Light Pseudoscalar Higgs boson in NMSSM

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Outline

- Motivations for NMSSM
- The scenario of a very light $A_1$ in the zero mixing limit
- Decays of very light $A_1$
- Associated production with a pair of charginos
- Predictions at the ILC and LHC
Little hierarchy problem

Higgs boson mass $m_H > 115$ GeV. From the radiative corrections to $m_H^2$:

$$m_H^2 \leq m_Z^2 + \frac{3}{4\pi^2} y_t^2 m_t^2 \ln \left( \frac{m_t^2}{m_t^2} \right)$$

we require $m_t \gtrsim 1000$ GeV.

RGE effect from $M_{\text{GUT}}$ to $M_{\text{weak}}$:

$$\Delta m_{H_u}^2 \approx - \frac{3}{4\pi^2} y_t^2 m_t^2 \ln \left( \frac{M_{\text{GUT}}}{M_{\text{weak}}} \right) \approx -m_t^2$$

We need to obtain

$$O(100^2 \text{ GeV}^2) = (1000 \text{ GeV})^2 - (990 \text{ GeV})^2$$

a fine tuning of $O(10^{-2})$. 
Motivations

1. Relieve the fine tuning in the little hierarchy problem (Dermisek and Gunion 2005).

2. Additional decay modes available to the Higgs boson such that the LEP bound could be evaded.

3. A natural solution to the $\mu$ problem.

4. More particle contents in the Higgs sector and in the neutralino sector.

Here we are interested in a decouple scenario – the extra pseudoscalar boson entirely decouples from the MSSM pseudoscalar.
Fine Tuning of NMSSM

(Dermisek, Gunion 2005)

"+": dominance of $h_1 \rightarrow A_1 A_1$, "×": $m_{h_1} > 114$ GeV (evade the LEP constraint)

$$F = \text{Max}_a \left| \frac{d \log m_Z}{d \log a} \right|, \quad a = \mu, \ B_\mu, \ldots$$
Higgs Sector

Superpotential:

\[ W = \mathcal{h}_u \hat{Q} \hat{H}_u \hat{U}^c - \mathcal{h}_d \hat{Q} \hat{H}_d \hat{D}^c - \mathcal{h}_e \hat{L} \hat{H}_u \hat{E}^c + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3. \]

Higgs fields:

\[ H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \\ H_u^- \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad S. \]

Tree-level Higgs potential: \( V = V_F + V_D + V_{\text{soft}}: \)

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

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

\[ V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\lambda A_S H_u H_d + \frac{1}{3} \kappa A \kappa S^3 + \text{h.c.}] \]
In the electroweak symmetry, the Higgs fields take on VEV:

\[
\langle H_d \rangle = \frac{1}{\sqrt{2}} (v_d^0), \quad \langle H_u \rangle = \frac{1}{\sqrt{2}} (0 v_u), \quad \langle S \rangle = \frac{1}{\sqrt{2}} v_s
\]

Then the mass terms for the Higgs fields are:

\[
V = \left( H_d^+ \ H_u^+ \right) \mathcal{M}_{\text{charged}}^2 \left( \begin{array}{c} H_d^- \\ H_u^- \end{array} \right)
\]

\[
+ \frac{1}{2} \left( \Im m H_d^0 \ \Im m H_u^0 \ \Im m S \right) \mathcal{M}_{\text{pseudo}}^2 \left( \begin{array}{c} \Im m H_d^0 \\ \Im m H_u^0 \\ \Im m S \end{array} \right)
\]

\[
+ \frac{1}{2} \left( \Re e H_d^0 \ \Re e H_u^0 \ \Re e S \right) \mathcal{M}_{\text{scalar}}^2 \left( \begin{array}{c} \Re e H_d^0 \\ \Re e H_u^0 \\ \Re e S \end{array} \right)
\]
We rotate the charged fields and the scalar fields by the angle $\beta$ to project out the Goldstone modes. We are left with

$$V_{\text{mass}} = m_{H^\pm}^2 H^+ H^- + \frac{1}{2} (P_1 \ P_2) \mathcal{M}_P^2 \left( \begin{array}{c} P_1 \\ P_2 \end{array} \right) + \frac{1}{2} (S_1 \ S_2 \ S_3) \mathcal{M}_S^2 \left( \begin{array}{c} S_1 \\ S_2 \\ S_3 \end{array} \right)$$

where

$$\mathcal{M}_{P\,11}^2 = M_A^2,$$

$$\mathcal{M}_{P\,12}^2 = \mathcal{M}_{P\,21}^2 = \frac{1}{2} \cot \beta_s \left( M_A^2 \sin 2\beta - 3\kappa v_s^2 \right),$$

$$\mathcal{M}_{P\,22}^2 = \frac{1}{4} \sin 2\beta \cot^2 \beta_s \left( M_A^2 \sin 2\beta + 3\kappa v_s^2 \right) - \frac{3}{\sqrt{2}} \kappa A \kappa v_s,$$

with

$$M_A^2 = \frac{\lambda v_s}{\sin 2\beta} \left( \sqrt{2} A_\alpha + \kappa v_s \right)$$
Pseudoscalar Higgs bosons

The pseudoscalar fields, $P_i$ ($i = 1, 2$), is further rotated to mass basis $A_1$ and $A_2$, through a mixing angle:

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

with

$$
\tan \theta_A = \frac{M_{P12}^2}{M_{P11}^2 - m_{A1}^2} = \frac{1}{2} \cot \beta_s \frac{M_A^2 \sin 2\beta - 3\lambda \kappa v_s^2}{M_A^2 - m_{A1}^2}
$$

In large $\tan \beta$ and large $M_A$, the tree-level pseudoscalar masses become

$$
m_{A2}^2 \approx M_A^2 (1 + \frac{1}{4} \cot^2 \beta_s \sin^2 2\beta),
$$

$$
m_{A1}^2 \approx -\frac{3}{\sqrt{2}} \kappa v_s A_\kappa
$$
Small $m_{A_1}$ and tiny mixing $\theta_A$

A very light $m_{A_1}$ is possible if

$$\kappa \to 0 \quad \text{and/or} \quad A_\kappa \to 0$$

while keeping $v_s$ large enough. It is made possible by a PQ-type symmetry. Also, $\tan \theta_A$ in the limit of small $m_{A_1}$ becomes

$$\theta_A \simeq \tan \theta_A \simeq \frac{1}{2} \cot \beta_s \sin 2\beta \simeq \frac{v}{v_s \tan \beta}$$

For a sufficiently large $\tan \beta$ and $v_s$ we can achieve $\theta_A < 10^{-3}$. 
Parameters of NMSSM

Parameters in addition to MSSM:

\[ \lambda, \kappa \hspace{1cm} \text{(in the superpotential)} \]

\[ A_\lambda, A_\kappa \hspace{1cm} \text{(in } V_{\text{soft}} \text{)} \]

\[ v_s \]

We trade

\[ \lambda, v_s \longrightarrow \lambda, \mu_{\text{eff}} \quad \text{because} \quad \lambda v_s / \sqrt{2} = \mu \]

We also trade

\[ \kappa, A_\lambda, A_\kappa \longrightarrow M_A^2, M_{A_1}^2, \theta_A \]

Therefore, we use the following inputs:

\[ \mu, M_{A_1}^2, \theta_A, M_A^2 \]

\( \mu \) determines the chargino sector, \( M_{A_1}^2 \) and \( \theta_A \) directly determines the decay and production of \( A_1 \).
Pseudoscalar couplings with fermions

The coupling of the pseudoscalars $A_i$ to fermions

$$\mathcal{L}_{Aq\bar{q}} = -i \frac{g m_d}{2m_W} \tan \beta \left( - \cos \theta_A A_2 + \sin \theta_A A_1 \right) \bar{d}\gamma_5 d, $$

$$-i \frac{g m_u}{2m_W} \frac{1}{\tan \beta} \left( - \cos \theta_A A_2 + \sin \theta_A A_1 \right) \bar{u}\gamma_5 u$$

The coupling of $A_i$ to charginos comes from the usual Higgs-Higgsino-gaugino source and, specific to NMSSM, from the term $\lambda \hat{S}\hat{H}_u \hat{H}_d$ in the superpotential:

$$\mathcal{L}_{A\chi^+\chi^+} = i\tilde{\chi}_i^+ \left( C_{ij} P_L - C_{ji}^* P_R \right) \tilde{\chi}_j^+ A_2 + i\tilde{\chi}_i^+ \left( D_{ij} P_L - D_{ji}^* P_R \right) \tilde{\chi}_j^+ A_1,$$

where

$$C_{ij} = \frac{g}{\sqrt{2}} \left( \cos \beta \cos \theta_A U_{i1}^* V_{j2}^* + \sin \beta \cos \theta_A V_{i1}^* U_{i2}^* \right) - \frac{\lambda}{\sqrt{2}} \sin \theta_A U_{i2}^* V_{j2}^*,$$

$$D_{ij} = \frac{g}{\sqrt{2}} \left( - \cos \beta \sin \theta_A U_{i1}^* V_{j2}^* - \sin \beta \sin \theta_A V_{j1}^* U_{i2}^* \right) - \frac{\lambda}{\sqrt{2}} \cos \theta_A U_{i2}^* V_{j2}^* \cos \theta_A U_{i2}^* V_{j2}^*.$$
Decays of a light $A_1$

- $A_1$ decays through mixing with the MSSM-like $A_2$ into $q\bar{q}$, $\ell^+\ell^-$, $gg$
- $A_1 \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ and $\tilde{\chi}^0\tilde{\chi}^0$ if kinematically allowed.
- In zero-mixing and very light, via chargino loop,

$$A_1 \rightarrow \gamma\gamma$$
Partial Decay widths

The partial widths of $A_1$ into $f\bar{f}$, $\gamma\gamma$ and $gg$ are given by

$$\Gamma(A_1 \rightarrow f\bar{f}) = N_c \frac{G_\mu m_f^2}{4\sqrt{2}\pi} (\lambda_f^{A_1})^2 M_{A_1} (1 - 4m_f^2/M_{A_1}^2)^{1/2}$$

$$\Gamma(A_1 \rightarrow \gamma\gamma) = \frac{G_\mu \alpha^2 M_{A_1}^3}{128\sqrt{2}\pi^3} \left| \sum_{f} N_c Q_f^2 \lambda_f^{A_1} f(\tau_f) + 2 \sum_{i=1}^{2} \frac{M_W}{m_{\chi_i^\pm}} \lambda_{\chi_i}^{A_1} f(\tau_{\chi_i^\pm}) \right|^2$$

$$\Gamma(A_1 \rightarrow gg) = \frac{G_\mu \alpha_s^2 M_{A_1}^3}{64\sqrt{2}\pi^3} \left| \sum_{q} \lambda_f^{A_1} f(\tau_q) \right|^2$$

where $\lambda_{d,l}^{A_1} = \sin \theta_A \tan \beta$, $\lambda_u^{A_1} = \sin \theta_A \cot \beta$, and the chargino-$A_1$ coupling $\lambda_{\chi_i}^{A_1} = -D_{ii}/g$. 
$\text{Br}(A_1^{\pm} \rightarrow xx)$

- $M_{A_1} = 0.1 \text{ GeV}$, $\tan \beta = 10$
  - $\sin \theta_A$
  - $\cos \theta_A$

- $M_{A_1} = 5 \text{ GeV}$, $\tan \beta = 10$
  - $\sin \theta_A$
  - $\cos \theta_A$

- $M_{A_1} = 15 \text{ GeV}$, $\tan \beta = 30$
  - $\sin \theta_A$
  - $\cos \theta_A$

$\text{MA}_1 = 0.1 \text{ GeV}$, $\tan \beta = 10$

$\text{MA}_1 = 0.1 \text{ GeV}$, $\tan \beta = 30$

$\text{MA}_1 = 5 \text{ GeV}$, $\tan \beta = 10$

$\text{MA}_1 = 15 \text{ GeV}$, $\tan \beta = 30$
\[ \text{Br}(A_1 \to xx) \]

- $\epsilon = 10^{-4}$, $\tan \beta = 3$
- $\epsilon = 10^{-3}$
Production of the light $A_1$

Via decay of the Higgs boson (Dermisek, Gunion 2005; Dobrescu, Landsberg, Matchev 2001)

\[ h \rightarrow A_1 A_1 \rightarrow 4\gamma \]

Since $A_1$ is very light and so energetic that the two photons are very collimated. It may be difficult to resolve them.

In the limit of zero mixing, the couplings of $A_1$ to higgsinos are unsuppressed, from the term $\lambda S H_u H_d$ in the superpotential.

We consider the associated production of $A_1$ with a chargino pair. The $A_1$ radiates off the chargino leg and so will be less energetic. The two photons from $A_1$ decay is easier to be resolved.
Associated production with a pair of charginos

The charginos can decay into a charged lepton or a pair of jets plus missing energy. Therefore, the final state can be

- 2 charged leptons + a pair of photons + $E_T$
- A charged lepton + 2 jets + a pair of photons + $E_T$
- 4 jets + a pair of photons

The leptonic branching ratio can be large if $\tilde{\nu}$ or $\tilde{\ell}$ is light.
Cross Section at $e^+e^-$ colliders

$e^-e^+ \rightarrow \chi_1^+ \chi_1^- A_1$

$E_{CM} = 0.5$ TeV

$\mu = 150$ GeV, $M_2 = 500$ GeV

$\lambda = 1$, $\sin \theta_A = 10^{-4}$

$\mu = 150$ GeV, $M_2 = 500$ GeV, $\tan \beta = 10$, $\lambda = 1$, $\sin \theta_A = 10^{-4}$
Cross Section at the LHC

\[ \mu = 150 \text{ GeV}, \quad M_2 = 500 \text{ GeV}, \quad \tan \beta = 10, \quad \lambda = 1, \quad \sin \theta_A = 10^{-4}. \]
Conclusions

1. NMSSM can have a very light pseudoscalar Higgs boson, which has very small mixing with the MSSM pseudoscalar.

2. Such a light $A_1$ may be hidden in the Higgs decay $h \to A_1 A_1$ such that the LEP bound on the Higgs is evaded.

3. It can survive the constraints from $K$ and $B$ decays, such as $b \to s A_1$, $B_s \to \mu^+ \mu^-$, $B - \overline{B}$ mixing, $\Upsilon \to A_1 \gamma$ by taking the mixing angle $\theta_A \to 0$.

4. Associated production of $A_1$ with a chargino or a neutralino pair can reveal the $A_1$ even in the zero mixing.

5. The signature can be: $2\ell + 2 \gamma + \not{E}_T$. The event rates are sizable for detectability.