Light Pseudoscalar Higgs boson in Neutralino Decays in the Next-to-Minimal Supersymmetric Standard Model

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Outline

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- The Higgs Sector and Neutralino Sector in the NMSSM
- The Neutralino Decay in the NMSSM
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Introduction
Hierarchy Problem

The SM has a fine tuning problem in calculating the self-energy of Higgs.

\[ \Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2} \left[ -2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots \right] \]

\[ \Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots \right] \]

One of the resolution to this hierarchy problem is to introduce the supersymmetric extend of SM.
The Minimal Supersymmetric Standard Model (MSSM) has additional fine tuning, the $\mu$ problem.

$$W = \hat{u}^c \hat{h}_u \hat{Q} \hat{H}_u - \hat{d}^c \hat{h}_d \hat{Q} \hat{H}_d - \hat{e}^c \hat{h}_e \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \approx -\mu^2 - m_{H_u}^2$$

One of the way out is to consider the replacement of the massive coupling by a singlet.

$$\mu \hat{H}_u \hat{H}_d \rightarrow \lambda \hat{S}(\hat{H}_u \hat{H}_d)$$
The Next to Minimal Supersymmetric Standard Model

\[ W = \hat{u}^c h_u \hat{Q} \hat{H}_u - \hat{d}^c h_d \hat{Q} \hat{H}_d - \hat{e}^c h_e \hat{L} \hat{H}_d + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3 \]

- To solve hierarchy problem for scalar field.
- To solve the \( \mu \) problem in MSSM.
- To avoid PQ symmetry with adding cubic \( \hat{S}^3 \) term.
The expected Higgs decay modes in SM:

\[ h \rightarrow b\bar{b} \sim 74\% \]
\[ \rightarrow gg, WW^*, \tau\tau \sim 7\% \]
\[ \rightarrow c\bar{c} \sim 4\% \]

The search of SM Higgs at LEP:

\[ e^+ e^- \rightarrow Zh \rightarrow 4\text{jets} \ (h \rightarrow b\bar{b})(Z \rightarrow q\bar{q}) \]
\[ \rightarrow \text{missing energy} \ (h \rightarrow b\bar{b})(Z \rightarrow \nu\bar{\nu}) \]
\[ \rightarrow 2\text{jets} + l^+ l^- \ (h \rightarrow b\bar{b})(Z \rightarrow l^+ l^-), \ l = e, \mu \]
\[ \rightarrow 2\text{jets} + \tau^+ \tau^- \ (h \rightarrow b\bar{b})(Z \rightarrow \tau^+ \tau^-), \]
\[ (h \rightarrow \tau^+ \tau^-)(Z \rightarrow q\bar{q})\]
Introduction
SM Higgs Search

- To escape the constraint from LEP by introducing New Physics, one must consider either a smaller $ZZH$ coupling or alternative decay mode for Higgs.
- In NMSSM, $B(h \rightarrow aa)$ is large in many parameter space, and thus $B(h \rightarrow b\bar{b})$ would be small.
• The mass of Higgs, $H$, $h$, $a$, $H^\pm$, are highly tied in MSSM.
• The process $H \rightarrow aa$ occur when $m_a$ is small. In the corresponding parameter space, the $m_h$ is also small, and the $Z \rightarrow ha$ coupling is large. This has been excluded by LEP for no $ha$ production been detected.
• The unconstrained region of parameter space in MSSM correspond to $m_a \sim m_H \sim m_{H^\pm} > 120 - 130$ GeV, $m_h < 120 - 130$ GeV, so that $h \rightarrow aa$ is forbidden.
Introduction

Little Hierarchy Problem

The MSSM has little hierarchy problem from the constraint of LEP.

\[
\begin{align*}
    m_h &> 114 \text{GeV}, \\
    m_h^2 &\sim M_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2} \ln\left(\frac{m_t^2}{m_t}\right), \quad \Rightarrow \quad m_t \sim 600 \text{GeV}
\end{align*}
\]

\[
\delta m_{H_u}^2 \sim -\frac{3y_t^2 m_t^2}{4\pi^2} \ln(\Lambda/m_t^2), \quad \Rightarrow \quad |m_{H_u}| \sim m_t^2 \sim (600 \text{GeV})^2
\]

\[
\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -\mu^2 - m_{H_u}^2
\]

By the virtue of the process \( h_1 \rightarrow a_1 a_1 \), the NMSSM can at least alleviate this fine tuning.
Higgs Search at LHC

Search strategy of Higgs in SM and MSSM at LHC

1. $gg \rightarrow h/a \rightarrow \gamma\gamma$;
2. associated $Wh/a$ or $t\bar{t}h/a$ production with $\gamma\gamma l^\pm$ in the final state;
3. associated $t\bar{t}h/a$ production with $h/a \rightarrow b\bar{b}$;
4. associated $b\bar{b}h/a$ production with $h/a \rightarrow \tau^+\tau^-$
5. $gg \rightarrow h \rightarrow ZZ^{(*)} \rightarrow 4$ leptons;
6. $gg \rightarrow h \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\bar{\nu}$;
7. $WW \rightarrow h \rightarrow \tau^+\tau^-$;
8. $WW \rightarrow h \rightarrow WW^{(*)}$.

Higgs would be found for significance $> 10\sigma$ with integrated luminosity $200$ $fb^{-1}$ and Higgs to Higgs and higgs to sfermion decay mode to be kinematically forbidden in NMSSM.

Introduction
Higgs Search in NMSSM at LHC

- For Higgs to Higgs allowed parameter space, significance of above channel are small.
- The possible decay mode for pseudoscalar a are:

\[ a \rightarrow b\bar{b}, \tau^+\tau^-, 2\text{jets}, \gamma\gamma \]

- For \( m_a < 2m_\tau \), \( B(a \rightarrow \gamma\gamma) \) would dominate. The signature \( h \rightarrow aa \rightarrow 4\gamma \) is clean at LHC. arXiv:hep-ph/0503203
- For \( m_a > 2m_b \), \( B(a \rightarrow b\bar{b}) \) would dominate. The \( h \rightarrow aa \rightarrow jj\tau\tau \) mode is potential to have large significance in some region of the parameter space.
- There are still some parameter spaces that the statistical significance are quite small for \( 2b2\tau \) \((m_a > 2m_b)\) and \( 2j2\tau \) \((m_a < 2m_b)\) final states.
Introduction

Higgs Search in NMSSM at LHC

- $e^+e^- \rightarrow ha$ with 4$b$ and 6$b$ final states are constrained.
- $e^+e^- \rightarrow hZ \rightarrow aaZ$ with $Z + 4b$ final states are also constrained. arXiv:hep-ex/0410017

- The minimal fine tuning analysis predict SM-like $ZZh$ coupling, $m_h \sim 100$ GeV, $2m_\tau < m_a < 2m_b$ and $h$ decay via $h \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$. PRD73,111701; PRD76, 095006

- $m_a < 2m_b$ is favored. The mode $h \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ is natural and it would be the key mode for $h \rightarrow aa$ detection.

- Pseudoscalar $a$ could also be produced through $B$ meson decay $b \rightarrow sa_1$ and $\Upsilon$ decay.
In this work, we propose an potentially important production mode of pseudoscalar $a_1$.

$$\widetilde{\chi}^0_{2,3} \rightarrow \widetilde{\chi}^0_1 a_1$$
The superpotential of NMSSM is:

$$W = \hat{u}^c h_u \hat{Q} \hat{H}_u - \hat{d}^c h_d \hat{Q} \hat{H}_d - \hat{e}^c h_e \hat{L} \hat{H}_d + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3}\kappa \hat{S}^3$$

The corresponding Higgs potential at tree level is:

$$V_F = |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + \kappa S^2|^2$$
$$V_D = \frac{1}{8}g^2(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2}g^2|H_u^\dagger H_d|^2$$
$$V_{\text{soft}} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left[\lambda A_\lambda SH_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right]$$

Where

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \\ H_u^- \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad S$$
The NMSSM
The Scalar Potential

After electroweak symmetry breaking, the neutral Higgs would have non-zero VEV:

\[
\langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}, \quad \langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}}, \quad \langle S \rangle = \frac{v_s}{\sqrt{2}},
\]

Where we could parametrize with \( \tan \beta = \frac{v_u}{v_d} \), \((v_u^2 + v_d^2) = v^2\) with \( v = 246 \text{GeV} \).

The free parameters in the Higgs sector of CP conserving NMSSM are:

\[
\lambda, \kappa, A_\lambda, A_\kappa, \tan \beta, \mu_{\text{eff}}
\]

Where \( \mu_{\text{eff}} = \lambda v_s \), and the \( m_{H_u}^2 \), \( m_{H_d}^2 \), and \( m_S^2 \) can be eliminated by stationary condition.
The pseudoscalar mixing:

\[ V_{\text{mass}} = \frac{1}{2} (P_1 \ P_2) M_2^2 \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \]

With

\[ M_{-11}^2 = M_A^2, \]
\[ M_{-12}^2 = \frac{1}{2} (M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2) \cot \beta_s, \]
\[ M_{-22}^2 = \frac{1}{4} (M_A^2 \sin 2\beta + 3\lambda\kappa v_s^2) \cot^2 \beta_s \sin 2\beta - 3\kappa v_s A_k/\sqrt{2}. \]

Where \( M_A^2 = \frac{\lambda v_s}{\sin 2\beta} (\sqrt{2} A_\lambda + \kappa v_s), \) and

\[ \begin{pmatrix} A_2 \\ A_1 \end{pmatrix} = \begin{pmatrix} \cos \theta_A & \sin \theta_A \\ -\sin \theta_A & \cos \theta_A \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \]
The neutralino is the mixing between neutral gaugino and higgsino:

\[
\mathcal{L} = -\frac{1}{2} (\psi^0)^T M_5 \psi^0 + h.c.
\]

Where the \( \psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}) \) with \( M_5 \):

\[
\begin{pmatrix}
M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W & 0 \\
0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W & 0 \\
-m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu & -\lambda v s_\beta / \sqrt{2} \\
m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 & -\lambda v c_\beta / \sqrt{2} \\
0 & 0 & -\lambda v s_\beta / \sqrt{2} & -\lambda v c_\beta / \sqrt{2} & 2\kappa v_s / \sqrt{2}
\end{pmatrix}
\]

The \( M_1 \) and \( M_2 \) are the soft mass of bino and wino. So that:

\[
\tilde{\chi}_i^0 = N_{ij} \psi_j^0 = N_{i1} \tilde{B}^0 + N_{i2} \tilde{W}^0 + N_{i3} \tilde{H}_d^0 + N_{i4} \tilde{H}_u^0 + N_{i5} \tilde{S}
\]
We scan over the parameter space using NMHDECAY v2.0.1

\[
\begin{aligned}
\lambda : & \quad 0 - 0.7, \\
\kappa : & \quad -0.7 - 0.7, \\
\tan \beta : & \quad 1 - 40, \\
M_1 : & \quad 0 - 1000 \text{ GeV}, \\
M_2 : & \quad 0 - 1000 \text{ GeV}, 
\end{aligned}
\]
The Neutralino Decay in the NMSSM

NMHDECAY tests

- Mass square of Higgs, squarks and sleptons to be positive.
- Yukawa coupling has no Landau pole below GUT scale.
- Physical minimal of scalar potential is deeper than the $\langle H \rangle = 0$ one.
- Constraints from LEP.

$e^+ e^- \rightarrow hZ$ with $h \rightarrow b \bar{b}$, $h \rightarrow \tau^+ \tau^-, h \rightarrow 2 \text{jets}$, $h \rightarrow \gamma \gamma$;

$e^+ e^- \rightarrow ha$ with $ha \rightarrow 4b$, $ha \rightarrow 4\tau$, $ha \rightarrow aaa \rightarrow 6b$,

$hZ \rightarrow aaZ$ with $aa \rightarrow 4 \text{jets}$, $2 \text{jet} + cc$, $2 \text{jet} + \tau \tau$, $4 \tau'$s, $cccc$, $\tau \tau + cc$, and $aaZ \rightarrow 4b + 2 \text{jets}$

- Constraints from B physics.

$3.07 \times 10^{-04} < B(b \rightarrow s\gamma) < 4.07 \times 10^{-04}$,

$4.99 \times 10^{-01} < \delta M_d < 5.15 \times 10^{-01}$,

$1.753 \times 10^{+01} < \delta M_s < 1.801^{+01}$,

$B(Bs \rightarrow \mu^+ \mu^-) < 5.8^{-08}$,

$3.40 \times 10^{-05} < B(B^+ \rightarrow \tau^+ + \nu_\tau) < 2.30 \times 10^{-04}$. 
The Neutralino Decay in the NMSSM

Scan Result

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<th>Steps</th>
<th>Number of points</th>
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<tr>
<td>Total used</td>
<td>10,000,000</td>
</tr>
<tr>
<td>Scanned after NMHDECAY</td>
<td>41,318</td>
</tr>
<tr>
<td>$B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1) &gt; 0.1$</td>
<td>3,260</td>
</tr>
<tr>
<td>$B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1) &gt; 0.5$</td>
<td>2,030</td>
</tr>
</tbody>
</table>

![Graph showing $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1)$ vs $m_{a_1}$ (GeV)]
The Neutralino Decay in the NMSSM
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<td>(a) $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1) &gt; 0.1$</td>
<td>3,260</td>
</tr>
<tr>
<td>$B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1) &gt; 0.5$</td>
<td>2,030</td>
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<tr>
<td>(b) $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1) &gt; 0.1$</td>
<td>5,839</td>
</tr>
<tr>
<td>$B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1) &gt; 0.5$</td>
<td>720</td>
</tr>
<tr>
<td>(c) $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z) &gt; 0.1$</td>
<td>3,286</td>
</tr>
<tr>
<td>$B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z) &gt; 0.5$</td>
<td>1,005</td>
</tr>
</tbody>
</table>
The Neutralino Decay in the NMSSM

Neutralino Production

We study the relative branching ratios $\tilde{q}_{L,R} \rightarrow q \tilde{\chi}^{0}_{1,2}$ with $|g_{L,R} q \bar{q} \tilde{\chi}^{0}_{2}/g_{q} q \bar{q} \tilde{\chi}^{0}_{1,2}|^2$ using the constraint $B(\tilde{\chi}^{0}_{2,3} \rightarrow \tilde{\chi}^{0}_{1} a_1) > 0.5$.
Summary

- The NMSSM model has the process $h_1 \rightarrow a_1 a_1$ to release the constraints on SM Higgs from LEP.
- In this work we propose that the process $\tilde{\chi}^0_{2,3} \rightarrow \tilde{\chi}^0_1 a_1$ is potentially more important to be the source of pseudoscalar in NMSSM.
- Squark could decay into $\tilde{\chi}^0_{2,3}$ and then $\tilde{\chi}^0_{2,3} \rightarrow \tilde{\chi}^0_1 a_1$ would take place. If the gluino and squark are light enough, this channel would dominate the pseudoscalar production in NMSSM at LHC.
- The dominated decay channels of $a_1$ are $a_1 \rightarrow b\bar{b}$ and $a_1 \rightarrow \tau^+\tau^-$. It has been shown that the 2 $\tau$ mode is favored. The $h_1 \rightarrow a_1 a_1$ process could also enhance the $\tau$ final state in collider. So that would have lots of $\tau$ filled in the collider.