Some Decays of Neutral Higgs Bosons in the NMSSM

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Abstract. To solve the µ problem of the Minimal Supersymmetric Standard Model (MSSM), a single field S is added to build the Next Minimal Supersymmetric Standard Model (NMSSM). Vacuum enlarged with non-zero vevs of the neutral-even CP is the combination of $H_u$, $H_d$ and S. In the NMSSM, the higgs sector is increased to 7 higgs (compared with 5 higgs in the MSSM), including three higgs which are even-CP $h_{1,2,3}$ ($m_{h1} < m_{h2} < m_{h3}$), two higgs which are odd-CP $a_{1,2}(m_{a1} < m_{a2})$ and a couple of charged higgs $H^\pm$. The decays higgs into higgs is one of the remarkable new points of the NMSSM. In this paper we study some decays of neutral Higgs bosons. The numerical results are also presented together with evaluations.

1. Introduction
The simplest version of supersymmetry is the Minimal Supersymmetric Standard Model (MSSM). This version is limited by two problems: the µ and the hierarchy [1, 3, 4, 7]. The simple supersymmetry, which is beyond the MSSM, is the Next Minimal Supersymmetric Standard Model (NMSSM). The special characteristic of Higgs boson in the NMSSM is the decay of Higgs into Higgs. It is remarkable that the lightest state a1 of the odd-CP Higgs can play the role of a pseudo-goldstone, which has a small mass and can lead to the predominated decay of the even-CP $h \rightarrow a_{1}a_{1}$ [2]. The even-CP Higgs and the heavy odd-CP Higgs can be generated at LEP in $e^+e^- \rightarrow ha$, but they may not be discovered because the dominant h decay were not searched for. There are different ways to make the mass of Higgs boson increased in the MSSM and in the beyond MSSM. One simple way is to study the beyond singlet of the MSSM which contains one term $\lambda \hat{S} \hat{H}_u \hat{H}_d$ in the super-potential, this is the term that contributes $\lambda^2 v^2 \sin^2 2\beta$ at $v = 174$ GeV to the squared mass of even-CP Higgs [10] and therefore, it can make the mass of Higgs boson increased over the limit of independent decay state. It should be noted that this contribution is maximum with $\tan \beta \sim 1$. Thus, a condition in which the lightest odd-CP Higgs with its mass is under $2m_t$, the two lightest even-CP Higgs boson and the charged Higgs boson can be found in the MSSM. All of them can be generated at LEP and they are now being searched for.

The neutral Higgs sector in the NMSSM includes the following states: three even-CP and two odd-CP. Many analysis is on Higgs sector in the NMSSM [5] have shown that, in the specific physical state of the even-CP Higgs, there is a strong mix between the doublet state and the singlet SU(2) with the reduction in the interaction of gauge boson. The study on light Higgs...
The soft breaking supersymmetry sector is regulated in SLHA2: and vectors in the corresponding spaces. The supersymmetry breaking term $L_{soft}$. In the NMSSM, the terms of the super-potential $W_{higgs}$ are dependent on superfield Higgs $\hat{H}_d$, $\hat{H}_u$ and $\hat{S}$ (here, we follow the SLHA2 regulations, however $\hat{H}_u$ is also written as $\hat{H}_d$ and $\hat{H}_d$ is also written as $\hat{H}_1$):

$$W_{Higgs} = \left( \mu + \lambda \hat{S} \right) \hat{H}_u.\hat{H}_d + \xi_F \hat{S} + \mu' \hat{S}^2 + \frac{\kappa}{3} \hat{S}^3.$$  \hspace{1cm} (1)

with: $\lambda, \kappa$ is the non-dimension coupling Yukawa, $\mu, \mu'$ is the supersymmetry mass, $\xi_F$ is the square supersymmetry mass parameter.

From (1), Yukawa interaction of quark and lepton superfield are added to

$$W_{Yukawa} = h_u \hat{H}_u, \hat{Q} \hat{U}_R + h_d \hat{H}_d, \hat{Q} \hat{D}_R + h_e \hat{H}_d, \hat{L} \hat{E}_R.$$  \hspace{1cm} (2)

Here, the Yukawa interaction $h_u, h_d, h_e$ and the superfields $\hat{Q}, \hat{U}_R, \hat{D}_R, \hat{L}, \hat{E}_R$ are the matrices and vectors in the corresponding spaces.

The soft breaking supersymmetry sector is regulated in SLHA2:

$$-L_{soft} = m^2_{\hat{H}_u} |H_u|^2 + m^2_{\hat{H}_d} |H_d|^2 + m^2_{\hat{S}} |S|^2 + m^2_{\hat{Q}} |Q|^2 + m^2_{\hat{U}_R} |U_R|^2$$

$$+ m^2_D |D_R|^2 + m^2_L |L|^2 + m^2_E |E_R|^2$$

$$+ (h_u A_u Q.H_u U_R - h_d A_d Q.H_d D_R - h_e A_e L.H_d E_R)$$

$$+ \lambda A_h H_u. H_d S + \frac{1}{3} \kappa A_s S^3 + m^2_{\hat{H}_u} \hat{H}_d + m^2 S^2 + \xi_S S + h c). \hspace{1cm} (3)$$

(definition $m^2_{\hat{H}_u} = B u, m^2_{\hat{H}_d} = B' \mu'$)

In the super-potential (1) we have supersymmetry parameters $\mu, \mu'$ and $\xi_F$ (the soft supersymmetry interactions break the parameters $m^2_{\hat{S}}, m^2_S$ and parameter $\xi_S$ in (3)), however, some terms are not eliminated in some different solutions for simple NMSSM with a part of invariant super-potential when $\mu = \mu' = \xi_F = 0$

$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u. \hat{H}_d + \frac{\kappa}{3} \hat{S}^3.$$  \hspace{1cm} (4)

Then, eliminating the parameters $m^2_{\hat{S}}, m^2_S$ and $\xi_S$ in (3), combining the vevs of $\hat{S}$ in the weak sector or in the breaking supersymmetry to define $\mu$:

$$\mu_{eff} = \lambda s.$$  \hspace{1cm} (5)

The matter of $\mu$ in MSSM has been solved then. As any supersymmetry theory with invariant super-potential sector (ternary), the Lagrangians, which contain the soft supersymmetry violation conditions specified by (3), have one $Z_3$ symmetry randomly, which is corresponding to the multiplication of all chiral superfields with $e^{2\pi i/3}$ . The invariant super-potential (4) is presented like the invariant $Z_3$. The symmetry $Z_3$ will be broken by non-dimension terms in the super-potential (1). The model with super-potential (1) is the NMSSM. The invariant $Z_3$ Higgs sector is defined by seven parameters
\(\lambda, \kappa, m_{H_d}^2, m_{H_u}^2, m_S^2, A_\lambda, A_\kappa\). The expressions of Higgs mass matrix in the invariant \(Z_3\) of the NMSSM show that invariant \(Z_3\) is obtained when:

\[
m_{33}^2 = m_{33}' = \xi_S = \mu = \mu' = \xi_F = 0.
\]  

(6)

From the supersymmetry gauge interaction and soft supersymmetry breaking conditions, we obtain Higgs potential:

\[
V_{\text{Higgs}} = |\lambda(H_u^+H_d - H_u^0H_d^0)|^2 + \mu S^2 + 2\mu'S + \xi_F|^2 \\
+ (m_{H_u}^2 + |\mu + \lambda S|^2(|H_u^0|^2 + |H_d^0|^2) + (m_{H_d}^2 + |\mu + \lambda S|^2(|H_u^0|^2 + |H_d^0|^2) \\
+ \frac{g_1^2 + g_2^2}{8}(|H_u^0|^2 + |H_d^0|^2 - |H_u^0|^2 - |H_d^0|^2) + \frac{\xi_v}{2}|H_u^0H_d^0 + H_u^0H_d^0|^2 \\
+ m_S^2S^2 + \frac{1}{2}(\lambda A_\lambda(H_u^0H_d - H_u^0H_d^0)S + \frac{1}{2}\kappa A_uS^3 + m_S^2(H_u^0H_d^0 - H_u^0H_d^0) \\
+ m_S^2S^2 + \xi_S + h.c.
\]  

(7)

where \(g_1\) and \(g_2\) present gauge interaction U(1) and SU(2).

The even-CP Higgs sector has three mixed states, which are the real parts of \(H_u, H_d\) and \(S\). The largest mass state \(h\), which is nearly the same with SM, interacts with electroweak Gauge boson, this state has squared mass \(M_h^2\) given by [5, 6]:

\[
M_h^2 = M_0^2\cos^22\beta + \lambda^2v^2\sin^22\beta + \text{rad.corr} + \Delta_{\text{mix}}
\]  

(8)

The diagonal elements of matrix in the singlet sector are given by (with the assumption that \(s > \upsilon_u, \upsilon_d\))

\[
M_{ss}^2 \simeq ks (A_k + 4ks)
\]  

(9)

The term \(\Delta_{\text{mix}}\) in (8) is derived from the mixture of doublet and singlet

\[
\Delta_{\text{mix}} \simeq \frac{4\lambda^2s^2v^2(\lambda - ks\sin 2\beta)^2}{M_h^2 - M_{ss}^2}
\]  

(10)

where \(M_h^2\) is given by \(M_0^2\) and has no mixed term.

Studying the decay of new particles in the Model will bring us the hope of finding out these particles as well as verifying the correctness of that Model [8]. In this paper we study some decays of neutral Higgs bosons. The numerical results are also shown in graph to evaluate the influence of \(m_{a_1}\) and \(\phi\) on the decay width and on the lifetime of Higgs bosons.

2. Some decays of neutral Higgs bosons in the NMSSM

\[\text{Figure 1. Feynman diagram for some decays of neutral Higgs.}\]

The amplitudes which are calculated to tree level have the following forms:

\[
M_0(h \rightarrow a_1a_1) = \frac{g_{a_1}}{2\cos\theta_w} \cos \beta \cos(\alpha + \beta)
\]  

(11)
Fig.3 shows that the influence of $m_0 = 0.00636(1/s)$, and the lifetime of $h$ is relatively significant. When considering the variation $4 GeV < m_{a_1} < 8 GeV$, we can see that the variation can decrease the value of decay width by $0.05\%$ and increase the value of the decay width by 3 times and decrease the value of the lifetime of $a_1$ by 5 times. The obtained result of decay width $a_1 \to \tau\bar{\tau}$ is around $0.00633 - 0.00636(1/s)$, and the lifetime of $h_1$ is around 157.2 - 158.0 (s).

Fig.4 shows that the influence of $m_0 = 0.00006(1/s)$, and the lifetime of $a$ is around 157,2 - 158,0 (s).

The decay widths which are calculated to tree level are:

$$M_0(a_1 \to \tau\bar{\tau}) = \bar{u}^a(F_1, s) \left( \frac{ig_{m_w}}{2m_w} \right) \tan \beta (\gamma_5)_a \nu(\bar{F}_2, s)$$ (12)

$$M_0(a_1 \to c\bar{c}) = \bar{u}^a(F_1, s) \left( \frac{g_{m_w}}{2m_w \sin \beta} U_{12}^P (\gamma_5)_{a} \right) v(\bar{F}_2, s)$$ (13)

$$M_0(h_2 \to H^+H^-) = A = -igm_w (U_{a_1}^S \cos \beta + U_{a_2}^S \sin \beta)$$

$$- \frac{igm_w}{2 \cos \theta_w} (U_{a_1}^S \sin \beta + U_{a_1}^S \cos \beta) \cos 2\beta + i \frac{\lambda^2}{\sqrt{2}} (v_1 U_{a_2}^S + v_2 U_{a_1}^S) \sin 2\beta$$

$$- \frac{i}{\sqrt{2}} \lambda U_{a_1}^S [(2kx + A_\lambda) \sin \beta + 2\lambda x]$$ (14)

The decay widths which are calculated to tree level are:

$$\Gamma_0(h_1 \to a_1 a_1) = \frac{g^2 m_w^2 \cos^2 \beta \cos^2 (\alpha + \beta) (m_h^2 - 4m_{a_1}^2)^{1/2}}{64\pi \cos^2 \theta_w}$$ (15)

$$\Gamma_0(a_1 \to \tau\bar{\tau}) = \frac{g^2 m_w^2 \tan^2 \beta (2m_{a_1}^2 - 3m_{\tau}^2) (m_{a_1}^2 - 4m_{\tau}^2)^{1/2}}{64\pi m_{a_1}^2 m_w^2 \cos^2 \beta}$$ (16)

$$\Gamma_0(a_1 \to c\bar{c}) = \frac{|U_{12}^P|^2 g^2 m_w^2 (m_{a_1}^2 - 2m_{\tau}^2)}{128\pi m_{a_1}^2 m_w^2 \sin^2 \beta} \sqrt{m_{a_1}^4 - 4m_{a_1}^2 m_{\tau}^2}$$ (17)

$$\Gamma_0(h_2 \to H^+H^-) = \frac{|A|^2}{16\pi m_{h_2}^4} \sqrt{m_{h_2}^4 - 4m_{h_2}^2 m_H^2}$$ (18)

3. Numerical Results

To study the influence of the mass $m_{a_1}$ and $\phi$ on the Higgs decay process, we use two set of parameters [5, 9] for programming numerical calculation: $\lambda = 0.8; x = 200e^{i\phi}; k = 0.1; m_H = 100; \tan\beta = 3; \sin \alpha = -0.58; A_k = 6; A_\lambda = 486$. Perform the numerical calculations we obtain the graphs from Fig.2 to Fig.6.

From Fig.2, when considering the variation of $m_{a_1}$ from $4 GeV < m_{a_1} < 8 GeV$, we can see that the variation can decrease the value of decay width by $0.05\%$ and increase the value of the lifetime of $h_1$ to $0.05\%$. The obtained result of decay width $h_1 \to a_1 a_1$ is around $0.00633 - 0.00636(1/s)$, and the lifetime of $h_1$ is around 157.2 - 158.0 (s).

Fig.3 shows that the influence of $m_{a_1}$ on the decay width and on the lifetime of $a_1$ in the decay $a_1 \to \tau\bar{\tau}$ is relatively significant. When considering the variation $4 GeV < m_{a_1} < 8 GeV$, we see that the variation can increase the value of decay width to 5 times and decrease the value of the lifetime of $a_1$ by 5 times. The obtained result of decay width $a_1 \to \tau\bar{\tau}$ is around $0.000015 - 0.00006(1/s)$, and the lifetime of $a_1$ is around 157.2 - 158.0 (s).

Fig.4 shows that the influence of $m_{a_1}$ on the decay width and on the lifetime of $a_1$ in the decay $a_1 \to c\bar{c}$ is also relatively significant. When considering the variation $4 GeV < m_{a_1} < 8 GeV$, we see that the variation can increase the value of decay width to 3 times and decrease the
Figure 2. Influence of $m_{a_1}$ on the decay width and on the lifetime of $h_1$ in the decay $h_1 \rightarrow a_1 a_1$.

Figure 3. Influence of $m_{a_1}$ on the decay width and the lifetime of $a_1$ in the decay $a_1 \rightarrow \tau \bar{\tau}$.

Figure 4. Influence of $m_{a_1}$ on the decay width and on the lifetime of $a_1$ in the decay $a_1 \rightarrow c \bar{c}$.

value of the lifetime of $a_1$ by 3 times. The obtained result of decay width $a_1 \rightarrow c \bar{c}$ is around $4.10^{-7} - 12.10^{-7}$ (1/s), and the lifetime of $a_1$ is around $0.9.10^6 - 2.9.10^7$ (s).

If the CP violation is considered, the influence of $\phi$ (choose $m_{a_1} = 5$GeV) on the decay width and the lifetime of $a_1$ in the decay $a_1 \rightarrow c \bar{c}$ is quite significant (Fig.5).

Specifically, the influence of $\phi$ on the decay width and on the lifetime of $a_1$ in the decay $a_1 \rightarrow c \bar{c}$ is relatively significant. If we consider the variation from $0 < \phi < 0.2$ (rad), the variation can increase value of decay width to 0.6% and decrease the value of the lifetime of $a_1$ by 2%. The obtained result of decay width $a_1 \rightarrow c \bar{c}$ is about $5, 75.10^{-7} - 6,3.10^{-7}$ (1/s), and the lifetime of $a_1$ is about $1, 59.10^6 - 1,73.10^6$ (s).
Figure 5. Influence of $\phi$ on the decay width and on the lifetime of $a_1$ in the decay $a_1 \rightarrow c\bar{c}$.

Figure 6. Influence of $\phi$ on the decay width and on the lifetime of $a_1$ of the decay $h_2 \rightarrow H^+ H^-$.  

From Fig.6 we can see that the influence of $\phi$ on the decay width and on the lifetime of $h_2$ in the decay $h_2 \rightarrow H^+ H^-$ is relatively significant. If we consider the variation from $0 < \phi < 0.2\text{(rad)}$, the variation can contribute to increase the value of decay width to 60% and decrease the value of the lifetime of $h_2$ by 40%. The obtained result of decay width $h_2 \rightarrow H^+ H^-$ is about $0.4 - 1.8(1/s)$, and the lifetime of $h_2$ is about $0.55 - 3(s)$.

4. Conclusion
In the NMSSM, a single superfield is added with complex scalar field components, this leads to the appearance of seven Higgs in the NMSSM (including three even-CP Higgs $h_{1,2,3}$ ($m_{h1} < m_{h2} < m_{h3}$), two odd-CP Higgs $a_{1,2}$ ($m_{a1} < m_{a2}$) and a pair of charged Higgs $H^\pm$). We have obtained many interesting results from studying some decays of neutral Higgs in this paper:
- There are many decay channels of neutral Higgs in the NMSSM, especially the decays Higgs to Higgs
- The influence of $m_{a1}$ and $\phi$ on some decays is relatively significant. We need to pay attention to this element when studying theories as well as paying attention to the decay experiments of neutral Higgs
- The lifetime of neutral Higgs in some decays is relatively short, and this brings us the hope that we can find Higgs soon.
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