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NEW PARTICLE SEARCHES HAUNTED BY VIRTUAL 'LIGHTEST SUPERSYMMETRIC PARTICLE'S

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ABSTRACT

Relatively light sneutrinos which are experimentally allowed and theoretically not unfavourable, may significantly affect the currently popular search strategies for supersymmetric particles by decaying predominantly into an invisible channel. In such cases the second lightest neutralino also becomes invisible. Consequences of such a scenario in relation to the ongoing searches at the Tevatron and LEP-II are discussed.

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The search for supersymmetry (SUSY) [1] is a high priority programme at all the ongoing high energy accelerators. Even if these searches yield negative results, the effort will continue in the already planned colliders like the LEP-II or the LHC. The strategy for hunting SUSY particles hinges on one crucial assumption: there is a single, stable, weakly interacting (and therefore invisible) particle, the so-called lightest supersymmetric particle (LSP). It is further assumed that by virtue of a conserved quantum number (R-parity), all other superparticles eventually decay into the LSP. The LSP, therefore, carries missing transverse energy ($\cancel{E}_T$) which is traditionally regarded as the most distinctive signature of SUSY particles.

The minimal supersymmetric extension of the standard model (MSSM) contains four neutralinos ($\tilde{N}_i$, $i=1-4$) which are physical states obtained as linear combinations of the superpartners of the neutral gauge and Higgs bosons. In the currently favoured models, the lightest among them ($\tilde{N}_1$) is assumed to be the LSP [1].

The purpose of this letter is to emphasize that there may exist SUSY particles which, though unstable, decay dominantly into invisible channels. This occurs if the sneutrinos ($\tilde{\nu}$) are sufficiently light. As its consequence, in a certain region of the parameter space the second lightest neutralino ($\tilde{N}_2$) also decays into invisible final states. These particles, hereafter called virtual LSP's, may act as additional sources of $\cancel{E}_T$ and can significantly affect the strategies for SUSY search, as will be discussed below with primary reference to the Tevatron experiments.

To be more specific, we consider the situation where the $\tilde{\nu}$'s are heavier than $\tilde{N}_1$, lighter than $\tilde{N}_2$, χ_2 (χ_2 =lighter chargino), and much lighter than all other SUSY particles. This scenario is not excluded by any existing experimental bounds on the sparticle masses. For reasonably large gluino masses, $\tilde{N}_1$ may have a substantial Zino component [2]. The invisible two-body decay mode $\tilde{\nu} \rightarrow \nu \tilde{N}_1$ thus opens up and

completely dominates over others, being the only kinematically allowed two-body decay of the $\tilde{g}$ neutrinos. Moreover, in such cases the $\tilde{N}_2$ which almost always has a dominant Zino component, is heavier than $\tilde{\nu}$, and decays primarily through the process $\tilde{N}_2 \rightarrow \nu\tilde{\nu}$. Thus, in addition to $\tilde{N}_1$, both $\tilde{\nu}$ and $\tilde{N}_2$ become invisible and behave as virtual LSP's.

In Table 1, $B(\tilde{\nu} \rightarrow \nu\tilde{N}_1)$ is given as a function of $m_{\tilde{\nu}}$ for a representative combination of parameters allowed by the LEP data [3,4]¹. As expected, the branching ratio (BR) decreases rapidly as the channels $\tilde{\nu} \rightarrow \nu\tilde{N}_2$ and $\tilde{\nu} \rightarrow l\chi_2$ become kinematically accessible. Nonetheless, it follows from Table 1 that over a considerable region of the parameter space, a significant fraction of the $\tilde{\nu}$'s produced in colliders will decay invisibly. We have checked that the three-body (like $Wl\tilde{N}_1$), four-body (like $lq\bar{q}\tilde{N}_1$) and loop-induced decays [6] are insignificant in the range of $m_{\tilde{\nu}}$ shown in Table 1.

We now discuss the impact of such virtual LSP's on the currently active SUSY searches. We shall restrict ourselves to the choice $m_{\chi_2} > m_{\tilde{\nu}}$. The most recently published bounds on the squark and gluino masses [7] are based on *jets* + $\cancel{E}_T$ events at the Tevatron. In conventional scenarios these are expected to arise due to gluino

¹The masses and the couplings of the charginos and the neutralinos are determined by three parameters. A convenient choice is $m_{\tilde{g}}$ (the gluino mass), $\tan\beta$ (the ratio of the vacuum expectation values of the two neutral Higgs bosons) and m_{χ_2} . For given $m_{\tilde{g}}$ and $\tan\beta$, m_{χ_2} is bounded both from above [4] and below [3,4]. For the choice given in the text, $45\text{GeV} \leq m_{\chi_2} \leq 84\text{GeV}$. For $m_{\chi_2} = 81\text{GeV}$, The neutralino masses are 36 GeV, 70 GeV, 122 GeV and 130 GeV. In principle, for each m_{χ_2} , two values of the more commonly used parameter μ (the Higgsino mass parameter) are allowed. Hence in principle two sets of parameters pertaining to the neutralino sector are possible. However, for gluino masses within the striking range of the Tevatron ($m_{\tilde{g}} \leq 250\text{GeV}$, say), one of them is almost always ruled out [3,4,6].

and/or squark production followed by either direct or cascade decay into the LSP. For a relatively large $m_{\tilde{g}}$, the BR for the direct decay $\tilde{g} \rightarrow q\bar{q}\tilde{N}_1$ can be much smaller compared to the other three-body decays $\tilde{g} \rightarrow q\bar{q}\tilde{N}_i (i > 1)$, $\tilde{g} \rightarrow q\bar{q}\chi_2$ over a large region of the parameter space [8]. In particular, the decay $\tilde{g} \rightarrow q\bar{q}\chi_2$ may occur with a BR as large as 50-60 per cent. The LSP's that are produced from the decays of $\tilde{N}_i (i > 1)$ and χ_2 are much softer and quite often fail to pass the stringent p_T -cuts. This weakens the mass limits compared to the ones derived by assuming the dominance of direct decays [7,9].

The extraction of the above mass limits will be even more complicated if virtual LSP's are present. If the $\tilde{N}_2$ acts as a virtual LSP, the decay $\tilde{g} \rightarrow q\bar{q}\tilde{N}_2$ would not lead to a softer p_T -signal. However, approximately 50 per cent of the gluinos decay to χ_2 [8]. In the scenario under consideration, the χ_2 decays into $l\bar{\nu}$ (where $l = e$ or μ ; we assume the sneutrinos to be degenerate) with $BR = 2/3$. This may drastically reduce the *jets* + $\cancel{E}_T$ signal and enhance the *jets* + *leptons* + $\cancel{E}_T$ events. Among the latter, the like-sign dilepton (LSD) events are especially clean for the purpose of SUSY search [10]. We, however, caution the reader that the hardness of the p_T -spectrum of the final state leptons depends crucially on $\Delta m = m_{\chi_2} - m_{\tilde{\nu}}$. For the purpose of illustration we present in figure 1 the p_T -spectrum of the softer electron in LSD events arising out of gluino pairs, for two values of Δm , for given $m_{\tilde{g}}$. In practice, the p_T -spectrum of the harder leptons turns out to be similar in this case. The shift of the peak of the spectrum for the larger value of Δm should be noted. Obviously, the lepton identification criterion becomes more complicated as the leptons in the final state become softer.

Let us now consider in some detail the other popular SUSY search strategy, based on the LSD events. As has already been discussed in the last paragraph, the presence

of virtual LSP's enhances this signal rather spectacularly. This is primarily due to the fact that in the conventional scenarios (no light sneutrinos), the LSD cross-section which owes itself to the decay $\chi_2 \rightarrow \tilde{N}_1 W^*$ is suppressed by the square of a small ($\approx 22\%$) branching ratio for the virtual W going to either an electron or a muon. In our case, however, $B(\chi_2 \rightarrow \tilde{\nu} + e \text{ or } \mu)$ is $\approx 66\%$. This leads to a larger LSD yield. We illustrate this in Figure 2, having used a parton level Monte Carlo where only LSD's from $\tilde{g}\tilde{g}$ -pairs have been taken into account. Being conservative, we have assumed that $m_{\tilde{\chi}} = m_{\tilde{g}} + 125\text{GeV}$, and have not considered the enhancement of the signal [11] that may arise if $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ events are also taken into account. The same kinematical cuts as those used in reference 10 have been used by us. It is interesting to note that our conservative LSD cross-sections are of the same level as the optimistic results obtained in reference 11 (with $m_{\tilde{\chi}} \approx m_{\tilde{g}}$). A novel feature of Figure 2 is that the LSD signal does not decrease monotonously with the gluino mass, which is the case in the conventional scenario [10,11]. The suppression of the cross-section for small $m_{\tilde{g}}$ is due to the fact that here Δm is rather small. The stringent p_T -cuts on the leptons, therefore, reduces the cross-section, as discussed above. Further, the lepton isolation cut becomes more effective as the p_T -cuts are increased and reduces the cross-section to some extent [12]. It is expected that by the end of 1994 the Fermilab Tevatron will accumulate an integrated luminosity of 100pb^{-1} [12]. It follows from Figure 2 that gluino masses in the range 150-200 GeV can then be probed in the scenario under consideration. If the main injector upgrade makes it possible to accumulate 1fb^{-1} of luminosity by the end of this century [13], gluinos of higher masses may also become accessible.

As luminosity accumulates at the Tevatron, processes with lower cross-sections may also become relevant in the SUSY hunt programme [14,15]. Virtual LSP's can signifi-

cantly affect these search strategies as well. For example, in the conventional scenarios the process [14,15] $p\bar{p} \rightarrow W^+ X \rightarrow \chi_2 \tilde{N}_2 \rightarrow 3l + \cancel{E}_T$ can probe SUSY parameter ranges which are competitive with the reach of LEP-II [15]. In models with virtual LSP's, thanks to the decay $\tilde{N}_2 \rightarrow \nu\bar{\nu}$, the final state for the above process may consist only of a single lepton (from $\chi_2 \rightarrow l\bar{\nu}$) + $\cancel{E}_T$. This will obviously be overwhelmed by the backgrounds from $W \rightarrow l\nu$. On the other hand if the invisible decay channel of $\tilde{N}_2$ is closed but $\chi_2 \rightarrow l\bar{\nu}$ is still allowed (which happens over a narrow region of the parameter space), the $3l + \cancel{E}_T$ signal will be larger than those in reference 15 due to the large BR for $\chi_2 \rightarrow l\bar{\nu}$.

The presence of virtual LSP's can, however, strengthen the hadronically quiet $2l + \cancel{E}_T$ signal coming from χ_2 -pair production followed by the decay $\chi_2 \rightarrow l\bar{\nu}$. In the conventional scenario this cannot compete with the background from WW production [15]. The cross-section for the latter process is about 10pb [16], while the $\chi_2\chi_2$ production cross-section is only $\sim 1\text{pb}$. Since similar BR's are involved in the signal and the background, the signal does not seem to be promising [15]. If, on the other hand, virtual LSP's are present, the situation changes drastically since $B(\chi_2 \rightarrow l\bar{\nu}) \approx 2/3$, and is greater than $B(W \rightarrow l\nu)$, $l = e, \mu$. The signal cross-section is then estimated to be $4/9\text{pb}$, while the background cross-section is approximately $2/5\text{pb}$. Moreover, the $\cancel{p}_T$ from χ_2 -decays is much harder than that from W -decays (or equivalently the $\cancel{p}_T$ spectrum of the LSD's in the signal will be peaked at a lower value). The isolation of the signal from the background is therefore a distinct possibility. A more quantitative analysis of this is in progress.

So far we have guided ourselves solely from phenomenological considerations. If one considers N=1 supergravity models [17] with a common sfermion mass and a common

gaugino mass at the unification scale, then virtual LSP's in the mass range discussed here favour $m_{\tilde{\tau}} < m_{\tilde{g}}$ and $\tan\beta > 1$. For example, using the model of reference 18, one obtains $m_{\tilde{\tau}}^2 = m_{\tilde{g}}^2 - 0.73m_{\tilde{g}}^2 + 0.5m_{\tilde{g}}^2 \cos 2\beta$. With $m_{\tilde{g}} = 225\text{GeV}$, $\tan\beta = 3$ and $55\text{GeV} \leq m_{\tilde{\tau}} \leq 70\text{GeV}$, one obtains $m_{\tilde{\tau}} \approx 210\text{GeV}$. As has been already discussed, such a scenario will enhance our conservatively estimated LSD cross-sections through $\bar{q}q$, $\bar{g}g$ production in addition to $\tilde{g}\tilde{g}$ -pairs. It is also to be noted that it is possible to motivate from the above types of models situations where the sneutrinos are lighter than χ_2 and the second lightest neutralinos, whereas the charged sleptons are somewhat heavier ($m_{\tilde{l}}^2 - m_{\tilde{\nu}}^2 = -m_{\tilde{g}}^2 \cos 2\beta$). This situation is distinct from the recently considered ones [19] where the charged sleptons are also equally light, thereby allowing $\tilde{N}_2$ to decay into the $\tilde{l}\tilde{l}$ channel. A mass splitting between the $\tilde{l}$ and the $\tilde{\nu}$ leads to nearly complete invisibility of three superparticles, which makes this scenario a particularly interesting one in connection with SUSY search strategies.

The most obvious way to confirm the existence of relatively light virtual LSP's (or to put limits on their masses) would be to look for $e^+e^- \rightarrow \gamma + \text{nothing}$ at LEP-II. In conventional SUSY scenarios both $\nu\bar{\nu}$ and $\tilde{N}_1\tilde{N}_1$ pairs contribute to this kind of effect. With virtual LSP's, $\tilde{\nu}\tilde{\nu}$ and $\tilde{N}_2\tilde{N}_2$ will also contribute and jack up the cross-section. A detailed analysis of the constraints that may arise therefrom is in progress.

In summary, we emphasize that virtual LSP's in the MSSM are neither experimentally ruled out nor theoretically unaesthetic. Their presence may radically alter the popular signals for SUSY search and affect the existing bounds on squark and gluino masses. The like-sign dilepton signals seems to be the favoured one for SUSY search even in models with virtual LSP's.

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TABLE CAPTION

Table 1:

The branching ratio of a sneutrino into the invisible mode as a function of the sneutrino mass. $m_{\tilde{g}} = 200\text{GeV}$, $\tan\beta = 2$, $m_{\chi_1} = 81\text{GeV}$.

FIGURE CAPTIONS

Figure 1:

The p_T -spectrum of the softer electron in LSD events, with $m_{\tilde{g}}(m_{\chi_1}) = 150\text{Gev}(72\text{ Gev})$ (solid line) and $m_{\tilde{g}}(m_{\chi_1}) = 225\text{Gev}(88\text{ Gev})$ (dashed line). In each case $m_{\tilde{\nu}} = 60\text{GeV}$, $\tan\beta = 2$, $\mu = -100\text{GeV}$.

Figure 2:

The LSD cross-section from gluino-pair production as a function of the gluino mass, with (i) $m_{\tilde{\nu}} = 60\text{GeV}$, $\tan\beta = 2$, $\mu = -100\text{GeV}$ (solid line), (ii) $m_{\tilde{\nu}} = 55\text{GeV}$, $\tan\beta = 2$, $\mu = -300\text{GeV}$ (dashed line), (iii) $m_{\tilde{\nu}} = 55\text{GeV}$, $\tan\beta = 3$, $\mu = -100\text{GeV}$ (short dashed line).

Table 1

$m_{\tilde{\nu}}(\text{GeV})$	50	70	75	80	85	90
$B(\tilde{\nu} \longrightarrow \nu \tilde{N}_1)$	1.0	1.0	0.85	0.65	0.41	0.24

Fig.1.

Fig.2.