Four Body Decay of the Stop Squark at the Upgraded Tevatron

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Abstract

We investigate the prospect of stop squark search at Tevatron RUN-II in mSUGRA motivated as well as unconstrained supersymmetric models, when the lighter stop squark turns out to be the next lightest supersymmetric particle (NLSP). In this case the decay into a 4-body final state consisting of a b quark, the lightest neutralino and two light fermions may compete with the much publicized loop induced two body decay into a charm quark and the lightest neutralino. We systematically study the parameter space in mSUGRA where the lighter stop squark turns out to be the NLSP and calculate the branching ratios of the competing channels in both models. Our results show that the four body decay may indeed be the main discovery channel particularly in the low tan $\beta$ scenarios. We discuss the detectability of stop squark pairs in the 4-body decay channel leading to one lepton with 2 or more jets accompanied by a large amount of missing energy. We also studied the corresponding background processes and the kinematic cuts required to suppress them using parton level Monte Carlo simulations. We have commented upon with illustrative examples, the required revision of the existing mass limits of the stop NLSP assumed to decay solely into the loop induced 2-body channel in the presence of the competing 4-body decay.

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I. Introduction

The Minimal Supersymmetric Standard Model (MSSM) \[1\] is a well motivated extension of the Standard Model (SM). As of now, neither there is any evidence of it nor has it been ruled out by the electroweak precision measurements at LEP \[2\]. Unfortunately, we are not equipped with any information about the range of superparticle masses from the theoretical point of view. On the other hand, from the experimental side, there are some lower bounds from the non-observation of superparticles in colliders, such as LEP \[3\] and Tevatron RUN-I \[4\].

The up type squark of the third generation - the stop squark, the superpartner of the top quark - is something special. It is because, of the large top Yukawa coupling which controls the evolution of the soft-supersymmetry breaking masses of the left and right handed stop squarks, $\tilde{t}_L, \tilde{t}_R$, via the Renormalisation Group equations. This tends to reduce these masses, compared to the other squark masses \[5\]. Moreover, because of the large top quark mass, the two weak states $\tilde{t}_L, \tilde{t}_R$ may mix very strongly leading to a relatively large splitting between the two physical mass eigenstates $\tilde{t}_1, \tilde{t}_2$ \[6\] (in our notation $m_{\tilde{t}_2} > m_{\tilde{t}_1}$). Interestingly, the mass of the lighter states $\tilde{t}_1$ may be even below the top mass. In fact, it is quite conceivable that it happens to be the next lightest supersymmetric particle (NLSP), the lightest neutralino $\tilde{\chi}^0_1$ being the lightest supersymmetric particle (LSP) by assumption.

In the coming years the second phase of Tevatron experiments, the RUN-II, will start operating with an integrated luminosity of at least 2 fb$^{-1}$ per experiment at 2 TeV center of mass energy, which is about ten times larger than the acquired luminosity in RUN-I with center of mass energy 1.8 TeV. With a further luminosity upgrade it is expected to collect a luminosity of something like 15-20 fb$^{-1}$ after a few years of operation. The phenomenology of the stop squark could be of special interest, since it might be the only strongly interacting sparticle within the kinematic range of RUN-II experiments. It is, therefore, very important to fix up the strategies for isolating the stop signal for all conceivable decay modes.

Currently, the search for stop at LEP \[3\] and Tevatron RUN-I \[7\] experiments have yielded negative results. The most stringent bound comes from Tevatron experiments which puts a lower limit on lighter stop mass $m_{\tilde{t}_1} \geq 119$ GeV for $m_{\chi^0_1} = 40$ GeV and this limit becomes slightly weaker for higher value of $m_{\chi^0_1}$, e.g, $m_{\tilde{t}_1} \geq 102$ GeV for $m_{\chi^0_1} = 50$ GeV \[7\]. In deriving these limits, it was assumed that the loop induced, flavor changing decay into a charm quark and the LSP \[8\],

$$\tilde{t}_1 \to c\chi^0_1$$  \hspace{1cm} (1)

occurs with 100% branching ratio (BR) - until recently assumed to be a valid assumption if the $\tilde{t}_1$ state happens to be the NLSP. In the R parity conserving model, LSP cannot decay further and escapes the detector resulting a large imbalance of transverse energy. The stop signal is tagged through identifying jets and missing energy. Since the production of stop pairs is dominantly via QCD and depends on its mass only, the above limits from the Tevatron are fairly model independent, except for the dependence on $m_{\chi^0_1}$, which influences the efficiency of the kinematical cuts.
In the minimal supersymmetric extension of the standard model with arbitrary soft breaking masses of the superparticles, the stop may be the NLSP. However, the stop NLSP may also be realized in more constrained models like the minimal version of the supergravity model (mSUGRA). The latter is the most economical model in the context of supersymmetry (SUSY) searches in colliders.

In the mSUGRA model, the supersymmetry breaking takes place in hidden sector which is communicated to the visible sector by gravitational interactions. The mass spectrum of sparticles at a lower energy scale can be obtained by the Renormalisation Group equations from the inputs at some higher scale, which is usually assumed to be the Grand Unification theory (GUT) scale ($M_G$). In mSUGRA models, these input at $M_G$ are the common scalar mass ($m_0$), the common gaugino mass ($m_{1/2}$), the tri-linear scalar coupling term ($A_0$), tan $\beta$ (the ratio of two vacuum expectation values of the two higgs doublets which generate the masses of the fermions and gauge bosons through electroweak symmetry breaking) and the sign of $\mu$, (the higgsino mass parameter) [5]. The magnitude of $\mu$ is fixed by the radiative electroweak symmetry breaking condition (REWSB) [9]. Surprisingly due to the interplay of these parameters, which we will discuss later, there is a substantial region of mSUGRA parameter space where the $\tilde{t}_1$ happens to be the NLSP and sometimes the only squark within the striking range of the Tevatron.

The authors of [10, 11] have emphasized that a competing channel of $\tilde{t}_1$ decay may be there even if the stop is the NLSP. The 4-body decay of $\tilde{t}_1$ into a b quark, the LSP and two approximately massless fermions [10, 11],

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 f\bar{f}$$

via heavier SUSY particles, may also have significant decay rates, or even dominate over the loop induced decay mode, eq.1, for certain regions of the MSSM or mSUGRA parameter space. As a consequence, this 4-body decay mode along with stop pair production in colliders may yield final states containing a lepton plus jets accompanied by huge amount of missing energy [4]. This event topology appears to be indeed different in comparison to the final state resulting from the loop induced stop decay eq.1. The new observation on the 4-body decay, therefore, necessitates revision of the strategy to detect the signal of $\tilde{t}_1$ when it is the NLSP.

In the framework of most of the SUSY models, stop squarks has many interesting decay modes depending on its mass. If it is sufficiently heavy, then the main decay modes occurs through top quarks and neutralinos,

$$\tilde{t}_1 \rightarrow t\tilde{\chi}_j^0 \ (j = 1 - 4)$$

if it is kinematically allowed. There is also another competitive decay channel through charged current interactions into bottom quarks and a lighter chargino($\tilde{\chi}_1^\pm$),

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$$

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4It is to be noted that similar final states occur from the production of other SUSY particle (e.g., squarks, gluinos) and their subsequent cascade decays in colliders [4]. These signals are used in conventional SUSY searches.
If these modes are not kinematically accessible, but still $m_{\tilde{t}_1}$ heavy enough, then the 3-body decay modes to bottom quarks, a $W$ boson or a charged higgs scalar $H^\pm$ and neutralinos, $\tilde{t}_1 \rightarrow bW^+\tilde{\chi}_j^0$ or $\tilde{t}_1 \rightarrow bH^+\tilde{\chi}_j^0$ (j=1-4), can be accessible [12]. These decay channels, particularly, the $W$ boson final states may be dominant in absence of the 2-body decay channels, eq.(3,4). Beside these 3-body decay modes, in the light slepton scenario which may arise in some mSUGRA models, lighter stop can decay with a final states containing sleptons [8, 11, 13, 14],

$$\tilde{t}_1 \rightarrow b\ell\tilde{\nu} ; \tilde{t}_1 \rightarrow b\tilde{\ell}\nu$$

(5)

The search prospects of $\tilde{t}_1$ state at Tevatron experiments has been investigated by many authors [1, 13, 14, 16, 17, 18]. These studies were carried out by considering the 2-body decay mode of $\tilde{t}_1$ into a $b$ quark and a lighter chargino, eq.4, yielding a single lepton or a dilepton pair plus large amount of missing energy with some hadronic activities following the cascade decays of $\tilde{\chi}_1^+$ into a LSP and massless fermions, $\tilde{\chi}_1^+ \rightarrow \chi_1^0 f\bar{f}$. Though this final state has the same particle content as in eq.2, the kinematical characteristics are quite different in the two cases. Hence a slightly different set of kinematical cuts is needed for isolating the channel, in eq.2, from the background.

Similar studies were also carried out for the same signal with different kinematics in the light slepton scenario where $\tilde{t}_1$ decays via 3-body into a $b$ quark and a charged slepton (lepton) and neutrino (sneutrino), eq.5. The SUSY searches take a dramatic turn in the high tan $\beta$ regime where lighter staus($\tilde{\tau}_1$), the SUSY partner of tau lepton turns out to be very light, even may be the NLSP. It yields a huge number of tau leptons in the SUSY particle production and their cascade decays in colliders [19]. In Ref. [18] discovery potential of $\tilde{t}_1$ states has been studied for Tevatron RUN-II in high tan $\beta$ regime.

However, the discovery potential of $\tilde{t}_1$ of the stop NLSP decaying dominantly into the 4-body final state, especially in the context of the mSUGRA model, has not yet been studied systematically for the upgraded Tevatron. The purpose of this work is to investigate this possibility further. In our study, we concentrated on the channel with a single lepton plus 2 or more jets accompanied by large amount of missing energy. This final state appears from stop pair production following the semileptonic decay of one $\tilde{t}_1$ and hadronic decay of the other. We also discuss the possible sources of SM backgrounds and optimize the set of cuts to minimize the contamination.

Our investigation is based on models which conserves R parity. In R parity breaking models, few more channels of $\tilde{t}_1$ decay open up which depend on R parity violating couplings. The collider phenomenology of $\tilde{t}_1$ in presence of R parity breaking SUSY model will be discussed elsewhere [20].

We have organized our paper as follows. In Sec. II, we have isolated the region of the parameter space where lighter stop happens to be the NLSP in the mSUGRA model. In Sec. III, the key points of stop decay patterns have been mentioned. The parameter spaces, both in mSUGRA and MSSM, where the branching ratio of the 4-body decay is significant, are identified. In Sec. IV, we investigate the signal of $\tilde{t}_1$ in the 4-body decay channel by triggering single lepton plus jet with missing energy channel. We also estimate the corresponding SM
backgrounds after minimizing them by imposing kinematical cuts. We conclude in Sec.V with a few remarks. We have also commented on the possibility of revision in the current mass limits in the presence of the competing 4-body decay mode along with illustrative examples.

II. Stop NLSP in the mSUGRA model

In this section we focus our attention on the parameter space in the mSUGRA model where the stop is the NLSP. As discussed in the introduction the model is characterised by five free parameters: $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$ and sign($\mu$).

For a given $m_0$, $m_{1/2}$, $\tan\beta$ and sign($\mu$), the stop turns out to be the NLSP for a range of $A_0$ ($|A_{0\text{min}}| \leq |A_0| \leq |A_{0\text{max}}|$). The sign of $A_0$ is required to be the opposite to that of $\mu$ in order to produce larger mixing in the stop mass matrix. For $|A_0| \leq |A_{0\text{min}}|$ the mixing is small and the lighter stop becomes heavier than the chargino. For $|A_0| \geq |A_{0\text{max}}|$, the lighter stop becomes lighter than the lightest neutralino which is also the lightest supersymmetric particle. An additional constraint on $|A_{0\text{max}}|$ exist in principle due to the requirement that the vacuum must not break charge and color symmetry (the CCB condition) [21]. However, quite often this constraint becomes redundant in the mSUGRA model since the requirement that the stop be heavier than the LSP produces a stronger bound at least in the low $m_0$, $m_{1/2}$ scenario. Moreover the upper bound is in general unimportant for this paper, since the BR of the 4-body decay is significant only when $m_{\tilde{t}_1}$ is close to $m_{\tilde{\chi}_1^\pm}$ so that the chargino is of relatively small virtuality. This happens for $A_0$ close to $A_{0\text{min}}$.

For illustration, in Fig.1 we present the stop mass as a function of $A_0$ for different $\tan\beta$, $m_0=200$, $m_{1/2}=145$, and $\mu > 0$ (all masses and mass parameters in this paper are in GeV). Here $m_{\tilde{\chi}_1^\pm}=106$ for $\tan\beta=5$ which varies modestly with $\tan\beta$. Only those values of $A$ are considered for which the $\tilde{t}_1$ is the NLSP. As seen from the figure $|A_{0\text{max}}|$ nearly equal to 565 and $|A_{0\text{min}}|$ nearly equal to 510 for $\tan\beta=3$. For a given $A_0$, the mass of the lighter stop is larger for larger $\tan\beta$ since mixing is reduced by the $\mu$ in the stop mixing matrix.

Similar information for $m_0=140$, $m_{1/2}=180$, $\mu > 0$ is given in Fig.2. In Fig.2 we find that higher masses of the stop NLSP are allowed since here $m_{\tilde{\chi}_1^\pm}$ is somewhat larger. Here $m_{\tilde{\chi}_1^\pm}=136$ for $\tan\beta=5$ which varies modestly with $\tan\beta$.

If $m_0 >> m_{1/2}$, then $m_{\tilde{t}_1}$ tends to increase, unless $A_0$ is properly tuned so that a large mixing in the stop mass matrix still leads to a low mass stop NLSP. Beyond some large value of $m_0$ extreme fine tuning is needed which is rather unaesthetic.

On the otherhand for $m_{1/2} >> m_0$, quite often a large $A_0$ is needed to produce a stop NLSP, which is in conflict with the invariance of the vacuum under charge-color symmetry [21]. Even if the CCB condition is disregarded, we find that in a very narrow range of $A_0$ we have the stop NLSP. Otherwise a slepton NLSP scenario is obtained over most of the parameter space. Thus in this paper we shall focus our attention on scenarios with $m_0 \sim m_{1/2}$.

It is clear from Fig.1 and Fig.2 that if the BR of the loop induced decay is indeed
Figure 1: Trilinear coupling ($A_0$) vs. Masses of the stop NLSP ($m_{\tilde{t}_1}$) for $\tan\beta=3,5,7,9,11$ where $m_0=200$, $m_{1/2}=145$, and sign($\mu$)=+ve in mSUGRA model.

Figure 2: Same as in Fig.1, but for $m_0=140$, $m_{1/2}=180$, and sign($\mu$)=+ve.
100% as is normally assumed, then the limits from LEP and Tevatron are already sufficiently restrictive and can exclude a large region of the mSUGRA parameter space (in particular certain ranges of $A_0$ for given values of other mSUGRA parameters will be excluded). It is also reasonable to hope that RUN-II at a much higher luminosity will extend this probe to a much larger region of the parameter space. However, as emphasized in the introduction, the 4-body decay, eq.2, can indeed compete with the loop induced 2-body decay and reduce its BR significantly [7, 11]. This will be illustrated with several examples in the context of the mSUGRA model in the next section. The existing limits on $m_{\tilde{t}_1}$, therefore, may require a revision. **We shall try to illustrate estimate the required revision in section III.**

More importantly, when new and stronger limits come from RUN-II, the interplay of the two competing channels should be kept in mind. Such limits will depend not only on $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}^0_1}$, but also on the relative BRs of the two competing channels for stop decay and, hence, on other SUSY parameters.

### III. Stop decay branching ratios

As mentioned in Sec.I, when the $\tilde{t}_1$ is the NLSP, two decay channels are allowed which are competitive with each other - the loop induced flavor changing decay mode, eq.1 [8] and 4-body final states with nearly massless fermions, the bottom quark and the LSP, eq.2 [10, 11].

The 4-body decay mode of lighter stop, eq.2 occurs through many diagrams mediated by:

(a) $W$ and/or $H^\pm$ with virtual $t$, $b$ and $\tilde{\chi}^\pm_{1,2}$, (b) virtual $\tilde{\chi}^\pm_{1,2}$ with $\tilde{\ell}$ or $\tilde{\nu}_\ell$. The dependence of 4-body decay rates on supersymmetric parameters has been discussed in great detail in the paper of Ref. [10, 11]. Nevertheless, few comments are in order:

- Among all the diagrams, only few have significant contributions. As for example, the diagrams mediated by $H^\pm$ and $W$ are heavily suppressed because, $m_{H^\pm}$ are larger than $M_W$ and Yukawa coupling between $H^\pm$ and fermions are suppressed by respective fermion masses. In addition to these, the diagrams mediated by squarks have very little contribution as those are expected to be larger($\geq 250$) [22] than $\tilde{t}_1$ state. The top quark mediated diagrams do not give large contributions unless $m_{\tilde{t}_1} \sim m_t + m_{\tilde{\chi}^0_1}$.

- The diagrams which expected to give a significant contribution to the 4-body decay rate are mediated by charginos $\tilde{\chi}^\pm_i(i=1,2)$ and sleptons ($\tilde{\ell}$, $\tilde{\nu}_\ell$). When the virtuality between $\tilde{t}_1$ and $\tilde{\chi}^\pm_i$, $\tilde{\ell}$ or $\tilde{\nu}_\ell$ is not very large then these diagrams do give a large contributions. As for example, the diagrams involving tau sleptons which could be rather light because of mixing (especially, for high $\tan \beta$ [18]) may contribute appreciably.

In the MSSM the soft breaking parameters can be chosen arbitrarily. One can, therefore, suppress the loop decay to the extent one requires. Now if the stop is chosen to be the NLSP, the 4-body decay will automatically have a large branching ratio. For the detectable signal, which we consider, one also needs a significant leptonic BR of the stop (see section...
This can be achieved by choosing relatively light sleptons. In the following we shall illustrate this with different inputs.

What, however, is interesting is that even in a constrained model like mSUGRA, one can have a significant BR for the 4-body decay in some appropriate region of the parameter space. Moreover, a significant leptonic BR can be accommodated in a small but interesting region.

We first consider the unconstrained MSSM model. As is well-known the loop decay width is controlled by the parameter $\epsilon$ which denotes the amount of $\tilde{t}^L,R - \tilde{c}^L$ mixing and enters in the decay width formula as,

$$\Gamma(\tilde{t}_1 \to c\chi^0_1) = \frac{4}{\alpha}|\epsilon|^2 f^2 m_{\tilde{t}_1} \left(1 - \frac{m_{\chi^0_1}^2}{m_{\tilde{t}_1}^2}\right)^2$$

The detailed expressions for $\epsilon$ and the function $f$ can be found in Ref. [8, 10] and Ref. [10, 13] respectively. If the mixing angle $\theta_t$ in the stop sector is chosen appropriately so that it yields very small value of the $\epsilon$ parameter, the loop decay is reduced drastically [10, 11]. This effect is shown in Fig.3. The choice of the SUSY parameters for this figure are as follows assuming gaugino mass unification: the SU(2) gaugino mass parameter $M_2=180$, the higgsino mass parameter $\mu = +400$, $\tan\beta=4$. This three parameters completely defines the Chargino and Neutralino sector. We have taken CP-odd neutral higgs mass $M_A=150$ which requires to calculate the neutral higgs to obtain the value of the $\epsilon$ parameter. The others MSSM parameters requires for calculating the stop branching ratios are the following: the common scalar squark mass $m_{\tilde{q}}=500$, common slepton mass $m_{\tilde{\ell}}=175$, the trilinear coupling in the bottom sector $A_b=300$, the trilinear coupling in the tau sector $A_\tau=200$. With these parameters, $\cos\theta_{\tilde{t}_1}=0.11$ which leads to a very small $\epsilon$. Because of this the loop decay BR sharply falls as soon the 4-body decay is kinematically allowed. The total BR for the four body decay exceeds the loop decay BR for $m_{\tilde{t}_1} \approx 95$ and approaches 100% for slightly higher values of $m_{\tilde{t}_1}$. For our parameter set $m_{\tilde{t}_1} \approx 162$. Thus the 4-body BR can be rather large even for charginos of relatively high virtuality. We have checked that even if this smaller value of the angle $\theta_t$ is not used so that $\epsilon$ is somewhat larger, the enhancement of the 4-body decay BR, though less dramatic, still exist over a significant region of the parameter space. Moreover the leptonic BR of the stop is greater than 10%. This, as we shall see in the next section, as adequate for the detection of the 4-body decay of the stop in the channel studied by us.

We are now in a position to reexamine the possible impact of the large BR of the 4-body decay channel on the current and future limits on $m_{\tilde{t}_1}$. For the choice of parameters in Fig.3, $m_{\tilde{\chi}_1^0}=86.41$. For such a large value of the LSP mass, no limit on $m_{\tilde{t}_1}$ is currently available. However, the expected mass limits from at RUN-II needs careful handling. As we see from Fig.3 the total BR of the 4-body decay approaches 100% for $m_{\tilde{t}_1} \geq 100$. Obviously, the searches for $\tilde{t}_1$ NLSP in this mass range should be based on the 4-body decay channel.

We now turn our attention to the 4-body BR in the mSUGRA model. We present the 4-body BR as a function of $m_{\tilde{t}_1}$ (Fig. 4 and 5). The choices of SUSY parameters are as
in Fig.1 and Fig.2 respectively. In Fig.4, $m_{\tilde{\chi}_1^\pm} \approx 103$, although its precise value depends on $\tan\beta$. We find that the BR is appreciable when low values of $\tan\beta$ are considered and the virtuality of the chargino is small. This is because the loop decay rapidly increases with $\tan\beta$. Thus total 4-body BR $> 10\%$ is allowed only for $\tan\beta \lesssim 7$. Thus the phenomenology of the stop NLSP and its 4-body decay is interesting for a rather limited region of the $A_0$-$\tan\beta$ parameter space.

For the set of parameters in Fig.4, $m_{\tilde{\chi}_1^0} \approx 55$. In this scenario the current mass limit from the Tevatron based on the loop decay is $m_{\tilde{t}_1} \gtrsim 100$. However, in the $\tan\beta=3$ scenario the total BR of 4-body decay is quite sizable for $m_{\tilde{t}_1} \approx 85$. Hence masses significantly lower than 100 cannot be excluded a priori. It follows from Fig.4 that for $\tan\beta \lesssim 5$ the 4-body decay may indeed play a significant role in the discovery of $\tilde{t}_1$. In fact for the entire range $3 \lesssim \tan\beta \lesssim 5$ both the decay modes eq.(1,2) of the stop NLSP should be taken into account. Negative results from stop search on the other hand, already excludes certain ranges of the $A_0$ parameter. For example, the low BR of the 4-body decay for $\tan\beta > 5$ indicate that the current limits from Tevatron RUN-I based on the loop decay of $\tilde{t}_1$ are valid for these $\tan\beta$. Referring back to Fig.1, we find that, e.g, $A_0 \gtrsim 525$ is excluded for $\tan\beta=7$ and $m_0$, $m_{1/2}$, $\text{sign}(\mu)$ as given above. This limit is certainly stronger than the one obtained from the CCB condition or from the requirement that stop be heavier than the LSP. Moreover, the limit from the CCB condition does not hold if the SU(2)$\otimes$U(1) breaking minimum happens to be a false vacuum with a life time larger than the age of the Universe. In contrast the limits
Figure 4: The branching ratio $\text{BR}(\tilde{t}_1 \to b\tilde{\chi}^0_1 f'\bar{f})$ as a function of stop ($m_{\tilde{t}_1}$) for $\tan\beta=3,5,7,9,11$ (dashed lines) in mSUGRA model, where $m_0=200$, $m_{1/2}=145$, and sign($\mu$)=+ve. The solid line is the leptonic branching ratio for $\tan\beta=3$.

Figure 5: Same as in Fig.4, but for $m_0=140$, $m_{1/2}=180$ and sign($\mu$)=+ve.
from collider searches are free from this ambiguity. The upper limit on $A_0$ can be further strengthened from stop searches in the $\tilde{t}_1 \rightarrow b\chi^+_1$ channel.

The conclusion from Fig.5 are similar except for the fact that the allowed values of $m_{\tilde{t}_1}$ are somewhat larger in this case. From Fig.5 it follows that $\tan\beta \gtrsim 5$ the current limits from RUN-I are valid. Combining the results of Fig.2 and Fig.5 we find, e.g., $|A_0| \lesssim 600$ for $\tan\beta = 7$ violates the CDF constraint on the stop mass.

In order to get a viable signal from 4-body stop decay it is important that the BR of decays into electrons and muons be significant. This requirement further restricts the interesting region of the parameter space. For a given $m_1/2$ this BR decreases as $m_0$ is increased. This happens simply because the sleptons get heavier. Of course when $m_0$ is sufficiently large the BR becomes independent of $m_0$ since in this situation only the $W$-exchange diagram contributes. In both Fig.4 and Fig.5, we find that it is possible to obtain the leptonic BR $\geq 10\%$ for suitable choices of the SUSY parameters. This may be adequate for the detectability of the 4-body stop decays as we shall see in the next section.

IV. Stop production: Signal and Backgrounds

In hadron colliders, stop pairs are produced via gluon-gluon fusion and quark-antiquark annihilation as,

$$gg, q\bar{q} \rightarrow \tilde{t}_1^\dagger \tilde{t}_1^* \tag{7}$$

The production cross section depends only on the mass of $\tilde{t}_1$ without any dependence on the mixing angle in the stop sector, since it is a pure QCD process. The total pair production cross section at the Tevatron for $\sqrt{s} = 2$ TeV is $\simeq 15 - 0.3$ pb which is 40% larger than the cross section for $\sqrt{s} = 1.8$ TeV, for the range of $m_{\tilde{t}_1} \sim 100 - 200$. The QCD corrections enhance this cross section by $\sim 30\%$ over most of SUSY parameter space accessible at Tevatron [24].

We investigate the signal of stop pair production in the channel $\ell + \text{jets}(\geq 2) + p_T$, assuming that one stop decays leptonically and the other hadronically, i.e.,

$$\tilde{t}_1 \rightarrow b\chi^0_1 \ell \nu_\ell; \quad \tilde{t}_1^* \rightarrow b\chi^0_1 q\bar{q}', \tag{8}$$

where $q=u,d,c,s$ and $\ell = e, \mu$. The same event topology also appears from top pair production,

$$p\bar{p} \rightarrow tt; \quad t \rightarrow bqq'; \quad \tilde{t} \rightarrow bqq' \tag{9}$$

with a $\frac{1}{27}$ branching ratio suppression. Other main sources of non negligible SM backgrounds come from $W$ boson pair production accompanied by QCD jets, $p\bar{p} \rightarrow W^+W^-, W+2\text{jets}, WW\ell_j$, with one $W \rightarrow \ell \nu_\ell$ and jets coming either from the other $W$ or from QCD shower.

We have analyzed the signal and background cross section using parton level Monte Carlo simulation without taking into account the fragmentation effects of jets. In our calculation we set renormalisation and fragmentation scale, $Q^2 = \hat{s}$ and used CTEQ4M [25] for the parton distributions in proton. The energy of the visible particles in the signal, depends on $\Delta m = m_{\tilde{t}_1} - m_{\chi^0_1}$; the larger the value of $\Delta m$, the harder is the momentum of leptons and
jets in the final state and one obtains a better efficiency of the cuts. We computed the signal cross section for a wide range of $m_{\tilde{t}_1}$ values varying $m_{\tilde{\chi}^0_1}$ by fixing $r$, $r = \frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}^0_1}}$, where $r > 1$.

The cross section for the process $p\bar{p} \rightarrow W + 2$ jets has been estimated using MADGRAPH [26]. We have cross checked the cross sections with the numbers quoted in Ref. [27] and found that they are consistent within a few percent. Similarly, we also generated the process $p\bar{p} \rightarrow W W j$ using the same code.

For the selection of events, we use the following cuts for the transverse momentum $p_T$, the rapidity $\eta$ and missing energy $p_T$. The lepton or jet isolation is selected using a cut on $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$, where $\Delta \phi$ and $\Delta \eta$ are the difference of azimuthal angle and rapidity respectively, between two jets or one jet and one lepton.

1. Number of jets, $n_j \geq 2$, if they satisfy the $p_T^j > 20$, $|\eta_j| < 2.5$ with $\Delta R(j, j) > 0.7$. We require that there be at least one tagged b jet.

2. Leptons are selected, if $p_T^\ell > 10$ and $|\eta_\ell| < 2.5$ with $\Delta R(\ell, j) > 0.5$.

3. We require missing energy $p_T > 25$.

4. We require azimuthal angle between lepton and the direction of missing momentum be $45^0 < \Delta \phi(\ell, p_T) < 160^0$.

5. We demand $H_T < 120$, where $H_T = p_T^\ell + p_T$.

Here cuts (1-3) are event selection cuts where as the cuts (4-5) are for background rejection. We have imposed comparatively harder cuts on jets to minimize the background from W boson production. We have noticed that among the isolated jets, almost one is always a taggable b jet.

In Table 1, we show the response of the background processes to these cuts. In background processes, the source of lepton and invisible momentum are W decays. Since, in the $t\bar{t}$ background process, particularly, eq.9, the final state particles are expected to be more energetic relatively to the particles in the signal, the cut [5] kills the $t\bar{t}$ background by $\sim 30\%$ without much affecting the signal for $m_{\tilde{t}_1} \sim 100$. However, it is evident from Table 1, the requirement of $H_T < 120$ is not helpful to suppress the SM backgrounds from W boson production with or without jets. The signal cross section, as for example, for $m_{\tilde{t}_1} = 120$ and $m_{\tilde{\chi}^0_1} = 60$, turns out to be $0.39 \, pb$. Evidently, the level of signal cross section is much below the level of background. To reject backgrounds further, we exploited another kinematic variable, the transverse mass constructed from the transverse momentum and and missing energy [15]:

$$m_T = \sqrt{2p_T^\ell p_T(1 - \cos[\Delta \phi(\ell, p_T)] \right)}$$

Fortunately, in top and W backgrounds, the lepton and much of the invisible momentum originate from a single W decay leading to a Jacobian peak which is absent in the signal process. We studied and found that the $m_T$ distribution for the signal is highly populated.
towards lower values. Therefore, by demanding $m_T < 45$, the background cross section is reduced severely. This is reflected in Table.1, in the the last row. As for example, the most dominant background after cuts [1-5] is from $W+2$ jets. It is suppressed by one order of magnitude because of $m_T$ cuts where as $t\bar{t}$ is suppressed by a factor of $\sim 3$ with a modest loss in signal cross section. As we see from the last row, the combined background cross section turns out to be 0.22 pb leading to $\sim 440$ events per year with the expected luminosity 2 fb$^{-1}$ per year.

| Cuts             | $tt$ | $W+2$ jets | $WW$ | $WWj$ |
|------------------|------|------------|------|-------|
| [1,2]            | .82  | 11         | 1    | .13   |
| [3]              | .32  | 8          | .72  | .10   |
| [4]              | .25  | 7          | .64  | .09   |
| $m_T < 45$ GeV   | .08  | .06        | .07  | .01   |

Table 1: The Background cross sections (in pb) after implementation of kinematical cuts described in the text. Respective branching ratio suppression factors are included.

We have computed the signal cross section for some representative values of $r=2, 1.5, 1.3$. In Fig.6, we present the signal cross sections (solid lines) subject to all kinematic cuts as described above including the cut on $m_T$. The suppression due to the BR of 4-body decay is not included. This will be discussed below in the context of different models. For comparison, we also give the stop pair production cross sections (dashed lines) in the same figure. Recall that the hardness of the final state particles in the signal depends on $\Delta m$. Larger values of $\Delta m$ mean, higher value of acceptance efficiency. This explains, the rapid decrease of signal cross section as shown in Fig.6 for smaller value of $r$, say 1.3.

To convert this signal cross section into event rates, we have to multiply the signal cross sections in Fig.6 by the respective branching ratio suppression for $\tilde{t}_1$ decay, i.e by $\epsilon_{br} = 2$. $\text{Br}(\tilde{t}_1 \rightarrow b\chi^0\ell\nu_\ell)$. $\text{Br}(\tilde{t}_1 \rightarrow b\chi^0qq') (\ell = e, \mu)$. In Sec.III, we have discussed the decay rates of stop in these channels for representative values of SUSY parameters. It follows from Fig.3-5 that the value of $\epsilon_{br}$ may vary from a few percent to $\sim 20\%$. For the parameter set in Fig.3 we find that $m_{\chi^0}\approx 87$. Thus for $m_{\tilde{t}_1} = 135, r \approx 1.5$. For this $m_{\tilde{t}_1}$, $\epsilon_{br} \approx 20\%$. On the other hand from Fig.6 the corresponding signal cross-section is 0.09 pb. Putting all these together one can expect for 2 fb$^{-1}$ of integrated luminosity approximately 36 signal events (S). From Table 1 the total number of background events (B) is estimated to be 440, leading to a rather modest $S/\sqrt{B}$ ratio.

To reject the background further, we can impose an additional requirement in event selection by tagging one of the jets as a b jet. We know, the major upgradations of CDF and D0 detectors are underway. Among the improvements the capability to trigger on displaced vertices from b quark decays using a precise microvertex detector, is very encouraging. It may be possible, to achieve a sufficient b-tagging efficiency, like $\sim 50\%$ or so [3]. Therefore, exploiting this facilities we can improve $S/\sqrt{B}$ by demanding at least one b jet in signal events.
at the cost of paying a price for b-tagging efficiency in the event number. This requirement leads to suppression of the backgrounds from $W$ boson production to an enormous amount as there is no b jet in the resulting final state. However, there is a chance that an ordinary quark jet may fake as a b jet, but this probability is very very small [28]. The, requirement of at least one tagged b jet in the signal will help to get rid of the background process, except for the ones from $t\bar{t}$, which is not at a negligible level. Nevertheless we gain in $S/\sqrt{B}$ by paying a price for b-tagging efficiency by a factor of 2 in the number of signal events.

Turning to the mSUGRA parameter set in Fig.4 with $m_{\tilde{t}_1} \simeq 54$ we find that for $m_{\tilde{t}_1} \approx 100$, $r \simeq 2$. A relatively large signal cross-section as given by Fig.6 leads 100 events in spite of the suppression factor $\epsilon_{br} \simeq 20\%$, as can be read off from Fig.4 for $\tan\beta=3$. The $S/\sqrt{B}$ ratio thus obtained is quite encouraging even without b tagging. From Fig.5 it is clear that $\epsilon_{br} \simeq 20\%$ can be easily realized in the low $\tan\beta$ scenario.

We now discuss the discovery limit of $\tilde{t}_1$ in the channel considered in a fairly model independent way. We have seen above that $\epsilon_{br} \approx 20\%$ can be realised in a variety of models with $\tan\beta=3-4$ and this will be used in our analysis as a representative value. It is now easy to see from Fig.6 that for $m_{\tilde{t}_1}=120$ one ends up with $S/\sqrt{B}=4(2)$ for $r \simeq 2(1.5)$ and an integrated luminosity of 2 fb$^{-1}$. For $r \simeq 2$ the search limit can be extended to $\sim 150$ for this $\epsilon_{br}$.

The prospect looks even better for the high luminosity option with an integrated luminosity $\sim 15$ fb$^{-1}$ which is expected to accumulate after few years of running. In that option, discovery limit of $m_{\tilde{t}_1}$ might be better in the proposed channel, even for lower values of $r$ and $\epsilon_{br}$.

Before ending this section, we note that there is a possibility of detecting the 4-body decay of $\tilde{t}_1$ through the jet plus missing energy channel with or without b-tagging. This final state occurs in stop pair production when both the stops decay hadronically, eq. 2. This channel looks promising since the corresponding suppression factor $\epsilon_{br}$ is rather mild. However in considering this channel, one has to worry about the huge QCD background. Nevertheless, it is worthwhile to examine the observability of $\tilde{t}_1$ in this channel. We have not discussed this in our present analysis as it is beyond the scope of parton level calculations.

V. Conclusions

In conclusion we reiterate that the 4-body decay of $\tilde{t}_1$ may indeed play an important role in stop searches at the upgraded Tevatron if it happens to be the NLSP. Especially for low values of $\tan\beta (=3 - 4)$ this may be the main discovery channel.

We have delineated the mSUGRA parameter space where the $\tilde{t}_1$ is the NLSP. For a given $m_0$, $m_{1/2}$, $\tan\beta$, sign($\mu$), a range of values of the trilinear coupling $A_0$ yields a stop NLSP.

We have studied the BR of the four body decay of $\tilde{t}_1$ in both mSUGRA and MSSM models. We found it to be numerically significant and sometimes even the dominant decay mode in a large region of parameter space with low $\tan\beta$ ($3 \lesssim \tan\beta \lesssim 5$). Here the much studied loop induced 2-body decay of $\tilde{t}_1$ is suppressed (Fig.3-5). The 4-body leptonic BR of
Figure 6: Cross sections(pb) for stop pair production(dashed line) and signal cross section(solid lines) subject to all kinematical cuts, including cut on $m_T$, for some representative values of $r$, where $r = \frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_0^1}}$. Here the branching ratio suppression due to the stop decays is not included.

$\tilde{t}_1$ which is an essential ingredient of stop search in the channel proposed by us is also found to be appreciable.

In view of the 4-body decay the current limits on $m_{\tilde{t}_1}$ from Tevatron RUN-I based on the assumption that the loop induced decay of $\tilde{t}_1$ occurs with 100% BR, needs revision and becomes somewhat model dependent. It follows from Fig.4 that the current limit $m_{\tilde{t}_1} \geq 102$ for $m_{\tilde{\chi}_0^1}=50$ will be significantly relaxed for $\tan \beta \approx 3$, since the corresponding BR of the loop induced decay is indeed small. For $3 \leq \tan \beta \leq 5$, the 4-body decay is likely to have nontrivial impact on stop searches at the upgraded Tevatron. For $\tan \beta \approx 5$ the loop decay practically overwhelms the 4-body decay. For such values of $\tan \beta$ the curent limits from Tevatron RUN-I are valid and strong upper limits on $|A_0|$ can be placed in mSUGRA models for a given set of SUSY parameters as is clearly seen from Fig.1 and 2. These limits are more restrictive than the ones obtained from the CCB condition or from the requirement that $\tilde{\chi}_1^0$ be the LSP. Thus while the constraint on the $m_0-m_{1/2}$ plane from squark-gluino searches [4] is fairly independent of $A_0$, this parameter can be strongly constrained from the negative result of stop search for each allowed $m_0-m_{1/2}$ pair.

We studied the viability of discovering the stop in the leptons+jets+$E_T$ channel which arise when one of the stops decays leptonically and the other decays hadronically via the 4-body mode. We have listed the Standard Model backgrounds and the kinematical cuts (see the Table) to suppress them. This discovery limits sensitively depends on $\epsilon_{\tilde{t}e}$ which
are model dependent in general and on \( r \). Our studies of the BR in a variety of models in Sec.III indicate that \( \epsilon_{br} \approx 20\% \) is a fairly representative choice. Armed with this information we have estimated the discovery limit to be \( m_{\tilde{t}_1} = 120(150) \) for \( r = 1.5(2) \) for an integrated luminosity \( 2 \text{ fb}^{-1} \) without requiring b-tagging. We have discussed qualitatively how the search prospect improves if b-tagging and higher accumulated luminosity after the proposed luminosity upgrade are available. The possibility of stop search in the jets+ \( E_T \) channel which has a less severe branching ratio suppression(\( \epsilon_{br} \)) is also discussed.

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