

Experimental constraints on nMSSM and implications on its phenomenology

Junjie Cao^{1,2}, Heather E. Logan², Jin Min Yang³

¹ *Department of Physics, Henan Normal University, Xinxiang 453007, China*

² *Ottawa Carleton Institute for Physics,*

Carleton University, Ottawa, K1S 5B6 Canada

³ *Key Laboratory of Frontiers in Theoretical Physics,*

Institute of Theoretical Physics, Academia Sinica, Beijing 100190, China

Abstract

We examine various direct and indirect experimental constraints on the nearly minimal supersymmetric standard model (nMSSM) and obtain the following observations: (i) Current experiments stringently constrain the parameter space, setting a range of $1 \sim 37$ GeV for the lightest neutralino $\tilde{\chi}_1^0$, $30 \sim 140$ GeV ($1 \sim 250$ GeV) for the lightest CP-even (CP-odd) Higgs boson, and $1.5 \sim 10$ for $\tan \beta$; (ii) To account for the dark matter relic density, besides the s-channel exchange of a Z-boson, the s-channel exchange of a light A_1 (the lightest CP-odd Higgs boson) can also play an important role in LSP annihilation. Compared with the Z-exchange annihilation channel, the A_1 exchange channel is more favored by muon $g - 2$ data and allows much broader regions for the parameters; (iii) In a large part of the allowed parameter space the SM-like Higgs boson may dominantly decay to $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ or $A_1 A_1$ and the conventional visible decays (e.g. into bottom quarks) are severely suppressed.

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Because the minimal supersymmetric standard model (MSSM) suffers from the μ -problem, some non-minimal supersymmetric models have recently been intensively studied, among which an attractive one is the nearly minimal supersymmetric standard model (nMSSM) [1, 2]. This model extends the MSSM by one singlet superfield \hat{S} with the superpotential [3]

$$W = W_{MSSM} + \lambda \varepsilon_{ij} \hat{H}_u^i \hat{H}_d^j \hat{S} + \xi_F M_n^2 \hat{S}, \quad (1)$$

where W_{MSSM} is the superpotential of the MSSM without the μ -term, the second term on the right side is the interaction of the singlet \hat{S} with the Higgs doublets \hat{H}_u and \hat{H}_d , and the last term is the tadpole term. This superpotential differs from that of the next-to-minimal supersymmetric standard model (NMSSM) [4] in that the tadpole term of the nMSSM replaces the trilinear singlet term $\kappa \hat{S}^3$ of the NMSSM. Due to this tadpole term, W has no discrete symmetry and so the nMSSM is free of the domain wall problem suffered by the NMSSM. The tadpole term also gives rise to a vacuum expectation value (vev) for the singlet, controlled by $\xi_F M_n^2$. Though it is SUSY-preserving, this tadpole term can naturally be of the SUSY breaking scale – e.g., in the $N = 1$ supergravity model with a discrete R-symmetry [20] such a tadpole term is generated at a high loop level and thus is naturally small [3]. A nonzero singlet vev at the SUSY breaking scale generates an effective μ term from the $\lambda \varepsilon_{ij} \hat{H}_u^i \hat{H}_d^j \hat{S}$ term with the desired order of magnitude, solving the μ problem of the MSSM. These theoretical virtues motivate further phenomenological study of the nMSSM. Because of the absence of the trilinear singlet term, the spectrum and phenomenology of the nMSSM can be quite different from those of the NMSSM.

With the running of the LHC, all low energy supersymmetric models will soon be put to the test. To explore these models at the LHC, it is very important to determine the parameter space allowed by current experiments. In this work we comprehensively examine experimental constraints on this model from the direct experimental searches for Higgs bosons and sparticles, the precision electroweak measurements at LEP/SLD, the cosmic dark matter relic density from WMAP, and the muon anomalous magnetic moment. We also consider the theoretical constraints from the stability of the Higgs potential and the perturbativity of the theory up to the grand unification scale. After analyzing the allowed parameter space, we discuss some phenomenology of this model.

We start our analysis by recapitulating the basics of the nMSSM. With the superpotential

in Eq. (1), the corresponding soft-breaking terms are given by [1, 5]

$$V_{\text{soft}} = V_{MSSM} + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_u^2 |H_u|^2 + \tilde{m}_S^2 |S|^2 \\ + (\lambda A_\lambda \varepsilon_{ij} H_u^i H_d^j S + \xi_S M_n^3 S + \text{h.c.}) \quad (2)$$

where V_{MSSM} contains the soft breaking terms for gauginos and sfermions in the MSSM, and $\tilde{m}_{u,d,S}$, A_λ and $\xi_S M_n^3$ are soft breaking parameters. Noting that the tadpole terms do not induce any interactions, one can conclude that, except for the tree-level Higgs boson masses and the minimization conditions, the theory is the same as the well-known NMSSM with the trilinear singlet term set to zero [5]. The nMSSM predicts three CP-even and two CP-odd neutral Higgs bosons as well as five neutralinos [1, 5]. The mass of the lightest neutralino (assumed to be the LSP) arises from the mixing of the singlino with higgsinos and is given by [6]

$$m_{\tilde{\chi}_1^0} \simeq \frac{2\mu\lambda^2(v_u^2 + v_d^2)}{2\mu^2 + \lambda^2(v_u^2 + v_d^2)} \frac{\tan\beta}{\tan^2\beta + 1} \quad (3)$$

where $\tan\beta = v_u/v_d$, $\mu = \lambda\langle s \rangle$, and v_u , v_d and $\langle s \rangle$ are the vevs of the Higgs fields H_u , H_d and S , respectively.

In our calculations we extend the packages NMSSMTools [7] and micrOMEGAs [8] to the nMSSM. We use the modified NMSSMTools to calculate the Higgs boson masses and their decays including all known radiative corrections. We use the modified micrOMEGAs to calculate the dark matter relic density. The parameters relevant to our analysis are λ , A_λ , $\tan\beta$, $m_A \equiv 2(\mu A_\lambda + \lambda \xi_F M_n^2)/\sin 2\beta$, $\mu \equiv \lambda\langle s \rangle$, \tilde{m}_S , the gaugino masses M_1 and M_2 , and the soft SUSY breaking parameters in the squark/slepton sectors. We assume all these parameters to be real and specify their values at the weak scale.

Since we are only interested in the properties of the Higgs bosons and neutralinos and these properties are affected little by the soft parameters in the squark/slepton sectors, we specify these parameters before our scan. Noting that a heavy stop (\tilde{t}) is helpful for the Higgs sector to evade the LEP constraints and a light smuon ($\tilde{\mu}$) is needed in the nMSSM to explain the muon anomalous magnetic moment a_μ , we assume all the soft breaking parameters (soft masses and trilinear A -parameters) to be 1 TeV for the (\tilde{t}, \tilde{b}) sector and 100 GeV for the $(\tilde{\nu}_\mu, \tilde{\mu})$ sector. We will briefly discuss the results with a lower $m_{\tilde{t}}$ and those with different $m_{\tilde{\mu}}$ when the a_μ constraint is switched on. For the other soft breaking parameters in the squark/slepton sector, we uniformly set them to be 1 TeV since the considered constraints

are not sensitive to them. Moreover, we assume the grand unification relation for the gaugino masses, $M_1 = (5g'^2/3g^2)M_2$. With the above assumptions, we scan over the remaining seven parameters in the following ranges: $0.1 \leq \lambda \leq 0.7$, $1 \leq \tan \beta \leq 10$, $-1 \text{ TeV} \leq A_\lambda \leq 1 \text{ TeV}$, $50 \text{ GeV} \leq m_A, \mu, M_2 \leq 1 \text{ TeV}$ and $0 < \tilde{m}_S \leq 200 \text{ GeV}$. Note that in the nMSSM $\tan \beta > 10$ is not allowed by the dark matter relic density because $m_{\tilde{\chi}_1^0}$ is suppressed by large $\tan \beta$ (see Eq. (3)) and a light $\tilde{\chi}_1^0$ is difficult to annihilate sufficiently.

In our scan we consider the following constraints: (1) The dark matter relic density, $0.0945 < \Omega h^2 < 0.1287$ [9]. We require $\tilde{\chi}_1^0$ to account for this density. (2) The a_μ constraint, $a_\mu^{exp} - a_\mu^{SM} = (29.5 \pm 8.8) \times 10^{-10}$ [10]. We require the nMSSM contribution to explain the deviation at the 2σ level. (3) The LEP bound on invisible Z decay, $\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 1.76 \text{ MeV}$ [11] (we also apply this bound to the decay $Z \rightarrow h_1 A_1$ with h_1 being the lightest CP-even Higgs boson); the LEP-II upper bound on $\sigma(e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0)$, which is 10^{-2} pb for $i = 1$, $j > 1$ and 10^{-1} pb for $i, j > 1$ (summed over i and j) [12]; and the lower mass bounds on sparticles from direct searches at LEP and the Tevatron [11]. (4) Constraints from the direct search for Higgs bosons at LEP-II, which limit all possible channels for the production of Higgs bosons. (5) Constraints from precision electroweak observables such as ρ_{lept} , $\sin^2 \theta_{eff}^{lept}$, m_W and R_b . (6) The perturbativity of the nMSSM up to the grand unification scale and the stability of the Higgs potential which requires that the physical vacuum of the Higgs potential is the true minimum of the potential.

The above constraints have been encoded in NMSSMTools [7], except for (5). In Ref. [13] we extended the code by adding (5); here we extend all these constraints to the nMSSM scenario. Since the hadronic contribution to a_μ^{SM} remains under discussion [10], in the following we will present results both with and without considering the a_μ constraint.

Our scan sample is 2.5 billion random points in the parameter space given above. With all the constraints except a_μ , only about 6 thousand points survive. This is mainly because the dark matter relic density stringently constrains the mass and couplings of the LSP, and consequently, only a small portion of the parameter space is allowed (as shown explicitly in Figs.1-4 below). Among the surviving points, about 60% are characterized by $m_{A_1} \geq m_Z$ and $30 \text{ GeV} \leq m_{\tilde{\chi}_1^0} \leq 37 \text{ GeV}$, in which $\tilde{\chi}_1^0$ mainly annihilates through Z -boson exchange to give the required dark matter relic density [1]. For most of the other points, both $\tilde{\chi}_1^0$ and A_1 are predominantly singlet-like with roughly $2m_{\tilde{\chi}_1^0} \sim m_{A_1}$, in which the exchange of a light

A_1 is the main annihilation channel of $\tilde{\chi}_1^0$ (this annihilation channel, similar to the case of Table III in [14] for the NMSSM, has not been studied for the nMSSM in the literature).

If we switch on the a_μ constraint, the surviving points are reduced to 1.4 thousand, among which about 60% (70%) satisfy $m_{A_1} < 60$ GeV ($m_{A_1} < m_Z$). This indicates that the current a_μ measurement can constrain the model stringently, and that it favors LSP annihilation through exchange of a light A_1 rather than a Z -boson. Note that in the above we fixed $m_{\tilde{\mu}} = 100$ GeV. If we increase $m_{\tilde{\mu}}$, even fewer scan points will survive. For example, raising $m_{\tilde{\mu}}$ to 150 GeV eliminates about half the remaining points with $m_{A_1} < m_Z$ and nearly all the points with $m_{A_1} \geq m_Z$. For $m_{\tilde{\mu}} = 200$ GeV, none of our scan points survive the a_μ constraint, which implies that smuons must be lighter than about 200 GeV. This conclusion is unique to the nMSSM. The underlying reason is that in SUSY models, the leading chargino/neutralino contribution to δa_μ is proportional to $\tan\beta/m_{\tilde{\mu}}^N$ with $N \geq 2$ [14, 15]. In the MSSM or NMSSM, $\tan\beta$ can be quite large [13] and thus $m_{\tilde{\mu}}$ is not stringently constrained by a_μ ; but in the nMSSM, $\tan\beta$ is bounded from above ($\lesssim 10$) by the dark matter relic density and hence $m_{\tilde{\mu}}$ must be light.

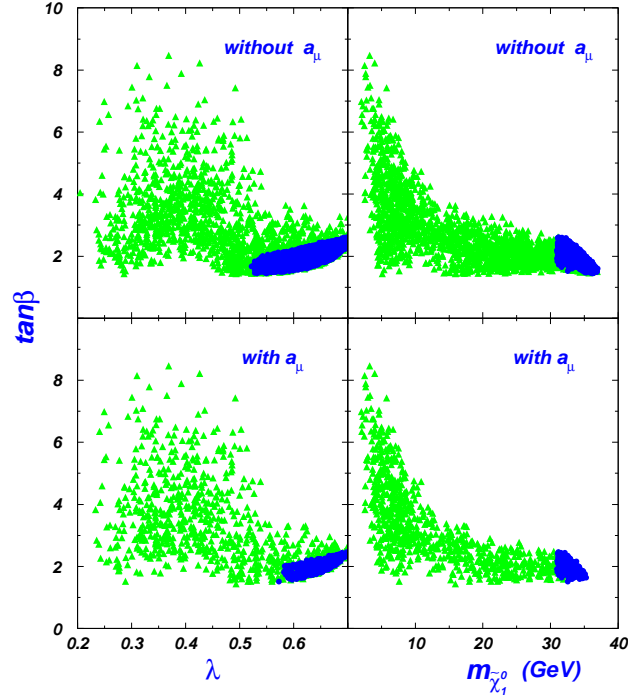


FIG. 1: Parameter scan points allowed by current experiments. The dark bullets (light triangles) correspond to $m_{A_1} \geq m_Z$ ($m_{A_1} < m_Z$), with $\tilde{\chi}_1^0$ mainly annihilating through exchanging a Z -boson (a light A_1) to give the required dark matter relic density.

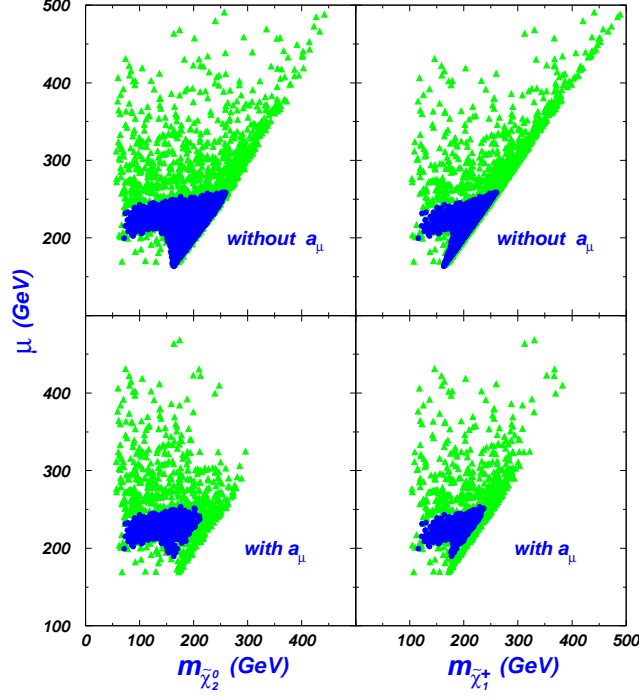


FIG. 2: Same as Fig. 1, but showing dependence on μ , $m_{\tilde{\chi}_2^0}$, and $m_{\tilde{\chi}_1^+}$.

In Figs. 1 and 2 we display the surviving points as functions of various parameters. As we pointed out before, the strongest constraints come from the dark matter relic density. These figures show that if only the Z exchange is responsible for the density (dark bullets), the parameters λ , $\tan\beta$, μ , $m_{\tilde{\chi}_{1,2}^0}$ and $m_{\tilde{\chi}_1^+}$ are all constrained in quite narrow ranges; however, if the light A_1 exchange is considered (light triangles), the allowed parameter ranges are significantly more spread out.

Note that we checked by using the modified NMSSMTools that b - s transitions such as $b \rightarrow s\gamma$ and B_s^0 - \bar{B}_s^0 mixing do not impose any meaningful constraints on the surviving samples in the case of no squark flavor mixings. We also checked that for samples with $m_{A_1} \lesssim 10$ GeV, the branching ratio for $\Upsilon \rightarrow \gamma A_1$ is less than its experimental upper bound of 1×10^{-4} [19].

The following additional comments are in order. (i) We call $\tilde{\chi}_1^0$ singlino-like when the coefficient of the singlino component in $\tilde{\chi}_1^0$ is larger than $1/\sqrt{2}$ (so its square is larger than $1/2$). In general the higgsino or gaugino components in $\tilde{\chi}_1^0$ are not negligible even when $\tilde{\chi}_1^0$ is singlino-like. In fact, it is the higgsino components in $\tilde{\chi}_1^0$ that are mainly responsible for the LSP annihilation coupling discussed above. For annihilation via Z exchange, the typical coefficient of the H_u -type higgsino component in $\tilde{\chi}_1^0$ is 0.4, and we checked that as

the higgsino components increase, the coupling of $\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z$ increases and consequently the relic density drops [1]. For annihilation via A_1 exchange, the typical coefficient for the higgsino component in $\tilde{\chi}_1^0$ is 0.2 and for the doublet-Higgs component in A_1 is 0.15. Since the couplings of $\tilde{\chi}_1^0 \tilde{\chi}_1^0 A_1$ and $A_1 \bar{f} f$ (where f is a light fermion) are suppressed, annihilation via A_1 exchange is too weak to produce the required relic density except in the funnel region $2m_{\tilde{\chi}_1^0} \sim m_{A_1}$ [14]. (ii) The requirement $\tilde{m}_S < 200$ GeV in our scan is taken from Ref. [1] which studied electroweak baryogenesis. We checked that a larger range of \tilde{m}_S does not change our conclusions qualitatively; it only increases the number of surviving samples with $m_{A_1} > m_Z$ and raises the upper bound of m_{A_1} . We did not impose the requirement of successful electroweak baryogenesis in our scan since there exist other ways to explain the origin of the matter-antimatter asymmetry in the Universe [1]. (iii) A heavy \tilde{t} is not necessary in the nMSSM for the SM-like Higgs boson to evade the LEP bound since the Higgs boson mass can be enhanced at tree level by a contribution from λ [4]. We checked that a lighter \tilde{t} in our scan does not change our conclusions; it only decreases the number of the surviving points.

As shown above, if we consider all the constraints including a_μ with $m_{\tilde{\mu}} = 100$ GeV, the mass spectrum is limited to the following ranges: $1\text{GeV} \lesssim m_{A_1} \lesssim 250\text{GeV}$, $30\text{GeV} \lesssim m_{h_1} \lesssim 140\text{GeV}$, $70\text{GeV} \lesssim m_h \lesssim 145\text{GeV}$ (h is the lightest doublet-dominant CP-even Higgs boson, usually called the SM-like Higgs boson; in some cases h can be h_1), $1\text{GeV} \lesssim m_{\tilde{\chi}_1^0} \lesssim 37\text{GeV}$, $50\text{GeV} \lesssim m_{\tilde{\chi}_2^0} \lesssim 300\text{GeV}$ and $105\text{GeV} \lesssim m_{\tilde{\chi}_1^\pm} \lesssim 400\text{GeV}$. In such allowed mass ranges, the phenomenology of the Higgs bosons and sparticles may be quite peculiar and different from the MSSM. A comprehensive study of the phenomenology of this model at the Tevatron and the LHC is beyond the scope of this paper; instead we present the following brief discussion.

First, consider the Higgs bosons. The dominant decay of A_1 may be either $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ or $b\bar{b}$ for $m_{A_1} > 2m_b$, and we checked that the $A_1 \tilde{\chi}_1^0 \tilde{\chi}_1^0$ interaction is mainly induced by the higgsino components of $\tilde{\chi}_1^0$ and/or the doublet components of A_1 [7]. The dominant decay mode of the SM-like Higgs boson h can be any of the following: $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \tilde{\chi}_2^0, A_1 A_1, h_1 h_1$. In Fig. 3 we show the branching ratios of h and A_1 decays into the LSP and $b\bar{b}$. For $m_{A_1} \gtrsim 60$ GeV, both h and A_1 can decay predominantly into LSP pairs and the decay into $b\bar{b}$ is strongly suppressed. Since the branching ratio of $h \rightarrow b\bar{b}$ is suppressed below 10% in most of the allowed parameter space due to the presence of new competing decay modes, conventional

searches for a light SM-like CP-even Higgs boson at the LHC will be quite hopeless. For example, our results indicate that for about 60% of the surviving points, the final decay products of h are two or four LSPs. For these points, weak boson fusion with $h \rightarrow$ invisible is a good search channel [17]. Our results also indicate that for about 16% of the surviving points, h decays predominantly to $4b$. In this case, W/Zh production may be a good channel to detect h [18].

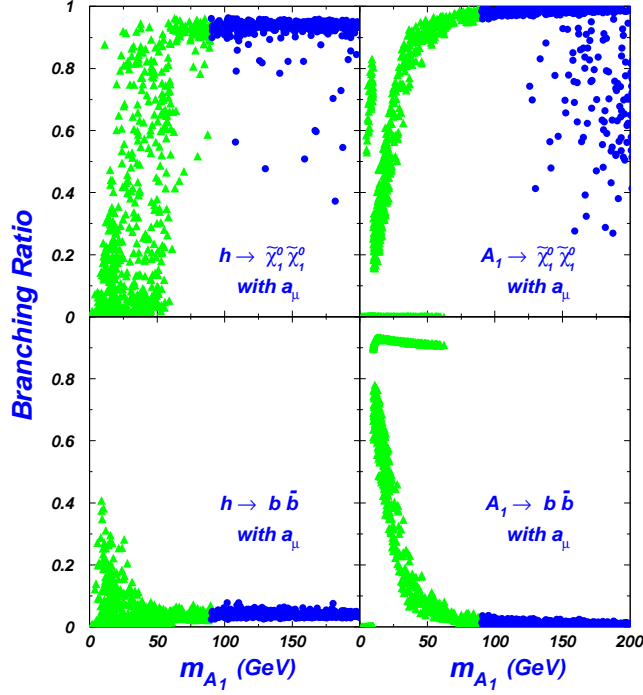


FIG. 3: Same as Fig. 1, but for the branching ratios of h and A_1 versus m_{A_1} with all constraints imposed including a_μ . The effect of the a_μ constraint is to reduce the number of surviving points, as shown in Figs. 1 and 2.

Second, consider smuon production at the LHC. If we take the a_μ constraint seriously, the smuon should be lighter than 200 GeV, which implies that it would be copiously produced either directly or from cascade decays of other particles at the LHC, and should be visible at the LHC. We checked that due to the non-negligible gaugino component of $\tilde{\chi}_1^0$, the decay width of $\tilde{\mu} \rightarrow \mu \tilde{\chi}_1^0$ is about several MeV, so the decay length of smuon is not macroscopic (for a heavy charged particle with macroscopic decay length, its signals at the LHC may be quite special [16]).

Third, consider the next-to-lightest neutralino $\tilde{\chi}_2^0$ at the LHC. As shown in Fig.4, $\tilde{\chi}_2^0$ is bino-like for $m_{\tilde{\chi}_2^0} \lesssim 150$ GeV, and may be higgsino-like for $m_{\tilde{\chi}_2^0} > 150$ GeV. We checked that

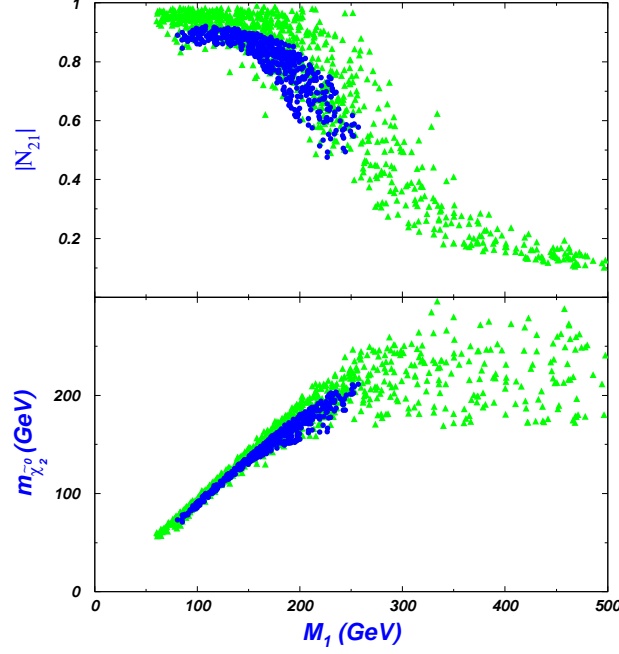


FIG. 4: Same as Fig. 1, but showing dependence on M_1 , $m_{\tilde{\chi}_2^0}$ and $|N_{21}|$ with all constraints imposed including a_μ . N_{21} denotes the coefficient of the bino component in $\tilde{\chi}_2^0$.

the main decay products of $\tilde{\chi}_2^0$ can be $\tilde{\chi}_1^0 h_1$, $\tilde{\chi}_1^0 A_1$, $\tilde{\chi}_1^0 h$, or $\tilde{\chi}_1^0 Z$ and there is a large portion of the surviving samples in which $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 A_1(h_1, h) \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$. If $\tilde{\chi}_2^0$ is the NLSP and it mainly decays into $3\tilde{\chi}_1^0$, it will be copiously produced from the cascade decay of squarks and gluinos [2], and can be easily mistaken as the LSP. From Fig.4 one can also learn that the gaugino mass M_1 is bounded from 50 GeV to 500 GeV. This implies by the gaugino mass unification relation that the gluino mass varies from about 300 GeV to 3 TeV, which could be accessible at the LHC.

In summary, we examined the current experimental constraints on the nMSSM. We found that the parameter space of this model is stringently constrained by current experiments, and in the allowed parameter space the phenomenology of this model may be quite peculiar. Such tightly constrained parameter space could make this model readily tested (either verified or excluded) at the LHC. In addition, since in this model the dark matter particle is constrained in a narrow mass range, the astrophysical dark matter experiments may also be able to cast some light on this model.

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[20] Such a discrete R-symmetry is, of course, broken by the SUSY-breaking soft terms, as well as by the source of SUSY-breaking, which could be a non-zero constant superpotential induced by the spontaneous breaking in the hidden sector or by condensation phenomena. Although this constant in the superpotential may be utilized to cancel the cosmological constant, for phenomenological study it is usually assumed that all R-symmetry violation is encoded in the soft SUSY-breaking terms.