

Light Pseudoscalar Higgs boson  
in  
NMSSM

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## Outline

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

## Little hierarchy problem in SUSY

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

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

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

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

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

We need to obtain

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

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

## Various approaches to the Little hierarchy problem

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- Little Higgs models (Arkani et al.), with  $T$  parity (Cheng, Low)
- Twin Higgs models (Chacko et al.)
- Reducing the  $h \rightarrow b\bar{b}$  branching ratio, or the  $ZZh$  couplings, such that the LEP II production rate is reduced. **To evade the LEP II bound.**
- Add singlets to MSSM  $\rightarrow$  NMSSM or other variants.
- By **reducing the RGE effects on  $m_H^2, \mu, B$  terms** (e.g., mixed modulus-anomaly mediation, K. Choi et al.)

## Motivations for NMSSM

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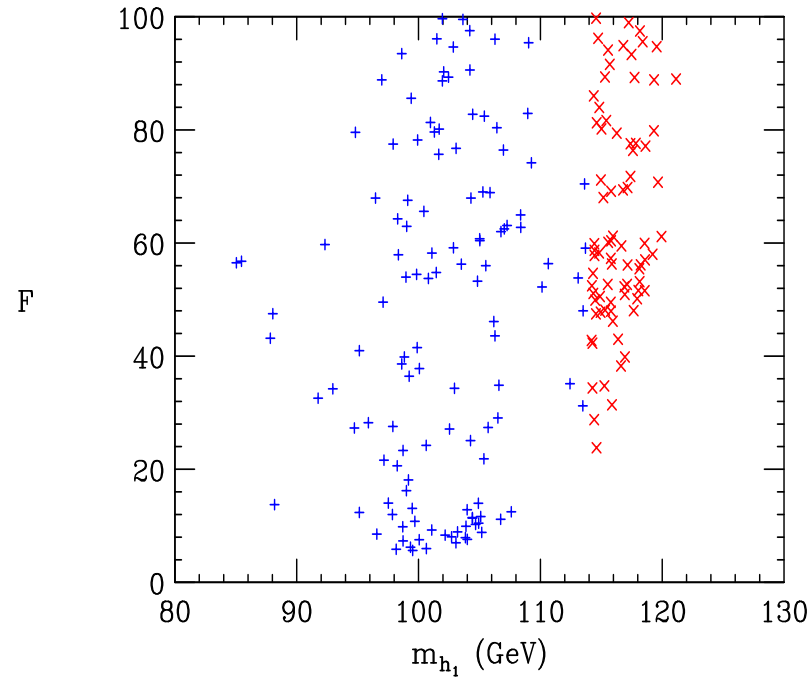
1. Relieve the fine tuning in the little hierarchy problem (Dermisek and Gunion 2005).
2. Additional decay modes available to the Higgs boson such that the LEP bound could be evaded.
3. A natural solution to the  $\mu$  problem.
4. More particle contents in the Higgs sector and in the neutralino sector.

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)

$\tan\beta=10, M_{1,2,3}(m_Z)=100,200,300 \text{ GeV}$



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

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

## The NMSSM Superpotential

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Superpotential:

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

When the scalar field  $S$  develops a VEV  $\langle S \rangle = v_s / \sqrt{2}$ , the  $\mu$  term is generated

$$\mu_{\text{eff}} = \lambda \frac{v_s}{\sqrt{2}}$$

## Higgs Sector

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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:  $V = V_F + V_D + V_{\text{soft}}$ :

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

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

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.}]$$

Minimization of the Higgs potential links  $M_{H_u}^2$ ,  $M_{H_d}^2$ ,  $M_S^2$  with VEV's of  $H_u, H_d, S$ .



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

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

Then the mass terms for the Higgs fields are:

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

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

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

where

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

with

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

The charged Higgs mass:

$$M_{H^\pm}^2 = M_A^2 + M_W^2 - \frac{1}{2} \lambda^2 v^2$$

## Pseudoscalar Higgs bosons

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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

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

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

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

Small  $m_{A_1}$  and tiny mixing  $\theta_A$

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

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

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  $\theta_A < 10^{-3}$ .

- Or we can set

$$M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2 = \sqrt{2}\lambda v_s (A_\lambda - \sqrt{2}\kappa v_s) \approx 0$$

to get an even smaller  $\theta_A$ .

## Parameters of NMSSM

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Parameters in addition to MSSM:

$$\begin{array}{ll} \lambda, \kappa & \text{(in the superpotential)} \\ A_\lambda, A_\kappa & \text{(in } V_{\text{soft}}) \\ v_s & \end{array}$$

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

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The coupling of the pseudoscalars  $A_i$  to fermions

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

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:

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

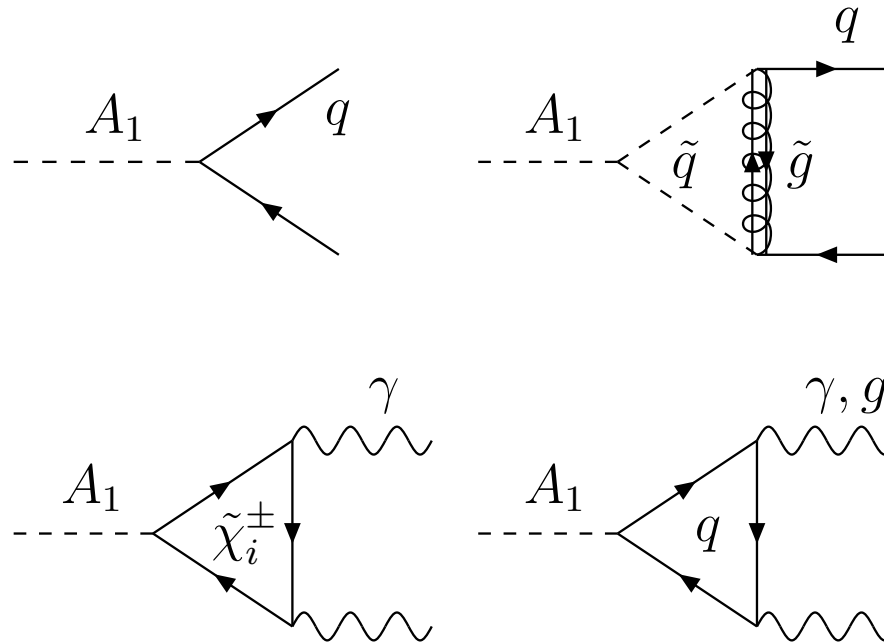
where

$$\begin{aligned} C_{ij} &= \frac{g}{\sqrt{2}} \left( \cos \beta \cos \theta_A U_{i1}^* V_{j2}^* + \sin \beta \cos \theta_A V_{j1}^* U_{i2}^* \right) - \frac{\lambda}{\sqrt{2}} \sin \theta_A U_{i2}^* V_{j2}^*, \\ D_{ij} &= \frac{g}{\sqrt{2}} \left( -\cos \beta \sin \theta_A U_{i1}^* V_{j2}^* - \sin \beta \sin \theta_A V_{j1}^* U_{i2}^* \right) - \frac{\lambda}{\sqrt{2}} \cos \theta_A U_{i2}^* V_{j2}^* \end{aligned}$$

## Phenomenology of a light pseudoscalar boson

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- Decay of  $A_1$
- $H \rightarrow A_1 A_1$
- Associated production of  $A_1$

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

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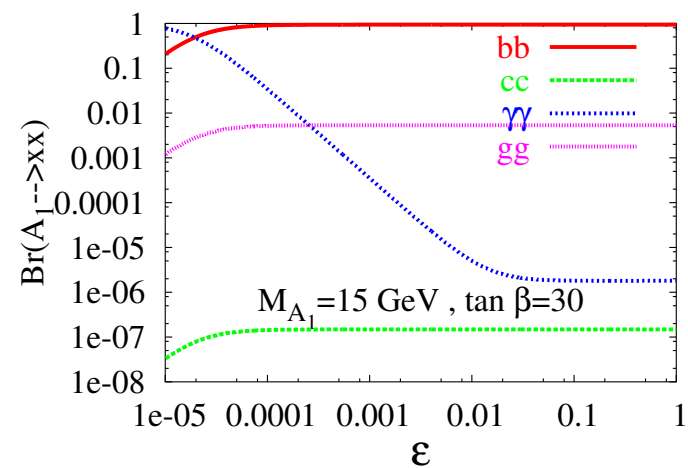
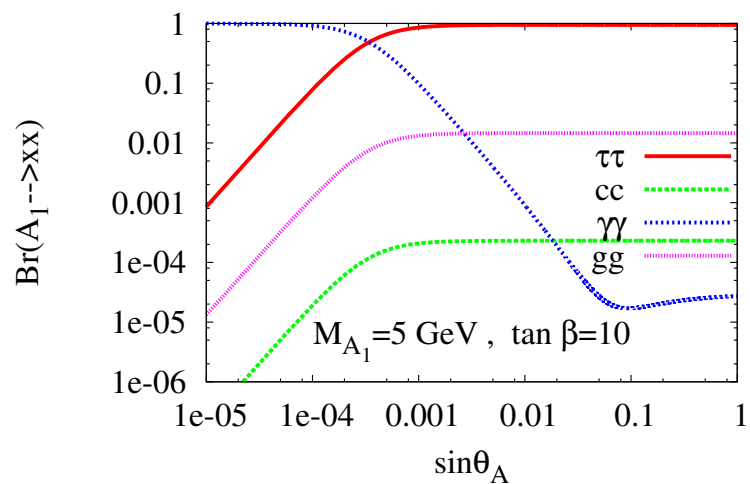
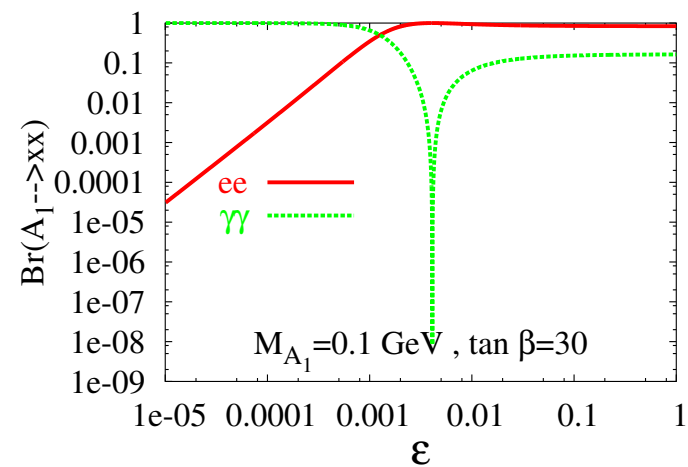
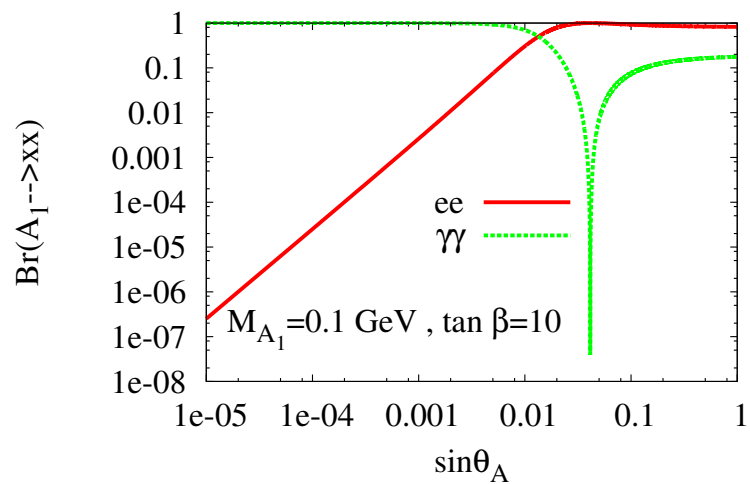
The partial widths of  $A_1$  into  $f\bar{f}$ ,  $\gamma\gamma$  and  $gg$  are given by

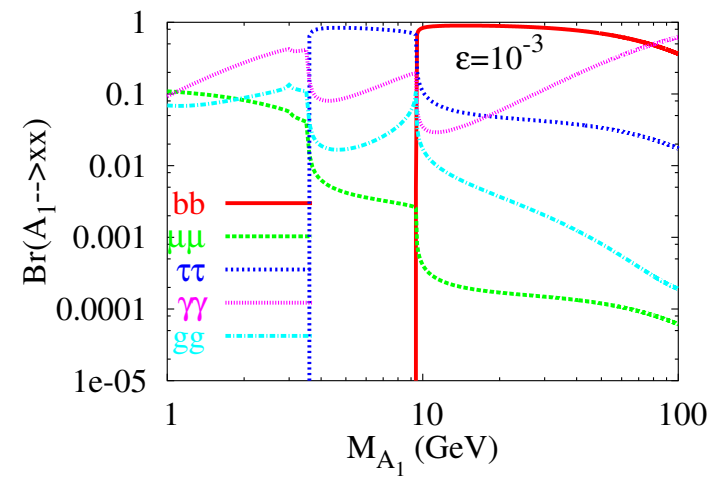
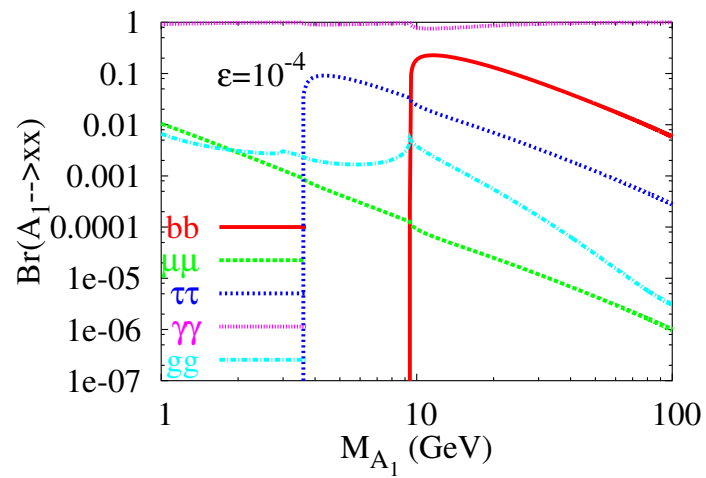
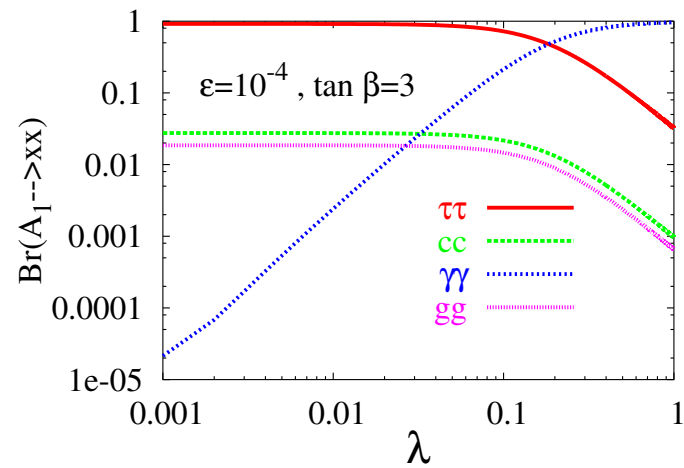
$$\Gamma(A_1 \rightarrow f\bar{f}) = N_c \frac{G_\mu m_f^2}{4\sqrt{2}\pi} (\lambda_f^{A_1})^2 M_{A_1} (1 - 4m_f^2/M_{A_1}^2)^{1/2}$$

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

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

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





Production:  $H \rightarrow A_1 A_1$

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Even in the zero-mixing limit, the  $A_1$  can still couple to the Higgs boson via  $\lambda A_\lambda S H_u H_d$  term.

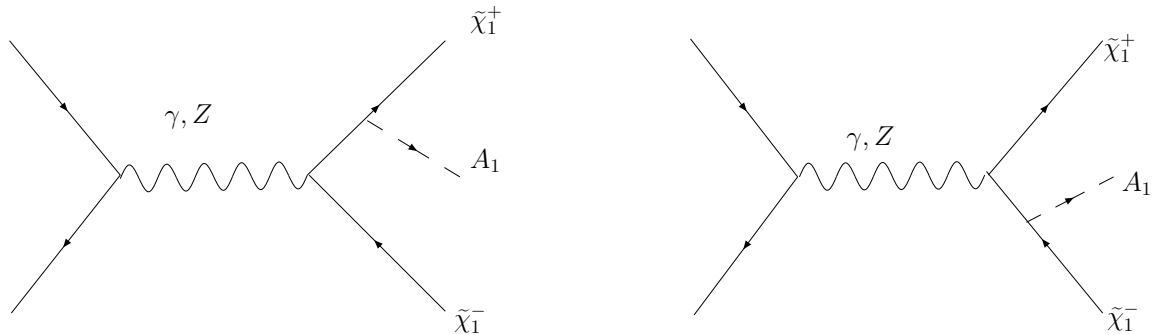
So  $A_1$  can be produced in the decay of the Higgs boson (Dermisek, Gunion 2005; Dobrescu, Landsberg, Matchev 2001)

$$h \rightarrow A_1 A_1 \rightarrow 4\gamma, 4\tau$$

Since  $A_1$  is very light and so energetic that **the two photons are very collimated. It may be difficult to resolve them.** Effectively, like  $h \rightarrow \gamma\gamma$ .

If the mixing angle is larger than  $10^{-3}$  and  $A_1$  is heavier than a few GeV, it can decay into  $\tau^+ \tau^-$ . Thus, **4 $\tau$ s in the final state** (Graham, Pierce, Wacker 2006).

## Associated production with a pair of charginos



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.

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 +  $\cancel{E}_T$
- A charged lepton + 2 jets + a pair of photons +  $\cancel{E}_T$
- 4 jets + a pair of photons

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

## Rate dependence

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In the zero-mixing limit, the size of  $\tilde{\chi}_1^+$ - $A_1$  coupling:

$$-\frac{\lambda}{\sqrt{2}} \cos \theta_A U_{12}^* V_{12}^*$$

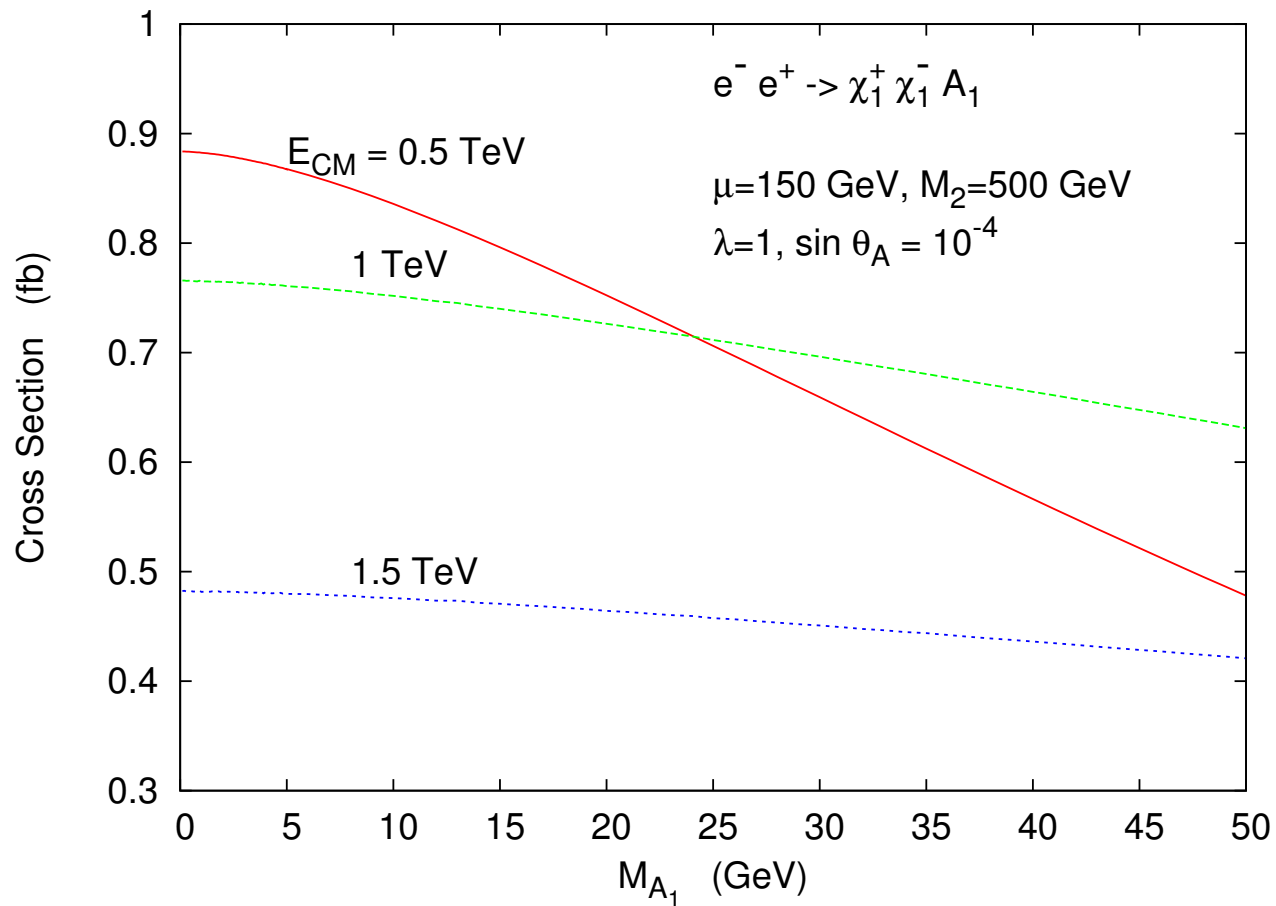
It implies a larger higgsino component of  $\tilde{\chi}_1^+$  can enhance the cross section. We choose

$$\mu = 150 \text{ GeV} \quad M_2 = 500 \text{ GeV}$$

The other parameters are

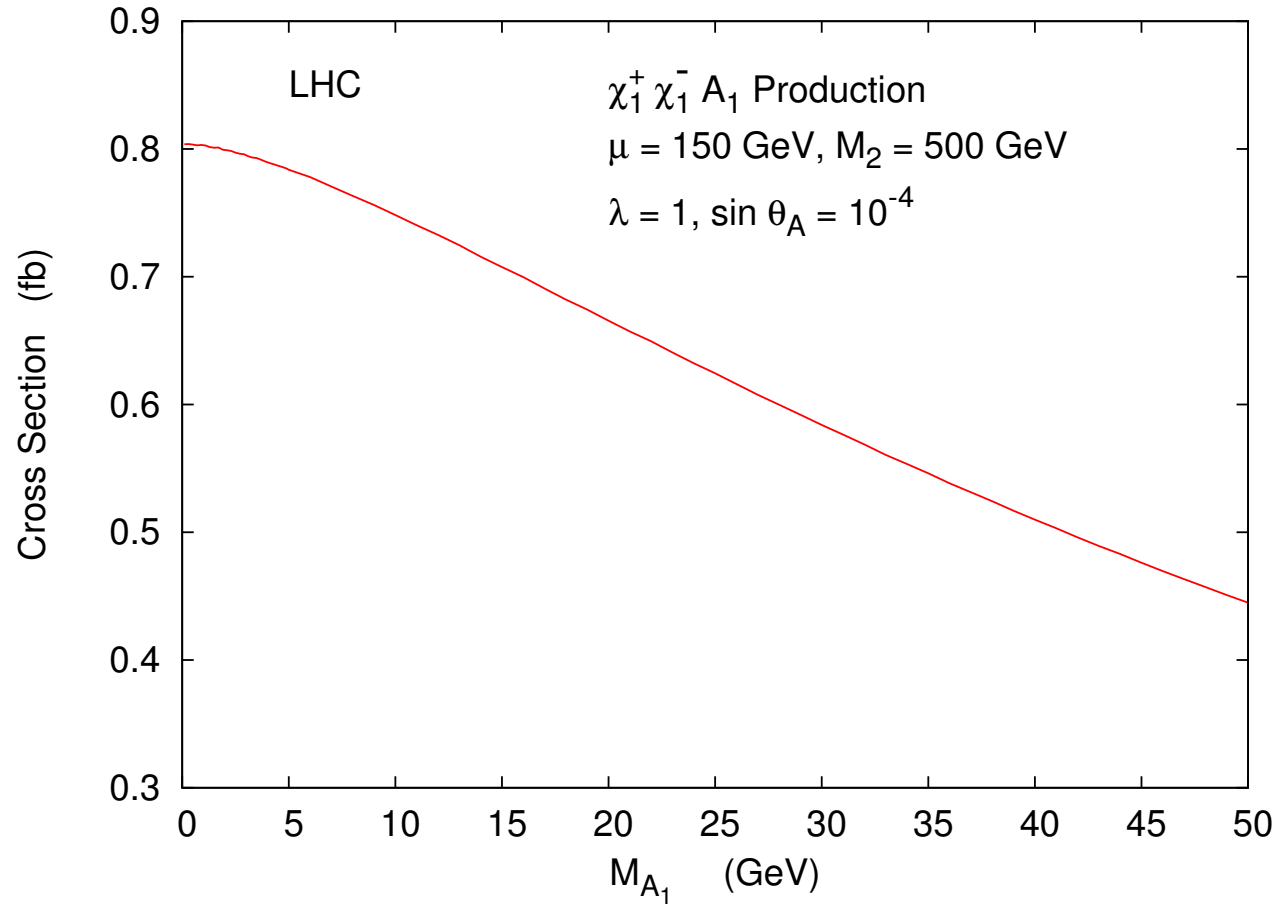
$$\lambda = 1, \quad \sin \theta_A = 10^{-4}, \quad \tan \beta = 10$$

Little dependence on  $\tan \beta$  and  $\sin \theta_A$  as long as it is small.

Cross Section at  $e^+e^-$  colliders

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

## Cross Section at the LHC



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



## Resolving the two photons

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The crucial part is to resolve the  $\gamma\gamma$  pair from  $A_1$  decay, otherwise it would look a single photon. We impose

$$p_{T_\gamma} > 10 \text{ GeV} \quad |\eta_\gamma| < 2.6$$

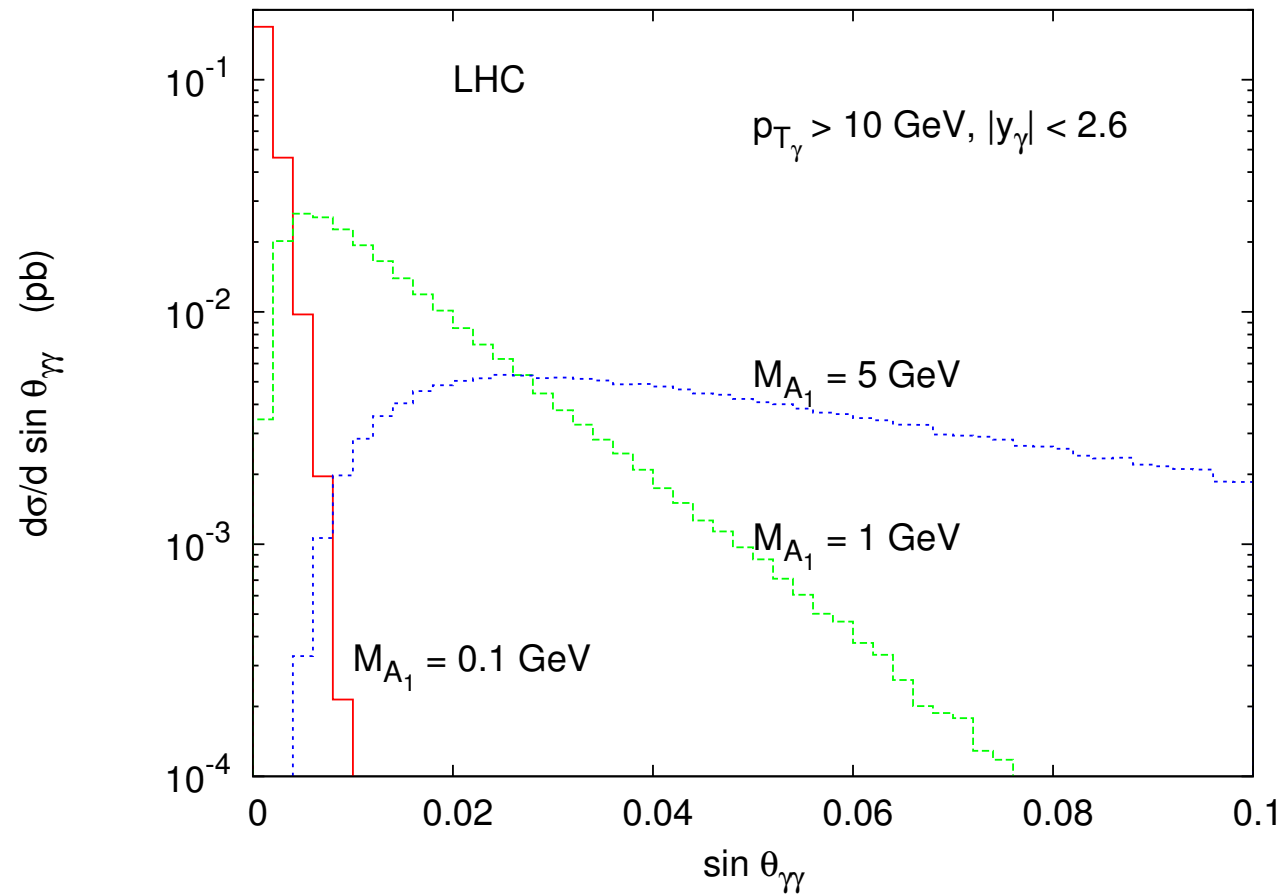
which are in accord with the ECAL of the CMS detector

The “preshower” detector of the ECAL has a strong resolution to resolve the  $\gamma\gamma$  pair. It is intended to separate the background  $\pi^0 \rightarrow \gamma\gamma$  decay from the  $H \rightarrow \gamma\gamma$ .

It has a resolution as good as 6.9 mrad

Then we look at the angular separation of the two photons

## Opening angle distribution



Cross sections in fb for associated production of  $\tilde{\chi}_1^+ \tilde{\chi}_1^- A_1$  followed by  $A_1 \rightarrow \gamma\gamma$ . The cuts applied to the two photons are:  $p_{T\gamma} > 10$  GeV,  $|y_\gamma| < 2.6$ , and  $\theta_{\gamma\gamma} > 10$  mrad.

$M_{A_1}$ ( GeV)	Cross Section (fb)
0.1	0.0
0.2	0.011
0.3	0.0405
0.4	0.078
0.5	0.12
1	0.26
2	0.38
3	0.42
4	0.44
5	0.44

## Conclusions

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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  $h \rightarrow A_1 A_1$  such that the LEP bound on the Higgs is evaded.
3. It can survive the constraints from  $K$  and  $B$  decays, such as  $b \rightarrow s A_1$ ,  $B_s \rightarrow \mu^+ \mu^-$ ,  $B - \bar{B}$  mixing,  $\Upsilon \rightarrow A_1 \gamma$  by taking the mixing angle  $\theta_A \rightarrow 0$ .
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:  $2\ell + 2\gamma + \cancel{E}_T$ . The event rates are sizable for detectability.