Eur. Phys. J. C 46, 521–526 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02522-x

THE EUROPEAN PHYSICAL JOURNAL C

Dark matter constraints on gaugino/Higgsino masses in split supersymmetry and their implications at colliders

F. Wang[1], W. Wang[1], J.M. Yang[2,1,a]

[1] Institute of Theoretical Physics, Academia Sinica, Beijing 100080, P.R. China
[2] CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, P.R. China

Received: 21 December 2005 / Revised version: 7 February 2006 /
Published online: 31 March 2006 –

Abstract. In split supersymmetry, gauginos and Higgsinos are the only supersymmetric particles that are potentially accessible at soon-to-be-completed colliders. While direct experimental research, such as the LEP and Tevatron experiments, have given robust lower bounds on the masses of these particles, cosmic dark matter can give some upper bounds and thus have important implications for research at future colliders. In this work we scrutinize such dark matter constraints and show the allowed mass range for charginos and neutralinos (the mass eigenstates of gauginos and Higgsinos). We find that the lightest chargino must be lighter than about 1 TeV under the popular assumption $M_1 = M_2/2$ and about 2 or 3 TeV in other cases. The corresponding production rates of the lightest chargino at the CERN large hadron collider (LHC) and the International Linear Collider (ILC) are also given. While in some parts of the allowed region the chargino pair production rate can be larger than 1 pb at the LHC and 100 fb at the ILC, other parts of the region correspond to very small production rates, and thus there is no guarantee of finding the charginos of split supersymmetry at future colliders.

PACS. 14.80.Ly; 95.35.+d

1 Introduction

Given the importance of supersymmetry in both particle physics and string theory, searching for supersymmetry seems to be a crucial task in present and future colliders. The soon-to-be-completed LHC will be able to explore the supersymmetric particles up to a few TeV, and the ILC will allow precision testing of supersymmetry. Of course, there is no guarantee that supersymmetry will be found at these collders since the masses of the supersymmetric particles are basically unknown. As is well known, to solve the fine-tuning problem in particle theory, supersymmetric particles should be below the TeV scale, and thus the LHC would be a factory of supersymmetric particles. However, in the recently proposed split supersymmetry [1], the supersymmetric solution of the fine-tuning problem in particle physics is abandoned (inspired by the need to fine-tune for the cosmological constant), while the virtues of supersymmetry in preserving grand unification as well as providing the cosmic dark matter candidate are still retained. As a result, the mass scale of all sfermions as well as the many heavy Higgs bosons can be very large while the gaugino/Higgsino mass scale may still be below the TeV scale. While split supersymmetry has the obvious virtue of naturally avoiding the notorious supersymmetric flavor problem, it predicts that no supersymmetric scalar particles except a light Higgs boson will be accessible in future particle colliders. Thus, if split supersymmetry is the true story,[1] the only way to reveal supersymmetry at the colliders is through gaugino or Higgsino productions.

Among the gauginos and Higgsinos, the gluino is the only colored particle and thus may be most copiously produced in the gluon-rich environment of the LHC. However, the gluino is usually speculated to be much heavier than other gauginos and Higgsinos. It has been shown [3] that the grand unification requirement can allow a gluino as heavy as 18 TeV. Furthermore, if the dark matter is assumed to be the gravitino produced from the late decay of the metastable gluino that froze out in the early universe, it was found [4] that the gluino must be heavier than approx. 14 TeV and thus impossible to access at the LHC. Thus to explore split supersymmetry we should not focus only on gluino productions; the productions of the electroweakly interacting gauginos and Higgsinos (which mix into two charged particles called charginos and four neutral particles called neutralinos) should also be considered, although their production rates at the LHC are much lower. Of course, if the LHC can discover supersym-

[a] e-mail: jmyang@itp.ac.cn

[1] Some studies [2] show that split supersymmetry is quite natural from the top-down view.

metry and then the ILC takes on the task of a precision test, the productions of charginos and neutralinos at the ILC will play the dominant role. For both the LHC and the ILC, the production of charginos will give good signatures since the subsequent decays yield energetic leptons. To facilitate collider searches for charginos and neutralinos, the preestimation of their allowed mass regions is important.

While direct experimental research, such as the LEP and Tevatron experiments, have given robust lower bounds for the masses of charginos and neutralinos, the cosmic dark matter can give some upper bounds and thus have important implications for searches at future colliders. Therefore, although the consequence of split supersymmetry in the dark matter issue has been considered to some extent in the literature [3–6], in this work we scrutinize the dark matter constraints on the masses of charginos and neutralinos and evaluate the corresponding production rates at the LHC and ILC.

This work is organized as follows. In Sect. 2 we recapitulate the parameter space of the sector of charginos and neutralinos. In Sect. 3 we examine the dark matter constraints. We will show the constraints on (a) the original parameter space, (b) the masses of charginos and neutralinos, and (c) the production rates at the LHC and ILC. Conclusions are given in Sect. 4.

Note that for the supersymmetry parameters we adopt the notation in [7]. We work in the framework of the minimal supersymmetric model (MSSM) and assume that the lightest supersymmetric particle is the lightest neutralino, which alone makes up cosmic dark matter. Also, we fix the parameter $\tan\beta = 40$ since a large value of $\tan\beta$ is favored by current experiments and since, in the region of large $\tan\beta (\gtrsim 10)$, our results are not sensitive to $\tan\beta$.

2 Parameter space of charginos and neutralinos

The chargino mass matrix is given by

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}, \quad (1)$$

and the neutralino mass matrix is given by

$$\begin{pmatrix} M_1 & 0 & -m_Z \sin\theta_W \cos\beta & m_Z \sin\theta_W \sin\beta \\ 0 & M_2 & m_Z \cos\theta_W \cos\beta & -m_Z \cos\theta_W \sin\beta \\ -m_Z \sin\theta_W \cos\beta & m_Z \cos\theta_W \cos\beta & 0 & -\mu \\ m_Z \sin\theta_W \sin\beta & -m_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}, \quad (2)$$

where M_1 and M_2 are respectively the $U(1)$ and $SU(2)$ gaugino mass parameters, μ is the mass parameter in the mixing term $-\mu\epsilon_{ij} H_1^i H_2^j$ in the superpotential, and $\tan\beta \equiv v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets. The diagonalization of (1) gives two charginos $\chi^+_{1,2}$ with the convention $M_{\chi^+_1} < M_{\chi^+_2}$, while the diagonalization of (2) gives four neutralinos $\chi^0_{1,2,3,4}$ with the convention $M_{\chi^0_1} < M_{\chi^0_2} < M_{\chi^0_3} < M_{\chi^0_4}$. Thus the masses and mixings of charginos and neutralinos are determined by four parameters: M_1, M_2, μ, and $\tan\beta$.

The current constraints [8] on these parameters are divided into two classes: (1) direct constraints from experimental searches of supersymmetric particles and (2) indirect constraints from some precisely measured low-energy processes or physical quantities via supersymmetric quantum effects. For split supersymmetry, almost all indirect constraints from low-energy processes, such as various B-decays, drop out since the supersymmetric loop effects in these processes usually involve sfermions, which are superheavy in split supersymmetry. The most stringent direct bounds are from LEP experiments [9]: (1) the lighter chargino χ^+_1 must be heavier than about 103 GeV; (2) the LSP must be heavier than about 47 GeV; (3) the value of $\tan\beta$ must be larger than 2.

Note that in addition to the direct lower bound from LEP II, theoretically a large $\tan\beta$ helps to push up the lightest Higgs boson mass and thus ameliorate the stress between the experimental lower bound and the theoretical upper bound on the lightest Higgs boson mass.[2] Thus in our analyses we assume a large $\tan\beta$ and fix it at 40. We verified that in the region of large $\tan\beta(\gtrsim 10)$, our results are not sensitive to $\tan\beta$.

We assume that the cosmic dark matter is composed only of the LSP, which is assumed to be the lightest neutralino χ^0_1. (If the gravitino is assumed to be the LSP and comprise the dark matter, it will incur some severe cosmological constraints [11].)

The thermal relic density of the lightest neutralino from the freeze-out can be calculated from the Boltzmann equation, which involves the thermal averaged cross section of neutralino annihilations. In our work we use the package DarkSUSY [12], and we verified that the package micrOMEGAs [13] gave results similar to those in our study. In calculating the cross section of neutralino annihilations, many additional supersymmetric parameters are involved, the most important of which are sfermion masses and M_A (the mass of CP-odd Higgs bosons). Since we focus only on split supersymmetry, all sfermion masses and M_A are superheavy, so any diagrams involving a sfermion or a heavy Higgs boson makes negligible contributions to neutralino annihilations. Actually, we found that as long as the sfermion mass or M_A gets heavier than about 10 TeV, the effects of sfermions or heavy Higgs bosons decouple, as shown in Figs. 1 and 2. The peak in Fig. 1(b) happens around the "A-funnel" resonance point $M_A \approx 2M_{\chi^0_1}$.

[2] The upper mass limit of the lightest Higgs boson is relaxed to about 150 GeV in split supersymmetry [1]. However, if the right-handed neutrinos are introduced into split supersymmetry with a see-saw mechanism, the large neutrino Yukaka couplings can lower the lightest Higgs boson mass by a few tens of GeV [10].

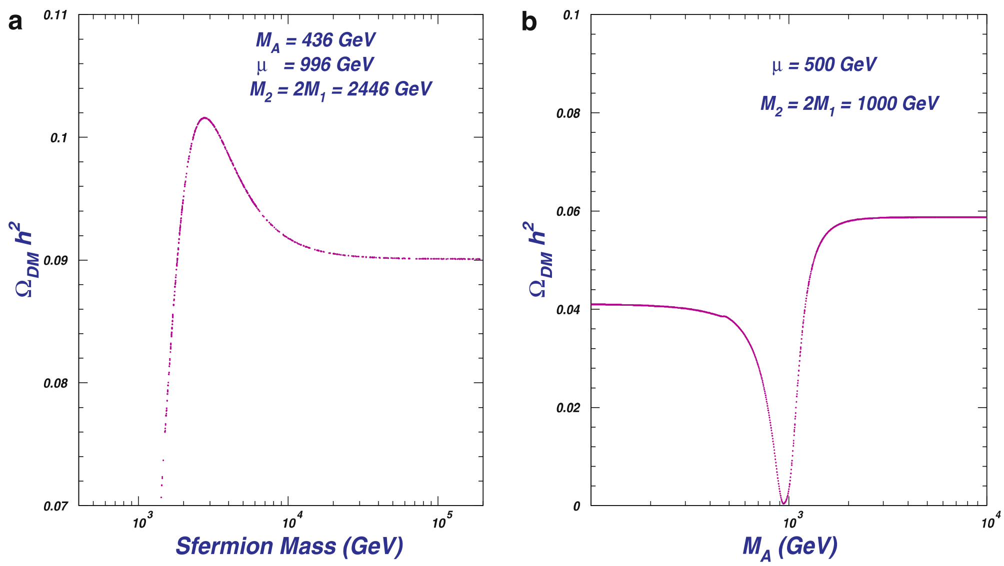

Fig. 1. Neutralino relic density vs. **a** sfermon mass and **b** M_A

3 WMAP dark matter constraints

The 2σ allowed region for the dark matter relic density is

$$0.094 < \Omega_{\mathrm{CDM}} h^2 < 0.129\,, \quad (3)$$

which can be inferred from the Wilkinson microwave anisotropy probe (WMAP) measurements [14]. In what follows we present the 2σ allowed regions for four cases: (1) $M_1 = M_2/2$, (2) superheavy μ, (3) superheavy M_2, and (4) superheavy M_1. In our calculations we fix a "superheavy" mass at 100 TeV since it is high enough for the relevant supersymmetric particles to decouple from the neutralino annihilations. In each case we present the allowed region for (a) the original parameter space, (b) the chargino mass $M_{\chi_1^+}$ vs. the neutralino mass $M_{\chi_1^0}$, and (c) the cross section of chargino pair production at the LHC and the ILC vs. the chargino mass $M_{\chi_1^+}$. Note that we just give the tree-level cross sections and do not include the one-loop corrections [15]. The center-of-mass energy is 14 TeV for the LHC and is assumed to be 1 TeV for the ILC [16]. The results are represented in Figs. 2–5, where the dot-dashed line is the LEP II lower limit on the chargino mass.

(1) $M_1 = M_2/2$: This case is well motivated since the supergravity models predict the unification relation $M_1 = \frac{5}{3} M_2 \tan^2\theta_W \simeq 0.5 M_2$. In the low-mass region for both M_2 and μ in Fig. 2a, the dark matter is the mixing of gauginos and Higgsinos. The strip with very large M_2 corresponds to Higgsino dark matter, while the strip with very large μ corresponds to gaugino dark matter (the mixing of bino and wino). From Fig. 2b we see that both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ are upper bounded by

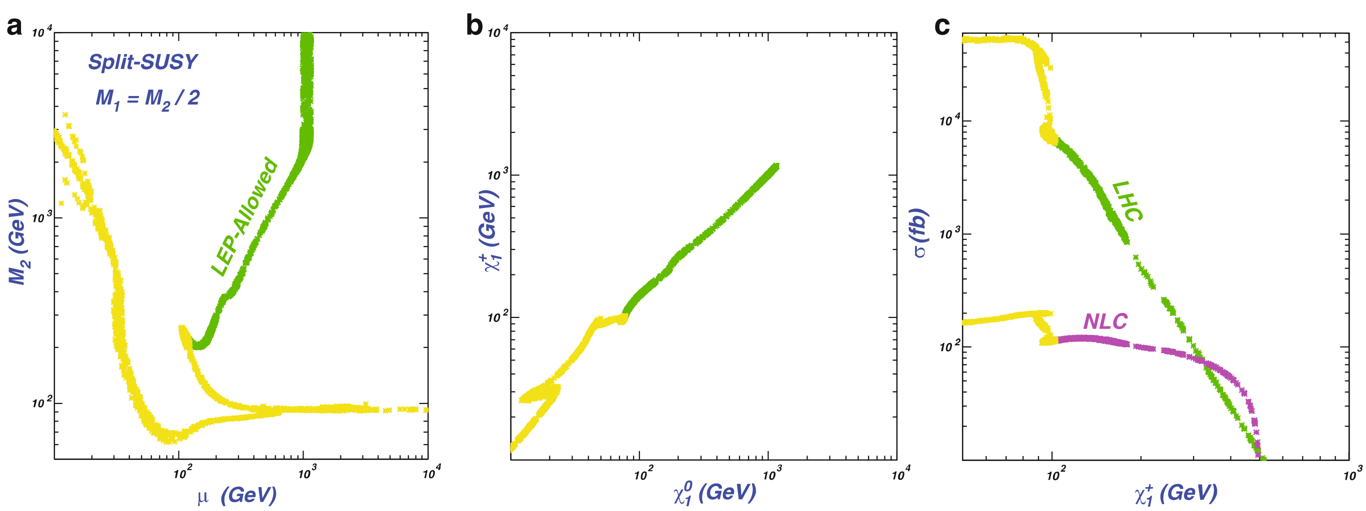

Fig. 2. WMAP 2σ allowed region (*shaded area*) in case of $M_1 = M_2/2$. The *light shaded region* (*yellow*) is not allowed by LEP experiments

about 1 TeV. Figure 2c shows that in the allowed region the cross section of chargino pair production at the LHC can reach a few pb for a light chargino but drops rapidly as the chargino gets heavy. The cross section at the ILC can reach 100 fb for a light chargino in the allowed region.

(2) Superheavy μ: This case was proposed and favored by some authors [17] because the μ problem [18] is avoided and a crude gauge coupling unification is preserved. In the low-mass region for both M_2 and M_1 in Fig. 3a, the dark matter is the mixing of bino and wino, while the region with large M_1 corresponds to wino dark matter. Figure Fig. 3b shows that both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ are upper bounded by about 3 TeV. Figure 3c shows that in the allowed region the cross section of chargino pair production at the LHC can reach 10 pb for a light chargino but drops rapidly as the chargino gets heavy. The cross section at ILC can reach 200 fb for a light chargino in the allowed region.

(3) Superheavy M_2: In the low-mass region for both M_1 and μ in Fig. 4a, the dark matter is the mixing of bino and Higgsinos. When M_1 (μ) gets very large, a strip remains that corresponds to Higgsino (bino) dark matter. The chargino mass $M_{\chi_1^+}$ is upper bounded by about 3 TeV, and the neutralino mass $M_{\chi_1^0}$ is upper bounded by about 1 TeV. For a light chargino in the allowed region, the cross section of chargino pair production can reach the level of 1 pb at LHC and 100 fb at the ILC.

(4) Superheavy M_1: In Fig. 5a the strip with large M_2 (μ) corresponds to Higgsino (wino) dark matter. As shown in Fig. 5b, both the chargino mass $M_{\chi_1^+}$ and the neutralino mass $M_{\chi_1^0}$ are lower bounded by about 1 TeV and upper

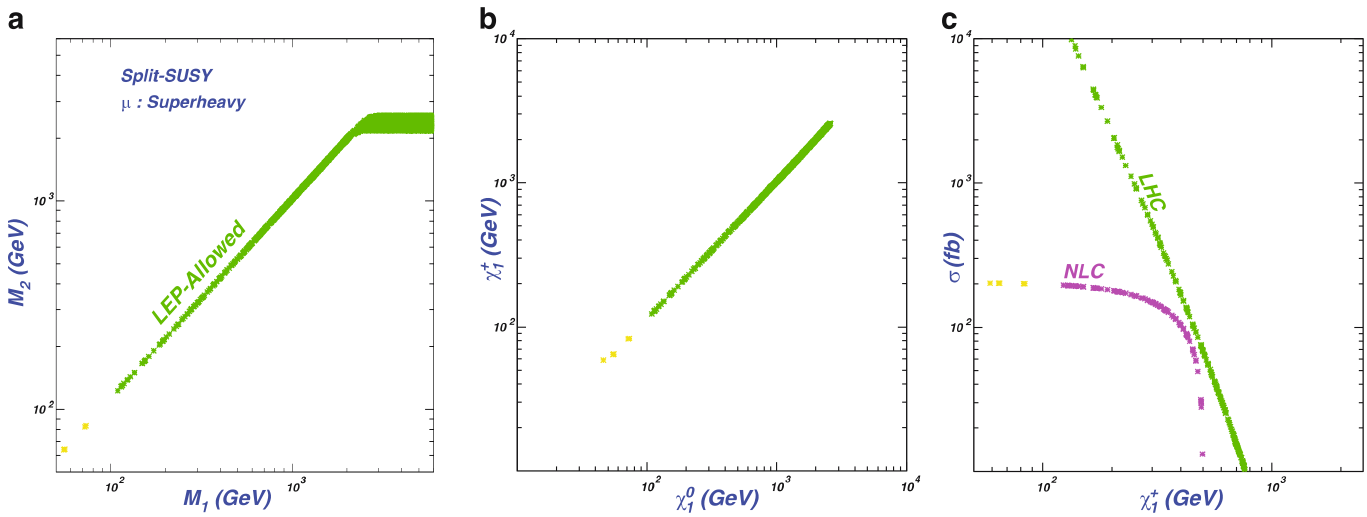

Fig. 3. WMAP 2σ allowed region (*shaded area*) in case of superheavy μ. The *light shaded region* (*yellow*) is not allowed by LEP experiments

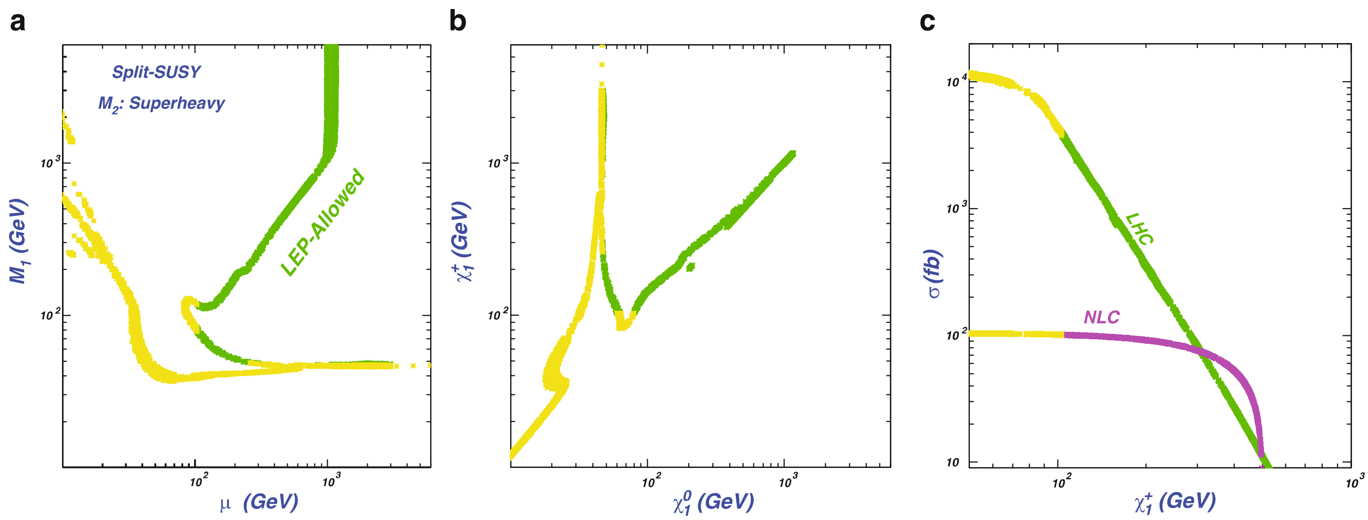

Fig. 4. WMAP 2σ allowed region (*shaded area*) in case of superheavy M_2. The *light shaded region* (*yellow*) is not allowed by LEP experiments

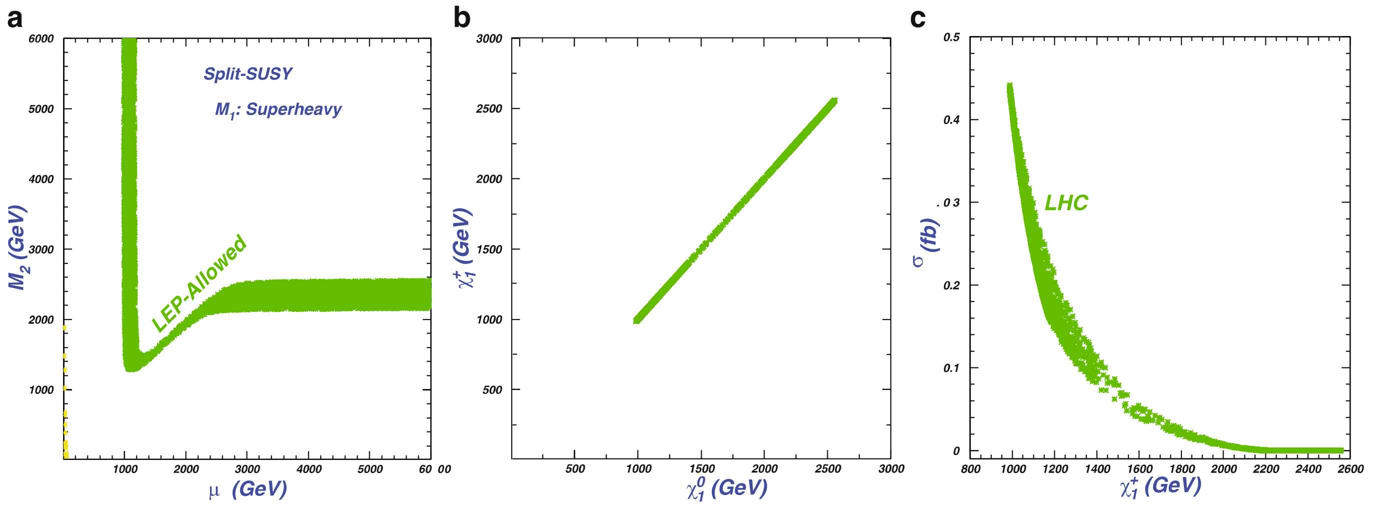

Fig. 5. WMAP 2σ allowed region (*shaded area*) in case of superheavy M_1. The *light shaded region* (*yellow*) is not allowed by LEP experiments

bounded by about 2.5 TeV. Thus the charginos cannot be pair produced at the ILC with c.m. energy of 1 TeV. Although the charginos can be pair produced at the LHC, the cross section is very small, as shown in Fig. 5c.

Note that while chargino pair production at a rate of 100 fb at the ILC may not be hard to observe due to the collider's clean environment (chargino pair production is regarded as a good way to test split supersymmetry at the ILC [19]), searching for chargino pair production with a cross section of pb level at the LHC may be quite challanging. The chargino χ_1^+ decays into a neutralino χ_1^0 and a pair of fermions (two jets or a charged lepton plus a neutrino). So the signature of chargino pair production is (1) two energetic leptons plus missing energy or (2) one energetic lepton plus two jets plus missing energy. Let us take the latter signature, i.e., $\ell + 2j + P_T^{\rm miss}$, as an example. The huge background comes from Wjj. In order to substantially reduce this background, we may apply a cut on the transverse mass defined by

$$m_T = \sqrt{(P_T^\ell + P_T^{\rm miss})^2 - (P_T^\ell + P_T^{\rm miss})^2}\,. \qquad (4)$$

m_T is always less than M_W (and peaks just below M_W) if the only missing energy comes from a neutrino from W decay, which is the case for the Wjj background events. For the signal, m_T is spread about equally above and below M_W due to the large extra missing energy from the neutralinos. Therefore, we may, for example, require $m_T > 90$ GeV. Given the importance of chargino pair production as a test of split supersymmetry at the LHC, detailed Monte Carlo studies with a consideration of various backgrounds are needed, which is beyond the scope of this work.

4 Conclusion

In split supersymmetry, gauginos and Higgsinos are the only supersymetric particles that are possibly accessible at the LHC or the ILC. The masses of these particles are subject to the stringent constraints of cosmic dark matter. Under the assumption that the lightest neutralino is the LSP and constitutes the dark matter in the universe, we scrutinized the dark matter constraints on the masses of charginos and neutralinos. We considered several cases: (1) $M_1 = M_2/2$, (2) superheavy μ, (3) superheavy M_2, and (4) superheavy M_1. We found that the lightest chargino χ_1^+ must be lighter than approx. 1 TeV in the first case and approx. 2 or 3 TeV in other cases. In the first three cases, the corresponding production rate of the chargino pair at the LHC (ILC) can reach the level of pb (100 fb) in some parts of the allowed region and thus hopefully be observable. But in the last case, the chargino must be heavier than approx. 1 TeV and thus has a too small production rate to be observale at the LHC. Thus, overall, there is no guarantee of finding the charginos of split supersymmetry at the LHC or ILC.

Acknowledgements. We thank Bing-Lin Young and Fuqiang Xu for discussions. This work is supported in part by National Natural Science Foundation of China.

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