The Supersymmetric Leptophilic Higgs Model

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Introduction

With the LHC now running, it will hopefully provide some final answers to the nature of electroweak symmetry breaking.

• Many possible models of electroweak symmetry breaking exist, but without a means to probe the phenomenon directly it is impossible to discern exactly how it is accomplished.

• Thus it is important that we be prepared to encounter any of a variety of possibilities as the LHC generates important results.

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- Simplicity - it is a minimal extension of the single Higgs doublet in the Standard Model
- Supersymmetry - supersymmetric models require at least two Higgs doublets

Introduction

It is usually assumed that the leptons couple to the same doublet as the down-type quarks.

Type I: Up-type quarks, down-type quarks, and leptons all couple to one doublet, while no fermions couple to the other doublet

Type II: Up-type quarks couple to one doublet while down-type quarks and leptons couple to the other doublet

Introduction

An alternative possibility that has not been as widely studied is that both the up-type and down-type quarks couple to one doublet, while the leptons couple to the other doublet.

$\rightarrow$ We will refer to this setup as the *Leptophilic Higgs Model*

A Brief Overview of the L2HDM

The Model

In the Leptophilic Two Higgs Doublet Model (L2HDM) we have two complex scalar doublets Φ_q and Φ_ℓ, as well as a discrete $\mathbb{Z}_2$ symmetry under which $\Phi_\ell \to -\Phi_\ell$ and $e_{R_i} \to -e_{R_i}$. All other fields are invariant under the symmetry.

The symmetry is responsible for the leptophilic structure of the model since it prevents the quark doublet from coupling to leptons and the leptonic doublet from coupling to quarks.

A Brief Overview of the L2HDM

The Yukawa Lagrangian is given by

$$\mathcal{L} = -\Big[Y^u_{ij}\, \overline{u}_{R_i} \widetilde{\Phi}^\dagger_q \cdot Q_{L_j} + Y^d_{ij}\, \overline{d}_{R_i} \Phi^\dagger_q \cdot Q_{L_j} + Y^\ell_{ij}\, \overline{e}_{R_i} \Phi^\dagger_\ell \cdot E_{L_j} + \text{h.c.} \Big]$$

where

$$Q_{L_i} = \begin{pmatrix} u_{L_i} \\ d_{L_i} \end{pmatrix},\; E_{L_i} = \begin{pmatrix} \nu_{L_i} \\ e_{L_i} \end{pmatrix},\; \text{and} \ldots$$

$$\Phi_X = \begin{pmatrix} \phi^+_X \\ \frac{1}{\sqrt{2}}\left(v_X + \phi^0_{Xr} + i\phi^0_{Xi}\right) \end{pmatrix}$$

In the above equations $X = q$ or ℓ, and $\widetilde{\Phi}_q = i\sigma_2 \Phi_q$.

A Brief Overview of the L2HDM

The two complex doublets have eight degrees of freedom resulting in a physical spectrum of two neutral scalars, a pseudoscalar, and a charged pair.

The remaining three degrees of freedom are the goldstone bosons, eaten by the $W^{\pm}$ and Z.

- A characteristic aspect of the model is that it gives the charged scalars an enhanced coupling to neutrinos and charged leptons when the ratio of vevs, $\tan\beta = v_q/v_\ell$, is large
- This ratio can be much larger than in conventional 2HDM before running into problems with perturbativity and unitarity

A Supersymmetric Version?

We want to extend the L2HDM to incorporate supersymmetry!

The minimal leptophilic model compatible with supersymmetry requires four Higgs doublets.

• Two doublets are required to give mass to the up-type and down-type quarks (due to the analyticity of the superpotential)

• An additional doublet is required in order for the model to be leptophilic

• Yet another doublet is consequentially required to ensure anomaly cancelation

The SLHM

To construct the Supersymmetric Leptophilic Higgs Model (SLHM) we add two doublets H_0 and H_ℓ to the MSSM. The four scalar doublets, along with their weak hypercharges, are shown in the table below

Φ	H_u	H_d	H_0	H_ℓ
$U_Y(1)$	$+1/2$	$-1/2$	$+1/2$	$-1/2$

Next we impose a discrete $\mathbb{Z}_2$ symmetry, under which the superfields E, H_0, and H_ℓ transform as $X \to -X$ while all other fields remain unchanged.

The SLHM

The most general superpotential respecting R-parity, gauge symmetry, and the $\mathbb{Z}_2$ symmetry that we can write down is:

$$W = y_u UQH_u - y_d DQH_d - y_\ell ELH_\ell + \widetilde{\mu}_1 H_u H_d + \widetilde{\mu}_2 H_0 H_\ell$$

In accordance with supersymmetry, the Higgs sector potential is given by the sum of the F-terms, D-terms, and V_{Soft} respectively:

$$V = \sum_{i=1}^{k} \left| \frac{\partial W}{\partial H_i} \right|^2 + \frac{1}{2} \sum_a \left| \sum_{i=1}^{k} g^a H_i^\dagger T^a H_i \right|^2 + V_{\text{Soft}}$$

The SLHM

After expanding the expression from the previous slide, we obtain:

$$\begin{aligned} V = \; & m_u^2|H_u|^2 + m_d^2|H_d|^2 + m_0^2|H_0|^2 + m_\ell^2|H_\ell|^2 \\ & + \left(\mu_1^2 H_u H_d + \mu_2^2 H_0 H_\ell + \mu_3^2 H_u H_\ell + \mu_4^2 H_0 H_d + \text{h.c.}\right) \\ & + \frac{g^2}{8} \sum_a \left| H_u^\dagger \sigma^a H_u + H_d^\dagger \sigma^a H_d + H_0^\dagger \sigma^a H_0 + H_\ell^\dagger \sigma^a H_\ell \right|^2 \\ & + \frac{g'^2}{8} \left| |H_u|^2 - |H_d|^2 + |H_0|^2 - |H_\ell|^2 \right|^2, \end{aligned}$$

The additional parameters originate from the soft SUSY breaking potential V_{soft}.

The SLHM

As with the ordinary L2HDM, each of the Higgs doublets contains four real degrees of freedom. The physical spectrum of scalar particles therefore includes:

- Four neutral scalars
- Three pseudoscalars
- Three charged pairs

The remaining three degrees of freedom are again the goldstone bosons, which are responsible for giving mass to the $W^{\pm}$ and Z bosons.

The SLHM

The mass matrices are parameterized in terms of the mixing angles α, β, β_ℓ, which are defined in terms of the Higgs vevs v_u, v_d, v_0, and v_ℓ so that:

$$v_u = v \sin\alpha \sin\beta, \qquad v_d = v \sin\alpha \cos\beta,$$

$$v_0 = v \cos\alpha \sin\beta_\ell, \qquad v_\ell = v \cos\alpha \cos\beta_\ell$$

- Here we have $v^2 = v_u^2 + v_d^2 + v_0^2 + v_\ell^2 = (246 \text{ GeV})^2$

The SLHM

The mass matrices in the $\{u, d, 0, \ell\}$ basis:

$$M_N^2 = \begin{pmatrix} M_1^2 & -\frac{1}{2}M_Z^2 s_\alpha^2 s_{2\beta} - \mu_1^2 & \frac{1}{2}M_Z^2 s_{2\alpha} s_\beta s_{\beta_\ell} & -\frac{1}{2}M_Z^2 s_{2\alpha} s_\beta c_{\beta_\ell} - \mu_3^2 \\ -\frac{1}{2}M_Z^2 s_\alpha^2 s_{2\beta} - \mu_1^2 & M_2^2 & -\frac{1}{2}M_Z^2 s_{2\alpha} c_\beta s_{\beta_\ell} - \mu_4^2 & \frac{1}{2}M_Z^2 s_{2\alpha} c_\beta c_{\beta_\ell} \\ \frac{1}{2}M_Z^2 s_{2\alpha} s_\beta s_{\beta_\ell} & -\frac{1}{2}M_Z^2 s_{2\alpha} c_\beta s_{\beta_\ell} - \mu_4^2 & M_3^2 & -\frac{1}{2}M_Z^2 c_\alpha^2 s_{2\beta_\ell} - \mu_2^2 \\ -\frac{1}{2}M_Z^2 s_{2\alpha} s_\beta c_{\beta_\ell} - \mu_3^2 & \frac{1}{2}M_Z^2 s_{2\alpha} c_\beta c_{\beta_\ell} & -\frac{1}{2}M_Z^2 c_\alpha^2 s_{2\beta_\ell} - \mu_2^2 & M_4^2 \end{pmatrix},$$

$$M_A^2 = \begin{pmatrix} \lambda_1 & \mu_1^2 & 0 & \mu_3^2 \\ \mu_1^2 & \lambda_2 & \mu_4^2 & 0 \\ 0 & \mu_4^2 & \lambda_3 & \mu_2^2 \\ \mu_3^2 & 0 & \mu_2^2 & \lambda_4 \end{pmatrix}, \qquad M_{H^\pm}^2 = M_A^2 + \Delta M^2,$$

$$\Delta M^2 = M_W^2 \begin{pmatrix} s_\alpha^2 c_\beta^2 + c_\alpha^2 c_{2\beta_\ell} & \frac{1}{2}s_\alpha^2 s_{2\beta} & \frac{1}{2}s_{2\alpha} s_\beta s_{\beta_\ell} & \frac{1}{2}s_{2\alpha} s_\beta c_{\beta_\ell} \\ \frac{1}{2}s_\alpha^2 s_{2\beta} & s_\alpha^2 s_\beta^2 - c_\alpha^2 c_{2\beta_\ell} & \frac{1}{2}s_{2\alpha} c_\beta s_{\beta_\ell} & \frac{1}{2}s_{2\alpha} c_\beta c_{\beta_\ell} \\ \frac{1}{2}s_{2\alpha} s_\beta s_{\beta_\ell} & \frac{1}{2}s_{2\alpha} c_\beta s_{\beta_\ell} & c_\alpha^2 c_{\beta_\ell}^2 + s_\alpha^2 c_{2\beta} & \frac{1}{2}c_\alpha^2 s_{2\beta_\ell} \\ \frac{1}{2}s_{2\alpha} s_\beta c_{\beta_\ell} & \frac{1}{2}s_{2\alpha} c_\beta c_{\beta_\ell} & \frac{1}{2}c_\alpha^2 s_{2\beta_\ell} & c_\alpha^2 s_{\beta_\ell}^2 - s_\alpha^2 c_{2\beta} \end{pmatrix}.$$

Constraining the SLHM

In this model we have many unknown parameters:

$\rightarrow \tan\alpha, \tan\beta, \tan\beta_\ell, m_u, m_d, m_0, m_\ell, \mu_1, \mu_2, \mu_3, \mu_4$

We set out to determine which regions of parameter space are not excluded by theoretical and experimental considerations.

Constraining the SLHM

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1. Yukawa Coupling Perturbativity
2. Tree Level Unitarity
3. The Anomalous Muon Magnetic Moment
4. Direct Searches at LEP

Perturbativity Constraints

For this constraint we simply demand that the Yukawa couplings remain smaller than 4π. The Yukawa couplings can be expressed in terms of the Higgs vevs, which we have parameterized in terms of the mixing angles $\alpha, \beta, \beta_\ell$.

$$\left(1+\frac{1}{\tan^2\alpha}\right)\left(1+\frac{1}{\tan^2\beta}\right) < \frac{8\pi^2 v^2}{m_t^2} \approx 13^2,$$
$$\left(1+\frac{1}{\tan^2\alpha}\right)\left(1+\tan^2\beta\right) < \frac{8\pi^2 v^2}{m_b^2} \approx 520^2,$$
$$\left(1+\tan^2\alpha\right)\left(1+\tan^2\beta_\ell\right) < \frac{8\pi^2 v^2}{m_\tau^2} \approx 1235^2.$$

Unitarity Constraints

Requiring perturbative unitarity of fermion anti-fermion scattering places upper bounds on the fermion masses. The condition that must be satisfied is:

$$|\Re(a_J)| \leq 1/2$$

We consider scattering via the exchange of a Higgs boson. Our bounds come from imposing this condition on the $J = 0$ partial wave amplitude. It is calculated from a sum over s- and t-channel helicity amplitudes in the high energy limit.

Unitarity Constraints

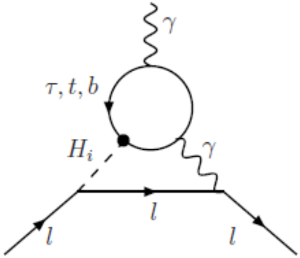
For the SLHM we obtain the following constraints:

$$\frac{G_F m_t^2}{4\pi\sqrt{2}} < \sin^2\alpha \sin^2\beta,$$
$$\frac{G_F m_b^2}{4\pi\sqrt{2}} < \sin^2\alpha \cos^2\beta,$$
$$\frac{G_F m_\tau^2}{4\pi\sqrt{2}} < \cos^2\alpha \cos^2\beta_\ell.$$

These conditions prevent very large values of $\tan\beta$, capping it at around 300. They also prevent combinations of $\tan\alpha$ and $\tan\beta$ values on the order to several tenths.

Muon Magnetic Moment

We consider ordinary one loop contributions as well as two loop Barr-Zee contributions to the muon's magnetic moment.



In both cases however, no constraint can be obtained since the neutral scalar mass is so much greater than the muon mass.

LEP Constraints

The largest constraints come from direct searches at LEP, where $X = b, \tau$ the production mechanism is the Higgs-strahlung process $e^+e^- \to hZ$.

- The coupling between the lightest neutral scalar, h, and Z-pairs must be sufficiently small to explain why LEP has not seen the scalar.

LEP has provided bounds on $BR(h \to X\overline{X})\xi^2$, where ξ is the ratio of the ZZh coupling in some prospective model to that of the Standard Model.

LEP Constraints

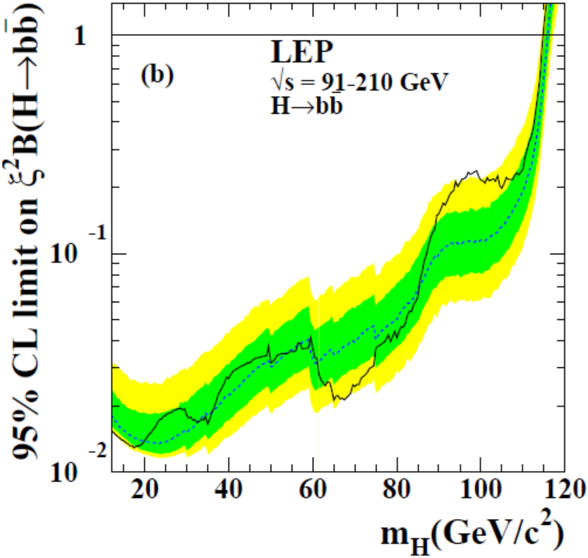
For the SLHM we find:

$$\xi^2 = \left| U_{11} \sin\alpha \sin\beta + U_{21} \sin\alpha \cos\beta + U_{31} \cos\alpha \sin\beta_\ell + U_{41} \cos\alpha \cos\beta_\ell \right|^2$$

Hence by calculating the mass of the h as well as the quantity $BR(h \to X\overline{X})\xi^2$ for $X = b$ and τ, we can compare the results for the SLHM to LEP bounds.

- This enables us to perform a scan of parameter space to determine the favored regions of the SLHM.

LEP Constraints



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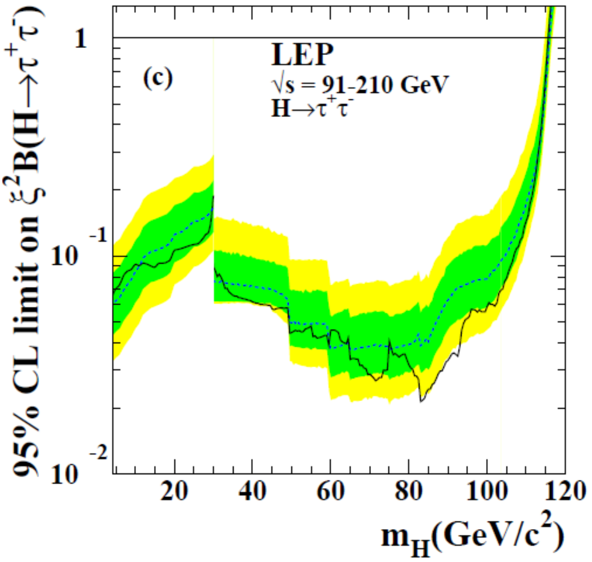
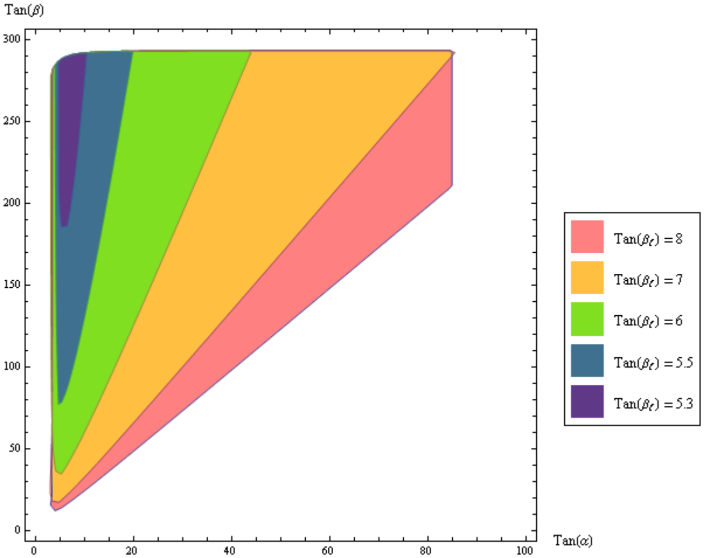


Parameter Space



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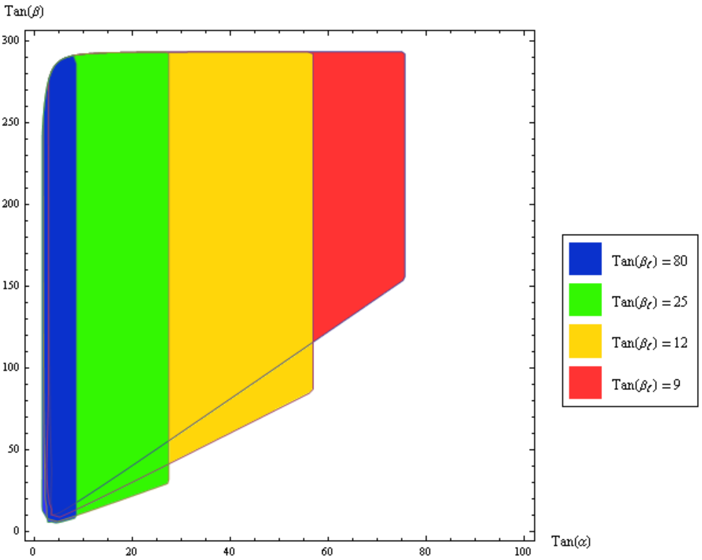

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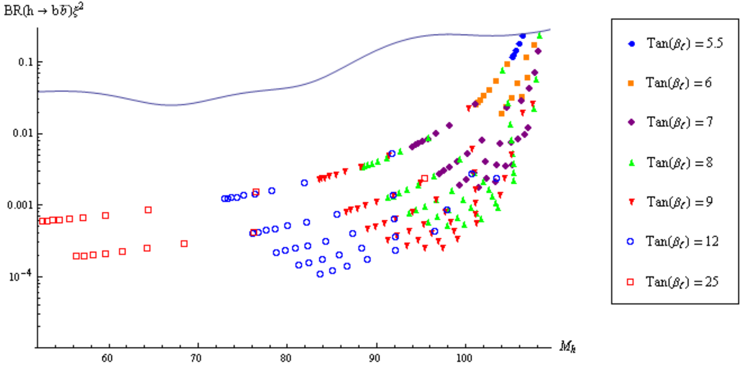

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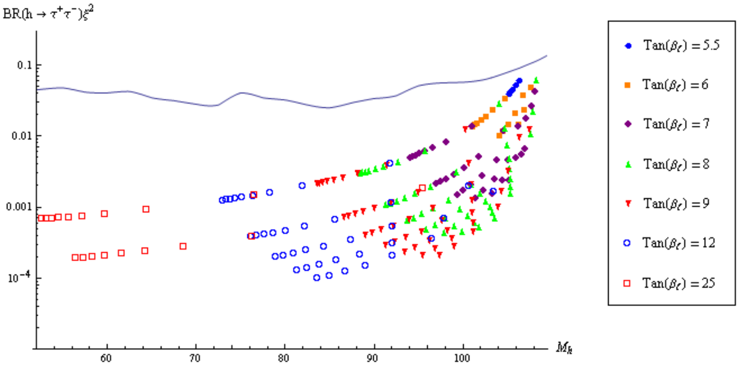

Phenomenology

Since the ZZh and WWh couplings are small in the regions of parameter space being considered, the total decay width for the h is approximated by:

$$\Gamma = \Gamma(h \to b\bar{b}) + \Gamma(h \to \tau^+\tau^-)$$

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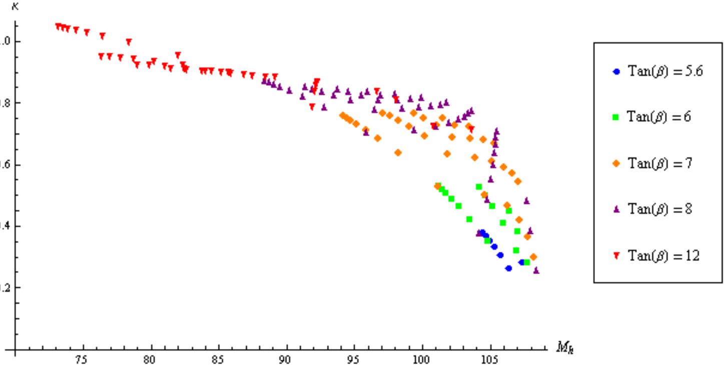
- The quantity of importance to the h decay is the ratio $\kappa = \Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$

Phenomenology



Phenomenology

When the h mass approaches 115 GeV, the corresponding value of κ approaches its Standard Model value of 0.1.

For lighter h masses, the value of κ increases. Thus the SLHM can have a relatively light Higgs that has a much larger branching ratio to τ-pairs than the Standard Model.

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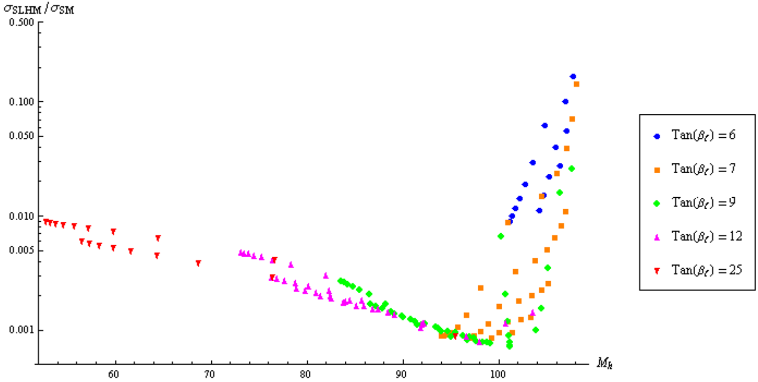
- Since the h does not couple strongly to gauge bosons, Higgs production via Higgs-strahlung is not feasible. We therefore consider gluon fusion as a production mechanism...

Phenomenology

Here we have a logplot of the ratio of the production cross section of the lightest neutral scalar by gluon fusion in the SLHM to the Standard Model.



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From the previous plot one can see that the gluon fusion production cross section of h is small, especially so around 90 - 105 GeV.

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▶ The second lightest neutral scalar, η, is only slightly heavier than the h, at around 110 Gev for much of allowed parameter space.

Its coupling to gauge bosons is near that of the Standard Model so it can be produced via Higgs-strahlung. It also has a gluon fusion production similar to that of the Standard Model Higgs.

Summary

• The lightest scalar is difficult to produce, typically has a mass between 75 - 110 GeV, and has enhanced branching fractions to leptons.

• The second lightest neutral scalar has a mass around 110 GeV and is similar to the Standard Model Higgs.

• The heavier neutral scalars couple very weakly to gauge bosons and would decay almost entirely into b-pairs and τ-pairs.

END!