Testing the AMSB Model via $e^+ e^- \rightarrow \gamma \tilde{\chi}^+ \tilde{\chi}^-$

Amitava Datta
Department of Physics, Visva-Bharati, Santiniketan - 731 235, India.
Shyamapada Maity
Department of Physics, Tamralipta Mahavidyalaya, Tamluk - 721636, West Bengal, India.

ABSTRACT

The possibility of detecting the signature of a nearly invisible charged wino (\tilde{\chi}^\pm) decaying into a soft pion and the LSP(\tilde{\chi}_1^0), predicted by the Anomaly Mediated Symmetry Breaking model, via the process $e^+ e^- \rightarrow \gamma \tilde{\chi}^+ \tilde{\chi}^-$ at the Next Linear Collider has been explored. Using the recently, proposed bounds on slepton and wino masses derived from the condition of stability of the electroweak symmetry breaking vacuum and employing some standard kinematical cuts to suppress the background, we find that almost the whole of the allowed parameter space with the slepton mass less than 1 TeV, can be probed at $\sqrt{s} = 500$ GeV. Determination of the slepton and the chargino masses from this signal is a distinct possibility. Any violation of the above mass bound will suggest that the standard vacuum is unstable and we are living in a false vacuum.

\footnote{adatta@juphys.ernet.in}
\footnote{On leave of absence from Jadavpur University}
\footnote{shyama@juphys.ernet.in}
Supersymmetry (SUSY) has now been widely accepted as an elegant alternative to the standard model (SM). The current experimental limits on the masses of the superpartners show that, even if they exist, they must be significantly heavier than the corresponding SM particles. Thus SUSY must be broken. The mechanism of this breaking is still unknown although several interesting models have been proposed. Without such a specific SUSY breaking mechanism, the most general minimal supersymmetric extension of the standard model (MSSM) contains a large number of soft breaking (SB) terms. The resulting model with a large number of unknown parameters is, however, not very predictive. Thus one attempts to construct a constrained MSSM with additional theoretical assumptions on SUSY breaking.

In the minimal supergravity (mSUGRA) type models [1, 2] one assumes that all the SM particles and their superpartners belong to the observable sector (OS). SUSY breaking takes place in hidden sector (HS), whose fields are all singlets under the SM gauge group and are very heavy. A contact interaction between the HS and the OS fields is introduced in the Kähler potential by gravitational interactions which is suppressed by the Planck mass squared. This tree-level interaction induces SUSY breaking in the OS; in such models the gravitino mass is of the order of 1 TeV. These models with the additional constraint of radiative electroweak symmetry breaking [3] have only five more free parameters compared to the SM.

Recently, it has been pointed out that if the OS and the HS fields belong to two distinct 3-branes separated by a finite distance along a fifth compactified dimension, the above mechanism for transmitting SUSY breaking from the HS to the OS fails. However, a superconformal anomaly may induce the SUSY breaking in the OS. Such soft breaking terms are also present in SUGRA type models, but they are suppressed in comparison to the usual soft-breaking terms. To generate the weak scale masses of the sparticles, the gravitino mass must be of the order of tens of TeV. Such models are generically known as anomaly-mediated SUSY breaking (AMSB) models [4, 5].

AMSB, along with the radiative electroweak symmetry breaking condition, fixes the particle spectrum completely in terms of three parameters: \(m_{3/2}\) (the gravitino mass), \(\tan \beta\) (the ratio of the vacuum expectation values (VEV) of the two Higgs fields), and \(\text{sign}(\mu)\). The gaugino masses \(M_1, M_2,\) and \(M_3\), and the trilinear couplings (generically denoted by \(A\)) can be obtained from the relevant renormalization group (RG) \(\beta\)-functions and anomalous dimensions. The sfermion masses, as well as the Higgs mass parameters, are also determined by \(m_{3/2}\). Unfortunately, for sfermions that do not couple to asymptotically free gauge groups (i.e., the left and right sleptons, \(\tilde{L}_L, \tilde{L}_R, l = e, \mu, \tau\)), the masses come out to be tachyonic. The remedy is sought by putting a positive definite mass squared term \(m_0^2\) in the GUT scale boundary conditions. Such terms can be justified by appealing to the presence of extra field(s) in the bulk. These models with a universal \(m_0\) for all scalars are called the minimal AMSB (mAMSB) models [4, 5]. The phenomenology of such models has been at the focus of attention of many recent studies [6, 7, 8, 9, 10, 11], and our discussions will be restricted within the framework of mAMSB models.

One can determine the complete particle spectrum in terms of the above free parameters. A crucial prediction very relevant for this paper is as follows [4, 5, 6, 7, 8]: the lighter chargino(\(\tilde{\chi}^{\pm}\)) is almost degenerate with the lightest neutralino(\(\tilde{\chi}_1^0\)), which we assume to be
the lightest supersymmetric particle (LSP). Both of them are heavily dominated by the wino component.

The near degeneracy leads to the most striking experimental signature of AMSB models, based on the “nearly invisible” decay of the relatively long lived $\tilde{\chi}^{\pm}$ to the LSP and a soft charged pion: $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}_{1}^{0} \pi^{\pm}$. If $M_{2} \geq 80$ GeV \[6\], then $\Delta m = m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}_{1}^{0}} > m_{\pi^{\pm}}$. Consequently the decay mode $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}_{1}^{0} \pi^{\pm}$ dominates over a large region of the allowed parameter space (APS), where the $\pi^{\pm}$ is rather soft for relatively small $\Delta m$. Thus the chargino decays almost invisibly and the conventional search strategies involving acoplanar leptons and/or jets + missing energy may not be applicable.

Due to the small $\Delta m$, however, the chargino has other distinguishing characteristics which may be exploited in detecting them. For example, they may have macroscopic decay lengths. This may lead to heavily ionising tracks in the vertex detector without corresponding activities in the calorimeter or in the muon chamber. Moreover the tracks end in soft pions which may be observable, if the impact parameters are clearly non zero and $p_{T}^{\pi}$ is sufficiently large. These features may be utilised to identify $\tilde{\chi}^{\pm}$ production in the off-line analysis if the event can be suitably triggered on.

There is a lower limit on $m_{3/2}$ coming from the lower bound $m_{\tilde{\chi}^{\pm}}^{\text{min}} = 86$ GeV \[12\] on charginos decaying through the soft pion mode from direct searches at LEP. This limit is roughly $m_{3/2} \sim 28-32$ TeV. The detection of these charginos are of crucial importance since they may happen to be the only sparticle (apart from the LSP) within the striking range of an early version of the Next Linear Collider (NLC) at $\sqrt{s} = 500$ GeV.

The search strategies for nearly invisible charginos were first studied by Chen et. al. \[13, 14\] in the context of other models with such charginos. It was noted that for $m_{\pi^{\pm}} < \Delta m < 230$ MeV, the charginos may pass through several layers of a typical vertex detector leaving behind a heavily ionising track which by itself is a distinctive feature. However, for $\Delta m$ in the upper half of the above range, they may only pass through one or two inner layers of the vertex detector which may be difficult to distinguish from, e.g., random hits due to detector noise. However, such charginos often end up in a soft pion with an impact parameter (b) significantly larger than the impact parameter resolution ($b_{\text{res}}$) which is typically $\sim 10^{-1}$ cm \[14\]. If $\Delta m > 230$ MeV the chargino tracks in the vertex detector could be too short for proper identification. However, the soft pions are usually more energetic in this case which may correspond to a better impact parameter resolution. Consequently the impact parameter of the pion may be appreciably larger than $b_{\text{res}}$ inspite of the small chargino decay length.

Any of the above features may suffice to identify nearly invisible charginos in the off line analysis. However, triggering based on activities in the vertex detector alone may be problematic. Hence the process $e^{+}e^{-} \rightarrow \gamma \tilde{\chi}^{+}\tilde{\chi}^{-}$ was recommended, where the hard $\gamma$ and missing energy in the final state can be easily triggered on. The activities in the vertex detector and/or soft pions may dramatically reduce the background from processes like $e^{+}e^{-} \rightarrow \gamma \nu\bar{\nu}$

The purpose of this note is to study the viability of this channel at NLC with $\sqrt{s} = 500$ GeV within the framework of mAMSB models. We wish to emphasize that so far as this process is concerned the mAMSB model is much more predictive and interesting than other models involving invisible charginos and radiative EW symmetry breaking.
The signal cross section is given by i) four $t$ channel sneutrino exchange diagrams. ii) four $s$ channel $Z$-exchange diagrams iii) four $s$ channel $\gamma$ exchange diagrams \cite{13, 14, 15}. In the most general case the production cross section depends on the parameters $\mu$, $\tan \beta$ and $M_2$ through the chargino mass and mixing angles. These three parameters in addition to the sneutrino mass controls the size of the cross section. In the mAMSB model the lighter chargino is a wino to a very good approximation. Thus the mixing angles ($\sim 1$) mildly depend on SUSY parameters. As a result the cross sections is effectively a function of two parameters only $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\nu}}$. As was shown by Chen et. al. (to be reviewed below), $m_{\tilde{\chi}^\pm}$ can be determined from the kinematics alone. Thus the size of the cross section may suffice to determine $m_{\tilde{\nu}}$, although this mass could be well outside the kinematic reach of the collider, which is quite possible for NLC at $\sqrt{s} = 500$ GeV.

The cross section for the process $e^+e^- \rightarrow \gamma \tilde{\chi}^+\tilde{\chi}^-$ was first computed for models with $m_{\tilde{\nu}} \sim 1$ TeV or larger \cite{13, 14}. In this case the $t$ - channel $\tilde{\nu}$ exchange diagrams were justifiably neglected. However, for lower $m_{\tilde{\nu}}$ the cross section may be significantly smaller \cite{15}. This happens due to destructive interferences between $s$-channel($\gamma$, $Z$ exchange) and $t$- channel diagrams. The full cross section valid for all $m_{\tilde{\nu}}$ is given in \cite{15}.

In the AMSB models the sleptons and sneutrinos may indeed be rather light depending on the choice of the common scalar mass $m_0$. This leaves open the possibility that the cross section could be significantly smaller than that obtained in the large $m_0$ limit (see below for details). Fortunately as has been pointed out recently, there is a lower bound on $m_0$ resulting in a corresponding bound on $m_{\tilde{\nu}}$ and $m_{\tilde{\chi}^\pm}$ ($m_{\tilde{\nu}} \gtrsim 330$ GeV most conservatively) \cite{16}. This lower bound excludes the possibility of direct slepton pair production at NLC with $\sqrt{s} = 500$ GeV. Thus $\tilde{\chi}^\pm$ and $\tilde{\chi}_1^0$ are the only sparticles accessible to this accelerator.

The above bound arises by requiring that E-W symmetry breaking minimum of the scalar potential be deeper than all possible charge/colour breaking minima \cite{17}. Moreover, thanks to the same constraints, there is an upper bound on the lighter chargino mass for a given $m_0$ (or slepton mass) (see table). The numbers in this table are slightly different from the corresponding numbers in Table II of \cite{16}. This is due to the fact that we have taken into account loop induced electroweak radiative correction \cite{6} to the chargino mass. The possible effects of this correction were commented upon in \cite{16} but they were not included in the numerical results.

From the table it is clear that the lighter chargino mass is predicted to be within the striking range of NLC at $\sqrt{s} = 500$ GeV for a wide range of slepton masses. Thus the signal of nearly invisible charginos is quite likely to be seen. The absence of this signal on the other hand would rule out a large part of the interesting parameter space of this model.

The above lower bound on the sparticles masses may be evaded by requiring that the present SU(2)$\times$U(1) symmetry breaking minimum is a metastable false vacuum which in principle can decay into much deeper true vacuum breaking charge and colour symmetry. However, the decay time is larger than the age of the universe \cite{18}. In view of this interesting suggestion the measurement of the slepton and the chargino mass as sketched above acquires special significance. If the mass indeed turn out to violate the bounds of \cite{16} then that would strongly indicate that we are living in a false vacuum.

In the mSUGRA models the violation of certain bounds on the $A$ parameter \cite{17} indicate the existence of a charge colour breaking vacuum. Since this parameter is not directly related to any mass, this experimental test is not straightforward. In contrast testing the bounds
on \(m_{\tilde{\chi}^\pm}\) or \(m_{\tilde{\nu}_L}\) is rather unambiguous from the experimental point of view.

In Fig. 1 we present the cross section at \(\sqrt{s} = 500\) GeV in the mAMSB model as a function \(m_{\tilde{\nu}}\) for \(m_{\tilde{\chi}^\pm} = 100, 150, 200\) GeV. From the figure it is seen that the cross section first decreases and then increases with increasing of \(m_{\tilde{\nu}}\). For small \(m_{\tilde{\nu}}\) the \(t\)-channel diagrams dominate and the effect of interference is relatively weak. For larger \(m_{\tilde{\nu}}\) interference effect is very prominent. This interference being destructive in nature, with the increasing of \(m_{\tilde{\nu}}\) the cross section increases. It is clear from the figure that once \(m_{\tilde{\chi}^\pm}\) is measured from the kinematics (see below) \(m_{\tilde{\nu}_L}\), or \(m_{\tilde{\nu}}\) may be obtained from the size of the cross section.

The kinematical cuts used in computing the cross section are \(p_T^\gamma \geq 10\) GeV, \(10^\circ \leq \theta^\gamma \leq 170^\circ\). These cuts are required to remove the radiative Bhabha and other backgrounds [13].

In the table we present the cross section with above kinematical cuts on the \(\gamma\) and the soft pion (see below). From the table it is clear that the entire allowed range of \(m_{\tilde{\chi}^\pm}\) except for \(m_0 \approx 1\) TeV, leads to hundreds of background free events at NLC with \(\sqrt{s} = 500\) GeV and \(L = 50\) fb\(^{-1}\).

We next analyse the track length of the \(m_{\tilde{\chi}^\pm}\) and the impact parameter of the soft pion to check whether these characteristics are adequate to make the signal background free.

Although \(\sigma\) is largely insensitive to \(\tan \beta\) and \(\text{sign} \mu\), the track length \(l\) of the chargino depends sensitively on these parameters, where \(l = \beta \tau_{\text{lab}}\). This is due to the fact that \(\Delta m\) and, hence, the \(\tilde{\chi}^\pm\) life time in its rest frame \(\tau\) depends quite a bit on these parameters. We have studied the distributions of these two observables for the entire parameter space allowed by the bounds of [16].

We find that at \(\sqrt{s} = 500\) GeV, \(l \lesssim 4\) cm. This is due to the fact that at low \(M_2\) (i.e. small \(m_{\tilde{\chi}^\pm}\)), \(\Delta m\) is large [6]. This lead to a small \(\tau\) and consequently a short track. On the other hand for large \(M_2\) although \(\Delta m\) is favourable, \(\beta\) at \(\sqrt{s} = 500\) GeV is not enough to give a long track.

In [14] the characteristics of a typical Silicon Vertex Detector (SVD) has been quoted from a CDF report [19]. From the analysis of [14] it is clearer that for \(l \lesssim 4\) cm. a chargino is, not likely to traverse more than a few inner layers of the vertex detector and this characteristic may not be sufficiently distinctive for suppressing the background. However, the estimates of [14] are based on the CDF-II detector. It is quite possible that the vertex detector at NLC will have layers closer to the beam pipe. The fact that the beam at NLC will be narrower than that at Tevatron strengthens this expectation. If that is the case then even \(l \lesssim 4\) cm. may help to reduce the background. The impact parameter of the pion is, however, large enough for the bulk of the APS and helps to reduce the background even if \(l\) is small. Assuming an impact parameter resolution \(b_{\text{res}} \sim 0.1\) cm [14], we have required \(b > 0.5\) cm as the criterion for the detectability of the pion. In fact \(b_{\text{res}}\) could be significantly smaller [14] depending on the pion energy. Our assumption is, therefore, quite conservative.

For all \(m_0\) in the table, except for \(m_0 = 1\) TeV, the number of events with at least one detectable soft pion exceeds 10 as long as \(m_{\tilde{\chi}^\pm}\) is below the upper bound \((m_{\tilde{\chi}^\pm})_{\text{max}}\). For \(m_0 = 1000\) GeV and \(\tan \beta = 5\) a \(\tilde{\chi}^\pm\) with mass close to the upper limit lies outside the kinematic reach of NLC with \(\sqrt{s} = 500\) GeV (see table). The search limit in this case is found to be \(m_{\tilde{\chi}^\pm} = 219\) GeV. The corresponding \(b\) distributions of the pion is shown in fig-2. Requiring \(b > 0.5\) cm, fig-2 corresponds to 10 events.
It is quite possible that at higher $\sqrt{s}$ the chargino track length will be significantly larger. This is illustrated in Fig-3. We have taken $m_{\tilde{\chi}^\pm} = 262$ which corresponds to the upper bound on $m_{\tilde{\chi}^\pm}$ for $m_0 = 1$ TeV, and $\sqrt{s} = 1$ TeV. According to \cite{14} for $\beta_{\text{lab}} \gtrsim 7$ cm, the charginos will pass through at least four layers of the SVD. Thus for entire allowed range of the chargino masses corresponding to $m_0 = 1$ TeV, glimpses of heavily ionising chargino tracks can be seen in the SVD at $\sqrt{s} = 1$ TeV.

We next discuss the determination of $[m_{\tilde{\chi}^\pm}]$ from the observable $m_{Z^*} \equiv \langle (p^{e^+} + p^{e^-} - p^\gamma)^{1/2} \rangle / 2$ \cite{13, 14}. It follows that $m_{Z^*} \gtrsim m_{\tilde{\chi}^\pm}$ for the signal. The results for $\sqrt{s} = 500$ GeV are shown in fig-4 for $m_{\tilde{\chi}^\pm} = 100, 150, 200$. Although the kinematical cuts distort the lower edge of the distribution to some extent, $m_{\tilde{\chi}^\pm}$ can be measured with an accuracy of a few percent except for $m_{\tilde{\chi}^\pm} \gtrsim 200$ GeV.

Once $m_{\tilde{\chi}^\pm}$ is determined $m_{\tilde{\nu}}$ can be measured to a good approximation from the size of the cross section. Even if $m_{\tilde{\nu}}$ is determined approximately, this information, with some luck, may be utilised in distinguishing the mAMSB model from other competing models with small $\Delta m$. For example in the string motivated model of \cite{13, 14} the slepton mass is necessarily large ($\sim 1$ TeV) and as discussed above the cross section for the same $m_{\tilde{\chi}^\pm}$ is expected to be larger.

This illustrates the advantage of this signal over a similar discovery channel, $pp \rightarrow \tilde{\chi}^+\tilde{\chi}^-g$, at hadron colliders (J. Feng et. al. in \cite{8}). In the later case neither $m_{\tilde{\chi}^\pm}$ nor the slepton mass can be reliably measured from the observed signal. Thus the underlying model may not be identified.

The model underlying the nearly invisible charginos may be unearthed by exploiting the advent of polarised electron beams. For example, with a right polarised beam for which the $t$ - channel diagrams decouple, the cross section will be significantly larger than the unpolarised cross section if the slepton masses happen to be small. In contrast in the string motivated model with heavy sleptons cross sections are not likely to show any drastic change. The computation of the signal for polarised beams is under progress.

In conclusion we reiterate that the signal $e^+e^- \rightarrow \gamma \tilde{\chi}^+\tilde{\chi}^-$ looks very promising in the mAMSB model. Most interestingly there is i) a lower bound on the slepton mass ($m_{\tilde{\nu}} \geq 330$ GeV) and ii) an upper bound on chargino mass(see table) for a given slepton mass \cite{16} which makes this model very predictive. In view of these bounds $\tilde{\chi}^\pm$ and $\tilde{\chi}^0_1$ are the only sparticles within the striking range of NLC at $\sqrt{s} = 500$ GeV.

For a wide range of common scalar mass ($m_0 \lesssim 1$ TeV) the signal can be detected by exploiting the soft pions from $\tilde{\chi}^\pm$ decay for the entire allowed range of $m_{\tilde{\chi}^\pm}$. For $m_0 = 1$ TeV, $m_{\tilde{\chi}^\pm} \leq 219$ can be detected at $\sqrt{s} = 500$ GeV. Assuming the charcteristics of typical SVD \cite{14} it appears that the chargino tracks in the SVD may not be long enough to be observable at $\sqrt{s} = 500$ GeV. However, for $\sqrt{s} = 1$ TeV chargino tracks with sufficient length which end in a soft pion can be probed in SVD.

The measurement of $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\nu}}$ from the $m_{Z^*}$ distribution and from the total cross section has been discussed. This measurements would be of crucial importance because if the bounds of \cite{16} are violated, that would strongly indicated that we are living in a false vacuum \cite{18}. Further this mass determination, with some luck, may reveal the model underlying these invisible charginos.

The muon anomalous magnetic moment has recently been measured by E821 Collaboration at Brookhaven \cite{20} with an unprecedented precision. Apparently there is a 2.6
Table: Upper bounds on $m_{\tilde{\chi}^\pm}$ and corresponding $\sigma_{\tilde{\chi}^\pm\tilde{\chi}^-\gamma}$ for given values of $m_0$ at $\sqrt{s} = 500$ GeV. The kinematical cuts are discussed in the text.

| $\tan\beta$ | sign of $\mu$ | $m_0$ | $m_{3/2}$ | $(m_{\tilde{\chi}^\pm})_{max}$ | $\sigma$ in fb |
|-------------|----------------|------|-----------|---------------------|----------------|
| 5           | +              | 500  | 35.8      | 123.12              | 22.35         |
| 5           | -              | 500  | 35.7      | 116.23              | 29.30         |
| 5           | +              | 700  | 51.6      | 177.53              | 5.71          |
| 5           | -              | 700  | 51.5      | 173.56              | 13.19         |
| 5           | +              | 1000 | 76.0      | 262.96              | -             |
| 5           | -              | 1000 | 75.9      | 261.61              | -             |
| 35          | +              | 500  | 33.3      | 111.45              | 28.46         |
| 35          | -              | 500  | 33.5      | 110.85              | 30.16         |
| 35          | +              | 700  | 48.2      | 163.99              | 13.04         |
| 35          | -              | 700  | 48.5      | 164.21              | 14.52         |
| 35          | +              | 1000 | 71.1      | 245.25              | -             |
| 35          | -              | 1000 | 71.5      | 246.19              | -             |

$\sigma$ discrepancy between the experimental result and the SM prediction (for discussions and references to earlier works see, e.g., [20, 21]). However, this statement is based on the assumption that the computation of the hadronic corrections to the muon anomalous moment, which is the largest source of uncertainty in the SM prediction, is under control. There is already a claim that if these corrections are computed in a way different from that in [22], which [20, 21] quote, then there may be agreement between the SM and the data [23]. Thus ruling out the SM or some specific extension of it on the basis of the alleged discrepancy requires a cautious approach.

If, however, the SM prediction is accepted at its face value, then one of the recent analyses indicates that the mAMSB model is disfavoured by the data [24]. On the contrary it has been shown in [25] that while this model with low $\tan\beta$ is indeed disfavoured, the one with large $\tan\beta$ is allowed. A critical reexamination of these claims are beyond the scope of this paper.

It may be noted that the bounds of [16] are quite restrictive for large $\tan\beta$ and the signal cross section is observable for large as well as small values of this parameter (see the table). At the moment, therefore, the model and a large part of the APS scanned in this paper has no obvious conflict with the data on muon anomalous magnetic moment.
Fig. 1: The variation of $\sigma_{\tilde{\chi}^+ \tilde{\chi}^- \gamma}$ with $m_{\tilde{\nu}}$ for three values of $m_{\tilde{\chi}^\pm}$ at $\sqrt{s} = 500$ GeV.

Fig. 2: Impact Parameter distribution for $m_{\tilde{\chi}^\pm} = 219$ GeV at $= \sqrt{s}$ 500 GeV.
Fig. 3: Decay Length distribution for $m_{\tilde{\chi}^\pm} = 263$ GeV at $\sqrt{s} = 1000$ GeV

Fig. 4: $m_{Z^*}$ distribution for three values of $m_{\tilde{\chi}^\pm}$ at $\sqrt{s} = 500$ GeV

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