TIFR/TH/05-13

Looking for a Heavy Higgsino LSP in Collider and Dark Matter Experiments

Utpal Chattopadhyay[a], Debajyoti Choudhury[b], Manuel Drees[c], Partha Konar[d] and D.P. Roy[d]

[a] Department of Theoretical Physics, Indian Association for the Cultivation of Science, Raja S.C. Mallik Road, Kolkata 700 032, India

[b] Department of Physics and Astronomy, University of Delhi, Delhi 110007, India

[c] Physikalisches Institut der Universität Bonn, Nussallee 12, 53115 Bonn, Germany

[d] Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India

Abstract

A large part of the mSUGRA parameter space satisfying the WMAP constraint on the dark matter relic density corresponds to a higgsino LSP of mass $\simeq 1$ TeV. We find a promising signal for this LSP at CLIC, particularly with polarized electron and positron beams. One also expects a viable monochromatic γ-ray signal from its pair annihilation at the galactic center at least for cuspy DM halo profiles. All these results hold equally for the higgsino LSP of other SUSY models like the non-universal scalar or gaugino mass models and the so–called inverted hierarchy and more minimal supersymmetry models.

1. Introduction

Weak scale supersymmetry (SUSY) is the most popular extension of the standard model (SM) because it is endowed with three unique features [1]. It provides (1) a natural solution to the hierarchy problem of the SM, (2) a plausible candidate for the cold dark matter of the universe in the form of the lightest superparticle (LSP), and (3) unification of the SM gauge couplings at the GUT scale. However it also suffers from two problems.

(i) *Little Hierarchy Problem:* The LEP limit on the mass of an SM–like Higgs boson [2],

$$m_h > 114 \text{ GeV}, \tag{1}$$

requires the average top squark mass to be well above M_Z [3]. In models where supersymmetry breaking is transmitted to the visible sector at an energy scale exponentially larger than the weak scale, this implies some fine-tuning of SUSY parameters to obtain the correct value of M_Z.

(ii) Flavor and CP Violation Problem: Generic SUSY models make fairly large contributions to CP violating processes with or without flavor violation, as represented by the K decay observable ϵ_K and the fermion electric dipole moments (EDM) respectively. Predictions for rates of CP–conserving flavor changing processes, like $\mu \to e\gamma$ decays, also often exceed experimental limits. SUSY parameters have to be chosen carefully to control these contributions. It should be noted here that the recently advocated split SUSY model [4] tries to solve the second problem by pushing up the scalar superparticle masses, but at the cost of dramatically aggravating the first problem.

The minimal supergravity model (mSUGRA) is by far the simplest potentially realistic model of weak scale supersymmetry [5]. It provides a very economical parametrisation of superparticle masses and couplings on the one hand and a natural explanation of the electroweak symmetry breaking (EWSB) phenomenon on the other [6]. The model is completely specified in terms of four continuous parameters and one sign, namely

$$m_0, m_{1/2}, A_0, \tan\beta \text{ and } \mathrm{sign}(\mu). \tag{2}$$

The first three entries represent the universal SUSY breaking scalar and gaugino masses and trilinear coupling at the GUT scale. μ is the supersymmetric Higgs(ino) mass parameter, while $\tan\beta$ is the ratio of the two Higgs vacuum expectation values. The flavor universality of scalar soft breaking terms avoids problems with flavor changing processes, while CP violation will be under control if the parameters in (2) are real.

In going down from the GUT scale to the weak scale the $SU_3 \times SU_2 \times U_1$ gaugino masses evolve like their respective gauge couplings, i.e.

$$\begin{aligned} M_1 &= (\alpha_1/\alpha_G) m_{1/2} \simeq (25/60) m_{1/2}, \\ M_2 &= (\alpha_2/\alpha_G) m_{1/2} \simeq (25/30) m_{1/2}, \\ M_3 &= (\alpha_3/\alpha_G) m_{1/2} \simeq (25/9) m_{1/2}. \end{aligned} \tag{3}$$

The higgsino masses are simply given by the μ parameter. The scalar masses at the weak scale are also related by Renormalization Group Equations (RGE) to the GUT scale mass parameters of eq.(2). A very important scalar mass at the weak scale is the mass of the Higgs boson H_2 that couples to the top quark. This mass appears in the EWSB condition

$$\mu^2 + M_Z^2/2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} \simeq -m_{H_2}^2. \quad (4)$$

The last equality holds for $\tan\beta \geq 5$, which is favored by the LEP limit of eq.(1) [2, 3]. $m_{H_2}^2$ is related to the GUT scale mass parameters by the solution of its RGE [7],

$$m_{H_2}^2 = C_1 m_0^2 - C_2 m_{1/2}^2, \quad (5)$$

where we have dropped contributions $\propto A_0$ for simplicity since they do not play any important role here. The coefficients C_1, C_2 depend on the gauge and Yukawa couplings. Thanks to the large negative contribution from the top Yukawa coupling, $C_2 \simeq 2$. On the other hand, $|C_1| \ll 1$, its value and sign depending on the exact values of SM parameters (in particular, on m_t and α_s), on the scale $m_{\rm SUSY}$ where the RG evolution is terminated, and on $\tan\beta$, with smaller $\tan\beta$ favoring smaller (possibly negative) C_1. This makes it easy to obtain a negative value of $m_{H_2}^2$ as required by the EWSB condition (4). This is the so-called radiative EWSB mechanism [6].

Combining eqs. (4) and (5), one sees that μ^2 is related to m_0^2 and $m_{1/2}^2$ by an ellipsoidal equation if $C_1 < 0$, in particular for low values of $\tan\beta$ (< 5). However, for moderate to large values of $\tan\beta$ (> 5), favored by the LEP limit of eq.(1), and large $m_{\rm SUSY}$, C_1 becomes positive, leading to a hyperbolic equation. These two cases have been described as ellipsoidal and hyperbolic branches of mSUGRA [8]. One sees from eqs. (3,4,5) that in the first case $M_1 < |\mu|$; and the lightest neutralino (LSP) is the Bino ($\tilde{B}$). However in the phenomenologically favored case of moderate to large $\tan\beta (\geq 5)$ one can have both $M_1 < |\mu|$ and $M_1 > |\mu|$, corresponding to a Bino and a higgsino LSP respectively [8]. We shall concentrate in this case. Since the sign of μ is not important for our analysis, we shall choose only positive sign for simplicity.

In the next section we study the dark matter (DM) relic density in the Bino and higgsino LSP domains of mSUGRA model following the second paper of ref.[8]. The relic density has been computed using the MicrOMEGAs code [9]. A comparison with cosmological data [10] on the relic DM density shows that a large fraction of mSUGRA points satisfying this data come from the higgsino LSP domain with $|\mu| \simeq 1$ TeV. In the following two sections we study the prospects of detecting the higgsino LSP in collider and DM search experiments, respectively. We find good prospect of detecting this particle at a 3 TeV linear collider like CLIC. There is also a good prospect of detecting it in the form of TeV scale gamma ray line from DM pair-annihilation in the galactic center for favorable profiles of galactic DM distribution. In the next section we shall show that all our results hold not only in mSUGRA but in a host of other SUSY models as well, which can naturally accommodate a higgsino LSP. Finally we shall conclude with a summary of our results.

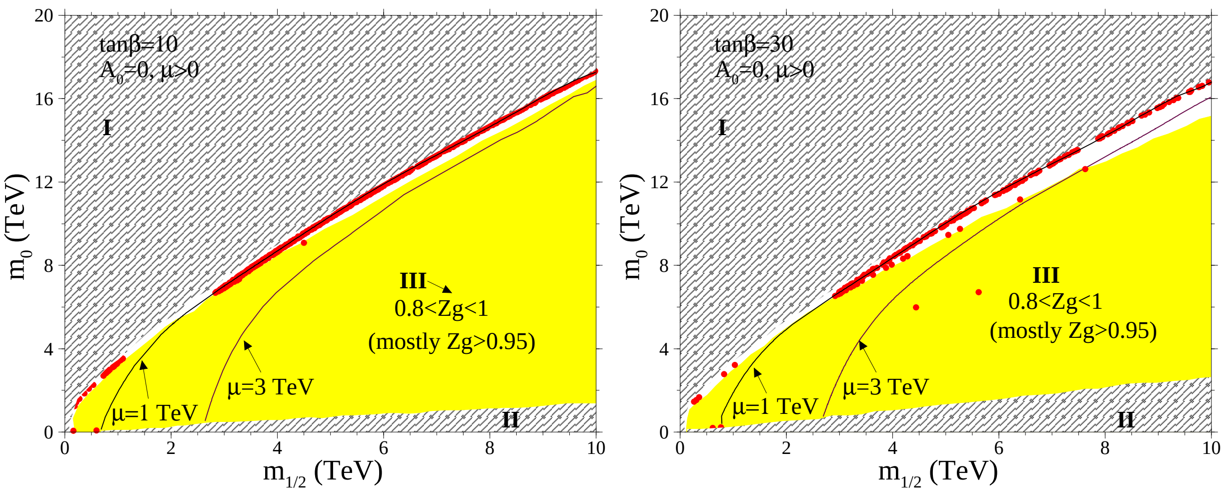

Figure 1: mSUGRA parameter space for $m_t = 178$ GeV, $A_0 = 0$ and $\tan\beta = 10$ (left) and 30 (right). The patterned regions marked I and II are disallowed by the EWSB condition and the constraint of a neutral LSP, respectively. In the large yellow region the LSP is Bino–like. Red points satisfy the constraint (8) on the dark matter relic density.

2. Higgsino LSP as DM in mSUGRA

Figs. 1 show the mSUGRA parameter space satisfying the EWSB condition for a moderate and a large value of $\tan\beta$. We have used our own code for the solution of the relevant RGE and the treatment of EWSB, including dominant loop corrections. The upper edge of the allowed (white) region corresponds to the hyperbolic boundary from eqs.(4,5) for the LEP limit of $|\mu| \geq 100$ GeV [2]. In fact, the bulk of this disallowed region (I) corresponds to $\mu^2 < 0$, i.e. no EWSB. In the bottom strip (II) the tau slepton $\tilde{\tau}_1$ becomes the LSP. This is disallowed by the astrophysical constraint requiring a neutral LSP [2]. Over the allowed region the LSP is the lightest neutralino, which can be a combination of gaugino and higgsino states, i.e.

$$\chi \equiv \tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0. \tag{6}$$

The gaugino component of the LSP is defined by the fraction

$$Z_g = N_{11}^2 + N_{12}^2. \tag{7}$$

The yellow (light shaded) region in Fig. 1 corresponds to a dominantly gaugino (in fact Bino $\tilde{B}$) LSP.

One sees from Fig. 1 that in most of the mSUGRA parameter space the LSP is dominantly $\tilde{B}$. Notice, however, that the bulk of this region is disallowed by the constraint on the DM relic density from cosmological data, in particular from the WMAP satellite experiment, [10]

$$\Omega_\chi h^2 = 0.113 \pm 0.017, \tag{8}$$

where $h = 0.71 \pm 004$ is the Hubble constant in units of 100 km/(s×Mpc) [2] and Ω is the relic density in units of the critical density. In fact, one usually finds an overabundance of DM relic density ($\Omega_\chi > 1$). This is because $\tilde{B}$ does not carry any gauge charge and hence does not couple to the gauge bosons. A Bino–like LSP therefore mostly annihilates via the exchange of sfermions, $\chi\chi \xrightarrow{\tilde{f}} f\bar{f}$, which is suppressed by the large sfermion mass. Only in some special cases like $m_\chi \simeq m_{\tilde{\tau}_1}$ and $m_\chi \simeq m_A/2$ can one get large co–annihilation $\chi\tilde{\tau}_1 \xrightarrow{\tau,\tilde{\tau}} \tau\gamma$ and pair annihilation $\chi\chi \xrightarrow{A} b\bar{b}, t\bar{t}$ rates respectively [11]. Correspondingly one can see a few (red) points of acceptable $\tilde{B}$ DM density near the lower boundary (co–annihilation); in mSUGRA resonant $A-$exchange becomes possible only for $\tan\beta \geq 50$.[1]

Most of the points satisfying the DM relic density constraint (8) are seen to lie very near the hyperbolic boundary [9]. The few points near the lower end of this boundary correspond to the so–called focus point region [13], where the LSP has a significant higgsino component, although it may be still dominated by $\tilde{B}$. Such an LSP couples via its higgsino component to W and Z bosons, and through gaugino–higgsino mixing to Higgs bosons, and can thus annihilate into both fermionic and bosonic final states. LHC signatures for the focus point region have been investigated in [14]. Note however that the large majority of DM–allowed points lie on the

$$m_\chi \simeq \mu = 1 \text{ TeV} \tag{9}$$

contour. For the chosen value of the top mass, $m_t = 178$ GeV, the DM constraint (8) is satisfied on this contour for $m_{1/2} \geq 3$ TeV and $m_0 \geq 6.5$ TeV; for the new preliminary world average top mass of 173 GeV [15], the lower bound on m_0 would be reduced to $\simeq 5.5$ TeV. This is the higgsino LSP domain of mSUGRA (gaugino fraction $Z_g \lesssim 0.1$).[2] In this region there is a near degeneracy among the lighter chargino and neutralino states, i.e.

$$m_\chi \simeq m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^+} \simeq \mu \simeq 1 \text{ TeV}. \tag{10}$$

So the major annihilation processes correspond to the pair and co–annihilation [16]

$$\tilde{\chi}_i^0\tilde{\chi}_i^0 \xrightarrow{\tilde{\chi}_1^+(\tilde{\chi}_j^0)} WW(ZZ),\ \tilde{\chi}_i^0\tilde{\chi}_1^+ \xrightarrow{W} \bar{f}_1 f_2,\ \tilde{\chi}_1^0\tilde{\chi}_2^0 \xrightarrow{Z} \bar{f}f, \tag{11}$$

where $i = 1, 2$ and $j = 2$ (1) for $i = 1$ (2). Although Z couples to a pair of χ via their higgsino components, the coupling is proportional to the difference $N_{13}^2 - N_{14}^2$ [17]. Hence it vanishes in the limit of $M_1, |\mu| \gg M_Z$, where the $\tilde{\chi}_{1,2}^0$ eigenstates correspond to the symmetric and antisymmetric combinations of $\tilde{H}_1^0$ and $\tilde{H}_2^0$. In the same limit, the off–diagonal $Z\tilde{\chi}_1^0\tilde{\chi}_2^0$ coupling reaches its maximal value. Thanks to the annihilation processes (11), the string of points satisfying the constraint (8) continues indefinitely upwards on the $\mu = 1$ TeV contour,

[1] There is also a small allowed region [12] with $m_\chi \simeq m_h/2$, h being the lighter CP–even Higgs boson; this is however not visible at the scales chosen in Fig. 1.

[2] There must be allowed points also in between the focus point and TeV higgsino–LSP regions. However, this DM–allowed strip is very narrow, since the transition between a lighter higgsino as LSP, with too small a relic density, and Bino–like LSP with much too high a relic density, is very rapid. The scan of parameter space used in Figs. 1 therefore found no allowed points for m_0 between 4 and 6.5 TeV.

whereas all other DM–allowed regions in mSUGRA are finite in the $(m_{1/2}, m_0)$ plane. In this sense the constraint (8) favors the higgsino LSP domain of the mSUGRA model.

On the other hand, Figs. 1 imply that in this domain all superparticles are quite heavy. We just saw that even the LSP has a mass near 1 TeV. Moreover, we needed $m_{1/2} \geq 3$ TeV and $m_0 \geq 6.5$ TeV for $m_t = 178$ GeV. This means that the electroweak gaugino $(\tilde{B}, \tilde{W})$ masses are at least in the few TeV range, while the masses of gluinos and all scalars (except for the lightest Higgs boson) are near 10 TeV or even higher. This aggravates the "little hierarchy" problem considerably; however, the finetuning required is still very much smaller than in split supersymmetry [4].

Higgsino and gaugino masses in the above range are still compatible with gauge coupling unification within the uncertainty of GUT scale thresholds. A sfermion mass scale near 10 TeV is adequate to solve the problems of flavor and CP violation even without assuming flavor universality [18]. This leads us to more general SUSY models, which we will comment on in Sec. 5. In the next two sections we investigate the prospects of probing scenarios with heavy higgsino–like LSP in collider and dark matter experiments. These phenomenological investigations are largely model–independent, so long as the remaining sparticles lie significantly above the higgsino–like states.

3. Probing the Higgsino LSP Region in Collider Experiments

Sfermion and gluino masses of $\gtrsim 10$ TeV and electroweak gaugino masses of at least a few TeV put them well out of reach of the LHC. The only superparticles which can be produced there with significant rates are the nearly degenerate charged and neutral higgsinos, χ_1^+ and $\chi_{1,2}^0$ of mass $\simeq 1$ TeV. We have computed the mass differences including radiative corrections [17] and found them to be restricted to the range

$$\delta m_c = m_{\chi_1^+} - m_{\chi_1^0} < 10 \text{ GeV}, \tag{12}$$

with $m_{\chi_2^0} - m_{\chi_1^0} \simeq 2\delta m_c$ for $\tan\beta \gg 1$. Thus the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay products will be too soft to be detected efficiently on top of the underlying event at a hadron collider. Therefore one has to tag the pair production of higgsinos at the LHC. The by far best tag is provided by the two forward jets j in $\tilde{\chi}$ pair production via vector boson fusion [19],

$$pp \to \chi_1^\pm \chi_i^0 jj, \chi_1^+ \chi_1^- jj, \chi_1^0 \chi_2^0 jj \quad (i = 1, 2). \tag{13}$$

We have computed the resulting higgsino signal at the LHC closely following [19] and a similar investigation for an invisibly decaying Higgs signal in [20]. The selection criteria used are: (i) two forward jets in opposite hemispheres with $E_T^j > 40$ GeV and $2 < |\eta_j| < 5$; (ii) $\Delta\eta_{jj} > 4$; (iii) $M_{\rm inv}(jj) > 1200$ GeV; (iv) $\not{E}_T > 100$ GeV; (v) $\Delta\phi_{jj} < 57^\circ$ and (vi) the central jet veto as defined in ref. [20]. The backgrounds come from $Z(\to \nu\nu)$ and $W(\to \ell\nu)$ production via electroweak (vector boson fusion) and QCD (higher order Drell–Yan) processes where

ℓ is assumed to escape detection for $p_T^\ell < 10$ GeV. Following [20] we have assumed the efficiency of the central jet veto to be 0.9, 0.82 and 0.28 for the signal, electroweak and QCD backgrounds respectively. The total background is 64 fb assuming conservatively the renormalization scale for α_s to be the lower jet-E_T. One expects to measure the background to a high precision of $\sim 1.2\%$ from the visible $Z \to \ell\bar{\ell}$ and $W \to \ell\nu$ events [20]. Adding this uncertainty in quadrature to the statistical error on the background, and assuming an integrated luminosity of 100 fb^{-1}, one thus needs a signal cross section of at least 5.5 fb for a 5σ discovery. Unfortunately the cross section after cuts for the production of higgsino–like charginos and neutralinos with mass near 1 TeV is several orders of magnitude below this value. We therefore conclude that the LHC will not be able to probe the region of parameter space we are interested in.

The most promising machine for detecting a 1 TeV higgsino LSP is the proposed 3 TeV linear e^+e^- collider CLIC [21]. We shall follow the strategy of ref.[22] for computing the signal and background cross sections. The same strategy has been followed by the LEP experiments for setting mass limits on a higgsino LSP [2]; in particular the OPAL collaboration [23] has used it to set a mass limit of 90 GeV. The higgsino pair production is tagged by a photon from initial–state radiation (ISR), i.e.[3]

$$e^+e^- \to \gamma\chi_1^+\chi_1^-, \gamma\chi_1^0\chi_2^0 \,. \tag{14}$$

If the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay products remain undetected, the main physics background is

$$e^+e^- \to \gamma\nu\bar{\nu}. \tag{15}$$

The photon is required to have an angle $\theta > 10^\circ$ relative the beam axis. Moreover it is required to satisfy

$$E_T^\gamma > E_T^{\gamma\ \min} = \sqrt{s}\frac{\sin\theta_{\min}}{1+\sin\theta_{\min}}, \tag{16}$$

which vetos the radiative Bhabha background $e^+e^- \to \gamma e^+e^-$, by kinematically forcing one of the energetic $e^\pm$ to emerge at an angle $> \theta_{\min}$. At CLIC energy of $\sqrt{s} = 3$ TeV,

$$E_T^{\gamma\ \min} = 50\ (100)\ \text{GeV for}\ \theta_{\min} = 1^\circ(2^\circ). \tag{17}$$

The OPAL detector has instrumentation for $e^\pm$ detection down to $\theta_{\min} = 2^\circ$, while it seems feasible to have it down to 1° at the future linear colliders [22]. We shall show results for both $E_T^{\gamma\ \min} = 50$ and 100 GeV. We shall also impose the recoil mass cut

$$M_{\rm rec} = \sqrt{s}(1 - 2E^\gamma/\sqrt{s})^{1/2} > 2m_\chi, \tag{18}$$

which is automatically satisfied by the signal (14). Fake photon background processes have been effectively suppressed by the OPAL collaboration [23] by requiring photon isolation and a minimum value for the total p_T, which are automatically satisfied by the signal as well as the $e^+e^- \to \gamma\nu\bar{\nu}$ background. Therefore we shall not impose these requirements.

[3] The cross sections for $\tilde{\chi}_i^0$ $(i = 1, 2)$ pair production are negligible, since the diagonal $\tilde{\chi}_i^0\tilde{\chi}_i^0 Z$ couplings are very small, as remarked earlier.

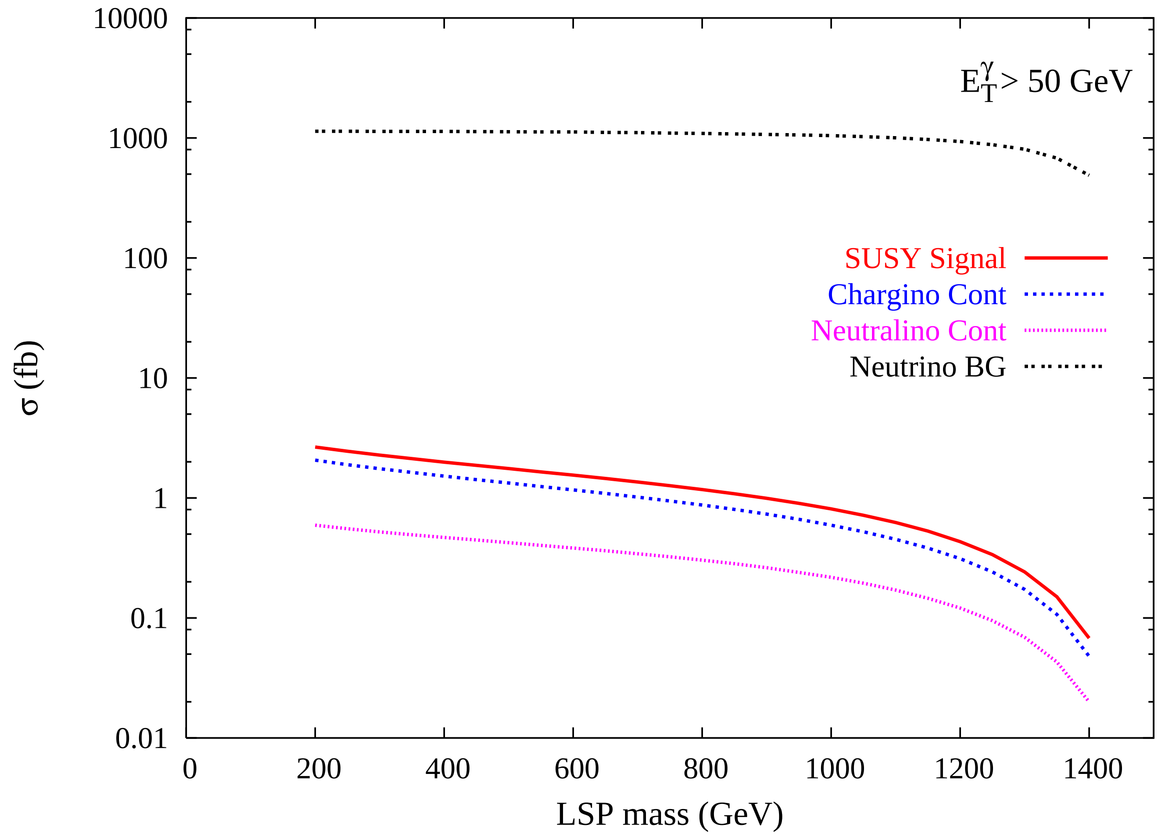

Figure 2: Cross sections for the higgsino signal (14) and the neutrino background (15) at CLIC ($\sqrt{s} = 3$) TeV, produced with a photon tag of $E_T^\gamma > 50$ GeV. Initial state radiation is included.

Fig. 2 shows the signal and the background cross sections from (14) and (15) respectively against the higgsino LSP mass, for $E_T^{\gamma \rm min} = 50$ GeV. In calculating these cross sections, we have included initial state radiation (ISR) effects by convoluting the hard $2 \to 3$ cross sections with electron distribution functions, as described in ref.[24]. This allows background events with on–shell Z boson, if there is an energetic ISR photon going down one of the beam pipes; ISR therefore increases the total background by a few %. We also computed the higher–order background process

$$e^+e^- \to Z\nu\bar{\nu}\gamma, \text{ where } Z \to \nu\bar{\nu}, \tag{19}$$

and found it to contribute about 10 fb after cuts – much less than the background (15), but still significantly more than the signal.

The signal cross section is reduced by ISR by $\sim 10\%$ for $m_\chi = 1$ TeV, since it effectively reduces the amount of phase space available. The same effect increases the signal for smaller LSP mass, since it increases the $s-$channel photon and Z propagators. The signal is dominated by the chargino pair production. For 1 TeV higgsino mass one expects a signal cross section of only ~ 0.8 fb against a background of ~ 1050 fb. Thus for the projected CLIC luminosity of 1000 fb^{-1} one expects 800 signal events against a background of 10^6, corresponding to $N_S/\sqrt{N_B} \simeq 0.8$ only. Evidently it is a hopeless situation unless one can suppress the background (15) by identifying the soft $\chi_1^\pm$ and $\tilde{\chi}_2^0$ decay products. This remains true when the cut on E_T^γ is increased to 100 GeV (not shown).

The method of identifying these particles would depend on the decay length $c\tau$, which depends strongly on the mass difference δm_c. This decay length has been estimated in ref. [22] for a specific model of an iso–triplet chargino. It is shown there that for $\delta m_c \leq 1$ GeV one expects to detect the chargino track and/or a decay $\pi^\pm(\ell^\pm)$ track with displaced vertex in a standard micro–vertex detector. One can easily check that the decay length of the charged higgsino is about twice as large as the iso–triplet chargino of [22]. Hence these tracks should be even more clearly detectable in this case.

But one expects prompt chargino decay for $\delta m_c > 1$ GeV, which holds over most of our parameter space of interest. For this case the OPAL collaboration [23] has found that the resulting charged tracks can be detected with $\geq 50\%$ efficiency for the signal, and used it to eliminate the $\gamma\nu\bar{\nu}$ background. For the present case such an efficiency corresponds to a respectable signal size of $\gtrsim 400$ events. However, a new problem arises at future linear colliders, which did not occur at LEP. The large charge density in the bunches gives rise to "beamstrahlung" when the two bunches cross. The collision of beamstrahlung photons can then form an underlying event containing several soft particles [25]. If this happens in the same bunch crossing as a hard $e^+e^- \to \gamma\nu\bar{\nu}$ annihilation, one obtains a similar final state topology as in the signal.

It is not possible to speculate at this stage on the level of this underlying event background at CLIC. All we can say is that an underlying event resembling the $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm$ decay products must not occur in more than 1% of all bunch crossings. Neglecting efficiencies, this would correspond to $\sim 10^4$ background against ~ 800 signal events for $m_\chi = 1$ TeV – i.e. $N_S/\sqrt{N_B} \sim 8$. We will see below that one can tolerate a higher level of underlying events from beamstrahlung if the e^+e^- beams are polarized. Finally, we note that beamstrahlung will also change the effective $e^\pm$ beam spectra, and hence the cross sections (14) and (15). These effects will need to be included once the beam characteristics have been fixed.

The reason for the large cross section for the background (15) compared to the signal processes (14) is the $t-$channel W exchange contribution to the background. This can be suppressed with right– (left–)handed polarization of the e^- (e^+) beam. In fact it is easy to see that for 100% polarization of one of the beams the background cross section will go down to the level of the signal. This is not feasible, of course. What we shall do instead is to estimate the signal and background for the same beam polarizations as envisaged for the ILC [26], i.e.

$$P_{e^-} = 0.8 \text{ (mostly right – handed) and } P_{e^+} = -0.6 \text{ (mostly left – handed).} \qquad (20)$$

It is easy to check that this corresponds to the following fractional luminosities

$$e_R^- e_L^+ : e_L^- e_R^+ : e_L^- e_L^+ : e_R^- e_R^+ = 0.72 : 0.02 : 0.08 : 0.18, \qquad (21)$$

while each was 0.25 in the unpolarized case. The dominant contribution to the background (15) from t-channel W exchange contributes only to the second combination $e^-_L e^+_R$. Hence it is suppressed by a factor of $.02/.25 = .08$. The higher–order background (19) is suppressed by a similar factor. One can also check that the $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ and $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ contributions to the signal (14) are modified by factors of 0.6 and 1.3 respectively, resulting in an overall suppression of the total signal by a factor 0.8. Fig. 3 shows the total signal and background cross sections for $E^\gamma_T > 50$ and 100 GeV. In either case one gets a $N_S/\sqrt{N_B} \simeq 2.1$ for the CLIC luminosity of 1000 fb^{-1}. But one has a better $N_S/N_B \simeq 400/39,000$ events for the $E^\gamma_T > 100$ GeV cut. Recall that this cut requires instrumentation down to 2° instead of 1° to eliminate the $\gamma e^+ e^-$ background. Hence this harder cut seems advantageous to us.

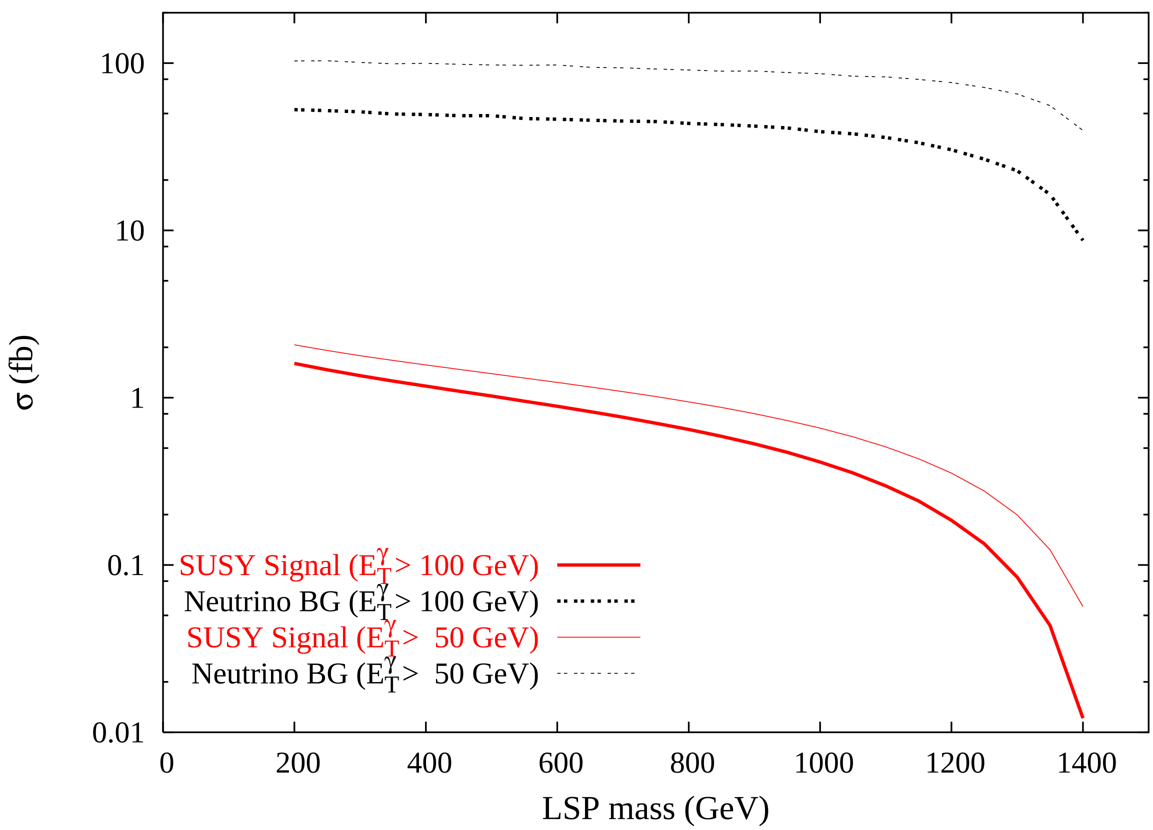

Figure 3: Cross sections of the higgsino signal (14) and neutrino background (15) at CLIC with polarized e^- and e^+ beams. Initial state radiation is included.

Fig. 4 shows the recoil mass distribution of the background (15) along with that of a 1 TeV higgsino signal (14) for both E^γ_T cuts and polarized beams; ISR has again been included. As discussed above the background can be suppressed if the soft $\tilde{\chi}^\pm_1$ or $\tilde{\chi}^0_2$ decay products can be detected. In case of the background, such soft particles can only come from beamstrahlung reactions like $\gamma\gamma \to \pi^+\pi^-, \ell^+\ell^-, \cdots$ underlying the background (15). Not all such reactions will lead to events with similar characteristics as the signal. For example, one can envision applying cuts on the angular distribution of the soft particles, which tend to peak at small angles in two–photon events, but are quite central for most signal events. Another possible discriminator is the p_T imbalance of the soft particles (i.e., not counting the hard tagging photon), which is expected to be larger for the signal than for the background. In devising such cuts, the characteristics of the (largely non–perturbative) background can be taken from measurements in the pure background region $M_{\rm rec} < 2m_\chi$. Comparing the observed cross section for the remaining background over the $M_{\rm rec} < 2$ TeV region with the prediction of Fig. 4 would give an estimate of the fraction of surviving background due to beamstrahlung. Since this fraction should be independent of $M_{\rm rec}$, one can use this to estimate the cross section of the surviving background in the $M_{\rm rec} > 2$ TeV signal region. Any excess over this estimate would represent the higgsino signal. One might even be able to estimate the higgsino mass from the threshold of the excess cross section. It is easy to see that underlying events from beamstrahlung at the 10% level (after cuts) correspond to a reduction of the background to 10% and hence will increase $N_S/\sqrt{N_B}$ ratio from 2 to ~ 6. Thus with polarized beams one can tolerate the underlying event at the 10% level.

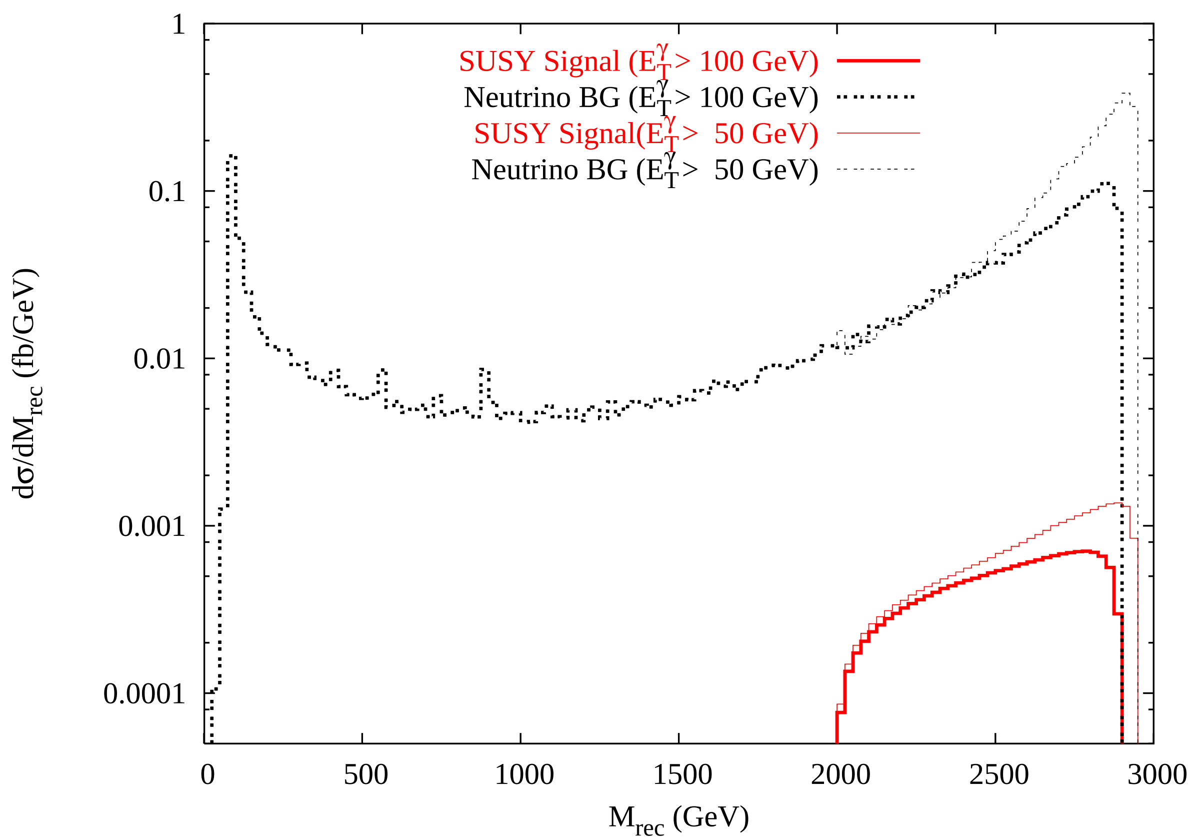

Figure 4: The recoil mass distributions of a 1 TeV higgsino signal (14) and the neutrino background (15) at CLIC with polarized e^- and e^+ beams. Initial state radiation is included.

4. Higgsino LSP Search in DM experiments

One can see from the second paper of ref. [8] that the higgsino LSP signal is too small to be measurable in direct dark matter search experiments. The reason is that the signal comes from spin–independent χp scattering, which is dominated by the Higgs boson (h, H) exchange. Since its coupling to a χ pair is proportional to the product of their higgsino and gaugino components, it is very small for a higgsino dominated LSP. The signal is further suppressed by the large LSP mass.

We have also checked that the neutrino signal coming from the χ pair annihilation at the solar core is too small to be measurable at an IceCUBE size detector. Here the signal size is determined by the spin–dependent χp scattering cross section via Z boson exchange, which is very small due to the suppressed diagonal $Z\chi\chi$ coupling; see the remark following eq.(11).

The most promising signal for TeV higgsino DM comes from the pair annihilation processes

$$\chi\chi \to \gamma\gamma, \chi\chi \to \gamma Z, \tag{22}$$

resulting in a monochromatic $\gamma-$ray line [27, 28]. The dominant contributions to these processes come from $W^\pm\chi_1^\mp$ loops, and are suppressed by only a M_W^2 factor in the denominator instead of m_χ^2. This results in a large cross section for $\gamma-$ray production from (22) for a TeV scale higgsino,

$$v\sigma_{\gamma\gamma} \sim v\sigma_{\gamma Z} \sim 10^{-28}\ \mathrm{cm^3s^{-1}}, \tag{23}$$

where v is the velocity of the DM particles in their cms frame. The resulting gamma ray flux[4] coming from an angle ψ relative to the galactic center is given by

$$\phi_\gamma(\psi) = \frac{N_\gamma v\sigma}{4\pi m_\chi^2}\int_{\text{line of sight}} \rho^2(\ell)d\ell(\psi), \tag{24}$$

where $\rho(\ell)$ is the dark matter energy density and $N_\gamma = 2$ (1) for the $\gamma\gamma$ (γZ) production process. This can be rewritten as [27]

$$\phi_\gamma(\psi) = 1.87\times 10^{-14}\left(\frac{N_\gamma v\sigma}{10^{-28}\ \mathrm{cm^3s^{-1}}}\right)\left(\frac{1\ \mathrm{TeV}}{m_\chi}\right)^2 J(\psi)\mathrm{cm^{-2}s^{-1}sr^{-1}}\,, \tag{25}$$

where

$$J(\psi) = \int_{\text{line of sight}} \rho^2(\ell)d\ell(\psi)/\left[(0.3\ \mathrm{GeV/cm^3})^2\cdot 8.5\ \mathrm{kpc}\right] \tag{26}$$

is the line integral scaled by the squared DM mass density in our neighborhood and by our distance from the galactic center.

Several Atmospheric Cerenkov Telescopes (ACT) have started recording or are on their way to record such $\gamma-$rays from the galactic center – i.e. MAGIC and VERITAS in the

[4]It has been pointed out very recently [29] that tree–level higher order processes, in particular $\chi\chi \to W^+W^-\gamma$, can increase the flux of photons with $E_\gamma \simeq m_\chi$ by up to a factor of 2. While significant, this enhancement is still much smaller than the uncertainty coming from the DM distribution near the center of the galaxy, as discussed below.

northern hemisphere and H.E.S.S. and CANGAROO in the south. One generally expects a concentration of DM in the galactic center; but its magnitude has a large uncertainty depending on the assumed profile of the DM halo density distribution [30, 31, 32]. The cuspy NFW profile [30] corresponds to

$$\langle J(0)\rangle_{\Delta\Omega=.001} \simeq 1000, \tag{27}$$

which represents the DM flux in the direction of the galactic center averaged over the typical ACT aperture of $\Delta\Omega = .001$ sr. Extreme distributions, like the spiked profile [31] and core profile [32], correspond to increase and decrease of this flux respectively by a factor of $\sim 10^3$.

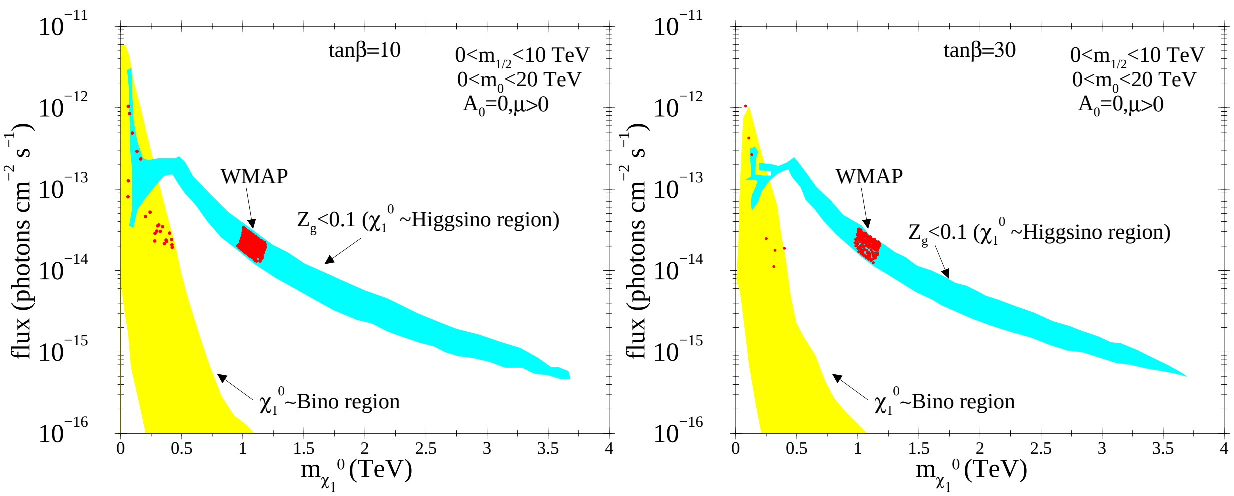

Figure 5: Monochromatic gamma ray flux from DM pair annihilation near the galactic center shown for the NFW profile of DM halo distribution and an aperture $\Delta\Omega = 10^{-3}$ sr.

We have computed the $\gamma-$ray line signal (25) for the NFW profile and the aperture $\Delta\Omega = .001$ sr using the Dark SUSY code [33]. Fig. 5 shows the resulting signal against the DM mass, where we have added the $\gamma\gamma$ and γZ contributions, since they give identical photon energy ($= m_\chi$) within the experimental resolution. This result agrees well with that of ref. [34]. The vertical spread in the higgsino band reflects the dependence of the annihilation cross section (23) on the mass difference δm_c. As noted in [34] the discovery limit of the above-mentioned ACT experiments goes down to 10^{-14} cm^{-2}s^{-1}. Thus for the NFW profile one expects a $\gamma-$ray line signal that should be detectable for the WMAP favored mass range of $m_\chi \simeq 1$ TeV. Recall that the signal rate will go up by a factor or of $\sim 10^3$ for the spiked profile [31], while it will go down by a similar factor for the core profile [32]. In the latter case it will fall below the discovery limit of these ACT experiments.

In fact, H.E.S.S. *did* detect TeV photons coming from the direction of the galactic center [35]. However, they observe a continuous spectrum extending beyond 10 TeV in energy, which can be described quite well by a power law. This is not what one expects from DM annihilation. In fact, the spectrum looks very similar to that of other "cosmic accelerators" observed by the H.E.S.S. telescopes. It is currently not clear whether this signals comes right from the center of our galaxy (defined as the location of a supermassive black hole), or from a nearby supernova remnant (SNR); in particular the SNR Sagittarius A East might be the culprit [36]. Note that SNR are known to emit TeV photons with power–law spectra. The H.E.S.S. collaboration is now working on improving their angular resolution. If the source of the observed TeV photons, whose flux is well above the detectable limit, continues to coincide with the galactic center within the resolution, the discovery of a line signal from DM annihilation at the center would become more difficult, since one would then have to look for a peak in the spectrum on top of a sizable smooth background.

5. Higgsino LSP in other SUSY Models

We have so far concentrated in the mSUGRA model for its simplicity and economy of parameters. However one can easily see that all our results hold for the higgsino LSP in a host of other SUSY models. This is because the relevant interactions are the higgsino interaction with the gauge bosons, which are completely determined by the gauge charges of $\tilde{H}_1$ and $\tilde{H}_2$ along with their mixing. Both these features are common to all variants of the minimal supersymmetric standard model (MSSM). Thus the cross sections for the higgsino annihilation processes (11), and the resulting higgsino masses (10) obtained using the constraint (8) on their relic density, are common to all MSSMs, as long as the other superparticles and heavy Higgs bosons have masses $\gtrsim$ 2 TeV. The same is true for the signals depicted in Figs. 2–5. This also explains why the DM results of Figs. 1 and 5 are essentially independent of all SUSY parameters except for the higgsino masses. We therefore have made no mention of these parameters while presenting the collider signals of Figs. 2–4. It should be mentioned here that the strip to the left of the DM allowed higgsino LSP range in Fig. 1 corresponds to an underabundance of DM relic density in the standard cosmological model. However, additional thermal and nonthermal mechanisms of DM production have been suggested [37, 38], which could enhance the DM relic density over its standard cosmological model value. In the presence of such mechanisms the DM allowed range will move to the $\mu < 1$ TeV region; and so will the higgsino LSP mass. In that case the collider and DM signals shown in Figs. 2,3 and 5 over the LSP mass range of 200 – 1000 GeV will become relevant.

We saw above that in the context of mSUGRA, a TeV higgsino can be the LSP only if sfermions lie near 10 TeV or even higher. This is adequate for suppressing FCNC processes even without assuming flavor universality of scalar soft breaking parameters. It also allows $\mathcal{O}(1)$ phases in the soft breaking sector without violating constraints on CP violating processes. This greatly opens up the allowed parameter space, even if one keeps the two soft breaking Higgs masses the same in order to achieve radiative EWSB. Examples for such models are the so–called inverted hierarchy and more minimal supersymmetry models [18]. At the cost of additional finetuning(s) [39], one can even entertain the idea of moving the sfermion masses to yet larger values, as in the split SUSY model [4].

We saw in Figs. 1 that mSUGRA predicts the LSP to be Bino–like over most of the theoretically allowed parameter space. This can be traced back to the fact that the coefficient C_2 in eq.(5) is quite large and positive, while $|C_1|$ is small, so that $|\mu| > M_1$ at the weak scale unless $m_0^2 \gg m_{1/2}^2$. C_1 can be increased if the Higgs soft breaking masses exceed the stop masses at the GUT scale [40]. On the other hand, C_2 can be reduced if the ratios M_1/M_3 and/or M_2/M_3 are increased [41] relative to their mSUGRA values (3). Models with non–universal scalar and/or non–universal gaugino masses therefore often can accommodate a higgsino–like LSP more easily than mSUGRA does. Finally, if one reduces the input scale, i.e. the scale where supersymmetry breaking is mediated to the visible sector [42], one simultaneously increases C_1 and reduces C_2, again making it easier to obtain a higgsino–like LSP. All our results will apply equally to these models.

6. Summary and Conclusions

We have seen that a higgsino–like LSP can be Dark Matter in a variety of supersymmetric models. In the most constrained case, the mSUGRA model, this remains a possibility for arbitrarily large values of m_0 and $m_{1/2}$, thereby greatly enlarging the cosmologically allowed region of parameter space. As discussed in Sec. 5. a higgsino–like LSP can also be realized in many extensions of the mSUGRA model.

In standard cosmology, and assuming that the LSP was in thermal equilibrium after the period of last entropy production, the LSP relic density can be calculated uniquely from its (co–)annihilation cross sections. In case of higgsino–like LSP one finds that a mass near 1 TeV is required. This makes sparticle searches at colliders quite challenging. In most models strongly interacting sparticles have masses at least a factor of 5 above the LSP mass; this is true in particular for all models with (approximate) gaugino mass unification near the scale of Grand Unification. This means that the usual SUSY signatures at the LHC will not work. We found in Sec. 3 that the production of two higgsino–like states in vector boson fusion also does not give rise to a detectable signal at the LHC if these states lie near 1 TeV. Moreover, the energy of the next (international) linear collider ILC will not be sufficient to produce pairs of TeV sparticles.

We therefore have to consider more futuristic colliders. We saw in Sec. 3 that the proposed 3 TeV e^+e^- collider CLIC offers quite good prospects, *if* the level of beamstrahlung induced underlying events can be kept under control. This can be achieved by designing the accelerator such that the flux of beamstrahlung photons remains small, and/or by building a sufficiently sophisticated detector so that the kinematic distributions of soft particles produced in two–photons events can be distinguished from those of the soft decay products of the heavier higgsino–like states $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$. We also saw that the ability to polarize the incident $e^\pm$ beams would be very helpful.

In order to show that a given particle forms the Dark Matter in the universe, one will eventually have to detect these relics. We saw in Sec. 4 that in case of a higgsino–like LSP the most promising search is that for a $\gamma-$ray line at $E_\gamma \simeq m_\chi$. The flux of such photons should peak in directions where DM particles accumulate. The by far most promising site is therefore the center of our galaxy. Unfortunately here the signal might be masked by the recently observed flux of TeV photons with a continuous spectrum extending beyond 10 TeV. Improved angular and/or energy resolution would be helpful in enhancing the signal to background ratio in this case.

We conclude that a TeV higgsino is a viable supersymmetric Dark Matter candidate. The large sparticle masses characteristic of such a scenario require some amount of finetuning, but alleviate problems with flavor–changing neutral currents and CP violation. Testing this scenario experimentally is challenging, but should be possible at future multi–TeV e^+e^- colliders like CLIC, and perhaps through the observation of a TeV $\gamma-$ray line in atmospheric Cerenkov telescopes. Finding TeV higgsinos either at colliders or in Dark Matter search experiments is certainly easier than finding gravitinos, which have been much discussed lately as possible Dark Matter candidates [43]. This scenario should therefore be taken seriously, in particular if the LHC fails to discover supersymmetry.

Acknowledgments

DC thanks the Physikalisches Institut of Bonn University for hospitality, and DST, India for financial assistance under a Swarnajayanti Fellowship. The work of MD was partially supported by the European Network for Theoretical Astroparticle Physics, ENTApP. DPR and UC thank the organizers of the 8th Workshop on High Energy Physics Phenomenology (WHEPP 8), where this investigation was initiated.

References

[1] See e.g., Perspectives in Supersymmetry, ed. G.L. Kane, World Scientific (1998); Theory and Phenomenology of Sparticles: M. Drees, R.M. Godbole and P. Roy, World Scientific (2005).

[2] Review of Particle Properties: S. Edelman et al, Phys. Lett. **B592**, 1 (2004).

[3] See e.g., Higgs Boson Theory and Phenomenology: M. Carena and H.E. Haber, Prog. Part. Nucl. Phys. **50**, 63 (2003).

[4] N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005) [hep–th/0405159]; G.F. Giudice and A. Romanino, Nucl. Phys. **B699**, 65 (2004) [hep–ph/0406088].

[5] A.H. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); R. Barbieri, S. Ferrara and C.A. Savoy, Phys. Lett. **B119**, 343 (1982); L. Hall, J. Lykken and S. Weinberg, Phys. Rev. **D27**, 2359 (1983).

[6] L. Ibáñez and G.G. Ross, Phys. Lett. **B110**, 215 (1982); K. Inoue et al., Prog. Theor. Phys. **68**, 927 (1982).

[7] M. Carena, M. Olechowski, S. Pokorski and C.E.M. Wagner, Nucl. Phys. **B426**, 269 (1994).

[8] K.L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. **D58**, 096004 (1998); U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. **D68**, 035005 (2003).

[9] G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, hep–ph/0405253.

[10] C.L. Bennett et. al., Astrophys. J. Suppl. **148**, 1 (2003) [astro–ph/0302207]; D.N. Spergel et al., Astrophys. J. Suppl. **148**, 175 (2003) [astro–ph/0302209] .

[11] See e.g., J.R. Ellis et al., Nucl. Phys. **B652**, 259 (2003); A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. **D68**, 043506 (2003) [hep–ph/0304080].

[12] A. Djouadi, M. Drees and J.–L. Kneur, hep–ph/0504090.

[13] J.L. Feng, K.T. Matchev and T. Moroi, Phys. Rev. **D61**, 075005 (2000), and Phys. Rev. Lett. **84**, 2322 (2000); J.L. Feng, K.T. Matchev and F. Wilczek, Phys. Rev. **D63**, 045024 (2001).

[14] U. Chattopadhyay, A. Datta, A. Datta, A. Datta and D.P. Roy, Phys. Lett. **B493**, 127 (2000); P.G. Mercadante, J.K. Mizukoshi and X. Tata, hep–ph/0506142; H. Baer, T. Krupovnickas, S. Profumo and P. Ullio, hep–ph/0507282.

[15] The Tevatron Electroweak Working Group, hep–ex/0507091.

[16] J. Edsjö and P. Gondolo, Phys. Rev. **D56**, 1879 (1997).

[17] M. Drees, M.M. Nojiri, D.P. Roy and Y. Yamada, Phys. Rev. **D56**, 276 (1997).

[18] A.G. Cohen, D.B. Kaplan and A.E. Nelson, Phys. Lett. **B388**, 588 (1996).

[19] A. Datta, P. Konar and B. Mukhopadhyaya, Phys. Rev. Lett. **88**, 181802 (2002).

[20] O. Eboli and D. Zeppenfeld, Phys. Lett. **B495**, 147 (2000).

[21] Physics at the CLIC Multi-TeV Linear Collider: CLIC Physics Working Group, hep–ph/0412251.

[22] C.H. Chen, M. Drees and J.F. Gunion, Phys. Rev. Lett. **76**, 2002 (1996) [hep–ph/9512230]; Phys. Rev. D55, 330 (1997) [hep–ph/9607421]; Addendum/Erratum [hep–ph/9902309].

[23] OPAL Collab., G.A. Abbiendi et al., Eur. Phys. J. **C29**, 479 (2003).

[24] M. Drees and R.M. Godbole, Z. Phys. **C59**, 591 (1993) [hep–ph/9203219].

[25] M. Drees and R.M. Godbole, Phys. Rev. Lett. **67**, 1189 (1991).

[26] See e.g., Physics Interplay of the LHC and the ILC: LHC/LC study group, hep–ph/0410364.

[27] L. Bergstrom, P. Ullio and J.H. Buckley, Astropart Phys. **9**, 137 (1998) [astro–ph/9712318].

[28] P. Ullio and L. Bergstrom, Phys. Rev. **D57**, 1962 (1998) [hep–ph/9706232].

[29] L. Bergstrom, T. Bringmann, M. Eriksson and M. Gustafsson, hep–ph/0507229.

[30] J.F. Navarro, C.S. Frenk and S.D.M. White, Astrophys. J. **462**, 563 (1996) and **490**, 493 (1997).

[31] J. Diemand, B. Moore and J. Stadel, Mon. Not. Roy. Astron. Soc. **353**, 624 (2004); B. Moore et al., Astrophys. J. **524**, L19 (1999).

[32] A. Burkert, Astrophys. J. **447**, L25 (1995).

[33] P. Gondolo, J. Edsjö, P. Ullio, J. Bergstrom, M. Schelke and E.A. Baltz, JCAP **0407**, 008 (2004) [astro–ph/0406204].

[34] J. Hisano, S. Matsumoto, M.M. Nojiri and O. Saito, hep–ph/0412403; J. Hisano, S. Matsumoto and M.M. Nojiri, Phys. Rev. **D67**, 075014 (2004), and Phys. Rev. Lett. **92**, 031303 (2004).

[35] The H.E.S.S. Collab., F. Aharonian et al., astro–ph/0408145.

[36] D. Grasso and L. Maccione, astro–ph/0504323.

[37] P. Salati, Phys. Lett. **B571**, 121 (2003) [astro–ph/0207396]; F. Rosati, Phys. Lett. **B570**, 5 (2003) [hep–ph/0302159].

[38] B. Murakami and J.D. Wells, Phys. Rev. **D64**, 015001 (2001); T. Moroi and L. Randall, Nucl. Phys. **B570**, 455 (2000); M. Fujii and K. Hamaguchi, Phys. Lett. **B525**, 143 (2002); W.B. Lin, D.H. Huang, X. Zhang and R.H. Brandenburger, Phys. Rev. Lett. **86**, 954 (2001).

[39] M. Drees, hep–ph/0501106.

[40] J.R. Ellis, T. Falk, K.A. Olive and Y. Santoso, Nucl. Phys. **B652**, 259 (2003).

[41] U. Chattopadhyay and D.P. Roy, Phys. Rev. **D68**, 033010 (2003).

[42] E. Gabrielli, S. Khalil, C. Muñoz and E. Torrente–Lujan, Phys. Rev. **D63**, 025008 (2001) [hep–ph/0006266].

[43] See e.g. J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, Phys. Lett. **B588**, 7 (2004), [hep–ph/0312262]; J.L. Feng, S. Su and F. Takayama, Phys. Rev. **D70**, 075019 (2004) [hep–ph/0404231]; L. Roszkowski and R. Ruiz de Austri, hep–ph/0408227.