A new signature for gauge mediated supersymmetry breaking

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Abstract

In theories with gauge mediated supersymmetry breaking, the scalar tau, ($\tilde{\tau}_1$) is the lightest superpartner for a large range of the parameter space. At the large electron positron collider (LEP 2) this scenario can give rise to events with four $\tau$ leptons and large missing energy. Two of the $\tau$'s (coming from the decays of $\tilde{\tau}_1$'s) will have large energy and transverse momentum, and can have similar sign electrical charges. Such events are very different from the usual photonic events that have been widely studied, and could be a very
distinct signal for the discovery of supersymmetry.

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The necessity of a light Higgs boson at the electroweak scale and the unification of the three Standard Model (SM) gauge couplings provide motivation for supersymmetric (SUSY) theories. However, the mechanism of supersymmetry breaking, and how it is communicated to the observable sector remains an intriguing problem. In most of the existing works, it is assumed that the supersymmetry is broken in a hidden sector at a scale of \( \sim 10^{11} \) GeV, and is communicated to the observable sector by gravitational interactions. Over the last decade the phenomenology of such supergravity theories has been extensively studied for colliders as well as for processes involving rare decays. A significant amount of flavor violation, both in the quark as well as the lepton sector, is expected in this class of theories. Recently, another class of models \([1]\) has become popular in which supersymmetry is broken in a hidden sector at a scale \( 10^{5} \) GeV, and is conveyed to the observable sector by the Standard Model gauge interactions. In these models the flavor violations at low energies are naturally small, since the flavor symmetric soft terms are introduced at a much lower scale than in the usual supergravity theories. These theories also have fewer parameters than the usual supergravity theories, and thus are somewhat more predictive. The most distinctive feature is that the gravitino is the lightest supersymmetric particle (LSP), and all superpartners must ultimately decay to it.

Another interesting aspect of a gauge mediated supersymmetry breaking (GMSB) models is that the next to lightest supersymmetric particle (NLSP) can be either the lightest neutralino (\( \chi_0 \)) or the lighter tau slepton (\( \tilde{\tau}_1 \)). The phenomenology for the case when \( \chi_0 \) is the NLSP has been extensively studied over the last six months \([2-9]\). This scenario could give rise to events like the one event of \( ee\gamma\gamma + missing\ energy \) \([2]\) observed by the CDF collaboration \([10]\) at the Fermilab Tevatron. However, there is a wide region of parameter space of this model where the \( \tilde{\tau}_1 \) is the NLSP, and, in that case, the phenomenology becomes very different. In this letter, we consider a scenario in which the signal for supersymmetry is very distinct, not present in the SM, and could lead to the discovery of supersymmetry at LEP2. This is the case in which \( \tilde{\tau}_1 \) is the NLSP, \( \chi_0 \) is the next to NLSP (NNLSP), and the mass of the \( \chi_0 \) is not much larger than that of \( \tilde{\tau}_1 \). There is a wide region of parameter space
in which this scenario holds, and also the $\chi_0$ is light enough to be pair produced at LEP2. Each $\chi_0$ then decays to a $\tau$ lepton and a $\tilde{\tau}_1$, with $\tilde{\tau}_1$ decaying to a $\tau$ and a gravitino ($\tilde{G}$). This gives rise to a final state with four $\tau$ leptons plus the missing energy of the undetected gravitinos. One pair of $\tau$ leptons (coming from the decay of the $\tilde{\tau}_1$'s) will have significantly larger energy and transverse momentum than the other two and can have same sign electric charge due to the Majorana nature of the $\chi_0$'s. Such events have no SM background, and the observation of few of these events at LEP2 would signal the discovery of supersymmetry.

We now discuss the parameter space for the GMSB models and the relevant region for our scenario. These parameters are $M, \Lambda, n, \tan \beta, \mu$ and $B$. $M$ is the messenger scale. In the minimal model of GMSB, messenger sector is just a single flavor of $5 + \bar{5}$ of $SU(5)$, and $M = \lambda < s >$, where $< s >$ is the VEV of the scalar component of the hidden sector superfields, and $\lambda$ is the Yukawa coupling. The parameter $\Lambda$ is equal to $< F_s > / < s >$, where $< F_s >$ is the VEV of the auxiliary component of $s$. $F_s$ can be $\sim F$ [11], where $F$ is the intrinsic SUSY breaking scale. In GMSB models, $\Lambda$ is taken around 100 TeV, so that the colored superpartners have masses around a TeV or less. The parameter $n$ is fixed by the choice for the messenger sector. The messenger sector representations should be vector like (for example, $5 + \bar{5}$ of $SU(5)$, $10 + \bar{10}$ of $SU(5)$ or $16 + \bar{16}$ of $SO(10)$) so that their masses are well above the electroweak scale. They are also chosen to transform as a GUT multiplet in order not to affect the gauge coupling unification in MSSM. This restricts $n(5 + \bar{5}) \leq 4$, $n(10 + \bar{10}) \leq 1$ in $SU(5)$, and $n(16 + \bar{16}) \leq 1$ in $SO(10)$ GUT for the messenger sector (one $n_{10} + n_{\bar{10}}$ pair corresponds to $n(5 + \bar{5})=3$). The parameter $\tan \beta$ is the usual ratio of the up ($H_u$) and down ($H_d$) type Higgs VEVs. The parameter $\mu$ is the coefficient in the bilinear term, $\mu H_u H_d$ in the superpotential, while the parameter $B$ is defined to be the coefficient in the bilinear term, $B \mu H_u H_d$ in the potential. In general, $\mu$ and $B$ depend on the details of the SUSY breaking in the hidden sector. We demand that the electroweak symmetry is broken radiatively. This determines $\mu^2$ and $B$ in terms of the other parameters of the theory. Thus, we are left with five independent parameters, $M, \Lambda, n, \tan \beta$ and sign($\mu$). The soft SUSY breaking gaugino and the scalar masses at the messenger scale $M$ are given by
\[ \tilde{M}_i(M) = n g \left( \frac{\Lambda}{M} \right) \frac{\alpha_i(M)}{4\pi} \Lambda. \]  
\[ \tilde{m}^2(M) = 2(n) f \left( \frac{\Lambda}{M} \right) \sum_{i=1}^{3} k_i C_i \left( \frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda^2. \]

where \( \alpha_i, i = 1, 2, 3 \) are the three SM gauge couplings and \( k_i = 1, 1, 3/5 \) for \( SU(3) \), \( SU(2) \), and \( U(1) \), respectively. The \( C_i \) are zero for gauge singlets, and \( 4/3, 3/4, \) and \( (Y/2)^2 \) for the fundamental representations of \( SU(3) \) and \( SU(2) \) and \( U(1)_Y \) respectively (with \( Y \) defined by \( Q = I_3 + Y/2 \)). Here \( n \) corresponds to \( n(5 + \bar{5}) \). \( g(x) \) and \( f(x) \) are messenger scale threshold functions with \( x = \Lambda/M \).

We have calculated the SUSY mass spectrum using the appropriate RGE equations with the boundary conditions given by equation (1) and (2), and varying the free parameters \( M, \Lambda, n, \tan \beta \) and \( \text{sign}(\mu) \). Although in principle the messenger scale is arbitrary (with \( M/\Lambda > 1 \)), in our analysis we have restricted \( 1 < M/\Lambda < 10^4 \). We choose \( \Lambda \sim 100 \text{ TeV} \). For the messenger sector, we choose \( 5 + \bar{5} \) of \( SU(5) \), and varied \( n(5 + \bar{5}) \) from 1 to 2. In addition to the current experimental bounds on the superpartner masses, the rate for \( b \rightarrow s\gamma \) decay puts useful constraints on the parameter space. In fact this rules out positive sign of \( \mu \) (depending on the convention, in this case we are using ref. [14]) almost completely. For negative \( \mu \), low \( M/\Lambda \) ratios are ruled out for the lower values for \( \Lambda \) (for example, for \( \tan \beta = 3 \) and \( n = 1 \), for \( M/\Lambda=1.1 \), \( \Lambda \) values up to 73 GeV, which corresponds to a neutralino mass of 117 GeV, are ruled out; for \( M/\Lambda=4 \), \( \Lambda \) values up to 67 GeV and neutralino masses up to 90 GeV are ruled out). It is found that for \( n = 1 \) and low values \( \tan \beta \) (\( \tan \beta \leq 25 \)), the lightest neutralino \( \chi_0 \) is the NLSP for \( M/\Lambda > 1 \). As \( \tan \beta \) increases, \( \tilde{\tau}_1 \) becomes the NLSP for most of the parameter space with lower values of \( \Lambda \). For \( n \geq 2 \), \( \tilde{\tau}_1 \) is the NLSP even for the low values of \( \tan \beta \) (for example, \( \tan \beta \gtrsim 2 \), and for \( n \geq 3 \), \( \tilde{\tau}_1 \) is again naturally the NLSP for most of the parameter space. We observe that for a large region of parameter space, we obtain the mass spectrum for the scenario we are interested in, namely \( \tilde{\tau}_1 \) is the
NLSP, $\chi_0$ is the NNLSP with both the particles being accessible in the LEP2 energies. In addition, we find the lighter electron mass, $\tilde{e}_1$ to be small enough to give rise to significant production cross section for the $\chi_0$ pair at LEP2 energies. For example, in Table 1, we give five sets of spectrum which we use for detail calculations.

We are now ready to discuss the pair production of the lightest neutralino $\chi_0$, the decay of the each neutralino to a $\tau$ and a scalar $\tilde{\tau}_1$, and the subsequent decay of $\tilde{\tau}_1$ to a $\tau$ and a gravitino. This leads to $4\tau$ final states with the missing energy carried away by the two unobserved gravitinos. In electron positron collisions, neutralino pair production comes from the $s$-channel $Z^0$ exchange and $t$ and $u$ channel $\tilde{e}_L$ and $\tilde{e}_R$ exchanges [15]. In our case, the lightest scalar electron state is essentially $\tilde{e}_R$, the exchange of which is responsible for over 95% of the cross sections.

The total cross-sections for the five cases of Table 1 are given in Table 2 for three LEP2 energies, $\sqrt{s} = 172, 182$ and 194 GeV (For scenario 2, $\chi_0$ is too heavy to be pair produced at $\sqrt{s} = 172$ GeV). Each of the produced $\chi_0$ will decay via the electroweak interaction to $\tau$ and $\tilde{\tau}_1$ with essentially a 100% branching ratios. (The only other decay mode to a photon and a gravitino is gravitational and hence negligible). Each of the $\tilde{\tau}$’s then decays to its only allowed decay mode, a $\tau$ and a gravitino. Thus, from $\chi_0$ pair production, we obtain final states with four $\tau$’s and two gravitinos. The decay, $\tilde{\tau}_1 \rightarrow \tau \tilde{G}$ is fast enough so that it takes place inside the detector. Thus, four $\tau$ leptons plus an average missing energy of more than 1/3 of the total beam energy will be a very distinct signal for supersymmetry. Such events have no SM background. (If $\sqrt{F}$ is much larger than a few 1000 TeV [16], then $\tilde{\tau}_1$ will decay outside the detector. In that case the signal will be 2 $\tau$ leptons and two heavy charged particles in the final states.)

We now discuss the expected number of events and their detailed characteristic signals at LEP energies for the five scenarios considered in Tables 1 and 2. To avoid the beam direction, we use the angular cut, $|\cos\theta| \leq 0.9$. One or more $\tau$ may be lost in this angular cone. In Table 2, we give the percentage of 4 $\tau$, 3 $\tau$, and 2 $\tau$ events satisfying this angular cut. For example, in scenario 5 at $\sqrt{s} = 172$ GeV, 69% of the events will have 4$\tau$, 27% will
be 3 $\tau$ and 4% , 2 $\tau$'s. This corresponds to about 23 events with 4 $\tau$ leptons for a luminosity of 100 pb$^{-1}$. At $\sqrt{s} = 194$ GeV, with a luminosity of 250 pb$^{-1}$, the corresponding number of events is about 23 for the scenario 1 and about 91 for scenario 5. The angular distribution of the most energetic $\tau$, the second most energetic $\tau$ is shown in Fig. 1 for scenario 5 at 172 GeV. Fig. 1 shows that the angular distributions are approximately isotropic. Same is true for the other cases. Thus, the percentages for the 4 $\tau$, 3 $\tau$ and 2 $\tau$ states with different angular cuts can be easily estimated. The average missing energies due to the two unobserved gravitino’s and zero or more unobserved $\tau$ are also given in Table 2. For example, at $\sqrt{s} = 172$ GeV and for scenario 5, the average missing energy for the 4 $\tau$ events is 77.1 GeV. Note that average missing energy fraction is somewhat larger than 1/3. This is because the massive $\tilde{\tau}_1$ scalar carries more than half of the energy of the $\chi_0$ so that each of the gravitinos carry somewhat more than the 1/6 of the total energy.

Other interesting features of the 4 $\tau$ events are the energy and $P_T$ distributions. Just as the gravitinos have more than their share of the energy, the $\tau$'s coming from the $\tilde{\tau}_1$ decay will have larger energy and $P_T$ than those coming from the $\chi_0$ decay. This is shown in Fig. 2, again for scenario 5 at 172 GeV. Since the neutralinos are Majorana particles, they decay equally to a $\tau^+$ or a $\tau^-$. Thus the two most energetic $\tau$ have the same probability of having the same sign of the electric charge as of having opposite sign. Out of the six possible pairs of $\tau$'s , one pair will have significantly higher $P_T$ than the other pairs (here, we define the $P_T$ of a pair to be the sum of the magnitudes of the two individual $p_T$ defined relative to the beam axis). This is clearly reflected in the $P_T$ distributions shown in Fig. 3, where the dotted curve represents the $P_T$ distributions of the pairs having maximum $P_T$ , solid curve corresponds to the pair having the next to maximum $P_T$ and so on. These distributions are again for scenario 5 at 172 GeV. The corresponding distributions for the other scenarios and beam energies are very similar. Such well separated $P_T$ distributions of the pairs can easily be tested with the accumulation of enough events and will be an interesting detailed signature of GMSB. If the SUSY signal is observed in the $4\tau$ mode, then the $3\tau$ and the $2\tau$ events could be studied to extract detailed information.
In the Standard Model four \( \tau \) events with no missing energy can be produced from the pair production of \( Z^0 \) and the subsequent decay of each \( Z^0 \) to a \( \tau^+\tau^- \) pair. However, such an event will have no missing energy, and the rate is small due to the small branching ratio for \( Z^0 \rightarrow \tau^+\tau^- \) \( (\sigma.B^2 \approx 10^{-3}pb) \). Another possible source of 4 \( \tau \) background is \( e^+e^- \rightarrow \gamma^*Z^0 \), with \( Z^0 \) decaying into \( \tau^+\tau^- \) and \( \gamma^* \) converting to \( \tau^+\tau^- \). We have estimated the cross section for this reaction to be 0.10 \( pb \) at the energies considered here, so again \( \sigma.B \) is very small \( \approx 10^{-3}pb \). We expect the similar reaction with two virtual photons to be small also. A SM process with 4 \( \tau \) and nonzero missing energy is \( e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-4\tau \) where the final \( e^+e^- \) are close to the beam direction. We have estimated the size of this process by inserting the cross section for \( \gamma\gamma \rightarrow 4 \) leptons given by Serbo \[17\] into an expression using the effective photon approximation \[18\]. We find the cross section to be \( \sim 6 \times 10^{-3}pb \). Thus, if our 4 \( \tau \) signal is big enough to be seen at LEP, there is no significant Standard Model background.

If one of the \( \tau \)'s is lost in the beam pipe, then \( Z^0Z^0 \) or \( Z^0\gamma^* \) production will give rise to a background for 3 \( \tau \) with missing energy. The 2\( \tau \) final states also have a significant background (comparable to the signal) from \( W \) pair production and the subsequent decay of the \( W \) to \( \tau \). Two \( \tau \) plus missing energy in the final states can also appear from the scalar \( \tau \) production and their subsequent decays into \( \tau \) and gravitino \[19\].

A detailed distribution of the decay products of the \( \tau \)s in the final state will be studied elsewhere \[19\]. Here we will only note that, with the existing experimental technology it is very hard to study the \( P_T \) distribution of the individual \( \tau \)'s or the pair of \( \tau \)'s, since each \( \tau \) can decay into various decay products e.g. leptons, mesons and missing energy (neutrinos). However 4 \( \tau \) plus missing energy is a spectacular signature, which can be detected without knowing the details of the decay products.

It is also interesting to note the effect of polarized beams. It is a characteristic of the gauge mediated models that the righthanded selectron mass is different from the left handed selectron mass (in gravity mediated models the left and right handed selectron masses are originated from the same universal mass terms at the GUT scale). Consequently a polarized \( e^+e^- \) collider can distinguish the gauge mediated model from the gravity mediated one. For
example, the $4\tau$ plus missing energy signal discussed in this paper will be much bigger for an electron beam with right handed polarization than for a beam with left handed polarization \cite{19}.

We have been somewhat conservative in choosing our scenarios (1 to 5). For example we restricted ourselves to the parameter space for which $m_{\tilde{\tau}_1} \gtrsim 65$ GeV. The current experimental bound allows much smaller values of $m_{\tilde{\tau}_1}$ (there is no new bound on this mass from LEP2 yet \cite{20}). A considerable region of allowed parameter space yields lower values of $m_{\tilde{\tau}_1}$, $m_{\chi_0}$ and $m_{\tilde{e}_R}$ and our $4\tau$ signal will be larger for these cases. Our general comments about the angular distribution of the $\tau$, the missing energy, and the energy and $P_T$ distributions of the $\tau$ will be unchanged. On the theoretical side, if the messenger sector is strongly coupled so that the colored gauginos get direct masses from non-perturbative dynamics, then the scalar $\tilde{\tau}_1$ will be the lightest NLSP over a much larger region of parameter space.

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TABLE CAPTIONS

Table 1: Mass spectrum for the superpartners in the scenarios 1 to 5. (1st and 2nd generation superpartner masses are almost same).

Table 2: For each scenario and beam energy the first line represents the total cross section for neutralino pair production, the 2nd and 3rd lines represent the branching ratios of 4τ, 3τ and 2τ final states from the cut on cosθ, and the 4th line represents the average missing energy associated with 4τ, 3τ and 2τ final states.

FIGURE CAPTIONS

Fig. 1: The angular distribution of the most energetic τ (dashed line) and the second most energetic τ (solid line). The third and fourth τ have distributions that are almost identical to the first and second. Note these curves are very flat - the distribution is almost isotropic.

Fig. 2: The distribution with energy of the most energetic τ (dashed line), second most energetic (solid line), third most energetic (dashed-dotted), and fourth most energetic (thick gray).

Fig. 3: The $P_T$ distribution of pairs of τ’s where $P_T$ is defined as $p_{iT} + p_{jT}$ where $p_{iT}$ is the magnitude of $p_T$ of particle i (i=1,4) relative to the beam axis.
|                | Scenario 1             | Scenario 2             | Scenario 3             | Scenario 4             | Scenario 5             |
|----------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| masses (GeV)   | $\Lambda = 63.7 \text{ TeV}$, $n=1$, $M = 4\Lambda$ | $\Lambda = 33 \text{ TeV}$, $n=2$, $M = 20\Lambda$ | $\Lambda = 60 \text{ TeV}$, $n=1$, $M = 10\Lambda$ | $\Lambda = 59.7 \text{ TeV}$, $n=1$, $M = 10\Lambda$ | $\Lambda = 28 \text{ TeV}$, $n=2$, $M = 40\Lambda$ |
| $\tan \beta$   | $= 31.5$              | $= 20$                 | $= 31.5$              | $= 28.5$              | $= 18$                 |
| $m_h$          | 121                    | 117                    | 120                    | 120                    | 114                    |
| $m_{H^\pm}$    | 366                    | 318                    | 356                    | 364                    | 278                    |
| $m_A$          | 357                    | 308                    | 347                    | 355                    | 266                    |
| $m_{\chi^0}$   | 85                     | 87                     | 80                     | 80                     | 72                     |
| $m_{\chi^1}$   | 158                    | 156                    | 149                    | 148                    | 128                    |
| $m_{\chi^2}$   | 350                    | 286                    | 345                    | 343                    | 249                    |
| $m_{\chi^3}$   | 364                    | 309                    | 358                    | 356                    | 275                    |
| $m_{\chi^\pm}$ | 157,367                | 155,312                | 149,361                | 127,277                | 158,367                |
| $m_{\tilde{t}_{1,2}}$ | 74,249                | 73,192                | 65,240                | 74,236                | 65,167                |
| $m_{\tilde{e}_{1,2}}$ | 120,236                | 96,184                | 116,225                | 115,224                | 85,159                |
| $m_{\tilde{t}_{1,2}}$ | 664,727                | 515,588                | 607,673                | 605,672                | 432,505                |
| $m_{\tilde{b}_{1,2}}$ | 698,740                | 558,586                | 641,686                | 643,683                | 472,497                |
| $m_{\tilde{u}_{1,2}}$ | 737,765                | 580,601                | 683,710                | 679,709                | 490,508                |
| $m_{\tilde{d}_{1,2}}$ | 735,769                | 580,606                | 681,715                | 678,711                | 490,514                |
| $m_{\tilde{g}}$   | 565                    | 587                    | 533                    | 530                    | 498                    |
| $\mu$          | -343                   | -278                   | -337                   | -336                   | -240                   |
| scenarios | $\sqrt{s}=172$ GeV | $\sqrt{s}=182$ GeV | $\sqrt{s}=194$ GeV |
|-----------|-----------------|-----------------|-----------------|
| **1**     | $\sigma=4.75 \times 10^{-3}$ pb | 5.91 $\times 10^{-2}$ pb | 0.14 pb |
|           | 66.2% (4$\tau$), 28.8% (3$\tau$), 4.77% (2$\tau$) | 66.5%, 28.6%, 4.53% | 67.4%, 27.8%, 4.41% |
|           | 76 (4$\tau$), 99 (3$\tau$), 124 (2$\tau$) (missing energy in GeV) | 80, 105, 130 | 85, 112, 139 |
| **2**     | 6.79 $\times 10^{-2}$ pb | 66.7%, 28.4%, 4.47% | 68.0%, 27.4%, 4.24% |
|           | 78, 104, 130 | 83, 110, 138 |
| **3**     | 6.84 $\times 10^{-2}$ pb | 0.14 pb | 0.23 pb |
|           | 66.7%, 28.5%, 4.48% | 67.5%, 27.8%, 4.49% | 68.3%, 27.4%, 4.09% |
|           | 71, 95.9, 120 | 75, 101, 129 | 80, 108, 137 |
| **4**     | 8.62 $\times 10^{-2}$ pb | 0.16 pb | 0.25 pb |
|           | 66.9%, 28.2%, 4.56% | 67.7%, 27.7%, 4.27% | 68.8%, 26.7%, 4.18% |
|           | 81, 103, 127 | 86, 109, 133 | 90, 116, 143 |
| **5**     | 0.33 pb | 0.43 pb | 0.52 pb |
|           | 69.0%, 26.7%, 4.08% | 69.8%, 26.0%, 4.02% | 70.7%, 25.2%, 3.81% |
|           | 77, 100, 124 | 81, 106, 132 | 87, 114, 141 |
Fig. 1
Fig. 2

Fig. 3