, 021 (2003) [arXiv:hep-ph/0204210].

[10] D. Cavalli *et al.*, arXiv:hep-ph/0203056.

[11] R. Kinnunen, S. Lehti, A. Nikitenko and P. Salmi, J. Phys. G **31**, 71 (2005) [arXiv:hep-ph/0503067].

[12] A. Belyaev, A. Blum, R. S. Chivukula and E. H. Simmons, arXiv:hep-ph/0506086.

[13] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, SCIPP-89/13

[14] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, arXiv:hep-ph/9302272.

[15] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. **108**, 56 (1998) [arXiv:hep-ph/9704448].

[16] G. 't Hooft, C. Itzykson, A. Jaffe, H. Lehmann, P. K. . Mitter, I. M. Singer and R. Stora, "Recent Developments In Gauge Theories. Proceedings, Nato Advanced Study Institute, Cargese, France, August 26 - September 8, 1979"

[17] K. G. Wilson, Phys. Rev. B **4**, 3184 (1971).

[18] K. G. Wilson and J. B. Kogut, Phys. Rept. **12**, 75 (1974).

[19] C. T. Hill and E. H. Simmons, Phys. Rept. **381**, 235 (2003) [Erratum-ibid. **390**, 553 (2004)] [arXiv:hep-ph/0203079].

[20] L. Susskind, Phys. Rev. D **20**, 2619 (1979).

[21] S. Weinberg, Phys. Rev. D **13**, 974 (1976).

[22] E. Farhi and L. Susskind, Phys. Rept. **74**, 277 (1981).

[23] R. Casalbuoni, A. Deandrea, S. De Curtis, D. Dominici, R. Gatto and J. F. Gunion, Nucl. Phys. B **555**, 3 (1999) [arXiv:hep-ph/9809523].

[24] K. D. Lane and M. V. Ramana, Phys. Rev. D **44**, 2678 (1991).

[25] K. D. Lane, Phys. Rev. D **60**, 075007 (1999) [arXiv:hep-ph/9903369].

[26] S. Dimopoulos and L. Susskind, Nucl. Phys. B **155**, 237 (1979).

[27] S. Dimopoulos, S. Raby and G. L. Kane, Nucl. Phys. B **182**, 77 (1981).

[28] J. R. Ellis, M. K. Gaillard, D. V. Nanopoulos and P. Sikivie, Nucl. Phys. B **182**, 529 (1981).

[29] B. Holdom, Phys. Rev. D **24**, 157 (1981).

[30] R. S. Chivukula, R. Rosenfeld, E. H. Simmons and J. Terning, arXiv:hep-ph/9503202.

[31] E. Eichten and K. D. Lane, Phys. Lett. B **90**, 125 (1980).

[32] M. Carena *et al.* [Higgs Working Group Collaboration], arXiv:hep-ph/0010338.

[33] M. Spira, Nucl. Instrum. Meth. A **389**, 357 (1997) [arXiv:hep-ph/9610350].

[34] C. T. Hill, Phys. Lett. B **345**, 483 (1995) [arXiv:hep-ph/9411426].

[35] K. D. Lane and E. Eichten, Phys. Lett. B **352**, 382 (1995) [arXiv:hep-ph/9503433].

[36] K. D. Lane, Phys. Lett. B **433**, 96 (1998) [arXiv:hep-ph/9805254].

[37] C. x. Yue, Q. j. Xu, G. l. Liu and J. t. Li, Phys. Rev. D **63**, 115002 (2001) [arXiv:hep-ph/0012332].

[38] S. Mrenna and J. D. Wells, Phys. Rev. D **63**, 015006 (2001) [arXiv:hep-ph/0001226].