Search for SUSY signatures in the Dilepton Channel at CDF

Abstract

One of the best channels for direct Supersymmetry searches is the dilepton channel (two high-p_T leptons + $\not\!\!E_T$). Many of the present limits for SUSY have been set at Run I of CDF. Run II will present further opportunities for either discovery of SUSY particles or setting better limits. Presented here are outlines of some of the more promising signatures in this channel: stop quark decay into dileptons and chargino/neutralino decay into dileptons. Also presented is a model that may help explain a softness in lepton p_T in the top dilepton sample at Run II of CDF using SUSY.

1 Introduction

Supersymmetric theories have long provided a theoretical framework which can overcome many of the shortfalls of the Standard Model. The major shortfall of Supersymmetry (SUSY), however, has been a complete lack of direct experimental measurements, to date. Many of the present limits for SUSY particles have been set by the CDF experiment, which looks at $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The CDF detector is further described here []. Many SUSY particle decay chains end in leptons. Since lepton events are relatively rare at hadron colliders, lepton signatures are a favorable channel in which to look for new phenomena.

The dilepton sample is also an interesting sample to search for new phenomena due to several curiosities. First, there is the number of events that was observed in the top dilepton sample at CDF during Run I. The predicted number of $t\bar{t}$ events in the dilepton channel

Selection	Expected	Observed
All	5.3	9
Lepton $E_T > 100$ GeV	1.1	2
$\not\!\!E_T > 100$ GeV	0.8	3

Table 1: Expected rates of dilepton $t\bar{t}$ production versus observed rates

in 110 pb^{-1} of data is 5.3 based on the measured cross-section of 6.5 pb (for the nominal theoretical cross-section of 4.7 pb the expected rate is 3.8). Also, for a top mass of 174 GeV, approximately 20 % of dilepton events from $t\bar{t}$ are expected to have a lepton with $E_T >$ 100 GeV and 15% are expected to have $\not{E}_T >$ 100 GeV. While within present statistical errors, these predicted values do vary from what was actually observed in Run I (Table 1). In fact, of the five events that were observed with $E_T >$ 100 GeV or $\not{E}_T >$ 100 GeV, only two are kinematically consistent with coming from a 174 GeV top quark. Second, there is the recently (Winter 2003) measured p_T distribution for leptons in the top dilepton candidate sample. This issue will be further discussed in Section 4. For all of the scenarios discussed, only R-parity conserving SUSY models will be considered.

2 Stop Squark Signals in the Dilepton Channel

2.1 Production and Decay

The large Yukawa coupling of the top quark (due to its high mass) has the consequence that its supersymmetric partner, the stop quark, could be the lightest of the SUSY quarks. From an experimental point of view, writing the SUSY Lagrangian in terms of mass eigenstates rather than the more customary weak eigenstates ($\tilde{t}_L$ and $\tilde{t}_R$) is useful. A compact form of the SUSY Lagrangian containing all quadratic terms with two stops is:

$$\mathcal{L}_{\tilde{t}} = -\Psi^\dagger {\mathbf{M_{stop}}}^2 \Psi \tag{1}$$

where the vector $\Psi \equiv (\tilde{t}_R, \tilde{t}_L)$ and $\mathbf{M_{stop}}$ is the mixing matrix, which is given by:

$${\mathbf{M_{stop}}}^2 = \begin{pmatrix} m^2_{\tilde{t}_L} + m^2_t + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta m^2_Z & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta & m^2_{\tilde{t}_R} + m^2_t + \frac{2}{3}\sin^2\theta_W \cos 2\beta m^2_Z \end{pmatrix} \tag{2}$$

It is useful to know the possible mass ranges of the stop for its search. In the framework of mSUGRA (minimal Supergravity), we can calculate the parameters of (2) at the EWK scale and then diagonalize (2). Given the large top quark mass ($m_t \sim 175$ GeV) the $\tilde{t}_L$ and $\tilde{t}_R$ mixing leads to significant mass splitting between the two mass states ($\tilde{t}_1, \tilde{t}_2$), allowing us to consider $\tilde{t}_1$ as being the lightest squark and thus the one upon which experimental searches at CDF will focus on. From hereon, $\tilde{t}_1$ will be referred to as $\tilde{t}$.

Leading order calculations for the production cross sections of $\tilde{t}\bar{\tilde{t}}$ via $q\bar{q}$ annihilation and gluon-gluon fusion are given by:

$$\sigma_{LO}(q\bar{q} \to \tilde{t}\bar{\tilde{t}}) = \frac{\alpha_s^2 \pi}{s}\frac{2}{27}\beta_1^3 \tag{3}$$

$$\sigma_{LO}(gg \to \tilde{t}\bar{\tilde{t}}) = \frac{\alpha_s^2 \pi}{s}\beta_1\left(\frac{5}{48} + \frac{31 m^2_{\tilde{t}}}{24 s}\right) + \frac{\alpha_s^2 \pi}{s}\left(\frac{2m^2_{\tilde{t}}}{3s} + \frac{m^4_{\tilde{t}}}{6s^2}\right)\log\left(\frac{1-\beta_1}{1+\beta_1}\right) \tag{4}$$

Since elementary particles (such as quarks or gluons) are not what are collided at hadron colliders, (3) does not give a complete picture of the production cross-section. Instead, the parton distribution functions of the proton and anti-proton must be taken into account. As a result, cross section falls exponentially with the stop mass. In the mass region of interest to this search ($m_{\tilde{t}} = 80 - 140$ GeV), the cross section drops from 44 pb to 1 pb. The lower limit for this region of interest is set by limits established at LEP II.

Assuming R-parity conserving SUSY insures the stability of the lightest supersymmetric particle (LSP). As a result, all supersymmetric particles will eventually decay into the LSP which is undetectable and thus shows up as $\not{E}_T$ in the detector. The $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ (analogous to the top quark decay $t \to Wb$) has only a small search window remaining at the Tevatron due to the high $\tilde{\chi}_1^{\pm}$ mass limit from LEP2. Other possible decay modes are the flavor-changing $\tilde{t} \to c\tilde{\chi}^0$, which is highly suppressed, and the 3-body decay of $\tilde{t} \to \tilde{l}\nu b$, which is mostly closed due to the slepton mass limit placed by LEP2. A fourth decay mode of $\tilde{t} \to l\tilde{\nu}b$ still remains open due to the present sneutrino mass limit of $m_{\tilde{\nu}} \geq 45$ GeV. The sneutrino is expected to decay to e, μ and τ with equal branching ratios. This decay mode will yield two opposite sign leptons, and two hadronic jets (from the b-quarks) and a considerable amount of $\not{E}_T$—a signal basically identical to that of dileptonic top quark decay.

2.2 Backgrounds

Again, a compelling reason to use the dilepton channel for SUSY searches is their relatively low SM backgrounds:

- $t\bar{t}$: $t\bar{t}$ decays can yield leptons from W and/or b decays. The branching ratio for this process is very small (indeed, the BR of top pairs decaying to dileptons is 5%). Isolation cuts can also help suppress this background.

- Heavy-flavor ($b\bar{b}$ and $c\bar{c}$) with semi-leptonic decay: While the branching ratio for these processes is low, the high rate of heavy-flavor production at CDF is very high. Isolation cuts can help reduce this background as well.

- Drell-Yan production: Higher order processes can contribute hadronic jets to create a dilepton signal. This background is fairly well studied as it is a primary source of background for the top-dilepton analysis.

- Diboson (WW, WZ, and ZZ) production: Reconstructing mass of the leptons to the boson mass can help identify this background. Also, for any decay involving a Z, two leptons will always reconstruct to the Z mass, thus, a specific mass window corresponding to the Z is removed from the sample.

- Vector boson decay (such as J/ψ and Υ) to leptons: Again, reconstruction of these resonances can help identify them and specific windows are removed to help eliminate the background.

- Fake/misidentified leptons.

2.3 Cuts

The dilepton cuts used in the stop search are as follows:

- At least one "tight" electron or muon: E_T (or p_T for muon) ≥ 10 GeV and $|\eta| \leq 1.0$

- A second"tight" electron or muon, or, a "loose" electron or muon: E_T (or p_T for muon) ≥ 6 GeV and $|\eta| \leq 1.0$
- Lepton isolation: total p_T of all tracks around the lepton within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$ should not exceed 4 GeV.
- At least one jet with $|\eta| \leq 1.0$ and $E_T \geq 15$ GeV
- Jets must be separated by $\Delta R \geq 0.7$ from both leptons.
- Require $m_{ll} \geq 12$ GeV to eliminate sequential B, J/ψ and Υ decays.
- Exclude leptons events of $76 < m_{ll} < 106$ GeV to eliminate Z events
- require $\not{E}_T \geq 15$ GeV
- Azimuthal angle separation: $\Delta\phi(l_1, \not{E}_T), \Delta\phi(l_2, \not{E}_T), \Delta\phi((l_1, l_2), \not{E}_T) > 30^\circ$ to eliminate Drell-Yan τ decays.

After the above cuts are used, the remaining SM background is almost entirely $t\bar{t}$. In the case of top decay, the leptons come from W decay and are thus very energetic. In the case of stop decay, the available energy in the decay depends on the difference in mass of the stop and the sneutrino, or, $\Delta m_{\tilde{t}-\tilde{\nu}}$. The possible signal regions are separated into small $\Delta m_{\tilde{t}-\tilde{\nu}}$ and large $\Delta m_{\tilde{t}-\tilde{\nu}}$.

For small $\Delta m_{\tilde{t}-\tilde{\nu}}$, the leptons and jets are soft. The energy that escapes detections is quite large, but since the sneutrinos should tend to be back-to-back, the measured $\not{E}_T$ is effectively reduced. Thus, we require the dilepton p_T, $p_T^{l_1,l_2} \leq 30$ GeV and $E_{T,\mathrm{jet}} + \not{E}_T \leq 160$ GeV, where $E_{T,\mathrm{jet}}$ is the transverse energy of the most energetic jet.

For large $\Delta m_{\tilde{t}-\tilde{\nu}}$, the leptons should be more energetic, so we require $p_T^{l_1,l_2} \leq 55$ GeV while requiring the same jet E_T and $\not{E}_T$ cut.

2.4 Results

A summary of events that pass each cut is shown in Table 2. Since no events were observed, we can place a 95% C.L. limit on the mass of the stop quark of $m_{\tilde{t}} \geq 135$ GeV. A plot showing the stop and sneutrino mass plane and regions that have been excluded is shown in Figure

3 Chargino/Neutralino to Trilepton

Another promising SUSY channel to search for in the dilepton sample is a chargino ($\tilde{\chi}_1^\pm$) and neutralino ($\tilde{\chi}_2^0$) decay to three leptons and missing energy. The specific decay chain considered in this search is:

$$\begin{aligned} \tilde{\chi}_1^\pm &\rightarrow l\nu_l\chi_1^0 \\ \tilde{\chi}_2^0 &\rightarrow l\bar{l}\chi_1^0 \\ \tilde{\chi}_2^0 &\rightarrow \tilde{l}_R l \end{aligned}$$

Figure 1: Stop and neutrino mass plane showing 1σ regions excluded by CDF and D0 Run I and LEP II

Selection	Data	Background	A	B
Initial cuts	176	155.3 ± 50.2	23.6 ± 8.9	34.5 ± 13.0
opp. sign & $\not\!\!E_T$	26	28.7 ± 8.6	12.9 ± 4.8	25.1 ± 9.5
$\Delta\phi(l_1, \not\!\!E_T), \Delta\phi(l_2, \not\!\!E_T), \Delta\phi((l_1, l_2)$	4	8.1 ± 2.4	6.7 ± 2.5	14.8 ± 5.6
small $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	1.5 ± 0.5	5.7 ± 2.1	-
large $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	2.1 ± 0.5	-	8.2 ± 3.1

Table 2: Summary of events that pass each cut in data, expected background, and expected stop signals. "A" represents a small $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}} = 100, m_{\tilde{\nu}} = 75$ GeV. "B" represents a large $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}} = 120, m_{\tilde{\nu}} = 60$ GeV.

The result would be the famous "trilepton" signature of three isolated leptons and $\not\!\!E_T$. The $\tilde{\chi}_1^0$ is the LSP which would escape the detector undetected. Since the neutral particles do not come in the same direction, the $\not\!\!E_T$ spectrum is broad.

3.1 Backgrounds and Cuts

The backgrounds and cuts for this search are very similar to those in the stop quark search in the dilepton channel. The presence of large $\not\!\!E_T$ in this signature makes it relatively easy to eliminate the larges background, Drell-Yan processes, which do not have significant $\not\!\!E_T$. The signature for trileptons does not suffer from irreducible SM backgrounds. is even "cleaner" than that for other SUSY signatures in the dilepton sample

3.2 Clean-Up/Further Cuts

For the Run II analysis (which does not have blessed results yet), a further set of cuts are madeaAfter selecting events that pass a basic dilepton trigger cut (as described in section 2) to further clean up the sample. The desire to have further "clean-up" cuts was motivated by the lessons learned in Run I and are based off of a 100k monte carlo sample. (Table 3).

Cut variable	value	data (%)	SUSY (%)
n leptons	3	66.4	79.4
Distance in z to hardest lepton	≤ 5 cm	30.0	70.1
First lepton	p_T (if μ) or E_T (if e) ≥ 12 GeV	14.9	67.5
Electron track (if electron)	yes	11.7	66.6
Muon stub (if muon)	yes	5.29	34.6
Electron cuts:			
E_T	≥ 4 GeV	2.15	27.3
E/p	≤ 2	1.45	25.8
Had/EM	≤ 0.055	0.79	24.5
Muon cuts			
p_T	≥ 4 GeV	0.30	17.9
$\|d_0\|$	≤ 0.2 cm	0.24	17.8
Hadronic Energy	≤ 6 GeV if $p_T \leq 100$ GeV, else $\leq (6 - 0.0280(p_T - 100))$ GeV	0.052	16.8

Table 3: Clean up cuts and their influence on data (using a 100k event MC sample)

3.3 Results

After all cuts are made, no events are seen. In particular, none of the candidate events pass the $\not\!\!E_T$ cut (see Table 4). Since no events are seen, limits can be placed on the available parameter space (a particular point in parameter space is excluded if the predicted number of events exceeds the number of events expected at the 95% confidence limit given that zero events are observed).

The limits set by CDF for Run I are:

$$\sigma_{\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0} \cdot \mathrm{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\pm} \to 3l + X) < 0.34 \text{ pb}$$
$$m_{\tilde{\chi}_1^{\pm}} > 81.5 \text{ GeV}$$
$$m_{\tilde{\chi}_2^0} > 82.2 \text{ GeV}$$

A detailed breakdown of the number of events that pass each cut is shown in Table 3.3 and a plot of $\sigma{\cdot}\mathrm{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3l + X)$ vs. $\tilde{\chi}_1^{\pm}$ mass with the limits set by the search is shown in Figure 2.

Cut	Events	Expected BG	Expected MSSM (MC)
Dilepton data set	3,270,448		
Trilepton data set	59		
Isolation	23		
Require e^+e^- or $\mu^+\mu^-$	23		
$\Delta R > 2$ GeV	9		
$\Delta\phi_{l_1,l_2} < 170°$	8	9.6 ± 1.5	6.2 ± 0.6
$J/\psi, \Upsilon, Z^0$ window removal	6	6.6 ± 1.1	5.5 ± 0.5
$\not{E}_T > 15$ GeV	0	1.0 ± 0.2	4.5 ± 0.4
Run I Total	0	1.2 ± 0.2	5.5 ± 0.4

Table 4: Summary of chargino/neutralino to trilepton findings in Run I of CDF

4 The Top Dilepton Sample

In Winter 2003, analysis on the first ~ 100 pb^{-1} of data was completed for CDF. A prominent channel for top quark production is the dilepton channel, where $t\bar{t} \to WbWb \to l\nu_l l\nu_l bb$. It became apparent that the p_T distribution for leptons in the top dilepton sample was softer than would be expected for mostly $t\bar{t}$ decay (see Figure 3). While this certainly could be due to statistical fluctuations, it is also an exciting possibility for observing non-SM physics. Certainly, within a MSSM framework, such a signature is a possibility.

4.1 Cuts and Data Sample

The basic cuts used in the top dilepton sample are:

- At least one tight, $p_T > 20$ GeV lepton with an associated track, and a central EM object with $p_T > 20$ GeV (or two such leptons with associated tracks) with $|\eta| < 1.0$ with at least one lepton isolated.
- At least two jects with $E_T > 10$ GeV and $|\eta| < 2.0$
- $\not{E}_T > 25$ GeV

Figure 2: $\sigma \cdot \mathrm{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3l + X)$ vs. $\tilde{\chi}_1^{\pm}$ mass for various points in SUSY parameter space. For all points, $\mu = -400$ GeV and $\tan\beta = 2$ while $m_{\tilde{q}}/m_{\tilde{g}} = 2.0$ for(a), 1.5 for (b), 1.2 for (c), and 1.0 for (d). The solid line represents the 95% CL upper limit based on observation of zero events in all channels at CDF. The dashed line is for single a single trilepton mode limit set by D0.

Figure 3: p_T distribution for leptons in the top dilepton sample of CDF

These cuts yielded a total of 10 candidate, opposite-sign, dilepton events (2 ee, 3 $\mu\mu$ and 5 $e\mu$). We will look at two scenarios that would contribute to creating a soft p_T distribution as seen in this data set. There are two SUSY scenarios which we will consider that could lead to such a soft lepton p_T distribution [7]

4.2 Chargino and Neutralino decay to dileptons

Assuming a specific SUSY model of (M_1, M_2, M_3, μ, $\tan\beta$, $m_{\tilde{l}_R}$, $m_{\tilde{l}_L}$, $m_{\tilde{q}}$) = (70 GeV, 145 GeV, 300 GeV, 500 GeV, 10, 110 GeV, 300 GeV, 800 GeV) and assuming the following mass relation:

$$m_{\tilde{q}}, m_{\tilde{g}}, m_{\tilde{l}_L} > m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm} > m_{\tilde{l}_R} > m_{\tilde{\chi}_1^0} \tag{5}$$

we find that $m_{\tilde{\chi}_1^0} = 67$ GeV, $m_{\tilde{\chi}_2^0} = 139$ GeV and $m_{\tilde{\chi}_1^\pm} = 138$ GeV.

The dominant decay mode of $\tilde{\chi}_2^0$ is $\tilde{\chi}_2^0 \rightarrow l\tilde{l}_R^* \rightarrow l\tilde{l}\tilde{\chi}_1^0$ and for $\tilde{\chi}_1^+$ is $\tilde{\chi}_1^+ \rightarrow W^{+*}\tilde{\chi}_1^0 \rightarrow l^+\nu\tilde{\chi}_1^0$ or $q\overline{q}'\tilde{\chi}_1^0$. Thus, production of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ can result a signature nearly identical to that of $t\bar{t}$ decaying in the dilepton mode.

Using the above described model, a `PYTHIA` simulation reveals a production cross-section of $\sigma_{p\overline{p}\rightarrow\tilde{\chi}_2^0\tilde{\chi}_1^\pm} = 303$fb. Gluino pair production will also contribute to this process with a cross-section of $\sigma_{p\overline{p}\rightarrow\tilde{g}\tilde{g}} = 273$fb. The branching ratio of $\tilde{g} \rightarrow \tilde{\chi}_2^0 q\overline{q}$ is 27% and $\tilde{g} \rightarrow \tilde{\chi}_1^\pm q\overline{q}'$ is 45%. In such decays, 66% of the leptons produced will have $p_T < 40$GeV.

4.3 Light $\tilde{t}$ Revisited

Another scenario which could result in the soft p_T distribution is that of a light stop decaying. Assuming the mass relation of:

$$m_{\tilde{g}} > m_{\tilde{l}_R}, m_{\tilde{t}_1} > m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{l}_L} > m_{\tilde{\nu}} \quad (6)$$

The gluino will decay to a top and stop quark 100% of the time. In this case, analogously to a top quark decaying, the stop will decay to a chargino and a b-quark. The decay chain of the stop will end in a lepton and $\not{E}_T$. If the $\tilde{t}_1$ is light, then it can be pair-produced, resulting in this decay chain:

$$p\overline{p} \to \tilde{t}_1\tilde{t}_1 \to \tilde{\chi}_1^+ b\tilde{\chi}_1^- \overline{b} \to l^+\tilde{\nu}bl^-\tilde{\nu}\overline{b} \to l^+\nu\tilde{\chi}_1^0 bl^-\overline{\nu}\tilde{\chi}_1^0\overline{b} \quad (7)$$

Thus, the final signature is the same as that of top pair production via the dilepton channel. Again, using a specific parameter space of: (M_1, M_2, μ, $\tan\beta$, $m_{\tilde{t}_R}$, $m_{\tilde{q}}$, A_t) = (90 GeV, 133 GeV, 500, 10, 140 GeV, 800 GeV, 800) . This case gives us a superpartner mass spectrum of: ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{g}$, $\tilde{\chi}_1^\pm$, $\tilde{e}_L$, $\tilde{\nu}$, $\tilde{t}_1$)= (88, 127, 325, 126, 124, 95, 147) GeV. Given these masses, the cross section for stop pair-production is 1.14 pb and that of gluino pair production is 0.14 pb. Again, using a `PYTHIA` simulation, 62% of the leptons produced have $p_T < 40$ GeV.

5 Conclusion

The dilepton channel continues to be an interesting place to look for experimental evidence of supersymmetry. Certainly some of the Run I measurements that were discussed can be improved upon in Run II. Also, it will be interesting to see whether the soft p_T distribution in the top dilepton sample for Run II will persist through the additional 100 pb_{-1} that has been collected since. Even if SUSY particles are not directly detected at the Tevatron, better limits can be placed such that discovery will be an easier task at the LHC.

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