Higgs sector of NMSSM in the light of Higgs Discovery

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Content:

- Higgs Discovery and NMSSM
- 125.7 GeV Higgs in NMSSM
- LHC constraint and its impact on parameter space
- Conclusion
Higgs Discovery: LHC has found a Higgs like particle.

\[ \text{Mass: } 125.7 \text{ GeV} \]

\[ \text{CMS: } \mu = 1.00 \pm 0.13 \]

\[ \implies \text{Consistent with Standard model but some discrepancy is still allowed.} \]

But SM suffers from Naturalness problem, need some mechanism to cancel the quadratic divergences, and possibility of the found Higgs as non-standard Higgs is not ruled out.

Possible solution is Supersymmetry:
So one possibility is this can be MSSM Higgs.
But it is difficult to get 125.7 GeV value in MSSM because:

In decoupling limit, upper bound on \( m_h \):

\[ m_h^2 = m_Z^2 \cos^2 2\beta + \delta_t^2 \]

\( \delta_t^2 \) comes from top squarks/ top quark loops

At large \( \tan \beta \) it requires \( \delta_t \sim 85 \text{ GeV} \)

To achieve this value we need ...
Motivation: Higgs Discovery and NMSSM

Heavy top squarks or large mixing in stop mass matrix:

But these give large contributions to quadratic term of Higgs potential \( \delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2} \left( m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \ln \frac{\Lambda}{m_t} \)

If \( m_{H_u}^2 \) becomes too large parameters of the theory has to be tuned to get correct scale of EWSB.

This motivated us to study non-minimal models.

[L.Hall et al. 1112. 2703]

One such model is Next-to-Minimal-supersymmetric-Standard-model abbreviated as NMSSM:

It was originally introduced to solve \( \mu \) problem of MSSM.

But it has importance in the context of Higgs discovery, because it also offers 125.7 GeV Higgs mass.
Introduction to NMSSM

MSSM: two Higgs doublets

\[
H_1 = \begin{bmatrix} H_1^0 \\ H_1^- \end{bmatrix}, \quad H_2 = \begin{bmatrix} H_2^+ \\ H_2^0 \end{bmatrix}
\]

NMSSM: two Higgs doublets + one singlet

\[
H_1 = \begin{bmatrix} H_1^0 \\ H_1^- \end{bmatrix}, \quad H_2 = \begin{bmatrix} H_2^+ \\ H_2^0 \end{bmatrix}, \quad S
\]

NMSSM: \(\rightarrow\) solves \(\mu\) problem
\(\rightarrow\) easy to accommodate 125.7 GeV Higgs boson found at LHC

S \(\rightarrow\) addition of CP even scalar
\(\rightarrow\) addition of CP odd scalar
\(\rightarrow\) addition of neutralino
\( \mu \) problem: Superpotential MSSM and NMSSM:

\[ W_{\text{MSSM}} = \mu . H_1 . H_2 - h_d H_1 . Q \bar{D} - h_u Q . H_2 \bar{U} - h_e H_1 . L \bar{E} \]

Expected \( \mu \) (since dimensionful parameter) \( \sim \) either zero or planck scale.

Correct phenomenology demand, \( \mu \sim EW \) scale: that is known as \( \mu \) problem.

NMSSM:

\[ W_{\text{NMSSM}} = \lambda H_1 . H_2 \ S + \frac{1}{2} \kappa S^3 - h_d H_1 . Q \bar{D} - h_u Q . H_2 \bar{U} - h_e H_1 . L \bar{E} \]

No dimensionful parameter and when \( S \) gets v.e.v,

\[ \mu_{\text{eff}} = \lambda v_s \]
NMSSM scalar potential and Parameters dependence:

\[ V = V_F + V_D + V_{\text{soft}}, \]

\[ V_F = |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + \kappa S^2|^2 \]

\[ V_D = \frac{1}{8}g^2(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2}g^2|H_u^\dagger H_d|^2 \]

\[ V_{\text{soft}} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + [\lambda A_\lambda SH_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c] \]

3 scalars: \(h_1, h_2, h_3\), 2 pseudo scalars \(a_1, a_2\), 2 charged \(H^\pm\)

Couplings: \(\lambda, \kappa\)

Soft parameters: \(A_\lambda, A_\kappa\)

Related to v.e.v: \(\tan \beta, \mu_{\text{eff}}\)

Radiative Corrections: \(m_Q^2, m_u^2, m_d^2, A_u, A_d\)
Upper bound on Higgs mass:

**MSSM:**

\[ m_h^2 = m_z^2 \cos^2 2\beta \]
\[ + \frac{3m_t^4}{4\pi^2 v^2} \left[ \ln \left( \frac{m_T^2}{m_t^2} \right) + \frac{A_t^2}{m_T^2} \left( 1 - \frac{A_t^2}{12m_T^2} \right) \right] \]

Tree level bound 91 GeV! Need large radiative corrections to achieve 125.7 \( \Rightarrow \) either heavy stops or large mixing

**NMSSM:**

\[ m_h^2 = m_z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \]
\[ - \frac{\lambda^2 v^2}{\kappa^2} (\lambda - \kappa \sin 2\beta)^2 \]
\[ + \frac{3m_t^4}{4\pi^2 v^2} \left[ \ln \left( \frac{m_T^2}{m_t^2} \right) + \frac{A_t^2}{m_T^2} \left( 1 - \frac{A_t^2}{12m_T^2} \right) \right] \]

Tree level bound 122 GeV! Do not have to rely on large radiative corrections to achieve 125.7 \( \Rightarrow \) light stops allowed stops

[U. Ellawanger et al. 0910.1785]

In our scan we found that even 200 GeV stops can give desired Higgs mass. In this sense NMSSM is more natural.
Higgs Spectrum:

Approximate solutions (large $\tan \beta$ and large $M_A$):

\[
m_{h_{1/2}}^2 = \frac{1}{2} \left( m_Z^2 + \frac{1}{2} \kappa v_s (4 \kappa v_s + \sqrt{2} A_\kappa) \right)
\]

\[
\pm \sqrt{\left[ m_Z^2 - \frac{1}{2} \kappa v_s (4 \kappa v_s + \sqrt{2} A_\kappa) \right]^2 + \cot^2 v_s \left[ 2 \lambda^2 v_s^2 - M_A^2 \sin^2 2\beta \right]^2}
\]

\[
m_{h_3}^2 = m_{a_2}^2 = m_A^2 \left( 1 + \frac{1}{2} \cot^2 \beta_s \sin^2 2\beta \right)
\]

\[
m_{a_1}^2 = -\frac{3 \kappa v_s A_\kappa}{\sqrt{2}}
\]

\[
m_{h_{\pm}} = m_A^2 + M_W^2 - \frac{1}{2} (\lambda v)^2
\]

[Miller et al. hep-ph/0304049]
\( \lambda, \kappa \) vs Higgs Mass:

\( \lambda \sim 0.25, \kappa \sim 0.25, \tan \beta \sim 7, A_\lambda \sim 550, A_\kappa \sim -500, \mu \sim 122 \)

\( A_t \sim 3000, A_b \sim 2000, m_{Q_3} = m_{u_3} = m_{d_3} = 1000 \)

Note: at \( \lambda = 0.21 \), \( h_2 \) becomes SM like and beyond that \( m_{h_1} \) falls down till it spoils the vacuum stability. This can explained from:

\[
m_{h_1}^2 + m_{h_2}^2 = \left( m_Z^2 + \frac{1}{2} \kappa v_s (4 \kappa v_s + \sqrt{2} A_\kappa) \right)
\]

Interesting: while \( h_2 \) SM like Higgs, singlet like (hence can pass LEP constraint) \( h_1 \) can be very even few GeV! We keep this point in mind and look for this kind of region - this we call our scenario Ia. Note: \( a_1 \) is heavy here.
Note: Vacuum stability restricts $A_\kappa$ from below and above. From above $m_{a_1}$ becomes -ve. From below $m_{h_1}$ becomes -ve. $m_{h_1}$ and $m_{a_1}$ are inversely correlated. This can explained from:

$$m_{h_1}^2 + m_{h_2}^2 = \left( m_Z^2 + \frac{1}{2} \kappa v_s (4 \kappa v_s + \sqrt{2} A_\kappa) \right)$$

$$m_{a_1}^2 = -\frac{3}{\sqrt{2}} \kappa v_s A_\kappa$$

Interesting: We can tune $A_\kappa$ to get very light singlet like $a_1$ (both for either $h_1$ SM like (scenario II) or $h_2$ SM like(scenario Ib)) or $h_1$ light(for $h_2$ SM like scenario I a) $a_1$ light for $A_\kappa \sim -10$ GeV and $h_1$ light for $A_\kappa \sim -450$ GeV
NMSSM can accommodate 125.7 GeV Higgs, simultaneously satisfying phenomenological constraints. Using NMSSMTools (U. Ellawanger et al.), considering all phenomenological constraints we identified the region of parameter space where:

Ia) $h_2$ is SM like, $h_1$ is very light

Ib) $h_2$ is SM like, $a_1$ is very light

II) $h_1$ is SM like, $a_1$ very light.

We ensured that the recent coupling measurements of scalar does not spoil our predictions.

**Reduced couplings:**

\[
\begin{align*}
g_{v}^{\text{NMSSM}} &= c_{v} g_{v}^{\text{SM}}, & g_{u}^{\text{NMSSM}} &= c_{u} g_{u}^{\text{SM}} \\
g_{d}^{\text{NMSSM}} &= c_{d} g_{d}^{\text{SM}}, & g_{g}^{\text{NMSSM}} &= c_{g} g_{g}^{\text{SM}} \\
g_{\gamma}^{\text{NMSSM}} &= c_{\gamma} g_{\gamma}^{\text{SM}}
\end{align*}
\]

Note: by SM like we mean that its couplings to fermions and bosons are same (or close to) SM couplings and $m = 125.7$ GeV
LHC Constraints:

Mass of \( h_1 \) or \( h_2 \) should lie within:

\[
122.7 \leq m_{h_{SM}} \leq 128.7
\]

Scenario Ia: NSM Channels: \( BR(\ h_1 \rightarrow h_1 h_1) \), \( BR(\ h_1 \rightarrow \tilde{\chi}_1^0 \chi_1^0) \)

Scenario Ib: NSM Channels: \( BR(\ h_1 \rightarrow a_1 a_1) \), \( BR(\ h_1 \rightarrow \tilde{\chi}_1^0 \chi_1^0) \)

Scenario II: NSM Channels: \( BR(\ h_1 \rightarrow a_1 a_1) \), \( BR(\ h_1 \rightarrow \tilde{\chi}_1^0 \chi_1^0) \)

Sum of all non-standard model BR’s has to satisfy:

\[
BR_{NS} \leq 0.58
\]

For \( h_1 \) or \( h_2 \) to be SM like, its couplings should be as:

\[
\begin{align*}
c_v &= 0.64 - 1.26 \\
c_u &= 0.97 - 2.28 \\
c_d &= 0.0 - 1.31 \\
c_g &= 0.51 - 1.09 \\
c_\gamma &= 0.66 - 1.37
\end{align*}
\]
### LHC constraints: Non Standard Branching fractions in Scenario I

<table>
<thead>
<tr>
<th>h_2SML</th>
<th>Non-Standard BR’s</th>
<th>Before LHC</th>
<th>After LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$BR(h_2 \rightarrow a_1 a_1)$</td>
<td>39.1</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>$BR(h_2 \rightarrow \chi^0_1 \chi^0_1)$</td>
<td>28.9</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>$BR(h_2 \rightarrow h_1 h_1)$</td>
<td>30.5</td>
<td>30.5</td>
</tr>
</tbody>
</table>
Impact of LHC constraint: Scenario I: $h_2$ is SM like

Reduced couplings of $h_1$

$C_u^{h_2} = \frac{S_{21}}{\sin \beta}$

$C_d^{h_2} = \frac{S_{22}}{\cos \beta}$

$C_v^{h_2} = \sin \beta S_{21} + \cos \beta S_{22} = \xi_2$

Standard Model limit:

Ideally $C_u^{h_2} = C_d^{h_2} = C_v^{h_2} = 1$

This limit has important consequences:

$S_{21} = \sin \beta, S_{22} = \cos \beta \implies \xi_2 = 1$

$\xi_i^2 = 1 \implies \xi_1 = \xi_3 = 0$

i.e $h_1, h_3$ VBF channel is closed

Further

$\sum \xi_i^2 m_i^2 = m_z^2 (\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 \beta) + \text{rad.} \implies$

$m_{h_2}^2 = m_z^2 (\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 \beta) + \text{rad}.$

i.e Singlet Decouples. $\implies h_2$ is purely doublet like
• Light $h_2$ would be mainly doublet like and will act as a SM like Higgs.
Scenario II, Doublet Component of $h_1$ decouples: its consequences

Around 125.7 GeV $h_1$ is mainly doublet like, which is ruled out by LHC constraint $\Rightarrow$ 2 SM like degenerate CP even Higgses of mass 125.7 GeV are disallowed, Note: Singlet like $h_1$ of mass 125.7 GeV still allowed but would be difficult to produce because..
Scenario I: It decouples from VBF channel

- $h_1$ of 125.7 GeV decouples from VBF channel.
Scenario I, $h_2$ being SM like, $m_{h_1}$ vs $m_{a_1}$, $\lambda$ vs $A_\kappa$

- $m_{h_1}$ and $m_{a_1}$ are inversely correlated.
- $A_\kappa$ separates out region of parameter space for scenario Ia and Ib.
Scenario I, $h_2$ being SM like, $m_{st1}$ vs $A_t$

- For light top squarks, large mixing is not necessary to get the value of 125.7 GeV.
LHC constraints: Non Standard Branching fractions Scenario II

<table>
<thead>
<tr>
<th>h₁ SML</th>
<th>Non-Standard BR’s</th>
<th>Before LHC</th>
<th>After LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$BR(h₁ → a₁a₁)$</td>
<td>26.2</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td>$BR(h₁ → χ₁^{0}χ₁^{0})$</td>
<td>26.0</td>
<td>26.0</td>
</tr>
</tbody>
</table>

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Impact of LHC constraint: Scenario II: $h_1$ is SM like

Reduced couplings of $h_1$

\[
C^{h_1}_u = \frac{S_{11}}{\sin \beta}
\]

\[
C^{h_1}_d = \frac{S_{12}}{\cos \beta}
\]

\[
C^{h_1}_v = \sin \beta S_{11} + \cos \beta S_{12} = \xi_1
\]

Standard Model limit:

Ideally $C^{h_1}_u = C^{h_1}_d = C^{h_1}_v = 1$

This limit has important consequences:

$S_{11} = \sin \beta, S_{12} = \cos \beta \quad \implies \quad \xi_1 = 1$

$\xi_i^2 = 1 \implies \xi_2 = \xi_3 = 0$

i.e $h_2, h_3$ VBF channel is closed

Further

\[
\sum \xi_i^2 . m_{h_i}^2 = m_z^2 (\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 \beta) + \text{rad.} \quad \implies \quad m_{h_1}^2 = m_z^2 (\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 \beta) + \text{rad.}
\]

$\implies S_{13} = 0$ i.e Singlet Decouples
Scenario II: For $C_v^{h_2}$ vs $m_{h_2}$

Note: As expected $m_{h_2}$ of mass near 125 GeV (i.e, doublet like) is tightly constrained LHC means only singlet like second lightest Higgs after LHC? constraint.
Scenario II: For $h_1$ SM like, $m_{h_2}$ vs $m_{a_1}$, $m_{st_1}$ vs $A_t$

- For light top squarks, large mixing is not necessary
For Scenario Ia, NMSSM predicts a singlet like CP even scalar: few GeV to 129 GeV.

For Scenario Ib, NMSSM predicts a singlet like CP odd scalar: few GeV to 500 GeV.

For Scenario II, NMSSM predicts a singlet like CP odd scalar: few GeV to 500 GeV.

How to produce them? This could be possibly produced in $h_2 \rightarrow xx$
Difficult to produce directly since they are singlet like. Predominant decay modes of $x \geq 10.5$ GeV: $x \rightarrow b\bar{b}$ $x = h_1$ or $a_1$. 

**LHC phenomenology: In progress**
Conclusion  

In context of Higgs Discovery NMSSM is more natural model as compare to MSSM and solves the $\mu$ problem of MSSM.  

LHC constraints do not destroy the well known fact that in NMSSM it is possible to have light stops without necessarily having maximal mixing.  

NMSSM predicts very light CP even as well as CP scalar, so has quite interesting phenomenology for LHC.  

2 degenerate SM like Higgs are not allowed after putting LHC constraints.  

Thanks for your attention.
### Range of parameter scanned

**Specific to Higgs sector**

- $\lambda \sim 0.1 - 0.8$
- $\kappa \sim 0.1 - 0.8$
- $\tan \beta \sim 1.5 - 30$
- $\mu (GeV) \sim 100 - 2000$
- $A_\lambda (GeV) \sim 0 - 1000$
- $A_\kappa (GeV) \sim -600, 100$

**Gaugino mass parameters (GeV)**

- $M_1 \sim 50 - 500$
- $M_2 \sim 50 - 500$

### Fixed parameters (GeV)

- $A_{D_3} = 2000, m_{D_3} = 1000$
- $A_{E_1} = A_{E_2} = 0, A_{E_3} = 1000$
- $m_{L_1} = m_{L_2} = 100, m_{L_3} = 1000$
- $m_{E_1} = m_{E_2} = 100, m_{E_3} = 1000$
- $m_{Q_1} = m_{Q_2} = m_{U_1} = m_{U_2} = m_{D_1} = m_{D_2} = 1000$
- $M_3 = 1200$

### Third generation (GeV)

- $A_t \sim -4000, 4000$
- $M_{Q_3} \sim 500 - 3000$
**Good range of parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$h_1$ SML, $m_{a_1} \leq \frac{m_{h_1}}{2}$</th>
<th>$h_2$ SML, $m_{h_1} \leq \frac{m_{h_2}}{2}$</th>
<th>$h_2$ SML, $m_{a_1} \leq \frac{m_{m_2}}{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.1 - 0.7</td>
<td>0.2 - 0.7</td>
<td>0.35 - 0.7</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.1 - 0.65</td>
<td>0.1 - 0.24</td>
<td>0.1 - 0.18</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>1.5 - 21</td>
<td>3 - 14</td>
<td>4 - 13</td>
</tr>
<tr>
<td>$\mu$ (GeV)</td>
<td>118 - 1993</td>
<td>150 - 398</td>
<td>150 - 231</td>
</tr>
<tr>
<td>$A_\lambda$ (GeV)</td>
<td>0 - 1999</td>
<td>564 - 1961</td>
<td>858 - 1991</td>
</tr>
<tr>
<td>$A_\kappa$ (GeV)</td>
<td>-100 - (+11)</td>
<td>-515 - (-146)</td>
<td>-52 - (+22)</td>
</tr>
</tbody>
</table>

**Table:** Range of parameters subject to all experimental constraints
The Higgs Sector of NMSSM

\[ \text{Re} [ H_1^0, H_2^0, S ] \] gives \( 3 \times 3 \) CP even Higgs mass matrix,

\[
\text{Diagonalization: } h_i = S_{ij} H_j^r \implies 3 \text{ CP even Higgses}
\]

\[ \text{Imm} [ H_1^0, H_2^0, S ] \] gives \( 3 \times 3 \) CP odd Higgs mass matrix,

\[
\text{Rotation: } A_i = R_{S_i}^\beta H_j^l, \quad A_i = [A, G, S]
\]

\[
\text{Dropping the Goldston mode } A_i' = [A, S]
\]

\[
\text{Diagonalization: } a_i = P_{ij} A_j' \implies 2 \text{ CP odd Higgses}
\]

\[ H^+ = [H_2^+, H_1^+] \] gives \( 2 \times 2 \) charged Higgs mass matrix

\[
\text{Diagonalization: } H_i^+ = R_{ij}^\beta H_j^+, \quad H_i^+ = [H^+, G^+]
\]

\[
\text{Dropping the Goldston mode } G^+ \implies 2 \text{ Charged Higgses}
\]
Higgs Mass (GeV) vs. \tan \beta

- CP-even
- CP-odd
- Charged
- 3GeV band

Higgs Mass (GeV) vs. \mu (GeV)

- CP-even
- CP-odd
- Charged
- 3GeV band

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Couplings and Non-Standard BR constraints from LHC (New)

\[ BR_{NS} \leq 0.58 \]

- \( c_v = 0.64 - 1.26 \)
- \( c_u = 0.97 - 2.28 \)
- \( c_d = 0.0 - 1.31 \)
- \( c_g = 0.51 - 1.09 \)
- \( c_\gamma = 0.66 - 1.37 \)

Theoretical constraints

- Positivity of \( m_{h_1}^2, m_{a_1}^2, m_{h_+}^2 \) i.e vacuum stability
- Problem in integration of RGEs
  - Convergence problem
  - \( \lambda, \tan \beta \) or \( \mu = 0 \)
Scenarios I: For $h_1$ SM like, Couplings of $a_1$

- This explains why very light $a_1$ has passed LEP bound in our scans. Because $a_1$ is inert for fermions.
LHC constraints: Scenario I

NMSSM in the light of Higgs Discovery slide 32 /34
LHC constraints: Scenario II

![Graphs showing constraints on parameters](image)

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Figure 4: Higgs contribution to $a_\mu$ as a function of $\tan \beta$ or $X_d$ for $m_{u_1} = 6.5$ GeV.