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

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Abstract

We point out another important production channel of a light pseudoscalar Higgs boson $a_1$ via the decays of neutralinos, including $\tilde{\chi}^0_{2,3} \rightarrow \tilde{\chi}^0_1 a_1$, in the framework of the NMSSM. We scan the whole parameter space using the most up-to-date version of NMHDECAY and search for regions where $B(\tilde{\chi}^0_{2,3} \rightarrow \tilde{\chi}^0_1 a_1) > 0.5$. If the gluino and squarks are light enough for copious production of SUSY events at the LHC, there would be numerous number of $\tilde{\chi}^0_{2,3}$ in subsequent decays of gluinos and squarks. Therefore, the production rates of $a_1$ via neutralino decays would be more important than $h \rightarrow a_1 a_1$ and others. Potentially, the final state is filled with many $\tau$ leptons, which can be reconstructed at the mass of $a_1$. This is a clean, observable, and distinguishable signature for NMSSM.

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I. INTRODUCTION

Supersymmetry is the leading candidate for the physics beyond the standard model (SM). It not only solves the gauge hierarchy problem, but also provides a dynamical mechanism for electroweak symmetry breaking and a natural candidate for the dark matter. The minimal version, the minimal supersymmetric standard model (MSSM), has suffered from what so called little hierarchy problem and the $\mu$ problem.

An extension with an extra singlet superfield, known as the next-to-minimal supersymmetric standard model (NMSSM) was motivated to provide a natural solution to the $\mu$ problem. The $\mu$ parameter in the term $\mu H_u H_d$ of the superpotential of the MSSM naturally has its value at either $M_{\text{Planck}}$ or zero (due to a symmetry). However, the radiative electroweak symmetry breaking conditions require the $\mu$ parameter to be of the same order as $m_Z$ for fine-tuning reasons. Such a conflict was coined as the $\mu$ problem [1]. In the NMSSM, the $\mu$ term is generated dynamically through the vacuum-expectation-value (VEV), $v_s$, of the scalar component of the additional Higgs field $S$, which is naturally of the order of the SUSY breaking scale. Thus, an effective $\mu$ parameter of the order of the electroweak scale is generated.

The NMSSM was recently revived because it was shown that it can effectively relieve the little hierarchy problem [2]. Due to the additional Higgs singlet field and an approximate PQ symmetry, the NMSSM naturally has a light pseudoscalar Higgs boson $a_1$. It has been shown [2] that, in most parameter space that is natural, the SM-like Higgs boson can decay into a pair of light pseudoscalar bosons with a branching ratio larger than 0.7. Thus, the branching ratio of the SM-like Higgs boson into $b\bar{b}$ would be less than 0.3 and so the LEP II bound is effectively reduced to around 100 GeV [3].

The dominance of $h \to a_1 a_1$ mode for the intermediate Higgs boson has significant impacts on the Higgs search strategies [4]. The most useful channel for intermediate Higgs boson, $h \to \gamma \gamma$ and $h \to WW^*$ would be substantially affected because $B(h \to \gamma \gamma)$ lowers by a factor of a few. So is the $h \to b\bar{b}$ in $Wh, Zh$ production. New search modes via $h \to a_1 a_1$ are mandatory. For example, $h \to a_1 a_1 \to 4b$ for $m_{a_1} > 2m_b$ via $Wh, Zh$ production with at least one charged lepton and 4$B$-tags in the final state has been shown to afford a clean signal of high significance and a full Higgs mass reconstruction at the LHC [5]. The associated Higgs production with gauge bosons or $t\bar{t}$ pairs was shown to be effective [6]. Similar studies
at the Tevatron were also performed [7]. Other possibilities like \( h \rightarrow a_1 a_1 \rightarrow 2b2\tau \) [8] and \( h \rightarrow a_1 a_1 \rightarrow 4\tau \) [8, 9] can further enhance the signal, especially when \( 2m_\tau < m_{a_1} < 2m_b \). In the extreme limit of zero mixing with the MSSM pseudoscalar, the singlet-like \( a_1 \) can decay into a pair of photons. In this case, \( h \rightarrow a_1 a_1 \rightarrow 4\gamma \) [10]. The light pseudoscalar \( a_1 \) can also be produced in non-Higgs decays. It can be produced in \( B \) meson decays [11, 12, 13], in \( \Upsilon \) decays [14] and other rare decays [15], and in associated production with chargino pair [16]. In some other contexts, a light pseudoscalar boson can also be frequently produced in association with a Higgs boson or a heavy quark pair [17]. There could also be other unconventional decay modes of the SM-like Higgs boson in the NMSSM, e.g., invisible decay into neutralinos [18]. A recent summary can be found in Ref. [19].

In this note we point out another important production channel of a light pseudoscalar Higgs boson \( a_1 \) via the decays of neutralinos, including \( \tilde{\chi}_2,3^0 \rightarrow \tilde{\chi}_1^0 a_1 \), in the framework of the NMSSM. This is potentially much more important than from the decay of the Higgs boson or from the associated production. In particular, if the gluino and squarks are light enough for copious production of SUSY events at the LHC, there would be numerous number of \( \tilde{\chi}_2,3^0 \) in subsequent decays of gluinos and squarks. Therefore, the production rates of \( a_1 \) via neutralino decays would be much more important than \( h \rightarrow a_1 a_1 \) and others. There is also the possibility of \( \tilde{\chi}_2,3^0 \rightarrow \tilde{\chi}_1^0 h \) followed by \( h \rightarrow a_1 a_1 \). It was argued in Refs. [2] that the mass \( m_{a_1} \) in most favorable parameter space is lighter than \( 2m_b \), and thus \( a_1 \rightarrow \tau^+\tau^- \) is the most frequent. In this case, SUSY events would be filled with many \( \tau \) leptons plus missing energies, with the corresponding \( \tau^+\tau^- \) reconstructed at the \( a_1 \) mass.

We scan the whole parameter space using the most up-to-date version of NMHDECAY [20] and search for regions where \( B(\tilde{\chi}_2,3^0 \rightarrow \tilde{\chi}_1^0 a_1) > 0.5 \). We show characteristics of this region of parameter space.

II. TWO BODY AND THREE BODY DECAYS OF NEUTRALINO

The superpotential of the NMSSM is given by

\[
W = h_u \tilde{Q} \tilde{H}_u \tilde{U}^c - h_d \tilde{Q} \tilde{H}_d \tilde{D}^c - h_e \tilde{L} \tilde{H}_u \tilde{E}^c + \lambda \tilde{S} \tilde{H}_u \tilde{H}_d + \frac{1}{3} \kappa \tilde{S}^3. \tag{1}
\]

where \( \tilde{Q}, \tilde{L}, \tilde{H}_u, \tilde{H}_d, \tilde{U}^c, \tilde{D}^c, \tilde{E}^c \), and \( \tilde{S} \) are the doublet quark and lepton, doublet up-type Higgs and down-type Higgs, singlet up-quark and down-quark, and the singlet scalar
superfields, respectively.

The Higgs sector of the NMSSM consists of the usual two Higgs doublets $H_u$ and $H_d$ and an extra Higgs singlet $S$. The extra singlet field is allowed to couple only to the Higgs doublets of the model, the supersymmetrization of which is that the singlet field only couples to the Higgsino doublets. Consequently, the couplings of the singlet $S$ to gauge bosons and fermions will only be manifest via their mixing with the doublet Higgs fields. After the Higgs fields take on the VEV’s and rotating away the Goldstone modes, we are left with a pair of charged Higgs bosons, 3 real scalar fields, and 2 pseudoscalar fields. In particular, the mass matrix for the two pseudoscalar Higgs bosons $P_1$ and $P_2$ is

$$V_{\text{pseudo}} = \frac{1}{2} (P_1 \ P_2) M_P^2 \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$$

(2)

with

$$M^2_{P_{11}} = M^2_A,$$

$$M^2_{P_{12}} = M^2_{P_{21}} = \frac{1}{2} \cot \beta_s \left( M^2_A \sin 2\beta - 3\lambda \kappa v^2_s \right),$$

$$M^2_{P_{22}} = \frac{1}{4} \sin 2\beta \cot^2 \beta_s \left( M^2_A \sin 2\beta + 3\lambda \kappa v^2_s \right) - \frac{3}{\sqrt{2}} \kappa A \kappa v_s,$$

(3)

where

$$M^2_A = \frac{\lambda v_s}{\sin 2\beta} \left( \sqrt{2} A + \kappa v_s \right),$$

(4)

and $\tan \beta = v_u/v_d$ and $\tan \beta_s = v_s/v$ and $v^2 = v_u^2 + v_d^2$. Here $P_1$ is the pseudoscalar in MSSM while $P_2$ comes from the singlet $S$ and from the effects of rotating away the Goldstone modes. The pseudoscalar fields are further rotated to the diagonal basis $(A_1, A_2)$ through a mixing angle $\theta_A$:

$$\begin{pmatrix} A_2 \\ A_1 \end{pmatrix} = \begin{pmatrix} \cos \theta_A & \sin \theta_A \\ -\sin \theta_A & \cos \theta_A \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$$

(5)

where the masses of $A_i$ are arranged such that $m_{A_1} < m_{A_2}$. At tree-level the mixing angle is given by

$$\tan \theta_A = \frac{M^2_{P_{12}}}{M^2_{P_{11}} - m^2_{A_1}} = \frac{1}{2} \cot \beta_s \frac{M^2_A \sin 2\beta - 3\lambda \kappa v^2_s}{M^2_A - m^2_{A_1}}.$$  

(6)
We also use $a_1$ to denote the $A_1$. The $a_1$ is mainly the singlet when $\theta_A$ is small. The couplings of $a_1$ to fermions scale with $\sin \theta_A$ while $a_1$ can have large couplings to Higgsinos and Higgs bosons via the $\lambda S H_u H_d$ term of the superpotential.

We use the publicly available code, NMHDECAY [20], to generate parameter space points. Currently, the code has imposed a number of experimental constraints, including the radiative $b \to s \gamma$ decay, the $B_d$ and $B_s$ mixing parameters, $B_s \to \mu^+ \mu^-$ decay, $B^+ \to \tau^+ \nu_\tau$ decay, and the relic density of the lightest neutralino. These experimental constraints can be turned on or off. The parameter space points presented in this section satisfy all the above constraints. Before we show the decay branching ratios of the second lightest neutralino, we would like to give the vertex factor that we are considering. The vertex factor $a_1-\tilde{\chi}_0^2-\tilde{\chi}_j^0$ is given by

$$L = \frac{\theta}{2} \sin \theta_A (N_{j2} - N_{j1} \tan \theta_w) (N_{i4} c_\beta - N_{i3} s_\beta) \frac{-\lambda \sqrt{2} \sin \theta_A (N_{j3} c_\beta + N_{j4} s_\beta) N_{i5} + \lambda N_{j3} N_{i4} - \kappa N_{i5} N_{j5}}{\sqrt{2}} \cos \theta_A + (i \leftrightarrow j).$$

The other competing channels for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + X$ include $X = h_1, Z$, and 3-body decays via off-shell particles. The detailed formulas will be shown in a future publication [22]. The 3-body decays are suppressed as long as at least one of the 2-body modes are open. We show in Fig. 1 the branching ratios of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + (a_1, h_1, Z, 3 \text{-body})$ for two sets of parameter space points, with varying $\kappa$ and $A_\kappa$ respectively. It is clear that $B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1)$ dominates in these two sets of points, which satisfy all experimental constraints and relic density of the LSP. The parameters $\kappa$ and $A_\kappa$ can be kept small by the approximate PQ and R symmetries, which guarantee the lightness of $a_1$.

Experimentally, the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1$ gives very interesting signatures. In typical SUSY events, a lot of gluinos or squarks are produced, which subsequently decay into the third or second lightest neutralinos, instead of directly decaying into the lightest one. Thus, there are numerous second lightest or third lightest neutralinos, which then decays into the lightest neutralino and the light pseudoscalar $a_1$. The $a_1$ then decays into either $b\bar{b}$ or $\tau^+ \tau^-$ depending on its mass. Therefore, the final state will be filled with many $\tau$ leptons, which can be carefully reconstructed at the mass of $a_1$. This is a clean, observable, and distinguishable signature for NMSSM.*

* In gauge-mediated models, excessive production of $\tau$ leptons is often the signature. However, it can be
III. DECAYS OF SQUARK INTO NEUTRALINOS

Here we show the relative branching ratios of a squark decaying into the lightest and second lightest neutralinos

$$\bar{q}_{L,R} \rightarrow q_{L,R} \tilde{\chi}_0^{0,1}$$

where we simply assume that the Yukawa coupling of the light quark is negligible compared with the gauge couplings. The couplings of $\bar{q}_{L,R}q_{L,R}\tilde{\chi}_i^{0}$ are given by

$$g_{\bar{q}_L u_L \tilde{\chi}_i^0} = -\frac{g}{\sqrt{2}} \left( N_{i2} + \frac{t_w}{3} N_{i1} \right) , \quad g_{\bar{q}_R u_R \tilde{\chi}_i^0} = \frac{gt_w}{\sqrt{2} 3} N_{i1} ,$$

$$g_{\bar{d}_L d_L \tilde{\chi}_i^0} = -\frac{g}{\sqrt{2}} \left( -N_{i2} + \frac{t_w}{3} N_{i1} \right) , \quad g_{\bar{d}_R d_R \tilde{\chi}_i^0} = -\frac{gt_w}{\sqrt{2} 3} N_{i1} .$$

We scan the parameter space points with the requirements defined by NMHDECAY, except for the relic density of the lightest neutralino, and $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1) > 0.5$ (details in the next section). With these parameter space points we calculate the squares of the relative gauge couplings:

$$\left| \frac{g_{\bar{q}_L R q_{L,R} \tilde{\chi}_2^0}}{g_{\bar{q}_L R q_{L,R} \tilde{\chi}_1^0}} \right|^2$$

distinguished between the gauge-mediated models and the NMSSM, because the right $\tau$ pair in NMSSM can be reconstructed at $m_{a_1}$ but not for the $\tau$ leptons in GMSB models.
which can roughly indicate the relative branching ratios without taking into account the masses in the final state. We show in Fig. 2 the squares of relative gauge couplings. It is clear that the squarks, whether left-handed or right-handed, can frequently decay into the second lightest neutralino, instead of just directly into the lightest one. Therefore, it is consistent with what we have pointed out in the Introduction that there are numerous second or even the third lightest neutralinos via production of squarks or gluinos in SUSY events. They will then decay into the lightest neutralino and the light pseudoscalar Higgs boson $a_1$. We will map the regions in parameter space that the branching ratio $B(\tilde{\chi}^0_{2,3} \rightarrow \tilde{\chi}^0_1 a_1) > 0.5$ in the next section.
IV. SCAN OF NMSSM PARAMETER SPACE

Here we scan for the parameter space using the most up-to-date version of NMHDECAY [20] in the following ranges of parameters

\[
\begin{align*}
\lambda &: 0 - 0.7, \quad A_\lambda : -1000 - 1000 \text{ GeV}, \\
\kappa &: -0.7 - 0.7, \quad A_\kappa : -10 - 10 \text{ GeV}, \\
\tan \beta &: 1 - 40, \quad \mu : -500 - 500 \text{ GeV}, \\
M_1 &: 0 - 1000 \text{ GeV}, \quad M_2 : 0 - 1000 \text{ GeV},
\end{align*}
\]  

where \(M_1\) and \(M_2\) are the bino and wino mass parameter, respectively. We ran for a total of 10 million random points in the parameter space. The successful points have to pass the criteria of NMHDECAY, including LEPII bounds, \(b \to s\gamma\), \(B_d\) and \(B_s\) mixing, \(B_s \to \mu^+\mu^-\) and \(B^+ \to \tau^+\nu_\tau\), but not the LSP relic density. From the pool of successful points we then calculate the branching ratio of \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1)\) and pick those with the branching ratio larger than 0.1. These points are shown in Fig. 3. It is easy to see those points with the branching ratio larger than 0.5 in the figure. We also show in Table I the reduction of the number of points under the requirements of NMHDECAY, and further under \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1) > 0.1\) and 0.5, respectively.

V. CONCLUSIONS

In this note we have scanned the parameter space of the NMSSM with the help of the code NMHDECAY. In a sizable fraction of the parameter space points, shown in Table I the branching ratio of \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1) > 0.5\). It indicates a potentially more important

| TABLE I: Total number of points used, that after scanned by NMHDECAY, and that after imposing \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1) > 0.1\) and 0.5. |
|---|---|
| Steps | Number of points |
|---|---|
| Total used | 10,000,000 |
| Scanned after NMHDECAY | 41,318 |
| \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1) > 0.1\) | 3,260 |
| \(B(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + a_1) > 0.5\) | 2,030 |
production channel of the light pseudoscalar Higgs boson $a_1$ via the decays of neutralinos, including $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 a_1$. It could be much more important than from the decay of the Higgs boson or from the associated production. In particular, if the gluino and squarks are light enough for copious production of SUSY events at the LHC, there would be numerous number of $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ in subsequent decays of gluinos and squarks. The $a_1$ then decays into either $b\bar{b}$ or $\tau^+\tau^-$ depending on its mass. Therefore, the final state will be filled with many $\tau$ leptons, which can be carefully reconstructed at the mass of $a_1$. This is a clean, observable, and distinguishable signature for NMSSM. There is also the possibility of $\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\chi}_1^0 h$ followed by $h \rightarrow a_1 a_1$, which again gives rise to multi-$\tau$-lepton final states.

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