Light Pseudoscalar Higgs boson
in
NMSSM

Kingman Cheung

SUSY06, Irvine

(with Abdesslam Arhrib, Tie-Jiun Hou, Kok-Wee Song, hep-ph/0606114)

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:

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

we require $m_{\tilde{t}} \gtrsim 1000\text{GeV}$.

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

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

We need to obtain

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

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

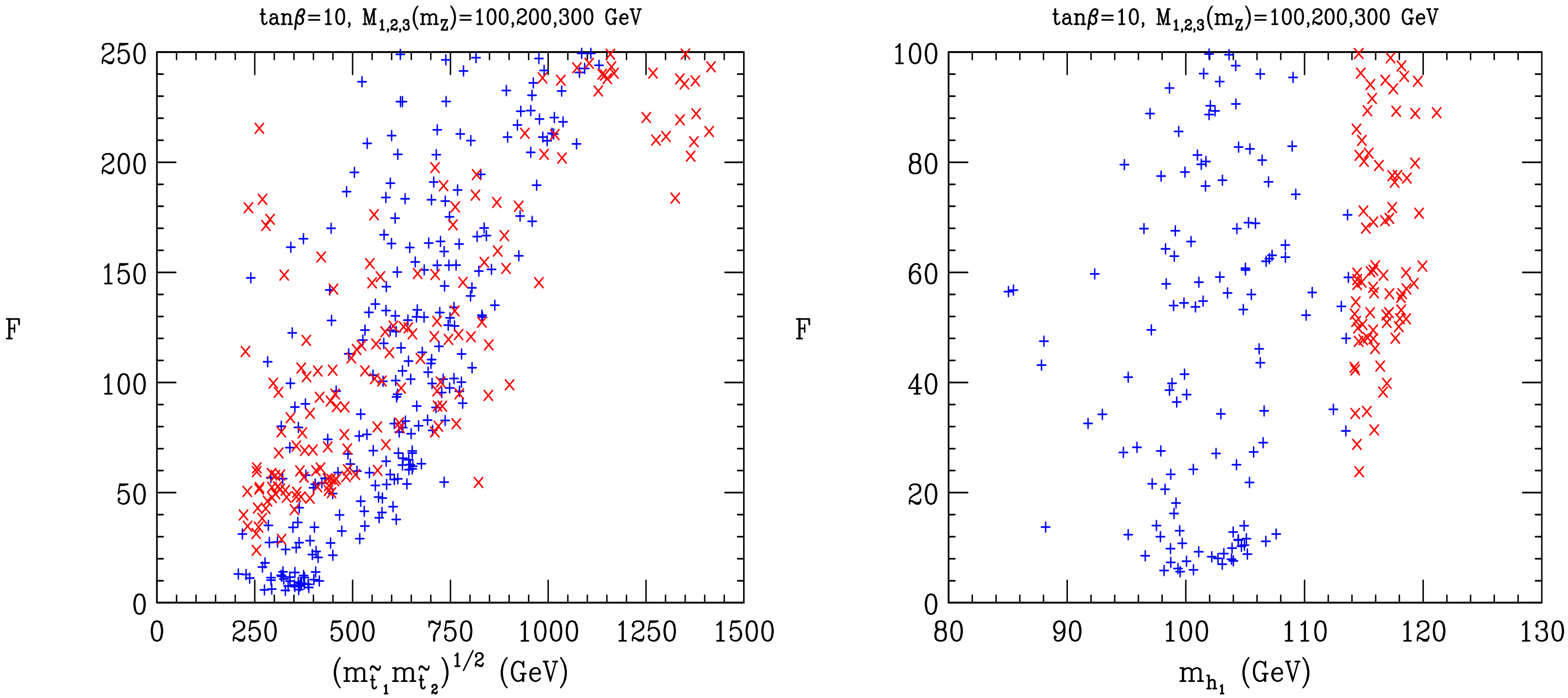
Motivations

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 μ 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 $h_1 \to A_1 A_1$, "×": $m_{h_1} > 114$ GeV (evade the LEP constraint)

$$F = \mathrm{Max}_a \left| \frac{d \log m_Z}{d \log a} \right| , \qquad a = \mu,\ B_\mu, \ldots$$

Higgs Sector

Superpotential:

$$W = \mathbf{h_u} \hat{Q}\, \hat{H}_u\, \hat{U}^c - \mathbf{h_d} \hat{Q}\, \hat{H}_d\, \hat{D}^c - \mathbf{h_e} \hat{L}\, \hat{H}_d\, \hat{E}^c + \lambda \hat{S}\, \hat{H}_u\, \hat{H}_d + \frac{1}{3} \kappa\, \hat{S}^3 .$$

Higgs fields:

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

Tree-level Higgs potential: $V = V_F + V_D + V_{\rm soft}$:

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

In the electroweak symmetry, the Higgs fields take on VEV:

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \binom{v_d}{0}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \binom{0}{v_u}, \qquad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

Then the mass terms for the Higgs fields are:

$$\begin{aligned} V &= \begin{pmatrix} H_d^+ & H_u^+ \end{pmatrix} \mathcal{M}^2_{\rm charged} \begin{pmatrix} H_d^- \\ H_u^- \end{pmatrix} \\ &+ \frac{1}{2} \begin{pmatrix} \Im m H_d^0 & \Im m H_u^0 & \Im m S \end{pmatrix} \mathcal{M}^2_{\rm pseudo} \begin{pmatrix} \Im m H_d^0 \\ \Im m H_u^0 \\ \Im m S \end{pmatrix} \\ &+ \frac{1}{2} \begin{pmatrix} \Re e H_d^0 & \Re e H_u^0 & \Re e S \end{pmatrix} \mathcal{M}^2_{\rm scalar} \begin{pmatrix} \Re e H_d^0 \\ \Re e H_u^0 \\ \Re e S \end{pmatrix} \end{aligned}$$

We rotate the charged fields and the scalar fields by the angle β to project out the Goldstone modes. We are left with

$$V_{\rm mass} = m^2_{H^\pm} H^+ H^- + \frac{1}{2}\,(P_1 \;\; P_2)\mathcal{M}^2_P \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} + \frac{1}{2}\,(S_1 \;\; S_2 \;\; S_3)\mathcal{M}^2_S \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

where

$$\begin{aligned}
\mathcal{M}^2_{P\,11} &= M_A^2 \,, \\
\mathcal{M}^2_{P\,12} &= \mathcal{M}^2_{P\,21} = \frac{1}{2}\cot\beta_s \left(M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2 \right) \,, \\
\mathcal{M}^2_{P\,22} &= \frac{1}{4}\sin 2\beta \cot^2\beta_s \left(M_A^2 \sin 2\beta + 3\lambda\kappa v_s^2 \right) - \frac{3}{\sqrt{2}}\kappa A_\kappa v_s \,,
\end{aligned}$$

with

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

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

$$\tan\theta_A = \frac{\mathcal{M}^2_{P\,12}}{\mathcal{M}^2_{P\,11} - m^2_{A_1}} = \frac{1}{2}\cot\beta_s\,\frac{M_A^2\sin 2\beta - 3\lambda\kappa v_s^2}{M_A^2 - m^2_{A_1}}$$

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

$$\begin{aligned} m^2_{A_2} &\approx M_A^2\,(1 + \frac{1}{4}\cot^2\beta_s\sin^2 2\beta), \\ m^2_{A_1} &\approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa \end{aligned}$$

Small m_{A_1} and tiny mixing θ_A

A very light m_{A_1} is possible if

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

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:

$\lambda,\ \kappa$	(in the superpotential)
$A_\lambda,\ A_\kappa$	(in $V_{\rm soft}$)
v_s	

We trade

$$\lambda,\ v_s \longrightarrow \lambda,\ \mu_{\rm eff} \qquad \text{because} \qquad \lambda v_s/\sqrt{2} = \mu$$

We also trade

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

Therefore, we use the following inputs:

$$\mu,\ M_{A_1}^2,\ \theta_A,\ M_A^2$$

μ determines the chargino sector, $M_{A_1}^2$ and θ_A directly determines the decay and production of A_1.

Pseudoscalar couplings with fermions

The coupling of the pseudoscalars A_i to fermions

$$\mathcal{L}_{Aq\bar{q}} = -i\frac{gm_d}{2m_W}\tan\beta\,(-\cos\theta_A A_2 + \sin\theta_A A_1)\,\bar{d}\gamma_5 d\,, \\ -i\frac{gm_u}{2m_W}\frac{1}{\tan\beta}\,(-\cos\theta_A A_2 + \sin\theta_A A_1)\,\bar{u}\gamma_5 u$$

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:

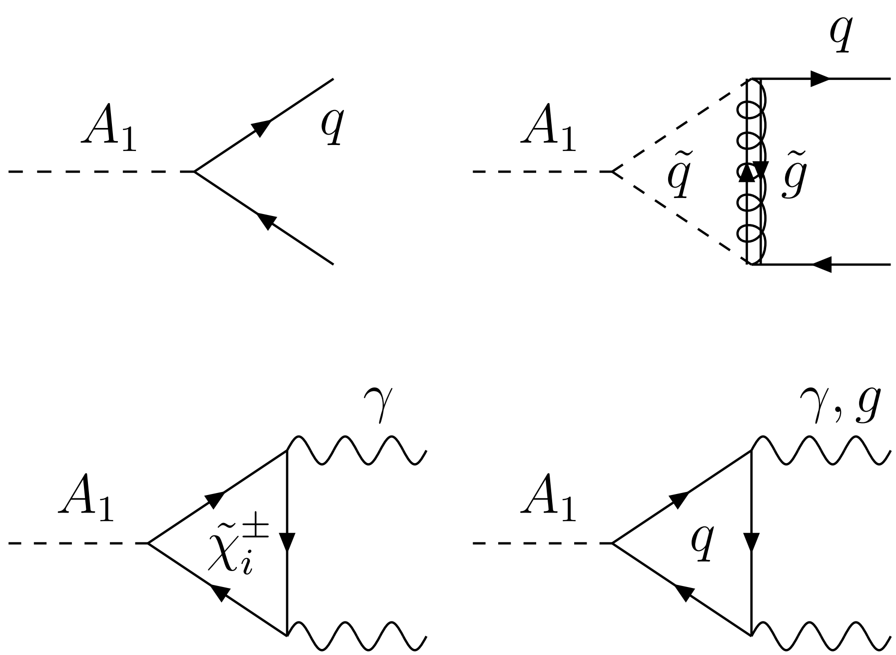
$$\mathcal{L}_{A\chi^+\chi^+} = i\overline{\widetilde{\chi}_i^+}\left(C_{ij}P_L - C^*_{ji}P_R\right)\widetilde{\chi}_j^+ A_2 + i\overline{\widetilde{\chi}_i^+}\left(D_{ij}P_L - D^*_{ji}P_R\right)\widetilde{\chi}_j^+ A_1\,,$$

where

$$C_{ij} = \frac{g}{\sqrt{2}}\left(\cos\beta\,\cos\theta_A\,U^*_{i1}\,V^*_{j2} + \sin\beta\,\cos\theta_A\,V^*_{j1}\,U^*_{i2}\right) - \frac{\lambda}{\sqrt{2}}\sin\theta_A\,U^*_{i2}V^*_{j2}\,,$$

$$D_{ij} = \frac{g}{\sqrt{2}}\left(-\cos\beta\,\sin\theta_A\,U^*_{i1}\,V^*_{j2} - \sin\beta\,\sin\theta_A\,V^*_{j1}\,U^*_{i2}\right) - \frac{\lambda}{\sqrt{2}}\cos\theta_A\,U^*_{i2}V^*_{j2}$$

Decays of a light A_1



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

$$A_1 \to \gamma\gamma$$

Partial Decay widths

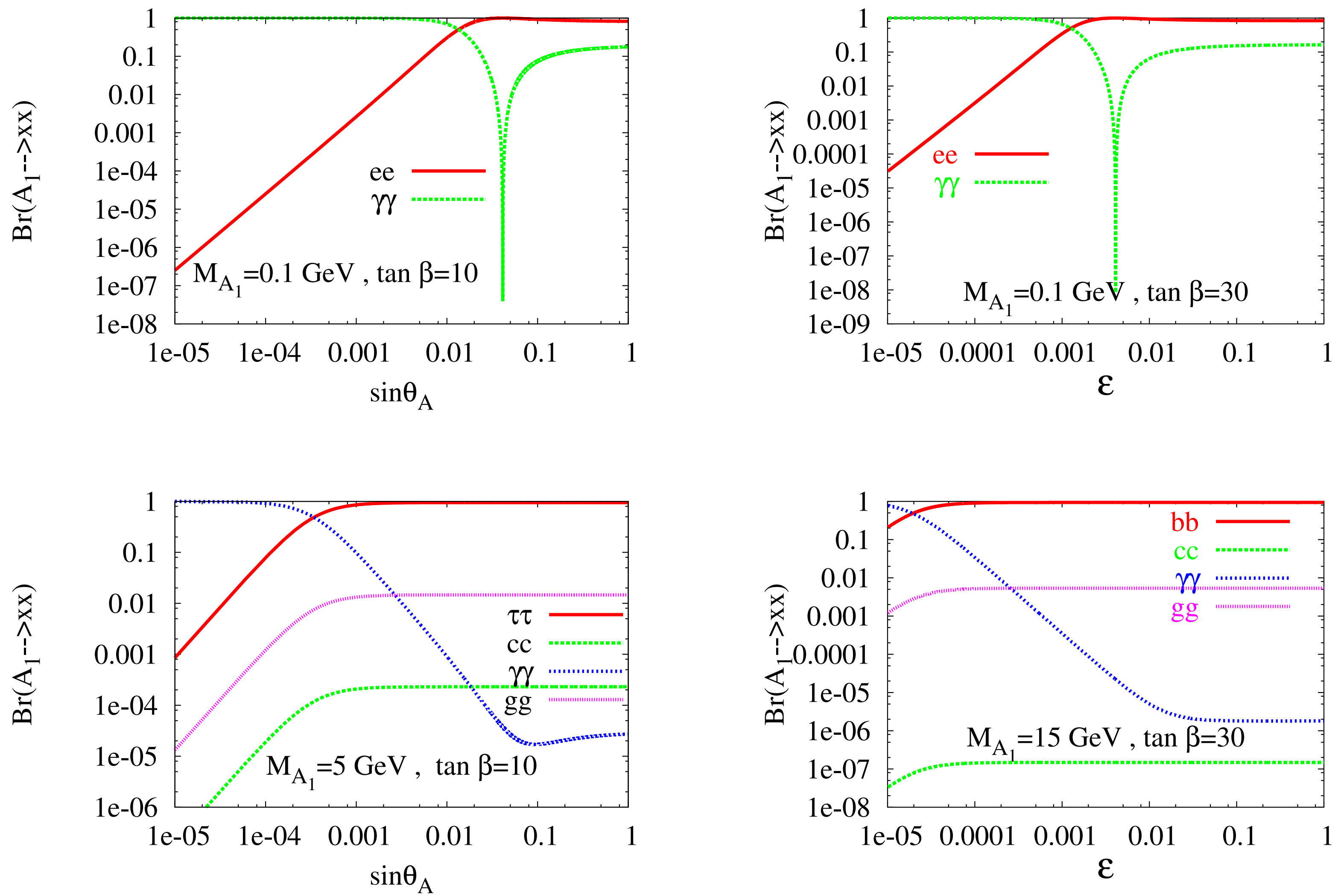
The partial widths of A_1 into $f\bar{f}$, $\gamma\gamma$ and gg are given by

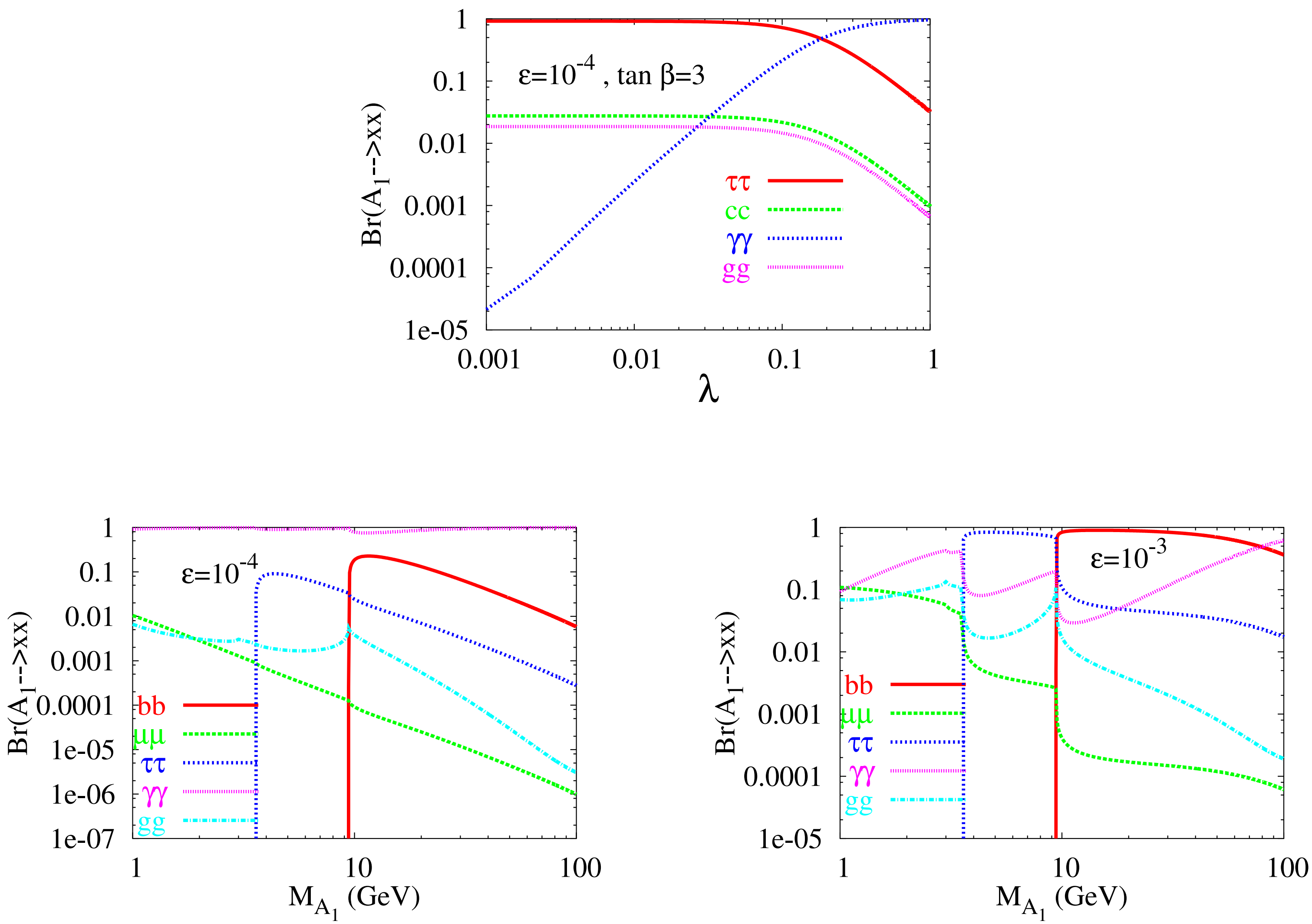
$$\Gamma(A_1 \to f\bar{f}) = N_c \frac{G_\mu m_f^2}{4\sqrt{2}\pi} (\lambda_f^{A_1})^2 M_{A_1} (1 - 4m_f^2/M_{A_1}^2)^{1/2}$$

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

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

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 $\lambda_{\chi_i}^{A_1} = -D_{ii}/g$.


Br(A1-->xx)
sinθA
ee
γγ
MA1=0.1 GeV , tan β=10
ε
MA1=0.1 GeV , tan β=30
ττ
cc
gg
MA1=5 GeV , tan β=10
bb
MA1=15 GeV , tan β=30


ε=10^-4 , tan β=3
Br(A1-->xx)
λ
ττ
cc
γγ
gg
ε=10^-4
ε=10^-3
bb
μμ
MA1 (GeV)

Production of the light A_1

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

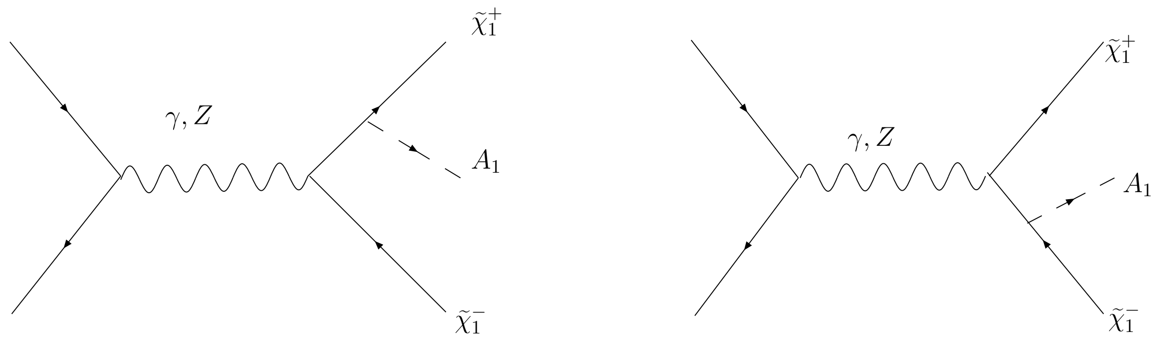
$$h \to A_1 A_1 \to 4\gamma$$

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

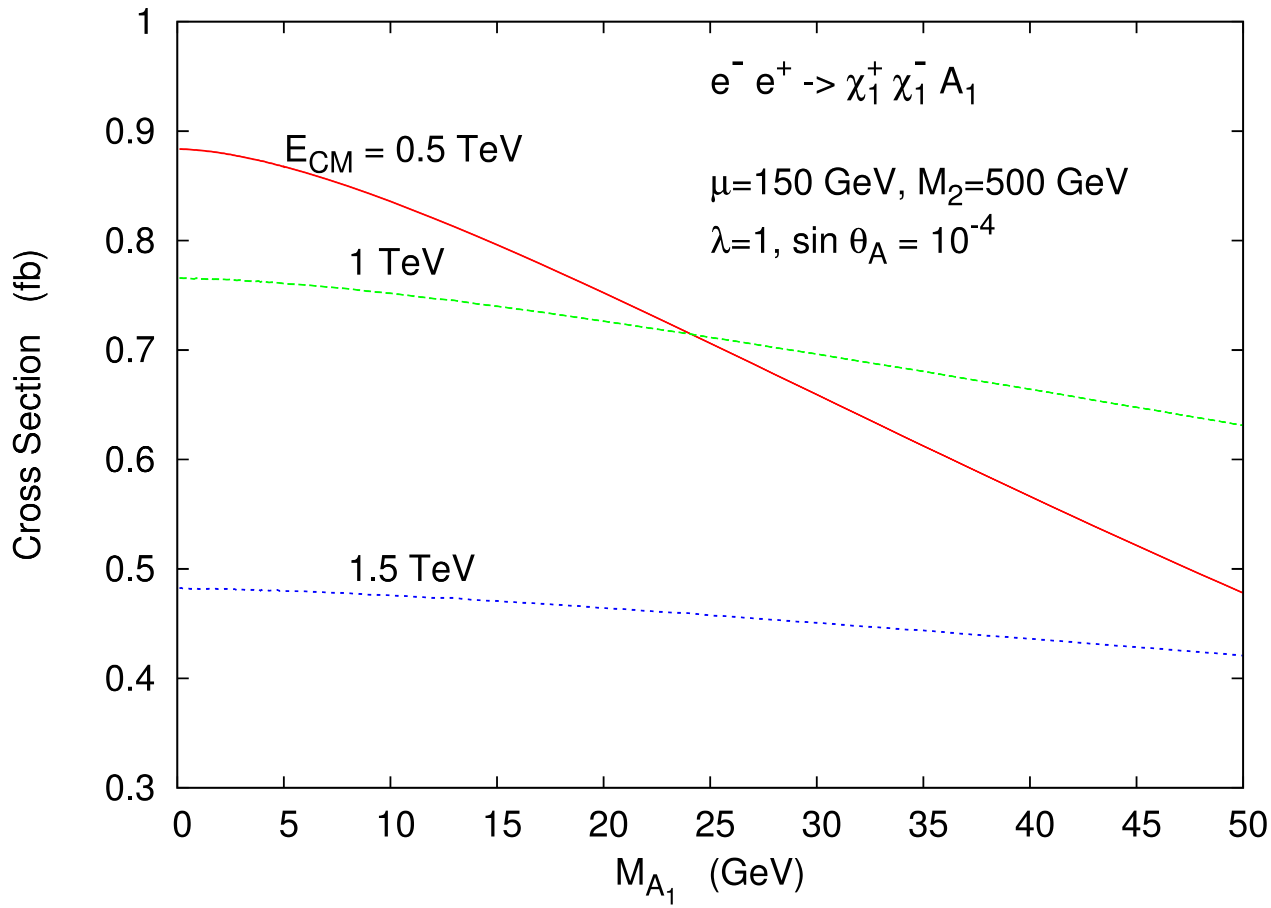


The charginos can decay into a charged lepton or a pair of jets plus missing energy. Therefore, the final state can be

- 2 charged leptons + a pair of photons + $\not{E}_T$
- A charged lepton + 2 jets + a pair of photons + $\not{E}_T$
- 4 jets + a pair of photons

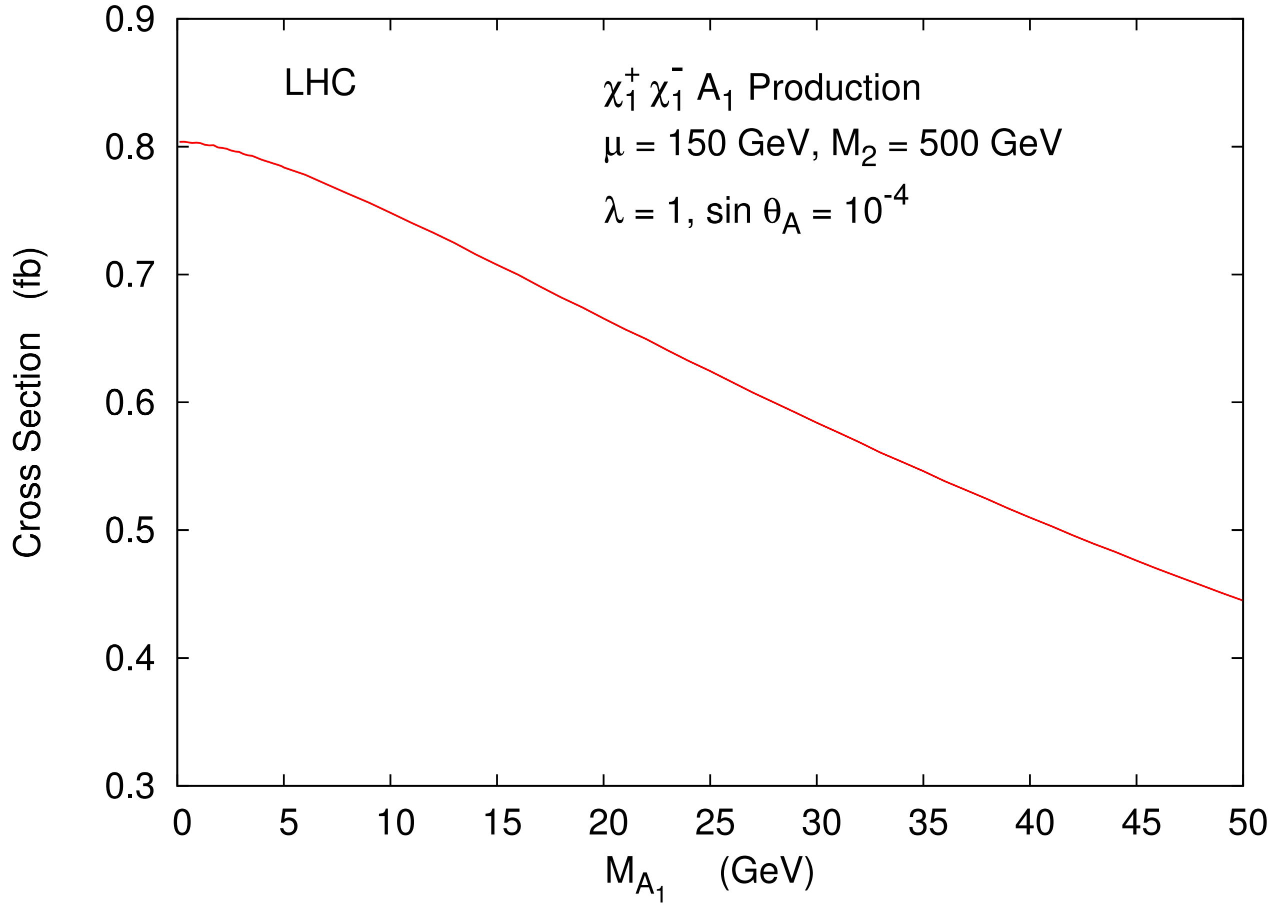
The leptonic branching ratio can be large if $\tilde{\nu}$ or $\tilde{\ell}$ is light.

Cross Section at e^+e^- colliders



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

Cross Section at the LHC



$\mu = 150$ GeV, $M_2 = 500$ GeV, $\tan\beta = 10$, $\lambda = 1$, $\sin\theta_A = 10^{-4}$.

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.