Received: *June 29, 2000,* Accepted: *August 23, 2000*
Revised: *July 24, 2000*

Linear Collider signal of a Wino LSP in anomaly mediated scenarios

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Abstract: Selectron (smuon) pair-production in a next generation Linear Collider, yielding a fast electron (muon) trigger, a visible heavily ionizing track and/or a resolved soft pion impact parameter and overall $\not{E}_T$, is shown to provide a smoking gun signature for Anomaly Mediated Supersymmetry Breaking models with a neutral Wino as the Lightest Supersymmetric Particle, nearly mass-degenerate with the lighter chargino.

Keywords: Supersymmetry Breaking, Beyond Standard Model.

JHEP08(2000)031

Understanding how supersymmetry breaks in the real world from a deeper, more fundamental, standpoint is a challenge in high energy physics today. An interesting recent idea in this direction has been that of Anomaly Mediated Supersymmetry Breaking (AMSB) [1], based on which a whole class of supersymmetric models [1]–[10] have emerged. A crucial signal in a high energy Linear Collider, namely $e^+e^- \rightarrow e^{\pm}(\mu^{\pm}) + soft\ \pi^{\mp} + \not{E}_T$, to test such a scenario, is proposed in this letter.

AMSB models are strongly motivated by String Theory which is defined in a higher dimensional spacetime and is valid at a very high energy scale. It is quite natural from that point of view to expect a low energy description of the physical world in four dimensions to inherit some of the features of the higher dimensional theory. This is indeed the case with AMSB scenarios. AMSB occurs when in such a higher dimension, one has a supergravity theory defined on two separated parallel 3-branes ((3 + 1)-dimensional subspaces) in a way that the Standard Model (SM) particles are localized on one of these while the supersymmetry breaking sector is localized on the other. There are no tree-level couplings between these two branes and thus the supersymmetry breaking sector is truly hidden. Gravity propagates in the bulk and the breakdown of supersymmetry is communicated from the hidden to the visible sector through the loop-induced super-Weyl anomaly. In the absence of tree-level interactions between the two 3-branes, this is the dominant contribution to the soft supersymmetry breaking parameters determining the masses of various superparticles. In the more commonly used Gravity Mediated Supersymmetry Breaking scenario [11], supergravity interactions directly communicate supersymmery breaking between the hidden and observable sectors at the tree level, so that loop-induced contributions from the super-Weyl anomaly, though present, are subdominant. A characteristic feature of AMSB models is that the stable LSP or *Lightest Supersymmetric Particle* ($\tilde{\chi}_1^0$) is almost exclusively a neutral Wino which is nearly mass-degenerate with the lighter chargino ($\tilde{\chi}_1^{\pm}$), also predominantly a Wino. Models with only AMSB have the problem of tachyonic sleptons; however, modified versions exist in which the sleptons have physical masses.

Though the quest for supersymmetry has been a major preoccupation of collider experimenters and phenomenologists alike, most of the searches and simulation studies so far have been based on the assumption of the LSP being predominantly a Bino; i.e. the superpartner of the $\mathrm{U}(1)_Y$ gauge boson. Various produced superparticles are expected to decay into the LSP accompanied by other particles of the Standard Model (SM). The LSP escapes detection carrying off missing transverse energy or $\not{E}_T$ which becomes the classic signature. There have, however, been a few papers [12]–[16] of late which have considered detection possibilities for scenarios in which a largely Wino LSP occurs. Our investigation belongs to this genre. We consider the pair production of left-selectrons (smuons) in e^+e^- interactions, followed by their decays[1] $\widetilde{e}(\widetilde{\mu}) \to e(\mu) + \widetilde{\chi}_1^0$, $\widetilde{e}(\widetilde{\mu}) \to \nu + \widetilde{\chi}_1^\pm$; $\widetilde{\chi}_1^\pm$ will further decay into $\widetilde{\chi}_1^0 + \pi^\pm$. Finally, there will be a fast $e^\pm(\mu^\pm)$ trigger, a displaced vertex which can be inferred from the impact parameter of a visible soft $\pi^\pm$ and/or a heavily ionizing track with high momentum (i.e. nearly straight in the magnetic field) and large $\not{E}_T$. Similar considerations just with selectrons can also be made for e^-e^- collision.

The chargino and the neutralino masses, in any version of the Minimal Supersymmetric Standard Model (MSSM) [17], are controlled by the following supersymmetry parameters at the weak scale: the Bino mass M_1, the Wino mass M_2, the Higgsino mass parameter μ and the ratio $\tan\beta$ of the two Higgs VEVs. The situation, with the LSP ($\widetilde{\chi}_1^0$) being largely the neutral Wino, obtains when one has

$$|M_2| < |M_1| \ll |\mu|\,. \tag{1}$$

One should emphasize that, within a MSSM framework, the mass-hierarchy (1) is very characteristic of AMSB models. For instance, in such models, after taking into account next-to-leading order corrections to the gaugino mass parameters, one finds [14] that $M_1 : M_2 \simeq 2.8 : 1$ as contrasted with $M_1 : M_2 \approx 1 : 2$ in gauge or usual supergravity mediated supersymmetry breaking models with gaugino masses unified at the grand unifying scale. The next-to-lightest superparticle in the AMSB case is the lighter chargino ($\widetilde{\chi}_1^\pm$) which is almost exclusively a Wino. Then the masses of $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$ are verly close and the small mass-splitting ΔM has the form [14]:

$$\begin{aligned}\Delta M = {} & \frac{M_W^4 \tan^2\theta_W}{(M_1 - M_2)\mu^2}\sin^2 2\beta\left[1 + \mathcal{O}\left(\frac{M_2}{\mu}, \frac{M_W^2}{\mu M_1}\right)\right] + \\ & + \frac{\alpha M_2}{\pi \sin^2\theta_W}\left[f\left(\frac{M_W^2}{M_2^2}\right) - \cos^2\theta_W f\left(\frac{M_Z^2}{M_2^2}\right)\right],\end{aligned} \tag{2}$$

with

$$\begin{aligned}f(x) \equiv -\frac{x}{4} + \frac{x^2}{8}\ln(x) + \frac{1}{2}\left(1 + \frac{x}{2}\right)\sqrt{4x - x^2}\,\Bigg[\tan^{-1}\left(\frac{2 - x}{\sqrt{4x - x^2}}\right) - \\ - \tan^{-1}\left(\frac{x}{\sqrt{4x - x^2}}\right)\Bigg].\end{aligned}$$

The second term in the r.h.s. of eq. (2) is the one-loop contribution which is dominated by gauge boson loops.

The mass-splitting ΔM of eq. (2) has been investigated numerically [13, 14] in various region of the parameter space consistent with eq. (1). The general conclusion is that

$$165\,\mathrm{MeV} \lesssim \Delta M \lesssim 1\,\mathrm{GeV}\,, \tag{3}$$

[1] These decay channels need not make all of the selectron (smuon) width. There are regions of parameter space where $\tilde{\chi}_2^{\pm,0}$ can be lighter than the selectron (smuon), but decays like $\tilde{e}(\tilde{\mu}) \to e(\mu)\tilde{\chi}_2^0$, $\nu\tilde{\chi}_2^\pm$, which open up there, are only a few percent of the branching ratio. Even so, we take these into account in our calculations.

with $\lim_{\mu\to\infty} \Delta M$ being 165 MeV. On the other hand, if a radiative electroweak (EW) symmetry breakdown is sought to be implemented in the AMSB scenario, the ratio $|\mu/M_2|$ has to be [14] approximately between 3 and 6. Given the LEP lower limit [18] of 56 GeV on the mass of the lighter chargino *for nearly degenerate* $\widetilde{\chi}_1^{\pm}, \widetilde{\chi}_1^0$ (in the anomaly-mediated Wino LSP scenario), it then follows that the upper limit on ΔM cannot be much in excess of 800 MeV. In that case we can take

$$165\,\mathrm{MeV} \lesssim \Delta M \lesssim 800\,\mathrm{MeV}\,. \tag{4}$$

Equation (4) means that the decay $\widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0 + \pi^{\pm}$ is kinematically allowed. The corresponding branching ratio is found to vary in the range 93%–96%, the balance being largely due to the decay modes $\widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0 + e + \nu_e$, $\widetilde{\chi}_1^0 + \mu + \nu_\mu$. The resulting soft pion with a sub-GeV energy may be detectable, in which case its impact parameter may allow one to infer a displaced vertex. On the other hand, the $\widetilde{\chi}_1^{\pm}$ may have a long enough decay length to show a high momentum heavily ionizing track which stops in some of the layers in the vertex detector. The experimental issues concerning methods of observing this decay have been discussed in the third paper of ref. [12] and in refs. [1, 14]. If the decay length[2] $c\tau$ of $\widetilde{\chi}_1^{\pm}$ is greater than 3 cm, it could be observable[3] though the $\pi^{\pm}$ may be too soft to be detected. Contrariwise, if $c\tau < 3\,\mathrm{cm}$, the track may not be observable but the soft charged pion is likely to be visible with its impact parameter b resolved. Thus the event, proposed by us, can be triggered by the fast charged lepton emanating from the decay of one of the sleptons while it can be identified uniquely in terms of the displaced vertex determined by the heavily ionizing charged track, which should be nearly straight in the magnetic field because of the high momentum, and/or the impact parameter b of the soft pion coming from the two-step decay of the other slepton.

In the anomaly mediated case, gaugino masses are proportional to the coefficients of the one-loop beta functions of the corresponding gauge couplings (generically denoted as g), while scalar masses are determined in terms of anomalous dimensions and beta functions of both gauge and Yukawa couplings (generically denoted as y). The expressions for the anomaly induced contributions to the soft masses are

$$M_\lambda = \frac{\beta_g}{g} m_{3/2}\,, \tag{5}$$

$$m_{\tilde{f}}^2 = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m_{3/2}^2\,, \tag{6}$$

$$A_y = \frac{\beta_y}{y} m_{3/2}\,, \tag{7}$$

[2]Here $c\tau = c\hbar p_{\tilde{\chi}^\pm}(M_{\tilde{\chi}^\pm}\Gamma_{\tilde{\chi}^\pm})^{-1}$ with $p_{\tilde{\chi}^\pm}$, $M_{\tilde{\chi}^\pm}$ and $\Gamma_{\tilde{\chi}^\pm}$, respectively being the momentum, mass and width (all in GeV) of the chargino.

[3]A CCD or APS vertex detector of radius 2.5 cm and a beam pipe of radius 2 cm, have been proposed [19] for TESLA. The chargino track should be identifiable if it covers several layers and also ends in the vertex detector.

where gaugino masses are denoted by M_λ, scalar masses are given the generic symbol $m_{\tilde{f}}$, $m_{3/2}$ is the mass of the gravitino which here is quite heavy ($\sim$ tens of TeV) and A_y are the trilinear soft parameters defined with the convention of the third paper of ref. [15]. The renormalization group beta and gamma functions are defined as $\gamma(g,y) \equiv d\ln Z/dt$, $\beta_g(g,y) \equiv dg/dt$ and $\beta_y(g,y) \equiv dy/dt$, t being the logarithmic scale variable.

The most striking feature of this AMSB scenario is the invariance of the expressions for soft SUSY breaking mass parameters eqs. (5)–(7) under renormalization group (RG) evolution. Thus, these parameters can be evaluated at any scale with the appropriate values of the gauge couplings at that particular scale. However, the mass squares of the sleptons, calculated in this way, turn out to be negative. These tachyonic sleptons constitute a major problem of this scenario. The most simple and economical way by which these slepton mass-squares can be made positive is to add [1] a common m_0^2 to all scalars and this is what we consider. However, our signal is also present for models [8, 9] where this positive term is non universal and arises from the D-term of a broken U(1) gauge symmetry. Of course, the addition of any such term destroys the RG invariance of eq. (6). Then, in order to get the correct values of the mass-squares of the scalars at the EW scale, one must take into account the RG evolution of these soft masses from a very high scale. In our calculations we have taken this to be the unification scale (≈ 1.5 *to* 2.0×10^{16} GeV) where all the three gauge couplings meet and the evolution of these couplings reproduces the measured values at the EW scale with $\alpha_s \simeq 0.118$. The evolution of gauge and Yukawa couplings has been determined by two-loop RG equations. The detailed expressions for scalar and gaugino masses as well as the trilinear A-parameters are given in refs. [14] and [15]. The Higgsino mass parameter μ has been computed using complete one-loop correction terms of the effective potential at the scale Q in such a way that it reproduces the correct pattern of EW symmetry breaking with Q chosen to be the geometric mean of the t-squark masses $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$. The supersymmetric correction to the mass of the bottom quark (sizable for large $\tan\beta$) has also been computed to one-loop. We have, moreover, accounted for the constraints coming from charge and color conservation as well as from the experimental lower limits [20] on various sparticle masses including $m_{\tilde{\chi}_1^\pm} > 56\,\mathrm{GeV}$ [18] and also from the requirement of the stau not being the LSP.

We have determined the slepton and chargino/neutralino sector of the MSSM mass spectrum completely in terms of $m_{3/2}$, m_0, $\tan\beta$ (the ratio of the two Higgs vacuum expectation values) and the sign of μ. We have checked that our results agree with those of previous authors [14, 15] for $\tan\beta = 3$ with $\mu < 0$ and $\mu > 0$ as well as for $\tan\beta = 30$ with $\mu < 0$ and $\mu > 0$. The LSP $\tilde{\chi}_1^0$ and the lighter chargino $\tilde{\chi}_1^\pm$ are found to be very nearly degenerate, as suggested by eq. (2). Indeed, we find ΔM not only to obey the inequality (3); but also to be a decreasing function of $m_{3/2}$, asymptotically reaching the lower bound of (3) when the latter gets very high. This

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function is quite insensitive to the value of m_0. The left and right selectron masses are also found to be almost degenerate. The tiny mass-difference between the latter comes mainly from one-loop corrections at the electroweak scale since the anomaly induced as well as D-term contributions are negligible in comparison. This, again, is a distinguishing feature of the AMSB scenario which is based on the assumption of a universal contribution to the mass-squared for scalars added to make the sleptons non tachyonic. An important point is that the region of parameter space where the masses of the selectrons (smuons) do not lie between those of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^{\pm,0}$, the latter being the higher chargino/neutralino, is not small, though this does not affect[4] our analysis. The other important aspect of the superparticle spectrum in such an AMSB scenario is that the squarks are significantly heavier (typically by at least a factor of four) than the sleptons, the squark masses being pushed up by the QCD coupling. This means that sleptons should be easier to discover in such models. This is why we have chosen to study slepton pair-production in a linear collider. Of course, one could also directly study the pair-production of charginos $\tilde{\chi}_1^{\pm}$, each decaying into $\tilde{\chi}_1^0$ and a soft pion. However, one would then need to have an additional [12] hard initial-state-radiated (ISR) photon to act as a trigger. The event rate there would be significantly less than that of slepton pair-production on account of the former process being radiative.

We have calculated the left-selectron (these would be mass eigenstates because of negligible left-right mixing) pair production cross section at an e^+e^- CM energy of 1 TeV for two values of $\tan\beta$, namely, 3 and 30, for $\mu < 0$ and $\mu > 0$. We have then folded into it the branching fractions for the decays mentioned in the first paragraph. The selection cuts that have been used on the decay products are as follows: (1) the transverse momentum of the lepton $p_T^{\ell} > 5\,\mathrm{GeV}$, (2) the pseudorapidities of the lepton and the pion $|\eta| < 2.5$, (3) the electron-pion isolation variable $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$, (4) the missing transverse energy $\not{E}_T > 20\,\mathrm{GeV}$ and (5) $p_T^{\pi} > 200\,\mathrm{MeV}$ for a detectable soft pion (N.B. the total momentum of the pion is in the range of hundreds of MeV). Contour plots in the $m_0 - m_{3/2}$ plane for various values of cross-sections (in fb) are shown in figure 1. The shaded regions are excluded by the constraints mentioned earlier; in addition, the selectron mass has been required not to exceed 500 GeV which is the kinematic limit for observability in a 1 TeV Linear Collider. The allowed region is somewhat smaller for large $\tan\beta$ because of stronger left-right mixing in the stau sector. We see that quite interesting regions in the $m_0 - m_{3/2}$ plane are covered for cross sections ranging from 10 fb to 125 fb. Our signal should thus generate $\mathcal{O}(10^4)$ events for an integrated luminosity of $500\,(\mathrm{fb})^{-1}$. These calculations have been done with projected TESLA parameters in mind [21]. For a scaled down linear collider, e.g. with a CM energy of 500 GeV and an integrated luminosity of $50\,(\mathrm{fb})^{-1}$, we would expect $\mathcal{O}(10^3)$ events.

[4]See, footnote 1.

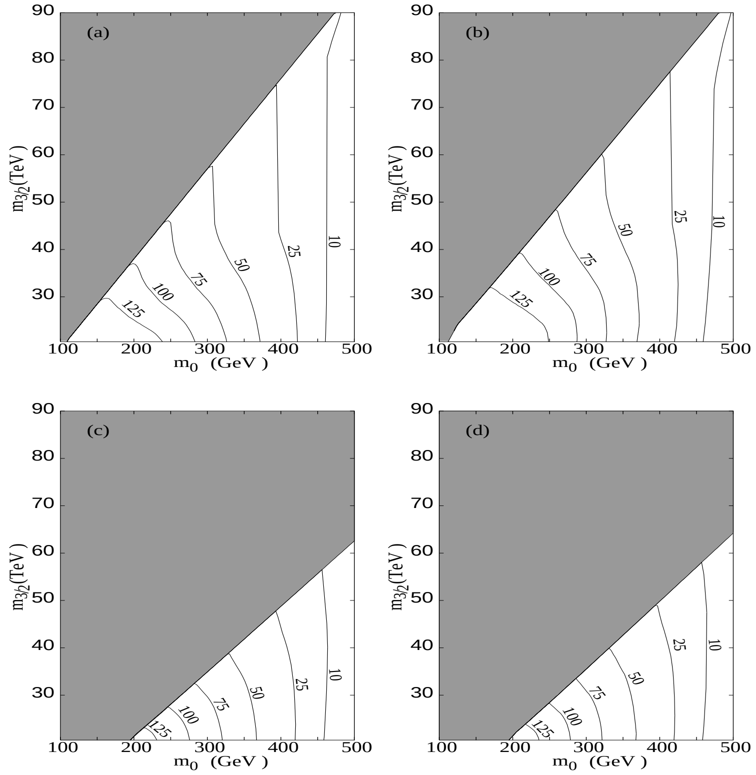

Figure 1: Constant cross section (in fb) contour plots in the $m_0 - m_{3/2}$ plane for (a) $\mu < 0$, $\tan\beta = 3$, (b) $\mu > 0$, $\tan\beta = 3$, (c) $\mu < 0$, $\tan\beta = 30$ and (d) $\mu > 0$, $\tan\beta = 30$.

We have also plotted the decay length $c\tau$ distribution of the chargino track in figure 2 with the same selection cuts as used in figure 1; in addition, we have chosen characteristic sample values of $m_0 = 230\,\text{GeV}$ and $m_{3/2} = 43\,\text{TeV}$, $\tan\beta = 3$ and $\mu < 0$ corresponding to $\Delta M = 182.8\,\text{MeV}$. We observe a plateau in the $c\tau$ distribution in the range 8.5 to 9.9 cm which can cover several layers in the vertex detector. Thus there is a reasonable chance of a direct observation of the chargino track. The transverse momentum (p_T^π) and the impact parameter b distributions of the soft pion are plotted in figures 3a and 3b, respectively with the same input parameters and selection cuts as for figure 2. The b-distribution extends till about 9.9 cm and peaks at around $b = 8.5\,\text{cm}$. It is clear from the p_T^π distribution that the minimum p_T^π cut of 200 MeV still leaves a substantial part of the allowed phase space for study. For such values of p_T^π, the 3σ impact parameter resolutions are typically [22] $\mathcal{O}(10^{-1})$ cm. Of course, we have chosen a particularly favorable region of the allowed MSSM parameter space. The numbers are not always so good in other regions. We have nonetheless checked that b is always significantly above the impact parameter resolution value. Hence the prospects of resolving the displaced vertex by measuring the soft pion impact parameter here are quite high. Let us comment finally that, if selectrons are replaced by smuons (with a fast muon used as a trigger), event rates are reduced typically by a factor of five on account of s-channel suppression.

An alternative MSSM scenario of nearly degenerate $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ (and $\tilde{\chi}_2^0$ as well) can arise [12] when $|\mu| \ll |M_{1,2}|$. In such a case a mass-difference $\Delta M(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0) \lesssim 1\,\mathrm{GeV}$ can be obtained with $m_{\tilde{\chi}_1^\pm} > 51\,\mathrm{GeV}$ [23] by setting [12] $|M_{1,2}| \gtrsim 5\,\mathrm{TeV}$ and $|\mu| \gtrsim M_Z/2$. Though this is a rather unnatural scenario and quite difficult to obtain in a phenomenologically viable model, we can ask whether our signal can be mimicked here. The answer is no. The two-body decays of selectrons, relevant for us, are highly suppressed in this other scenario on account of the factor m_e/M_W in the concerned couplings. The latter arises because $\tilde{\chi}_1^\pm$, $\tilde{\chi}_{1,2}^0$ are all almost exclusively higgsinos here. So selectrons primarily have three-body decays $\tilde{e} \to \nu_e W \tilde{\chi}_{1,2}^0$, $eZ\tilde{\chi}_{1,2}^0$ mediated by virtual heavier charginos/neutralinos ($\tilde{\chi}_2^\pm/\tilde{\chi}_2^0$), which are gauginos, with finals states dominated by jets. One can easily estimate the ratio of the partial widths of left selectron decays into two-body and three-body channels to be $\mathcal{O}(10^{-4})$ in this scenario demonstrating that the desired two-body decays would be unobservable. Therefore, unlike the soft pion plus hard ISR photon signal studied in ref. [12], our final state of a fast electron (muon) and a soft pion distinguishes AMSB models from the light higgsino scenario. We would like to highlight this new result which has emerged from the present work.

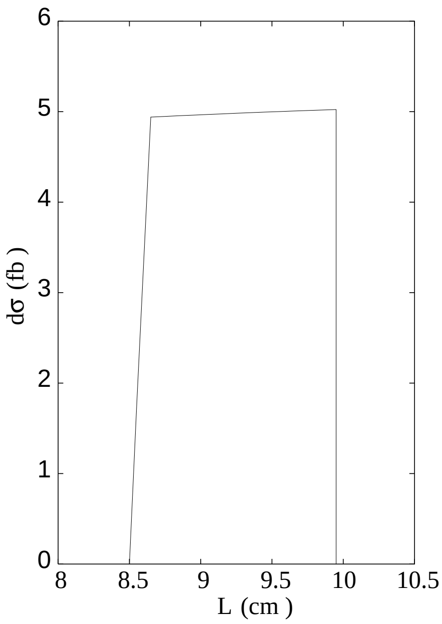

Figure 2: Chargino decay length distribution for the following set of input parameters: $m_{3/2}$=43 TeV, m_0=230 GeV, $\tan\beta$=3, and μ<0.

Let us also discuss the question of background to our signal. The signal can be classified into two categories. There is one in which we see a heavily ionizing nearly straight charged track ending with a soft pion with large impact parameter and $\not{E}_T$, the signal being triggered with a fast electron or a muon. In the other case, while the other aspects remain the same, one may not see the heavily ionizing charged track but the impact parameter of the soft pion can be resolved and measured to be large. In the first case the heavily ionizing charged track is due to the passage of a massive chargino with a very large momentum. Due to this reason the charged tarck will be nearly straight in the presence of the magnetic field. One cannot imagine a similar situation in the SM with such a nearly straight heavily ionizing charged track due to a very massive particle. An ionized charged track can possibly arise from the flight of a low energy charged pion, kaon or proton but it will curl significantly in the magnetic field. Another distinguishing feature of the charged track in our signal is that it will be terminated after a few layers in the vertex detector and there will be a soft pion at the end. In the second case, where the ionizing track is unseen, possible SM backgrounds can come from the following processes: $e^+ + e^- \to \tau^+ + \tau^-$ and

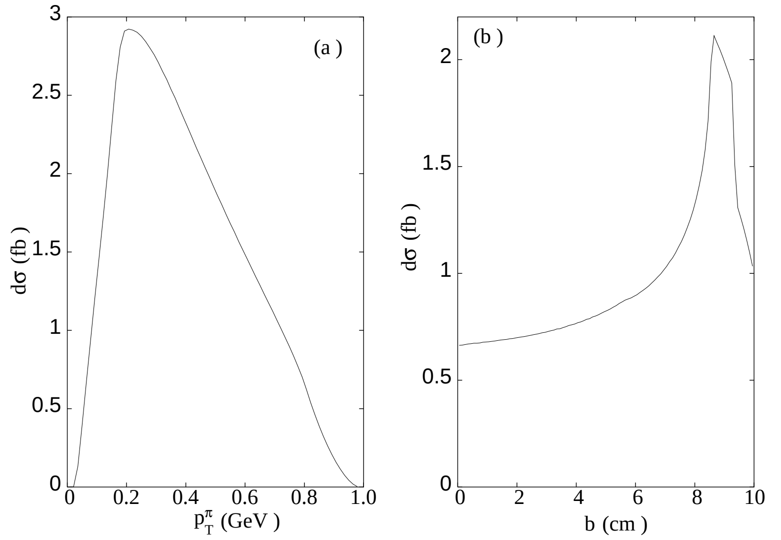

Figure 3: (a) Pion transverse momentum distribution and (b) the impact parameter distribution for the same set of input parameters as in figure 2.

$e^+ + e^- \to W^+ + W^-$. In the case of $e^+ + e^- \to \tau^+ + \tau^-$, one τ can have the three body decay $\tau \to e\nu_e\nu_\tau$ or $\mu\nu_\mu\nu_\tau$ and the other τ can go via the two body channel $\tau \to \pi + \nu_\tau$. Thus we can have a final state of the type $e(\mu) + \pi + \not{E}_T$. Since we are considering an (e^+e^-) CM energy of 1 TeV, and the pion comes from a sequence of two-body production and decay, it will have a fixed high momentum much in excess of 1 GeV. This will clearly separate this type of background from our signal since in our case the resulting pion is very soft with a momentum in the range of hundreds of MeV. In the case of $e^+ + e^- \to W^+ + W^-$ a similar argument follows. Here one W can go to $e(\mu) + \nu_e(\nu_\mu)$ and the other one can go to $\tau + \nu_\tau$. The τ can subsequently go to one π and a ν_τ, thereby producing the final state $e(\mu) + \pi + \not{E}_T$. As we have discussed just now, the resulting pion will have a very large momentum and again one can clearly separate the background from the signal.

In conclusion, we claim to have pinpointed a fast electron (muon) trigger, overall $\not{E}_T > 20$ GeV and a displaced vertex emitting a soft pion in the final state configuration as a distinct and unique linear collider signal of the AMSB scenario with a Wino LSP. A more detailed discussion of this as well as other linear collider signals of AMSB models will be given elsewhere.

Acknowledgments

This work came out of a study-project on *Anomaly Mediated Supersymmetry Breaking* at the Workshop on High Energy Physics Phenomenology *WHEPP-6* (Chennai, January, 2000). We thank the organizers as well as the other members of the project namely D. Choudhury, S. King, A. Kundu, B. Mukhopadhyaya, S. Raychaudhuri and

K. Sridhar for many fruitful discussions. We also thank U. Chattopadhyay for the use of his codes and M. Maity and N.K. Mondal for discussions of experimental issues.

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