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
- 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

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 $m_{\tilde{t}} \gtrsim 1000\mathrm{GeV}$.

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

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

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

Various approaches to the Little hierarchy problem

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

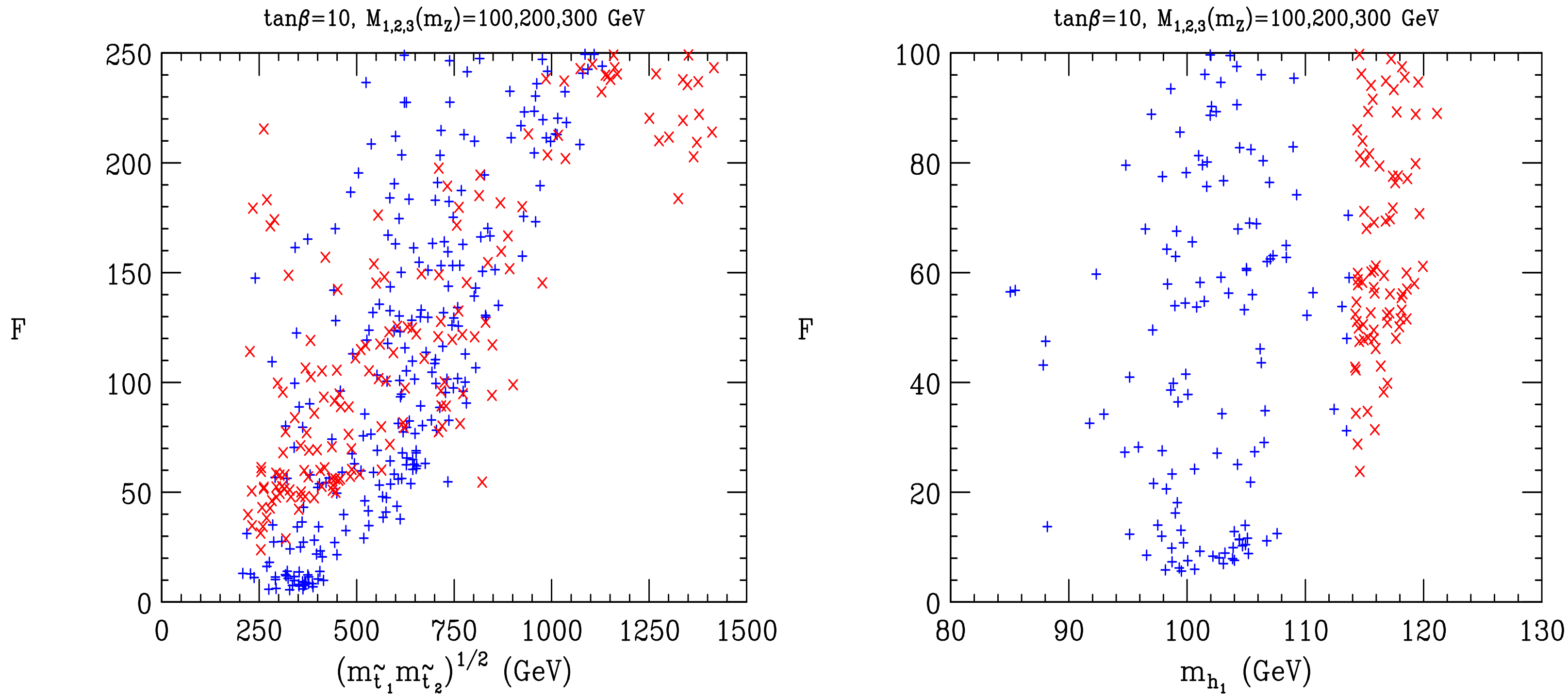
Motivations for NMSSM

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)

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

The NMSSM Superpotential

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 μ term is generated

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

Note that the W has a discrete Z_3 symmetry, which is used to avoid the $\hat{S}$ and $\hat{S}^2$ terms.

The Z_3 symmetry may cause domain-wall problem, which can be solved by introducing nonrenormalizable operators at the Planck scale to break the Z_3 symmetry through the harmless tadpoles that they generate.

Higgs Sector

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

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

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:

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

Then the mass terms for the Higgs fields are:

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

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

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

The charged Higgs mass:

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

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:

$$\lambda,\ \kappa \qquad \text{(in the superpotential)}$$

$$A_\lambda,\ A_\kappa \qquad \text{(in } V_{\rm soft}\text{)}$$

$$v_s$$

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

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

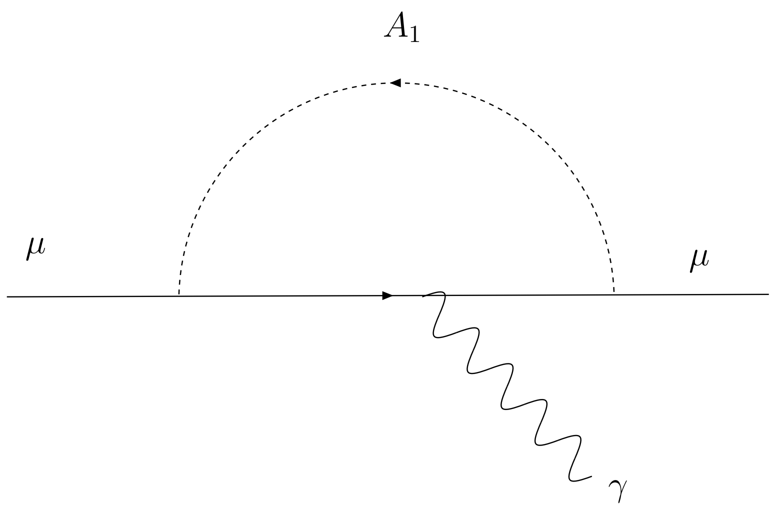
$$D_{ij} = \frac{g}{\sqrt{2}}\left(-\cos\beta\,\sin\theta_A\,U^*_{i1}\,V^*_{j2} - \sin\beta\,\sin\theta_A\,V^*_{j1}\,U^*_{i2}\right) - \frac{\lambda}{\sqrt{2}}\cos\theta_A\,U^*_{i2}V^*_{j2}$$

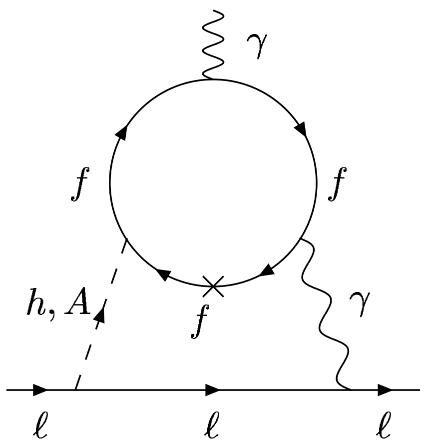
Phenomenology of a light pseudoscalar boson

- $g-2$
- Production via B decays
- Decay of A_1
- $H \to A_1 A_1$
- Associated production of A_1

$g-2$

Light pseudoscalar boson contributes largely at 1-loop and 2-loop levels:





We can have $t, b, \tau, \widetilde{\chi}_i^+$ in the upper loop.

One-loop contribution:

$$\Delta a_{\mu,1}^{A_i} = -\frac{\alpha_{\rm em}}{8\pi \sin^2\theta_{\rm w}} \frac{m_\mu^2}{M_W^2} \frac{m_\mu^2}{M_{A_i}^2} \left(\lambda_\mu^{A_i}\right)^2 F_A\left(\frac{m_\mu^2}{M_{A_i}^2}\right)$$

where

$$F_A(z) = \int_0^1 dx\, \frac{x^3}{zx^2 - x + 1}, \qquad \lambda_\mu^{A_1} = -\tan\beta \sin\theta_A$$

The two-loop contributions:

$$\Delta a_{\mu,2}^{A_i}(f) = \sum_{f=t,b,\tau} \frac{N_c^f\, \alpha_{\rm em}^2}{8\pi^2 \sin^2\theta_{\rm w}} \frac{m_\mu^2\, \lambda_\mu^{A_i}}{M_W^2}\, Q_f^2\, \lambda_f^{A_i} \frac{m_f^2}{m_{A_i}^2} G_A\left(\frac{m_f^2}{m_{A_i}^2}\right),$$

where

$$G_A(z) = \int_0^1 dx\, \frac{1}{x(1-x) - z} \ln \frac{x(1-x)}{z}$$

$$\Delta a_{\mu,2}^{A_i}(\widetilde{\chi}_j^+) = \frac{\alpha_{\rm em}^2}{4\pi^2 \sin^2\theta_{\rm w}} \frac{m_\mu^2\, \lambda_\mu^{A_i}}{m_W}\, G_{jj}^{A_i} \frac{m_{\widetilde{\chi}_j}}{m_{A_i}^2} G_A\left(\frac{m_{\widetilde{\chi}_j}^2}{m_{A_i}^2}\right)$$

where $G_{jj}^{A_1} = -D_{jj}/g$, $G_{jj}^{A_2} = -C_{jj}/g$.

In the limit of very small mixing:

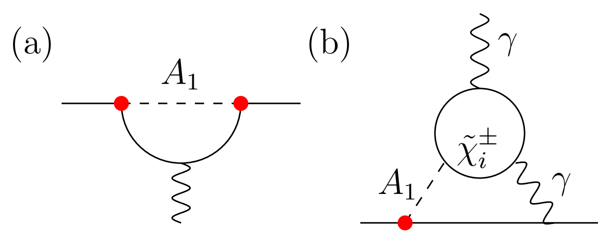
$$\mathcal{M}_P^2 = M_A^2 \begin{pmatrix} 1 & \epsilon \\ \epsilon & \delta \end{pmatrix} ,$$

where $\epsilon, \delta \ll 1$. In this case, the mass of A_1 and A_2, and the mixing angle θ_A are given by

$$m_{A_2}^2 \sim M_A^2(1+\epsilon^2), \quad m_{A_1}^2 \sim M_A^2 \delta, \quad \theta_A \sim \epsilon$$

The A_1 couplings simplify to

$$A_1 \widetilde{\chi}_i^+ \widetilde{\chi}_i^+ \sim -\frac{\lambda}{\sqrt{2}} U_{i2}^* V_{i2}^* \gamma^5, \quad A_1 \bar{u} u \sim \frac{g m_u}{2 m_W} \epsilon \cot\beta \gamma^5, \quad A_1 \bar{d} d \sim \frac{g m_d}{2 m_W} \epsilon \tan\beta \gamma^5$$



The leading contribution in ϵ is with $\widetilde{\chi}_1^+$ in the upper loop.

The Barr-Zee chargino loop contribution becomes

$$\Delta a_{\mu,2}^{A_1}(\widetilde{\chi}_{1,2}^+) = -\frac{\lambda\epsilon \tan\beta m_\mu^2}{2\pi s_W m_W^2}\left(\frac{\alpha}{2\pi}\right)^{\frac{3}{2}} \sum_{i=1}^{2} \frac{m_W}{m_{\widetilde{\chi}_i^+}} U_{i2}^* V_{i2}^* \left[1 + \log\frac{m_{\widetilde{\chi}_i^+}}{m_{A_1}}\right]$$

With the known SM values and the chargino mass at the electroweak scale $M_{\rm EW}$, λ and U, V are $\sim \mathcal{O}(1)$,

$$\Delta a_{\mu,2}^{A_1} \sim -2.5\times 10^{-11}(|\epsilon|\tan\beta)\log\frac{M_{\rm EW}}{m_{A_1}} \times sign(\epsilon\lambda)$$

$$\left|\Delta a_{\mu,2}^{A_1}\right| \lesssim 10^{-11} \qquad \text{for} \qquad \epsilon < 10^{-3}$$

The $g-2$ constraint can be safely satisfied if $\sin\theta_A$ is small enough.

Production via B meson decays

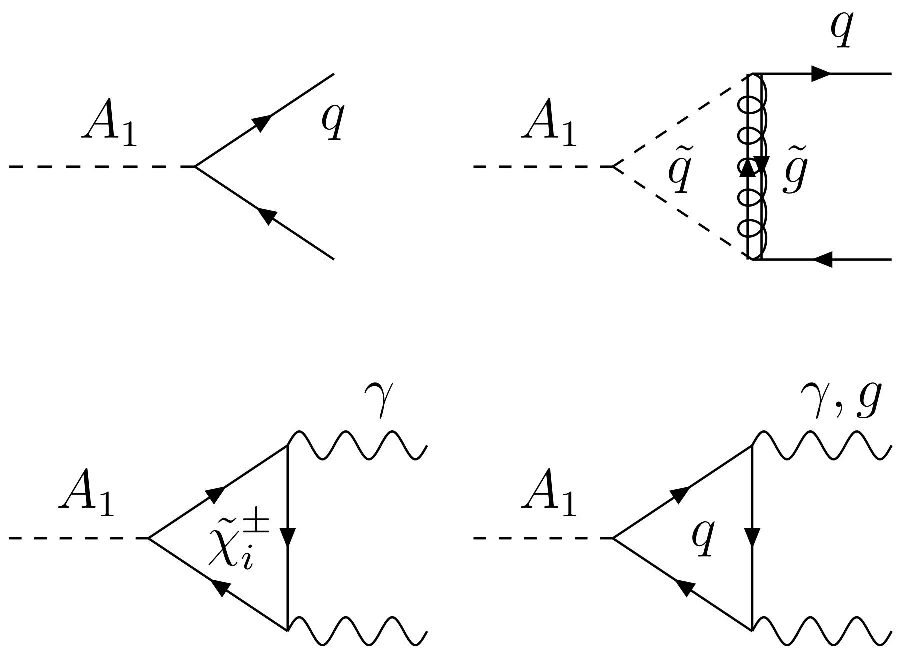
- $b \to sA_1$: (Hiller 2004)
  She studied $b \to s\gamma$, $b \to sA_1$, and $b \to s\ell\ell$, A_1 masses down to $2m_e$ cannot be excluded from these constraints.

- In Upsilon and J/ψ decays: (Gunion, Hooper, McElrath 2005)

$$\frac{\Gamma(V \to \gamma A_1)}{\Gamma(V \to \mu^+\mu^-)} = \frac{G_F m_b^2}{\sqrt{2}\alpha\pi} \left(1 - \frac{M_{A_1}^2}{M_V^2}\right) X^2 \sin^2\theta_A$$

where $X = \tan\beta(\cot\beta)$ for Υ (ψ).

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

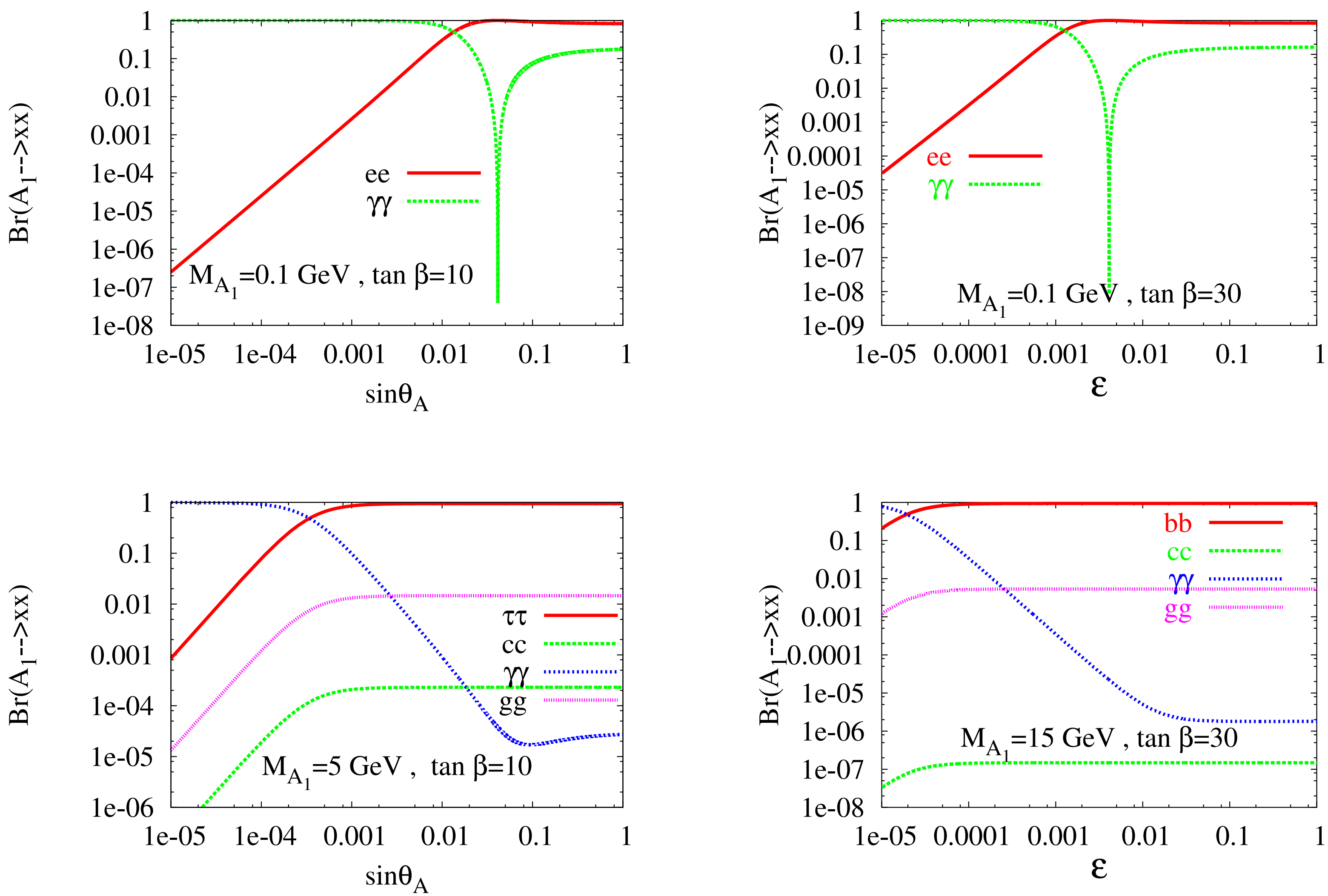
The partial widths of A_1 into $f\bar{f}$, $\gamma\gamma$ and gg are given by

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

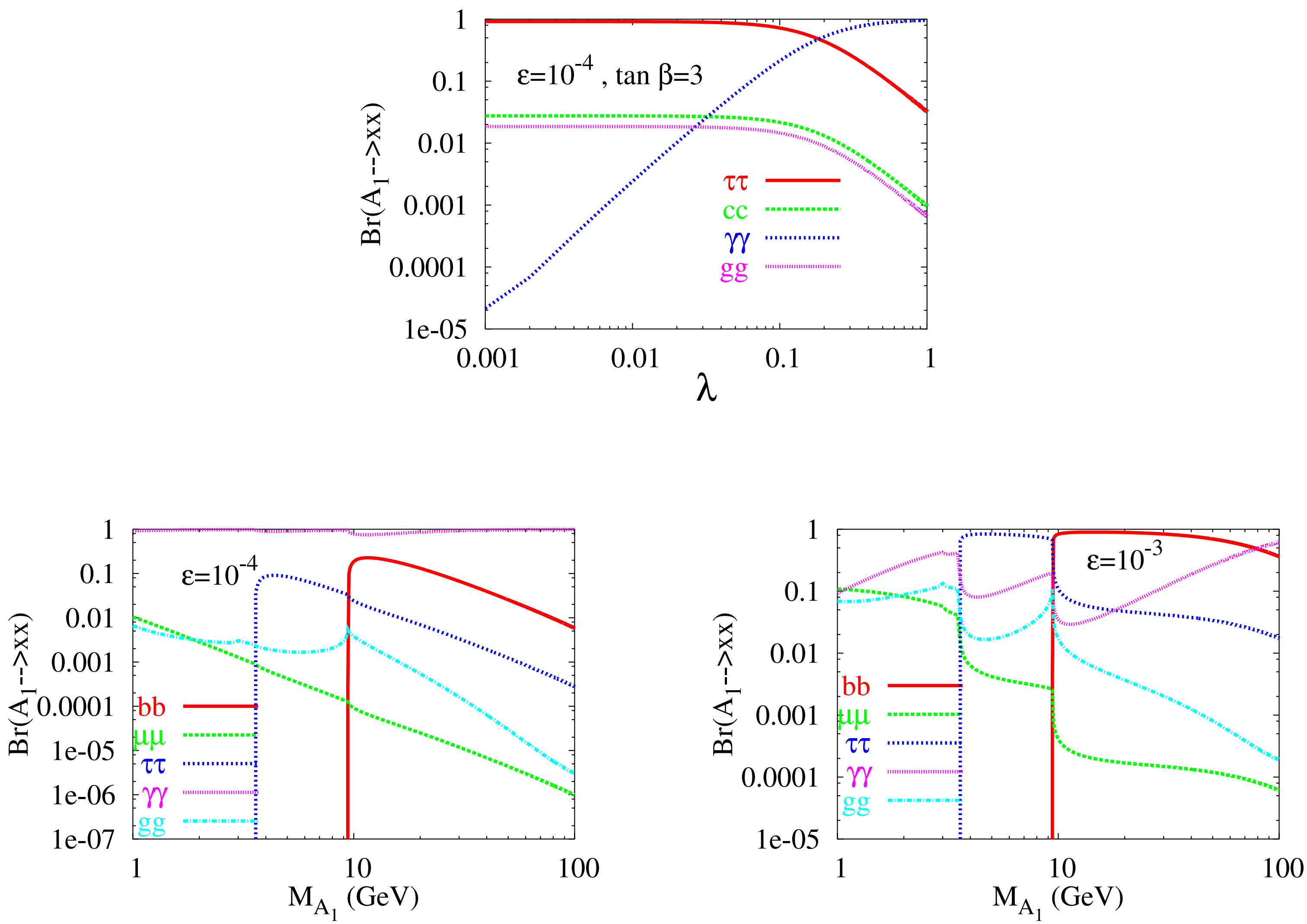
$$\Gamma(A_1 \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_{A_1}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 \lambda_f^{A_1} f(\tau_f) + 2 \sum_{i=1}^{2} \frac{M_W}{m_{\chi_i^\pm}} \lambda_{\chi_i}^{A_1} f(\tau_{\chi_i^\pm}) \right|^2$$

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

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)
ee
γγ
MA1=0.1 GeV , tan β=10
sinθA
MA1=0.1 GeV , tan β=30
ε
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)
ττ
cc
γγ
gg
λ
ε=10^-4
bb
μμ
ττ
γγ
gg
MA1 (GeV)
ε=10^-3
bb
μμ
ττ
γγ
gg
MA1 (GeV)

Production: $H \to A_1 A_1$

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.

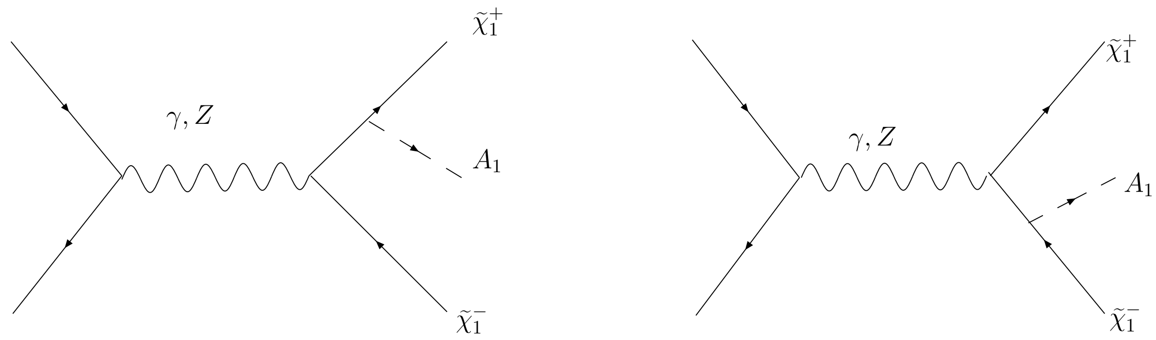
So A_1 can be produced in the decay of the Higgs boson (Dermisek,Gunion 2005; Dobrescu, Landsberg, Matchev 2001)

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

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 $h \to \gamma\gamma$.

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, 4τs 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 + $\not{E}_T$
- 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.

Rate dependence

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

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

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

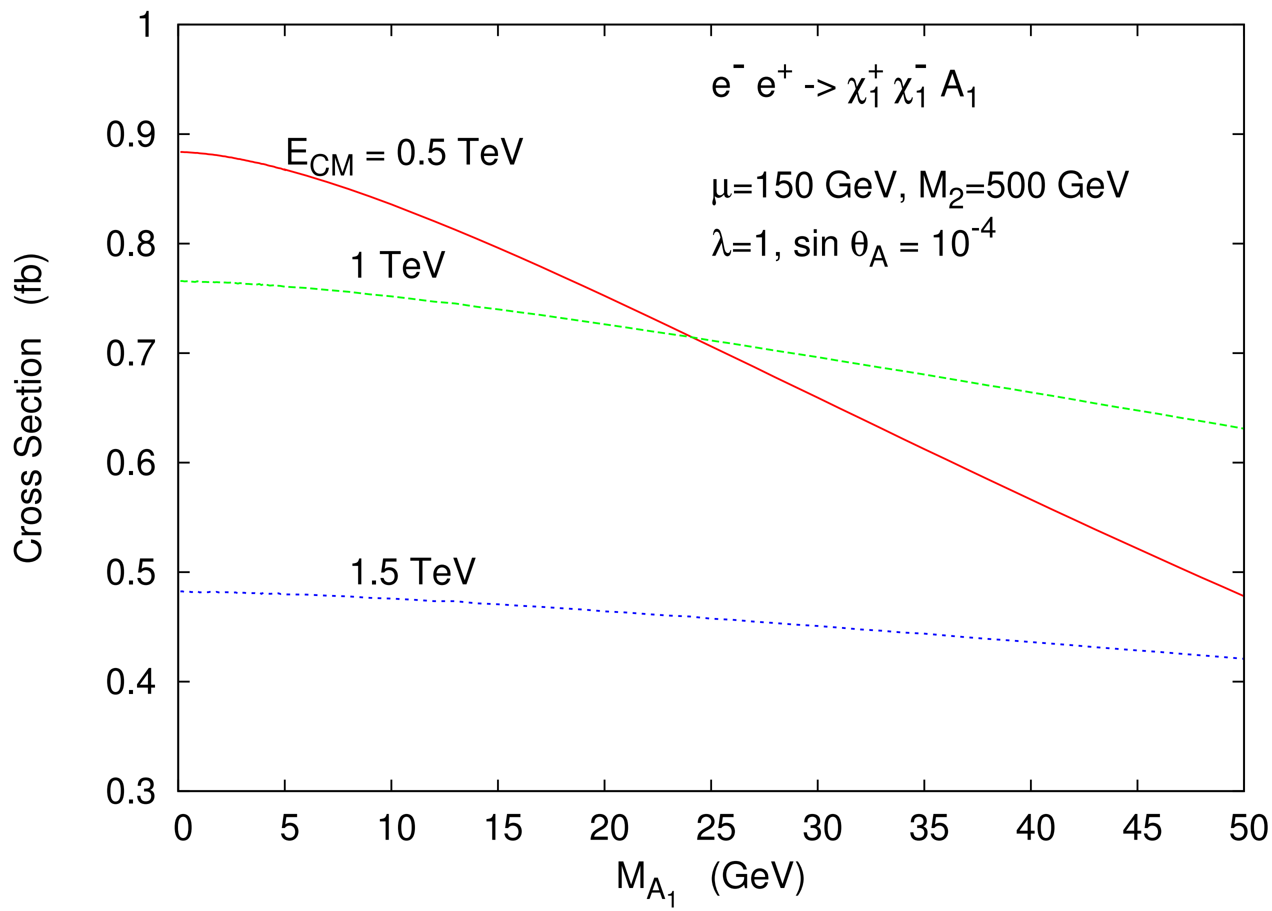
$$\mu = 150\ \mathrm{GeV} \qquad M_2 = 500\ \mathrm{GeV}$$

The other parameters are

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

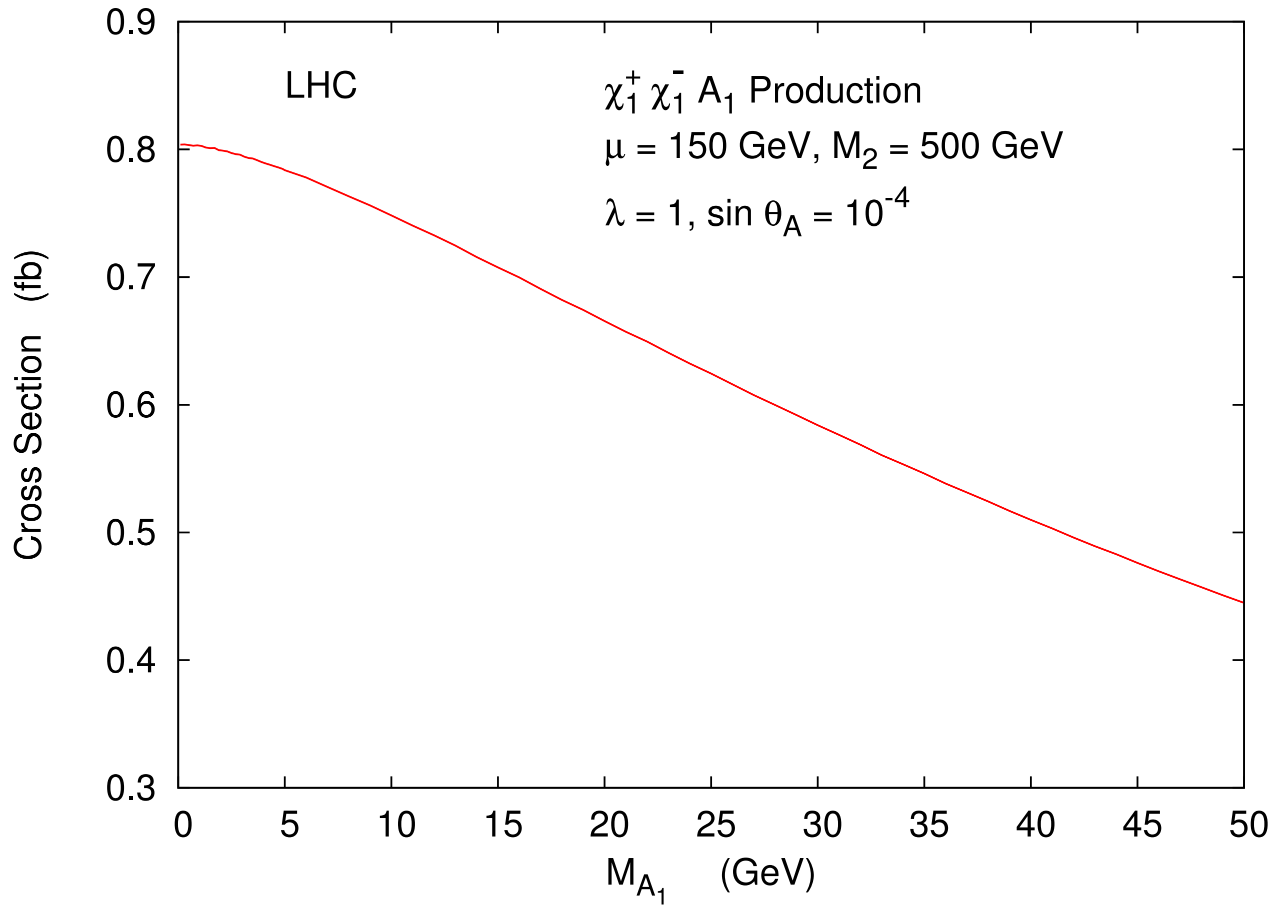
Little dependence on $\tan\beta$ and $\sin\theta_A$ as long as it is small.

Cross Section at e^+e^- colliders



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

Resolving the two photons

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

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

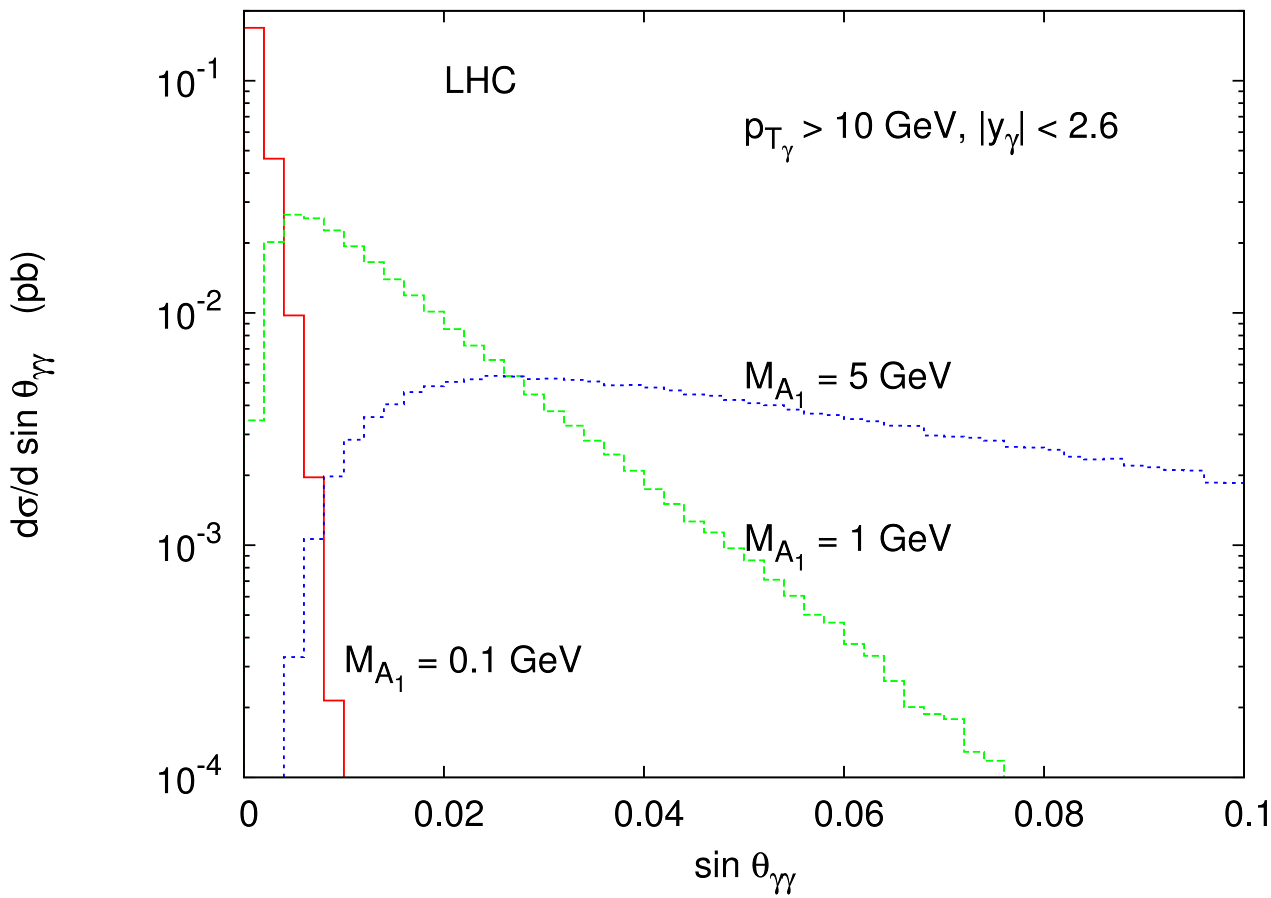
which are in accord with the ECAL of the CMS detector

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

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 $\widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1$ followed by $A_1 \to \gamma\gamma$. 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

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.