Squark Gluino Mass Limits Revisited For Nonuniversal Scalar Masses

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ABSTRACT

It is shown that if the sneutrino is the second lightest SUSY particle, then the decay products of squarks and gluinos produced at the TEVATRON collider tend to have i) more leptons, ii) smaller number of jets and iii) two or more carriers of $E_T$. This may relax the existing limits on the squark and gluino masses. This effect is likely to be even more striking as these limits improve with accumulation of data. Numerical results for signal cross sections are presented and compared with the ones obtained without a light sneutrino. The possibilities of accommodating this scenario in models motivated by $N = 1$ SUGRA are discussed.

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1 Introduction

Supersymmetry (SUSY) \cite{1} is one of the most important alternatives to the Standard Model (SM) with an elegant solution of the notorious naturalness problem, provided the masses of the superpartners are of the order of 1 TeV or less. The search for SUSY at the TeV scale is, therefore, a high-priority programme of current high energy physics. Extensive searches for SUSY at the present high energy accelerators including the Fermilab Tevatron \cite{4}, LEP-1 \cite{3} and LEP-1.5 \cite{4} have yielded negative results and have eliminated certain regions of the parameter space of the Minimal Supersymmetric extension of the Standard Model (MSSM)\cite{1}.

However, the parameter space of SUSY is so complicated that the limits on the sparticle masses obtained from these searches almost always involve certain simplifying assumptions. Past experiences reveal that such limits often require revisions once such assumptions are removed. As an example let us consider the early limits on squark (\tilde{q}) and gluino (\tilde{g}) masses (m_{\tilde{q}} and m_{\tilde{g}}) obtained by the UA1 \cite{5}, UA2 \cite{6} and CDF \cite{7} collaborations in the jets + missing transverse energy (\not{E_T}) channel. These were based on the assumption that these sparticles directly decay, with 100\% branching ratio (BR), into a pure photino, which was assumed to be the lightest supersymmetric particle (LSP). By virtue of this assumption apparently clean limits, independent of other SUSY parameters, were obtained on m_{\tilde{g}} and m_{\tilde{q}}.

Subsequently it was pointed out \cite{8} that the squarks and the gluino may also decay into other combinations of electroweak gauginos with significantly large BRs. These Gauginos eventually decay into the LSP which in general may not be a pure photino. Moreover the \not{E_T} spectrum of the LSP in this case is much softer. New analyses \cite{2} in this more general framework revealed that the limits on m_{\tilde{q}} and m_{\tilde{g}} were in fact less stringent than the earlier ones. Moreover these limits have some (weak) dependence on other SUSY parameters.

However, the present limits are also not free from assumptions. They are based on the predictions of the so called N=1 supergravity (SUGRA) motivated models \cite{9} with common scalar and gaugino masses at a high scale. An important byproduct of this assumption is that for a large region of the parameter space all scalar superpartners (including sleptons and sneutrinos) of the ordinary fermions turn out to be heavier than the unstable electroweak gauginos into which the squarks and gluinos decay. This in turn leads to specific decay
signatures of these sparticles (see below for the details) on which the current search strategies are based.

The above assumption though attractive is by no means compelling. The usual assumption that the MSSM is embedded into some Grand Unified Theory (GUT) usually implies, irrespective of the choice of any particular gauge group for the GUT, that all gauginos present in the model have a common mass at the GUT scale. The assumption of a common gaugino mass at the GUT scale is, therefore, largely model independent and like most of the phenomenological works on SUSY, we shall adopt this.

On the other hand the assumption of a common scalar mass at the GUT scale is less general. In fact many interesting works have shown in recent times that even within the SUGRA framework one can naturally accommodate nonuniversal scalar masses [10]. This nonuniversality may arise simply due the fact that SUGRA may generate common scalar masses at the Planck scale. The usual renormalisation group evolution from the Planck scale down to the GUT scale may then generate unequal scalar masses depending on the representations to which the scalars belong [11]. Further evolution of these masses down to the electroweak scale may lead to mass patterns significantly different from the conventional ones. There could be more involved mechanisms for nonuniversal scalar masses at the GUT scale. For example, such nonuniversality can manifest itself through D terms [12] when the GUT group breaks down to smaller gauge groups at lower energies. This nonuniversality is quite model dependent and depends also on the symmetry breaking chain. Moreover in recent literature the possibility of gauge mediated supersymmetry breaking has been discussed extensively [13]. Nonuniversality arises in this scenario naturally since the SUSY breaking mass terms depends on the standard model quantum numbers of the scalars.

Since it will be a tremendous loss to miss a SUSY signal due to assumptions inherent in the search strategies, we find it prudent to treat the scalar masses in a more phenomenological way. This is particularly justified in view of the above uncertainties in the scalar masses. We emphasize that certain mass patterns rather than specific choices for individual sparticle masses, lead to signatures quite different from the conventional ones. Towards the end of this paper we shall discuss the compatibility of these patterns with SUGRA motivated theories [3, 11, 12]. To be specific we work within the following framework.

The MSSM contains four spin-$\frac{1}{2}$ neutral sparticles. They 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 neutral gauginos or 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 \cite{1}. Within R-parity conserving models this is usually assumed to be the only carrier of $\not{E}_T$. Similarly, linear combinations of the superpartners of the $W$-boson and the charged Higgs boson give two physical charged gauginos or charginos. In the following only the lighter chargino ($\tilde{\chi}_1^\pm$) will be of practical consequences. With the usual assumption of a common gaugino mass at the GUT scale, the masses and the couplings of charginos and neutralinos depend only on three independent parameters. Usually these are taken as $\mu$, $\tan\beta$ and the gluino mass $m_{\tilde{g}}$ (which is related to the universal gaugino mass through the standard renormalisation group equations). Here $\mu$ is the soft mass parameter for higgsinos and $\tan\beta$ is the ratio of the vacuum expectation values of two neutral Higgs bosons in the MSSM.

If no further assumption is made then the masses of the scalars are totally independent of the gaugino-masses. Thus the sneutrinos ($\tilde{\nu}$, the superpartners of the neutrinos), though heavier than the LSP, could very well be lighter than the $\tilde{\chi}_1^\pm$, the second lightest neutralino ($\tilde{N}_2$) and other sparticles. As a consequence, the invisible two-body decay mode $\tilde{\nu} \rightarrow \nu\tilde{N}_1$ opens up and completely dominates over the 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 $m_{\tilde{g}}$ is in the range interesting for the SUSY searches at the Tevatron \cite{2}. Thus the $\tilde{\nu}$s, decaying primarily into an invisible channel, may act as additional sources of $E_T$ and can significantly affect the strategies for SUSY searches \cite{14, 15}. It is, therefore, called virtual or effective LSP (VLSP or ELSP) \cite{14, 16} in the context of SUSY searches. Within this basic framework one can think of two closely related VLSP scenarios with interesting phenomenological consequences.

I) In some regions of the parameter space right and left sleptons ($\tilde{l}_R$ and $\tilde{l}_L$) along with sneutrinos may be lighter than all electroweak gauginos except the LSP. By virtue of the SU(2) breaking mass splitting due to D terms

$$m_{\tilde{l}_L} = \sqrt{m_{\tilde{\nu}}^2 + 0.77D}$$

$$D = -M_Z^2 \cos 2\beta,$$  \hspace{1cm} \text{(1)} \hspace{1cm} \text{(2)}

the sneutrinos are always lighter than the left sleptons. We emphasize that the above relation holds in a model independent way as long as $SU(2)_L$ is a good symmetry above
the electroweak scale. Thus irrespective of the masses of the right sleptons, the sneutrinos will decay into the above invisible channel. By virtue of the assumed mass hierarchy the unstable gauginos will almost exclusively decay into sleptons or sneutrinos along with leptons and neutrinos via two body decay channels. The sleptons in turn will decay into leptons and the LSP. Thus decays of the electroweak gauginos into jets, which can occur only through three body modes, will be severely suppressed. Moreover the number of final states involving one or more leptons will increase. In contrast in the conventional scenario these gauginos dominantly decay into jets while only a small fraction of them decay into the leptonic channel. As we will see below, these will have nontrivial implications for the existing limits on $\tilde{m}_{\tilde{q}}$ and $\tilde{m}_{\tilde{g}}$ obtained through the jets $+ \not{E}_T$ channel.

II) In a more restricted region of the parameter space, the $\tilde{N}_2$ — which also has a dominant zino component — may decay almost entirely through the invisible channel $\tilde{N}_2 \rightarrow \nu \tilde{\nu}$. This happens if both $\tilde{l}_L$ and $\tilde{l}_R$ are heavier than the $\tilde{N}_2$. In this special case one obtains two VLSPs. Moreover, $\tilde{\chi}_1^\pm$, usually having a mass close to that of $\tilde{N}_2$, will decay into leptons and $\tilde{\nu}$s with almost 100 % BR. As in the previous case the final state will contain smaller number of jets and larger number of leptons compared to the conventional scenario.

Some consequences of both scenario I) and II) (as opposed to the conventional MSSM where the LSP is the only source of $\not{E}_T$) in the context of SUSY searches at both hadron and $e^+e^-$ colliders have been discussed in the literature [14, 15, 16, 17, 18]. In particular it was qualitatively argued in [14], that the then existing limits on the $\tilde{q}$ and the $\tilde{g}$ masses from the Tevatron collider, could be relaxed in this scenario. But no quantitative estimate was given. In this note we will critically reexamine the current D0 limits [2].

Let us reexamine the D0 [2] limit $m_{\tilde{q}} > 170$ GeV, for $m_{\tilde{g}} = 300$ GeV ( for $\mu = -250$ GeV and $\tan \beta = 2$ ). In this case the SUSY signal is almost entirely controlled by squark pair production. The produced squarks decay primarily into quarks and various electroweak gauginos. In the conventional scenario the unstable gauginos decay dominantly into jets and the LSP ($\not{E}_T$). Only a relatively small fraction decay into the leptonic channel. These quarks along with the quark coming from the primary squark decay contribute to the signal which is required to have at least three hard jets each having $E_T > 25$ GeV [2]. In the VLSP scenario on the other hand the gauginos decay almost entirely into leptons and $\not{E}_T$. Thus at the parton level each squark pair event will be associated with two jets only. Of course some events may still have three or more jets due to fragmentation of the quarks into
more than one jet and/or hard gluon radiations. Yet it is fair to conclude that the three jet cuts affect the signal severely and the existing limit may require revision.

The second point of interest stems from the fact that all the $\tilde{\chi}^{\pm}_{1}$ s and, depending on the slepton masses, some of the $\widetilde{N}_{2}$ s produced from squark decays, eventually decay into leptons. The signal will therefore be more severely affected by the lepton veto than in the conventional case. Of course the effect of the lepton veto will depend on the $E_{T}$ of the final state leptons which in turn depends on the masses of the gauginos on the one hand and that of the sneutrinos and the sleptons on the other. This point will be discussed in further details in the following.

Finally the $\not{E}_{T}$ spectrum is also of considerable interest. Since in this scenario a substantial part of the $N_{2}$s decay directly into an invisible mode and the $\tilde{\chi}^{\pm}_{1}$ s decay into a carrier of $E_{T}$ heavier than the LSP via a two body mode, the pattern of missing energy can in principle be different from the conventional case.

In Fig.1 we plot the number of jets (solid lines) in a sample of 10000 events generated by ISAJET - ISASUSY in the conventional (CONV) scenario defined by the parameter set (all masses and mass parameters are in GeV and cross sections are in pb)

i) $m_{\tilde{q}} = 170.0$ (where $m_{\tilde{q}}$ is the mass of five species of L and R squarks assumed to be degenerate in mass; as in the D0 paper. We do not include the stop quark in our analysis), $m_{\tilde{g}} = 300.0$, $\mu = -250.0$, $\tan \beta = 2.0$, $A=0$ and, following D0, all slepton and sneutrino masses are set equal to the squark mass (in practice any choice with sleptons and sneutrinos sufficiently heavier than $\tilde{\chi}^{\pm}$ and $N_{2}$ gives identical results).

In Fig.1 (dashed lines) we also present the same distribution for the parameter set ii) which is identical to i) except that we now introduce relatively light sneutrinos with $m_{\tilde{\nu}} = 50.0$ and the L type sleptons with mass given by eqn 1. For definiteness we have taken $m_{\tilde{\nu}_{L}} = m_{\tilde{\nu}_{R}}$ but this choice has little bearing on the final results. The relevant electroweak gaugino masses for set i) and ii) are $M_{\tilde{N}_{1}} = 48$, $M_{\chi_{1}^{\pm}} = 101.76$ and $M_{\tilde{N}_{2}} = 102.27$.

It is clear from Fig.1 that in the conventional scenario most of the events are associated with three or more jets. In contrast, the VLSP scenario represented by the parameter set ii) shows a peak at $N_{jet} = 2$ as expected. Thus a large fraction of the signal events will be removed by the three jet cut.

In Fig.2 we compare the $E_{T}$ spectrum of the softer lepton (the spectrum of both the leptons in the final state look quite similar). Again it is quite clear that the lepton veto
(defined below) affects scenario ii) quite severely.

Finally in Fig.3 we compare the $E_T$ spectrum for set i) (solid lines) and ii) (dashed lines). They turn out to be quite similar.

It is now natural to reexamine the limits on $m_{\tilde{q}}$ in scenario ii). While a rigorous new limit cannot be obtained without full detector simulations, the trend can be easily understood from our analysis. We apply the following cuts introduced in the D0 paper to reduce the SM background:

A) We require $E_T > 75$ GeV.
B) The signal is required to have three or more jets with $E_T > 25$ GeV and $|\eta| < 3.5$.
C) Jets are ordered in terms of decreasing $E_T$. We then require that the leading jet should not fall into the calorimeter crack, i.e., its pseudorapidity should not lie in the region $1.1 \leq |\eta| \leq 1.4$.
D) The angle $\delta \phi_k$ is defined as the azimuthal angle between the $k$th jet and the $E_T$ vector. Events having $\delta \phi_k > \pi - 0.1$ or $\delta \phi_k < 0.1$ for $k = 1, 2, 3$ are rejected. Events with $\sqrt{(\delta \phi_1 - \pi)^2 + (\delta \phi_2)^2} < 0.5$ are also rejected.
E) The lepton veto (there will be no electrons with $E_T > 20$ GeV and muons with $E_T > 15$ GeV) is then applied.

In table I we present the signal cross section ($\sigma_c$) after cuts for parameter sets i) and ii). The efficiencies of the cuts A) - E) can also be obtained from this table where the number of generated events is 10000. Since the lepton veto plays a major role in this analysis, we present results for three values of lepton detection efficiency (LDE): 100 %, 70 % and 60 % (the three numbers in the 8th and the last column). It follows from table I that the reduction of the cross section in scenario ii) compared to that in scenario i), is substantial even for LDE as low as 60%. It is also clear that the cuts B) and E) reduces the signal more drastically in scenario ii).

In order to have a rough idea about the changes in the squark mass limit we now compute the cross sections for the following sets of parameters:
i) which is the same as in ii) except that $m_{\tilde{q}} = 150$,
iiv) which is the same as in ii) but with $m_{\tilde{q}} = 160$.

The results are presented in tables I. We find that for low LDE both choice iii) and iv) give cross sections consistent with the one obtained for set i) which represents the published 95 % CL D0 limit on $m_{\tilde{q}}$, corresponding to a candidate sample of 14 events in $13.5 \pm 1.6$ pb$^{-1}$.
data, against an estimated background of $17.1 \pm 1.8 \pm 7.0_{-0.6}^{+1.8}$. Thus the current limits on $m_{\tilde{q}}$ for $m_{\tilde{g}} = 300.0$, is likely to be reduced by 10 - 20 GeV in the VLSP scenario.

At this point it might be interesting to examine the sensitivity of the signal to $m_{\tilde{\nu}}$. A clear advantage of SUSY search in the jets + $E_T$ channel will emerge from this discussion. In the VLSP scenario the unstable gauginos primarily decay into leptons giving enhanced signal in the leptonic channel compared to the conventional scenario. For example, SUSY signals from chargino pair production followed by their leptonic decays at both $e^+ - e^-$ and hadron colliders [10, 15] in the VLSP scenario have been discussed in the literature. The typical signal is a pair of hadronically quiet dileptons which can be separated from the apparently large W-W, Drell - Yan or two photon backgrounds by suitable kinematical cuts. However, in all these cases the resulting signal becomes weak if the mass difference between the chargino and the sneutrino is small. The reason is rather obvious. With heavier sneutrinos the signal leptons become softer and becomes indistinguishable from the Drell - Yan or two photon background. Similarly, the $2l$ (dilepton) + jets + $E_T$ signal is also significantly enhanced in the VLSP scenario compared to the conventional case [14, 15]. As we shall show below this signal also becomes weaker and no useful limit can be derived, if the above mass difference happens to be small.

On the other hand the limit that follows from the jets + $E_T$ channel for a large chargino - sneutrino mass difference is rather conservative. This is because for heavier sneutrinos the lepton veto affects the signal to a lesser extent and the squark mass limit become stronger. This is illustrated in table I for the parameter set v) which is the same as in iii) except that $m_{\tilde{\nu}} = 92$. With chargino masses as stated above the mass difference between the chargino and the sneutrino is about 10. The resulting enhancement of the cross section compared to set choice iii) is to be noted. We, however, emphasize that even in this case the reduction of the signal due to the 3 jet cut takes place. The signal, therefore, looks considerably different from the conventional one. We have also noted that the signal remains practically unaffected by specific choices of $m_{\tilde{\nu}}$, as long as the chargino sneutrino mass difference remain large. This has been verified by varying $m_{\tilde{\nu}}$ in the interval 50 - 75 GeV for the parameter set iii). For example with $m_{\tilde{\nu}} = 75$ GeV, we obtain $\sigma_e = 2.01, 2.11$ and 2.24 for three LDEs which is certainly consistent with the result for set iii) (see table I).

Although the above analysis is for a specific $m_{\tilde{q}}$ and $m_{\tilde{g}}$, we wish to stress that the current
D0 limits on $m_{\tilde{q}}$, for $m_{\tilde{g}} > m_{\tilde{q}}$, is likely to be affected by the VLSP scenario if $m_{\tilde{g}} < 400$ GeV. For $m_{\tilde{g}}$ in this range, squarks having masses within the current D0 limits are kinematically allowed to decay into $\tilde{\chi}_1^\pm$ and $\tilde{N}_2$. Due to hadronically quiet decays of these gauginos in the VLSP scenario as discussed above, relaxation of these limits is to be expected. For higher $m_{\tilde{g}}$, however, the limits on $m_{\tilde{q}}$ are rather weak and both the $\tilde{\chi}_1^\pm$ and the $\tilde{N}_2$ happen to be heavier than squarks having masses consistent with the current limits. These squarks decay directly into LSP with 100% BR. Thus the signal is similar both in the conventional and VLSP scenarios. As a result further relaxation of the existing limits is improbable, although as and when these limits get stronger VLSP effects should be taken into account.

We now turn our attention to the mass limits when the squarks and the gluinos are approximately degenerate in mass. The existing limit is $m_{\tilde{q}} \simeq m_{\tilde{g}} > 212$ GeV. In table II we present the cross section for the set of parameters with the kinematical cuts A) - E)

vi) $m_{\tilde{q}} \simeq m_{\tilde{g}} \simeq 212$. All other parameters as in set i).

vii) $m_{\tilde{q}} \simeq m_{\tilde{g}} \simeq 202$, $m_{\tilde{\nu}} = 50$ and $m_{\tilde{t}_L}$ as determined by eqn 1. For simplicity we also take $m_{\tilde{t}_L} = m_{\tilde{t}_R}$, although, as discussed earlier this choice has little bearing on the final result. Other SUSY parameters are chosen as above.

viii) $m_{\tilde{q}} \simeq m_{\tilde{g}} \simeq 205$ with other parameters as in vii).

Comparing the results in table II it is fair to conclude that a reduction of the existing limits by 7 - 10 GeV seems to be very likely. Although this relaxation is modest compared to that in the previous example, this set of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ deserves special attention. For this set a relatively light sneutrino can be accommodated more easily in SUGRA motivated frameworks [3, 11] as will be discussed below.

For $m_{\tilde{q}} >> m_{\tilde{g}}$, the existing limit $m_{\tilde{g}} > 146$ GeV is rather weak. For this $m_{\tilde{g}}$, $M_{\tilde{\chi}_1^\pm} \simeq 46$ GeV. Thus there is very little parameter space available for a light sneutrino. Any relaxation of the existing limit is therefore unlikely. However, as more data accumulates a significant improvement of this limit is expected. When that happens the VLSP scenario will have important bearings on the limits. This is because the parameter space available in the VLSP scenario in the $m_{\tilde{g}}$ - $m_{\tilde{\nu}}$ plane increases with $m_{\tilde{g}}$ [18].

We now turn our attention to the $2l +$ jets + $E_T$ channel. As has already been discussed [14, 13] the enhanced leptonic branching ratio of the unstable electroweak gauginos in the VLSP scenario is likely to give a larger signal in this channel. On the other hand the stringent cuts on the leptons required to suppress the SM background, make the signal very
sensitive to the mass difference between the gauginos and the scalars. In particular the mass difference between the lighter chargino and the sneutrino plays a crucial role as we shall presently see. The following kinematical cuts are imposed:

F) The signal is required to have at least two electrons with $E_T > 15$ GeV for $|\eta| < 2.5$.

G) It is further required that there be at least two jets with $E_T > 20$ GeV for $|\eta| < 2.5$.

H) $E_T$ is required to be $> 25$ GeV.

I) The invariant mass of the electrons $m_{ee}$ is required to satisfy $|m_{ee} - M_Z| > 12$ GeV. If this is not satisfied then $E_T$ is required to be $> 40$ GeV.

In Table III we present the effects of the above cuts on 10000 events generated by ISAS-USY - ISAJET [19] for the parameter sets i), ii) and ix) all parameters as in ii) but $m_{\tilde{\nu}} = 92$ GeV.

We have conservatively assumed only 30% efficiency for detecting two electrons. It follows from Table III that in contrast to the jets + $E_T$ channel, set ii) indeed gives a larger signal in the dilepton channel. When data for an integrated luminosity of $\approx 100$ pb$^{-1}$ is available, the VLSP scenario can indeed be probed in this channel. In this analysis we have restricted ourselves to electrons only. This is because the muon detection efficiency is poor for the D0 experiment. Even the CDF experiment has a rather limited angular coverage for muon detection. The physics of the search in the dimuon channel or $e-\mu$ channel in the VLSP scenario is, however, very similar. Inclusion of muons along with improvements in LDE will make SUSY search in the dilepton channel more attractive in the VLSP scenario.

As mentioned earlier the improved signal in the dilepton channel is expected to be strongly dependent on the sneutrino - chargino mass difference and is likely to become extremely weak when this difference is $\simeq 10$ GeV. This is illustrated in Table III with parameter set ix).

It may be noted that the CDF collaboration has recently published limits on squark - gluino masses based on searches in the dilepton channel [20]. It is however not possible to compare our results with theirs, since they used next to leading order cross sections for squark - gluino production [21].

We now turn our attention to the possibility of accommodating the VLSP scenario in N=1 SUGRA models with a common scalar mass at the GUT scale. A similar analysis was made in [16] but the squark gluino mass limits from TEVATRON were not taken into
account since the impact of the VLSP scenario on these limits were not known. The solution
of the standard RG equations does not give identical masses for L and R squarks of different
flavours although, apart from the top squarks, the masses are closely spaced. On the other
hand, the experimental limits are given in terms of a common squark mass. We identify this
with the average mass of two up and three down type squarks of both L and R types. Using
the standard results \[9\] we obtain:

\[ m_{\tilde{q}}^2 = m_0^2 + \frac{8}{9} m_{\tilde{g}}^2 - 0.63 M^2 - 0.05 D \] 

(3)

where \( m_0 \) and M are respectively the common scalar and gaugino mass at the GUT scale
and the constant D has been defined earlier. In order to reduce numerical uncertainties M
dependent terms have been written directly in terms of \( m_{\tilde{g}} \) wherever possible. Substituting
for \( m_0^2 \) in the standard expression for \( m_{\tilde{\nu}}^2 \), we obtain

\[ m_{\tilde{\nu}}^2 = m_{\tilde{q}}^2 - \frac{8}{9} m_{\tilde{g}}^2 + 1.15 M^2 + 0.55 D. \] 

(4)

M is related to \( m_{\tilde{g}} \) by the relation

\[ M = m_{\tilde{g}}(1 + \beta_3 t) \] 

(5)

where \( \beta_3 = \frac{3\alpha_0}{4\pi} \) and \( t = \ln \frac{M_G^2}{Q^2} \approx 66.0 \), \( M_G \) being the GUT scale and Q the appropriate low
energy scale. The value of \( \alpha_0 \), the SU(5) fine structure constant at \( M_G \), is uncertain mainly
due the present uncertainty in the value of the strong coupling constant. A recent fit \[22\]
gives \( \alpha_0^{-1} = 23.9 - 25.3 \). It can be readily checked from the above equation that due to
the above uncertainty \( m_{\tilde{\nu}} \) can vary considerably for given \( m_{\tilde{q}} \) and \( m_{\tilde{g}} \). For example, with \( m_{\tilde{q}} = 200 \) GeV, \( m_{\tilde{g}} = 215 \) GeV and \( \alpha_0 \) in the above range, \( m_{\tilde{\nu}} = 48 - 62 \) GeV. In the entire range
\( m_{\tilde{\nu}} < M_{\tilde{\chi}_1^\pm} \) and , hence sneutrinos decay invisibly. It is worthwhile to note that for \( m_{\tilde{g}} = 215 \) GeV, the above \( m_{\tilde{q}} \) is indeed close to the present D0 limit. Hence a revaluation of this
limit is indeed called for. For definiteness we shall use in the following \( \alpha_0^{-1} = 24.3 \) which is
a typical fit value of \[22\].

If the idea of a common scalar mass at the GUT scale is taken seriously, then the following
conclusions follow from the above equations.

- The present limit \( m_{\tilde{g}} \approx m_{\tilde{g}} = 212 \) GeV is not affected by the VLSP scenario, since
  in this case \( m_{\tilde{\nu}} \approx 92 \) GeV and is larger than \( M_{\tilde{\chi}_1^\pm} \). The same conclusion holds for \( m_{\tilde{q}} \)
  limits for lower \( m_{\tilde{g}} \).
For larger $m_{\tilde{g}}$, however, all squark masses are not allowed as they may lead to unacceptably low or even unphysical values for $m_{\tilde{\nu}}$ (the bound on $m_{\tilde{l}_R}$ from LEP 1.5 should also be kept in mind; this bound of course is the same in both conventional and VLSP scenarios). For example using the limit $m_{\tilde{\nu}} > 45$ GeV, one readily obtains for $m_{\tilde{g}} = 220$ GeV, $m_{\tilde{q}} > 202$ GeV. On the other hand for $m_{\tilde{q}} \approx 216$ GeV, $m_{\tilde{\nu}} \approx M_{\tilde{\chi}^\pm}$, which in this case is $\approx 86$ GeV. Thus in the narrow but interesting range $202 \text{ GeV} \leq m_{\tilde{q}} \leq 216$, the effect of the VLSP scenario should be taken into account. Similar ranges can be obtained for higher values of $m_{\tilde{g}}$.

As has been emphasized at the beginning of this paper, the idea of a common scalar mass at the GUT scale may be subjected to revision. For example if one assumes that all the scalars have a common mass at the Planck scale [11], which certainly is reasonable, then revision of eqn 3) and 4) is called for. Within the framework of a SU(5) GUT, the $\tilde{u}_L, \tilde{d}_L, \tilde{u}_R$ and $\tilde{l}_R$ belong to the 10 of SU(5). Their masses when evolved down to the GUT scale follow a certain pattern. On the other hand $\tilde{l}_L, \tilde{\nu}$ and $\tilde{d}_R$ belong to the $\bar{5}$ of SU(5). As a result their masses evolve differently. Using eqn 9 of [11], it is straightforward to show that the modified equations are:

\[
m^2_{\tilde{q}} = m^2_0 + 8.89 m^2_{\tilde{g}} - 0.22 M^2 - 0.05 D \tag{6}
\]

\[
m^2_{\tilde{\nu}} = m^2_{\tilde{q}} - 8.89 m^2_{\tilde{g}} + 1.07 M^2 + 0.55 D \tag{7}
\]

It is now follows that more regions of the parameter space opens up for the VLSP scenario. For example, with $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 205$ GeV, $m_{\tilde{\nu}} = 61$ GeV. Thus the relaxed limit discussed above is certainly compatible to a SUGRA motivated scenario. The VLSP scenario can now be accommodated, for almost all $m_{\tilde{g}}$s within the striking range of Tevatron, for $m_{\tilde{g}} \approx m_{\tilde{q}}$. As shown above, for $m_{\tilde{g}} > m_{\tilde{q}}$, the VLSP scenario can be accommodated for a range of $m_{\tilde{q}}$.

If the GUT group is SO(10), then all squarks and sleptons belong to the 16 plet. In this case even if a common scalar mass is generated at the Planck scale, the scalars will continue to have the same mass at the GUT scale. However, when SO(10) breaks down to groups of lower rank then as discussed in [12], nonuniversality of scalar masses may arise due to D term contributions. This will always happen if some of the heavy fields which are integrated out have nonuniversal SUSY breaking masses. For example if SO(10) directly breaks down to the SM, the initial conditions for different scalar masses at $M_G$ can be parametrised as follows [12]. For the $\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{l}_R$ we have at $M_G$
\[ m_0^2 = m_{16}^2 + \delta m^2 \]  

(8)

On the other hand the common mass for the $\tilde{d}_R, \tilde{l}_L$ and $\tilde{\nu}_L$ is given by

\[ m_0^2 = m_{16}^2 - 3\delta m^2 \]  

(9)

where $m_{16}$ is the common scalar mass at $M_G$ and $\delta m^2$, the D term contribution, is essentially a free parameter. The resulting eqns for the average squark mass squared and $m_{\tilde{\nu}}^2$ are modified to

\[ m_{\tilde{q}}^2 = m_0^2 + \frac{8}{9} m_{\tilde{g}}^2 - 0.63M^2 - 0.05D - 0.2\delta m^2 \]  

(10)

and

\[ m_{\tilde{\nu}}^2 = m_0^2 - \frac{8}{9} m_{\tilde{g}}^2 + 1.15M^2 + 0.55D - 2.8\delta m^2 \]  

(11)

For $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 205$ GeV, one obtains $m_{\tilde{\nu}} \approx 50$ GeV with $\delta m^2 \approx 1900$ GeV$^2$. Thus a light sneutrino can be easily accommodated. However, for this $\delta m^2$ the $\tilde{d}_R$ type squarks become considerably lighter than the other squarks. For example the mass difference between $\tilde{u}_R$ and $\tilde{d}_R$ type squarks become $\approx 20$ GeV. Thus one may question the idea of average squark mass. Perhaps a better parametrisation in this case will be to take an average mass for $\tilde{u}_L$ $\tilde{d}_L$ and $\tilde{u}_R$ squarks and a somewhat lower mass for the $\tilde{d}_R$ squarks. Such a scenario would then naturally lead to a relatively light sneutrino. Sparticle mass limits in this scenario will indeed be interesting.

In conclusion we reiterate that if the sneutrino is indeed the second lightest SUSY particle, then the decay signatures of the squarks and the gluinos become considerably different from the conventional ones. This may relax the existing limits on $m_{\tilde{q}}$ and $m_{\tilde{g}}$ obtained in the jets + $E_T$ channel. More importantly, the light sneutrino is likely to play a more prominent role as the limits get stronger with the accumulation of data. As noted earlier [14, 15], the signal in the 2l + jets + $E_T$ channel is enhanced while the signal in the trilepton + $E_T$ channel either gets depleted or become weaker in this scenario. Such a light sneutrino arise quite naturally in various SUGRA motivated frame works.

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Table Captions

Table-I : The number of events for parameter sets i)-v) have been shown after the
cuts A - E (see text). σₚ is the production cross section of gluino and/or squark pairs,
σₑ is the signal cross section after cuts. The three numbers in column E and in the last
column correspond to 100%, 70% and 60% LDE.

Table-II : The gluino-squark pair production (σₚ) and signal cross sections (σₑ) for
parameter sets (vi) - (viii) see text are shown.

Table-III : The number of dilepton events after cuts F - I are shown for parameter
sets (i),(ii) and (ix) (see text).

2 Figure Captions

Fig. 1 The distribution of jets with the number of events. The solid(dashed) lines correspond
to the parameter set(i)((ii)).

Fig. 2 The distribution of $E_T$ of soft leptons with the number of events following the conventions
of Fig. 1.

Fig. 3 The distribution of $E_T$ with the number of events following the conventions of Fig 1.
### Table-I

| Set | $m_{\tilde{g}}$ | $m_{\tilde{q}}$ | $m_{\tilde{\phi}}$ | $m_{\tilde{\chi}}$ | A   | B   | C   | D   | E   | $\sigma_p$ | $\sigma_c$ |
|-----|-----------------|-----------------|---------------------|---------------------|-----|-----|-----|-----|-----|-------------|-------------|
| i   | 300 170         | 170 170         | 4553                | 2114                | 1969| 1541| 1284| 1361| 1387| 16.5        | 2.12        |
|     |                 |                 |                     |                     |     |     |     |     |     | 2.24        | 2.29        |
| ii  | 300 170         | 50 79           | 4824                | 1750                | 1618| 1250| 830 | 956 | 998 | 16.6        | 1.37        |
|     |                 |                 |                     |                     |     |     |     |     |     | 1.58        | 1.65        |
| iii | 300 150         | 50 79           | 3937                | 1264                | 1175| 914 | 624 | 711 | 740 | 31          | 1.93        |
|     |                 |                 |                     |                     |     |     |     |     |     | 2.20        | 2.29        |
| iv  | 300 160         | 50 79           | 4512                | 1602                | 1492| 1163| 790 | 900 | 939 | 23          | 1.87        |
|     |                 |                 |                     |                     |     |     |     |     |     | 2.07        | 2.15        |
| v   | 300 150         | 92 111          | 3742                | 1087                | 1015| 805 | 743 | 762 | 768 | 31          | 2.3         |
|     |                 |                 |                     |                     |     |     |     |     |     | 2.36        | 2.38        |

### Table-II

| Set | $m_{\tilde{g}}$ | $m_{\tilde{q}}$ | $m_{\tilde{\phi}}$ | $m_{\tilde{\chi}}$ | $\sigma_p$ | $\sigma_c$ |
|-----|-----------------|-----------------|---------------------|---------------------|-------------|-------------|
| vi  | 212 212         | 212 212         |                     |                     | 10.9        | 2.15        |
|     |                 |                 |                     |                     | 2.30        | 2.35        |
| vii | 202 202         | 50 79           |                     |                     | 15.8        | 2.24        |
|     |                 |                 |                     |                     | 2.48        | 2.57        |
| viii| 205 205         | 50 79           |                     |                     | 14.2        | 2.09        |
|     |                 |                 |                     |                     | 2.33        | 2.41        |
| Set | $m_{\tilde{g}}$ | $m_{\tilde{q}}$ | $m_{\tilde{\nu}}$ | $m_{\tilde{t}}$ | F  | G  | H  | I  |
|-----|---------------|----------------|-------------------|----------------|----|----|----|----|
| i   | 300 170       | 170 170        |                   |                | 243| 217| 190| 190|
| ii  | 300 170       | 50 79          |                   |                | 287| 253| 232| 228|
| ix  | 300 170       | 92 111         |                   |                | 27 | 21 | 19 | 19 |
Fig. 1

Number of Jets

Number of events

"CONV" Scenario

"VLSP" Scenario
Fig. 2

Number of Events / 2 GeV

"CONV" Scenario

"VLSP" Scenario

$E_T$
Fig. 3

Number of Events/5 GeV

"CONV" Scenario

"VLSP" Scenario