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Associated production of a light pseudoscalar Higgs boson with a chargino pair in the NMSSM

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Abstract: In the next-to-minimal supersymmetric standard model (NMSSM), the unique $\lambda S H_u H_d$ in the superpotential gives rise to a coupling involving the lighter pseudoscalar Higgs boson and a pair of charged or neutral Higgsinos, even in the limit of zero mixing between the two pseudoscalar Higgs bosons. We study the associated production of a very light pseudoscalar Higgs boson with a pair of charginos. The novel signature involves a pair of charged leptons from chargino decays and a pair of photons from the pseudoscalar Higgs boson decay, plus large missing energy at the LHC and ILC. The signal may help us to distinguish the NMSSM from MSSM, provided that the experiment can resolve the two photons from the decay of the pseudoscalar Higgs boson.

Keywords: Supersymmetry Phenomenology, Extended Supersymmetry, Supersymmetric Standard Model.

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Contents

1. Introduction

Supersymmetry (SUSY) is one of the best motivated theories beyond the standard model (SM). Not only does it provide a natural solution to the gauge hierarchy problem, but also gives a dynamical mechanism for electroweak symmetry breaking and a natural candidate for dark matter. The most recent lower bound on the Higgs boson mass has been raised to 114.4 GeV [1]. This in fact puts some stress on the soft SUSY parameters, known as the little hierarchy problem, on the minimal supersymmetric standard model (MSSM). Since the Higgs boson receives radiative corrections dominated by the top squark loop, the mass bound requires the top squark mass to be heavier than 1 TeV. From the renormalization-group (RG) equation of $M^2_{H_u}$, the magnitude of $M^2_{H_u} \sim M^2_{\tilde{t}} \gtrsim (1000~\text{GeV})^2$. Thus, the parameters in the Higgs potential are fine-tuned at a level of a few percent in order to obtain a Higgs boson mass of $\mathcal{O}(100)$ GeV.

Such fine-tuning has motivated a number of solutions to relieve the problem. One of these is to add additional singlet fields to the minimal supersymmetric standard model (MSSM). The minimal version of the latter is realized by adding a singlet Higgs field to the MSSM, and becomes the next-to-minimal supersymmetric standard model (NMSSM). It has been shown [2] that in some corners of the parameter space, the Higgs boson can decay into a pair of very light pseudoscalars such that the LEP2 limit can be evaded. It has also been demonstrated that the fine-tuning or the little hierarchy problems are relieved [2]. Studies of a very light Higgs boson in addition to the SM-like Higgs boson in the NMSSM before the LEPII era can be found in refs. [3]. The NMSSM is in fact well motivated as it provides an elegant solution to the μ problem in SUSY. The μ parameter in the term $\mu H_u H_d$ of the superpotential of the MSSM naturally has its value at either M_{Planck} or zero (due to a symmetry). However, the radiative electroweak symmetry breaking conditions require the μ parameter to be of the same order as m_Z for fine-tuning reasons. Such a conflict is coined as the μ problem [4]. In the NMSSM, the μ term is generated dynamically through the vacuum-expectation-value (VEV), v_s, of the scalar component of the additional Higgs field S, which is naturally of the order of the SUSY breaking scale. Thus, an effective μ parameter of the order of the electroweak scale is generated. Explicitly, the superpotential of the NMSSM is given by

$$W = \mathbf{h_u}\hat{Q}\,\hat{H}_u\,\hat{U}^c - \mathbf{h_d}\hat{Q}\,\hat{H}_d\,\hat{D}^c - \mathbf{h_e}\hat{L}\,\hat{H}_d\,\hat{E}^c + \lambda\hat{S}\,\hat{H}_u\,\hat{H}_d + \frac{1}{3}\kappa\,\hat{S}^3. \tag{1.1}$$

It is well-known that that the superpotential has a discrete Z_3 symmetry, which may induce the harmful domain-wall effect [5]. One possible way out is to introduce some nonrenormalizable operators at the Planck scale that break the Z_3 symmetry through the harmless tadpoles that they generate [6].

Once the domain wall problem is solved, the NMSSM is phenomenologically very interesting. With the additional singlet Higgs field, there are one more CP-even and one more CP-odd Higgs bosons, and one more neutralino other than those in the MSSM. The Higgs phenomenology is much richer [8, 9], and so does the neutralinos [10 − 12]. One particular feature of the NMSSM is the allowable light pseudoscalar boson A_1, which is consistent with existing data. Since this A_1 mainly comes from the singlet Higgs field, it can escape all the experimental constraints when the mixing angle with the MSSM Higgs fields goes to zero. It was pointed out in ref. [2, 7] that even in the zero mixing limit, there is always a SM-like Higgs boson that decays into a pair of A_1's, which helps the Higgs boson to evade the LEP bound. The possibility to detect such light pseudoscalar Higgs bosons coming from the H_1 decay was studied using the two photon mode of the A_1, but the two photons may be too collimated for realistic detection [13]. Another possibility to detect such an almost decoupling case is to search for the four tau-leptons coming from $h^0 \to A_1 A_1 \to 4\tau$ decay [14]. Nevertheless, in the large $\tan\beta$ and large $\langle v_s \rangle$ limits, the mixing angle is extremely small and approaching zero, such that the decay of A_1 into tau-leptons or heavy quarks is negligible. Other considerations of the Higgs boson decaying into two light pseudoscalar bosons at hadronic colliders can be found in refs. [15]

In this work, we probe another novel signature in the zero-mixing limit. The unique term $\lambda S H_u H_d$ in the superpotential gives rise to the coupling of $\lambda S \tilde{H}_u \tilde{H}_d$, which includes the neutral and charged Higgsinos. We study the associated production of a light pseudoscalar Higgs boson with a chargino pair in the zero-mixing limit at the LHC and ILC. Provided that the pseudoscalar is very light and the mixing angle is less than 10^{-3}, the dominant decay mode of A_1 is a pair of photons. Thus, the novel signature for the production is a pair of charged leptons and a pair of photons plus large missing energy. Such a signal can distinguish NMSSM from the MSSM. We will show the production rates at the LHC and the ILC. One critical issue in identifying the two-photon decay of the light pseudoscalar Higgs boson is whether the two photons can be resolved. We will demonstrate the distribution of the opening angle between the two photons, from which one can tell to what extent the experiments can resolve the two photons. The CMS detector has a "preshower" in the ECAL that has the strong capability to resolve the two photons of the neutral pion decay as it is the most important background for the intermediate mass Higgs boson search. We can make use of this preshower in the ECAL to resolve the two photons of the A_1 decay. We will then show the cross section for the associated production after imposing the preshower requirements. Once we resolve the two photons in the decay of the pseudoscalar Higgs boson, we can differentiate the NMSSM from the MSSM.

The organization is as follows. In the next section, we describe the particular region of parameter space in which the light pseudoscalar Higgs boson decouples and decays into a pair of photons. In section III, we calculate the decay branching ratios of the A_1. We then calculate the associated production of the light pseudoscalar Higgs boson with a chargino pair in the zero-mixing limit at the LHC and ILC in section IV. We also work out the distribution of the opening angle of the photon pair. We conclude in section V.

2. Zero mixing limit

The Higgs sector of the NMSSM consists of the usual two Higgs doublets H_u and H_d and an extra Higgs singlet S. The extra singlet field is allowed to couple only to the Higgs doublets of the model, the supersymmetrization of which is that the singlet field only couples to the Higgsino doublets. Consequently, the couplings of the singlet S to gauge bosons and fermions will only be manifest via their mixing with the doublet Higgs fields. After the Higgs fields take on the VEV's and rotating away the Goldstone modes, we are left with a pair charged Higgs bosons, 3 real scalar fields, and 2 pseudoscalar fields. In particular, the mass matrix for the two pseudoscalar Higgs bosons P_1 and P_2 is

$$V_{\rm pseudo} = \frac{1}{2}\,(P_1 \;\; P_2)\mathcal{M}_P^2 \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \tag{2.1}$$

with

$$\begin{aligned}
\mathcal{M}^2_{P\,11} &= M_A^2 \,, \\
\mathcal{M}^2_{P\,12} &= \mathcal{M}^2_{P\,21} = \frac{1}{2}\cot\beta_s \,\left(M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2\right) \,, \\
\mathcal{M}^2_{P\,22} &= \frac{1}{4}\sin 2\beta \cot^2\beta_s \,\left(M_A^2 \sin 2\beta + 3\lambda\kappa v_s^2\right) - \frac{3}{\sqrt{2}}\kappa A_\kappa v_s \,,
\end{aligned} \tag{2.2}$$

where

$$M_A^2 = \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right) \,, \tag{2.3}$$

and $\tan\beta = v_u/v_d$ and $\tan\beta_s = v_s/v$ and $v^2 = v_u^2 + v_d^2$. Here P_1 is the one in MSSM while P_2 comes from the singlet S and from the effects of rotating away the Goldstone modes. The pseudoscalar fields are further rotated to the diagonal basis (A_1, A_2) through a mixing angle [9]:

$$\begin{pmatrix} A_2 \\ A_1 \end{pmatrix} = \begin{pmatrix} \cos\theta_A & \sin\theta_A \\ -\sin\theta_A & \cos\theta_A \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \tag{2.4}$$

where the masses of A_i are arranged such that $m_{A_1} < m_{A_2}$. At tree-level the mixing angle is given by

$$\tan\theta_A = \frac{\mathcal{M}^2_{P\,12}}{\mathcal{M}^2_{P\,11} - m^2_{A_1}} = \frac{1}{2}\cot\beta_s\,\frac{M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2}{M_A^2 - m^2_{A_1}} \tag{2.5}$$

In the approximation of large $\tan\beta$ and large M_A, which is normally valid in the usual MSSM, the tree-level CP-odd masses can be written as [9]

$$m^2_{A_2} \approx M^2_A\,(1+\frac{1}{4}\cot^2\beta_s\sin^2 2\beta), \tag{2.6}$$

$$m^2_{A_1} \approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa\ . \tag{2.7}$$

We are interested in the case that A_1 is very light. From eq. (2.7) it can be seen that m_{A_1} can be very small if either κ or A_κ is very small, which is made possible by a Pecci-Quinn (PQ) symmetry: $\kappa \to 0$ and $A_\kappa \to 0$. Also, in the PQ limit, $\kappa \to 0$, the mixing angle

$$\theta_A \approx \tan\theta_A \approx \frac{v}{v_s\tan\beta}\ , \tag{2.8}$$

which tends to very close to zero in the large $\tan\beta$ and large v_s limit, i.e., decoupling limit. On the other hand, we can achieve a small mixing angle by the cancellation between the two terms in the numerator of eq. (2.5), by setting

$$M^2_A\sin 2\beta - 3\lambda\kappa v^2_s = \sqrt{2}\lambda v_s\left(A_\lambda - \sqrt{2}\kappa v_s\right) \approx 0 \qquad \Rightarrow A_\lambda \approx \sqrt{2}\kappa v_s\ . \tag{2.9}$$

We have scanned the parameter space of NMSSM using NMHDECAY [8] with the following ranges of parameters: $0<\lambda<0.7$, $2<\tan\beta<40$, $0<\kappa<0.8$, -250 GeV $< A_\lambda < 250$ GeV, -250 GeV $< A_\kappa < 250$ GeV, and -250 GeV $< \mu < 250$ GeV. We can obtain a light pseudoscalar of mass around 40 GeV and a branching ratio $B(A_1\to\gamma\gamma) > 0.9$, though the value for $\lambda \approx 0.4$. [1] We mostly concern about a scenario of a very light pseudoscalar boson with a suppressed mixing angle to the SM fermions such that it can have a large branching ratio into a photon pair. Although it is difficult to achieve simultaneously a very light pseudoscalar and a small mixing in the NMSSM, it may be possible to achieve the scenario by further fine-tuning or by adding some other ingredients to the model. Nevertheless, the signal of our interest is still the associated production of the light pseudoscalar boson with a chargino pair, followed by photon decay of the pseudoscalar. Thus, from now on we do not concern about how precisely one has to tune the parameters to obtain small mixing angles and small mass for the pseudoscalar boson.

We have the following parameters in the NMSSM in addition to those of the MSSM: λ, κ, A_λ, A_κ, and v_s (m^2_S has been eliminated by one of the tadpole equations in the electroweak symmetry breaking.) Since $\lambda v_s/\sqrt{2} = \mu$, we can use μ and λ in place of v_s. Also from eqs. (2.3), (2.7) and (2.5) we can trade κ, A_λ, and A_κ for m^2_A, m_{A_1} and $\sin\theta_A$. The small m_{A_1} and small θ_A limit can be achieved by requiring $\kappa\to 0$ in eq. (2.7) and taking a large $\tan\beta$ and a relatively large v_s as in eq. (2.8). The small mixing angle, on the other hand, may also be achieved by the condition in eq. (2.9) such that the fine-tuned cancellation is possible to give a small value of $\tan\theta_A$. Therefore, when we present our signature cross section we will use m_{A_1} and $\sin\theta_A$ as our inputs.

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[1] In the second reference of [8], the bench-mark point #6 ($\lambda = 0.39$, $\kappa = 0.18$, $\tan\beta = 3.5$, $\mu = -245$ GeV, $A_\lambda = -230$ GeV, and $A_\kappa = -5$ GeV) has $m_{h_1} = 94$ GeV, $m_{a_1} = 40$ GeV and $B(a_1\to\gamma\gamma) = 0.98$. This is exactly the large $B(a_1\to\gamma\gamma)$ that we want to achieve, but the bench-mark point #6 has a somewhat smaller λ.

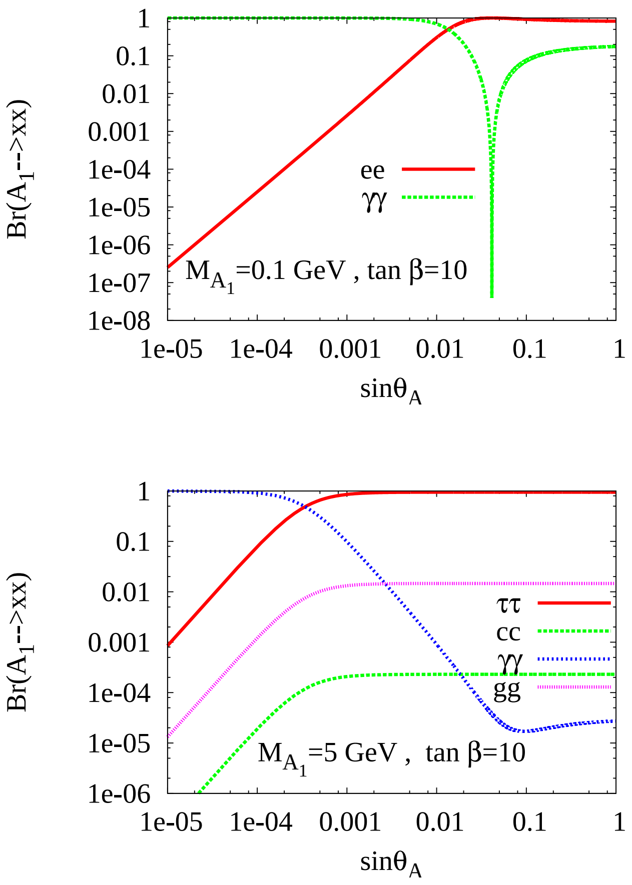

Figure 1: Decay branching ratios for the light pseudoscalar Higgs boson versus the mixing angle $\sin\theta_A$ for $\lambda = 1$, $\mu = 150\,\text{GeV}$, $M_2 = 500\,\text{GeV}$. (a) $m_{A_1} = 0.1\,\text{GeV}$ and (b) $m_{A_1} = 5\,\text{GeV}$.

3. Decay

A lot of existing constraints on the lightest pseudoscalar Higgs boson A_1 depend on the mixing angle $\sin\theta_A$. When $\sin\theta_A$ goes to zero, the A_1 decouples and behaves like the singlet. This light A_1 can be extremely light without violating any existing data. It was pointed out [2] that it can be produced in the scalar Higgs boson decay, $H_1 \to A_1 A_1$, which is due to the term $\lambda \hat{S}\hat{H}_u\hat{H}_d$ in the superpotential. We found in this work that there is another novel signature for this light A_1 from the same term. We calculate the associated production of A_1 with a pair of charginos, followed by $A_1 \to \gamma\gamma$ decay at hadronic and e^+e^- colliders. This is an undebatable signal of the decoupling regime of the NMSSM.

In the limit of zero mixing, the A_1 only couples to a pair of charginos and neutralinos. Therefore, the dominant decay mode is $\gamma\gamma$ via a chargino loop if m_{A_1} is very light. When we turn on the small mixing angle, other modes, such as $q\bar{q}$, $\ell^+\ell^-$, and gg, appear, which will eventually dominate when the mixing angle is larger than $O(10^{-3})$. We show a typical

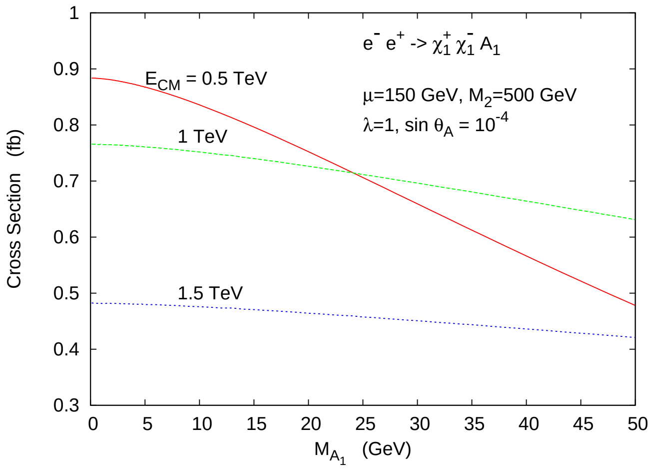

Figure 2: Production cross sections for $e^- e^+ \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1$ at the ILC with $\sqrt{s} = 0.5,\, 1,\, 1.5\,\mathrm{TeV}$. We have chosen $\lambda = 1$, $\sin\theta_A = 10^{-4}$, $\mu = 150\,\mathrm{GeV}$, $M_2 = 500\,\mathrm{GeV}$, and $\tan\beta = 10$.

decay branching ratio versus the mixing angle for $m_{A_1} = 0.1, 5\,\mathrm{GeV}$ in figure 1. When m_{A_1} is as light as $0.1\,\mathrm{GeV}$, only the e^+e^- and $\gamma\gamma$ modes are possible. The e^+e^- mode scales as $\sin^2\theta_A$, and so the e^+e^- mode increases sharply as $\sin\theta_A$ increases in figure 1(a). As m_{A_1} increases other $f\bar{f}$ modes open up, such as $\tau^+\tau^-, c\bar{c}, gg$. As long as $\sin\theta_A \lesssim 10^{-3}$ the $\gamma\gamma$ dominates the decay of A_1.

4. Associated production

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. The interaction is given by

$$\mathcal{L}_{A\chi^+\chi^+} = i\overline{\widetilde{\chi}_i^+}\left(C_{ij}P_L - C_{ji}^* P_R\right)\widetilde{\chi}_j^+\, A_2 + i\overline{\widetilde{\chi}_i^+}\left(D_{ij}P_L - D_{ji}^* P_R\right)\widetilde{\chi}_j^+\, A_1\ , \tag{4.1}$$

where

$$\begin{aligned} C_{ij} &= \frac{g}{\sqrt{2}}\left(\cos\beta\,\cos\theta_A\, U_{i1}^*\, V_{j2}^* + \sin\beta\,\cos\theta_A\, V_{j1}^*\, U_{i2}^*\right) - \frac{\lambda}{\sqrt{2}}\sin\theta_A\, U_{i2}^* V_{j2}^*\ , \\ D_{ij} &= \frac{g}{\sqrt{2}}\left(-\cos\beta\,\sin\theta_A\, U_{i1}^*\, V_{j2}^* - \sin\beta\,\sin\theta_A\, V_{j1}^*\, U_{i2}^*\right) - \frac{\lambda}{\sqrt{2}}\cos\theta_A\, U_{i2}^* V_{j2}^*\ , \end{aligned} \tag{4.2}$$

where $P_{L,R} = (1 \mp \gamma_5)/2$ are the chiral projectors.

We stress in passing that in the limit of zero mixing, the production of A_1 through the Drell-Yan process $e^+e^-/pp \to A_1\Phi$ is very suppressed. So is the gluon fusion since only quarks can mediate inside the loops. The associated production of A_1 with a chargino pair proceeds via the Feynman diagrams, in which the A_1 radiates off the chargino legs. The radiation off the intermediate Z is not considered in the very small mixing limit. Note that the production is proportional to $|\lambda\cos\theta_A U_{12}V_{12}|^2$, which implies a large Higgsino component in $\widetilde{\chi}_1^+$ is necessary for large cross sections. Details of the calculation will be

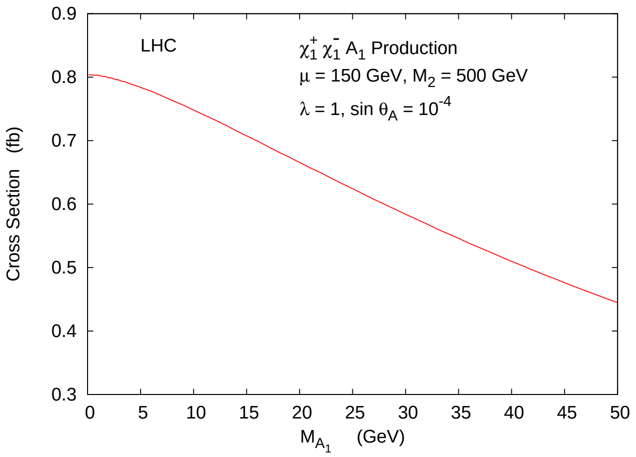

Figure 3: Production cross sections for $pp \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1$ at the LHC. We have chosen $\lambda = 1$, $\sin\theta_A = 10^{-4}$, $\mu = 150\,\mathrm{GeV}$, $M_2 = 500\,\mathrm{GeV}$, and $\tan\beta = 10$.

given in a future publication. We choose $\mu = 150\,\mathrm{GeV}$ and a much larger $M_2 = 500\,\mathrm{GeV}$, $\lambda = 1$ [2] and $\sin\theta_A = 10^{-4}$ in our results. We show the production cross sections at e^+e^- colliders versus m_{A_1} for $\sqrt{s} = 0.5, 1, 1.5\,\mathrm{TeV}$ in figure 2. Note that the cross section is insensitive to $\sin\theta_A$ as long as it is less than 10^{-2}. Also, in this near-zero mixing region, the cross section scales as λ^2. With $O(500)\,\mathrm{fb}^{-1}$ yearly luminosity at the ILC, the number of raw events is of the order of $O(500)$. The signature is very spectacular with a pair of charged leptons and a pair of photons with a large missing energy. In contrast to the process of $h \to A_1 A_1 \to 4\gamma$ [13], the photon pair is less collimated because the A_1 radiating off the chargino would not be as energetic as the A_1 from Higgs decay. Almost all SM backgrounds are reducible once the photon pair and the charged lepton pair are identified together with large missing energies.

The leptonic branching ratio of the chargino can increase if the slepton or sneutrino mass is relatively light. One can also increase the detection rates by including the hadronic decay of the charginos. Therefore, in the final state we can have (i) two charged leptons + two photons + $\not{E}_T$, (ii) one charged leptons + two jets + two photons + $\not{E}_T$, or (iii) 4 jets + two photons + $\not{E}_T$.

We show the production cross section for $pp \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1$ at the LHC in figure 3, with the same set of parameters as in figure 2. We obtain a cross section slightly shy of $O(1)$ fb. With a yearly luminosity of $100\,\mathrm{fb}^{-1}$ one can have about $O(100)$ raw events. It remains possible to detect the pseudoscalar Higgs boson and chargino decays. Experiments can search for the same final states that we listed for the ILC. Almost all SM backgrounds are reducible if the photon pair can be resolved and measured, together with the charged leptons or jets plus missing energies.

The critical issue here is whether the LHC experiment can resolve the two photons

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[2] We have considered the largest possible value of λ, which should be of the order of $O(1)$. The size is limited by the perturbativity argument when the Yukawa coupling is evolved to the GUT scale. We have followed the prescription from other papers. In general, the perturbativity argument is rather loose. There may be some other new physics that appear well below the GUT scale. But roughly $\lambda \approx O(1)$ is the upper

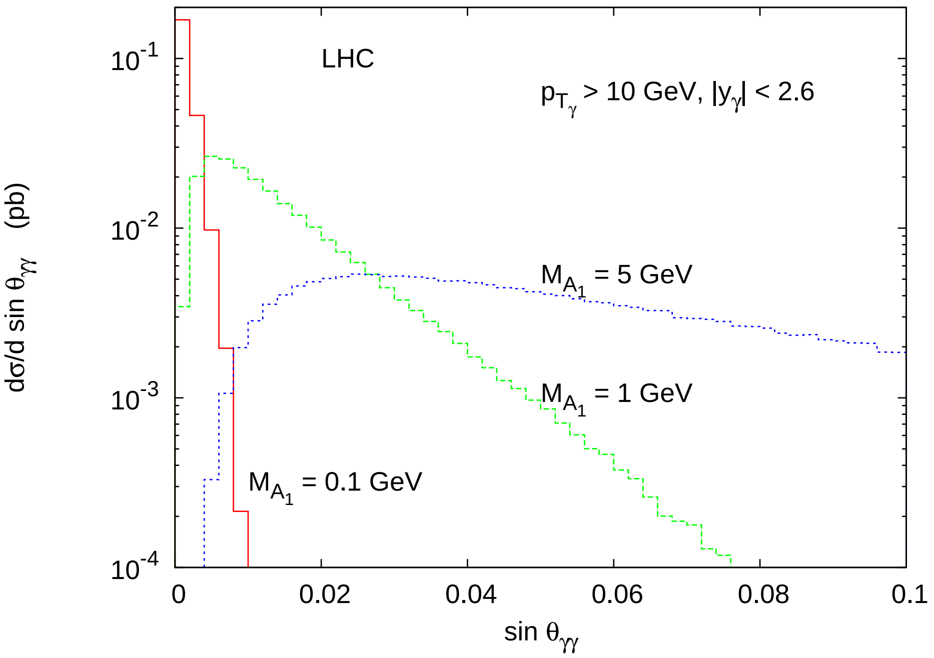

Figure 4: The differential cross section versus the sine of the opening angle between the two photons for $\lambda = 1$ and $\sin\theta_A = 10^{-4}$ at the LHC. Requirements of $p_{T\gamma} > 10\,\text{GeV}$ and $|y_\gamma| < 2.6$ are imposed.

in the decay of the pseudoscalar Higgs boson. We perform a monte carlo study for the production of $\widetilde{\chi}_1^+ \widetilde{\chi}_1^- A_1$ followed by the decay of $A_1 \to \gamma\gamma$. Since A_1 is a pseudoscalar, it is sufficient to study the $2 \to 2$ phase-space decay of A_1. We impose transverse momentum and rapidity requirements on the photons:

$$p_{T_\gamma} > 10\ \text{GeV}\,, \qquad |y_\gamma| < 2.6\,, \tag{4.3}$$

which are in accord with the ECAL of the CMS detector [17]. The resolution of the "preshower" detector quoted in the report is as good as 6.9 mrad. We shall use 10 mrad as our minimum separation of the two photons that the detector can resolve. We show the distribution of the sine of the opening angle between the two photons for $M_{A_1} = 0.1,\ 1,\ 5\,\text{GeV}$ in figure 4. It is easy to understand that for A_1 as light as 0.1 GeV all the cross sections are within the opening angle $\theta_{\gamma\gamma} < 0.01$ rad. When M_{A_1} increases to 1 GeV, more than half of the cross sections are beyond 0.01 rad. For M_{A_1} as large as 5 GeV almost all cross sections are beyond $\theta_{\gamma\gamma} > 0.01$ rad. We show the resultant cross sections for $M_{A_1} = 0.1 - 5\,\text{GeV}$ with $p_{T_\gamma} > 10$ GeV, $|y_\gamma| < 2.6$, and $\theta_{\gamma\gamma} > 0.01$ rad in table 1. Suppose the LHC can accumulate $O(500-1000)\,\text{fb}^{-1}$ luminosity, so M_{A_1} as low as $0.3 - 0.4\,\text{GeV}$ are possible to be detected. For a mere $O(100)\,\text{fb}^{-1}$ luminosity, the size of the cross section in table I shows that it is only possible to detect $m_{A_1} > 1\,\text{GeV}$.

The final issue is the background suppression. We have shown in figure 4 that for $m_{A_1} \sim 0.1\,\text{GeV}$, almost all cross section lies below $\theta_{\gamma\gamma} < 0.01$, which is our conserva-

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limit applied to λ for the perturbativity reason.

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

Table 1: 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: $p_{T_\gamma} > 10\,\text{GeV}$, $|y_\gamma| < 2.6$, and $\theta_{\gamma\gamma} > 10$ mrad.

tive choice of resolution according to the preshower detector of the CMS. However, when $m_{A_1} \gtrsim 1\,\text{GeV}$, more than half of the cross section survives this $\theta_{\gamma\gamma} > 0.01$ cut. We can also reconstruct the invariant mass of the photon pair to identify the pseudoscalar Higgs boson A_1 and separate it from the other SM mesons such as π^0 and η. Photon and lepton isolation cuts are the most useful ones to reject the jet-faking background and other QCD background. The remaining backgrounds are mostly gauge-boson pair and $t\bar{t}$ plus photons/jets production with the photons/jets radiating off fermion or gauge boson legs. Although they are irreducible, they are of higher order in couplings and should be small. Perhaps, the more serious background issue in the LHC environment may be the combinatorial background because of many photons within a jet. Again, using strong photon-pair isolation (that is without hadronic jets around the photon pair) one should be able to substantially reduce this background.

5. Discussions and conclusions

One may ask if a very light pseudoscalar Higgs boson is consistent with the muon anomalous magnetic moment $(g-2)$ because it can contribute substantially to $g-2$ at both 1-loop and 2-loop levels. However, it was shown that the 2-loop Barr-Zee type contributions with a light pseudoscalar can be of comparable size as the 1-loop contributions and opposite in sign [18]. Note that the contributions of the light A_1 of the NMSSM go to zero as $\sin\theta_A \to 0$. In the NMSSM, there could also be a light neutralino [12] that can contribute to $g-2$. In addition, there are many parameters in the MSSM, such as gaugino and sfermion masses, which the $g-2$ depends on. Thus, one can carefully take into account both 1- and 2-loop contributions and by adjusting the NMSSM parameters, such that the $g-2$ constraint is satisfied. There are other constraints on a light pseudoscalar from rare K and B meson decays, such as $b \to sA_1$ and $s \to dA_1$, $B - \overline{B}$ mixing, $B_s \to \mu^+\mu^-$, and $\Upsilon \to A_1\gamma$ [19, 12]. However, it is obvious that in these processes the light pseudoscalar interacts via the mixing with the MSSM pseudoscalar. Thus, in the limit of zero-mixing the constraints on the light A_1 can be easily evaded.

The major difference between MSSM and NMSSM is the existence of a singlet field, which gives rise to a scalar, a pseudoscalar, and a neutralino, in addition to the particle contents of the MSSM. We have shown that it is possible to have a very light pseudoscalar with a tiny mixing with the MSSM pseudoscalar. Such a light pseudoscalar boson is consistent with all existing constraints. The discovery mode has been shown [2] to be $H \to A_1 A_1$, which enjoys a large production cross section. However, the photon pair from the A_1 decay may be too collimated. In this paper, we have pointed out another unambiguous signature from the associated production of the light pseudoscalar with a pair of charginos at the LHC and ILC, with a pair of charged leptons and a pair of photons plus large missing energy in the final state. We have also shown that the event rates at the LHC and ILC should be enough to identify such a signature when M_{A_1} is larger than 1 GeV.

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