Early Higgs Boson Discovery in Non-minimal Higgs Sectors

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Particle physics models with more than one Higgs boson occur in many frameworks for physics beyond the standard model, including supersymmetry, technicolor, composite Higgs, and “little Higgs” models. If the Higgs sector contains couplings stronger than electroweak gauge couplings, there will be heavy Higgs particles that decay to lighter Higgs particles plus heavy particles such as W, Z, and t. This motivates searches for final states involving multiple W, Z, t, and bb pairs. A two Higgs doublet model with custodial symmetry is a useful simplified model to describe many of these signals. The model can be parameterized by the physical Higgs masses and the mixing angles α and β, so discovery or exclusion in this parameter space has a straightforward physical interpretation. We illustrate this with a detailed analysis of the process gg → A followed by A → hZ and h → WW. For mA ≃ 330 GeV, mh ≃ 200 GeV we can get a 4.5σ signal with 1 fb−1 of integrated luminosity at the Large Hadron Collider.

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Introduction—The Large Hadron Collider (LHC) is currently exploring the high-energy frontier at the TeV scale, and its main goal is to discover the origin of electroweak symmetry breaking. Most of the effort in this direction is devoted to the search for a Higgs boson with mass below roughly 150 GeV. This is motivated by the fact that the standard model with a light Higgs boson gives a good fit to precision electroweak data, and by supersymmetric models that predict a light Higgs boson. However, the minimal supersymmetric model generically predicts mh < mZ = 91 GeV for the lightest Higgs mass, violating the experimental limit mh > 114 GeV from searches at LEP [1]. The Higgs mass can get loop contributions that avoid the experimental bound, but at the cost of fine-tuning UV contributions to the Higgs mass at the percent level. Eliminating precisely this kind of tuning is the primary motivation for supersymmetry, and this has motivated a great deal of work on supersymmetric models to reduce this tuning (see for e.g. [2][4] and [5] for a more complete list of references). With or without supersymmetry, the precision electroweak fit is compatible with a heavier Higgs boson if there are additional particles with masses and couplings that break electroweak symmetry (see for e.g. [6]).

In this Letter, we study the phenomenology of non-minimal Higgs sectors with Higgs boson masses above 2mw. Non-minimal Higgs sectors occur in many frameworks for avoiding fine tuning of the Higgs sector, including new strong dynamics (“technicolor”) (for a review, see [7]), composite Higgs (see for e.g. [8][9]), and “little Higgs” theories (for reviews, see [10][11]). Heavy Higgs bosons are associated with Higgs sectors with stronger self-couplings, and are therefore particularly well-motivated in technicolor and composite Higgs models. In particular, Ref. [12] argued that spin-0 resonances are a generic and prominent feature of models with strong dynamics in the electroweak symmetry breaking sector, and the present work originated in the construction of simplified models to describe their collider phenomenology [13]. However, the collider signals we discuss are applicable to a much wider range of models.

Higgs bosons couplings are generally proportional to the masses of the particles to which they couple, so the Higgs particles tend to decay to the heaviest particles that are kinematically allowed. In the present context, this implies decays to lighter Higgs bosons, t, Z, W and b particles. In particular, we can have cascade decays leading to states containing several heavy standard model particles.

Simplified Model—To explore the phenomenology, we use a 2-Higgs doublet model as a simplified model [14]. This model possesses built-in, good high-energy behavior, has a simple parameter space, and can be simulated using state-of-the-art Monte Carlo tools. We impose SU(2) custodial symmetry as well as a discrete symmetry H2 → −H2 on the potential to simplify the model. The Higgs potential is then

\[ V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2 + h.c.)^2. \]

The physical particles consist of the CP-even neutral scalars h, H and a degenerate custodial SU(2) triplet (A, H±). The 6 parameters in the Higgs sector can be taken to be v = \sqrt{\nu_1^2 + \nu_2^2} = 246 GeV, mh, mH, mA, mH±, and the angles α and β defined conventionally by tan β = v_1/v_2, h = [cos α Re(H_1^0) − sin α Re(H_2^0)]/\sqrt{2}. The custodial SU(2) symmetry allows us to choose H1 to be the field that couples to the top quark, so all phenomenologically important couplings of the Higgs bosons are determined by these parameters.
Phenomenology—We now discuss the signals beyond those of the standard model when some of the Higgs bosons are heavy. If the $A$ is relatively light and has unsuppressed coupling to the top quark, it can be produced via $gg \to A$ (via a top loop) followed by $A \to t\bar{t}$ or $hZ$. If the $A$ is light but has suppressed coupling to the top quark (large $\tan \beta$) we have $gg \to H$ followed by $H \to AZ \to hZZ$. If the $A$ is very heavy, the dominant signal beyond the standard model is $gg \to H \to hh$. All of these signals produce light Higgses, $h$, which decay either to $bb$ (for $m_h \lesssim 2m_W$) or $WW/ZZ$ (for larger $m_h$). There are many modes, with the common feature that they involve production of multiple heavy standard model particles.

In this work we study the process $gg \to A(\ast) \to Zh$. If $m_h < 2m_W$ the dominant decay is $h \to bb$; in the context of supersymmetry, this has been discussed as a discovery mode of two Higgs bosons [15]. $Zh$ production also occurs in the standard model, and backgrounds can be suppressed by focusing on the kinematic region where the $h$ is boosted [16] [17]. In the present scenario this is enhanced by the intermediate $A$ in the production. Requiring $p_T(h) > 200$ GeV the intermediate $A$ is off-shell in our model, but there is still an enhancement of 10 times or more compared to the standard model, as illustrated in Fig. 1. Since this signal is already under detailed investigation by the LHC experiments, we will not discuss it further here.

We will study the case of a heavier $h$, where we have $gg \to Zh \to W^+W^-Z$ via an on-shell $A$. To our knowledge, this has not been previously investigated in the literature. We focus on $Z \to l^+l^-$ ($l = e$ or $\mu$), which suppresses all backgrounds that do not involve a $Z$. We consider $WW \to j j l^\pm + E_T$, which has a 29% branching ratio and allows us to reconstruct both the $h$ and the $A$. The final state $WW \to t^+l^- + E_T$ has branching ratio 4.5% and is very clean, but does not allow reconstruction of the $h$ (or $A$). Another possibility that we do not investigate here is $Zh \to ZZZ \to j j l^\pm l^\mp l^\mp$, which has a branching ratio approximately 0.2 times the mode we are considering. With more data, these modes will be useful in confirming the signal and its interpretation.

Because we require a leptonic $Z$, the only important backgrounds are those involving a $Z$. The largest background is $WZ + \text{jets}$. Other backgrounds we consider are $Z + \text{jets}$, $t\bar{t}Z$, and $ZZ + \text{jets}$. The signal was generated with up to 1 additional jet using MadGraph [18] with the 2HDM4TC model files [13], and applying a $K$-factor of 2.4 (extrapolating from [19]). Backgrounds were simulated using Alpgen [20] with up to one additional jet. Jet showering was done by Pythia [21] with MLM jet matching [22] for both the signal and backgrounds, and the detector response was simulated using PGS [23]. The $K$-factors used for the backgrounds are: $K_{WZ} = 1.6$ [24] [25], $K_Z = 1.6$ [20], $K_{ZZ} = 1.3$ [27] [28], and $K_{llZ} = 1.3$ [24].

We study a benchmark model with $m_A = 330$ GeV, $m_h = 200$ GeV, $m_{H} = 1$ TeV, $\sin \alpha = 1$, and $\tan \beta = 1$. The cross section for producing $A$ at the Tevatron is 190 fb. The CDF experiment has searched for the $WZ$ final state from $Zh$ associated production in the standard model [30]. Although this is a neural net analysis that cannot be directly compared with our model, the limit on the $WZ$ cross section is approximately 450 fb. We conclude that Tevatron searches are not sensitive to this model, and we focus on the prospects for discovery at the 7 TeV LHC.

For an LHC search, we require the events to pass one of the following lepton triggers: (i) single lepton with $p_T(e) > 30$ GeV or $p_T(\mu) > 20$ GeV; (ii) double lepton with $p_T(l_1) > 17$ GeV, $p_T(l_2) > 10$ GeV; (iii) triple lepton with $p_T(l_{1,2,3}) > 10$ GeV. All triggered leptons are required to be central, $|\eta_l| < 2.4$ and $|\eta_\mu| < 2.1$. These triggers are similar to those used in the 2011 LHC run. The selection cuts then require at least 3 central leptons with $p_T(l) > 8$ GeV and at least 2 jets with $|\eta_j| < 2.5$ and $p_T(j) > 30$ GeV. We then impose the following cuts: (i) $E_T > 20$ GeV. This effectively suppresses the $Z + \text{jets}$ background. (ii) We require that 2 same-flavor, opposite-sign leptons reconstruct to the $Z$ with $|m_{ll} - m_Z| < 7$ GeV. We estimate that loosening this cut further will allow $t\bar{t}$ backgrounds to be significant. (iii) We combine missing $p_T$ and the hardest remaining lepton (and, if that fails, the next hardest remaining lepton) to reconstruct to the $W$ mass. This will give either 2 solutions or no solutions. (iv) Two of the jets are re-
TABLE I: Signal and background cross sections (in fb) for the benchmark model at the 7 TeV LHC. The cuts are described in the text. The incorrect solutions from reconstructing the leptonic $W$ are not counted in this table.

| Process | Selection | $E_T$ | $Z(\ell \ell)$ | $W(E_T)$ | $W(jj)$ |
|---------|-----------|------|----------------|----------|---------|
| $WZ + 2, 3$ jets | 8.85 | 7.94 | 7.50 | 5.70 | 1.65 |
| $t\bar{t}Z + 0, 1$ jets | 0.932 | 0.896 | 0.675 | 0.475 | 0.293 |
| $Z + 2, 3$ jets | 2.30 | 0.848 | 0.587 | 0.586 | 0.226 |
| $ZZ + 1, 2, 3$ jets | 1.37 | 0.611 | 0.573 | 0.504 | 0.180 |
| Total Background | 13.4 | 10.3 | 9.34 | 7.26 | 2.35 |
| Signal + 0, 1 jets | 29.8 | 25.9 | 22.3 | 16.3 | 9.89 |

FIG. 2: Reconstructed $h$ mass for 1 fb$^{-1}$ of data at the 7 TeV LHC. There is a combinatoric doubling of events, since incorrect leptonic $W$ solutions are included.

required to reconstruct a $W$ with $|m_{jj} - m_W| < 25$ GeV. The effects of these cuts are shown in Table I. Even without the cuts, the signal is visible above the background for luminosity of order 1 fb$^{-1}$, but this requires an absolute comparison to simulated backgrounds. The cuts allow backgrounds to be determined by a sideband analysis, allowing for a robust discovery or exclusion. They are also required to reconstruct the $h$ and the $A$. Note that these cuts do not depend on the $h$ and $A$ masses, and should be effective for a wide range of $h$ and $A$ masses.

After these cuts, for an LHC luminosity of 1 fb$^{-1}$ at 7 TeV running we have approximately 10 signal events, corresponding to approximately 4.5$\sigma$ significance. With more data, one can reconstruct the $h$ and $A$ mass peaks. This is illustrated in Figs. 2 and 3 which are normalized to 1 fb$^{-1}$, but include additional Monte Carlo statistics to show the shape of the peak. These plots include the incorrect reconstructions of the leptonic $W$. Additional techniques may be applied to reduce the effect of these incorrect solutions, but it is already clear that the mass can be reconstructed from these distributions.

Conclusions—We have argued that models that have non-minimal Higgs sectors with heavier Higgs bosons are well-motivated, and generically lead to signals containing 3 or more heavy standard model particles: $t$, $Z$, $W$, and $b$. We have advocated a simplified 2 Higgs doublet model to parameterize these signals. We have illustrated the possible searches with the process $gg \to A(\pm) \to Zh$ followed either by $h \to bb$ or $WW/ZZ$. For the $WWZ$ final state we demonstrated that with as little as 1 fb$^{-1}$ of data at the 7 TeV LHC this can lead to discovery of both the $A$ and the $h$ Higgs bosons. We hope that this work will motivate additional searches for final states involving 3 or more heavy standard model particles.

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