DETECTING TOP SQUARKS AT THE TEVATRON

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ABSTRACT

We study the signal from the pair production of \(t\)-squarks at the Tevatron under the assumption that their two-body decay to charginos as well as their three-body decay to \(W\) bosons is kinematically forbidden. In this case, the stop dominantly decays via \(\tilde{t}_1 \rightarrow c \tilde{Z}_1\), so that the signal consists of two charm jets together with \(E_T\). We reevaluate this signal using ISAJET 7.01, and show that if the stop mass is below about 100 GeV, there should be as many as 50-70 events in the accumulated data sample of the CDF and D0 experiments even if the LSP is as heavy as 50 GeV. We have also studied the possibility of tagging the \(c\)-jet by its semileptonic \(\mu\) decay, but find that the event rates are too small for this to be viable except for values of stop and LSP masses that yield a robust signal via the conventional \(E_T\) search.

1. Introduction

The spectacular success of the recent Tevatron runs has enabled experimentalists to search for signals from a variety of extensions of the Standard Model (SM) including new gauge bosons, compositeness, exotic quarks, leptoquarks and, of primary interest to us, supersymmetric particles. The CDF Collaboration\(^[3]\), based on an analysis of 4.3 \(pb^{-1}\) of data have published limits of around 100 GeV (160 GeV if \(m_\tilde{q} = m_\tilde{g}\)) on the masses of squarks and gluinos of the minimal supersymmetric model (MSSM). By now, the D0 and CDF experiments at the Fermilab Tevatron have, between them, accumulated an integrated luminosity of almost 40 \(pb^{-1}\)\(^[2]\), and are expected to collect a data sample in excess of 100 \(pb^{-1}\) by the end of the current run. It is, therefore, reasonable to ask whether the large anticipated data sample opens up the possibility of detecting other sparticles at the Tevatron.

It has recently been pointed out\(^[3]\) that the multilepton signals from the cascade decays of gluinos and squarks, which provide indirect evidence for the existence of charginos(\(\tilde{W}_i\)) and neutralinos(\(\tilde{Z}_i\)), should make it possible to extend the Tevatron
search for gluinos and squarks to 250-300 GeV for the favourable case \( m_{\tilde{q}} \approx m_{\tilde{g}} \). It has also been shown\[1, 2\] that with an accumulated data sample of about 100 \( pb^{-1} \), the trilepton signal from the continuum \( \tilde{W}_1 \tilde{Z}_2 \) production\[3\] would enable the CDF and D0 experiments to extend the direct search for charginos and neutralinos to regions of MSSM parameter space beyond the range of LEP experiments. Continuing our study of other SUSY signals that may be accessible at the Tevatron, we focus here on the strategies for detection of the \( t \)-squark which can be considerably lighter\[4\] than all the other squarks even in supergravity models where all the sfermions have a common mass at an ultrahigh energy unification scale.

2. Why is the top squark different?

Supersymmetry must be a broken symmetry. Since the dynamics of SUSY breaking is as yet unknown, the breaking of supersymmetry is parametrized by a rather large number of soft SUSY-breaking parameters constrained only by SM gauge invariance. The proliferation of parameters can be reduced by making further assumptions about the symmetries of the dynamics of SUSY breaking. Within the simplest supergravity GUTS\[5\], SUSY breaking can be parametrized by a common scalar mass, a common gaugino mass together with a susy-breaking trilinear scalar coupling at unification scale. These masses and couplings are then evolved down to the weak scale, leading to the familiar relation “GUT relation” between the three gaugino masses. Since the first two generations of squarks and sleptons dominantly interact via gauge interactions, their masses evolve in the same way. As a result, these squarks (sleptons) are essentially degenerate, with squarks heavier than sleptons on account of their QCD interactions.

The masses of third generation squarks (\( \tilde{t}_L, \tilde{t}_R \) and \( \tilde{b}_L \)) are not expected to conform to these simple patterns because of their large Yukawa interactions. These reduce the diagonal masses in comparison to those of the other squarks, in much the same way that they drive a Higgs scalar mass squared to negative values, resulting in the radiative breaking\[8\] of electroweak symmetry. Furthermore, the Yukawa interactions also induce \( f_L-f_R \) mixing terms proportional to the corresponding fermion mass, and so, are most important for the \( t \)-squarks. These off-diagonal terms in the \( t \)-squark mass matrix split the top squark masses, reducing the mass of the lighter stop (\( \tilde{t}_1 \)) state even further. In fact, \( m_{\tilde{t}_1} \) may be as light as 50 GeV even if the other squarks and gluinos have masses of several hundred GeV. This led a group of us\[9\] to study the phenomenology of a light \( \tilde{t}_1 \) and its effect on the CDF top quark search at the Tevatron. It had been concluded that a \( \tilde{t}_1 \) with a mass just beyond the LEP limit could well have escaped detection in the analysis of the 1991 data sample. In this study we improve on this parton level study and reevaluate the stop signal using ISAJET 7.01/ISASUSY 1.0\[10\] with a view to assess the prospects for stop detection during the current Tevatron run.

3. Top-squark decay patterns.
The decay patterns of the top squark have been discussed at length in Ref. [9] and will only be briefly reviewed here. If $\tilde{t}_1$ is heavier than the the chargino, the tree-level two-body decay $\tilde{t}_1 \rightarrow b\tilde{W}^+_1$ dominates; in this case, stop pair production is signalled by $n-\text{leptons}+m-jet$ events ($n = 1$ or $2$) so that top quark pair production (whose cross section is an order of magnitude larger) is a formidable background. If $m_{\tilde{W}^+_1} + m_b \geq m_{\tilde{t}}_1 \geq M_W + m_b + m_{\tilde{Z}^0}$, the decay $\tilde{t}_1 \rightarrow bW\tilde{Z}^0_1$ dominates, and the situation is similar to that above. If this decay is kinematically forbidden (as is the case for stops in the mass range of interest), and the charginos as well as the sneutrinos are heavier than $\tilde{t}^+_1$, the flavour changing one loop decay $\tilde{t}_1 \rightarrow c\tilde{Z}^-_1$ dominates[11, 9] the tree level four-body decays of the stop. In the remainder of our analysis, we assume that the branching fraction for this two body loop decay is 100%.

4. Stop signals at the Tevatron.

Although $t$-squark production is not yet included in ISAJET, we can simulate the signals for stop pair production by generating $\tilde{b}_R$-pair events (which have the same production cross section as stop pairs) and using the FORCE command to decay the $\tilde{b}_R$ into a $c$-quark and an LSP. In our computation, we have used the set I structure functions of Eichten et. al. [12]. The production cross section is about twice as large as shown in Ref. [9]. This is partly due to a difference in structure functions, but, more importantly, due to a difference in the scale used in the evaluation of $\alpha_s$. Initial and final state parton showers, charm quark fragmentation and decay and the underlying event structure are also incorporated. Aside from QCD radiation, the stop signal then consists of two $c$ jets together with $E_T$ from the escaping LSP’s, and without $c$ tagging, is identical to the signals from squark production, where the squark directly decays to the LSP.

We have modelled the experimental conditions at the Tevatron by incorporating a toy calorimeter with segmentation $\Delta\eta \times \Delta\phi = 0.1 \times 0.09$ and extending to $|\eta| = 4$ into our simulation. We have assumed an energy resolution of $70/\sqrt{E_T}$ (15%/\sqrt{E_T}) for the hadronic (electromagnetic) calorimeter. Jets are defined to be hadron clusters with $E_T > 15$ GeV in a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$. We have also incorporated the following cuts and triggers:

(i) We require that the jets lie within $|\eta_j| \leq 3.5$. All jets are required to be separated by at least $30^\circ$ in azimuth from $E_T$.

(ii) We require $n_j \geq 2$, with at least one jet within $|\eta_j| \leq 1$.

(iii) If $n_j = 2$, we further require $\Delta\phi(j_1,j_2) \leq 150^\circ$.

(iv) We veto events containing leptons (from the $c$-jet) with $p_T(l) \geq 20$ GeV to reduce the background from $W \rightarrow l\nu$ ($l = e$ or $\mu$).

(v) We have required $E_T \geq 50$ GeV [1] to reduce backgrounds from QCD heavy flavours and mismeasured jets.

Aside from heavy flavour QCD and jet mismeasurement backgrounds, SM sources of $n \geq 2$ jets + $E_T$ events include, (a) $Z \rightarrow \nu\bar{\nu}$ production, (b) $W \rightarrow \tau\nu$ production (where the hadronically decaying $\tau$ is assumed to be one of the jets), and
(c) $W \to l \nu$ ($l = e$ or $\mu$), where the jets are due to initial state QCD radiation. We have not attempted to quantify the QCD backgrounds which are expected to be detector-dependent, but have been guided in our thinking by earlier experimental analyses[1] which suggest that the $Z$ and $W$ backgrounds just mentioned are indeed the dominant SM sources of these jet events with $E_T \geq 50$ GeV.

The $E_T$ distributions from the SM backgrounds (a-c) is shown in Fig. 1 along with the corresponding distribution from stop pair production for two representative choices of parameters where the stop decays via $\tilde{t}_1 \to c \tilde{Z}_1$: (A) $m_{\tilde{t}_1} = 85$ GeV, $m_{\tilde{Z}_1} = 20$ GeV, and (B) $m_{\tilde{t}_1} = 125$ GeV, $m_{\tilde{Z}_1} = 40$ GeV. The distributions shown here are before any cuts have been applied. We see that the $E_T$ cut (v) designed for reducing the QCD backgrounds also served to remove much of the $W$ and $Z$ backgrounds.

We have studied several distributions that might help to further distinguish the stop signal from background. The $p_T$ distribution of the fastest jet in the signal events for the two cases introduced above, as well as for the SM backgrounds (a-c) after the cuts (i-v) is shown in Fig. 2. As expected, the fast jets from the three background sources (which arise from QCD radiation) are softer than the corresponding jets from the signal – but for the $E_T$ requirement, the background distribution would have been backed up against the $p_{T_{min}}(j)$ cut of 15 GeV. In contrast, we see that the bulk of the signal events include a jet with $p_T \geq 50$ GeV even for the lighter stop case in the figure.

The azimuthal separation between the $\vec{E}_T$ and the nearest jet is shown in Fig. 3 for the stop signals and the $W$ and $Z$ backgrounds discussed above. We see that
Figure 2: The normalized $p_T(fast-jet)$ distribution from top squark pair production and related backgrounds at the Tevatron collider, after cuts discussed in the text.

the signal distribution is approximately flat as may be expected from the fact that $\vec{E}_T$ is made up of two independently produced LSPs. In contrast, since the jets in the background are recoiling against the produced $W$ or $Z$, the distribution tends to peak at large angular separation. We see that requiring $\Delta \phi \leq 90^\circ$ significantly increases the signal to background ratio.

Shown in Fig. 4 are contours of fixed signal cross sections in the $m_{\tilde{t}_1} - m_{\text{LSP}}$ plane including the cuts (i-v) together with (a) $\Delta \phi(j,\vec{E}_T) \leq 90^\circ$, and (b) if $\Delta \phi(j,\vec{E}_T) \leq 90^\circ$, $p_T(j_{\text{fast}}) \geq 50$ GeV; $p_T(j_{\text{fast}}) \geq 80$ GeV otherwise. The cuts in Fig. 4b retain more of the signal for heavier stops without letting in background events. Also shown on the figure are the background levels expected from $W$ and $Z$ events at the Tevatron.

Several comments are worthy of note:
(i) The $W \rightarrow \tau$ background shown in the figure assumes that the $\tau$, if it decays hadronically, can give rise to one of the two jets. Since $\tau$ jets almost always have a charged multiplicity of 1 or 3, we believe that it should be possible to discriminate these from the signal jets with high efficiency. Our purpose in showing these cross sections is to allow the reader to assess the $\tau - jet$ discrimination that is necessary to be able to see the $t$-squark signal. We see that a discrimination of 1:10 is ample for this purpose.

(ii) The background from $Z \rightarrow \nu \bar{\nu}$ production can be subtracted since it should be possible to directly measure high $p_T$ $Z$ decays to leptons and use the branching ratios measured at LEP.

(iii) The cross section (after cuts) for a stop with a mass of up to 100 GeV exceeds 2 pb for an LSP as heavy as 50 GeV. Thus in excess 50-70 stop events may already be
Figure 3: The azimuthal angle separation between $\vec{E}_T$ and closest jet from top squark pair production and from SM background processes at the Tevatron collider, after cuts.

present in the collective data sample of the CDF and D0 experiments; the corresponding background from $Z + jets$ production yields a comparable number of events. If heavy flavour and QCD backgrounds are indeed negligible, this would correspond to a 6-7$\sigma$ effect. This conclusion should, however, be viewed in proper perspective since we have not included any non-physics backgrounds in our analysis.

(iv) It is interesting to see that we find an observable signal even when the LSP is relatively heavy. This differs significantly from the conclusion of the parton level calculation of Ref.[9] where it was concluded that the signal would be unobservable for LSP masses much larger than 20 GeV. This conclusion was traced to the fact that for large values of $m_{\tilde{Z}_1}$, the two LSPs soaked up much of the energy so that the charm partons became too soft to pass the cuts. In our present calculation, the $\tilde{t}_1\bar{t}_1$ pair can be produced with substantial $p_T(\tilde{t}_1\bar{t}_1)$; the resulting final state charm jets can hence have substantial $p_T$ even if $m_{\tilde{Z}_1}$ is large.

Up to this point, we have made no use of the fact that the signal always contains $c$-quark jets. It is clear that SM backgrounds would be considerably reduced if it were to be possible to tag at least one of the $c$-quarks. This led us to consider the possibility of using a muon from the semi-leptonic decay of one of the $c$ quarks as a tag. The signal would then consist of $\mu + n_j \geq 2 + E_T \geq 50$ GeV, where the muon is within a cone of $\Delta R = 0.4$ about one of the jets. We require that $p_T(\mu) \geq 3$ GeV for the muon to be identifiable. We further require that either $\Delta \phi(j, E_T) \leq 90^\circ$ or $p_T(j_{fast}) \geq 50$ GeV. The signal cross section contours, with these cuts, are shown in Fig. 5 together with our background estimates from $W \rightarrow \tau\nu \rightarrow \mu\nu\nu\nu, W \rightarrow \mu\nu$
Figure 4: Contour plots in (pb) of top squark signal cross-sections after cuts, and associated background rates.
and $Z \rightarrow \nu \bar{\nu} + c\bar{c}$ or $b\bar{b}$ processes. To estimate these, we have generated 140K (130K) $W$ ($Z$) events of each type, and find 8,5 and 6 events, respectively, pass our cuts. It should be kept in mind that ISAJET does not include the full $2 \rightarrow 3$ matrix elements for $Zc\bar{c}$ or $Zb\bar{b}$ production; in our simulation, these events come from radiation of initial state gluons followed by splitting into $b\bar{b}$ or $c\bar{c}$ pairs.

Our conclusions from Fig. 5 are pessimistic. Even with an integrated luminosity of 100 $pb^{-1}$, there are just 5-10 tagged signal events for $m_{\tilde{t}}$ and $m_{\tilde{Z}}$ values where the $E_T$ signal in Fig. 4 might be difficult to observe above the $Z \rightarrow \nu \bar{\nu}$ background. Since the sum of SM backgrounds to the signal have comparable cross sections, we believe that it will be difficult to distinguish the stop signal over statistical fluctuations of the backgrounds. We further observe that the 0.2 $pb$ (this is the sum total of the three backgrounds) contour in Fig. 5 roughly tracks the contour with a cross section roughly equal to that from the $Z$ background in Fig. 4. We, therefore, infer that the use of muon tagging to extend the region where the stop signal might be observable in the $E_T$ sample even with several hundred $pb^{-1}$ of integrated luminosity does not appear viable. Observation of tagged $E_T$ events would, however, be important since it indicates that the signal might be due to the production of $\tilde{b}, \tilde{c}$ or, of course, $\tilde{t}$ squarks. We also remark that it would be worth investigating whether vertex tagging can be used to tag the charm jets in stop pair events to increase the signal to background.

5. Summary and outlook

Motivated by the fact that the $t$-squark may be considerably lighter than other squarks, we have reinvestigated its signals at the Fermilab Tevatron using
ISAJET 7.01 under the assumption that it decays via $\tilde{t}_1 \rightarrow c \tilde{Z}_1$. We have shown that in the $E_T$ data sample that has already been accumulated by the CDF and D0 experiments, there may well be 50-100, or more, stop events that should, after suitable cuts, be identifiable above $W$ and $Z$ backgrounds (these have previously been shown to dominate those from QCD) even if the LSP is relatively heavy (see Fig. 4). We also studied the possibility of tagging the charm jet via its semi-leptonic decay. While this led to an observable rate for stop events for values of parameters where the signal was observable by the conventional $E_T$ search (this would, within the MSSM context, indicate the production of a $c$-, $b$- or $t$-squark), the tagged signal (see Fig. 5) was found to be too small for larger values of stop and LSP masses.

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