SM-like h125: Additional Scalars & their Expected Experimental Signatures

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In Collaboration with:
M. Carena, H. Haber, I. Low & C. Wagner arXiv:1510.09137
S. Baum, K. Freese & B. Shakya arXiv:1703.07800

Baryon Lepton Violation 2017, Case Western Reserve University, May 15-18
The Higgs Lamp Post:
$m_h \sim 125$ GeV + SM-like

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No New States at the LHC!!!
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Alignment

\[ <h_{125}> \sim v_{SM} \]

SUSY $\rightarrow$ NMSSM
\[ W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \]

\[ -\mathcal{L}_{\text{soft}} = \lambda A_S S H_u H_d + \frac{1}{3} \kappa A_h S^3 \]

- 2 Doublets \((H_u, H_d)\) + Singlet \(S\)
- Singlet couples only to the Higgs Sector.
- vevs: \((H_u, H_d, S) = (v_u, v_d, v_S = \mu / \lambda)\)

- 3 CP-Even Higgses:
  - Mixing between all three \((H_u, H_d, S)\).
- 2 CP-Odd Higgses:
  - Mixtures of “MSSM” \(m_A\) and singlet.
- Charged Higgs
- Singlet-like CP-even and odd masses anti-correlated.
- Singlino mass: \(2 \kappa \mu / \lambda\)
\[
H_{SM} = \sin \beta H_u + \cos \beta H_d \\
H_{NSM} = -\cos \beta H_u + \sin \beta H_d
\]
\[
\langle H_{SM} \rangle = \nu \\
\langle H_{NSM} \rangle = 0
\]

- \( H_{SM} \) has completely SM-like couplings.
- Mixing between \( H_{SM} \) and \( H_{NSM} \), 
  
  “\( \cos (\beta - \alpha) \)”, gives non-SM behavior of observed \( h_{125} \).

If 
\[
\cos (\beta - \alpha) = 0
\]
SM-like HIGGS!!

ALIGNMENT
• Interaction basis: $(H_u, H_d, S)$
  - $H_u$: Couples only to up-type fermions
  - $H_d$: Couples only to down-type fermions
  - $S$: Only couples to Higgses

$$<H_u> = v_u$$
$$<H_d> = v_d$$
$$t_\beta = v_u/v_d$$
$$<S> = \mu/\lambda$$
• Interaction basis: \((H_u, H_d, S)\)
  - \(H_u\): Couples only to up-type fermions
  - \(H_d\): Couples only to down-type fermions
  - \(S\): Only couples to Higgses

• “Extended” Higgs basis: \((H_{NSM}, H_{SM}, S)\)
  - \(H_{NSM}\): \((\text{down, up, } V) = (y_d \ t_\beta, y_u / t_\beta, 0)\)
  - \(H_{SM}\): \((\text{down, up, } V) = (y_d, y_u, g_{hVV})\)

\[
\begin{align*}
<H_u> &= v_u \\
<H_d> &= v_d \\
t_\beta &= v_u / v_d \\
<S> &= \mu / \lambda
\end{align*}
\]

\[
\begin{align*}
<H_{NSM}>& = 0 \\
<H_{SM}>& = v
\end{align*}
\]
• Interaction basis: \((H_u, H_d, S)\)
  - \(H_u\): Couples only to up-type fermions
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  - \(H_{NSM}\): \((\text{down, up, } V) = (y_d t^\beta, y_u/t^\beta, 0)\)
  - \(H_{SM}\): \((\text{down, up, } V) = (y_d, y_u, g_{hVV})\)

• Mass basis: \((H^3, H^2, H^1)\)
  - \(H^i = \kappa_{NSM}^i H_{NSM} + \kappa_{SM}^i H_{SM} + \kappa_S^i S\)

\[<H_u> = v_u\]
\[<H_d> = v_d\]
\[t^\beta = v_u/v_d\]
\[<S> = \mu/\lambda\]

\[<H_{NSM}> = 0\]
\[<H_{SM}> = v\]
• Interaction basis: \((H_u, H_d, S)\)
  - \(H_u\): Couples only to up-type fermions
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  - \(S\): Only couples to Higgses

• “Extended” Higgs basis: \((H_{NSM}, H_{SM}, S)\)
  - \(H_{NSM}\): (down, up, \(V\)) = \((y_d t_\beta, y_u / t_\beta, 0)\)
  - \(H_{SM}\): (down, up, \(V\)) = \((y_d, y_u, g_{hVV})\)

• Mass basis: \((H^3, H^2, H^1) \rightarrow (H, h_{125}, hS)\)
  - \(H^i = \kappa_{NSM}^{i} H_{NSM} + \kappa_{SM}^{i} H_{SM} + \kappa_{S}^{i} S\)

\[
\begin{align*}
<H_u> &= v_u \\
<H_d> &= v_d \\
t_\beta &= v_u / v_d \\
<S> &= \mu / \lambda \\
<H_{NSM}> &= 0 \\
<H_{SM}> &= v \\

\text{Alignment:} \\
\kappa_{NSM}^{h_{125}} &= 0 \\
\kappa_{S}^{h_{125}} &= 0
\end{align*}
\]
125 GeV Higgs Naturally!

Alignment (No-Mixing):

\[ m_h^2 \simeq \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta\tilde{t} \]

\[ \Delta\tilde{t} = -\cos 2\beta (m_h^2 - M_Z^2) \]

Well Known

- 125 GeV Higgs
- Tree-level contribution to Higgs mass from \( \lambda \).
- \( \lambda \approx 0.65-0.7 \)
- Low \( \tan \beta \)
- Light Stops
• Perturbative up to GUT scale.
  • $\lambda_{\text{max}} \sim 0.7$, $\kappa_{\text{max}} \sim \lambda/2$

**Not so well known:**

• Leads to excellent Alignment (very little mixing with Heavy Higgs) in the $m_A$- tan $\beta$ plane.

\[
\lambda_{\text{alt}}^2 = \frac{m_h^2 - M_Z^2 c_2^2}{v^2 s_\beta^2}
\]

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, ‘15
Singlet Alignment

Singlino: \(2 \kappa \mu / \lambda \sim < \mu\)

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, ’15
• LSP could be stable on detector time-scales but unstable on universe time-scale
  • Consider collider phenomenology independent of cosmological constraints
• First question: Alignment with or without decoupling ??
  • Most interesting LHC phenomenology when all states light (no decoupling)
  • Pursue NMSSM parameter space using “alignment”
  • Pinpoint promising signatures
  • In particular will focus on mono-Higgs

Heavy Higgs Pheno
NMSSMTools Scans asking for SM-like h125

Decoupling
\(m_A < 3\) TeV

\[\chi^2_{\text{alt}} = \frac{m_h^2 - M_Z^2 c_2\beta}{\nu^2 s_\beta^2} \]

\[1 - \frac{m_A^2}{4\mu^2} s_\beta^2 - \frac{\kappa}{2\lambda} s_\beta^2 = 0\]

Misalignment?
• $m_{A_2} \sim m_{H_3}$
• Completely “MSSM”-like $A_2$ has $xsec \sim 2$ “MSSM”-like $H_3$
• Mixing with singlets will reduce these $xsec$
• $A_2$ can mix significantly with $A_1$ consistent with alignment conditions
  • Still comparable $xsec$ to $H_3$
  • Significant BR into non-standards: $\chi_i \chi_1$, $A_1 h_{125}$, $h_S Z$
• $H_3$ mixes less with singlet, but enough to also have significant non-standard decays:
  • $\chi_i \chi_1$, $h_S h_{125}$, $A_1 Z$
• Apart from $tt$, significant decays into $H_2 + H_1$ and neutralino/charginos

Generically:
Coupling to $h_{125}$ pair & ZZ, WW suppressed due to alignment.

$\tan \beta = 2$  $\tan \beta = 2.5$  $\tan \beta = 3$

$H_3$ BR ($A_2$ BR similar)

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If $A_1$ or $h_S > 2\chi$, $\text{BR}(\chi\chi)$ large
Otherwise MSSM-like BR

$A_2$ Non-Standard BR
• A/H\rightarrow Z h_s/a \rightarrow Z \text{ Visible}
  

• A/H \rightarrow h_{125} a/h_s \rightarrow h_{125} \text{ Visible}

(pseudoscalars cannot decay to WW)

Signatures?
Visible (bb/tt/WW)
Mono-Z

- $A/H \rightarrow \chi_3 \chi_1 \rightarrow Z \chi_1 \chi_1$

(CMS -- arXiv:1701.02042)

- $A/H \rightarrow Z h_S/a \rightarrow Z \chi_1 \chi_1$

$gg \rightarrow H_3 \rightarrow Z A_1 \rightarrow Z \chi_1 \chi_1$

$\Phi_a = A_1$

$\Phi_b = H_3$

$gg \rightarrow A_2 \rightarrow Z h_1 \rightarrow Z \chi_1 \chi_1$

$\Phi_a = A_2$

$\Phi_b = h_1$

$\Phi_{h_1/z} \rightarrow Z \chi_1 \chi_1$

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Mono-H

- $A/H \rightarrow \chi_3 \chi_1 \rightarrow h_{125} \chi_1 \chi_1$

$gg \rightarrow H_3/A_2 \rightarrow \chi_3 \chi_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$gg \rightarrow H_3 \rightarrow h_{\text{SM}} h_i \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$\Phi_a = h_i$

$\Phi_b = H_3$

$\Phi_a = A_2$

$\Phi_b = A_1$

$gg \rightarrow A_2 \rightarrow h_{\text{SM}} A_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$\Phi_a^2 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$\Phi_a^2 \rightarrow h_{\text{SM}} \Phi_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$\Phi_a^2 \rightarrow h_{\text{SM}} \Phi_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

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$\Phi_a^2 \rightarrow h_{\text{SM}} \Phi_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$

$\Phi_a^2 \rightarrow h_{\text{SM}} \Phi_1 \rightarrow h_{\text{SM}} \chi_1 \chi_1$
A. Can add up contributions from both $H_3$ and $A_2$

B. Expect stronger sensitivity — $h_{125}$ back-to-back with MET

Mono-Higgs (to $\gamma \gamma$)
Depending on mass spectrum, can have sensitivity $\sim$ sub-fb at 300 fb$^{-1}$

As expected much better reach for channel (B)

Model-Independent Reach?
As expected much better coverage from channel (B) – even when $tt$ open

S. Baum, K. Freese, NRS & B. Shakya, ‘17
Conclusions and Outlook

• $m_h = 125$ GeV + SM-like
  • Alignment: Decoupling or Prediction for parameters.

• NMSSM Higgs sector at low $\tan \beta$.
  • Perturbativity and the requirement of alignment with the singlet
    • light singlets (both CP-even and odd) and singlino + higgsinos (charged and neutral).
  • Large BR of non-SM Higgs into singlet like states + neutralinos
    • Mono-Higgs reach studied in detail
    • Complimentary channels:
      • mono-Z + Z-visibles ($tt, bb, WW$)
      • H-visibles ($tt, bb, WW$)
    • Generic 2HDM+Singlet may not have light neutralinos, but due to SM-like $h_{125}$, BRs of non-SM Higgs into $h_{125}$ pairs and WW/ZZ suppressed
\[ pp \rightarrow h(\gamma\gamma) + \chi \; \bar{\chi}, \ Z'_B \] model
\[ \sin^2 \theta = 0.3, \ g_q = 1/3, \ g_\chi = 1, \ m_\chi = 1 \text{ GeV} \]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tan\beta$</td>
<td>$1 - 5$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$0.5 - 1$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$-0.5 - 0.5$</td>
</tr>
<tr>
<td>$A_\lambda$</td>
<td>$-0.5 - 0.5$ TeV</td>
</tr>
<tr>
<td>$A_\kappa$</td>
<td>$-0.5 - 0.5$ TeV</td>
</tr>
<tr>
<td>$\mu_{\text{eff}}$</td>
<td>$-0.5 - 0.5$ TeV</td>
</tr>
<tr>
<td>$M_{Q_3}$</td>
<td>$1 - 10$ TeV</td>
</tr>
</tbody>
</table>

**TABLE I:** NMSSM parameter ranges used in NMSSMTools scans.
• How much “non-standardness” is allowed by h125 measurements??

• $\kappa_{NSM} H_{NSM} + \kappa_{SM} H_{SM} + \kappa_S S$

• Singlet: Only couples to Higgses

• Ratios to SM:
  • $g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/t\beta)$
  • $g_{hdd} = (\kappa_{SM} - \kappa_{NSM} t\beta)$
  • $g_{hVV} = \kappa_{SM}$

• Significant $\kappa_S$ OK
• Large $\kappa_{NSM}$ from sign change of $g_{hdd}$

Contamination allowed in h125 ??
• CMS 1505.03831

• Strong constraints on SM-like Higgs decay to $VV \sim 12-6\%$ SM value for masses 160-500 GeV.

Heavy H to VV ?
• Strong constraints on SM-like Higgs decay to V V ~12-6% SM value for masses 160-500 GeV.

• Only $\kappa^i_{SM}$ couples to V V

• What does this imply for SM and NSM components of extra Higgs??
  • $160 \text{ GeV} < m_{hS} < 350 \text{ GeV}$
  • $\text{BR}(WW+ZZ) \sim 1$
  • gF production XS impacted.

• With $\kappa^{h_{125}}_{NSM} \sim 0$
  • $\kappa^{hS}_{SM} \sim \kappa^{h_{125}}_{S}$
  • $\kappa^{h_{125}}_{S}$ smaller than allowed by $h_{125}$ measurements!

Direct Searches for heavy resonances?
• NMSSMTools + HiggsBounds/Signals
• Allowed “misalignment”

\[ \tan \beta = 2 \]

\[ \tan \beta = 2.5 \]

\[ \tan \beta = 3 \]

**Misalignment**

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, ’15
Singlet Spectra

Density of scan not relevant

\[ \kappa^{\text{max}}, \lambda = 0.65 \]

singlet always less than \( m_H/2 \)

\[ \tan \beta = 2 \quad \tan \beta = 2.5 \quad \tan \beta = 3 \]

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15
MSSM-like $A$ and $H$ decays into $tt$.

- Decay BR depends on $\tan \beta$

$\tan \beta = 2$, $\tan \beta = 2.5$, $\tan \beta = 3$.

MSSM-like $m_H$

MSSM-like $m_A$

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Apart from $tt$, significant decays into $H_2+H_1$ and neutralino/charginos.

Coupling to $h_{125}$ pair suppressed due to alignment.

$\tan \beta = 2$, $\tan \beta = 2.5$, $\tan \beta = 3$

MSSM-like H BR

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15

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• Into singlet-like H1/H2-Z and inos

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\[ S_{H,s} \approx -\frac{\lambda v}{2\mu} c_{2\beta} s_{2\beta} \]

\[
\begin{align*}
\text{BR} (A \rightarrow h_s Z) \\
\text{BR} (A \rightarrow \chi^0 \chi'^0) \\
\end{align*}
\]

. \( \tan \beta = 2 \)
. \( \tan \beta = 2.5 \)
. \( \tan \beta = 3 \)
• Singlet mainly decays to $bb$ and $WW$
XS factor ~ 4 at 14 TeV compared to 8 TeV

CMS PAS HIG-15-001

CMS 1505.03831

HVV/SM ~10%
XS factor ~ 4 at 14 TeV compared to 8 TeV

CMS PAS HIG-15-001

$gg \rightarrow A \rightarrow Z h_S \rightarrow ll bb$, $\sigma / \sigma_{\text{Obs. Lim}}$

- Currently Excluded
- $0.5 - 1$
- $0.1 - 0.5$
- $10^{-2} - 10^{-1}$
- $< 10^{-2}$

8 TeV

CMS 1505.03831
HVV/SM ~10%
h125 Components
- Tree-level mass matrix in the \((H_{NSM}, H_{SM}, S)\) basis:

\[
\begin{pmatrix}
    m_A^2 + s_{2\beta} \left( m_Z^2 - \frac{1}{2} \lambda^2 v^2 \right)
    & s_{2\beta} c_{2\beta} \left( m_Z^2 - \frac{1}{2} \lambda^2 v^2 \right)
    & -\frac{\lambda v \mu}{\sqrt{2}} c_{2\beta} \left( \frac{m_A^2}{2\mu^2} s_{2\beta} + \frac{\kappa}{\lambda} \right) \\
    c_{2\beta} m_Z^2 + \frac{1}{2} \lambda^2 v^2 s_{2\beta}
    & \frac{\lambda^2 v^2 s_{2\beta}}{4} \left( \frac{m_A^2 s_{2\beta}}{2\mu^2} - \frac{\kappa}{2\lambda} s_{2\beta} \right)
    & \sqrt{2} \lambda v \mu \left( 1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} \right)
\end{pmatrix}
\]

- **Alignment:** Mixing between \(H_{NSM}-H_{SM}=0\) & \(H_{SM}-S=0\)

- Alignment conditions, (+ stop corrections to always obtain \(h_{125}\)):

\[
\mathcal{M}_S^2(1, 2) = \frac{1}{t_\beta} \left[ c_{2\beta} m_Z^2 - \mathcal{M}_S^2(2, 2) + \lambda^2 v^2 s_{2\beta}^2 + \frac{3m_t^4 X_t \left( X_t - Y_t \right)}{4\pi^2 v^2 M_S^2} \left( 1 - \frac{X_t^2}{6 M_S^2} \right) \right] = 0
\]

\[
\mathcal{M}_S^2(2, 3) = 2\lambda v \mu \left( 1 - \frac{m_A^2 s_{2\beta}^2}{4\mu^2} - \frac{\kappa s_{2\beta}}{2\lambda} \right) = 0
\]

NSM-SM mixing cancels for

\[
\lambda_{alt}^2 = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_{2\beta}^2}
\]

"Extended" Higgs Basis
\[ W \supset \lambda S H_u H_d + \frac{M}{2} S^2 + \mu H_u H_d \quad V_{\text{soft}} \supset m_S^2 |S|^2 \]

\[ V \supset |F_S|^2 = |\lambda H_u H_d + MS|^2 \]

\[ \delta m_h^2 = \lambda^2 v^2 \sin^2 2\beta \left( 1 - \frac{M^2}{M^2 + m_S^2} \right) \]
• It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

\[ W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \]

\[ m_h^2 \simeq \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta \]

• It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis,

\[ M_Z^2 (1, 2) \simeq \frac{1}{\tan \beta} \left( m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta + \delta \right) \]

• The last term is the one appearing in the MSSM, that are small for moderate mixing and small values of \( \tan \beta \)

• So, alignment leads to a determination of lambda,

• The values of lambda end up in a very narrow range, between 0.65 and 0.7 for all values of tanbeta, that are the values that lead to naturalness with perturbativity up to the GUT scale

\[ \lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta} \]
It is clear from these plots that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided \( \lambda \) is of about 0.65.
• In the (“MSSM \( m_A \)”, Singlet) basis:

\[
M_P^2 = \begin{pmatrix}
   m_A^2 & \frac{\lambda v}{\sqrt{2}} \left( \frac{m_A^2}{2\mu} s_{2\beta} - \frac{3\kappa \mu}{\lambda} \right) \\
   \frac{1}{2} \lambda^2 v^2 s_{2\beta} \left( \frac{m_A^2}{4\mu^2} s_{2\beta} + \frac{3\kappa}{2\lambda} \right) - \frac{3\kappa A \kappa \mu}{\lambda} 
\end{pmatrix}
\]

\[
m_A^2 = \frac{\mu}{s_\beta c_\beta} \left( A_\lambda + \frac{\kappa \mu}{\lambda} \right).
\]

CP-Odd Mass Matrix
\[ \tan \beta = 2, \tan \beta = 2.5, \tan \beta = 3 \]

\[ \kappa_L, \lambda = 0.65 \]

\[ 0.25 \kappa_L, \lambda = 0.65 \]

\[ \left(1 - \frac{m_A^2 s_{2\beta}^2}{4 \mu^2} - \frac{\kappa s_{2\beta}}{2 \lambda}\right) = 0 \]
• Larger $\tan \beta \Rightarrow$ Heavier Stops $\Rightarrow$ Larger Fine Tuning

$k_L, \lambda = 0.65$

Fine-Tuning (No-mixing in stops)
• CP-even vs. Odd

Higgs Spectra

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• $H_1 H_1 / H_2 H_2$

H3 BR
- $tt + aZ$
- A1 H1 / A1 H2
- $t\bar{t} +$ chargino/neutralinos
\[16\pi^2 \frac{d\lambda^2}{dt} = \lambda^2 \left( 3h_t^2 + 3h_b^2 + h_{\tau}^2 + 4\lambda^2 + 2\kappa^2 - g_1^2 - 3g_2^2 \right) + \frac{\lambda^2}{16\pi^2} \left( -10\lambda^4 - 9h_t^4 - 9h_b^4 - 3h_{\tau}^4 - 8\kappa^4 - 9\lambda^2 h_t^2 - 9\lambda^2 h_b^2 \right) - 3\lambda^2 h_{\tau}^2 - 12\lambda^2 \kappa^2 - 6h_t^2 h_b^2 + 2g_1^2 \lambda^2 + \frac{4}{3} g_1^2 h_t^2 - \frac{2}{3} g_1^2 h_b^2 + 2g_1^2 h_{\tau}^2 + 6g_2^2 \lambda^2 + 16g_3^2 h_t^2 + 16g_3^2 h_b^2 + \frac{23}{2} g_1^4 + \frac{15}{2} g_2^4 + 3g_1^2 g_2^2 \right),
\]

\[16\pi^2 \frac{d \kappa^2}{dt} = \kappa^2 \left( 6\lambda^2 + 6\kappa^2 \right) + \frac{\kappa^2}{16\pi^2} \left( -24\kappa^4 - 12\lambda^4 - 24\kappa^2 \lambda^2 \right) - 18h_t^2 \lambda^2 - 18h_b^2 \lambda^2 - 6h_{\tau}^2 \lambda^2 + 6g_1^2 \lambda^2 + 18g_2^2 \lambda^2 \].
1. The gluon fusion production cross section of the would be heavy MSSM states (A and H) is enhanced due to the top Yukawa contributions at low tan $\beta$, and can be of the order of a few $pb$.

2. The non-standard Higgs bosons can have relevant decays into the lighter singlet like Higgs bosons as well as into the light electroweakinos.

3. The decay of non-standard Higgs bosons into tops, taus and bottoms will be suppressed due to the small values of tan $\beta$ and the presence of additional decays.