OBSERVING VIRTUAL LSPs AT LEP-II

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ABSTRACT

In the minimal supersymmetric extension of the Standard Model (MSSM) with R-parity conservation the possibility that the sneutrino and the second lightest neutralino decay dominantly into invisible channels and, in addition to the lightest neutralino, carry missing energy, is still open — both theoretically and experimentally. It is shown that for a large region of the parameter space allowed by LEP-I data, these particles can contribute significantly to the process \(e^+e^- \rightarrow \gamma + \text{nothing}\). This signal, if it exists, can be easily detected at LEP-II as an enhancement over the Standard Model or the conventional MSSM predictions.

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The search for supersymmetry (SUSY) at the TeV scale is a high-priority programme of current high energy physics. The parameter space of even the minimal supersymmetric extension of the standard model (MSSM)\cite{1} is, however, rather complicated. This has not yet been sufficiently restricted by experiments to make very accurate predictions. It should, therefore, be emphasised that until conclusive experimental evidence prefers one region of the above space over the others, all analyses of experimental data should be carried out keeping the consequences of the parameter space in mind.

As an example, let us note that the usual strategy for hunting for superparticles hinges on one crucial assumption: that, by virtue of a conserved quantum number — $R$-parity — there is a single, stable, weakly-interacting neutral superparticle, the so-called lightest supersymmetric particle (LSP). This particle, if produced, easily escapes detection and carries missing transverse energy ($E_T$) — traditionally regarded as the most distinctive signature of SUSY. Moreover as a result of the above conservation law all other superparticles decay into the LSP either directly or through cascades. The predictions for the latter decays are often dependent on the parameter space. Thus, apparently clean limits on the squark and gluino masses derived under the assumption that the gluino decays directly into the photino with 100% branching ratio \cite{2, 3} become somewhat more involved given the realistic possibility that the gluino can decay into other channels as well \cite{4}. This has been recognised in the latest experimental searches and SUSY parameter-dependent mass limits have been published in the literature \cite{3}.

In all the experimental searches carried out to date, however, it is still assumed that the LSP alone carries missing transverse energy ($E_T$). The purpose of this note is to draw attention to a significant region of the parameter space of MSSM (with $R$-parity conservation) which violates this assumption and to suggest a particularly sensitive probe
of this hitherto unexplored space.

The minimal supersymmetric extension of the standard model (MSSM) contains four spin-$\frac{3}{2}$ neutral particles. These particles are the superpartners of the photon, the $Z$-boson and the two neutral $CP$-even Higgs bosons. Linear combinations of these four states, the four neutralinos ($\tilde{N}_i$, $i=1,4$), are the physical states. In the currently-favoured models, the lightest neutralino ($\tilde{N}_1$) is assumed to be the LSP [1].

Recently the possibility has been emphasised [5, 6] that there may exist other superparticles which, though unstable, *decay dominantly into invisible channels*. This can occur if the sneutrinos ($\tilde{\nu}$) (the superpartners of the neutrinos), though heavier than the LSP, are lighter than the lighter chargino ($\tilde{\chi}_2^\pm$) and the second lightest neutralino ($\tilde{N}_2$) and are also lighter than all other superparticles. As a consequence, the invisible two-body decay mode $\tilde{\nu} \rightarrow \nu \tilde{N}_1$ opens up and completely dominates over others, being the only kinematically-allowed two-body decay channel for the sneutrinos. The other necessary condition for this scheme to work is that the $\tilde{N}_1$ has a substantial Zino (superpartner of the $Z$-boson) component. This, however, is almost always the case as long as the gluino (the superpartner of the gluon) has a mass ($m_{\tilde{g}}$) in the range interesting for the SUSY searches at the Tevatron [7]. Moreover, in such cases the $\tilde{N}_2$ — which also has a dominant Zino component — decays primarily through the process $\tilde{N}_2 \rightarrow \nu \tilde{\nu}$. These two particles ($\tilde{N}_2$ and $\tilde{\nu}$), decaying primarily into invisible channels, may act as additional sources of $E_T$ and can significantly affect strategies for SUSY searches [6]. They are, therefore, called *virtual* LSPs or VLSPs in the subsequent discussion. The above scenario, which is certainly consistent with all the experimental results on SUSY searches, can also be easily accommodated in the more constrained and theoretically-motivated models based on $N = 1$ Supergravity with common scalar and gaugino masses at a high scale [6].
Some consequences of the VLSP scenario (as opposed to the conventional MSSM where the LSP is the only source of missing $E_T$) mainly in the context of hadron colliders have been discussed in refs. [5, 6, 8, 9]. In this work, we consider the much cleaner process $e^+e^- \rightarrow \gamma + nothing(E_T)$ which will be of considerable importance at LEP-II and any other future high energy $e^+e^-$ colliders. In the standard model (SM) only $\nu\bar{\nu}$ pairs contribute to the final state. In the conventional MSSM both $\nu\bar{\nu}$ and $\tilde{N}_1\tilde{N}_1$ pairs contribute to this kind of effect. With VLSPs, however, there will be additional contributions from $\tilde{\nu}\tilde{\nu}$ and $\tilde{N}_i\tilde{N}_j \ (i,j = 1,2)$ which tend to increase the cross-section quite significantly. We have made a detailed analysis of this effect and find that a 15–20 \% enhancement of the cross-section over the prediction of the SM occurs in a significant region of the MSSM parameter space allowed by the experimental data (most notably from LEP-I [10]). Moreover, the bulk of the extra contribution comes from $\tilde{\nu}\tilde{\nu}$ pairs. Thus, such a signal, if detected, can be distinguished not only from the SM but also from the conventional MSSM without VLSPs.

We now turn to the cross-sections relevant for the process $e^+e^- \rightarrow \gamma + nothing(E_T)$. The most important contribution to this comes from $e^+e^- \rightarrow \gamma \tilde{\nu}\tilde{\nu}$. The amplitudes for the relevant Feynman diagrams are given in, for example, ref. [11] in the limit when the chargino is purely a Wino (superpartner of the $W$-boson). We have computed the full cross-section taking into account the chargino-mixing matrix. The formulae are somewhat cumbersome and will be presented elsewhere [12]. Our numerical results, however, agree with those given in ref. [11] in the appropriate limits. We have also computed the cross-section for the process $e^+e^- \rightarrow \gamma \tilde{N}_i\tilde{N}_j, \ (i,j = 1,2)$ taking the $4 \times 4$ neutralino mass matrix into account (the details will be presented in ref. [13]). Our results agree, in the appropriate limit, with the those of ref. [13] where $e^+e^- \rightarrow \gamma \tilde{N}_1\tilde{N}_1$ was obtained in
the limit when \( \tilde{N}_1 \) is a photino without any mixings. Finally we have calculated the full cross-section for the purely SM process \( e^+e^- \rightarrow \gamma\nu\bar{\nu} \) and checked that it agrees with the results of ref. [14] in the appropriate limits. It may be noted at this point that we have considered lowest order cross-sections only, radiative corrections being neglected. The effects of these will be considered elsewhere [12]. In any case, the only radiative corrections likely to cause changes which are at all significant are those due to emission of soft photons from the initial states. This is a well-known [15] effect and is likely to shift the peak in the photon energy distribution by a few GeV. This would not make it necessary to change the kinematical cuts (see below) very much, if at all.

Current bounds from LEP-I tell us that it is not possible to produce sneutrinos from the on-shell decay of a \( Z \)-boson produced in \( e^+e^- \) collisions with or without a radiated photon. However, this is certainly possible with neutrinos. As a result, the energy distribution of a radiated photon accompanied by neutrinos will have a resonant peak at some value close to \( \sqrt{s} - m_Z \) unlike the case for accompanying sneutrinos. This can help us reduce the signal-to-background ratio. In Fig. 1 we present the energy \( (E_\gamma) \) distribution of the photon from the signal \( (e^+e^- \rightarrow \gamma\nu\bar{\nu}) \) for \( m_\tilde{\nu} = 50 \text{ GeV}, \tan\beta = 2 \) and \( m_{\tilde{g}} = 200, 300 \text{ GeV} \) (upper and lower of the dotted histograms respectively) as well as the SM background (solid histogram) at \( \sqrt{s} = 190 \text{ GeV} \), where we have used a cut \( E_\gamma > 5 \text{ GeV} \), which is dictated by detector design and the removal of other backgrounds [16]. One observes that the background has a resonant peak in the vicinity of 75 GeV which is more or less in the right ballpark for \( \sqrt{s} = 190 \text{ GeV} \). It is now obvious that a cut of \( 5 \text{ GeV} < E_\gamma < 60 \text{ GeV} \) removes the peak and thereby reduces the background by about a third without affecting the signal significantly.

We next consider the angular distribution of the photon in the signal and the back-
ground, where $\theta_\gamma$ is the angle made by the photon with the beam direction. We find that without the cut on $E_\gamma$ the distributions look very similar. With the cut, however, most of the signal is contained in the region $40^\circ < \theta_\gamma < 120^\circ$ while the background is more or less uniformly distributed over the entire range of consideration. This is illustrated in Fig. 2 where the conventions are identical with those of Fig. 1. Accordingly we have chosen our second kinematical cut to be $40^\circ < \theta_\gamma < 120^\circ$. A combination of the two kinematic cuts optimises the signal-to-background ratio.

In Fig. 3 we plot the combined cross-section for the processes $e^+e^- \rightarrow \gamma\tilde{\nu}\tilde{\nu}$ and $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ as a function of $m_{\tilde{\nu}^\pm}$ at $\sqrt{s} = 190$ GeV. The coupling of the sneutrinos and the lighter chargino ($\tilde{\chi}_2^{\pm}$) as well as the $\tilde{\chi}_2^{\pm}$ mass which are relevant for the t-channel $\tilde{\chi}_2^{\pm}$ exchange diagrams (see, e.g., ref. [11]) depend on the SUSY parameters $\mu$, $\tan\beta$ and the gluino mass $m_{\tilde{g}}$. We have illustrated results for $m_{\tilde{g}} = 200$ GeV (the upper dashed band in Fig. 3) and 300 GeV (the lower dashed band in Fig 3). The widths of these bands are due to varying $\mu$ and $\tan\beta$ over their LEP-allowed values [10] consistent with the mass-spectrum required for the VLSP scenario. It should be noted that the lower value of $m_{\tilde{g}}$ is well within the striking range of direct searches at the Tevatron collider while the upper one is very likely to be beyond this range. For comparison we have also presented the cross-section for the purely SM process which corresponds to the middle one of the three solid lines in Fig 3. The other two solid lines are representative of the statistical fluctuations of the number of events expected from the standard model process assuming an integrated luminosity of 500 pb$^{-1}$. Thus, if the cross-section in the VLSP scenario is above the uppermost solid line, the effect cannot be interpreted as a fluctuation.

One should note that the considerations stated above already impose a cut of $40^\circ < \theta_\gamma < 140^\circ$.2
We note from Fig. 3 that a reasonable range of sneutrino masses can be probed at LEP-II particularly for the relatively low \( m_\tilde{\nu} \) case. It is also interesting to note that even if \( m_\tilde{\nu} \) is beyond the reach of direct searches at the Tevatron collider, it is not completely hopeless to look for SUSY signals at LEP-II if the VLSPs are present. This is especially so since the additional contributions of the \( \tilde{N}_i\tilde{N}_j \) pairs to the final state, though rather modest by themselves (see below), push up the signal and bring a significant part of the lower band above the upper line. We conclude, then, that the VLSP scenario has the potential of enhancing the cross-section for \( e^+e^- \rightarrow \gamma + \text{nothing} \) by 15 - 20 % above the SM prediction. We have compared this enhancement with the one that may arise due to the addition of one more stable neutrino (with mass comparable to the sneutrino) to the SM. We find that indeed the enhancement due to the VLSPs is in general comparable to and quite often significantly larger (depending on the SUSY parameters) than the similar effect produced by the above neutrino. This effect should, in fact, be discernable at any \( e^+e^- \) machine capable of revealing effects at the level of a few percent.

We now turn to the neutralino contributions to the signal. In Fig. 4 we present combined cross-sections for the processes \( e^+e^- \rightarrow \gamma \tilde{N}_1\tilde{N}_1 \) and \( e^+e^- \rightarrow \gamma \nu\bar{\nu} \) as a function of \( m_\tilde{l} \) (the slepton mass) at \( \sqrt{s} = 190 \text{ GeV} \). The two bands arise due to reasons explained above. Although we have varied the slepton mass over the entire LEP-allowed range, only the values in the higher side of the range are relevant for the VLSP scenario (since otherwise the lepton-slepton two-body decay channel will be open to the VLSPs). Nevertheless, we have considered the above range for \( m_\tilde{l} \) to demonstrate that in the conventional MSSM where only LSP pairs contribute to the final state, the signal is rather too small to be detected above the fluctuations. Among the neutralino pairs the contributions of \( \tilde{N}_1\tilde{N}_2 \) and \( \tilde{N}_2\tilde{N}_2 \) pairs are even smaller. As discussed above, all \( \tilde{N}_i\tilde{N}_j \)
pairs taken together \((i, j = 1, 2)\), can, however, enhance the signal by 5-8\% of the SM prediction.

A distinct enhancement over the SM prediction for, \(e^+e^- \rightarrow \gamma + nothing\), if detected at LEP-II, cannot, therefore, be explained by the conventional MSSM where the LSP is the only source of missing energy. Such an observation will strongly favour the VLSP scenario, which essentially means that there is a relatively light sneutrino and the parameter space of the MSSM is quite severely restricted to the area which leads to this scenario. On the other hand the absence of this signal will eliminate a considerable segment of a hitherto unexplored region of the MSSM parameter space.

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Figure Captions

Fig. 1. The differential cross-section for the process $e^+e^- \rightarrow \gamma + nothing$ as a function of $E_\gamma$ ($E_\gamma > 5$ GeV). The solid histogram is the Standard Model result. The dotted histograms represent contributions due to associated production of sneutrino pairs in the VLSP scenario for $m_{\tilde{\nu}} = 200$ GeV (upper histogram) and 300 GeV (lower histogram), with $m_{\tilde{\nu}} = 50$ GeV, $\mu = -200$ GeV, and $\tan \beta = 2$. The behaviour remains unchanged for different values of $m_{\tilde{\nu}}, \mu$ and $\tan \beta$.

Fig. 2. The differential cross-section for the process $e^+e^- \rightarrow \gamma + nothing$ as a function of $\theta_\gamma$. Cuts of $5$ GeV $< E_\gamma < 60$ GeV and $40^\circ < \theta_\gamma < 140^\circ$ have been imposed. The convention for the histograms and SUSY parameters are as in Fig. 1. The behaviour remains unchanged for different values of $m_{\tilde{\nu}}, \mu$ and $\tan \beta$.

Fig. 3. Variation of the total cross-section for the process $e^+e^- \rightarrow \gamma + nothing$ as a function of $m_{\tilde{\nu}}$. The middle one of the three solid lines indicates the Standard Model contribution, while the upper and lower ones represent fluctuations calculated on the basis of an integrated luminosity of 500 pb$^{-1}$. The upper (lower) dashed band represents the enhancement due to associated production of sneutrino pairs for $m_{\tilde{\nu}} = 200$ (300) GeV.

Fig. 4. Variation of the total cross-section for the process $e^+e^- \rightarrow \gamma + nothing$ as a function of $m_{\tilde{\nu}}$. The solid lines are the same as in Fig. 3. The upper (lower) dashed band represents the added contribution due to associated production of LSP pairs for $m_{\tilde{\nu}} = 200$ (300) GeV.
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